Precision W,Z Measurements at Colliders

Rencontre de Blois, Mai 2017

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Introduction - Precision Measurements in SM

- **Why** do we perform precise measurements of standard model processes?
    - Challenge theoretical calculation on most precise level!
- Look for deviations from standard model predictions
- Consistency in the EWK sector
    - Potential for finding evidence of physics beyond the standard model
- Study QCD and EWK interactions at extreme regions of phase space
    - Use high energy collisions

Experimental precision needed to challenge theory calculations: < **few %**
— achieved at hadron colliders —

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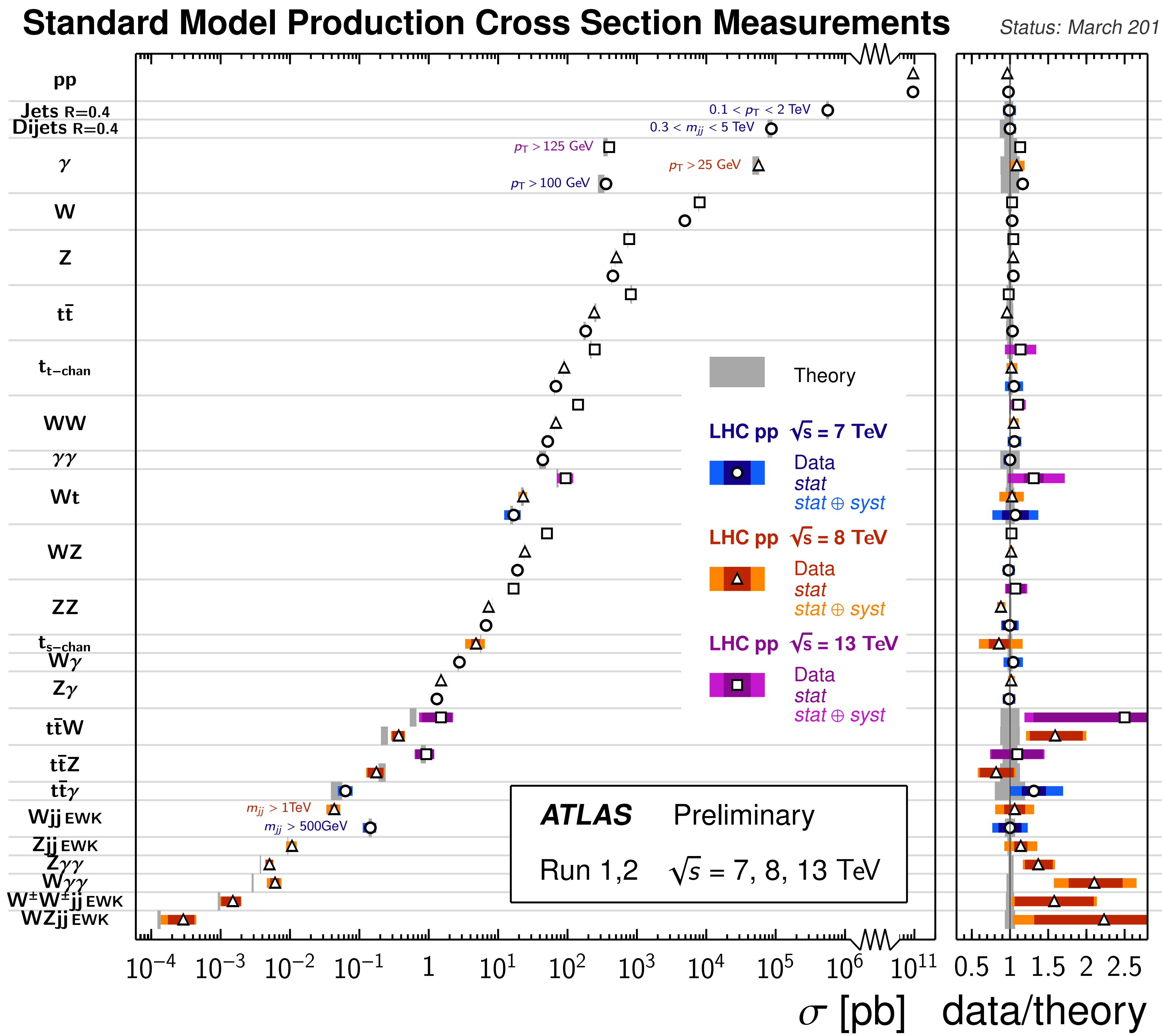
- Look for deviations from standard model predictions
- Consistency in the EWK sector
    - Potential for finding evidence of physics beyond the standard model
- Study QCD and EWK interactions at extreme regions of phase space
    - Use high energy collisions
- **Which prediction to compare to:**
    - State of the art Matrix Element calculations (NNLO)
        - Non-perturbative QCD, Resummation, Parton Shower
    - PDFs

See talks by **Fabrizio Caola** and **Peter Richardson**

Experimental precision needed to challenge theory calculations: < **few %**
— achieved at hadron colliders —

Overview of standard model measurements



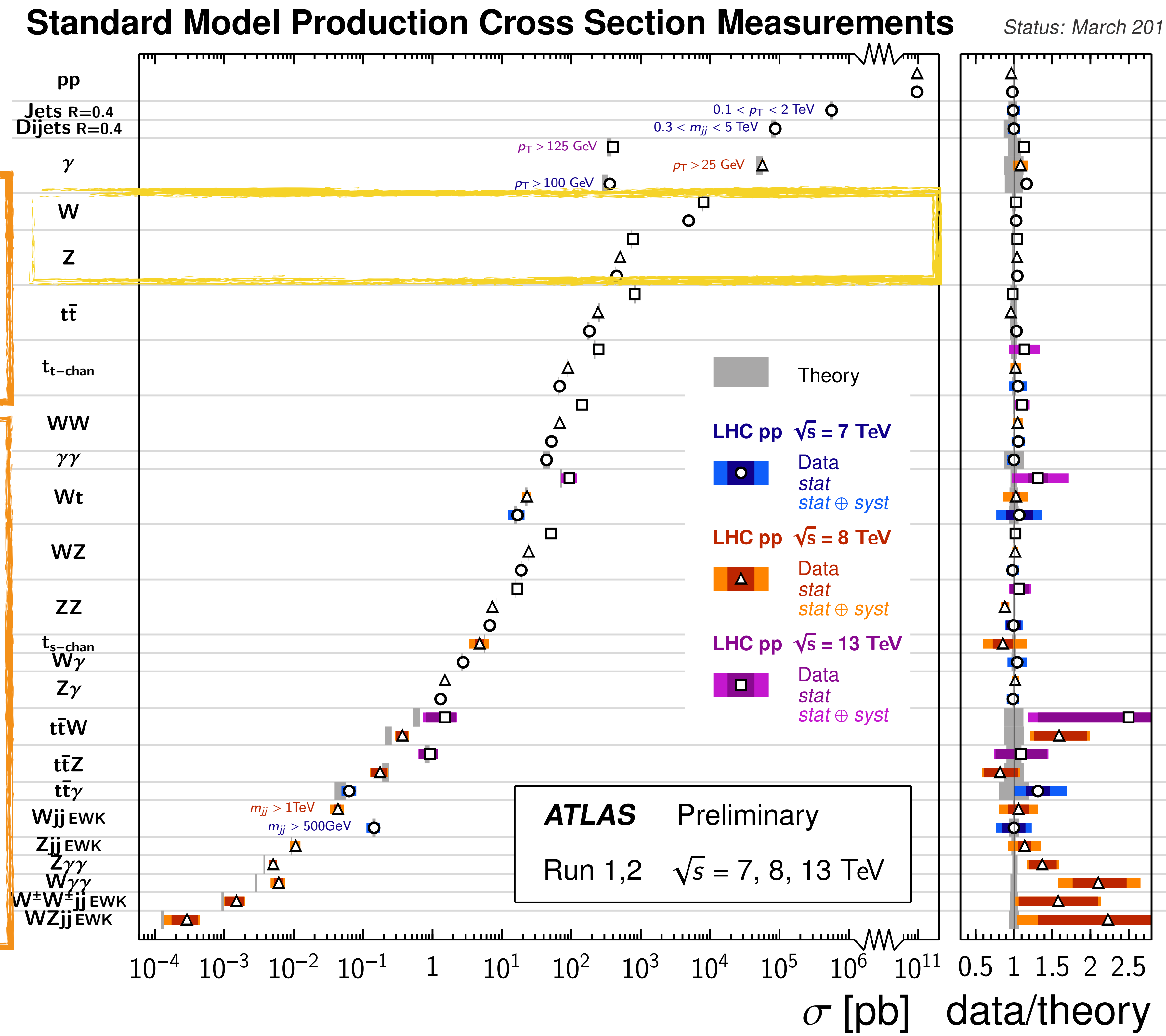
Overview of standard model measurements

- Vector Bosons + jets & ttbar:
  - next talk by Fabio Cossutti

- Multi-boson & EWK Boson production results covered in parallel session:

  - Higgs + Top + EW

Today!



Content

- W Mass measurement
  - Relies on other precision measurements
- Single Boson cross section measurements
  - Inclusive & differential
  - Impact on PDFs
- Angular distributions
  - Z Forward Backward asymmetry
  - Weak mixing angle
  - Z Angular Coefficients / Z Polarisation
- Summary

See **Tai-Hua Lin's** talk on ATLAS W mass measurement

See **Fabio Cossutti's** talk on tests of QCD @ colliders

Personal selection of results, many more available!

W-mass measurement

W mass @ LHC

arXiv:1701.07240

m_t m_H $m_?$

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r)$$

- Sensitive probe of SM EWK sector
- Sensitive to EWK corrections and modeling of boson kinematic

- Current SM predictions:
  Δm_W = 8 MeV arXiv: 1608.01509
- Extremely challenging measurement
- Relies on previous W,Z precision measurements!

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m_t m_H $m_?$

- Sensitive probe of SM EWK sector
- Sensitive to EWK corrections and modeling of boson kinematic
- PDF for simulation chosen by 7TeV W,Z inclusive cross section measurement
- p_T^Z constraint from measurement
- Uncertainty on spin correlations from 8 TeV Z - polarization measurement

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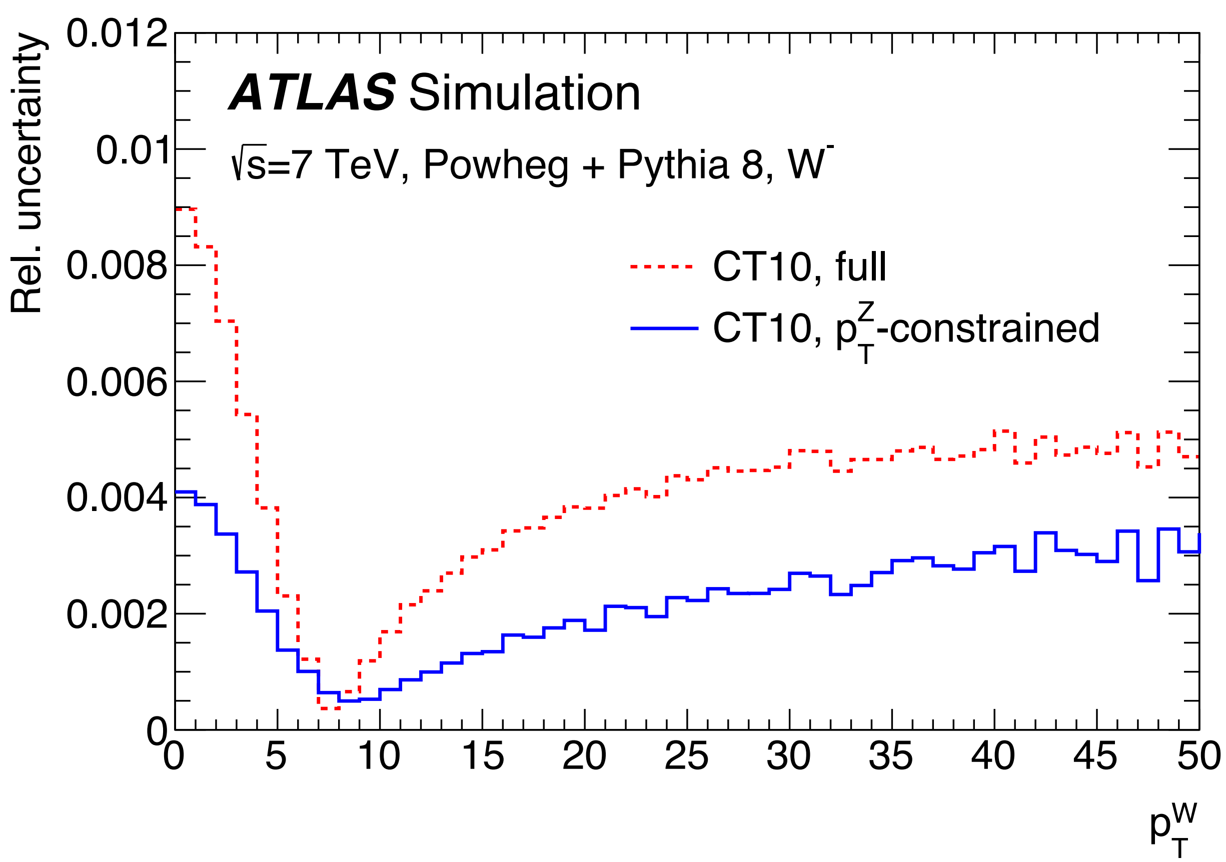

