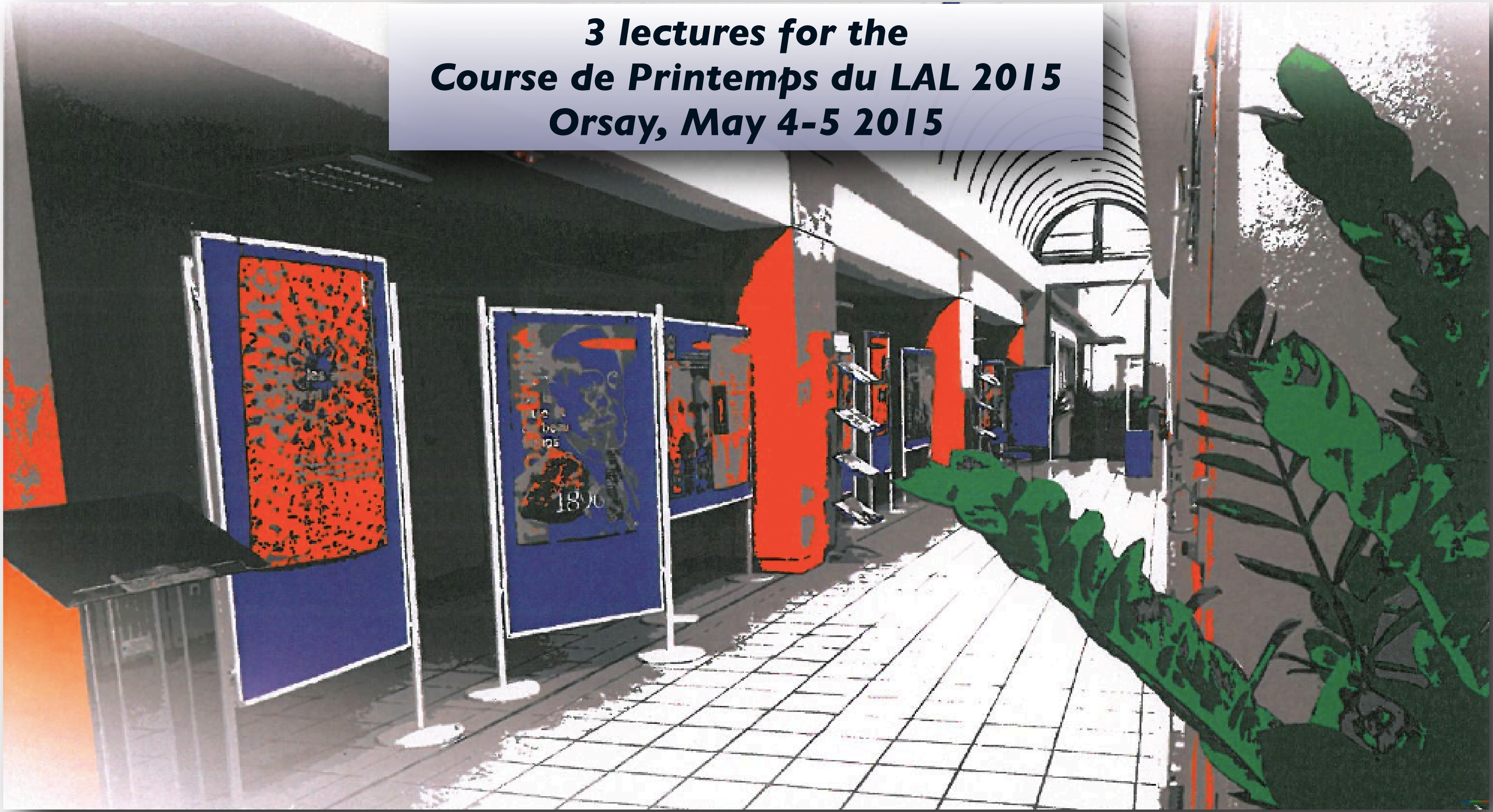
SM and BSM physics after the Higgs discovery



3 lectures for the
Course de Printemps du LAL 2015
Orsay, May 4-5 2015

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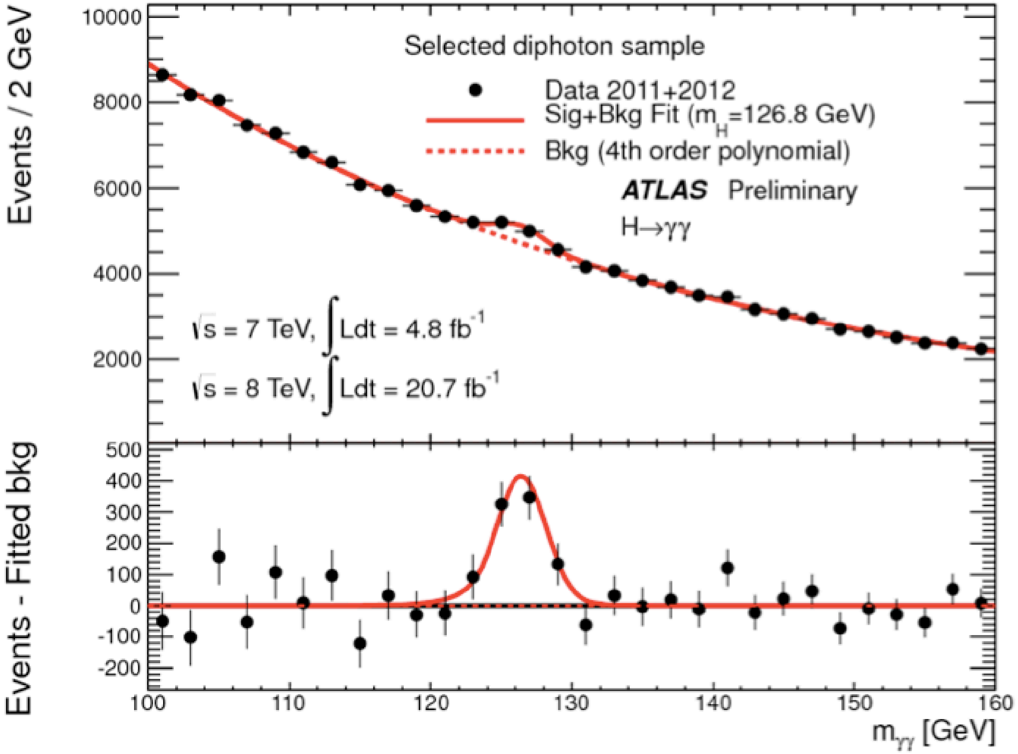
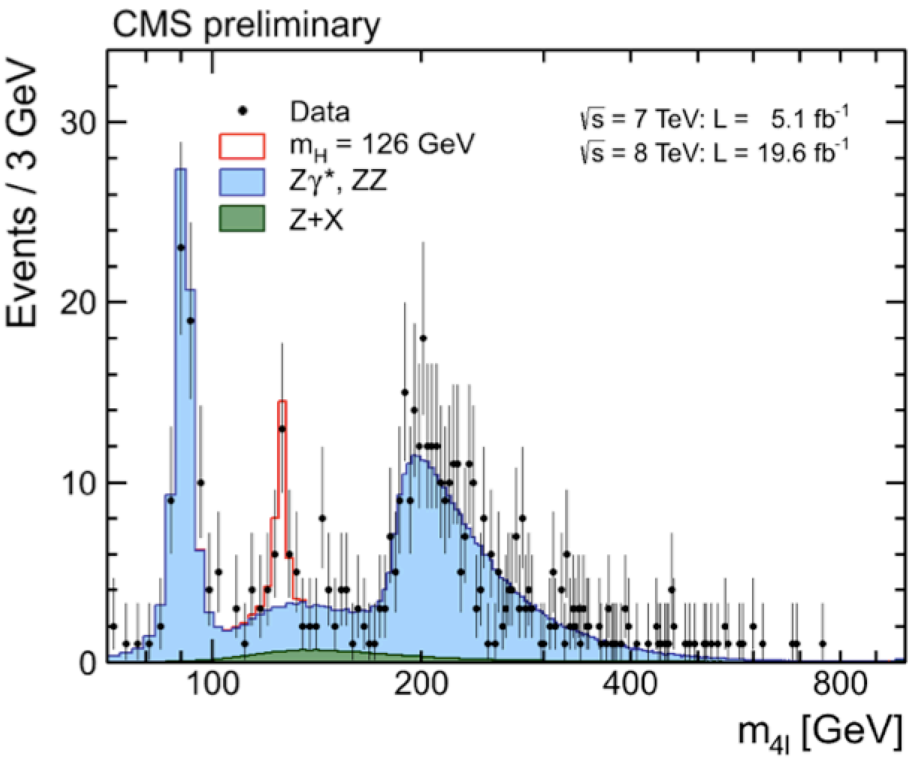
Key outcomes of 3 yrs at the LHC: # one

I: The Higgs signal has been detected through sharp mass peaks in several channels

II: Its production and decay rates are consistent with the SM expectation, at the +/– 20% level .....

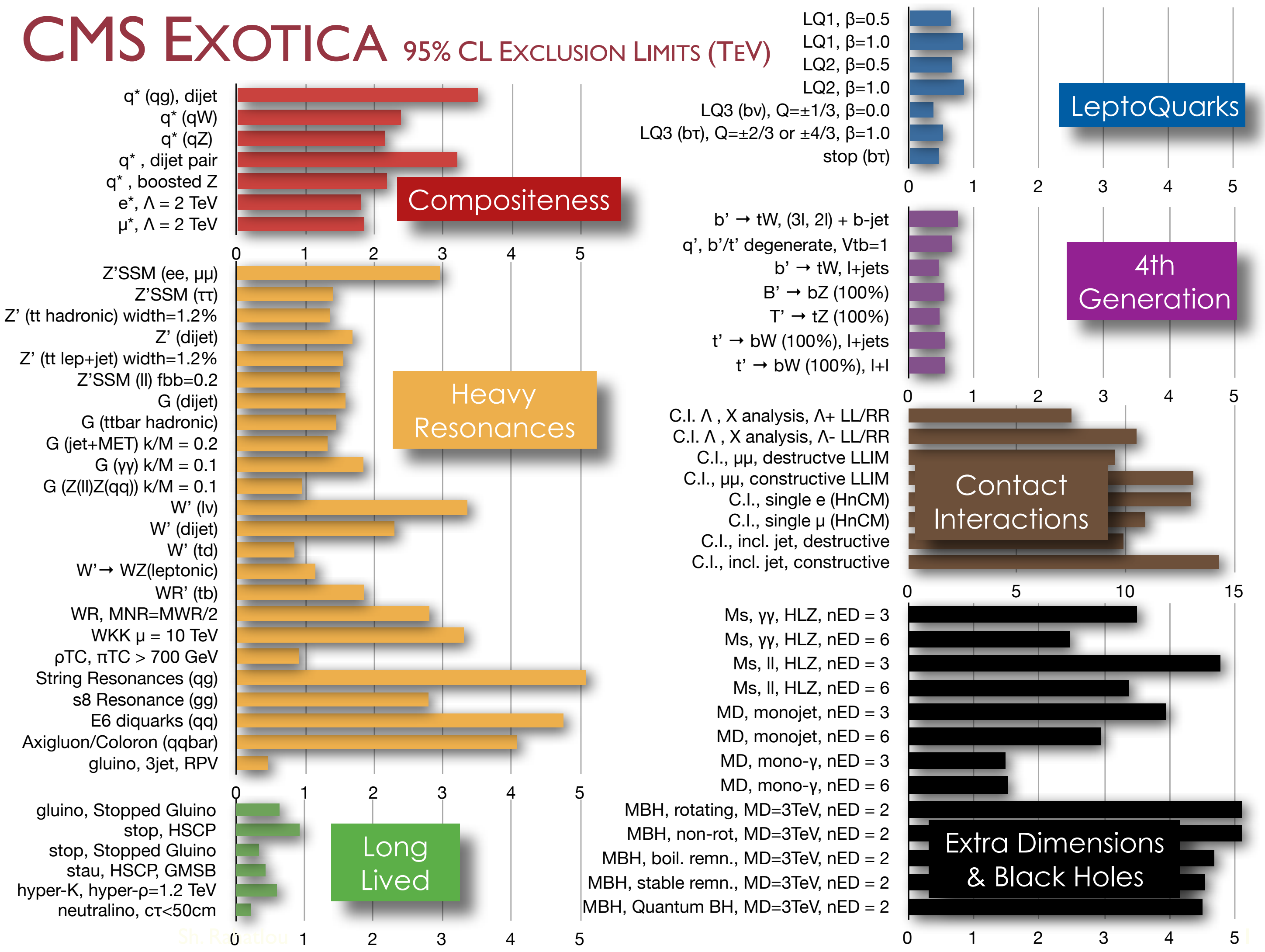




.... How far can we push the accuracy of these tests, and probe the mechanism of EWSB ?

Key outcomes of 3 yrs at the LHC: # two

No sign of BSM, in any of the places the experiments have searched .....

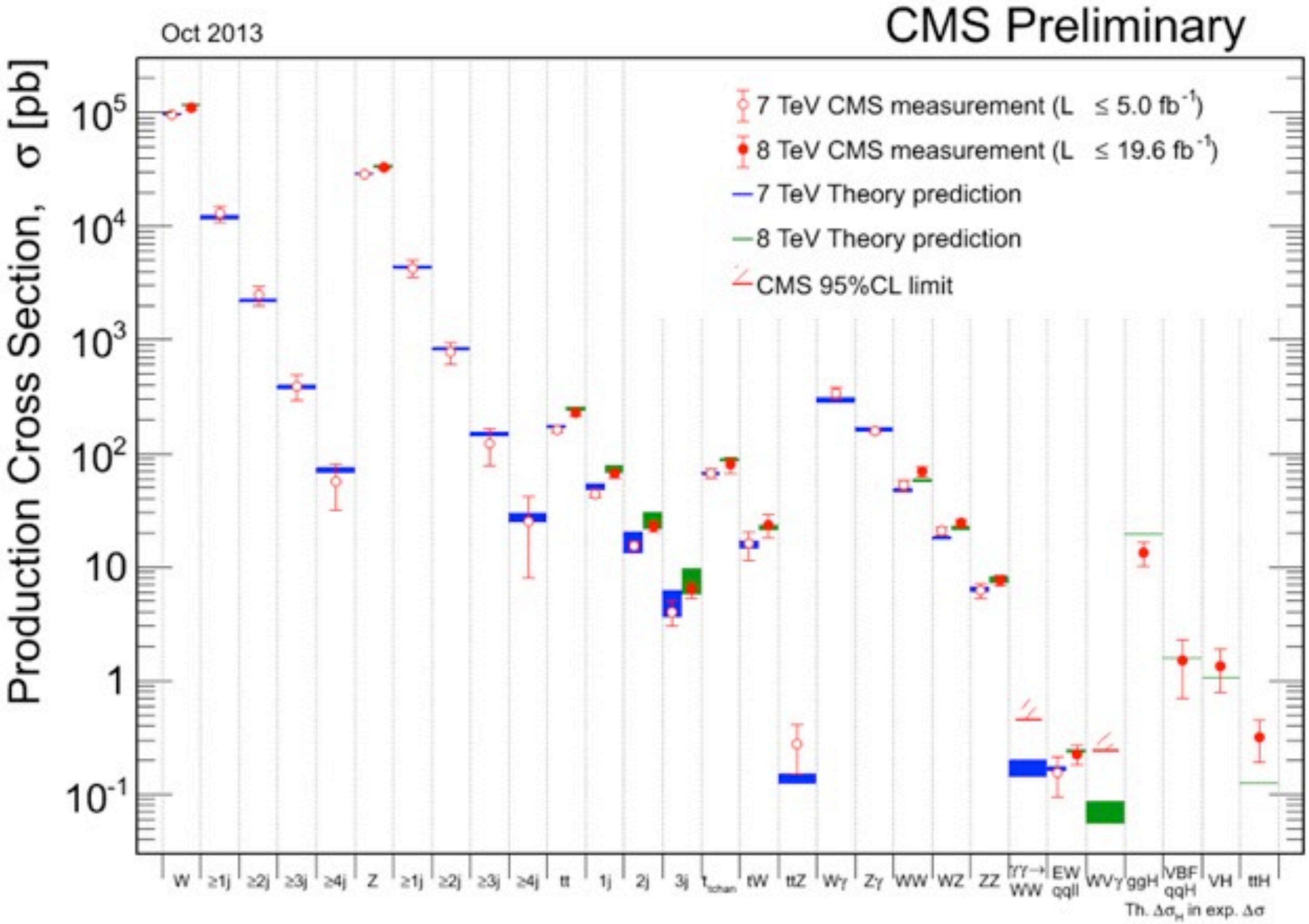


.... Where is everybody (DM, solution to the naturalness problem, sources of CPV, ...) ???

How do we access regions of parameters of BSM models where the search sensitivity is low?

Key outcomes of 3 yrs at the LHC: # three

The theoretical description of high-Q^2 processes at the LHC is very good ....



.... Can "precision" become a discovery tool ?

Status of BSM

- Until few yrs ago, we had a benchmark model, MSSM, expected to deliver the following:
  - low-mass Higgs h^0, no heavier than ~130 GeV
  - ~TeV scale squarks and gluinos, to be seen rapidly at the LHC
    - ⇒ solution to the naturalness problem
  - extra Higgses (A^0 /H^0 /$H^\pm$) observed at the LHC
  - MET signal, candidate for DM, possibly confirmed by direct detection
  - interesting flavour phenomenology
    - explanation of $(g\text{–}2)_\mu$
    - sizable deviations from SM in $B(B_S \to \mu^+ \mu^-)$
    - $\mu \to e\gamma$ observed at MEG, consistent with SUSY neutrino masses induced at the GUT scale
    - CPV in the Higgs or squark/gluino or Higgs sectors, to explain BAU
    - electric dipole moments (e, n) measured, consistent with previous point

- Given our knowledge 4-5 yrs back, all of this could have happened by now.
- Even models alternative to SUSY (extra dim, little Higgs, SILH, ...) had the potential of matching the “natural” predisposition of SUSY to solve problems and to provide rich phenomenological consequences across the fields (LHC, flavour, astro/cosmo)
- **None of the above happened.**
- Thus a radical change in attitude in BSM model building is taking place, focusing on schemes that address individual issues or anomalies, leaving for later the understanding of the “grand picture”
- The above scenario may still happen, with a few-year delay, perhaps stretching a bit the “naturalness”.
- This expectation is still high, and well justified

... in the meantime ...

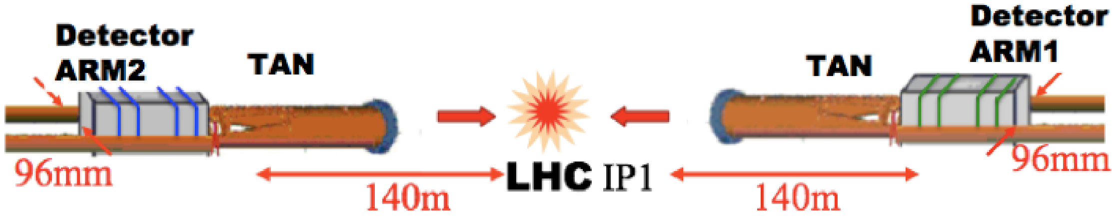
- SM phenomena guarantee a rich, challenging and fruitful pillar for the physics programme of the LHC
- The goals:
  - measurement of fundamental parameters (m_{top}, m_W, $\sin^2\theta_W$, α_S, CKM, Higgs couplings)
  - measurement of "non-Lagrangian" parameters of the SM (e.g. PDFs, heavy hadron spectroscopy, decay rates and properties, etc.)
  - studies of dynamics, particularly in extreme kinematical domains (very high energy) never probed before
    - interesting per se', to test our quantitative description of EW and strong interactions. In particular, of EW interactions at energies well above the EWSB scale
    - relevant to other branches of HEP, e.g. cosmic ray physics
    - validate tools used for precision measurements, and for BSM searches
    - potential to expose deviations induced by BSM effect

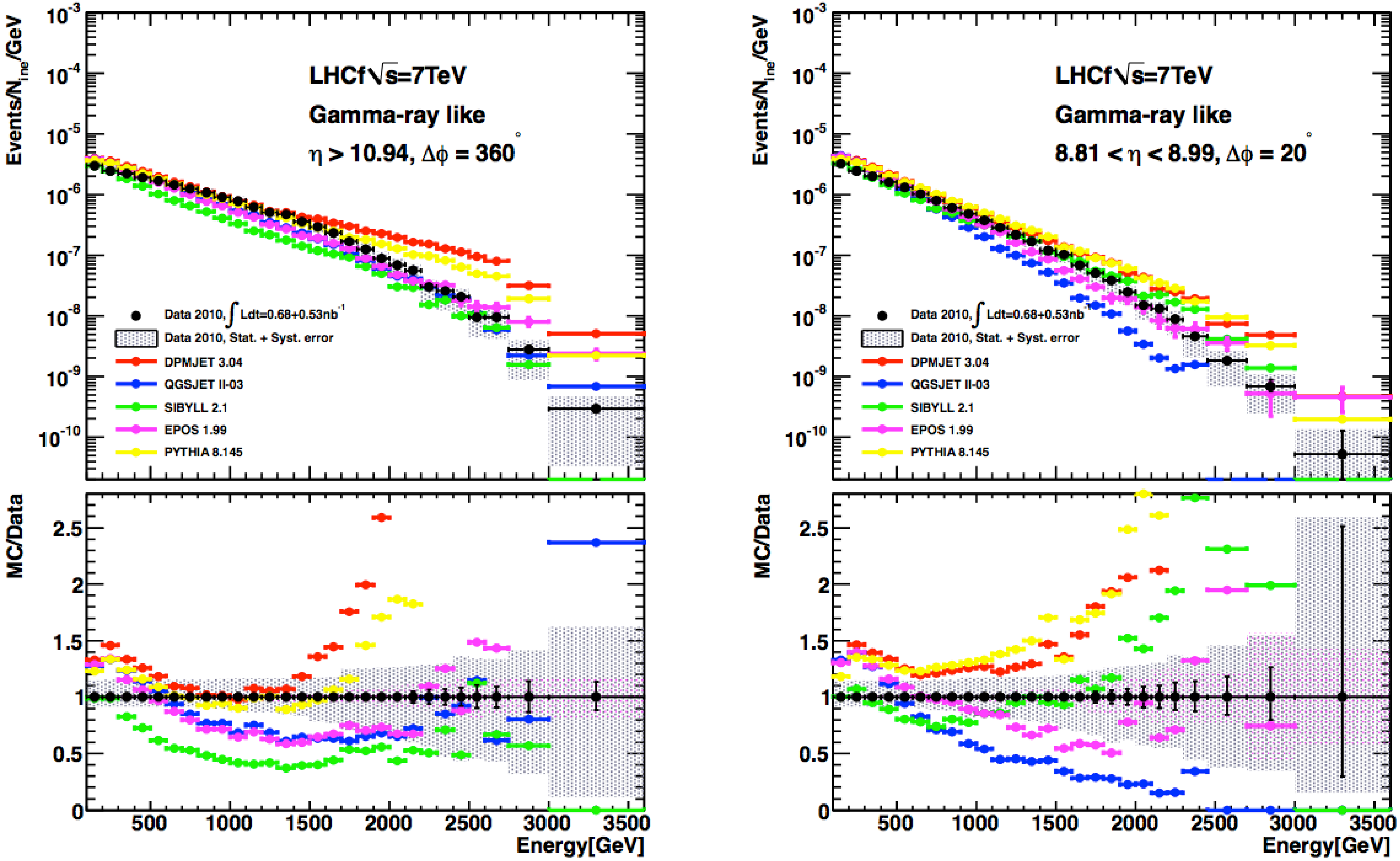
➡ *I will review a selected (limited) collection of SM topics, with emphasis on the challenge of precision*

LHCf: Very forward energy flow

"Measurement of zero degree single photon energy spectra for $\sqrt{s}$ = 7 TeV proton-proton collisions at LHC"

