Introduction to hadron collider physics

Theory challenges for LHC Physics

Dubna International Advanced School of Theoretical Physics

Helmholtz International Summer School

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Lecture 3

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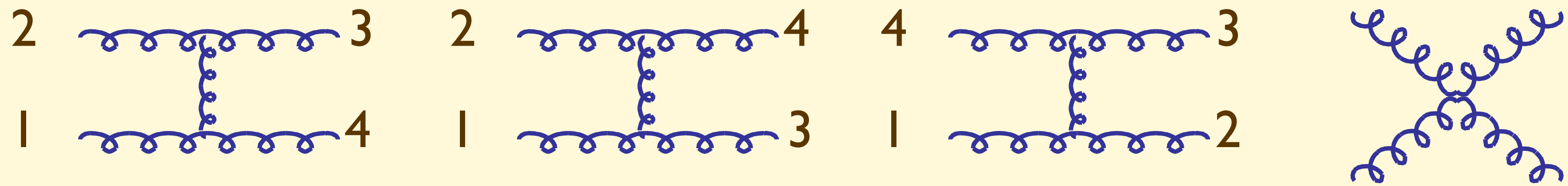
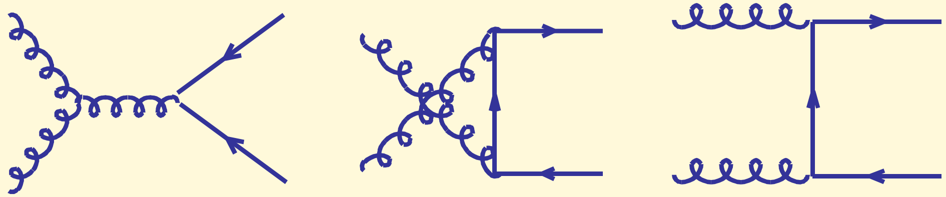
- Inclusive production of jets is the largest component of high-Q phenomena in hadronic collisions
- QCD predictions are known up to NLO accuracy
- Intrinsic theoretical uncertainty (at NLO) is approximately 10%
- Uncertainty due to knowledge of parton densities varies from 5-10% (at low transverse momentum, p_T to 100% (at very high p_T, corresponding to high-x gluons)
- Jet are used as probes of the quark structure (possible substructure implies departures from point-like behaviour of cross-section), or as probes of new particles (peaks in the invariant mass distribution of jet pairs)

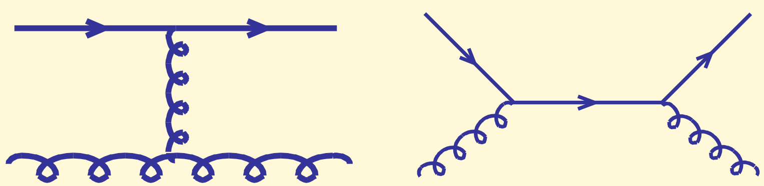
$gg \rightarrow gg$



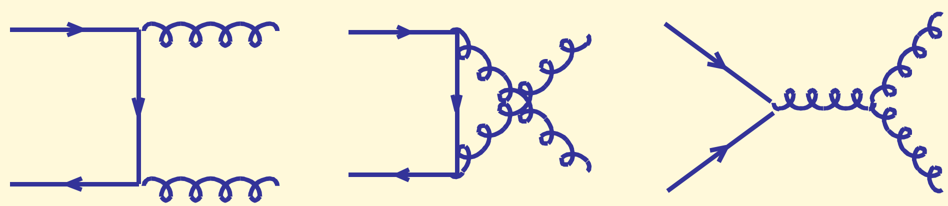
$gg \rightarrow q\bar{q}$



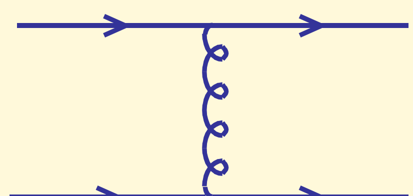
$qg \rightarrow qg$



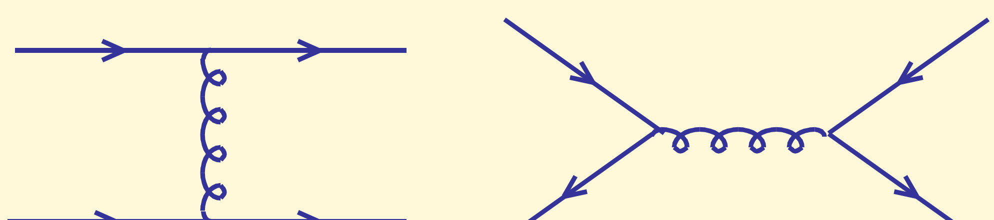
$q\bar{q} \rightarrow gg$



$qq' \rightarrow qq'$



$q\bar{q} \rightarrow q\bar{q}$



Phase space and cross-section for LO jet production

$$d[PS] = \frac{d^3p_1}{(2\pi)^2 2p_1^0}\frac{d^3p_2}{(2\pi)^2 2p_2^0}(2\pi)^4\delta^4(P_{in}-P_{out})\,dx_1\,dx_2$$

(a) $$\delta(E_{in}-E_{out})\,\delta(P^z_{in}-P^z_{out})\,dx_1\,dx_2 = \frac{1}{2E^2_{beam}}$$

(b) $$\frac{dp^z}{p^0} = dy \equiv d\eta$$

$$d[PS] = \frac{1}{4\pi S}\,p_T\,dp_T\,d\eta_1\,d\eta_2$$

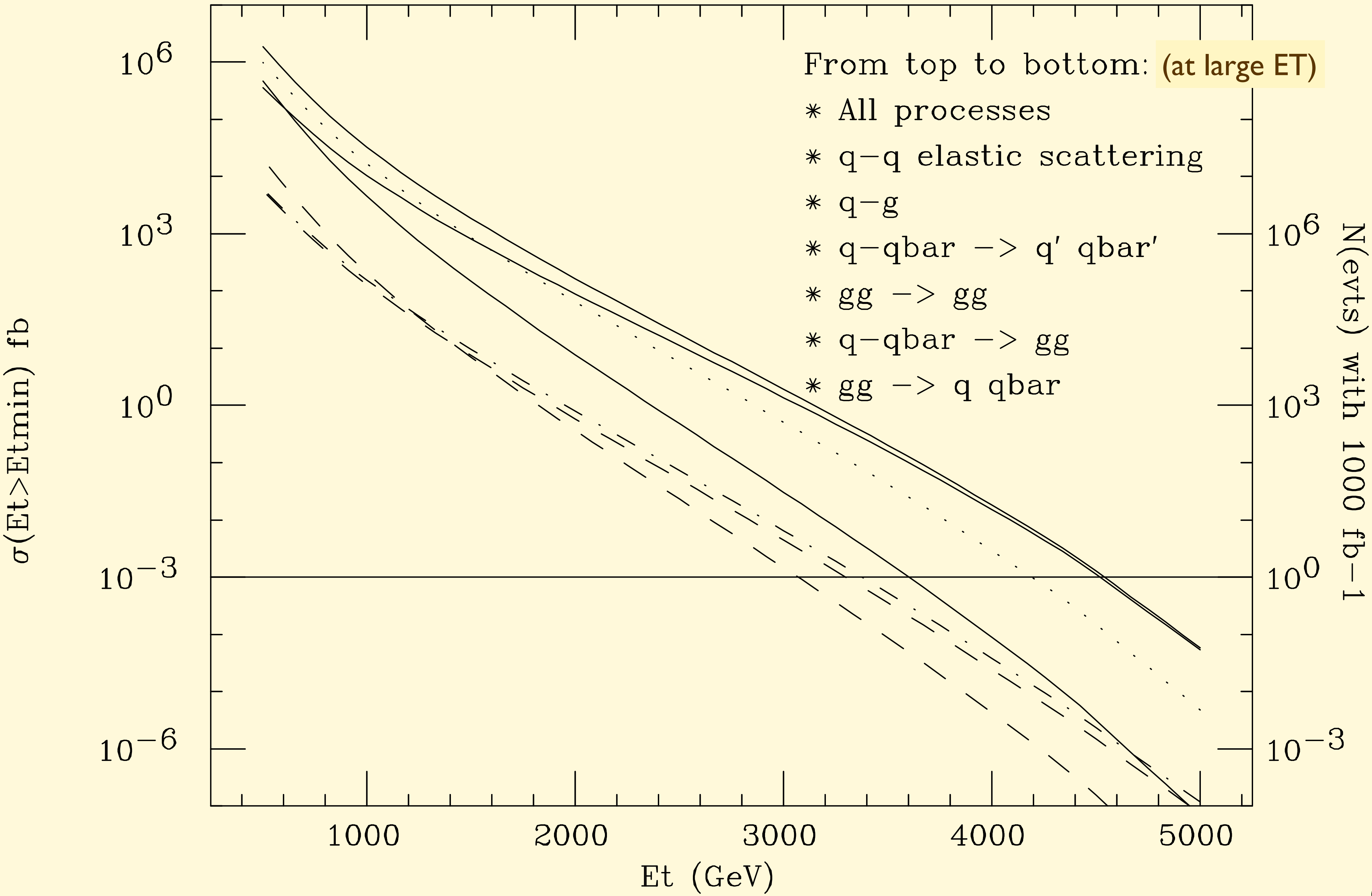
$$\frac{d^3\sigma}{dp_T d\eta_1 d\eta_2} = \frac{p_T}{4\pi S}\sum_{i,j} f_i(x_1)\,f_j(x_2)\,\frac{1}{2\hat{s}}\overline{\sum_{kl}}|M(ij\to kl)|^2$$

The measurement of pT and rapidities for a dijet final state uniquely determines the parton momenta x_1 and x_2. Knowledge of the partonic cross-section allows therefore the determination of partonic densities f(x)

Process	$\frac{d\hat{\sigma}}{d\Phi_2}$	at 90°
$qq' \to qq'$	$\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$	2.22
$qq \to qq$	$\left[\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right)-\frac{8}{27}\frac{\hat{s}^2}{\hat{u}\hat{t}}\right]$	3.26
$q\bar{q} \to q'\bar{q}'$	$\frac{4}{9}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$	0.22
$q\bar{q} \to q\bar{q}$	$\left[\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)-\frac{8}{27}\frac{\hat{u}^2}{\hat{s}\hat{t}}\right]$	2.59
$q\bar{q} \to gg$	$\left[\frac{32}{27}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{8}{3}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right]$	1.04
$gg \to q\bar{q}$	$\left[\frac{1}{6}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{3}{8}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right]$	0.15
$gq \to gq$	$\left[-\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{s}\hat{u}}+\frac{\hat{u}^2+\hat{s}^2}{\hat{t}^2}\right]$	6.11
$gg \to gg$	$\frac{9}{2}\left(3-\frac{\hat{t}\hat{u}}{\hat{s}^2}-\frac{\hat{s}\hat{u}}{\hat{t}^2}-\frac{\hat{s}\hat{t}}{\hat{u}^2}\right)$	30.4

Jet production rates at the LHC, subprocess composition

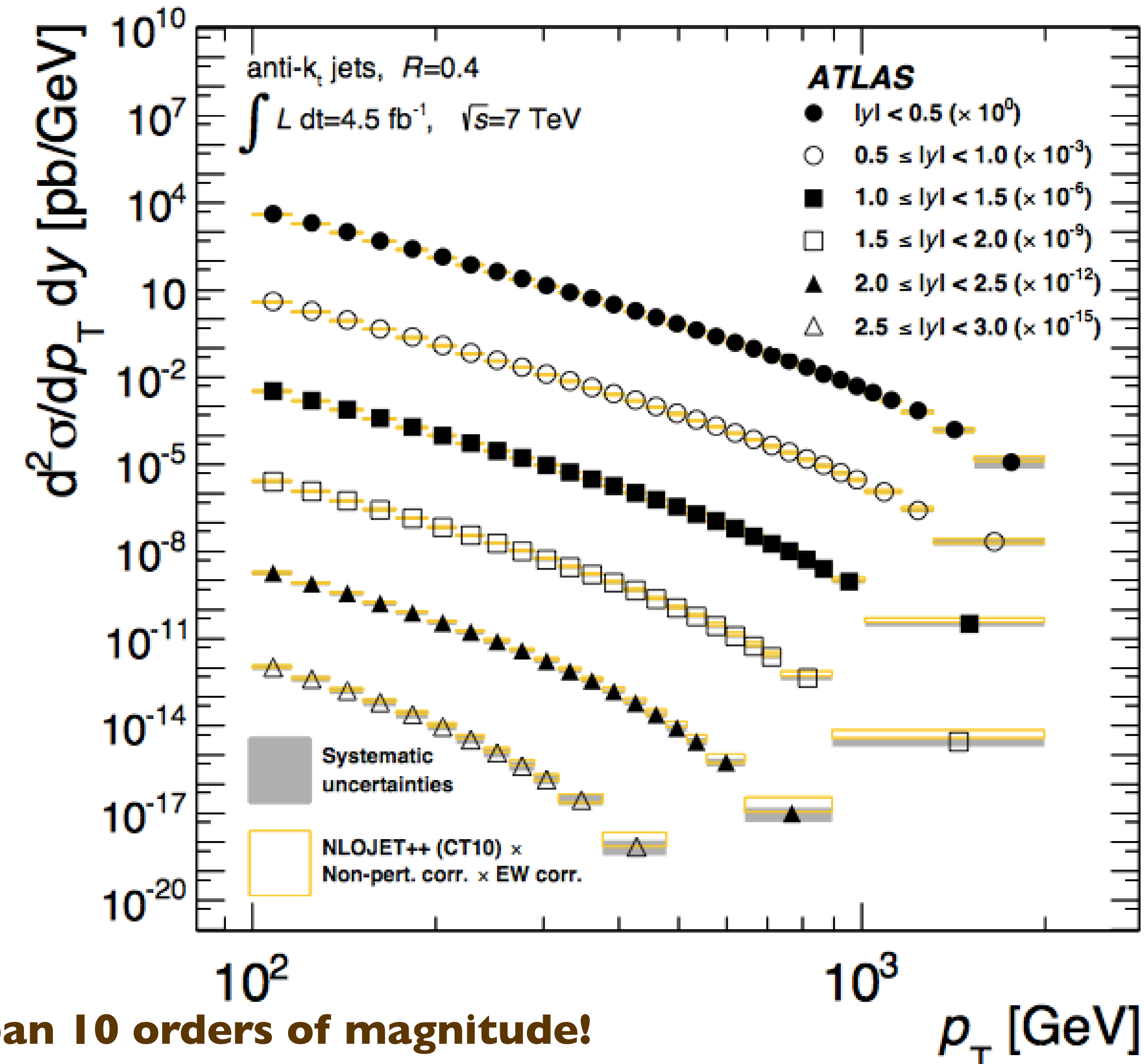
(this is at 14 TeV: results at 7 TeV are ~obtained by rescaling ET by 0.5)



