ISMD2017, Tlaxcala city, Mexico

Measurements of the Vector boson production with the ATLAS Detector

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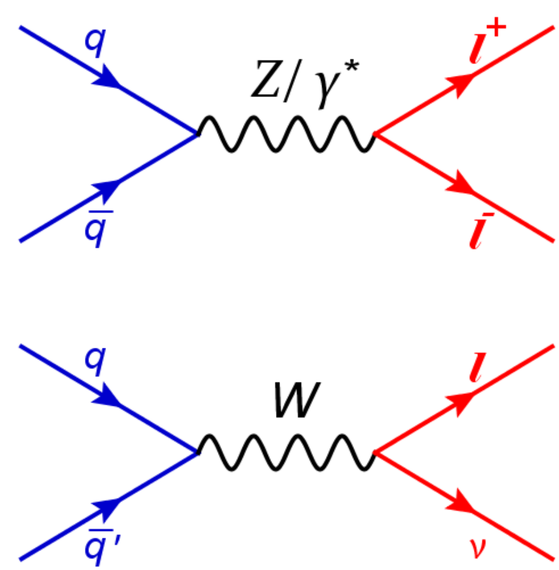
on behalf of the ATLAS experiment

11 September 2017

Motivation

- **W and Z boson production:**
  - clear signature
  - large statistics
  - small background contamination
- **W and Z boson are background to:**
  - SM measurements
  - Higgs measurements
  - new physics searches

Drell-Yan process



- **Precision measurements of W and Z boson production useful to:**
  - test SM and extract SM parameters → m_W, $\sin^2\theta_W$, etc.
  - probe the proton structure → constrain PDFs
  - test perturbative QCD → probe state-of-the-art theory predictions

Outline

Selection of recent results obtained with 7, 8 and 13 TeV ATLAS data

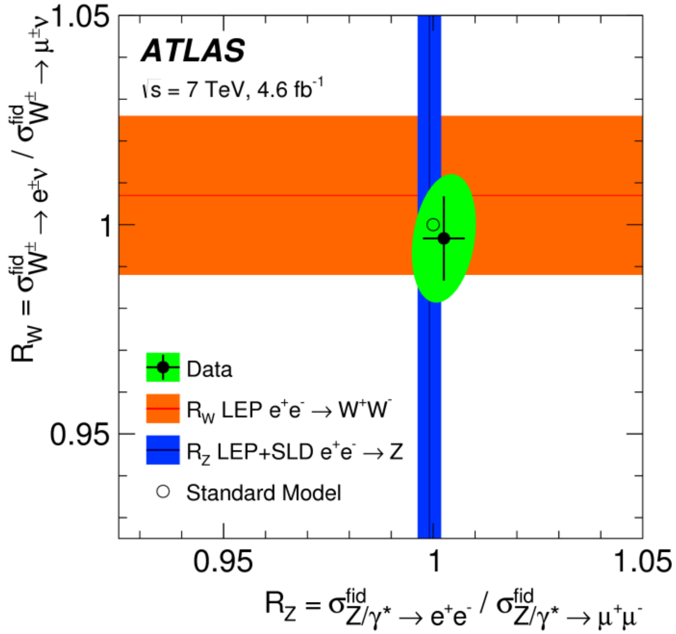
Measurement	Energy	7 TeV
W & Z cross section	7 TeV	Eur. Phys. J. C 77 (2017) 367
W & Z cross section	13 TeV	Phys. Lett. B 759 (2016) 601
tt/Z cross section ratio	7, 8, 13 TeV	JHEP 02 (2017) 117
Z+jets production	13 TeV	Eur. Phys. J. C77 (2017) 361
3D Z cross section	8 TeV	*https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2016-04/*
Angular coefficients of Z leptons	8 TeV	JHEP 08 (2016) 159
Anti-k_t algorithm splitting scales	8 TeV	JHEP 08 (2017) 026

Public ATLAS Standard Model results available at:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublications

W & Z cross section @ 7 TeV

Eur. Phys. J. C 77 (2017)

W & Z cross section @ 7 TeV [Eur. Phys. J. C 77 (2017)]

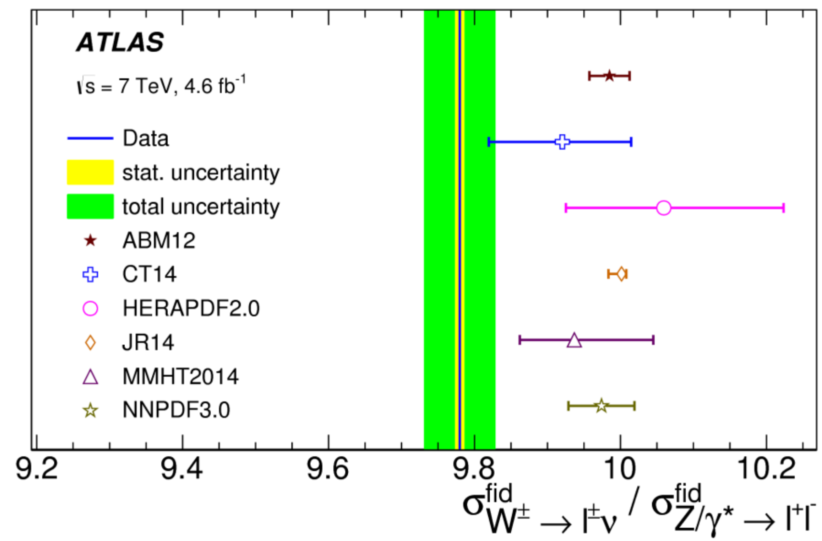


➢ $W(\to e\nu)/W(\to \mu\nu)$ & $Z(\to ee)/Z(\to \mu\mu)$

- ➢ High precision measurements (few %)
- ➢ Good agreement between data and SM
- ➢ In agreement with lepton universality
- ➢ W boson measurement:
  - ➢ As precise as previous best measurement
  - ➢ Higher precision than LEP combined

➢ $W(\to l\nu)/Z(\to ll)$

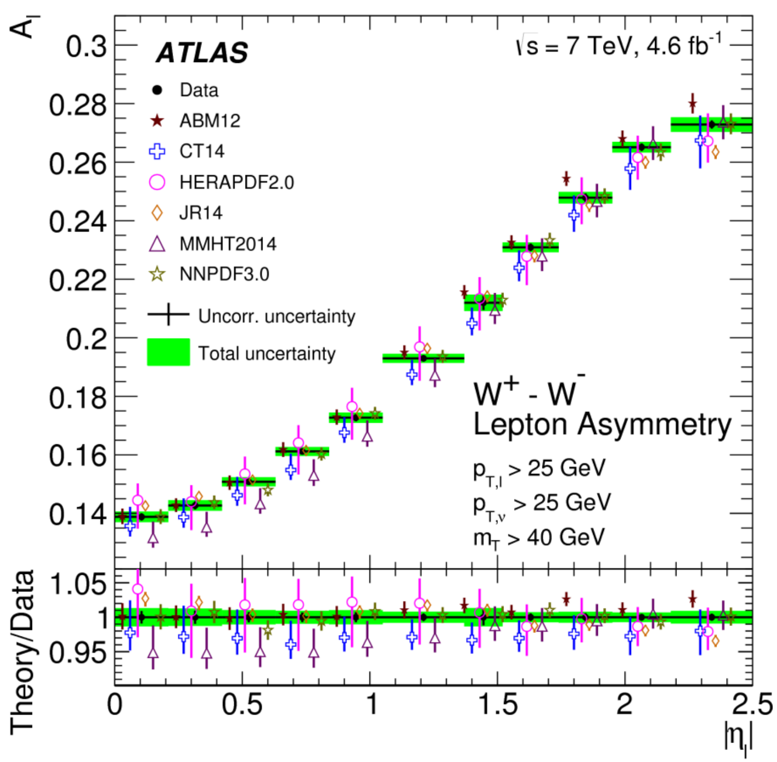
- ➢ High precision measurement:
  - ➢ Possibility to check agreement with predictions of different PDFs
- ➢ All predictions higher than data:
  - ➢ Need for improvement in the proton description



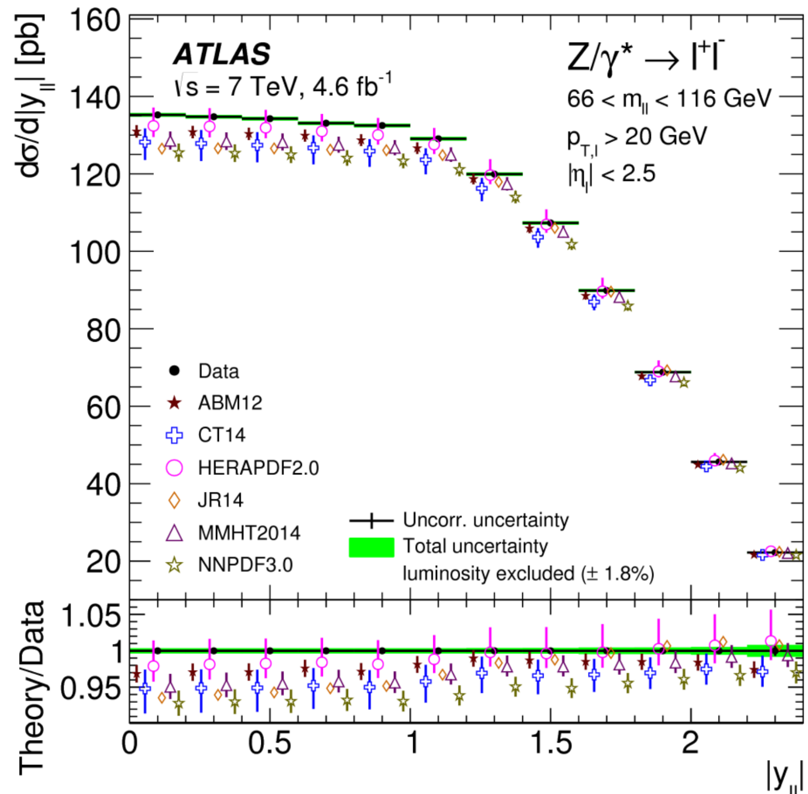
W & Z cross section @ 7 TeV Eur. Phys. J. C 77 (2017)

- **W charge asymmetry**
  - Good agreement with theory predictions
  - Experimental accuracy at the <1% level

$$A_\ell = \frac{d\sigma_{W^+}/d|\eta_\ell| - d\sigma_{W^-}/d|\eta_\ell|}{d\sigma_{W^+}/d|\eta_\ell| + d\sigma_{W^-}/d|\eta_\ell|}$$



- **Z cross section vs rapidity $|y_{ll}|$**
  - Good agreement for $|y_{ll}| > 1$
  - General disagreement for $|y_{ll}| < 1$
  - Discrepancy can be interpreted as enhanced strangeness PDFs

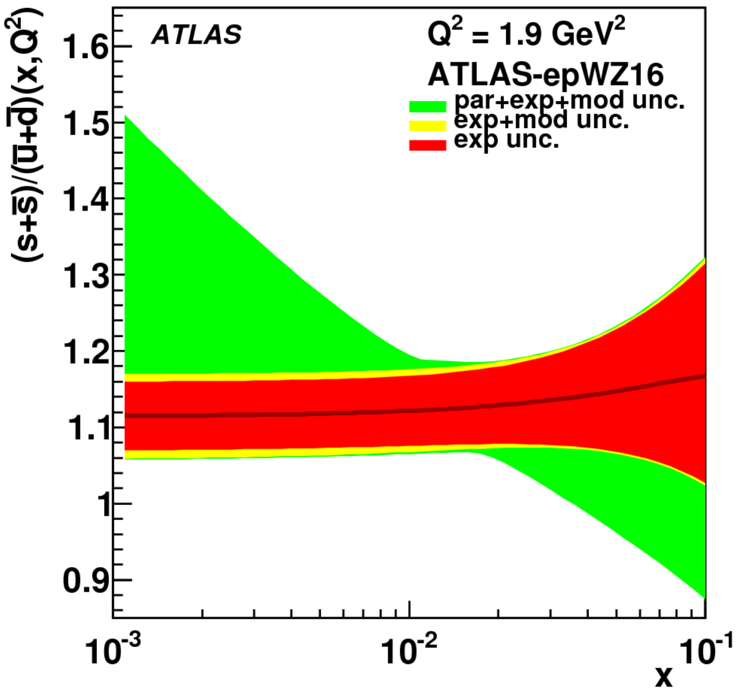


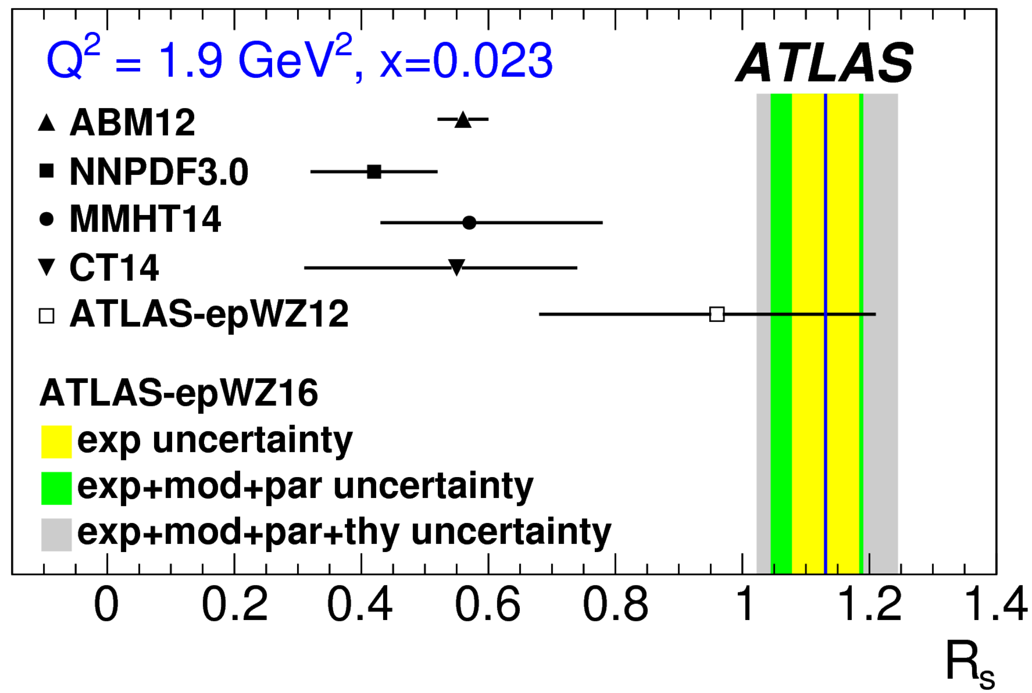
W & Z cross section @ 7 TeV [Eur. Phys. J. C 77 (2017)]

- **Exploiting results of this measurement:**
  - New ATLAS PDF: **ATLAS-epWZ16**
  - Constrain strange quark PDF (most sensitive region: Q^2 = 1.9 GeV^2, x = 0.023)
  - R_s compatible with unsuppressed strangeness at low x