W mass @ LHC - Result

arXiv:1701.07240

m_t

m_H

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$m_?$

- Current SM predictions:
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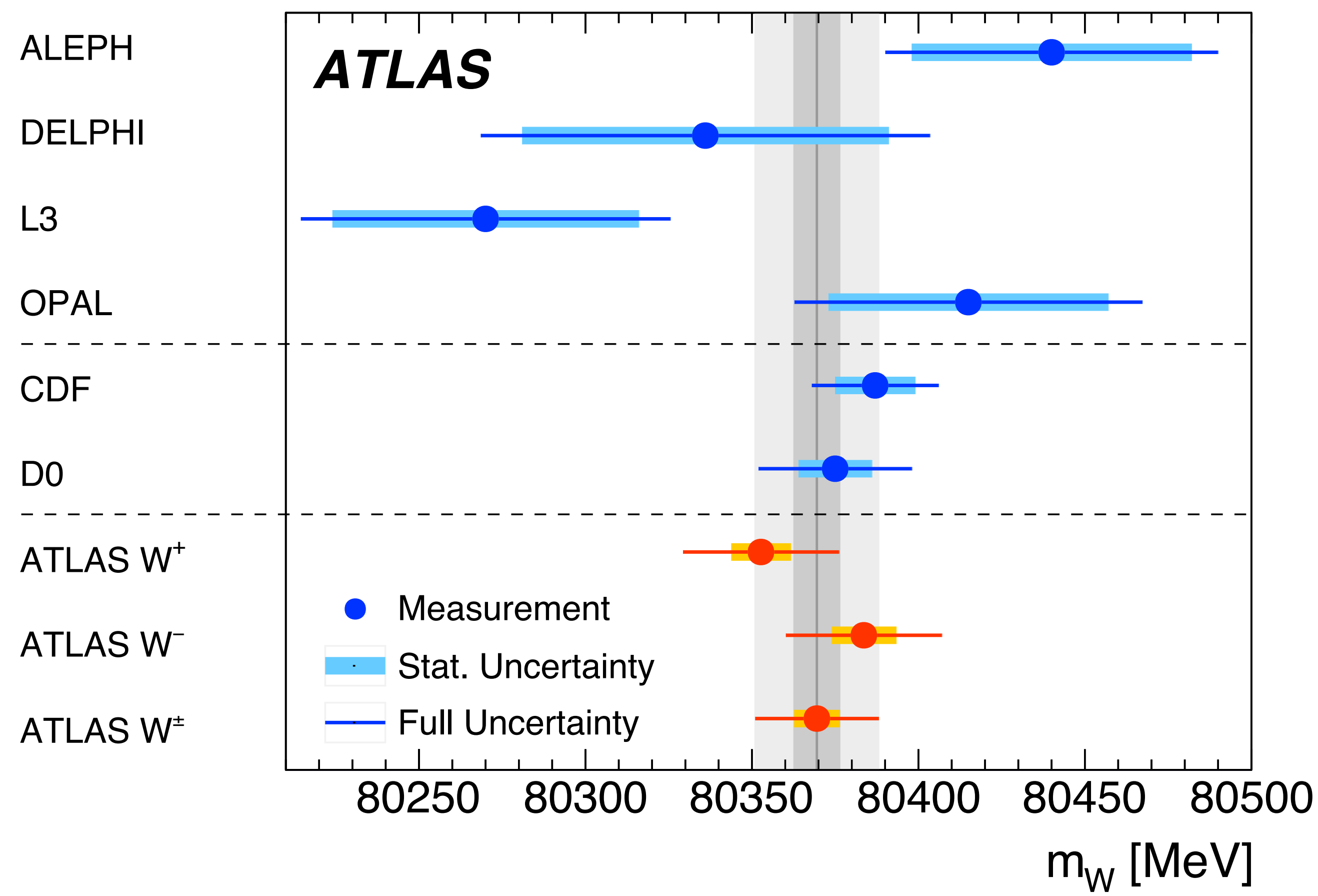
arXiv: 1608.01509

$$\begin{aligned} m_W &= 80370 \pm 7\,(\text{stat.}) \pm 11\,(\text{exp. syst.}) \pm 14\,(\text{mod. syst.})\ \text{MeV} \\ &= 80370 \pm 19\ \text{MeV}, \end{aligned}$$

- Sensitive variables: p_T^l & m_T
- Pushed precision of lepton & missing energy calibration to unprecedented accuracy
- Good agreement between hadron collider measurements



W mass @ LHC - Uncertainties

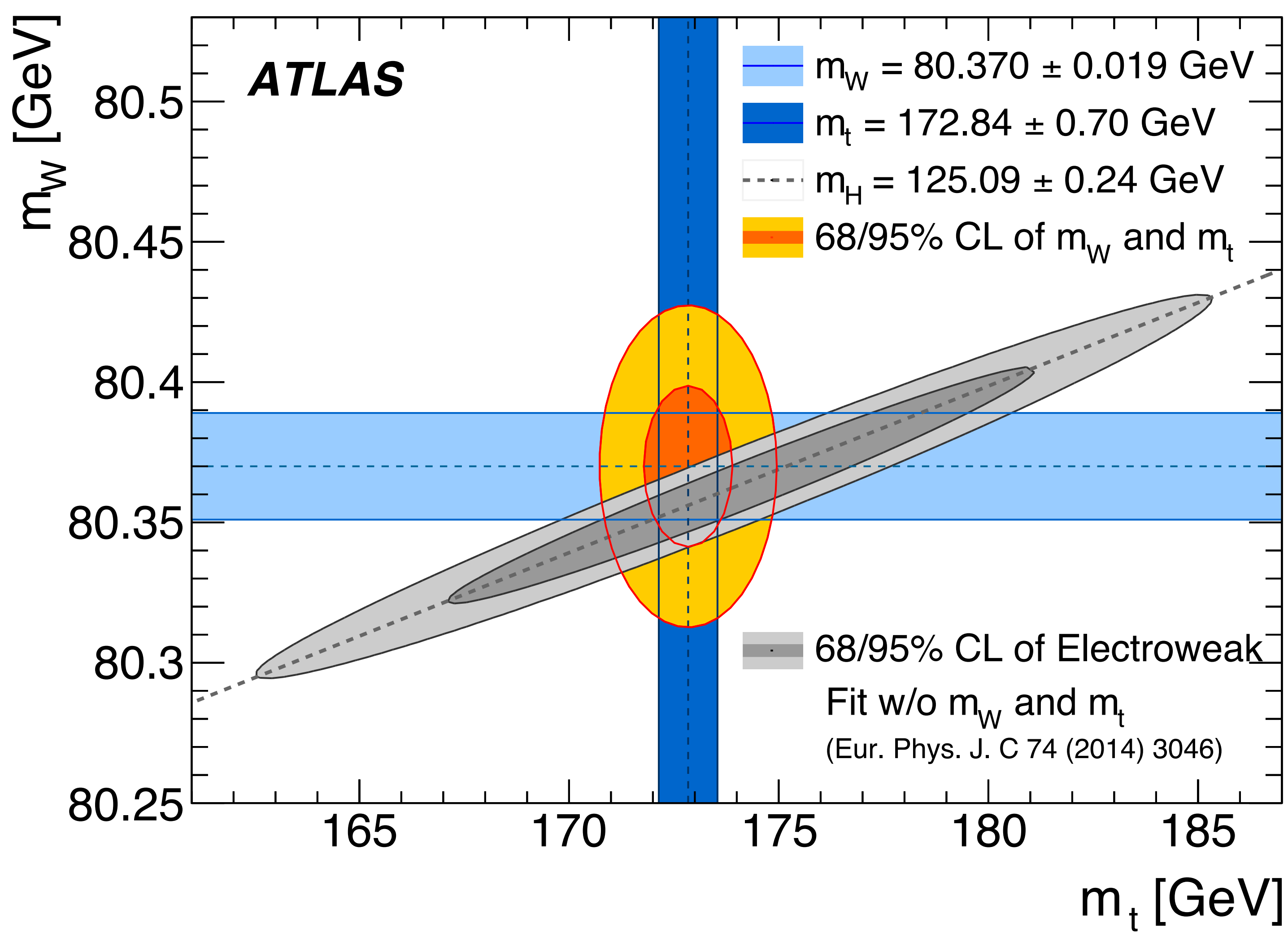
arXiv:1701.07240

Source		
	pT	mT
QCD modeling	11.6	12.9
e: E scale, eff	14.2	14.3
μ: pT scale, eff	9.8	9.7
Recoil corrections	2.6	13.0
EWK corrections	5.6	2.6

- **Largest uncertainties:**
  - Theory model
  - Electron experimental uncertainties

Precision test for consistency of standard model:

For more details:
See talk by **Tai-Hua Lin**,
today @ 16:50h



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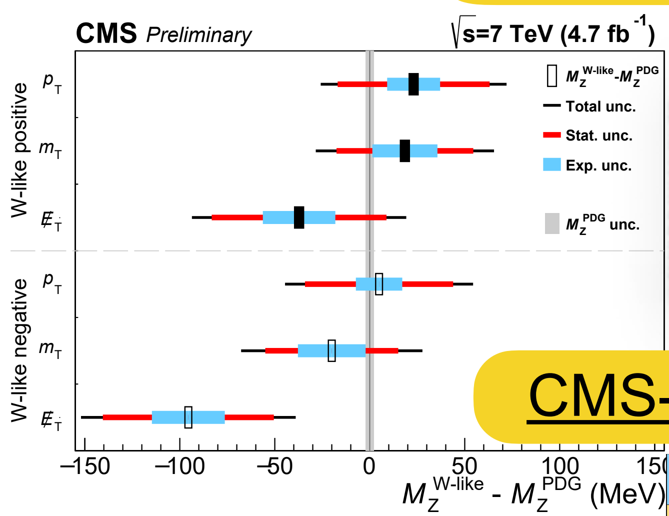
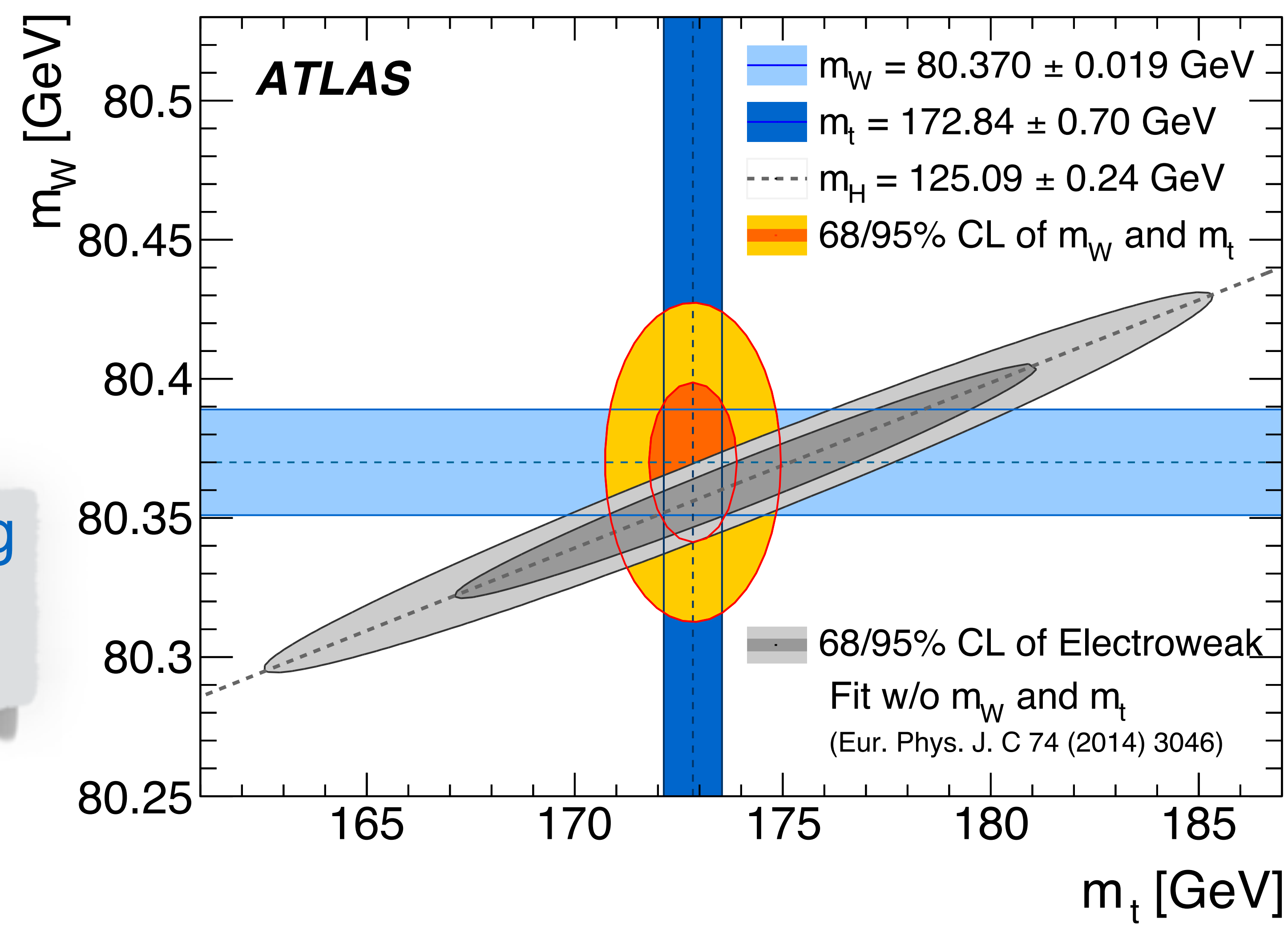


CMS also working on W-mass measurement

CMS-PAS-SMP-14-007



W,Z Boson inclusive & differential cross sections

W,Z - Boson Inclusive x-Section @ 7 TeV

- Measurement of the total & differential production cross sections
  - Electron & Muon final states
    - $W \to \ell\nu$: $|\eta_\ell| < 2.5$
    - $Z \to \ell\ell$: $|y_{\ell\ell}| < 3.6$, three bins in $m_{\ell\ell}$

arXiv:1612.03016

- Total production cross sections: **Uncertainty < 2.8 % total**
  Lumi: 1.8%, **exp. sys: W: ~1%, Z: 0.4%**

