Introduction to hadronic collisions: theoretical concepts and practical tools for the LHC

Lecture 4

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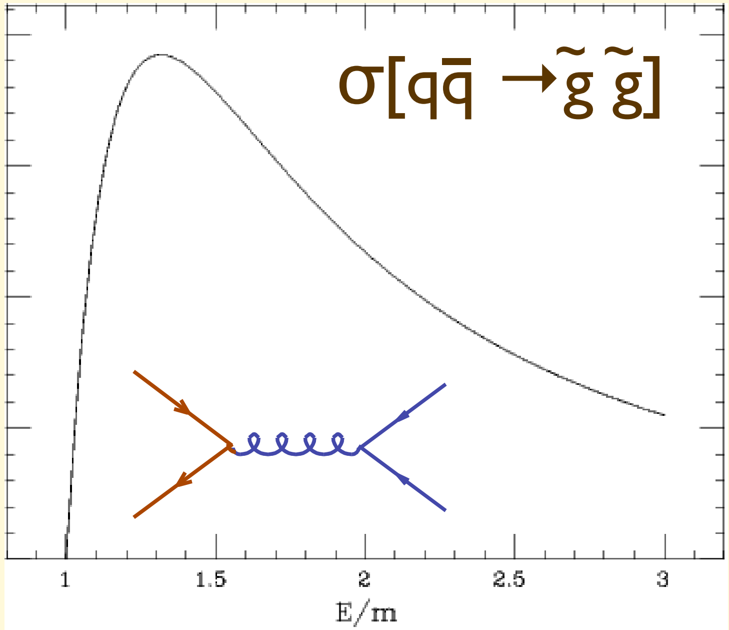
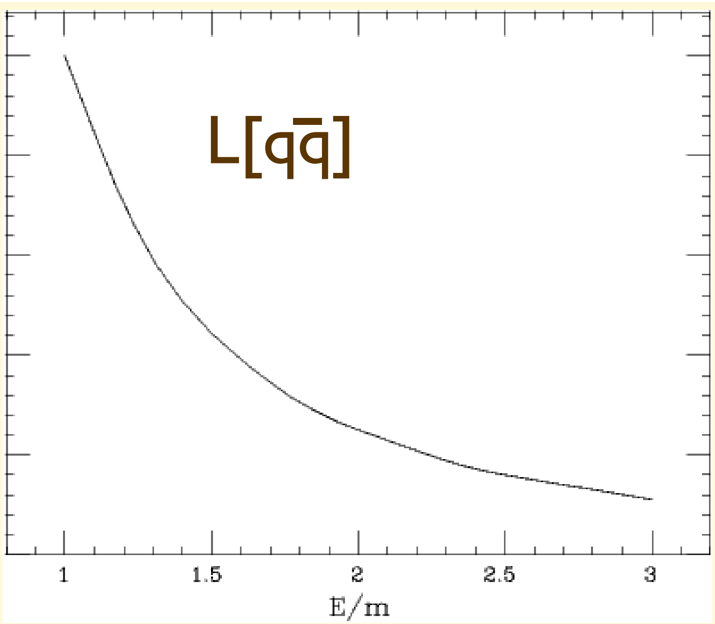
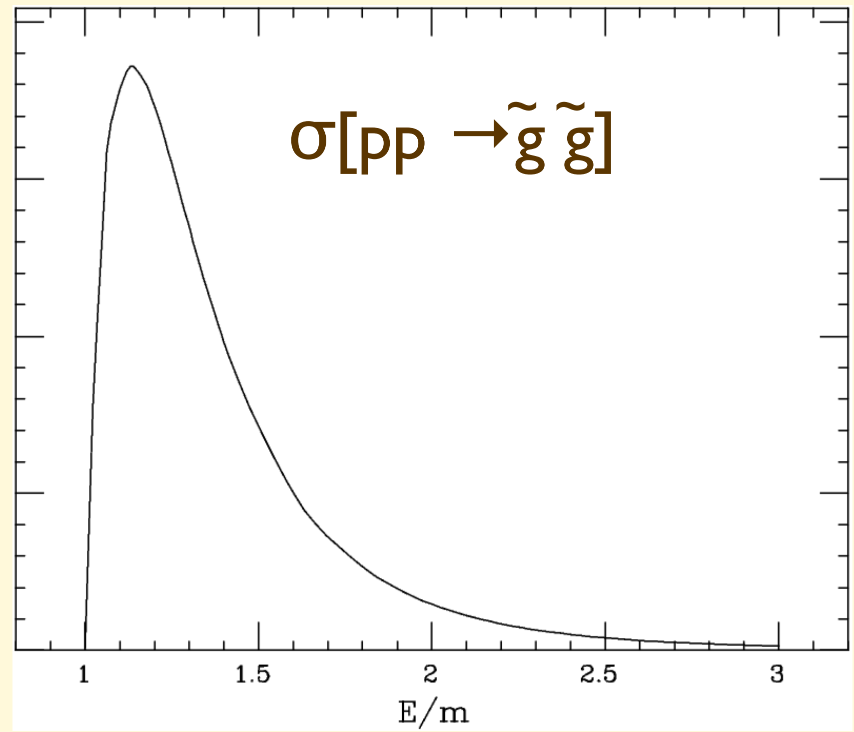
Ex: Gluino pair production

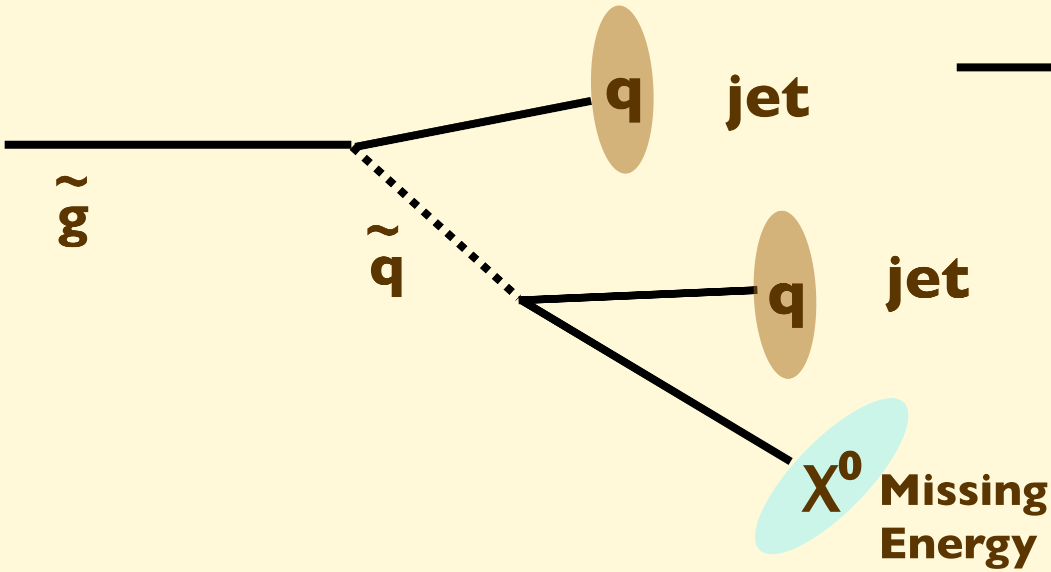


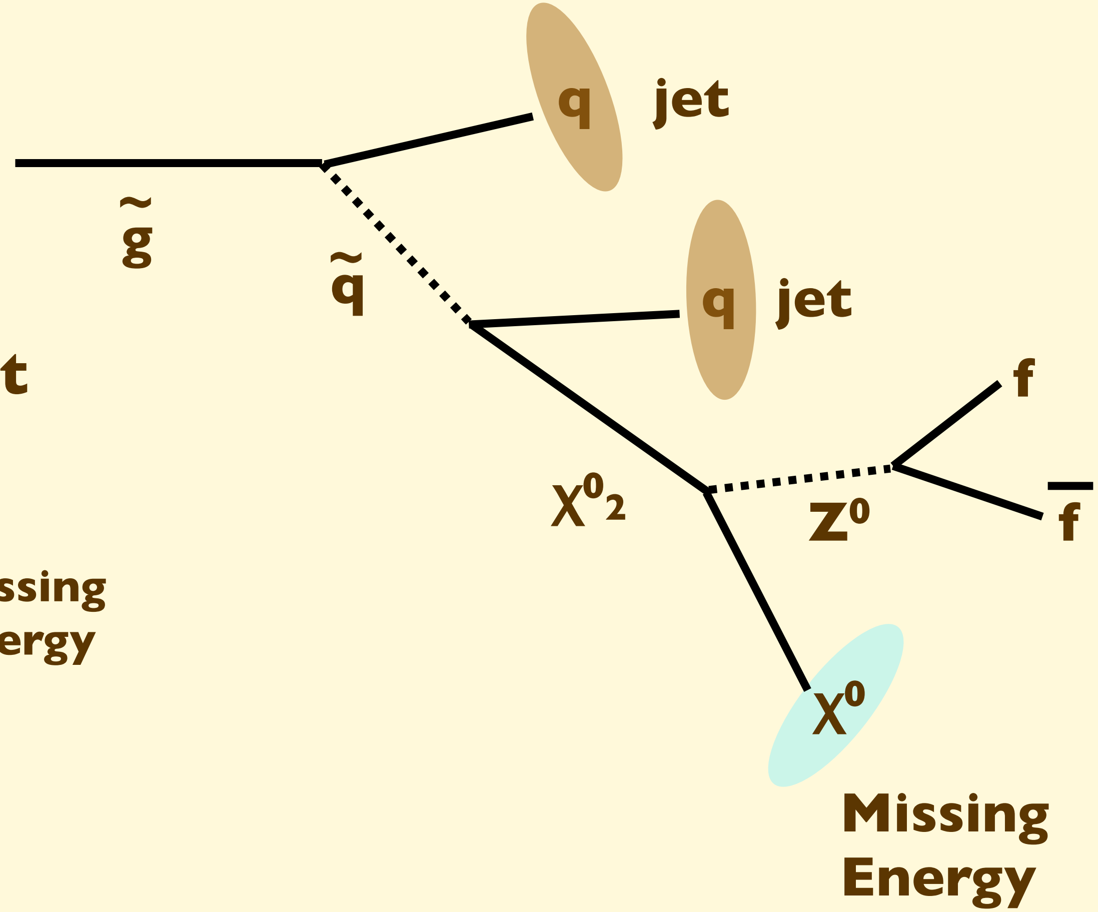


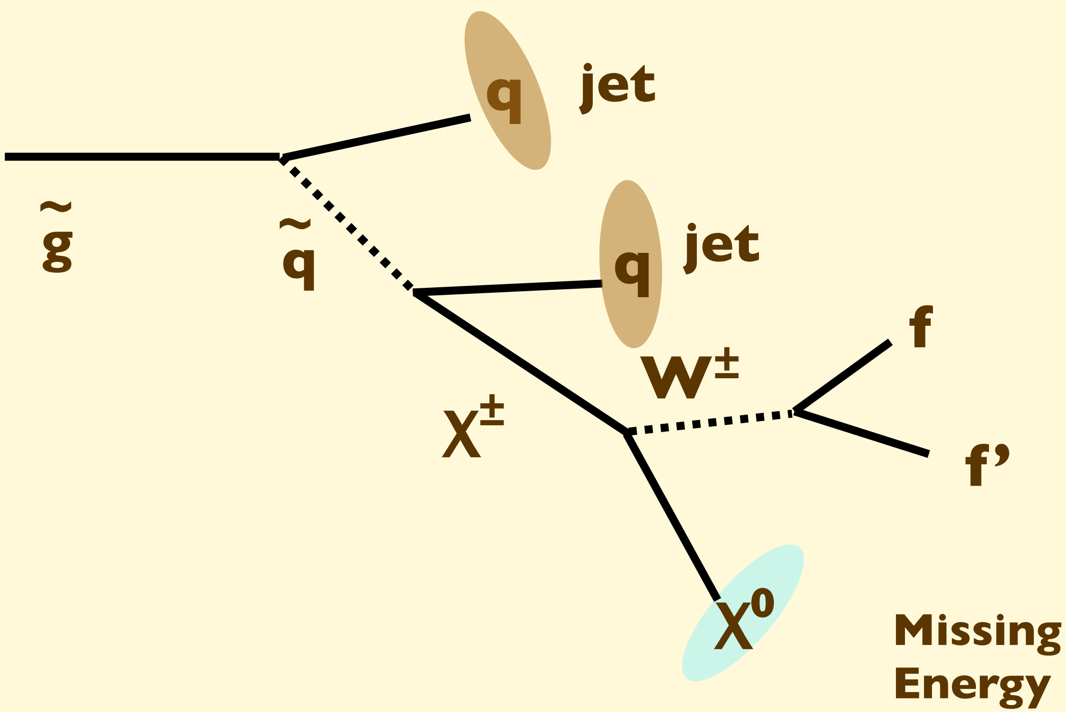


⇒ slow gluinos, β~0.5

Gluino final states

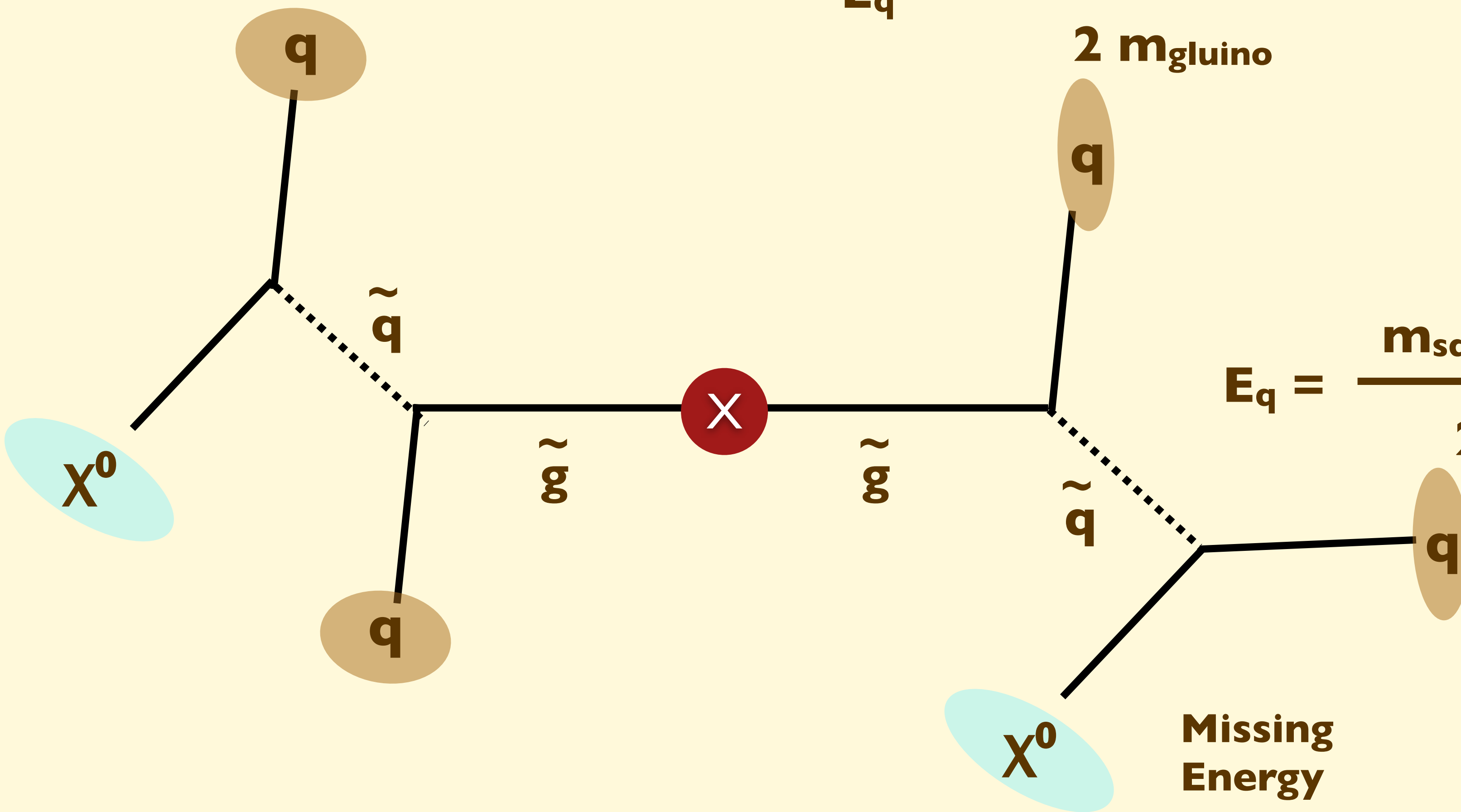






$\tilde{g} \rightarrow \geq 2$ jet + MET + $\geq 0\ \ell^\pm$

$\tilde{g}\,\tilde{g} \rightarrow$ 4 jet + MET



$$E_q = \frac{m_{gluino}^2 - m_{squark}^2}{2\, m_{gluino}}$$

$$E_q = \frac{m_{squark}^2 - m_X^2}{2\, m_{squark}}$$

Widely-spaced jets, no significant hierarchy in transverse energies and missing E_T