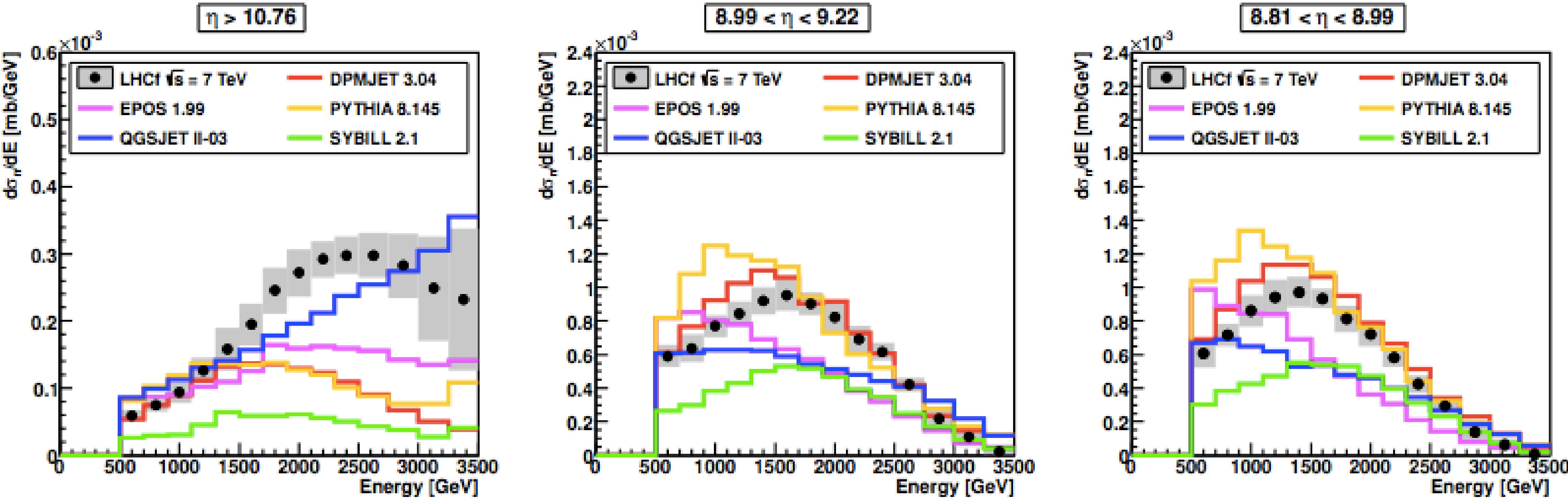
PLB 703 (2011) 128





LHCf: Very forward energy flow

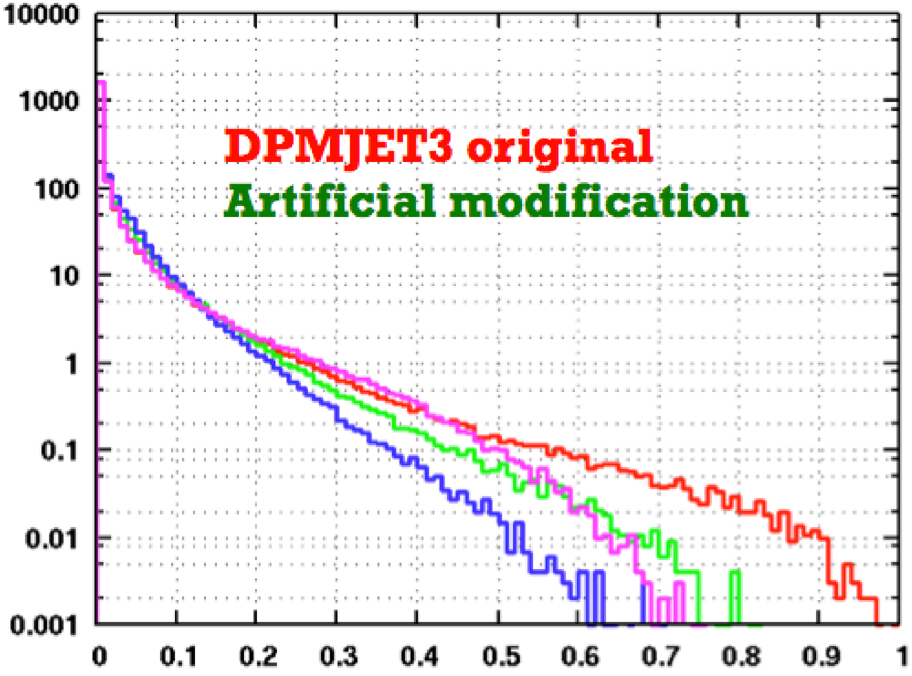
Neutron energy spectra, CERN-PH-EP-2015-056



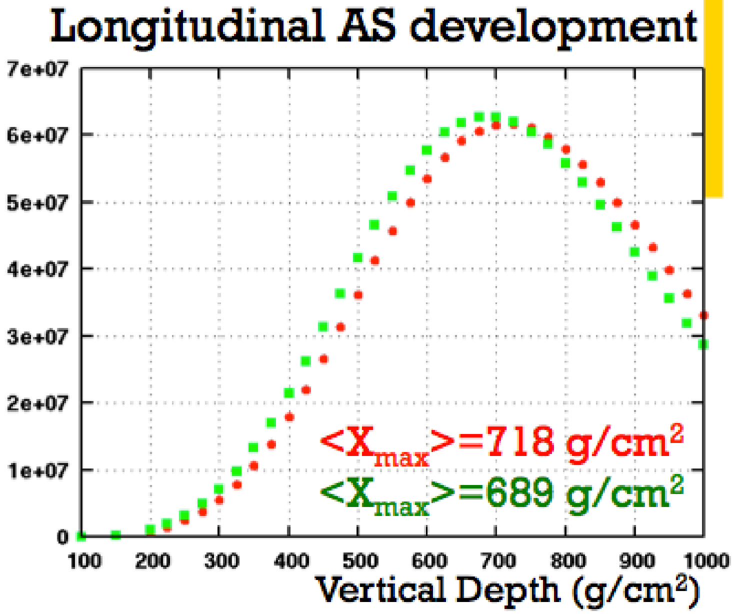
Codes best describing the gamma spectrum give the worst agreement with neutrons, and viceversa ….

Impact on modeling of HECR showers: first assessment

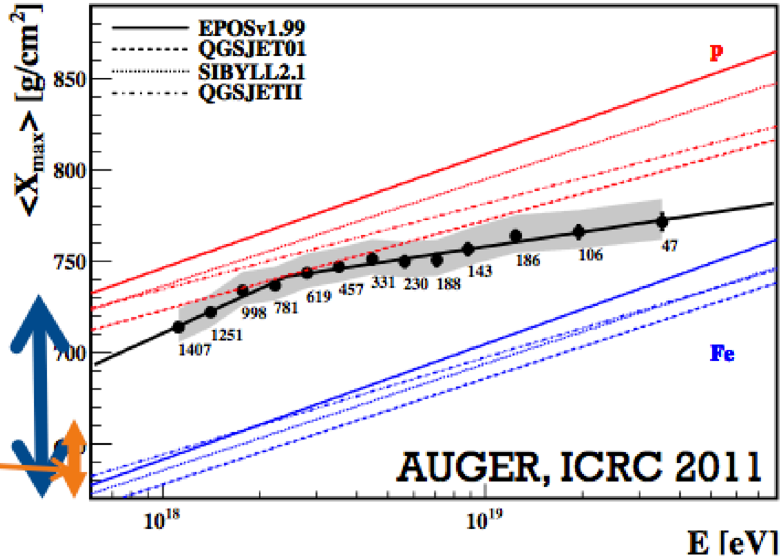
+ π^0 spectrum and air shower



π^0 spectrum at $E_{lab} = 10^{17}$eV

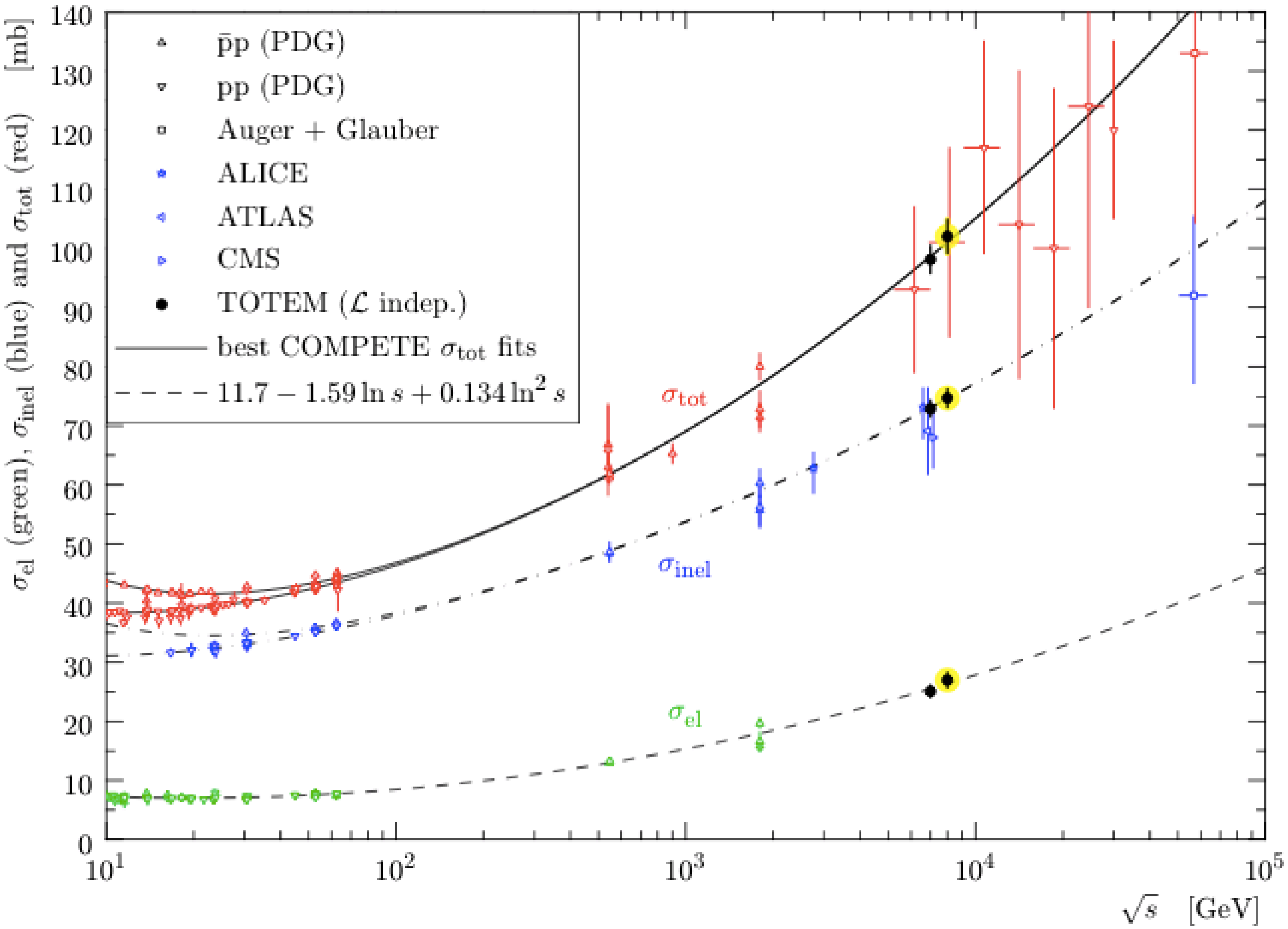


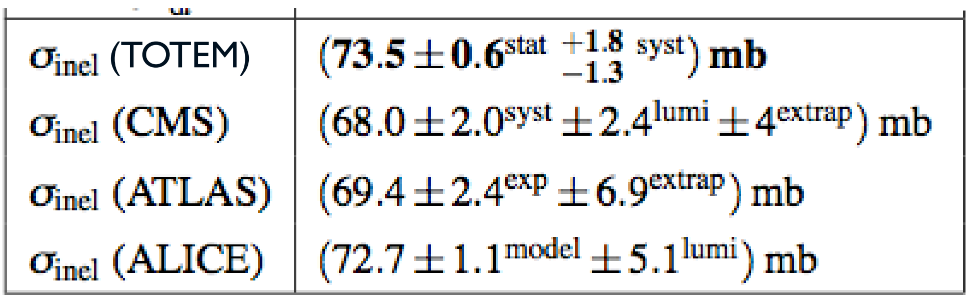
- ✓ Artificial modification of meson spectra (in agreement with differences between models)
- ✓ $\Delta\langle X_{max}(p\text{-}Fe)\rangle \sim 100$ g/cm²
- ✓ Effect to air shower ~ 30 g/cm²



AUGER, ICRC 2011

Elastic, inelastic, total cross sections

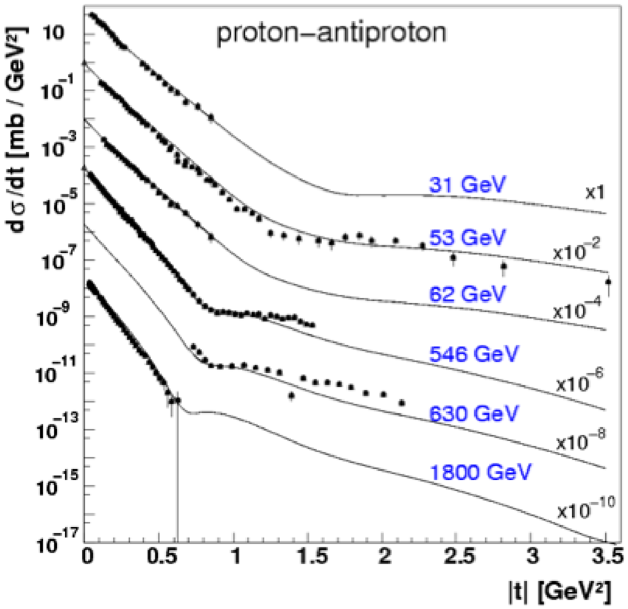


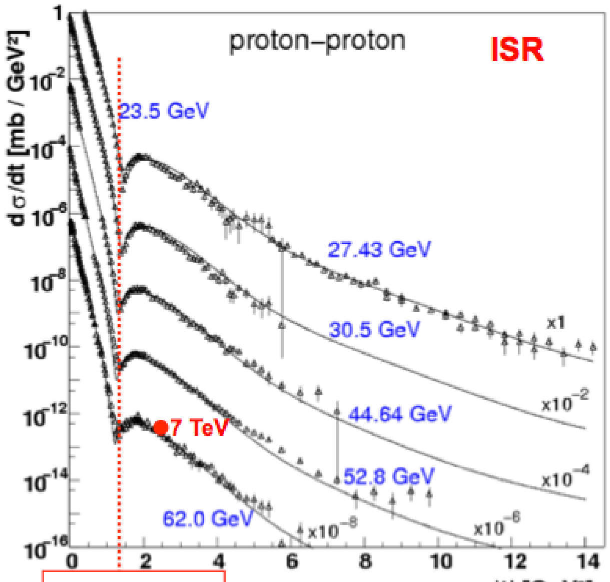


σ_{inel} (TOTEM)	**$(73.5 \pm 0.6^{\mathrm{stat}}\ {}^{+1.8}_{-1.3}\ {}^{\mathrm{syst}})$ mb**
σ_{inel} (CMS)	$(68.0 \pm 2.0^{\mathrm{syst}} \pm 2.4^{\mathrm{lumi}} \pm 4^{\mathrm{extrap}})$ mb
σ_{inel} (ATLAS)	$(69.4 \pm 2.4^{\mathrm{exp}} \pm 6.9^{\mathrm{extrap}})$ mb
σ_{inel} (ALICE)	$(72.7 \pm 1.1^{\mathrm{model}} \pm 5.1^{\mathrm{lumi}})$ mb

Valuable input for modeling of low-mass diffractive events

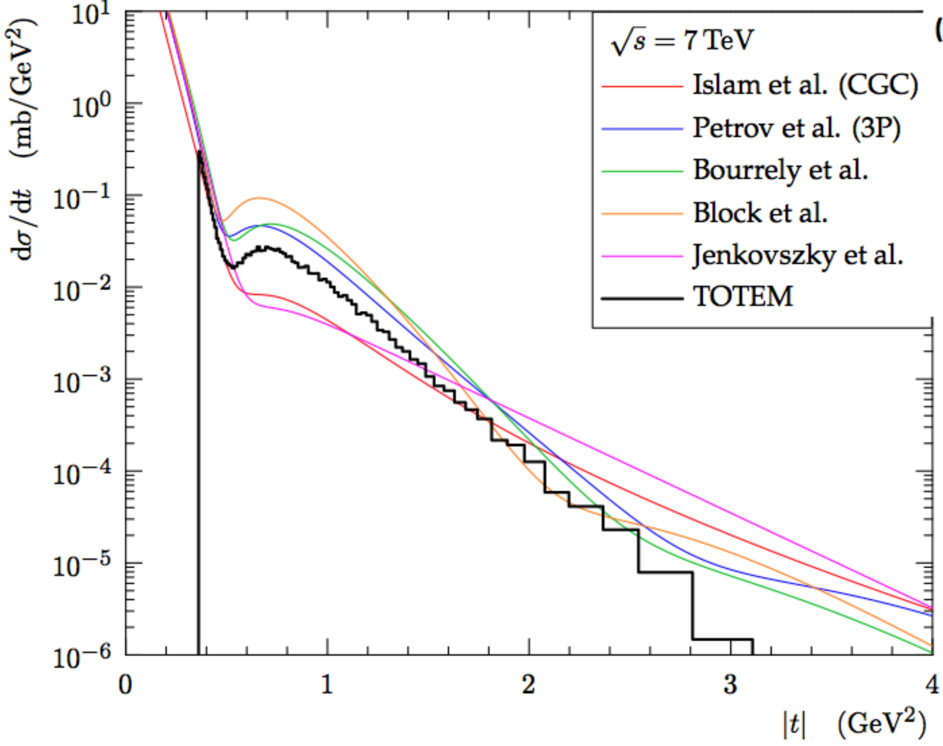
TOTEM: elastic cross section





~1.4 GeV^2

TOTEM: EPL 95 (2011) 41001

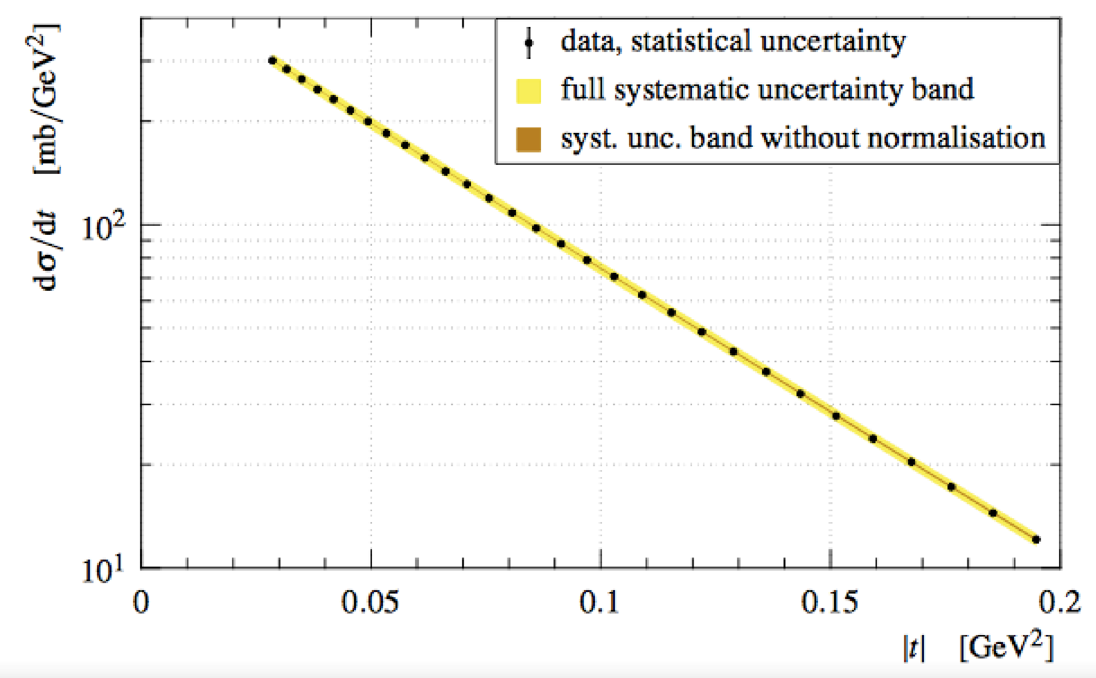


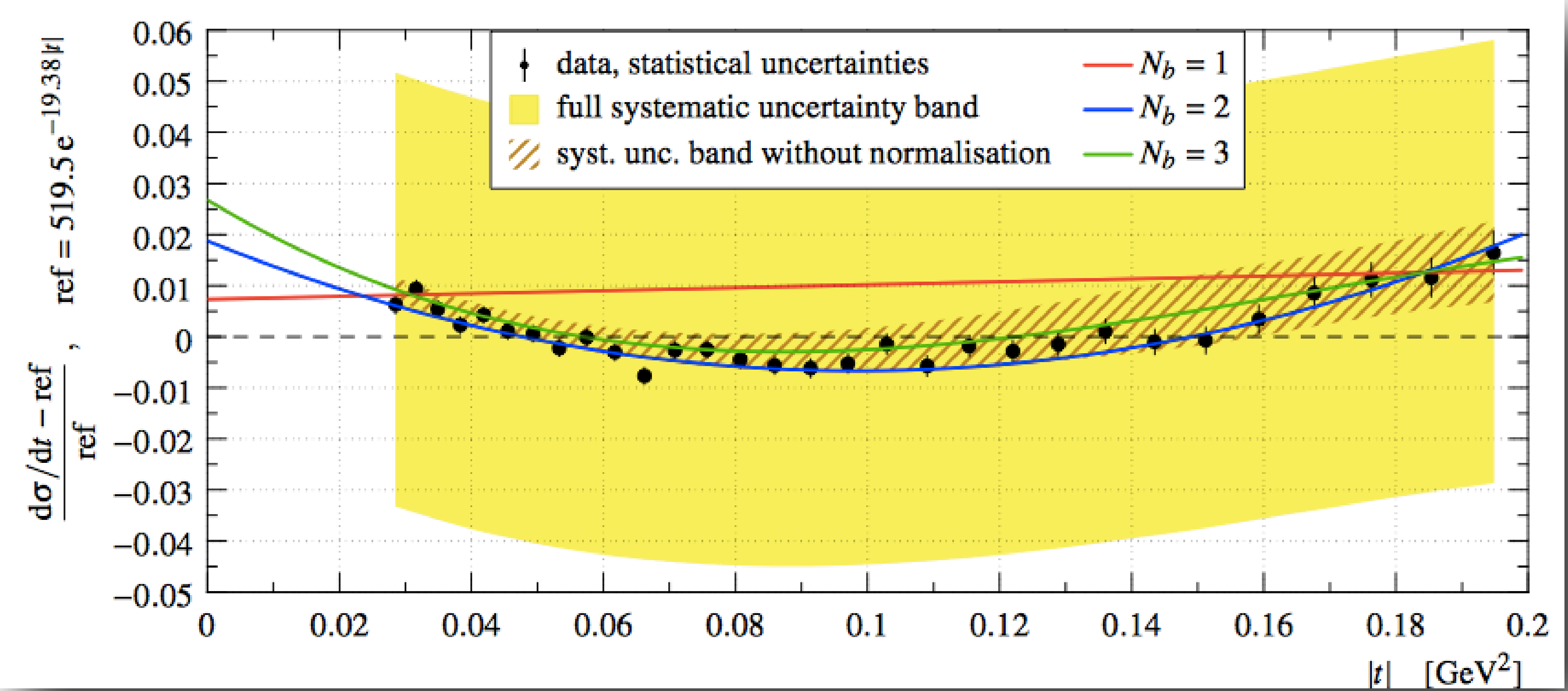
B (t=-0.4 GeV^2)	t_{DIP}	t^{-n} [1.5–2.5 GeV^2]
20.2	0.60	5.0
23.3	**0.51**	**7.0**
22.0	**0.54**	**8.4**
25.3	0.48	10.4
20.1	0.72	4.2
23.6 ± 0.5	0.53 ± 0.01	7.8 ± 0.3