		$\sigma^{tot}_{W\to\ell\nu}$ [pb]	total unc.:
W	$W^+ \to \ell^+\nu$	$6350 \pm 2\,(\text{stat}) \pm 30\,(\text{syst}) \pm 110\,(\text{lumi}) \pm 100\,(\text{acc})$	2.4%
	$W^- \to \ell^-\bar{\nu}$	$4376 \pm 2\,(\text{stat}) \pm 25\,(\text{syst}) \pm 79\,(\text{lumi}) \pm 90\,(\text{acc})$	2.8%
	$W \to \ell\nu$	$10720 \pm 3\,(\text{stat}) \pm 60\,(\text{syst}) \pm 190\,(\text{lumi}) \pm 130\,(\text{acc})$	2.2%
		$\sigma^{tot}_{Z/\gamma^*\to\ell\ell}$ [pb]	
Z	$Z/\gamma^* \to \ell\ell$	$990 \pm 1\,(\text{stat}) \pm 3\,(\text{syst}) \pm 18\,(\text{lumi}) \pm 15\,(\text{acc})$	2.4%

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- Dominating uncertainties (syst):
  - Signal modeling el. (W) 0.7%, $Z_{forward}$ 1.1%
- Experimental:
  - Multijet BG estimate (W only) < 0.7 %
  - Reconstruction efficiency ~ 0.2 %
  - Transverse momentum scale (W) ~ 0.2 %

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Most precise hadron collider result on single vector boson production

- 4.6 fb^{-1} @ 7 TeV CME
  - 29 M W candidates
  - 3 M Z candidates

Z Boson - x-Section in forward region @ 13 TeV

LHCb

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- Acceptance in forward region:
  - $2.0 < |\eta_\ell| < 4.5$, $p_T > 20$ GeV
  - $60 \text{ GeV} < m_{\ell\ell} < 120 \text{ GeV}$

Source	$\Delta\sigma_Z^{\mu\mu}$ [%]	$\Delta\sigma_Z^{ee}$ [%]
Statistical	0.5	0.9
Reconstruction efficiencies	2.4	2.4
Purity	0.2	0.5
FSR	0.1	0.2
Total systematic (excl. lumi.)	2.4	2.5
Luminosity	3.9	3.9

stat. sys. lumi. **total unc.:**

	total unc.
$\sigma_Z^{\mu\mu} = 198.0 \pm 0.9 \pm 4.7 \pm 7.7\,\text{pb},$	4.5%
$\sigma_Z^{ee} = 190.2 \pm 1.7 \pm 4.7 \pm 7.4\,\text{pb}.$	4.7%
$\sigma_Z^{\ell\ell} = 194.3 \pm 0.9 \pm 3.3 \pm 7.6\,\text{pb}$	4.3%

- **1.7% experimental uncertainty!**

Z Boson - x-Section in forward region @ 13 TeV

CMS-PAS-SMP-15-004

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- Acceptance:
  - $|\eta| < 2.5$, $p_T > 25$ GeV
  - 60 GeV < $m_{\ell\ell}$ < 120 GeV

		stat.	sys.	lumi.	total unc.:
σ(W⁺)	= 11370	± 50	± 230	± 550 pb	5.3%
σ(W⁻)	= 8580	± 50	± 160	± 410 pb	5.2%
σ(Z)	= 1910	± 10	± 40	± 90 pb	5.2%

- Dominating uncertainties:
  - Lumi: 4.8%
  - Lepton Reco: 2%
  - Theory: 1.5%

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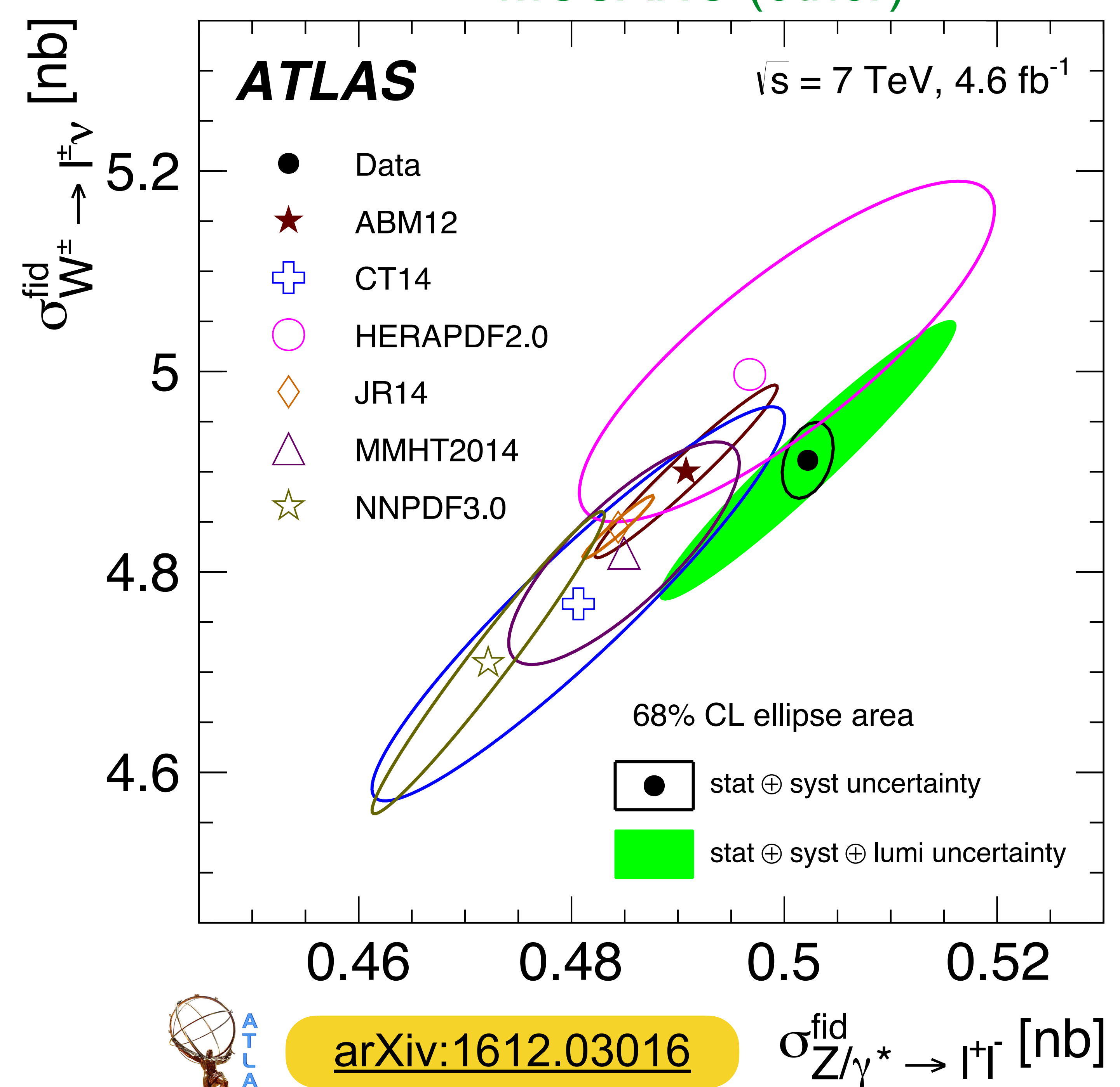
- **1.7% experimental uncertainty!**

W,Z - Boson Inclusive Cross-Section @ 7 TeV

Predictions:

- NNLO QCD using DYNNLO
- NLO EWK corrections using
  - PHOTOS (QED FSR)
  - MCSANC (other)



arXiv:1612.03016

W,Z - Boson Inclusive Cross-Section @ 7 TeV

- Ratio of σ(W) / σ(Z)
  - Luminosity uncertainty cancels
  - Exp. uncertainties cancel partially due to correlations

- Comparison to current PDFs yields interesting tension:
  - All considered PDFs yield larger W/Z cross section ratios than measured

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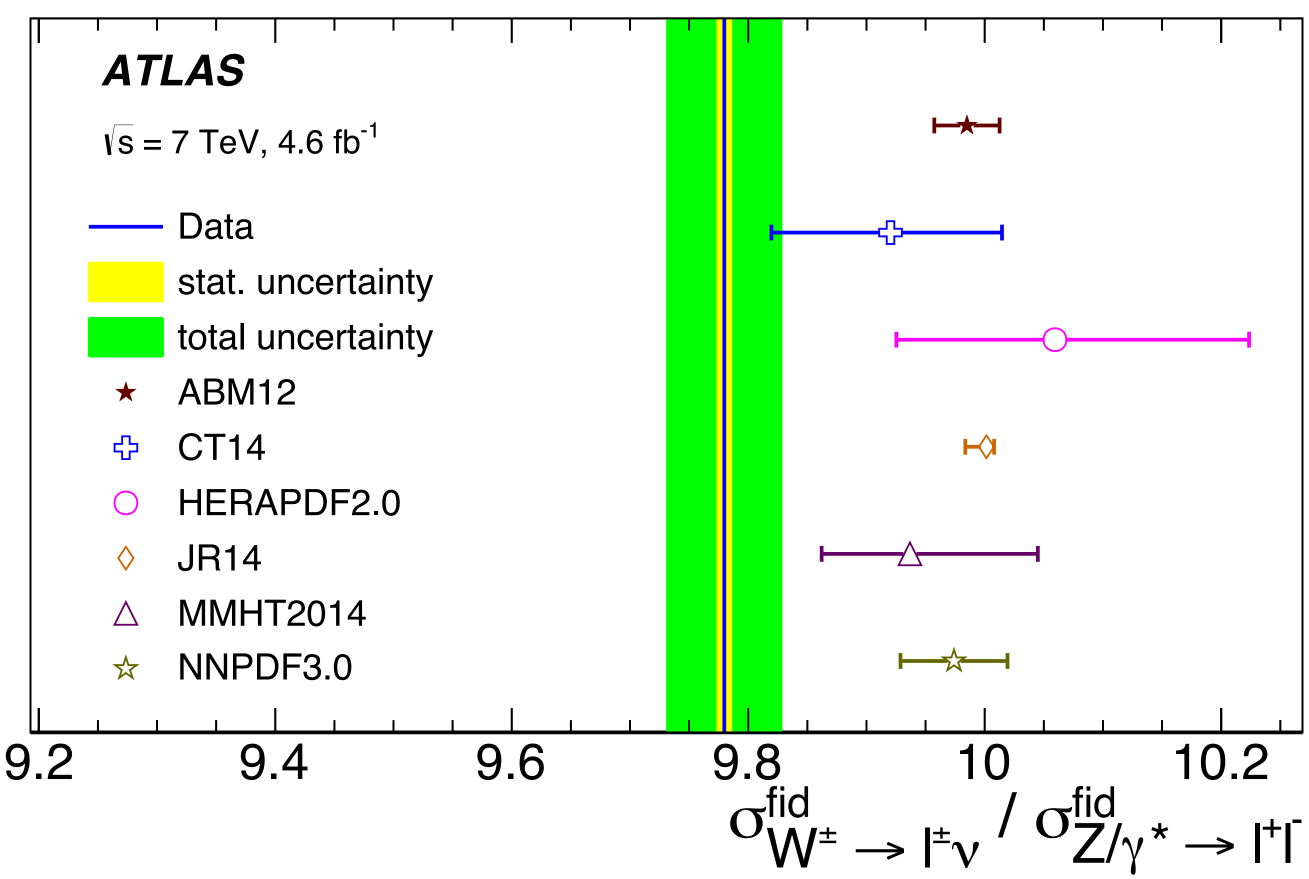
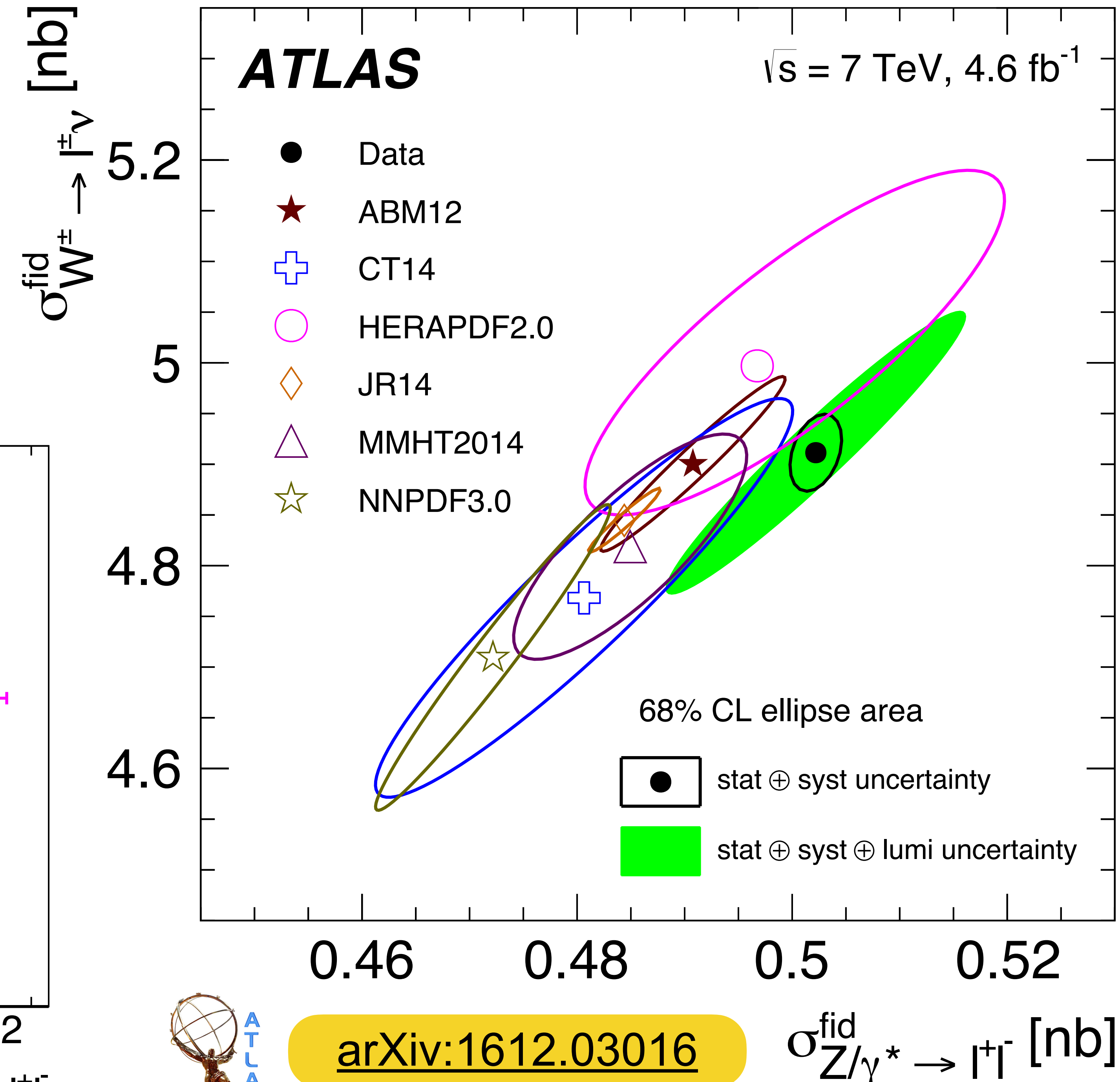