Some LHC results in jet physics

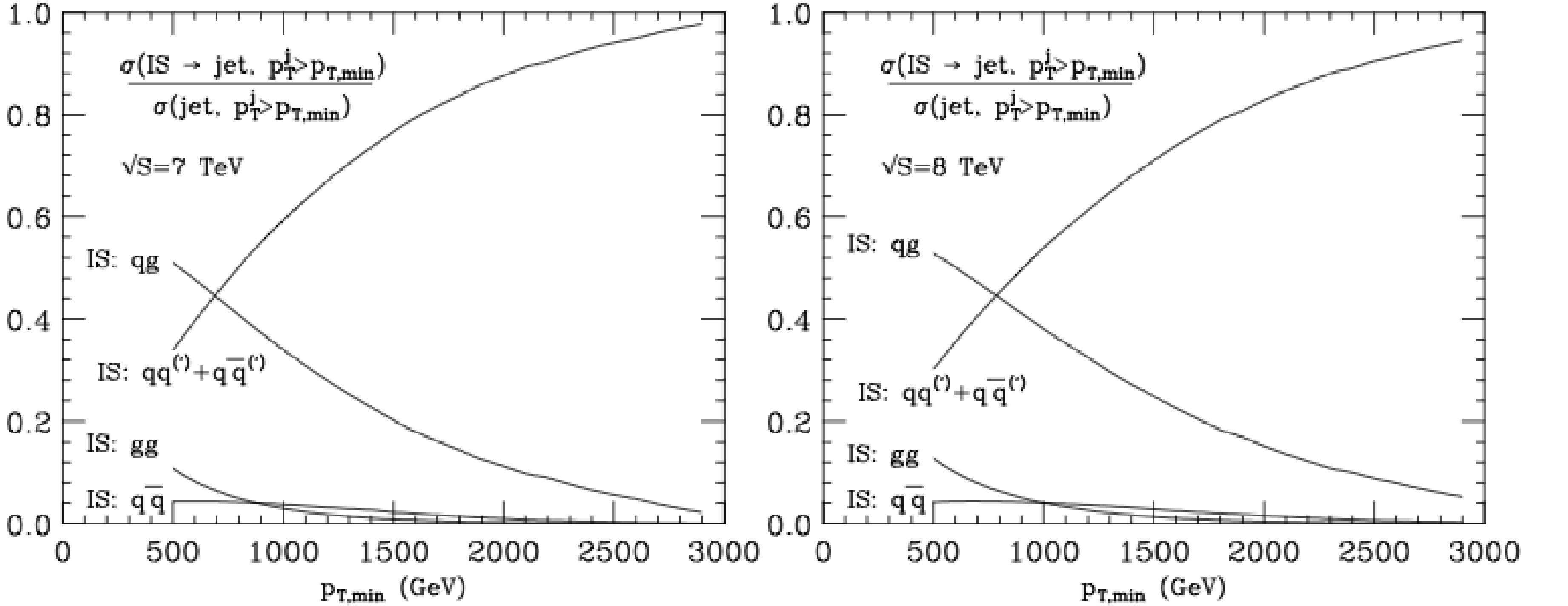
Example: Jet cross section

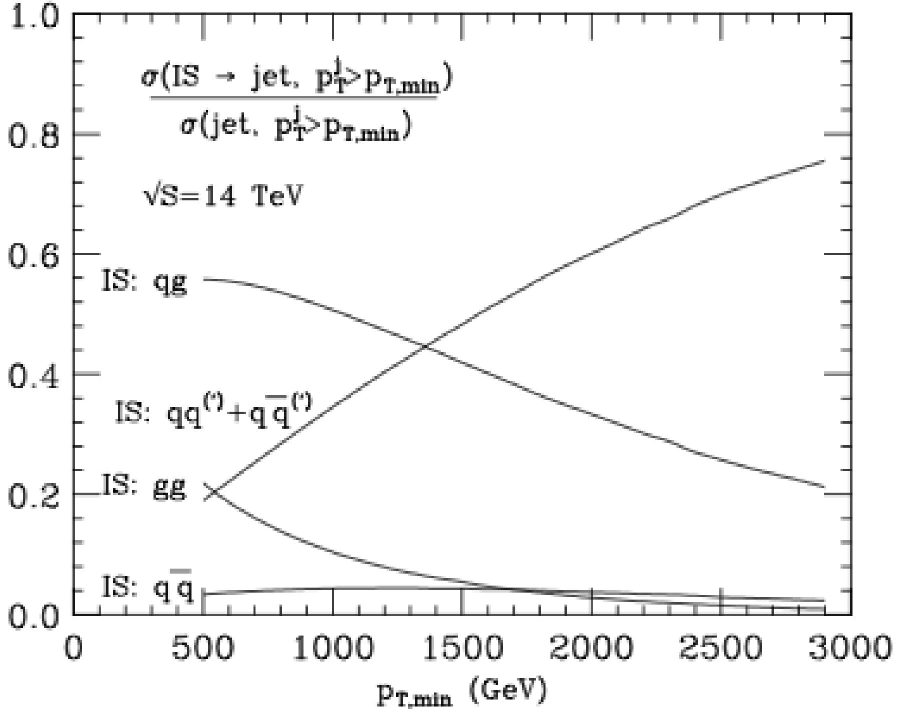
ATLAS, arXiv:1410.8857



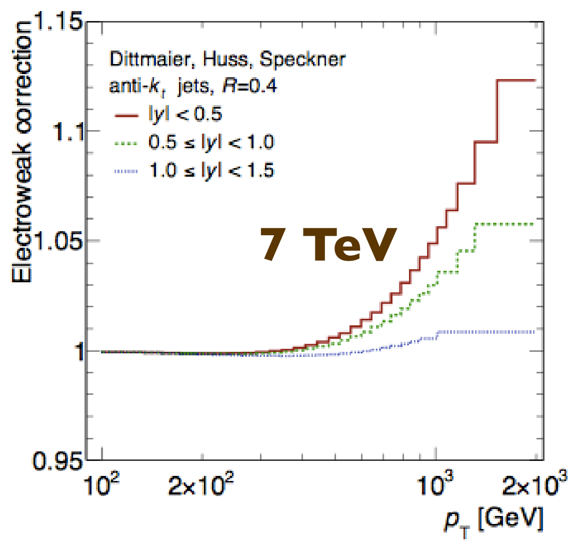
Rates span 10 orders of magnitude!

Initial state composition of inclusive jet events

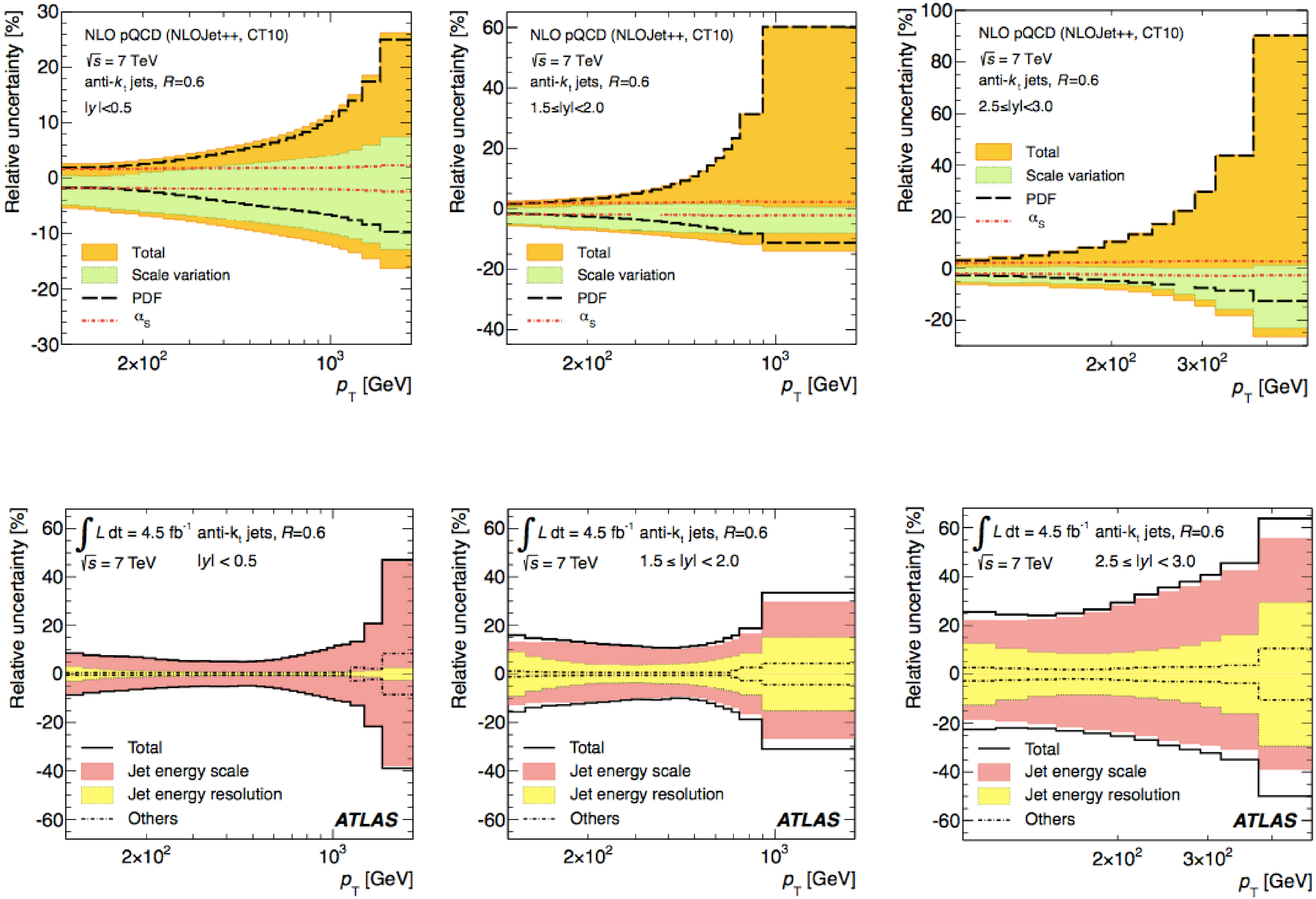




NB: Impact of virtual EW corrections:

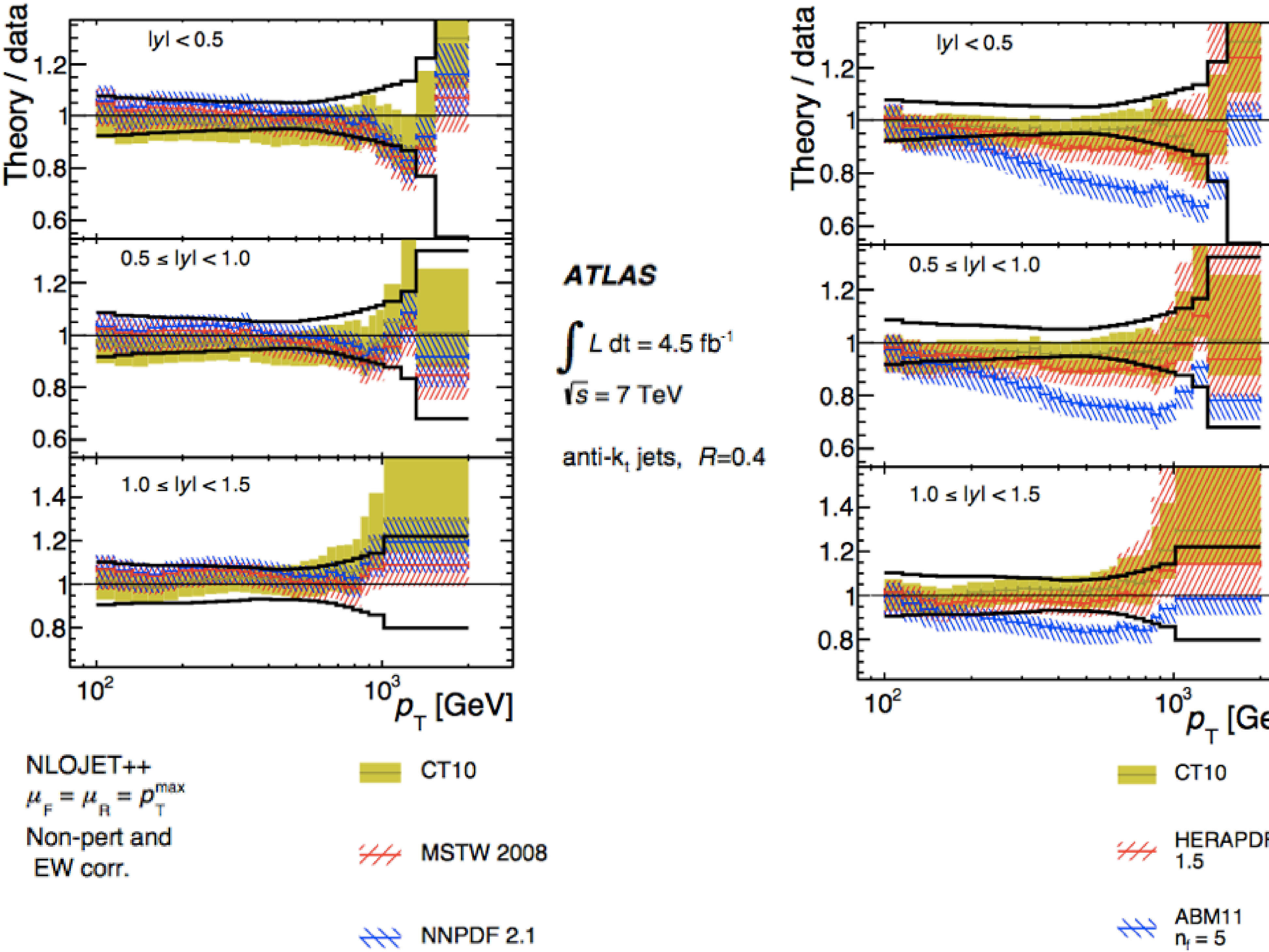


at p_T~2 TeV it's larger than qg contribution

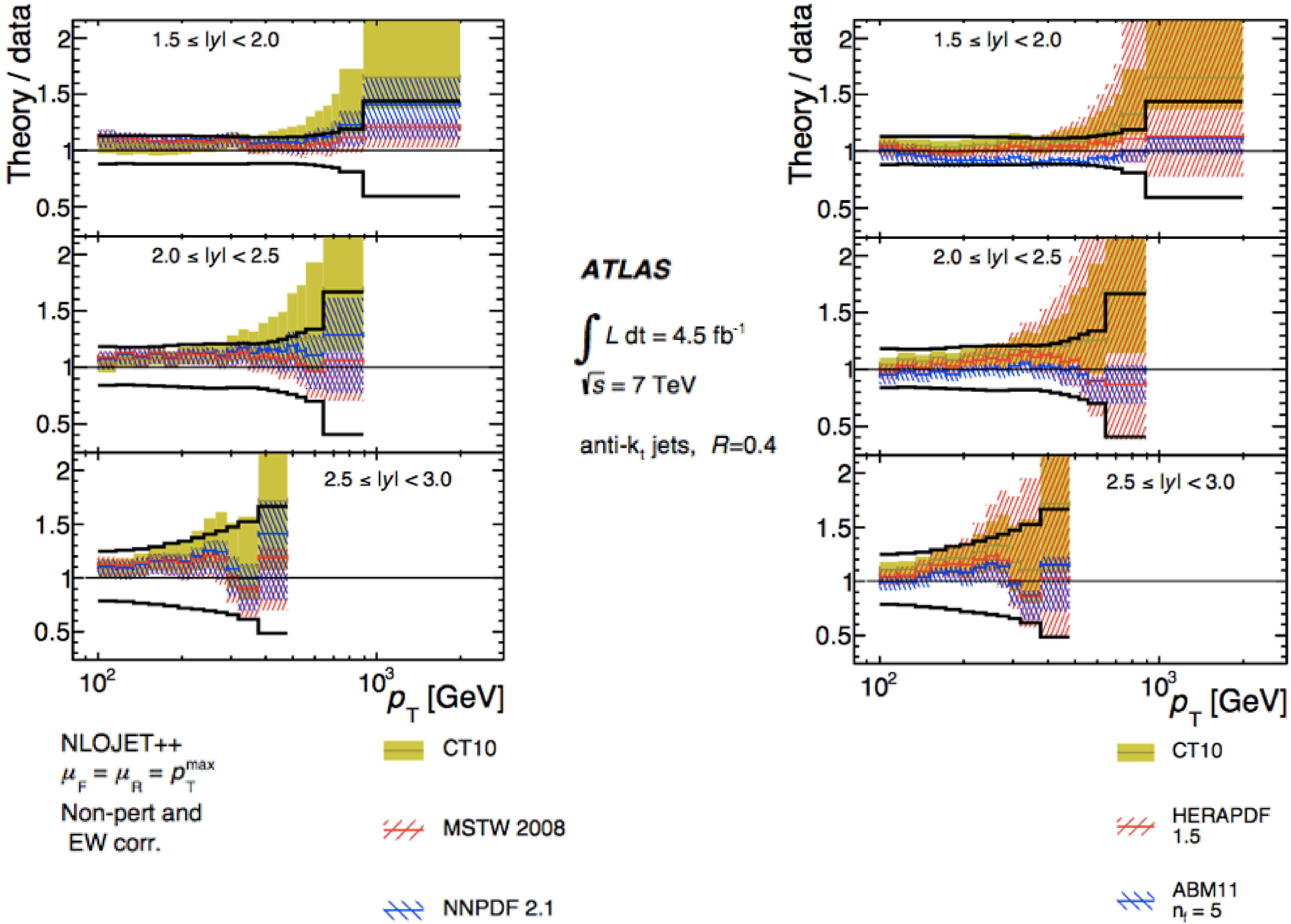


Relative uncertainty [%]
NLO pQCD (NLOJet++, CT10)
√s = 7 TeV
anti-k_t jets, R=0.6
|y|<0.5
1.5≤|y|<2.0
2.5≤|y|<3.0
Total
Scale variation
PDF
α_S
p_T [GeV]
2×10^2
10^3
3×10^2
∫ L dt = 4.5 fb^-1 anti-k_t jets, R=0.6
|y| < 0.5
1.5 ≤ |y| < 2.0
2.5 ≤ |y| < 3.0
Total
Jet energy scale
Jet energy resolution
Others
ATLAS

Central production, TH vs data
(TH: absolute prediction for both shape and normalization)

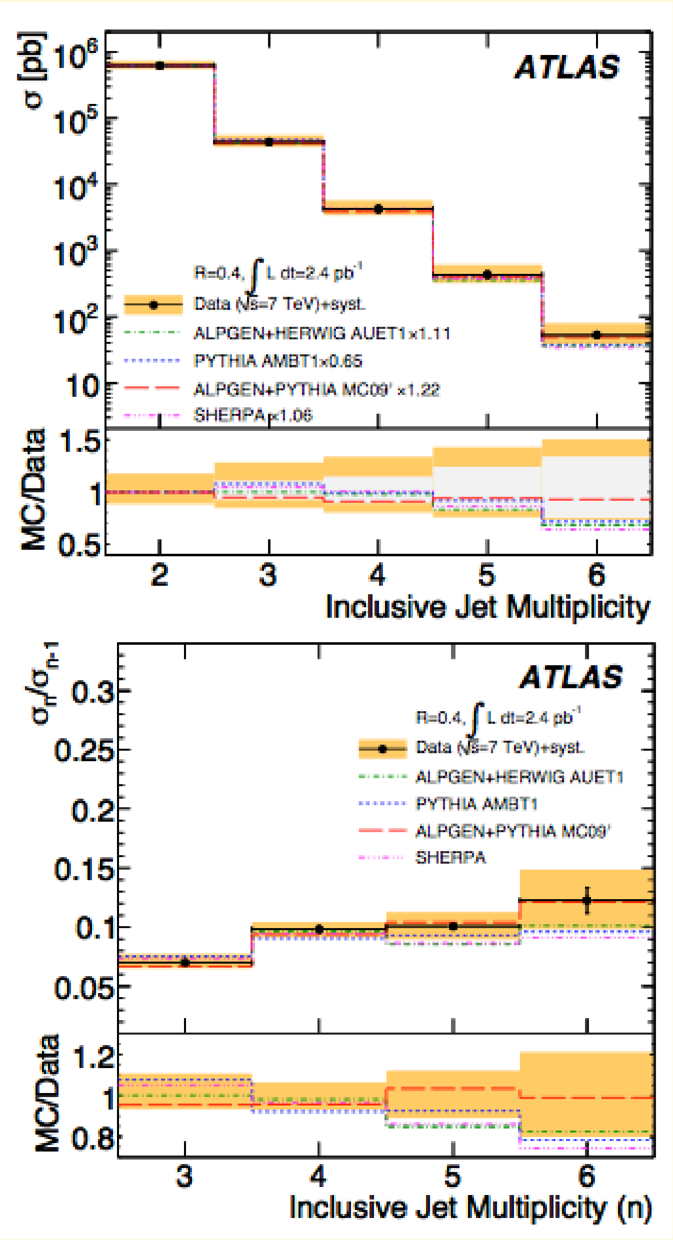


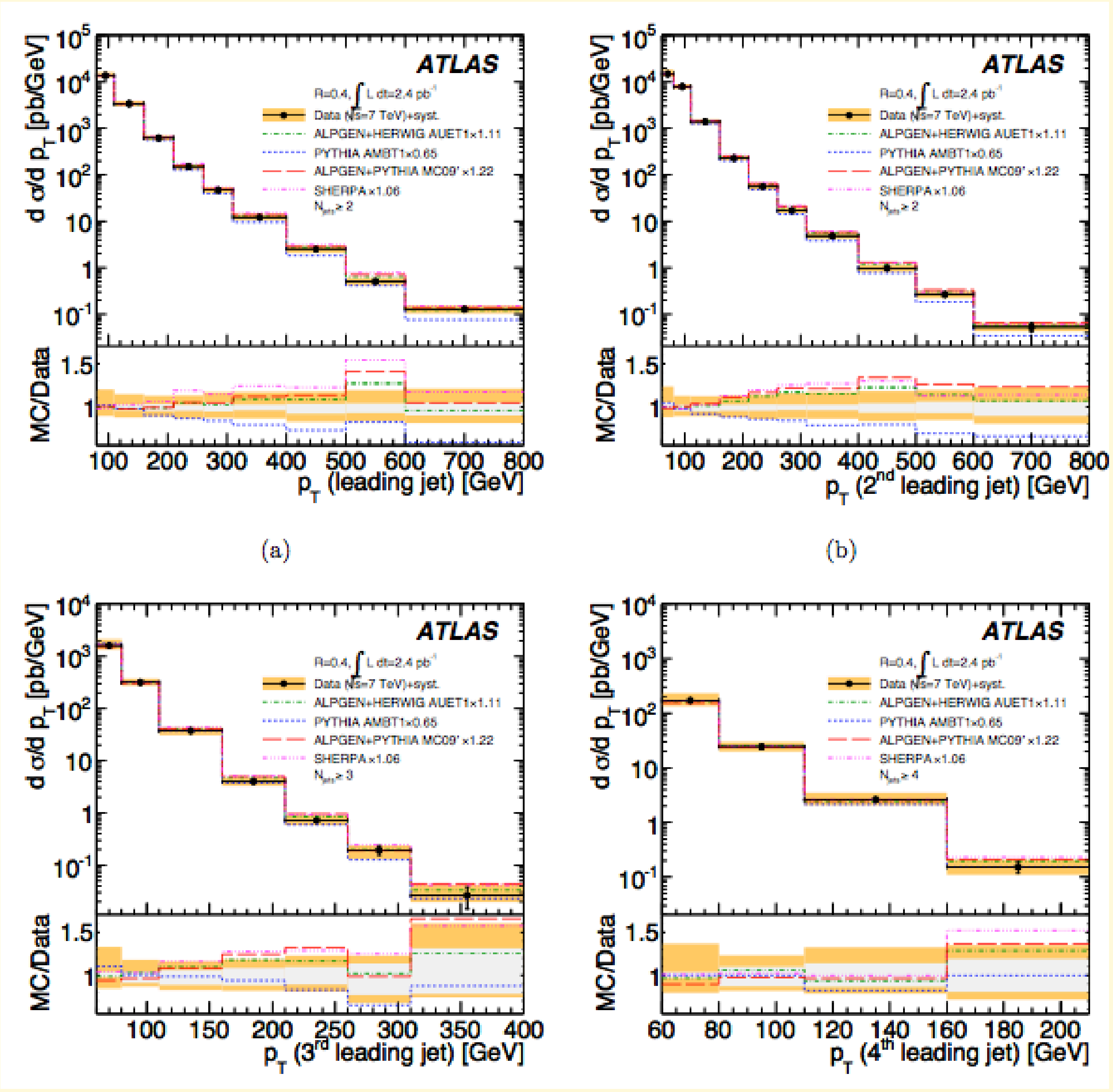
Forward production, TH vs data
(TH: absolute prediction for both shape and normalization)