More, available, data will allow to extend the measurement up to O(4-5 GeV^2)

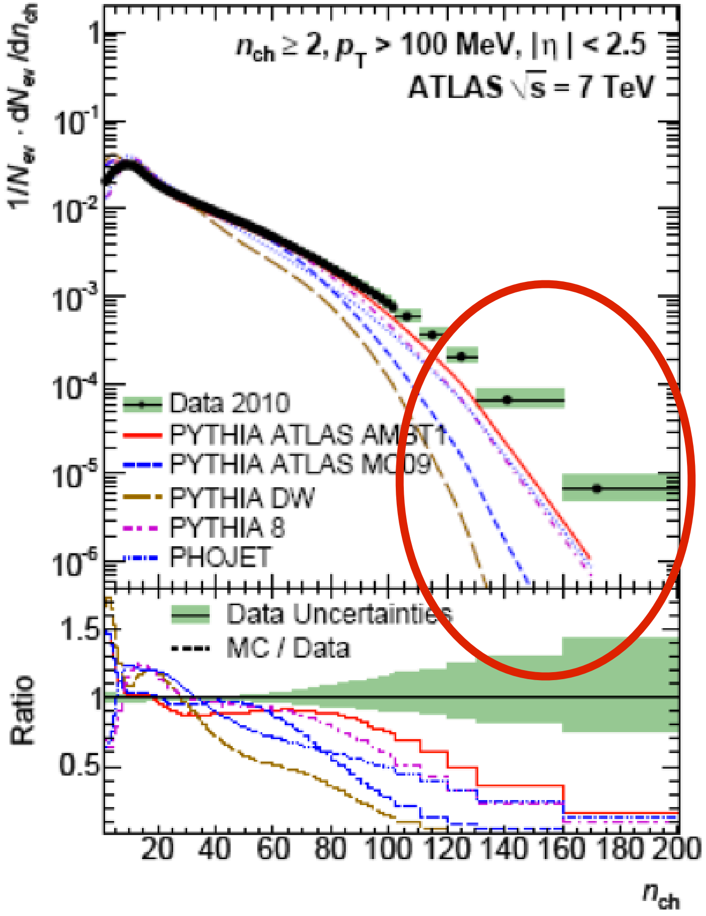
TOTEM: elastic cross section at t→0

Evidence for Non-Exponential Elastic Proton-Proton Differential Cross-Section at Low |t|, arXiv: 1503.08111

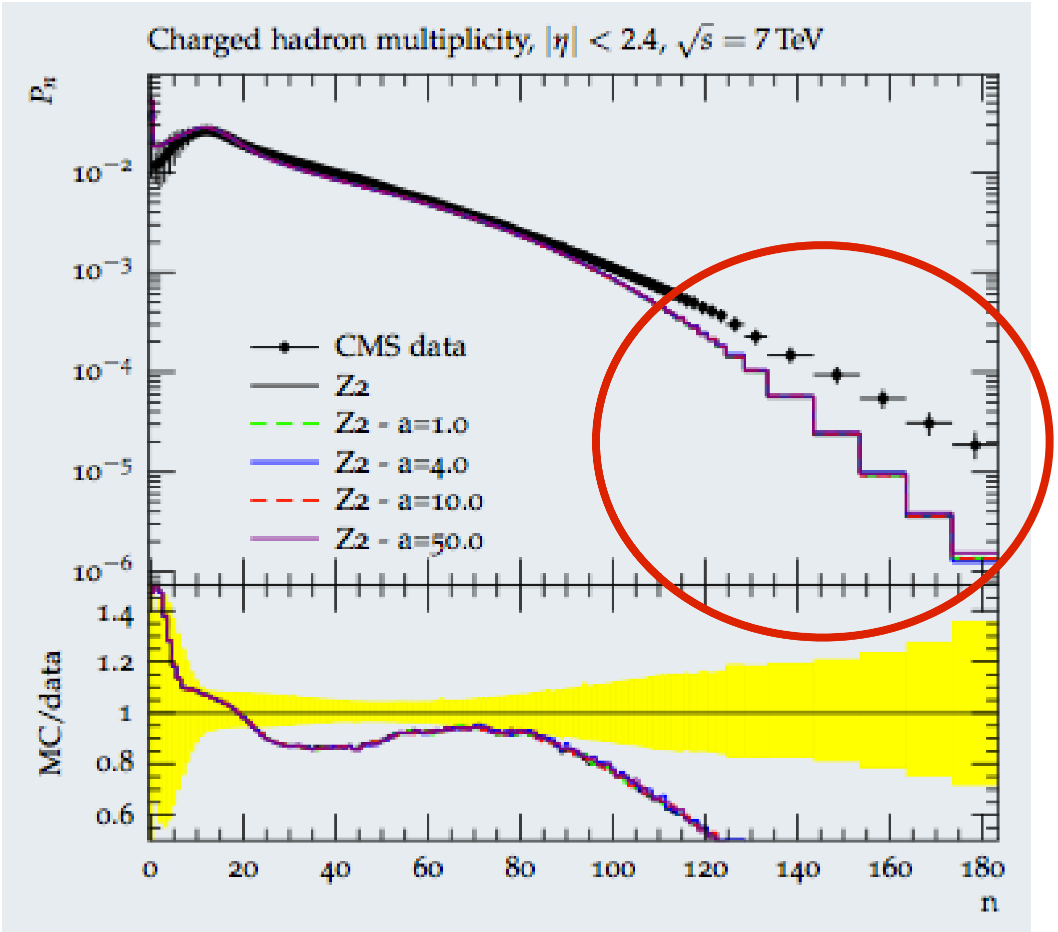




Properties of large-multiplicity final states in “0-bias” events



ATLAS, http://arxiv.org/pdf/1012.5104v2



S.Alderweireldt, MPI-2011

Need a detailed characterization of the structure of large-multiplicity final states:

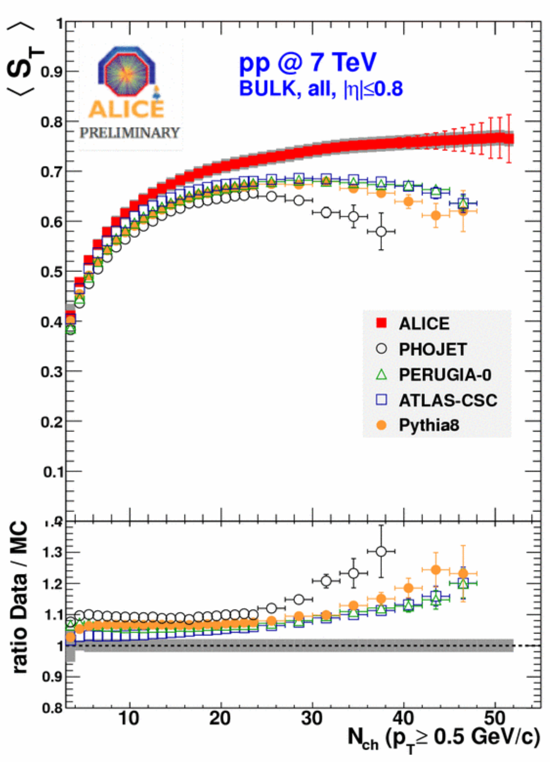
- **are they dominated by 2-jets back to back?**
- **are they dominated by many soft jets (e.g. multiple semi-hard collisions)**
- **do they look “fireball”-like (spherically symmetric)?**
- **does the track-pt spectrum of high-Nch events agree with MCs?**
- **y-distribution of very soft tracks in high-Nch events?**
- **.....**

Are we staring at something *fundamental*, or is this just QCD chemistry and MC-tuning?

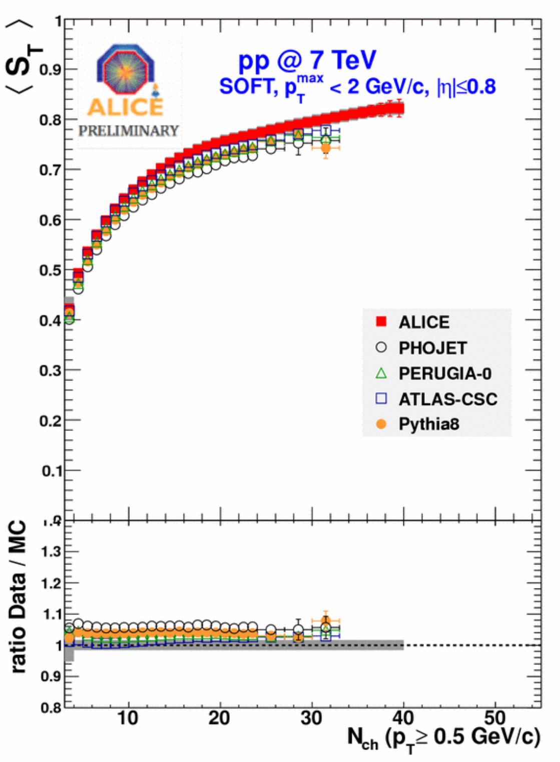
.... see also the CMS ridge effect

Further insight and puzzles on large-N_{ch} events

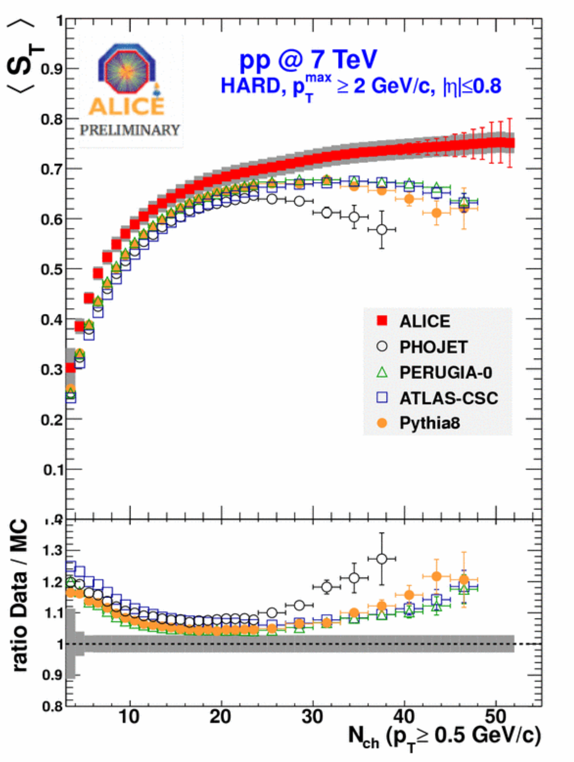
ALICE study of transverse sphericity vs N_{ch} **arXiv:1110.2278**



ALI-PREL-2668



ALI-PREL-2695



ALI-PREL-2677

Events are generically more spherical, less jetty, than MC.

Most of the discrepancy comes however from hard events, not soft ones

Given the smaller rapidity coverage of ALICE, the multiplicities used in this study, with N_{ch} up to ~50, probe final state consistent with those of extreme N_{ch} (>100) measured by ATLAS/CMS in a larger rapidity volume

Open challenge:

To prove that the underlying mechanisms of multiparticle production at high energy are *understood*, in addition to being simply *properly modeled*

High-Q^2 physics

Opportunities opened by LHC data

- High statistics and superior experimental precision
- Access to small rates:
  - rare final states (multijets, associated production of multiple EW and QCD objects)
  - high-energy final states (highest pt jets, highest mass DY, ...)
  - VBF final states
- EW radiative corrections:
  - impact on EW observables (V, VV production - V=W,Z)
  - impact on QCD observables (jet cross sections)
- New probes of PDFs:
  - large-x gluons (jet, top production)
  - heavy quarks (γQ, ZQ, WQ associated production)
- Correlations:
  - ratios of cross sections for different processes
  - ratios of cross sections at 7 vs 8 vs 14 TeV

Current challenges for the field: precision

Example: Theoretical uncertainties on production rates (Higgs XS WG, arXiv:1101.0593)

14 TeV	δ(pert. theory)	δ(PDF, α_S)
gg→H	± 10 %	± 7%
VBF (WW→H)	± 1 %	± 2%
qq→WH	± 0.5 %	± 4%
(qq,gg)→ZH	± 2 %	± 4%
(qq,gg)→ttH	± 8 %	± 9%

Improve with higher-loop calculations:
gg->H @ NNNLO **
ttH @ NNLO

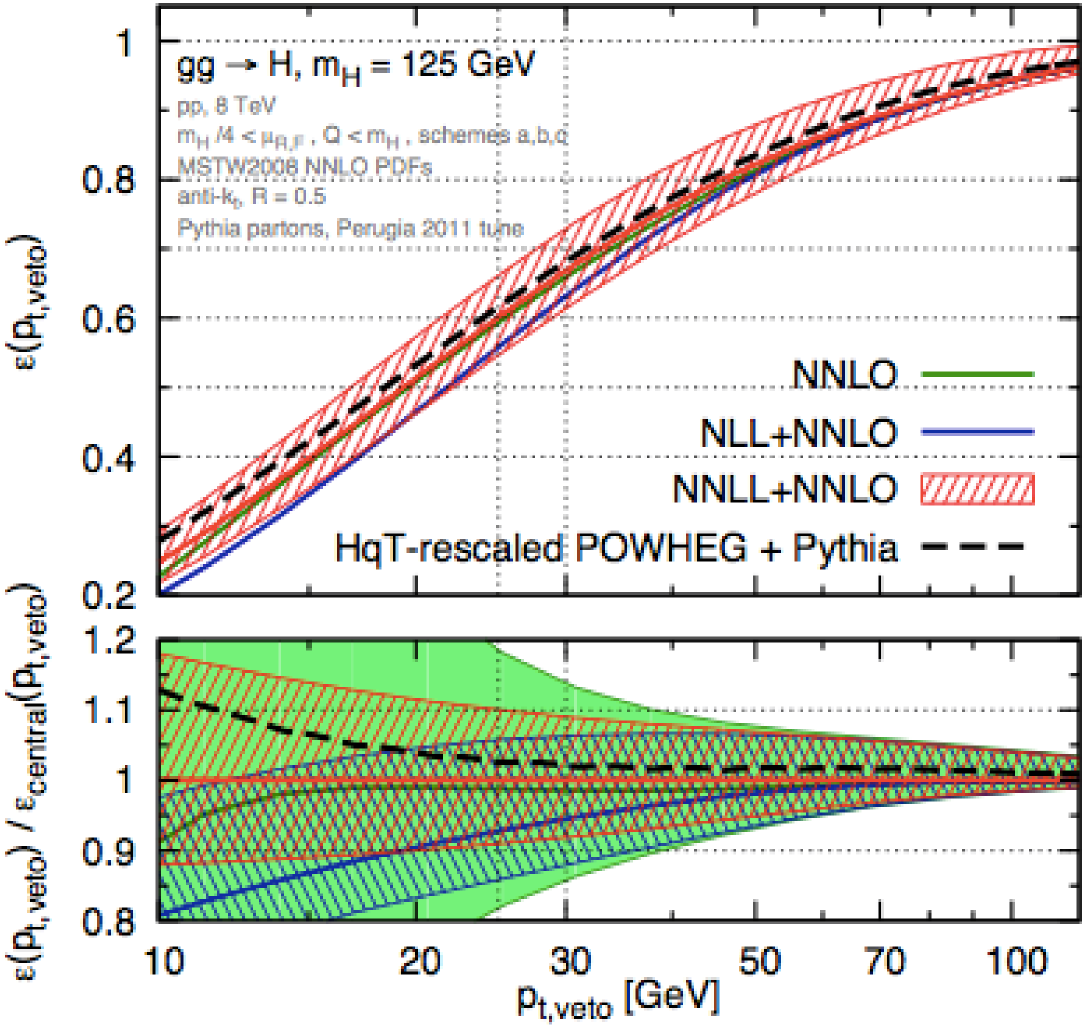
Improve with dedicated QCD measurements, and appropriate calculations

**** NNNLO gg->H recently completed (see later) ⇒ δ(pert. theory)~3%**

Anastasiou, Duhr, Dulat, Herzog, Mistlberger, arXiv:1503.06056

Current challenges for the field: accurate description of final states

- **to properly model experimental selection cuts**
- **to properly model the separation between signals and background**
- **to improve the sensitivity to rare and “stealthy” final states in BSM searches**

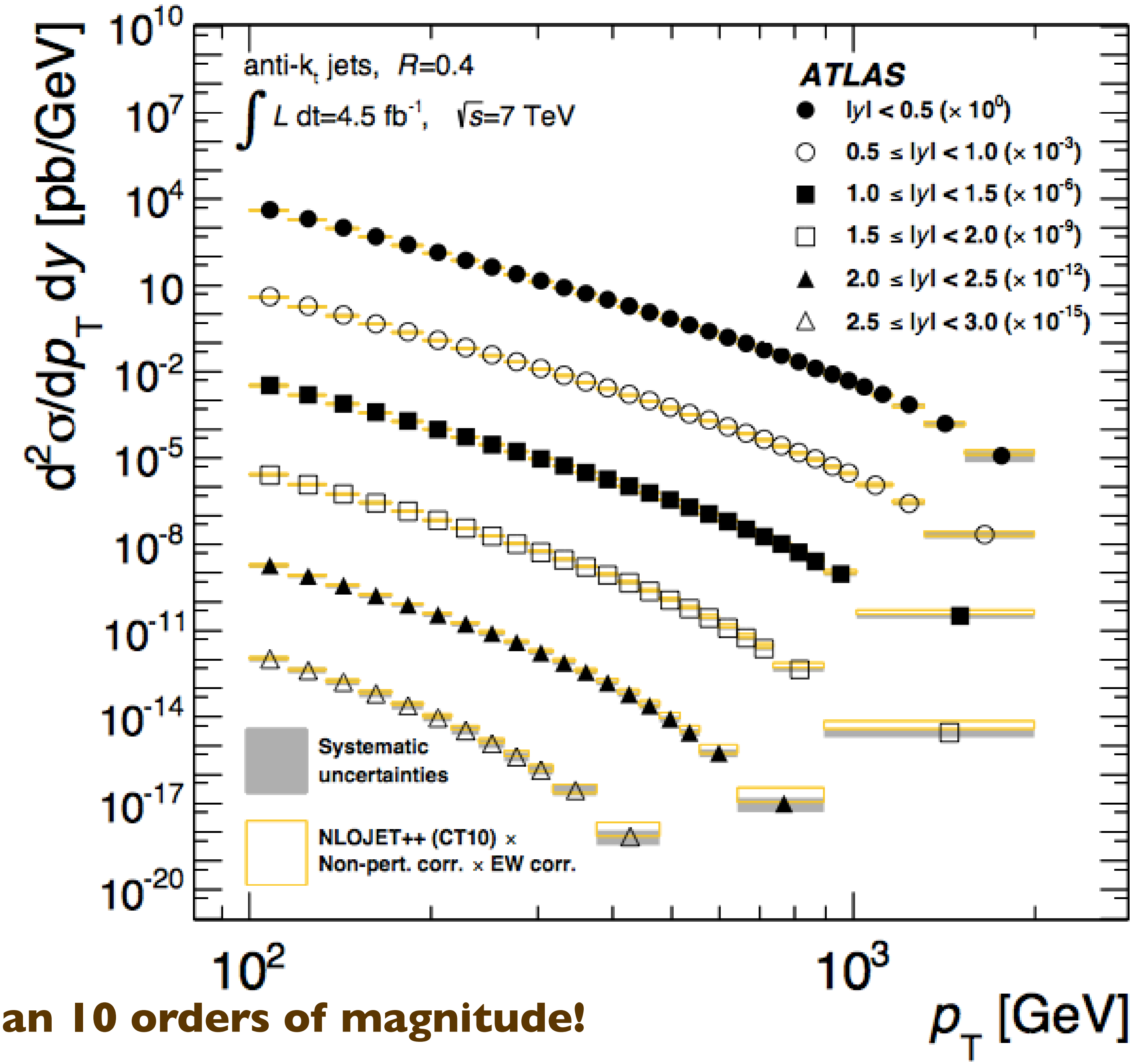


Ex. jet veto efficiency, required to reduce bg’s to H→WW*

Banfi, Monni, Salam, Zanderighi, arXiv:1206.4998

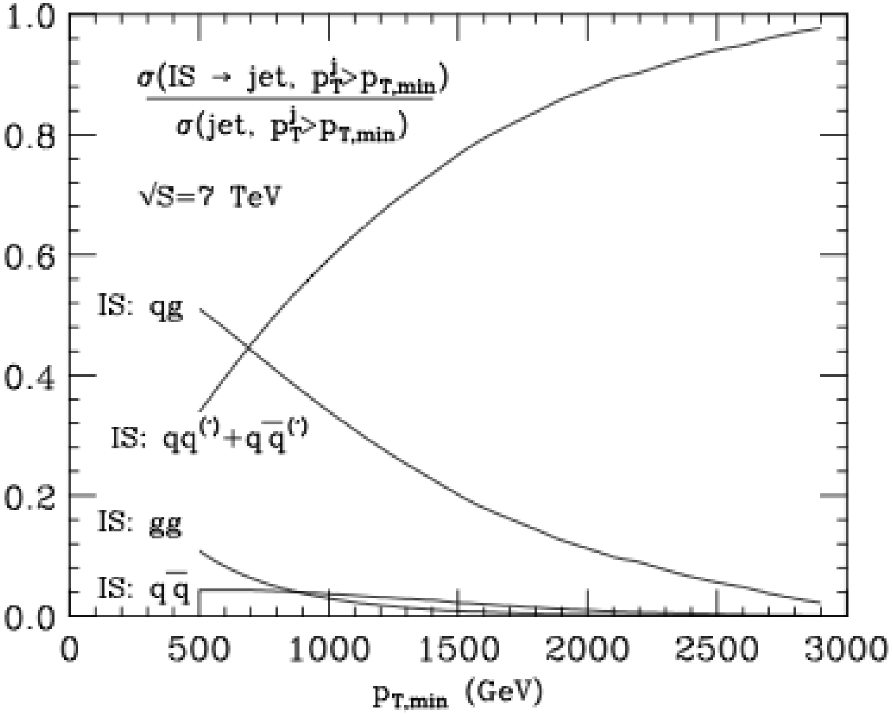
Example: Jet cross section

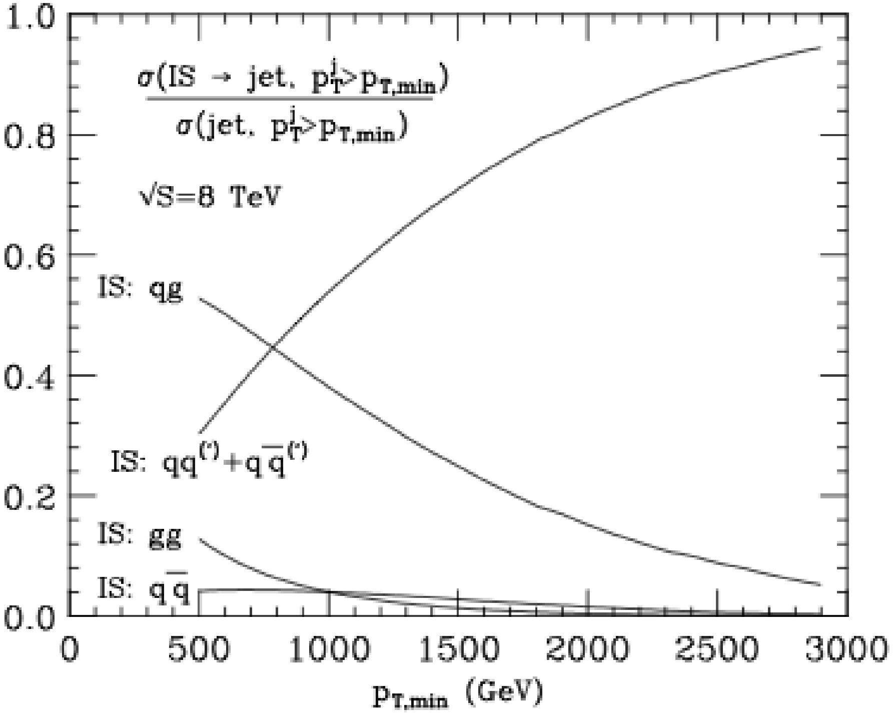
ATLAS, arXiv:1410.8857

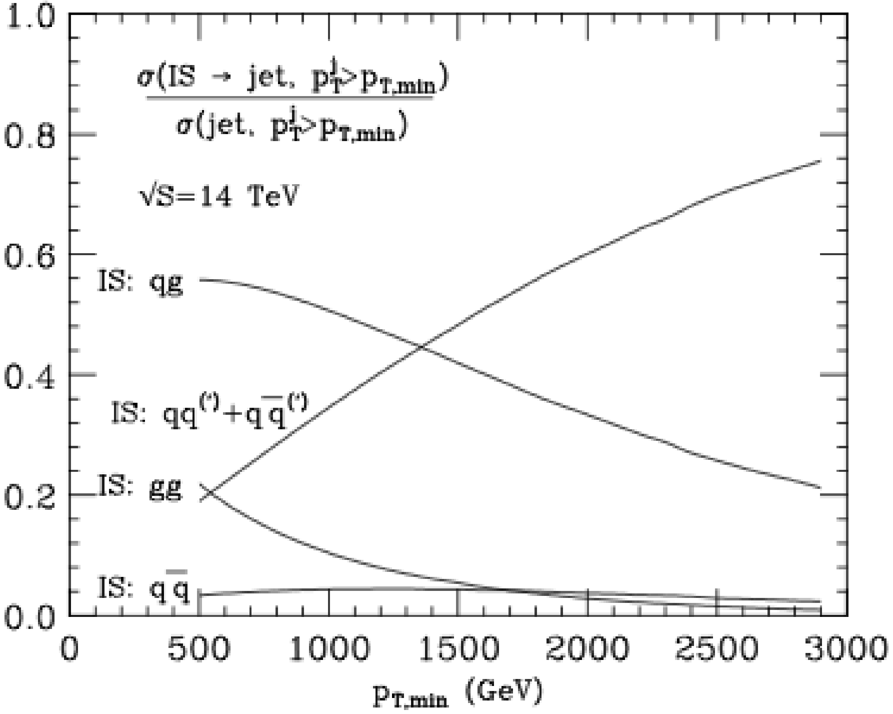


Rates span 10 orders of magnitude!