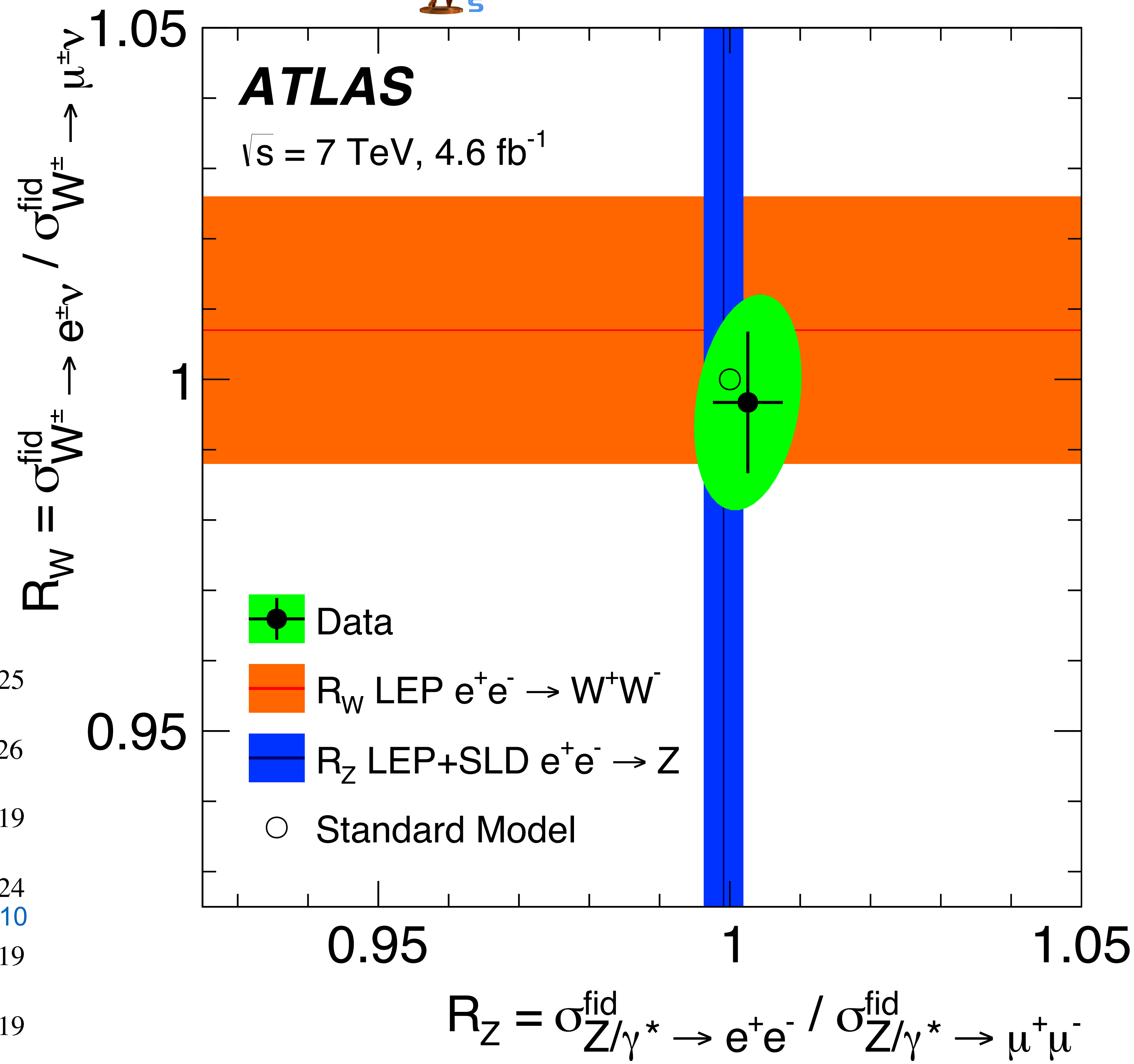


arXiv:1612.03016

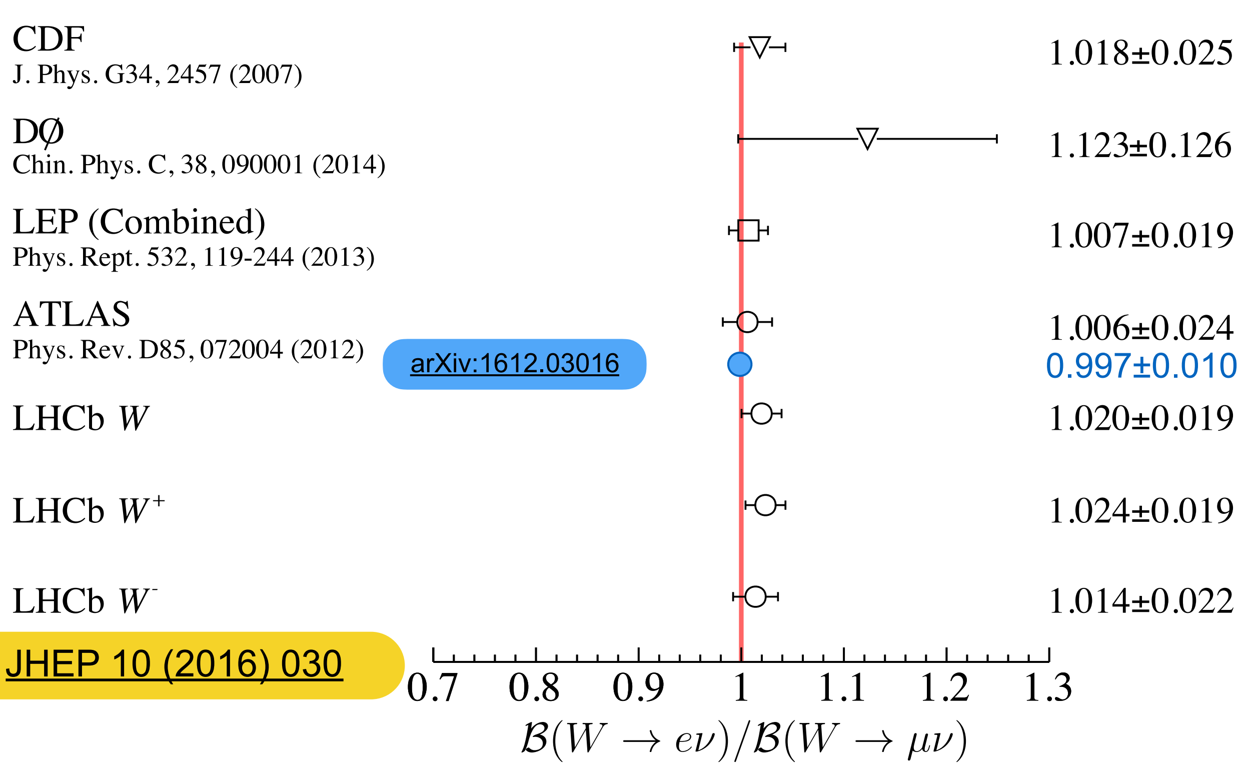
W,Z - Boson Inclusive Cross-Section

- Test of lepton universality for 1st and 2nd lepton generations:
- In good agreement with Standard Model
- Precision on R_W improved w.r.t. LEP result!
  - $R_W = 0.997 \pm 0.010$

arXiv:1612.03016



$R_Z = 1.0026 \pm 0.0050$



JHEP 10 (2016) 030

W,Z - Boson Differential Measurements - Rapidity

- Predictions:
  - NLO pQCD using FEWZ 3.1
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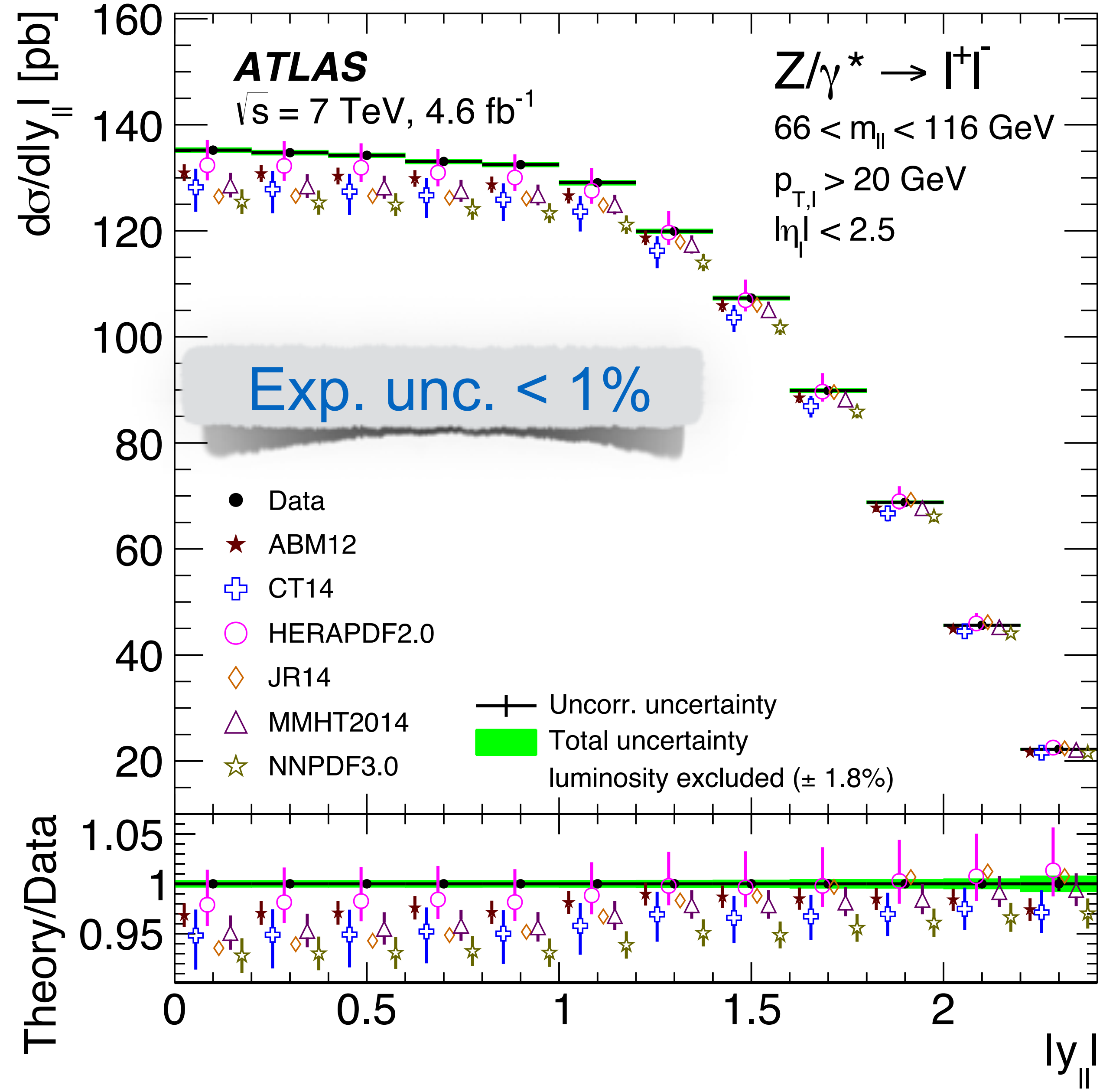

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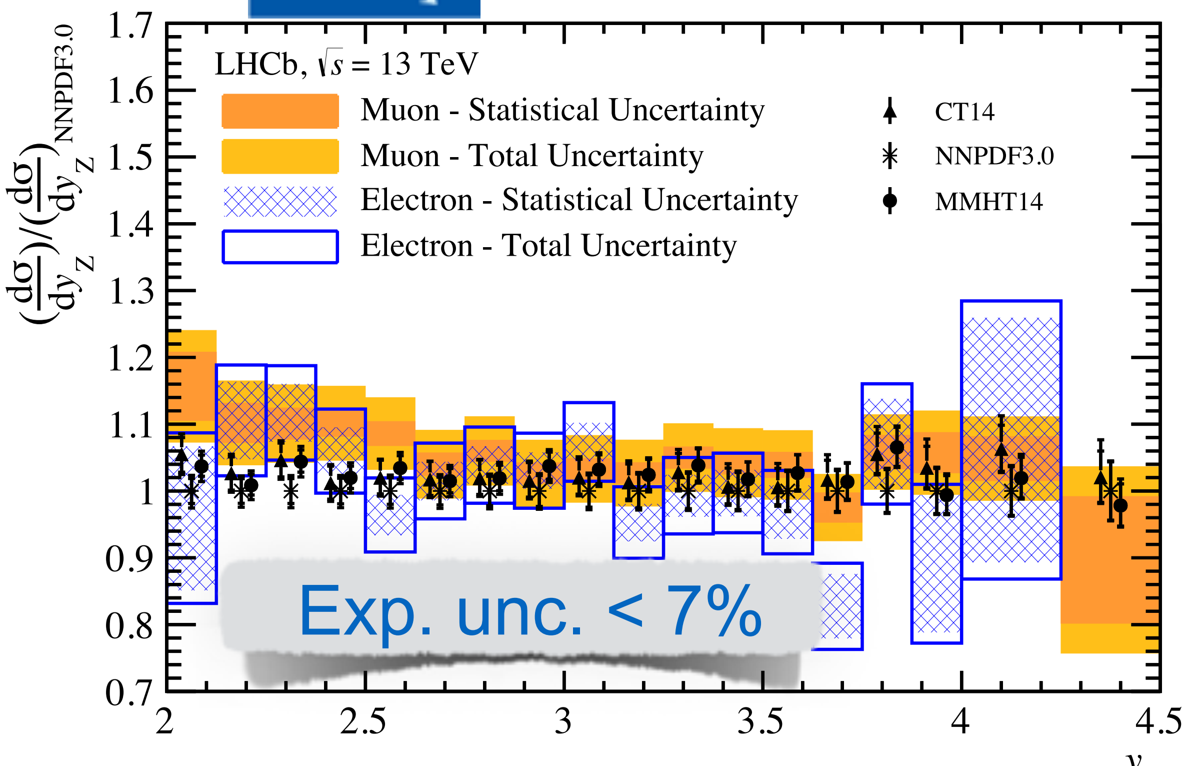