Multijets

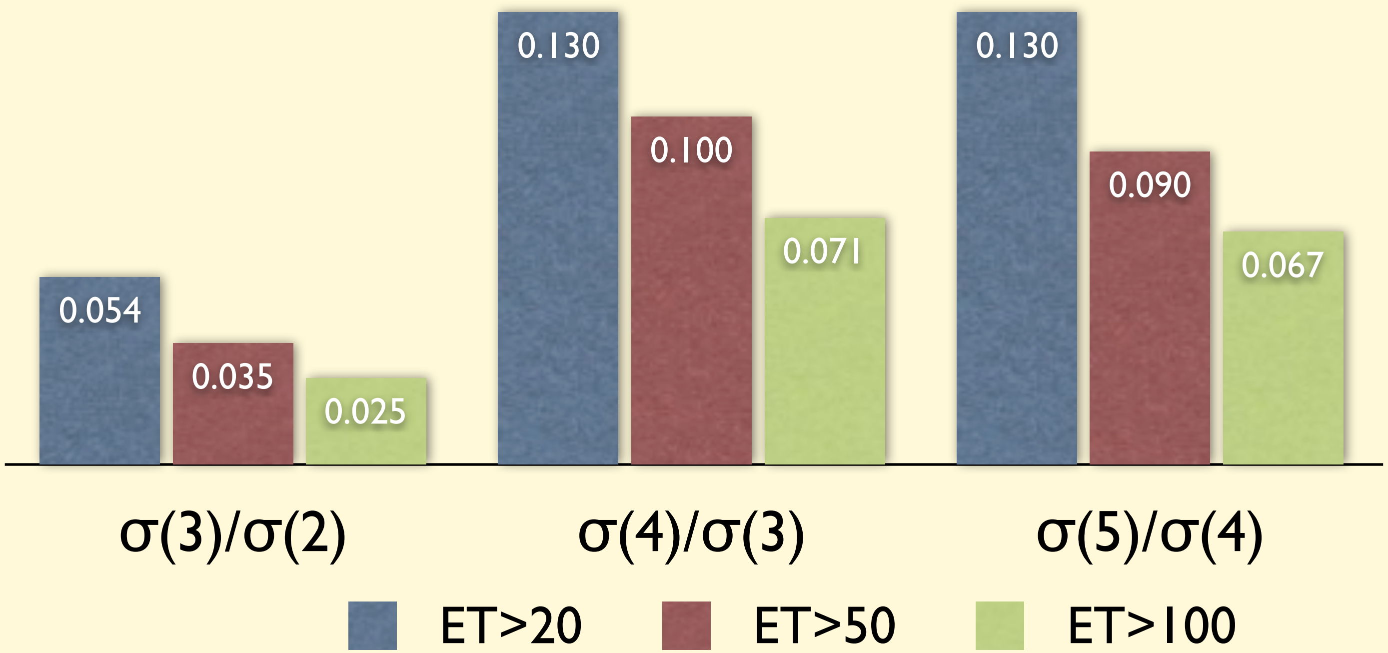
ATLAS, arXiv:1107.2092





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

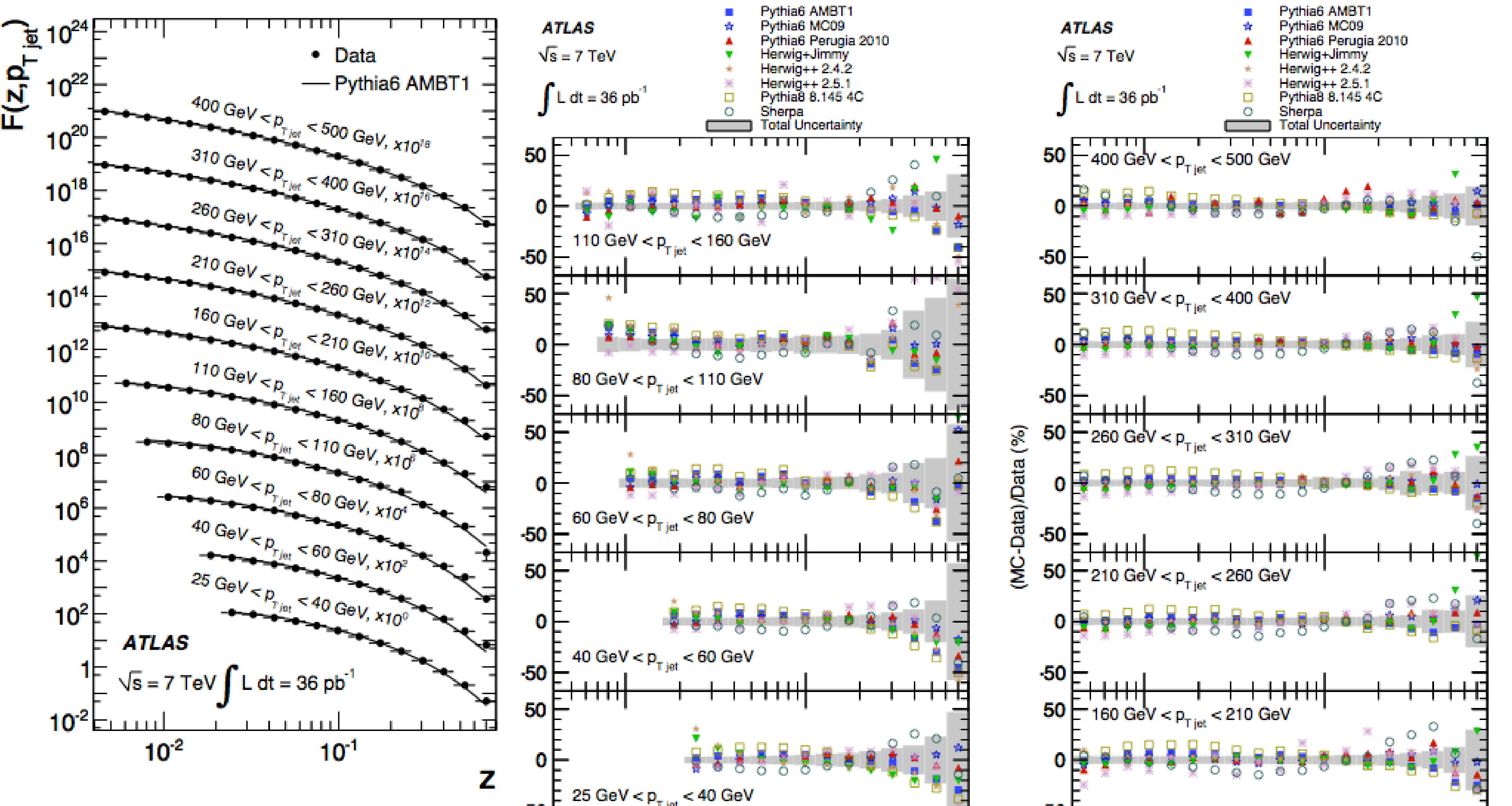
Multijet rates, vs $\sqrt{s}$, with $E_T^{jet} > 20$ GeV

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

High mass final states are dominated by multijet configurations

Jet fragmentation function

ATLAS, arXiv:1109.5816

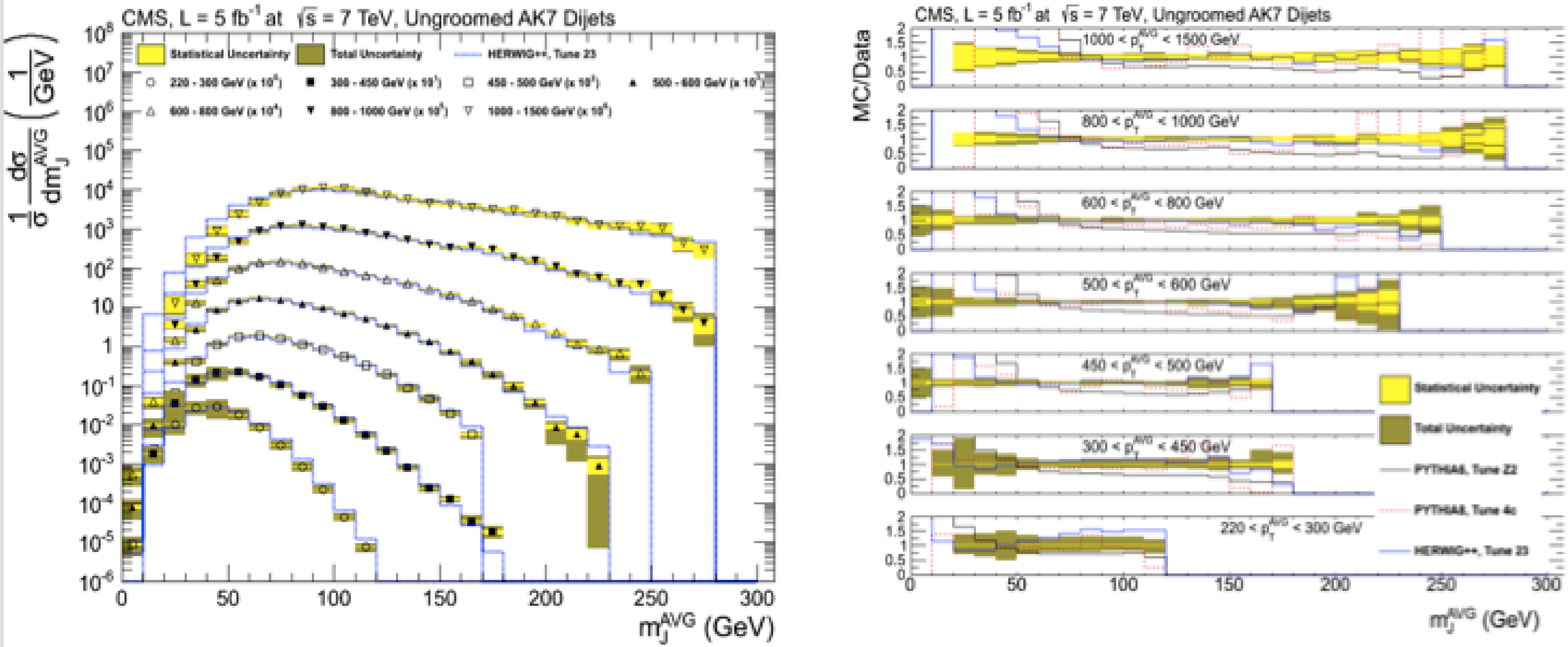


plus

- **jet shapes**
- **ptrel spectra**
- **<N_{ch}> and <z> distributions,**
- **....**

QCD jet mass measurement

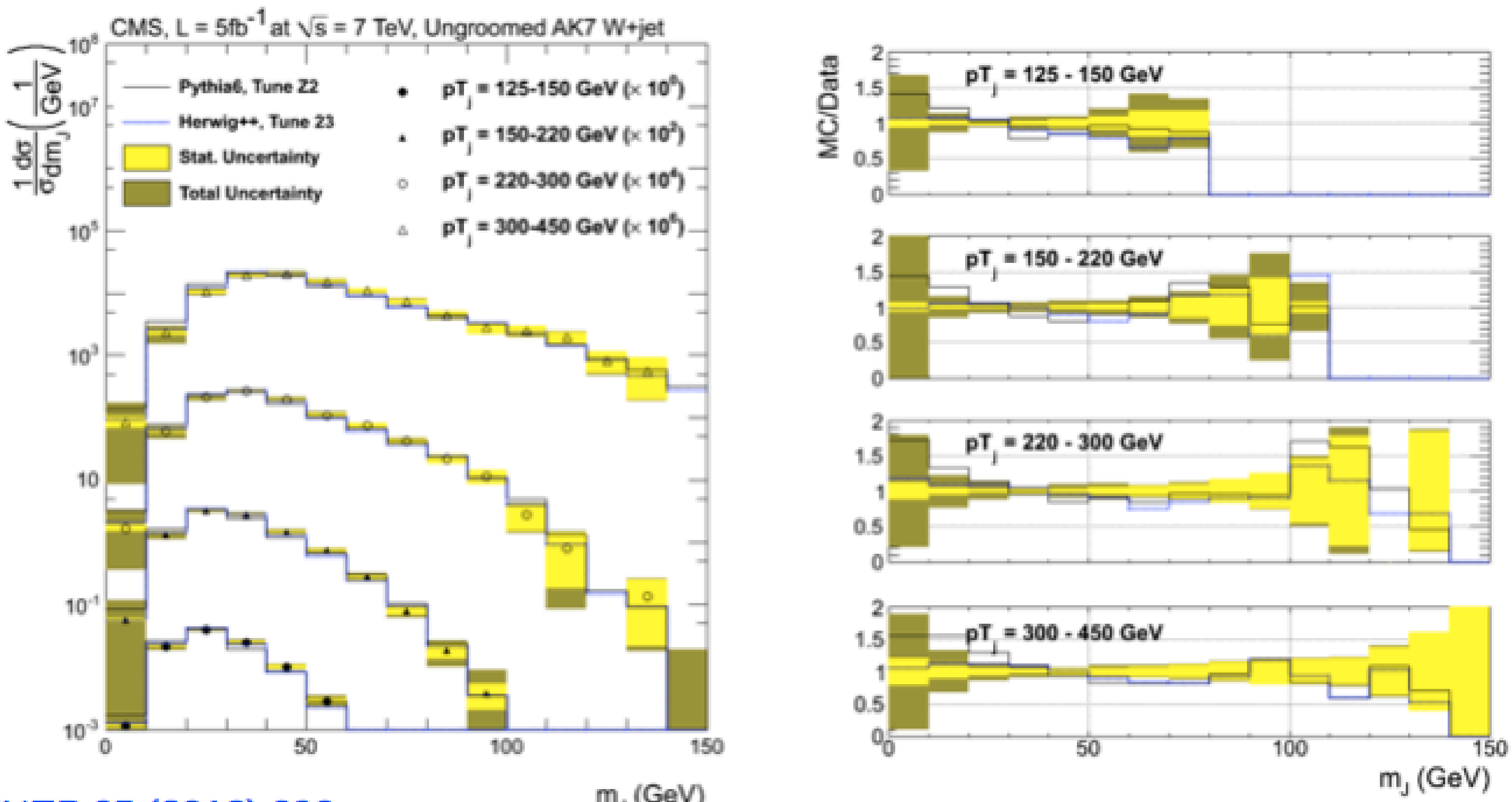
Processes with high mass jets (q/g initiated) are important backgrounds for many analyses in the boosted topology.