Typical analysis cuts (ATLAS):

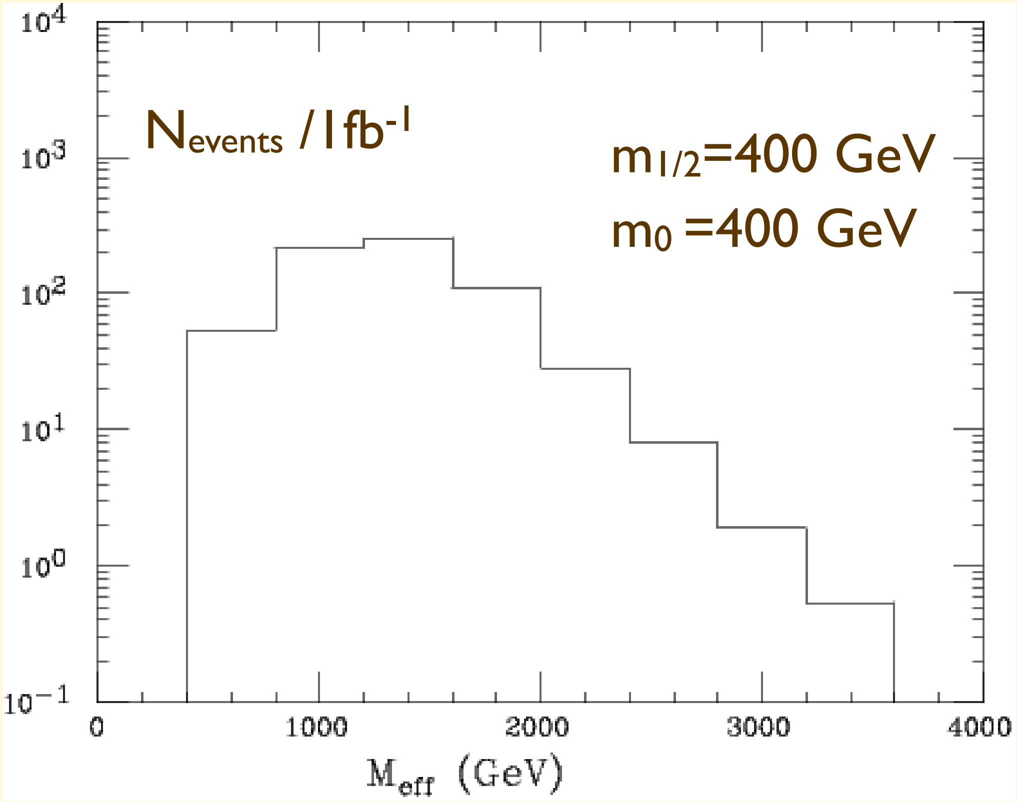
≥4jets, E_T>50 GeV   leading jet E_T>100 GeV

no lepton with E_T>20 GeV

MissET> max(100, 0.2 M_{eff})

M_{eff} = MET + $\sum_{i=1,..,4} E_T^i$

Transverse sphericity > 0.2



SM Backgrounds

Missing energy ⇒ νs ⇒ W/Z production

"Irreducible": individual events cannot be distinguished from the signal

Z+4jets, Z→ νν

"Reducible": individual events feature properties which distinguish them from the signal, but these can only be exploited with limited efficiency

W+3jets, W→ τν, τ→hadrons (jet)

τ jet has low multiplicity, and originates from a displaced vertex, because of τs lifetime

W+4jets, W→ e/μ ν, lepton undetected

e/μ can be detected, but cannot be vetoed with 100% efficiency, else the signal would be killed as well (e /μ may come from π conversions or decays)

tt → W+jets, with W→ leptons as above

In addition to the above, top decays have b's, but these cannot be detected and vetoed with 100% efficiency

“Instrumental”: individual events resemble the signal because of instrumental “effects” (namely instrumental deficiencies)

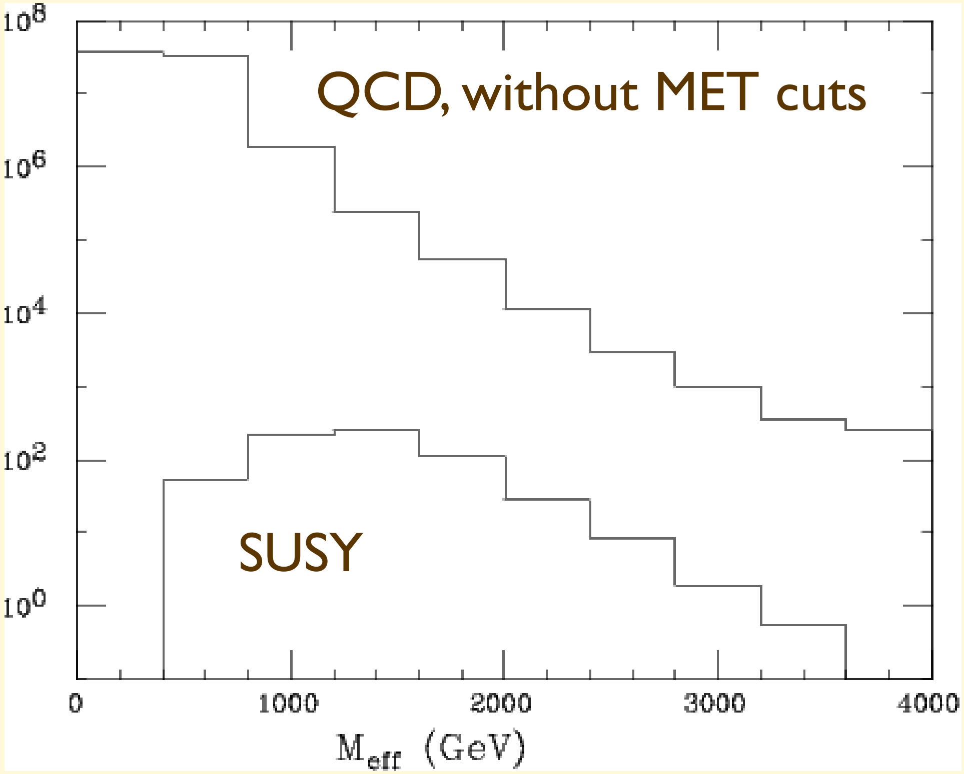
Multijets

The missing ET may originate from several sources:

Mismeasurement of the energy of individual jets

Incomplete coverage in rapidity (forward jets undetected)

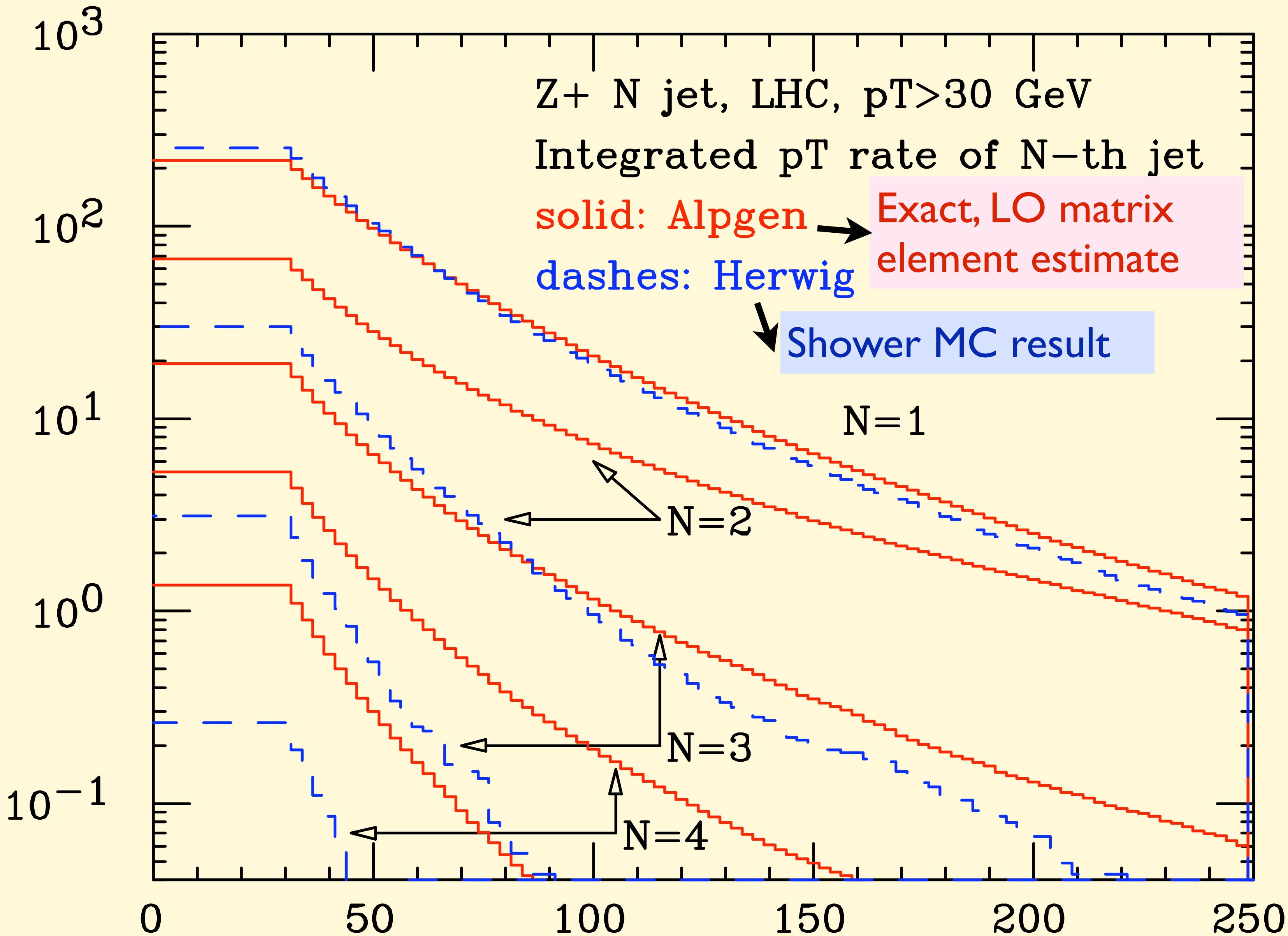
Accidental extra deposits of energy (cosmic rays on time, beam backgrounds, , electronic noise, etc.etc.etc.)



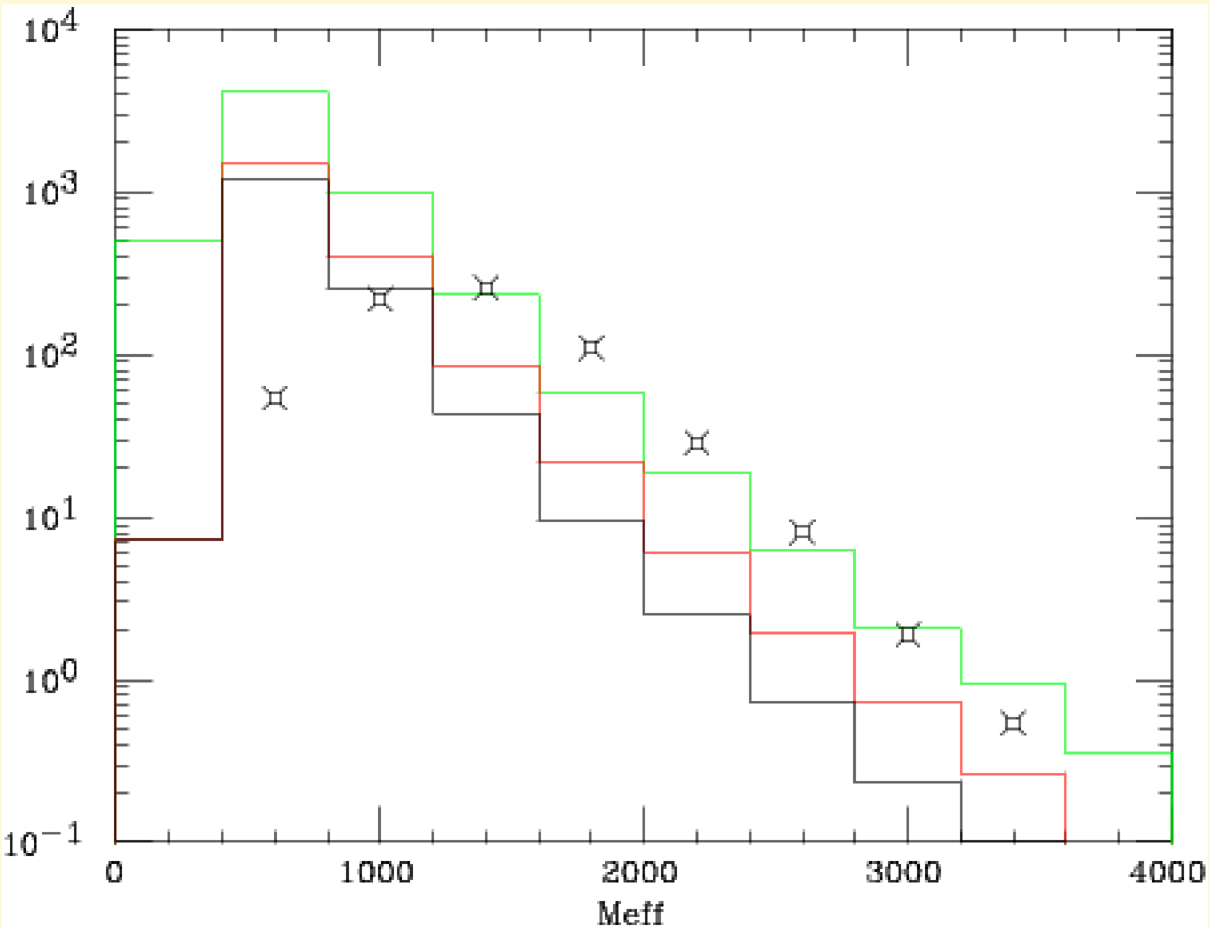
It is sufficient that these effects leave a permille fraction of the QCD rate for the signal to be washed away!

Z(→νν) + jets

1. Shower MC vs Matrix element results



Z(→νν) + jets



Jet cuts only

+ MET cut

+ ST cut

SUSY

Normalizing the bg rate using data ...