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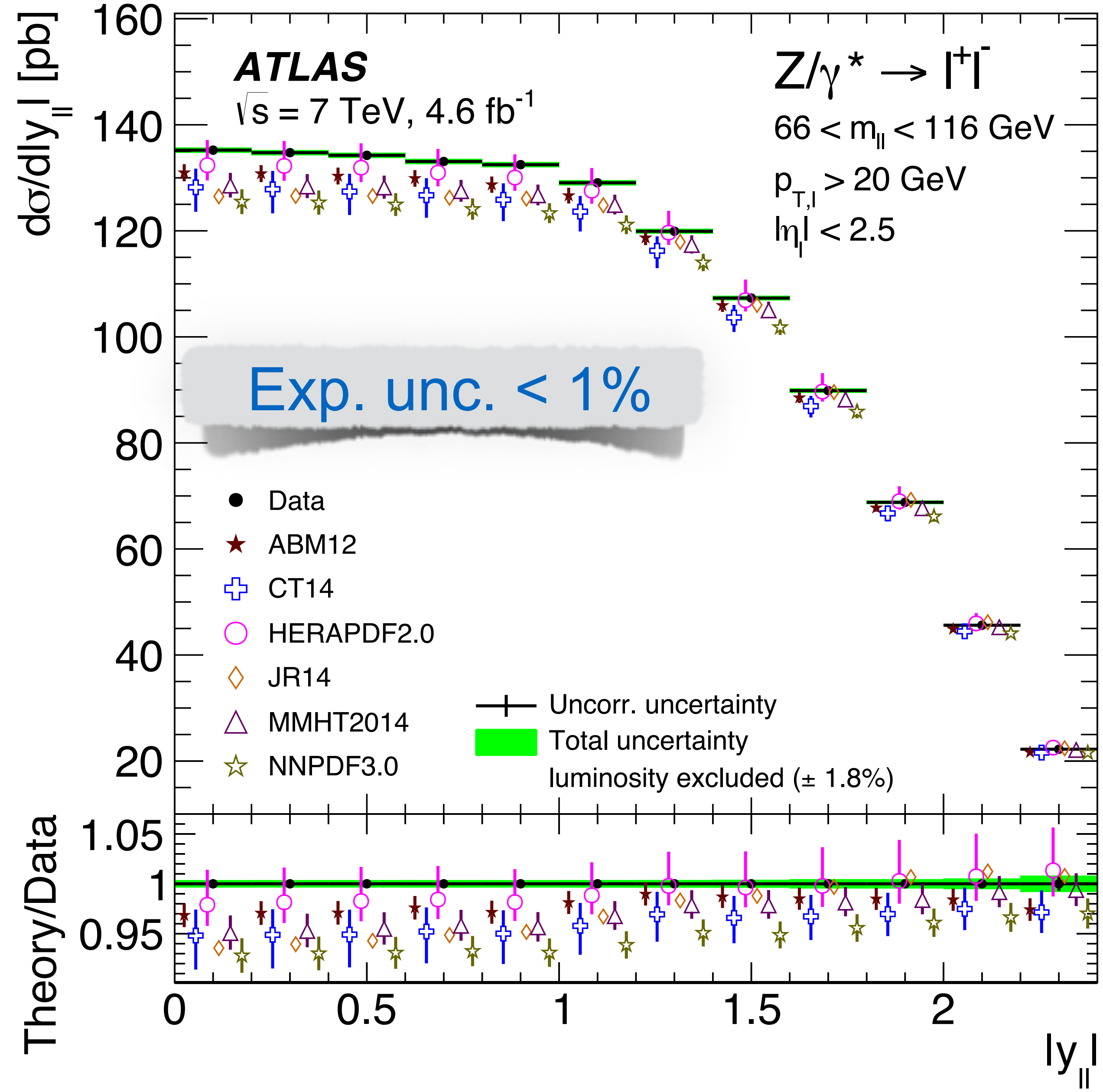
- Experimental uncertainties < Theory uncertainties!
  - for central rapidities

arXiv:1612.03016



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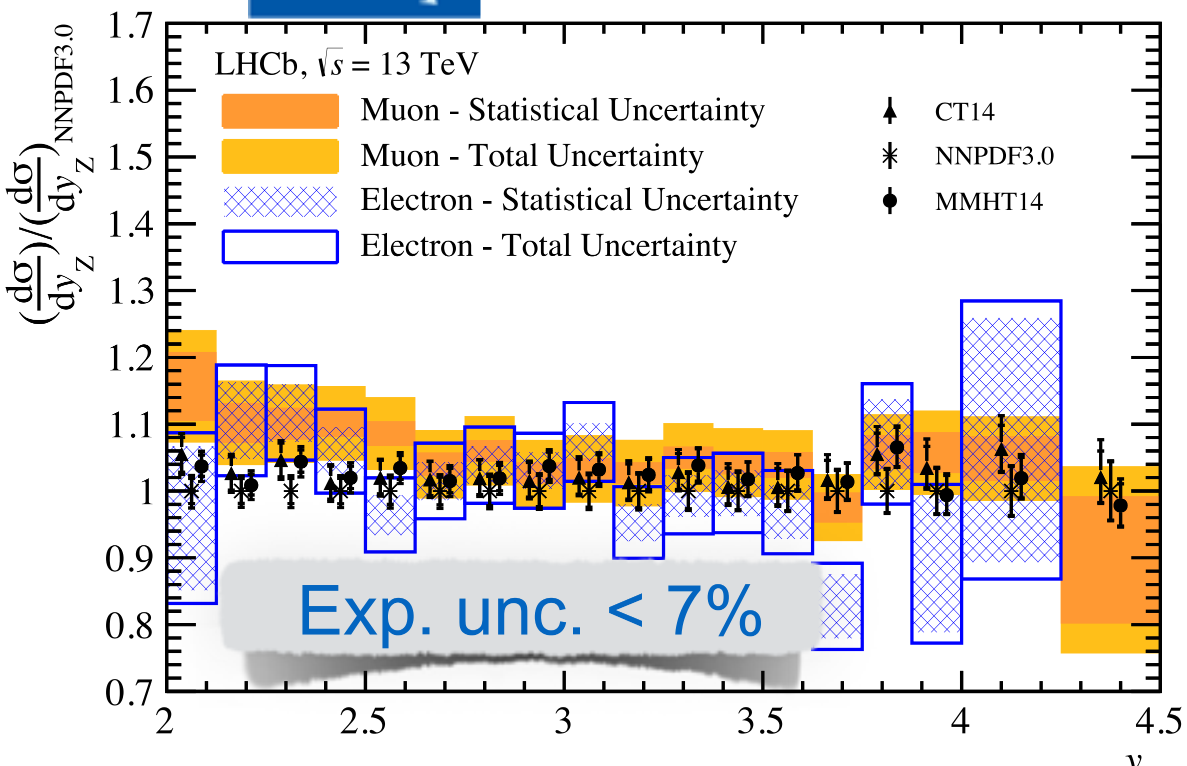

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- Comparison to various PDFs:
- Predicted cross section too low for |η| < 2.7
  - (except HERA 2.0 PDF)
  - Consistent between experiments
- Discrepancy in shape

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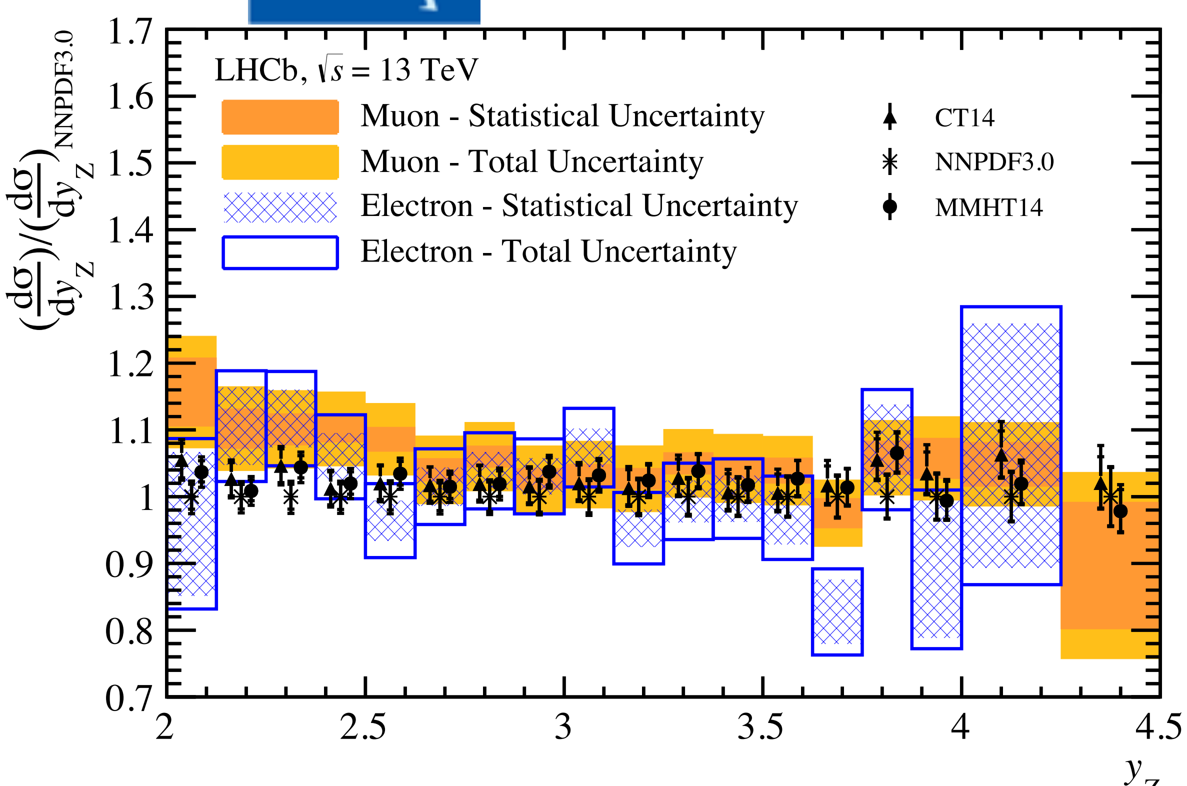