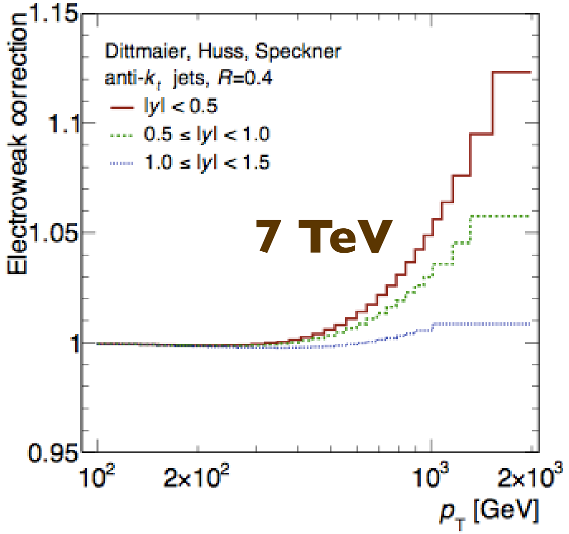
Initial state composition of inclusive jet events



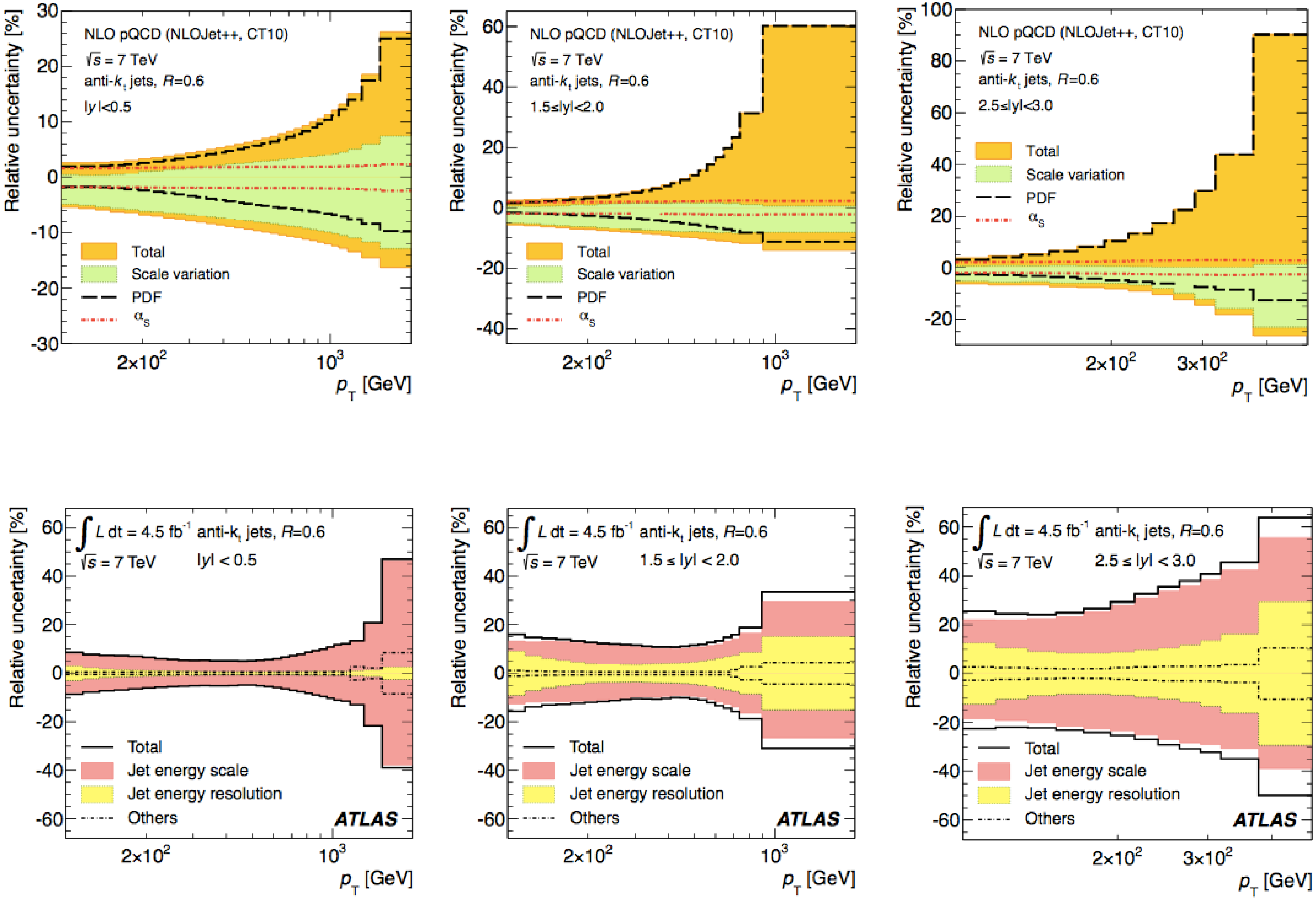




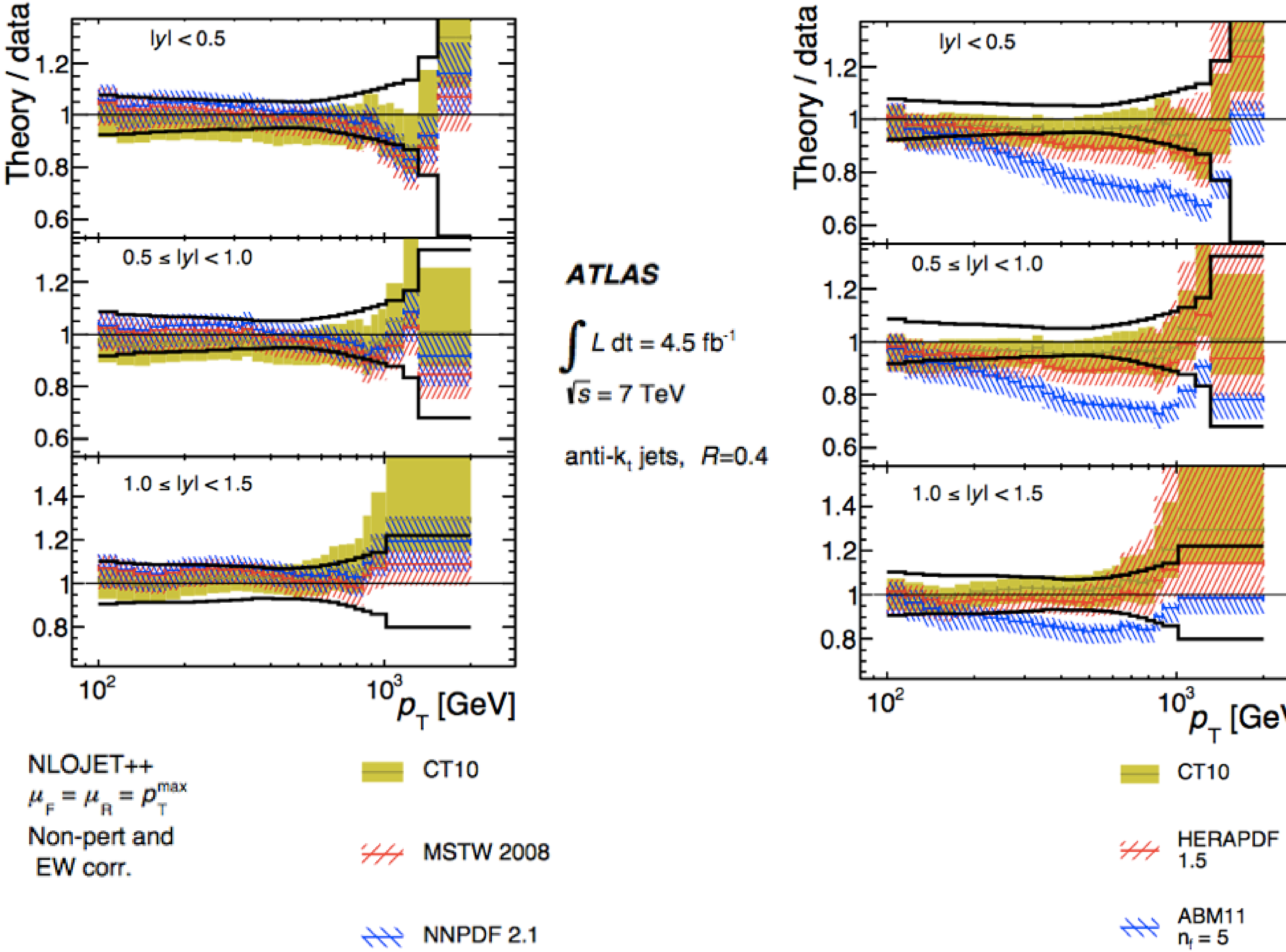
NB: Impact of virtual EW corrections:



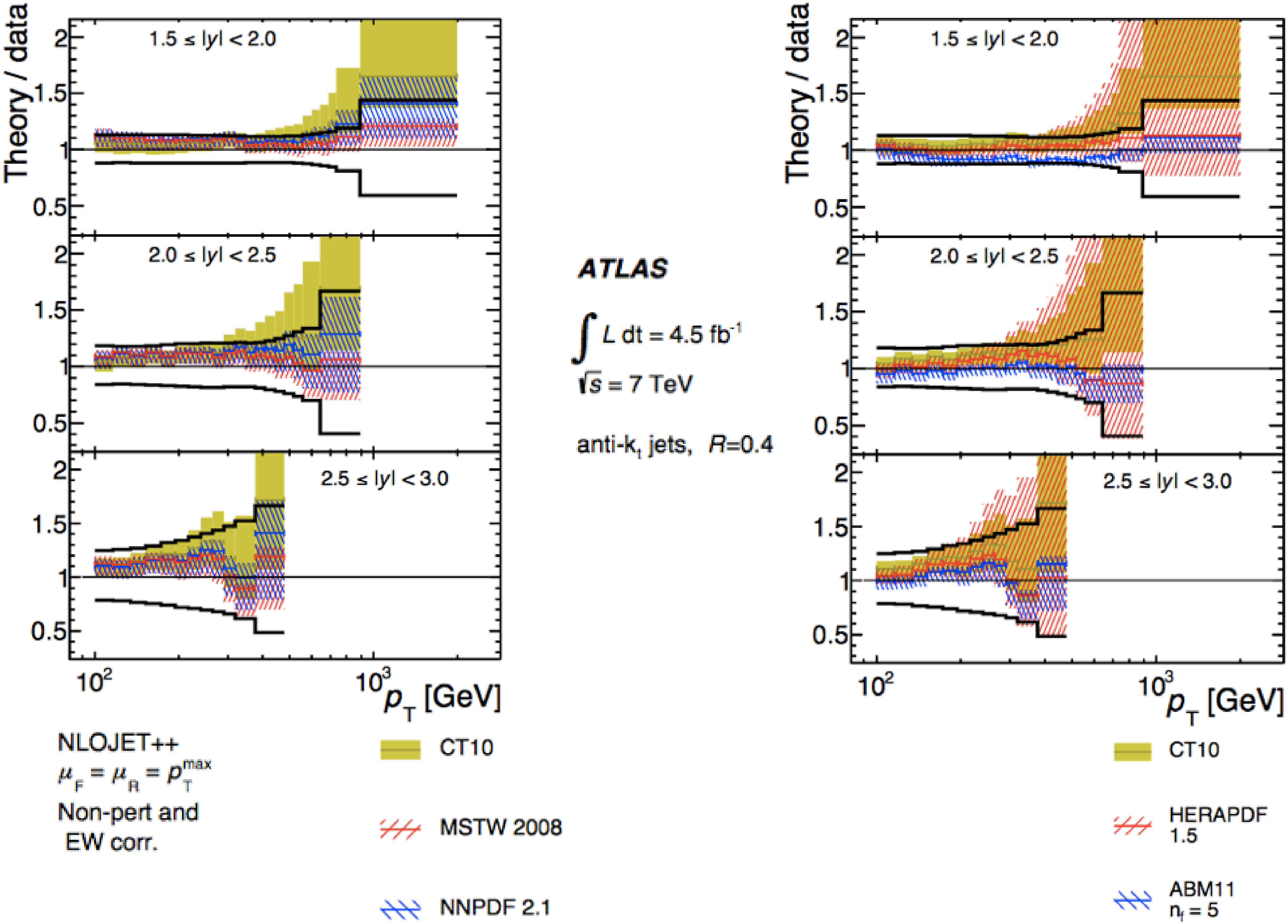
at p_T~2 TeV it's larger than qg contribution


NLO pQCD (NLOJet++, CT10)
$\sqrt{s}$ = 7 TeV
anti-k_t jets, R=0.6
$|y|<0.5$
Total
Scale variation
PDF
α_S
Relative uncertainty [%]
30
20
10
0
-10
-20
-30
2×10^2
10^3
p_T [GeV]
NLO pQCD (NLOJet++, CT10)
$\sqrt{s}$ = 7 TeV
anti-k_t jets, R=0.6
$1.5\leq|y|<2.0$
Total
Scale variation
PDF
α_S
Relative uncertainty [%]
60
40
20
0
-20
-40
2×10^2
10^3
p_T [GeV]
NLO pQCD (NLOJet++, CT10)
$\sqrt{s}$ = 7 TeV
anti-k_t jets, R=0.6
$2.5\leq|y|<3.0$
Total
Scale variation
PDF
α_S
Relative uncertainty [%]
100
80
60
40
20
0
-20
2×10^2
3×10^2
p_T [GeV]
$\int L\,dt$ = 4.5 fb^{-1} anti-k_t jets, R=0.6
$\sqrt{s}$ = 7 TeV
$|y|<0.5$
Total
Jet energy scale
Jet energy resolution
Others
ATLAS
Relative uncertainty [%]
60
40
20
0
-20
-40
-60
2×10^2
10^3
p_T [GeV]
$\int L\,dt$ = 4.5 fb^{-1} anti-k_t jets, R=0.6
$\sqrt{s}$ = 7 TeV
$1.5\leq|y|<2.0$
Total
Jet energy scale
Jet energy resolution
Others
ATLAS
Relative uncertainty [%]
60
40
20
0
-20
-40
-60
2×10^2
10^3
p_T [GeV]
$\int L\,dt$ = 4.5 fb^{-1} anti-k_t jets, R=0.6
$\sqrt{s}$ = 7 TeV
$2.5\leq|y|<3.0$
Total
Jet energy scale
Jet energy resolution
Others
ATLAS
Relative uncertainty [%]
60
40
20
0
-20
-40
-60
2×10^2
3×10^2
p_T [GeV]

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

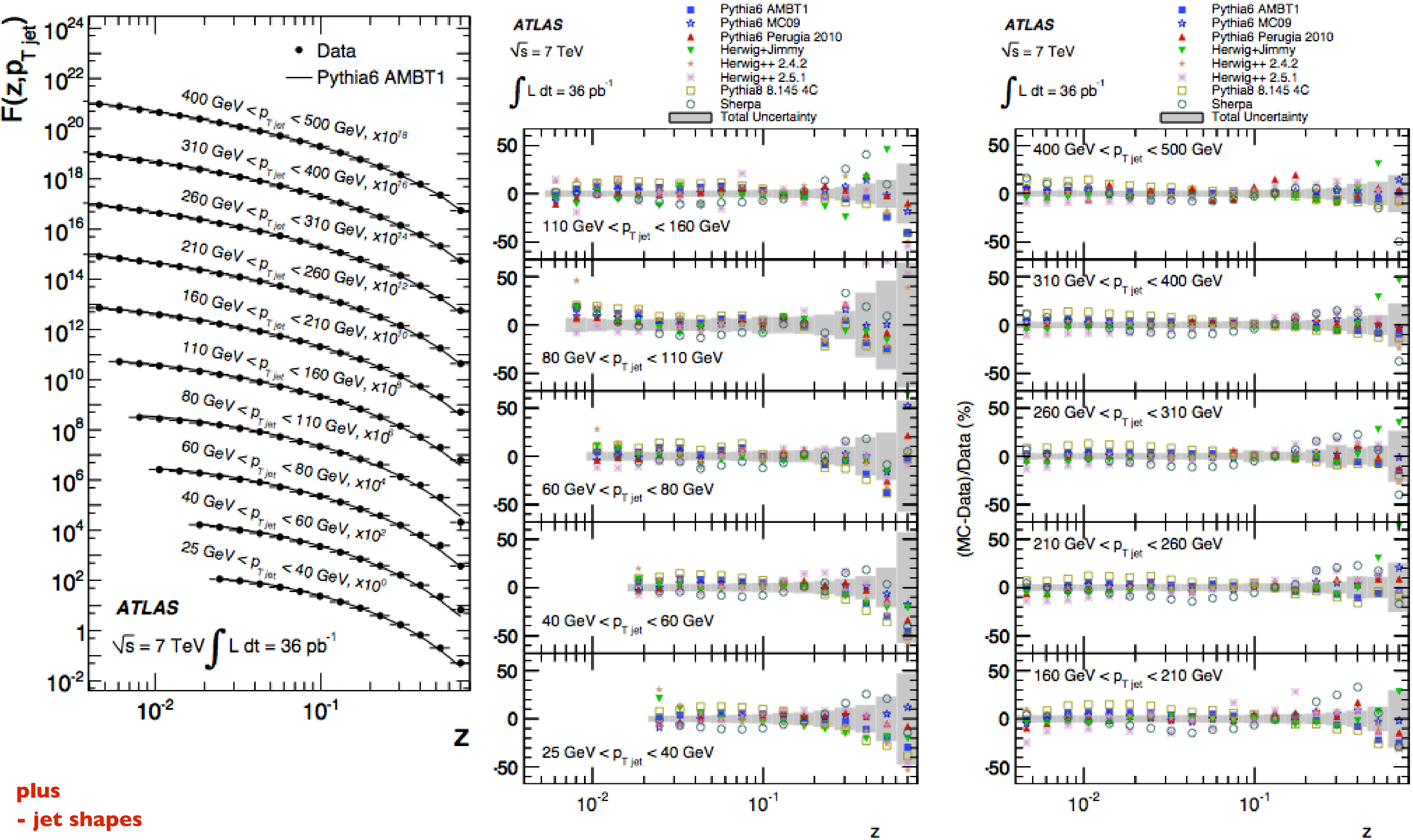


Forward production, TH vs data
(TH: absolute prediction for both shape and normalization)



Jet fragmentation function

ATLAS, arXiv:1109.5816

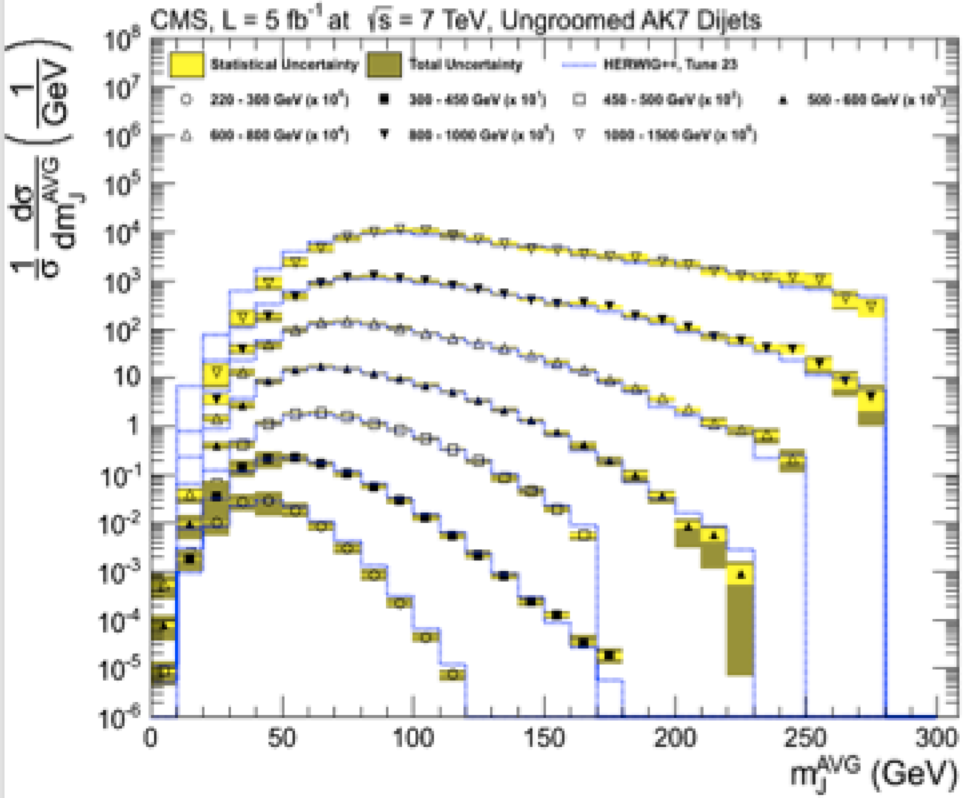


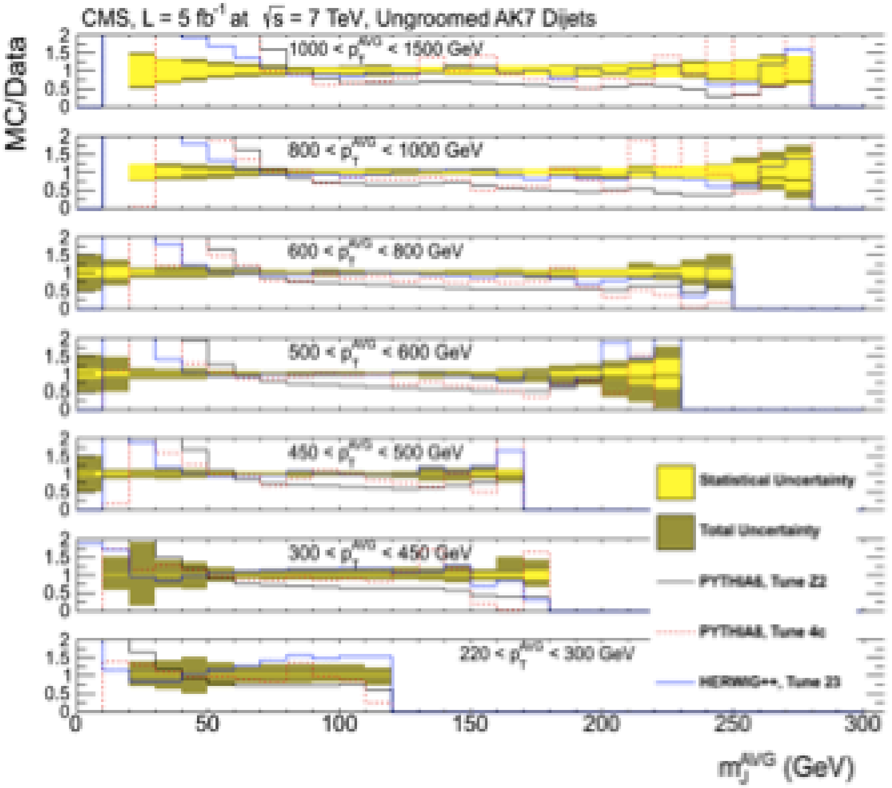
plus

- **jet shapes**
- **ptrel spectra**
- **$\langle N_{ch} \rangle$ and $\langle z \rangle$ distributions,**
- **....**