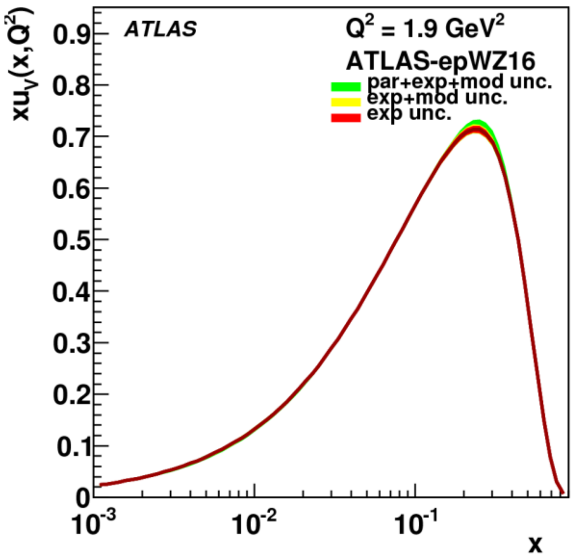
$$R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}}$$

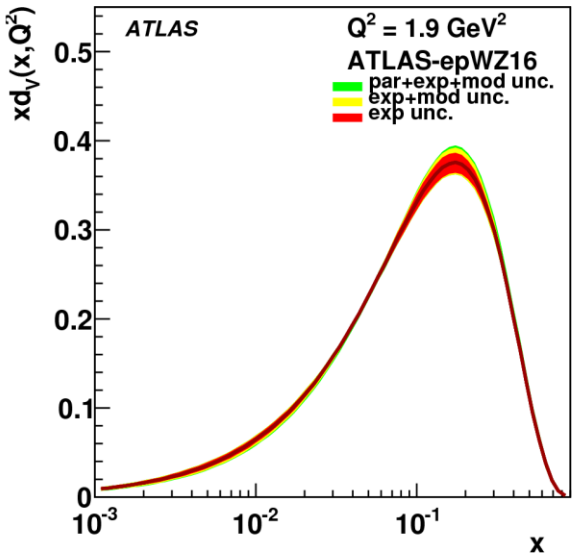
$$R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}} = 1.13 \pm 0.05\,(\mathrm{exp}) \pm 0.02\,(\mathrm{mod})\ ^{+0.01}_{-0.06}\,(\mathrm{par})$$



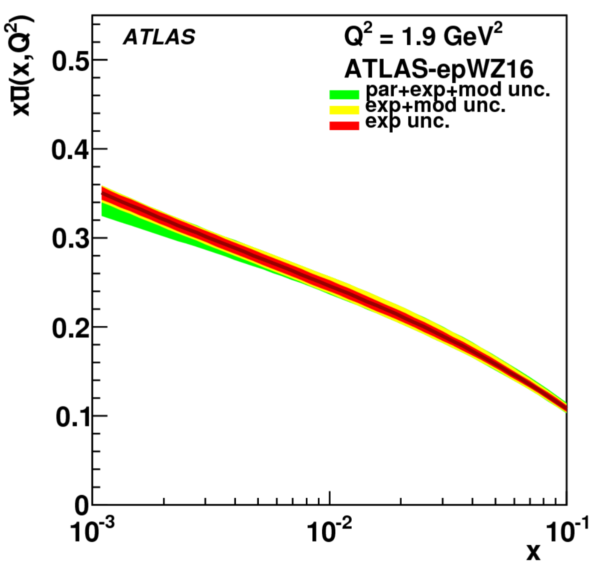


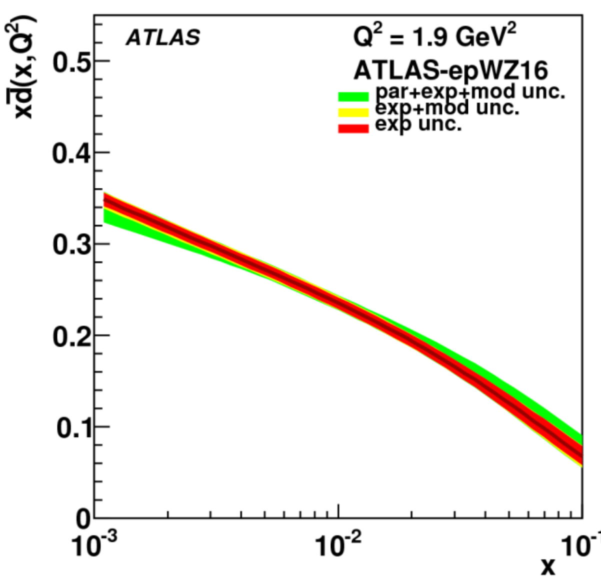
W & Z cross section @ 7 TeV [Eur. Phys. J. C 77 (2017)]

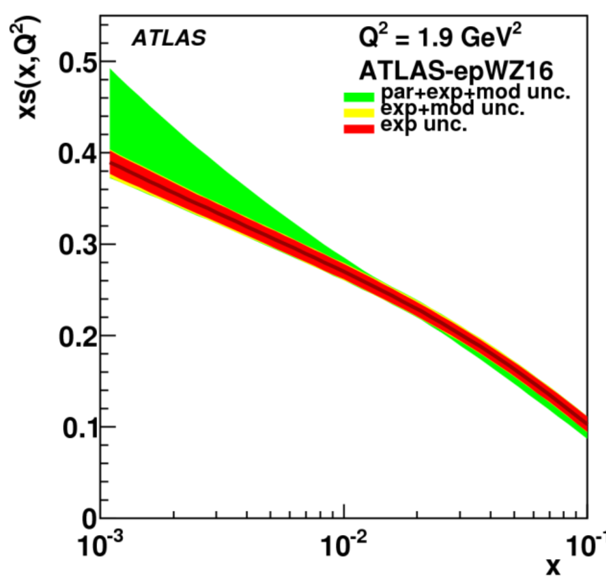




- ➢ W/Z ratio is sensitive to strange quark PDF
- ➢ Definitely accessing the proton structure
- ➢ New PDF developed: *ATLAS-epWZ16*
- ➢ Smaller uncertainties than ATLAS-epWZ12





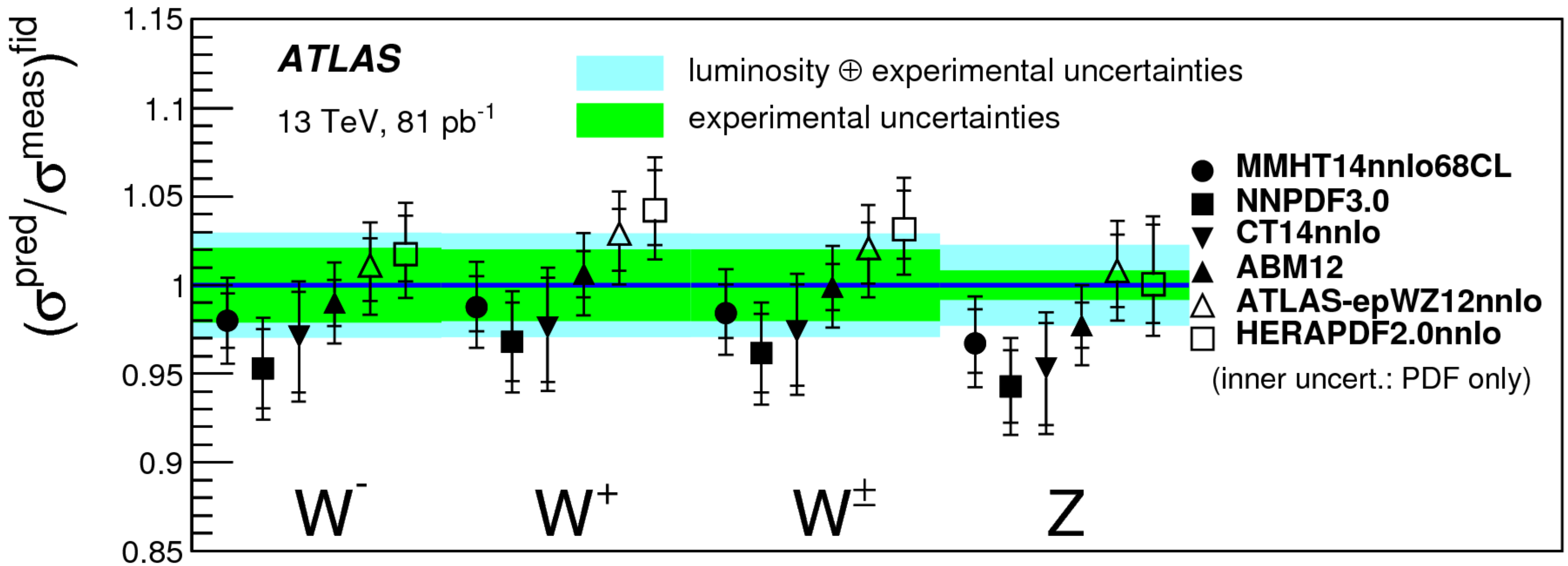


W & Z cross section @ 13 TeV

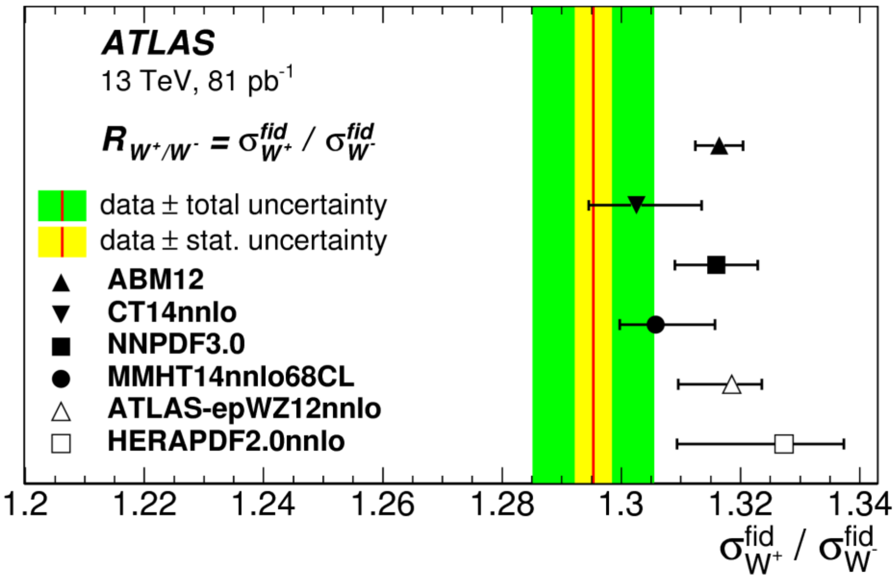
Phys. Lett. B 759 (2016) 601

W & Z cross section @ 13 TeV [Phys. Lett. B 759 (2016) 601]

- **W^+, W^-, $W^\pm$, Z separate cross sections**
- High precision measurements:
  - Z: 1%   (± 2.1% luminosity)
  - W: 2% (± 2.1% luminosity)
- Theoretical predictions uncertainty:
  - dominated by PDF (Z: 7%, W: 6%)
- Possible to constrain PDFs!



W & Z cross section @ 13 TeV [Phys. Lett. B 759 (2016) 601]

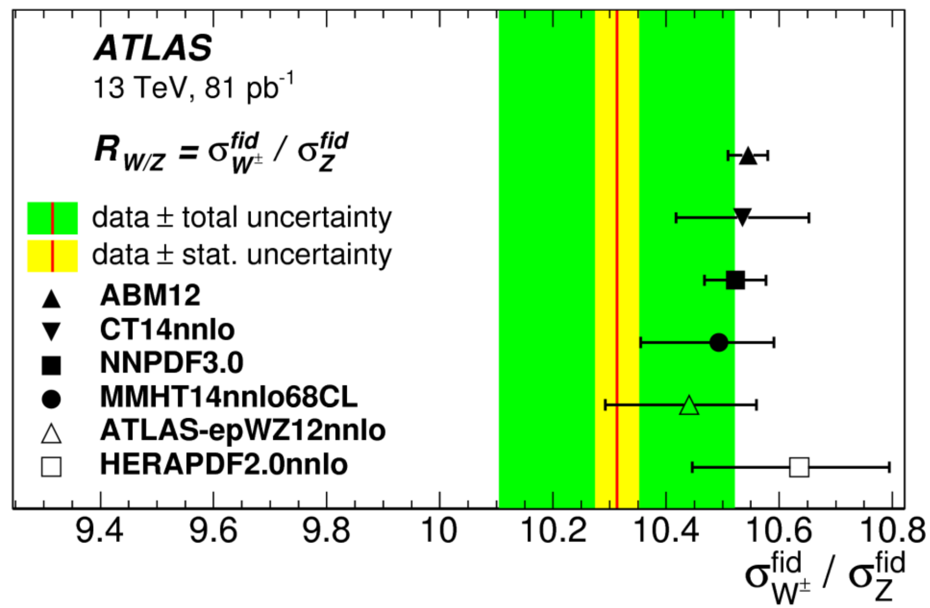


➢ W^+/W^- ratio

- ➢ High precision measurement (< 1%)
- ➢ Luminosity uncertainty canceled in ratio
- ➢ Discriminate among PDFs
  - ➢ CT14 & MMHT14: best description

➢ W/Z ratio

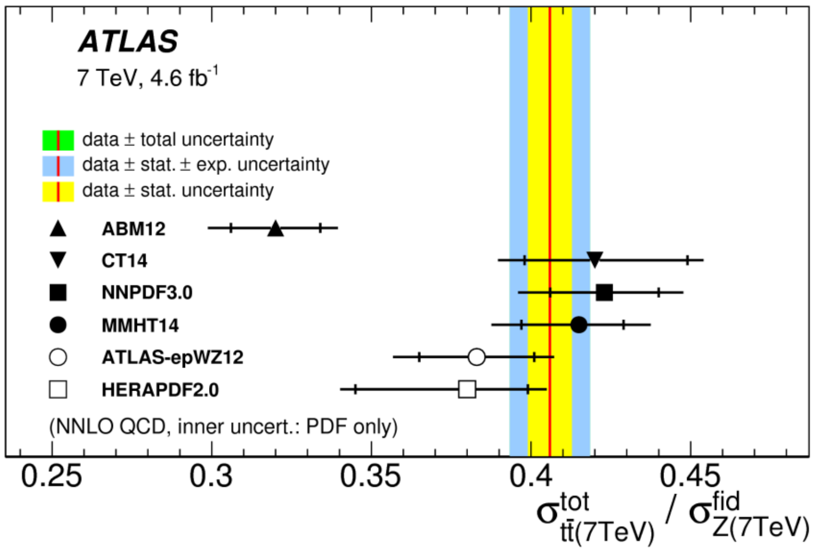
- ➢ Luminosity uncertainty canceled in ratio
- ➢ Results compatible with all PDFs (within uncertainties)
- ➢ ATLAS-epWZ12 (based on ATLAS data fits) gives the best description