Use Z->ee + multijets, apply same cuts as MET analysis but replace MET with ET(e^+e^-)

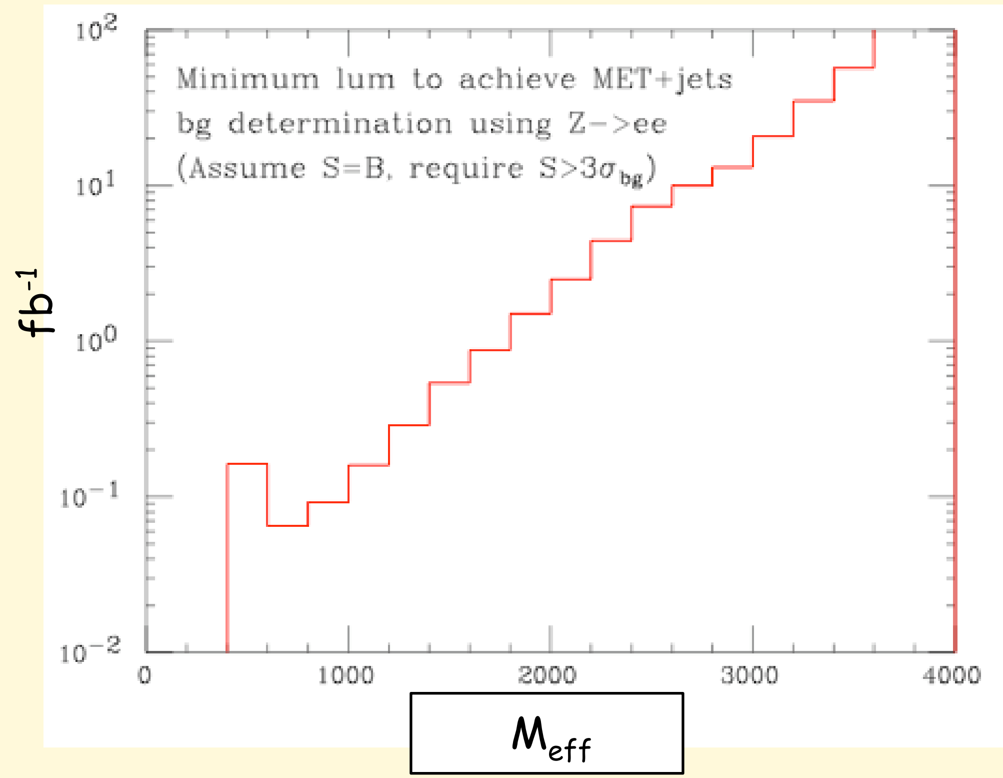
Extract $Z \to \nu\nu$ bg using, bin-by-bin:
$(Z \to \nu\nu) = (Z \to ee)\ B(Z \to \nu\nu)/B(Z \to ee)$

Assume that the SUSY signal is of the same size as the bg, and evaluate the luminosity required to determine the Z->nunu bg with an accuracy such that:

$N_{susy} > 3$ sigma

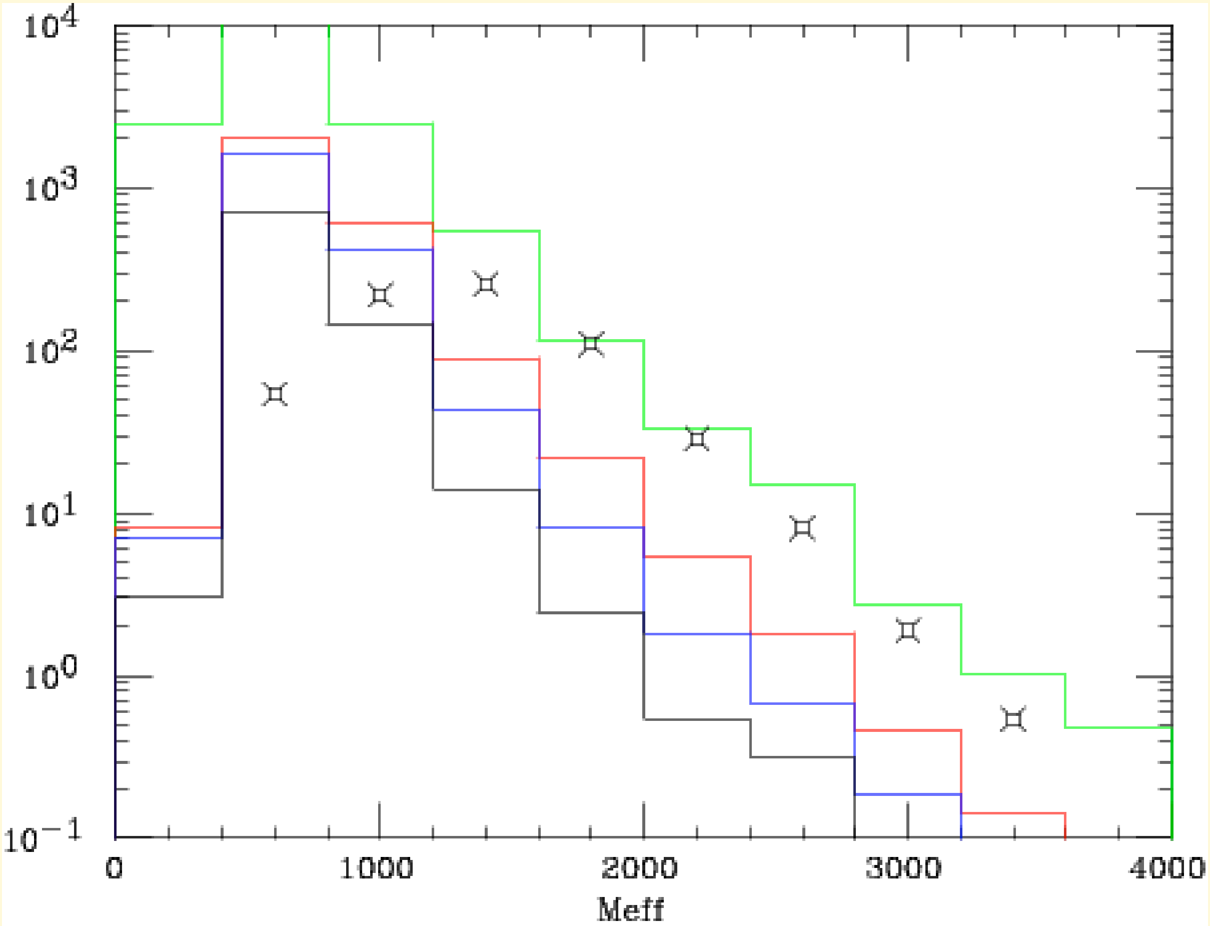
where

sigma=sqrt[$N(Z \to ee)$] * $B(Z \to \nu\nu)/B(Z \to ee)$



=> several hundred pb^{-1} are required. They are sufficient if we believe in the MC shape (and only need to fix the overall normalization). Much ore is needed if we want to keep the search completely MC independent

W(→lν) +4 jets



Jet cuts only

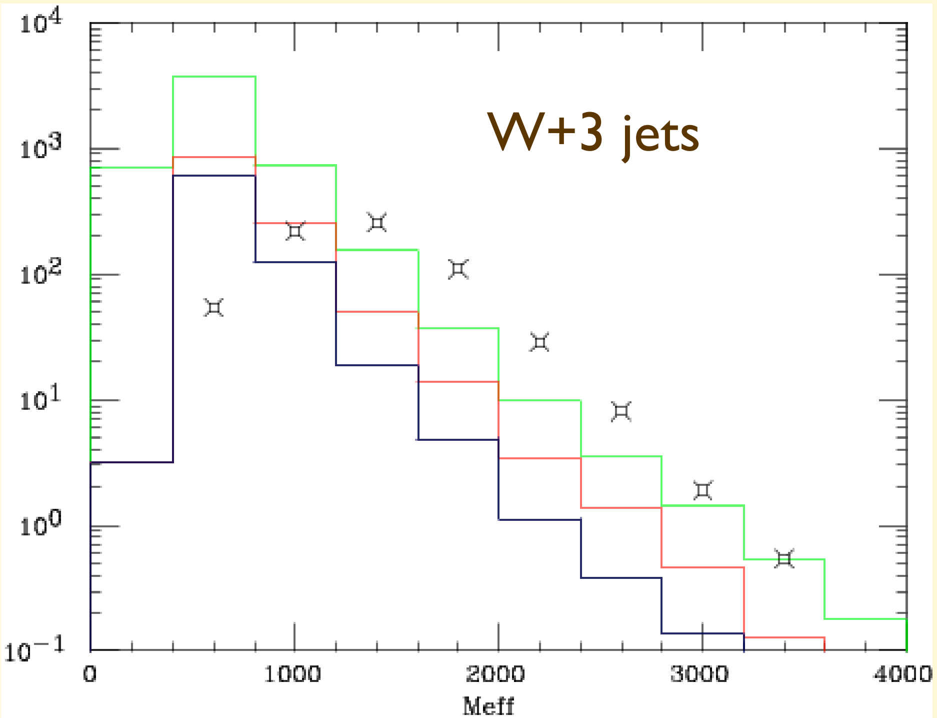
+ MET cut

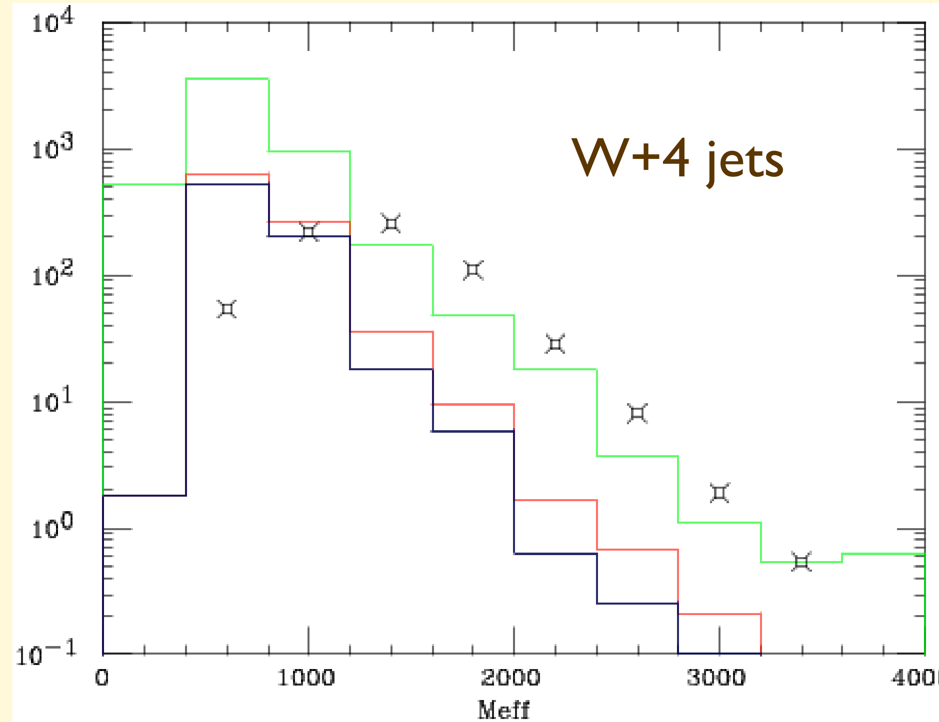
+ ST cut

+ pt_{lept}<20

SUSY

W(→tau-jet ν) + jets





Jet cuts only

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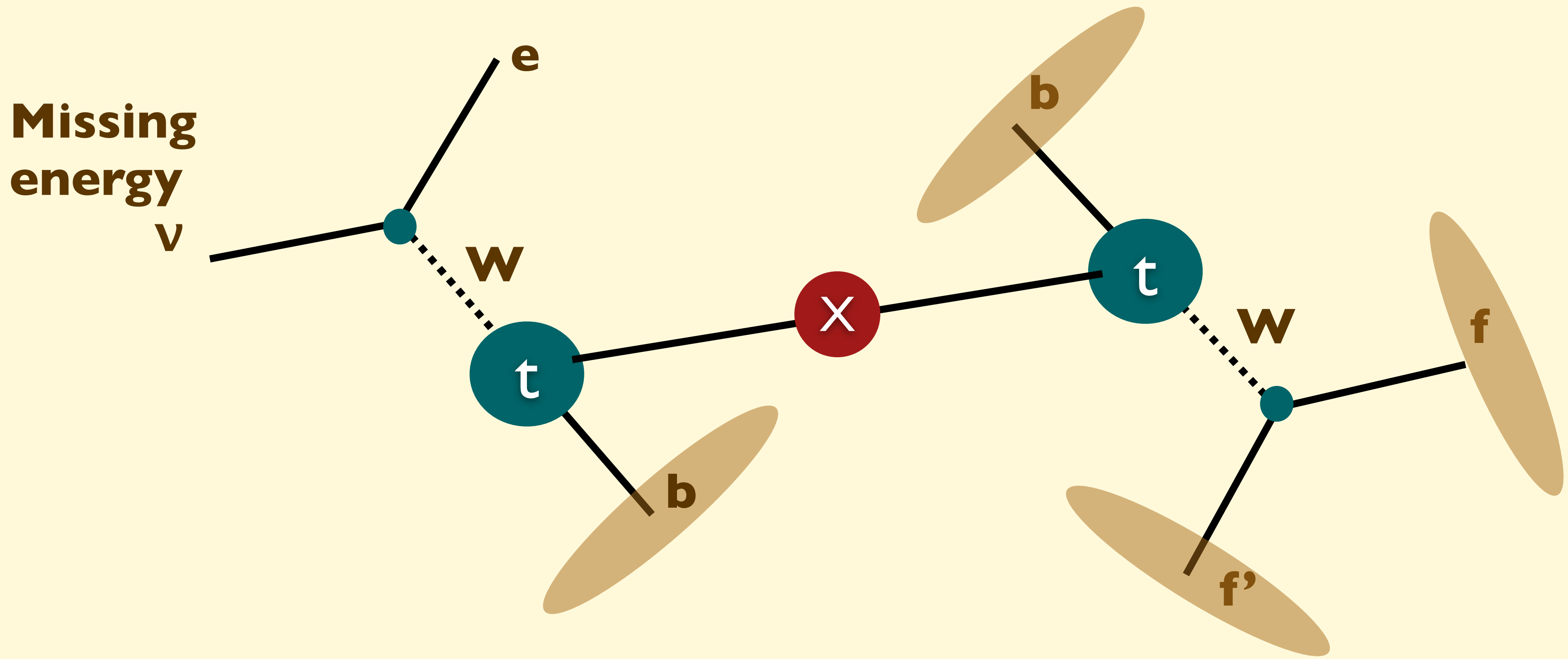
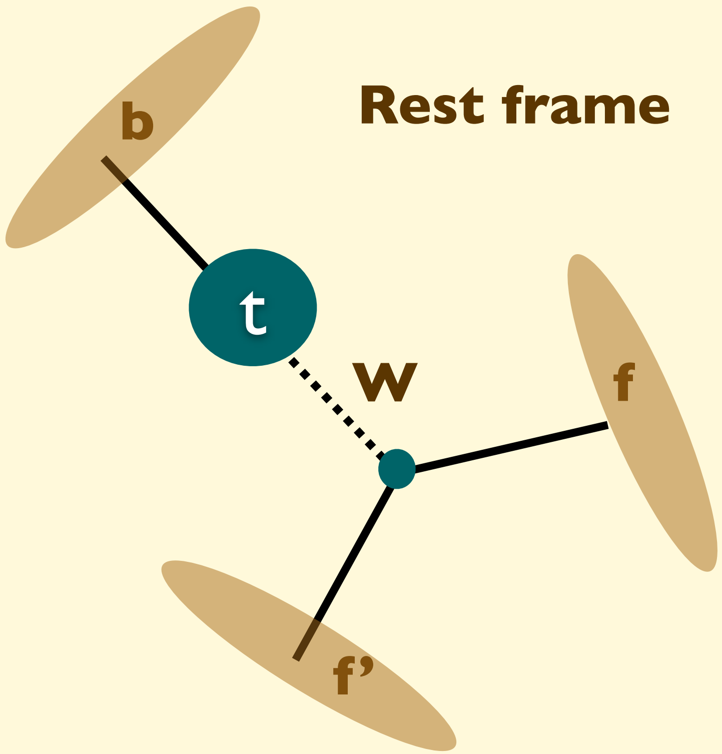
SUSY

Top final states



Top final states

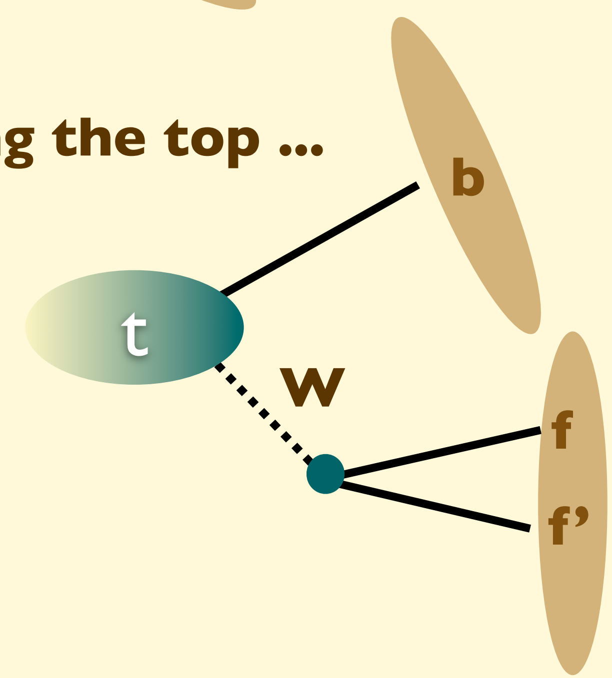
Rest frame

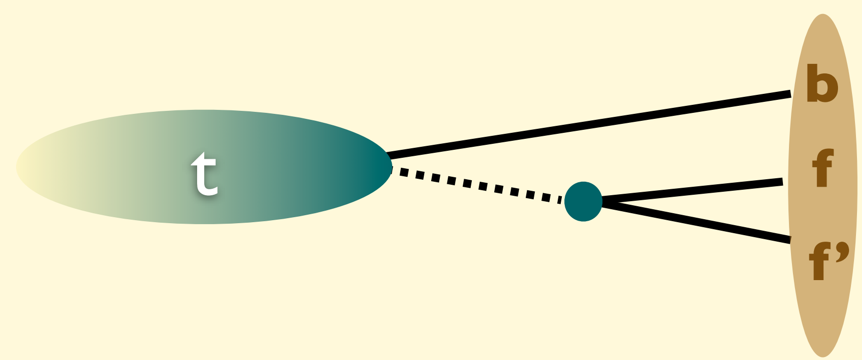


$$p_b = \frac{m_{top}^2 - m_W^2}{2\, m_{top}}$$

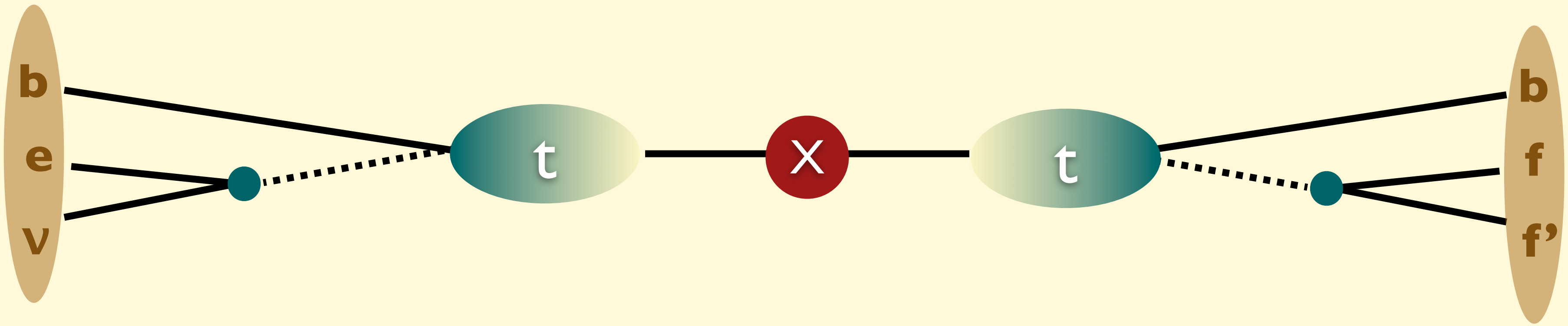
$$p_f^{max} = \frac{m_W}{2}\,\frac{m_{top}^2 + m_W^2}{2\, m_{top}\, m_W}$$

Boosting the top ...



