QCD at the LHC: status and prospects

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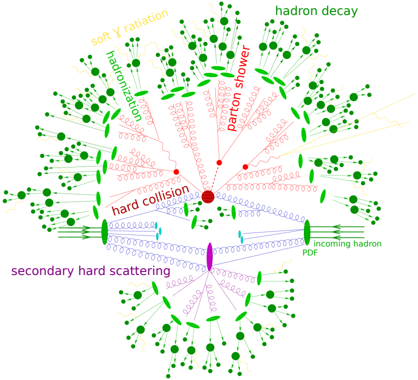
Thanks to factorization LHC hard hadronic collision described by:

- structure of the proton f
- hard scatter with perturbative theory

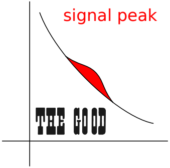
$$\sigma_X(p_1, p_2) = \sum_{a,b} \int_0^1 dx_1 dx_2 f_a(x_1 p_1, \mu_F^2) f_b(x_2 p_2, \mu_F^2) \times$$
$$\times \hat{\sigma}_{a,b\to X}\left(x_1, x_2, \alpha_s(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}\right)$$

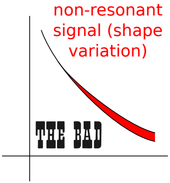
- parton shower, hadronisation and underlying event (UE) approximated by MC with tunable parameters
- All these aspects can be constrained by experimental results

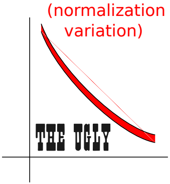


credit: sherpa-and-open-science-grid-predicting-emergence-jets

- perturbative QCD test in new phase space region: many measurements became sensitive to effects beyond NLO QCD
- QCD have a direct impact on the potential for precision measurements and discoveries
- is the background of most of the physics process (such as Higgs, BSM, ...)
- MC event generators have a large number of parameters related to non-perturbative (NP) effects
  - Improvement of Underlying Event description
  - Constrain proton-PDF: large systematics in many analyses ($gg \to H$, $t\bar{t}$, ...)
- Measure $\alpha_s(Q)$
- Probes: jets, photons, vector bosons



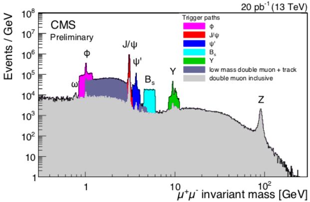


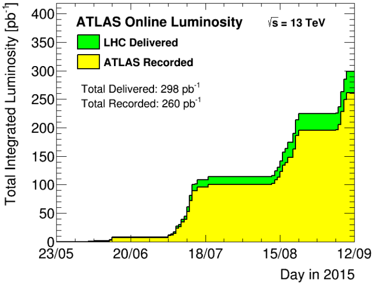


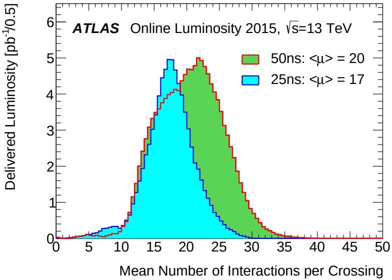
LHC and experiments status

13 TeV

- Run 2 started: $200\,\mathrm{pb}^{-1}$ at $\sqrt{s} = 13\,\mathrm{TeV}$
  - Run 1 ended in 2012: $5\,\mathrm{fb}^{-1}$ (7 TeV) + $20\,\mathrm{fb}^{-1}$ (8 TeV)
- New results using 50 ns data, L between $170\,\mu\mathrm{b}^{-1}$ and $85\,\mathrm{pb}^{-1}$
- Preliminary luminosity uncertainty: 9%
  - was 1.8-2.8% in Run1

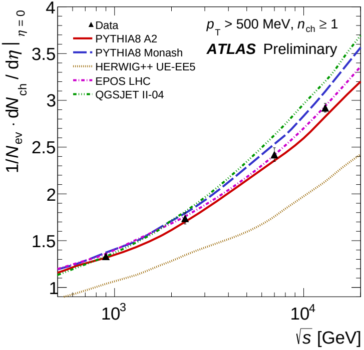


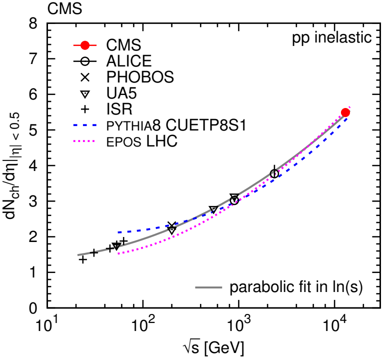




- CMS magnet issue: problems with the cryogenic system in providing liquid Helium. Currently the magnet can be operated, but the continuous uptime is still limited.

- Inclusive charged-particle measurements provide insight into the strong interaction in the low energy, non-perturbative QCD region
  - described by QCD-inspired models implemented in MC event generators with free parameters that can be constrained by measurements
- ATLAS: 1 charged particle with $p_T > 500\,\mathrm{MeV}$ and $|\eta| < 2.5$. Require exactly 1 PV.
- CMS: zero magnetic field. Two analyses: hit pairs in pixel (tracklet), tracks

