CP Violation and Rare Decays in the Standard Model and Beyond

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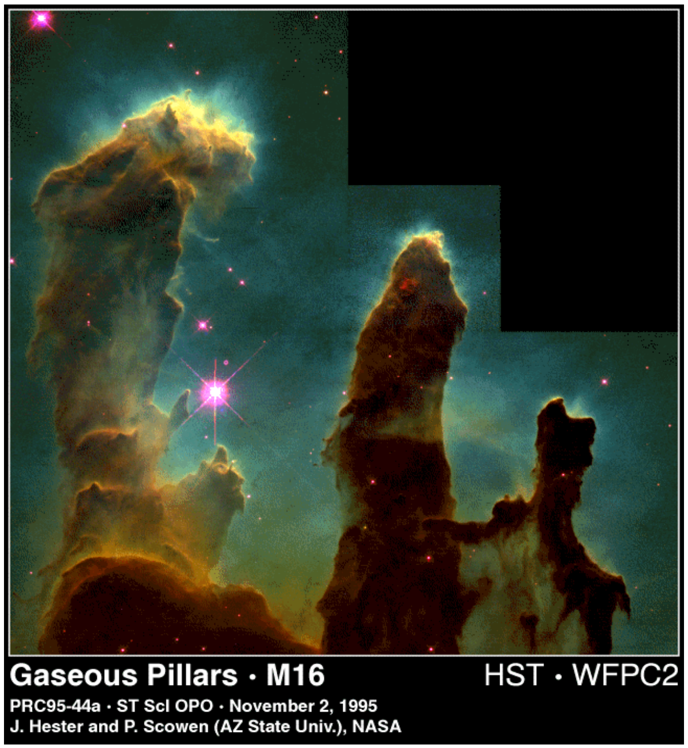
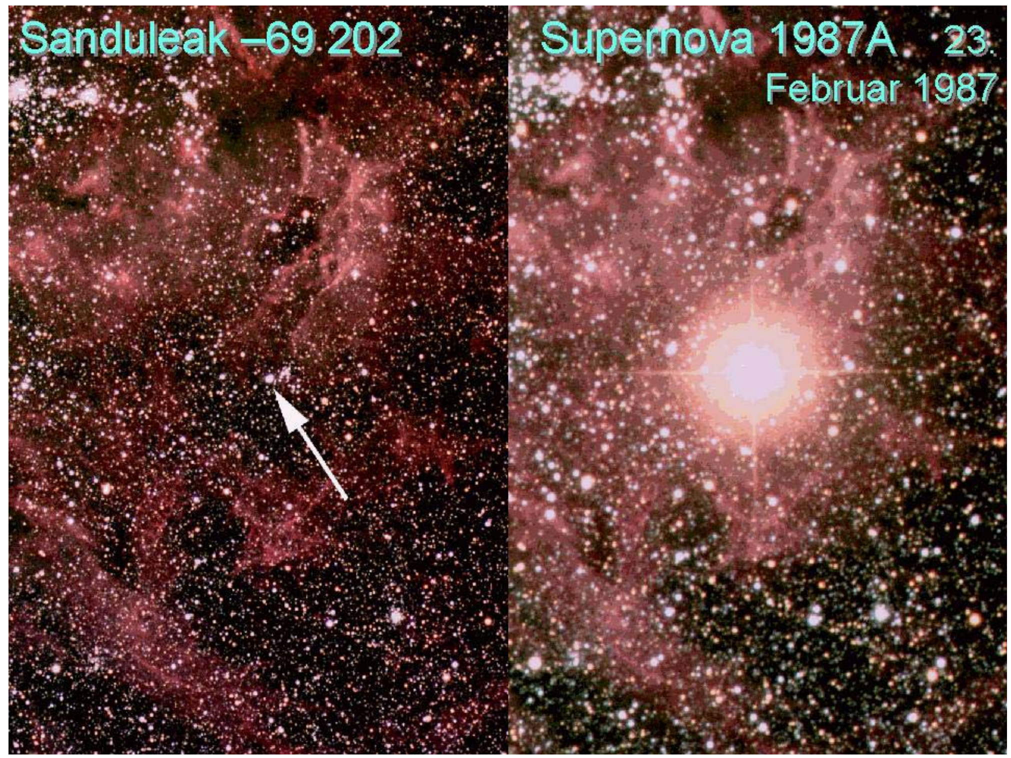
(Technical University Munich)

Rome, May 8th -11th

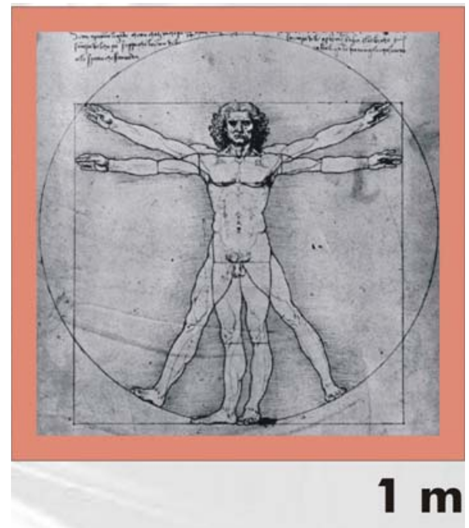
Buongiorno !

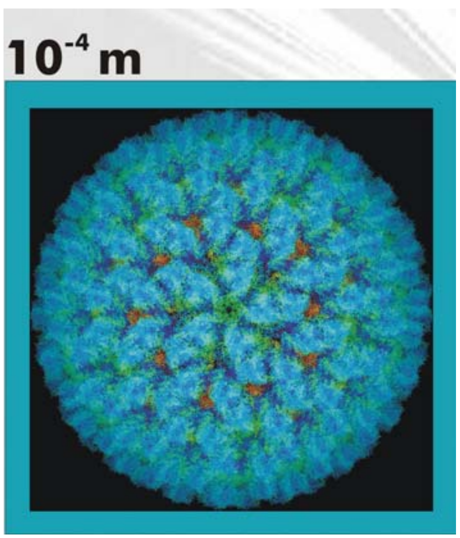
Overture 1

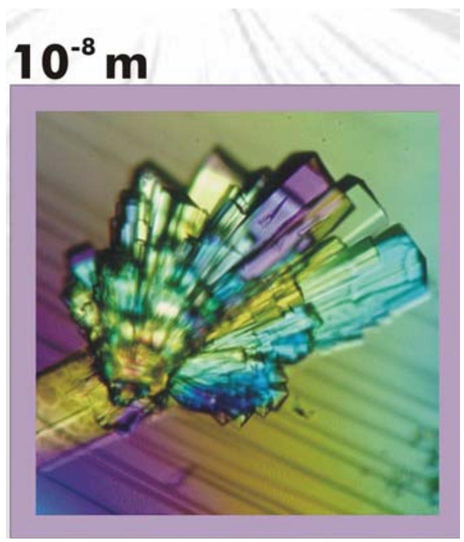

Gaseous Pillars · M16
HST · WFPC2
PRC95-44a · ST ScI OPO · November 2, 1995
J. Hester and P. Scowen (AZ State Univ.), NASA

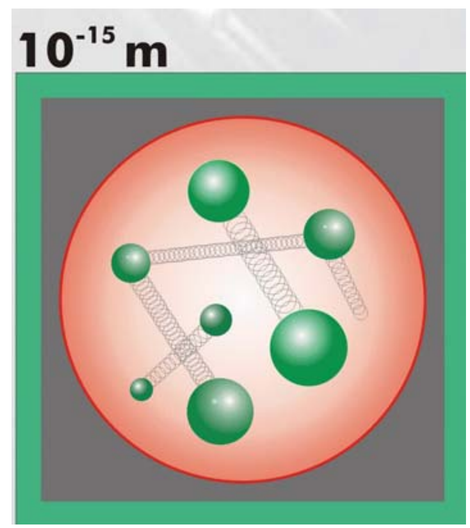

Sanduleak –69 202
Supernova 1987A
23. Februar 1987

Vastly Different Scales





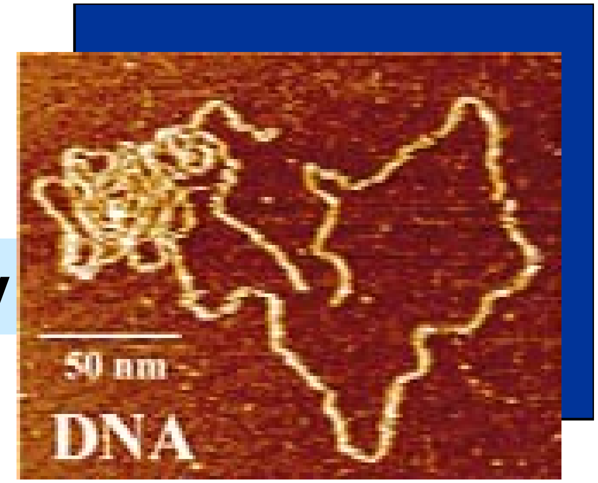




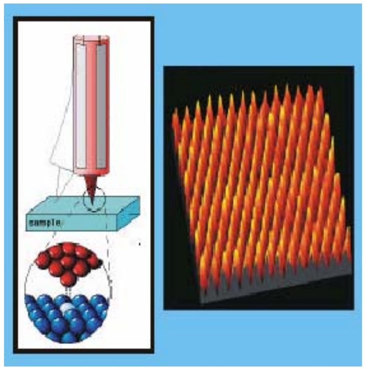
Quarks bound in the Proton

(Femtouniverse)

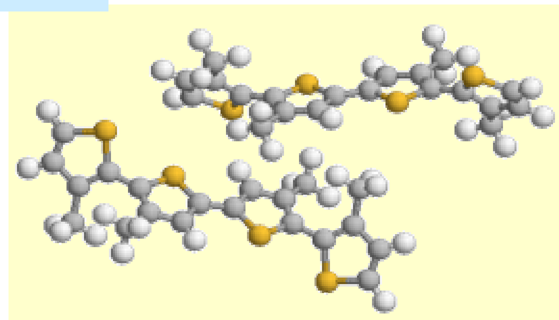
Nanotechnology



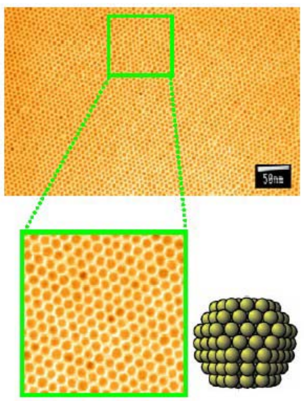
Physics

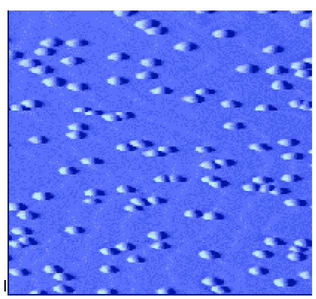


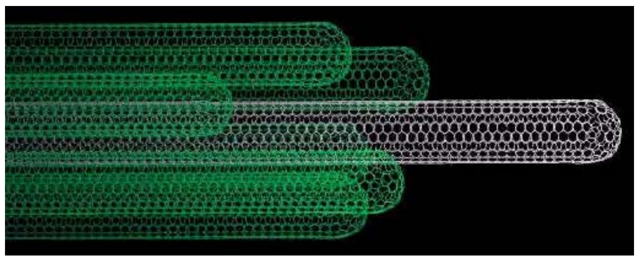
Chemistry



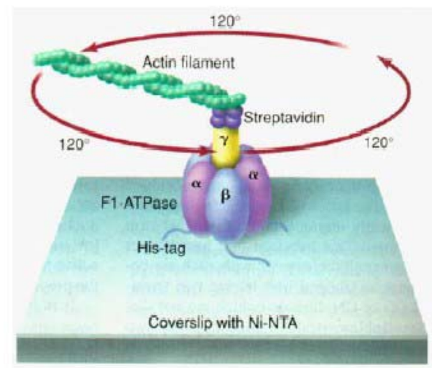
Materials



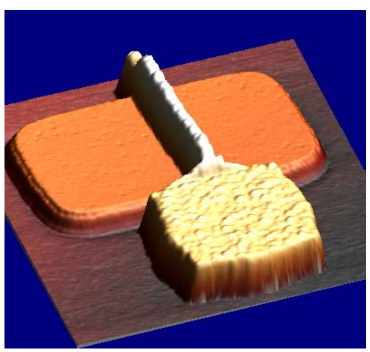


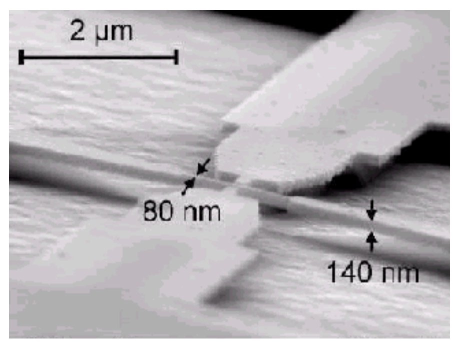


Biology

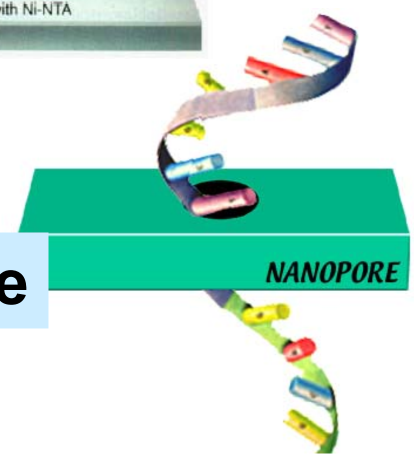


Technology





Medicine



Attouniverse

10^{-18}m

1000 times smaller than the Femtouniverse

10^{-15}m

1000000000 times smaller than the Nanouniverse

10^{-9}m

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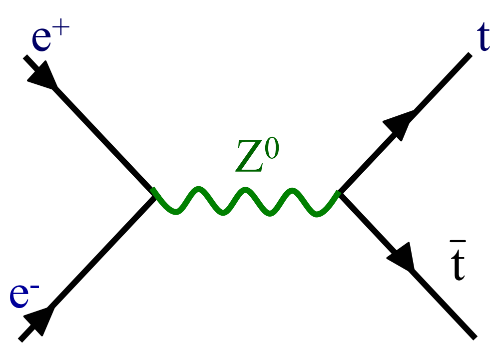
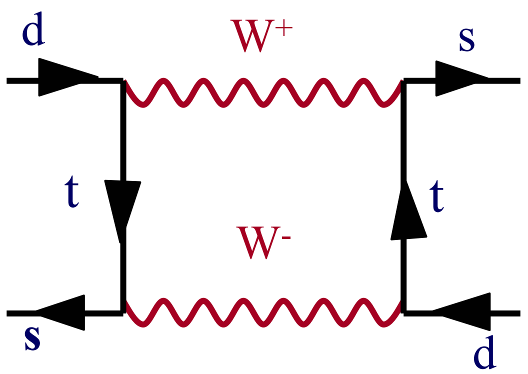




How to explore the Attouniverse ?

1. Directly :

Very high energy colliders:
CERN, SLAC, DESY, Fermilab, NLC, ...

2. Indirectly :

Use Femtouniverse and Quantum Effects
to study Attouniverse and smaller universes.

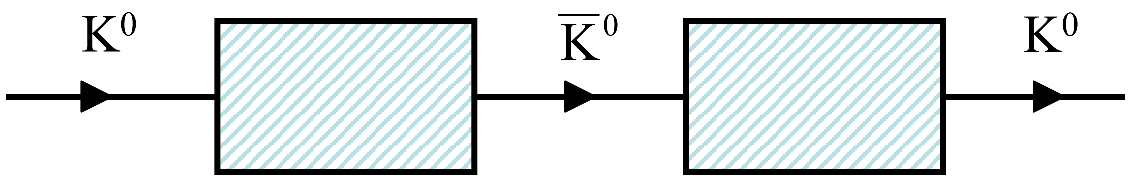
★

"Kaon-Factories" , "B-Meson Factories"

$K^0 - \overline{K}^0$ Mixing (Oscillations)

$K^0 = d\bar{s}$

$\overline{K}^0 = \bar{d}s$



(discovered in 1960)

$\Rightarrow$ K^0 and $\overline{K}^0$ are not Mass Eigenstates

Mass Eigenstates :

$$K_L = \frac{K^0 + \overline{K}^0}{\sqrt{2}} \qquad K_S = \frac{K^0 - \overline{K}^0}{\sqrt{2}}$$

(L = Long) (S = Short)

$$M(K_L) \cong M(K_S) = 0.5 \text{ GeV}$$

★ $M(K_L) - M(K_S) = 3.5 \cdot 10^{-15} \text{GeV}$

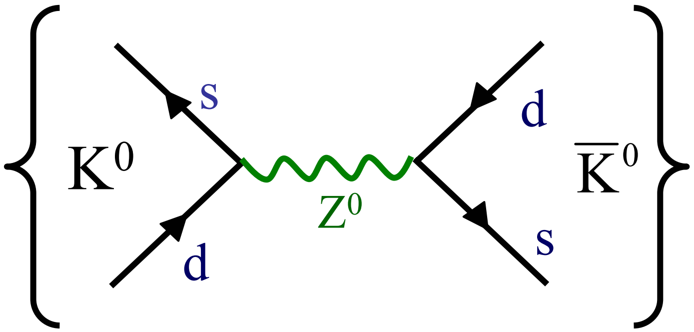
$\equiv \Delta M_K$

$$\frac{\tau(K_L)}{\tau(K_S)} \cong 600$$ ★

$M \equiv$ mass

$\tau \equiv$ Life Time

Could ordinary Weak Interactions explain ΔM_K ?



$$\Delta M_K = \left[2\cdot 10^{-2}\,\mathrm{GeV}^3\right] G_F \left[\frac{M_W^2}{M_Z^2}\right]$$

$$G_F \cong 1.1\cdot 10^{-5}\,\mathrm{GeV}^{-2}$$

$$M_Z \cong 91\ \mathrm{GeV}$$

$$\Delta M_K \cong 2\cdot 10^{-7}\,\mathrm{GeV}$$

Disaster !!!
Missed by
8 orders of
magnitude !!!

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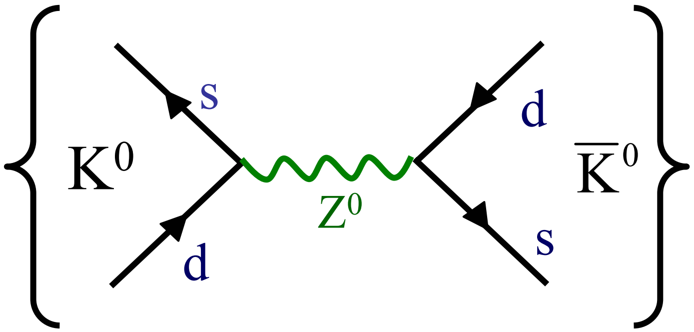

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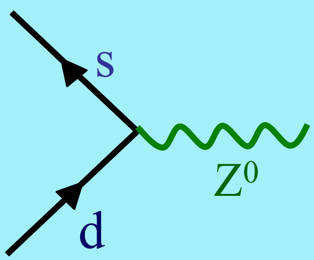

$= 0$

GIM Mechanism

(1971)

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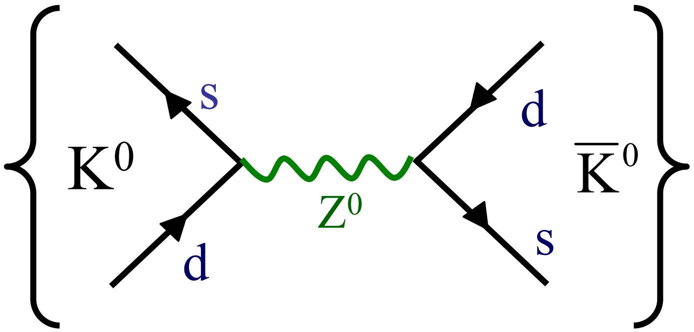

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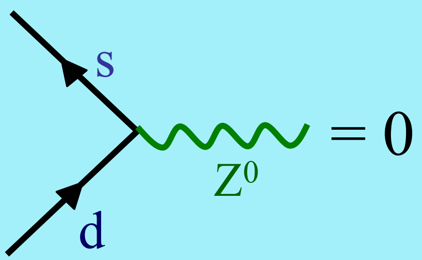

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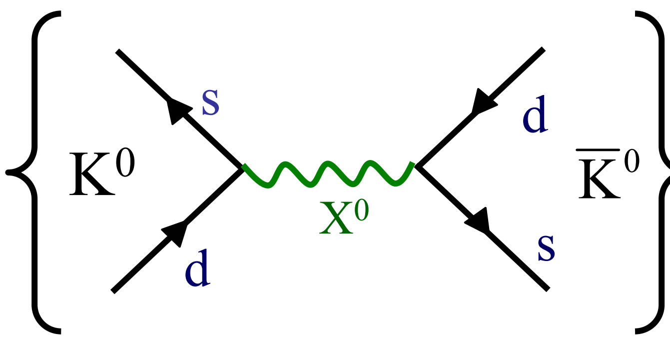


$$\left\{ \Delta M_K \cong 2\cdot 10^{-7}\left[\frac{M_Z^2}{M_X^2}\right]\mathrm{GeV} = 3.5\cdot 10^{-15}\,\mathrm{GeV} \right\}$$

$$\left\{ M_X \cong 10^6\,\mathrm{GeV} \right\}$$

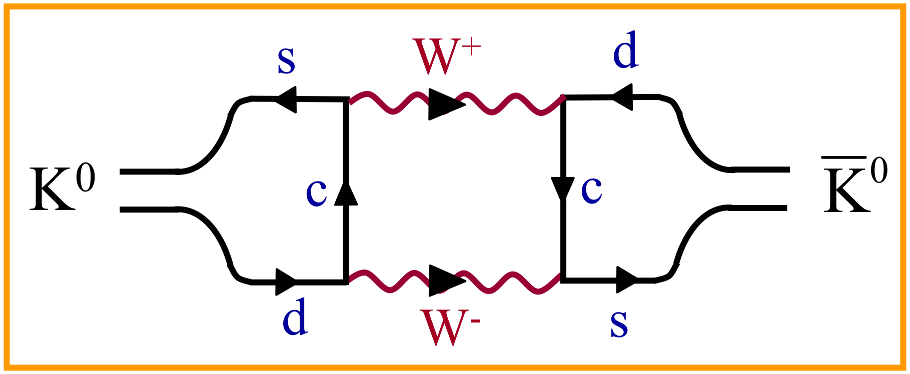
Testing
10^{-22}m !

New very heavy neutral boson !

ΔM_K in the Standard Model

Gaillard-Lee (March 1974)

$\lambda \cong 0.22$



$$\left\{ \begin{array}{l} \Delta M_K = \left[1.4\ \mathrm{GeV}^5\right] G_F^2 \lambda^2 \left[\dfrac{m_c^2}{M_W^2}\right] \\ G_F \cong 1.2 \cdot 10^{-5}\,\mathrm{GeV}^{-2} \end{array} \right\}$$

$$\Delta M_K = 10^{-11}\,\mathrm{GeV}\left[\frac{m_c^2}{M_W^2}\right] = 3.5 \cdot 10^{-15}\,\mathrm{GeV}$$

$$m_c = \sqrt{3.5} \cdot 10^{-2} M_W = 1.5\ \mathrm{GeV}$$

(Prediction !!)

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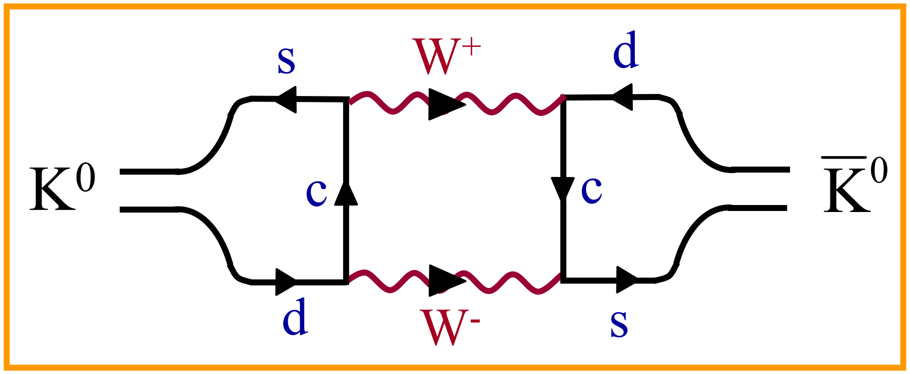

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(Prediction !!)

November Revolution
1974
Discovery of $\bar{c}c$ State
(SLAC, Brookhaven)

$$M_{\bar{c}c} \cong 3.1\ \mathrm{GeV}$$

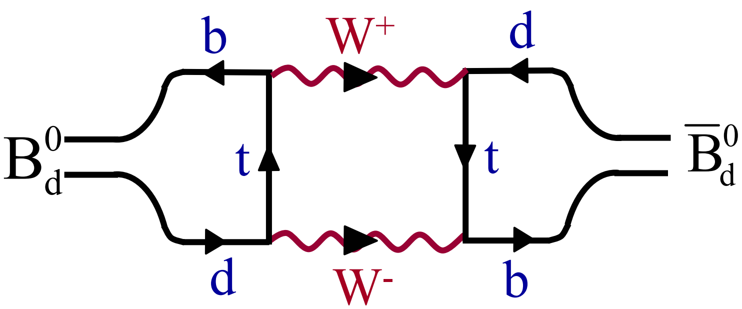
$$m_c \cong 1.5\ \mathrm{GeV} \quad !!$$

Prediction confirmed !

Similar Studies: 1974-1994

$B_d^0 - \overline{B}_d^0$ Oscillations

DESY 87

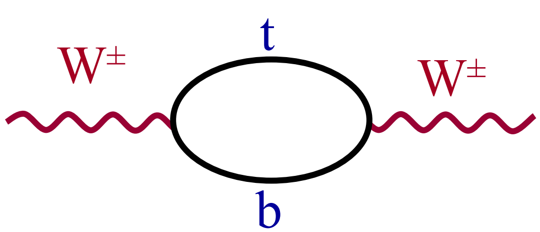


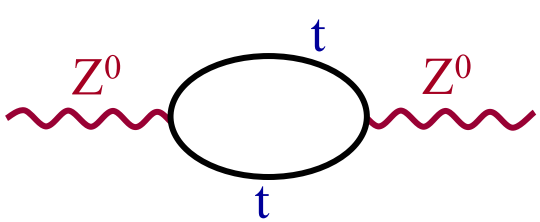
$+ \quad \Delta M_{B_d} \cong 4 \cdot 10^{-13}\,\mathrm{GeV}$ ⇒

(Prediction)

$m_t \approx 150\ \mathrm{GeV}$
± 30

Electroweak Precision Studies





CERN, SLAC (1989-1994)

⇒

$m_t \approx 150\ \mathrm{GeV}$
± 20

(Prediction)

1994
Discovery of the Top Quark (Fermilab)

$m_t = 172.7 \pm 2.9\ \mathrm{GeV}$

First Lessons

1. Very rare processes allow to probe very short distance scales.

2. Before claiming New Physics it is essential to make precise calculations (higher order corrections).

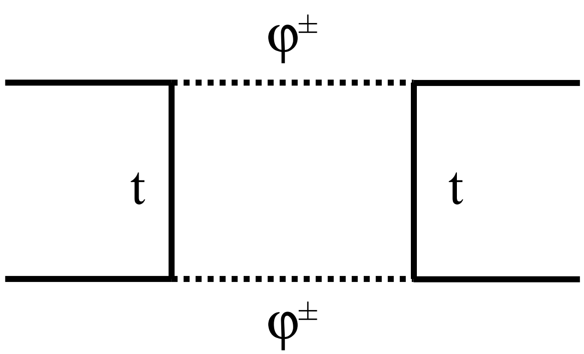
3. Low Energy Processes can give information about heavy particles prior to their discovery.

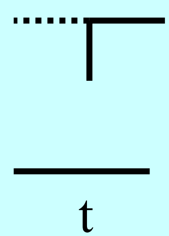
Non-Decoupling of the Top Quark from Low Energy Processes

In QCD and QED very heavy particles ($m_H \to \infty$) do not influence low energy processes: Appelquist-Carazzone Decoupling Theorem

In the $SU(2)_L \otimes U(1)_Y$ the decoupling can be violated by couplings of heavy particles that increase with the heavy particle mass.

Goldstone-Boson



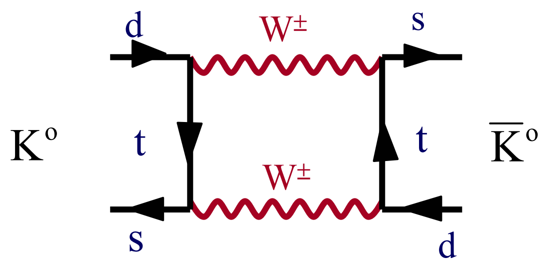


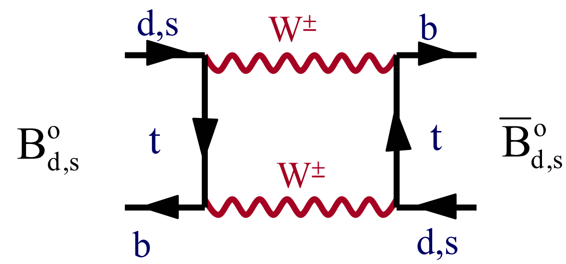
$\sim m_t$

$\sim \dfrac{1}{m_t}$

$$m_t^4 \cdot \frac{1}{m_t^2} = m_t^2$$

View at Short Distance Scales

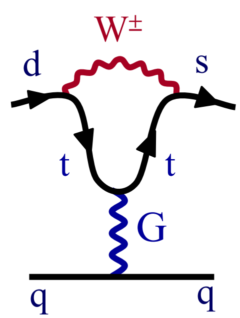


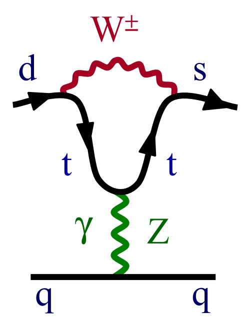


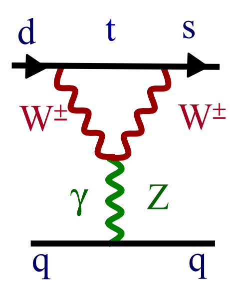
~~C~~P ε_K-Parameter
ΔM (K_L-K_S)

$B^o_d - \overline{B}^o_d$ Mixing

ε'

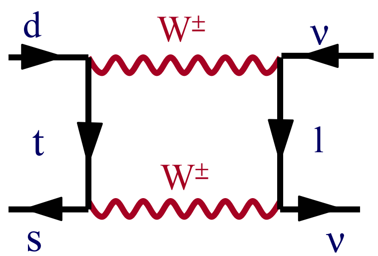


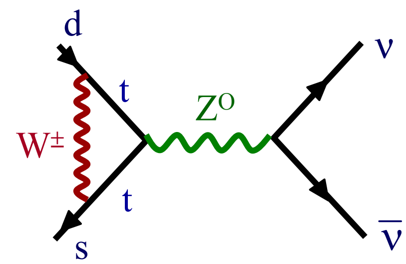


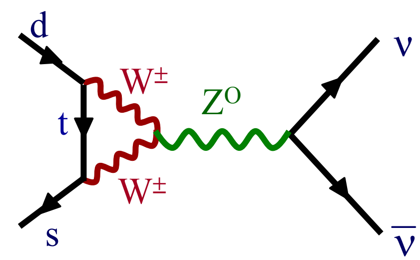


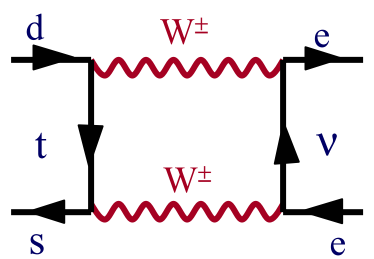
View at Short Distance Scales

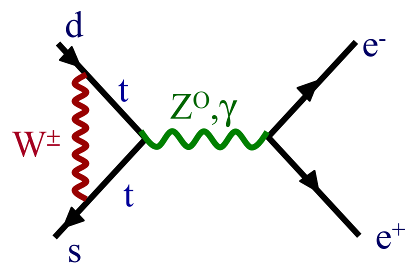
$\boxed{K^+ \to \pi^+ \nu\bar{\nu},}$ $K_L \to \pi^0 \nu\bar{\nu}$ $\boxed{K_L \to \mu\bar{\mu}\,,}$ $B \to \mu\bar{\mu}$, $B \to X_S \nu\bar{\nu}$

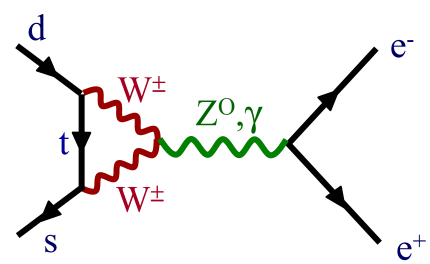




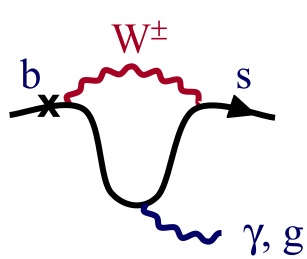








$K_L \to \pi^0 e^+ e^-$ $\boxed{B \to X_s e^+ e^-,\ X_s \mu\bar{\mu}}$



$\boxed{B \to X_s \gamma \qquad B \to K^* \gamma}$

$B \to X_d \gamma$ $b \to s$ gluon

Goals for these Lectures

1. Develop Formalism for Rare Processes:
   CP-Violating Transitions, CP-Asymmetries and
   Rare Decays within Gauge Theories
2. Apply this Formalism to the Standard Model and its simplest Extensions
3. Develop a systematic Procedure for Probing New Physics with these Processes
4. Identify most interesting Problems and Questions

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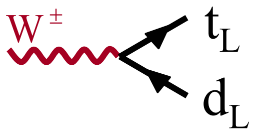
3. Develop a systematic Procedure for Probing New Physics with these Processes
4. Identify most interesting Problems and Questions
5. Make these Lectures enjoyable to Students as much as possible

Overture 2

Four Basic Properties in the SM

1. **Charged Current Interactions only between left-handed Quarks**



$$\frac{g_2}{2\sqrt{2}}\gamma_\mu(1-\gamma_5)\cdot V_{td}$$

2. **Quark Mixing**

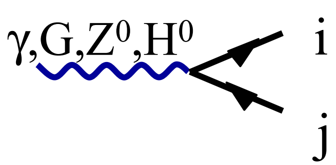
{ Weak Eigenstates } ≠ {Mass Eigenstates }

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{ub} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

(Weak Eigenstates) (Unitarity CKM-Matrix) (Mass Eigenstates)

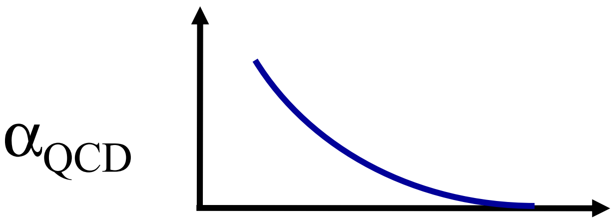
3. **GIM Mechanism**

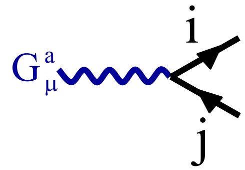
Natural suppression of FCNC

{ 

$= 0$ } ⇒ {Loop Induced Decays, sensitive to short distance flavour dynamics}

4. Asymptotic Freedom





$$g_{QCD} T^a_{ij} \gamma_\mu$$

Q

$$\alpha_{QCD} = \frac{g^2_{QCD}}{4\pi}$$

LD ⇦ RG ⇨ SD

$$\alpha_{QCD}(Q) = \frac{4\pi}{\beta_0 \ln\left(Q^2/\Lambda^2_{\overline{MS}}\right)}\left[1 - \frac{\beta_1}{\beta_0^2}\frac{\ln\ln\left(Q^2/\Lambda^2_{\overline{MS}}\right)}{\ln\left(Q^2/\Lambda^2_{\overline{MS}}\right)} + \ldots\right]$$

$$\Lambda^{(5)}_{\overline{MS}} = 235 \pm 30\ \text{MeV} \qquad \alpha^{(5)}_{\overline{MS}}(M_Z) = 0.1187 \pm 0.0020$$

SD = Short Distances (Perturbation Theory)

⇧

RG = Renormalization Group Effects

⇩

LD = Long Distances (Non-Perturbative Physics)

Kobayashi-Maskawa Picture of CP Violation

CP Violation arises from a single phase δ in $W^{\pm}$ interactions of Quarks

ud: $c_{12}c_{13}$	us: $s_{12}c_{13}$	ub: $s_{13}e^{-i\delta}$
cd: $-s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta}$	cs: $c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta}$	cb: $s_{23}c_{13}$
td: $s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta}$	ts: $-s_{23}c_{12}-s_{12}s_{23}s_{13}e^{i\delta}$	tb: $c_{23}c_{13}$

Four Parameters: $(\theta_{12} \approx \theta_{cabibbo})$

$s_{12} = |V_{us}|, \quad s_{13} = |V_{ub}|, \quad s_{23} = |V_{cb}|, \quad \delta$

$c_{ij} \equiv \cos\theta_{ij}\ ;\ s_{ij} \equiv \sin\theta_{ij}\ ;\ c_{13} \cong c_{23} \cong 1$

Wolfenstein Parametrization

Parameters: λ, A, ρ, η

	d	s	b
u	$1-\frac{\lambda^2}{2}$	λ	V_{ub}
c	$-\lambda$	$1-\frac{\lambda^2}{2}$	V_{cb}
t	V_{td}	V_{ts}	1

$\lambda=0.22$

$V_{us}=\lambda+0(\lambda^7)$

$V_{cb}=A\lambda^2+0(\lambda^8)$

$V_{ts}=-A\lambda^2+0(\lambda^4)$

$(A=0.83\pm0.02)$

$$V_{ub} \equiv A\lambda^3(\rho - i\eta) \qquad V_{td} = A\lambda^3(1-\bar{\rho}-i\bar{\eta})$$

$$\bar{\rho} = \rho\left(1-\frac{\lambda^2}{2}\right) \qquad \bar{\eta} = \eta\left(1-\frac{\lambda^2}{2}\right)$$

(AJB, Lautenbacher, Ostermaier, 94)

$$R_b \equiv \sqrt{\bar{\rho}^2+\bar{\eta}^2} = \left(1-\frac{\lambda^2}{2}\right)\frac{1}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right|$$

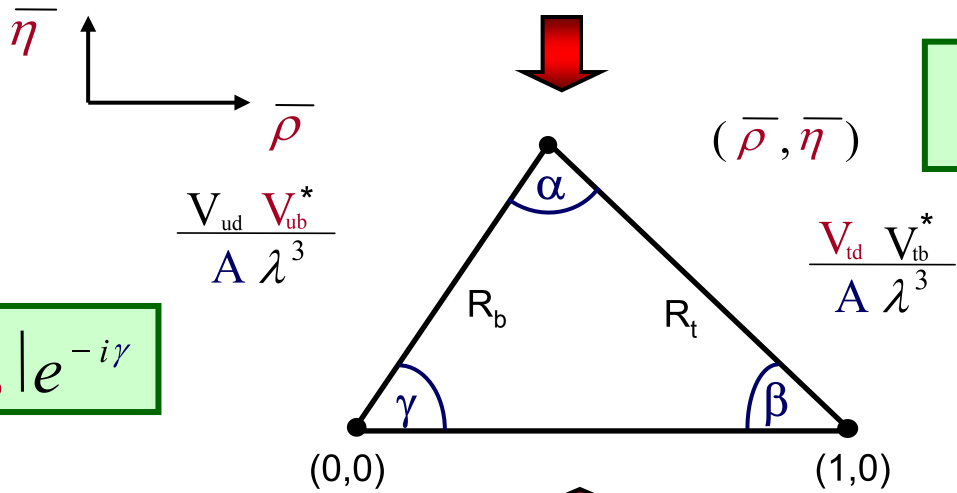
Circle around $(\bar{\rho},\bar{\eta})=(0,0)$

$$R_t \equiv \sqrt{(1-\bar{\rho})^2+\bar{\eta}^2} = \frac{1}{\lambda}\left|\frac{V_{td}}{V_{cb}}\right|$$

Circle around $(\bar{\rho},\bar{\eta})=(1,0)$

Unitarity Triangle

$$V_{ud}\,V_{ub}^{*} + V_{cd}\,V_{cb}^{*} + V_{td}\,V_{tb}^{*} = 0$$



$$\frac{V_{ud}\,V_{ub}^{*}}{A\,\lambda^{3}}$$

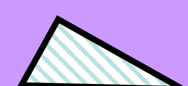
$$\frac{V_{td}\,V_{tb}^{*}}{A\,\lambda^{3}}$$

$\bar{\eta} \neq 0$ Signals CP Violation

$$V_{ub} = |V_{ub}|\,e^{-i\gamma}$$

$$V_{td} = |V_{td}|\,e^{-i\beta}$$

An Important Target of Particle Physics

$$J_{CP} = \lambda^{2}\,|V_{cb}|^{2}\,\bar{\eta} = 2 \cdot$$ 

Area of unrescaled UT

Particular Definition of λ, A, ρ, η

$$s_{12} \equiv \lambda$$
$$s_{23} \equiv A\,\lambda^2$$
$$s_{13}e^{i\delta} \equiv A\,\lambda^3(\rho - i\eta)$$

BLO: Phys.Rev. (94); (Schmidtler, Schubert)

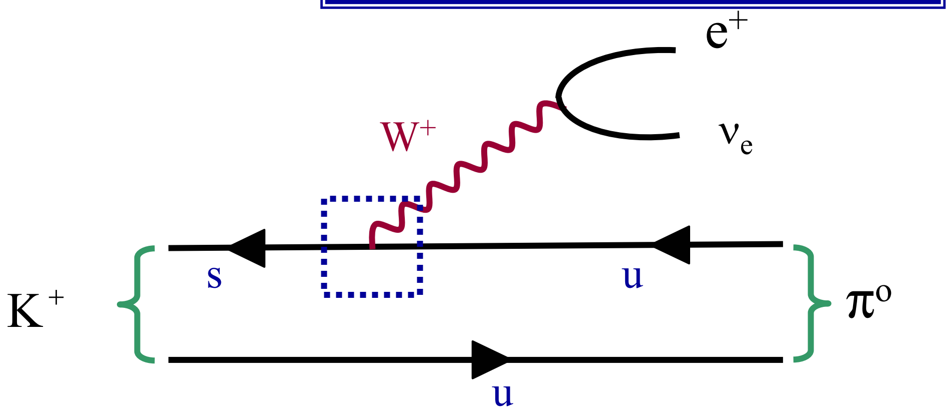
At $0(\lambda^5)$ equivalent to (Branco, Lavoura, 88)

Basic Virtues of this Definition:

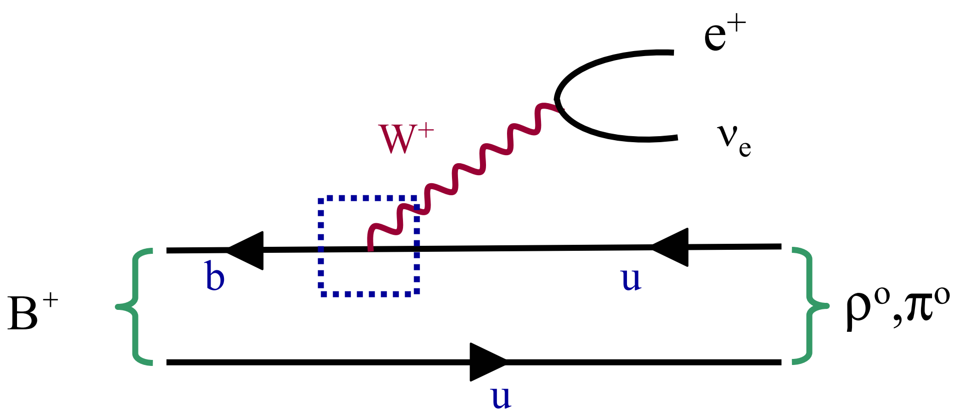
$$V_{us} = \lambda + 0\left(\lambda^7\right)$$
$$V_{ub} = A\lambda^3(\rho - i\eta)$$
$$V_{cb} = A\lambda^2 + 0\left(\lambda^8\right)$$
$$V_{td} = A\lambda^3(1 - \bar{\rho} - i\bar{\eta})$$

The apex of UT given by $(\bar{\rho}, \bar{\eta})$ (BLO)

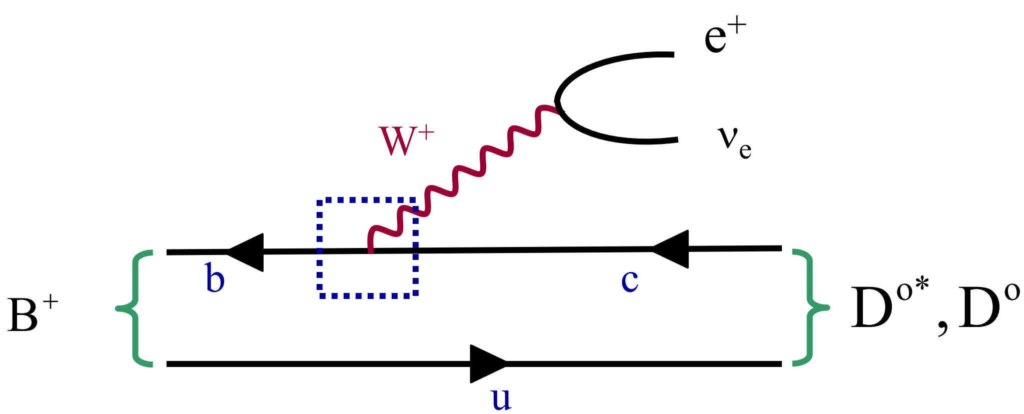
Tree Level Decays



V_{us}



V_{ub}



V_{cb}

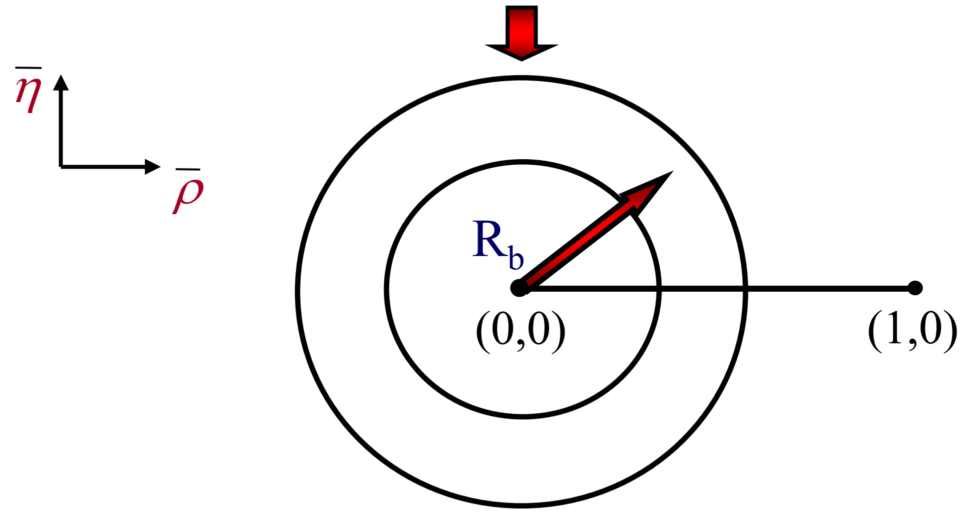
Information from Tree Level Decays

$$|V_{us}| = 0.225 \pm 0.002 \qquad = \lambda$$

$$|V_{cb}| = (41.5 \pm 0.8)\cdot 10^{-3} \qquad (A = 0.83 \pm 0.02)$$

2004: $$\left|\frac{V_{ub}}{V_{cb}}\right| = (0.092 \pm 0.012) \qquad (R_b = 0.40 \pm 0.06)$$

2005: $$(0.102 \pm 0.005) \qquad (0.44 \pm 0.02)$$



Unitarity Clock

Apex of Unitarity Triangle somewhere on this Band

To find it **GO TO**

Loop Induced Decays

CP-Violation in K-Decays

CP-Violation in B-Decays

$$F_1^{th}(\lambda, A, \overline{\eta}, \overline{\rho}) = F_1^{exp}$$

$$F_2^{th}(\lambda, A, \overline{\eta}, \overline{\rho}) = F_2^{exp}$$

$$F_3^{th}(\lambda, A, \overline{\eta}, \overline{\rho}) = F_3^{exp}$$

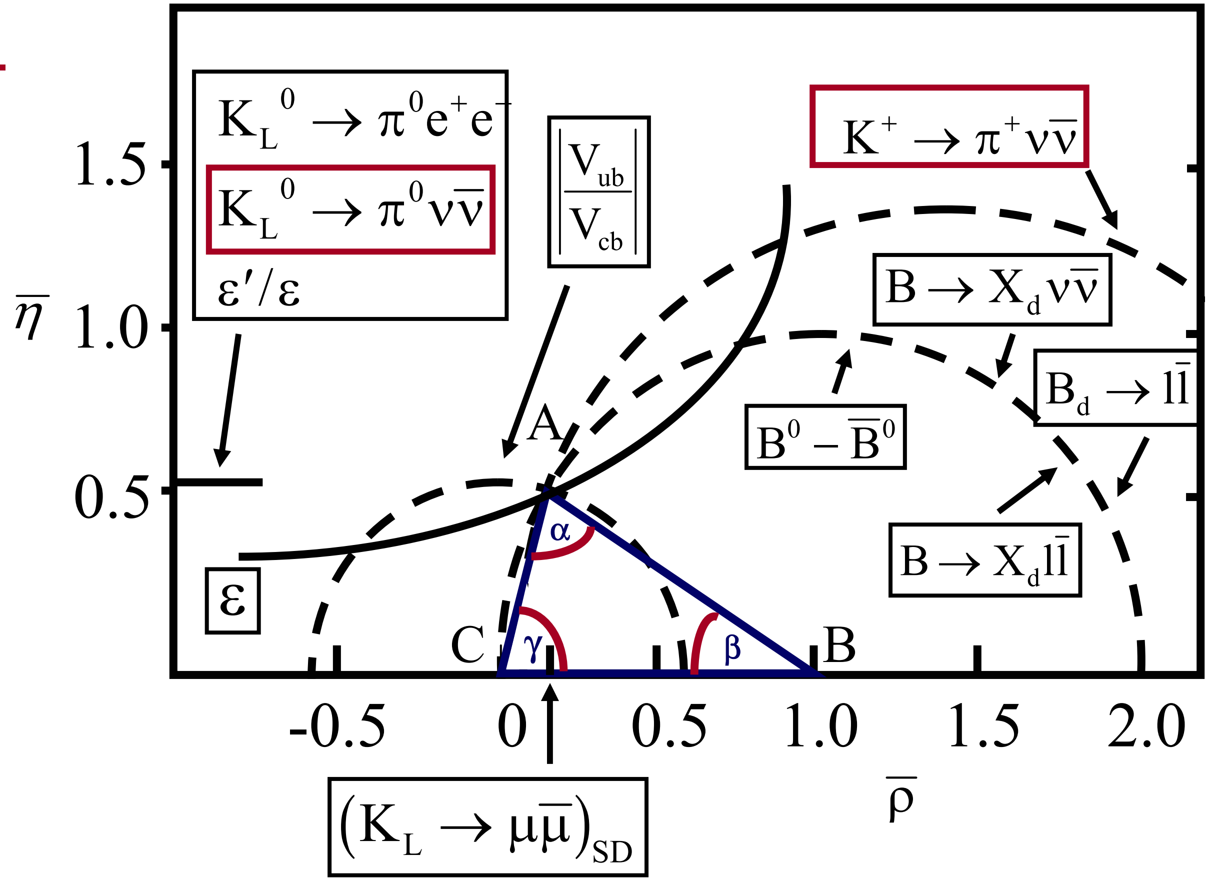
etc.

$\Downarrow$

Determination of the Unitarity Triangle

Hunting Δ with Rare and ~~CP~~ Decays

2012:



★ **Quark Mixing and CP Violation closely related in the St. Model**

★ $\left\{ \begin{array}{l} \text{CP Asymmetries} \\ \text{in} \\ \text{B – Decays} \end{array} \right\} \Rightarrow \left\{ \begin{array}{c} \alpha \\ \beta \\ \gamma \end{array} \right\}$

Lecture I

1. TH Framework
2. Various Types of ~~CP~~

Lecture II

3. Standard Analysis of Δ
4. α, β, γ from B´s
5. $K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \nu\bar{\nu}$

Lecture III

6. Rare B- and K-Decays
7. Models with MFV

Lecture IV

8. Going Beyond MFV
9. Little Higgs Models with T Parity
10. Outlook

Literature

<u>Buchalla, AJB, Lautenbacher</u>

Rev. Mod. Phys. 68 (1996) 1125

<u>AJB, Fleischer</u>

in Heavy Flavours II (World Scientific) (1998) (hep-ph / 9704376)

<u>AJB</u>

★ Les Houches Lectures (1997) (hep-ph / 9806471)
Erice Lectures (2000) (hep-ph / 0101336)
★ Spain Lectures (2004) (hep-ph / 0505175)

<u>Y. Nir</u>

Scottish Universities Summer School (hep-ph / 0109090)

<u>The BABAR Physics Book</u>

<u>B-Physics at the LHC</u> (hep-ph / 0003238)

<u>Books</u>: Branco, Lavoura, Silva;
Bigi, Sanda

<u>B Physics at the Tevatron</u> (Run II and Beyond) (hep-ph/0201071)

<u>Fleischer:</u>

Physics Reports (hep-ph/0207108)

1.