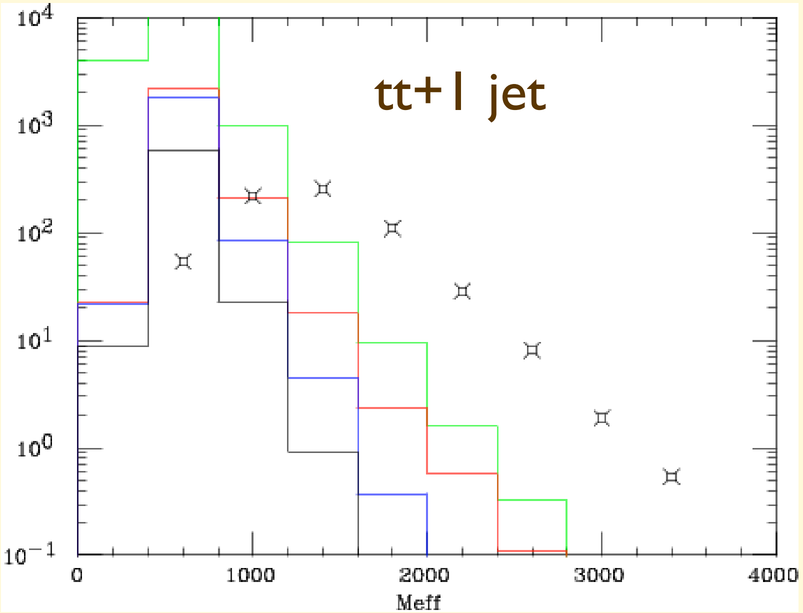


Top final states



Large Meff leads to highly collimated final states

Sphericity and multi-jet cuts very effective against the leading-order t-tbar contribution!



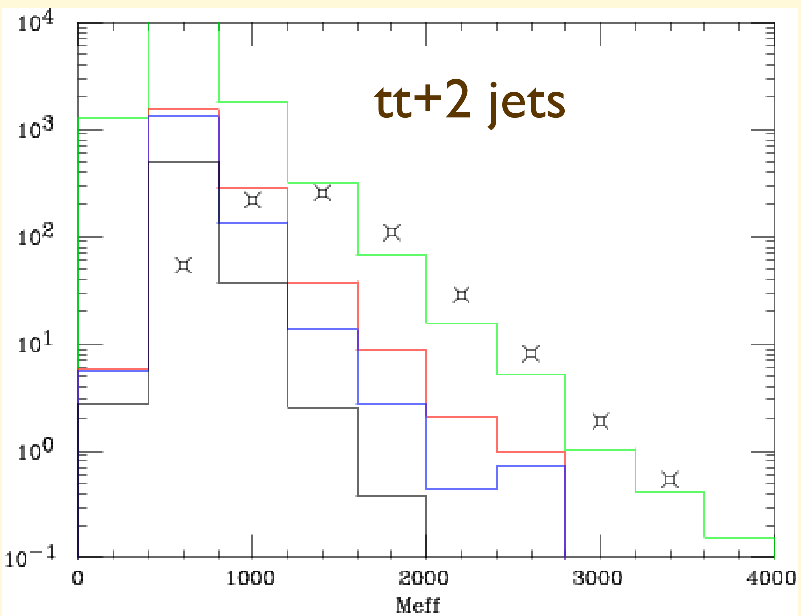
Jet cuts only

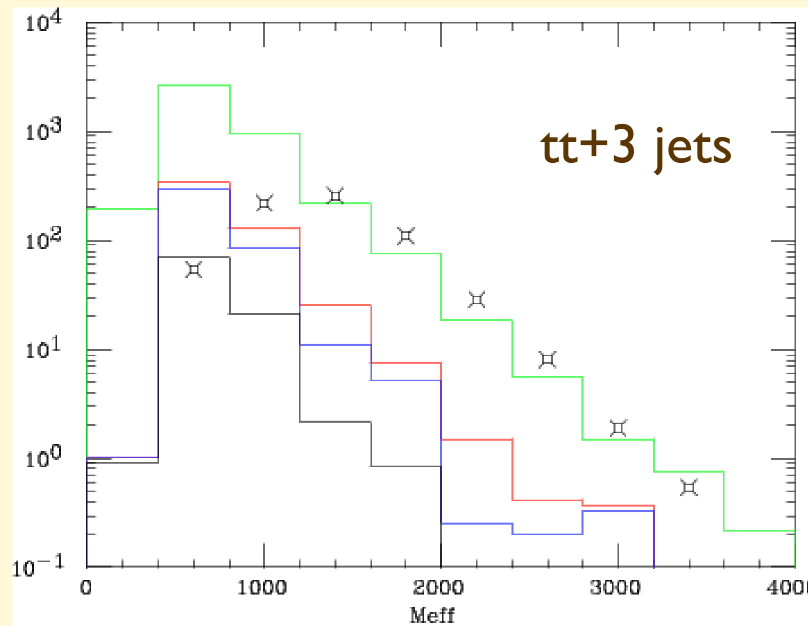
+ MET cut

+ ST cut

+ pt_{lept}<20

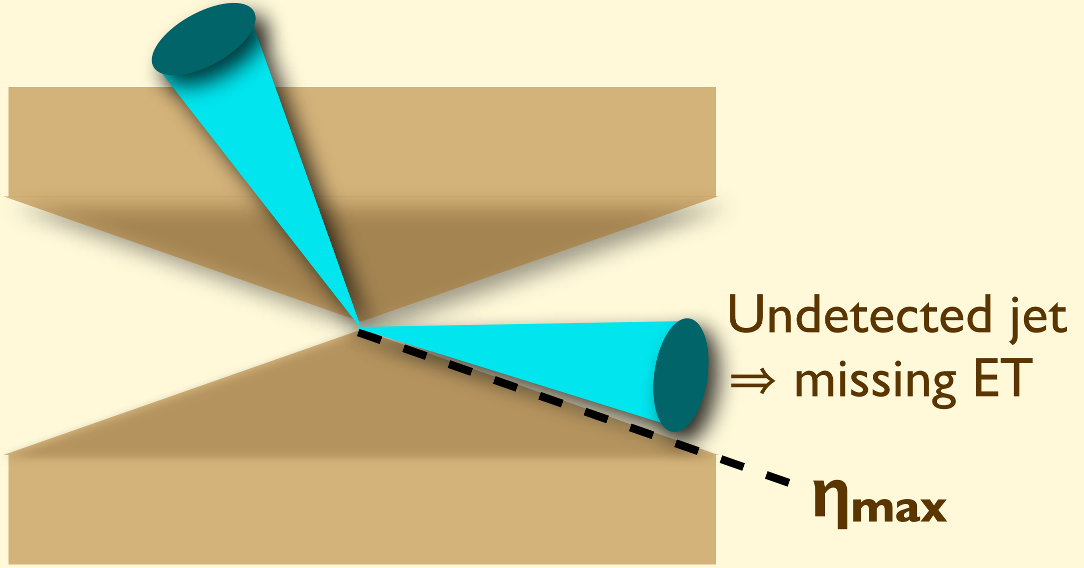
SUSY



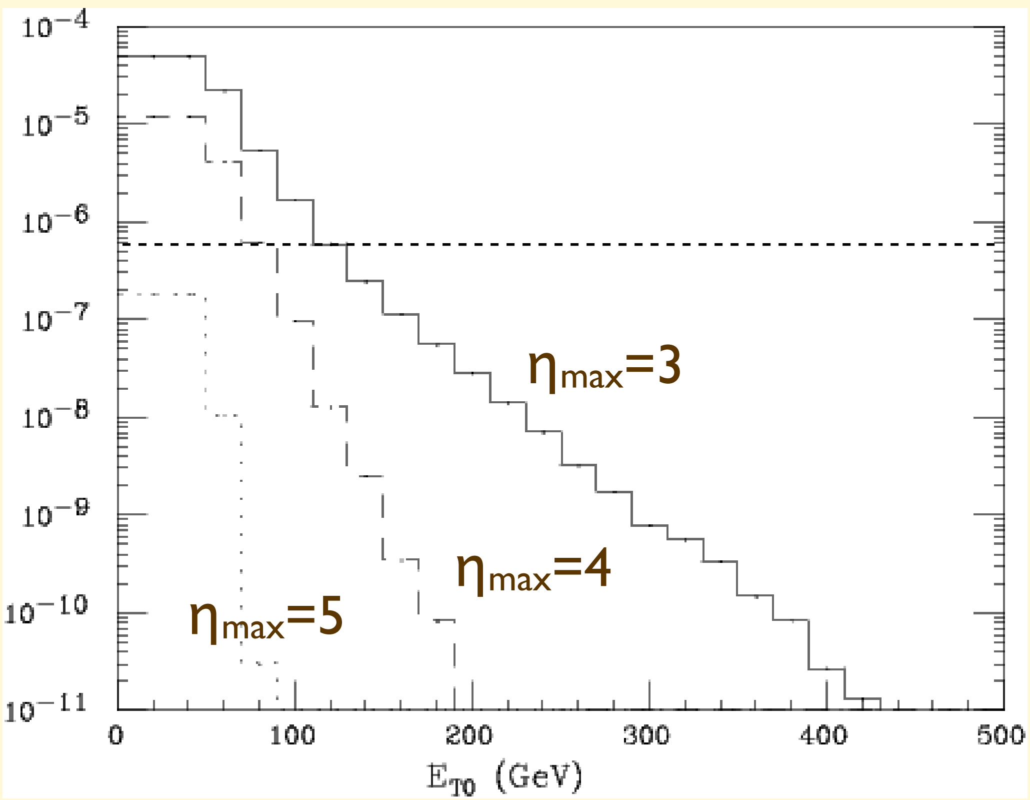


All jet multiplicities contribute at approximately the same level!!

Instrumental sources of missET: incomplete calorimeter η coverage



σ(jet-jet with MET> E_{To}) / σ(pp→X)

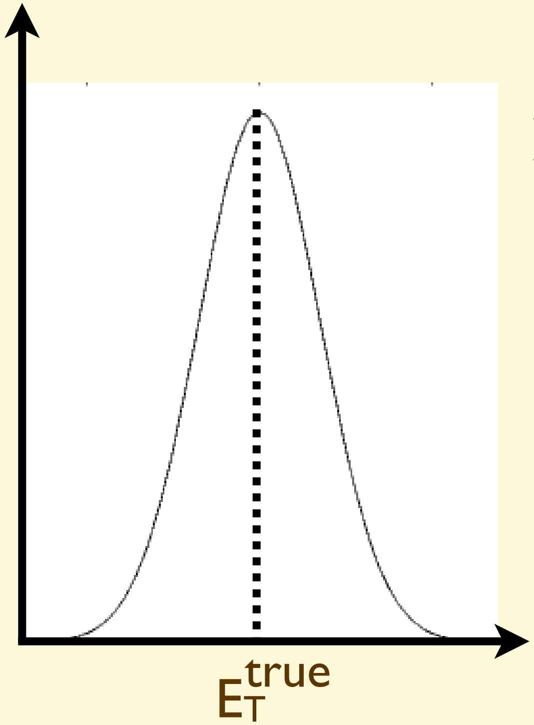


cfr:
$\sigma(W\to l\nu)/\sigma(pp\to X) \approx 6 \times 10^{-7}$

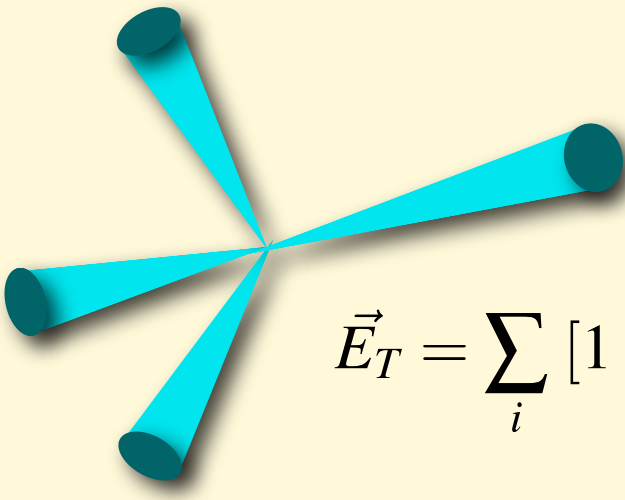
NB:
At $L=10^{34}\ cm^{-2}\ s^{-1}$,
$\langle N(pp\ collisions)\rangle \approx 20$

⇒ **probability 20x larger**

Instrumental sources of missET: jet energy resolution



$$\mathrm{Prob}[p_T] \propto \exp - \frac{(p_T - p_T^{\mathrm{true}})^2}{\sigma^2} \qquad \sigma = C\sqrt{E_T^{\mathrm{true}}/\mathrm{GeV}}, \quad C = O(1)$$

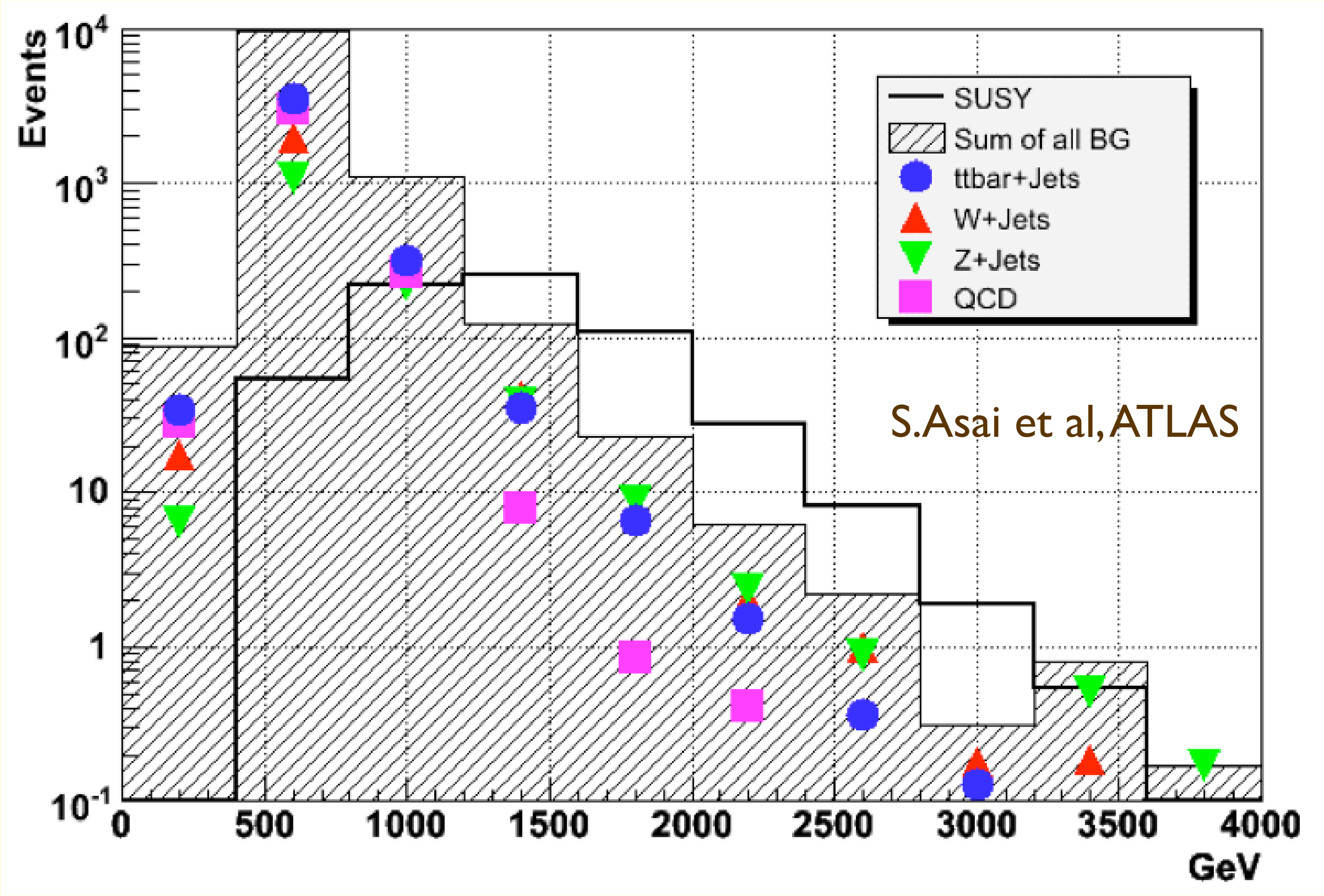


$$\vec{E}_T = \sum_i [1+\delta_i]\,\vec{p}_{T,i}^{\,\mathrm{true}} = \sum_i \delta_i\,\vec{p}_{T,i}^{\,\mathrm{true}}$$

$$\langle |\vec{E}_T|^2 \rangle = \sum_{i,j} \langle \delta_i \delta_j \rangle \vec{p}_{T,i} \cdot \vec{p}_{T,j} \qquad \langle \delta_i \delta_j \rangle = \frac{C^2}{p_{T,i}} \delta_{ij}$$