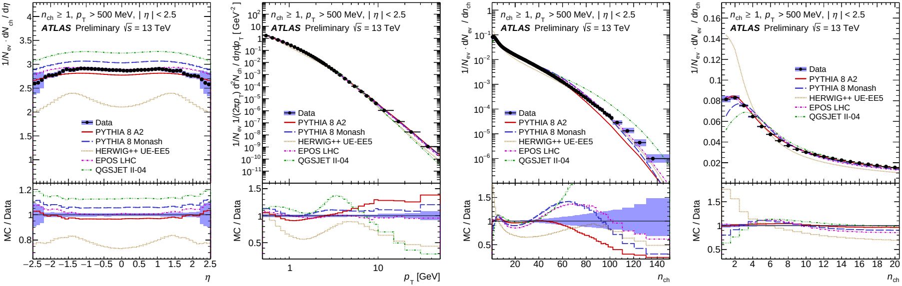


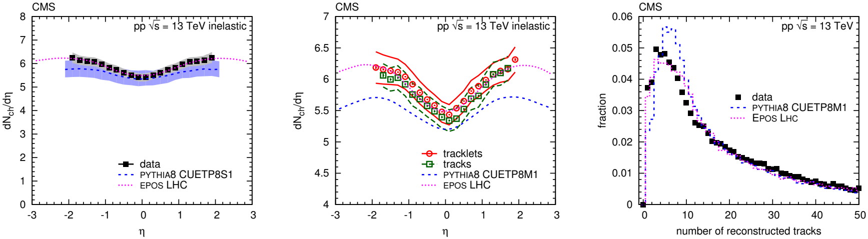


- EPOS and PYTHIA 8 A2 describe the dependence on $\sqrt{s}$ very well

Minimum bias
Differential distributions

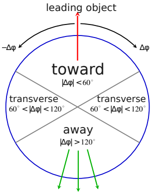
13 TeV



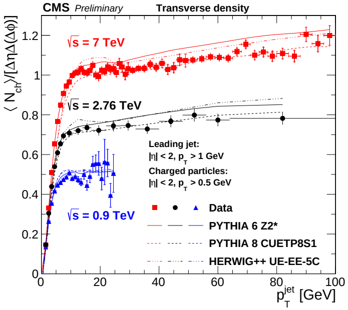


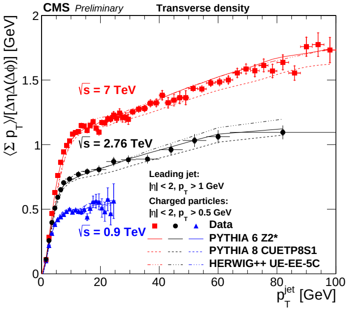
- the EPOS and PYTHIA 8 tunes describe the data most accurately

- Indirect study: impossible to separate UE from hard process
- Observables: densities of particle multiplicity and E_T flow as functions of $\Delta\phi$ angle between leading object (tracks, jets, Z)
- Transverse and toward (only Z) regions are sensitive to the UE

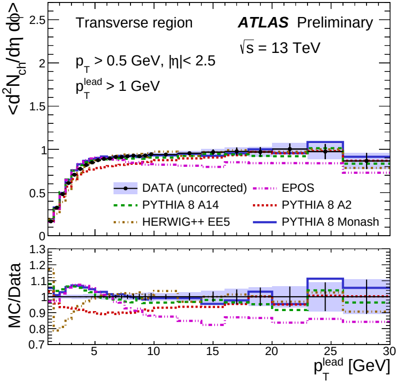


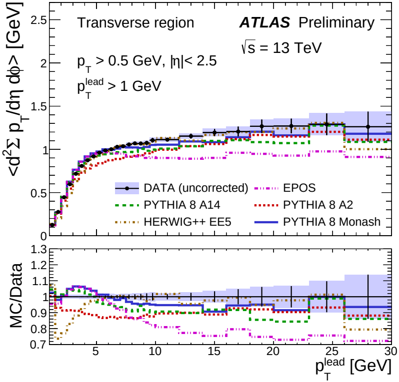
- NEW result at $\sqrt{s} = 2.76$ TeV using jets:





- Require leading track $p_T > 1$ GeV, exactly 1 PV
- Detector level distribution



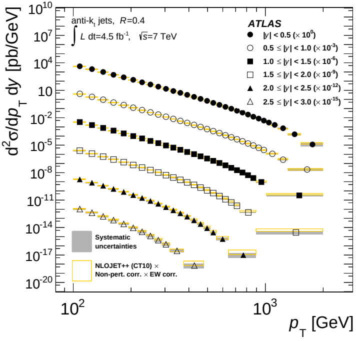


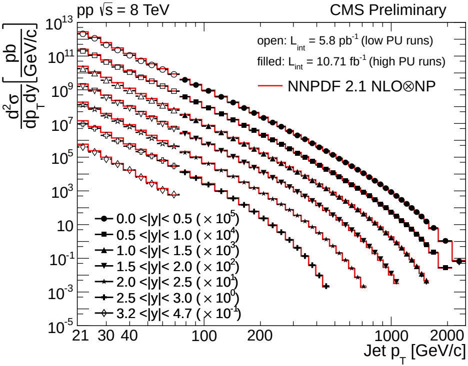
- +20% of UE wrt 7 TeV
- discriminating power between different MC models, most models describe the data reasonably. EPOS has no hard component.

Inclusive jet cross section

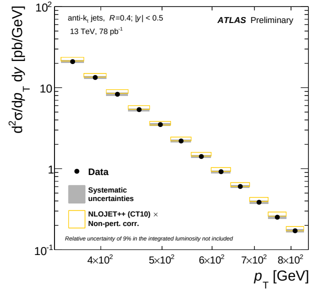
8 TeV: CMS-PAS-SMP-12-012, CMS-PAS-FSQ-12-031; 2.76/8: CMS-PAS-SMP-14-017
7 TeV: Phys. Rev. D 87 (2013) 112002, JHEP02(2015)153, 2.76/7: EPJC (2013) 73 2509

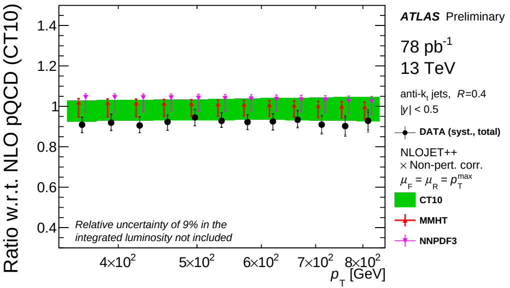
- test pQCD over many orders of magnitude (20 GeV-2 TeV), different $\sqrt{s}$.
- sensitive to soft QCD using different jet clustering
- sensitive to α_s and PDF (gluon, high-x)
- experimental unc: jet energy scale, luminosity; theory unc: PDF, scale, NP corrections, α_S
- Cross section ratios (comparing different $\sqrt{s}$) partially cancel the correlated uncertainties





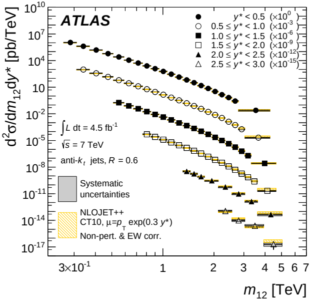
- Anti-k_T, $R = 0.4$, $|y| < 0.5$

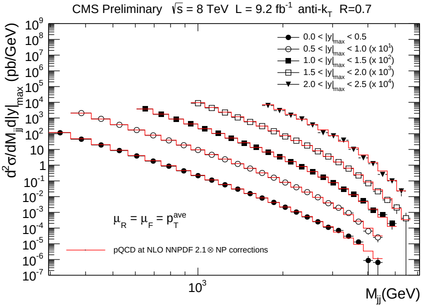




- The predictions are consistent with the data, and more precise measurements over a wider kinematic region are foreseen as more data are collected.
- compare data NLO QCD calculation (NLOJET++) with different PDFs

- Constrain gluon PDF at high-x, discriminate between PDF sets (e.g. p-value ABM11 $< 0.1\%$)
- NLO prediction + NLO EW + NP: NLOJet++, POWHEG