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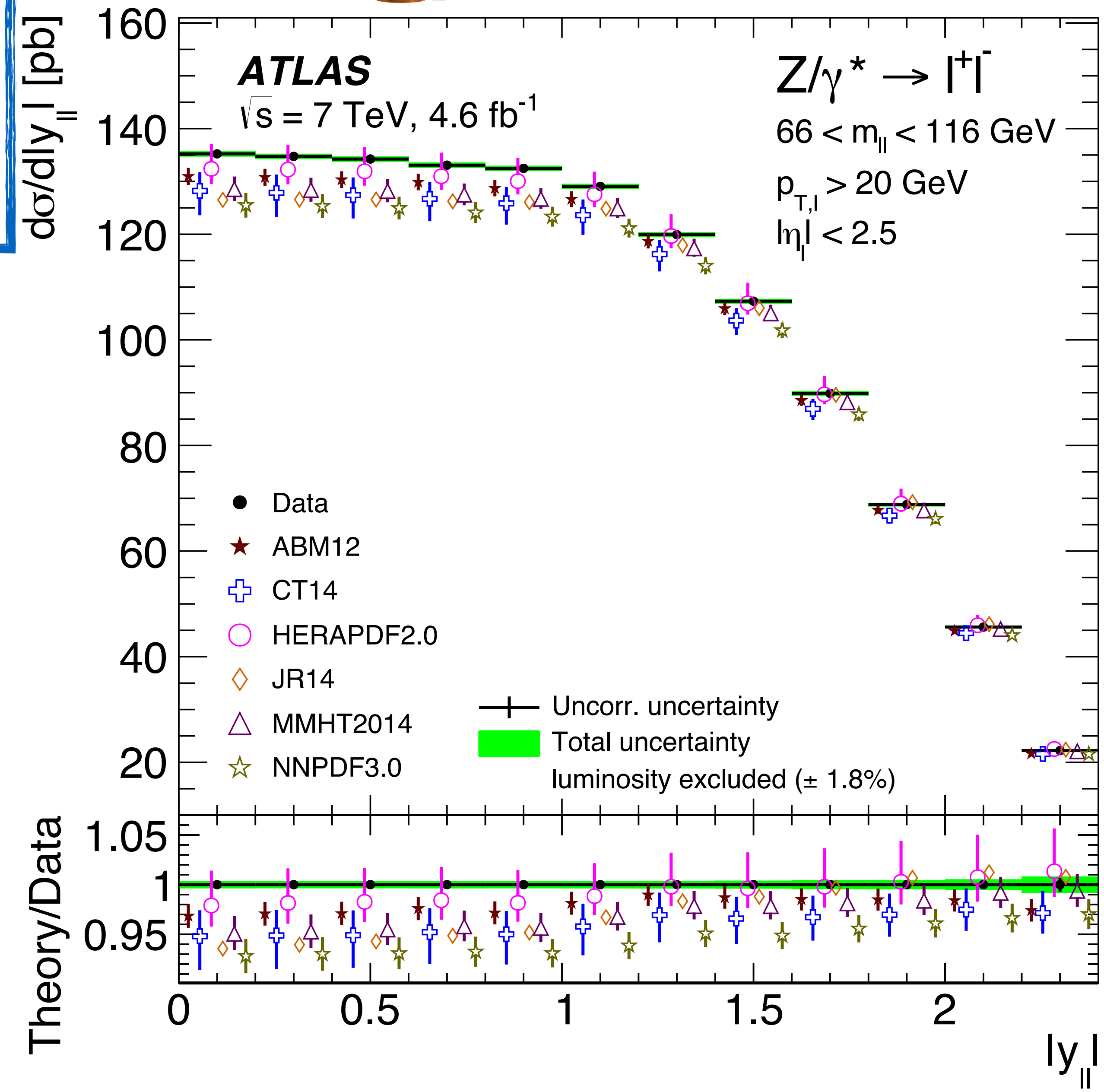
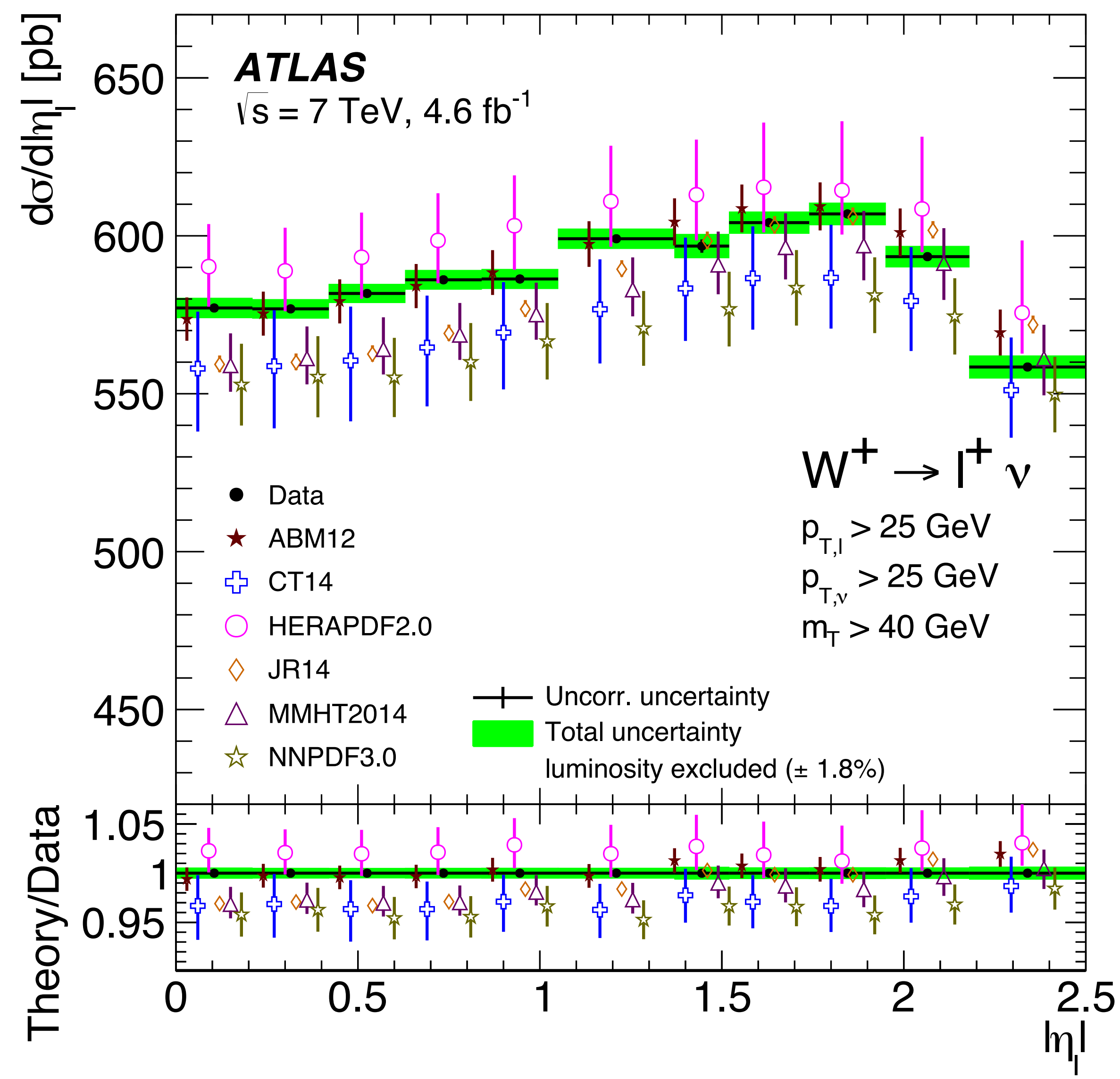


- W boson (pseudo-) rapidity

arXiv:1612.03016



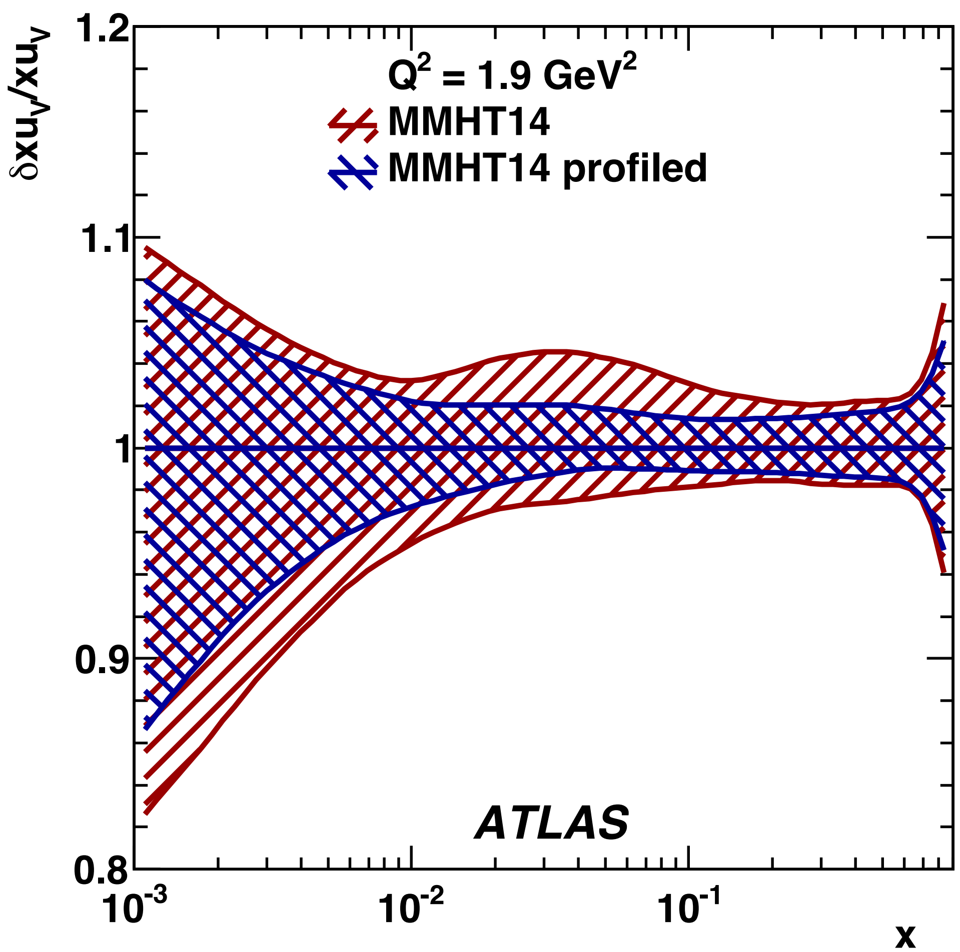
W,Z - Boson Differential Measurements - Rapidity

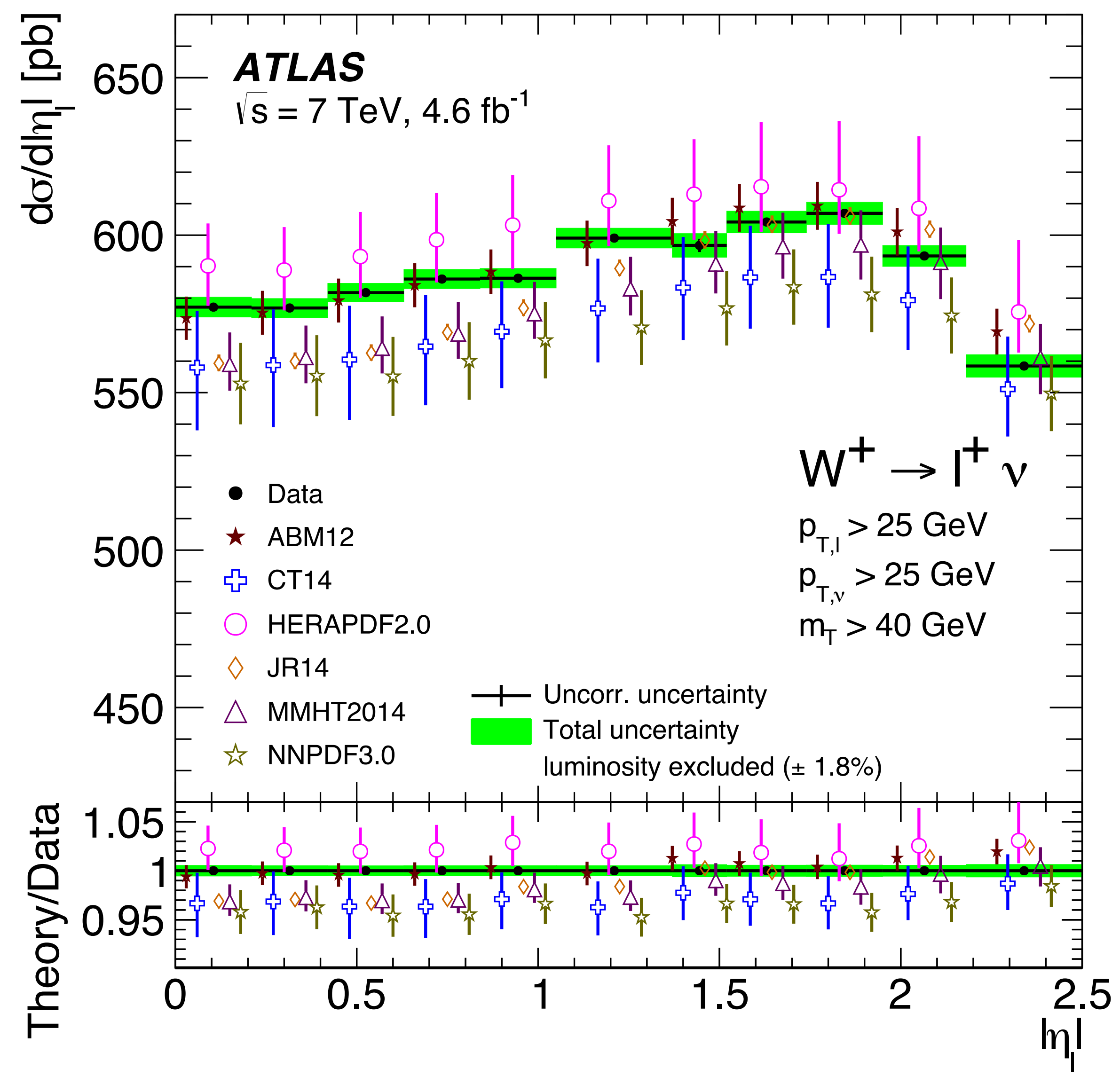
arXiv:1612.03016

- W boson (pseudo-) rapidity

- Measurements sensitive to PDF
  - Impact on PDF evaluated using profiling
    - Significant reduction of PDF uncertainty!

- Relative uncertainty on u-Quark PDF





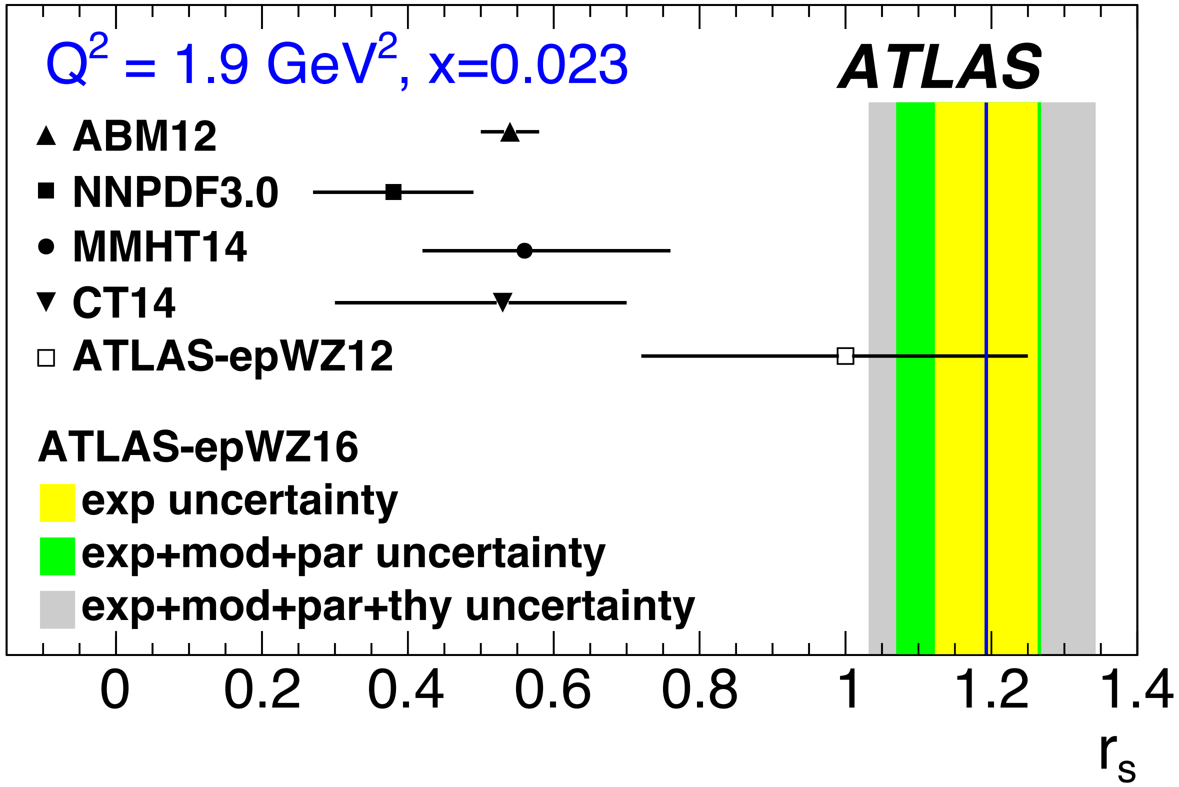
W,Z - Boson Differential Measurements @ 7 TeV