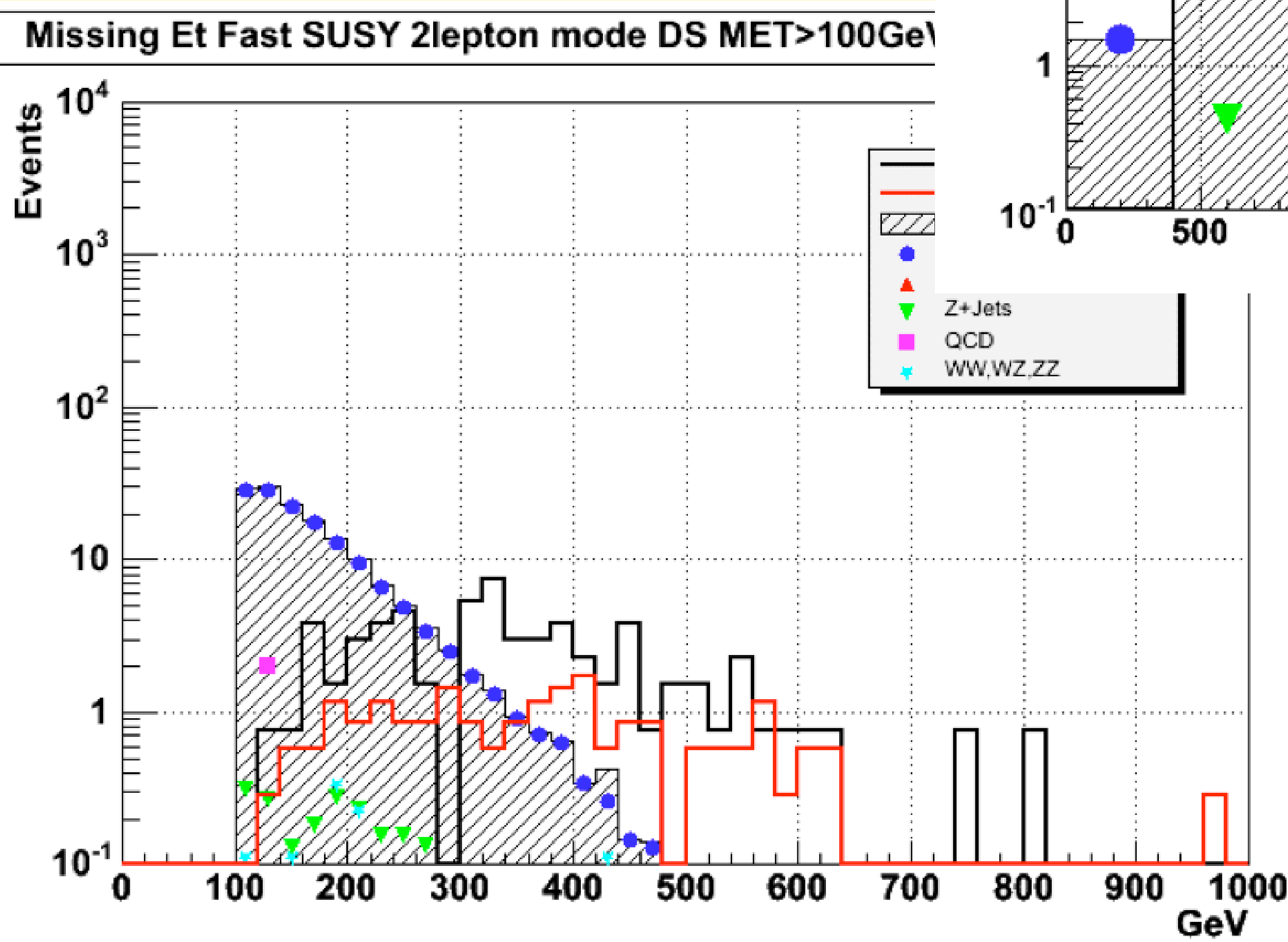
$$\langle \mathrm{MET} \rangle = C \sqrt{\sum_i p_{T,i}}$$

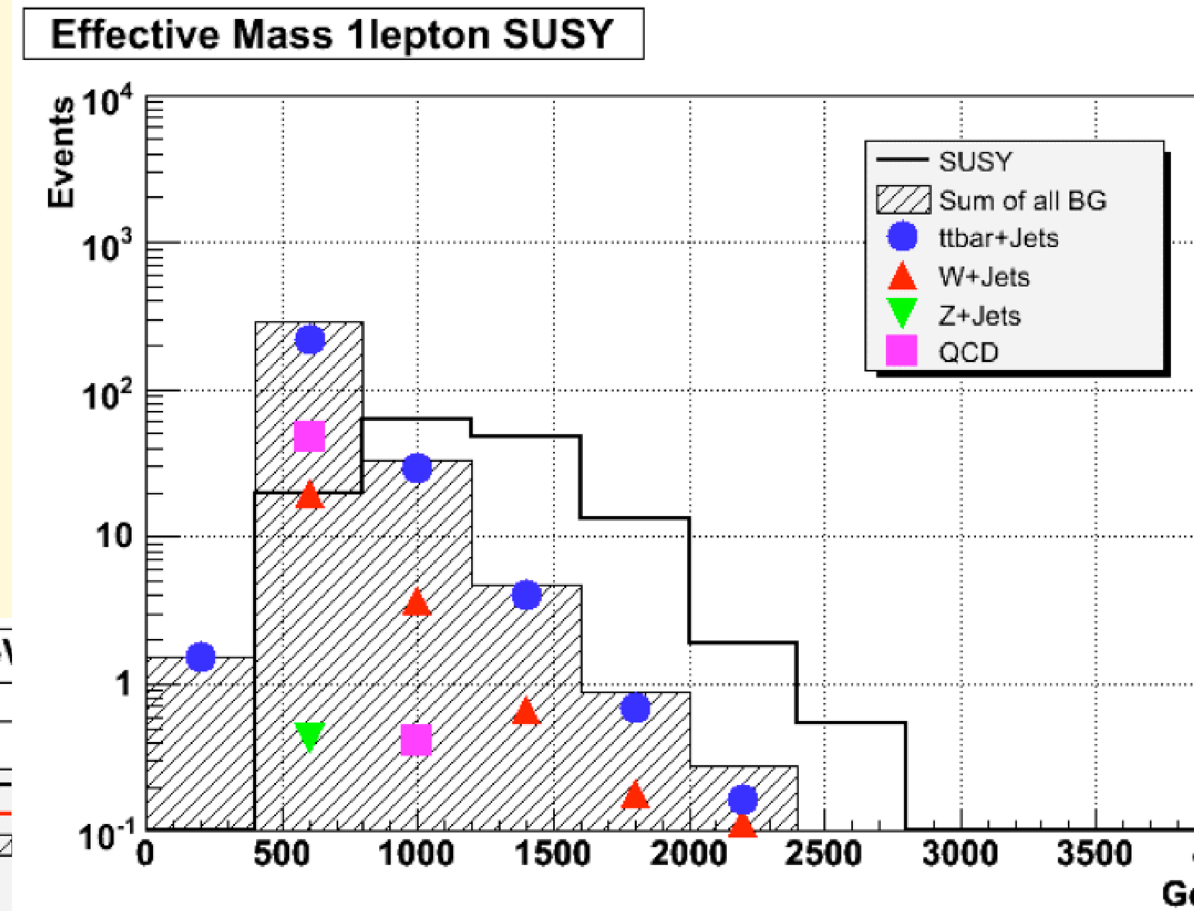
Overall result, after the complete detector simulation, etc....



Adding leptons ...

S.Asai et al, ATLAS

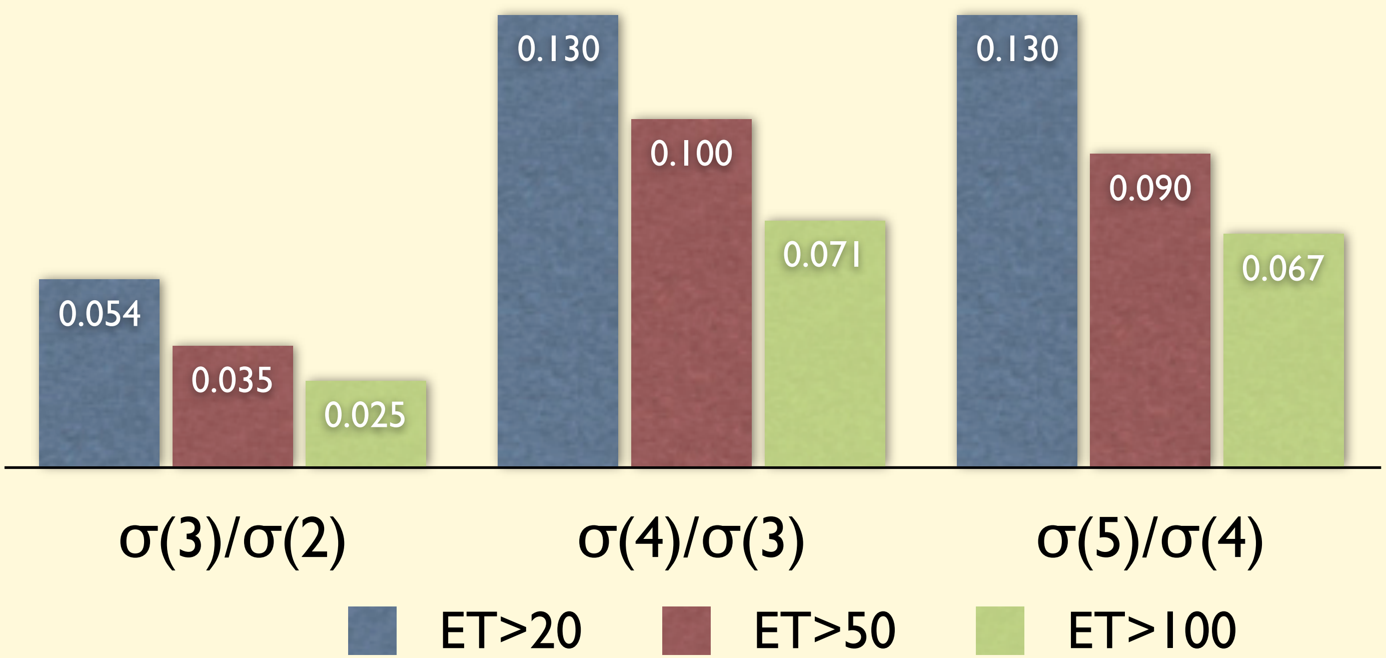




Some properties of rates for multijet final states

Multijet rates

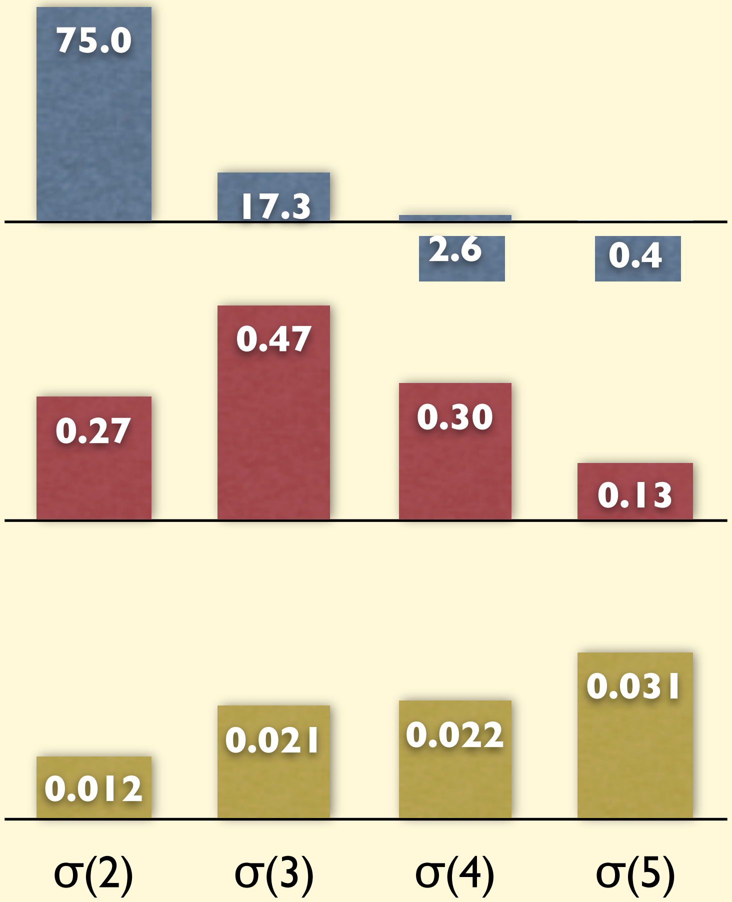
σ [μb]	N jet=2	N jet=3	N jet=4	N jet=5
E_T^{jet} >20 GeV	350	19	2.6	0.35
E_T^{jet} >50 GeV	12.7	0.45	0.045	0.004
E_T^{jet} >100 GeV	0.85	0.021	0.0015	0.0001



- The higher the jet E_T threshold, the harder to emit an extra jet
- When several jets are already present, however, emission of an additional one is less suppressed

Multijet rates, vs $\sqrt{s}$, with $E_T^{jet} > 20$ GeV

σ [μb]	N jet=2	N jet=3	N jet=4	N jet=5
$\sqrt{s} > 100$ GeV	75	17.3	2.6	0.37
$\sqrt{s} > 500$ GeV	0.27	0.47	0.30	0.13
$\sqrt{s} > 1000$ GeV	0.012	0.021	0.022	0.031