QCD jet mass measurement

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

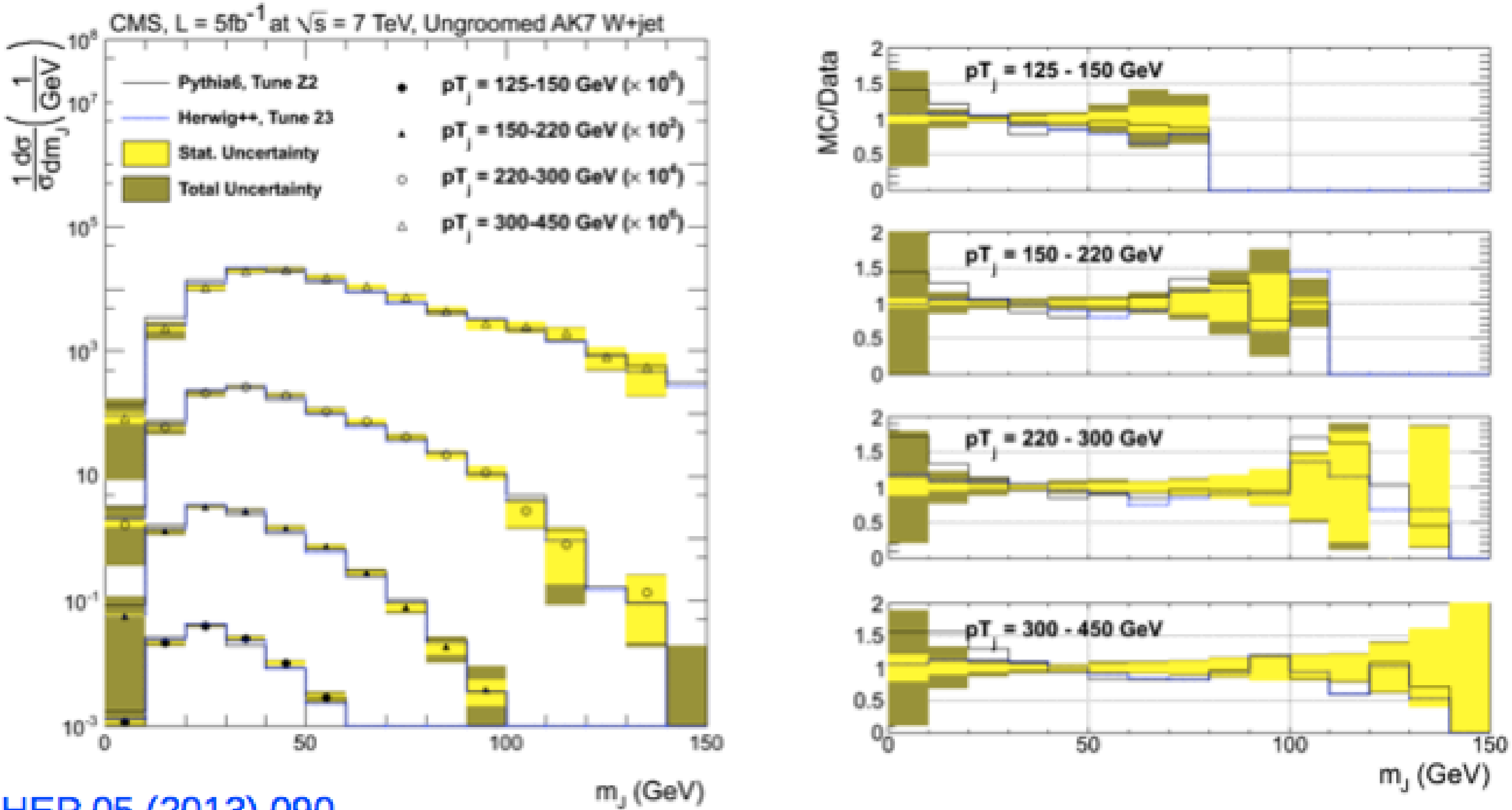




JHEP 05 (2013) 090
CMS-SMP-12-019

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

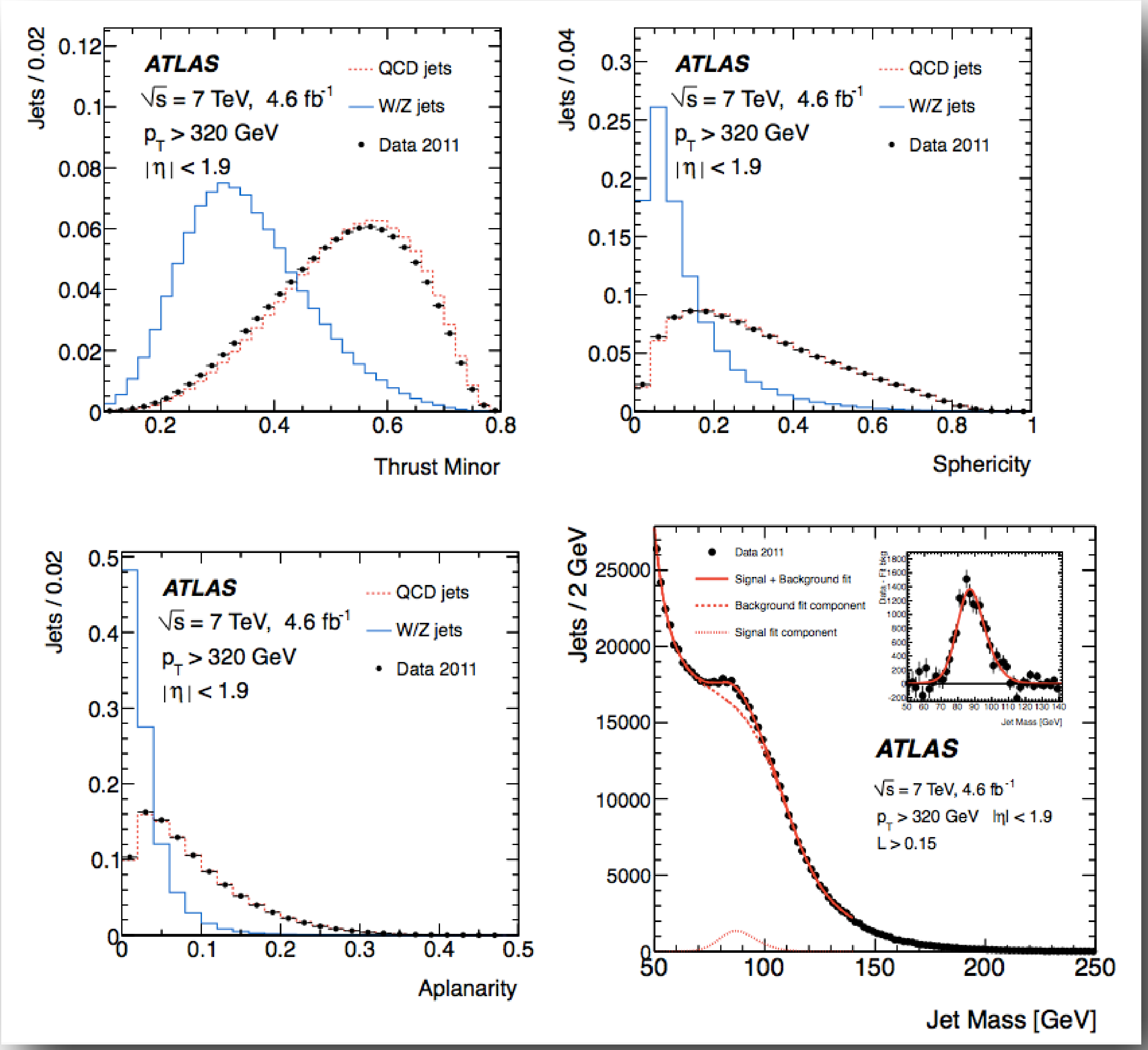
Extract

σ_{W+Z} = 8.5±0.8(stat)±1.5(syst) pb

ATLAS, J.Phys. 16 (2014) 113013

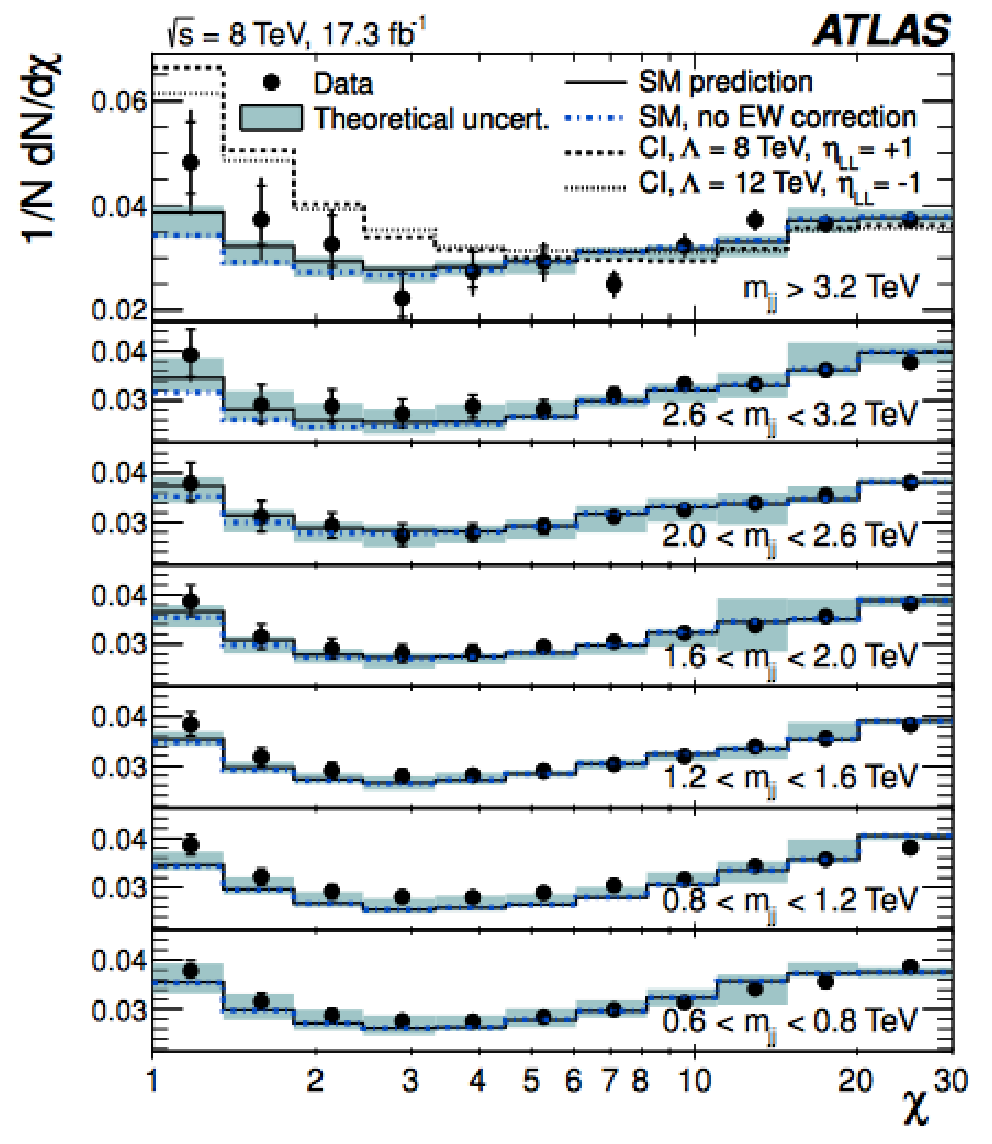
NLO:

σ_{W+Z} = 5.1±0.5 pb



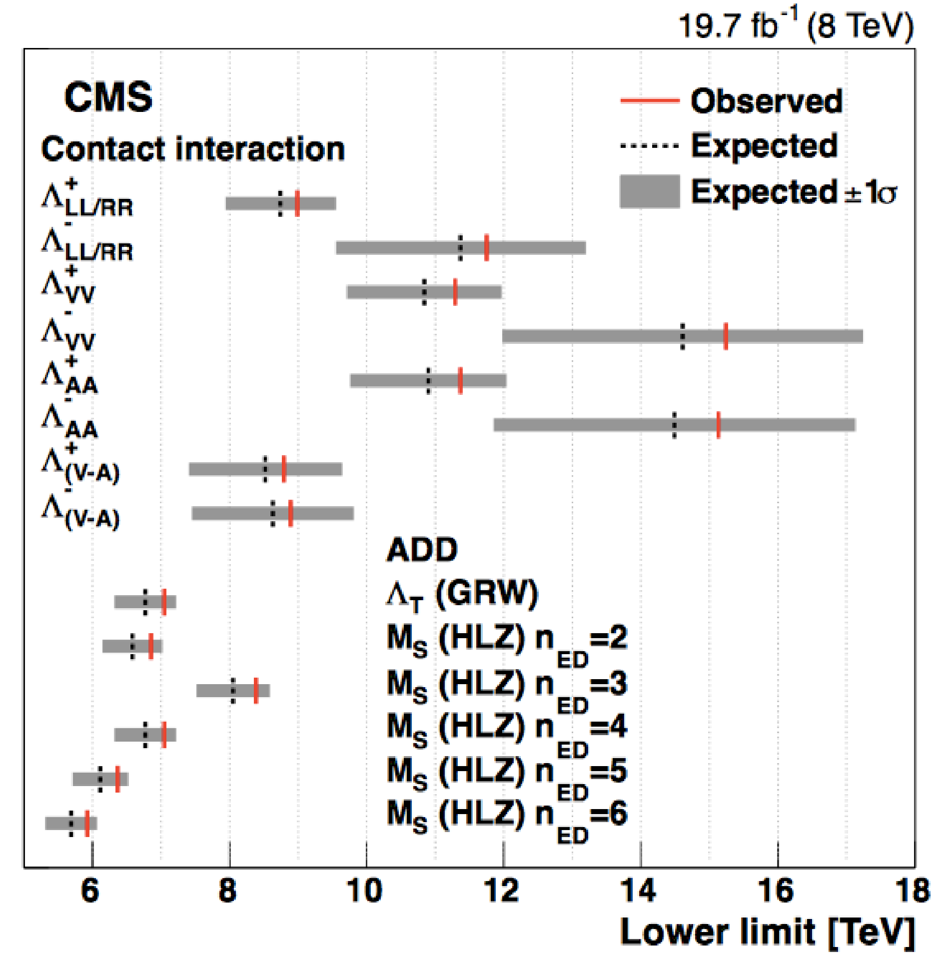
Constraints on quark contact interactions

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



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

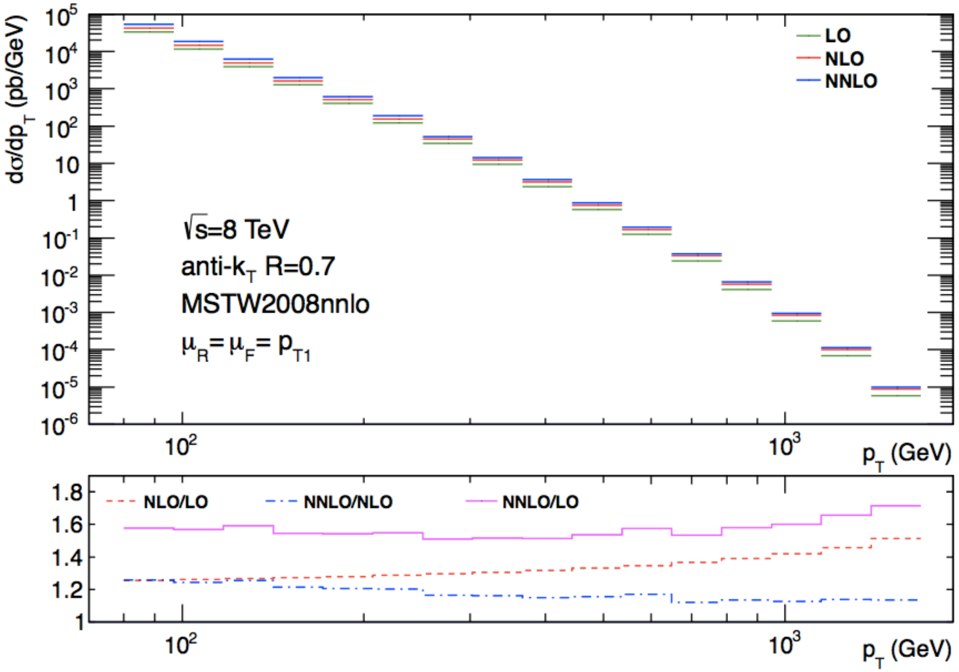
CMS, http://arxiv.org/abs/1411.2646

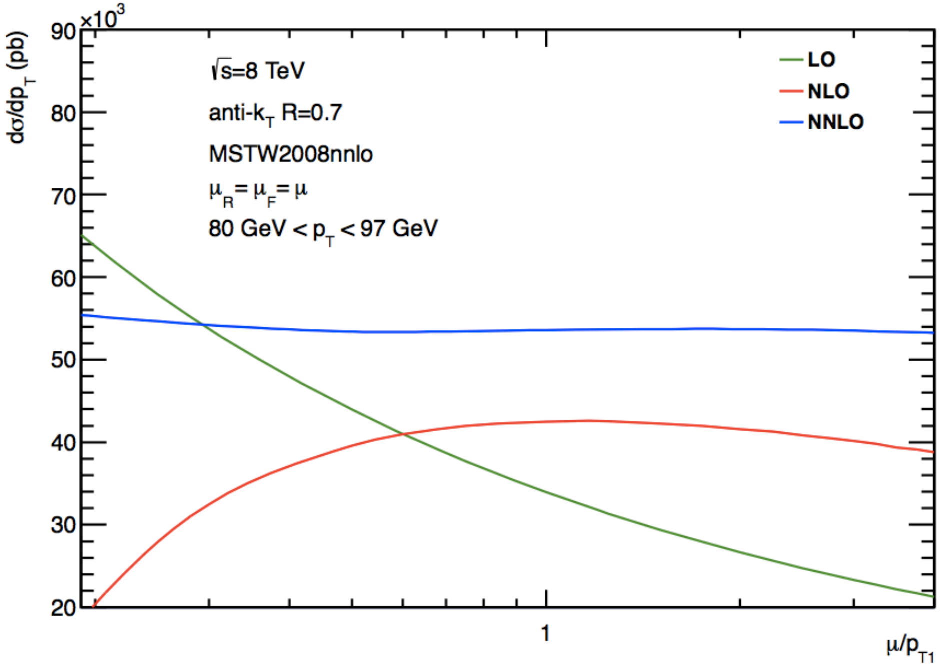


Quarks appear pointlike even at the distances probed by the LHC, up to scales in the range of (10 TeV)$^{-1}$

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

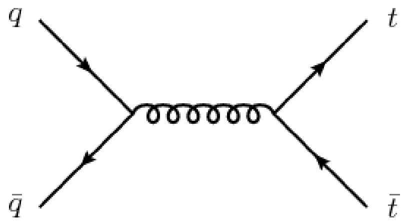
NNLO scale systematics ~ few % ...
- does this survive if $\mu_F \neq \mu_R$?

Notice that NNLO outside the NLO scale-variation band

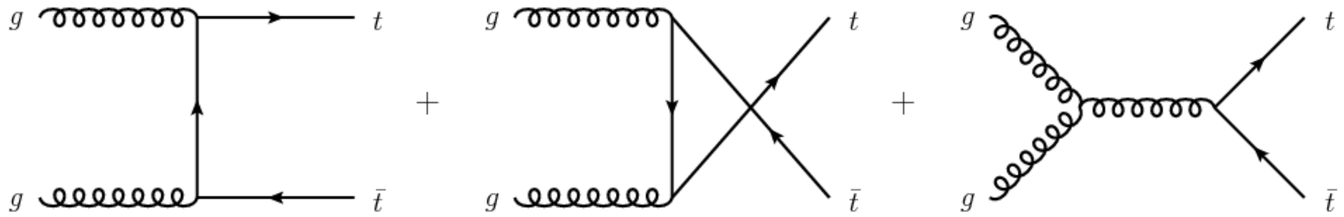
At this level of precision, there are other things one should start considering. E.g. non-perturbative systematics and EW corrections