Theoretical Framework

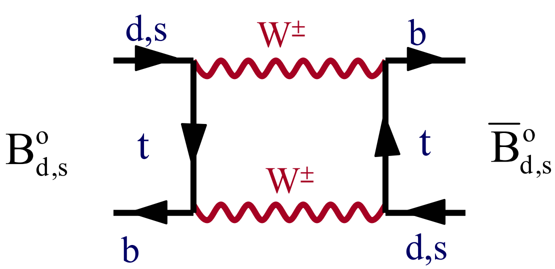
Starting Point :

$$\mathcal{L} = \mathcal{L}_{SM}\left(g_i, m_i, V^i_{CKM}\right) + \mathcal{L}_{NP}\left(g^{NP}_i, m^{NP}_i, V^i_{NP}\right)$$

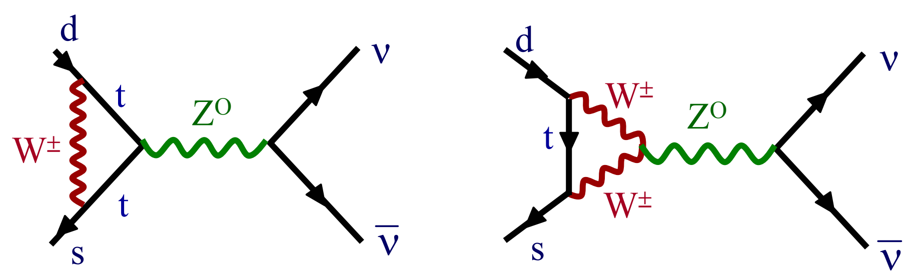
Goal :

Identify the effects of $\mathcal{L}_{NP}$ in weak decays in the presence of the background from $\mathcal{L}_{SM}$

First Implication from $\mathcal{L}$: Feynman Diagrams



$B^o_d - \overline{B}^o_d$ Mixing



$K^+ \to \pi^+ \nu\bar{\nu}, \;\; K_L \to \pi^0 \nu\bar{\nu}$

+ NP

Two challenges :

1. Theory formulated in terms of quarks but experiments involve their bound states (K, B, D)

2. NP takes place at very short distance scales (10^{-19}-10^{-18}m), while K, B, D live at 10^{-16}-10^{-15}m.

Two challenges :

1. Theory formulated in terms of quarks but experiments involve their bound states (K, B, D)

2. NP takes place at very short distance scales (10^{-19}-10^{-18}m), while K, B, D live at 10^{-16}-10^{-15}m.

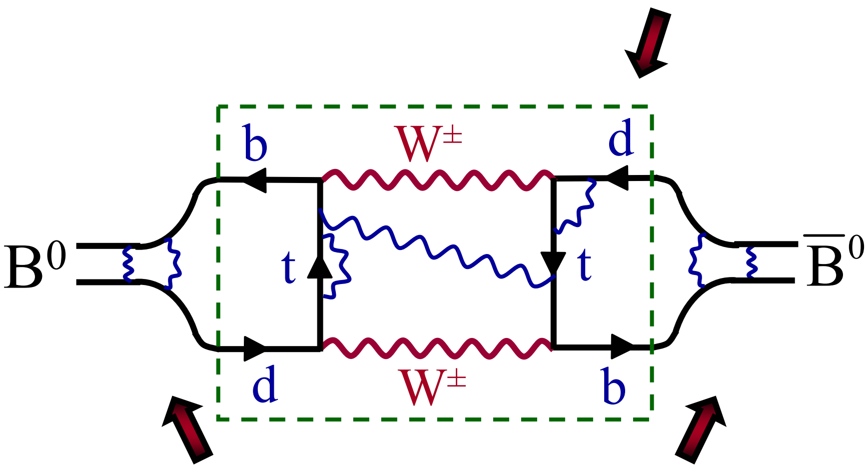
Solution : Effective Theories, OPE, Renormalization Group

$\Rightarrow$ Separation of SD from LD
+ Summation of large $\log(\mu_{SD} / \mu_{LD})$

The Problem of Strong Interactions

$B_d^0 - \overline{B}_d^0$ Mixing (SM)

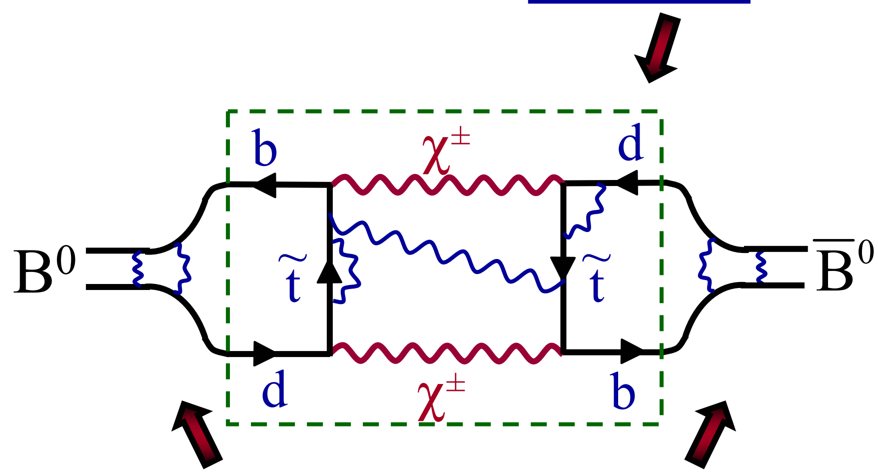
Short Distance



Long Distance

$B_d^0 - \overline{B}_d^0$ Mixing (MSSM)

Short Distance



Long Distance

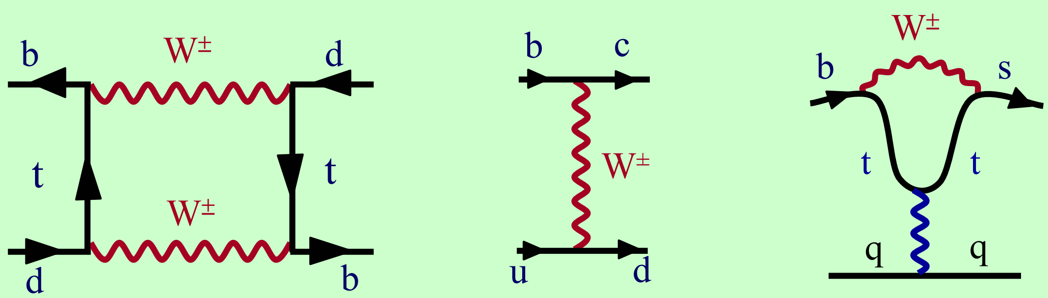
SD : <u>Perturbative</u>
(Asymptotic Freedom)

LD : <u>Non-Perturbative</u>
(Confinement)

Effective Field Theory

Full Theory

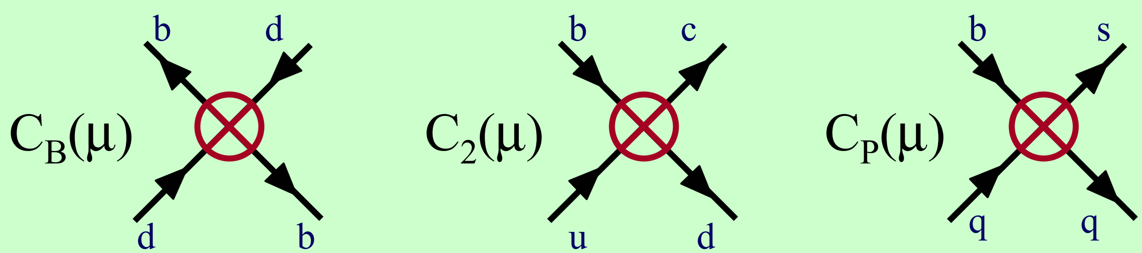
($W^{\pm}$, Z^0, G, γ, t, H^0, b, u, d, s, c, l)



$\mu \geq M_W$

Effective Theory

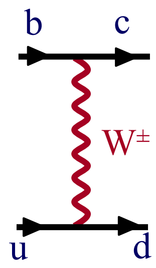
(G, γ, b, u, d, s, c, l)



$\mu \cong 0(m_b)$

"Generalized Fermi Theory" with calculable "couplings" $C_B(\mu)$, $C_2(\mu)$,...

Simplest Example of Operator Product Expansion



$$= \left[\bar{c}\gamma_\mu(1-\gamma_5)b\right]\left[V_{cb}\, i\,\frac{g_2}{2\sqrt{2}}\right]\left[\frac{-i}{k^2-M_W^2}\right]\left[\bar{d}\gamma^\mu(1-\gamma_5)u\right]\left[V_{ud}^*\, i\,\frac{g_2}{2\sqrt{2}}\right]$$

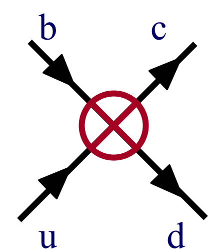
$$= \frac{g_2^2}{8}\,\frac{i}{k^2-M_W^2}\,V_{cb}V_{ud}^*\left(\bar{c}b\right)_{V-A}\left(\bar{d}u\right)_{V-A}$$

$$\frac{i}{k^2-M_W^2} = -\frac{i}{M_W^2} + 0\left(\frac{k^2}{M_W^2}\right)$$

$$\frac{G_F}{\sqrt{2}} = \frac{g_2^2}{8M_W^2}$$

To get H_{eff} multiply by i

$$H_{eff} = \underbrace{\frac{G_F}{\sqrt{2}}V_{cb}V_{ud}^* \cdot 1}_{\text{Wilson Coefficient}} \cdot \underbrace{\left(\bar{c}b\right)_{V-A}\left(\bar{d}u\right)_{V-A}}_{\text{Local Operator}}$$



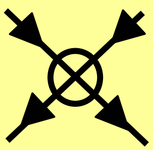
Important: **QCD corrections generate new operators and make WC μ-dependent : $C_i(\mu)$**

Operator Product Expansion

$\left\{\begin{matrix}\text{Wilson}\\\text{Coefficients}\end{matrix}\right\}$ $\left\{\begin{matrix}\text{Local}\\\text{Operators}\end{matrix}\right\}$

$$H_{\mathrm{eff}} = \frac{G_F}{\sqrt{2}} V_{\mathrm{CKM}} \sum_i C_i(\mu)\, Q_i$$

Q_i ⟺



Four Quark Interaction Vertex $(\bar{s}d)_{V-A}(\bar{s}d)_{V-A}$

$C_i(\mu)$ ⟺ **Coupling Constants** $C(\mu) = \left[\dfrac{\alpha_s(M_W)}{\alpha_s(\mu)}\right]^{\frac{6}{23}}$

$\{K, B, D, \ldots\}$

$$A(M \to F) = \frac{G_F}{\sqrt{2}} V_{\mathrm{CKM}} \sum_i C_i(\mu) \langle F | Q_i(\mu) | M \rangle$$

$\left\{\begin{matrix}\pi\pi,\ \pi\nu\bar{\nu}\\ \mu\bar{\mu},\ K^*\gamma, \ldots\end{matrix}\right\}$

M_W — $\mu = 0(1\ \mathrm{GeV}, m_b)$ — 0

Short — RG — Long Distance

$\left\{\begin{matrix}\text{Top}\\\text{SUSY}\\ H^{\pm}\ldots\end{matrix}\right\}$ $\left\{\begin{matrix}\text{Renormalization Group}\\ \sum\left(\alpha_s \log\frac{M_W}{\mu}\right)^n\end{matrix}\right\}$ $\left\{\begin{matrix}\text{Lattice, } 1/N\\ \text{HQET, QCDS}\\ \text{ChPTh}\end{matrix}\right\}$

$$\langle \bar{K}^0 | (\bar{s}d)_{V-A}(\bar{s}d)_{V-A} | K^0 \rangle = \frac{8}{3} \hat{B}_K F_K^2 m_K^2 [\alpha_s(\mu)]^{2/9}$$

Operators

Current-Current

$$Q_1 = \left(\bar{s}_\alpha u_\beta\right)_{V-A}\left(\bar{u}_\beta d_\alpha\right)_{V-A} \qquad Q_2 = \left(\bar{s}u\right)_{V-A}\left(\bar{u}d\right)_{V-A}$$

QCD-Penguins

$$Q_3 = \left(\bar{s}d\right)_{V-A}\sum_{q=u,d,s}\left(\bar{q}q\right)_{V-A} \qquad Q_4 = \left(\bar{s}_\alpha d_\beta\right)_{V-A}\sum_{q=u,d,s}\left(\bar{q}_\beta q_\alpha\right)_{V-A}$$

$$Q_5 = \left(\bar{s}d\right)_{V-A}\sum_{q=u,d,s}\left(\bar{q}q\right)_{V+A} \qquad \boxed{Q_6 = \left(\bar{s}_\alpha d_\beta\right)_{V-A}\sum_{q=u,d,s}\left(\bar{q}_\beta q_\alpha\right)_{V+A}}$$

Electroweak-Penguins

$$Q_7 = \frac{3}{2}\left(\bar{s}d\right)_{V-A}\sum_{q=u,d,s} e_q\left(\bar{q}q\right)_{V+A} \qquad \boxed{Q_8 = \frac{3}{2}\left(\bar{s}_\alpha d_\beta\right)_{V-A}\sum_{q=u,d,s} e_q\left(\bar{q}_\beta q_\alpha\right)_{V+A}}$$

$$Q_9 = \frac{3}{2}\left(\bar{s}d\right)_{V-A}\sum_{q=u,d,s} e_q\left(\bar{q}q\right)_{V-A} \qquad Q_{10} = \frac{3}{2}\left(\bar{s}_\alpha d_\beta\right)_{V-A}\sum_{q=u,d,s} e_q\left(\bar{q}_\beta q_\alpha\right)_{V-A}$$

Basic Structure of Decay Amplitudes

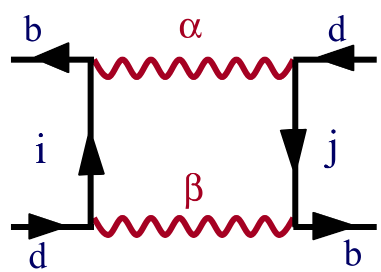
A =	Long Distance Contribution	QCD Renormalization Group Factor η^{QCD}	Short Distance Contributions $0(M_W, m_t)$
	Hadronic Matrix Element (Non-Perturbative)	QCD – Effects $0(m_b) \leq \mu \leq 0(M_W)$ $0(m_c)$ (RG improved Perturbation Theory)	Tree Diagrams Penguin Diagrams Box Diagrams (Perturbation Theory)

Deriving $H_{eff}\left(B_d^0 - \overline{B}_d^0\right)$ and $\Delta M_d\left(B_d^0 - \overline{B}_d^0\right)$ in 7 Steps

$\Phi^{\pm}$ - Goldstone Bosons Must be taken into account except in a Unitarity Gauge

Step 1 : Calculate Box Diagrams

$$\sum_{i,j=u,c,t} \quad \sum_{\alpha,\beta=W^{\pm},\Phi^{\pm}}$$



$$\equiv \sum_{i,j=u,c,t} F\left(x_i, x_j\right)\left(V_{ib}^* V_{id}\right)\left(V_{jb}^* V_{jd}\right) Q$$

UG : see AJB, Poschenrieder, Uhlig; hep-ph/0410309

Step 2 : Use

$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$

Multiply by i and keep only $V_{td}V_{tb}^*$ part

$$x_i \equiv \frac{m_i^2}{M_W^2}$$

$$H_{eff}^{(\Delta B=2)} = \frac{G_F^2}{16\pi^2} M_W^2 \left(V_{tb}^* V_{td}\right)^2 \quad S_0\left(x_t\right) \quad Q\left(\Delta B = 2\right)$$

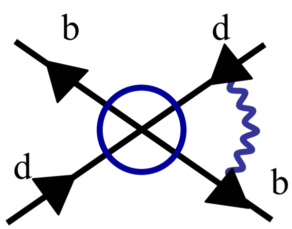
$$S_0\left(x_t\right) = \tilde{F}\left(x_t, x_t\right) + \tilde{F}\left(x_u, x_u\right) - 2\tilde{F}\left(x_t, x_u\right)$$

$$Q\left(\Delta B = 2\right) = \left(\overline{b}d\right)_{V-A}\left(\overline{b}d\right)_{V-A}$$

$$x_u = 0$$

Step 3 : Include QCD Corrections in the Leading Logarithmic Approximation

= Gluon



$$\left\{ \;+\;\dots \right\} \Rightarrow \left\{ S_0(x_t) \rightarrow \left[\frac{\alpha_s(\mu_W)}{\alpha_s(\mu_b)}\right]^{6/23} S_0(x_t) \equiv C(\mu_b) \right\}$$

Wilson Coefficient of $Q(\Delta B=2)$

$$\mu_W = 0(M_W) \qquad\qquad \mu_b = 0(m_b)$$

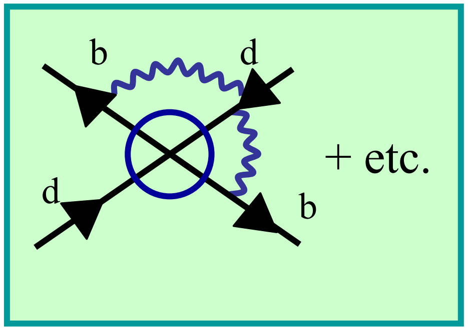
Problems with LO $\equiv$ LLA : Sensitivity to the choices of

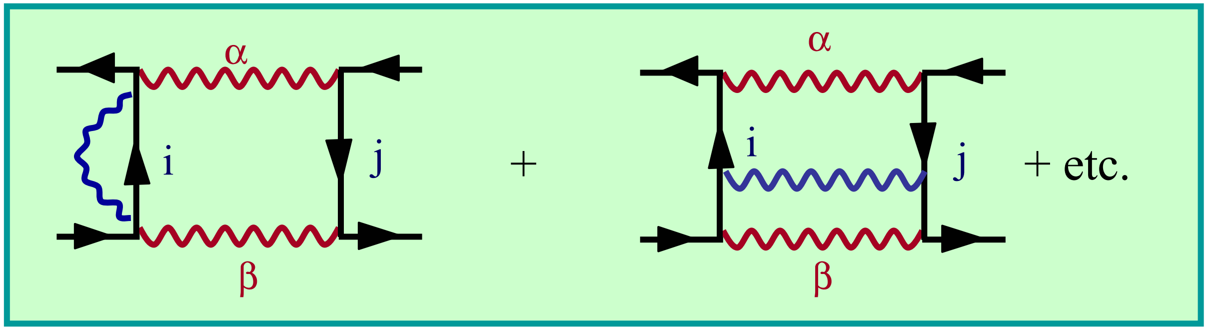
i)	μ_W	$80\ \text{GeV} < \mu_W < 300\ \text{GeV}$
ii)	μ_b	$2.5\ \text{GeV} < \mu_b < 5\ \text{GeV}$
iii)	μ_t	$x_t = \dfrac{m_t^2(\mu_t)}{M_W^2}$
		$80\ \text{GeV} < \mu_t < 300\ \text{GeV}$

Step 4 : Include Next to Leading QCD Corrections

(AJB, Jamin, Weisz 1990)

Requires:





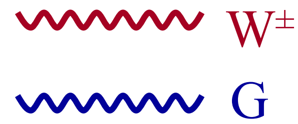
Pages 101-103 Les Houches Lectures

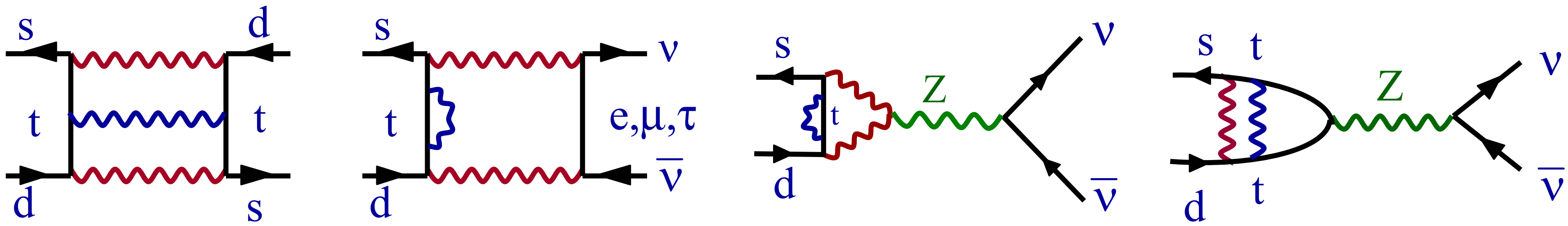
$$H_{\mathrm{eff}}^{(\Delta B=2)} = \frac{G_F^2}{16\pi^2} M_W^2 \left(V_{tb}^* V_{td}\right)^2 \underbrace{S_0(x_t)\ \tilde{\eta}_B^{QCD} \left[\frac{\alpha_S(\mu_W)}{\alpha_S(\mu_b)}\right]^{6/23} \left(1 + J_5 \frac{\alpha_S(\mu_b) - \alpha_s(\mu_W)}{4\pi}\right)}_{\text{Independent of } \mu_W \text{ and } \mu_t \text{ but still dependent on } \mu_b} Q(\Delta B = 2)$$

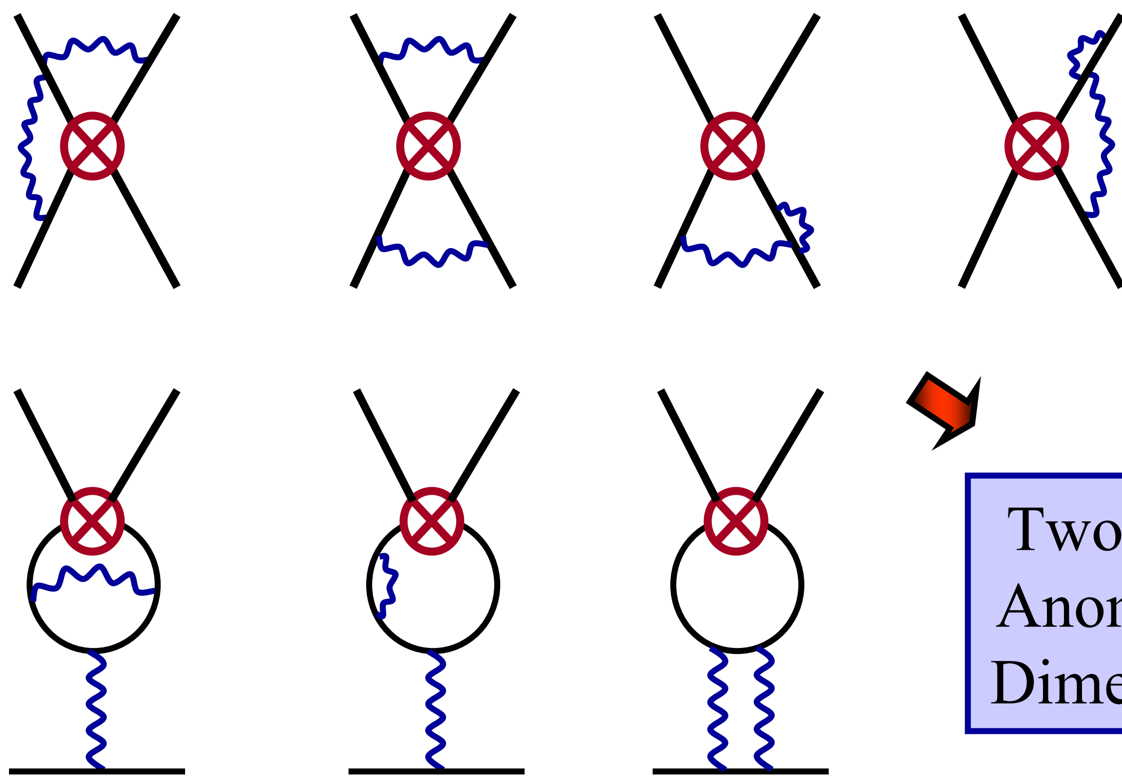
$$\tilde{\eta}_B^{QCD} = 1 + \frac{\alpha_s(\mu_W)}{4\pi} G(\mu_W, \mu_t)$$

$$J_5 = 1.627$$

Typical Two-Loop Diagrams







Two-Loop
Anomalous
Dimensions

Step 5 : Calculate the Matrix Element $\langle Q(\Delta B=2)\rangle$

$$\langle \bar{B}_d^0 | Q(\Delta B=2) | B_d^0 \rangle = \frac{8}{3} B_B(\mu_b) F_B^2 m_B^2$$

F_B = B-Meson Decay Constant

This μ_b – dependence cancels the one in $H_{eff}^{\Delta B=2}$

Step 6 : Put $\langle H_{eff}^{\Delta B=2}\rangle$ in a manifestly μ_w, μ_t, μ_b independent Form

$$\eta_B^{QCD} \equiv \tilde{\eta}_B^{QCD} \left[\alpha_s(\mu_w)\right]^{6/23} \left(1 - J_5 \frac{\alpha_s(\mu_w)}{4\pi}\right)$$

with $\mu_t = m_t$

μ_w - independent

$$\hat{B}_B \equiv B_B(\mu_b) \left[\alpha_s(\mu_b)\right]^{-6/23} \left(1 + J_5 \frac{\alpha_s(\mu_b)}{4\pi}\right)$$

μ_b – independent

$S_0(x_t)$ evaluated at $\mu_t = m_t$

Step 7 : Calculation of $\Delta M_d\left(B_d^0 - \overline{B}_d^0\right)$

Use $$\Delta M_d = \frac{1}{m_b}\left|\left\langle \overline{B}_d^0 \middle| H_{\rm eff}^{(\Delta B=2)} \middle| B_d^0 \right\rangle\right|$$

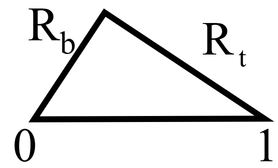
$$\Rightarrow \quad \Delta M_d = \frac{G_F^2}{6\pi^2} m_b M_w^2 \underbrace{\left(\hat{B}_d F_{B_d}^2\right)}_{\text{independent of } \mu_b} \underbrace{\eta_B^{QCD}\ S_0(x_t)}_{\text{independent of } \mu_w,\, \mu_t} |V_{td}|^2$$

$$\sqrt{\hat{B}_d} F_{B_d} = \left(235^{+33}_{-41}\right) \text{MeV}$$

$$\eta_B^{QCD} = 0.551 \pm 0.006$$

$$S_0(x_t) = \frac{4x_t - 11x_t^2 + x_t^3}{4(1-x_t)^2} - \frac{3x_t \log x_t}{2(1-x_t)^3} \approx 2.46\left(\frac{m_t}{170\text{GeV}}\right)^{1.52}$$

$(\Delta M)_{d,s}$, $|V_{td}|/|V_{ts}|$ and R_t



$$(\Delta M)_d = \frac{0.50}{ps}\left[\frac{\sqrt{\hat{B}_d}F_{Bd}}{230\text{MeV}}\right]^2\left[\frac{|V_{td}|}{7.8\cdot 10^{-3}}\right]^2\left[\frac{\eta_B}{0.55}\right]\left[\frac{S(x_t)}{2.34}\right]$$

$$(\Delta M)_s = \frac{18.4}{ps}\left[\frac{\sqrt{\hat{B}_s}F_{Bs}}{270\text{MeV}}\right]^2\left[\frac{|V_{ts}|}{0.040}\right]^2\left[\frac{\eta_B}{0.55}\right]\left[\frac{S(x_t)}{2.34}\right]$$

$$S(x_t) = 2.42 \pm 0.12$$

$$\eta_B = 0.55 \pm 0.01$$

AJB, Jamin, Weisz

$$|V_{td}| = \lambda |V_{cb}| R_t$$

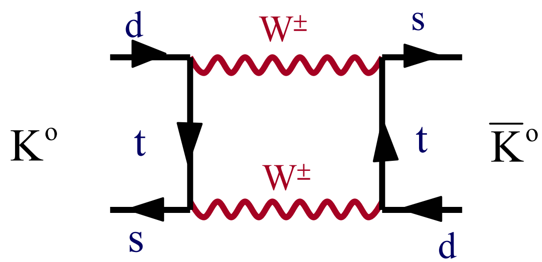
$$|V_{ts}| = |V_{cb}|\left(1 - \frac{\lambda^2}{2} + \bar{\rho}\lambda^2\right)$$

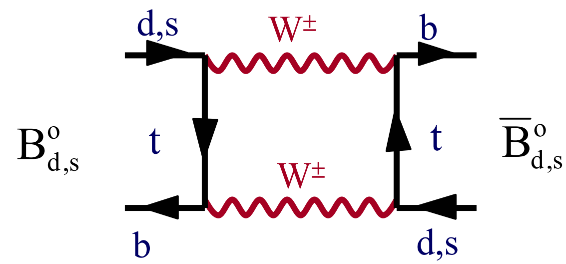
$$\xi = \frac{\sqrt{\hat{B}_s}F_{B_s}}{\sqrt{\hat{B}_d}F_{B_d}} = 1.23 \pm 0.06$$

$$\frac{|V_{td}|}{|V_{ts}|} = 1.01\,\xi\sqrt{\frac{\Delta M_d}{\Delta M_s}}$$

$$R_t = 0.90\sqrt{\frac{\Delta M_d}{0.50/ps}}\sqrt{\frac{18.4/ps}{\Delta M_s}}\left[\frac{\xi}{1.22}\right]$$

View at Short Distance Scales



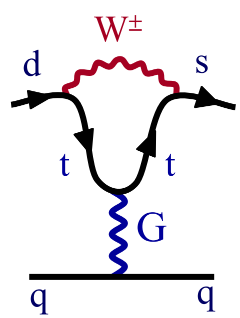


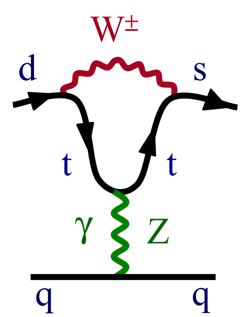
$\cancel{C}P$ ε_K-Parameter

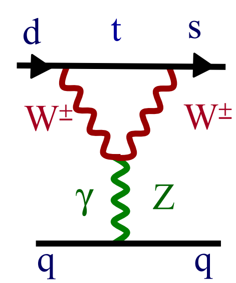
ΔM $(K_L\text{-}K_S)$

$B^o_d - \overline{B}^o_d$ Mixing

ε'

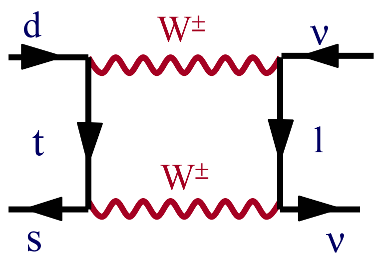


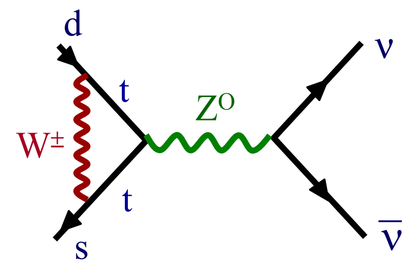


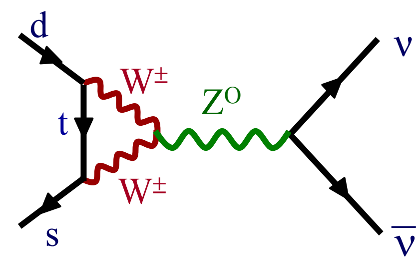


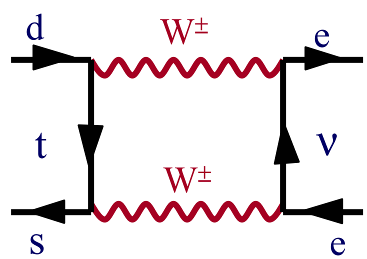
View at Short Distance Scales

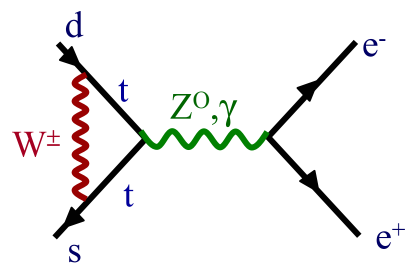
$\boxed{K^+ \to \pi^+ \nu\bar{\nu},}$ $K_L \to \pi^0 \nu\bar{\nu}$ $\boxed{K_L \to \mu\bar{\mu},}$ $B \to \mu\bar{\mu},$ $B \to X_S \nu\bar{\nu}$

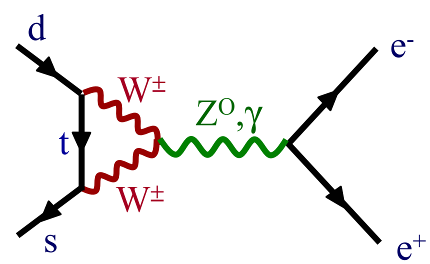




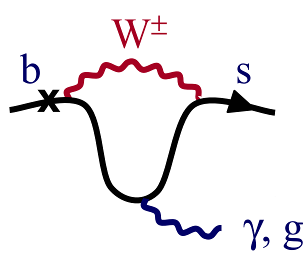








$K_L \to \pi^0 e^+ e^-$ $\boxed{B \to X_s e^+ e^-,\ X_s \mu\bar{\mu}}$



$\boxed{B \to X_s \gamma \qquad B \to K^* \gamma}$

$B \to X_d \gamma$ $\quad b \to s$ gluon

Penguin-Box Expansion (SM)

Buchalla, AJB, Harlander (90)

The m_t dependence of all K and B Decays resides in 7 Basic Universal Functions $F_i(x_t)$

$$x_t = \frac{m_t^2}{M_W^2}$$

$$A(\text{Decay}) = \sum_i B_i \eta^i_{QCD} V^i_{CKM} F_i(x_t)$$

F_i : S, X, Y, Z, E, E', D'

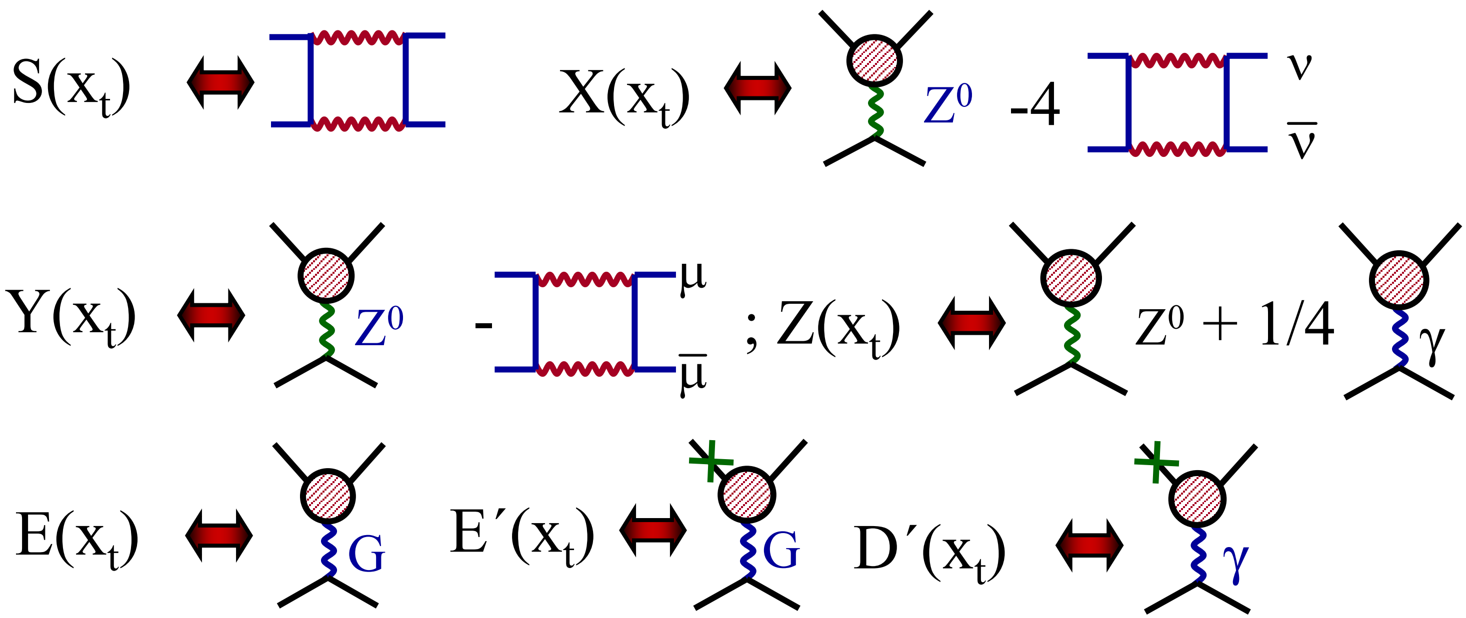
(Gauge Invariant set of functions)

Relation to OPE:

RG

$$C_i(\mu) = \sum_j U_{ij}(\mu, M_W) \underbrace{\left[\sum_r H_{jr} F_r(x_t)\right]}_{C_j(M_W)} = \sum_r \eta^{QCD}_{ir} F_r(x_t)$$

Decay	Contributing Functions
$B_d^0 - \bar{B}_d^0,\ B_s^0 - \bar{B}_s^0,\ \varepsilon$	$S(x_t)$
$K \to \pi\nu\bar{\nu},\ B \to X_s\nu\bar{\nu}$	$X(x_t)$
$K_L \to \mu\bar{\mu},\ B \to l\bar{l}$	$Y(x_t)$
ε'	$Z(x_t),\ X(x_t),\ Y(x_t),\ E(x_t)$
$K_L \to \pi^0 e^+ e^-$	$Y(x_t),\ Z(x_t),\ E(x_t)$
$B \to X_s e^+ e^-$	$Y(x_t),\ Z(x_t),\ D'(x_t), E'(x_t), E(x_t)$
$B \to X_s\gamma$	$D'(x_t),\ E'(x_t)$



m_t Dependence of Basic Universal Functions

$$S(x_t) \equiv S_0(x_t) = 2.46\left[\frac{m_t}{170\mathrm{GeV}}\right]^{1.52}$$

$$X(x_t) = 1.57\left[\frac{m_t}{170\mathrm{GeV}}\right]^{1.15} \qquad Y(x_t) = 1.02\left[\frac{m_t}{170\mathrm{GeV}}\right]^{1.56}$$

$$Z(x_t) = 0.71\left[\frac{m_t}{170\mathrm{GeV}}\right]^{1.86} \qquad E(x_t) = 0.26\left[\frac{m_t}{170\mathrm{GeV}}\right]^{-1.02}$$

$$D'(x_t) = 0.38\left[\frac{m_t}{170\mathrm{GeV}}\right]^{0.60} \qquad E'(X_t) = 0.19\left[\frac{m_t}{170\mathrm{GeV}}\right]^{0.38}$$

Master Formula for Weak Decays

AJB (2001)
hep-ph/0101336
hep-ph/0109197

Non-Perturbative Factors in the SM

QCD RG Factors

Short Distance Loop Functions (Penguins, Boxes)

New Flavour-Changing Parameters

Represent different Dirac and Colour Stuctures

$$A(\mathrm{Decay}) = B_i \;\eta^i_{QCD}\; V^i_{CKM}\left[F^i_{SM} + F^i_{New}\right] + B^{New}_i\left[\eta^i_{QCD}\right]^{New} V^i_{New}\left[G^i_{New}\right]$$

(Summation over i)

$\mathrm{New} \equiv \mathrm{NP}$

Non-Perturbative Factors beyond SM

Short Distance Loop Functions Penguins, Boxes

$F^i_{SM}, \; F^i_{New}, \; G^i_{New}$ **: Fully calculable in Perturbation Theory**

$\eta^i_{QCD}, \; \left[\eta^i_{QCD}\right]^{New}$ **: Fully calculable in RG improved Perturbation Theory**

$B_i, \; B^{New}_i$ **: Require Non-Perturbative Methods or can be extracted from leading decays**

$\left(\text{represent } \langle Q_i \rangle\right)$

Fully calculable in the SM

Possible Dirac Structures in $K^0 - \bar{K}^0$ and $B^0_{d,s} - \bar{B}^0_{d,s}$

SM:

$$\gamma_\mu (1-\gamma_5) \otimes \gamma^\mu (1-\gamma_5)$$

Beyond SM:

$$\gamma_\mu (1-\gamma_5) \otimes \gamma^\mu (1+\gamma_5)$$

$$(1-\gamma_5) \otimes (1+\gamma_5)$$

$$(1-\gamma_5) \otimes (1-\gamma_5)$$

$$\sigma_{\mu\nu} (1-\gamma_5) \otimes \sigma^{\mu\nu} (1-\gamma_5)$$

MSSM with large tanβ
General Supersymmetric Models
Models with complicated Higgs System

NLO $\left[\eta^i_{QCD}\right]^{New}$: Ciuchini, Franco, Lubicz, Martinelli, Scimemi, Silvestrini

AJB, Misiak, Urban, Jäger

Three Simple Scenarios

Inami Lim Functions

SM :

$$A(\text{Decay}) = \sum_i B_i\, \eta^i_{QCD}\, V^i_{CKM} \underbrace{F^i_{SM}}_{\text{real}}(m_t)$$

MFV :

$$A(\text{Decay}) = \sum_i B_i\, \eta^i_{QCD}\, V^i_{CKM} \underbrace{\left[F^i_{SM} + F^i_{New}\right]}_{\text{real}}$$

(Minimal Flavour Violation)

AJB, Gambino, Gorbahn, Jäger, Silvestrini
D'Ambrosio, Giudice, Isidori, Strumia

Enhanced Z^0-Penguins :

$$A(\text{Decay}) = \sum_i B_i\, \eta^i_{QCD}\, V^i_{CKM} \left[\underbrace{F^i_{SM}}_{\text{real}} + \underbrace{\Delta^i_{New}}\right]$$

Dominated by Z^0-Penguins with a New Complex Phase

AJB, Colangelo, Isidori, Romanino, Silvestrini
Buchalla, Hiller, Isidori; Atwood, Hiller
AJB, Fleischer, Recksiegel, Schwab

Two more complicated Scenarios

MSSM (MFV)
(large tanβ)

(Higgs penguin)

$$A\left(\text{Decay}\right)=\sum_i B_i\,\eta^i_{QCD}\,V^i_{CKM}\left[F^i_{SM}+\overbrace{F^i_{New}}^{\text{real}}\right]$$

$$+\sum_i B_i^{New}\left[\eta^i_{QCD}\right]^{New}V^i_{CKM}\underbrace{\left[G^i_{New}\right]}_{\text{real}}$$

General
MSSM

Z'-Models
L-R Models
Multi-Higgs
Models

$$A\left(\text{Decay}\right)=\sum_i B_i\,\eta^i_{QCD}\,V^i_{CKM}\left[F^i_{SM}+\overbrace{F^i_{New}}^{\text{complex}}\right]$$

$$+\sum_i B_i^{New}\left[\eta^i_{QCD}\right]^{New}V^i_{New}\underbrace{\left[G^i_{New}\right]}_{\text{complex}}$$

Inclusive Decays

(Generally TH cleaner than Exclusive Decays)

Examples: $B \to X_s\gamma,\ B \to X_s\mu^+\mu^-,\ B \to X_s\nu\bar{\nu}$

$X_s \equiv$ all final states with $\Delta S = 1$ quantum number

1. Construction of H_{eff} as in the case of Exclusive Decays

2. The branching ratios calculated perturbatively from b-quark decay diagrams

3. Non-Perturbative Effects $\sim \Lambda^2_{QCD} / m_b^2$ (~ 5%)

Heavy Quark Expansions:

Chay, Georgi, Grinstein (1990)
Bigi, Shifman, Uraltsev, Vainshstein (1992)
Manohar, Wise (1993); Mannel (1993)

2.

Particle Mixing and Various Types of CP Violation

Express Review of $B^0 - \overline{B}^0$ Mixing

Flavour Eigenstates

$$B^0 = (\overline{b}d)$$

$$\overline{B}^0 = (b\overline{d})$$

$$CP|B^0\rangle = -|\overline{B}^0\rangle$$
$$CP|\overline{B}^0\rangle = -|B^0\rangle$$

In the absence of $B^0 - \overline{B}^0$ Mixing:

$$|B^0(t)\rangle = |B^0(0)\rangle \exp[-i\,Ht]$$
$$|\overline{B}^0(t)\rangle = |\overline{B}^0(0)\rangle \exp[-i\,Ht]$$

$$H = \underbrace{M}_{\text{Mass}} - i\underbrace{\frac{\Gamma}{2}}_{\text{Width}}$$

Time Evolution in the Presence of Mixing

$$i\frac{d\psi(t)}{dt} = \hat{H}\,\psi(t) \qquad \psi(t) = \begin{pmatrix} |B^0(t)\rangle \\ |\overline{B}^0(t)\rangle \end{pmatrix}$$

Hermitian Matrices with positive (real) eigenvalues

$$\hat{H} = \hat{M} - i\frac{\hat{\Gamma}}{2} = \begin{pmatrix} M_{11} - i\frac{\Gamma_{11}}{2} & M_{12} - i\frac{\Gamma_{12}}{2} \\ M_{21} - i\frac{\Gamma_{21}}{2} & M_{22} - i\frac{\Gamma_{22}}{2} \end{pmatrix}$$

M_{ij}-transition with virtual intermediate states

Γ_{ij}- transition with physical intermediate states

$$M_{21} = M_{12}^* \qquad \Gamma_{21} = \Gamma_{12}^*$$

Express Review of B^0-$\overline{B}^0$ Mixing

- **Flavour Eigenstates**

$$B_d^0 = \left(\overline{b}d\right)$$
$$\overline{B}_d^0 = \left(b\overline{d}\right)$$
$$B_s^0 = \left(\overline{b}s\right)$$
$$\overline{B}_s^0 = \left(b\overline{s}\right)$$

see:
Erice (2000)
Spain (2004)
$\left(K^0 - \overline{K}^0\right)$

- **Mass Eigenstates**

$$B_{H,L} = p\,B^0 \pm q\,\overline{B}^0$$
$$\frac{q}{p} = \frac{2M_{12}^* - i\Gamma_{12}^*}{\Delta M - i\,\dfrac{\Delta\Gamma}{2}}$$
$$\Delta M = M\left(B_H\right) - M\left(B_L\right)$$
$$\Delta\Gamma = \Gamma\left(B_H\right) - \Gamma\left(B_L\right)$$

All exact formulae from $K^0 - \overline{K}^0$ system apply
but now: $\left|M_{12}\right| >> \left|\Gamma_{12}\right|$ $\Rightarrow$

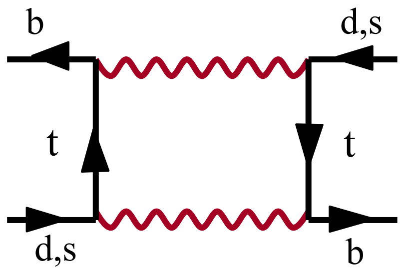
◆ Master Formulae (B^0-$\bar{B}^0$)

$$\Delta M = 2\left|M_{12}\right|$$

$$\Delta\Gamma = 2\frac{\mathrm{Re}\left(M_{12}\Gamma_{12}^*\right)}{\left|M_{12}\right|}$$

$$\frac{q}{p} \cong \frac{M_{12}^*}{\left|M_{12}\right|}\left[1 - \frac{1}{2}\mathrm{Im}\left(\frac{\Gamma_{12}}{M_{12}}\right)\right]$$

$$M_{12}^* = \left\langle \overline{B}^0 \middle| H_{\mathrm{eff}} \middle| B^0 \right\rangle \approx$$



$$\left(M_{12}^*\right)_d \sim \left(V_{td}V_{tb}^*\right)^2 \qquad \left(M_{12}^*\right)_s \sim \left(V_{ts}V_{tb}^*\right)^2$$

$$V_{td} = \left|V_{td}\right|e^{-i\beta} \qquad V_{ts} = \left|V_{ts}\right|e^{-i\beta_s} \qquad \left(\beta_s \cong 0\right)$$

$$\frac{q}{p} \cong e^{i2\varphi_M} \qquad \varphi_M = \begin{cases} -\beta & B_d^0 - \overline{B}_d^0 \\ -\beta_s & B_s^0 - \overline{B}_s^0 \end{cases}$$

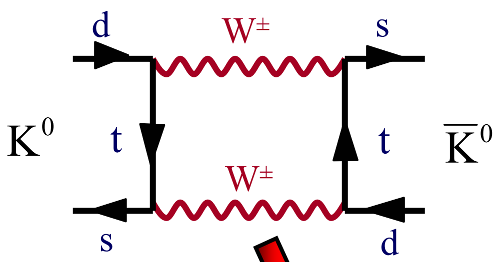
(Pure Phase)

Indirect and Direct $\not{C}\!\not{P}$ in $K_L \to \pi\pi$

$$K_{1,2} = \frac{K^0 \mp \overline{K}^0}{\sqrt{2}}$$

$$CP\left|K^0\right\rangle = -\left|\overline{K}^0\right\rangle$$

$(K^0 - \overline{K}^0 \text{ Mixing})$

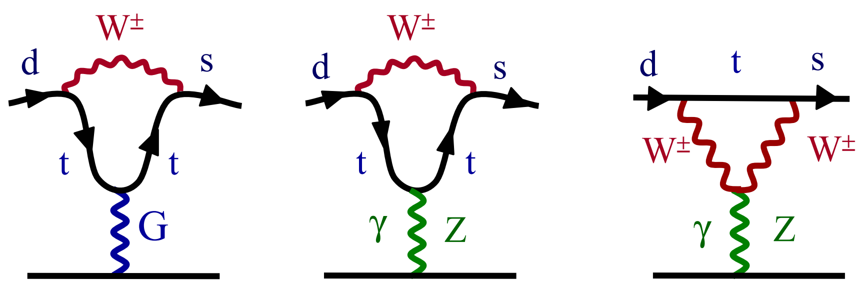


Mass Eigenstates are not CP Eigenstates

indirect CP violation (ε)

$$K_L = \overset{(-)}{K}_2 + \varepsilon \overset{(+)}{K}_1 \quad \xrightarrow{\varepsilon} \quad \overbrace{\pi^+\pi^-,\ \pi^0\pi^0}^{CP\ (+)}$$

direct CP-Violation (ε′)



$$\eta_{+-} \equiv \frac{A\left(K_L \to \pi^+\pi^-\right)}{A\left(K_S \to \pi^+\pi^-\right)} = \varepsilon + \varepsilon'$$

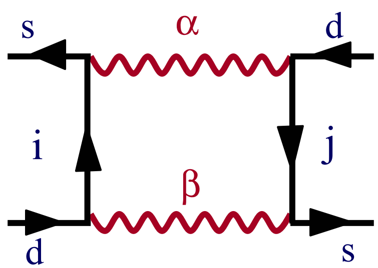
$$\eta_{00} \equiv \frac{A\left(K_L \to \pi^0\pi^0\right)}{A\left(K_S \to \pi^0\pi^0\right)} = \varepsilon - 2\varepsilon'$$

ε′=0 in Superweak Models
Wolfenstein (64)

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = \frac{1}{6}\left(1 - \left|\frac{\eta_{00}}{\eta_{+-}}\right|^2\right)$$

Master Formulae for $K^0 - \overline{K}^0$ and ε_K

$$\sum_{i,j=u,c,t} \; \sum_{\alpha,\beta=W^\pm,\Phi^\pm}$$



$$\equiv \sum_{i,j=u,c,t} F\left(x_i, x_j\right)\left(V_{is}^* V_{id}\right)\left(V_{js}^* V_{jd}\right) Q$$

$$M_{12} = \frac{G_F^2}{12\pi^2} F_K^2 \hat{B}_K m_K M_W^2 \Big[\underbrace{\tilde{\lambda}_c^2 \eta_1^{QCD} S_0(x_c)}_{\text{Dominates } \Delta M_K} + \underbrace{\tilde{\lambda}_t^2 \eta_2^{QCD} S_0(x_t) + 2\tilde{\lambda}_c \tilde{\lambda}_t \eta_3^{QCD} S_0(x_c, x_t)}_{\text{Dominates } \varepsilon_K} \Big]$$

$$\tilde{\lambda}_i = V_{is} V_{id}^*$$

$$\Delta M_K = 2 \,\mathrm{Re}\, M_{12}$$

$$\varepsilon_K = \frac{\exp(i\pi/4)}{\sqrt{2}\,\Delta M_K} \,\mathrm{Im}\, M_{12}$$

$\eta_2^{QCD} = 0.57 \pm 0.01$ (AJB, Jamin, Weisz, 90)

$$\left.\begin{array}{l} \eta_1^{QCD} = 1.32 \pm 0.32 \\ \eta_3^{QCD} = 0.47 \pm 0.05 \end{array}\right\} \text{(Herrlich, Nierste, 94, 95)}$$

February 2006

$$\Delta M_K = \left(0.5301 \pm 0.0016\right) \cdot 10^{-2} \,/\, \mathrm{ps}$$

$$\Delta M_d = \left(0.503 \pm 0.006\right) / \,\mathrm{ps}$$

$$\Delta M_s > \quad 16 / \,\mathrm{ps} \quad \left(95\%\ \mathrm{C.L.}\right)$$

$$1/\,\mathrm{ps} = 6.582 \cdot 10^{-13}\,\mathrm{GeV}$$

$$\varepsilon = \left(2.280 \pm 0.013\right) \cdot 10^{-3} e^{i\pi/4}$$

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = \left(16.6 \pm 1.6\right) \cdot 10^{-4}$$

March 2006

DØ : $19/\text{ps} \le \Delta M_s \le 21/\text{ps}$ 90% C.L.