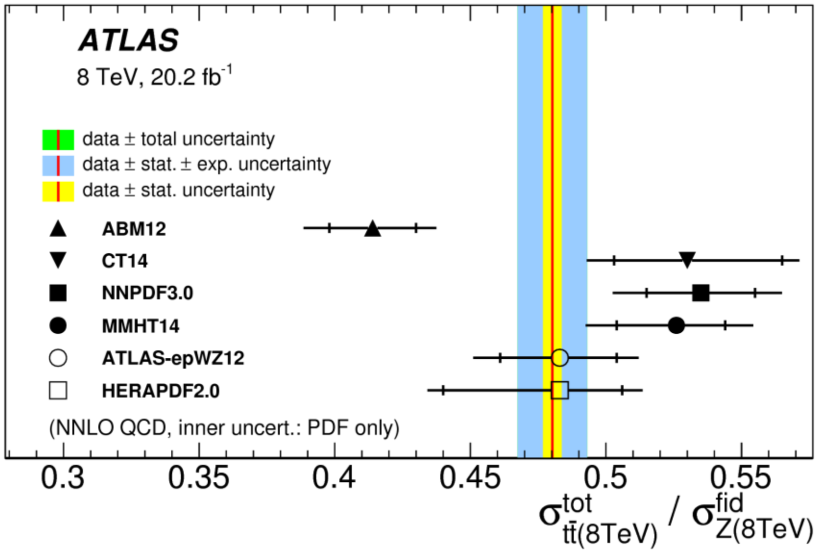


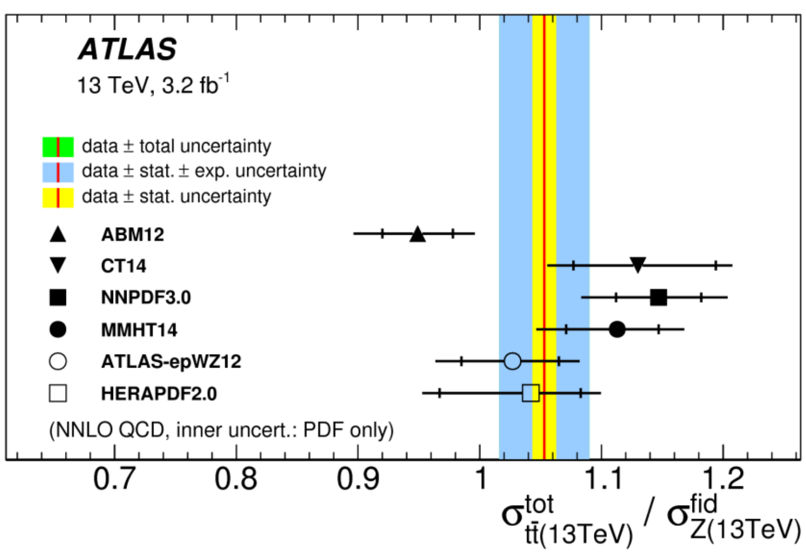
tt/Z cross section ratio @ 7, 8, 13 TeV

JHEP 02 (2017) 117

tt/Z cross section ratio @ 7, 8, 13 TeV [JHEP 02 (2017) 117]





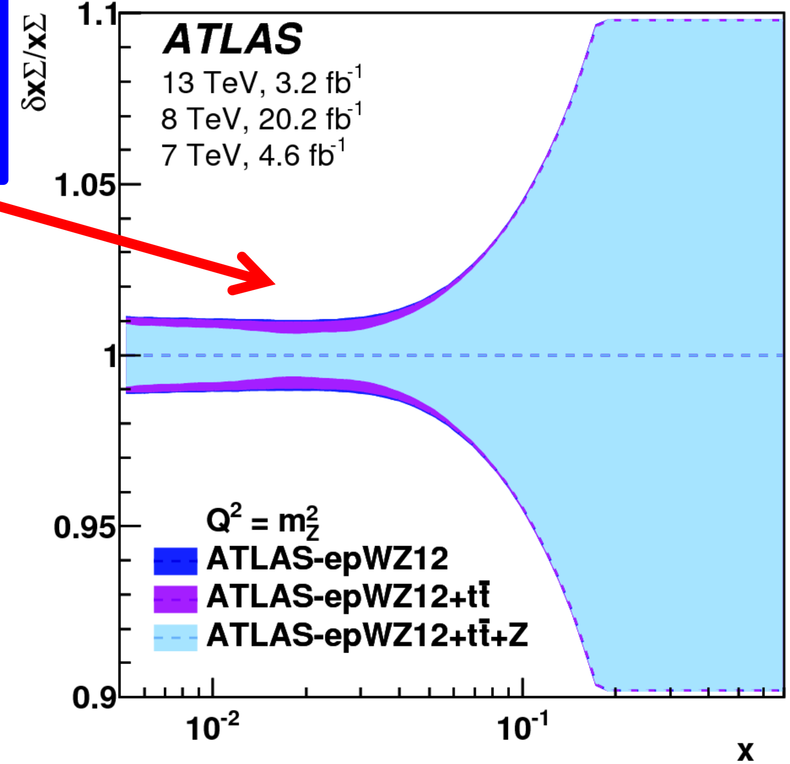


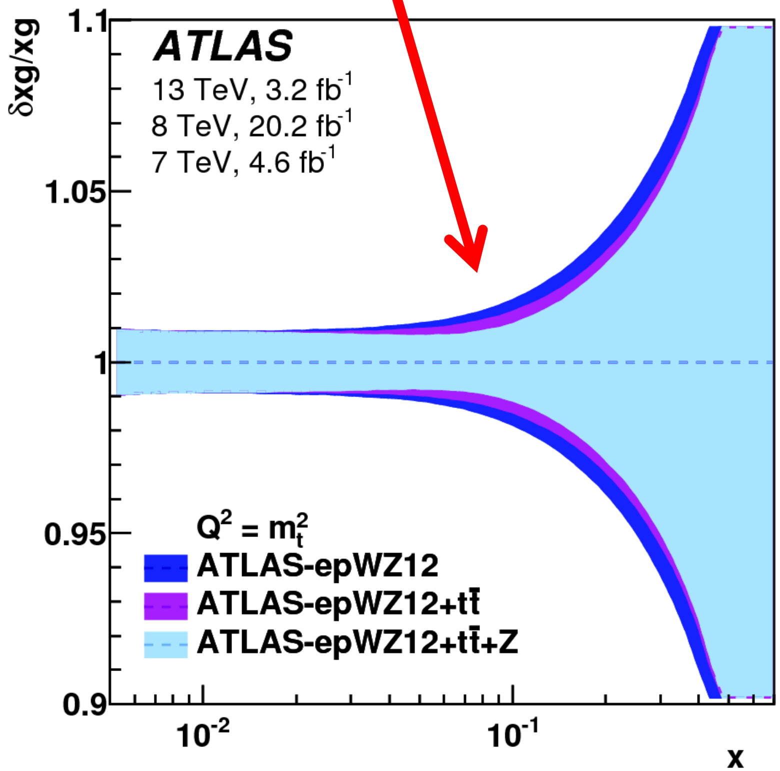
$$R_{t\bar{t}/Z} = \frac{\sigma_{t\bar{t}}}{0.5(\sigma_{Z\to ee} + \sigma_{Z\to\mu\mu})}$$

- Systematics cancel out in the ratio
- Results more precise than prediction!
- Good agreement with different PDF
- Best sensitivity at 8 and 7 TeV
- Measured also tt/Z double ratio
  - 13/8 TeV, 13/7 TeV, 8/7 TeV

tt/Z cross section ratio @ 7, 8, 13 TeV [JHEP 02 (2017) 117]

- **Exploiting the tt/Z results:**
  - Profile ATLAS-epWZ12 to constrain:
    - light sea quark PDF
    - gluon PDF



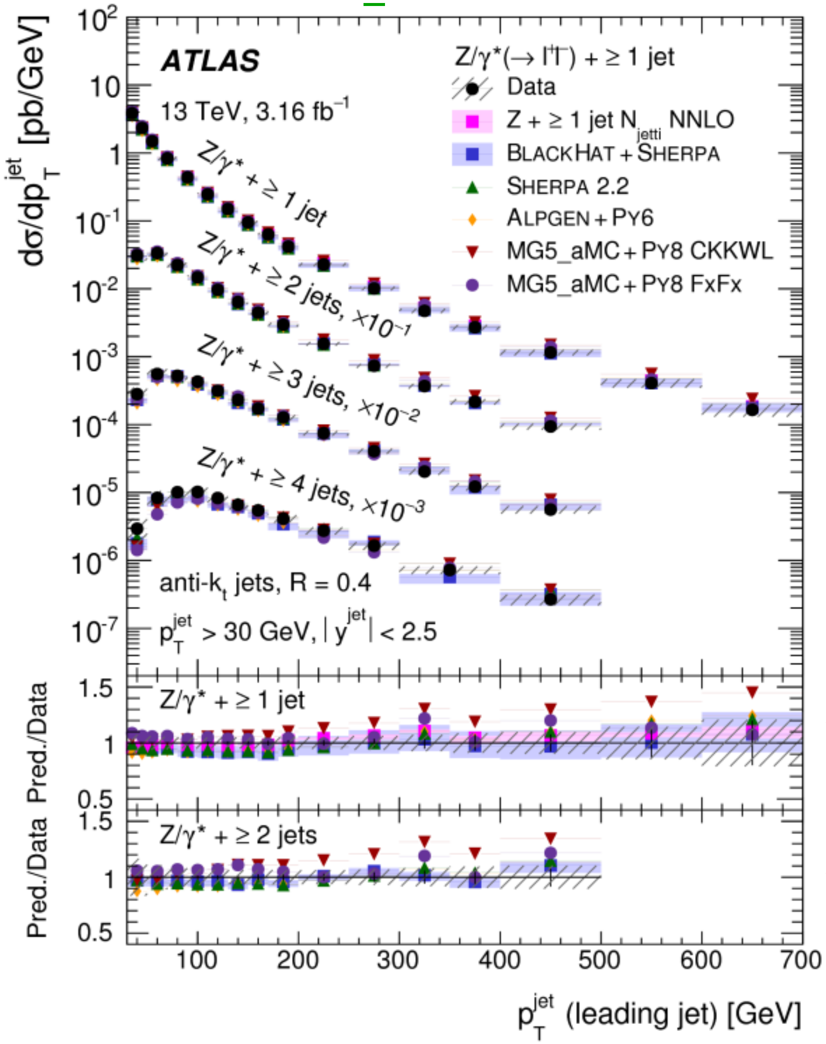


Z+jets cross section @ 13 TeV

Eur. Phys. J. C77 (2017) 361

Z+jets cross section @ 13 TeV [Eur. Phys. J. C77 (2017) 361]

Jet p_T spectrum



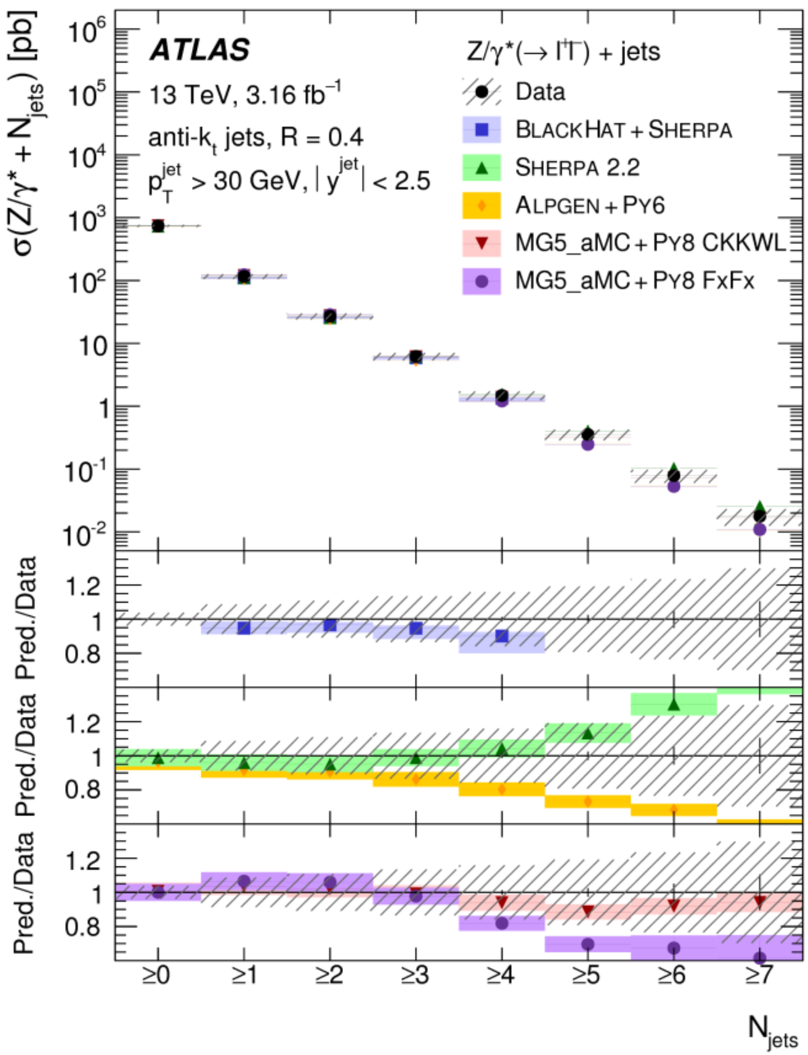
- **Z+jets cross section**
- State-of-the-art predictions:
  - **NNLO (Z+ ≥1jet Njetti)**
  - **NLO (BlackHat+Sherpa)**
  - **LO (various)**

- **LO MG5_aMC+PY8 CKKWL & FxFx** too hard jet p_T spectrum
- **LO Alpgen+PY6**, **NLO Sherpa 2.2**, **NLO BlackHat+Sherpa**, **NNLO Njetti**, show good agreement with data

- LO predicts too hard jet spectrum (p_T > 200 GeV)

Z+jets cross section @ 13 TeV [Eur. Phys. J. C77 (2017) 361]

Jet multiplicity



- **Z+jets cross section**
- State-of-the-art predictions:
  - ~~NNLO (Z+ ≥1jet Njetti)~~
  - **NLO (BlackHat+Sherpa)**
  - **LO (various)**

- Reasonable agreement up to 3 jets
- **LO MG5_aMC+PY8 CKKWL** seems OK
- **LO Alpgen+PY6**, **NLO Sherpa 2.2**, **NLO MG5_aMC+PY8 FxFx** systematic trend deviating from data

- Mismodeling for high jet multiplicity ($N_{jets} \geq 4$)

3D Z cross section @ 8 TeV

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2016-04/

3D Z cross section @ 8 TeV to be published soon

- **Triple differential Z boson cross section as a function of: m_{ll}, $|y_{ll}|$, cos θ***
- Collin-Soper frame:
  - rest frame of the (Z boson) di-lepton system
- lepton cos θ*: measured from z-axis, symmetric to the 2 incoming partons