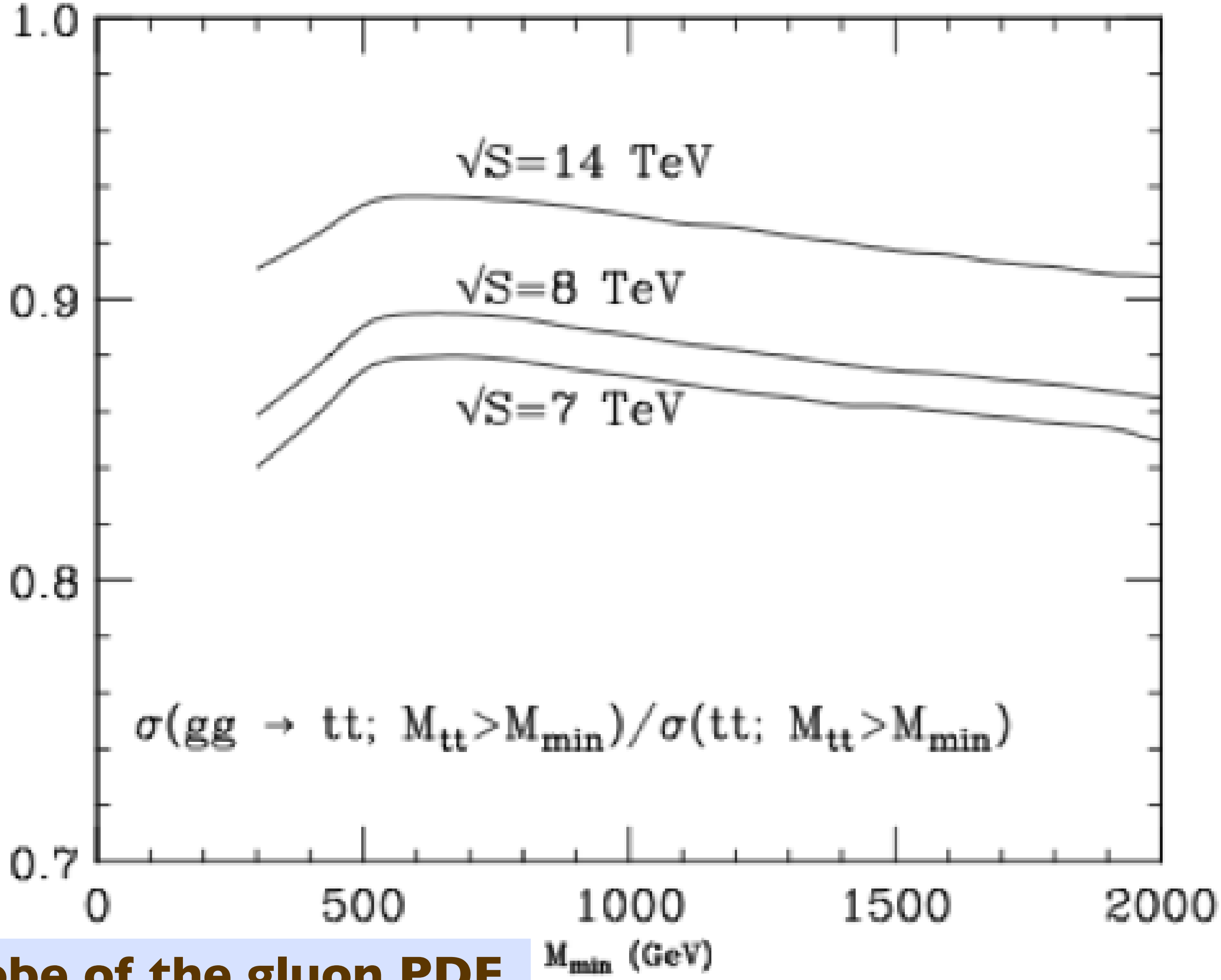
Top quark production

Production dominated by gg initial state up to very large p_T



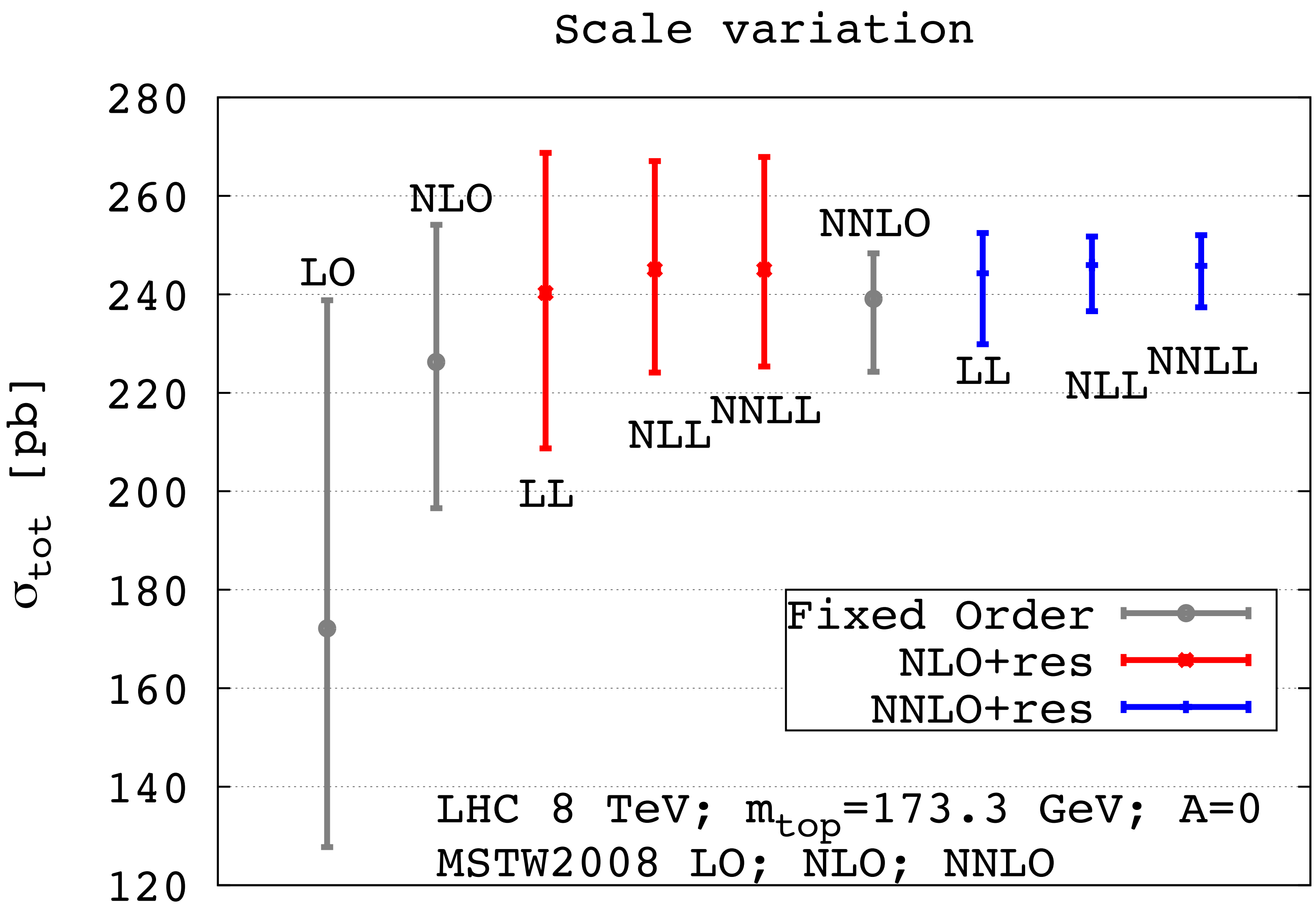
vs





⇒ sensitive probe of the gluon PDF

Great precision reached with the completion of the NNLO calculation

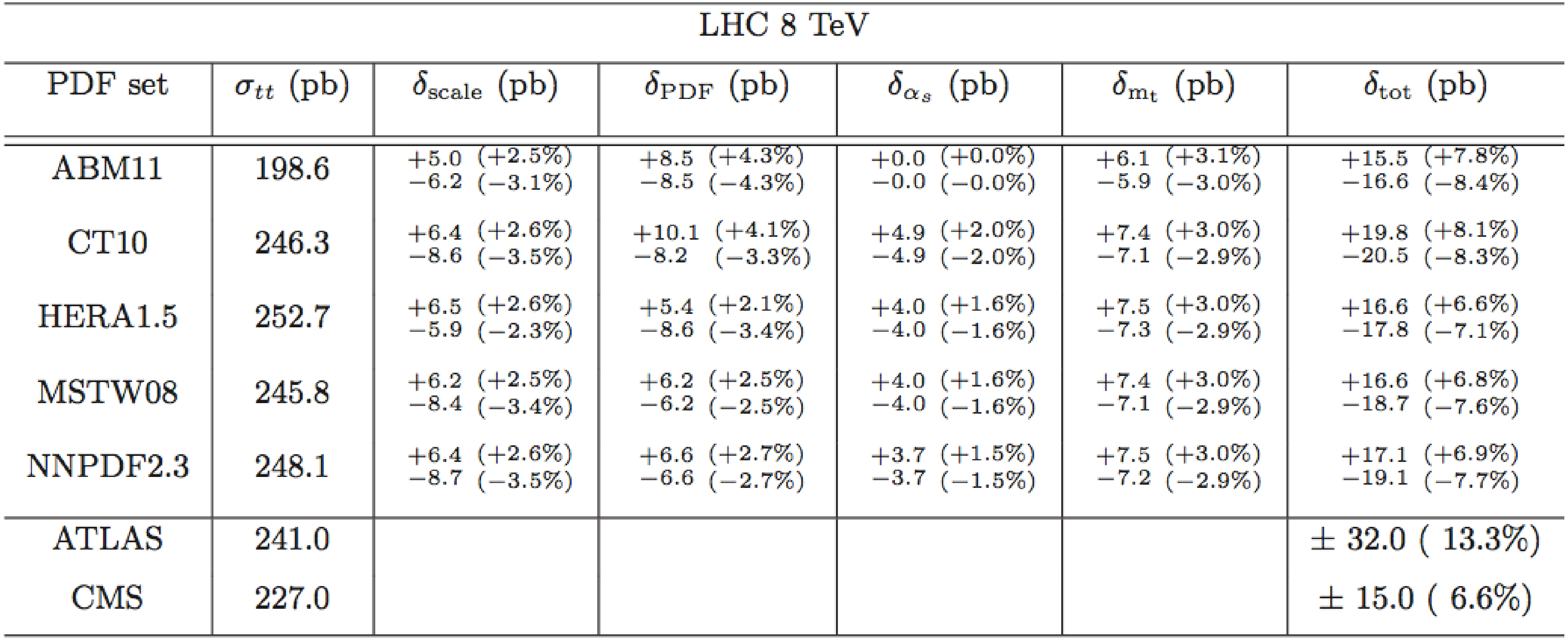


Independent μ_R , μ_F variation, with $\mu_0 = m_{top}$,
$0.5\ \mu_0 < \mu_{R,F} < 2\ \mu_0$ and
$0.5 < \mu_R / \mu_F < 2$

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

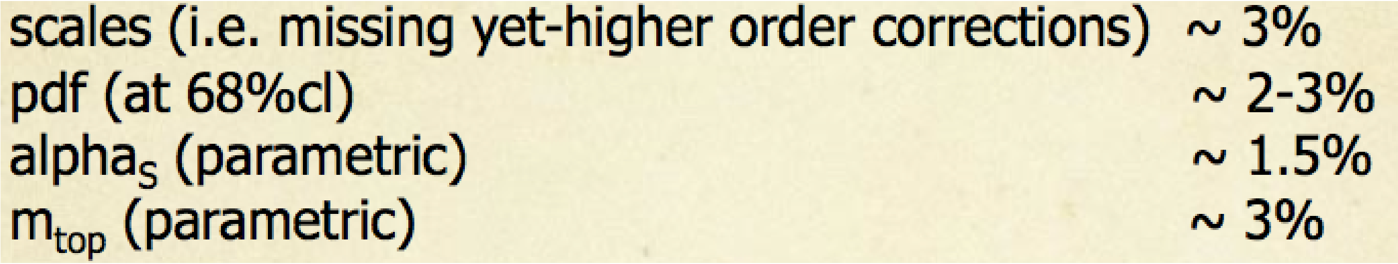
M. Czakon, M. Mangano, A. Mitov, J. Rojo arXiv:1303.7215



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 (+2.5%) −6.2 (−3.1%)	+8.5 (+4.3%) −8.5 (−4.3%)	+0.0 (+0.0%) −0.0 (−0.0%)	+6.1 (+3.1%) −5.9 (−3.0%)	+15.5 (+7.8%) −16.6 (−8.4%)
CT10	246.3	+6.4 (+2.6%) −8.6 (−3.5%)	+10.1 (+4.1%) −8.2 (−3.3%)	+4.9 (+2.0%) −4.9 (−2.0%)	+7.4 (+3.0%) −7.1 (−2.9%)	+19.8 (+8.1%) −20.5 (−8.3%)
HERA1.5	252.7	+6.5 (+2.6%) −5.9 (−2.3%)	+5.4 (+2.1%) −8.6 (−3.4%)	+4.0 (+1.6%) −4.0 (−1.6%)	+7.5 (+3.0%) −7.3 (−2.9%)	+16.6 (+6.6%) −17.8 (−7.1%)
MSTW08	245.8	+6.2 (+2.5%) −8.4 (−3.4%)	+6.2 (+2.5%) −6.2 (−2.5%)	+4.0 (+1.6%) −4.0 (−1.6%)	+7.4 (+3.0%) −7.1 (−2.9%)	+16.6 (+6.8%) −18.7 (−7.6%)
NNPDF2.3	248.1	+6.4 (+2.6%) −8.7 (−3.5%)	+6.6 (+2.7%) −6.6 (−2.7%)	+3.7 (+1.5%) −3.7 (−1.5%)	+7.5 (+3.0%) −7.2 (−2.9%)	+17.1 (+6.9%) −19.1 (−7.7%)
ATLAS	241.0					± 32.0 (13.3%)
CMS	227.0					± 15.0 (6.6%)

TH and parametric uncertainties are all of similar size:

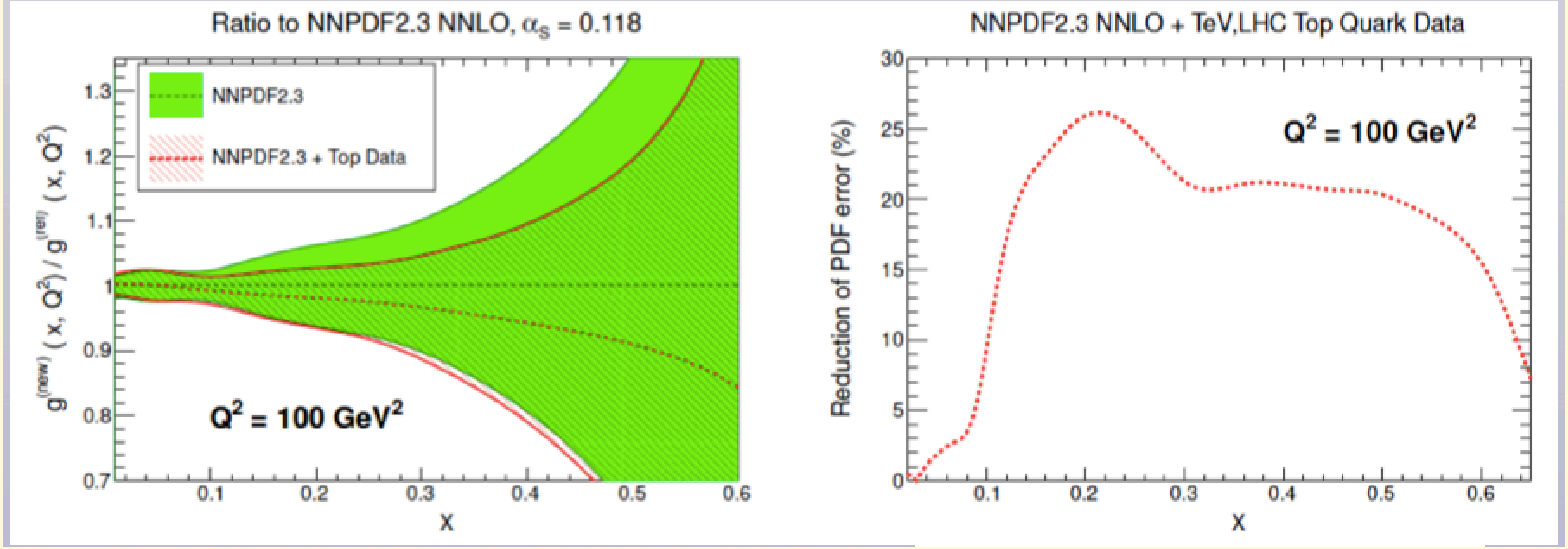


	scales (i.e. missing yet-higher order corrections)	~ 3%
	pdf (at 68%cl)	~ 2-3%
$\Delta\alpha_S = \pm 0.0007 \Longrightarrow$	alpha$_S$ (parametric)	~ 1.5%
$\Delta m_{top} = \pm 1$ GeV $\Longrightarrow$	m_{top} (parametric)	~ 3%

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

8TeV/7TeV and 14TeV/8TeV cross section ratios: the ultimate precision

MLM and J.Rojo, arXiv:1206.3557

$E_{1,2}$: different beam energies

X,Y: different hard processes

$$R_{E_2/E_1}(X) \equiv \frac{\sigma(X,E_2)}{\sigma(X,E_1)} \longrightarrow$$

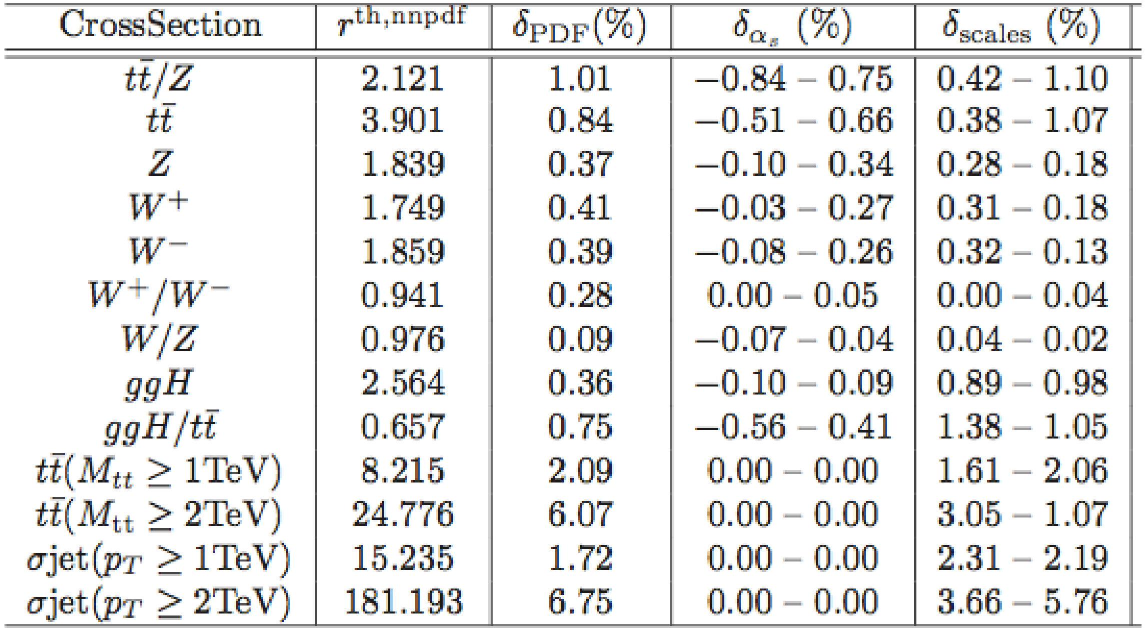
- TH: reduce “scale uncertainties”
- TH: reduce parameters’ systematics: PDF, m_{top}, α_S, ... at E_1 and E_2 are fully correlated
- TH: reduce MC modeling uncertainties
- EXP: reduce syst’s from acceptance, efficiency, JES, ...

$$R_{E_2/E_1}(X,Y) \equiv \frac{\sigma(X,E_2)/\sigma(Y,E_2)}{\sigma(X,E_1)/\sigma(Y,E_1)} \equiv \frac{R_{E_2/E_1}(X)}{R_{E_2/E_1}(Y)} \longrightarrow$$

- TH: possible further reduction in scale and PDF syst’s
- EXP: no luminosity uncertainty
- EXP: possible further reduction in acc, eff, JES syst’s (e.g. X,Y=W^+,W^-)

Following results obtained using best available TH predictions: NLO, NNLO, NNLL resummation when available

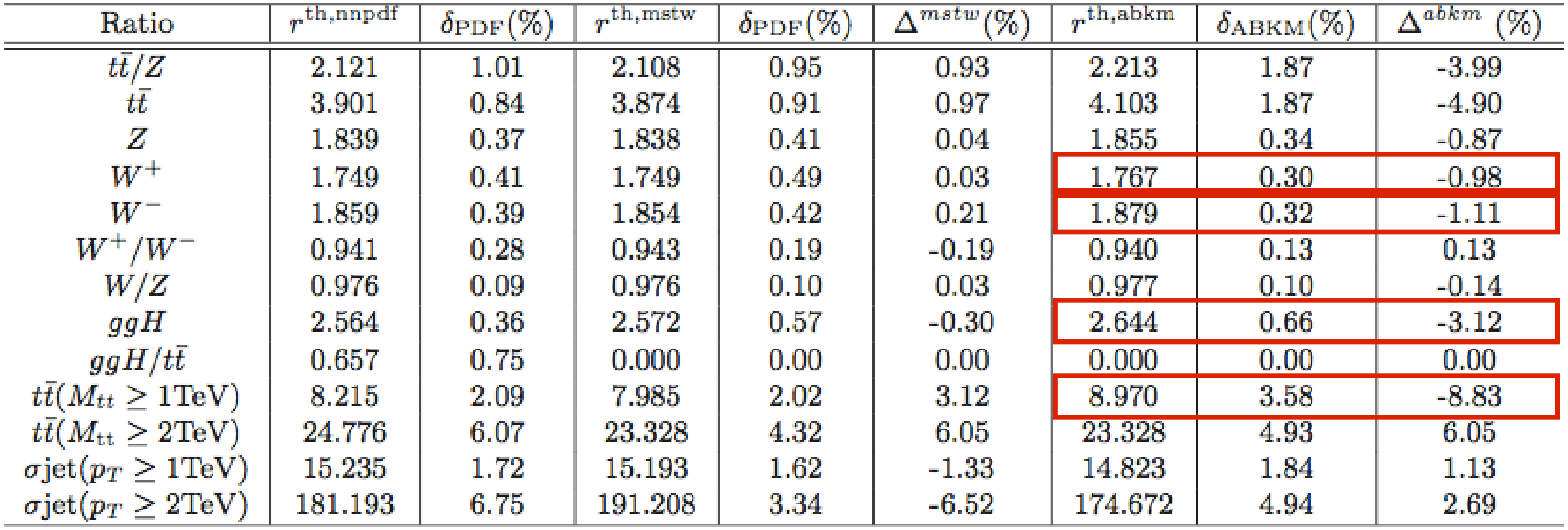
14 TeV / 8 TeV: NNPDF results



CrossSection	$r^{\rm th,nnpdf}$	$\delta_{\rm PDF}(\%)$	δ_{α_s} (%)	$\delta_{\rm scales}$ (%)
$t\bar{t}/Z$	2.121	1.01	−0.84 – 0.75	0.42 – 1.10
$t\bar{t}$	3.901	0.84	−0.51 – 0.66	0.38 – 1.07
Z	1.839	0.37	−0.10 – 0.34	0.28 – 0.18
W^+	1.749	0.41	−0.03 – 0.27	0.31 – 0.18
W^-	1.859	0.39	−0.08 – 0.26	0.32 – 0.13
W^+/W^-	0.941	0.28	0.00 – 0.05	0.00 – 0.04
W/Z	0.976	0.09	−0.07 – 0.04	0.04 – 0.02
ggH	2.564	0.36	−0.10 – 0.09	0.89 – 0.98
$ggH/t\bar{t}$	0.657	0.75	−0.56 – 0.41	1.38 – 1.05
$t\bar{t}(M_{tt} \geq 1\rm TeV)$	8.215	2.09	0.00 – 0.00	1.61 – 2.06
$t\bar{t}(M_{tt} \geq 2\rm TeV)$	24.776	6.07	0.00 – 0.00	3.05 – 1.07
σjet$(p_T \geq 1\rm TeV)$	15.235	1.72	0.00 – 0.00	2.31 – 2.19
σjet$(p_T \geq 2\rm TeV)$	181.193	6.75	0.00 – 0.00	3.66 – 5.76

- $\delta<10^{-2}$ in $W^\pm$ ratios: absolute calibration of 14 vs 8 TeV lumi
- $\delta\sim10^{-2}$ in $\sigma(tt)$ ratios
- $\delta_{\rm scale} < \delta_{\rm PDF}$ at large $p_T^{\rm jet}$ and M_{tt}: constraints on PDFs

14 TeV / 8 TeV: NNPDF vs MSTW vs ABKM



Ratio	$r^{\rm th,nnpdf}$	$\delta_{\rm PDF}(\%)$	$r^{\rm th,mstw}$	$\delta_{\rm PDF}(\%)$	$\Delta^{mstw}(\%)$	$r^{\rm th,abkm}$	$\delta_{\rm ABKM}(\%)$	Δ^{abkm} (%)
$t\bar{t}/Z$	2.121	1.01	2.108	0.95	0.93	2.213	1.87	-3.99
$t\bar{t}$	3.901	0.84	3.874	0.91	0.97	4.103	1.87	-4.90
Z	1.839	0.37	1.838	0.41	0.04	1.855	0.34	-0.87
W^+	1.749	0.41	1.749	0.49	0.03	1.767	0.30	-0.98
W^-	1.859	0.39	1.854	0.42	0.21	1.879	0.32	-1.11
W^+/W^-	0.941	0.28	0.943	0.19	-0.19	0.940	0.13	0.13
W/Z	0.976	0.09	0.976	0.10	0.03	0.977	0.10	-0.14
ggH	2.564	0.36	2.572	0.57	-0.30	2.644	0.66	-3.12
$ggH/t\bar{t}$	0.657	0.75	0.000	0.00	0.00	0.000	0.00	0.00
$t\bar{t}(M_{tt} \geq 1\rm TeV)$	8.215	2.09	7.985	2.02	3.12	8.970	3.58	-8.83
$t\bar{t}(M_{tt} \geq 2\rm TeV)$	24.776	6.07	23.328	4.32	6.05	23.328	4.93	6.05
σjet$(p_T \geq 1\rm TeV)$	15.235	1.72	15.193	1.62	-1.33	14.823	1.84	1.13
σjet$(p_T \geq 2\rm TeV)$	181.193	6.75	191.208	3.34	-6.52	174.672	4.94	2.69