April 2006

CDF : $\Delta M_s = 17.33 \begin{array}{c} +0.42 \\ -0.21 \end{array} \pm 0.07$

$$\left(\Delta M_s\right)_{SM} = \left(18 \pm 4.8\right)/\text{ps} \qquad \text{Direct}$$

$$\left(21.5 \pm 2.6\right)/\text{ps} \qquad \text{UTfit}$$

Modern Classification of CP Violation

We have:

Particle-Antiparticle Mixing

and

Decay

1. CP Violation in Mixing
2. CP Violation in Decay
3. CP Violation in the Interference of Mixing and Decay

Classification of $\cancel{CP}$ in B- and K-Decays

(Nir 99),...

1. CP Violation in Mixing

$$B_{H,L} = p\left|B^0\right\rangle \pm q\left|\overline{B}^0\right\rangle$$

Mass Eigenstates

$\cancel{CP}$: $\boxed{|q/p| \neq 1}$ ⇒ (Not CP Eigenstates)

$$a_{SL} = \frac{\Gamma\left(\overline{B}^0(t) \to l^+\nu X\right) - \Gamma\left(B^0(t) \to l^-\nu X\right)}{\Gamma\left(\overline{B}^0(t) \to l^+\nu X\right) + \Gamma\left(B^0(t) \to l^-\nu X\right)}$$

$$a_{SL} = \frac{1-|q/p|^4}{1+|q/p|^4} = \operatorname{Im}\frac{\Gamma_{12}}{M_{12}}$$

$$\hat{H} = \hat{M} - i\frac{\hat{\Gamma}}{2}$$

Observed in K-system: $\operatorname{Re}\varepsilon_K \neq 0$

$\overline{B}^0 \to B^0 \to l^+\nu X$

(Phase Difference)

$B^0 \to \overline{B}^0 \to l^-\nu X$

"wrong charge" leptons

$$a_{SL} \approx 0\left(10^{-3}\right)$$

Hadronic Uncertainties in Γ_{12}, M_{12}

2. CP Violation in Decay

$$A_f = \langle f | H^{weak} | B \rangle \quad \bar{A}_{\bar{f}} = \langle \bar{f} | H^{weak} | \bar{B} \rangle$$

$$\cancel{CP}: \quad \boxed{\left|\bar{A}_{\bar{f}} / A_f\right| \neq 1} \qquad f \xrightarrow{CP} \bar{f}$$

$$\boxed{a_{f^\pm}^{Decay} = \frac{\Gamma\left(B^+ \to f^+\right) - \Gamma\left(B^- \to f^-\right)}{\Gamma\left(B^+ \to f^+\right) + \Gamma\left(B^- \to f^-\right)} = \frac{1 - \left|\bar{A}_{f^-} / A_{f^+}\right|^2}{1 + \left|\bar{A}_{f^-} / A_{f^+}\right|^2}}$$

Requires at least two different contibutions with different <u>weak</u> (φ_i) and <u>strong</u> (δ_i) phases

$$A_f = \sum_i A_i e^{i(\delta_i + \varphi_i)} \qquad \bar{A}_{\bar{f}} = \sum_i A_i e^{i(\delta_i - \varphi_i)} \qquad \left(A_2 << A_1\right) \qquad r \equiv \frac{A_2}{A_1} << 1$$

$$i = 1,\ 2$$

$$\boxed{a_{f^\pm}^{Decay} \approx -2r \sin\left(\delta_2 - \delta_1\right) \sin\left(\varphi_2 - \varphi_1\right)}$$

Observed in K-system: $\boxed{\mathrm{Re}\, \varepsilon'_K \neq 0}$

Hadronic Uncertainties in A_i, δ_i

B^0-Decays into CP-Eigenstate

$$\left.\begin{array}{l} B^0 \to \overline{B}^0 \\ B^0 \to B^0 \end{array}\right\} \to f$$

ΔM = Difference between Mass Eigenstates in $(B^0, \overline{B}^0)$ System

$f \equiv f_{CP}$ = CP eigenstate
η_f = CP-parity = ± 1

Time-dependent asymmetry:

$$a_{CP}(t,f) = \frac{\Gamma\left(B^0(t)\to f\right) - \Gamma\left(\overline{B}^0(t)\to f\right)}{\Gamma\left(B^0(t)\to f\right) + \Gamma\left(\overline{B}^0(t)\to f\right)}$$

$$a_{CP}(t,f) = a_{CP}^{Decay}\cos(\Delta M t) + a_{CP}^{\text{"mix-ind"}}\sin(\Delta M t)$$

$$a_{CP}^{Decay} = \frac{1-|\xi_f|^2}{1+|\xi_f|^2} \equiv C_f \qquad a_{CP}^{\text{"mix-ind"}} = \frac{2\,\mathrm{Im}\,\xi_f}{1+|\xi_f|^2} \equiv -S_f$$

$$\xi_f = \underbrace{\exp[i2\varphi_M]}_{\text{Mixing}} \frac{\overline{A}_f\left(\overline{B}^0 \to f\right)}{A_f\left(B^0 \to f\right)}$$

Decay Amplitudes

For a **single** decay contribution or sum of contributions with **the same weak phase**

$$\xi_f = -\eta_f \exp[i2\varphi_M]\cdot\exp[-i2\varphi_D]$$

$$|\xi_f|^2 = 1 \qquad \varphi_D\text{: weak phase in the } B^0 \text{ decay}$$

$\Rightarrow$ ξ_f = given only in terms of CKM phase

$$a_{CP}^{decay} = 0$$

Dominance of a single CKM Amplitude

A_{Tree}, A_P	- hadronic matrix elements
δ_T, δ_P	- final state interaction phases
φ_T, φ_P	- weak CKM phases

$$\frac{\overline{A}_f\left(\overline{B}^0 \to f\right)}{A_f\left(B^0 \to f\right)} = -\eta_f \left[\frac{A_{Tree} e^{i(\delta_T - \varphi_T)} + A_P e^{i(\delta_P - \varphi_P)}}{A_{Tree} e^{i(\delta_T + \varphi_T)} + A_P e^{i(\delta_P + \varphi_P)}}\right]$$

Tree Dominance

$$\frac{\overline{A}_f\left(\overline{B}^0 \to f\right)}{A_f\left(B^0 \to f\right)} = -\eta_f e^{-i2\varphi_T}$$

(Pure Phase)
Very Clean !

Penguin Dominance

$$\frac{\overline{A}_f\left(\overline{B}^0 \to f\right)}{A_f\left(B^0 \to f\right)} = -\eta_f e^{-i2\varphi_P}$$

(Pure Phase)
Very Clean !

Also pure phase if $\varphi_T = \varphi_P$!! $\left(\text{Example: } B_d^0 \to J/\psi\, K_S\right)$

3. CP Violation in the Interference of Mixing and Decay

Misnomer: ("Mixing induced CP-Violation")

$$a_{CP}(t,f) = \mathrm{Im}\,\xi_f \sin(\Delta M t)$$

$$\mathrm{Im}\,\xi_f = \eta_f \sin(2\varphi_D - 2\varphi_M) \equiv -S_f$$

Very clean
TH

Measures the difference between the phases of B^0-$\bar{B}^0$ mixing ($2\varphi_M$) and of decay amplitude ($2\varphi_D$)

Examples:

$B_d^0 \to \psi K_S$: $\varphi_D = 0 \quad \varphi_M = -\beta \quad \eta_f = -1$

$$\mathrm{Im}\,\xi_{\psi K_S} = -\sin 2\beta$$

$B_d^0 \to \pi^+\pi^-$: $\varphi_D = \gamma \quad \varphi_M = -\beta \quad \eta_f = +1$

$$\mathrm{Im}\,\xi_{\pi\pi} = \sin(2(\gamma+\beta)) = -\sin 2\alpha$$

$K_L \to \pi^0 \nu\bar{\nu}$: Measures the difference between the phases in K^0-$\bar{K}^0$ mixing and $\bar{s} \to \bar{d}\nu\bar{\nu}$ amplitude

B^0-Decays into CP Eigenstates

$$\left(\text{Two Contributions} \quad r = \frac{A_2}{A_1} << 1\right)$$

$$a_{CP}\left(t,f\right) = C_f \cos\left(\Delta M t\right) - S_f \sin\left(\Delta M t\right)$$

$$C_f = -2r\sin\left(\varphi_1 - \varphi_2\right)\sin\left(\delta_1 - \delta_2\right)$$

$$S_f = -\eta_f\left[\sin 2\left(\varphi_1 - \varphi_M\right) + 2r\cos 2\left(\varphi_1 - \varphi_M\right)\sin\left(\varphi_1 - \varphi_2\right)\cos\left(\delta_1 - \delta_2\right)\right]$$

φ_i = weak phases $\qquad$ δ_i = strong phases

$$\left\{r = 0\right\} \Rightarrow \quad C_f = 0 \qquad S_f = -\eta_f \sin 2\left(\varphi_1 - \varphi_M\right)$$

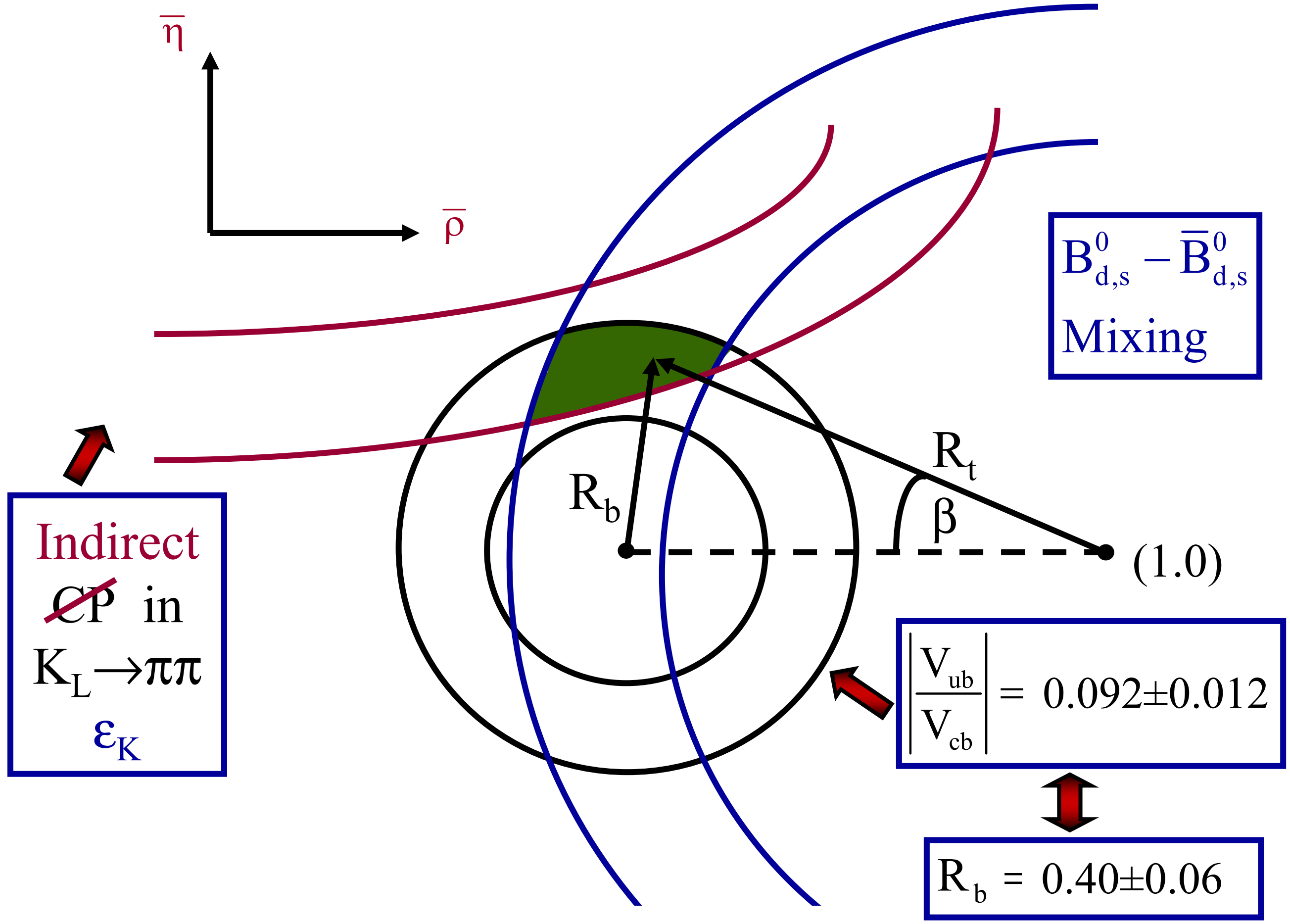
Comparison of Two-Languages

CP violation in mixing	$\equiv$	Manifestation of indirect $\cancel{CP}$
CP violation in decay	$\equiv$	Manifestation of direct $\cancel{CP}$
CP violation in interference of mixing and decay	$\equiv$	With a single decay it is impossible to state whether $\cancel{CP}$ in mixing or decay. But $\mathrm{Im}\,\xi_{f_1} \neq \mathrm{Im}\,\xi_{f_2}$ signals CP violation in decay (Direct $\cancel{CP}$)

3.

Standard Analysis of Unitarity Triangle

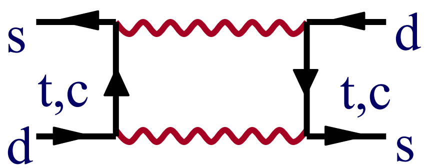
Standard Analysis of UT



Relevant Parameters

$$\hat{B}_K,\ F_{B_d}\sqrt{\hat{B}_{B_d}},\quad \xi = F_{B_s}\sqrt{\hat{B}_{B_s}} / F_{B_d}\sqrt{\hat{B}_{B_d}} \quad \Leftrightarrow \quad \varepsilon_K \qquad \Delta M_d \qquad \Delta M_s / \Delta M_d$$

Indirect CP in $K_L \to \pi\pi$

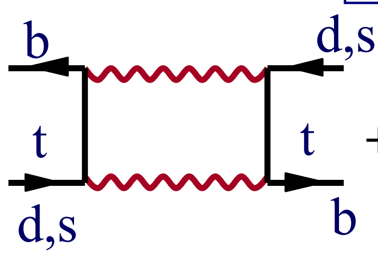
$\Big\{$ Im 

+ QCD $\Big\}$ $\Rightarrow$ ε_K $\Leftarrow$ {Experiment}

exp:

$$\varepsilon_K = (2.280 \pm 0.013) \cdot 10^{-3} e^{i\frac{\pi}{4}}$$

$B^0_{d,s} - \overline{B}^0_{d,s}$ Mixing

$\Big\{$ 

+ QCD $\Big\}$ $\Rightarrow$ $(\Delta M)_{d,s}$ $\Leftarrow$ {CLEO
ARGUS
4∗LEP,SLD
BaBar
Belle}

$$(\Delta M)_{d,s} \equiv M\left(B^0_H\right)_{d,s} - M\left(B^0_L\right)_{d,s}$$

Mass Eigenstates

exp:

$$(\Delta M)_d = (0.503 \pm 0.006)/\,\text{ps}$$

$$(\Delta M)_s = (17.4 \pm 0.3)/\,\text{ps} \quad \text{(CDF)}$$

Basic Formulae

1. ε_K - Hyperbola

$$\boxed{\bar{\eta}\left[\left(1-\bar{\rho}\right)A^2F_{tt}\eta_{QCD}^{tt}+P_c\left(\varepsilon\right)\right]A^2\hat{B}_K=0.213}$$

$\eta_{QCD}^{tt}=0.57\pm0.01;\quad P_C\left(\varepsilon\right)=0.28\pm0.05;\quad F_{tt}=2.42\pm0.12$

$\left(F_{tt}\equiv S\left(x_t\right)\right)$

2. $B_d^0-\bar{B}_d^0$ Mixing Constraint

$$\boxed{R_t=0.86\left[\frac{0.041}{\left|V_{cb}\right|}\right]\sqrt{\frac{2.34}{F_{tt}}}\sqrt{\frac{\Delta M_d}{0.50/ps}}\left[\frac{230MeV}{\sqrt{\hat{B}_d}F_{B_d}}\right]\sqrt{\frac{0.55}{\eta_B^{QCD}}}}$$

$\left|V_{cb}\right|=0.041\pm0.001;\quad \Delta M_d=\left(0.503\pm0.006\right)/ps;\quad \eta_B^{QCD}=0.55\pm0.01$

3. $B_s^0-\bar{B}_s^0$ Mixing Constraint ($\Delta M_d/\Delta M_s$)

$$\boxed{R_t=0.90\sqrt{\frac{\Delta M_d}{0.50/ps}}\sqrt{\frac{18.4/ps}{\Delta M_s}}\left[\frac{\xi}{1.22}\right]}$$

$$\boxed{\xi=\frac{\sqrt{\hat{B}_s}F_{B_s}}{\sqrt{\hat{B}_d}F_{B_d}}}$$

$\Delta M_s=(17.4\pm0.3)/ps$ (CDF)

4. $\sin 2\beta$ from $A_{CP}(\psi K_S)$

$$A_{CP}(\psi K_S) \equiv -a_{\psi K_S} \sin(\Delta M_d t)$$

$$a_{\psi K_S} = \sin 2\beta \qquad \text{(SM)}$$

$$\sin 2\beta_{\psi K_S} = \begin{cases} 0.79 \pm \begin{matrix} 0.41 \\ 0.44 \end{matrix} & \text{(CDF)} \\ 0.741 \pm \underset{\text{(stat)}}{0.067} \pm \underset{\text{(syst)}}{0.033} & \text{(BaBar)} \\ 0.719 \pm 0.074 \pm 0.035 & \text{(Belle)} \end{cases}$$

$$\left(\text{ALEPH}: 0.84 \begin{matrix} +0.82 \\ -1.04 \end{matrix} \pm 0.16\right)$$

$$\sin 2\beta = 0.726 \pm 0.037 \quad \left(a_{\psi K_s}\right)$$

(Before Summer 2005)

$$\beta = \begin{cases} (23.3 \pm 1.6)^{\mathrm{O}} \\ (66.7 \pm 1.6)^{\mathrm{O}} & \text{(excluded in the SM)} \end{cases}$$

$$(\sin\beta \cong 0.40 \pm 0.03)$$

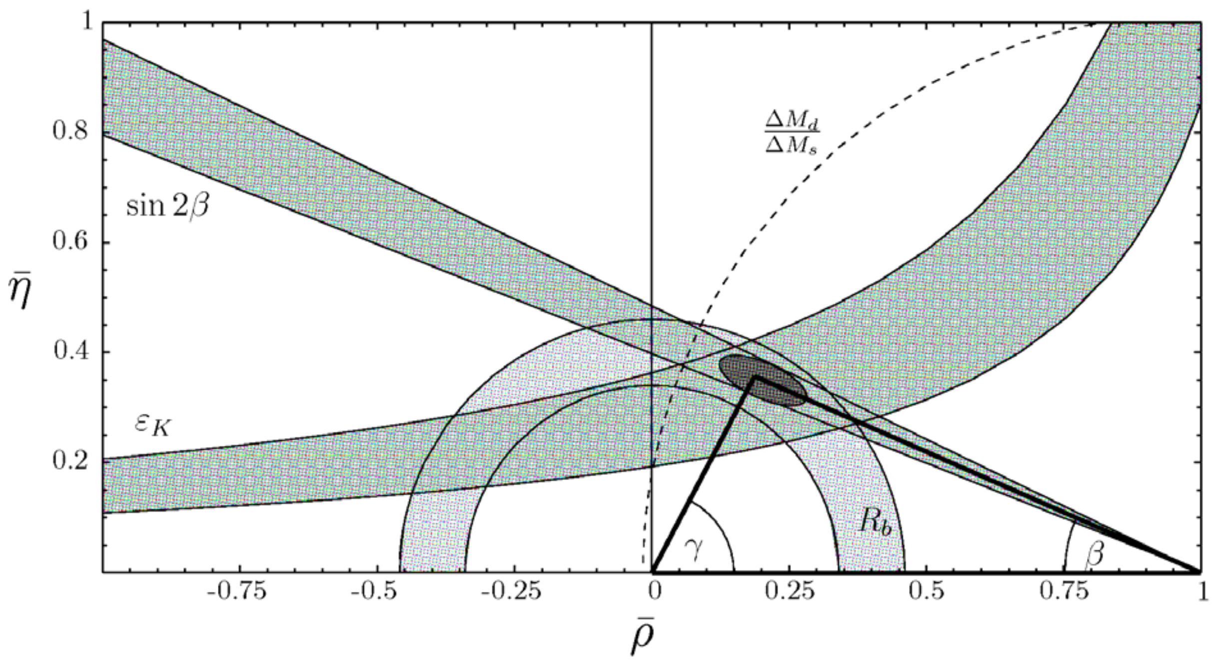
Crucial Parameters in SM and Beyond

$\lvert V_{us}\rvert = \lambda$	0.225 ± 0.001	
$\lvert V_{ub}\rvert$	$(4.23 \pm 0.35)\cdot 10^{-3}$	
$\lvert V_{cb}\rvert$	$(41.6 \pm 0.7)\cdot 10^{-3}$	★
$\left\lvert \frac{V_{ub}}{V_{cb}} \right\rvert$	0.102 ± 0.012	★
$m_t(m_t)$	(163.8 ± 3.2) GeV	
$\hat{B}_K$	0.79 ± 0.10	(ε_K)
$\sqrt{\hat{B}_s} F_{B_s}$	(262 ± 35) MeV	(ΔM_s)
$\xi = \frac{\sqrt{\hat{B}_s} F_{B_s}}{\sqrt{\hat{B}_d} F_{B_d}}$	1.24 ± 0.08	$\left(\frac{\Delta M_s}{\Delta M_d}\right)$

Valid for all extensions of SM !!

Unitarity Triangle 2004

AJB, Schwab, Uhlig



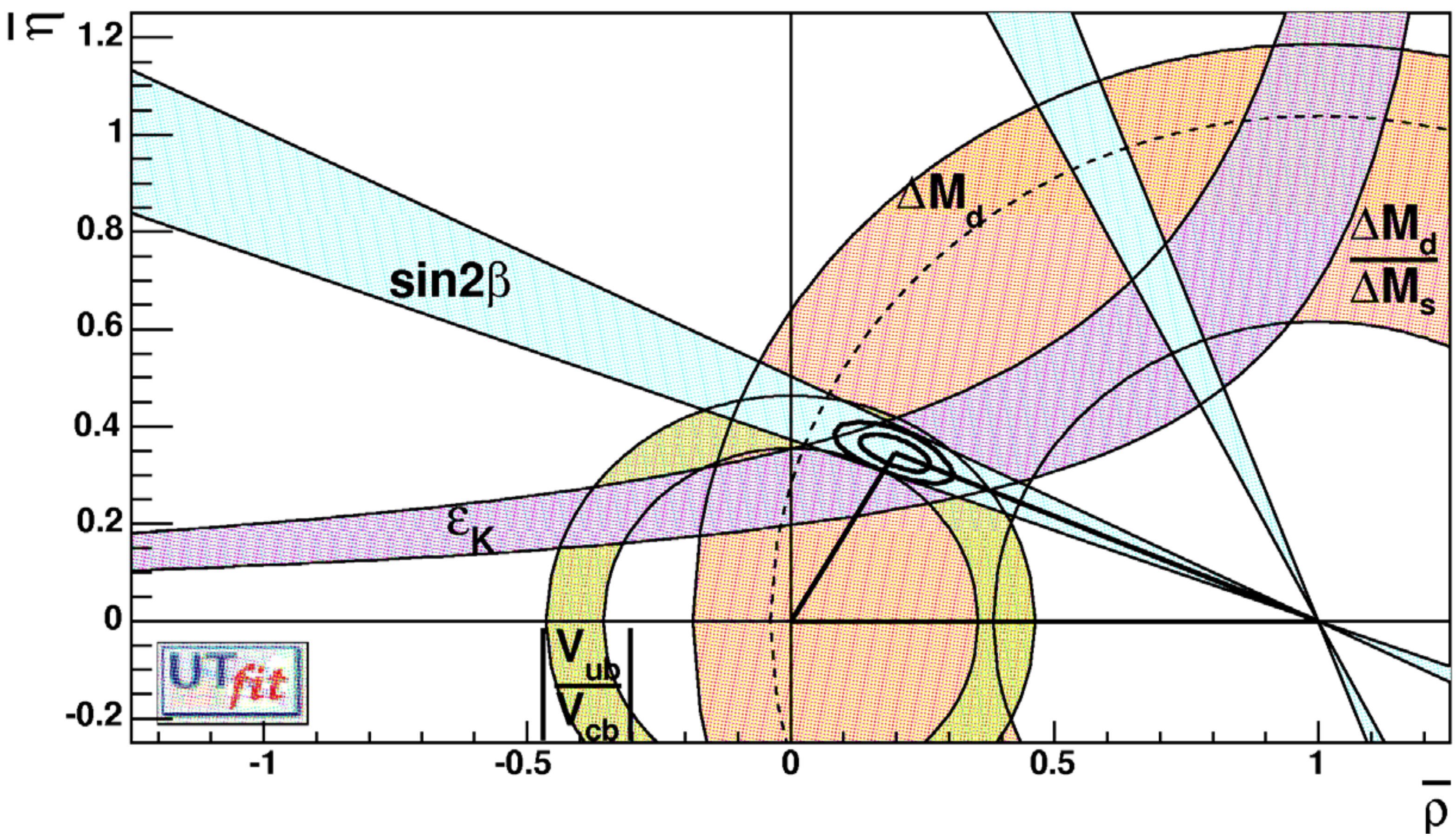
$$\overline{\eta} = 0.354 \pm 0.027$$
$$\overline{\rho} = 0.187 \pm 0.059$$

$$\gamma = (62.2 \pm 8.2)^{o}$$
$$R_t = 0.887 \pm 0.059$$
$$R_b = 0.400 \pm 0.039$$
$$|V_{td}| = (8.24 \pm 0.54) \cdot 10^{-3}$$

$$\mathrm{Im}\,\lambda_t = (1.40 \pm 0.12) \cdot 10^{-4}$$
$$\lambda_t = V_{ts}^{*} V_{td}$$

Unitarity Triangle 2005

UTfit collaboration : Bona et al.



Summer 2005 News

New Physics ?

$$(\sin 2\beta)_{\psi K_s} = \boxed{0.726 \pm 0.037} \Rightarrow \boxed{0.687 \pm 0.032} \star$$

$$m_t(m_t) = \boxed{168 \pm 4\ \text{GeV}} \Rightarrow \boxed{163.0 \pm 2.7\ \text{GeV}}$$

$$\left|\frac{V_{ub}}{V_{cb}}\right| = \boxed{0.092 \pm 0.012} \Rightarrow \boxed{0.102 \pm 0.005}$$

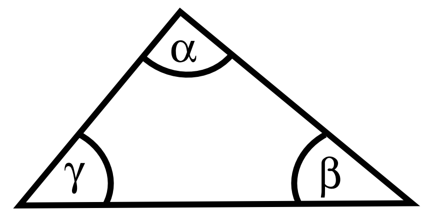
UT fitters

New $\left|\frac{V_{ub}}{V_{cb}}\right|, \quad m_t(m_t)$ $\Rightarrow$

$$(\sin 2\beta)_{\substack{\text{UT sides}\\ +\varepsilon_K}} = \boxed{0.791 \pm 0.034} \star$$

$$(\sin 2\beta)_{\text{total}} = \boxed{0.734 \pm 0.024}$$

4.



α, β, γ
from
B-Decays

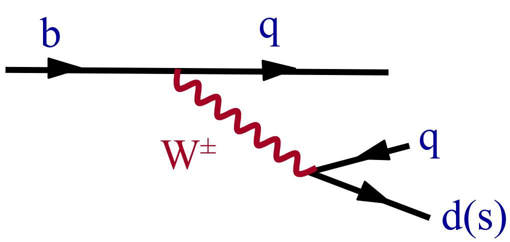
$$V_{td} = |V_{td}|e^{-i\beta}$$

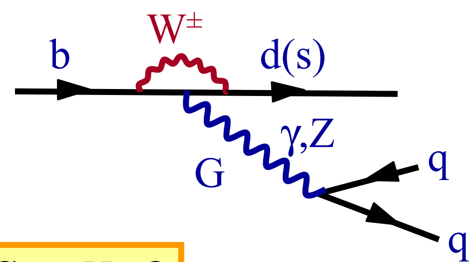
$$V_{ts} = |V_{ts}|e^{-i\beta_s}$$

$$V_{ub} = |V_{ub}|e^{-i\gamma}$$

Basic Contributions

Class I — Decays with Trees and Penguins

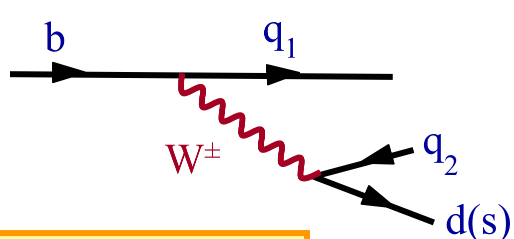




$q = u, c$

$b \to c\bar{c}s$
$b \to c\bar{c}d$
$b \to u\bar{u}s$
$b \to u\bar{u}d$

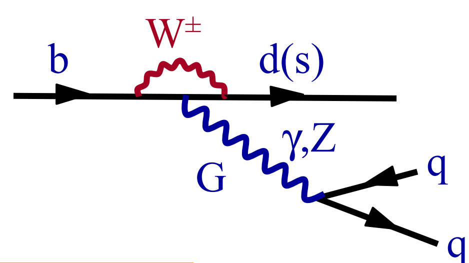
Class II — Trees only



$b \to c\bar{u}s$
$b \to c\bar{u}d$
$b \to u\bar{c}s$
$b \to u\bar{c}d$

$q_1 \neq q_2 \in \{u, c\}$

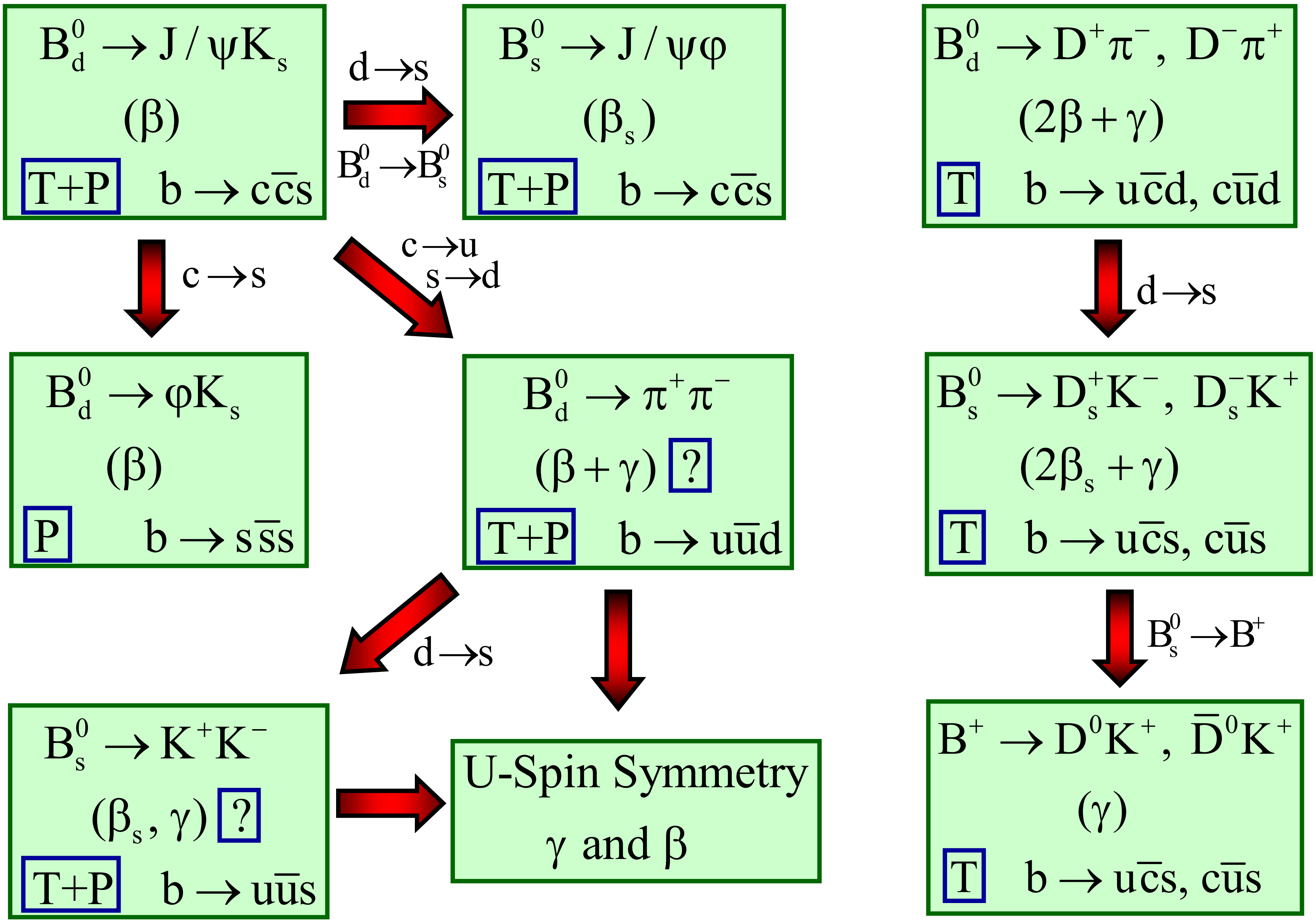
Class III — Penguins only



$b \to s\bar{s}s$
$b \to s\bar{s}d$
$b \to d\bar{d}s$
$b \to d\bar{d}d$

$q = d, s$

α, β, γ from B-Decays



B^0-Decays into CP-Eigenstate

$$\left.\begin{array}{l} B^0 \to \overline{B}^0 \\ B^0 \to B^0 \end{array}\right\} \to f$$

ΔM = Difference between Mass Eigenstates in $(B^0, \overline{B}^0)$ System

$f \equiv f_{CP}$ = CP eigenstate

η_f = CP-parity = ± 1

Time-dependent asymmetry:

$$a_{CP}(t,f) = \frac{\Gamma\left(B^0(t) \to f\right) - \Gamma\left(\overline{B}^0(t) \to f\right)}{\Gamma\left(B^0(t) \to f\right) + \Gamma\left(\overline{B}^0(t) \to f\right)}$$

$$\boxed{\begin{array}{l} a_{CP}(t,f) = a_{CP}^{\mathrm{Decay}} \cos(\Delta M t) + a_{CP}^{\mathrm{"mix-ind"}} \sin(\Delta M t) \\[2ex] a_{CP}^{\mathrm{Decay}} = \dfrac{1 - |\xi_f|^2}{1 + |\xi_f|^2} \equiv C_f \qquad a_{CP}^{\mathrm{"mix-ind"}} = \dfrac{2\,\mathrm{Im}\,\xi_f}{1 + |\xi_f|^2} \equiv -S_f \end{array}}$$

$$\xi_f = \underbrace{\exp[i2\varphi_M]}_{\text{Mixing}} \frac{\overline{A}_f\left(\overline{B}^0 \to f\right)}{A_f\left(B^0 \to f\right)}$$

Decay Amplitudes

For a **single** decay contribution or sum of contributions with **the same weak phase**

$$\boxed{\begin{array}{l} \xi_f = -\eta_f \exp[i2\varphi_M] \cdot \exp[-i2\varphi_D] \\ |\xi_f|^2 = 1 \qquad \varphi_D\text{: weak phase in the } B^0 \text{ decay} \end{array}}$$

$\Rightarrow$ ξ_f = given only in terms of CKM phase

$a_{CP}^{\mathrm{decay}} = 0$

$B^0(\overline{B}^0)$-Decays into CP-Eigenstates

$$\begin{tikzcd}[column sep=small] & \overline{B}^0 \arrow[dr, "\text{(Decay)}"] & \\ B^0 \arrow[ur, "\text{(Mixing)}"] \arrow[dr] & & f \\ & B^0 \arrow[ur] & \end{tikzcd}$$

$$\begin{tikzcd}[column sep=small] & B^0 \arrow[dr, "\text{(Decay)}"] & \\ \overline{B}^0 \arrow[ur, "\text{(Mixing)}"] \arrow[dr] & & f_{CP} = \eta_f f \\ & \overline{B}^0 \arrow[ur] & \end{tikzcd}$$

$\eta_f = \pm 1$ CP Parity

Basic dynamical quantity:

Weak phase in B^0 Decay : $\varphi_D = 0,\ \beta,\ \gamma$

$$\xi_f \equiv \underbrace{\exp\left(i2\varphi_M\right)}_{\text{Mixing}} \underbrace{\frac{\overline{A}_f\left(\overline{B}^0 \to f\right)}{A_f\left(B^0 \to f\right)}}_{\text{Decay Amplitudes}}$$

$$= -\eta_f \exp\left(i2\varphi_M\right) \cdot \exp\left(-i2\varphi_D\right)$$

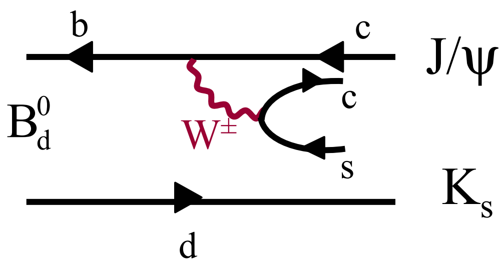
In the case of a single decay contribution or contributions with the same weak phase

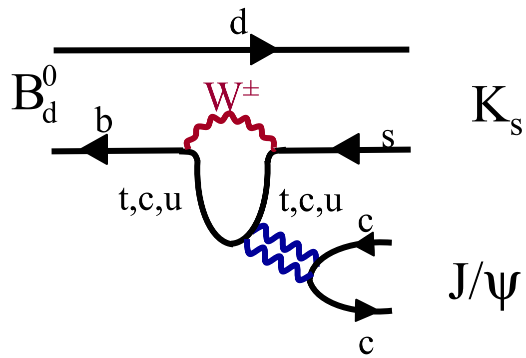
$$\varphi_M = \begin{cases} -\beta & \left(B_d^0 - \overline{B}_d^0 \text{ mixing}\right) \\ \underbrace{-\beta_s}_{\approx 1^0} & \left(B_s^0 - \overline{B}_s^0 \text{ mixing}\right) \end{cases}$$

EXP $\Rightarrow$ $\operatorname{Im} \xi_f = \eta_f \sin 2\left(\varphi_D - \varphi_M\right)$ ★

$B_d^0 \to J/\psi K_S$ and β

$$V_{td} = |V_{td}| e^{-i\beta}$$





$$V_{cs}V_{cb}^* \cong A\lambda^2$$
$$V_{us}V_{ub}^* \cong A\lambda^4 R_b e^{i\gamma}$$
$$V_{ts}V_{tb}^* = -V_{cs}V_{cb}^* - V_{us}V_{ub}^*$$

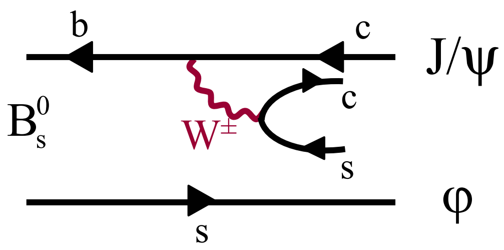
$$A\left(B_d^0 \to J/\psi K_S\right) = V_{cs}V_{cb}^*\left(A_T + P_c\right) + V_{us}V_{ub}^* P_u + V_{ts}V_{tb}^* P_t$$
$$= V_{cs}V_{cb}^*\left(A_T + P_c - P_t\right) + V_{us}V_{ub}^*\left(P_u - P_t\right)$$

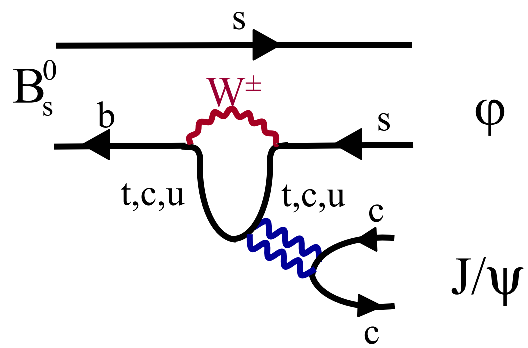
(Dominance of a single phase)

$$\left\{ \begin{array}{l} \left|\dfrac{V_{us}V_{ub}^*}{V_{cs}V_{cb}^*}\right| \le 0.02 \\ \dfrac{P_u - P_t}{A_t + P_c - P_t} << 1 \end{array} \right\} \Rightarrow \left\{ \begin{array}{l} \varphi_D = 0 \\ \varphi_M = -\beta \\ \left|\xi_{\psi K_S}\right| = 1 \end{array} \right\} \Rightarrow \left\{ \begin{array}{l} a_{CP}^{mix}\left(\psi K_S\right) = \eta_{\psi K_S} \sin 2\left(\varphi_D - \varphi_M\right) = -\sin 2\beta \\ a_{CP}^{dir}\left(\psi K_S\right) = 0 \qquad a_{CP}\left(\psi K^+\right) \cong 0 \\ \boxed{C_{\psi K_S} = 0} \qquad \boxed{S_{\psi K_S} = \sin 2\beta} \end{array} \right\}$$

$B_s^0 \to J/\psi\varphi$ and β_s

$$V_{ts} = |V_{ts}| e^{-i\beta_S}$$





Differs from

$B_d^0 \to J/\psi K_S$ only by

"spectator" quark $d \to s$

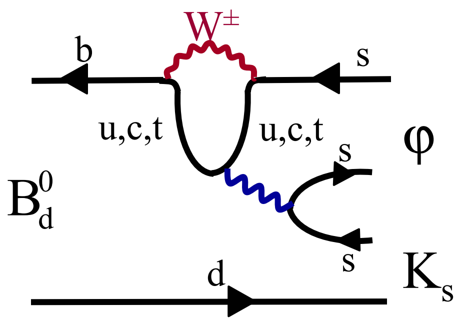
$(\varphi_D = 0)$

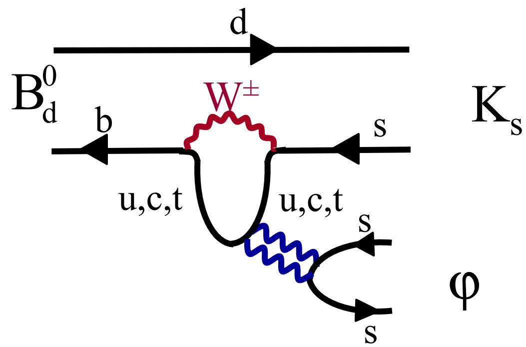
Complication: $(J/\psi\varphi)$ admixture of CP = + and CP = −

(Can be resolved: see Page 40: "B-Decays at the LHC ")

$$\begin{Bmatrix} \varphi_D = 0 \\ \varphi_M = -\beta_S \cong -\lambda^2\eta \\ |\xi_{\psi\varphi}| = 1 \end{Bmatrix} \Rightarrow \begin{Bmatrix} a_{CP}^{mix} = \sin 2(\varphi_D - \varphi_M) \cong \underbrace{2\lambda^2\eta}_{2\beta_S} \cong 0.03 \\ a_{CP}^{dir} \cong 0 \\ \text{A lot of room for New Physics!} \end{Bmatrix}$$

$B_d^0 \to \varphi K_S$ and β (Pure Peguin Decay)





$$V_{cs}V_{cb}^* \cong A\lambda^2$$
$$V_{us}V_{ub}^* \cong A\lambda^4 R_b e^{i\gamma}$$
$$V_{ts}V_{tb}^* = -V_{cs}V_{cb}^* - V_{us}V_{ub}^*$$

$$A\left(B_d^0 \to \varphi K_S\right) = V_{cs}V_{cb}^* P_c + V_{us}V_{ub}^* P_u + V_{ts}V_{tb}^* P_t$$
$$= V_{cs}V_{cb}^*\left(P_c - P_t\right) + V_{us}V_{ub}^*\left(P_u - P_t\right)$$

(Dominance of a single phase)

$$\left\{\begin{array}{l} \left|\dfrac{V_{us}V_{ub}^*}{V_{cs}V_{cb}^*}\right| \le 0.02 \\ \dfrac{P_u - P_t}{P_c - P_t} \approx 0(1) \end{array}\right\} \Rightarrow \left(\begin{array}{c}\text{neglecting} \\ V_{us}V_{ub}^*\end{array}\right) \left\{\begin{array}{l} a_{CP}^{mix}\left(\varphi K_S\right) = -\sin 2\beta = a_{CP}^{mix}\left(\psi K_S\right) \\ \boxed{C_{\varphi K_S} \approx 0} \quad \boxed{S_{\psi K_S} = S_{\varphi K_S} = \sin 2\beta} \\ \left|S_{\psi K_S} - S_{\varphi K_S}\right| \le 0.04 \ (\text{SM}) \end{array}\right\}$$

Grossman, Isidori, Worah, London, Soni

First Results for $B_d^0 \to \varphi K_S$

$$(\sin 2\beta)_{\phi K_S} = \begin{cases} +0.45 \pm 0.43 \pm 0.07 & \text{(BaBar)} \\ -0.96 \pm 0.50 \, {}^{+0.11}_{-0.09} & \text{(Belle)} \end{cases}$$

World Averages

$$S_{\phi K_S} = -0.05 \pm 0.24$$
$$C_{\psi K_S} = -0.15 \pm 0.33$$

(Belle)

$$S_{\eta' K_S} = 0.76 \pm 0.36$$
$$C_{\eta' K_S} = -0.26 \pm 0.22$$

(BaBar)

$$S_{\eta' K_s} = 0.02 \pm 0.35$$

(fully consistent with SM)

$$\left| S_{\varphi K_S} - S_{\psi K_S} \right| \cong 0.88 \pm 0.34$$

(Violation of SM by 2.6σ)

but $S_{\varphi K_S} \neq S_{\eta' K_S}$ possible as non-leading terms could be different

Grossman, Isidori Worah

Ciuchini Silvestrini

New Physics:

Enhanced QCD Penguins
Z^0 Penguins, ..

Hiller, Raidal, Ciuchini + Silvestrini
Fleischer, Mannel

Present Results for $B_d^0 \to \varphi K_s$

$$\left(\sin 2\beta\right)_{\phi K_s} = \begin{cases} 0.50 \pm 0.25 \pm 0.06 & \text{(BaBar)} \\ 0.06 \pm 0.33 \pm 0.09 & \text{(Belle)} \end{cases}$$

World Averages: (2005) $S_{\varphi K_s} = 0.34 \pm 0.20$ $C_{\varphi K_s} = -0.04 \pm 0.17$

To be compared with $S_{\psi K_s} \approx 0.73$

New Physics?