JHEP 05 (2013) 090
CMS-SMP-12-019

Dijet typology (gluon enriched)

QCD jet mass measurement



JHEP 05 (2013) 090
CMS-SMP-12-019

V+jet typology (quark enriched): agreement with data is slightly better

Reconstruct W/Z→jj from broad jets at large p_T

Likelihood discriminant using (i) thrust minor (ii) sphericity (iii) aplanarity

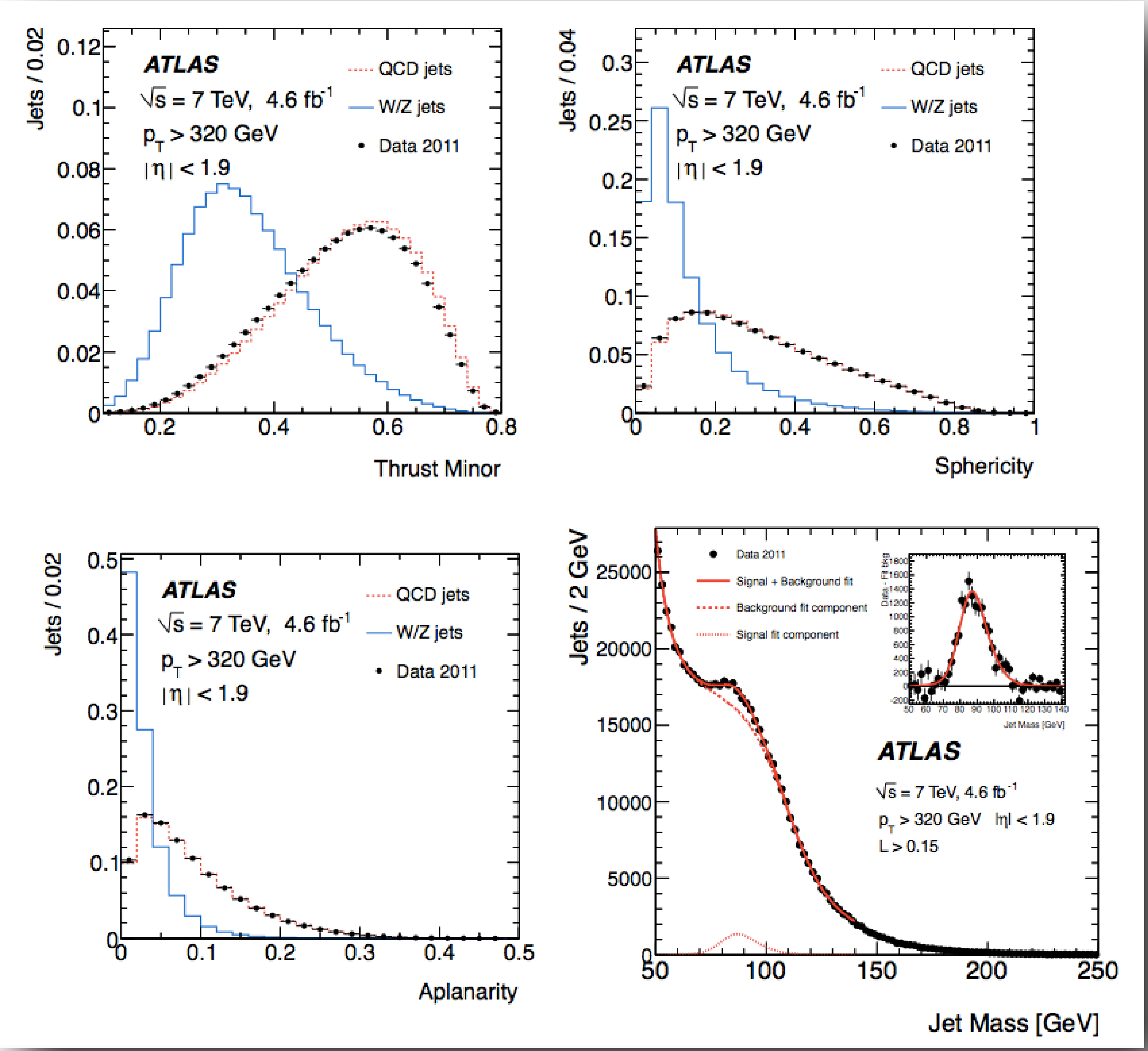
Extract

σ_{W+Z} = 8.5±0.8(stat)±1.5(syst) pb

ATLAS, J.Phys. 16 (2014) 113013

NLO:

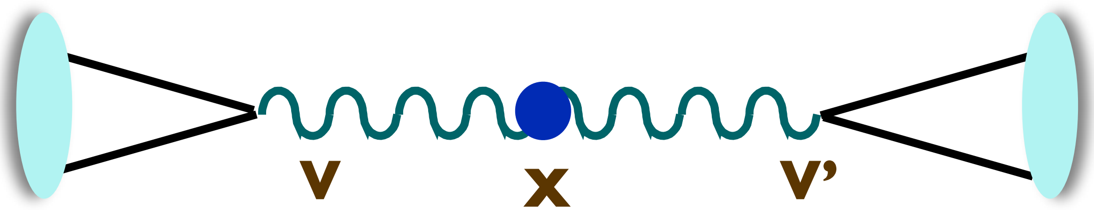
σ_{W+Z} = 5.1±0.5 pb



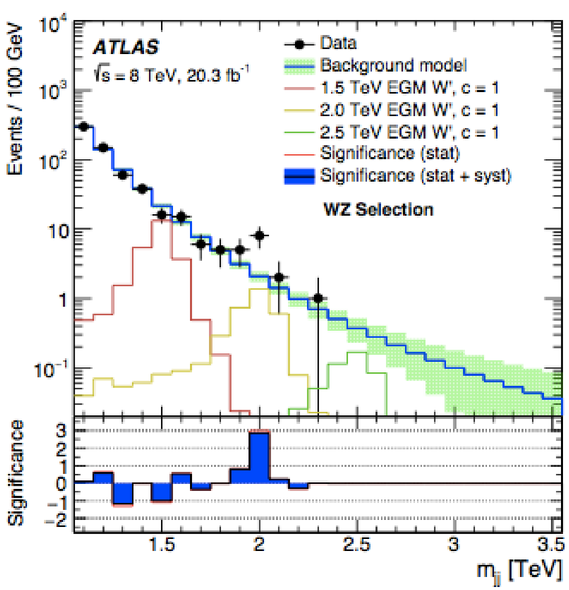
Example in use of W/Z -> jj

ATLAS, arXiv:1506.00962

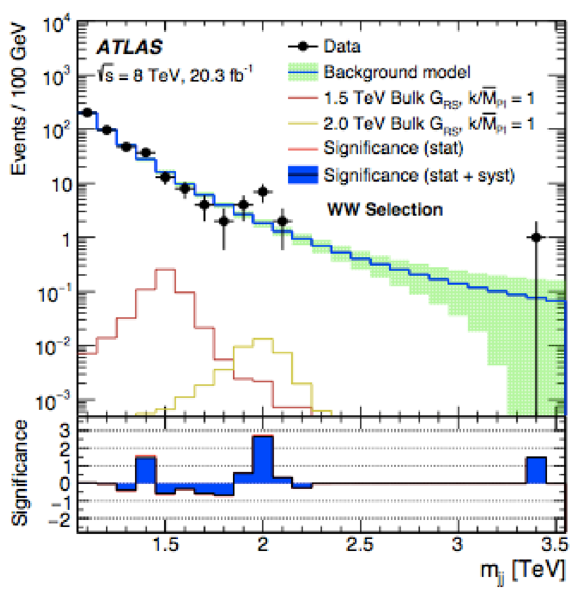
pp→X→VV' →jet jet, with V(')=W,Z fully hadronic decays



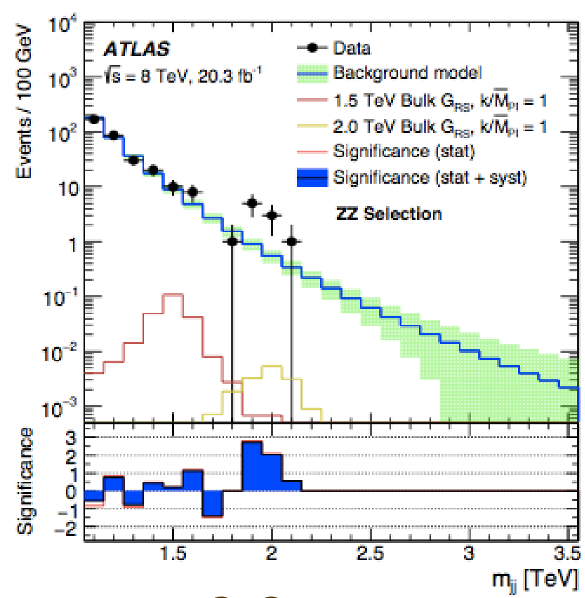
$| m_j - m_V | < 13$ GeV



3.5σ *local*



2.6σ



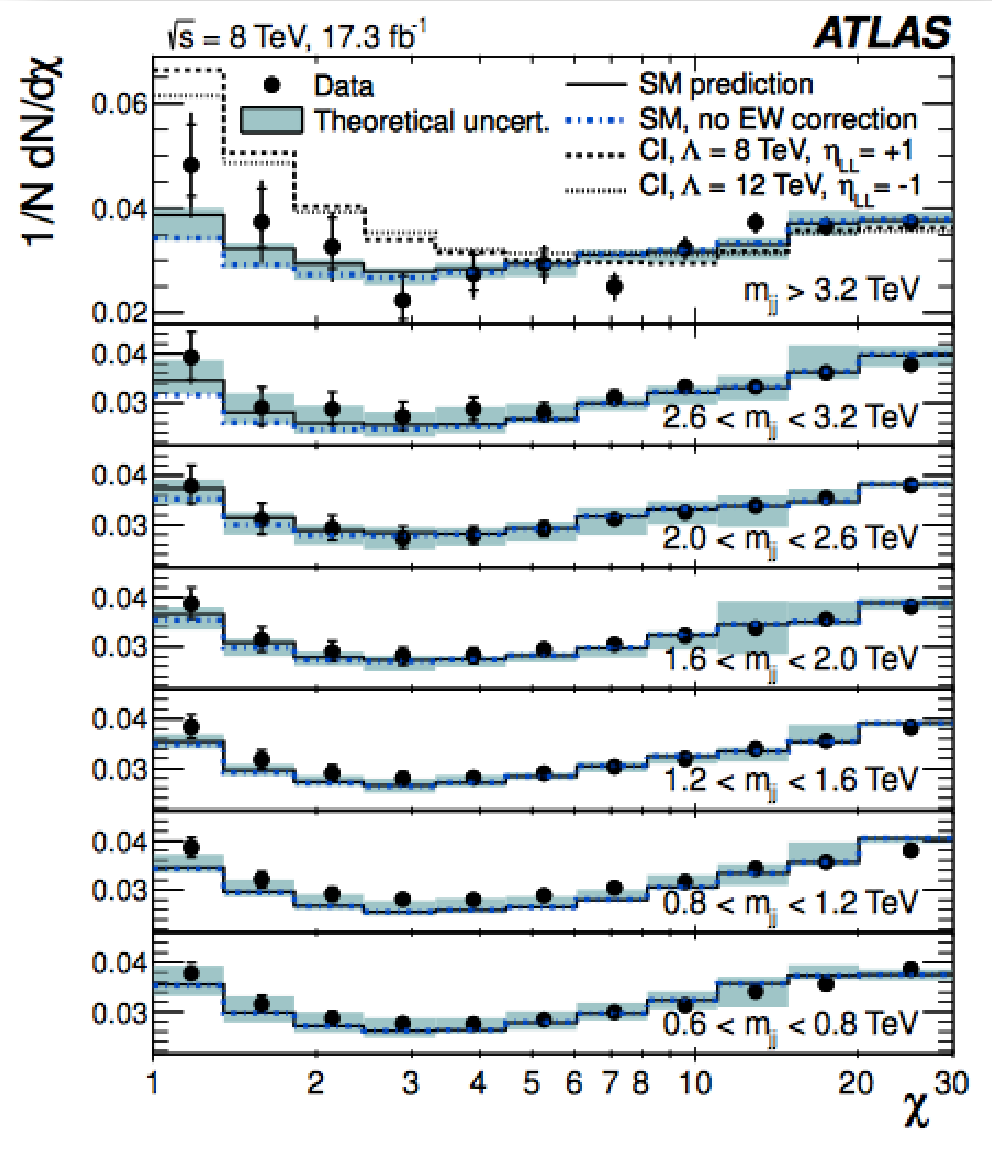
2.9σ

→**2.4σ *global***, accounting for the whole range of m_{jj} and for ZZ, WW, WZ modes

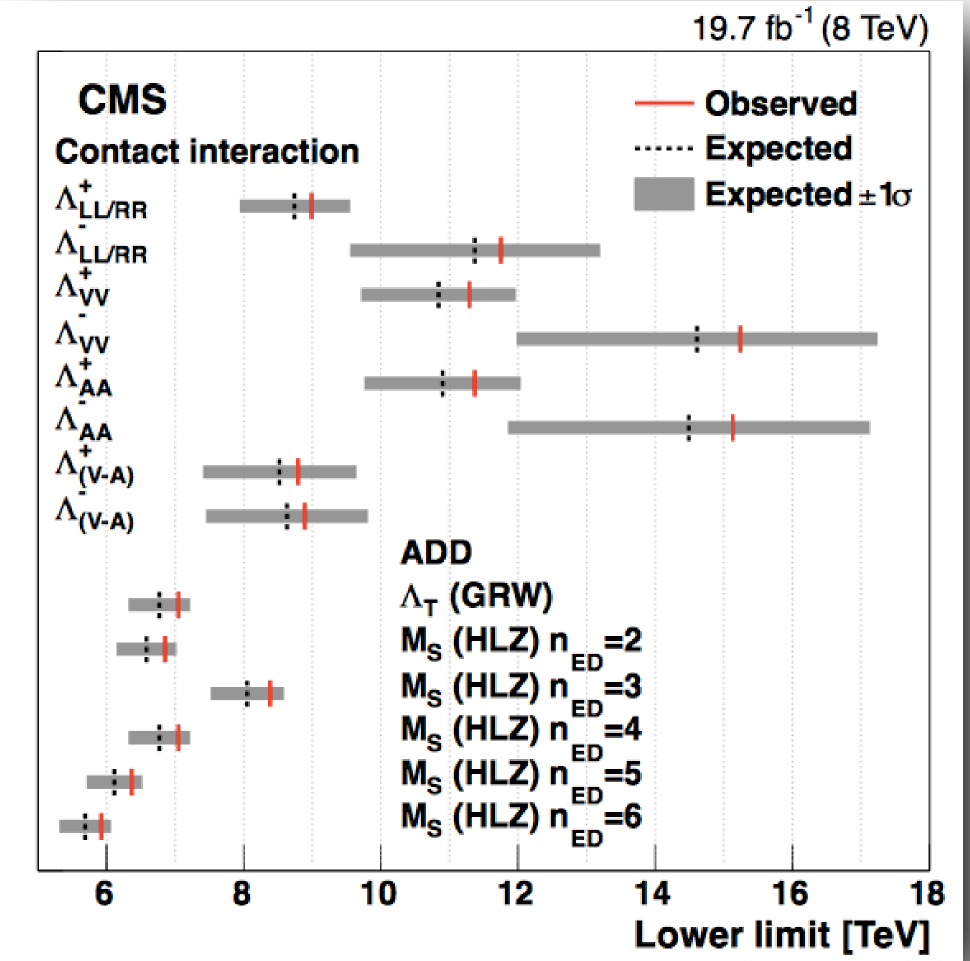
NB: the excesses are strongly correlated: $| m_j - m_V | < 13$ GeV allows the same event to belong to more than one selection among WZ, WW and ZZ