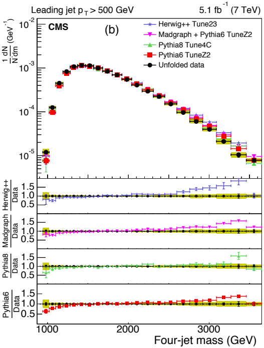


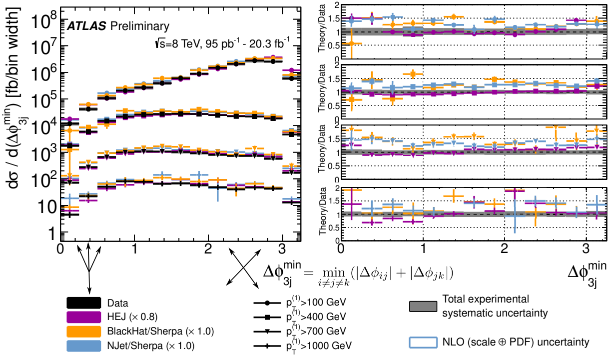
- dominant uncertainty: jet energy scale
- good agreement with NLOJET++ prediction

Multijet cross section

Eur. Phys. J. C 75 (2015) 302

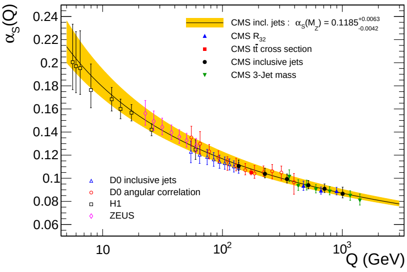
- CMS: Topological variables sensitive to QCD color factors, spin of the gluons, hadronisation models.
  - Discrepancy at high mass from all models may be due to PDF errors (CTEQ6).

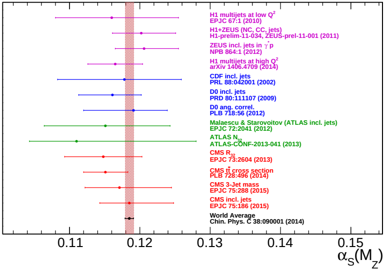




- ATLAS NEW: four-jet differential cross sections in $\sqrt{s} = 8$ TeV, several variables depending on the jet momenta and angular distributions
  - NLO predictions (BlackHat/Sherpa and NJet/Sherpa): compatible with data within large theoretical uncertainties (O(30%) at low momenta)
  - HEJ (all-order resummation) provides a good description of angular variables

- only parameter of QCD (except for quark masses)
- Many measurement sensitive: inclusive jet cross section, 3-jet mass, R_{32} (3-jet/2-jet cross section), event shapes (ATLAS), $t\bar{t}$ cross section (CMS)
- At LHC it is possible to measure $\alpha(Q)$ at high-Q $\rightarrow$ sensitive to New Physics





- Good agreement with prediction from analysis a 2-loop solution to the RGE as a function of the scale Q up to TeV scale
- Very precise $\alpha_s(M_Z)$ from $t\bar{t}$ + CT10: 2.4% (also thanks to NNLO predictions):

$$\alpha_s(M_Z) = 0.1151 \pm 0.0018(\sigma_{tt}^{\text{meas}})^{+0.0018}_{-0.0016}(\text{PDF})^{+0.0008}_{-0.0007}(\mu_{R,F})^{+0.0012}_{-0.0013}(m_t^{\text{pole}}) \pm 0.0007(E_{LHC})$$

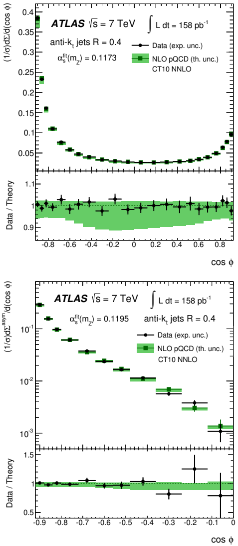
- Similar technique used in e^+e^- and HERA using multijet.
- less affected by experimental effects and PDF than absolute cross-section measurements.

$$TEEC = \frac{1}{\sigma}\sum_{ij}\int \frac{d\sigma}{dx_{T_i}dx_{T_j}d(\cos\phi)} x_{T_i}x_{T_j}dx_{T_i}dx_{T_j}$$

$$ATTEC = TEEC|_{\phi} - TEEC|_{\pi-\phi}$$

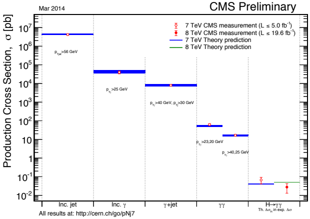
$x_{T_i} = E_{T_i}/\sum_k E_{T_k}$ $\phi =$ azimuthal angle between two jets
sum over all the jet pairs

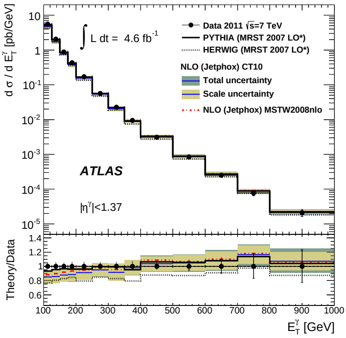
- Experimental distributions in agreement with NLO calculation
- Optimize $\chi^2(\alpha_s)$ varying NLOJet++ prediction
- Precise $(+5.6\%, -2.4\%)$ $\alpha_s(M_Z)$ from TEEC with CT10

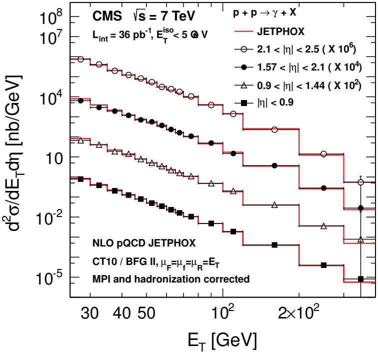


$$\alpha_s(M_Z) = 0.1173 \pm 0.0010(\text{exp})^{+0.0063}_{-0.0020}(\mu_{R,F}) \pm 0.0017(\text{PDF}) \pm 0.0002(\text{NPC})$$

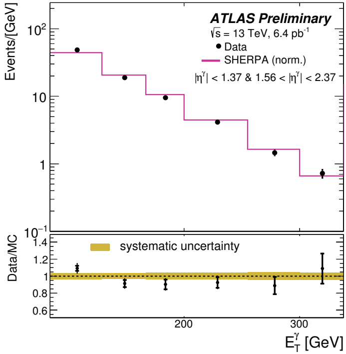
- pQCD test in a cleaner environment, less hadronisation
- Isolation requirement to avoid the large contribution of photons from neutral-hadron decays
- can be used to constrain PDF (ATL-PHYS-PUB-2013-018)