2006 : $S_{\varphi K_s} = 0.49 \pm 0.17$

Decays to CP non-eigenstates and γ

$\overset{(-)}{B}{}^0_d \to D^{\pm}\pi^{\mp}$

(Dunietz+Sachs)

$d \to s$

$\overset{(-)}{B}{}^0_s \to D_s^{\pm}K^{\mp}$

Aleksan, Dunietz, Kayser

- $B^0_d\left(B^0_s\right)$ and $\overline{B}^0_d\left(\overline{B}^0_s\right)$ can decay to the same final state
- Requires full time-dependent analysis:
  4 time dependent rates

  $B^0_{d,s}(t) \to f, \quad \overline{B}^0_{d,s}(t) \to f,$

  $B^0_{d,s}(t) \to \overline{f}, \quad \overline{B}^0_{d,s}(t) \to \overline{f},$
- Tree diagrams only

$$\xi_f = e^{i2\varphi_M}\frac{A\left(\overline{B}^0 \to f\right)}{A\left(B^0 \to f\right)}$$

$$\begin{matrix} \overline{B}^0 & \searrow & \\ \updownarrow & & f \\ B^0 & \nearrow & \end{matrix}$$

$$\xi_{\overline{f}} = e^{i2\varphi_M}\frac{A\left(\overline{B}^0 \to \overline{f}\right)}{A\left(B^0 \to \overline{f}\right)}$$

$$\begin{matrix} \overline{B}^0 & \searrow & \\ \updownarrow & & \overline{f} \\ B^0 & \nearrow & \end{matrix}$$

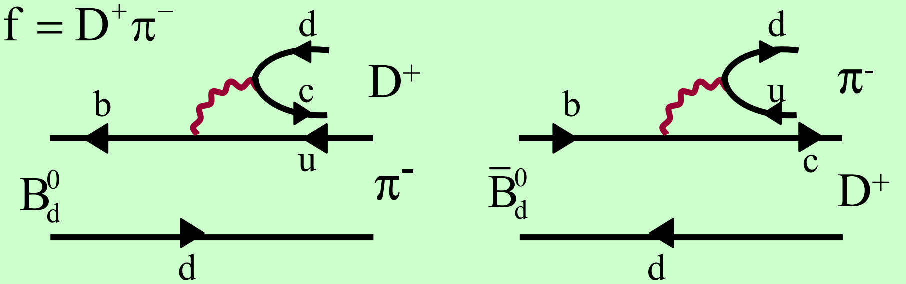
$$\varphi_M = \begin{cases} -\beta & B^0_d \\ -\beta_s & B^0_s \end{cases}$$

$$\boxed{\xi_f \cdot \xi_{\overline{f}} = F\left(\gamma, \beta_{(s)}\right)}$$

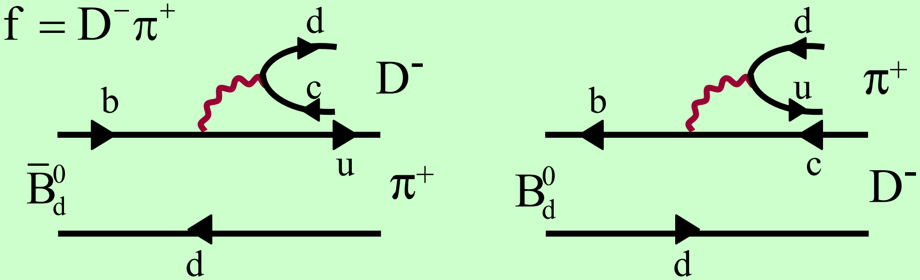
(Dunietz, Sachs)

$B_d^0 \to D^{\pm}\pi^{\mp},\ \bar{B}_d^0 \to D^{\pm}\pi^{\mp}$ and γ

$f = D^+\pi^-$



$\bar{f} = D^-\pi^+$



$\left(M_f A\lambda^4 R_b e^{i\gamma}\right)$ $\left(\bar{M}_f A\lambda^2\right)$ $\left(\bar{M}_{\bar{f}} A\lambda^4 R_b e^{-i\gamma}\right)$ $\left(M_{\bar{f}} A\lambda^2\right)$

$$\xi_f^{(d)} = e^{-i2\beta}\frac{A\left(\bar{B}_d^0 \to f\right)}{A\left(B_d^0 \to f\right)} = e^{-i(2\beta+\gamma)}\frac{1}{\lambda^2 R_b}\frac{\bar{M}_f}{M_f}$$

$$\xi_{\bar{f}}^{(d)} = e^{-i2\beta}\frac{A\left(\bar{B}_d^0 \to \bar{f}\right)}{A\left(B_d^0 \to \bar{f}\right)} = e^{-i(2\beta+\gamma)}\lambda^2 R_b\frac{\bar{M}_{\bar{f}}}{M_{\bar{f}}}$$

$$\bar{M}_f = M_{\bar{f}} \qquad M_f = \bar{M}_{\bar{f}}$$

Hadronic Matrix Elements

$$\xi_f^{(d)} \cdot \xi_{\bar{f}}^{(d)} = e^{-i2(2\beta+\gamma)}$$

$2\beta+\gamma$ without hadronic uncertainties

(β known)

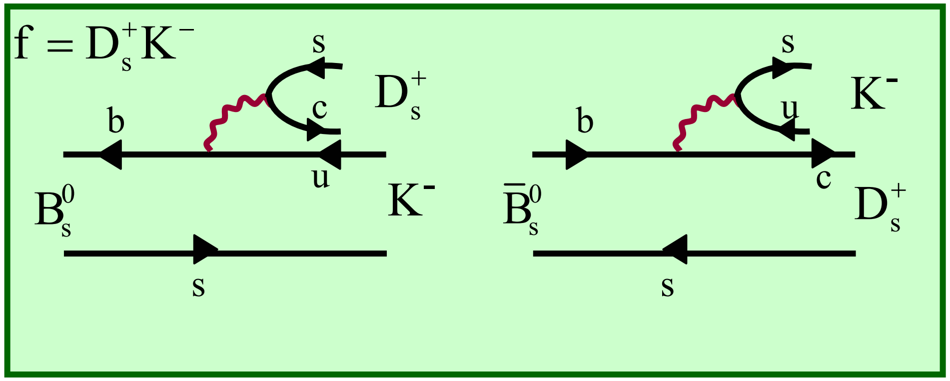
γ

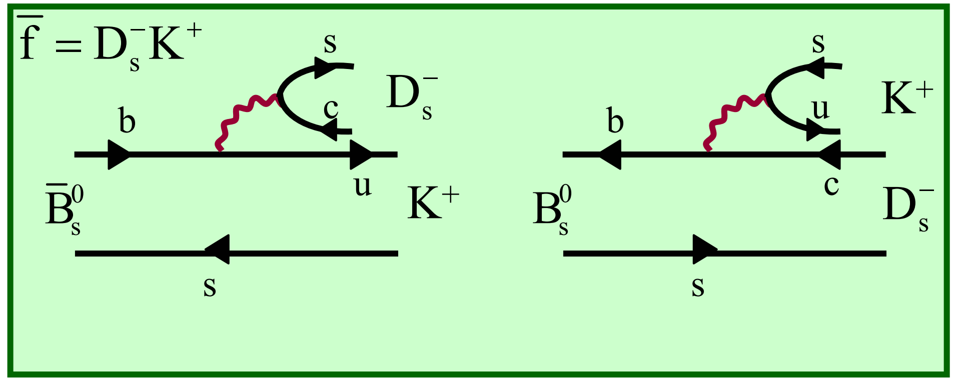
Small Interference: difficult exp. task

Aleksan
Dunietz
Kayser

$B_s^0 \to D_s^{\pm} K^{\mp},\ \bar{B}_s^0 \to D_s^{\pm} K^{\mp}$ and γ

Directly obtained from $B_d^0, \bar{B}_d^0 \to D^{\pm}\pi^{\mp}$ through $\boxed{d \to s}$





$\left(M_f A\lambda^3 R_b e^{i\gamma}\right)$ $\left(\bar{M}_f A\lambda^3\right)$ $\left(\bar{M}_{\bar{f}} A\lambda^3 R_b e^{-i\gamma}\right)$ $\left(M_{\bar{f}} A\lambda^3\right)$

In analogy to $B_d^0, \bar{B}_d^0 \to D^{\pm}\pi^{\mp}$

$$\xi_f^{(s)} \cdot \xi_{\bar{f}}^{(s)} = e^{-i2(2\beta_s+\gamma)}$$

$2\beta_s + \gamma$ without hadronic uncertainties

γ

β_s from $B_s^0 \to \varphi\psi$

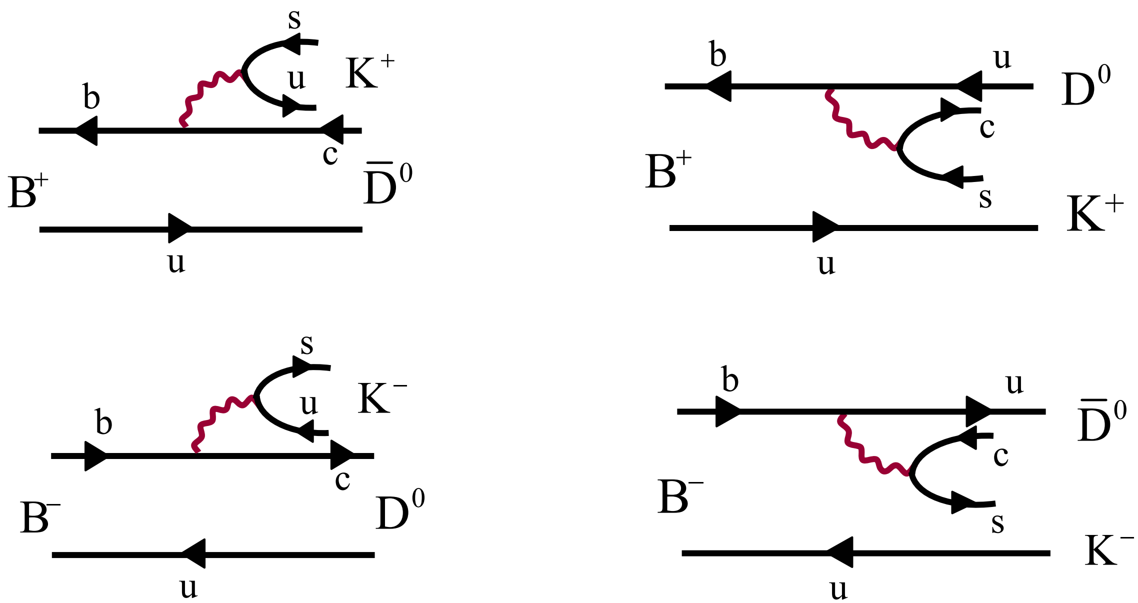
β_s – phase in $B_s^0 - \bar{B}_s^0$

Much bigger interference than in $B_d^0, \bar{B}_d^0 \to D^{\pm}\pi^{\mp}$

$B^{\pm} \to D^0 K^{\pm},\ \bar{D}^0 K^{\pm}$ and γ

(Gronau + Wyler)

Directly obtained from $B_s^0,\ \bar{B}_s^0 \to D_s^{\pm} K^{\pm}$ through $\boxed{B_s \to B^{\pm}}$



$\boxed{K^+\bar{D}^0 \neq K^+ D^0}$

Need

$B^+ \to D_+^0 K^+$

$$D_+^0 = \frac{1}{\sqrt{2}}\left(D^0 + \bar{D}^0\right)$$

To each process only single diagram contributes

$$A\left(B^+ \to \bar{D}^0 K^+\right) = A\left(B^- \to D^0 K^-\right)$$

$$A\left(B^+ \to D^0 K^+\right) = A\left(B^- \to \bar{D}^0 K^-\right) e^{2i\gamma}$$

$0\left(A\lambda^3\right)$

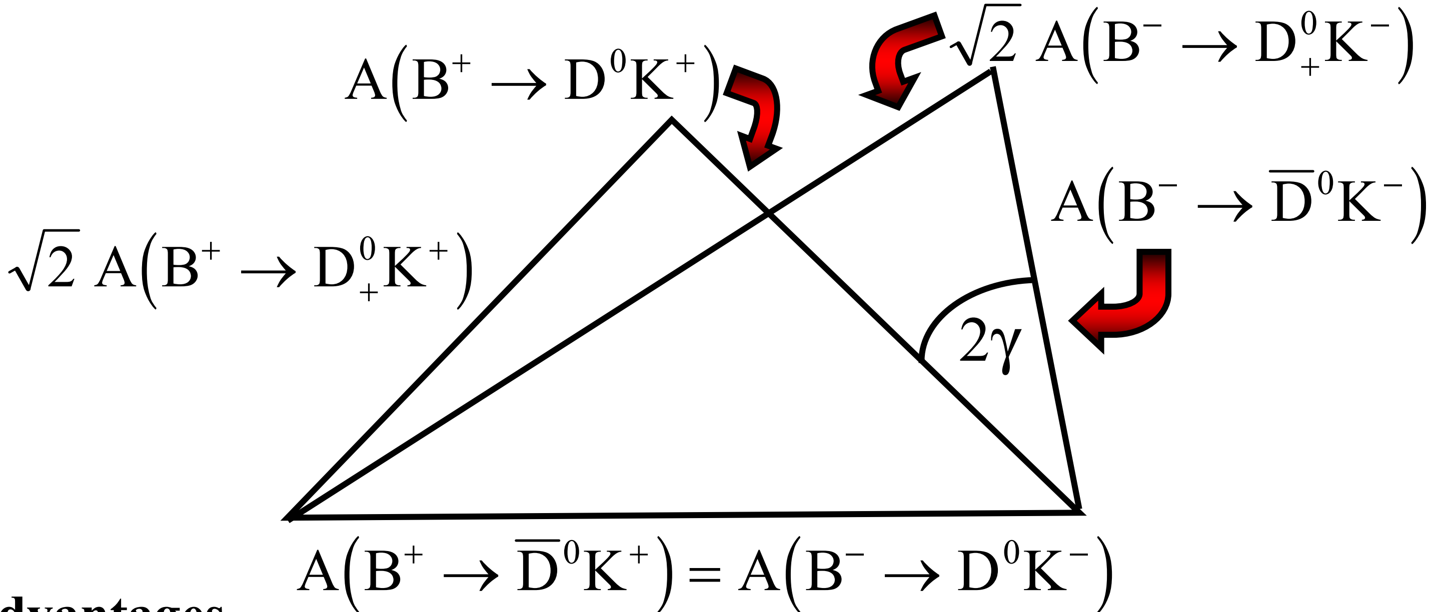
$0\left(A\lambda^3 R_b\right)$ Colour suppressed

Gronau-Wyler Method for γ

$$\sqrt{2}\,A\left(B^+ \to D^0_+ K^+\right) = A\left(B^+ \to D^0 K^+\right) + A\left(B^+ \to \overline{D}{}^0 K^+\right)$$

$$\sqrt{2}\,A\left(B^- \to D^0_+ K^-\right) = A\left(B^- \to \overline{D}{}^0 K^-\right) + A\left(B^- \to D^0 K^-\right)$$

$$D^0_+ = \frac{1}{2}\left(\left|D^0\right\rangle + \left|\overline{D}{}^0\right\rangle\right) \qquad CP = +$$



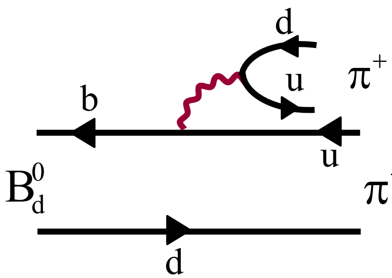
Advantages

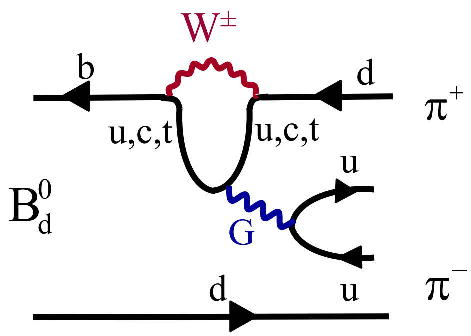
- Pure Trees
- No tagging
- No time dependent measurements
- Only rates

Disadvantages

- $Br\left(B^+ \to D^0 K^+\right) \sim 0\left(10^{-6}\right)$
- $Br\left(B^+ \to \overline{D}{}^0 K^+\right) \sim 0\left(10^{-4}\right)$
- Detection of D^0_+

$B_d^0 \to \pi^+\pi^-$ and α





$$V_{ub}^* V_{ud} = A\lambda^3 R_b e^{i\gamma}$$
$$V_{cb}^* V_{cd} = A\lambda^3$$
$$V_{tb}^* V_{td} = -V_{ub}^* V_{ud} - V_{cb}^* V_{cd}$$

$$A\left(B_d^0 \to \pi^+\pi^-\right) = V_{ub}^* V_{ud}\left(A_T + P_u\right) + V_{cb}^* V_{cd} P_c + V_{tb}^* V_{td} P_t$$
$$= V_{ub}^* V_{ud}\left(A_T + P_u - P_t\right) + V_{cb}^* V_{cd}\left(P_c - P_t\right)$$

$$\left|\frac{V_{cb}^* V_{cd}}{V_{ub}^* V_{ud}}\right| = \frac{1}{R_b} \approx 0(2)$$
$$\frac{P_c - P_t}{A_T + P_u - P_t} = \frac{P_{\pi\pi}}{T_{\pi\pi}} \quad ?$$

Dominance of a single amplitude uncertain

Assuming
$$\frac{P_{\pi\pi}}{T_{\pi\pi}} << 1$$

$$\boxed{\varphi_D = \gamma} \quad \boxed{\varphi_M = -\beta} \quad \boxed{\left|\xi_{\pi\pi}\right| = 1}$$

$$a_{CP}^{mix} = \eta_{\pi\pi} \sin 2\left(\varphi_D - \varphi_M\right) = \sin 2\left(\gamma + \beta\right) = -\sin 2\alpha$$

$$\boxed{a_{CP}^{dir} = 0} \quad \boxed{C_{\pi\pi} = 0} \quad \boxed{S_{\pi\pi} = \sin 2\alpha}$$

Results for $B_d^0 \to \pi^+\pi^-$

$$C_{\pi\pi} = \begin{cases} -0.09 \pm 0.15 \pm 0.04 & \text{(BaBar)} \\ -0.58 \pm 0.15 \pm 0.07 & \text{(Belle)} \end{cases}$$

Consistent with 0

$\cancel{CP}$

$$S_{\pi\pi} = \begin{cases} -0.30 \pm 0.17 \pm 0.03 & \text{(BaBar)} \\ -1.00 \pm 0.21 \pm 0.07 & \text{(Belle)} \end{cases}$$

Consistent with 0

$\cancel{CP}$

World Average: $C_{\pi\pi} = -0.37 \pm 0.11 \qquad S_{\pi\pi} = -0.61 \pm 0.16$

Isospin analysis (Gronau + London)
Model independent determination of α

Model independent upper bound
(Grossman, Quinn; Charles)

$$\sin^2(\alpha_{\rm eff} - \alpha) \le \frac{\mathrm{Br}\left(B^0 \to \pi^0\pi^0\right)}{\mathrm{Br}\left(B^+ \to \pi^+\pi^0\right)}$$

$$\sin 2\alpha_{\rm eff} \equiv \frac{\mathrm{Im}\,\xi_{\pi\pi}}{|\xi_{\pi\pi}|}$$

Model dependent determination of α using $(P_{\pi\pi}/T_{\pi\pi})_{TH}$

Beneke, Buchalla, Neubert, Sachrajda: small $C_{\pi\pi}$

Keum,Li,Sanda: large $C_{\pi\pi}$

Ciuchini, Silvestrini et al.
Buchalla, Safir;
AJB, Fleischer, Recksiegel, Schwab
Gronau, Rosner et al.
Ali, Lunghi, Parkhomenko

$\boxed{\text{U-Spin Strategies}}$ (d↔s)

Fleischer:

$$\left\{\begin{matrix} B_d^0 \to \pi^+\pi^- \\ B_s^0 \to K^+K^- \end{matrix}\right\} \Rightarrow \boxed{\beta, \gamma}$$

$$\left\{\begin{matrix} B_d^0 \to J/\psi K_s \\ B_s^0 \to J/\psi K_s \end{matrix}\right\} \Rightarrow \boxed{\gamma}$$

$$\left\{\begin{matrix} B_d^0 \to D^+D^- \\ B_s^0 \to D_s^+D_s^- \end{matrix}\right\} \Rightarrow \boxed{\gamma}$$

Uncertainty from
U-Spin breaking

Gronau + Rosner; Chiang Wolfenstein:

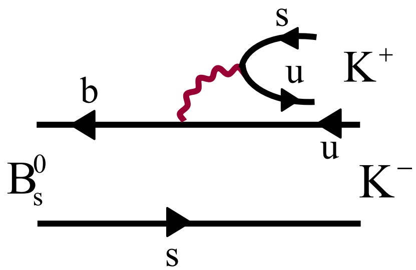
$$\left\{\begin{matrix} B_d^0 \to \pi^-K^+ \\ B_s^0 \to \pi^+K^- \end{matrix}\right\} \Rightarrow \boxed{\gamma}$$

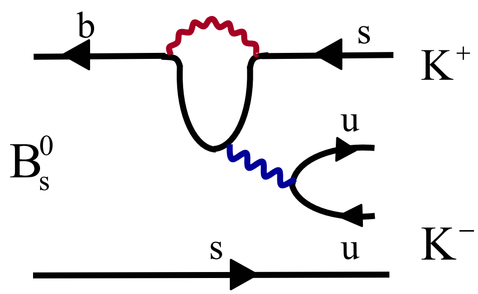
Uncertainty from U-Spin breaking,
rescattering, colour suppressed
EW-Penguins

$B_d^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ (β and γ)

(Fleischer)

$\left\{ \text{Replace in } B_d^0 \to \pi^+\pi^- : \ d \to s \right\}$





$$V_{ub}^* V_{us} = A\lambda^4 e^{i\gamma} R_b$$
$$V_{cb}^* V_{cs} = A\lambda^2$$
$$V_{tb}^* V_{ts} = -V_{ub}^* V_{us} - V_{cb}^* V_{cs}$$

$$A\left(B_s^0 \to K^+K^-\right) = V_{ub}^* V_{us}\left(A_T' + P_u' - P_t'\right) + V_{cb}^* V_{cs}\left(P_c' - P_t'\right)$$

U-Spin Symmetry:

$$\frac{P_{\pi\pi}}{T_{\pi\pi}} = \frac{P_c - P_t}{A_T + P_u - P_t} = \frac{P_c' - P_t'}{A_T' + P_u' - P_t'} = \frac{P_{KK}}{T_{KK}} \equiv d e^{i\delta}$$

strong phase

$a_{CP}^{mix}\left(B_d^0 \to \pi^+\pi^-\right)$ $a_{CP}^{mix}\left(B_s^0 \to K^+K^-\right)$

$a_{CP}^{dir}\left(B_d^0 \to \pi^+\pi^-\right)$ $a_{CP}^{dir}\left(B_s^0 \to K^+K^-\right)$

$d, \ \delta, \ \boxed{\beta, \gamma}$ subject to U-Spin breaking corrections

$\left(\beta_s \text{ from } B_s \to J/\psi\varphi\right)$

β present in $B_d^0 - \overline{B}_d^0$ mixing

$V_{td} = |V_{td}| e^{-i\beta}$
$V_{ub} = |V_{ub}| e^{-i\gamma}$
$V_{ts} = |V_{ts}| e^{-i\beta_s}$

Golden Measurements

(Essentially no TH uncertainties)

1. Decays into CP-Eigenstates (time evolution)

$B_d^0 (\bar{B}_d^0) \to \psi K_s \Rightarrow \beta$ $\quad B_s^0 (\bar{B}_s^0) \to \psi\varphi \Rightarrow \beta_s$

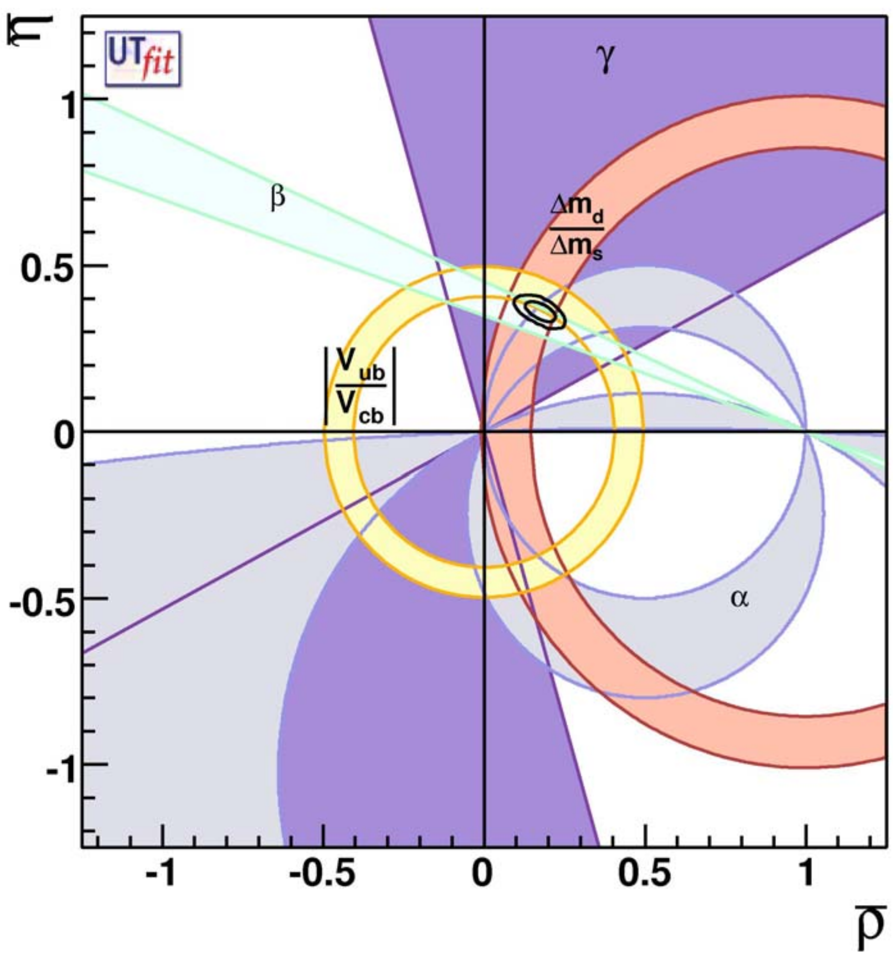
2. Decays into CP non-Eigenstates (time evolution)

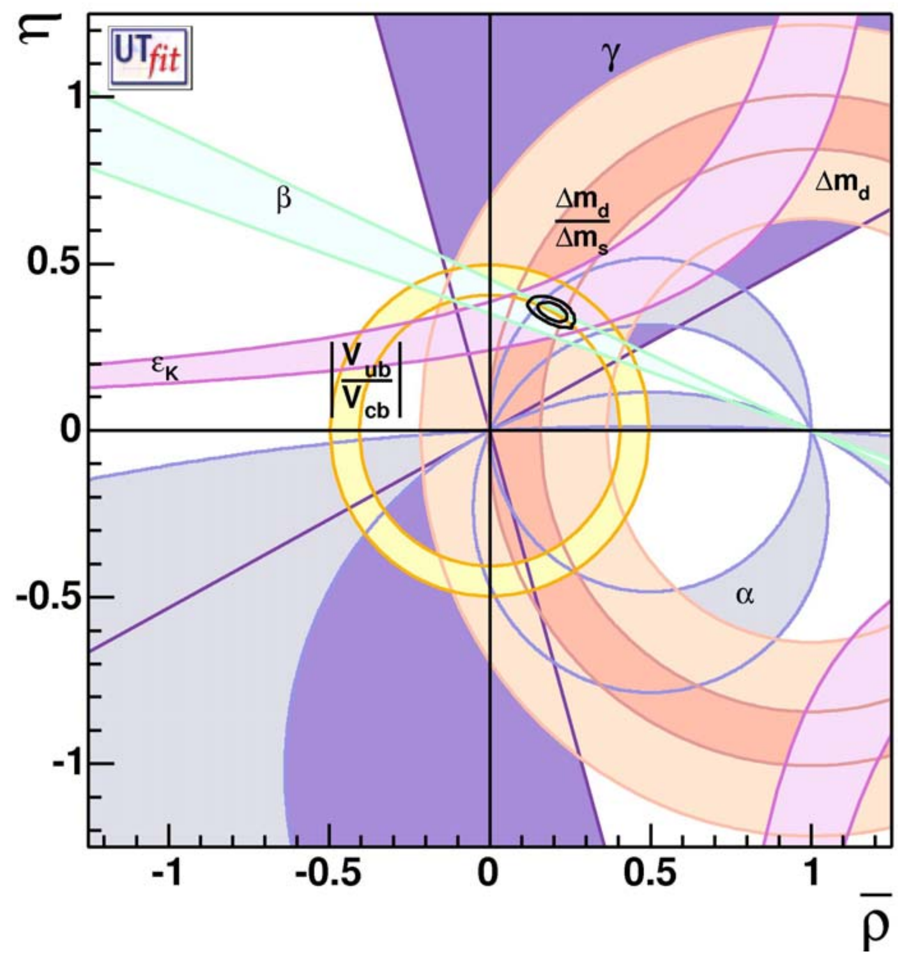
$B_d^0 (\bar{B}_d^0) \to D^{\pm}\pi^{\mp} \Rightarrow 2\beta + \gamma$ $\quad B_s^0 (\bar{B}_s^0) \to D_s^{\pm} K^{\mp} \Rightarrow 2\beta_s + \gamma$

3. $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ (branching ratios)

$Br(K^+ \to \pi^+ \nu\bar{\nu})$
$Br(K_L \to \pi^0 \nu\bar{\nu})$ $\Rightarrow \beta$ and γ

Unitarity Triangle 2006





5.

$$K_L \to \pi^0 \nu \bar{\nu}$$

$$K^+ \to \pi^+ \nu \bar{\nu}$$

Master Formula for Weak Decays

AJB (2001)
hep-ph/0101336
hep-ph/0109197

Non-Perturbative Factors in the SM	QCD RG Factors	Short Distance Loop Functions (Penguins, Boxes)	New Flavour-Changing Parameters

Represent different Dirac and Colour Stuctures

$$A(\mathrm{Decay}) = B_i\ \eta^i_{QCD}\ V^i_{CKM}\left[F^i_{SM} + F^i_{New}\right] + B^{New}_i\left[\eta^i_{QCD}\right]^{New} V^i_{New}\left[G^i_{New}\right]$$

(Summation over i)

Master Formula for Weak Decays

AJB (2001)
hep-ph/0101336
hep-ph/0109197

Non-Perturbative Factors in the SM	QCD RG Factors	Short Distance Loop Functions (Penguins, Boxes)	New Flavour-Changing Parameters

Represent different Dirac and Colour Stuctures

$$A(\mathrm{Decay}) = B_i\ \eta^i_{QCD}\ V^i_{CKM}\left[F^i_{SM} + F^i_{New}\right] + B_i^{New}\left[\eta^i_{QCD}\right]^{New} V^i_{New}\left[G^i_{New}\right]$$

(Summation over i)

$$A\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = B_+\left[\lambda_c \tilde{P}_c + \lambda_t X(v)\right]$$
$$A\left(K_L \to \pi^0 \nu\bar{\nu}\right) = B_L\ \mathrm{Im}\left(\lambda_t X(v)\right)$$

$$\lambda_c = V^*_{cs} V_{cd}$$
$$\lambda_t = V^*_{ts} V_{td}$$

B_+, B_L from $K^+ \to \pi^0 e^+ \nu$

$$X(v) = |X(v)| e^{i\theta_x}$$

v = parameters (m_t, ...)

Pure Short Distance Dynamics

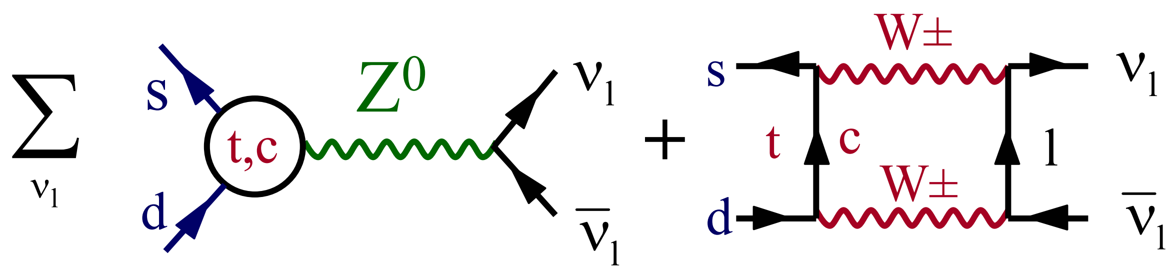
AJB, Romanino, Silvestrini (98)

$$\theta_x = \begin{cases} 0 & \mathrm{SM} \\ 0, \pi & \mathrm{MFV} \end{cases}$$

(AJB, Fleischer)

$K^+ \to \pi^+ \nu \bar{\nu}$

$\boxed{V_{td}}$



+ QCD Corrections:

Dib, Dunietz, Gilman LO (91)
Buchalla + AJB NLO (94)

$\underline{x_t = \overline{m}_t^2 / M_W^2}$

$$H_{eff} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2\theta_W} \sum_{\nu_l} \left(\lambda_c X_{NL}^l + \lambda_t X(x_t)\right) Q$$

$$\lambda_c = V_{cs}^* V_{cd} \qquad \lambda_t = V_{ts}^* V_{td} \qquad Q = (\bar{s}d)_{V-A} (\bar{\nu}\nu)_{V-A}$$

$$X(x_t) = X_0(x_t) + \frac{\alpha_s}{4\pi} X_1(x_t) \equiv \eta_x X_0(x_t)$$

$$X_1(x_t) = \tilde{X}_1(x_t) + \underbrace{8x_t \frac{\partial X_0(t)}{\partial x_t} \ln \frac{\mu_t^2}{M_W^2}}$$

$\boxed{\overline{m}_t(\mu_t)}$

For $\mu_t \cong m_t$

$\eta_x = 0.995$

Cancels μ_t-dependence in $X_0(x_t(\mu_t))$

$\boxed{X_{NL} \approx 10^{-3}}$

$\boxed{X(x_t) = 0.65 \cdot x_t^{0.575}}$

$$\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right)$$

- **Take:** $$H_{eff}\left(K^+ \to \pi^0 e^+ \nu\right) = \frac{G_F}{\sqrt{2}} V_{us}^* (\bar{s}u)_{V-A} (\bar{\nu}e)_{V-A}$$
- **Use: Isospin Symmetry**
$$\left\langle \pi^+ \middle| (\bar{s}d)_{V-A} \middle| K^+ \right\rangle = \sqrt{2} \left\langle \pi^0 \middle| (\bar{s}u)_{V-A} \middle| K^+ \right\rangle$$
- **For single ν with $m_{\pi^+} = m_{\pi^0}$**

$$\boxed{\frac{\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right)}{\mathrm{Br}\left(K^+ \to \pi^0 e^+ \nu\right)} = \frac{\alpha^2}{V_{us}^2\, 2\pi^2 \sin^4\theta_W} \left|\lambda_C X_{NL} + \lambda_t X(x_t)\right|^2}$$

- **Include Isospin breaking corrections** Marciano+ Parsa (95)

$$\left\{\begin{array}{l} m_{\pi^+} \neq m_{\pi^0} \\ \text{Isospin violation in } K \to \pi \text{ formfactors} \\ \text{Electromagnetic corrections affecting} \\ \bar{s} \to \bar{u} e^+ \nu \;\; \text{but not } \bar{s} \to \bar{d} \nu\bar{\nu} \end{array}\right\} \Rightarrow$$

Additional Factor

$$\boxed{r_{K^+} = 0.901}$$

Summing over 3 ν's

$$\mathrm{Br}\left(K^+\right)=\kappa_+\left[\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5}X(x_t)\right)^2+\left(\frac{\mathrm{Re}\,\lambda_c}{\lambda}P_c+\frac{\mathrm{Re}\,\lambda_t}{\lambda^5}X(x_t)\right)^2\right]$$

$$\kappa_+ = r_{K^+}\frac{3\alpha^2\mathrm{Br}\left(K^+\to\pi^0e^+\nu\right)}{2\pi^2\sin^4\theta_W}\lambda^8 = 4.84\cdot10^{-11}\left[\frac{\lambda}{0.224}\right]^8$$

$$\alpha = 1/128;\quad \sin^2\theta_W = 0.23;\quad \mathrm{Br}\left(K^+\to\pi^0e^+\nu\right)=4.87\cdot10^{-2}$$

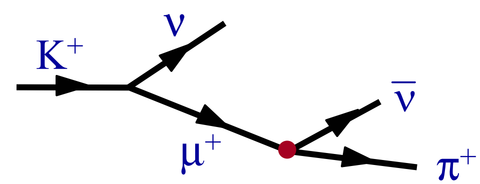
$$P_c = \frac{1}{\lambda^4}\left[\frac{2}{3}X^e_{NL}+\frac{1}{3}X^\tau_{NL}\right]=0.39\pm\overbrace{0.07}^{(m_c,\mu_c)}$$

			LO		NLO
μ_c, μ_t Uncertainty Br, $\lvert V_{td}\rvert$	:	Br	$\pm$ 22%	$\Rightarrow$	$\pm$ 7%
		$\lvert V_{td}\rvert$	$\pm$ 14%		$\pm$ 4%

$$\left\{\overline{m}_t(\mu_t),\overline{m}_c(\mu_c):\ 100\text{ GeV}\le\mu_t\le300\text{ GeV};\ 1\text{ GeV}\le\mu_c\le3\text{ GeV}\right\}$$

LD Effects < 5%
Rein, Sehgal
Hagelin, Littenberg
Lu, Wise; Fajfer

Smallness of LD related to absence of internal γ contributions (present in $K_L\to\pi^0e^+e^-, K_L\to\mu\bar{\mu}$)



$$\boxed{Br\left(K_L \to \pi^0 \nu\bar{\nu}\right)}$$

- **Consider one ν-flavour and denote:**

$$F \equiv \frac{G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2\theta_W}\left(\lambda_c X_{NL} + \lambda_t X(x_t)\right)$$

$$\boxed{H_{eff} = F\left(\bar{s}d\right)_{V-A}\left(\bar{\nu}\nu\right)_{V-A} + F^*\left(\bar{d}s\right)_{V-A}\left(\bar{\nu}\nu\right)_{V-A}}$$

- **Now:**

$$\boxed{K_L = \frac{1}{\sqrt{2}}\left((1+\bar{\varepsilon})\left|K^0\right\rangle + (1-\bar{\varepsilon})\left|\overline{K}^0\right\rangle\right)}$$

$$CP\left|K^0\right\rangle = -\left|\overline{K}^0\right\rangle; \qquad C\left|K^0\right\rangle = \left|\overline{K}^0\right\rangle$$

- $$\boxed{\begin{aligned} A\left(K_L \to \pi^0 \nu\bar{\nu}\right) = \frac{1}{\sqrt{2}}\Big(&F(1+\bar{\varepsilon})\left\langle\pi^0\left|\left(\bar{s}d\right)_{V-A}\right|K^0\right\rangle \\ &+F^*(1-\bar{\varepsilon})\left\langle\pi^0\left|\left(\bar{d}s\right)_{V-A}\right|\overline{K}^0\right\rangle\Big)\left(\bar{\nu}\nu\right)_{V-A}\end{aligned}}$$

- $$\left\langle \pi^0 \middle| \left(\bar{d}s\right)_{V-A} \middle| \overline{K}^0 \right\rangle = -\left\langle \pi^0 \middle| \left(\bar{s}d\right)_{V-A} \middle| K^0 \right\rangle$$

$$\boxed{A\left(K_L \to \pi^0 \nu\bar{\nu}\right) = \frac{1}{\sqrt{2}} \Big[\underbrace{F(1+\bar{\varepsilon}) - F^*(1-\bar{\varepsilon})}_{\approx 2\,\mathrm{Im}\,\lambda_t X(x_t)} \Big] \left\langle \pi^0 \middle| \left(\bar{s}d\right)_{V-A} \middle| K^0 \right\rangle \cdot \left(\bar{\nu}\nu\right)_{V-A}}$$

$\left(\mathrm{Im}\,\lambda_c = -\mathrm{Im}\,\lambda_t\right)$

$\left(X_{NL} \ll X(x_t)\right)$

- $$\left\langle \pi^0 \middle| \left(\bar{s}d\right)_{V-A} \middle| K^0 \right\rangle = \left\langle \pi^0 \middle| \left(\bar{s}u\right)_{V-A} \middle| K^+ \right\rangle$$

- $\left\{ \begin{array}{l} \text{Isospin Breaking} \\ \text{(Marciano, Parsa)} \end{array} \right\} \Rightarrow \left\{ r_{K_L} = 0.944 \right\}$

- **Summing over ν**

$$\boxed{Br\left(K_L \to \pi^0 \nu\bar{\nu}\right) = \kappa_{K_L} \left[\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right]^2}$$ ★

$$\kappa_{K_L} = \frac{\tau_{K_L}}{\tau_{K^+}} \frac{r_{K_L}}{r_{K^+}} \kappa_{K^+} = 2.12 \cdot 10^{-10} \left[\frac{\lambda}{0.224} \right]^8$$

Waiting for Precise Measurements of $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$

AJB, Schwab, Uhlig (04)

1. Present Status within SM (TH and Parametric Uncertainties)

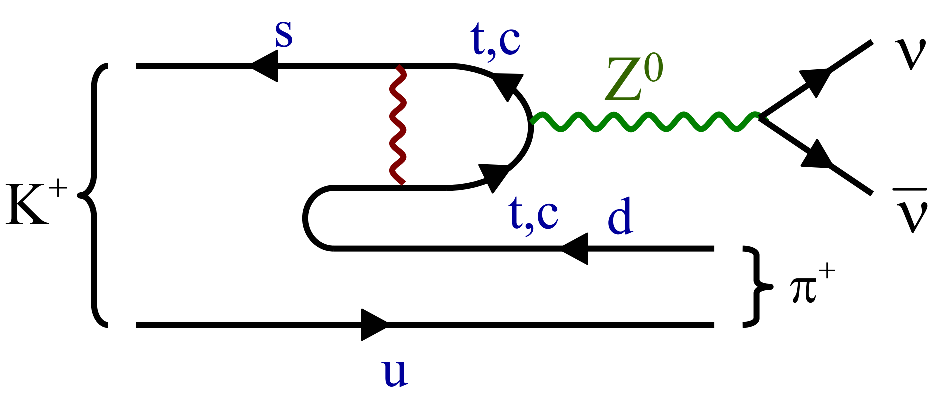
2. Impact of Present and Future Measurements of $K \to \pi\nu\bar{\nu}$ on CKM

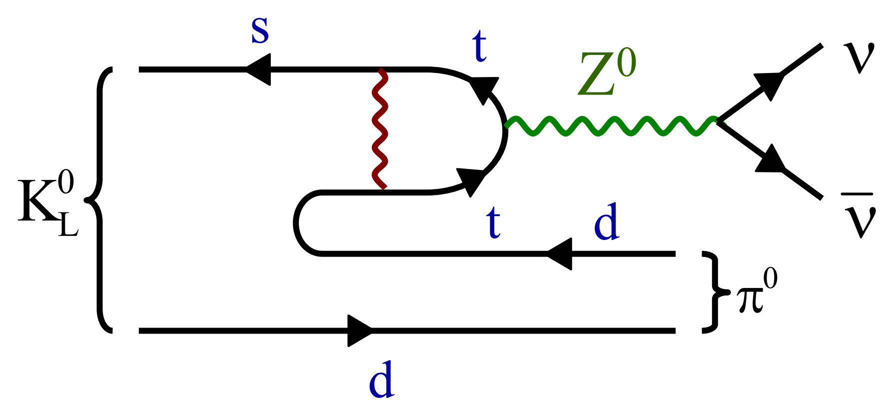
3. $K \to \pi\nu\bar{\nu}$ in Scenarios with New Complex Phases in EWP and $B_d^0 - \bar{B}_d^0$ Mixing

4. Interplay of $K \to \pi\nu\bar{\nu}$ with

   ~~CP~~ in B Decays
   $\Delta M_d/\Delta M_s$, Rare Decays

Decays $K \to \pi\nu\bar{\nu}$





Isospin Symmetry

$$\left\langle \pi^+ \middle| (\bar{s}d)_{V-A} \middle| K^+ \right\rangle = \sqrt{2} \left\langle \pi^0 \middle| (\bar{s}u)_{V-A} \middle| K^+ \right\rangle$$

$$\left\langle \pi^0 \middle| (\bar{s}d)_{V-A} \middle| K^0 \right\rangle = \left\langle \pi^0 \middle| (\bar{s}u)_{V-A} \middle| K^+ \right\rangle$$

Leading Decay: $\boxed{K^+ \to \pi^0 e^+ \nu}$

Isospin Breaking:

Marciano, Parsa (Suppression)

K^+(10%) K_L(5%)

Long Distance:

K^+: +(6±2)% Isidori, Mescia, Smith (2005)

K_L: ≤1% Buchalla, Isidori

Express Review of $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ and $K_L \rightarrow \pi^0 \nu\bar{\nu}$

AJB
Schwab
Uhlig
hep-ph/0405132

NLO: Buchalla + AJB (94); NNLO: AJB, Gorbahn, Haisch, Nierste (05)

SM: $\boxed{Br\left(K^+ \rightarrow \pi^+ \nu\bar{\nu}\right) = (8.0 \pm 1.1) \cdot 10^{-11}}$ $\boxed{Br\left(K_L \rightarrow \pi^0 \nu\bar{\nu}\right) = (2.8 \pm 0.6) \cdot 10^{-11}}$

Exp: $\boxed{Br\left(K^+ \rightarrow \pi^+ \nu\bar{\nu}\right) = \left(14.7 \begin{array}{c} +13.0 \\ -8.9 \end{array}\right) \cdot 10^{-11}}$ $\boxed{Br\left(K_L \rightarrow \pi^0 \nu\bar{\nu}\right) < 5.9 \cdot 10^{-7} (\text{KTeV})}$

Brookhaven: E787, E949
(CKM, NA48, JPARC, ..)

Soon improved by E391a !!!
(J-PARC, ...)

$\boxed{2.9 \cdot 10^{-7}}$
90% C.L.

TH very clean : $\left(\begin{array}{c}\text{With improved} \\ \text{CKM parameters} \\ \sim 2008\end{array}\right)$ $\Rightarrow$

$$\sigma\left(Br\left(K^+ \rightarrow \pi^+ \nu\bar{\nu}\right)\right) < 5\%$$
$$\sigma\left(Br\left(K_L \rightarrow \pi^0 \nu\bar{\nu}\right)\right) < 5\%$$

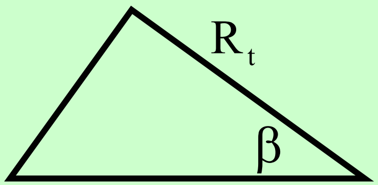
Very clean determination of Unitarity Triangle

$\sigma(Br) \cong 10\%$	$\sigma(\sin 2\beta \cong 0.04)$	$\sigma(\gamma) = 9^o$	$\sigma(\lvert V_{td}\rvert) = 7\%$
$\sigma(Br) \cong 5\%$	$\sigma(\sin 2\beta \cong 0.025)$	$\sigma(\gamma) = 5^o$	$\sigma(\lvert V_{td}\rvert) = 4\%$

Basic Formulae for $K^+ \to \pi^+ \nu\bar{\nu}$ (SM)

$$X \equiv X(m_t)$$

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = 4.8\cdot 10^{-11}\left[A^4 R_t^2 X^2 + 2P_c A^2 R_t X\cos\beta + P_c^2\right]$$



$$= 10^{-11}\left[\underset{\text{(top)}}{4.2} + \underset{\text{(top-charm)}}{3.1} + \underset{\text{(charm)}}{0.7}\right]$$

$$A = \frac{|V_{cb}|}{\lambda^2} \cong 0.83$$

Buchalla AJB (94) NLO)

$$P_c = 0.367 \pm \underbrace{0.033}_{\Delta m_c = 50\,\text{MeV}} \pm \underbrace{0.037}_{\text{theory}} \pm \underbrace{0.009}_{\alpha_s} \cong 0.37 \pm 0.07$$

BGHN NNLO (05)

$$P_c = 0.371 \pm 0.031_{m_c} \pm \underbrace{0.009}_{\text{theory}} \pm \underbrace{0.009}_{\alpha_s} = 0.37 \pm 0.04$$

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)_{SM} = \left[8.0 \pm \underbrace{0.5}_{P_c} \pm \underbrace{0.8}_{\text{CKM}}\right]10^{-11} \cong (8.0 \pm 1.1)10^{-11}$$

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left[14.7\,^{+13.0}_{-8.9}\right]10^{-11}$$

E787 (2)
E949 (1)
<u>3 Events</u>

QCD Corrections to $K \to \pi\nu\bar{\nu}$

LO | NLO | NNLO

Charm Part

$$P_c = \frac{4\pi}{\alpha_s(\mu_c)} P_c^{(0)} + P_c^{(1)} + \frac{\alpha_s(\mu_c)}{4\pi} P_c^{(3)}$$

$$\mu_c = 0(m_c)$$

Vainshtein, Zakharov, Novikov Shifman (1977)
Ellis, Hagelin (1983)
Dib, Dunietz, Gilman (1991)

Buchalla
AJB
(1994)

AJB
Gorbahn
Haisch
Nierste
(2005)

$$x_t = \frac{m_t^2(\mu_t)}{M_W^2}$$

Top Part

$$X^{SM}(x_t) = X_0(x_t) + \frac{\alpha_s(\mu_t)}{4\pi} X_1(x_t)$$

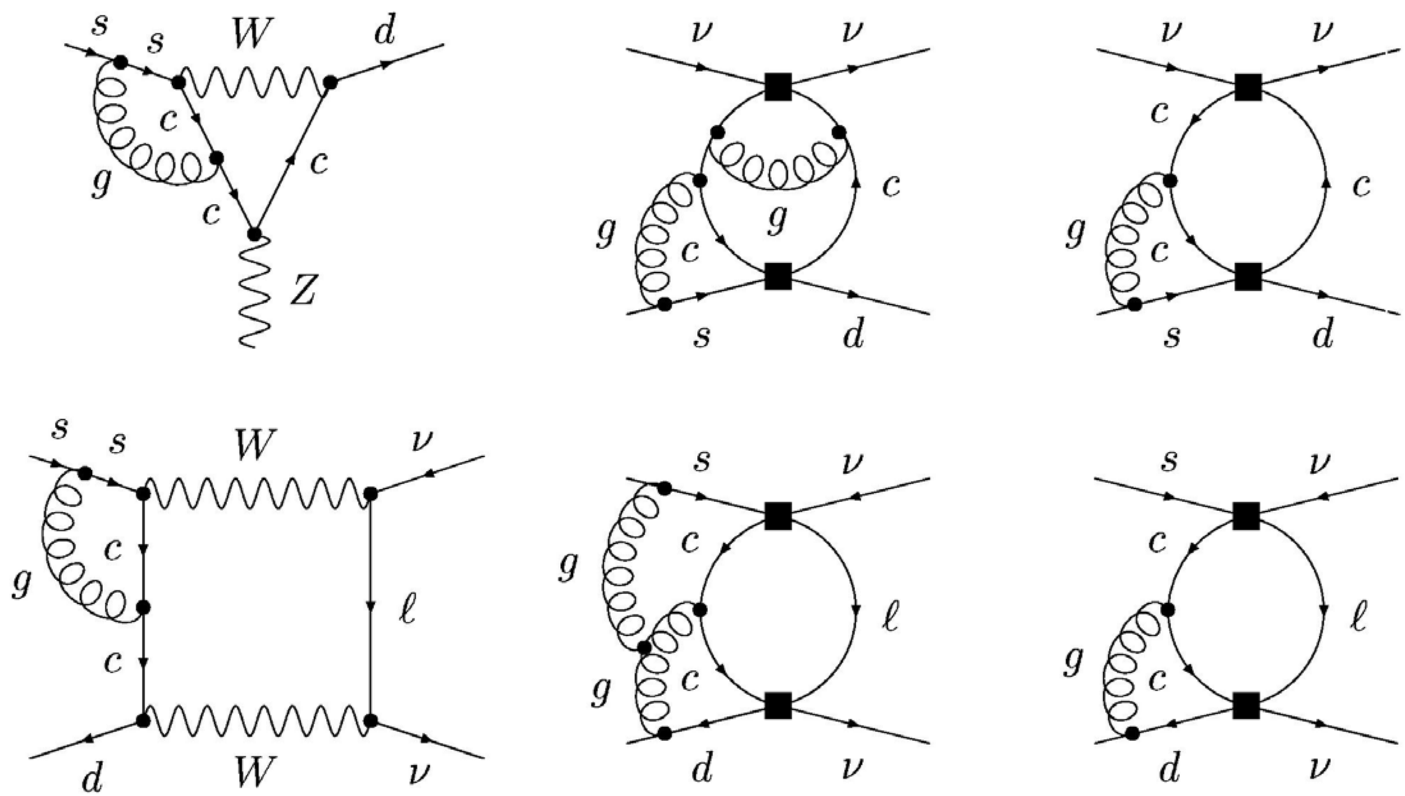
Inami, Lim (81)
AJB (81)

Buchalla, AJB (93)
Misiak, Urban (98)

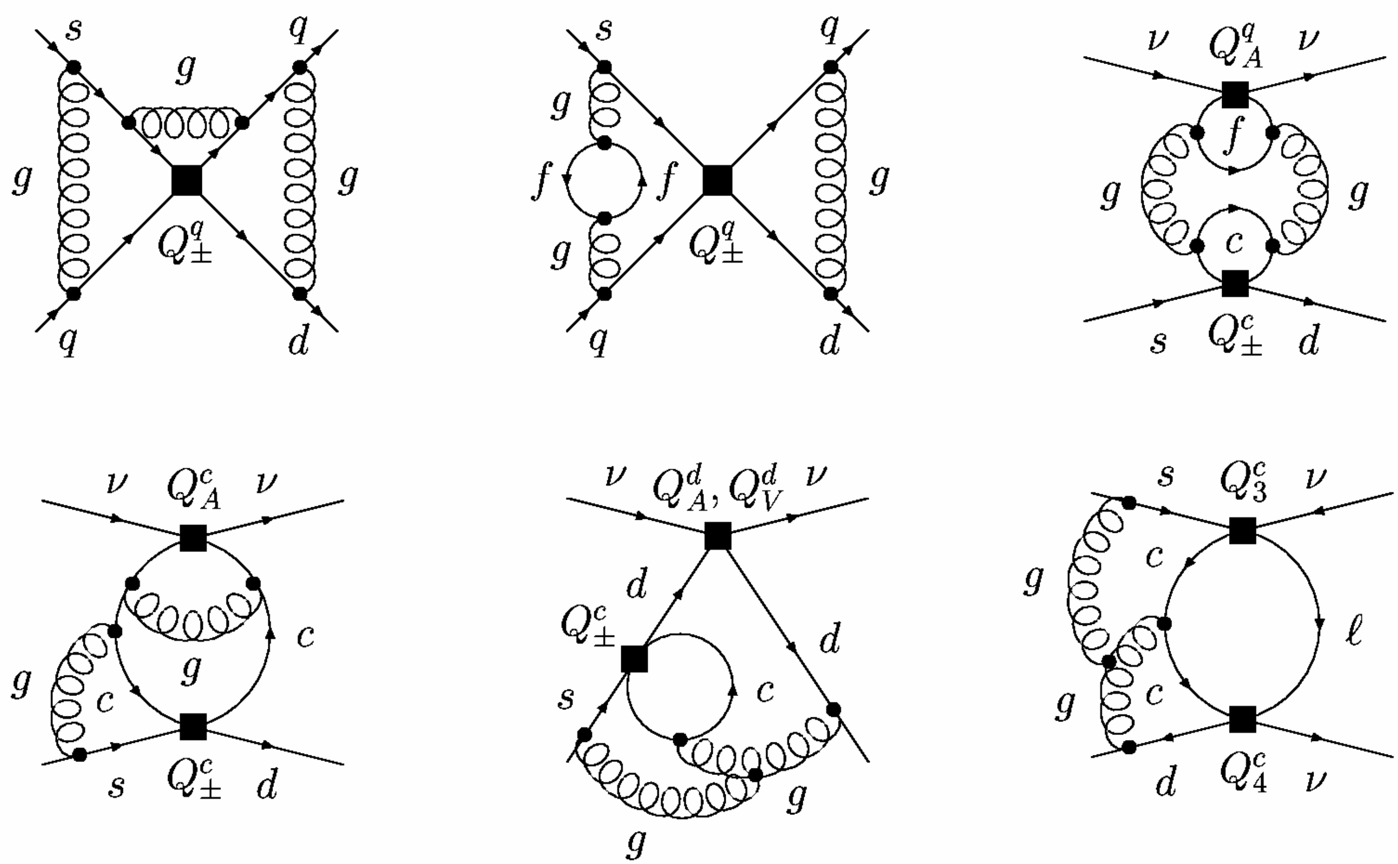
C_i (μ_w)