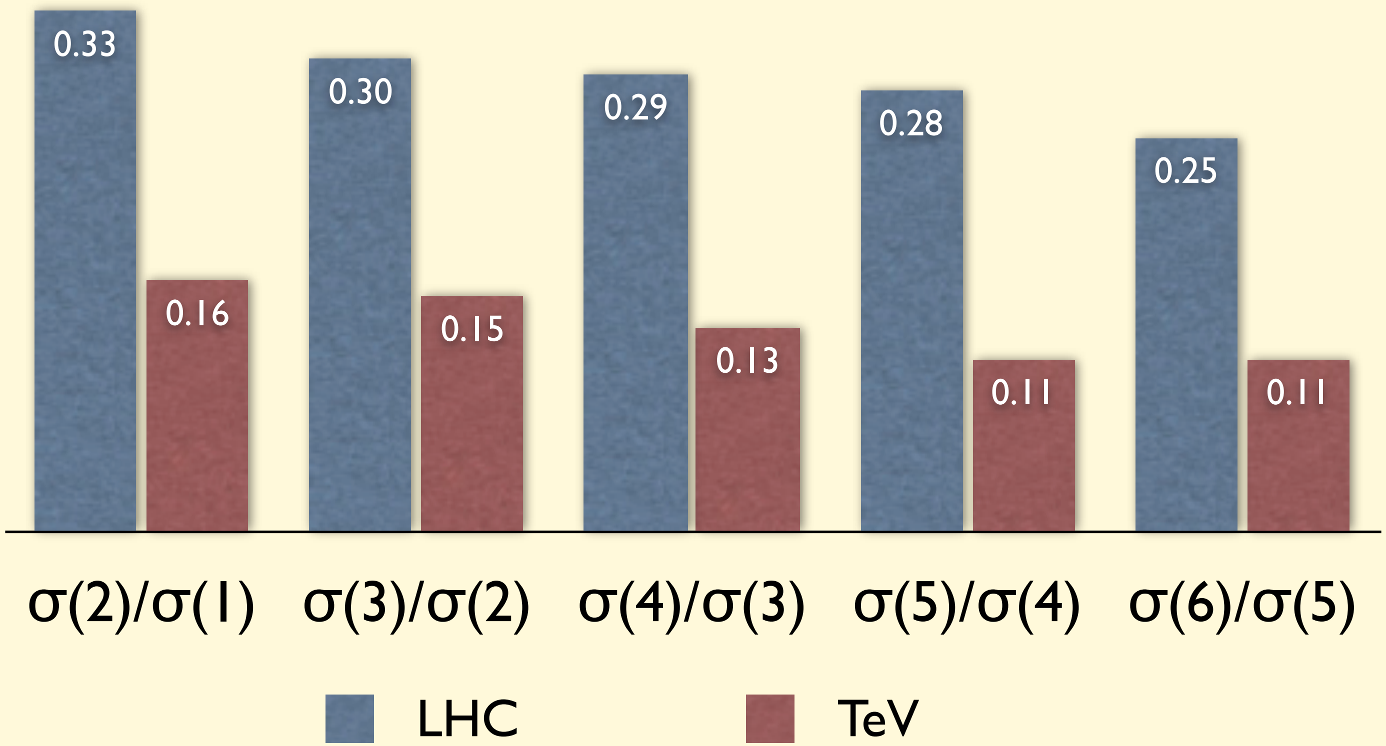


High mass final states are dominated by multijet configurations

W+Multijet rates

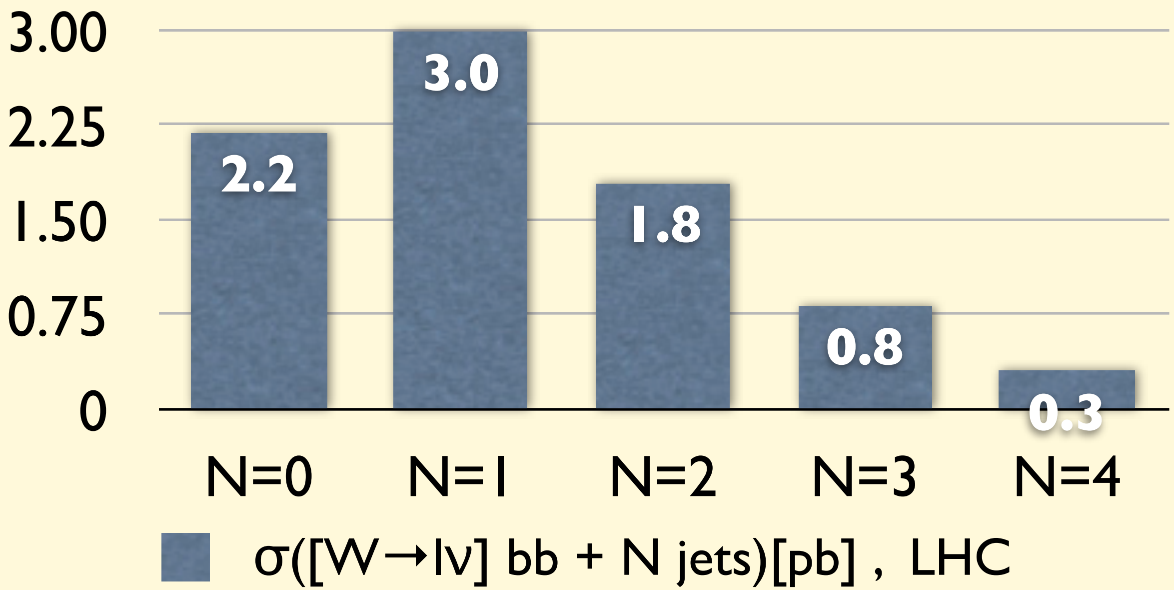
σxB($W\to e\nu$)[pb]	N jet=1	N jet=2	N jet=3	N jet=4	N jet=5	N jet=6
LHC	3400	1130	340	100	28	7
Tevatron	230	37	5.7	0.75	0.08	0.009

E_T(jets) > 20 GeV , $|\eta|<2.5$, $\Delta R>0.7$



- Ratios almost constant over a large range of multiplicities
- $O(\alpha_s)$ at Tevatron, but much bigger at LHC

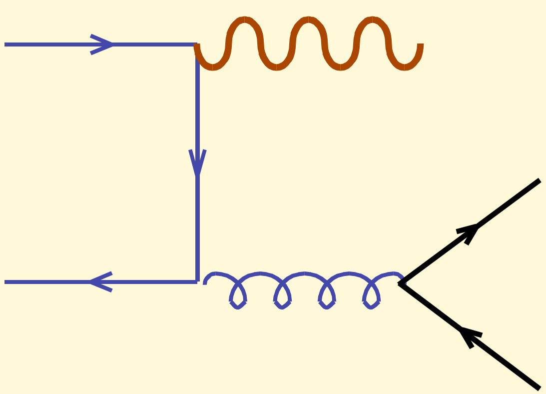
Wbb+jets rates

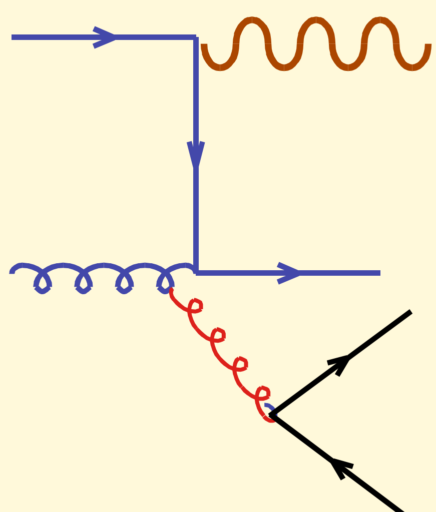


Pattern of multiplicity distribution very different than in W+jets!

In pp collisions (contrary to the Tevatron, p-pbar) :

$N_{jet}=0 \propto \alpha_s^2$ x Lum(q qbar) $\approx$ $N_{jet}=1 \propto \alpha_s^3$ x Lum(q g)





Beware of naive α_s power counting!!

Leptons

Experimentally, electrons, muons and taus are entirely different objects. Their identification requires different components of the detector, different techniques, and is subject to different backgrounds.

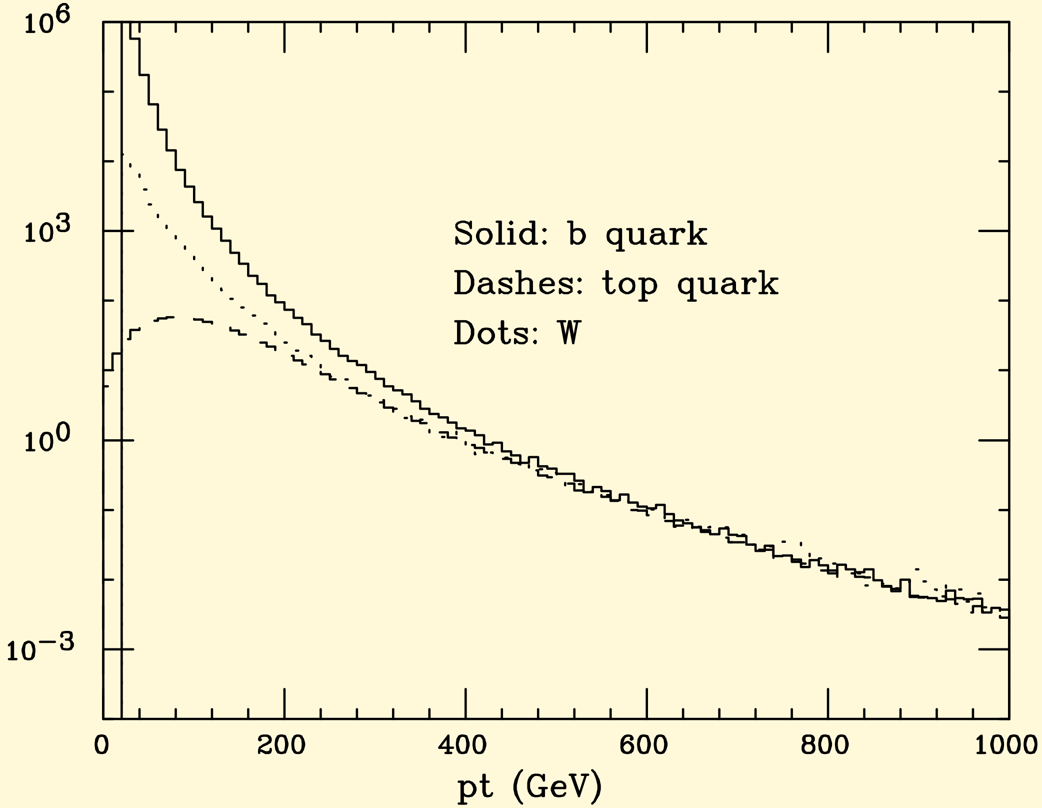
As seen from a theorists, all leptons are produced the same. Nevertheless there is a large variety of possible production mechanisms, each one of them leading to different overall properties of the final state. When considering leptons as a signal for new physics, it is important to have a clear picture of their irreducible SM sources

Single lepton

Sources of single high-pt leptons:

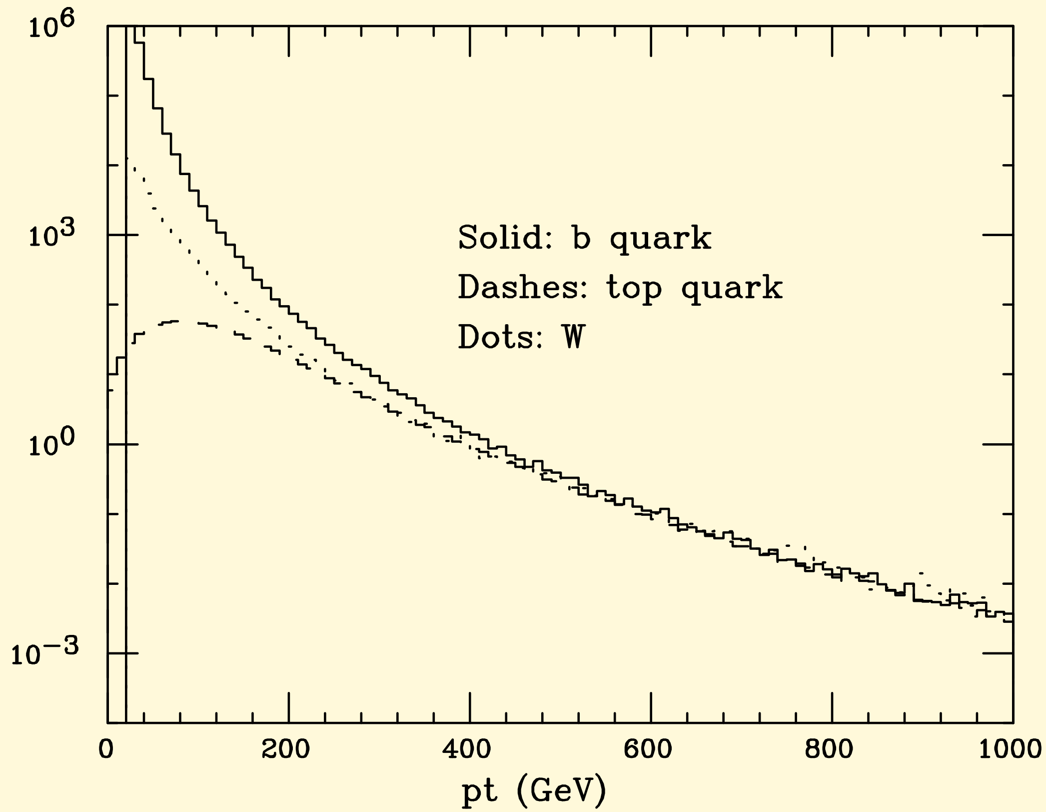
- $W \to e/\mu + \nu$
- $Z \to \tau\tau \to e/\mu + X$
- $b \to e/\mu + X$
- $t \to Wb \to e/\mu + \nu + b$

Differential Rates



- At large pt b and t production ~ equal !
- At large pt, W and heavy quark production ~ equal!

Differential Rates



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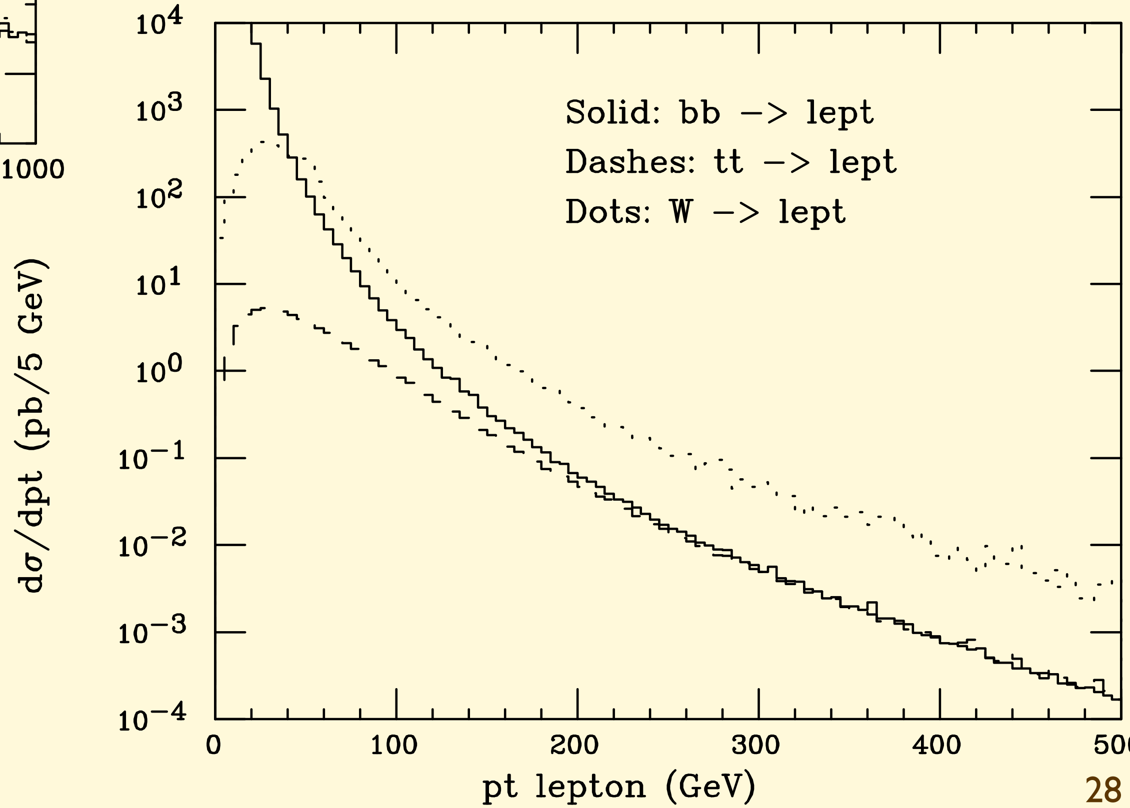

* W → lepton is a 2-body decay, b/t → lepton is 3-body: lepton takes a larger fraction of momentum in W decay => harder spectrum, larger rate at higher pt in W production

* The global features of the event accompanying the lepton will clearly be very different in each case. Which of the three processes will dominate in a given analisys, will therefore depend on the details

How come Q and W spectra are comparable at large Et?