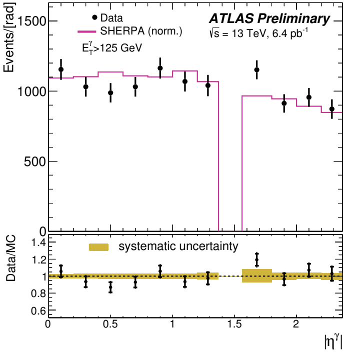






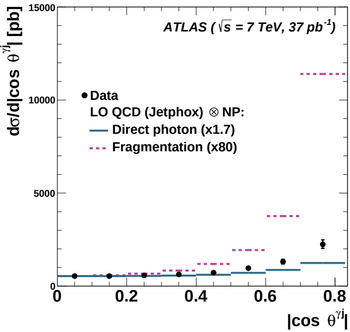
- $6.4\,\text{pb}^{-1}$, $E_T^\gamma > 125$ GeV, $|\eta^\gamma| < 2.37$ except crack region
- $E_T^{\text{iso}} < 4.8\,\text{GeV} + 4.2 \times 10^{-3} \times E_T^\gamma$
- comparison with Sherpa 2.1+CT10 full simulation, no unfolding

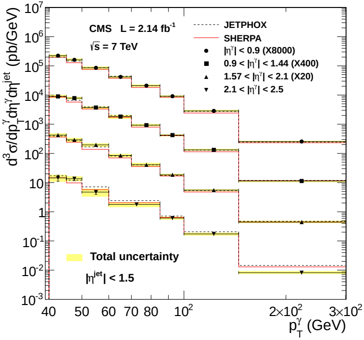




- Main uncertainty: photon energy scale (2-8%)

- angular correlation between γ and j, $\cos\theta^* = \tanh(\Delta y/2)$ sensitive to spin of exchanged particle, separation of fragmentation
- can constrain PDF (EPL 101 (2013) 61002)
- reducible background of $H \to \gamma\gamma$
- can be used to tune the relative contributions of direct and fragmentation processes
- used to calibrate jets



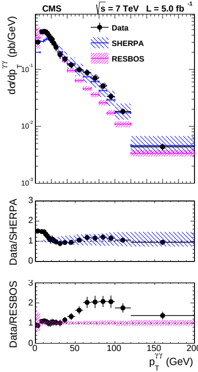


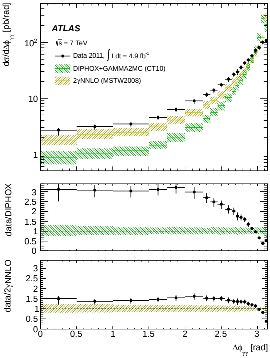
- The NLO QCD provides good description of the data, except for $\Delta\phi_{\gamma j}$

Diphoton cross section

JHEP01(2013)086, Eur. Phys. J. C 74 (2014) 3129

- pQCD test, sensitive to fragmentation ($\Delta\phi_{\gamma\gamma}$, $p_T^{\gamma\gamma}$), spin of intermediate resonances ($\cos(\theta^*_{\gamma\gamma})$). Important NNLO box contribution.
- irreducible background of $H \to \gamma\gamma$
- challenging predictions: production is sensitive to the emission of soft gluons in the initial state and to the NP fragmentation





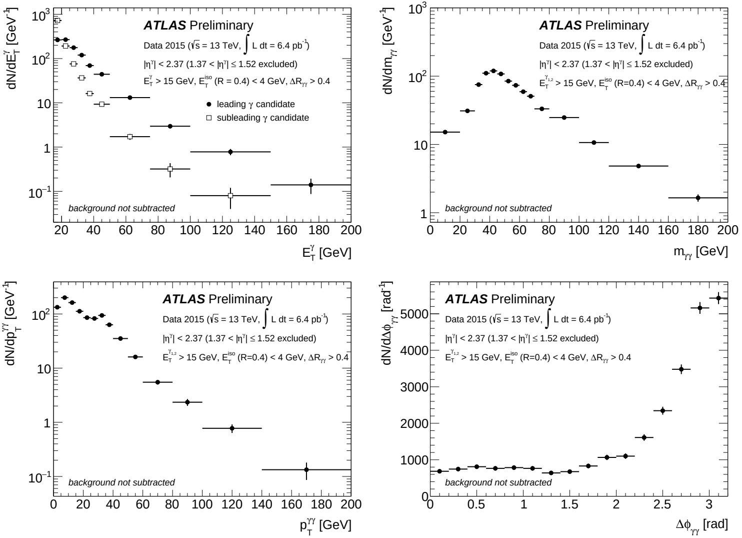
- 2γ NNLO and Sherpa predict the $p_T^{\gamma\gamma}$ shoulder $\simeq 65\,\mathrm{GeV}$ GeV observed in the data. This is expected since Sherpa includes up to three extra jets at the matrix element level.
- larger disagreement in low $\Delta\phi_{\gamma\gamma}$: expected because initial-state soft gluon radiation is divergent at NLO, without soft gluon resummation

Di-photons studies @ 13 TeV

ATL-PHYS-PUB-2015-020

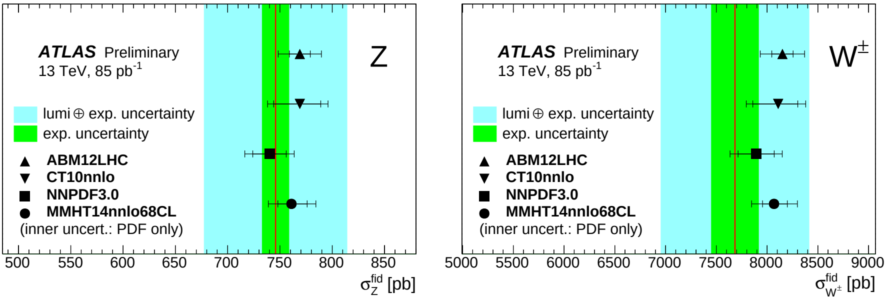
13 TeV

- 6.4 pb^{-1}, $E_T^{\gamma} > 15$ GeV, $|\eta^{\gamma}| < 2.37$ except crack region, $E_T^{\text{iso}} < 4$ GeV, $\Delta R_{\gamma\gamma} > 0.4$
- background not subtracted ($\simeq 40\%$ of the leading, $\simeq 50\%$ of the subleading)



13 TeV

- Test of QCD (NNLO predictions)
- Fiducial cross section of Z and $W^{\pm}$ production at 13 TeV.