Constraints on quark contact interactions

ATLAS, http://arxiv.org/abs/1504.00357



CMS, http://arxiv.org/abs/1411.2646



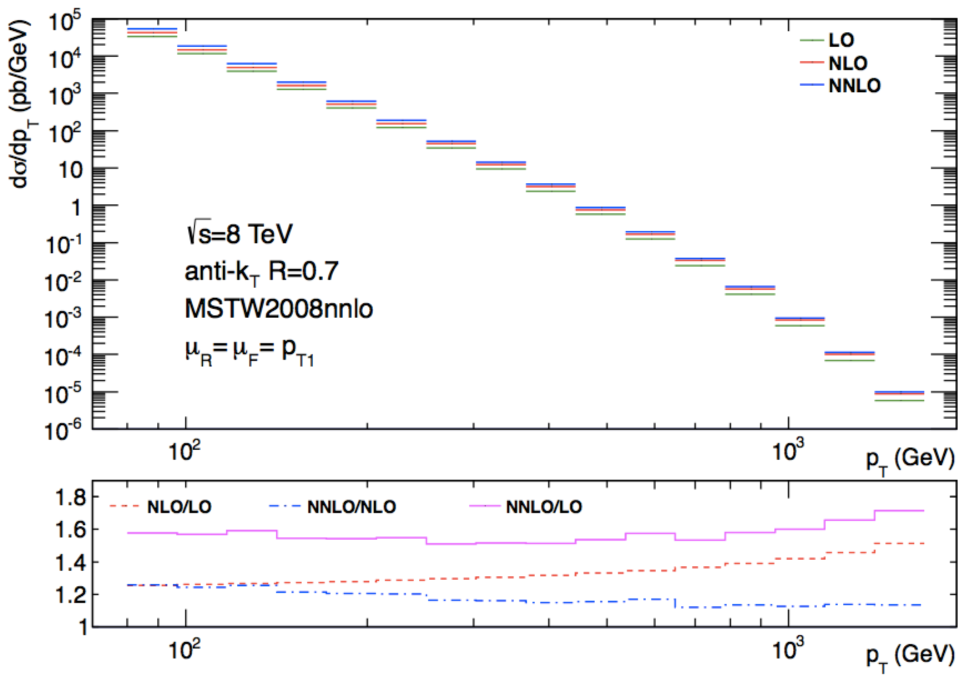
Quarks appear pointlike even at the distances probed by the LHC, up to scales in the range of (10 TeV)$^{-1}$

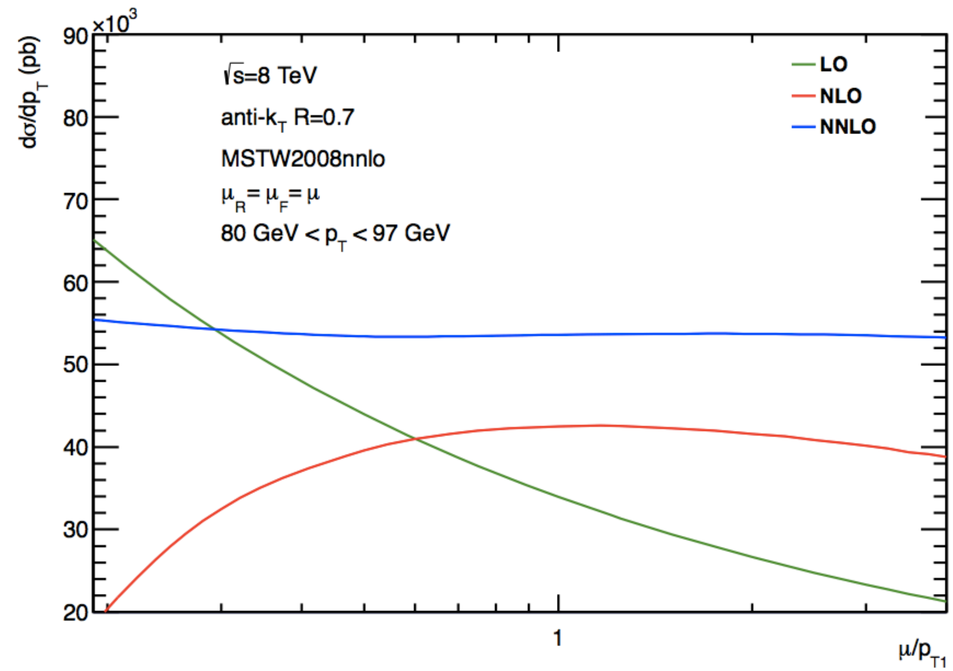
$$\chi = \frac{1+|\cos\theta^*|}{1-|\cos\theta^*|}$$

NB: $$\mathrm{d}\chi = 2\,\frac{\mathrm{d}\cos\theta}{\sin^4(\theta/2)}$$

Inclusive jet cross section at NNLO

"Second order QCD corrections to jet production at hadron colliders: the all-gluon contribution", A. Gehrmann-De Ridder, T. Gehrmann, E.W. N. Glover, J. Pires, arXiv:1301.7310





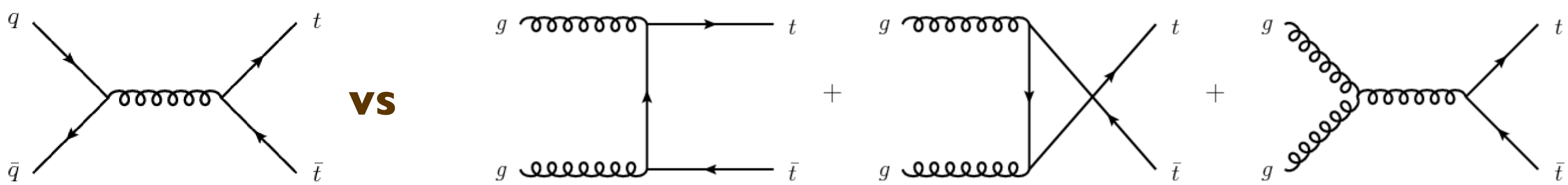
NNLO/NLO ~ 1.2

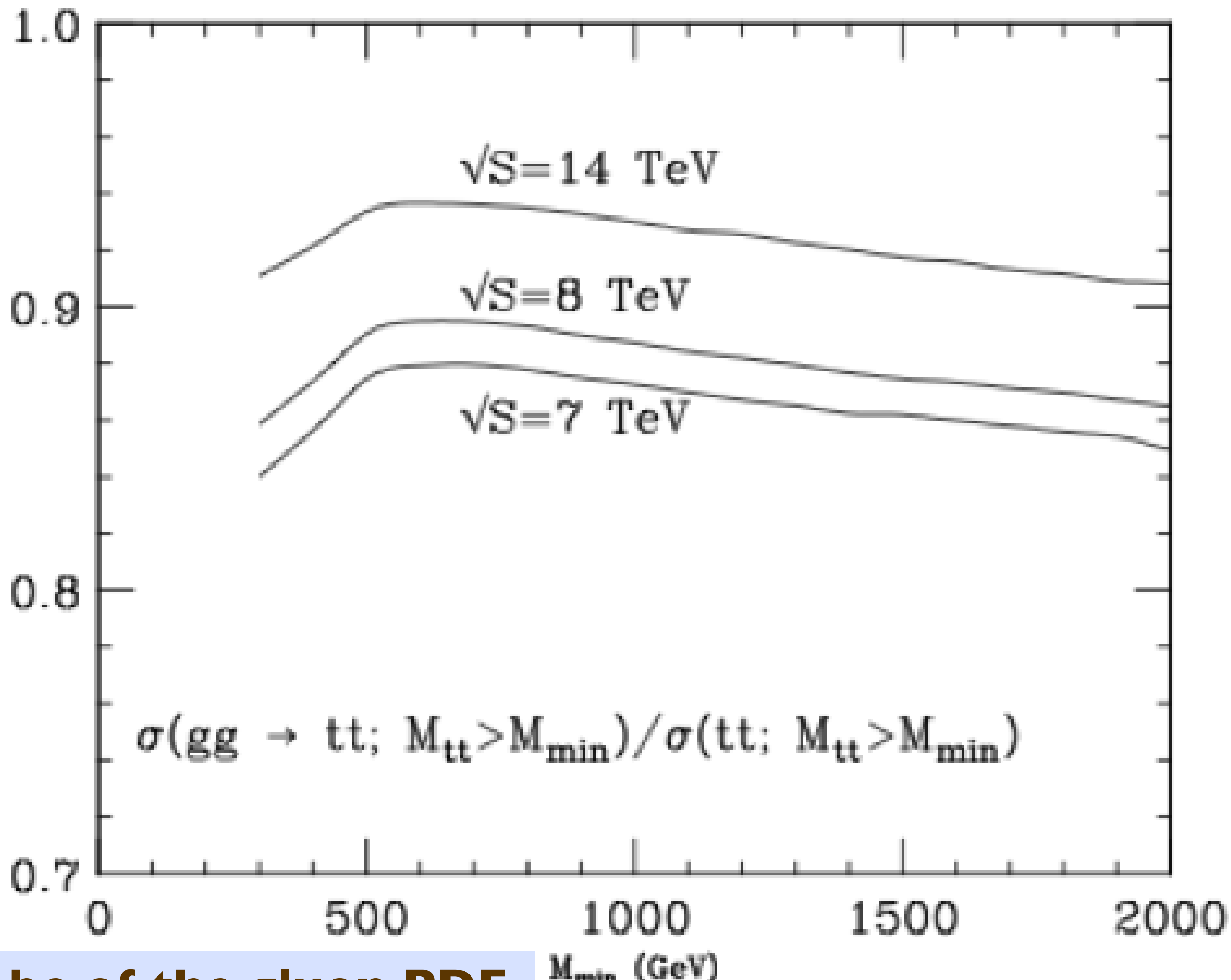
NNLO scale systematics ~ few % ...
- does this survive if $\mu_F \neq \mu_R$?

Notice that NNLO outside the NLO scale-variation band

Top quark production

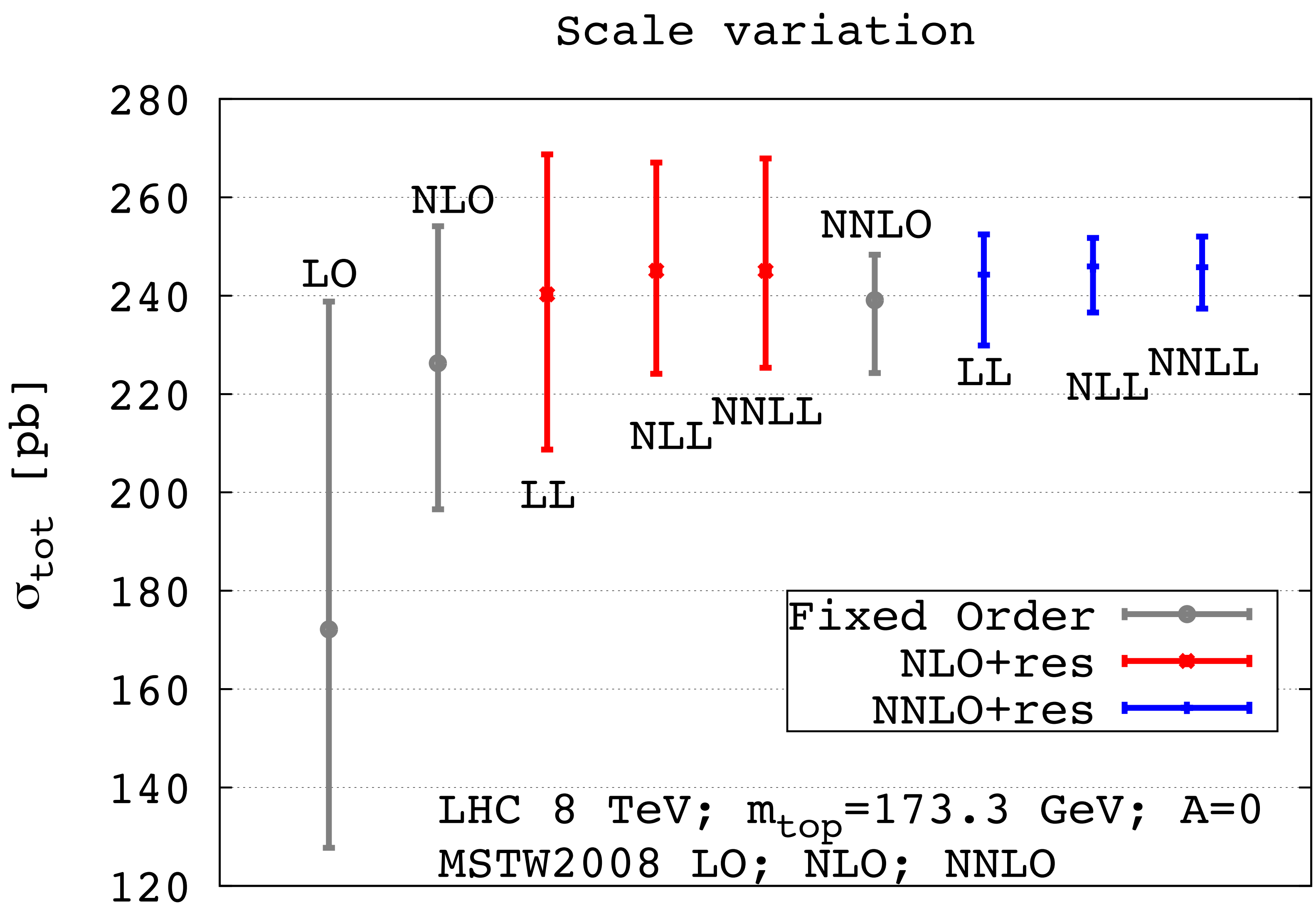
Production dominated by gg initial state up to very large p_T





⇒ sensitive probe of the gluon PDF

Great precision reached with the completion of the NNLO calculation



Independent μ_R , μ_F variation, with $\mu_0 = m_{top}$,
$0.5\ \mu_0 < \mu_{R,F} < 2\ \mu_0$ and
$0.5 < \mu_R / \mu_F < 2$