3-Loop Anomalous Dimensions

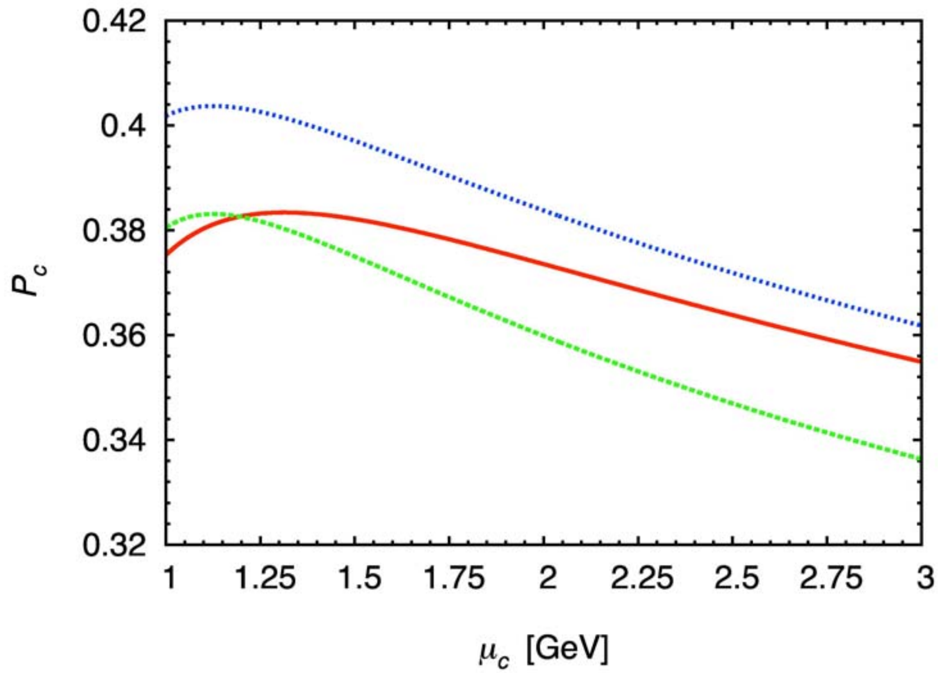
Matrix Elements



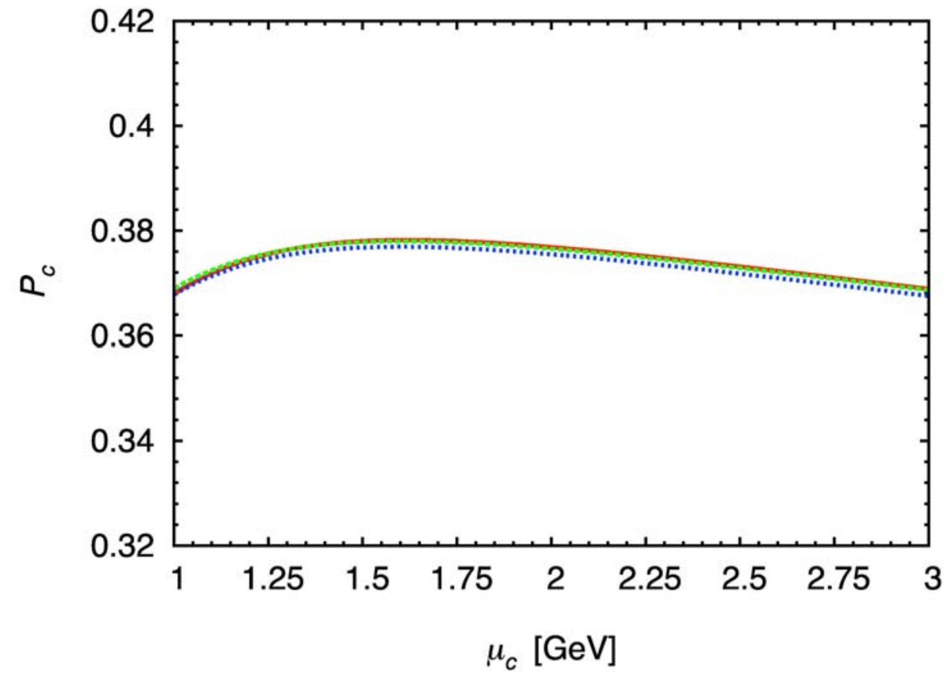
No Comments


s
q
g
g
g
$Q^q_\pm$
q
d
s
q
g
f
f
g
$Q^q_\pm$
g
q
d
ν
Q^q_A
ν
f
g
g
c
s
$Q^c_\pm$
d
ν
Q^c_A
ν
c
g
g
c
s
$Q^c_\pm$
d
ν
Q^d_A, Q^d_V
ν
d
$Q^c_\pm$
d
s
c
g
g
s
Q^c_3
ν
g
c
ℓ
g
c
d
Q^c_4
ν

$P_c(\mu_c)$ for various calculations of $\alpha_s(\mu_c)$ from $\alpha_s(M_Z)$

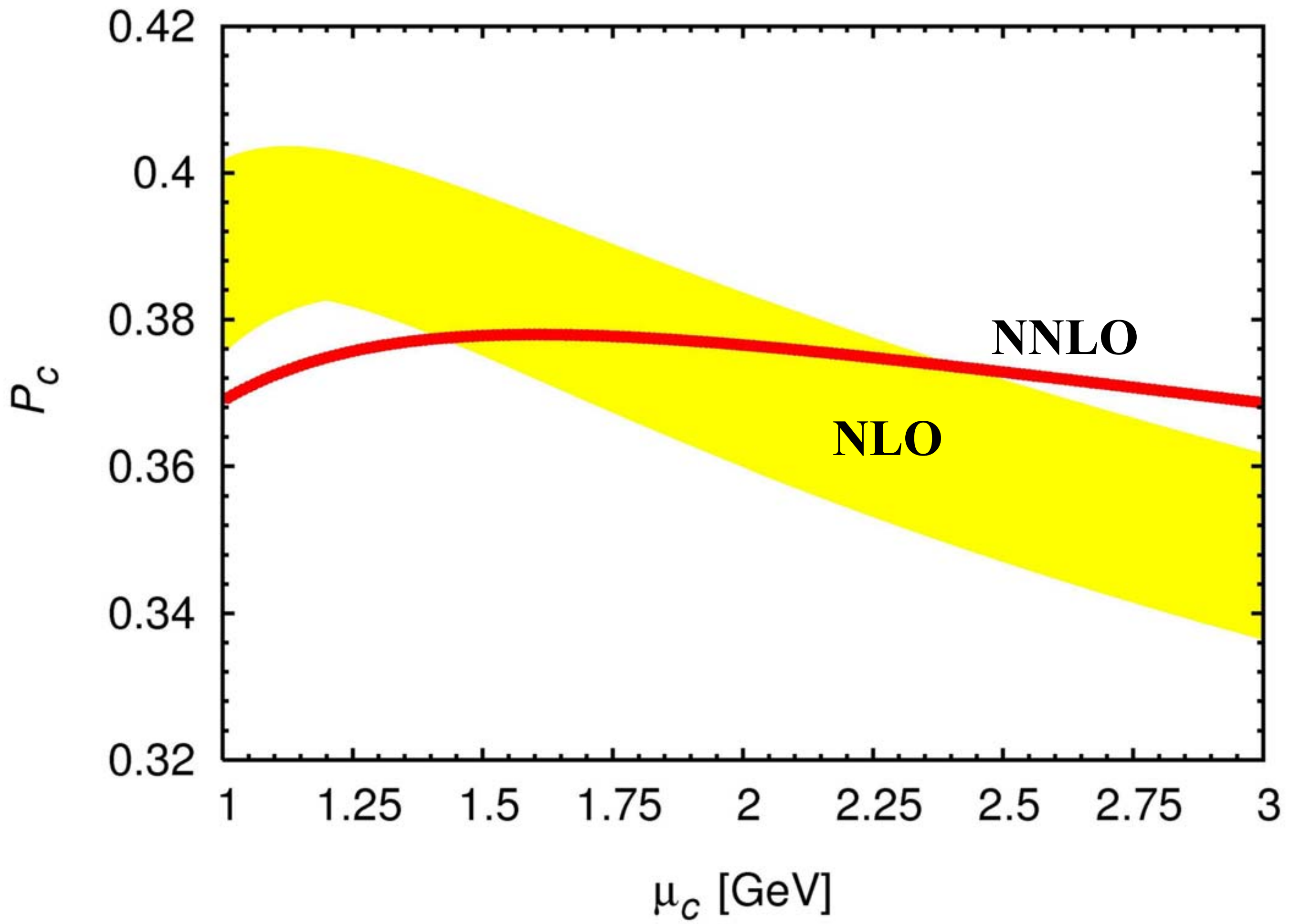


NLO



NNLO

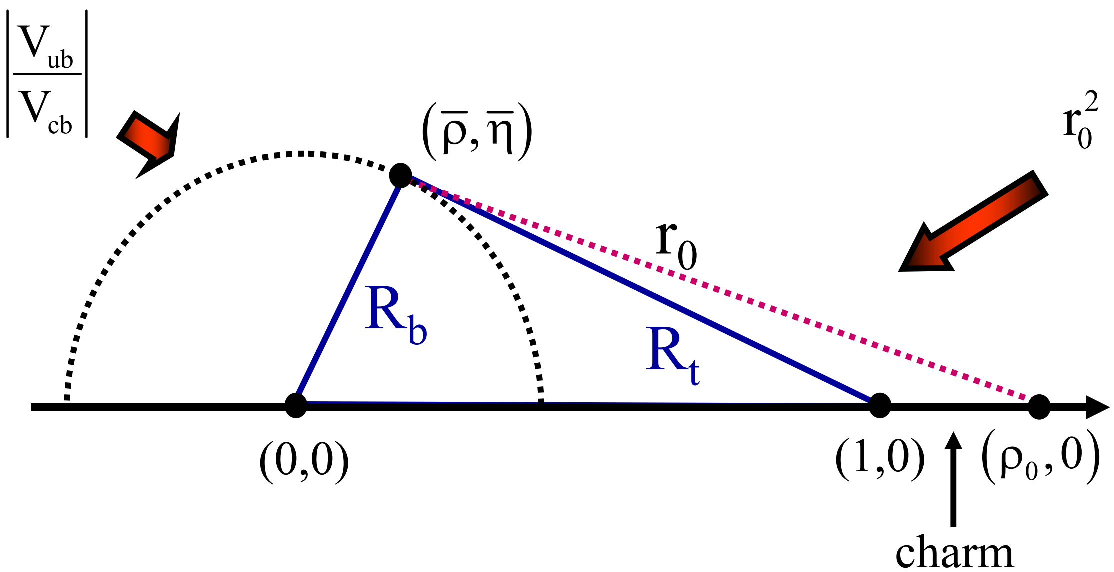
Reduction of TH Error in P_c



$K^+ \to \pi^+ \nu\bar{\nu}$ in the $(\bar{\rho}, \bar{\eta})$ Plane

$$\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = 4.31 \cdot 10^{-11} A^4 X^2(m_t) \frac{1}{\sigma}\left[\left(\sigma\bar{\eta}\right)^2 + \left(\rho_0 - \bar{\rho}\right)^2\right]$$

$$\sigma = \frac{1}{\left(1-\lambda^2/2\right)^2} \qquad \rho_0 = 1 + \frac{P_c}{A^2 X(m_t)} \approx 1.4$$



$$r_0^2 = \frac{1}{A^4 X^2(m_t)}\left[\frac{\sigma \mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right)}{4.31 \cdot 10^{-11}}\right]$$

$$R_t = 1 + R_b^2 - 2\bar{\rho}$$

$$V_{td} = A\lambda^3\left(1 - \bar{\rho} - i\bar{\eta}\right)$$

$$\left|V_{td}\right| = \lambda \left|V_{cb}\right| R_t$$

Anatomy of $|V_{td}|$ from $K^+ \to \pi^+ \nu\bar{\nu}$

AJB
Schwab
Uhlig

$$\frac{\sigma(|V_{td}|)}{|V_{td}|} = 0.39\frac{\sigma(P_c)}{P_c} + 0.70\frac{\sigma(Br(K^+))}{Br(K^+)} + \frac{\sigma(|V_{cb}|)}{|V_{cb}|}$$

Present:	$\pm$ 4%	$\pm$ (Very Large)	$\pm$ 2%	
$\left.\begin{matrix}\sigma(Br(K^+)) = 10\% \\ \sigma(P_c) = 0.03\end{matrix}\right\}$	$\pm$ 3%	$\pm$ 7%	$\pm$ 1.4%	(Scenario I)
$\left.\begin{matrix}\sigma(Br(K^+)) = 5\% \\ \sigma(P_c) = 0.02\end{matrix}\right\}$	$\pm$ 2%	$\pm$ 3.5%	$\pm$ 1%	(Scenario II)

Determination
at 4-5% possible

Theoretically clean Relations

D´Ambrosio + Isidori (02)

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \bar{\kappa}_+ \left|V_{cb}\right|^4 X^2 \left[R_t^2 \sin^2\beta + \left(R_t \cos^2\beta + \frac{\lambda^4 P_c}{\left|V_{cb}\right|^2 X} \right)^2 \right]$$

$$R_t \sim \xi \frac{\sqrt{\Delta M_d}}{\sqrt{\Delta M_s}} \qquad \bar{\kappa}_+ = 7.64 \cdot 10^{-6} \qquad P_c = 0.37 \pm 0.04$$

AJB, Schwab, Uhlig (04)

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \bar{\kappa}_+ \left|V_{cb}\right|^4 X^2 \left[T_1^2 + \left(T_2 + \frac{\lambda^4 P_c}{\left|V_{cb}\right|^2 X} \right)^2 \right]$$

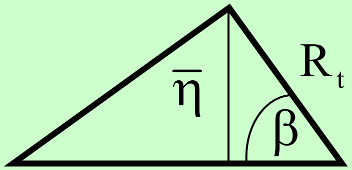
$$T_1 = \frac{\sin\beta \sin\gamma}{\sin\left(\beta + \gamma\right)} \qquad T_2 = \frac{\cos\beta \sin\gamma}{\sin\left(\beta + \gamma\right)}$$

(Direct $\not{C}\not{P}$)

Basic Formulae for $K_L \to \pi^o \nu\bar{\nu}$

(SM) Buchalla AJB (NLO)

$$Br\left(K_L \to \pi^o \nu\bar{\nu}\right) = 2.8 \cdot 10^{-11} \left[\frac{\bar{\eta}}{0.35}\right]^2 \left[\frac{|V_{cb}|}{41.5 \cdot 10^{-3}}\right]^4 \left[\frac{X}{1.48}\right]^2$$



$$= \left(2.8 \pm \overbrace{0.6}^{\text{CKM}}\right) \cdot 10^{-11}$$

(AJB Schwab Uhlig)

E391a : $Br\left(K_L \to \pi^o \nu\bar{\nu}\right) < 2.9 \cdot 10^{-7}$

Future: E391a, JHF

Model independent bound (Grossman, Nir)

$$Br\left(K_L \to \pi^o \nu\bar{\nu}\right) \leq 4.4\, Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) \leq 1.4 \cdot 10^{-9}\,(90\%\,C.L.)$$

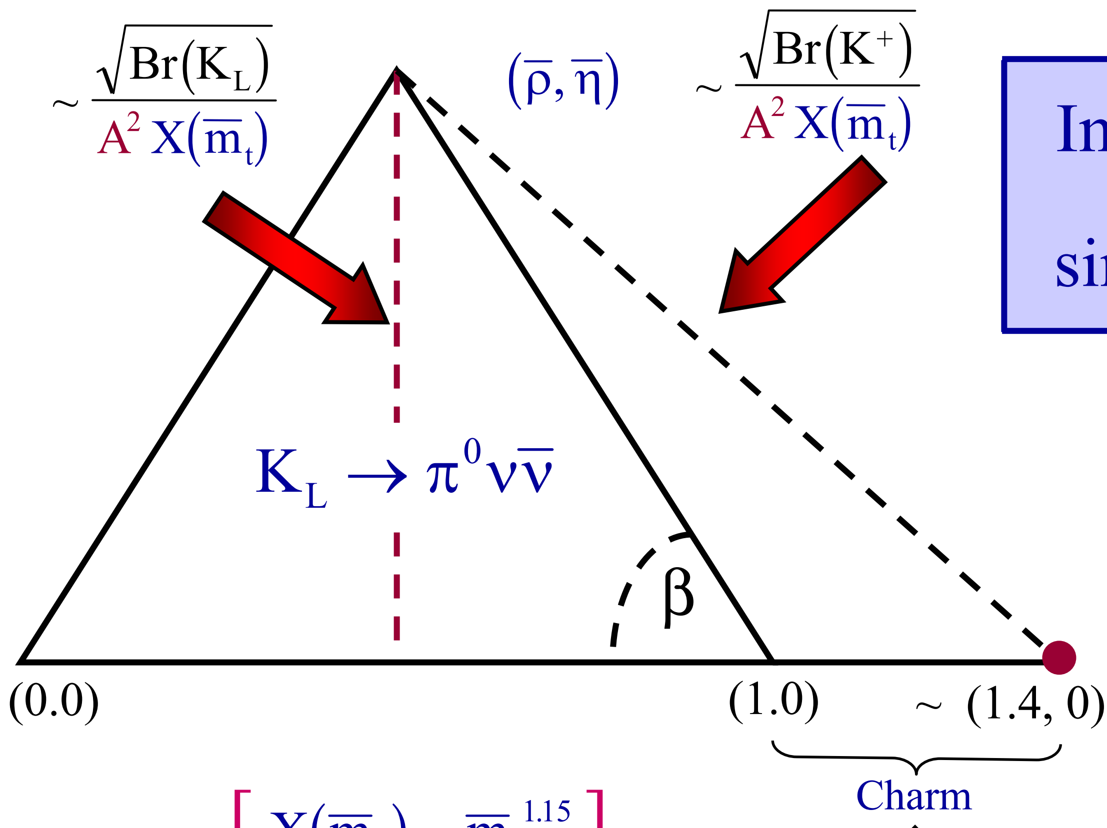
E391a could get the first non-trivial upper bound.

$$\boxed{\bar{\eta} = R_t \sin\beta}$$

E391 (JHF): ~ 1000 Events

UT from $K \to \pi\nu\bar{\nu}$

Buchalla
AJB



$$\mathrm{Im}\,\lambda_t = F_1\left(\overline{m}_t, Br(K_L)\right)$$

$$\sin 2\beta = F_2\left(P_c, Br(K_L), Br(K^+)\right)$$

$$\lambda_t = V_{ts}^* V_{td}$$

$\sin 2\beta$ $(K \to \pi\nu\bar{\nu})$ ⟺ $\sin 2\beta$ $(B \to J/\psi, K_s)$ $\to \varphi K_s$

$[\, X(\overline{m}_t) \sim \overline{m}_t^{\,1.15} \,]$

$(0.37 \pm 0.04) \Rightarrow P_c \sim \frac{P_c}{A^2 X(\overline{m}_t)}$

K-Physics ⟺ B - Physics

Test of SM and Beyond

The Angle β from $K \to \pi\nu\bar{\nu}$

Buchalla, AJB (94)
AJB, Schwab, Uhlig (04)

BSU:

$$\frac{\sigma(\sin 2\beta)}{\sin 2\beta} = 0.31\frac{\sigma(P_c)}{P_c} + 0.55\frac{\sigma(Br(K^+))}{Br(K^+)} \pm 0.39\frac{\sigma(Br(K_L))}{Br(K_L)}$$

$\sigma(\sin 2\beta) =$	± 0.041	$\pm$?	$\pm$?	(Present)
$\sigma(\sin 2\beta) =$	0.017	± 0.039	± 0.028	(Scenario I) Br´s at 10%
$\sigma(\sin 2\beta) =$	0.011	± 0.020	± 0.014	(Scenario II) Br´s at 5%

TH very clean

$\sigma(\sin 2\beta) \approx 0.02 - 0.03$ requires $\sigma(Br's) \leq 5\%$

The Angle γ from $K \to \pi\nu\bar{\nu}$

AJB, Schwab, Uhlig (04)

$$\frac{\sigma(\gamma)}{\gamma} = 0.75\frac{\sigma(P_c)}{P_c} + 1.32\frac{\sigma(Br(K^+))}{Br(K^+)} + 0.07\frac{\sigma(Br(K_L))}{Br(K_L)} + 4.1\frac{\sigma(|V_{cb}|)}{|V_{cb}|}$$

$\sigma(\gamma) =$	$\pm 8.3^\circ$	$\pm ?$	$\pm ?$	$\pm 4.9^\circ$	(Present)
$\sigma(\gamma) =$	$\pm 3.7^\circ$	$\pm 8.5^\circ$	$\pm 0.4^\circ$	$\pm 3.8^\circ$	(Scenario I) Br´s at 10%
$\sigma(\gamma) =$	$\pm 2.5^\circ$	$\pm 4.2^\circ$	$\pm 0.2^\circ$	$\pm 2.5^\circ$	(Scenario II) Br´s at 5%

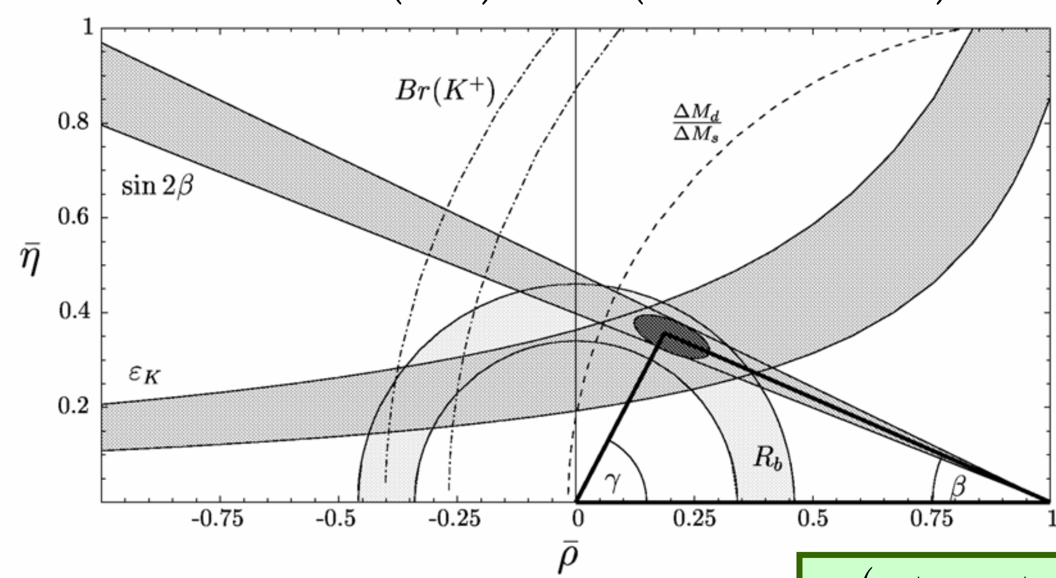
TH very clean

$\sigma(\gamma) \approx \pm 5^\circ$ requires $\sigma(Br(K^+)) \leq 5\%$

Unitarity Triangle 2004

(AJB, Schwab, Uhlig)

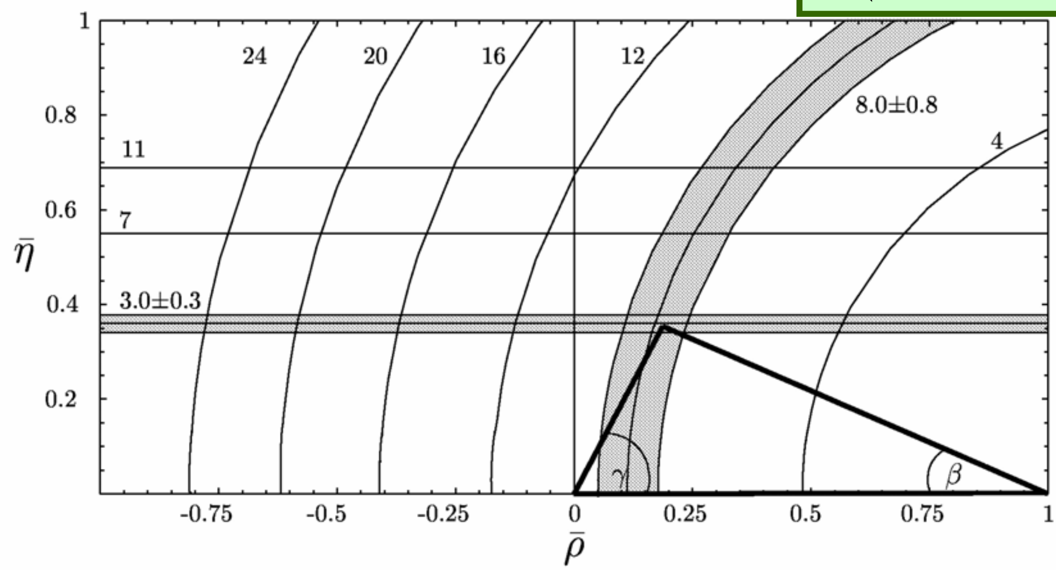
$$\mathrm{Br}\left(K^{+}\right) \equiv \mathrm{Br}\left(K^{+} \to \pi^{+}\nu\bar{\nu}\right) = 14.7 \cdot 10^{-11}$$



$$P_c = \underline{\underline{0.37}} \pm 0.04$$

m_c, V_{cb}, μ_c

$\mathrm{Br}\left(K^{+} \to \pi^{+}\nu\bar{\nu}\right)$



$\mathrm{Br}\left(K_L \to \pi^{0}\nu\bar{\nu}\right)$

Unitarity Triangle from $K \to \pi\nu\bar{\nu}$

(2012)

6.

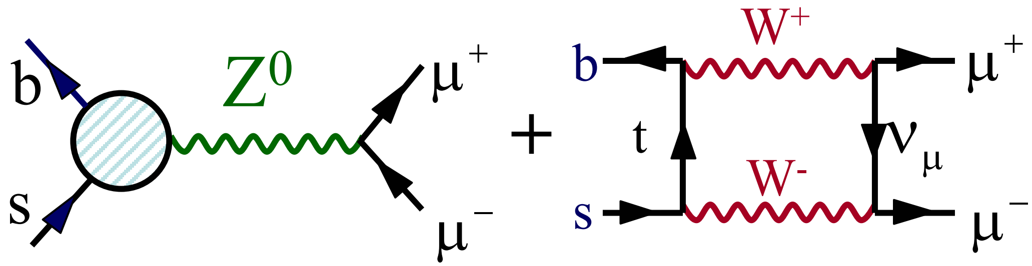
Rare B and K Decays

$$B_{s,d} \to \mu^+\mu^- \qquad B \to X_{s,d}\,\nu\bar{\nu}$$

$$B \to X_s\gamma \qquad B \to X_s l^+ l^-$$

$$K_L \to \pi^0 l^+ l^-$$

$B_s \to \mu^+\mu^-$



$+$ QCD Corrections

Buchalla, AJB (93)
Misiak, Urban (98)

$$Br\left(B_s \to \mu^+\mu^-\right) = 3.8\cdot 10^{-9}\left[\frac{\tau(B_s)}{1.46\mathrm{ps}}\right]\left[\frac{F_{B_s}}{230\mathrm{MeV}}\right]^2\left[\frac{|V_{ts}|}{0.040}\right]^2\left[Y(x_t)\right]^2$$

$$Y(x_t) = 1.02\left[\frac{m_t(m_t)}{170\mathrm{GeV}}\right]^{1.56} \approx 1 \qquad F_{B_s} = (230 \pm 30)\mathrm{MeV}$$

$$\tau(B_s) = (1.46 \pm 0.05)\mathrm{ps}$$

(Dominant uncertainty)

SM: $Br\left(B_s \to \mu^+\mu^-\right) = (3.7 \pm 1.0)\cdot 10^{-9}$

$Br\left(B_s \to \mu^+\mu^-\right) < 1\cdot 10^{-7}$

CDF 95% C.L.

$B_d \to \mu^+\mu^-$ (just replace s→d)

$$\mathrm{Br}\left(B_d \to \mu^+\mu^-\right) = 1.0 \cdot 10^{-10}\left[\frac{\tau(B_d)}{1.54\,\mathrm{ps}}\right]\left[\frac{F_{B_d}}{190\,\mathrm{MeV}}\right]^2\left[\frac{|V_{td}|}{0.008}\right]^2\left[Y(x_t)\right]^2$$

$$\tau(B_d) = (1.540 \pm 0.014)\,\mathrm{ps} \qquad F_{B_d} = (189 \pm 27)\,\mathrm{MeV}$$

$$|V_{td}| = (8.24 \pm 0.54) \cdot 10^{-3}$$

SM: $\mathrm{Br}\left(B_d \to \mu^+\mu^-\right) = (1.04 \pm 0.34) \cdot 10^{-10}$

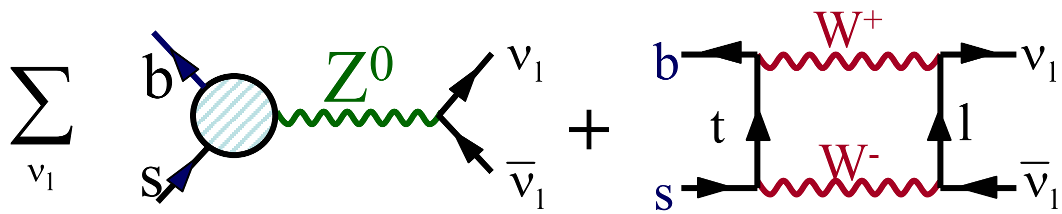
CDF: $\mathrm{Br}\left(B_d \to \mu^+\mu^-\right) < 3 \cdot 10^{-8}$ (95% C.L.)

$$\frac{F_{B_s}}{F_{B_d}} = 1.22 \pm 0.06$$

$$\frac{\mathrm{Br}\left(B_s \to \mu^+\mu^-\right)}{\mathrm{Br}\left(B_d \to \mu^+\mu^-\right)} = \frac{\tau(B_s)}{\tau(B_d)}\frac{m_{B_s}}{m_{B_d}}\left[\frac{F_{B_s}}{F_{B_d}}\right]^2\left[\frac{|V_{ts}|}{|V_{td}|}\right]^2$$

Useful measurement of $|V_{td}|$

$B \to X_s \nu\bar{\nu}$



+ QCD Corrections

Buchalla, AJB (93)
Misiak, Urban (98)

$$Br(B \to X_s \nu\bar{\nu}) = 1.58 \cdot 10^{-5} \left[\frac{|V_{ts}|}{0.040}\right]^2 [X(x_t)]^2$$

$$[X(x_t)] = 1.57 \left(\frac{m_t(m_t)}{170\,\mathrm{GeV}}\right)^{1.15}$$

SM: $Br(B \to X_s \nu\bar{\nu}) = (3.66 \pm 0.21) \cdot 10^{-5}$

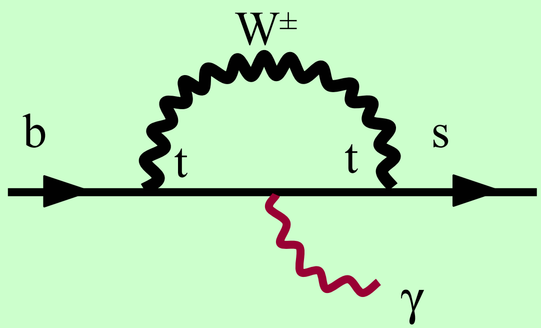
ALEPH: $Br(B \to X_s \nu\bar{\nu}) < 6.4 \cdot 10^{-4}$

$$\frac{Br(B \to X_d \nu\bar{\nu})}{Br(B \to X_s \nu\bar{\nu})} = \frac{|V_{td}|^2}{|V_{ts}|^2}$$

Theoretically cleanest measurement of $|V_{td}|/|V_{ts}|$ ★

Long Distance Effects neglegible: Buchalla, Isidori, Rey

$B \to X_s \gamma$



+ Large SD QCD Corrections

γ = on shell

Bertolini, Borzumati, Masiero (1987)
Deshpande, Lo, Trampetic, Eilam, Singer (1987)

Dominant Operator : $Q_7 = m_b \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$

(Magnetic Penguins)

QCD Enhancement (~ 3) governed by the Mixing of Q_7 with

$Q_2 = (\bar{b}c)_{V-A} (\bar{c}s)_{V-A}$

$$Br(B \to X_s \gamma) = \begin{cases} (3.52 \pm 0.30) \cdot 10^{-4} & \text{CLEO, BaBar, Belle} \\ (3.70 \pm 0.30) \cdot 10^{-4} & \text{SM} \end{cases}$$

Sensitive to New Physics! Important for constraining Supersymmetry !!

NLO-QCD Corrections Saga 1994-2002

1993 : Identification of strong: Ali, Greub; AJB, Misiak, Münz, Pokorski
μ_b dependence (~ 60%)

Initial Conditions : Adel, Yao (93); Greub, Hurth (97); AJB, Kwiatkowski, Pott (97)
Ciuchini, Degrassi, Gambino, Giudice (97)

Two and Three-Loop Anomalous Dimensions : AJB, Jamin, Lautenbacher, Weisz (92); Ciuchini, Franco, Martinelli, Reina (93)
Misiak, Münz (95) (Two-Loop Mixing of Magnetic Operators)
Chetyrkin, Misiak, Münz (97) (Three-Loop Mixing between Q_7 and Q_2)

Operator Matrix Elements : Greub, Hurth, Wyler (1996)
AJB, Czarnecki, Misiak, Urban (2001)

Review:
AJB, Misiak (2003)

Gluon Bremstrahlung : Ali, Greub (91)
Pott (95)

$B \to X_s\gamma$ beyond NLO $\to$ NNLO

2001: Gambino, Misiak (significant uncertainty due to m_c)

⇨ Go beyond NLO

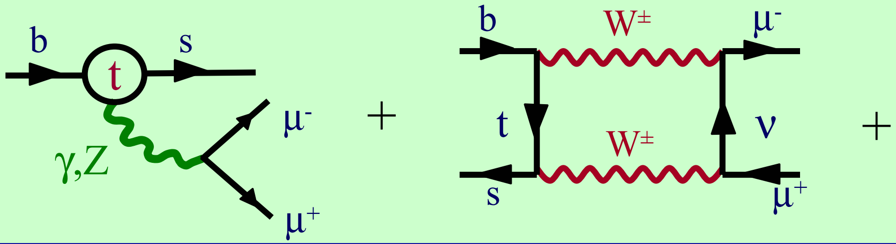
Considerable Progress made:

- Misiak, Steinhauser (2004) — Initial Conditions
- Bieri, Greub, Steinhauser (2003) — Matrix Elements (first steps)
- Gorbahn, Haisch (2005)
- Gorbahn, Haisch, Misiak (2005) — Three-Loop Mixing of Magnetic Penguins

4-Loop Mixing $Q_2 \leftrightarrow Q_7$: Czakon, Haisch, Gorbahn, Steinhauser, ...

$B \to X_s \mu^+ \mu^-$

Hou, Willey, Soni (87)



Smaller Magnetic Penguins

QCD (LO): Grinstein, Savage, Wise (89)

QCD (NLO): Misiak (94)
AJB + Münz (94)

Operators:

$$Q_{9V} = (\bar{s}b)_{V-A}(\bar{\mu}\mu)_V$$
$$Q_{10V} = (\bar{s}b)_{V-A}(\bar{\mu}\mu)_A$$

$+$

$$Q_7 = m_b \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$$

Known from $B \to X_s \gamma$

$$\frac{d\sigma}{ds} \approx \frac{\alpha^2}{4\pi}(1-s)^2 |V_{ts}|^2 \left[(1+2s)\left(|C_9(s)|^2 + |C_{10}|^2\right) + 4\left(1+\frac{2}{s}\right)|C_7|^2 + 12 C_7 C_9 \right]$$

$$s = \frac{\left(P_{\mu^+} + P_{\mu^+}\right)^2}{m_b^2}$$

$$C_9(s) = P_0^{NLO}(s) + \frac{Y(x_t)}{\sin^2\theta_w} - 4Z(x_t)$$

$$C_{10} = -\frac{Y(x_t)}{\sin^2\theta_w}$$

$[\ \ ] = U(s)$

Recent Developments on $B \to X_s \mu^+ \mu^-$

NNLO QCD

Bobeth, Misiak, Urban (2000)
Ghinculov, Hurth, Isidori, Yao (2002-2004)
Asatryan, Asatrian, Greub, Walker (2002-2004)
Asatrian, Asatryan, Hovhannisyan, Poghosyan (2004)
Bobeth, Gambino, Gorbahn, Haisch (2004)

$$\mathrm{Br}\left(B \to X_s l^+ l^-\right) = \begin{cases} (4.5 \pm 1.0) \cdot 10^{-6} & \text{Exp} \\ (4.4 \pm 0.7) \cdot 10^{-6} & \text{SM} \end{cases}$$

(low s region)

(below $c\bar{c}$ resonance)

In order to test better look at $A_{FB}(s) \equiv$ Forward – Backward Asymmetry

(see Section 6)

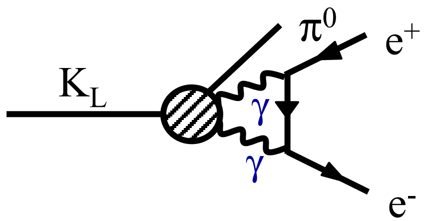
$$A_{FB}(s) = -3C_{10} \frac{\left[sC_9(s) + 2C_7\right]}{U(s)}$$

Vanishes at s_0: $s_0 C_9(s_0) + 2C_7 = 0$

Theoretically clean; sensitive to New Physics.

$\boxed{K_L \to \pi^0 e^+ e^-}$ (3 contributions)

1. $K_L \to \pi^0\gamma\gamma \to \pi^0 e^+ e^-$ ⇐ **CP conserving**



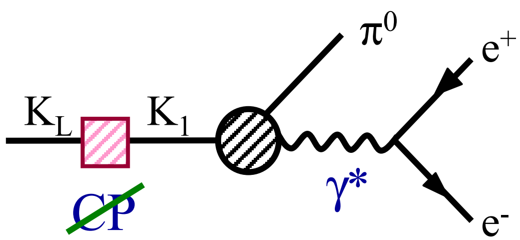
Donoghue, Holstein, Valencia, Ecker, Pich, de Rafael, Flynn, Randall, Seghal, Heiliger, Fajfer (95)
Cohen, Ecker, Pich (93)
Donoghue, Gabbiani (95)
Ambrosio, Portoles (97)

[Using KTeV (99) $K_L \to \pi\gamma\gamma$]

2. $K_L \xrightarrow{K_1} \pi^0\gamma^* \to \pi^0 e^+ e^-$ ⇐ **indirect ~~CP~~**

$\boxed{K_L \cong K_2 + \varepsilon K_1}$

★ $\left(K_S \to \pi^0 e^+ e^-\right.$ helps here!$\left.\right)$

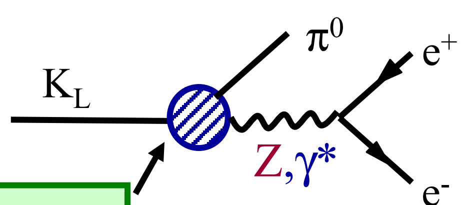


Ecker, Pich, de Rafael (91)
Heiliger, Seghal (93)
Donoghue, Gabbiani (95)
Fajfer (95)

3. $K_L \xrightarrow{K_2} \pi^0\gamma^* \to \pi^0 e^+ e^-$ ⇐ **direct ~~CP~~**

★ (TH very clean!)

New Physics can enter here



The action of Z^0, γ Penguins

LO: { Dib, Dunietz, Gilman; Flynn, Randall; Buchalla, AJB, Harlander

NLO: AJB, Lautenbacher, Misiak, Münz (94)

Present Status on $K_L \to \pi^0 e^+ e^-$, $K_L \to \pi^0 \mu^+ \mu^-$

Buchalla, D´Ambrosio, Isidori; Isidori, Smith, Unterdorfer

$l = e, \mu$

$$Br\left(K_L \to \pi^0 l^+ l^-\right) = \left[\underbrace{C^l_{mix}}_{\substack{\text{indirect} \\ \cancel{CP}}} + \underbrace{C^l_{int}\left(\frac{Im\lambda_t}{10^{-4}}\right)}_{\substack{\text{Interference of} \\ \text{direct and indirect}}} + \underbrace{C^l_{dir}\left(\frac{Im\lambda_t}{10^{-4}}\right)^2}_{\text{direct}} + \underbrace{C^l_{CPC}}_{\substack{\text{CP} \\ \text{conserving}}}\right] \cdot 10^{-12}$$

$$C^e_{mix} \cong 22.6 \pm 7.0$$
$$C^e_{int} \cong 7.4 \pm 1.5$$
$$C^e_{dir} \cong 2.4 \pm 0.2$$
$$C^e_{CPC} \cong 0$$

$$C^\mu_{mix} \cong 5.3 \pm 1.6$$
$$C^\mu_{int} \cong 1.9 \pm 0.4$$
$$C^\mu_{dir} \cong 1.0 \pm 0.1$$
$$C^\mu_{CPC} \cong 5.2 \pm 1.6$$

$$Br\left(K_L \to \pi^0 e^+ e^-\right) = \left(3.7\,{}^{+1.1}_{-0.9}\right) \cdot 10^{-11}$$

$$Br\left(K_L \to \pi^0 \mu^+ \mu^-\right) = \left(1.5 \pm 0.3\right) \cdot 10^{-11}$$

7.

Minimal Flavour Violation (MFV)

a) Generalities

b) Model with one Universal Extra Dimension

c) Littlest Higgs Model

d) MSSM at low tanβ

Review: AJB hep-ph/0310208

Generalities

$$A(\text{Decay}) = \sum_i B_i \eta^i_{QCD} V^i_{CKM} \underbrace{\overbrace{\left[F^i_{SM} + F^i_{New}\right]}^{F_i(v)}}_{\text{real}}$$

AJB, Gambino, Gorbahn, Jäger, Silvestrini
D'Ambrosio, Giudice, Isidori, Strumia

K and B Physics related to each other

1. All flavour changing processes governed by V^i_{CKM} .

2. Only SM Operators are relevant.

3. New Physics enters only through 7 Master Functions

$$F_i(v) = S(v), X(v), Y(v), Z(v), D'(v), E'(v), E(v)$$

$v =$ collects parameters specific to a given MFV model.

SM: $\boxed{v = x_t}$

Universal Unitarity Triangle

AJB, Gambino, Gorbahn, Jäger, Silvestrini (00)

In the full class of MFV-models it is possible to construct quantities that depend on CKM parameters but in which the dependence on new physics parameters cancels out

CKM Matrix determined without "New Physics Pollution"

Universal Unitarity Triangle

Examples

$$R_t = 0.90\sqrt{\frac{\Delta M_d}{0.50/\mathrm{ps}}}\sqrt{\frac{18.4/\mathrm{ps}}{\Delta M_s}}\left[\frac{\xi}{1.22}\right]$$

$$a_{\psi K_s} = \sin 2\beta$$

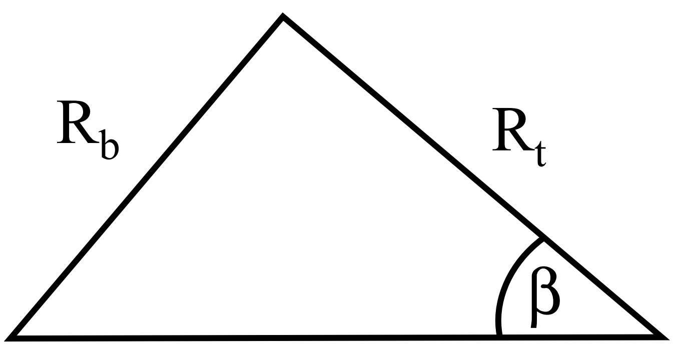
Universal Unitarity Triangle 2004

AJB, Schwab, Uhlig

Use only quantities that are independent of parameters specific to a given Minimal Flavour Violation model

$$\left|\frac{V_{ub}}{V_{cb}}\right| \Rightarrow R_b = \frac{\left(1-\lambda^2/2\right)}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right|$$

$$\frac{\Delta M_d}{\Delta M_s} \Rightarrow R_t = \frac{\xi_{th}}{\lambda}\sqrt{\frac{\Delta M_d}{\Delta M_s}} \qquad a_{\psi K_s} \Rightarrow \sin 2\beta$$



$$\xi_{th} = \frac{\sqrt{\hat{B}_s}\,F_{B_s}}{\sqrt{\hat{B}_d}\,F_{B_d}}$$

SM UT versus UUT of MFV

BSU (04)

SM

$$\bar{\eta} = 0.354 \pm 0.027$$
$$\bar{\rho} = 0.187 \pm 0.059$$

$$\gamma = (62.2 \pm 8.2)$$
$$R_t = 0.887 \pm 0.059$$
$$R_b = 0.400 \pm 0.039$$
$$|V_{td}| = (8.24 \pm 0.54) \cdot 10^{-3}$$

$$\mathrm{Im}\,\lambda_t = (1.40 \pm 0.12) \cdot 10^{-4}$$
$$\lambda_t = V_{ts}^* V_{td}$$

MFV

$$\bar{\eta} = 0.360 \pm 0.031$$
$$\bar{\rho} = 0.174 \pm 0.068$$

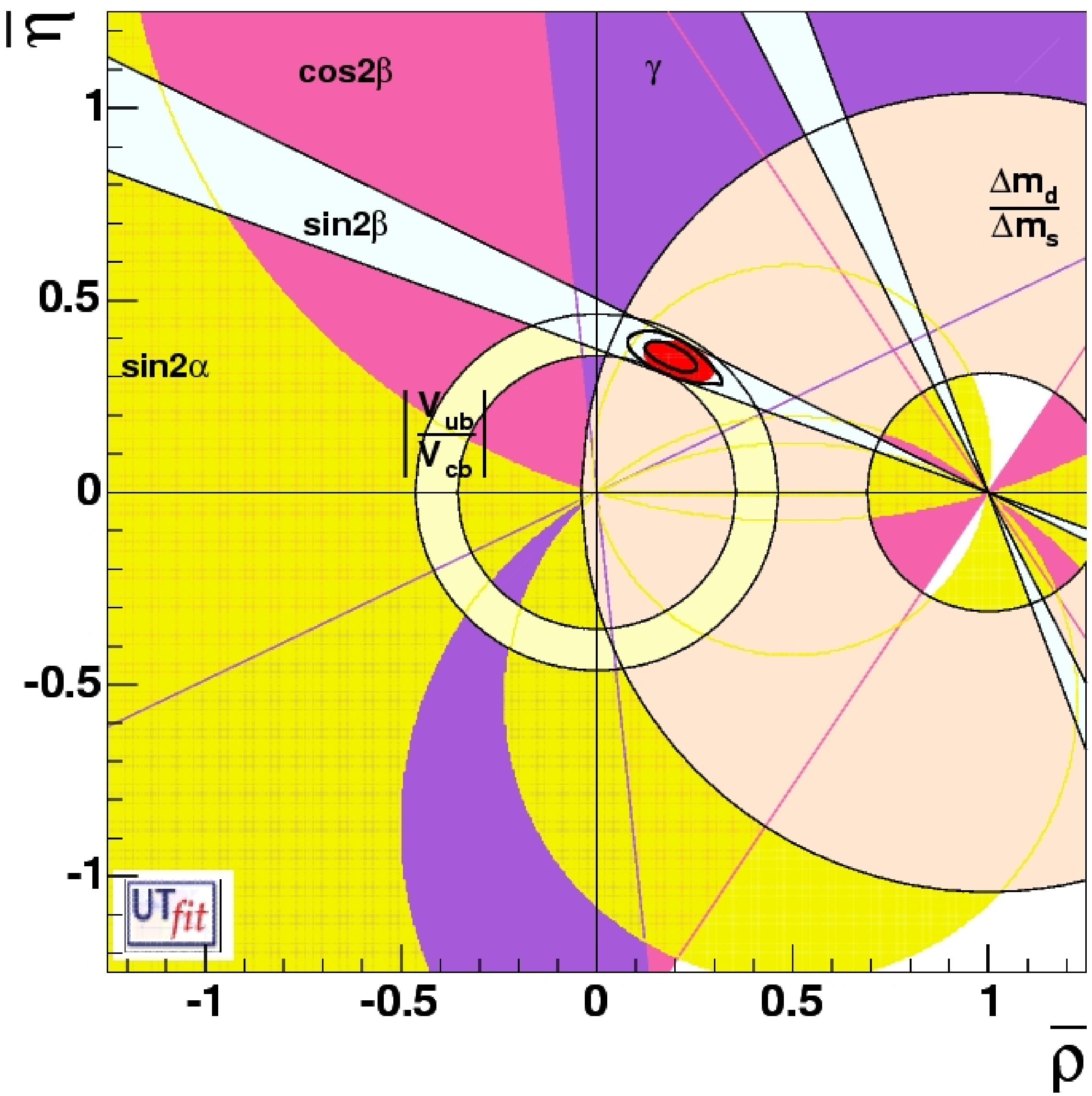
$$\gamma = (64.2 \pm 9.6)$$
$$R_t = 0.901 \pm 0.064$$
$$R_b = 0.400 \pm 0.044$$
$$|V_{td}| = (8.38 \pm 0.62) \cdot 10^{-3}$$

$$\mathrm{Im}\,\lambda_t = (1.43 \pm 0.14) \cdot 10^{-4}$$

UUT of MFV rather close to SM UT ☆

Universal Unitarity Triangle (MFV)

UTfit Collaboration : Bona et al.



MFV "Sum Rules"

Relations that do not involve the Master Functions X, Y, Z, S, etc.

Violation of these relations signals new flavour (CP) violating interactions beyond CKM or new operators that are strongly suppressed in SM

Examples

$$(\sin 2\beta)_{\pi\nu\bar{\nu}} = (\sin 2\beta)_{\psi K_s}$$

$$\frac{Br(B_s \to \mu^+\mu^-)}{Br(B_d \to \mu^+\mu^-)} = \frac{\tau(B_s)}{\tau(B_d)}\frac{m_{B_s}}{m_{B_d}}\left[\frac{F_{B_s}}{F_{B_d}}\right]^2\left[\frac{|V_{ts}|}{|V_{td}|}\right]^2$$

$$\frac{\Delta M_d}{\Delta M_s} = \frac{m_{B_d}}{m_{B_s}}\frac{\hat{B}_d}{\hat{B}_s}\frac{F_{B_d}^2}{F_{B_s}^2}\frac{|V_{td}|^2}{|V_{ts}|^2}$$

$$\frac{Br(B \to X_d \nu\bar{\nu})}{Br(B \to X_s \nu\bar{\nu})} = \frac{|V_{td}|^2}{|V_{ts}|^2}$$

Impact of a Modified $|V_{td}|$

$$\left\{\Delta M_d \approx |V_{td}|^2 \cdot [S_{SM}(m_t) + \Delta s]\right\} \Rightarrow \boxed{|V_{td}|^2 \approx \frac{\Delta M_d}{[S(m_t) + \Delta s]}}$$

$$\boxed{Br(B_d \to \mu^+\mu^-) \approx |V_{td}|^2 \cdot [Y_{SM}(m_t) + \Delta Y]^2 \approx \Delta M_d \frac{[Y_{SM}(m_t) + \Delta Y]^2}{[S(m_t) + \Delta s]}}$$

But :

$$\boxed{Br(B_s \to \mu^+\mu^-) \approx |V_{ts}|^2 \cdot [Y_{SM}(m_t) + \Delta Y]^2}$$

$$|V_{ts}| \approx |V_{cb}| \quad \text{(CKM Unitarity)}$$

$$\left\{\begin{array}{l}\Delta S > 0 \\ \text{in most} \\ \text{extensions}\end{array}\right\} \Rightarrow \boxed{\left(\frac{Br(B_s \to \mu^+\mu^-)}{Br(B_d \to \mu^+\mu^-)}\right)_{NP} > \left(\frac{Br(B_s \to \mu^+\mu^-)}{Br(B_d \to \mu^+\mu^-)}\right)_{SM}}$$

Intriguing Property of Models with Minimal Flavour Violation

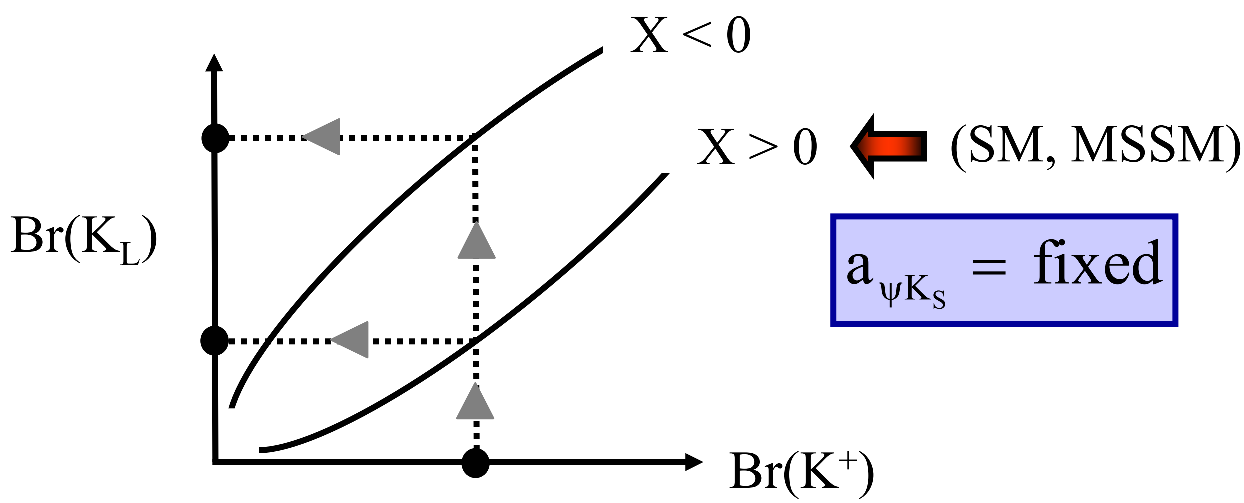
AJB, Fleischer (01)

$$Br(K_L) = F\left(Br\left(K^+\right),\ a_{\psi K_S},\ \mathrm{sgn}\left(X\right)\right)$$

TH very clean

Independently of any parameters, for given $Br(K^+)$ and $a_{\psi K_S}$ only <u>two values</u> of $Br(K_L)$ possible.