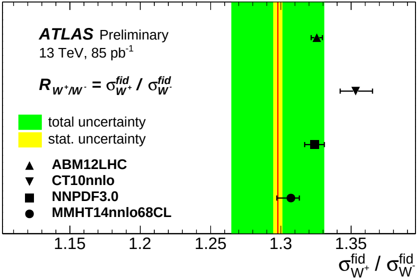


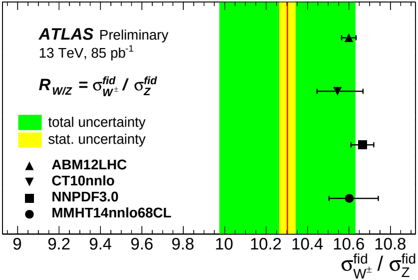
- Cross section experimental precision is already comparable to PDF uncertainties (except for preliminary 9% luminosity error)
- Factor $\simeq$ 2 comparing $\sigma_{13\,\text{TeV}}/\sigma_{7\,\text{TeV}}$
- In addition boson production can constrain PDF from p_T and y distribution (major theoretical uncertainty on inclusive cross section)

$W^{\pm}$ and Z boson production
Ratios of cross sections

13 TeV

- Many uncertainties cancel in ratios of cross sections (luminosity)
- Powerful tools to constrain PDF uncertainties:
  - $R_{W/Z}$ constrains the s-quark distribution, also depends on EW parameter and Br
  - R_{W^+/W^-} is mostly sensitive to the difference of u_v and d_v distributions at low x. Starting from a precision of about 2% (now 2.5%), R_{W^+/W^-} begins to have significant constraining power to PDFs [arXiv: 0901.0002 [hep-ph]]





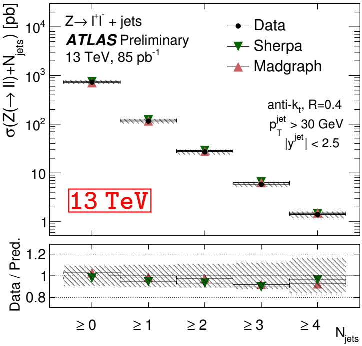
- R_{W^+/W^-}: accuracy of the experimental result is comparable to the spread among predictions with different PDFs: 2.5% precision
- $R_{W/Z}$: predictions agree within the uncertainties (3.2%)

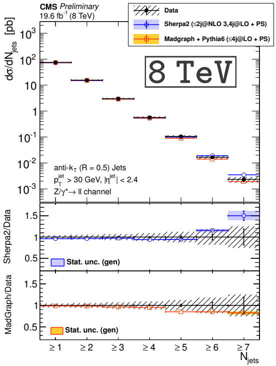
$Z + \text{jets}$

CMS-PAS-SMP-13-007, Eur. Phys. J. C (2015), ATLAS-CONF-2015-041

13 TeV

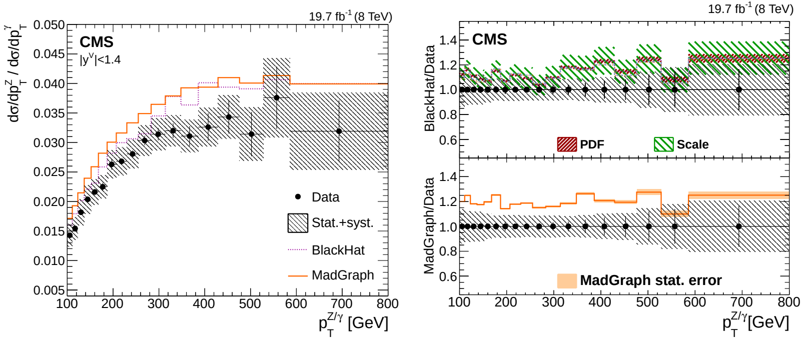
- almost background free
- test of pQCD, background for Higgs boson and exotics





- Data/theory discrepancy used to improve MC
- ATLAS 13 TeV: matrix elements are calculated for up to two partons at NLO, and up to four additional partons at LO. One of the first analysis to use Sherpa 2.1

- At high p_T^V and at LO $\sigma_{Zj}/\sigma_{\gamma j}$ as a function of p_T is expected to become constant
- At higher energies, EW corrections and QCD processes can introduce a dependence of the cross section on logarithmic terms of the form $\log(p_T^Z/m_Z)$ that can become large
- jet and luminosity uncertainties cancel in the ratio $R_{\text{dilep}} = \frac{\sigma_{Z\to ll}(p_T^Z > 314\,\text{GeV})}{\sigma_{\gamma}(p_T^{\gamma} > 314\,\text{GeV})}$

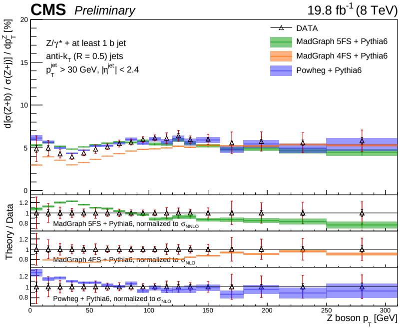


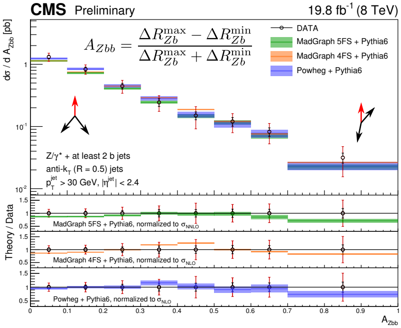
- MADGRAPH+PYTHIA6 (LO+PS) overestimate R_{dilep} by 1.21 ± 0.08, BlackHat (NLO) by 1.18 ± 0.14. Similarly for $n_{\text{jet}} \geq 1, 2, 3$ or $H_T > 300\,\text{GeV}$ and $n_{\text{jets}} \geq 1$.
- simulations reproduce p_T^Z / p_T^{γ} better than the individual p_T^Z or p_T^{γ}

$Z + b$ jet cross section

CMS-PAS-SMP-14-010

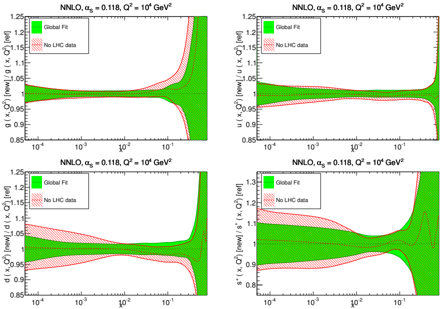
- $pp \to Z + (\geq 1b)$ dominant background for HZ and many BSM or $+(\geq 2b)$
- differential cross section σ_{1b}, σ_{2b} ratio $\sigma_{1b}/\sigma_{\text{jet}}$
- LO MADGRAPH 5 (4 partons in the final state) (4FS/5FS) rescaled to NNLO FEWZ inclusive cross section. NLO POWHEG (5FS)
- Many variables sensitive to b-PDF, gluon splitting, gluon radiation in the final state and New Physics.