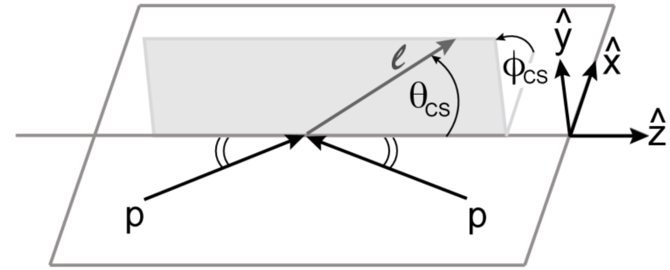
$$cos\theta^* = \frac{p_{Z,ll}}{m_{ll}|p_{Z,ll}|}\frac{p_1^+p_2^- - p_1^-p_2^+}{\sqrt{m_{ll}^2 + p_{T,ll}^2}}$$

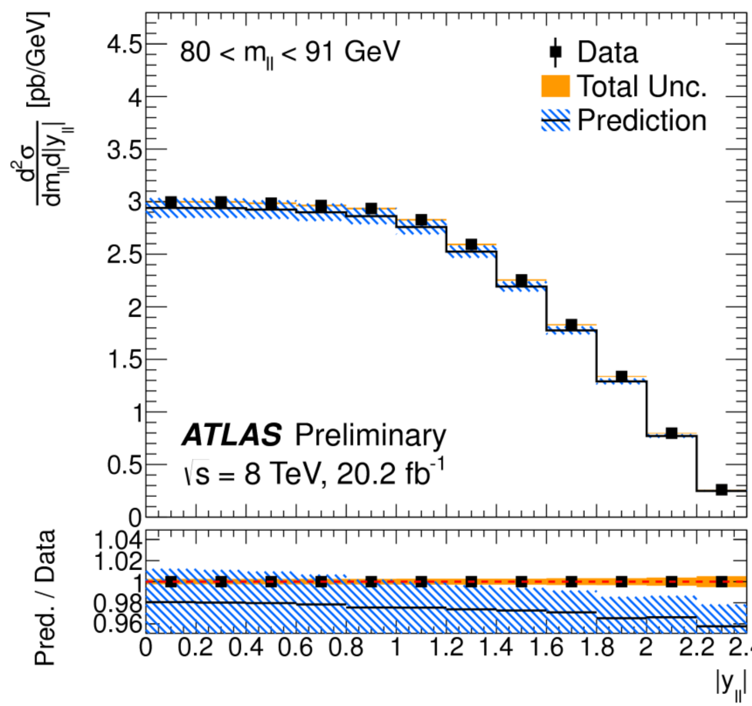
- A_{FB} (forward-backward asymmetry)
  - related to weak mixing angle $\sin^2\theta_W$
  - change sign at m_Z
  - increase with y_{ll}

$$A_{FB} = \frac{d^3\sigma(cos\theta^* > 0) - d^3\sigma(cos\theta^* < 0)}{d^3\sigma(cos\theta^* > 0) + d^3\sigma(cos\theta^* < 0)}$$

- Overall good agreement with Powheg+Pythia8
- Precision: 0.5% (± 1.9% luminosity)
- Prediction tends to underestimate data

Z boson rest frame (Collins-Soper)

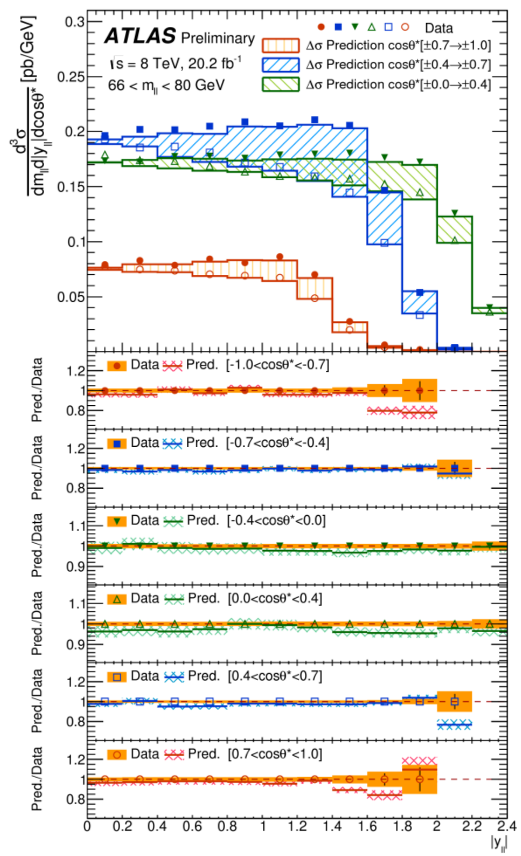




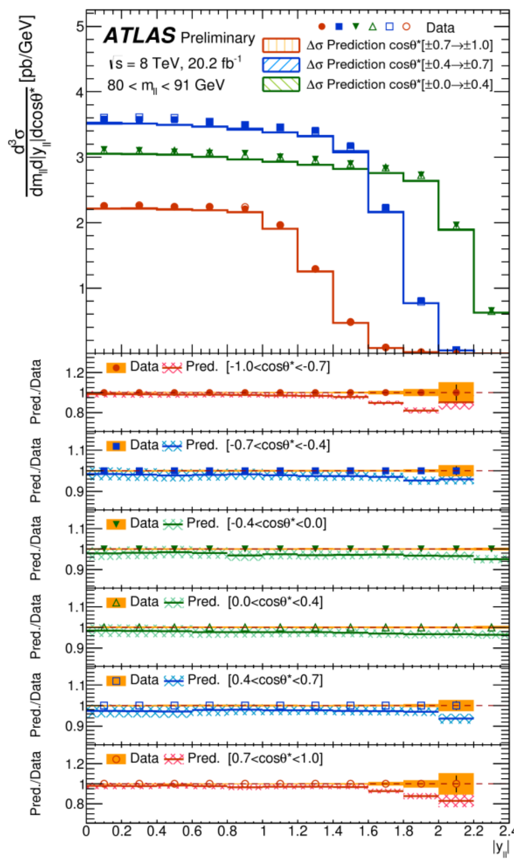
3D Z cross section @ 8 TeV [to be published soon]

- A_{FB} change signs at m_Z:
- from positive… … to == 0 … … then negative!

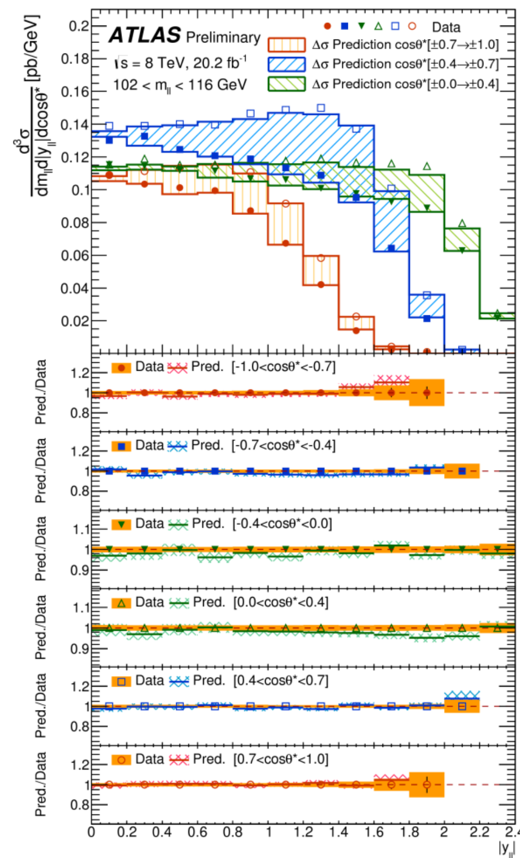
- m_{ll}: 66-80 GeV
- cos θ* > 0 ● ▲ ■
- cos θ* < 0 ○ △ □



- m_{ll}: 80-91 GeV
- cos θ* > 0 ≈ cos θ* < 0
- ● ▲ ■ ≈ ○ △ □



- m_{ll}: 102-116 GeV
- cos θ* < 0 ○ △ □
- cos θ* > 0 ● ▲ ■



Z leptons angular coefficients @ 8 TeV

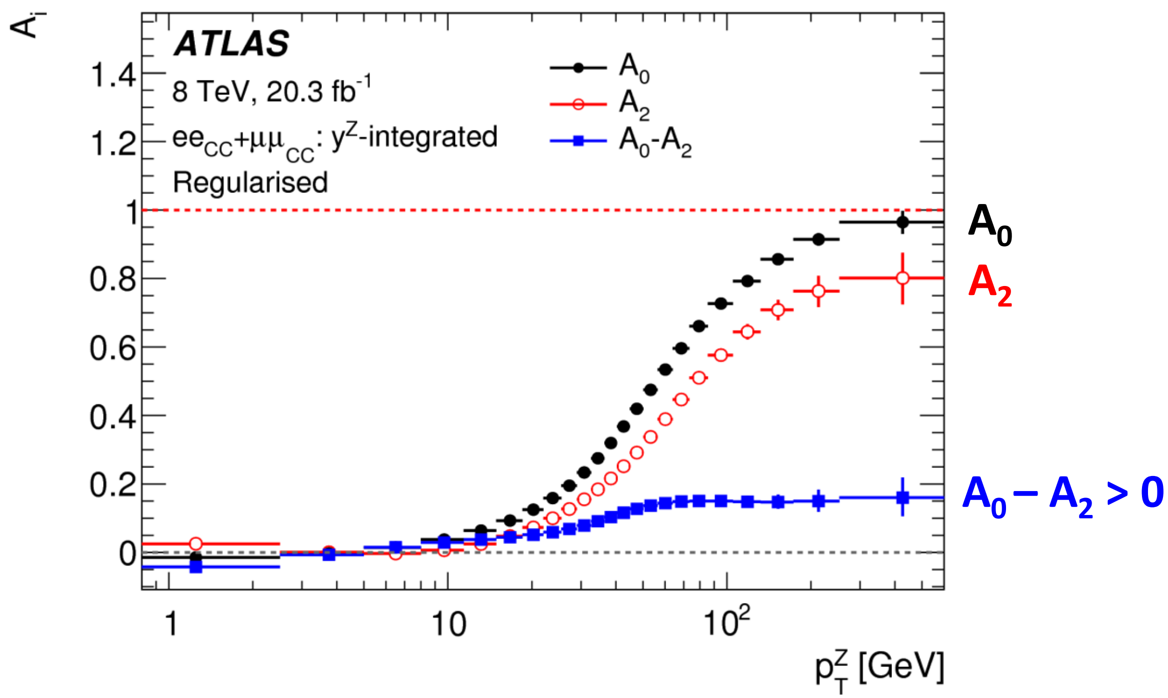
JHEP 08 (2016) 159

Z leptons angular coefficients @ 8 TeV JHEP 08 (2016) 159

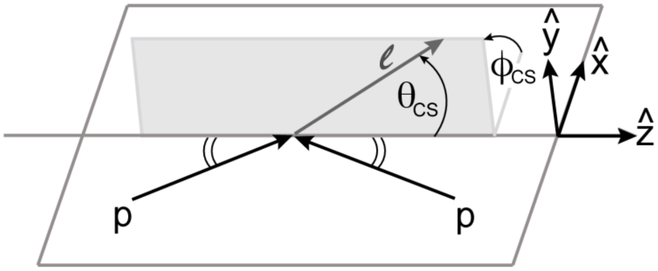
➢ DY leptons angular correlations (θ and ϕ)

- described by angular coefficients $A_0 \ldots A_7$
- A_i measured in 3 Y_Z bins and integrated in Y_Z

- Results:
  - Evidence for higher than zero $A_0 - A_2$
  - Evidence for non zero $A_{5,6,7}$



Z boson rest frame (Collins-Soper)



$$\langle \frac{1}{2}(1-3\cos^2\theta)\rangle = \frac{3}{20}(A_0 - \frac{2}{3});$$

$$\langle \sin 2\theta \cos\phi \rangle = \frac{1}{5}A_1;$$

$$\langle \sin^2\theta \cos 2\phi \rangle = \frac{1}{10}A_2;$$

$$\langle \sin\theta \cos\phi \rangle = \frac{1}{4}A_3;$$

$$\langle \cos\theta \rangle = \frac{1}{4}A_4;$$

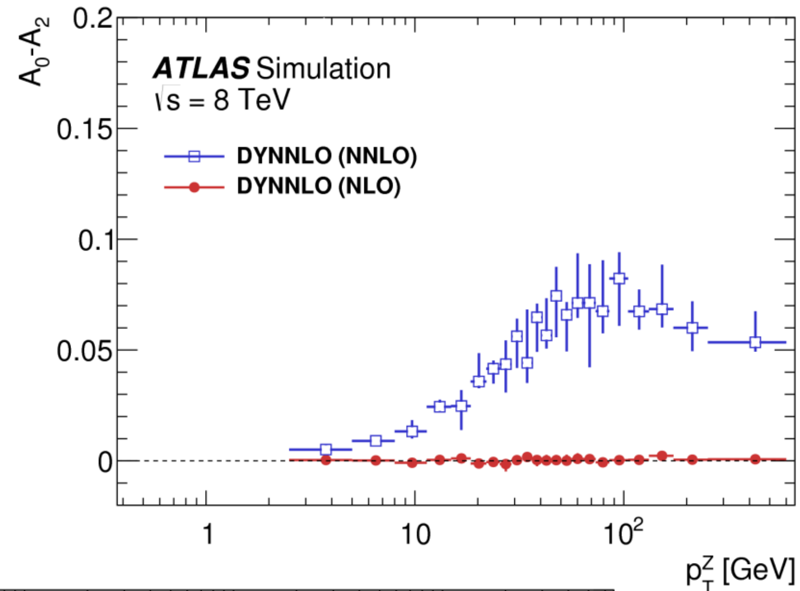
$$\langle \sin^2\theta \sin 2\phi \rangle = \frac{1}{5}A_5;$$

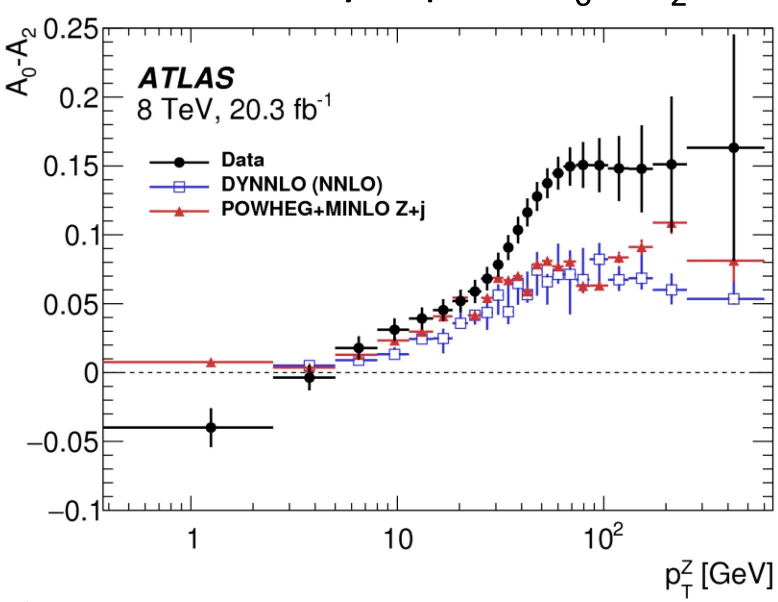
$$\langle \sin 2\theta \sin\phi \rangle = \frac{1}{5}A_6;$$