Baernreuther, Czakon, Mitov arXiv:1204.5201
Czakon, Mitov arXiv:1207.0236
Czakon, Mitov arXiv:1210.6832
Czakon, Fiedler, Mitov arXiv:1303.6254

Phenomenological study of ttbar production at NNLO

M. Czakon, M. Mangano, A. Mitov, J. Rojo arXiv:1303.7215

LHC 8 TeV						
PDF set	σ_{tt} (pb)	$\delta_{\rm scale}$ (pb)	$\delta_{\rm PDF}$ (pb)	δ_{α_s} (pb)	δ_{m_t} (pb)	$\delta_{\rm tot}$ (pb)
ABM11	198.6	$^{+5.0}_{-6.2}$ $^{(+2.5\%)}_{(-3.1\%)}$	$^{+8.5}_{-8.5}$ $^{(+4.3\%)}_{(-4.3\%)}$	$^{+0.0}_{-0.0}$ $^{(+0.0\%)}_{(-0.0\%)}$	$^{+6.1}_{-5.9}$ $^{(+3.1\%)}_{(-3.0\%)}$	$^{+15.5}_{-16.6}$ $^{(+7.8\%)}_{(-8.4\%)}$
CT10	246.3	$^{+6.4}_{-8.6}$ $^{(+2.6\%)}_{(-3.5\%)}$	$^{+10.1}_{-8.2}$ $^{(+4.1\%)}_{(-3.3\%)}$	$^{+4.9}_{-4.9}$ $^{(+2.0\%)}_{(-2.0\%)}$	$^{+7.4}_{-7.1}$ $^{(+3.0\%)}_{(-2.9\%)}$	$^{+19.8}_{-20.5}$ $^{(+8.1\%)}_{(-8.3\%)}$
HERA1.5	252.7	$^{+6.5}_{-5.9}$ $^{(+2.6\%)}_{(-2.3\%)}$	$^{+5.4}_{-8.6}$ $^{(+2.1\%)}_{(-3.4\%)}$	$^{+4.0}_{-4.0}$ $^{(+1.6\%)}_{(-1.6\%)}$	$^{+7.5}_{-7.3}$ $^{(+3.0\%)}_{(-2.9\%)}$	$^{+16.6}_{-17.8}$ $^{(+6.6\%)}_{(-7.1\%)}$
MSTW08	245.8	$^{+6.2}_{-8.4}$ $^{(+2.5\%)}_{(-3.4\%)}$	$^{+6.2}_{-6.2}$ $^{(+2.5\%)}_{(-2.5\%)}$	$^{+4.0}_{-4.0}$ $^{(+1.6\%)}_{(-1.6\%)}$	$^{+7.4}_{-7.1}$ $^{(+3.0\%)}_{(-2.9\%)}$	$^{+16.6}_{-18.7}$ $^{(+6.8\%)}_{(-7.6\%)}$
NNPDF2.3	248.1	$^{+6.4}_{-8.7}$ $^{(+2.6\%)}_{(-3.5\%)}$	$^{+6.6}_{-6.6}$ $^{(+2.7\%)}_{(-2.7\%)}$	$^{+3.7}_{-3.7}$ $^{(+1.5\%)}_{(-1.5\%)}$	$^{+7.5}_{-7.2}$ $^{(+3.0\%)}_{(-2.9\%)}$	$^{+17.1}_{-19.1}$ $^{(+6.9\%)}_{(-7.7\%)}$
ATLAS	241.0					$\pm$ 32.0 (13.3%)
CMS	227.0					$\pm$ 15.0 (6.6%)

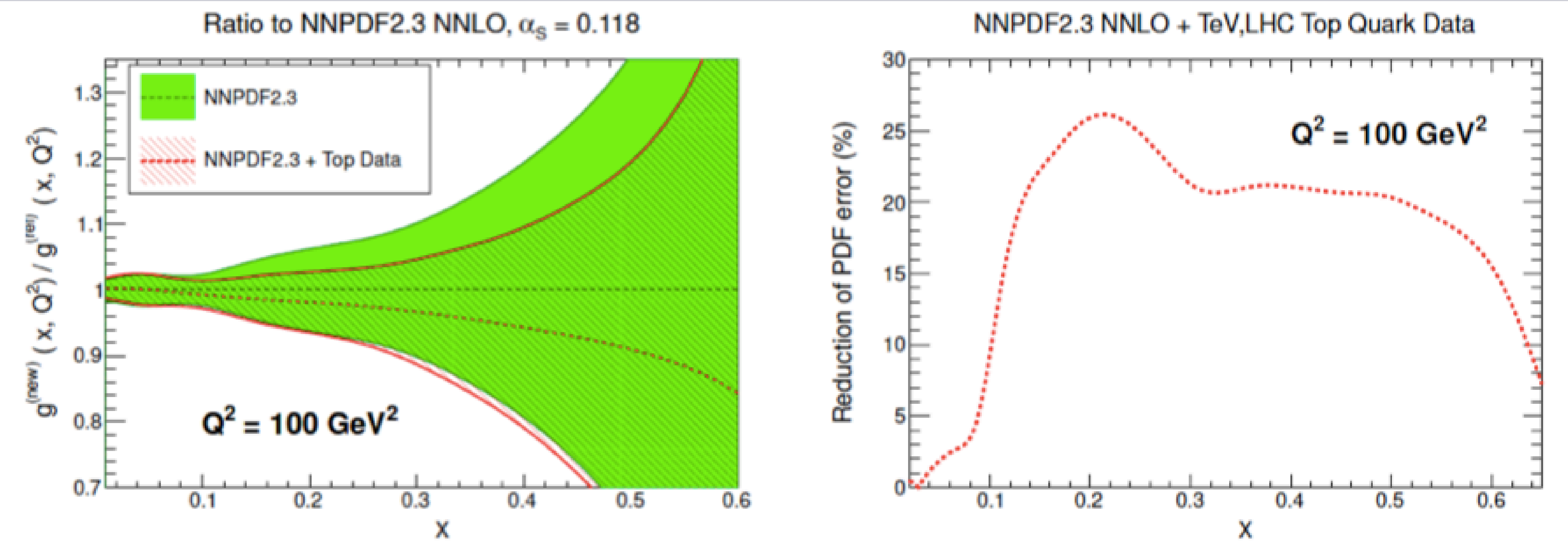
TH and parametric uncertainties are all of similar size:

	scales (i.e. missing yet-higher order corrections)	~ 3%
	pdf (at 68%cl)	~ 2-3%
$\Delta\alpha_S = \pm 0.0007 \Longrightarrow$	alpha$_S$ (parametric)	~ 1.5%
$\Delta m_{top} = \pm 1$ GeV $\Longrightarrow$	m_{top} (parametric)	~ 3%

Constraining the gluon PDF with σ(tt)

M. Czakon et al arXiv:1303.7215

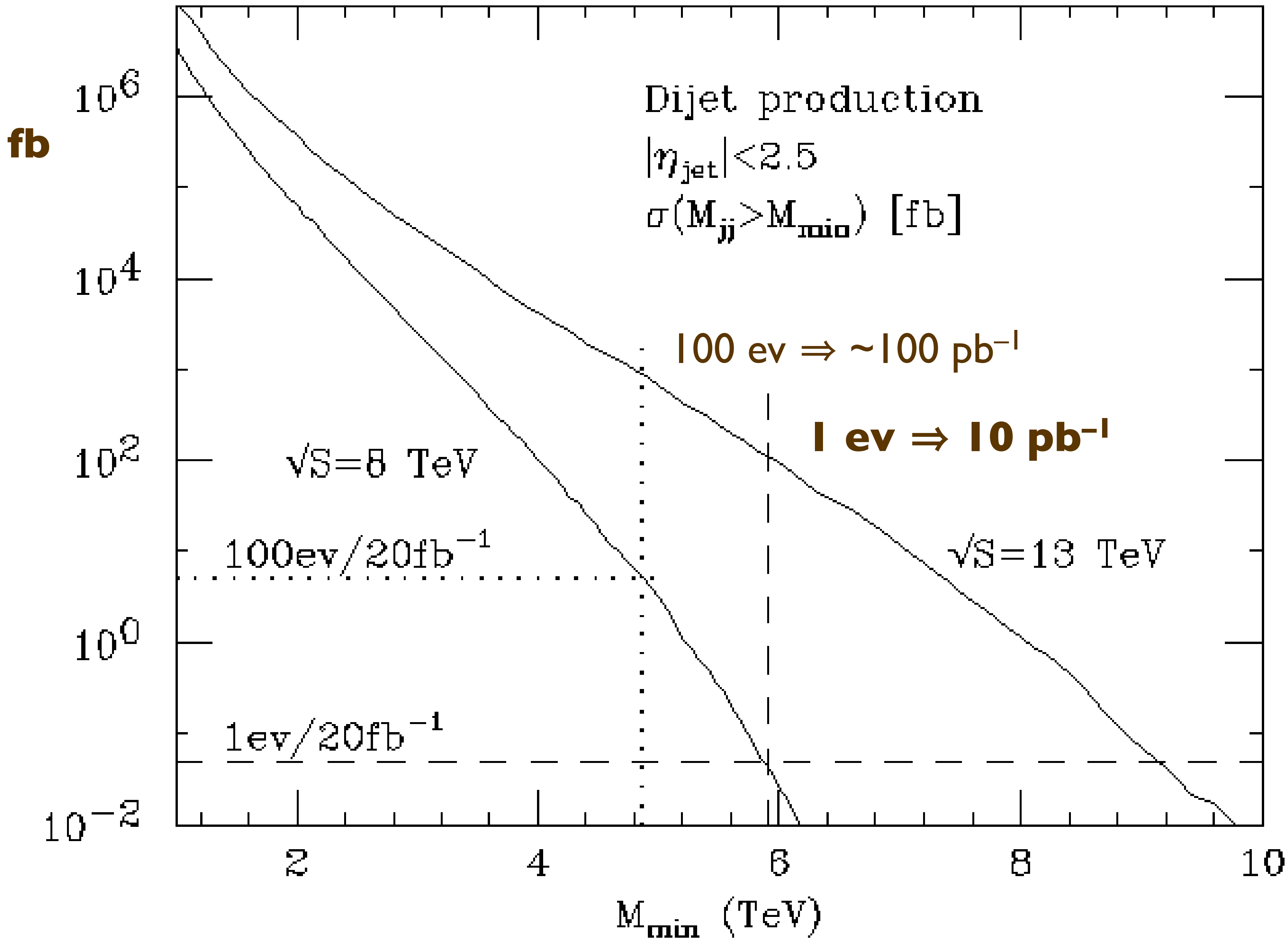
- Top quark cross-section data **discriminates between PDF sets**
- In addition, it can also be used to **reduce the PDF uncertainties** within a single PDF set
- We included the most precise top quark data into the **NNPDF2.3** global PDF analysis



Collider	Ref	Ref+TeV	Ref +TeV+LHC7	Ref+TeV+LHC7+8
Tevatron	7.26 ± 0.12	-	-	-
LHC 7 TeV	172.5 ± 5.2	172.7 ± 5.1	-	-
LHC 8 TeV	247.8 ± 6.6	248.0 ± 6.5	245.0 ± 4.6	-
LHC 14 TeV	976.5 ± 16.4	976.2 ± 16.3	969.8 ± 12.0	969.6 ± 11.6

How long before run 2 extends the discovery reach of run 1?

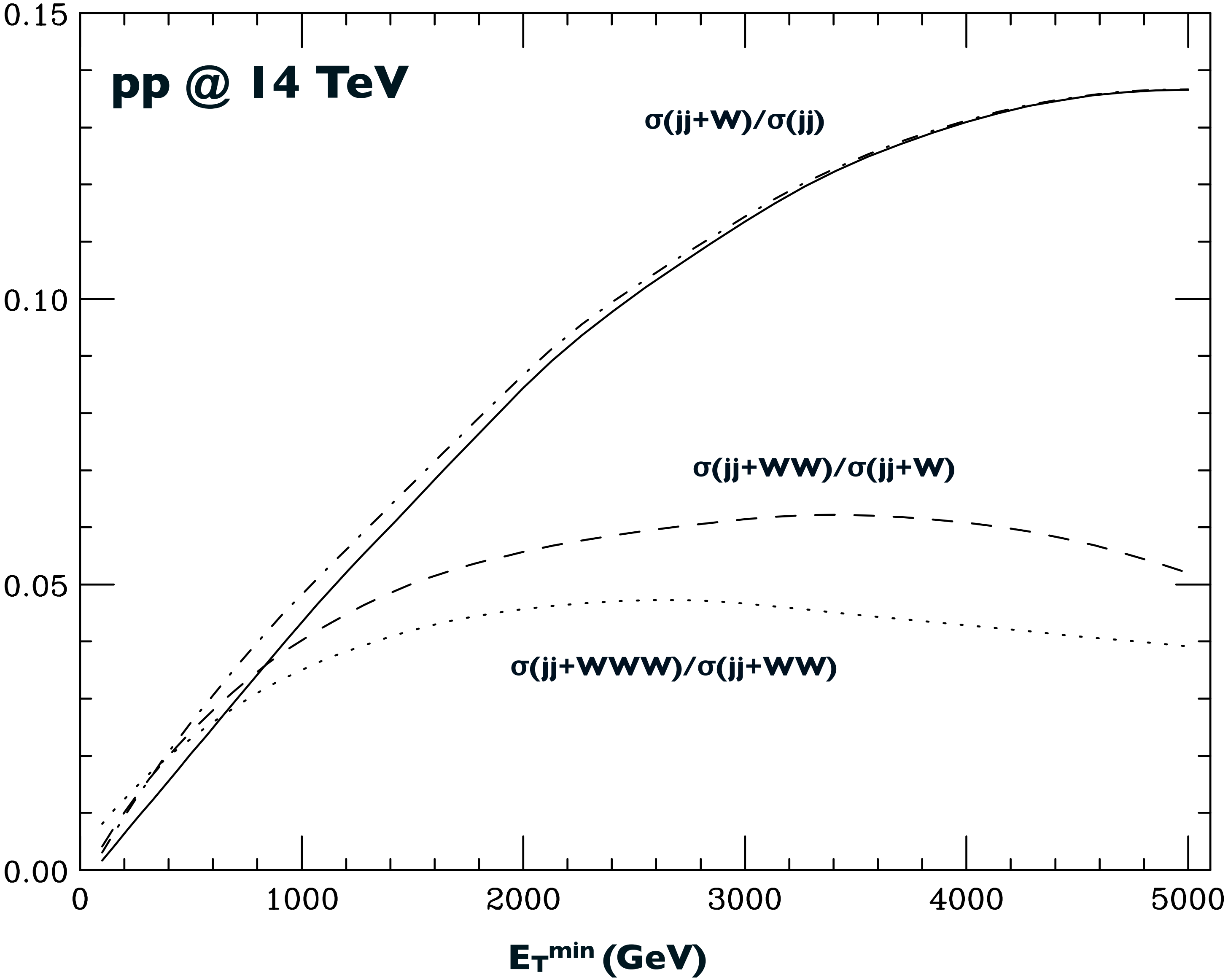
Rate comparison 8 vs 13 TeV: dijet production