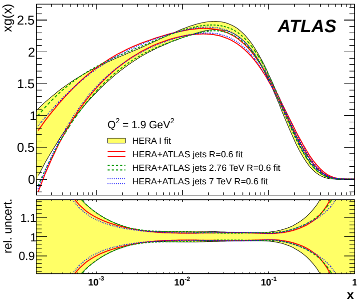




- General good agreement. 4FS normalization is underestimated by about 20%. 4FS fails to describe the $\sigma_b/\sigma_{\text{jet}}$ vs the leading b-jet p_T

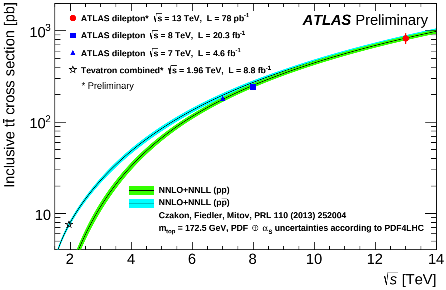
- important theoretical uncertainty (ggH, W precision, New Physics at high energy, ...)
- quark PDF constrained from vector bosons (asymmetry, $W + c$, $Z + b$ not yet) and DY at high/low-mass
- Associate production of heavy quarks may be sensitive to sea contribution, but scale uncertainty still dominant
- Top production can be important in the high-x region
- Jet measurements constrain gluon (and quarks) at mid-to-high x
- photon-jet with lower systematics can constrain gluon and light-quark PDF.

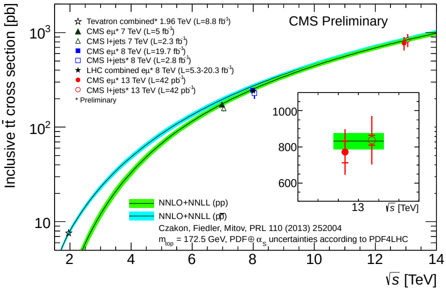




- See more in Alberto's talk

- only 2% of $t\bar{t}$ decay in $e\mu$ channel, but high purity
- test of QCD, domanainated by gluon-gluon fusion. Sensitive to gluon PDF, α_s, m_t, NP
- inclusive cross section from TOP++2: NNLO pQCD + NNLL soft gluon resummation
- use as observables the number of events with 1 or 2 b-jets





- Main uncertainties: luminosity, hadronisation model, electron efficiency. Statistical error quite important at 13 TeV.
- Measurement (uncertainty $\sim$ 15%, was $\sim$ 3.5% at 7,8 TeV) compatible with prediction (uncertainty $\sim$ 5%)

Conclusions

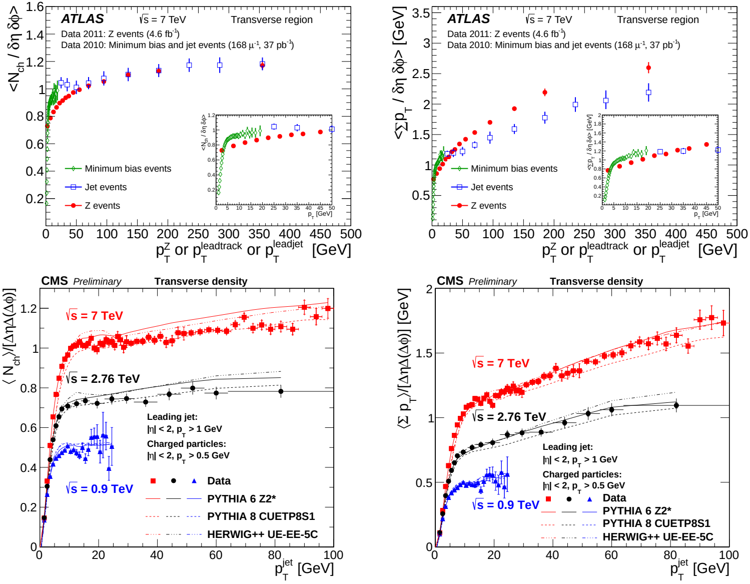
- LHC experiments have extended the pQCD tests in new kinematic regions using jets, photons and vector bosons:
  - jet production to multi-TeV scale
  - no deviations from the QCD RGE running are being observed up to TeV scale
  - ...
- Possible to tune MC simulation, e.g. gluon splitting
- Good understanding of QCD process very important at LHC: theoretical and experimental improvement
- Many measurements can constrain proton PDFs and some have been included in recent PDFs set
- The ratios of cross-sections (jets, V+j) between 13 TeV and 8 TeV are very interesting for PDF constraints
- Need for NNLO calculations for jet processes to improve precision of α_s. Theoretical scale uncertainties dominate.
- Many topics not covered in this talk, see ATLAS EXPERIMENT CMS