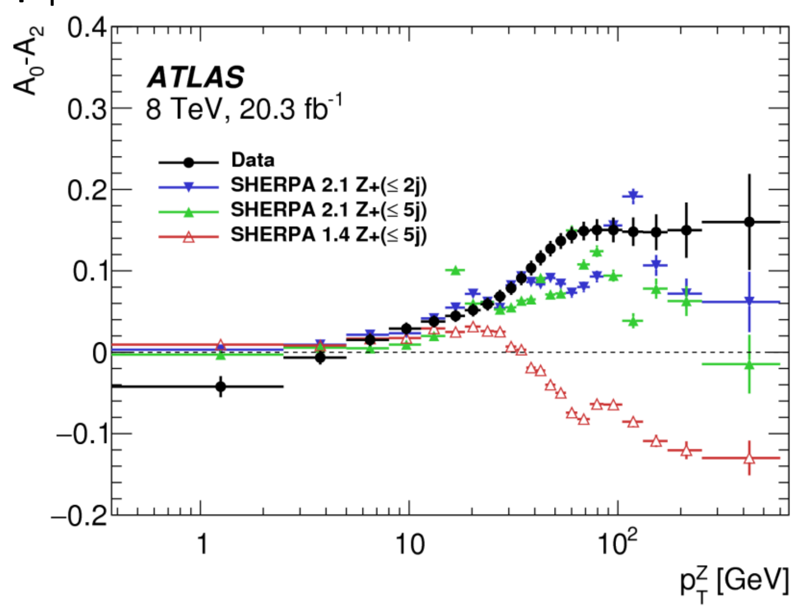
$$\langle \sin\theta \sin\phi \rangle = \frac{1}{4}A_7.$$

Z leptons angular coefficients @ 8 TeV [JHEP 08 (2016) 159]

- Lam-Tung relation broken: $A_0 - A_2 > 0$
- Confirm needs for higher order corrections
- Data almost factor 2 larger than predictions:
  - pQCD calculations: **DYNNLO (NNLO)**
  - MC's at V+j NLO: **POWHEG+MINLO Z+j**
  - **Sherpa 2.1** better than **Sherpa 1.4**
- Several recently published predictions:
  - improve data/MC comparison
  - do not fully explain $A_0 - A_2$ at high p_T





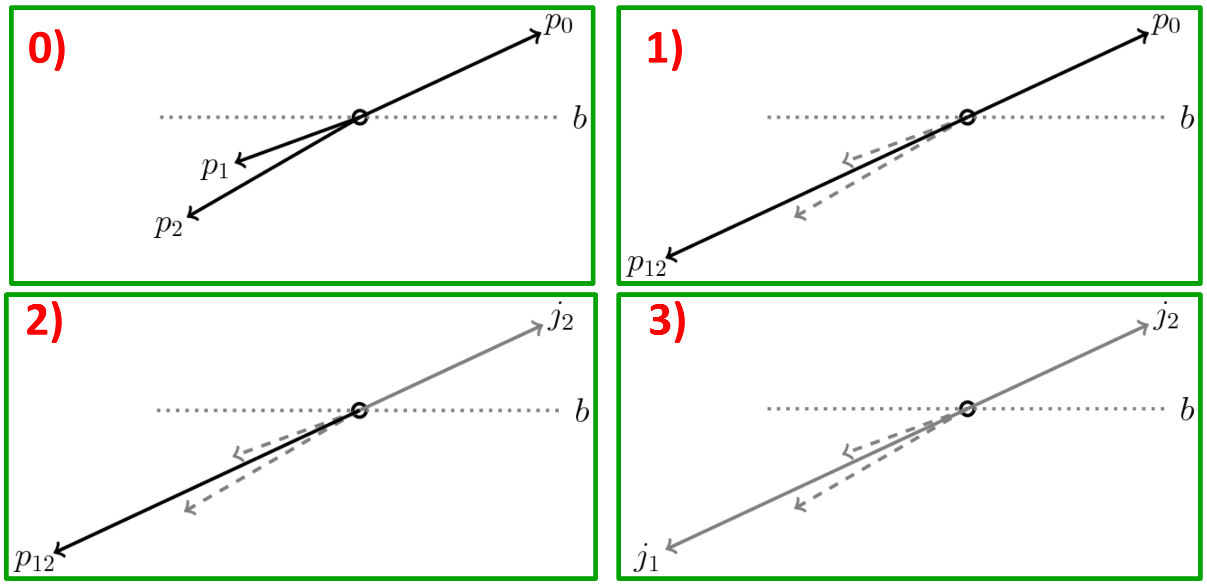


anti-k_t splitting scales @ 8 TeV

JHEP 08 (2017) 026

anti-k_t splitting scales @ 8 TeV JHEP 08 (2017) 026

- **Z(→ll) + jets: jet clusterization in steps with anti-k_t algorithm**
- Inputs: charged particle tracks (p_T > 400 MeV, $|\eta|$< 2.5)
- Associating tracks with minimum distance criteria:
  - distance between tracks or between tracks and beam axes



Clusterization steps:

0) p_n tracks as input

1) minimum distance between p_1 and p_2 tracks → track p_{12}

2) minimum distance between p_0 and axes → jet j_2

3) minimum distance between p_{12} and axes → jet j_1

$$d_k = \min_{i,j}(d_{ij}, d_{ib})$$

$$d_{ij} = \min\left(p^2_{\mathrm{T},i}, p^2_{\mathrm{T},j}\right) \times \frac{\Delta R^2_{ij}}{R^2}$$

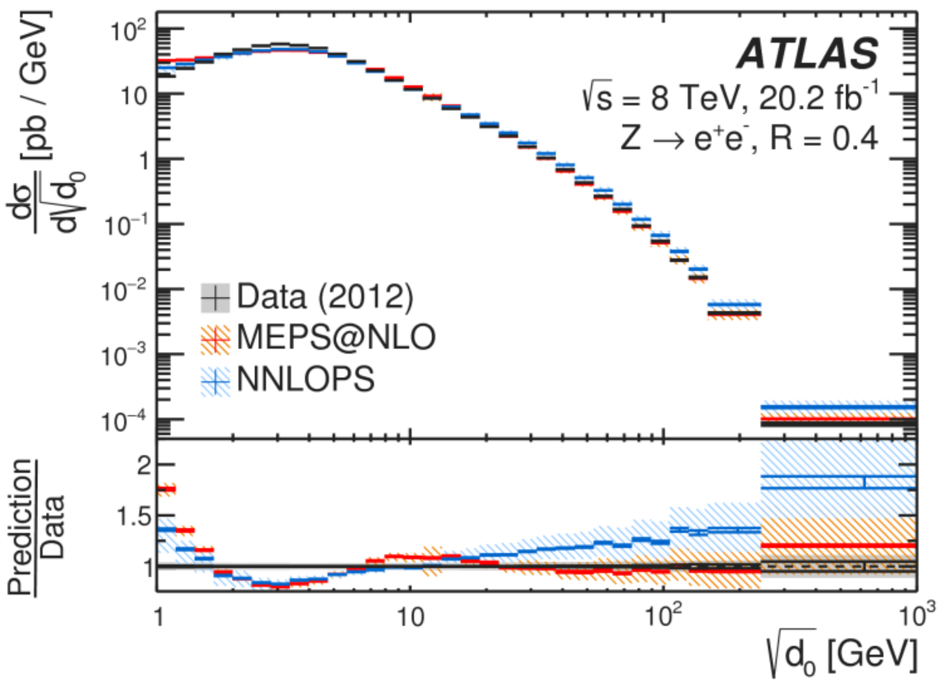
$$d_{ib} = p^2_{\mathrm{T},i},$$

- **0th splitting scale** ($\sqrt{d_0}$): p_T of the leading k_t-jet
- **Nth splitting scale** ($\sqrt{d_N}$): distance at which an N-jet event resolved as (N+1)

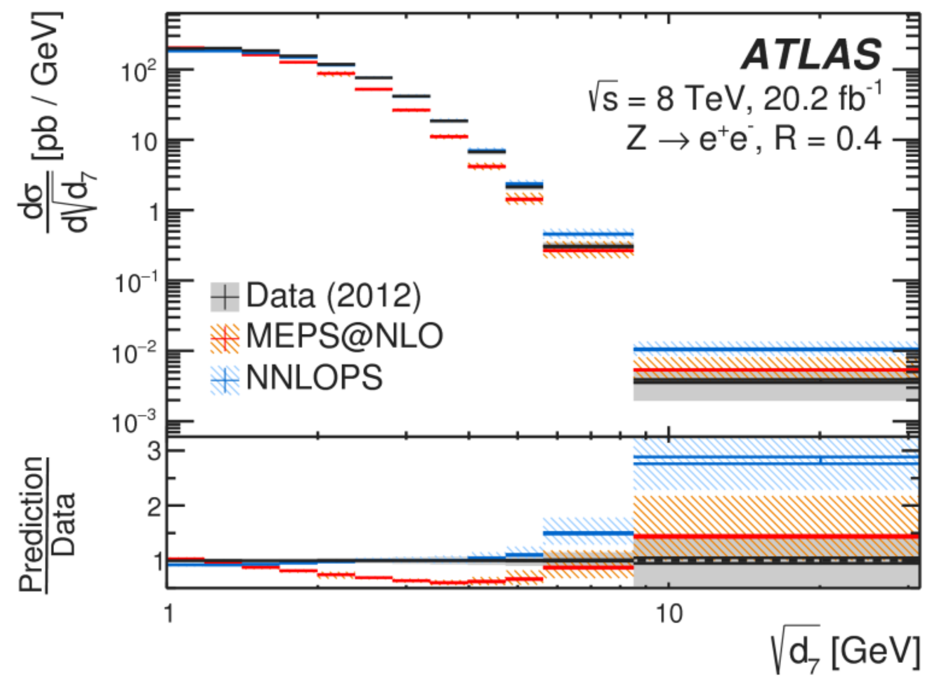
anti-k_t splitting scales @ 8 TeV JHEP 08 (2017) 026

- Theoretical predictions: **Sherpa (MEPS@NLO)**, **Powheg+Pythia8 (NNLOPS)**
- Measurements provided from 0th to 7th splitting scales
- Observe significant differences between measurement and predictions
- Compatible results for: Z(→ee) and Z(→μμ) channels; R = 0.4 and R = 1.0

- Low splitting scales (0th)
- **MEPS@NLO** better from 10 GeV



- High splitting scales (7th)
- **NNLOPS** better up to 3 GeV



Summary

Summary

- ATLAS precision measurements with 7, 8 and 13 TeV data
  - Very high precision: 1-2%
  - W(→eν)/W(→μν) ratio: higher precision than LEP combined
- Possibility to cancel out systematics with cross section ratios
  - W^+/W^- ratio, W/Z ratio, tt/Z ratio
- Higher precision than theoretical predictions:
  - Improve PDFs not compatible with data results
  - Provide inputs for new PDFs: *new* ATLAS-epWZ16
  - Underline the needs for higher order corrections
- Remaining discrepancies motivate further work to improve modelling and precision

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  - Underline the needs for higher order corrections
- Remaining discrepancies motivate further work to improve modelling and precision
- **ATLAS precision measurements are a powerful mean to improve our understanding of perturbative QCD!**

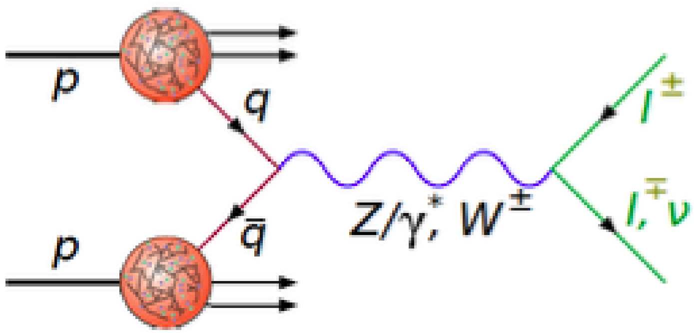
Thanks for your attention!

→ BACKUP ←

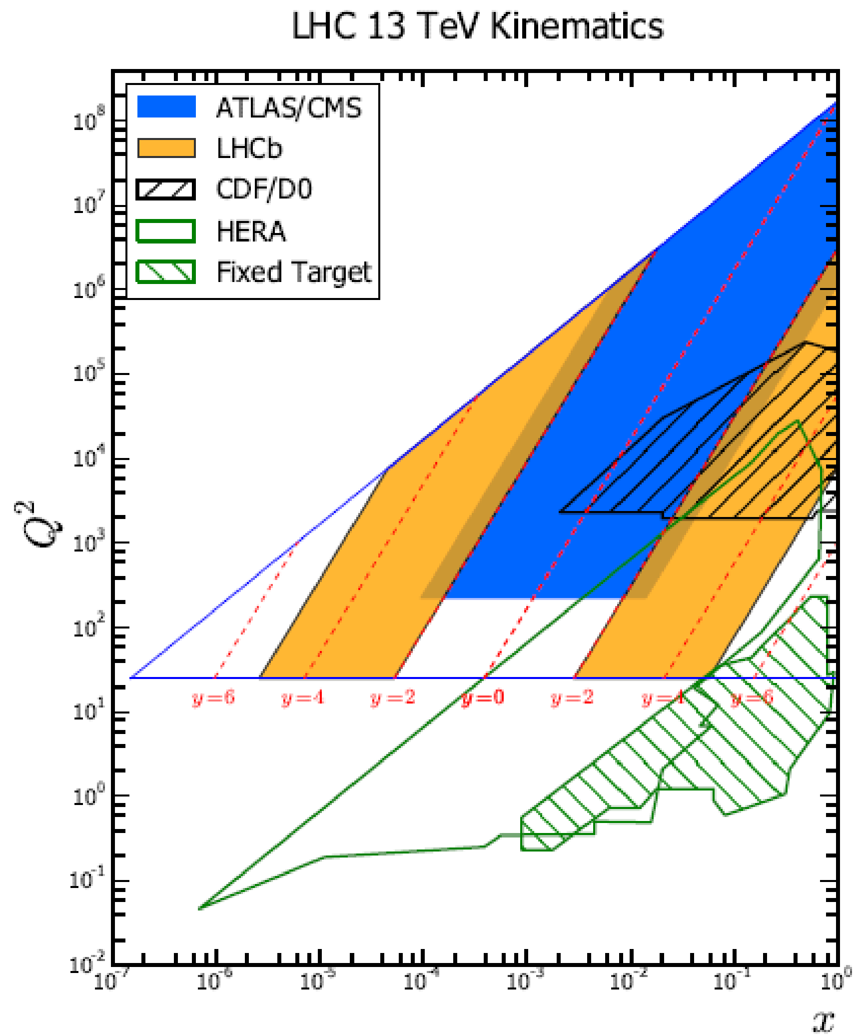
Drell-Yan production

ATLAS/CMS and LHC-b complementary:

- Probes Bjorken-x in range $10^{-4} < x < 1$
- Low & high x accessed by off-shell data



- Total and differential cross-sections in boson (lepton) kinematics (y, p, f*, …)
- Cross-section ratios (W+/W-, W/Z, …)



Excellent detector calibration:

- Typical experimental systematics ~1%
- Luminosity systematics (2-3%) and also other contributions cancel in ratios

General information on measurement methods

Total and fiducial cross-section:

$$\sigma^{fid}_{W/Z} = \frac{N^{W/Z} - B^{W/Z}}{C_{W/Z} L_{int}}$$

$N^{W/Z}$ - candidate events in data
$B^{W/Z}$ - background events
$C_{W/Z}$ - efficiency correction factor
L_{int} - luminosity

$$\sigma^{tot}_{W/Z} = \frac{\sigma^{fid}_{W/Z}}{A_{W/Z}}$$

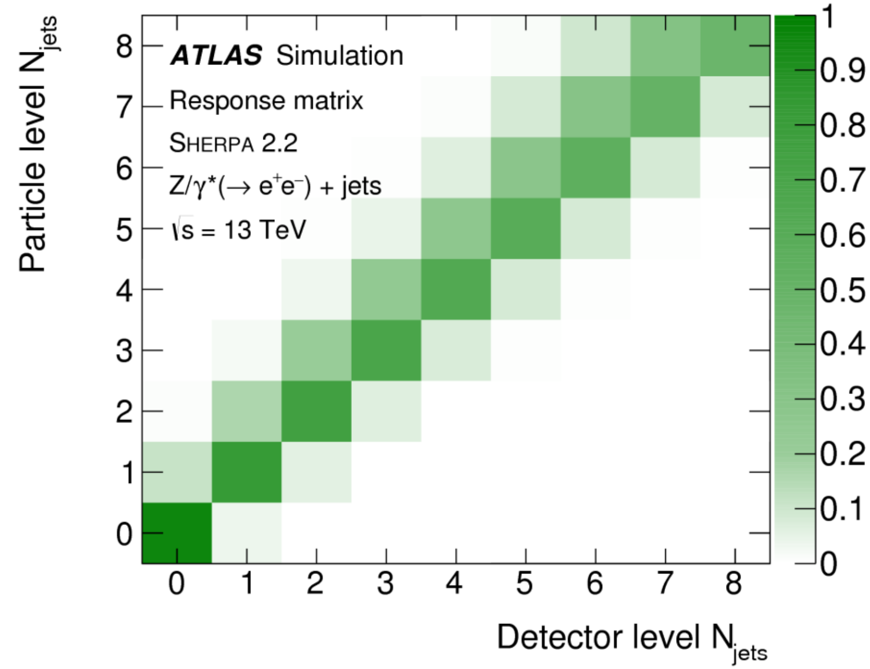
$A^{W/Z}$ - acceptance

"Particle level" measurements:

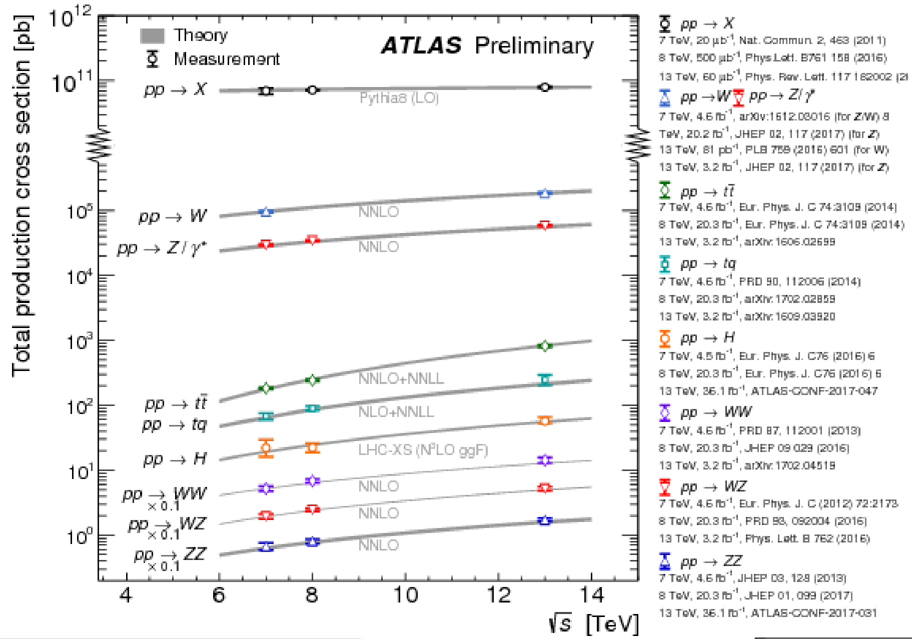
- unfolding with MC corrects
- for detector effects;
- leptons "dressed" with QED FSR

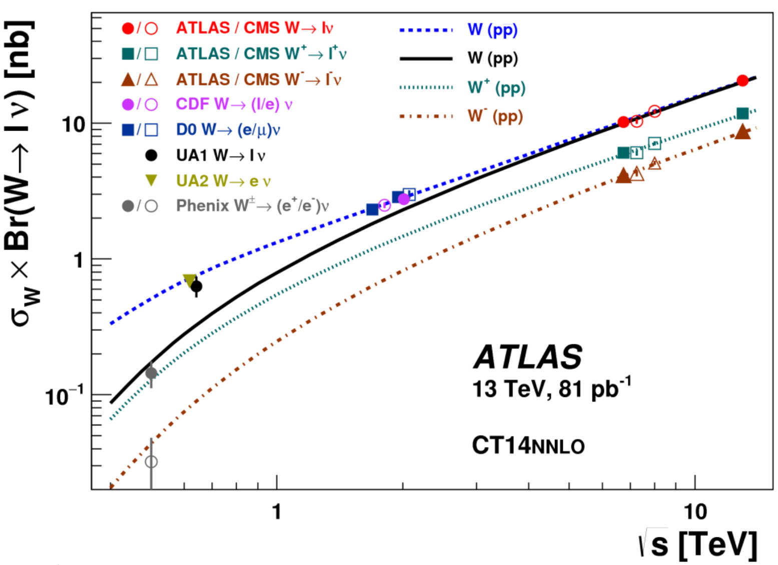
Main systematic uncertainties:

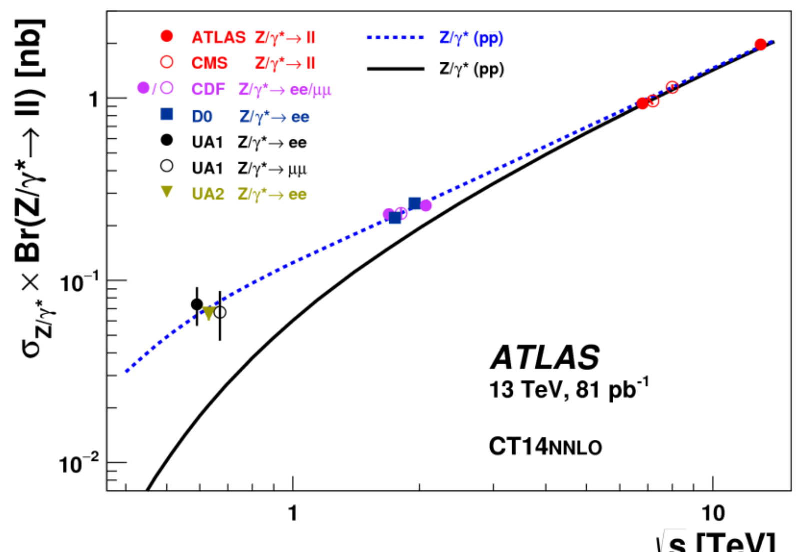
- jet energy scale
- background (on W)
- unfolding



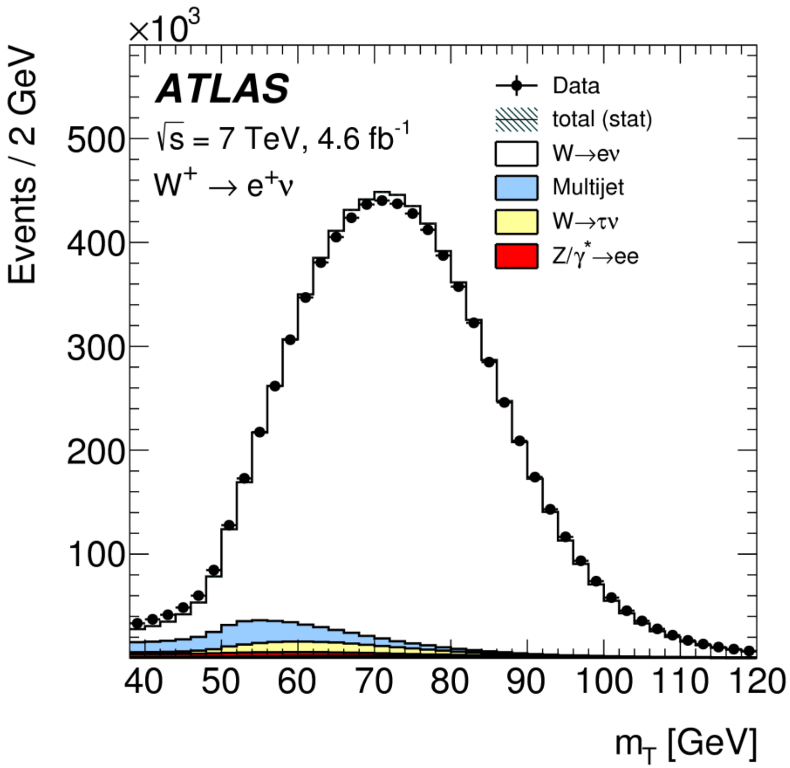
ATLAS W & Z cross sections

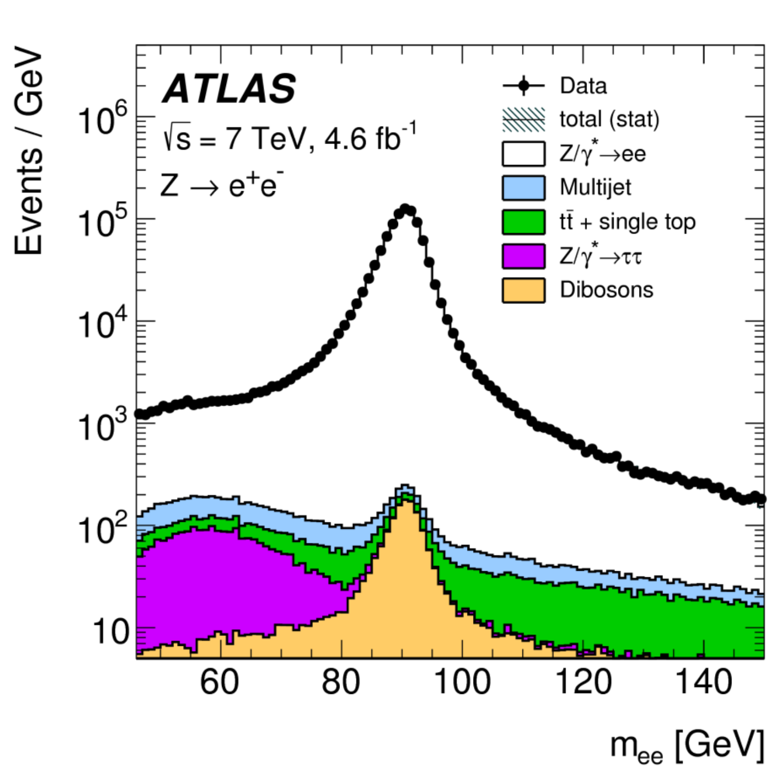






W & Z cross section @ 7 TeV [Eur. Phys. J. C 77 (2017)]





Selected candidates:

W->eν: ~13M

W->μν: ~16M

Z->ee: 1M (CC), 320k (CF)

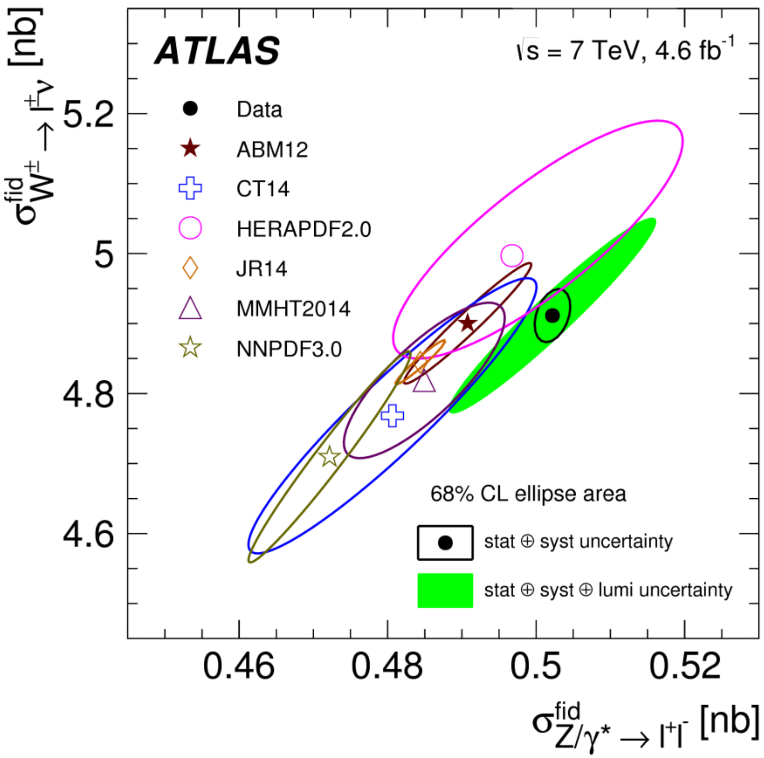
Z->μμ: 1.6M

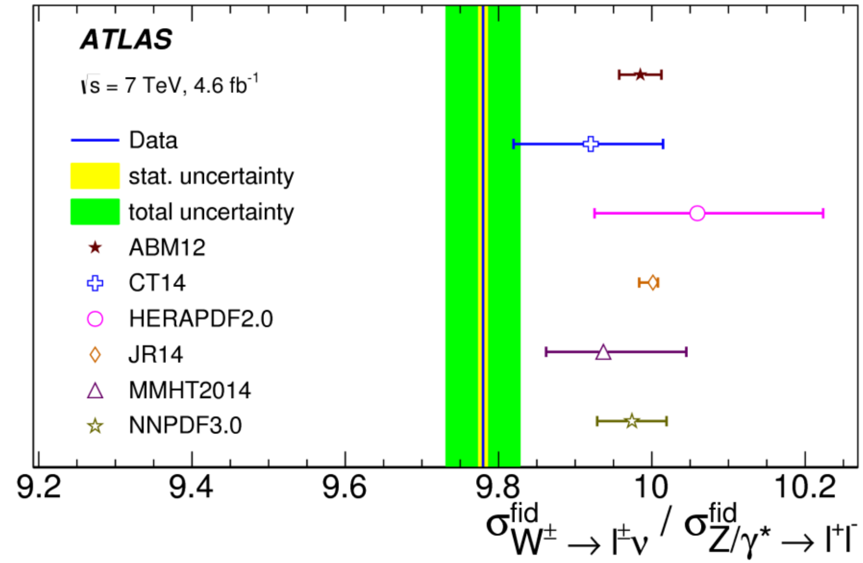
Background contamination:

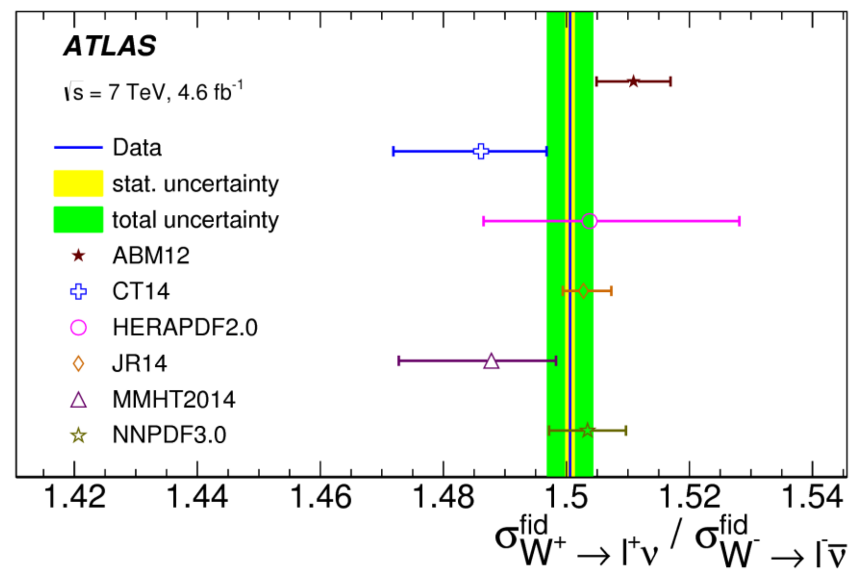
W->lν:~7-9%

Z->ll: ~1-3%

W & Z cross section @ 7 TeV [Eur. Phys. J. C 77 (2017)]

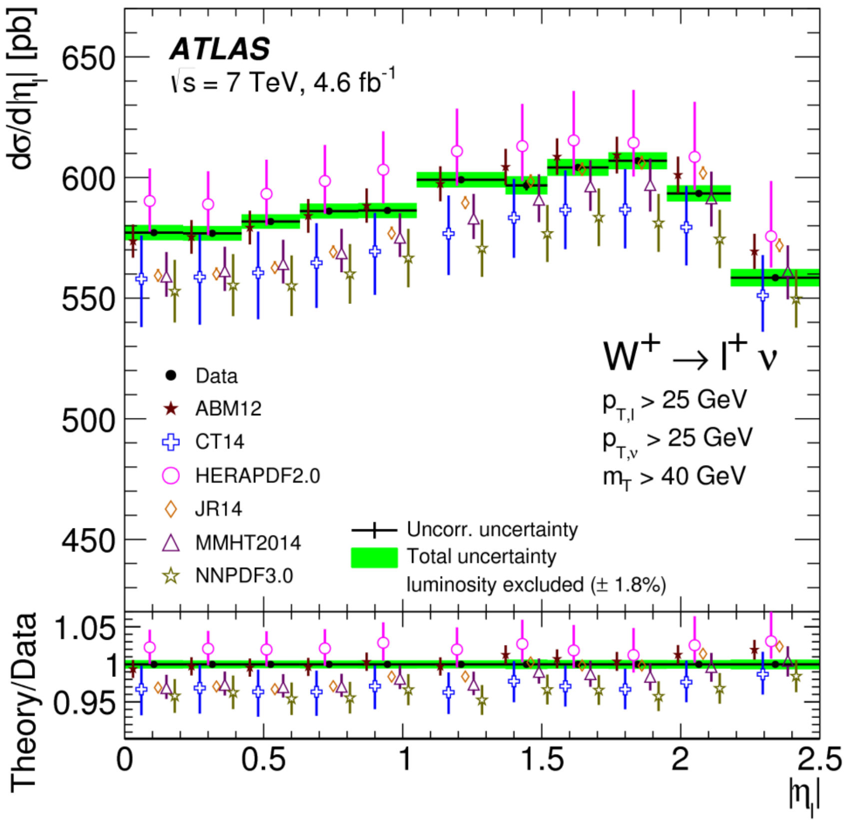




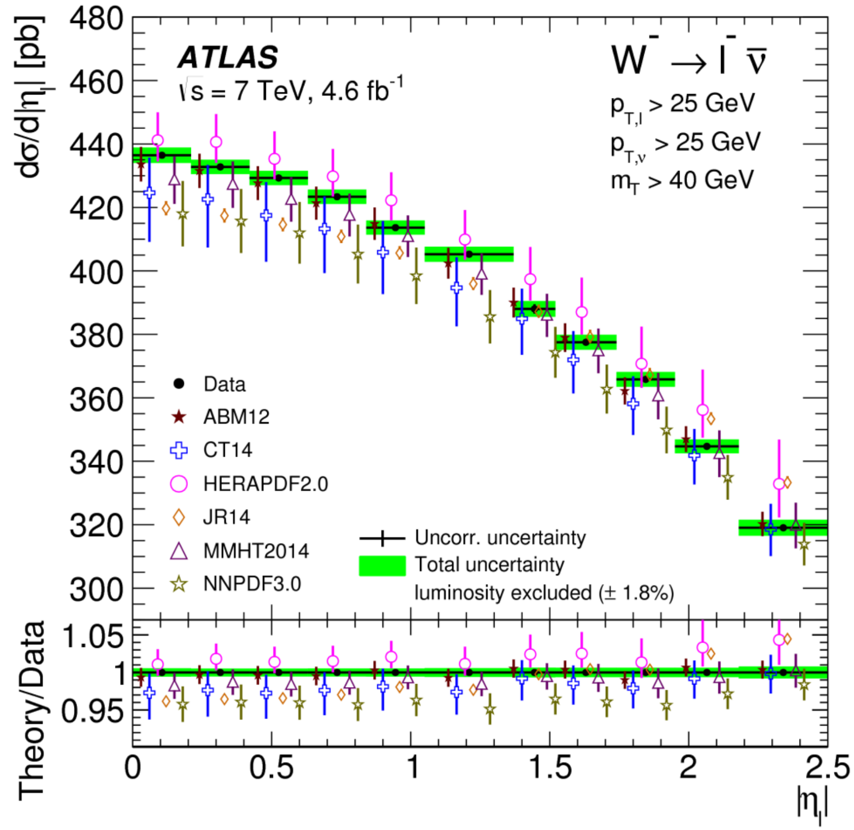


W & Z cross section @ 7 TeV [Eur. Phys. J. C 77 (2017)]

W^+ differential

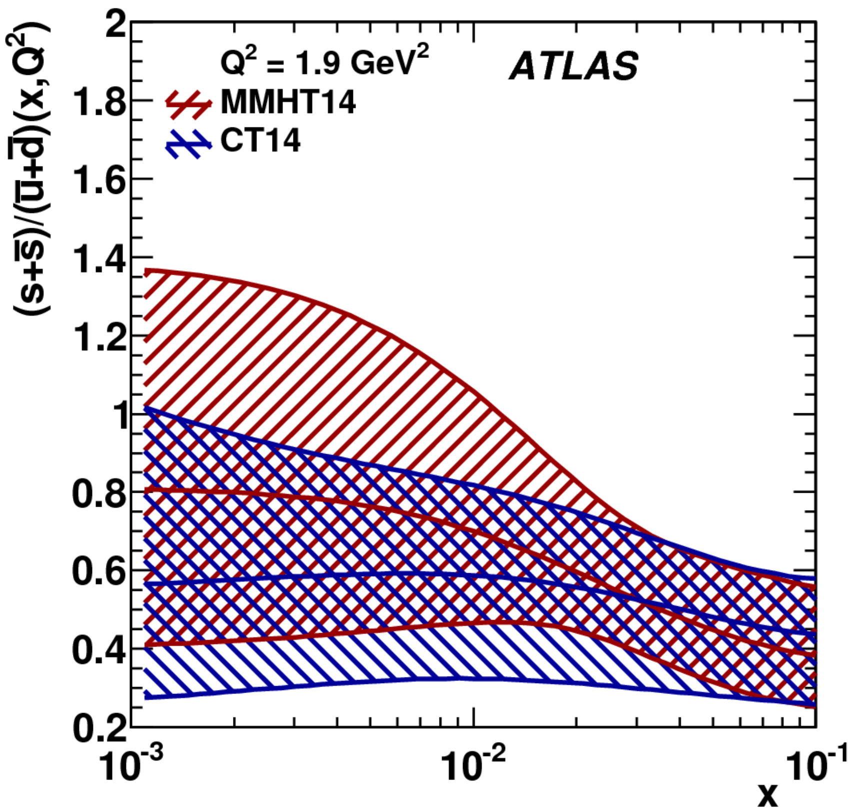


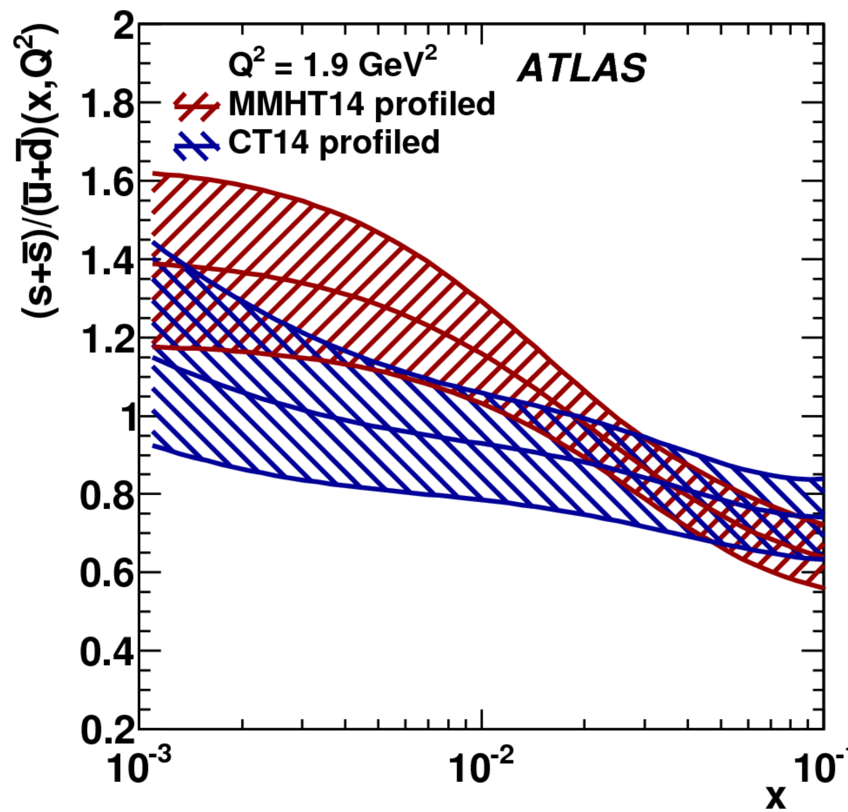
W^- differential



- All predictions (but **HERAPDF2.0**) lower than measurements, with large PDF uncertainties
- Large strange-quark component in W production which is theoretically not well constrained
- Uncertainty on measured shape is 0.1-0.2%: discrepancy in shape

W & Z cross section @ 7 TeV Eur. Phys. J. C 77 (2017)





Profiling results:

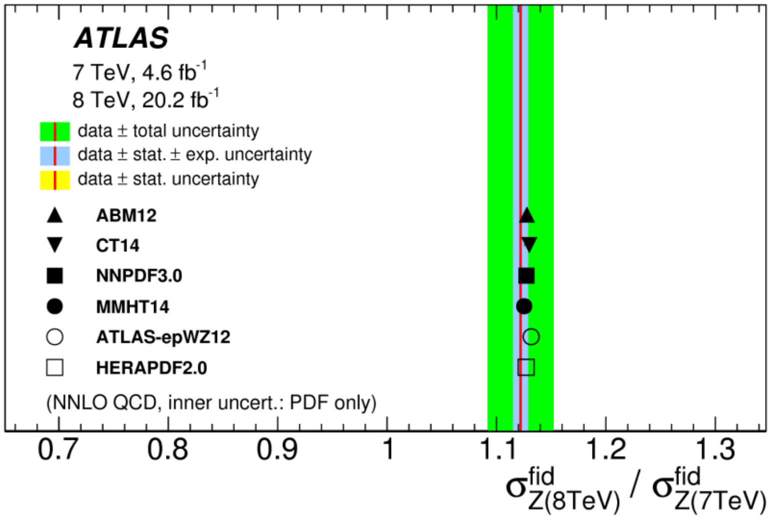
- significantly reduced uncertainties
- central values are increased towards unity

Unsuppressed strange fraction:

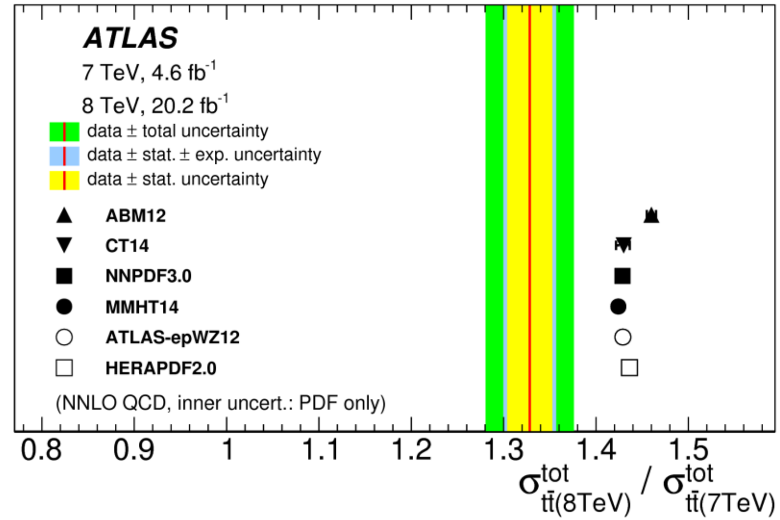
- in contradictions to most contemporary PDF sets (strange fraction around 0.5)
- however: large parametrisation uncertainty

tt/Z cross section ratio @ 7, 8, 13 TeV [JHEP 02 (2017) 117]