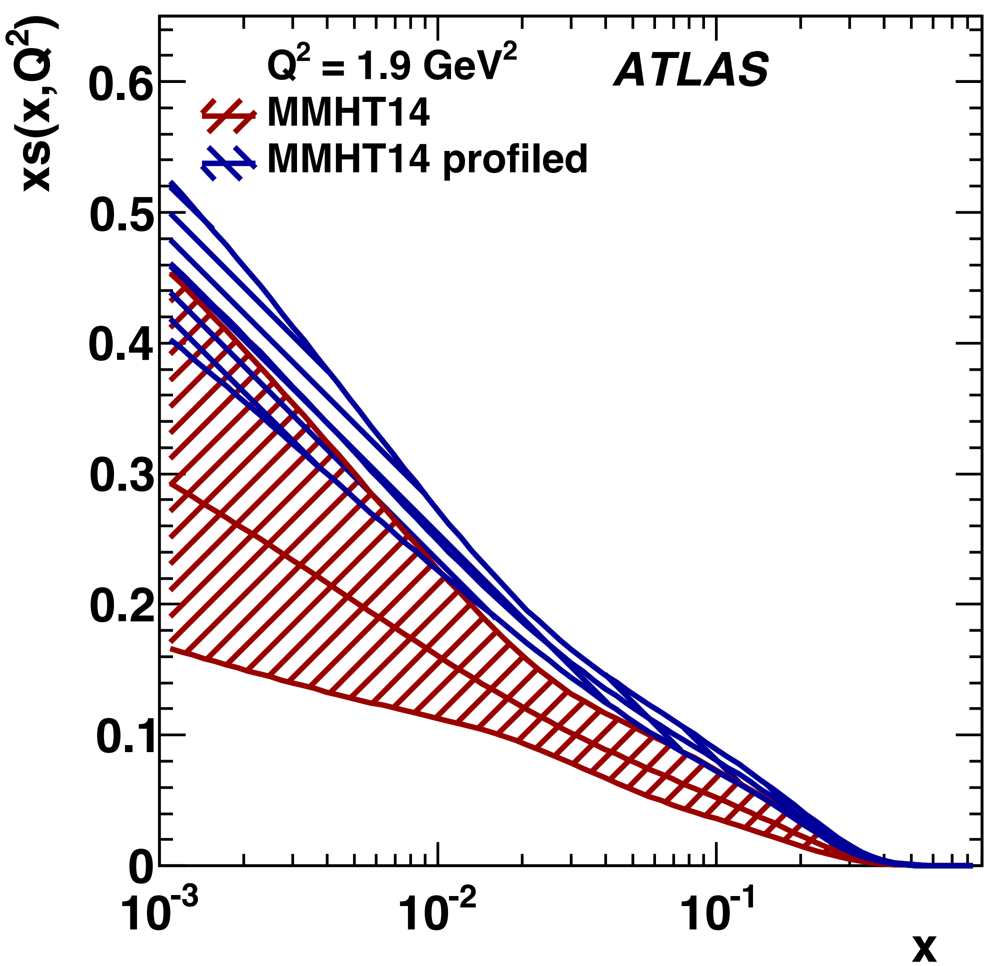
arXiv:1612.03016

- Extraction of the strange quark density:

$$r_s = \frac{s+\bar{s}}{2\bar{d}} = 1.19 \pm 0.07\,(\text{exp}) \;\pm 0.02\,(\text{mod})\;^{+0.02}_{-0.10}\,(\text{par})$$

- Strangeness in quark sea unsuppressed!
  - Confirmed results from 2010 data





- PDF profiling used to study impact of measurement on given PDF
  - Uncertainty significantly reduced
  - Central values changed

W → eν: Differential Charge Asymmetry

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

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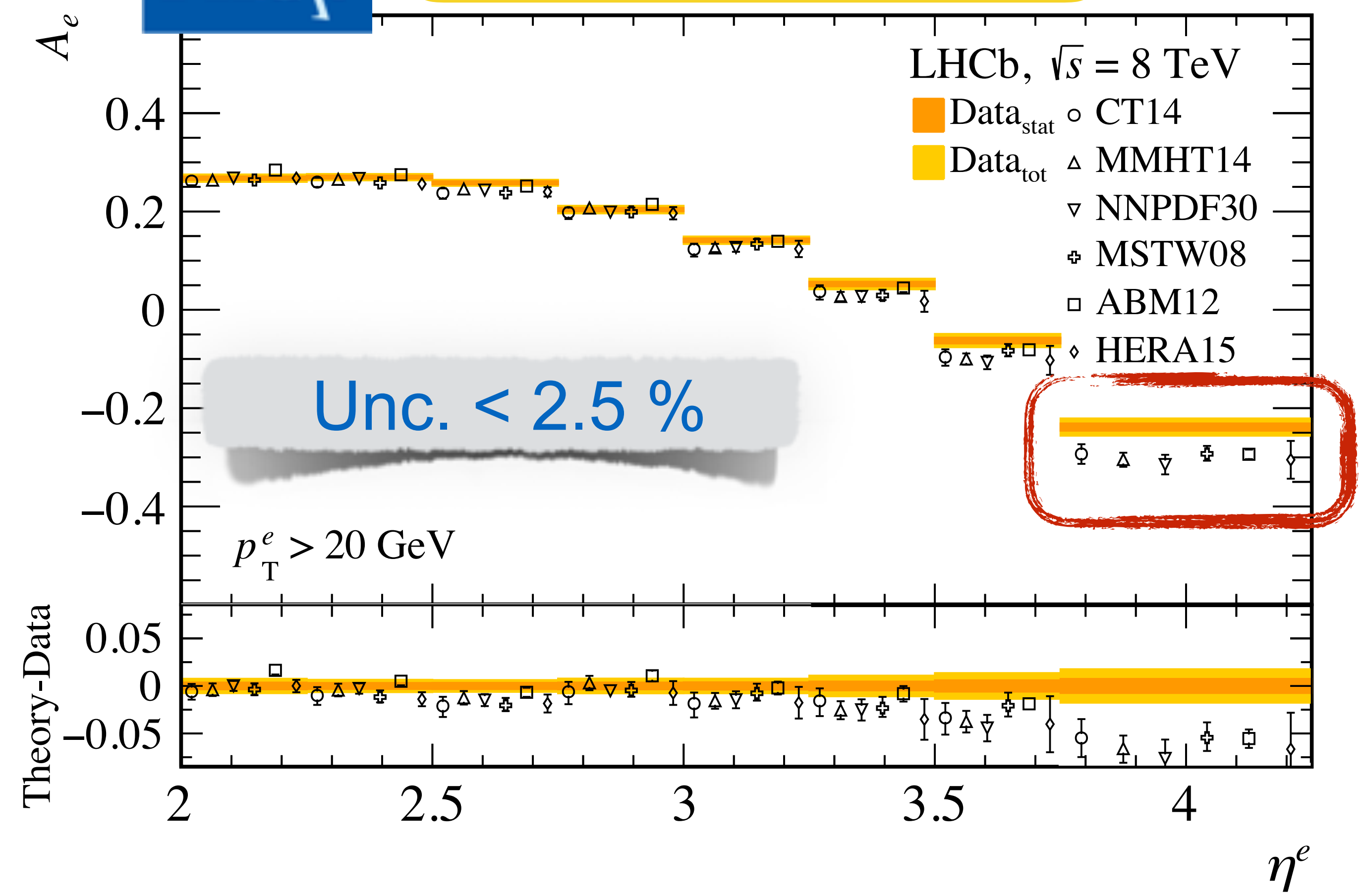
- High |η| region very sensitive to PDF effects
  - Significant deviation between data and predictions



- Largest uncertainties:
  - Momentum scale: 1.8%
  - PID, FSR modeling: 0.6%
  - Track reconstruction: 0.5%

Source	Uncertainty [%]		
	$\sigma_{W^+\to e^+\nu_e}$	$\sigma_{W^-\to e^-\bar{\nu}_e}$	$R_{W^\pm}$
Statistical†	0.19	0.24	0.30
Yield (statistical)†	0.28	0.40	0.48
Yield (systematic)	1.42	1.79	0.51
Efficiency (statistical)†	0.55	0.55	0.21
Efficiency (systematic)	1.11	1.14	0.54
FSR corrections†	0.05	0.07	0.09
Acceptance corrections (statistical)†	0.00	0.01	0.01
Acceptance corrections (systematic)	0.15	0.15	0.00
Charge mis-identification†	—	—	0.02
Systematic	1.91	2.23	0.91
Beam energy	1.00	0.86	0.14
Luminosity	1.16	1.16	—
Total	2.46	2.67	0.97

Z p_T spectrum - Φ^* measurement

- Instead of direct transverse momentum measurement:
- Related quantity: Φ^* $\sqrt{2}m_Z\phi^*_\eta \approx p_{\mathrm{T}}^{ll}$
- Depends only on measured angles
  - Better resolution compared to momentum measurements

$$\phi^*_\eta = \tan\left(\frac{\pi - \Delta\phi}{2}\right)\cdot\sin(\theta^*_\eta)$$

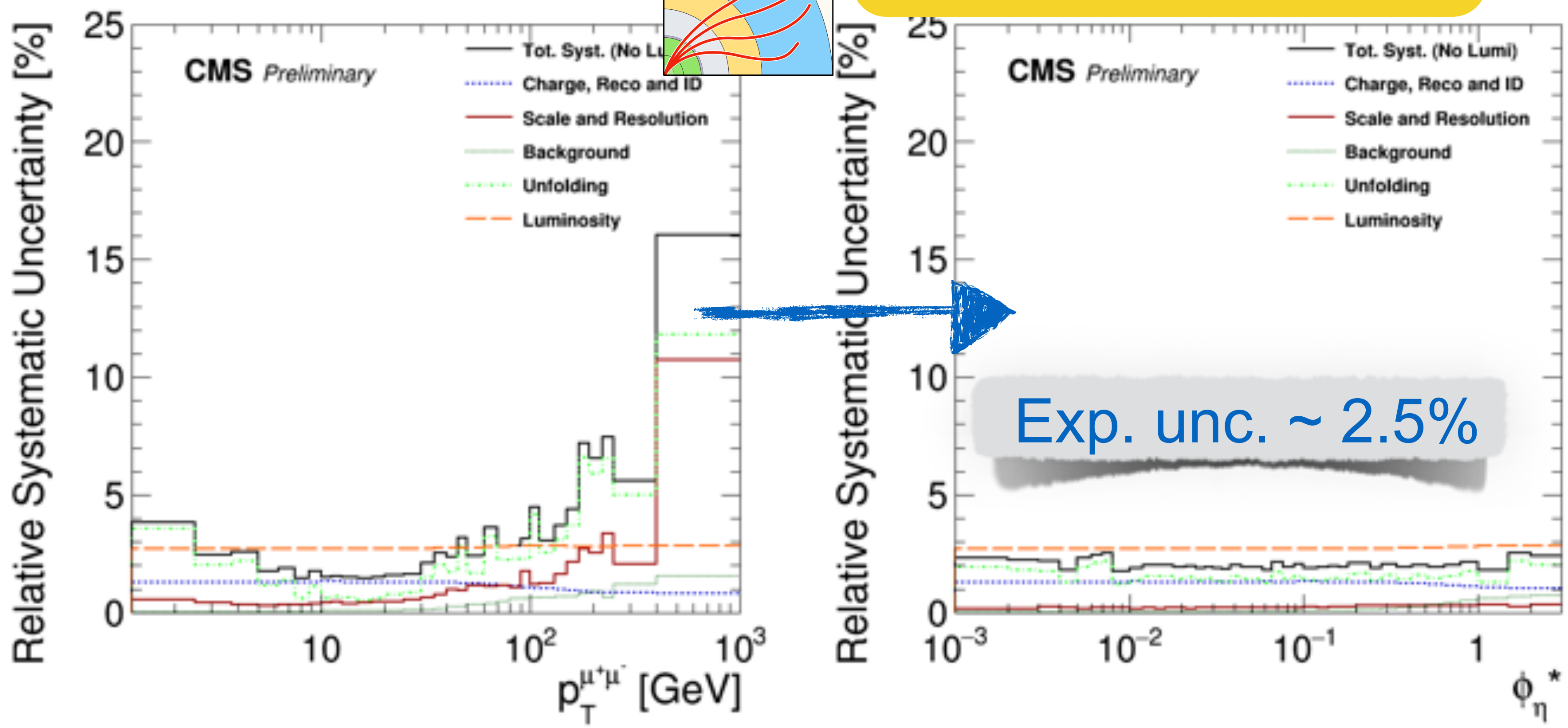
azimuthal angle between the two leptons

$$\theta^*_\eta = \arccos\left(\tanh\left(\frac{\eta^- - \eta^+}{2}\right)\right)$$