$X < 0$ very unlikely

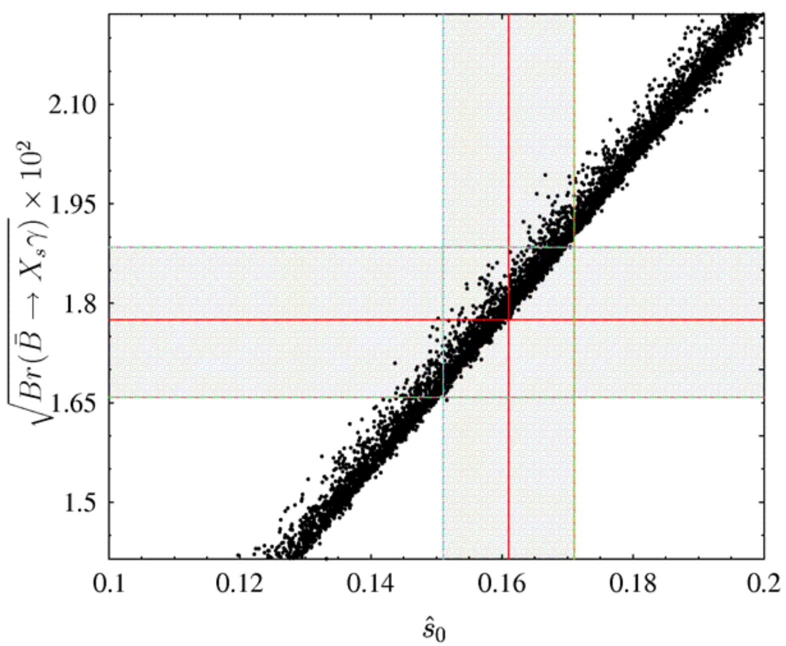


$a_{\psi K_S} = \text{fixed}$

Correlation: $Br(B \to X_s\gamma) \leftrightarrow \hat{s}_0$ in $A_{FB}(B \to X_s l^+ l^-)$

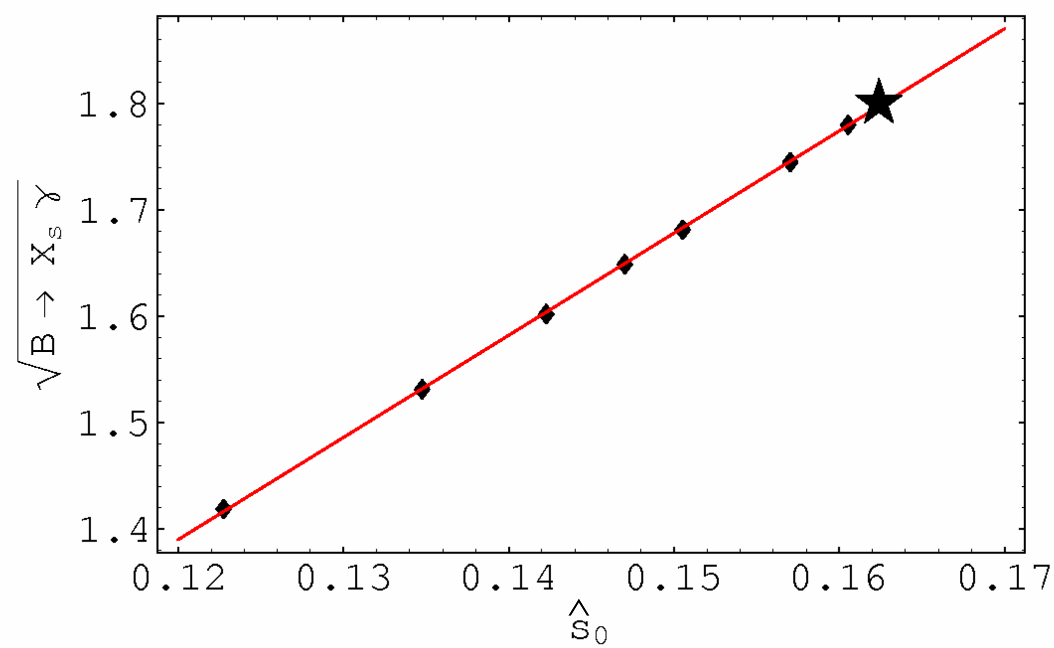
MSSM (MFV)

(Bobeth, AJB, Ewerth)



Universal Extra Dimensions

(AJB, Poschenrieder, Spranger, Weiler)



Relations between $\Delta M_{s,d}$ and $B_{s,d} \to \mu\bar{\mu}$ in Models with Minimal Flavour Violation

(AJB, hep-ph/0303060)

$$\Delta M_q \sim \hat{B}_q F_{B_q}^2 \left|V_{tq}\right|^2 S\left(x_t, x_{new}\right)$$

$$Br\left(B_q \to \mu\bar{\mu}\right) \sim F_{B_q}^2 \left|V_{tq}\right|^2 Y^2\left(x_t, \bar{x}_{new}\right)$$

Large hadronic uncertainties due to $F_{B_q}^2$

$$F_{B_d}\sqrt{\hat{B}_d} = (214 \pm 38)\,\mathrm{MeV} \qquad F_{B_d} = (189 \pm 27)\,\mathrm{MeV}$$

$$F_{B_s}\sqrt{\hat{B}_s} = (262 \pm 35)\,\mathrm{MeV} \qquad F_{B_s} = (230 \pm 30)\,\mathrm{MeV}$$

$$\hat{B}_d = 1.28 \pm 0.10$$

$$\hat{B}_s = 1.30 \pm 0.10 \qquad \frac{\hat{B}_s}{\hat{B}_d} = 1.02 \pm 0.04$$

(No problems with chiral logs and quenching)

$Br\left(B_{s,d} \to \mu\bar{\mu}\right)$ from $\Delta M_{s,d}$

$$Br\left(B_q \to \mu\bar{\mu}\right) = 4.40 \cdot 10^{-10} \frac{\tau\left(B_q\right)}{\hat{B}_q} \frac{Y^2\left(x_t, \bar{x}_{new}\right)}{S\left(x_t, x_{new}\right)} \Delta M_q$$

No dependence on $F^2_{B_q}$

SM:

$$Br\left(B_s \to \mu\bar{\mu}\right) = 3.42 \cdot 10^{-9} \left[\frac{\tau\left(B_s\right)}{1.46\text{ps}}\right]\left[\frac{1.30}{\hat{B}_s}\right]\left[\frac{\overline{m}_t\left(m_t\right)}{164\text{ GeV}}\right]^{1.6}\left[\frac{\Delta M_s}{18.0/\text{ps}}\right]$$

$$Br\left(B_d \to \mu\bar{\mu}\right) = 1.02 \cdot 10^{-10} \left[\frac{\tau\left(B_d\right)}{1.54\text{ps}}\right]\left[\frac{1.28}{\hat{B}_d}\right]\left[\frac{\overline{m}_t\left(m_t\right)}{164\text{ GeV}}\right]^{1.6}\left[\frac{\Delta M_d}{0.50/\text{ps}}\right]$$

$$\Delta M_s = \left(17.33\,^{+0.42}_{-0.21} \pm 0.07\right)/\text{ps} \quad \Rightarrow \quad Br\left(B_s \to \mu\bar{\mu}\right) = \left(3.36 \pm 0.32\right) \cdot 10^{-9}$$

$$\Delta M_d = \left(0.507 \pm 0.005\right)/\text{ps} \quad \Rightarrow \quad Br\left(B_d \to \mu\bar{\mu}\right) = \left(1.04 \pm 0.09\right) \cdot 10^{-10}$$

Moreover new Physics Effects can be easier seen

BBGT (2006)

Testing MFV through $B_{s,d} \to \mu\bar{\mu}$ and $\Delta M_{s,d}$

$$\frac{Br(B_s \to \mu\bar{\mu})}{Br(B_d \to \mu\bar{\mu})} = \underbrace{\frac{\hat{B}_d}{\hat{B}_s}}_{(1.02 \pm 0.04)} \underbrace{\frac{\tau(B_s)}{\tau(B_d)} \frac{\Delta M_s}{\Delta M_d}}_{\text{Experiment}}$$

Valid in MFV models in which only SM operators relevant.

Violation of this relation would indicate the presence of new operators and generally of non-minimal flavour violation.

BBGT (2006)

Implications of ΔM_s Measurement for Rare Decays

(Model independent "magic numbers" of CMFV)

$$\frac{Br\left(B_s \to \mu^+\mu^-\right)}{Br\left(B_d \to \mu^+\mu^-\right)} = 32.4 \pm 1.9$$

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.212 \pm 0.011$$

$$\frac{Br\left(B \to X_s \nu\bar{\nu}\right)}{Br\left(B \to X_d \nu\bar{\nu}\right)} = 22.3 \pm 2.2$$

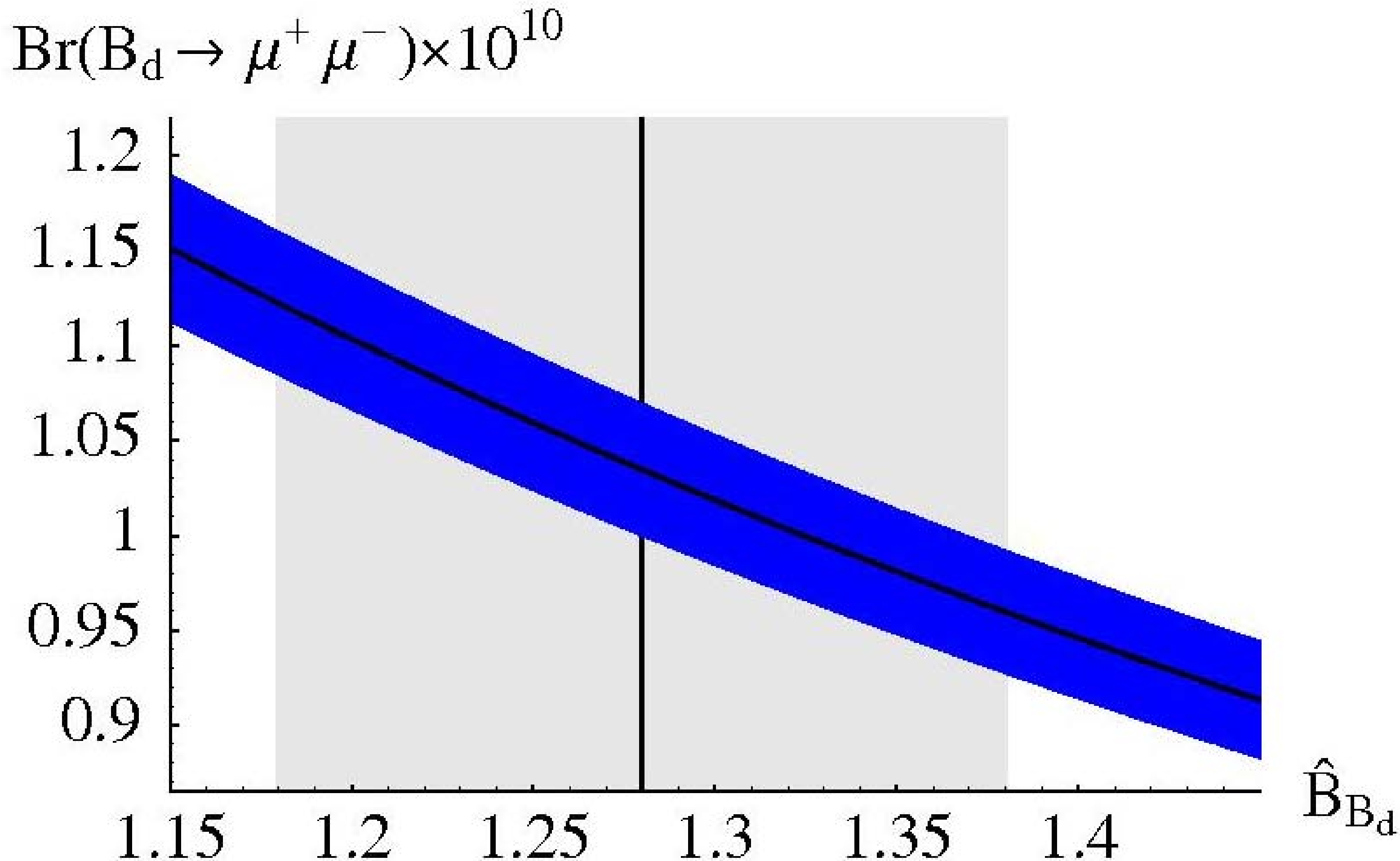
$$Br\left(B_s \to \mu^+\mu^-\right)_{SM} = \left(3.35 \pm 0.32\right) \cdot 10^{-9}$$

$$Br\left(B_d \to \mu^+\mu^-\right)_{SM} = \left(1.03 \pm 0.09\right) \cdot 10^{-10}$$

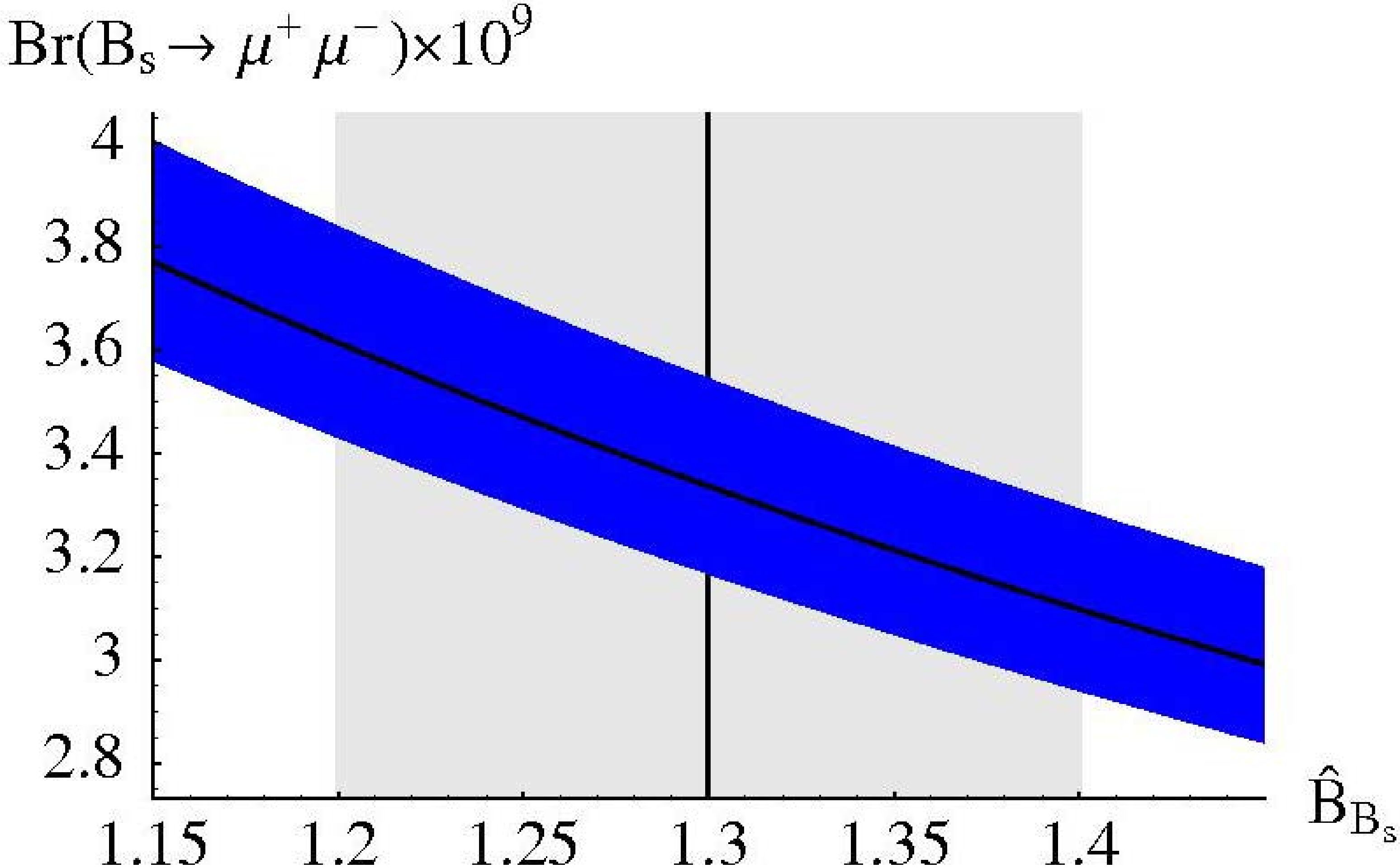
$$> 1 \cdot 10^{-7}$$

$$> 3 \cdot 10^{-8}$$

CDF (95% C.L.)



$Br(B_d \to \mu^+ \mu^-) \times 10^{10}$
1.2
1.15
1.1
1.05
1
0.95
0.9
1.15
1.2
1.25
1.3
1.35
1.4
$\hat{B}_{B_d}$



$\mathrm{Br}(B_s \to \mu^+ \mu^-) \times 10^9$
4
3.8
3.6
3.4
3.2
3
2.8
1.15
1.2
1.25
1.3
1.35
1.4
$\hat{B}_{B_s}$

First Model independent Tests of MFV

Tree Level Decays → **Reference Unitarity Triangle** (Independent of New Physics)

$$\left(R_b\right)_{true} = 0.440 \pm 0.037$$

$$\gamma_{true} = \left(71 \pm 16\right)^o$$

$$\left(\sin 2\beta\right)_{true} \cong 0.780 \pm 0.05$$

$$\sin 2\beta = S_{\psi K_s}$$

$$R_t \approx \sqrt{\frac{\Delta M_d}{\Delta M_s}}$$

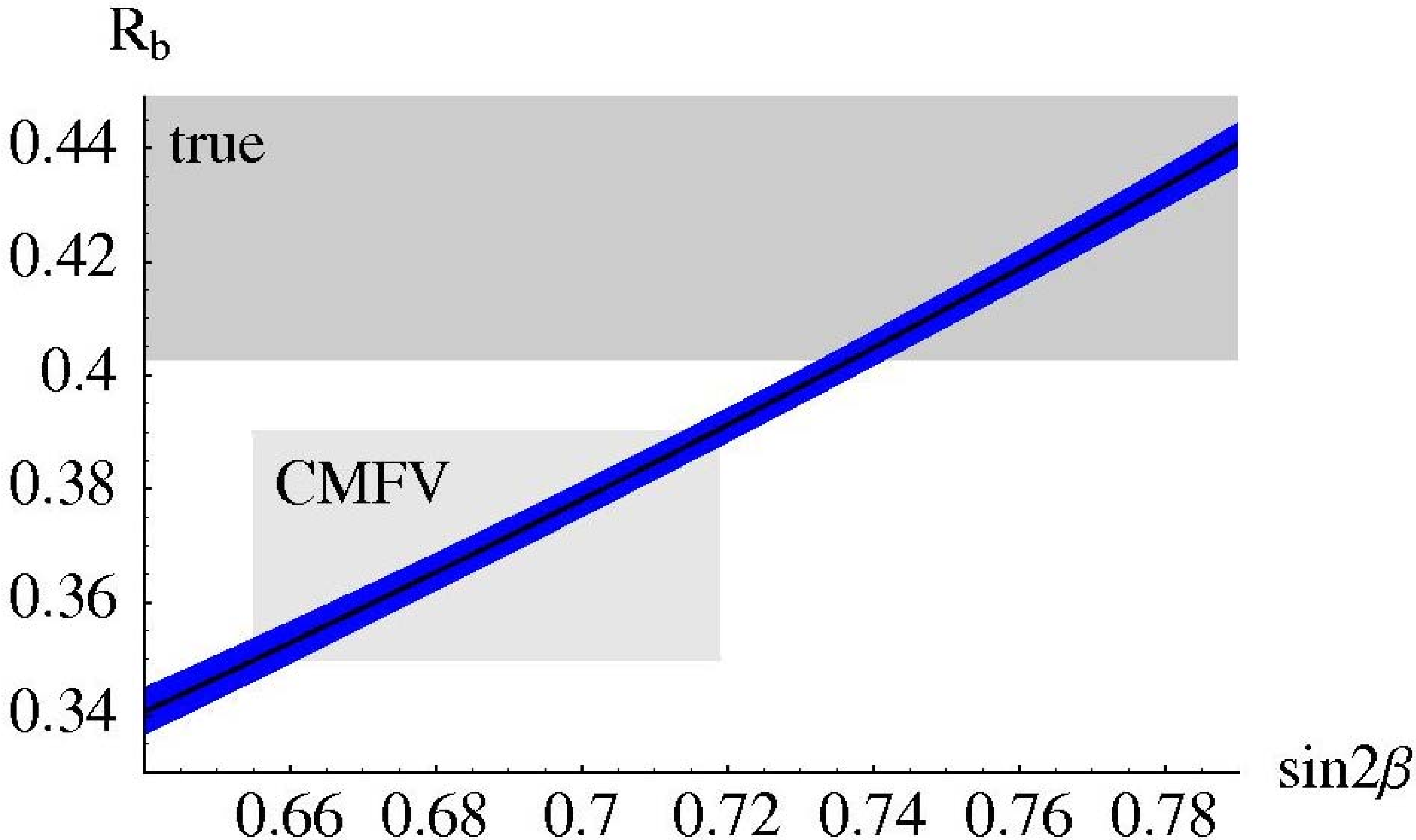
→ **Universal Unitarity Triangle for MFV**

$$\left(R_b\right)_{CMFV} = 0.370 \pm 0.020$$

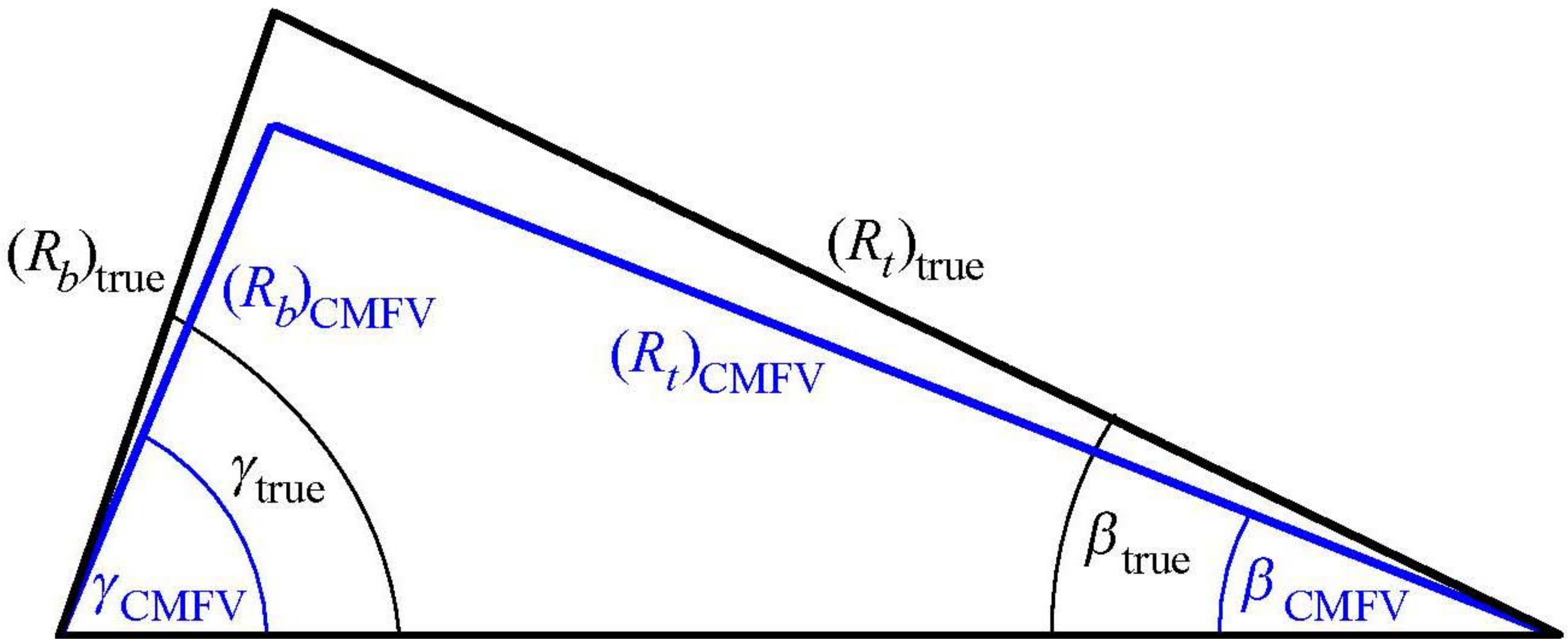
$$\gamma_{CMFV} = \left(67.4 \pm 6.8\right)^o$$

$$\left(\sin 2\beta\right)_{CMFV} \cong 0.687 \pm 0.032$$

The R_b - sin2β Problem



Reference Unitarity Triangle and UUT (CMFV)



Is ΔM_s smaller than $(\Delta M_s)_{SM}$?

$$(\Delta M_s)_{CDF} = \left(17.33\,{}^{+0.42}_{-0.21} \pm 0.07\right)/\,\mathrm{ps}$$

$$(\Delta M_s)^{SM}_{UTfit} = (21.5 \pm 2.6)/\,\mathrm{ps}$$

$$(\Delta M_s)^{SM}_{CKMfitter} = \left(21.7 \pm {}^{5.9}_{4.2}\right)/\,\mathrm{ps}$$

Essentially all models with CMFV predicted $\Delta M_s > (\Delta M_s)_{SM}$

But MSSM with MFV and large $\tan\beta$ $\Rightarrow$ $\Delta M_s < (\Delta M_s)_{SM}$

(AJB, Chankowski, Rosiek, Slawianowska (2002))

Correlated with enhancement of $Br(B_{s,d} \to \mu^+\mu^-)$

Recently also: Foster, Okamura, Roszkowski (05)
Carena, Menon, Noriega-Papaqui, Synkan, Wagner (06)
Isidori, Paradisi (06)

Important Tests for MFV

$$S_{\psi K_s} = \sin\left(2\beta + 2\varphi^{\text{new}}_{B_d}\right)$$

$$S_{\psi\varphi} = \sin\left(2|\beta_s| - 2\varphi^{\text{new}}_{B_s}\right) \approx \underset{\uparrow\,\text{BBGT}}{-}\sin\left(2\varphi^{\text{new}}_{B_s}\right)$$

$$\varphi^{\text{new}}_{B_d} \cong -(3.9 \pm 2.6)^{o}$$

$$(CP = +1)$$

$$|\beta_s| \cong 1^{o}$$

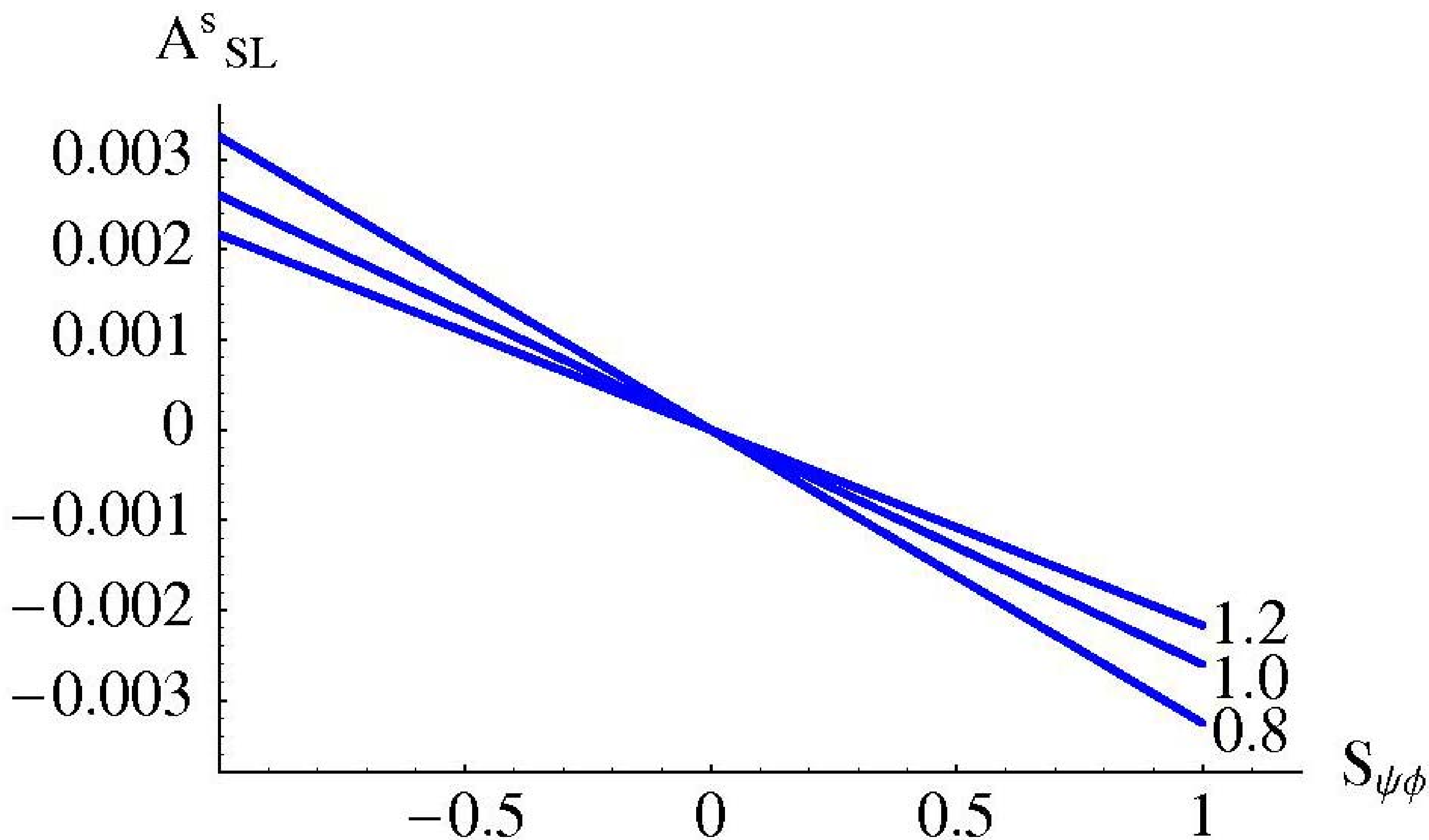
$$A^{S}_{SL} \approx -\text{Re}\left(\frac{\Gamma_{12}}{M_{12}}\right)^{SM} \frac{\sin 2\varphi_{B_s}}{C_{B_s}}$$

$$C_{B_s} \equiv \frac{\Delta M_s}{(\Delta M_s)_{SM}}$$

$$\{S_{\psi\varphi} + A^{S}_{SL}\} \Rightarrow$$ Measurement of C_{B_s}

Blanke, AJB, Guadagnoli, Tarantino (2006)

$$C_{B_s} = -\left|\text{Re}\left(\frac{\Gamma_{12}}{M_{12}}\right)^{SM}\right| \frac{\sin 2\varphi_{B_s}}{A^{S}_{SL}}$$


A^s_{SL}
0.003
0.002
0.001
0
−0.001
−0.002
−0.003
1.2
1.0
0.8
$S_{\psi\phi}$
−0.5
0
0.5
1

The Impact of Universal Extra Dimensions on FCNC Processes

Based on:

AJB, M. Spranger, A. Weiler ≡ (BSW) (hep-ph/0212143)

AJB, A. Poschenrieder, M. Spranger, A. Weiler (hep-ph/0306158)

The Next Steps

1. ACD Model in D = 5

2. Impact of KK on Inami-Lim Functions

3. Impact on:

$\Delta,\ \ \varepsilon_K,\ \ \Delta M_{d,s},\ \ K \to \pi\nu\bar{\nu}$

$K_L \to \mu\bar{\mu},\ B \to X_{d,s}\nu\bar{\nu},\ B_{s,d} \to \mu\bar{\mu}$

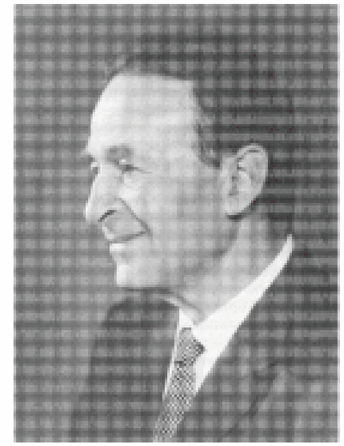
$B \to X_s\gamma,\ \ B \to X_s\text{gluon},\ \ \varepsilon'/\varepsilon$

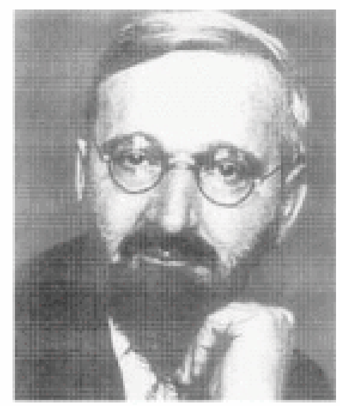
$B \to X_s\mu\bar{\mu},\ \ K_L \to \pi^0 e^+ e^-,$

4. Conclusions

Introduction to the Model

Kaluza (1921) and Klein (1926)
Unification of gravity and electrodynamics in $D = 5$ compactified on S^1.





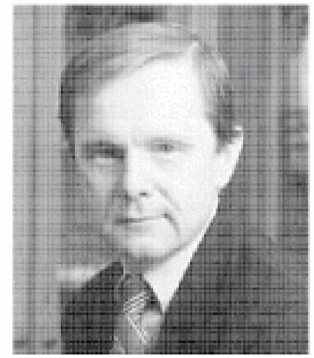
Some extra dimensional Models:

- brane world: SM on brane, gravity in the bulk, localization mechanism
- gravity and gauge bosons in bulk, fermions on brane $R^{-1} >$ few TeV, localization mechanism
- Universal extra dimensions (UED): everything in the bulk, no localization mechanism required, gravity not considered

ACD Model

Appelquist, Cheng, and Dobrescu (ACD)

hep-ph/0012100



- All SM fields live in the bulk $D = 4 + 1$, Gravity not considered.
- Orbifold: Replace S^1 by S^1/Z_2
- Simple extension of SM, 1 extra parameter (R, radius of ED), boundary terms set to zero
- provides excellent dark-matter candidate
  Servant,Tait '02; Cheng,Feng,Matchev '02
- bounds on $1/R$ are rather weak
  $1/R \gtrsim 250$ GeV, $M_H > 250$ GeV,
  $1/R \gtrsim 300$ GeV, $M_H < 250$ GeV. Appelquist,Yee '02

Appelquist, Cheng, Dobrescu Model (ACD) (D = 5)

Universal Extra Dimensions: All SM fields live in extra dimensions

Particle Content in an Effective D = 4 Theory

SM Fields (n = 0) (Zero Modes) + Corresponding KK Models (n = 1, 2, ...) $W^{\pm}_{(n)},\ Z^{0}_{(n)},$ etc.

+

Additional Physical Scalar Modes $a^{0}_{(n)},\ a^{\pm}_{(n)};\ n = 1, 2, \ldots$

Single New Parameter: Compactification Scale $1/R$

$$1/R \geq \begin{cases} 250\ \text{GeV}\ (M_H > 250\ \text{GeV}) \\ 300\ \text{GeV}\ (M_H < 250\ \text{GeV}) \end{cases}$$

(ACD, AY: Electroweak Precision Observables)

Mass Spectrum

$$M^2_{\gamma(n)} = \frac{n^2}{R^2}$$

$$M^2_{Z(n)} = \frac{n^2}{R^2} + M^2_Z$$

$$M^2_{W(n)} = \frac{n^2}{R^2} + M^2_W$$

$$m^2_{q(n)} = \frac{n^2}{R^2} + m^2_q$$

$$m^2_{l(n)} = \frac{n^2}{R^2} + m^2_l$$

$$m^2_{a^\pm(n)} = \frac{n^2}{R^2} + M^2_W \qquad n \geq 1$$

$$m^2_{a^0(n)} = \frac{n^2}{R^2} + M^2_Z \qquad n \geq 1$$

$(n = 0, 1, 2 \ldots)$

Interactions

1. Full Set of Feynman Rules in BSW
2. Vertices depend on n/R
3. Conservation of KK Parity $\Rightarrow$ Absence of tree level KK contributions
4. Minimal Flavour Violation (CKM Matrix; no new operators)

Properties Relevant for FCNC Processes

$\boxed{\varepsilon_K, \Delta M_{d,s}}$: $S(x_t, 1/R) = S_0(x_t) + \sum_{n=1}^{\infty} S_n\left(x_t, \frac{n}{R}\right)$ $\begin{pmatrix}\Delta F=2 \\ \text{Boxes}\end{pmatrix}$

$\left(x_t = \frac{m_t^2}{M_W^2}\right)$

$\boxed{\begin{array}{l} K^+ \to \pi^+ \nu\bar{\nu} \\ K_L \to \pi^0 \nu\bar{\nu} \\ B \to X_{s,d} \nu\bar{\nu} \end{array}}$: $X(x_t, 1/R) = X_0(x_t) + \sum_{n=1}^{\infty} C_n\left(x_t, \frac{n}{R}\right)$

$\overbrace{(C_0\text{-}4B_0)}^{}$

SM

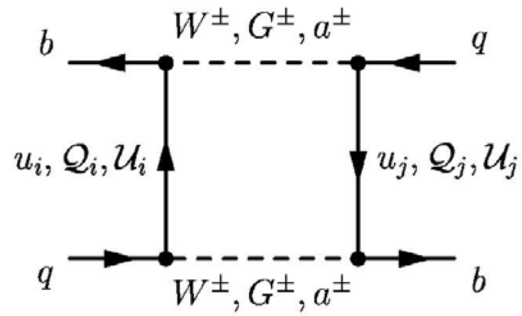
$\boxed{\begin{array}{l} B_{s,d} \to \mu^+\mu^- \\ K_L \to \mu^+\mu^- \end{array}}$: $Y(x_t, 1/R) = \overbrace{Y_0(x_t)}^{}\ + \sum_{n=1}^{\infty} C_n\left(x_t, \frac{n}{R}\right)$

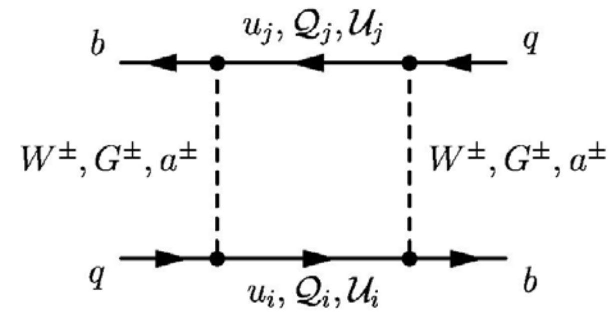
$(C_0\text{-}B_0)$

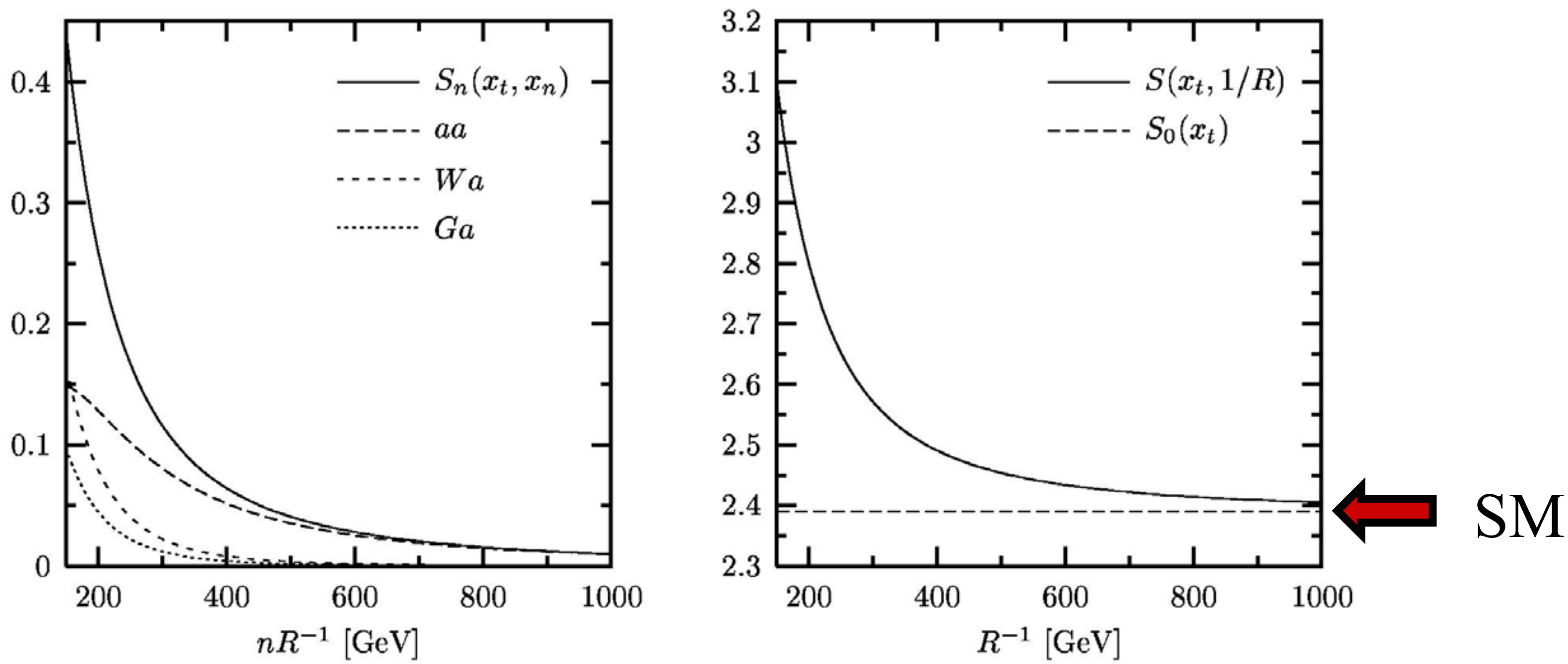
$\boxed{\begin{array}{c} Z^0 \\ \text{Penguins} \end{array}}$

GIM mechanism improves significantly the convergence of the sum over the $(KK)_t$ Modes and essentially removes the contributions of $(KK)_{u,c}$ in the first two generations.

Results for the Function $S(x_t, 1/R)$







(a)

(b)

Basic Formulae for UT Analysis

1. ε_K - Hyperbola

$$\bar{\eta}\left[\left(1-\bar{\rho}\right)A^2F_{tt}\eta_{QCD}^{tt}+P_c\left(\varepsilon\right)\right]A^2\hat{B}_K=0.213$$

$$F_{tt}^{SM}=S_0\left(x_t\right)$$
$$F_{tt}^{ACD}=S\left(x_t,1/R\right)$$

$\eta_{QCD}^{tt}=0.57\pm0.01;\quad P_C\left(\varepsilon\right)=0.28\pm0.05;$

2. $B_d^0-\bar{B}_d^0$ Mixing Constraint

$$R_t=0.86\left[\frac{0.041}{\left|V_{cb}\right|}\right]\sqrt{\frac{2.34}{F_{tt}}}\sqrt{\frac{\Delta M_d}{0.50/ps}}\left[\frac{230MeV}{\sqrt{\hat{B}_d}F_{B_d}}\right]\sqrt{\frac{0.55}{\eta_B^{QCD}}}$$

$$\left\{F_{tt}^{ACD}>F_{tt}^{SM}\right\}$$
$$\Downarrow$$
$$\left\{R_t^{ACD}<R_t^{SM}\right\}$$

$\left|V_{cb}\right|=0.041\pm0.001;\quad \Delta M_d=\left(0.503\pm0.006\right)/ps;\quad \eta_B^{QCD}=0.55\pm0.01$

3. $B_s^0-\bar{B}_s^0$ Mixing Constraint ($\Delta M_d/\Delta M_s$)

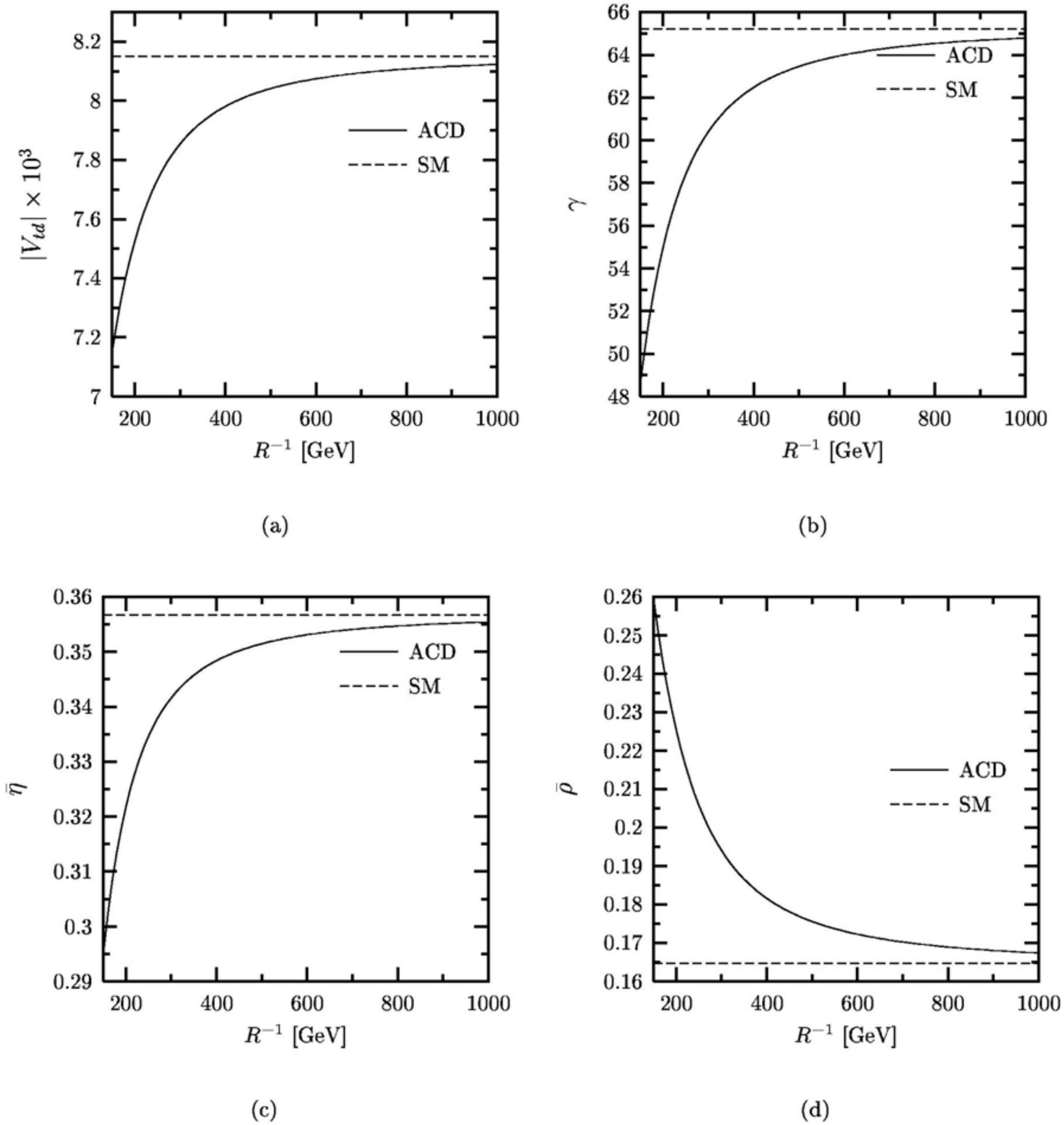
$$R_t=0.90\sqrt{\frac{\Delta M_d}{0.50/ps}}\sqrt{\frac{18.4/ps}{\Delta M_s}}\left[\frac{\xi}{1.22}\right]$$

$$\xi=\frac{\sqrt{\hat{B}_s}F_{B_s}}{\sqrt{\hat{B}_d}F_{B_d}}$$

(No dependence on 1/R)

$\Delta M_s>14.4/ps$ (95% C.L.) LEP (SLD)

Implications for Unitarity Triangle



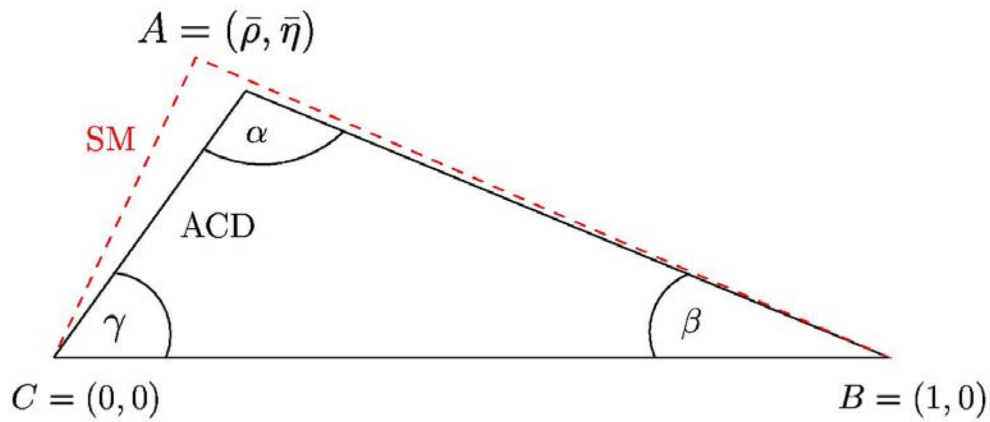
1/R = 200 (300) GeV

Suppressions :

$\lvert V_{td} \rvert$	:	8%	(4%)
$\bar{\eta}$	:	11%	(4.5%)
γ	:	10^{o}	(5^{o})

Unitarity Triangle in the ACD Model

1/R = 200 GeV

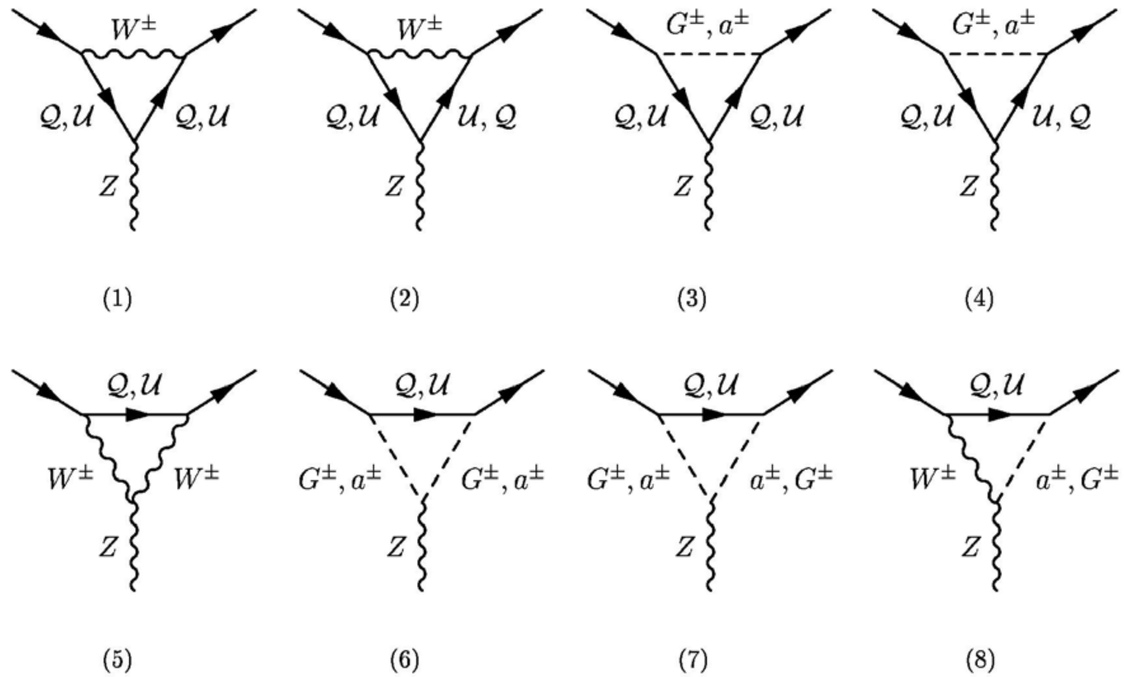


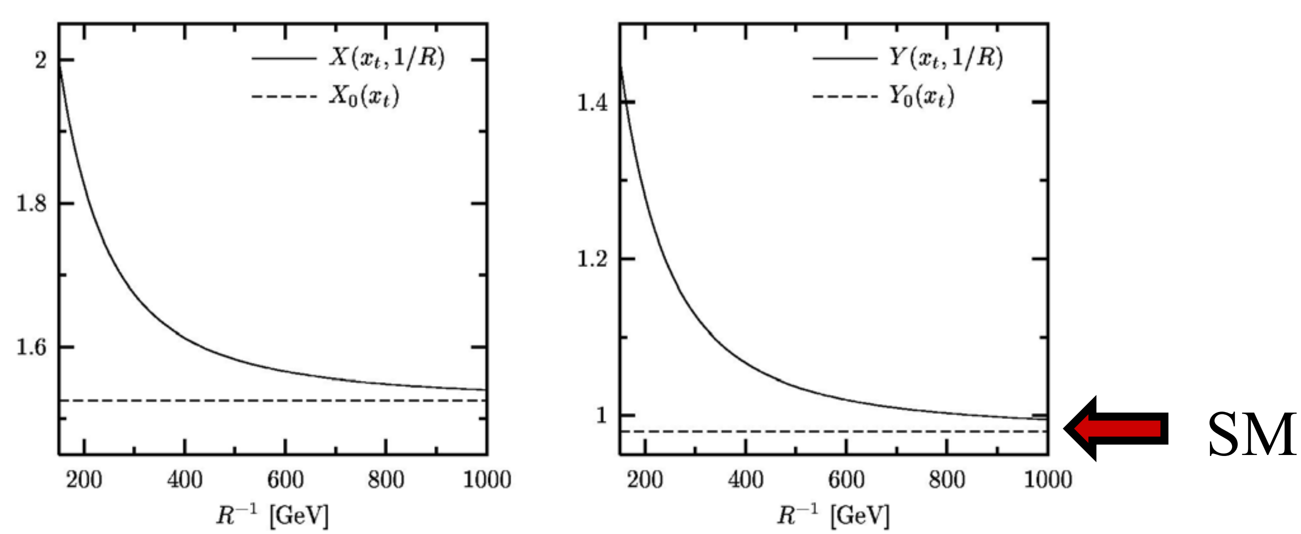
At $\quad 1/R = 200\ \text{GeV} \qquad \gamma_{SM} = 65^\circ \rightarrow \gamma_{ACD} = 49^\circ$

but at $\ 1/R = 300\ (400)\ \text{GeV} \quad \gamma_{ACD} = 60^\circ (63^\circ)$

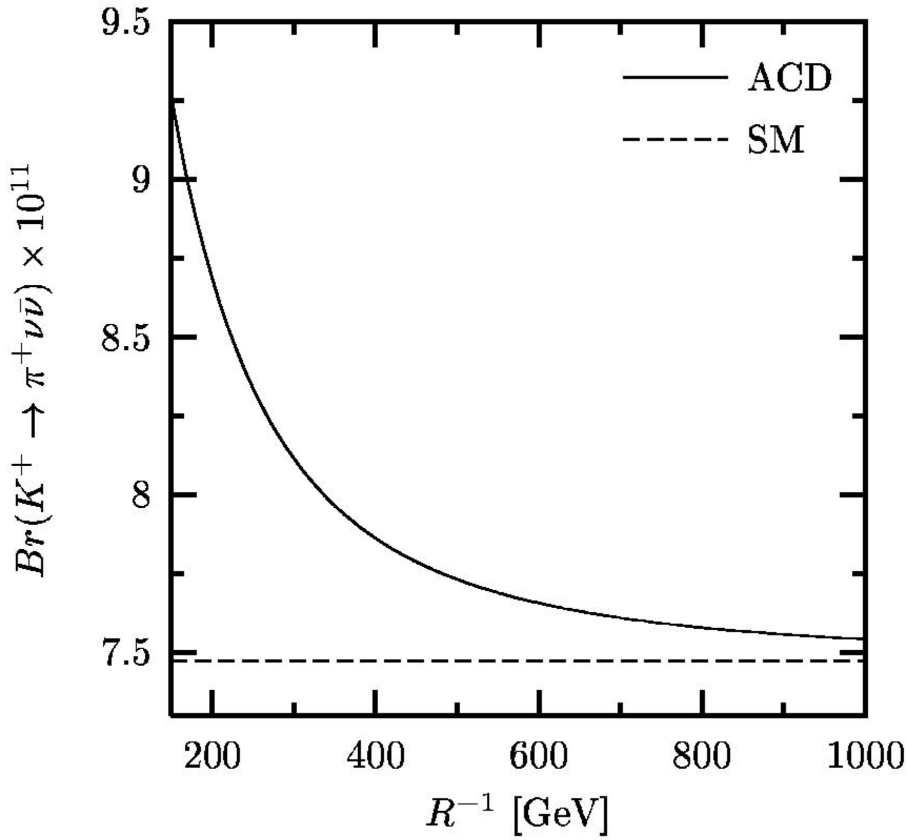
Very difficult to see the difference in view of hadronic uncertainties.