- Several examples of 3-4σ discrepancies between predictions of different PDF sets, even in the case of W and Z rates

Xsection ratios as probes of BSM contributions

Assume the final state **X** receives both SM and BSM contributions:

$$\sigma^{exp}(pp \to X) = \sigma^{SM}(pp \to X) + \sigma^{BSM}(pp \to X)$$

Define the ratio:

$$R^X_{7/8} = \frac{\sigma^{exp}(pp \to X; 7\ \mathrm{TeV})}{\sigma^{exp}(pp \to X; 8\ \mathrm{TeV})} = \frac{\sigma^{exp}_X(7)}{\sigma^{exp}_X(8)}$$

We easily get:

$$R^X_{7/8} \sim \frac{\sigma^{SM}_X(7)}{\sigma^{SM}_X(8)} \times \left\{ 1 + \frac{\sigma^{BSM}_X(7)}{\sigma^{SM}_X(7)}\ \Delta_{7/8}\left[\frac{\sigma^{BSM}_X}{\sigma^{SM}_X}\right] \right\}$$

where:

$$\Delta_{7/8}\left[\frac{\sigma^{BSM}_X}{\sigma^{SM}_X}\right] = 1 - \frac{\sigma^{BSM}_X(8)/\sigma^{SM}_X(8)}{\sigma^{BSM}_X(7)/\sigma^{SM}_X(7)} \sim 1 - \frac{\mathcal{L}^{BSM}_X(8)/\mathcal{L}^{BSM}_X(7)}{\mathcal{L}^{SM}_X(8)/\mathcal{L}^{SM}_X(7)} = \Delta_{7/8}\left[\frac{\mathcal{L}^{BSM}_X}{\mathcal{L}^{SM}_X}\right]$$

Therefore:

relative BSM contamination

$$\frac{\delta R^{X}_{7/8}}{R^{X}_{7/8}} = \frac{\delta R^{SM}_{7/8}}{R^{SM}_{7/8}} + \frac{\sigma_X^{BSM}(7)}{\sigma_X^{SM}(7)} \times \Delta_{7/8}\left[\frac{\mathcal{L}_X^{BSM}}{\mathcal{L}_X^{SM}}\right]$$

theory systematics in 7→8 TeV extrapolation

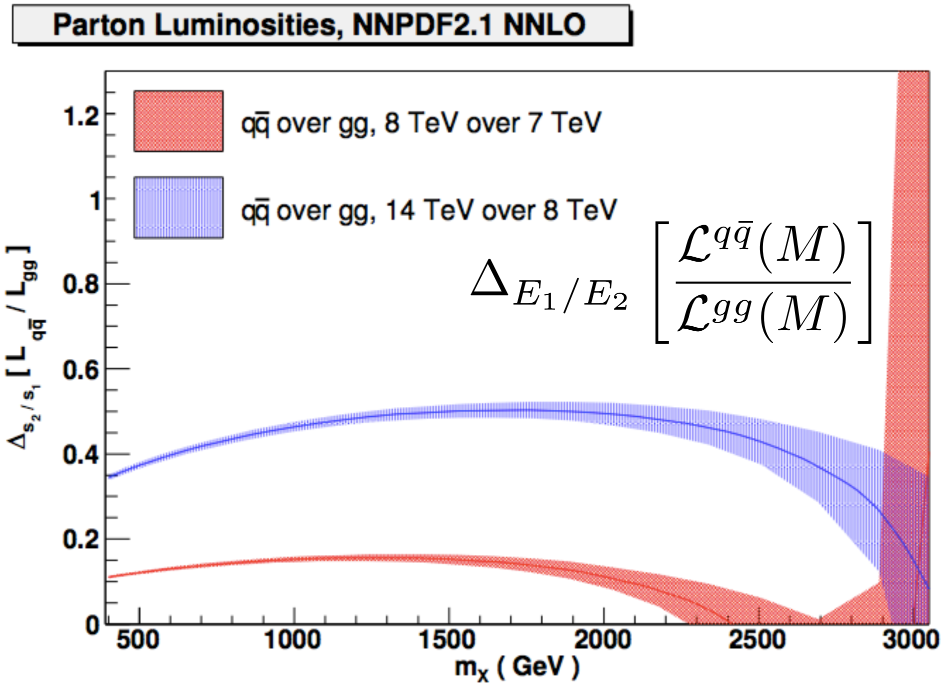
Energy dependence of the relative BSM contamination

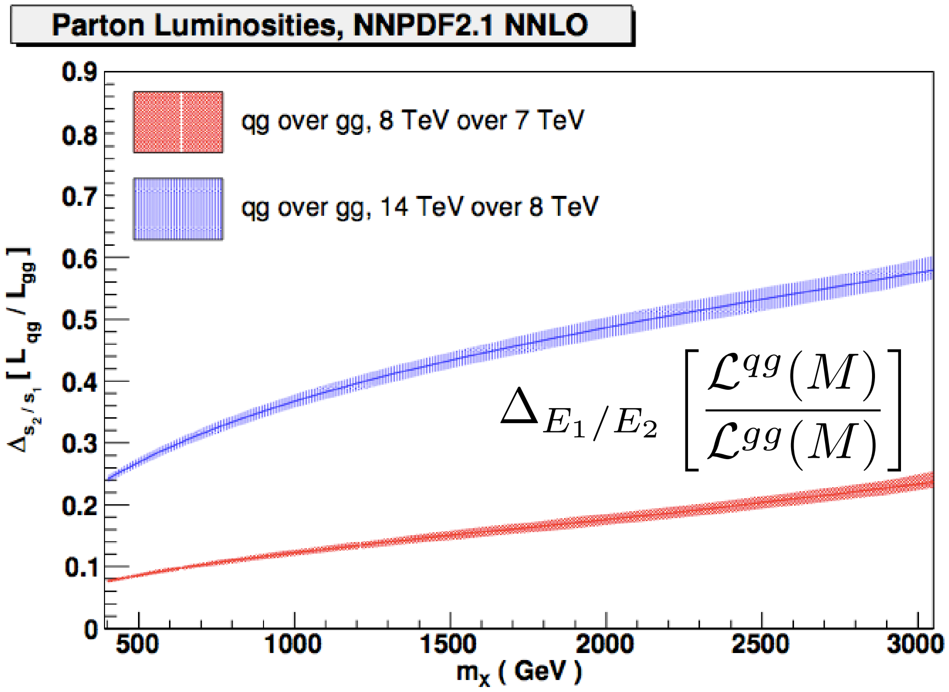
E.g., assuming $\sigma_{SM}(pp\to X)=\sigma(gg\to X)$ and $\sigma_{BSM}(pp\to X)=\sigma(qq\to X)$ (*)

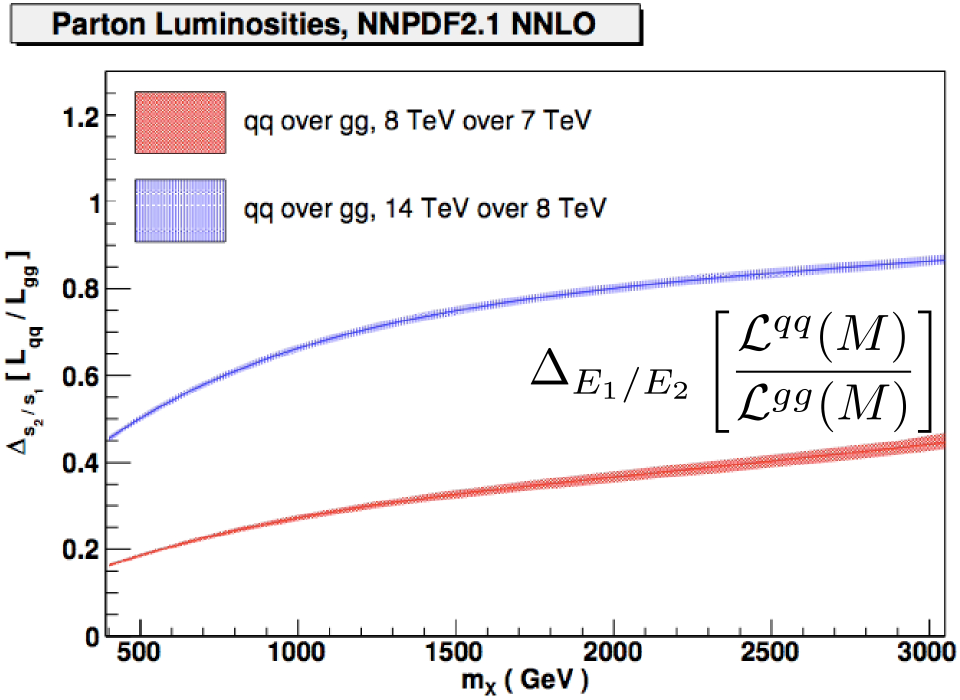
$$\Delta_{7/8}\left[\frac{\mathcal{L}_X^{BSM}}{\mathcal{L}_X^{SM}}\right] = \Delta_{7/8}\left[\frac{\mathcal{L}^{q\bar{q}}(M)}{\mathcal{L}^{gg}(M)}\right]$$

(*) e.g. SM: gg→tt and BSM: qqbar→Z'→tt

Examples of E-dependence of luminosity ratios







Given the sub-% precision of the SM ratio predictions, there is sensitivity to BSM rate contributions at the level of few% (to be improved with better PDF constraints, especially for 8/14 ratios)

Finally, where PDF systematics are negligible, and if there is no new physics, Xsection (double)ratios provide excellent benchmarks for calibration, anaysis validation, etc.

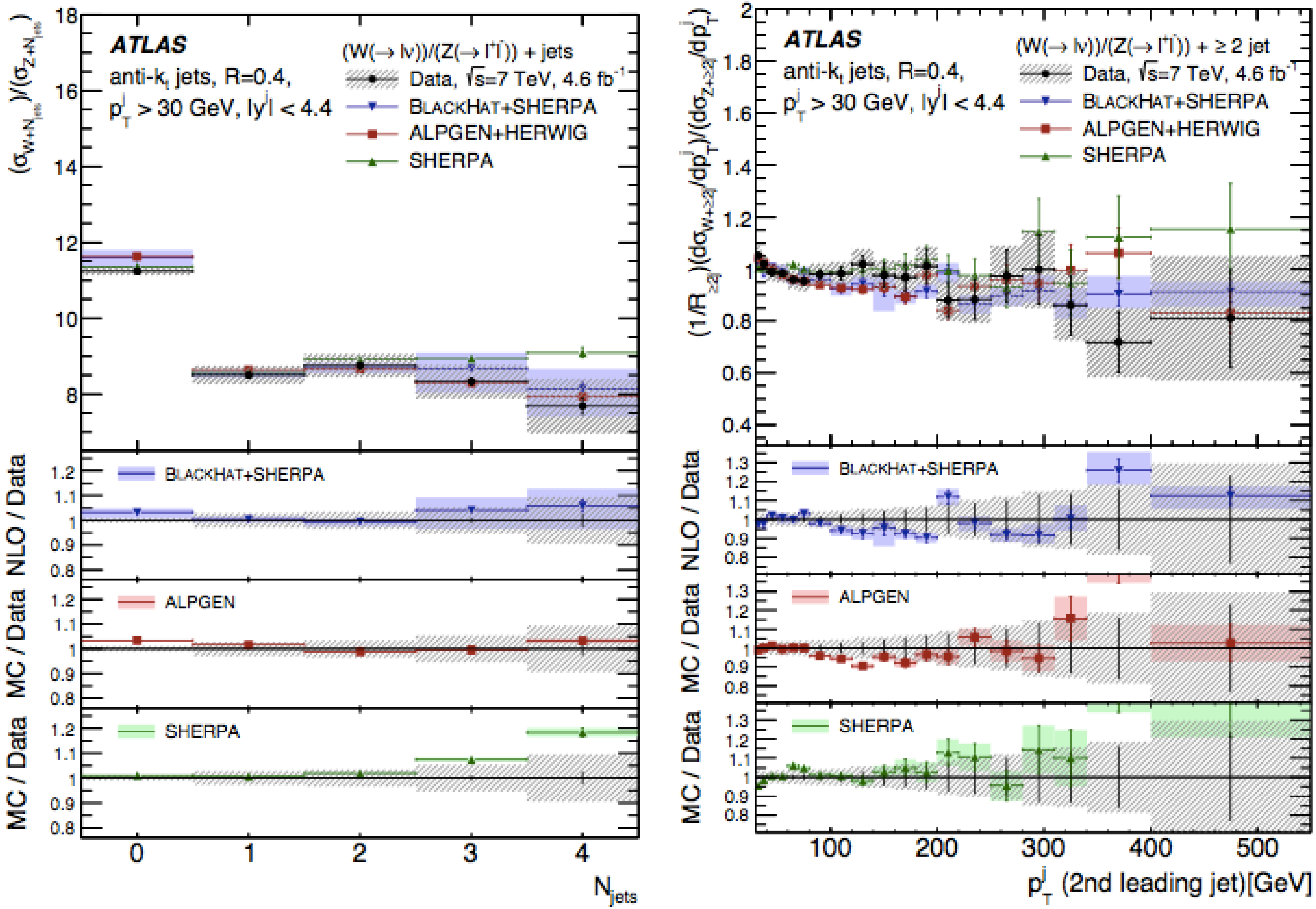
Powerful diagnostic tool when coming back after 2 yrs of shut-down!

Experimental challenge to match this precision. Requires great degree of correlation in the systematics of the analyses at different energies (eff's, bg subtraction, JES, ...)

Coherent efforts to plan the analyses having in mind the needs of XS (double)ratios are worth consideration

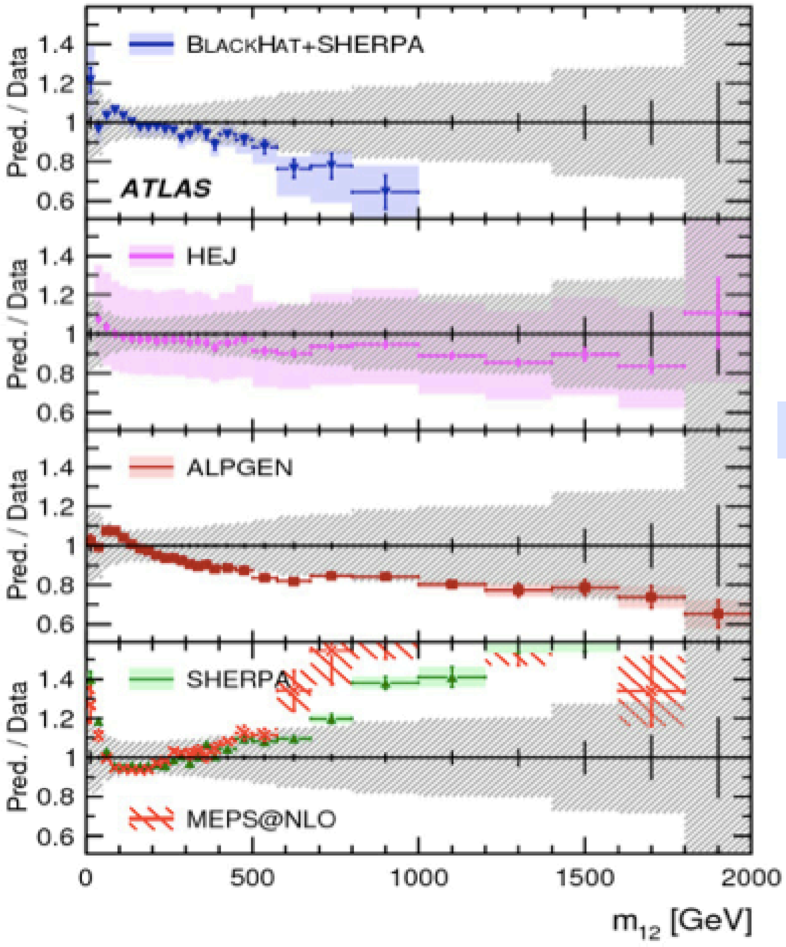
(W+jets)/(Z+jets) ratios

ATLAS, Eur. Phys. J. C (2014) 74:3168

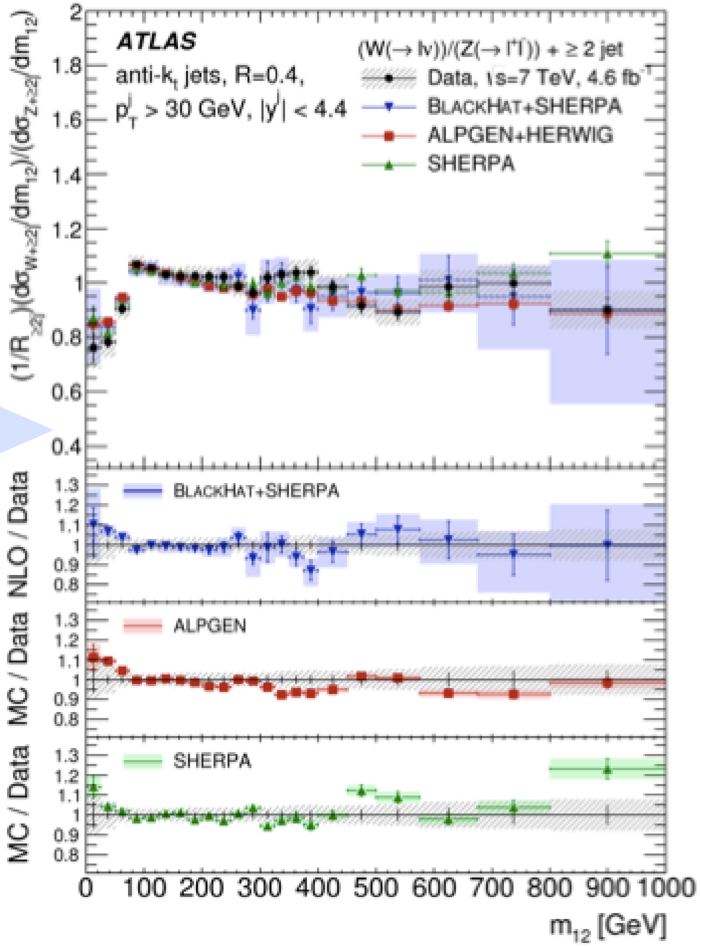


Potential for %-level precision comparisons between TH and data

W+jets



W+jets / Z+jets

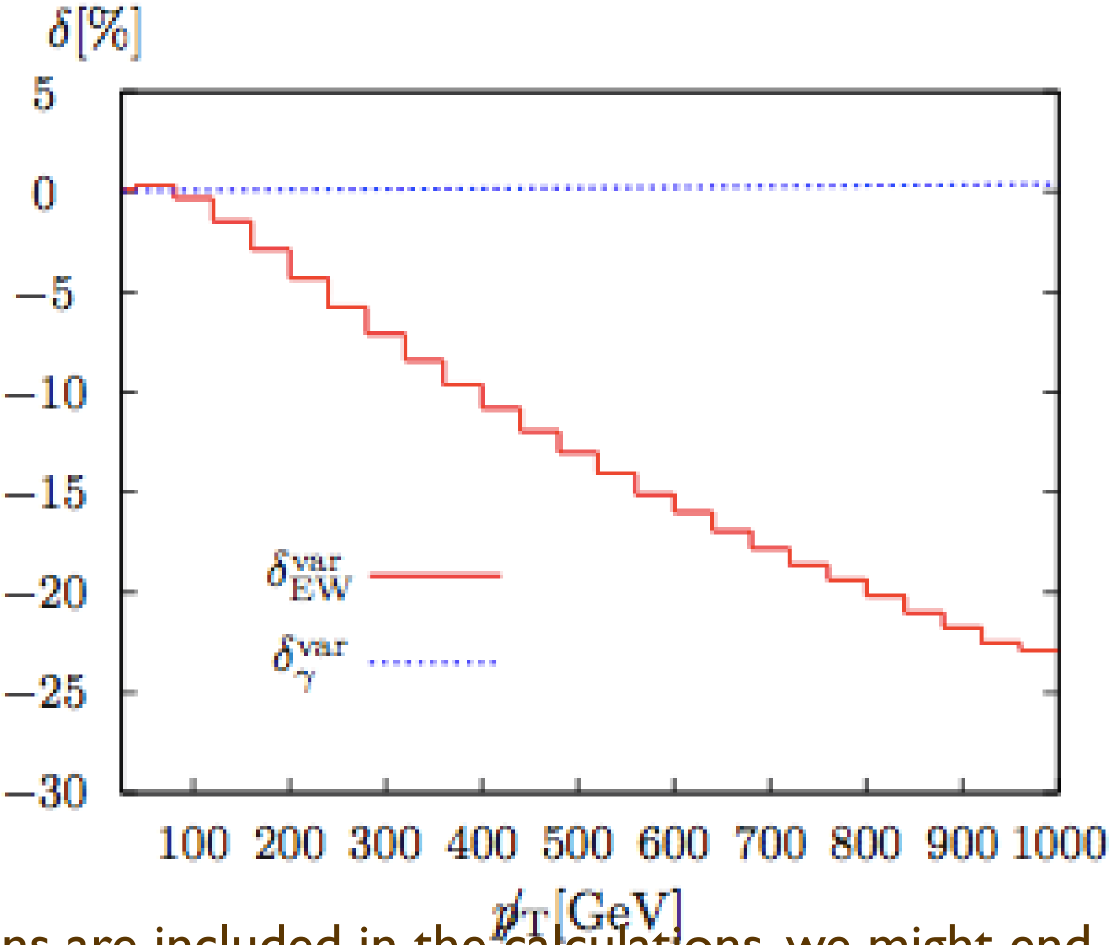


Possible mis-modeling of individual processes cancels in the ratios. Ratios are more robust. Ratios can therefore be affected by BSM physics, feeding only the W or the Z channel

EW effects at very high energy. Example:

Jet+MET spectrum from (Z→νν)+jet: corrections due to pure EW and pure EM corrections

Denner, Dittmaier, Kasprzik, Mück, arxiv:1211.5078v2

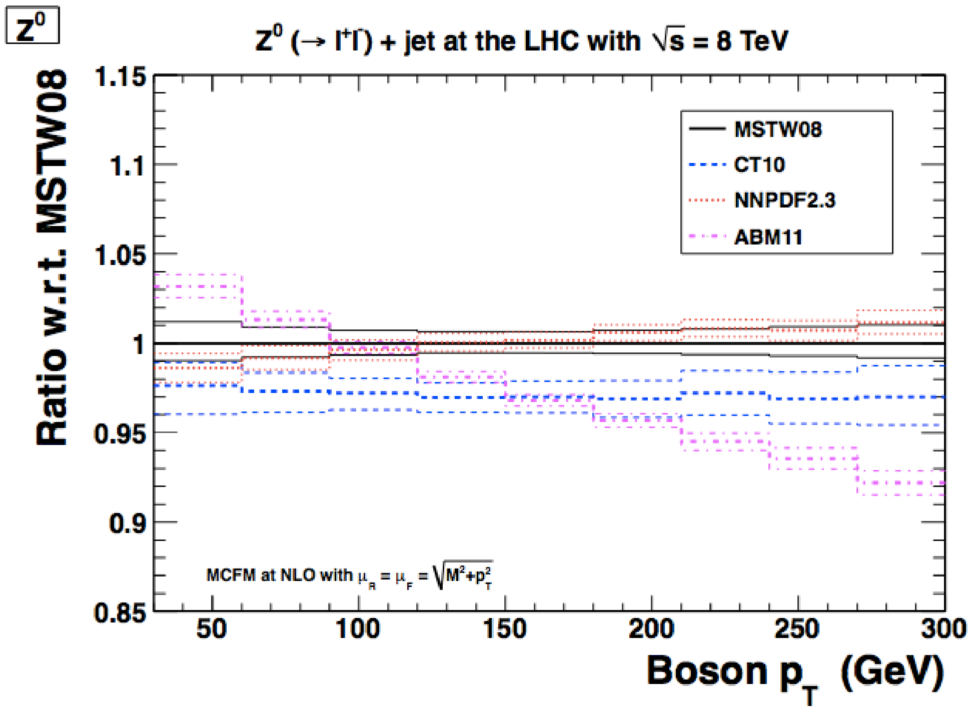


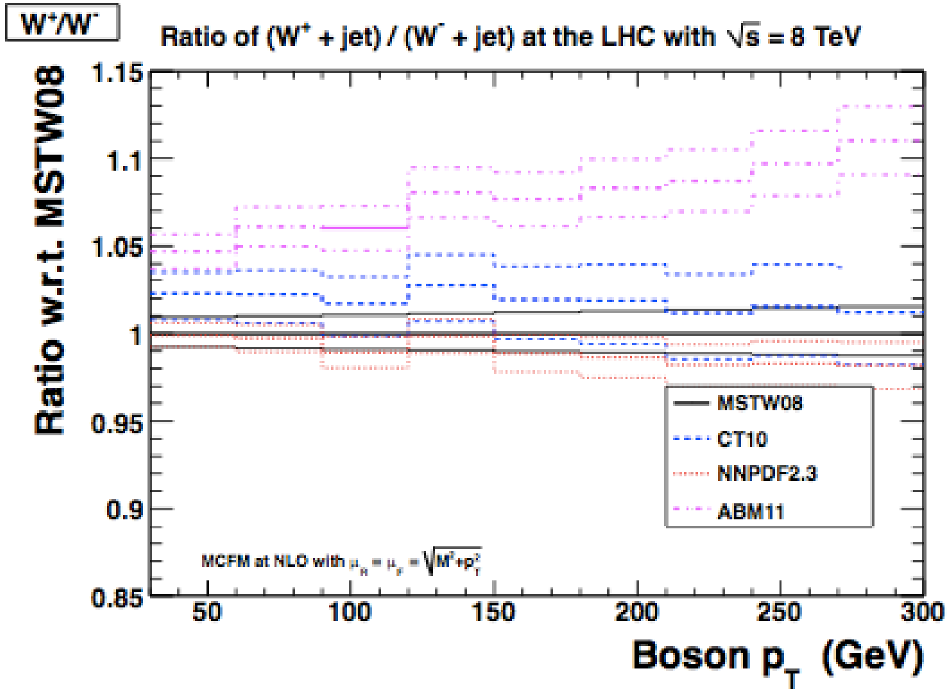
Unless EW corrections are included in the calculations, we might end up removing possible differences between data and QCD predictions for the Z pt spectrum by retuning the QCD MCs!