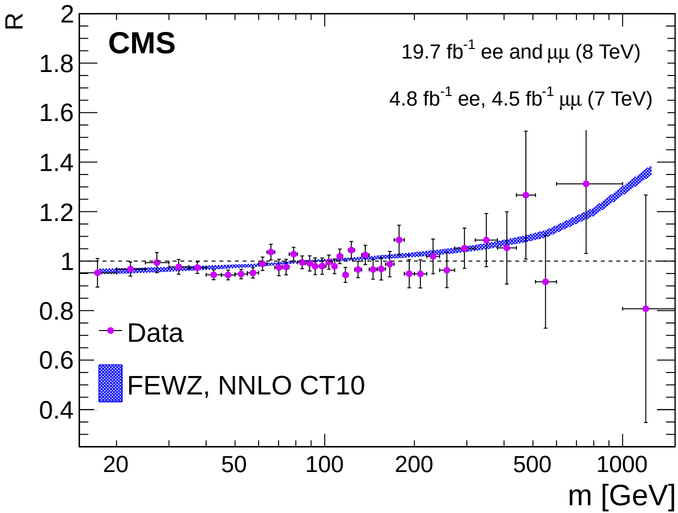
Section 3

Backup

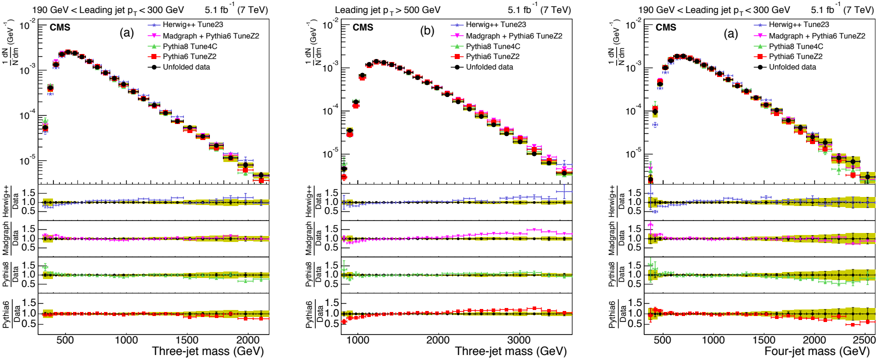
Underlying event at 7 TeV

Eur.Phys.J.C74 (2014) 2965





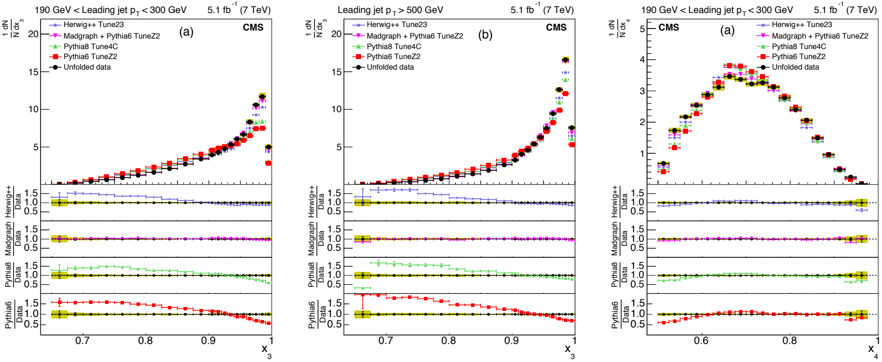
CMS
19.7 fb^{-1} ee and μμ (8 TeV)
4.8 fb^{-1} ee, 4.5 fb^{-1} μμ (7 TeV)
Data
FEWZ, NNLO CT10
R
m [GeV]
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
20
50
100
200
500
1000

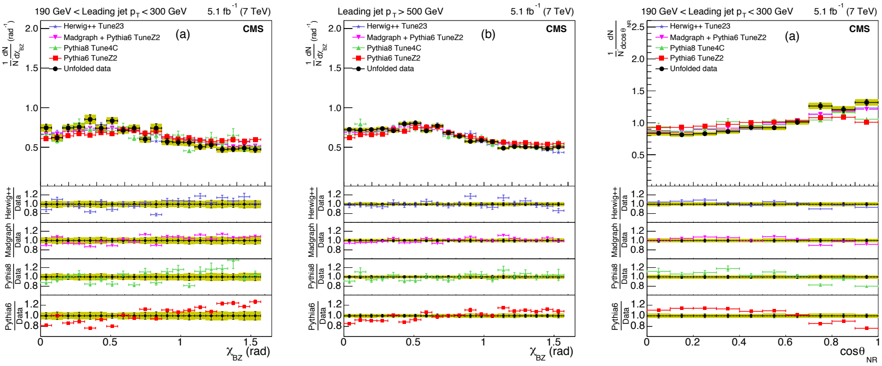


190 GeV < Leading jet p_T < 300 GeV
5.1 fb^{-1} (7 TeV)
CMS
(a)
Herwig++ Tune23
Madgraph + Pythia6 TuneZ2
Pythia8 Tune4C
Pythia6 TuneZ2
Unfolded data
$\frac{1}{N}\frac{dN}{dm}$ (GeV^{-1})
Herwig++ / Data
Madgraph / Data
Pythia8 / Data
Pythia6 / Data
Three-jet mass (GeV)
Leading jet p_T > 500 GeV
5.1 fb^{-1} (7 TeV)
CMS
(b)
Herwig++ Tune23
Madgraph + Pythia6 TuneZ2
Pythia8 Tune4C
Pythia6 TuneZ2
Unfolded data
Three-jet mass (GeV)
190 GeV < Leading jet p_T < 300 GeV
5.1 fb^{-1} (7 TeV)
CMS
(a)
Herwig++ Tune23
Madgraph + Pythia6 TuneZ2
Pythia8 Tune4C
Pythia6 TuneZ2
Unfolded data
Four-jet mass (GeV)

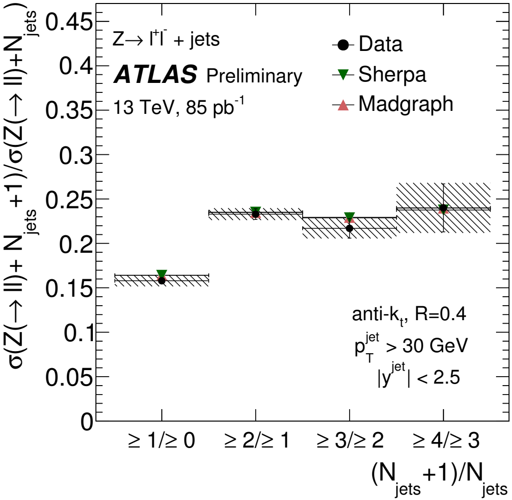
Multijet distributions

Eur. Phys. J. C 75 (2015) 302





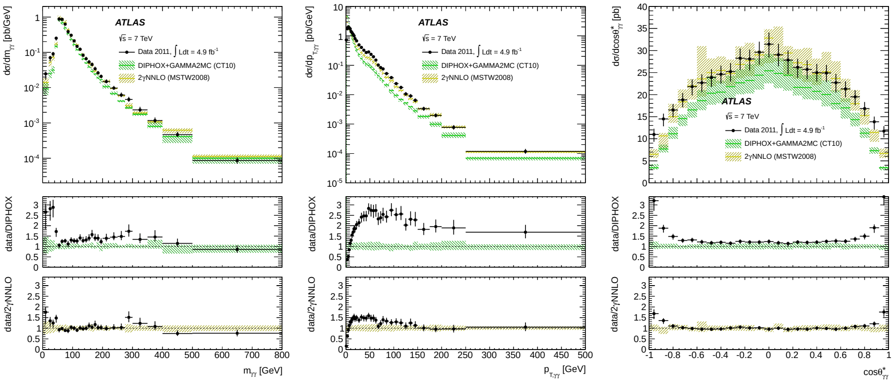
190 GeV < Leading jet p$_T$ < 300 GeV
5.1 fb^{-1} (7 TeV)
Herwig++ Tune23
Madgraph + Pythia6 TuneZ2
Pythia8 Tune4C
Pythia6 TuneZ2
Unfolded data
(a)
CMS
Herwig++ / Data
Madgraph / Data
Pythia8 / Data
Pythia6 / Data
χ_{BZ} (rad)
$\frac{1}{N}\frac{dN}{d\chi_{BZ}}$ (rad^{-1})
Leading jet p$_T$ > 500 GeV
(b)
$\frac{1}{N}\frac{dN}{d\cos\theta_{NR}}$
$\cos\theta_{NR}$



σ(Z(→ ll)+ N_jets +1)/σ(Z(→ ll)+N_jets)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Z→ l+l- + jets
ATLAS Preliminary
13 TeV, 85 pb-1
Data
Sherpa
Madgraph
anti-kt, R=0.4
pT jet > 30 GeV
|y jet| < 2.5
≥ 1/≥ 0
≥ 2/≥ 1
≥ 3/≥ 2
≥ 4/≥ 3
(N_jets +1)/N_jets