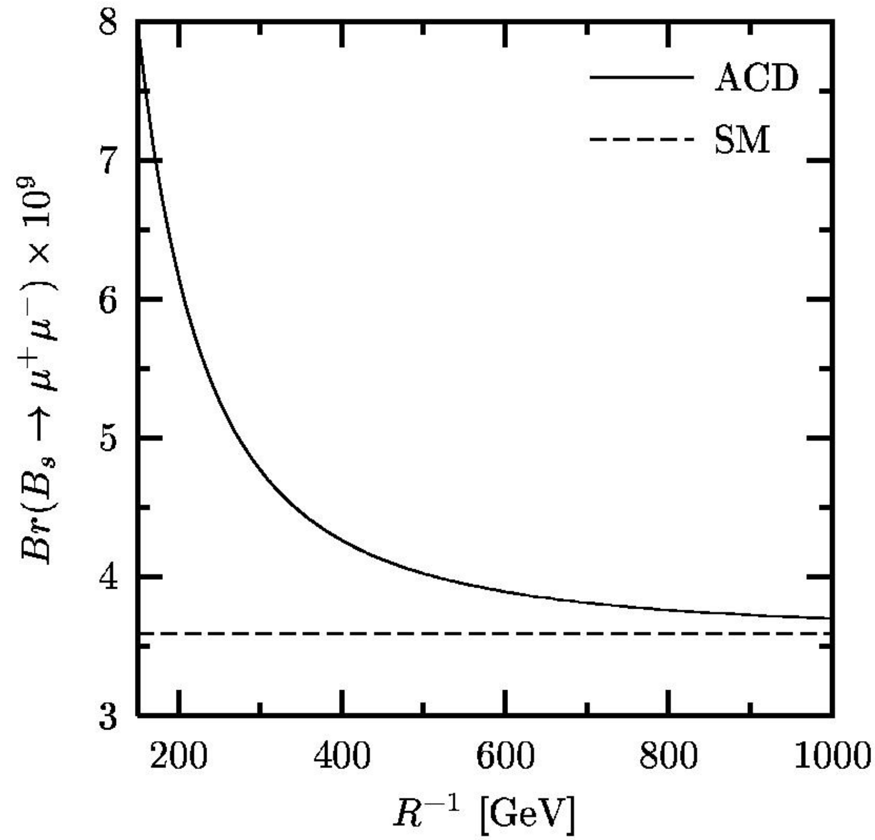
Results for the Functions $X(x_t, 1/R)$, $Y(x_t, 1/R)$





Implications for Rare K and B Decays

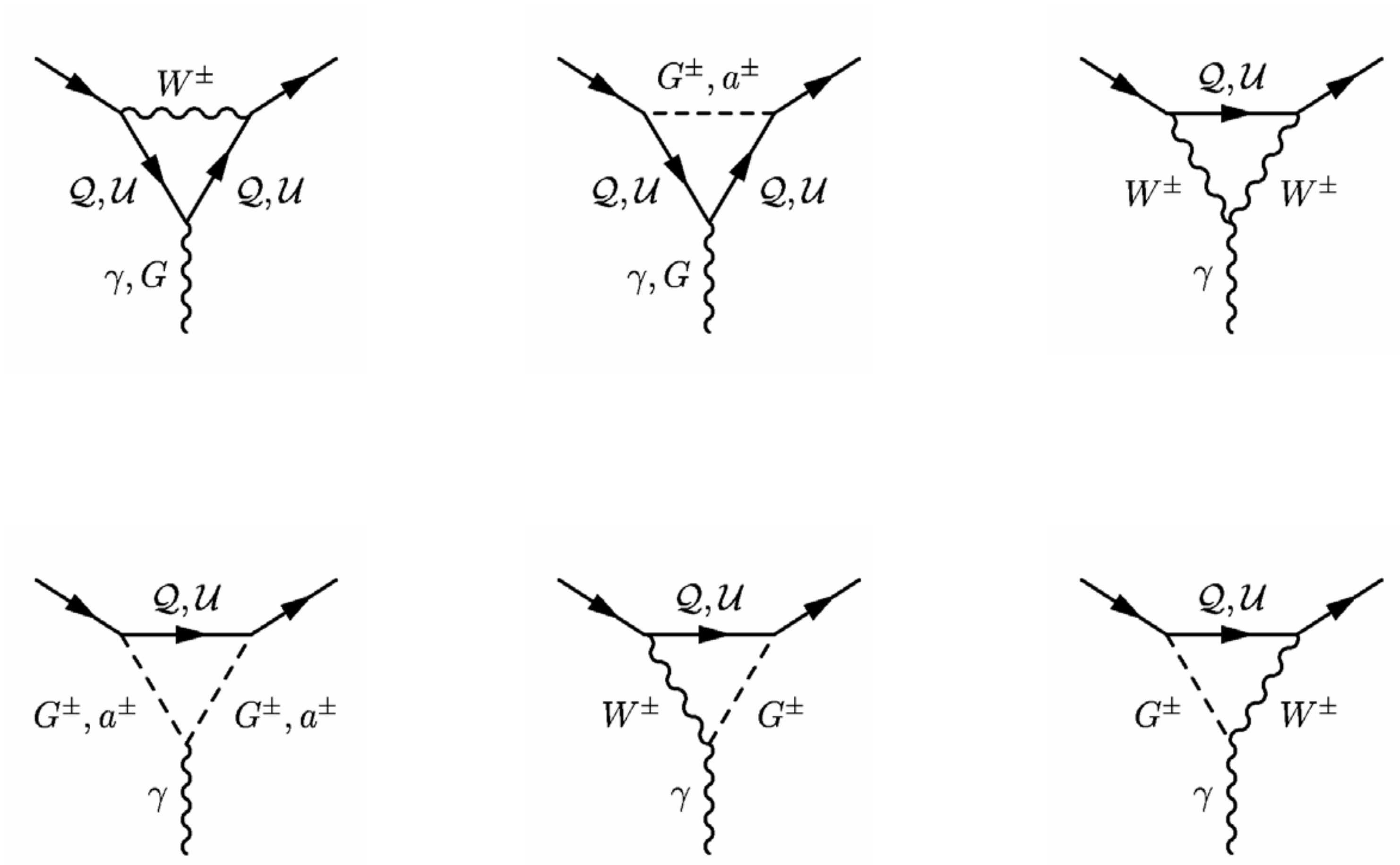




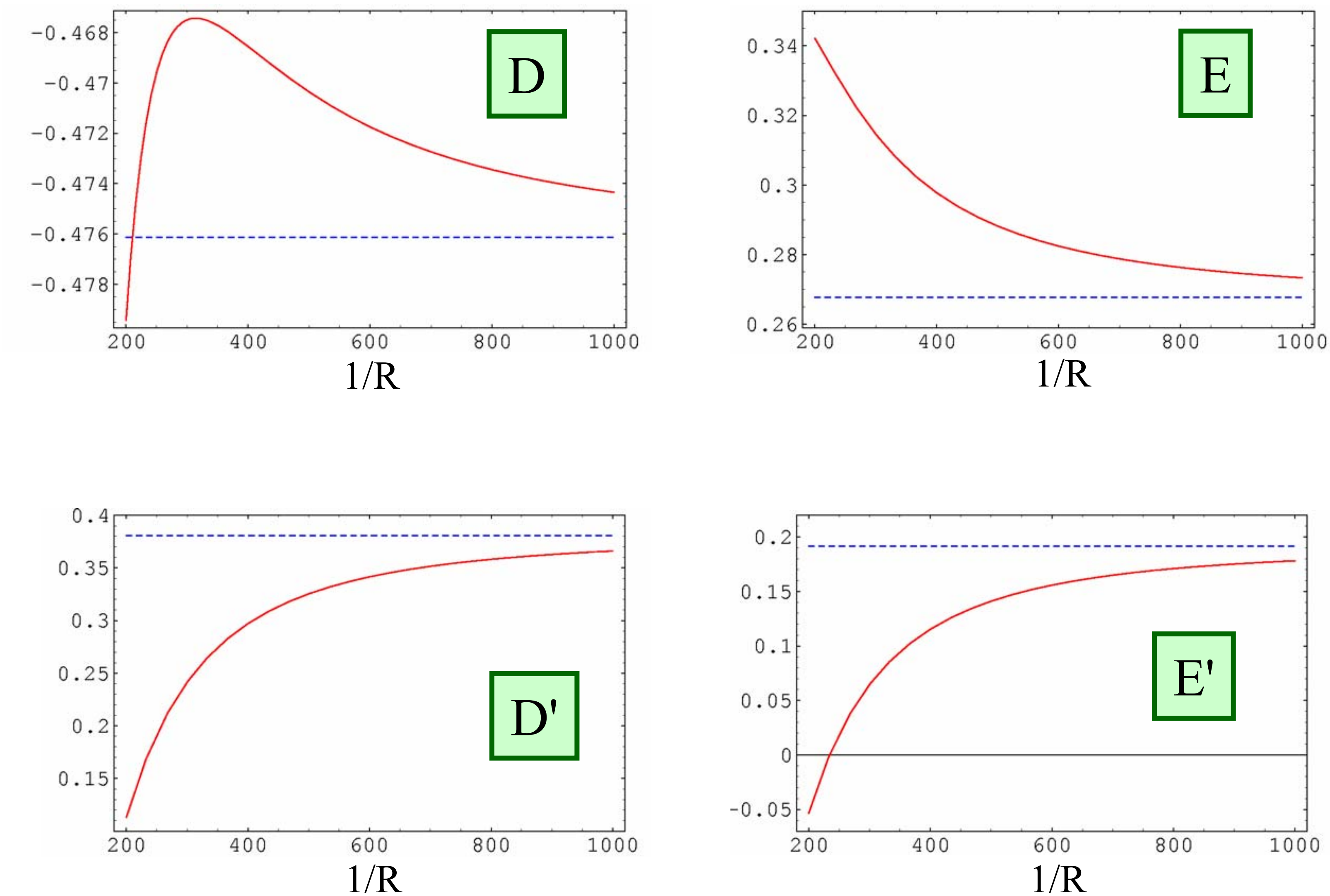
The Impact of Universal Extra Dimensions on $B \to X_s\gamma$, $B \to X_s\mu^+\mu^-$, $K_L \to \pi^0 e^+ e^-$

Andrzej J. Buras, Anton Poschenrieder,
Michael Spranger, Andreas Weiler

Diagrams Contributing to D, E, D', E'



Results for D, E, D', E'



Impact of KK on $B \to X_s \gamma$

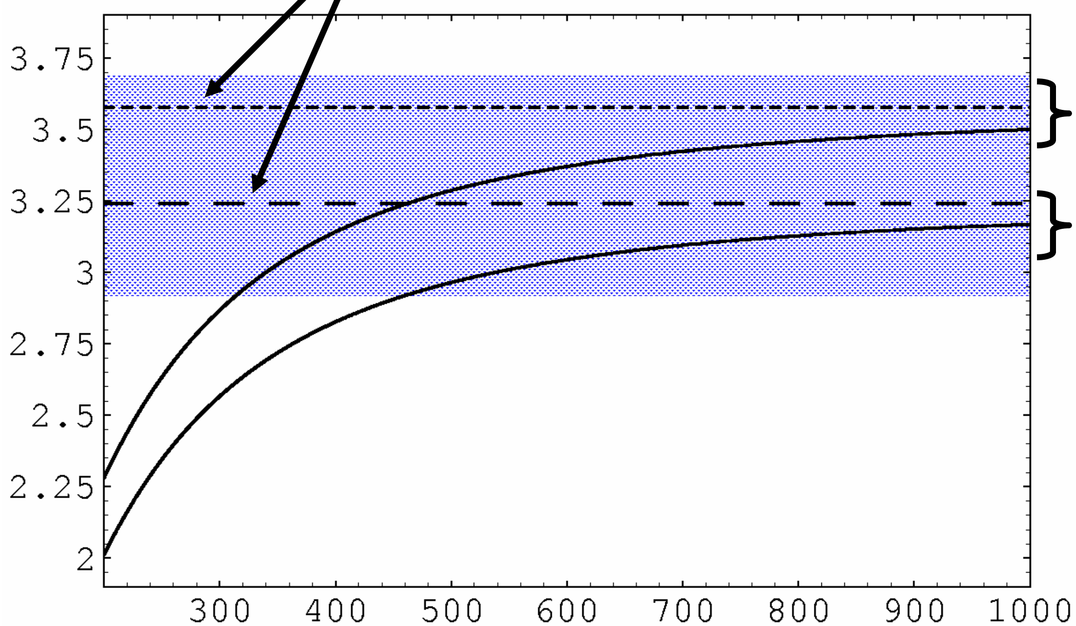
$$\left.\begin{array}{l}\text{CLEO}\\ \text{ALEPH}\\ \text{BaBar}\\ \text{Belle}\end{array}\right\} Br(B \to X_s\gamma) = \left(3.28\begin{array}{l}+0.41\\-0.36\end{array}\right)\cdot 10^{-4}$$

SM

$$(3.57 \pm 0.30)\cdot 10^{-4}$$

$$\text{Gambino} + \text{Misiak} \quad \left(\frac{m_c^2}{m_b^2} = 0.22\right)$$

SM



$$Br(B \to X_s\gamma)$$
$$\left[10^{-4}\right]$$

$m_c^2/m_b^2 = 0.22$

$m_c^2/m_b^2 = 0.29$

1/R

Impact of KK on $B \to X_s \mu\bar{\mu}$

$$\left\{\begin{array}{c}\text{Integration}\\ \text{over}\\ \text{full dileption}\\ \text{mass spectrum}\end{array}\right\}$$

$$\mathrm{Br}\left(B \to X_s \mu\bar{\mu}\right) = \left(7.9 \pm 2.1 \begin{array}{c} +2.0 \\ -1.5 \end{array}\right) \cdot 10^{-6} \quad (\text{Belle})$$

$$\text{SM}: \quad (4.1 \pm 0.7) \cdot 10^{-6} \quad (\text{Ali, Lunghi, Greub, Hiller})$$

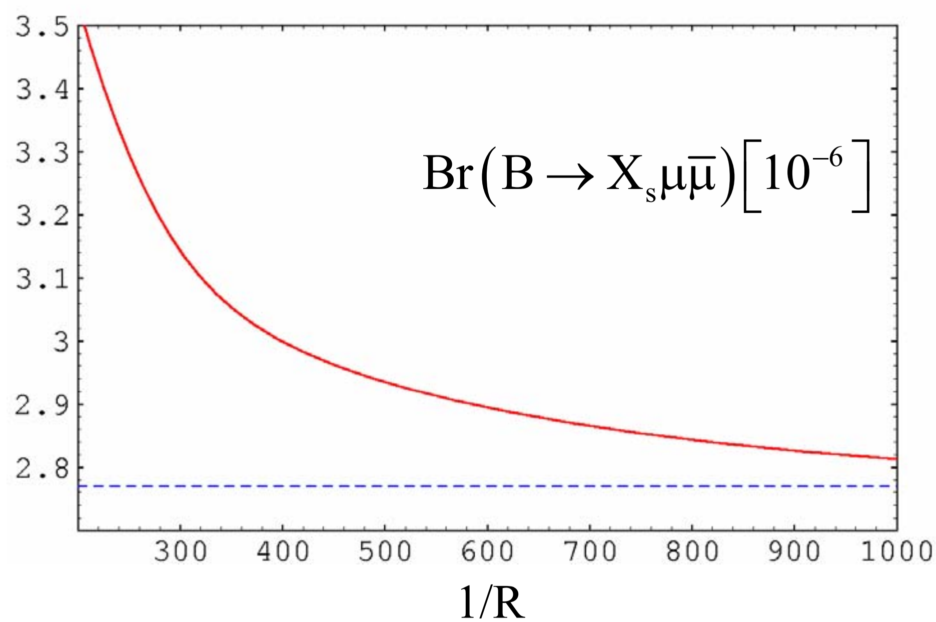
$$\text{ACD}: \quad (4.8 \pm 0.8) \cdot 10^{-6} \quad (\text{BPSW; } 1/R = 300\text{GeV})$$

$$\hat{s} = \frac{\left(P_{\mu_+} + P_{\mu_-}\right)^2}{m_b^2}$$

$$\left\{\begin{array}{c}\text{Integration}\\ \text{over}\\ \text{low dileption}\\ \text{mass spectrum}\end{array}\right\}$$

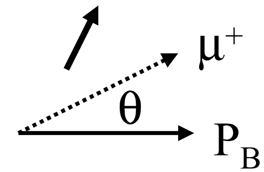
$$0.05 \lesssim \hat{s} \lesssim 0.25$$

$$\text{SM}: \quad (2.75 \pm 0.45) \cdot 10^{-6}$$



Forward-Backward Asymmetry in $B \to X_s \mu^+ \mu^-$ (SM)

$$A_{FB}(\hat{s}) = \frac{1}{\Gamma(b \to c e \bar{\nu})} \int_{-1}^{+1} d\cos\theta_L \frac{d^2\Gamma(b \to s\mu^+\mu^-)}{d\hat{s}\cos\theta_L} \mathrm{sgn}(\cos\theta_L)$$



$$A_{FB}(\hat{s}) = -3\tilde{C}_{10} \frac{\left[\hat{s}\,\mathrm{Re}\,\tilde{C}_9^{\mathrm{eff}}(\hat{s}) + 2C_{7\gamma}^{(0)\mathrm{eff}}\right]}{U(\hat{s})}$$

$$\hat{s}_0 \cong -\frac{2C_{7\gamma}^{(0)\mathrm{eff}}}{\mathrm{Re}\,\tilde{C}_9^{\mathrm{eff}}(\hat{s}_0)}$$

$$C_9 \leftrightarrow (\bar{s}b)_{V-A}(\bar{\mu}\mu)_V$$
$$C_{10} \leftrightarrow (\bar{s}b)_{V-A}(\bar{\mu}\mu)_A$$
$$C_{7\gamma} \leftrightarrow B \to X_s\gamma$$

SM :

$\mathrm{NLO}: \quad \hat{s}_0 \cong 0.14 \pm 0.02$ — **Ali Mannel Morozumi**

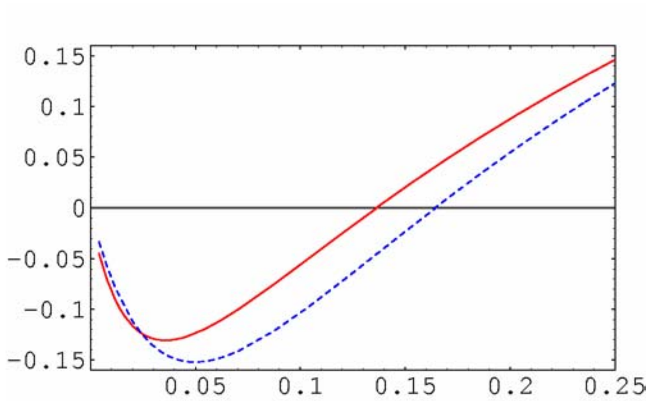
$\mathrm{NNLO}: \quad \hat{s}_0 \cong 0.162 \pm 0.008$

Asatrian, Asatrian, Greub, Walker, Bieri Hovhannisyan

Ghinculov, Hurth, Isidori, Yao

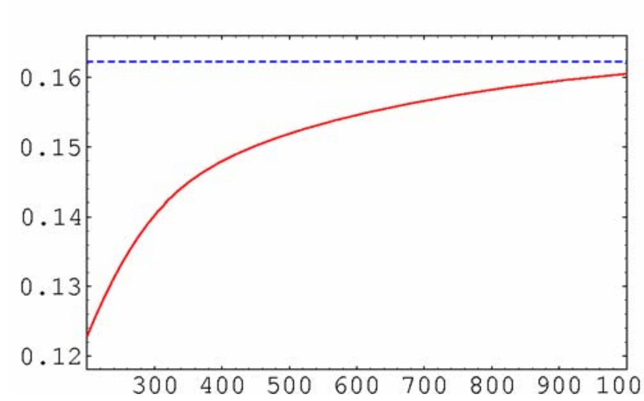
Impact of KK on $A_{FB}(\hat{s})$

$A_{FB}(\hat{s})$



$\hat{s}$

$\hat{s}_0$

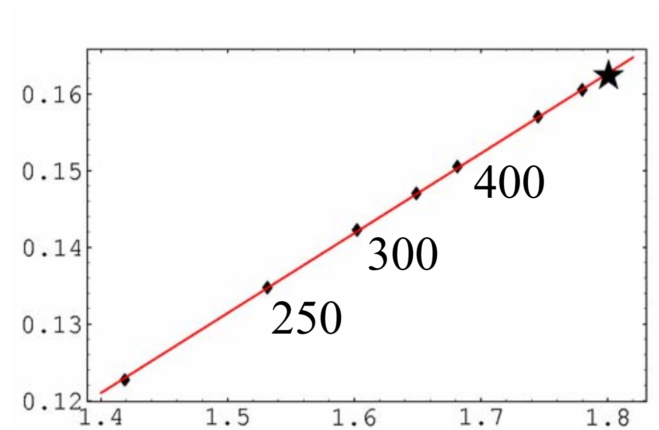


$1/R$

$$\left\{ \begin{array}{c} \widetilde{C}_9^{\text{eff}} \ \text{very} \\ \text{weakly affected} \end{array} \right\}$$

$$\hat{s}_0 \sim \sqrt{Br(B \to X_s \gamma)}$$

$\hat{s}_0$



$\sqrt{Br(B \to X_s \gamma)}$

Summary

1. ACD Model consistent with the data on FCNC Processes with $1/R \cong 300$ GeV

2. Only small impact on UT relative to the SM

3. $\boxed{\text{Enhancements}}$: $\boxed{K^+ \to \pi^+ \nu\bar{\nu}(9\%)}$, $K_L \to \pi^0 \nu\bar{\nu}(10\%)$

   $\boxed{1/R = 300\ \text{GeV}}$ $\boxed{B \to X_s \mu\bar{\mu}(12\%)}$, $B \to X_d \nu\bar{\nu}(12\%)$

   $B \to X_s \nu\bar{\nu}(21\%)$, $K_L \to \mu^+\mu^-(20\%)$

   $B_d \to \mu^+\mu^-(23\%)$, $B_s \to \mu^+\mu^-(33\%)$

4. $\boxed{\text{Suppressions}}$: $\boxed{B \to X_s \gamma(20\%)}$, $B \to X_s \text{gluon}(40\%)$

   $\boxed{\hat{s}_0 : 0.162 \to 0.142}$; ε'/ε

5. With improved Exp+Th for $B \to X_s\gamma$ and $\hat{s}_0$ strong lower bound on 1/R could be obtained.

FCNC Processes in the "Littlest" Higgs Model

LH Model : Arkani-Hamed, Cohen, Katz, Nelson (2002)

FCNC Processes : AJB, Poschenrieder, Uhlig : hep-ph/0410309 $B^0_{d,s} - \overline{B}^0_{d,s}$ Mixing
0501230 Rare Decays
05xxyyy Technical Details

New Effect generally below 30%

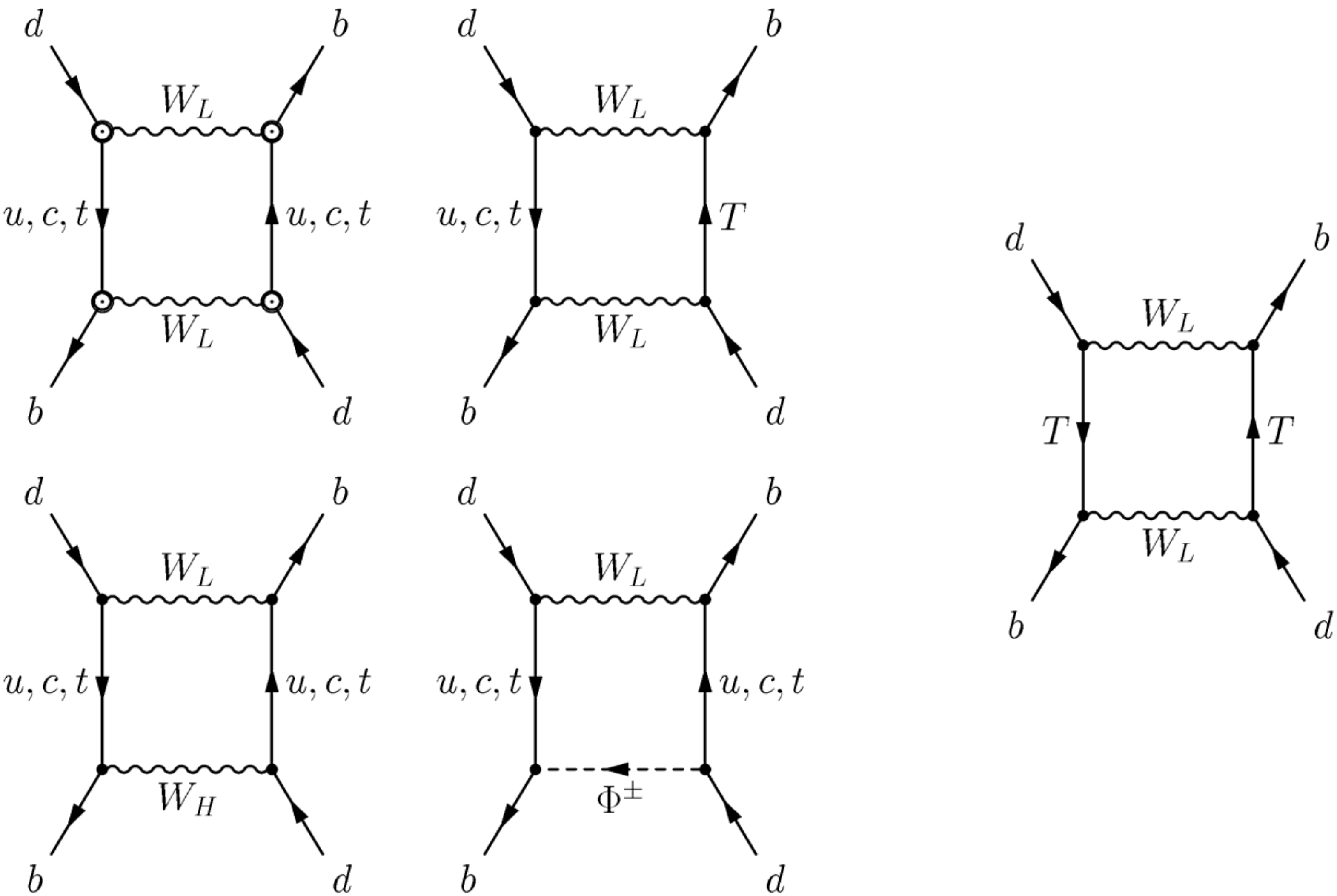
A symphony of penguin and box diagrams with

SM	New Particles	
$W^\pm_L,\ Z^0_L$	$W^\pm_H,\ Z^0_H,\ A^0_H$	(new Gauge Bosons)
t	$T,\ \Phi^\pm$	(new heavy top, charged scalar)

New Particles $m_i > 1$ TeV

Related work: Choudhury, Gaur, Goyal, Mahajan, 0407050 (confirmed our results)
Choudhury, Gaur, Joshi, McKellar, 0408125 (?)

Movement 1



d
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W_L
u, c, t
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W_L
b
d
d
b
W_L
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T
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d
d
b
W_L
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u, c, t
W_H
b
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b
W_L
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$\Phi^{\pm}$
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b
W_L
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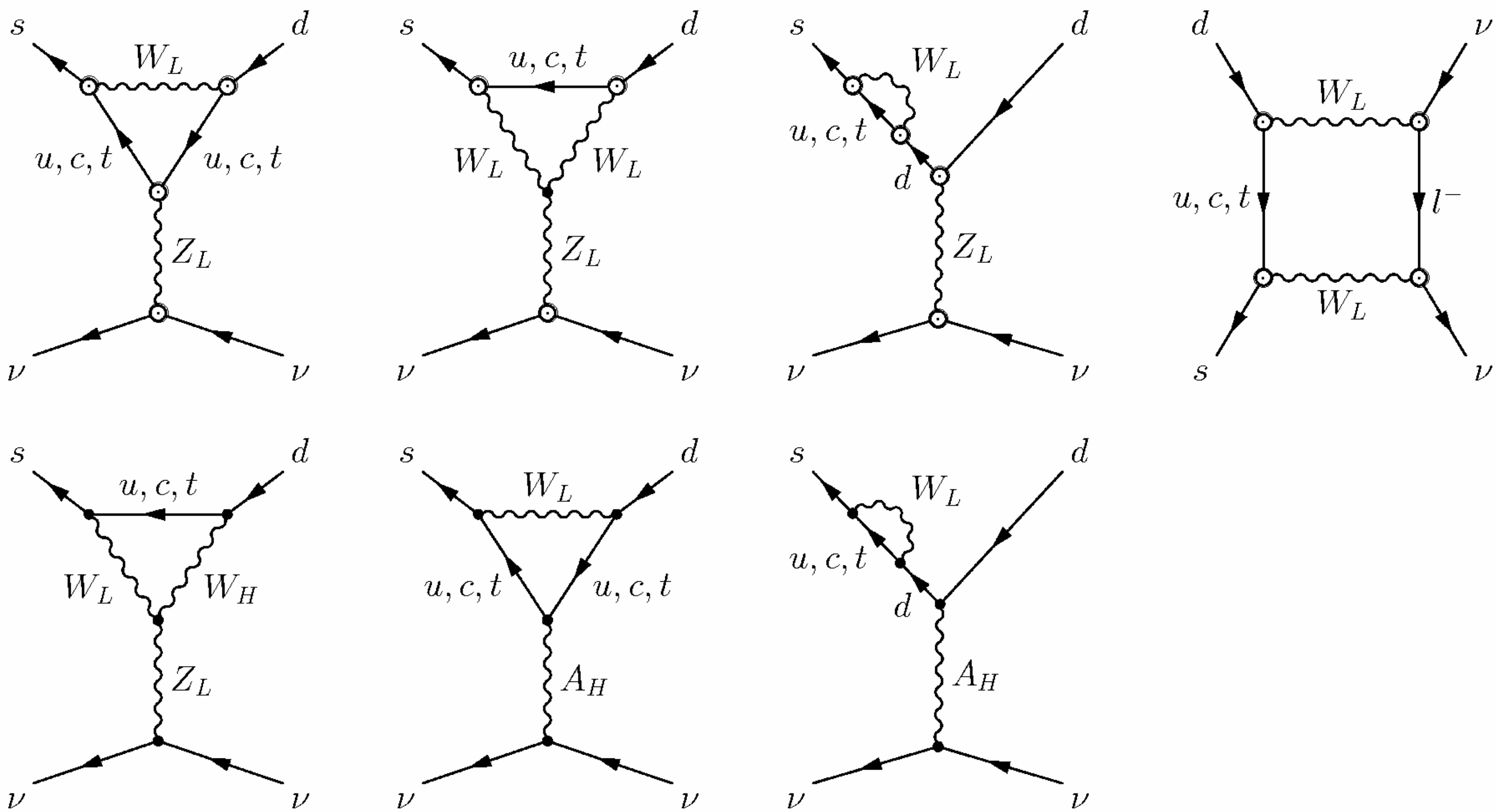
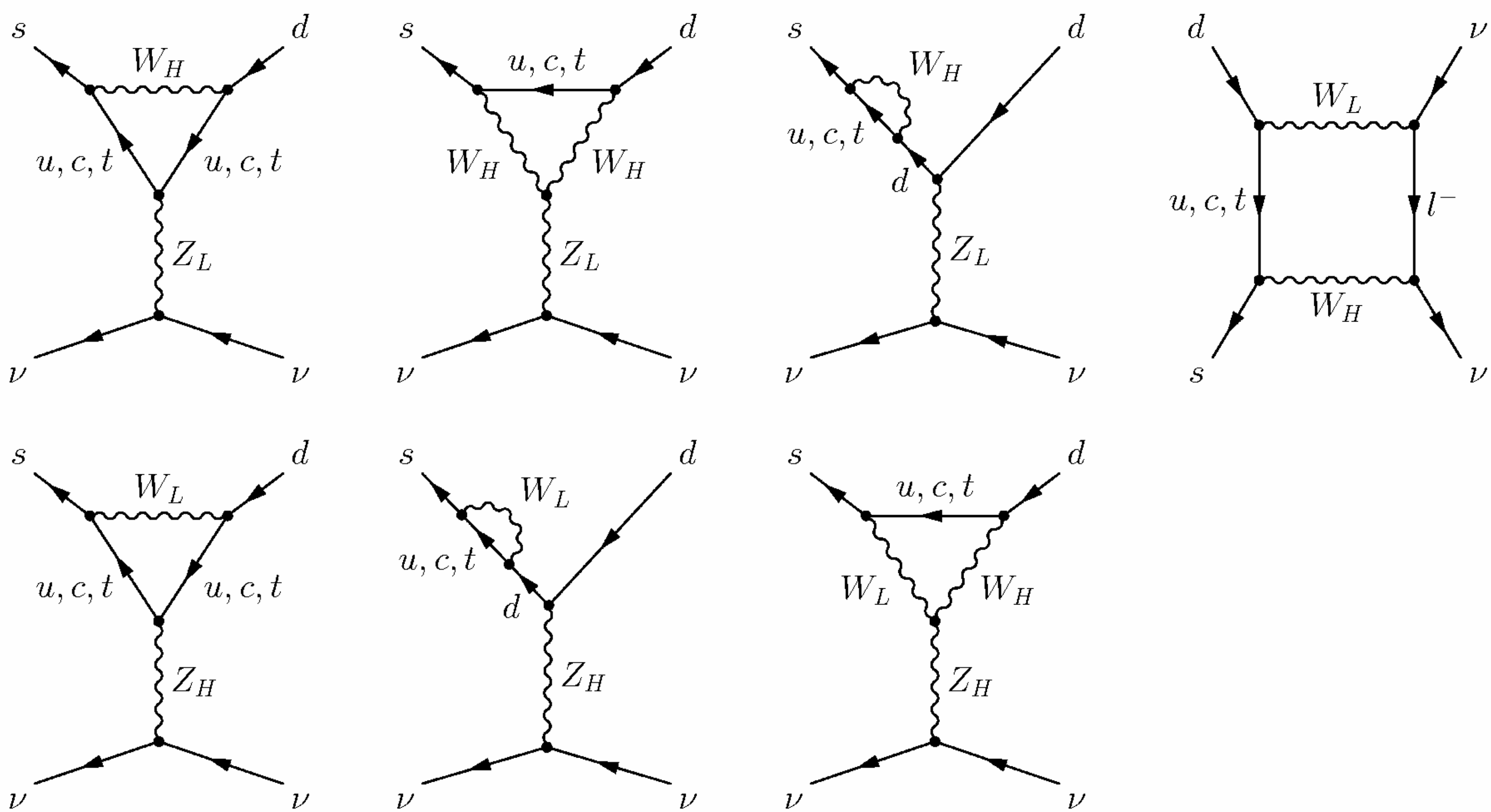
T
W_L
b
d

Movement 2



Movement 3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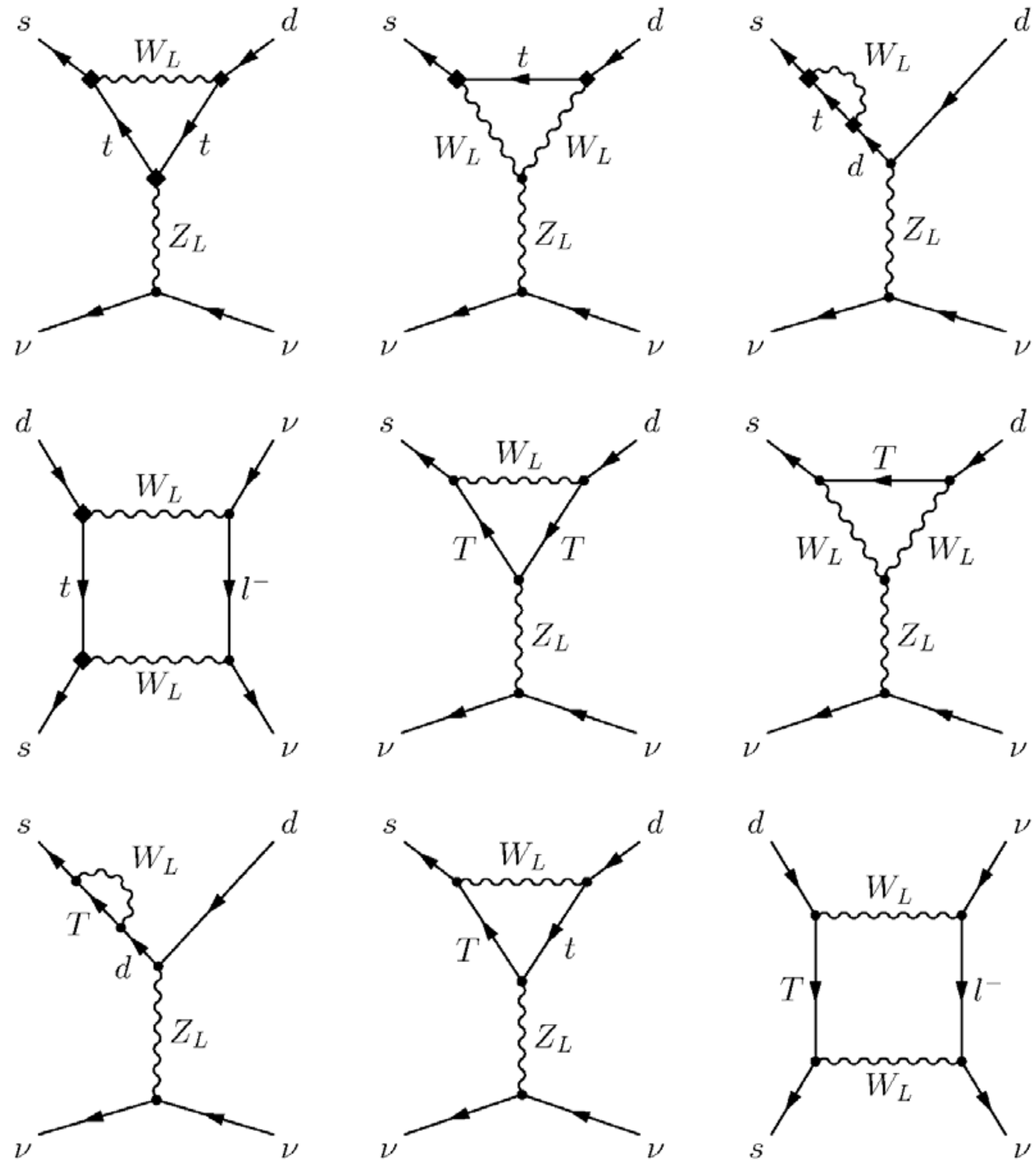
ν

Movement 4


s d W_L t t Z_L ν ν
s d t W_L W_L Z_L ν ν
s d W_L t d Z_L ν ν
d ν W_L t l⁻ W_L s ν
s d W_L T T Z_L ν ν
s d T W_L W_L Z_L ν ν
s d W_L T d Z_L ν ν
s d W_L T t Z_L ν ν
d ν W_L T l⁻ W_L s ν

FCNC Processes in MSSM (MFV)

Classic Paper : Bertolini, Borzumati, Masiero, Ridolfi (1991)

Last Analysis : AJB, Gambino, Gorbahn, Jäger, Silvestrini (2000)

$$\boxed{T(Q) \equiv \frac{Q_{MSSM}}{Q_{SM}}}$$

Isidori, Mescia, Paradisi
Smith, Trine (06)

$$0.65 \le T(K^+ \to \pi^+ \nu\bar{\nu}) \le 1$$

$$0.41 \le T(K_L \to \pi^0 \nu\bar{\nu}) \le 1$$

$$0.73 \le T(B \to X_s \nu\bar{\nu}) \le 1.34$$

$$0.68 \le T(B_s \to \mu\bar{\mu}) \le 1.53$$

Governed by the modification of $\underbrace{X(v)}_{\text{enhanced or suppressed}}$ and $V_{td} \Downarrow$

Governed by the modification of the functions $\underbrace{X(v)\ ,\ Y(v)}_{\text{enhanced or suppressed}}$

V_{ts} not modified

MFVfit Collaboration

(BBBEPSW)
hep-ph/0505110

Use the existing results for

1. UUTfit
2. $B \to X_s \gamma$
3. $B \to X_s l^+ l^-$
4. $K^+ \to \pi^+ \nu \bar{\nu}$

$$X_{max}(v) = 1.95 \qquad Y_{max}(v) = 1.43$$
$$(X_{SM} \cong 1.53) \qquad (Y_{SM} \cong 0.99)$$

Model Independent Upper Bounds within MFV Scenario

Conclusion : Large Departures from SM within MFV not possible

Upper Bounds on Rare K and B Decays from MFV

Bobeth, Bona, AJB, Ewerth, Pierini, Silvestrini, Weiler hep-ph/0505110

Branching Ratios	MFV (95%)	SM (95%)	SM (68%)	Exp
$Br(K^+ \to \pi^+ \nu\bar{\nu}) \cdot 10^{11}$	<11.9	<10.9	8.3±1.2	$14.7^{+13.0}_{-8.9}$
$Br(K_L \to \pi^0 \nu\bar{\nu}) \cdot 10^{11}$	<4.6	<4.2	3.1±0.6	$<5.9 \cdot 10^4$
$Br(B \to X_s \nu\bar{\nu}) \cdot 10^5$	<5.2	<4.1	3.7±0.2	<64
$Br(B_s \to \mu^+\mu^-) \cdot 10^9$	<7.4	<5.9	3.7±1.0	$<5.0 \cdot 10^2$
$Br(B_d \to \mu^+\mu^-) \cdot 10^{10}$	<2.2	<1.8	1.1±0.4	$<1.6 \cdot 10^3$

8.

Going beyond MFV

1. MSSM at large $\tan\beta$

2. New Complex Phase in Z^0 Penguins

Three Simple Scenarios

Inami Lim Functions

SM :

$$A(\text{Decay}) = \sum_i B_i\, \eta^i_{QCD}\, V^i_{CKM} \underbrace{F^i_{SM}}_{\text{real}}(m_t)$$

MFV :

(Minimal Flavour Violation)

$$A(\text{Decay}) = \sum_i B_i\, \eta^i_{QCD}\, V^i_{CKM} \underbrace{\left[F^i_{SM} + F^i_{New}\right]}_{\text{real}}$$

AJB, Gambino, Gorbahn, Jäger, Silvestrini
D'Ambrosio, Giudice, Isidori, Strumia

Enhanced Z^0-Penguins :

$$A(\text{Decay}) = \sum_i B_i\, \eta^i_{QCD}\, V^i_{CKM} \left[\underbrace{F^i_{SM}}_{\text{real}} + \underbrace{\Delta^i_{New}}\right]$$

Dominated by Z^0-Penguins with a New Complex Phase

AJB, Colangelo, Isidori, Romanino, Silvestrini
Buchalla, Hiller, Isidori; Atwood, Hiller
AJB, Fleischer, Recksiegel, Schwab

Two more complicated Scenarios

MSSM (MFV) (large tanβ)

(Higgs penguin)

$$A\left(\text{Decay}\right)=\sum_i B_i\,\eta^i_{\text{QCD}}\,V^i_{\text{CKM}}\left[\overbrace{F^i_{\text{SM}}+F^i_{\text{New}}}^{\text{real}}\right]+\sum_i B^{\text{New}}_i\left[\eta^i_{\text{QCD}}\right]^{\text{New}}V^i_{\text{CKM}}\underbrace{\left[G^i_{\text{New}}\right]}_{\text{real}}$$

General MSSM

Z'-Models
L-R Models
Multi-Higgs Models

$$A\left(\text{Decay}\right)=\sum_i B_i\,\eta^i_{\text{QCD}}\,V^i_{\text{CKM}}\left[\overbrace{F^i_{\text{SM}}+F^i_{\text{New}}}^{\text{complex}}\right]+\sum_i B^{\text{New}}_i\left[\eta^i_{\text{QCD}}\right]^{\text{New}}V^i_{\text{New}}\underbrace{\left[G^i_{\text{New}}\right]}_{\text{complex}}$$

The Case of large tanβ in MSSM

h_i = Yukawa couplings

SM :

$$\begin{Bmatrix} m_b = h_b v \\ m_t = h_t v \end{Bmatrix} \Rightarrow \{h_b << h_t\} \Rightarrow$$

Couplings of b, s, d, μ, τ, e to Higgs particles can be neglected

MSSM :

$$\begin{Bmatrix} m_b = h_b v_D \\ m_t = h_t v_U \end{Bmatrix} \Rightarrow \left\{ \begin{array}{c} h_b \approx h_t \\ \text{if} \\ \tan\beta = \dfrac{v_U}{v_D} >> 1 \end{array} \right\} \Rightarrow$$

$$v = \sqrt{v_U^2 + v_D^2}$$

{ Couplings of b, s, τ, μ to Higgs particles **<u>cannot</u>** be neglected }

Implications :

1. Enhancement Factors in Higgs-Fermion Vertices $\sim \boxed{\tan\beta \cdot m_b}$
2. Higgs Penguins cannot be neglected
3. New relevant Vertices imply **new Operators**

MSSM with MFV but large $\tan\beta$

$$\tan\beta = \frac{v_2}{v_1}$$

$$A(\mathrm{Decay}) = \sum_i B_i\, \eta^i_{QCD}\, V^i_{CKM}\left[F^i_{SM} + \overbrace{F^i_{New}}^{\text{real}}\right]$$
$$+\sum_i B_i^{New}\left[\eta^i_{QCD}\right]^{New} V^i_{CKM}\underbrace{\left[G^i_{New}\right]}_{\text{real}}$$

$B_s \to \mu^+\mu^-$

ΔM_s

$$O_A = \left[\bar{b}\gamma_\mu(1-\gamma_5)s\right]\left[\bar{\mu}\gamma^\mu\gamma_5\mu\right]$$

SM Operators

$$Q^{VLL} = \left[\bar{b}\gamma_\mu(1-\gamma_5)s\right]\left[\bar{b}\gamma^\mu(1-\gamma_5)s\right]$$

$$O_S = m_b\left[\bar{b}(1-\gamma_5)s\right]\left[\bar{\mu}\mu\right]$$
$$O_P = m_b\left[\bar{b}(1-\gamma_5)\right]\left[\bar{\mu}\gamma_5\mu\right]$$

← New Operators →

$$Q_1^{LR} = \left[\bar{b}\gamma_\mu(1-\gamma_5)s\right]\left[\bar{b}\gamma^\mu(1+\gamma_5)s\right]$$
$$Q_2^{LR} = \left[\bar{b}(1-\gamma_5)s\right]\left[\bar{b}(1+\gamma_5)s\right]$$
$$Q_1^{SLL} = \left[\bar{b}(1-\gamma_5)s\right]\left[\bar{b}(1-\gamma_5)s\right]$$
$$Q_2^{SLL} = \left[\bar{b}\sigma_{\mu\nu}(1-\gamma_5)s\right]\left[\bar{b}\sigma_{\mu\nu}(1-\gamma_5)s\right]$$

Correlation between ΔM_s and $B^0_{s,d} \to \mu^+ \mu^-$ in Supersymmetry at Large $\tan\beta$

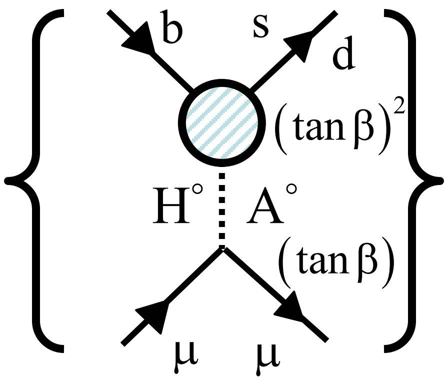
Based on: *AJB, Chankowski, Rosiek, Slawianowska (hep-ph/0207241) (hep-ph/0210121)*

MSSM at large tanβ

$\left(B_{s,d} \to \mu^+\mu^-\right)$

In MSSM at large tanβ
(CKM still the only source of Flavour and CP Violation)

Strong Enhancement



$$\left\{\begin{array}{l} Br\left(B_{s,d} \to \mu\bar{\mu}\right) \sim \left(\tan\beta\right)^6 \\ 10^{-6}\left(10^{-7}\right) \text{ possible} \\ SM \sim 10^{-9} \end{array}\right\}$$

Babu, Kolda
Chankowski, Slawianowska
Bobeth, Ewerth, Krüger, Urban
Huang, Liao, Yan, Zhu
Isidori, Retico
Dedes, Dreiner, Nierste
Dedes, Pilaftis
Chankowski, Rosiek
Foster, Okumura, Roszkowski

$\boxed{Br\left(B_s \to \mu\bar{\mu}\right) < 1.0 \cdot 10^{-7} \quad (CDF)}$ 95% C.L.

$\boxed{Br\left(B_d \to \mu\bar{\mu}\right) < 3.0 \cdot 10^{-8} \quad (CDF)}$ 95% C.L. 90% C.L.