Very-high pt data on the Z pt spectrum are crucial to assess that the effect is indeed so large!

Large-pt production of gauge bosons as a probe of gluon PDF in the region of relevance to gg→H production

S.Malik and G.Watt, arXiv:1304.2424





NB Already at 300 GeV the EW effects are as large as the PDF uncertainties we'd like to eliminate ....

⇒ great potential for becoming a crucial element in the PDF measurement programme, will need the calculation of $d\sigma/dp_T(Z)$ at NNLO -- in progress..,

Define

$d\sigma_{jj}(W)$:

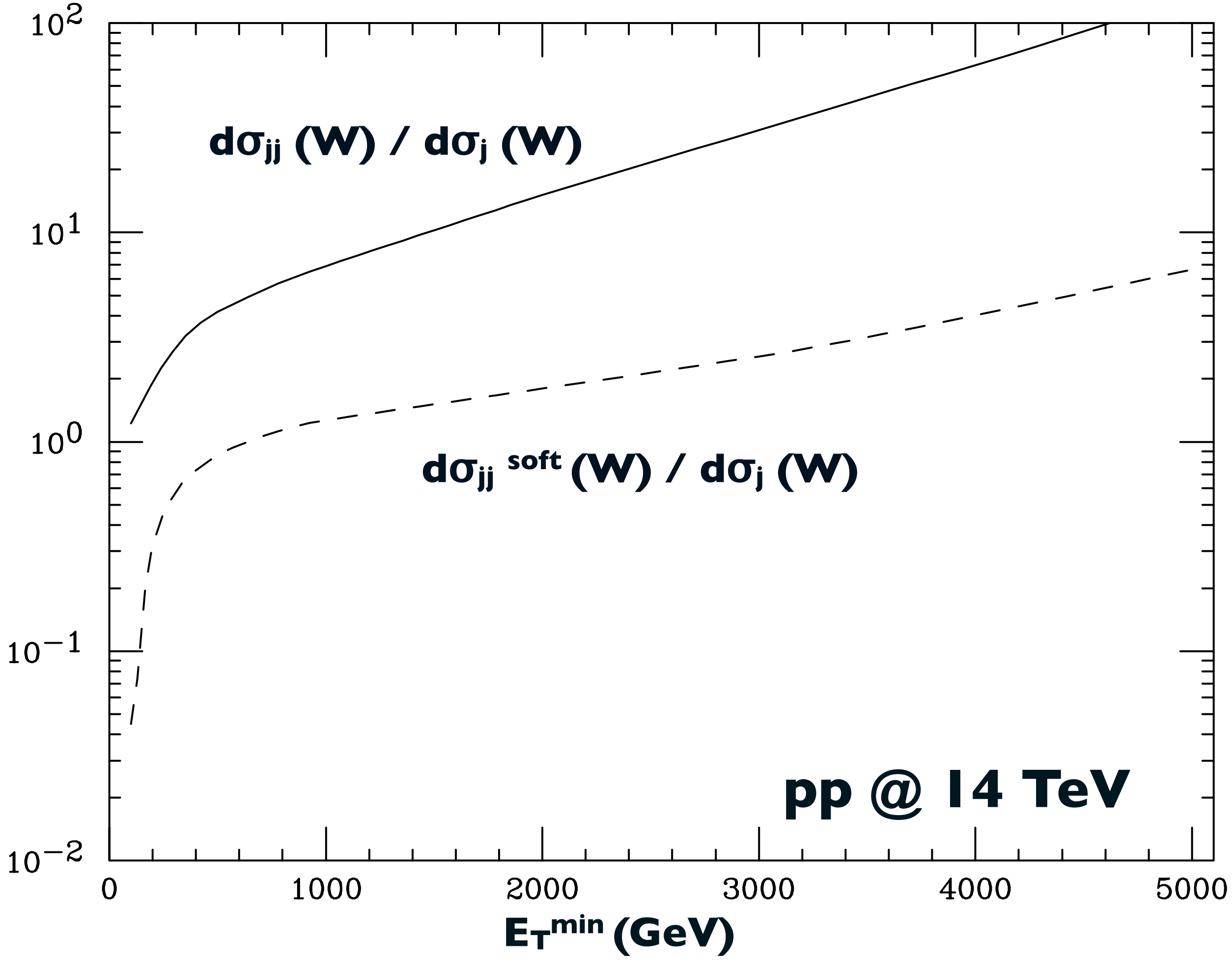
inclusive W production rate, in events with 2 jets of $E_T>30$ GeV, $|\eta|<5$, with $E_T^{\text{(leading jet)}} > E_T^{\min}$

$d\sigma_{jj}^{\text{soft}}(W)$:

same, with $E_T^{\text{jet 1}} < 0.2 \times E_T^{\text{jet 2}}$

$d\sigma_{j}(W)$:

same, with just 1 jet

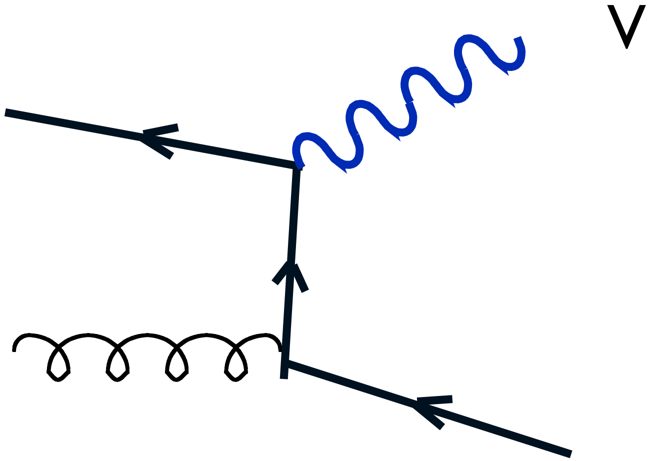


- $\sigma_j \ll \sigma_{jj} \Rightarrow$ the dynamics is dominated by kinematical configurations other than W+jet

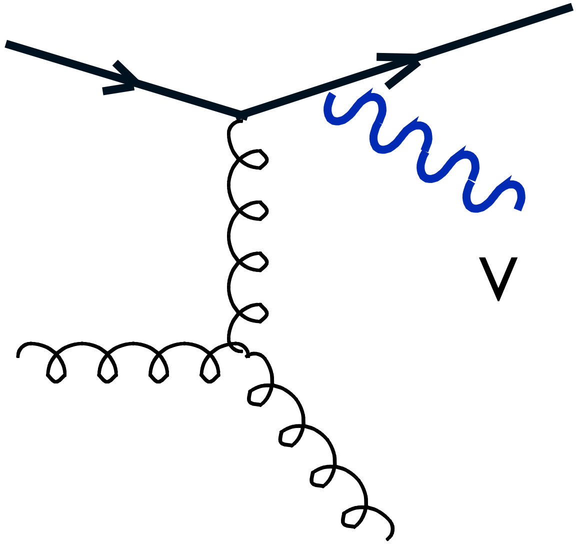
- $\sigma_{jj}^{\text{soft}} \ll \sigma_{jj} \Rightarrow$ the rate is dominated by final states with a second hard jet, so $E_T^{\min} > 30$ GeV protects against large logs

Production of gauge bosons in high-energy final states ($\sqrt{s} \gg M_V$)

$O(\alpha_s)$



⇒ $\sqrt{s} \approx p_T^V \gg M_V$

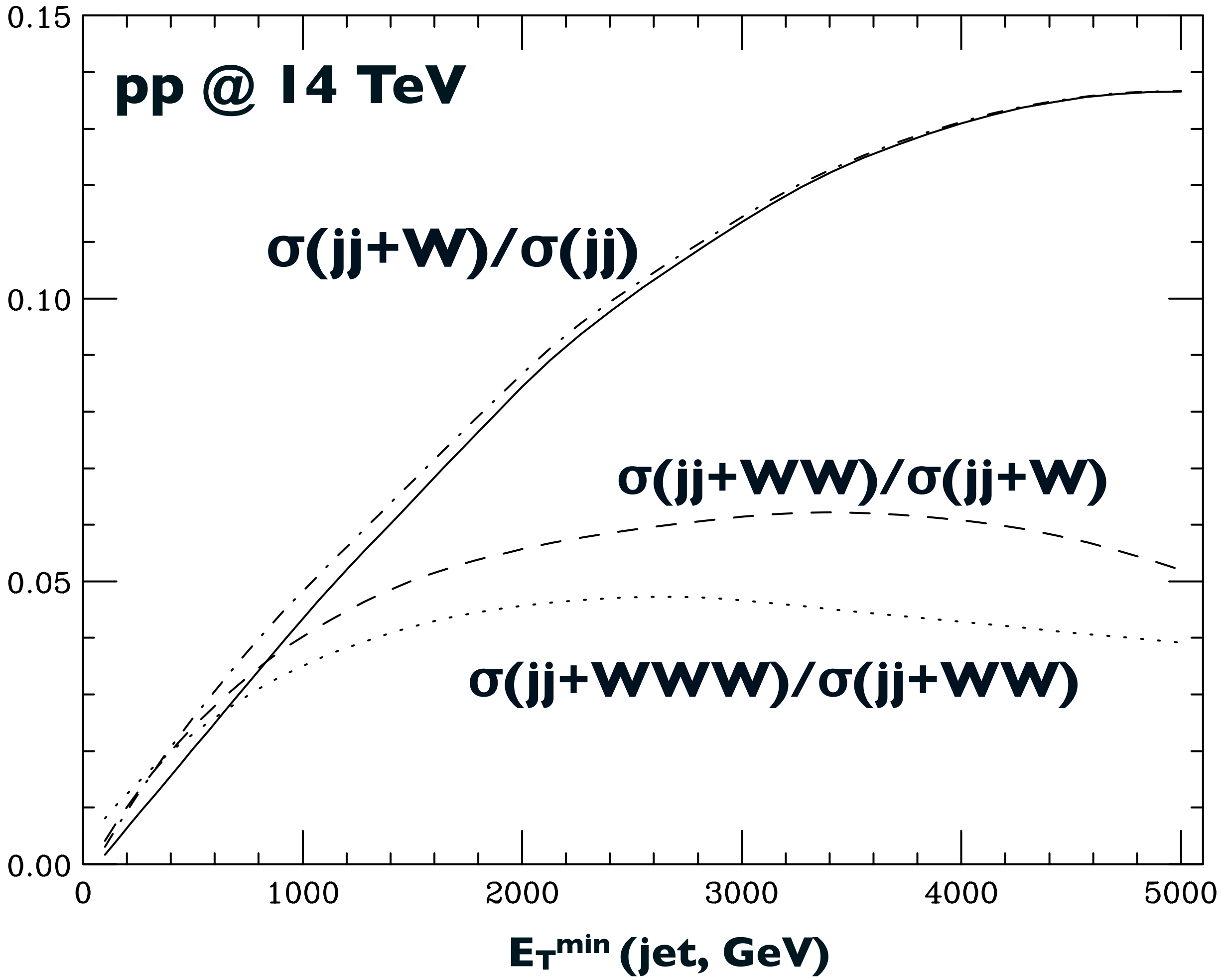


$O(\alpha_s^2)$, but enhanced by t-channel g exchange, and by $\log(p_T^{jet}/M_W)$

⇒ could be larger than $O(\alpha_s)$

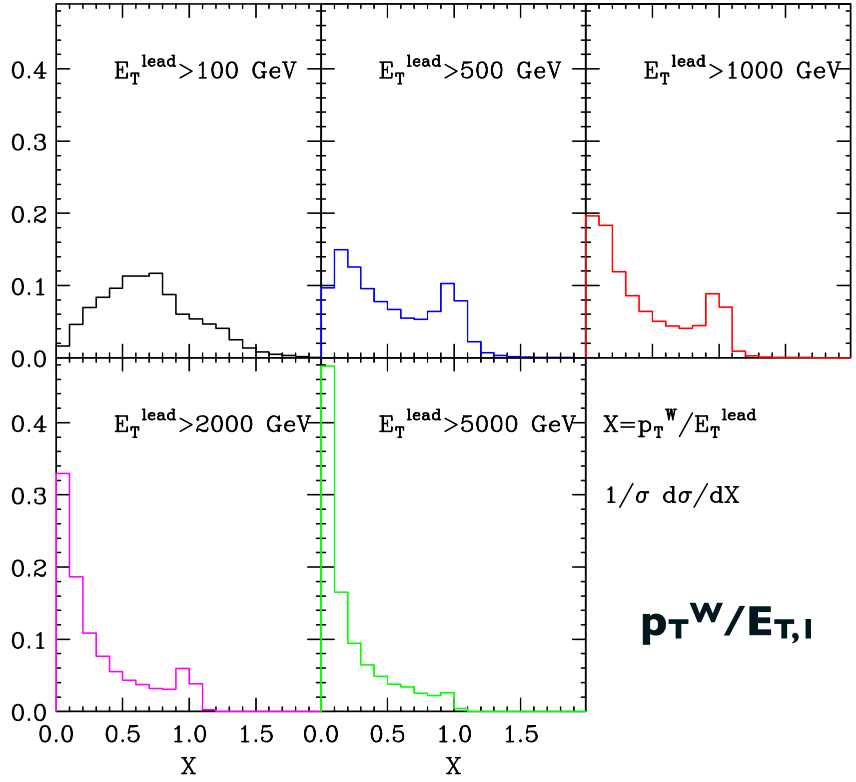
⇒ no strong ordering between p_T^V and M_V

W production, in events with high-E_T jets

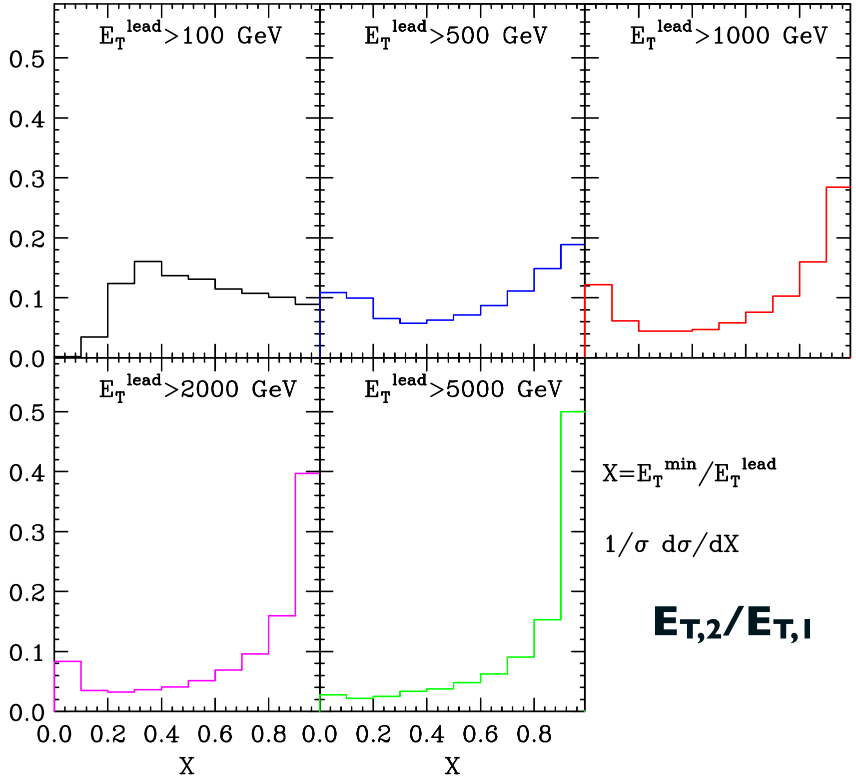


Dotdashes: σ(jj) in the denominator replaced by σ(jj, no gg→gg)

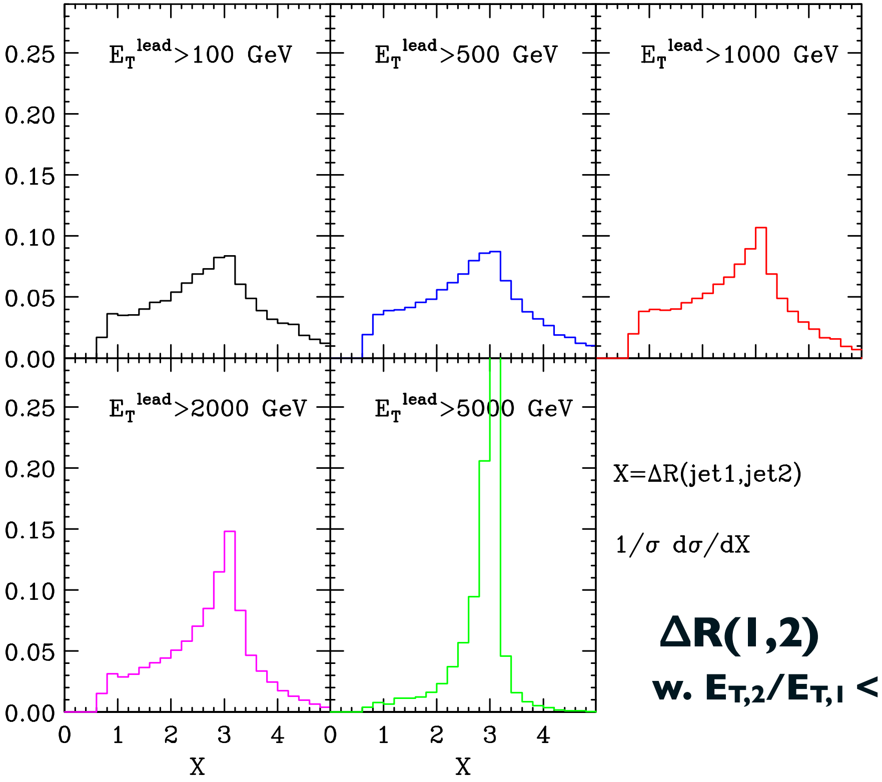
- **Substantial increase of W production at large energy: over 10% of high-ET events have a W or Z in them!**
- **It would be interesting to go after these W and Zs, and verify their production properties**



$p_T^W/E_{T,1}$

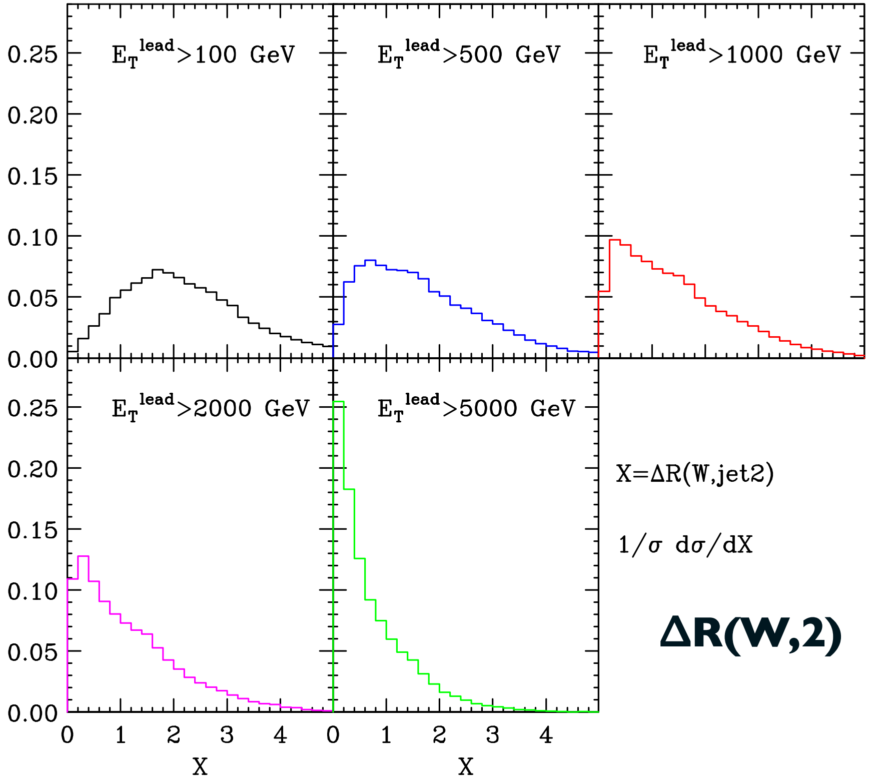


$E_{T,2}/E_{T,1}$



ΔR(1,2)

w. $E_{T,2}/E_{T,1}$ < 0.2



ΔR(W,2)

Multi-gauge boson production:

WWW → 3lept's

$\sigma(W) = 100$ nb

$\sigma(WW) = 50$ pb $\qquad \sigma(WW) / \sigma(W) = 0.5 \times 10^{-3}$

$\sigma(WWW) = 60$ fb $\qquad \sigma(WWW) / \sigma(WW) = 10^{-3}$

$\sigma(WWW \rightarrow 3\ell) = 0.7$ fb $\Rightarrow$ 20 events/30 fb^{-1} $\qquad \ell = e, \mu$

ZWW → 4lept's

$\sigma(Z) = 30$ nb

$\sigma(ZW) = 20$ pb $\qquad \sigma(ZW) / \sigma(Z) \sim 10^{-3}$

$\sigma(ZWW) = 50$ fb $\qquad \sigma(ZWW) / \sigma(ZW) \sim 2 \times 10^{-3}$

$\sigma(ZWW \rightarrow 4\ell) = 0.15$ fb $\Rightarrow$ 5 events/30 fb^{-1} $\qquad \ell = e, \mu$

$\sigma(W) / \sigma(Z) \sim 3$

$\sigma(WW) / \sigma(ZW) \sim 2.5$

$\sigma(WWW) / \sigma(ZWW) \sim 1.2$

Ratio determined by couplings to quarks, u/d PDF

↓

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