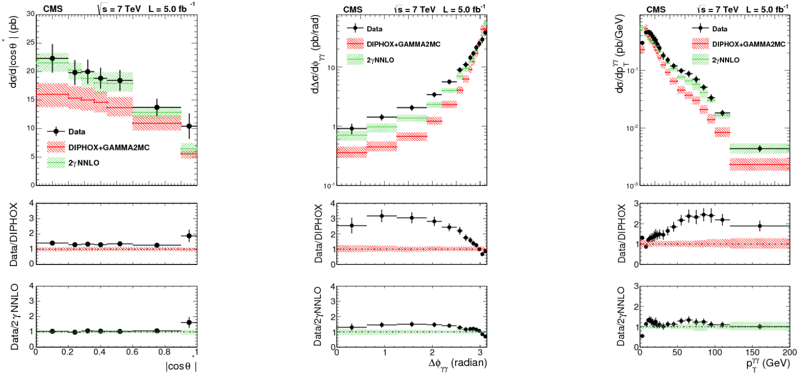
Diphoton cross section

JHEP01(2013)086



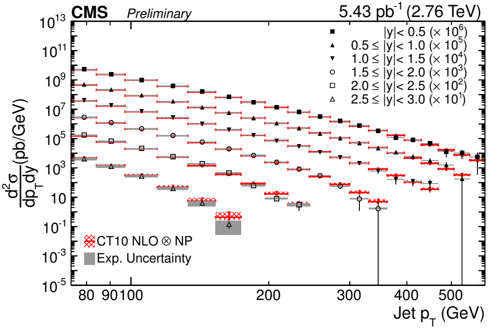
Diphoton cross section

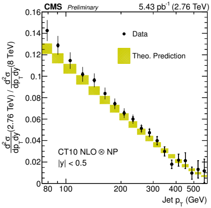
Eur. Phys. J. C 74 (2014) 3129

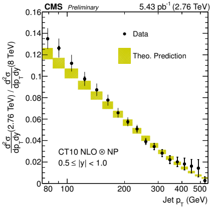


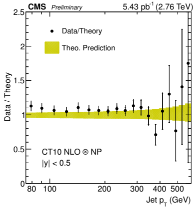
Jet at 2.76 TeV and ratio with 8 TeV

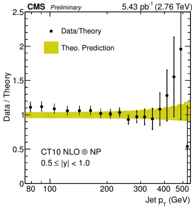
CMS-PAS-SMP-14-017





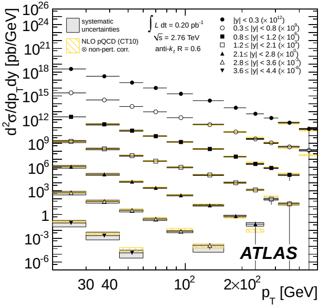


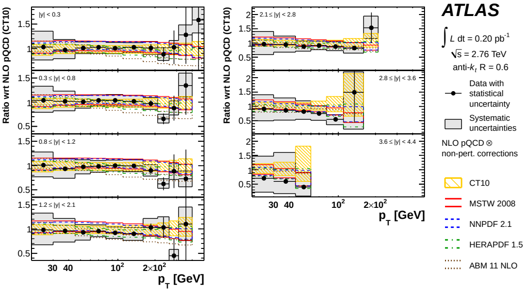




Jet at 2.76 TeV and ratio with 7 TeV

EPJC (2013) 73 2509

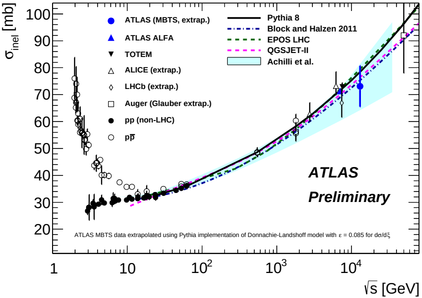


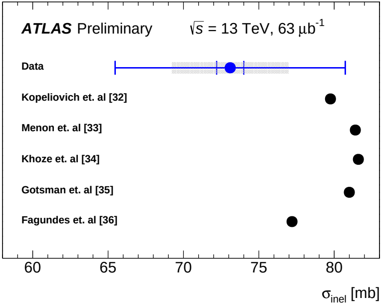


Inelastic cross section

ATLAS-CONF-2015-038

13 TeV

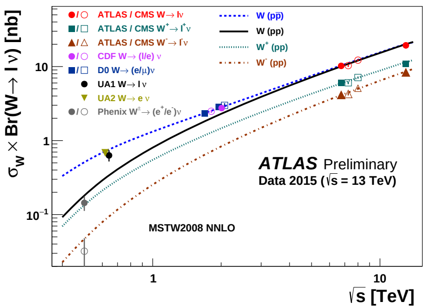


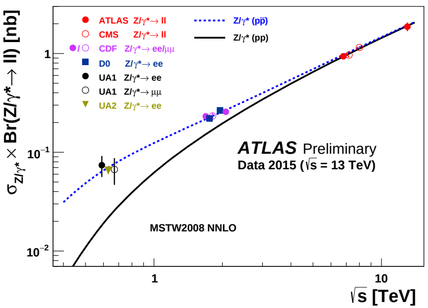


$$65.2 \pm 0.8(\text{exp.}) \pm 5.9(\text{lum.})\text{mb} \quad \text{fiducial region } M_X > 13\,\text{GeV}$$

$$73.1 \pm 0.9(\text{exp.}) \pm 6.6(\text{lum.}) \pm 3.8(\text{extr.})\text{mb}$$

13 TeV


ATLAS / CMS W→ lν
ATLAS / CMS W+→ l+ν
ATLAS / CMS W-→ l-ν
CDF W→ (l/e) ν
D0 W→ (e/μ)ν
UA1 W→ l ν
UA2 W→ e ν
Phenix W±→ (e+/e-)ν
W (pp̄)
W (pp)
W+ (pp)
W- (pp)
ATLAS Preliminary
Data 2015 (√s = 13 TeV)
MSTW2008 NNLO
σW × Br(W→ l ν) [nb]
√s [TeV]


ATLAS Z/γ*→ ll
CMS Z/γ*→ ll
CDF Z/γ*→ ee/μμ
D0 Z/γ*→ ee
UA1 Z/γ*→ ee
UA1 Z/γ*→ μμ
UA2 Z/γ*→ ee
Z/γ* (pp̄)
Z/γ* (pp)
ATLAS Preliminary
Data 2015 (√s = 13 TeV)
MSTW2008 NNLO
σZ/γ* × Br(Z/γ*→ ll) [nb]
√s [TeV]