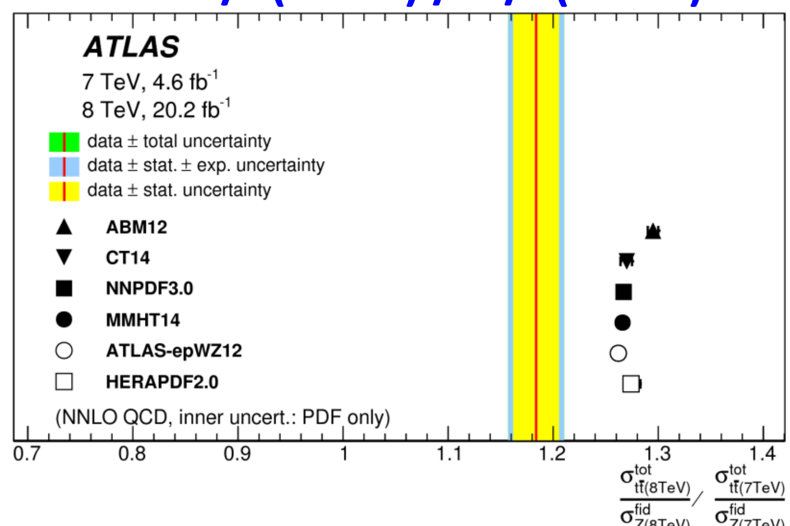
Z(8 TeV)/Z(7 TeV)



tt(8 TeV)/tt(7 TeV)



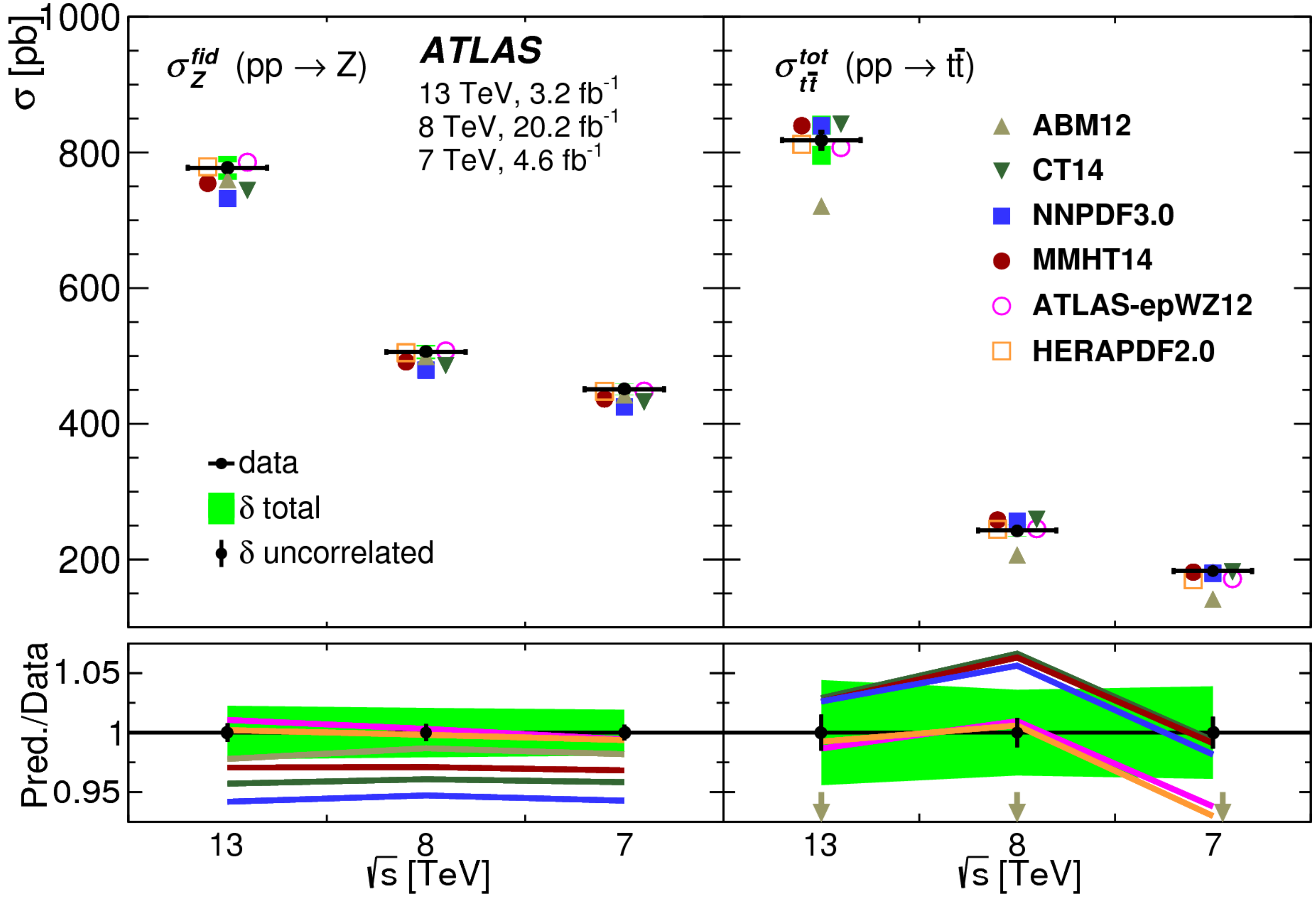
tt/Z(8 TeV) / tt/Z(7 TeV)



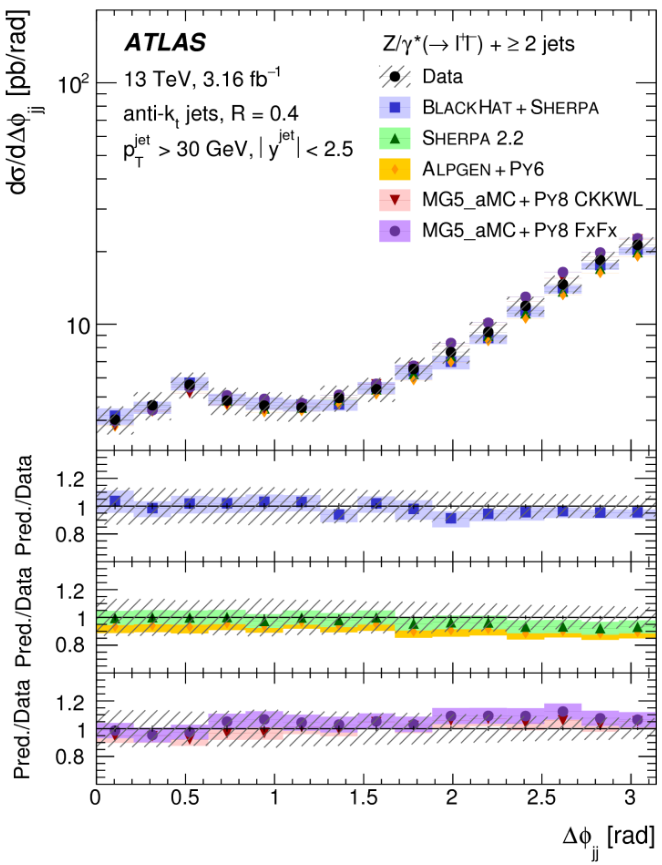
- **tt/Z double ratio measurement**
- 13/8 TeV, 13/7 TeV, 8/7 TeV (this slide)
- Further reduce uncertainties
- Discrepancy between data and MC for 8/7 TeV ratio
- Room for improvements
  - Mainly in the tt cross section

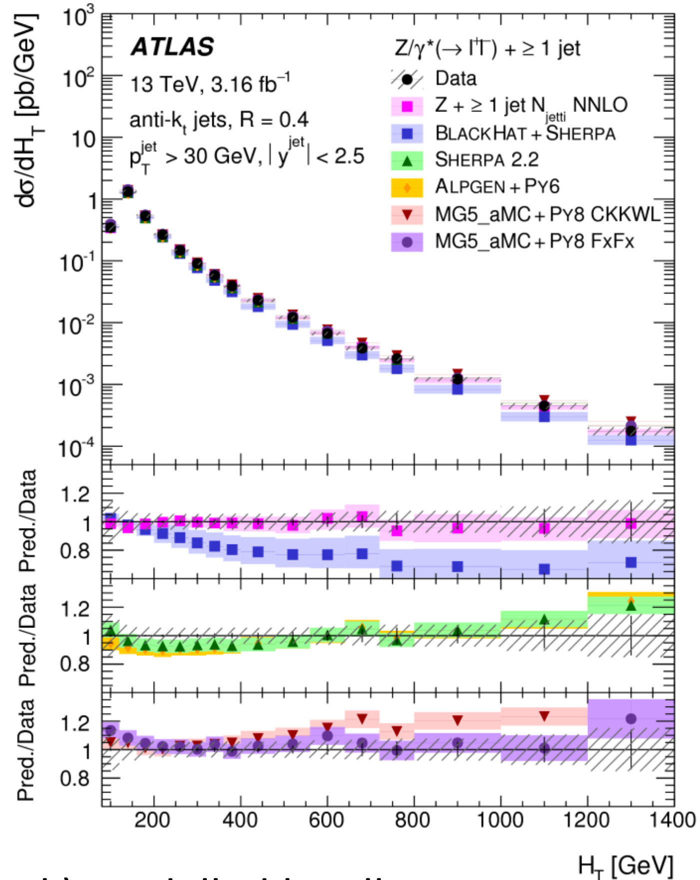
tt/Z cross section ratio @ 7, 8, 13 TeV JHEP 02 (2017) 117

6 cross sections used to profile ATLAS-epWZ12 PDF set



Z+jets cross section @ 13 TeV [Eur. Phys. J. C77 (2017) 361]





$$H_T = \sum_{\ell, jets} |p_T|$$

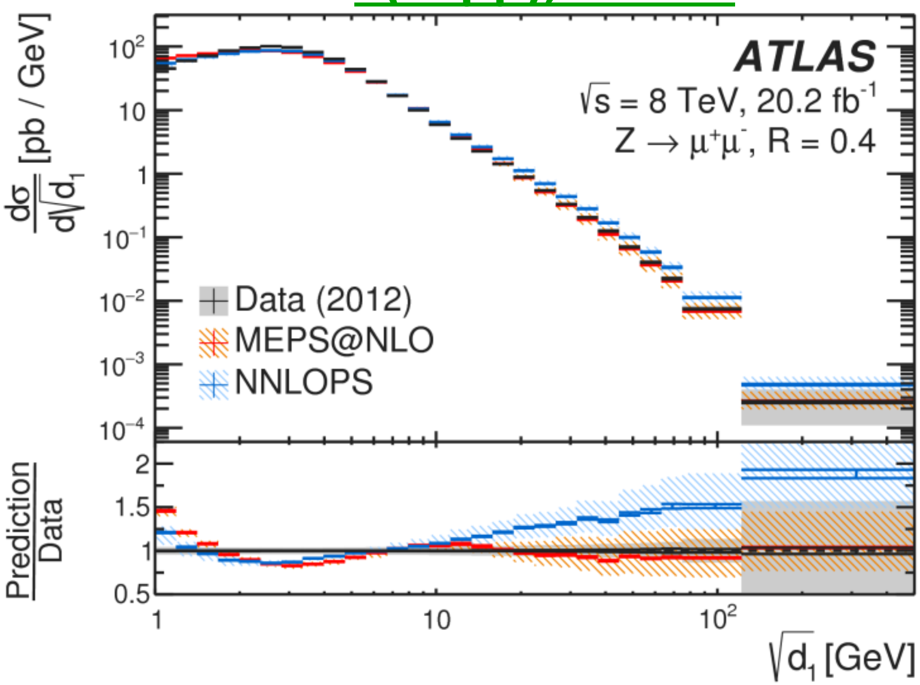
- Relative jet topology (mostly back-to-back) modelled by all
- **MG5_aMC+PY8 CKKWL** overestimates contribution at large H_T (hard jets)
- **BlackHat+Sherpa** (fixed order NLO) underestimates at H_T > 300 GeV due to missing contribution from higher parton multiplicities (higher orders in pQCD)
  - solved with **Njetti NNLO**

anti-k_t splitting scales @ 8 TeV JHEP08 (2017) 026

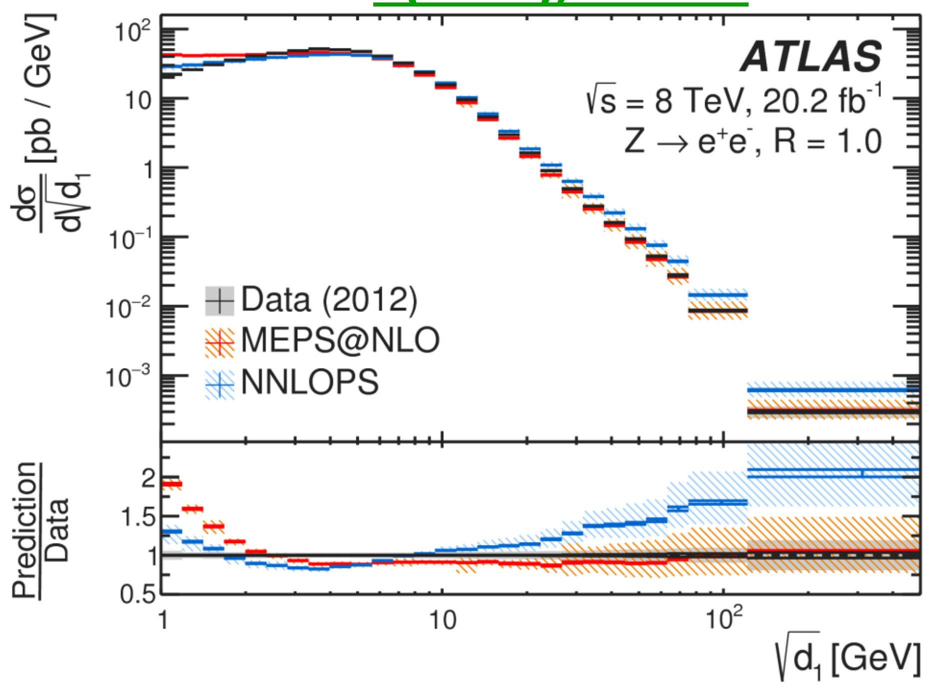
- Measurements provided from 0^{th} to 7^{th} splitting scales
- Observe significant differences between measurement and predictions
- Compatible results for:
  - $Z(\rightarrow ee)$ and $Z(\rightarrow \mu\mu)$ channels
  - R = 0.4 and R = 1.0

1^{th} splitting scale

$Z(\rightarrow \mu\mu)$, R = 0.4



$Z(\rightarrow ee)$, R = 1.0



Astonishing precision at 7 TeV (compared to 13 TeV)