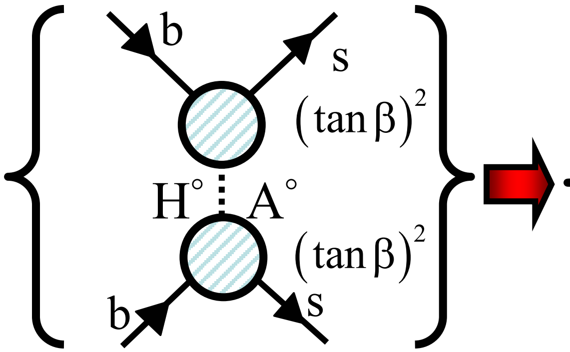
MSSM at large tanβ (cont.)

(ΔM_s)

$B_s^0 - \bar{B}_s^0$ Mixing

(Double-Higgs Peguin)

Suppression



$$\Delta M_s \approx (\Delta M_s)^{SM} - c(\tan\beta)^4$$

AJB, Chankowski, Rosiek
Slawianowska (2001, 2002)

Correlation between SUSY effects in $Br(B_{s,d} \to \mu\bar{\mu})$ and ΔM_s

Negligible contributions to ΔM_d, ε_K

Clear violation of K↔B MFV relations

<u>Subsequent analyses</u>: D‘Ambrosio, Giudice, Isidori, Stumia
Dedes, Pilaftis

$$\left\{\begin{array}{l}\text{Double}\\ \text{Higgs}-\text{Penguin}\end{array}\right\} \Rightarrow \left\{\Delta M_S^{DP} \sim -(\tan\beta)^4 \frac{F_{B_s}^2}{M_A^2} \frac{\varepsilon_Y^2}{(1+\tilde{\varepsilon}_3 \tan\beta)^2 (1+\varepsilon_0 \tan\beta)^2}\right\}$$

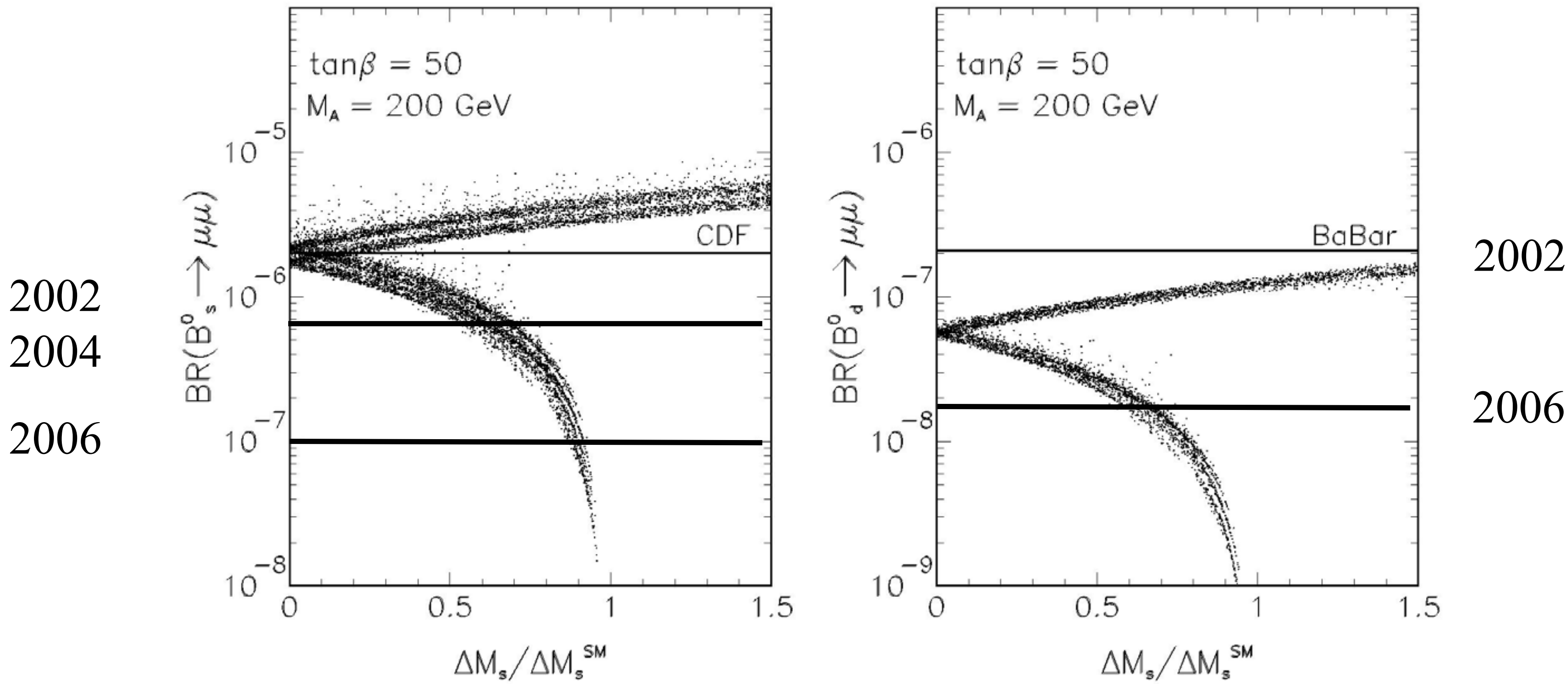
$$\left\{[\text{Higgs}-\text{Penguin}]^2\right\} \Rightarrow \left\{Br(B_s \to \mu\bar{\mu}) \sim (\tan\beta)^6 \frac{F_{B_s}^2}{M_A^4} \frac{\varepsilon_Y^2}{(1+\tilde{\varepsilon}_3 \tan\beta)^2 (1+\varepsilon_0 \tan\beta)^2}\right\}$$

$\varepsilon_Y,\ \varepsilon_0,\ \overline{\varepsilon}_3$ - Functions of SUSY parameters

$$\boxed{\frac{Br(B_d^0 \to \mu^+\mu^-)}{Br(B_s^0 \to \mu^+\mu^-)} \cong \left[\frac{F_{B_d}}{F_{B_s}}\right]^2 \left|\frac{V_{td}}{V_{ts}}\right|^2 \left|\frac{M_{B_d}}{M_{B_s}}\right|^5}$$

$\mathrm{Br}\left(B_{s,d} \to \mu^+\mu^-\right)$ vs $(\Delta M_s)^{\exp} / (\Delta M_s)^{SM}$ in SUSY at Large $\tan\beta$

AJB, Chankowski, Rosiek, Slawianowska, hep-ph/0207241



Numerical Results

$$0.8 \leq \frac{(\Delta M_s)^{\exp}}{(\Delta M_s)^{SM}} \leq 0.95$$

$\Rightarrow$

$$6 \cdot 10^{-7} \geq Br^{\max}\left(B_s \to \mu^+\mu^-\right) \geq 3 \cdot 10^{-8}$$

$$1.8 \cdot 10^{-8} \geq Br^{\max}\left(B_d \to \mu^+\mu^-\right) \geq 1 \cdot 10^{-9}$$

$$Br\left(B_s \to \mu^+\mu^-\right)_{\exp} < 1 \cdot 10^{-7} \qquad \text{(CDF)}$$

$$Br\left(B_d \to \mu^+\mu^-\right)_{\exp} < 3 \cdot 10^{-8} \qquad \text{(CDF)}$$

Blanke, AJB, Guadagnoli
Tarantino (06)

$$Br\left(B_s \to \mu^+\mu^-\right)_{SM} = \left(3.36 \pm 0.32\right) \cdot 10^{-9}$$

$$Br\left(B_d \to \mu^+\mu^-\right)_{SM} = \left(1.04 \pm 0.09\right) \cdot 10^{-10}$$

Conclusions

1. For $(\Delta M_s)^{\exp} \geq (\Delta M_s)^{SM}$ substantial enhancements of $Br(B_{s,d} \to \mu^+\mu^-)$ not possible without new sources of flavour violation (beyond CKM)

2. Observation of $Br(B_s \to \mu^+\mu^-) \geq 10^{-8}$

$$Br(B_d \to \mu^+\mu^-) \geq 10^{-9}$$

will imply either $(\Delta M_s)^{\exp} < (\Delta M_s)^{SM}$

and/or new sources of flavour violation (beyond CKM)

3. In order to find out $\dfrac{(\Delta M_s)^{\exp}}{(\Delta M_s)^{SM}}$

$\Leftarrow$ (CDF, DØ)

$\Leftarrow$ F_{B_s}, B_i

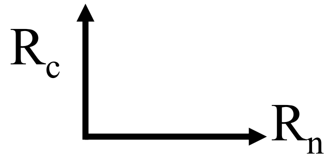
(BFRS)

The B →πK Puzzle

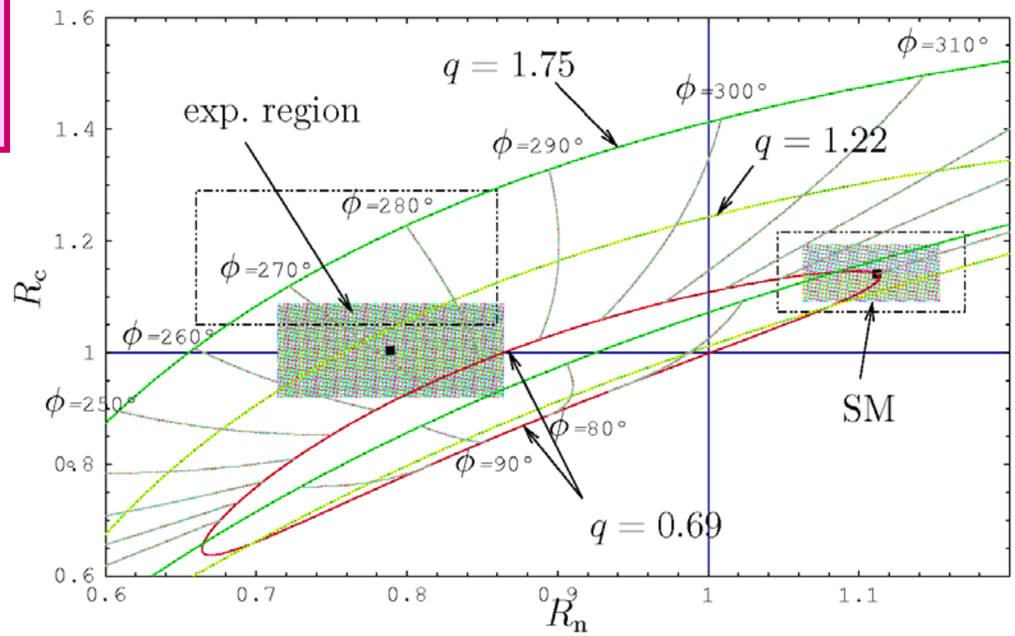
EWP = $q e^{i\varphi}$

$$R_c = 2\left[\frac{Br(B^{\pm} \to \pi^0 K^{\pm})}{Br(B^{\pm} \to \pi^{\pm} K^0)}\right]$$

$$R_n = \frac{1}{2}\left[\frac{Br(B^0 \to \pi^- K^+)}{Br(B^0 \to \pi^0 K^0)}\right]$$



SM: $q = 0.69$, $\varphi = 0$ — Neubert Rosner



Best Values
(including rare
decay constraint)

$q \approx 0.92$
$\varphi \approx -85^{o}$ — BFRS

$(R_c)_{SM} = 1.14 \pm 0.05$
$(R_n)_{SM} = 1.11 \pm 0.05$

$R_c = 1.17 \pm 0.12$
$R_n = 0.76 \pm 0.10$

Exp: before ICHEP 04

Rare Decays

$R_c = 1.00 \begin{smallmatrix} +0.12 \\ -0.08 \end{smallmatrix}$
$R_n = 0.82 \begin{smallmatrix} +0.12 \\ -0.11 \end{smallmatrix}$

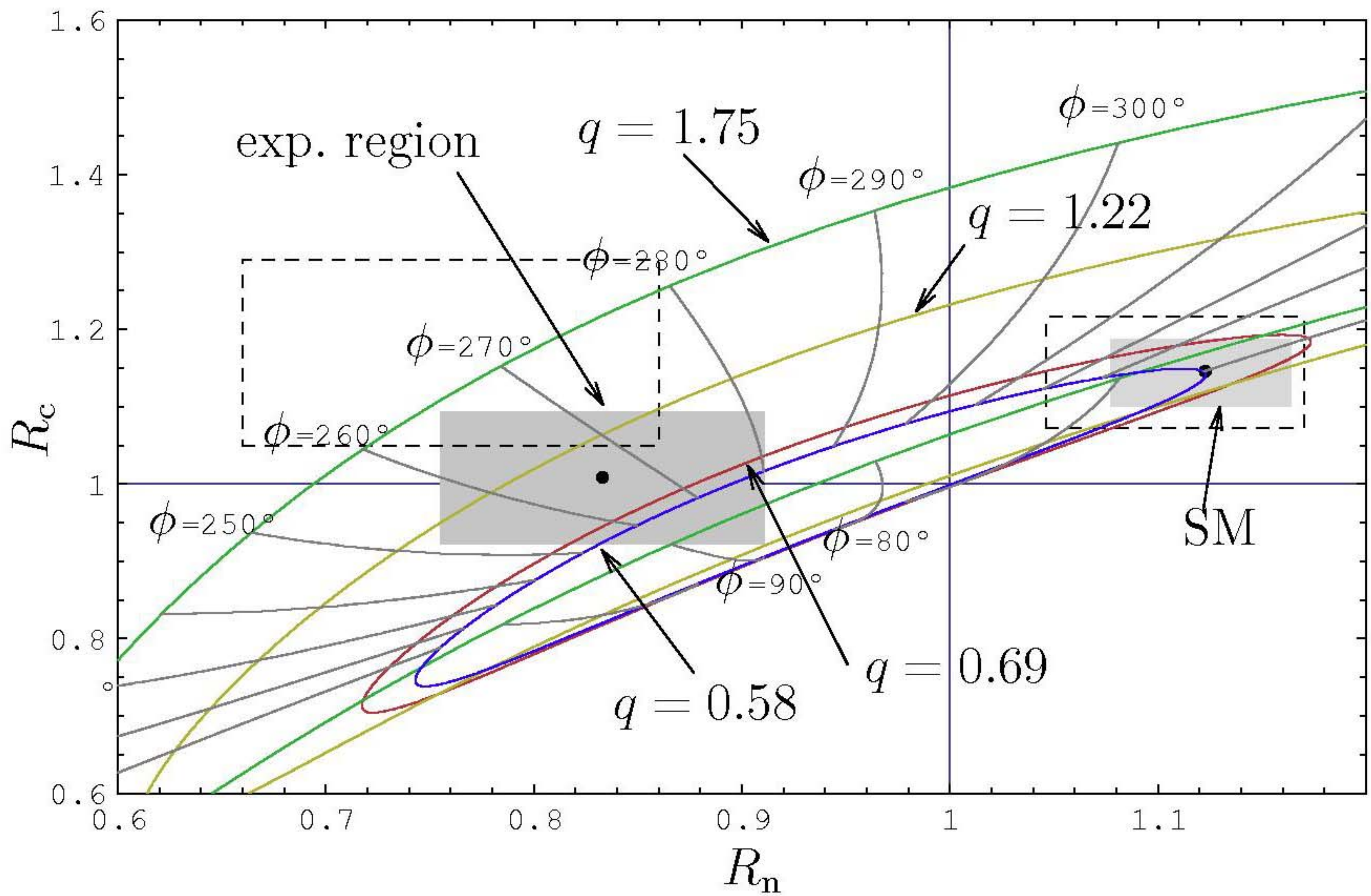
BFRS Expectation
of June 04

$R_c = 1.00 \pm 0.08$
$R_n = 0.79 \pm 0.08$

Exp: after ICHEP 04

CLEO
BaBar
Belle

Status 2006

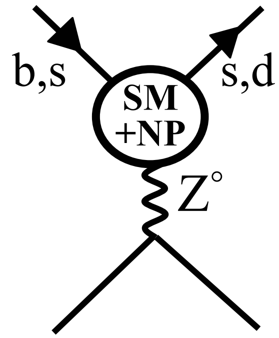


1.6
1.4
1.2
1
0.8
0.6
0.6
0.7
0.8
0.9
1
1.1
R_c
R_n
exp. region
$q = 1.75$
$q = 1.22$
$q = 0.69$
$q = 0.58$
ϕ=300°
ϕ=290°
ϕ=280°
ϕ=270°
ϕ=260°
ϕ=250°
ϕ=80°
ϕ=90°
SM

Relation: $B \to \pi K$ ⟺ Rare K and B Decays

BFRS

Fundamental
<u>Short Distance</u>
Physics of EWP
$\mu = 0(m_t)$:



$$\sim X\big(\overbrace{m_t, \tilde{m}, \text{ new phases}}^{v}\big) \qquad \nu\bar{\nu}$$

$$\sim Y\big(m_t, \tilde{m}, \text{ new phases}\big) \qquad \mu\bar{\mu}$$

RG

$B \to \pi K$

(q, φ)

$\mu = 0(m_b)$

$K \to \pi\nu\bar{\nu},\ B \to X_S\mu^+\mu^-$

$K_L \to \pi^0\mu^+\mu^-,\ B_{d,s} \to \mu^+\mu^-$

$B \to X_{d,s}\nu\bar{\nu}$

Renormalization group :

$$|X(v)|e^{i\theta_X} = 2.35\ qe^{i\varphi} - 0.09 \approx 2.2 \cdot e^{-i86^o}$$

$$|Y(v)|e^{i\theta_Y} = 2.35\ qe^{i\varphi} - 0.64 \approx 2.2 \cdot e^{-i100^o}$$

$X_{SM} = 1.53$

$Y_{SM} = 0.98$

Implications for $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^o \nu\bar{\nu}$

$$Br\left(K^+ \to \pi^+\nu\bar{\nu}\right)_{SM} = (7.8 \pm 1.2)\cdot 10^{-11} \Rightarrow (7.5 \pm 2.1)\cdot 10^{-11} \Leftarrow$$

Enhancement of |X| compensated by destructive "top-charm" interference

☆ $$Br\left(K_L \to \pi^o\nu\bar{\nu}\right)_{SM} = (3.0 \pm 0.6)\cdot 10^{-11} \Rightarrow \boxed{(3.1 \pm 1.0)\cdot 10^{-10}}$$

☆ Strong Violation of the "Golden" Relation :

Buchalla, AJB (94)

SM: $(\sin 2\beta)_{\pi\nu\bar{\nu}} = (\sin 2\beta)_{\psi K_S}$

Here: $-\left(0.69 {+0.23 \atop -0.41}\right) \neq 0.74 \pm 0.05$

$\sin 2\beta_X$

$$\beta_X = \beta - \theta_X$$
$$X = |X| e^{i\theta_X}$$

$\beta_X \cong 110^o$

☆ FIG

Saturation of the model-independent Grossman-Nir bound :

$$Br\left(K_L \to \pi^o\nu\bar{\nu}\right) \le 4.4 \; Br\left(K^+ \to \pi^+\nu\bar{\nu}\right)$$

Here:
$$\frac{Br\left(K_L \to \pi^o\nu\bar{\nu}\right)}{Br\left(K^+ \to \pi^+\nu\bar{\nu}\right)} \approx 4.4 \;\; \sin^2(\beta_X) \approx 4.2 \pm 0.2$$

New Complex Phase in Z^0 Penguins

Enhanced Z^0-Penguins : $A(\text{Decay}) = \sum_i B_i\, \eta^i_{QCD}\, V^i_{CKM} \Big[\underbrace{F^i_{SM}}_{\text{real}} + \underbrace{\Delta^i_{New}} \Big]$

Dominated by Z^0-Penguins with a New Complex Phase

AJB, Colangelo, Isidori, Romanino, Silvestrini
Buchalla, Hiller, Isidori; Atwood, Hiller
AJB, Fleischer, Recksiegel, Schwab

Just replace: $C(x_t) \to |C(v)| e^{i\varphi_C}$

φ_C = new complex Phase

$X(x_t) \to |X(v)| e^{i\theta_X}$

$Y(x_t) \to |Y(v)| e^{i\theta_Y}$

Impact of $X = |X| e^{i\theta_X}$ on $K_L \to \pi^o \nu\bar{\nu}$

$$\frac{Br(K_L \to \pi^o \nu\bar{\nu})}{Br(K_L \to \pi^o \nu\bar{\nu})_{SM}} = \underbrace{\left|\frac{X}{X_{SM}}\right|^2}_{\approx 2} \underbrace{\left[\frac{\sin(\beta - \theta_X)}{\sin\beta}\right]^2}_{\approx 5}$$

$\beta\text{-}\theta_X \approx 110^o$

$\beta \cong 24^o$

$$Br(K_L \to \pi^o \nu\bar{\nu}) = (3.0 \pm 0.6) \cdot 10^{-11} \Rightarrow (3.1 \pm 1.0) \cdot 10^{-10}$$

(SM) (Here)

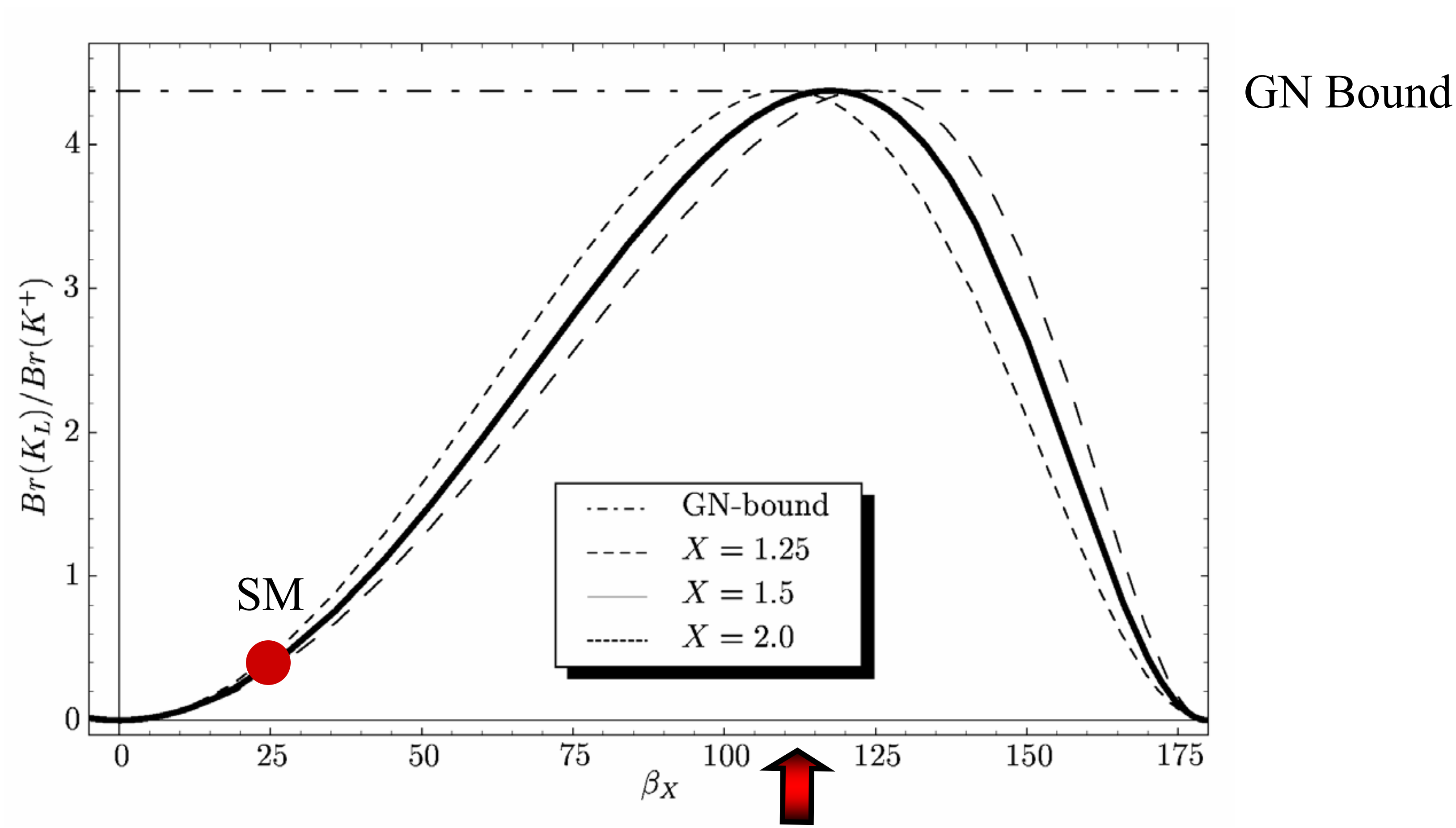
$$\frac{Br(K_L \to \pi^o \nu\bar{\nu})}{Br(K^+ \to \pi^+ \nu\bar{\nu})} = \underset{(SM)}{0.4} \Rightarrow 4.2$$

< 4.4 Grossman-Nir bound

Order of magnitude enhancement !!

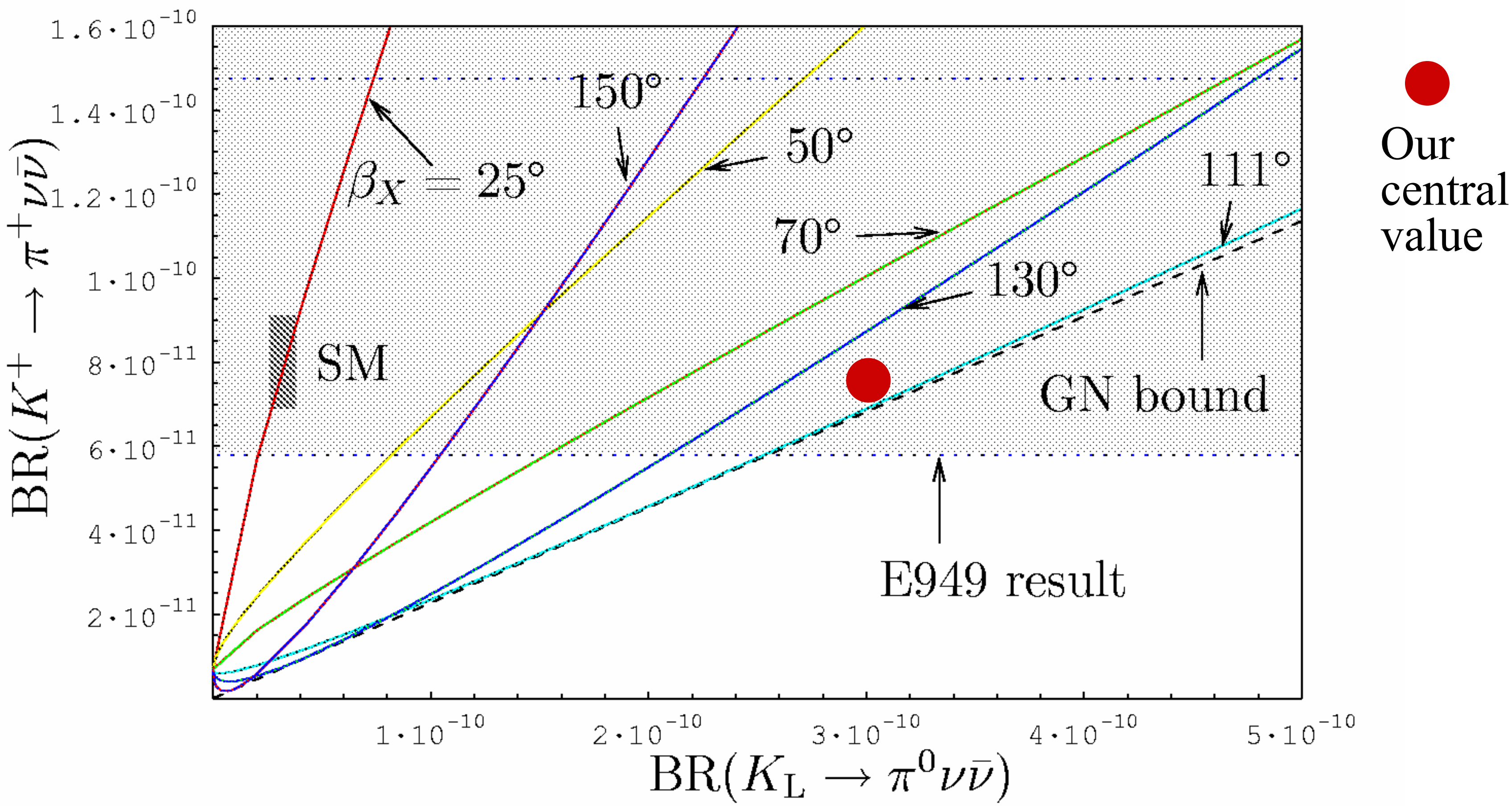
$$\frac{Br\left(K_L \to \pi^0 \nu\bar{\nu}\right)}{Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)} \text{ versus } \beta_X$$

BSU (04)



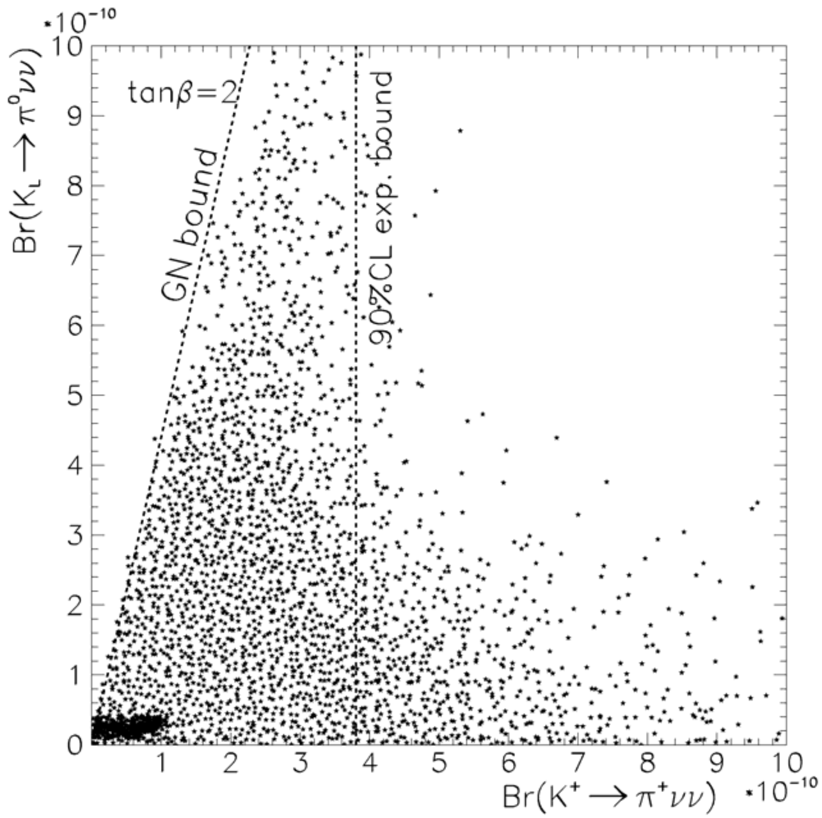
$K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ with $X = |X|e^{i\theta_x}$ (BFRS)

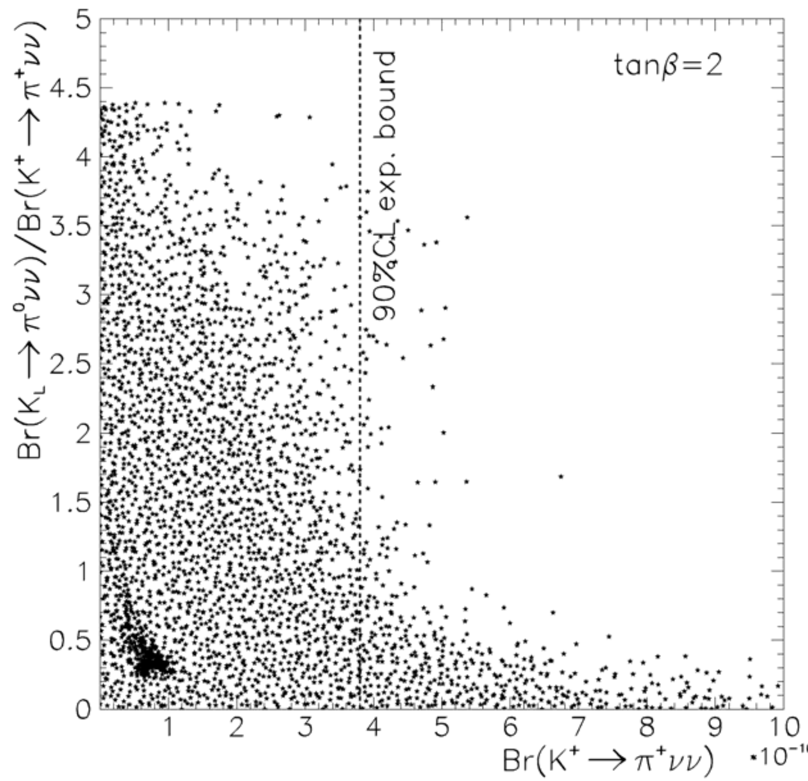
$$\beta_x = \beta - \theta_x$$



$K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^0 \nu\bar{\nu}$ from a general MSSM

AJB, Ewerth, Jäger, Rosiek (04)





A new analysis: Isidori, Mescia, Paradisi, Smith, Trine

Other Impacts on Rare K and B Decays

Could it be seen
by Belle, BaBar ?

$$\frac{Br\left(B \to X_{s,d}\nu\bar{\nu}\right)}{Br\left(B \to X_{s,d}\nu\bar{\nu}\right)_{SM}} \approx 2.0$$

$$Br\left(B \to X_s\nu\bar{\nu}\right) \approx 7 \cdot 10^{-5}$$

Could it be seen
at Tevatron ?
Will be seen at LHC!

$$\frac{Br\left(B_{s,d} \to \mu^+\mu^-\right)}{Br\left(B_{s,d} \to \mu^+\mu^-\right)_{SM}} \approx 2.5$$

$$Br\left(B_s \to \mu^+\mu^-\right) \approx 1 \cdot 10^{-8}$$

$$Br\left(B_d \to \mu^+\mu^-\right) \approx 3 \cdot 10^{-10}$$

Spectacular Effects in
FB CP Asymmetry in
$B_d \to K^*\mu^+\mu^-$

Lepton polarization
asymmetries in $b \to sl^+l^-$
(Choudhury, Gaur, Cornell (04))

BUT: $(\sin 2\beta)_{\varphi K_S} > (\sin 2\beta)_{\psi K_S} \approx 0.73$

Consistent with BaBar (0.50±0.25±0.06)
but

0.06±0.33±0.09 (Belle)

Z'-models can explain both πK and Belle (Barger et al, 0406126)
but no relation to $K \to \pi\nu\bar{\nu}$, $B \to \mu\mu$

Impact on $K_L \to \pi^o e^+ e^-$ and $K_L \to \pi^o \mu^+ \mu^-$

$$Br\left(K_L \to \pi^o e^+ e^-\right)_{SM} = \left(3.7\,{}^{+1.1}_{-0.9}\right)\cdot 10^{-11}$$

Dominated by <u>indirect</u> $\cancel{CP}$
(Buchalla, D'Ambrosio, Isidori)
(Friot, Greynat, de Rafael)

$\Rightarrow$

$$\left(9.0 \pm 1.6\right)\cdot 10^{-11}$$

Dominated by <u>direct</u> $\cancel{CP}$
BFRS

Isidori
Smith
Unterdorfer

$$Br\left(K_L \to \pi^o \mu^+ \mu^-\right) = \left(1.5 \pm 0.3\right)\cdot 10^{-11}$$

Dominated by CP-conserving
+ indirect $\cancel{CP}$

$\Rightarrow$

$$\left(4.3 \pm 0.7\right)\cdot 10^{-11}$$

Dominated by <u>direct</u> $\cancel{CP}$
ISU

KTeV:

$$Br\left(K_L \to \pi^o e^+ e^-\right) < 2.8\cdot 10^{-10}$$

$$Br\left(K_L \to \pi^o \mu^+ \mu^-\right) < 3.8\cdot 10^{-10}$$

9.

Little Higgs Models with T Parity

Littlest Higgs Models

Non-linear Sigma-Models

valid up to $(4\pi f) \equiv \Lambda$

Original model: Arkani-Hamed, Cohen, Katz, Nelson (2002)

LH

$f \approx O(1\mathrm{TeV})$

Global: $SU(5) \longrightarrow SO(5)$

Local: $[SU(2) \otimes U(1)]_1 \otimes [SU(2) \otimes U(1)]_2 \longrightarrow SU(2)_L \otimes U(1)_Y$

(g_1) (g'_1) (g_2) (g'_2)

Model with T-Parity: Cheng, Low (2003)

LHT

Theory symmetric under $[SU(2) \otimes U(1)]_1 \longleftrightarrow [SU(2) \otimes U(1)]_2$

$g_1 = g_2$ $g'_1 = g'_2$

Littlest Higgs Models without and with T-Parity

New particles: (with O(f) masses)

LH

Gauge Bosons: $W^{\pm}_{H}$, Z^{0}_{H}, A^{0}_{H}

Fermions: T

Scalars: $\Phi^{\pm}$,…

LHT

T-even Sector

SM Particles + T_{+}

T-odd Sector

Gauge Bosons: $W^{\pm}_{H}$, Z^{0}_{H}, A^{0}_{H}

Fermions: T_{-}, Mirror Fermions

Scalars: $\Phi^{\pm}$,…

The World of Mirror Fermions

Required to cut-off large 4-fermion operators constrained by LEP

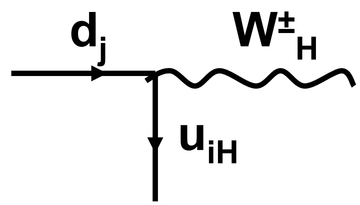
$$\begin{pmatrix} u_{1H} \\ d_{1H} \end{pmatrix} \quad \begin{pmatrix} u_{2H} \\ d_{2H} \end{pmatrix} \quad \begin{pmatrix} u_{3H} \\ d_{3H} \end{pmatrix}$$

Vectorial couplings under $SU(2)_L$

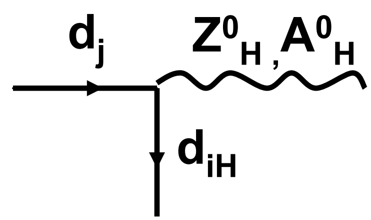
Similarly for Leptons

$m^u_{Hi} = m^d_{Hi}$ $\quad$ $i=1,2,3$
to first order in v/f

New Flavour Interactions involving SM fermions, Mirror Fermions and $W^\pm_H$, Z^0_H, A^0_H



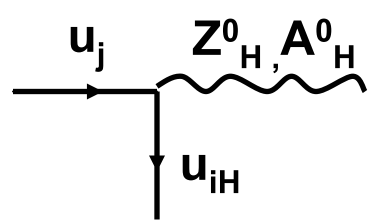
$\sim \ (V_{Hd})_{ij}\, \gamma_\mu\, (1-\gamma_5)$

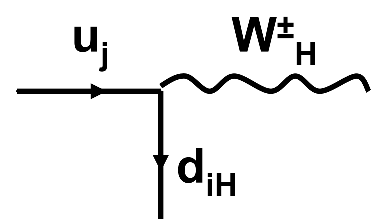


$\sim \ (V_{Hd})_{ij}\, \gamma_\mu\, (1-\gamma_5)$

$V^\dagger_{Hu}\, V_{Hd} = V_{CKM}$

$(V_{Hu})_{ij}$ for:





General Structure of the Amplitudes

LH (CMFV Model)

Non-perturbative factors

Real functions

$$A(Decay) = \sum_i B_i^{SM} \eta_{QCD}^i V_{CKM}^i F_i(m_t, m_T, m_{W_H}, \ldots)$$

LHT

Real functions

$$A(Decay) = \sum_i B_i^{SM} \eta_{QCD}^i \left[V_{CKM}^i F_i(m_t, m_T) + V_{Hd}^i G_i(m_H^u, m_H^d, W_H^{\pm}, Z_H^0, A_H^0) \right]$$

T-even contribution: CMFV
T-odd contribution: New CP and Flavour violating Interactions but SM operators

Problems of LH without T-Parity

1.

Custodial SU(2) Symmetry violated at tree level → $f \geq 2$ TeV → Effects in FCNC <u>small</u>
[AJB,Poschenrieder,Uhlig] (hep-ph/0410309) [Choudhury et al.]

$$\frac{M_W^2}{M_Z^2} = \cos^2\theta_W\left(1 + O\left(\frac{v^2}{f^2}\right)\right)$$

2. $\sin(2\beta) - R_b$ Problem not solved

3. $(\Delta M_s)_{LH} > (\Delta M_s)_{SM}$

Go to LHT!

10.

Short Outlook

Targets for 2005-2012

$|V_{us}|$, $|V_{cb}|$, $|V_{ub}|$, γ
from tree level decays

Improved F_{B_d}, F_{B_s}
$\hat{B}_d$, $\hat{B}_s$, B_i^{NP}, ξ,...

$K^+ \to \pi^+ \nu\bar{\nu}$
$K_L \to \pi^0 \nu\bar{\nu}$
$B \to X_{d,s} \nu\bar{\nu}$

$B_{d,s} \to l^+ l^-$
ΔM_s

Improved
$Br(B \to X_s \gamma)$
$Br(B \to X_s l^+ l^-)$
+ Exclusive Modes

FB-Asymmetries $(B \to X_s l^+ l^-,\ K^* l^+ l^-)$
$\not{CP}$ in $B \to X_s \gamma$, $K^* \gamma$
$\not{CP}$ – FB Asymmetries $(B \to X_s l^+ l^-,\ K^* l^+ l^-)$

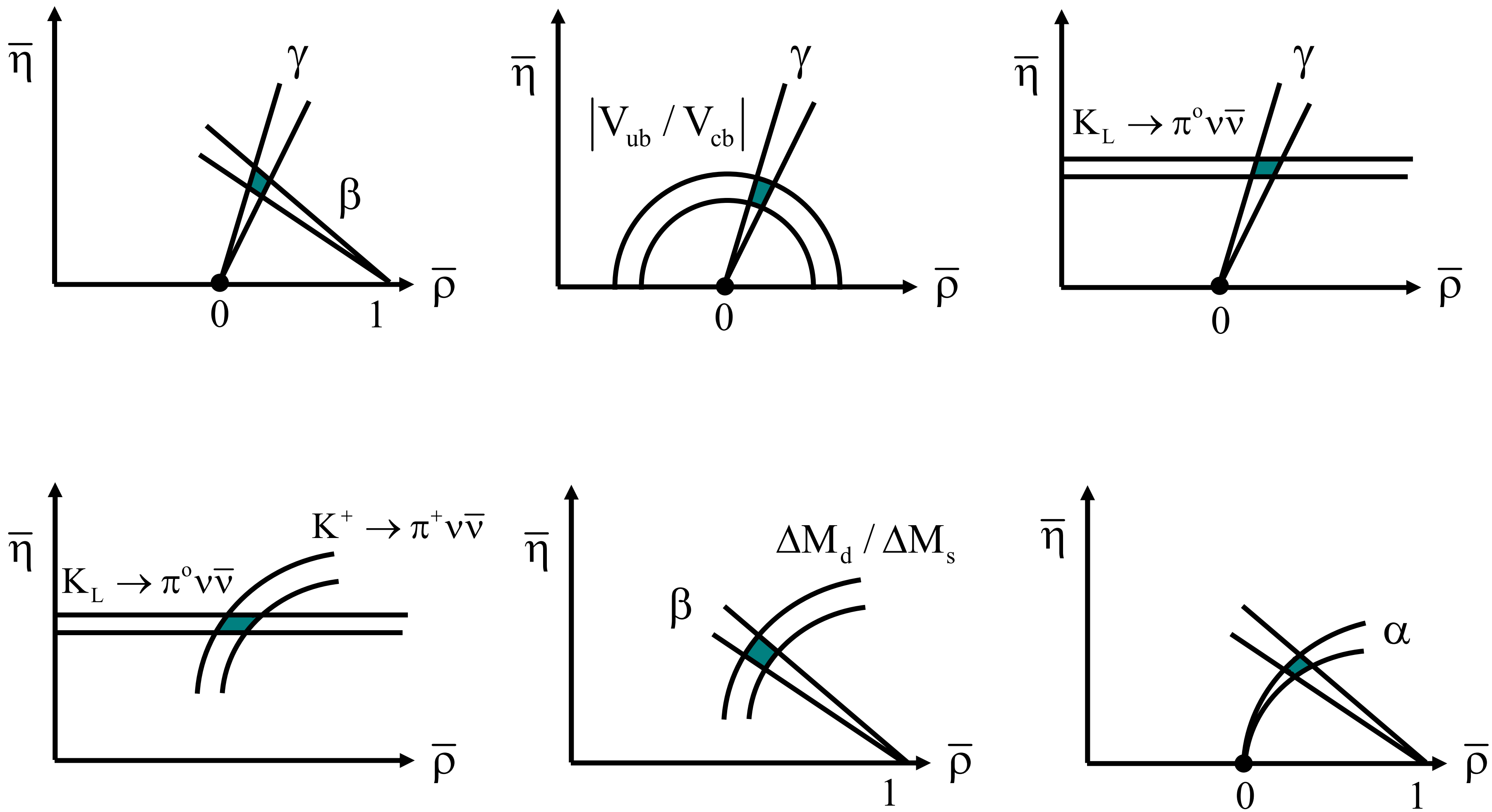
$K_L \to \pi^0 e^+ e^-$
$K_L \to \pi^0 \mu^+ \mu^-$
$K_L \to \mu^+ \mu^-$ (TH)
$\varepsilon' / \varepsilon$ (TH)

Resolution of
$B \to \pi K$ Puzzle
$B \to \pi\pi$ Puzzle
$B \to \varphi K_s$ Puzzle
$B \to \eta' K$ Puzzle

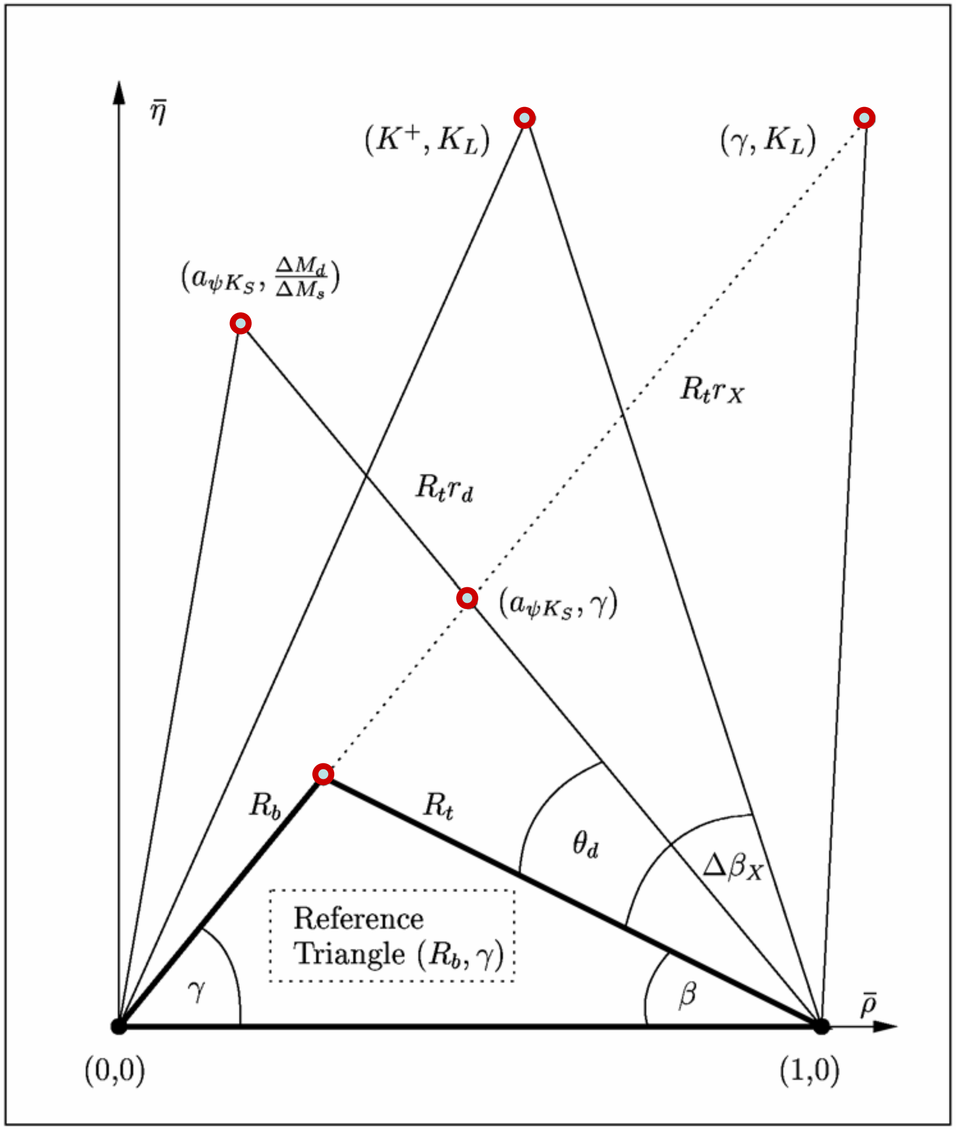
A_{CP}^{dir}, A_{CP}^{mix}
in
2 – Body
$B_{d,s}$, $B^{\pm}$
decays

Correlations with
Electric Dipole Moments
$\mu \to e\gamma$
$(g-2)_\mu$
Lepton Flavour Violation

Searching for New Physics

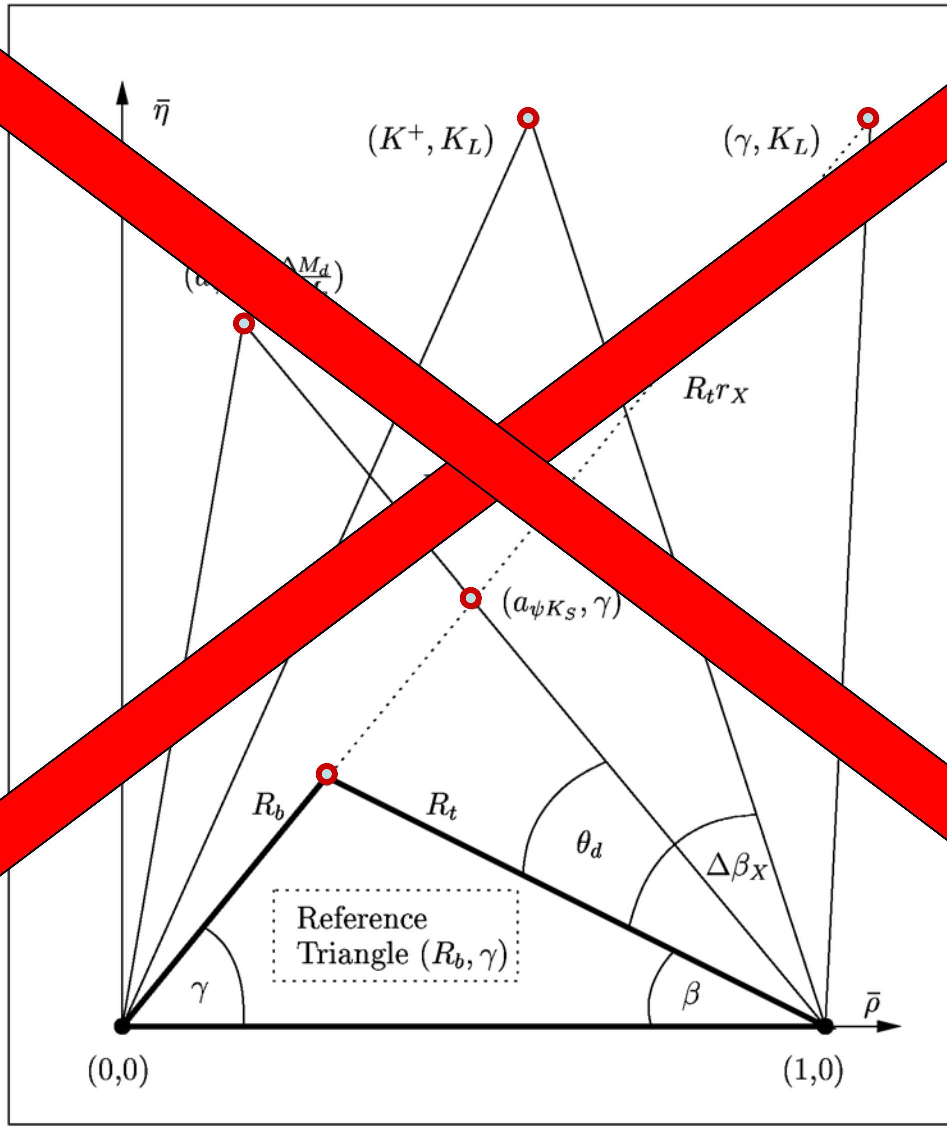


The 2012 Vision of the Unitarity Triangle



AJB
Schwab
Uhlig

The 2012 Vision of the Unitarity Triangle



JB
Sc b
Uhlig

The Future until 2012 should be very exciting

and even more exciting after 2012