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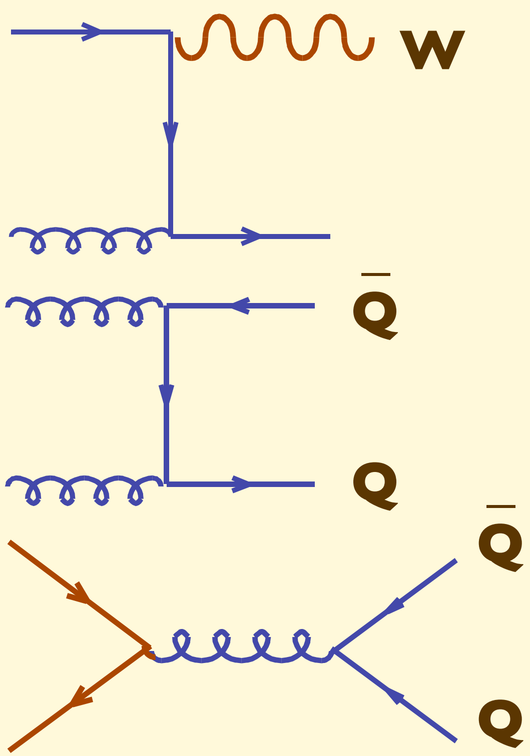
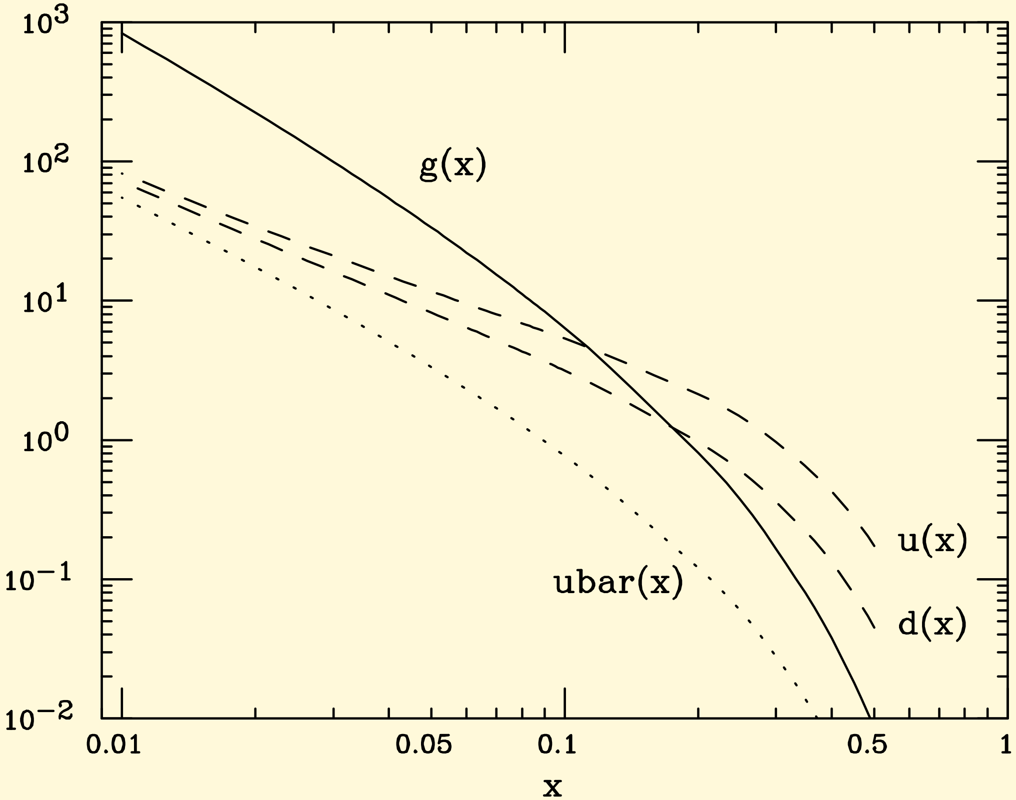
The LO processes for QQ production are weighted by the gg or qqbar luminsity, which drops at large mass much more rapidly than L(qg)





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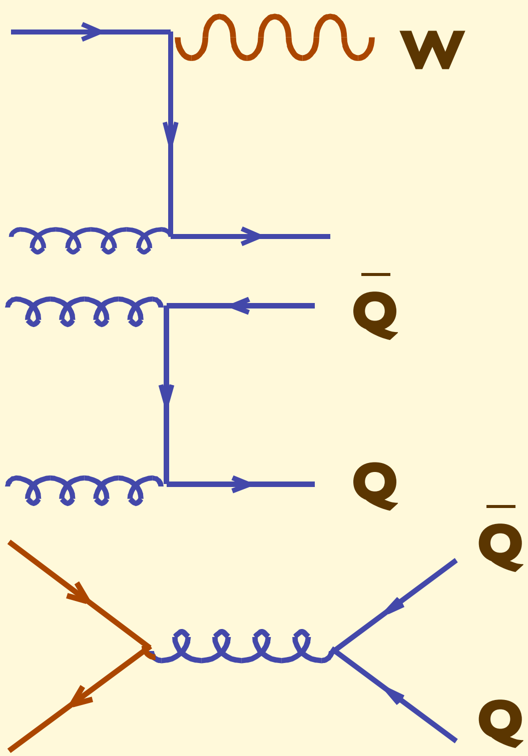

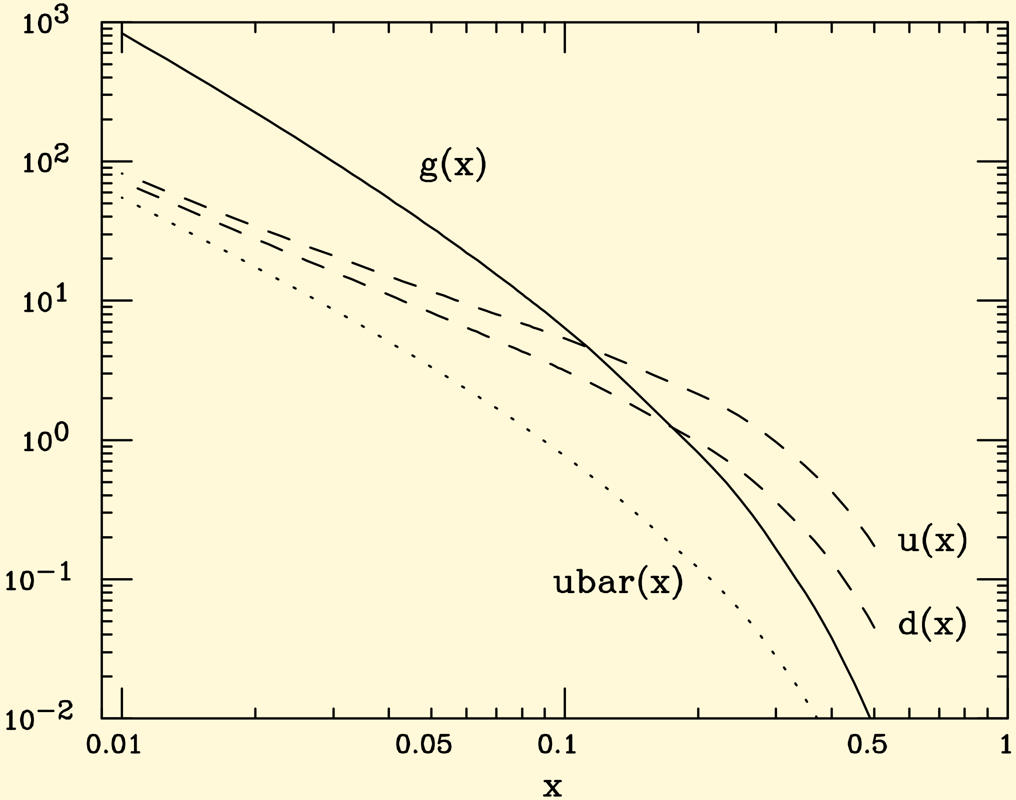

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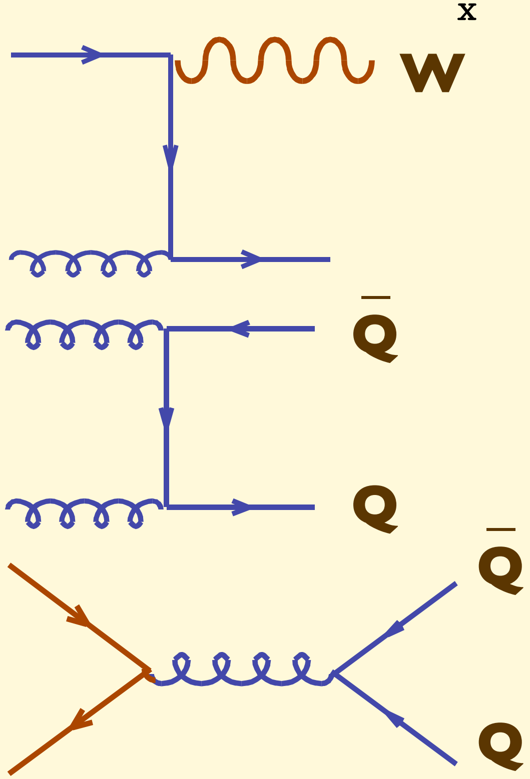
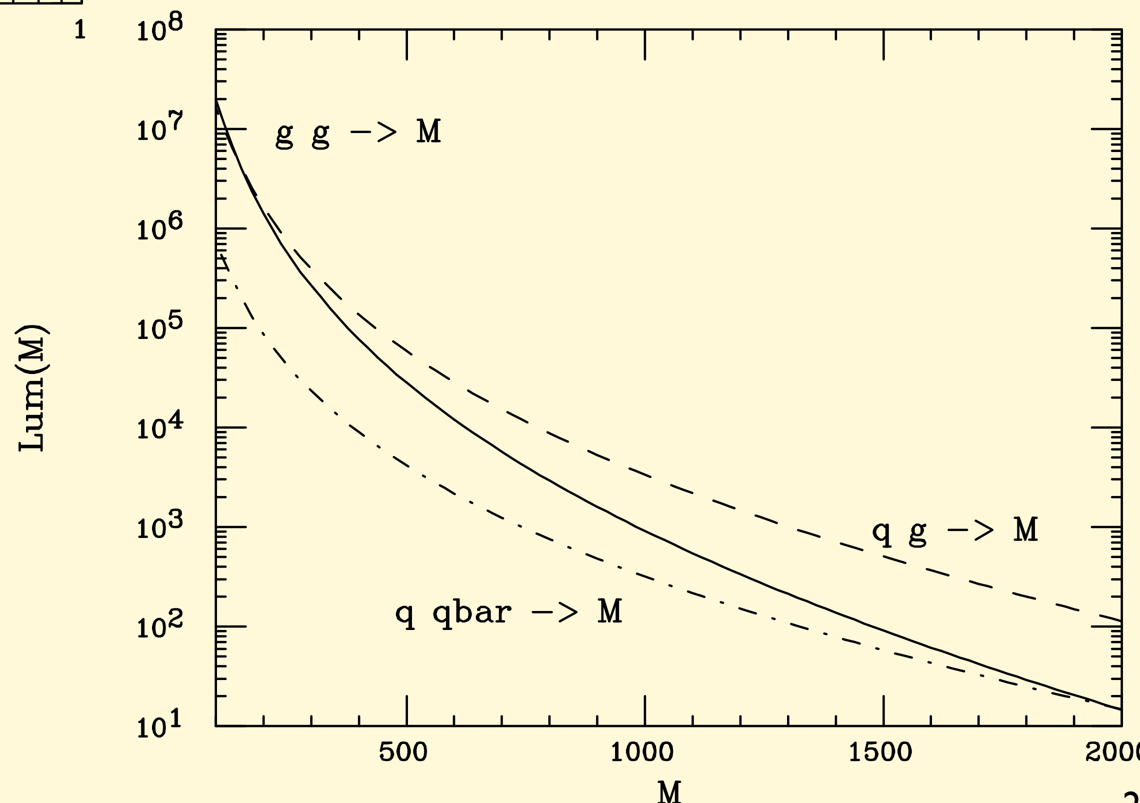
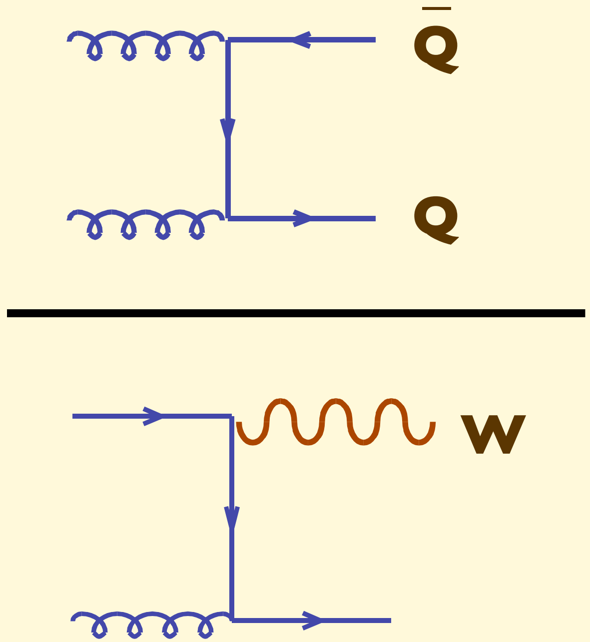






Quark colour charge

Initial state colour averages

~1/3 at 90°

$$= \frac{C_F \alpha_s}{1/2 \times \alpha_w} \times \left(\frac{N}{N^2-1}\right) \times \frac{1}{1/2} \times F(s \leftrightarrow u)$$

Quark weak charge

V-A, only L-handed quarks

$$\approx \quad \frac{\alpha_s}{\alpha_W} \sim 3$$

Dileptons

One lepton W: 160 nb

WW	tt	Z
75pb	500pb	50nb
2l+MET, no jets	2l+MET, jets, b's	2l, m(ll)=mZ, no MET, no jets

Dilepton production dominated by top pairs!

Trileptons

WWW	ttW	ZW
130fb	500fb	28pb

ttW ~ 10^{-3} tt => trilepton contribution from tt, with 3rd lepton form b→l decay, important => require isolation!

Quadrileptons

WWWW	tttt	ZWW
0.6fb	12fb	100fb

ZWWW=0.7fb

Ratios

W/Z	WW / WZ	WWW / WWZ	WWWW / WWWZ
3	2.5	1.3	1

Ratio determined by couplings to quarks, u/d asymmetry of proton

Ratio determined by couplings among W/Z, SU(2) invariance

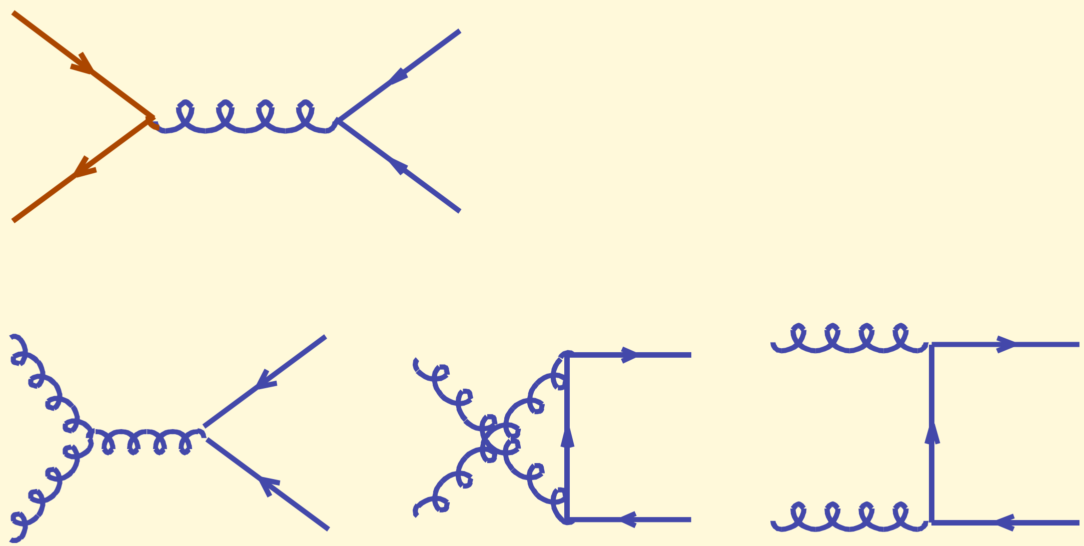
WW/W	WWW / WW	WWWW / WWW
.5E-3	2E-3	5e-3