Remarks

- Large statistics of jets with E_T in the multi-TeV range =>
  - start measurements of large EW effects

W production in dijet events



$\sigma(jj+W)/\sigma(jj)$

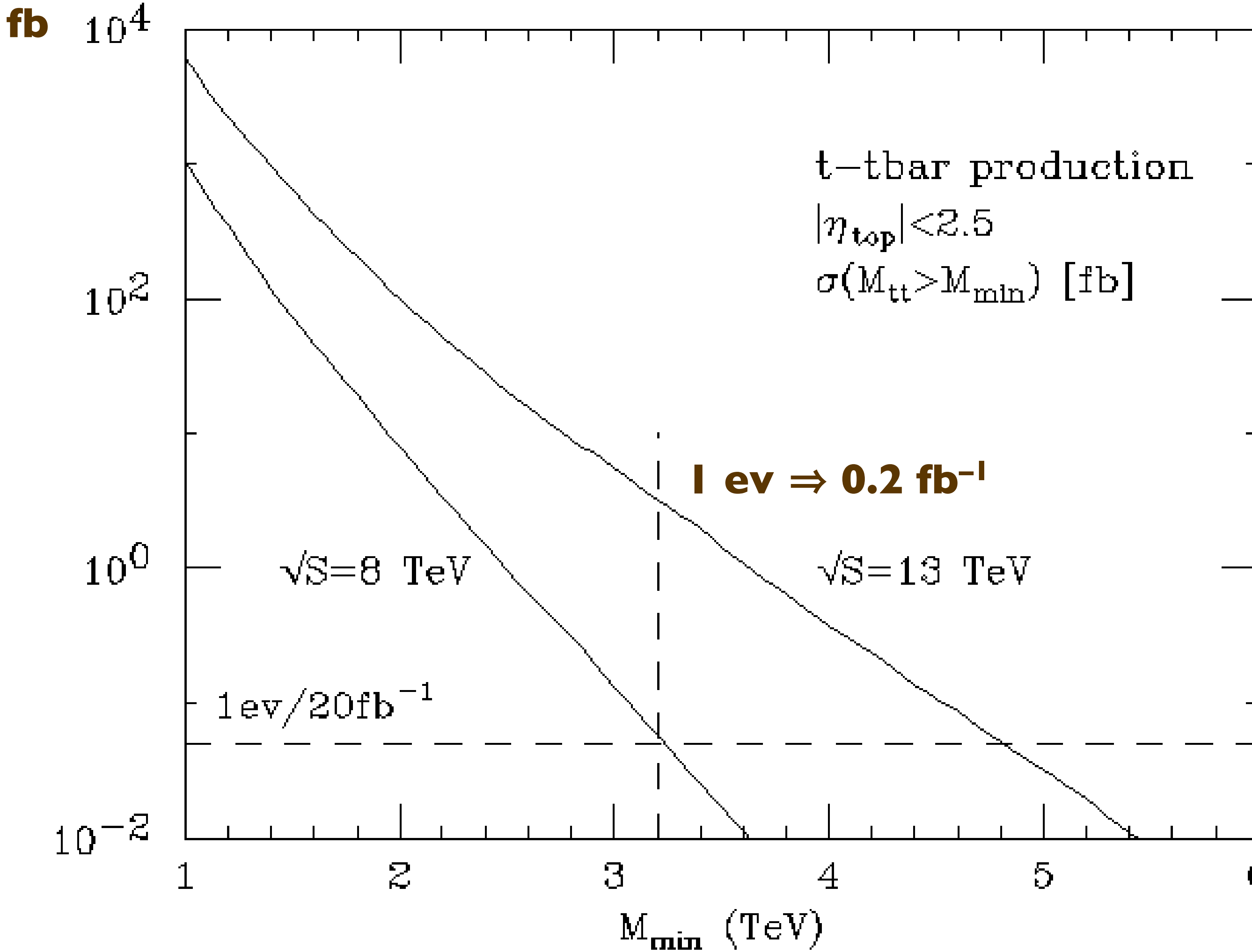
with

$E_{T,\text{leading jet}} > E_T^{min}$

Dotdashes: $\sigma(jj)$ in the denominator replaced by $\sigma(jj, \text{no } gg\rightarrow gg)$

- **Substantial increase of W production at large energy: over 10% of high-ET events have a W or Z in them!**
- **It would be interesting to go after these W and Zs, and verify their emission properties**

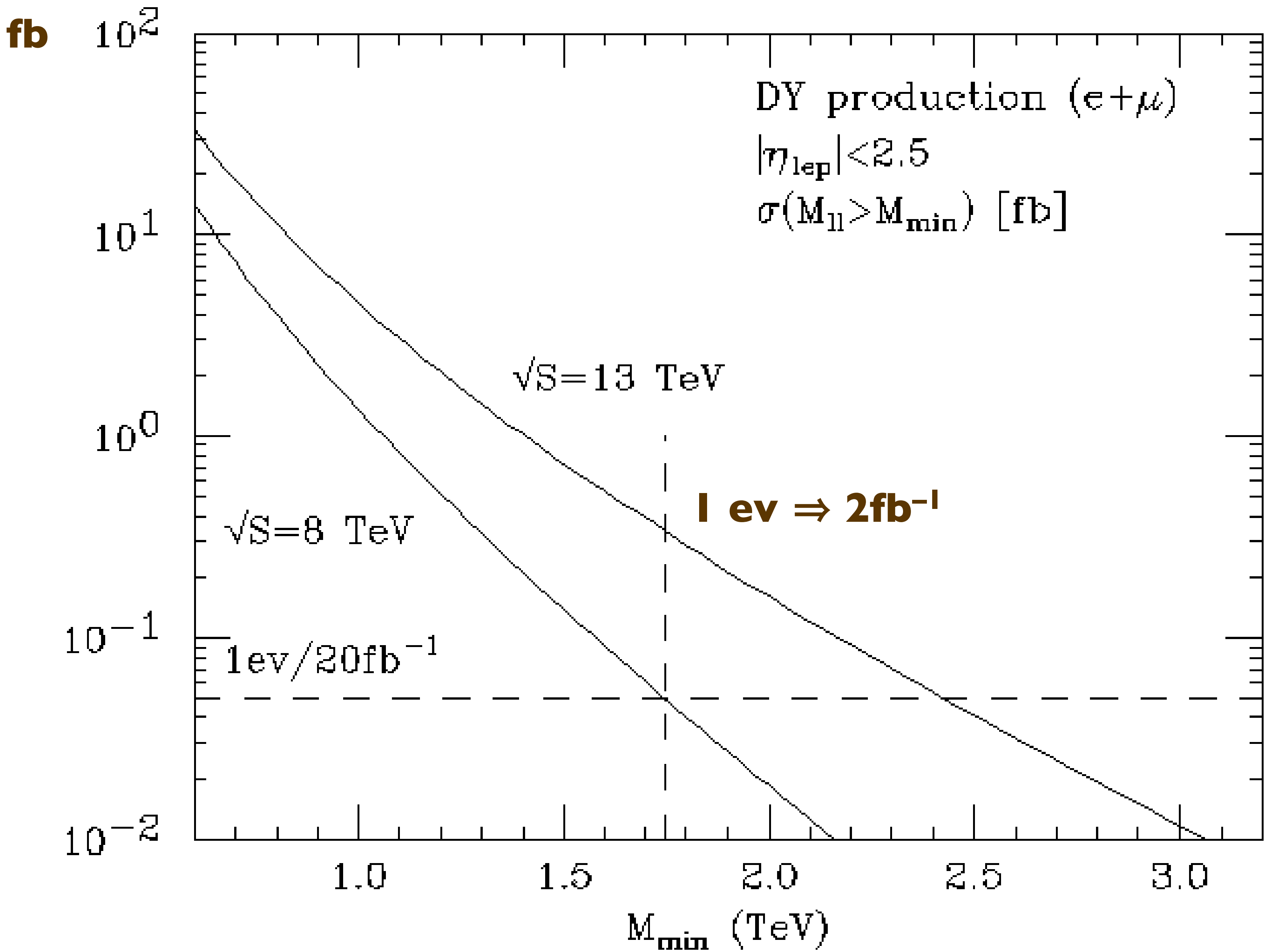
Rate comparison 8 vs 13 TeV: t tbar production



Remarks

- After ~20 fb^{-1} top quark E_T probed above 2-3 TeV =>
  - Lorentz factor γ larger than 10:
    - top jet ~ b jet at LEP !
  - all top decay products within a cone with R<0.1
    - “hyper”-boosted regime for top tagging ...

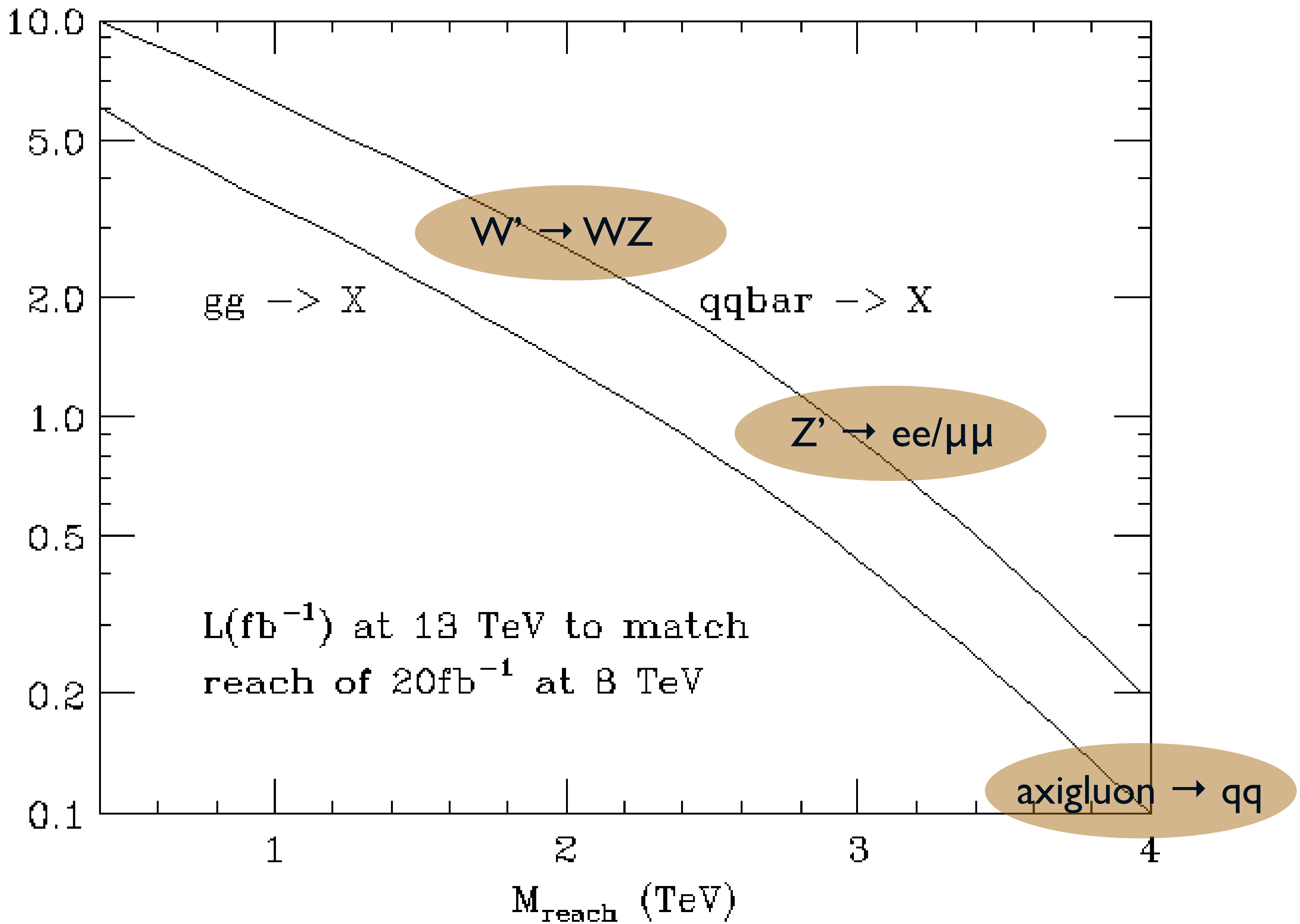
Rate comparison 8 vs 13 TeV: Drell-Yan production



the rule of thumb ....

- The more strongly coupled is a process,
  - ➡ the larger is the mass scale that was explored/constrained during Run 1,
    - ➡ the larger is the cross section gain from 8→13 TeV,
      - ➡ the sooner Run 2 will catch up and extend the search potential

13 TeV luminosity required to match BSM sensitivity reached so far (20fb^{-1}) at 8 TeV



See also http://collider-reach.web.cern.ch, by Salam and Weiler

Observation

- For what concerns the extension of the discovery reach at high mass, nothing in the future of the LHC programme will match the step forward from 20 fb^{-1} at 8 TeV to 100 fb^{-1} at 13 TeV