ZW / W	ZWW / WW	ZWWW / WWW
.5E-3	4E-3	7e-3

1W

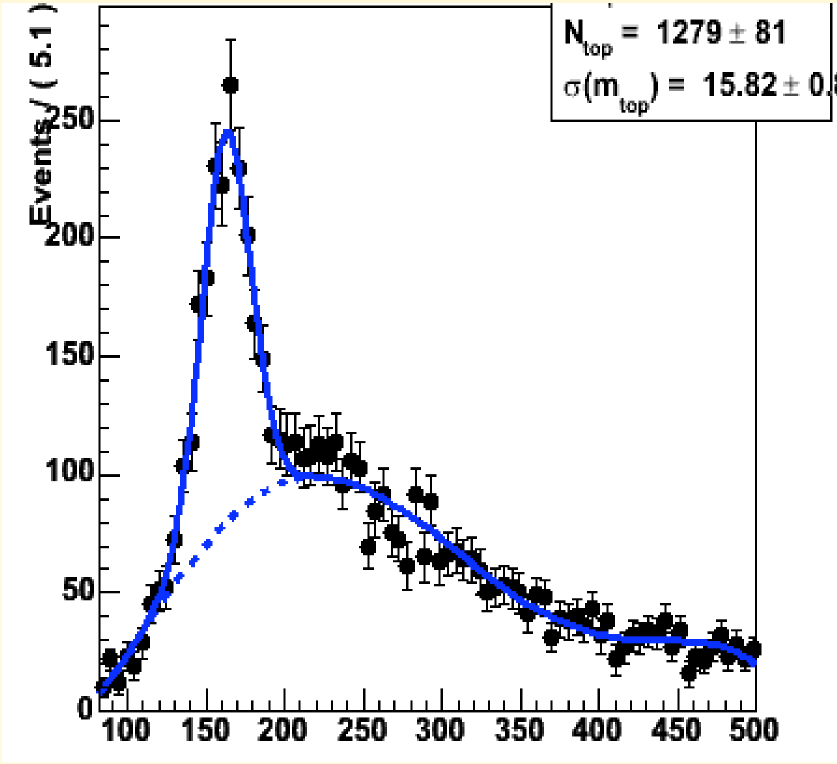
$\sim 10^{-3}$

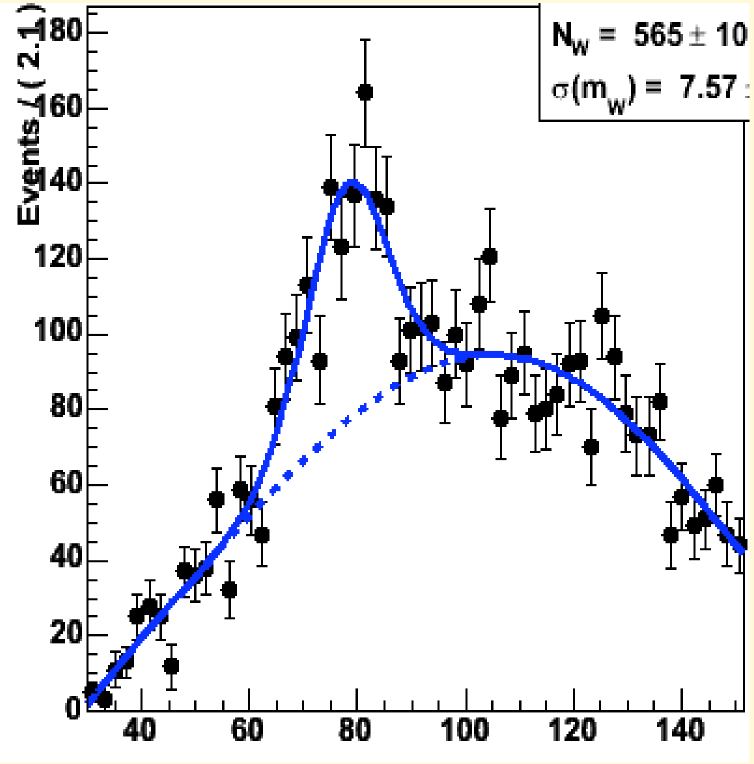
Top production and bgs



	σ(tt) [pb]	σ(W+X)	σ(W+bbX) [ptb>20 GeV]	σ(W+bbjj X) [ptb,ptj >20 GeV]
Tevatron	6	20×10^3	3	0.16
LHC	800	160×10^3	20	16
Increase	x 100	x 10	x 10	x 100

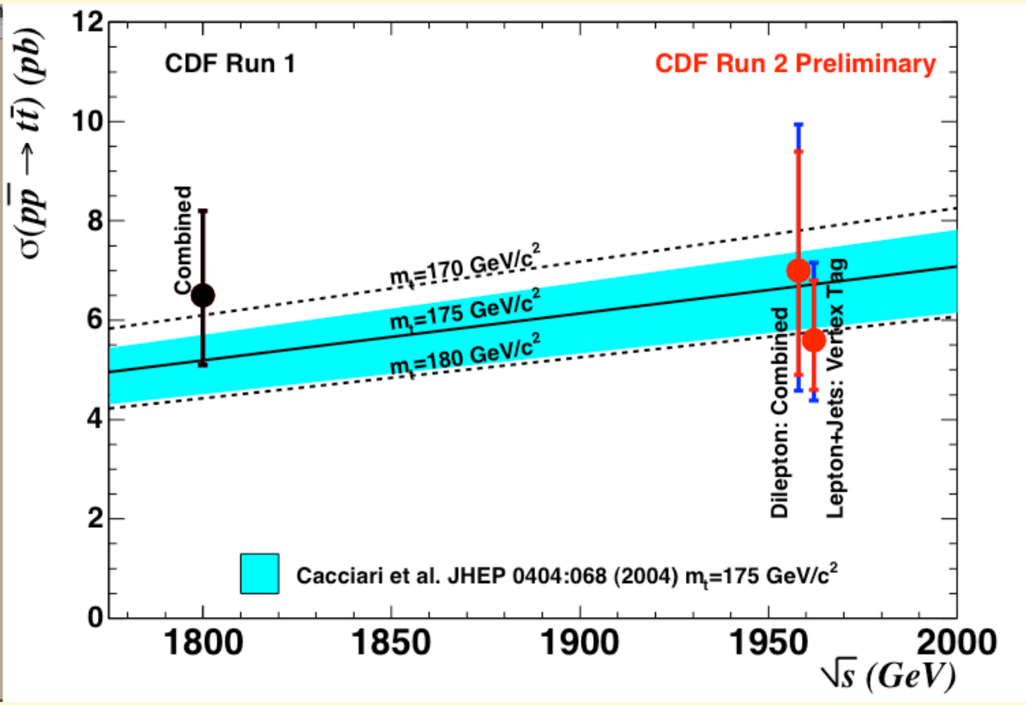
Missing	$E_T > 20$ GeV	
1 lepton	$P_T > 20$ GeV	No b-tagging required
4 jets(R=0.4)	$P_T > 40$ GeV	

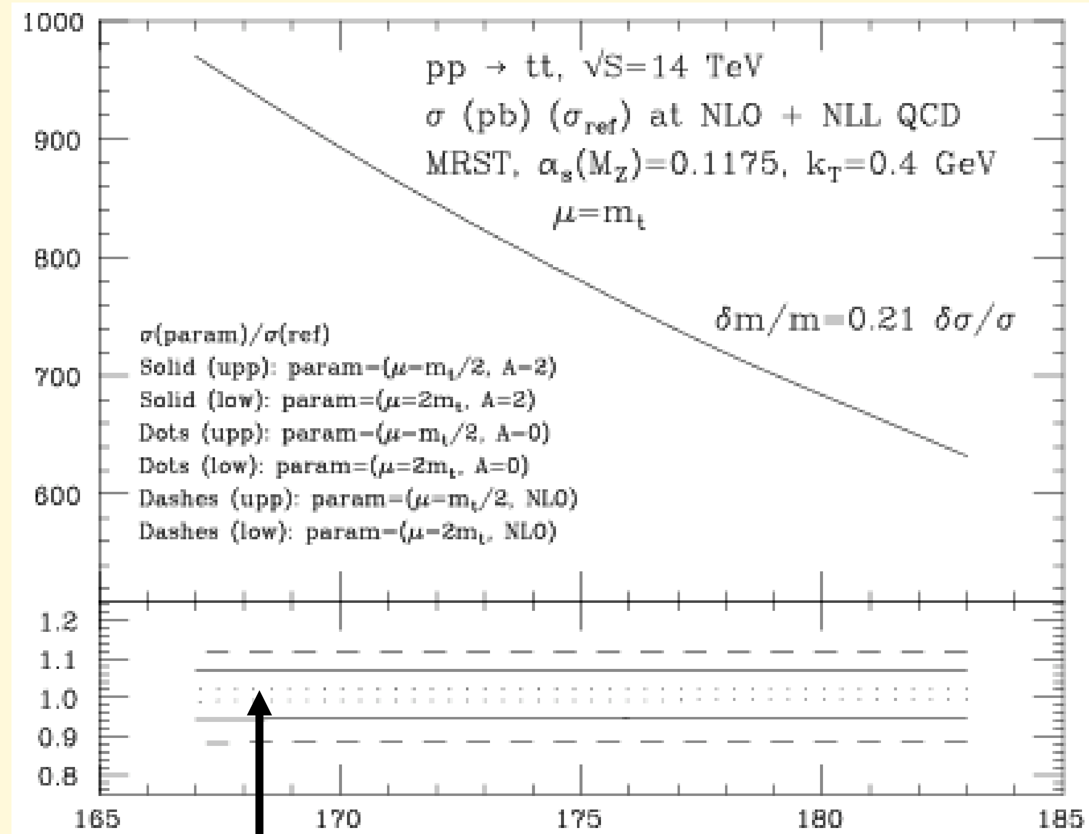




The signal is clearly visible over the background, even without b tagging

tt cross-section





$\sigma_{tt}^{FNAL} = 6.5\text{pb}\ (1 \pm 5\%_{scale} \pm 7\%_{PDF})$

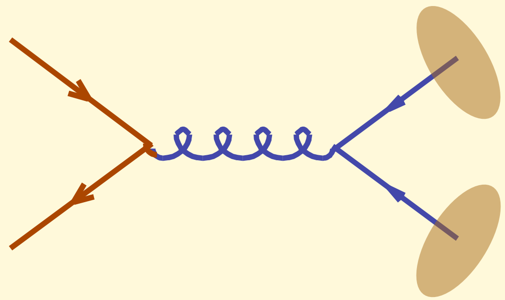
Scale unc: $\pm$ 12%$_{NLO}$ => $\pm$ 5%$_{NLO+NLL}$)

$\Delta\sigma = \pm 6\%$ => $\Delta m = \pm 2$ GeV

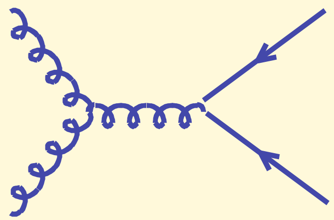
$\sigma_{tt}^{LHC} = 840\text{pb}\ (1 \pm 5\%_{scale} \pm 3\%_{PDF})$

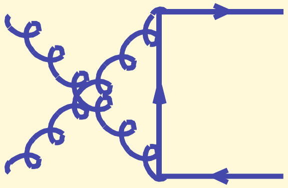
b jets

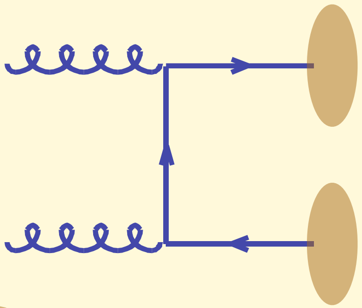
$O(\alpha_S^2)\ L_{q\ qbar}$



$O(\alpha_S^2)\ L_{gg}$

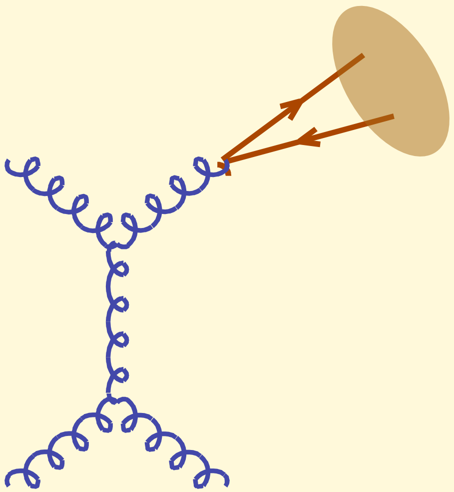






$O(\alpha_S^2)\ L_{gg} \times \alpha_S\ \mathrm{Log}\ (Q/mb)$

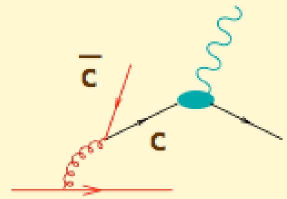
Asymptotically in Q, the probability of finding a b quark inside a gluon jet is 1 !



* Single b-jet in the event.
* b momentum only a fraction of the jet energy => soft muons

From Lecture 1:

Example: charm in the proton



$$\frac{dc(x,Q)}{dt} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dy}{y}\, g(y,Q)\, P_{qg}\left(\frac{x}{y}\right)$$

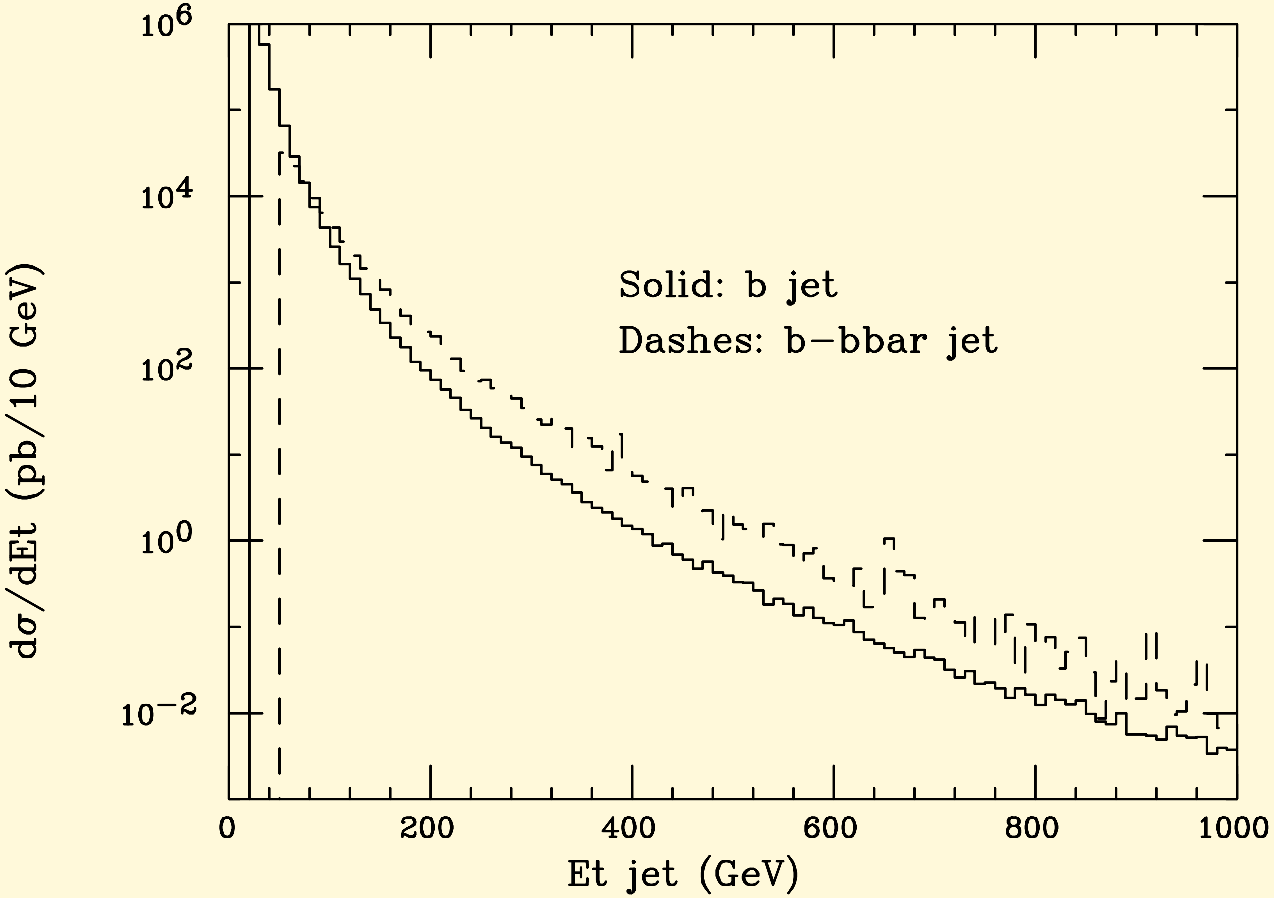
Assuming a typical behaviour of the gluon density: $g(x,Q) \sim A/x$

and using $P_{qg}(x) = \frac{1}{2}\left[x^2 + (1-x)^2\right]$ we get:

$$\frac{dc(x,Q)}{dt} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dy}{y}\, g(x/y,Q)\, P_{qg}(y) = \frac{\alpha_s}{2\pi}\int_x^1 dy\,\frac{A}{x}\frac{1}{2}\left[y^2+(1-y)^2\right] = \frac{\alpha_s}{6\pi}\frac{A}{x}$$

and therefore: $$\boxed{c(x,Q) \sim \frac{\alpha_s}{6\pi}\log\left(\frac{Q^2}{m_c^2}\right) g(x,Q)}$$

If $g(x) = \delta(1-x) \Rightarrow \int dx\, c(x) =$ $\boxed{\frac{\alpha_s}{6\pi}\log\left(\frac{Q^2}{m_c^2}\right)}$



While the rate at high ET is dominated by b-bbar jets, triggers selecting high-pT b quarks (e.g. a trigger on the muon pT) will select b-jets.