Z p_T spectrum - Φ^* measurement - 13 TeV results

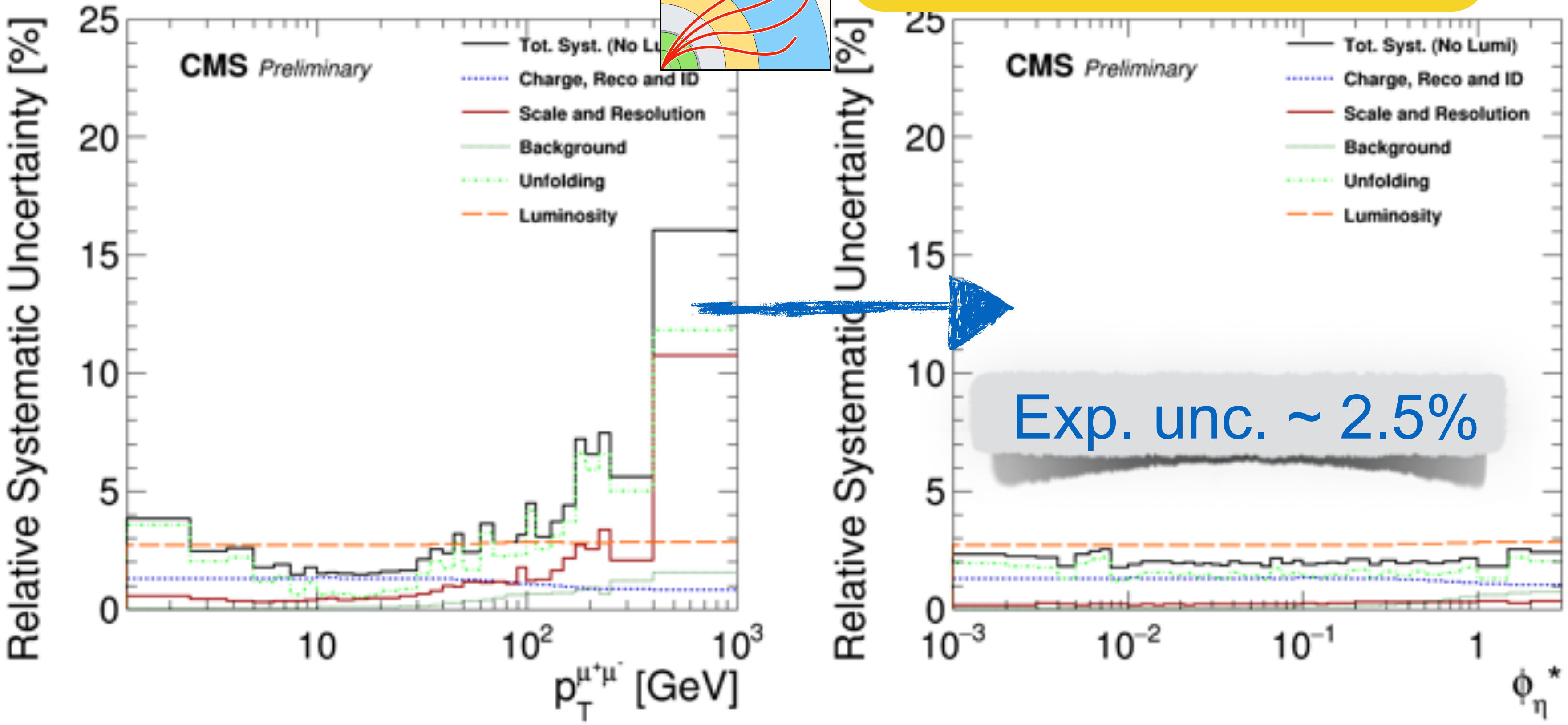
CMS-PAS-SMP-16-009

- $p_T \rightarrow \Phi^*$
  - large reduction of uncertainties



Z p_T spectrum - Φ^* measurement - 13 TeV results

CMS-PAS-SMP-16-009

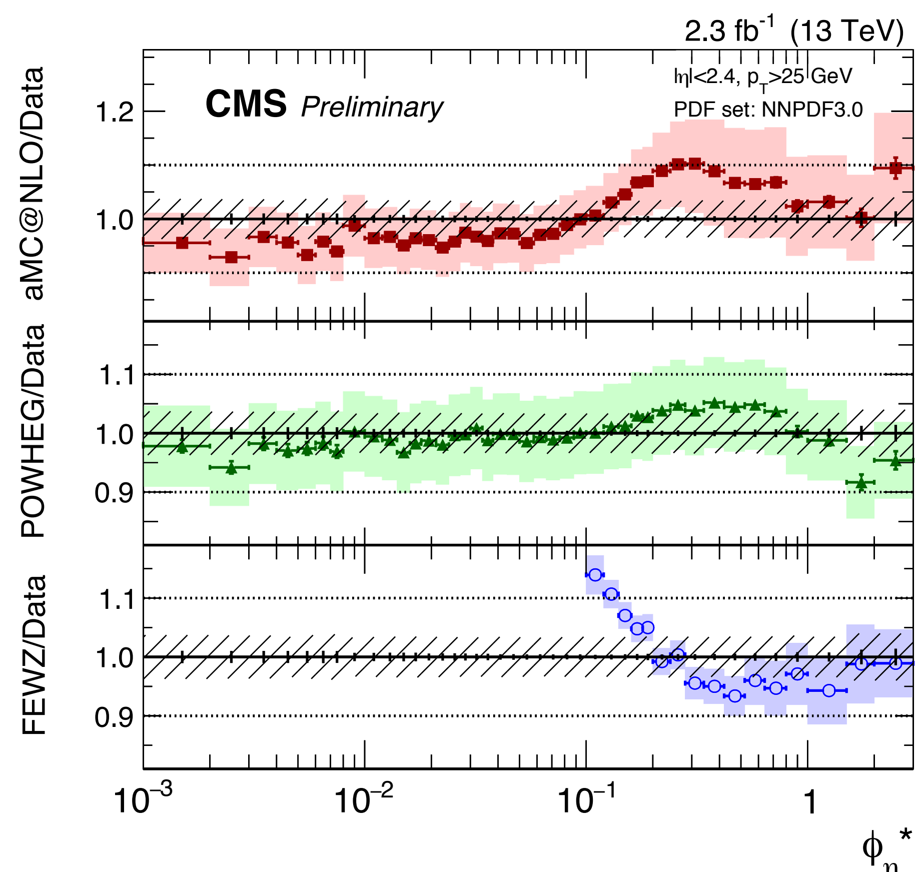


- $p_T \rightarrow \Phi^*$
  - large reduction of uncertainties

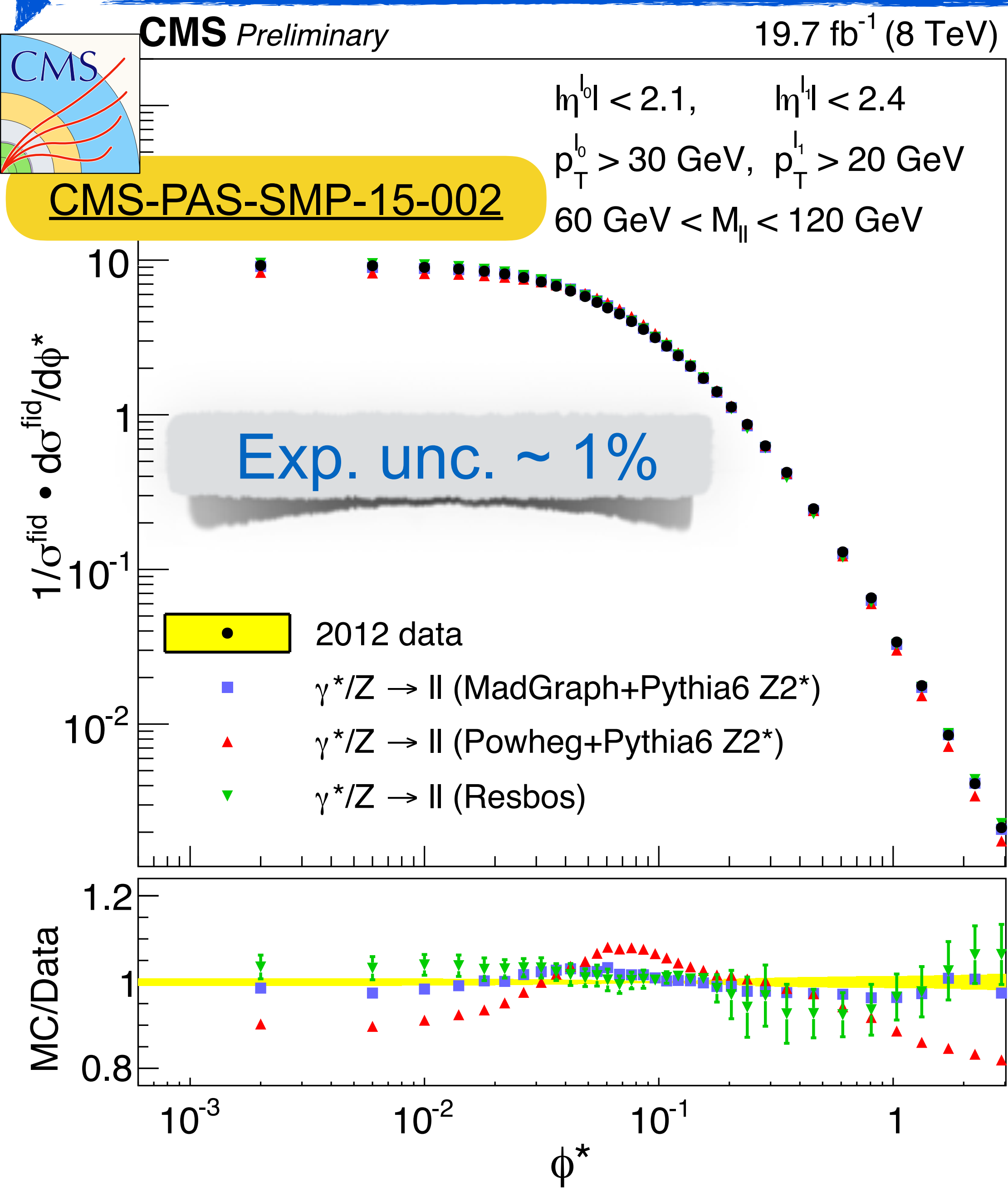
- FEWZ can not model low pT / Φ^* region

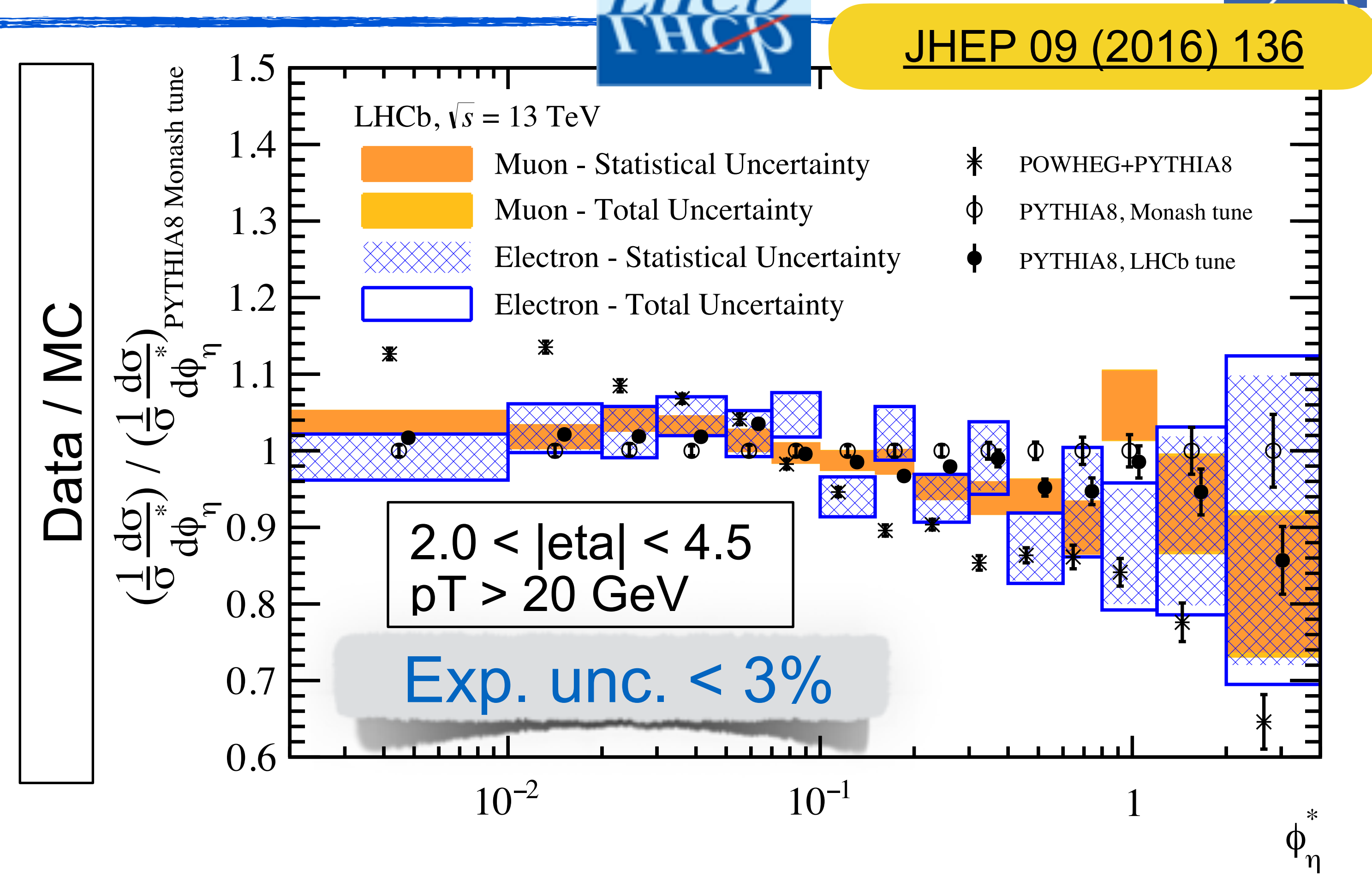
- aMC@NLO shows deviations from data in high Φ^* region

- 13 TeV results much less precision than 7 & 8 TeV measurements



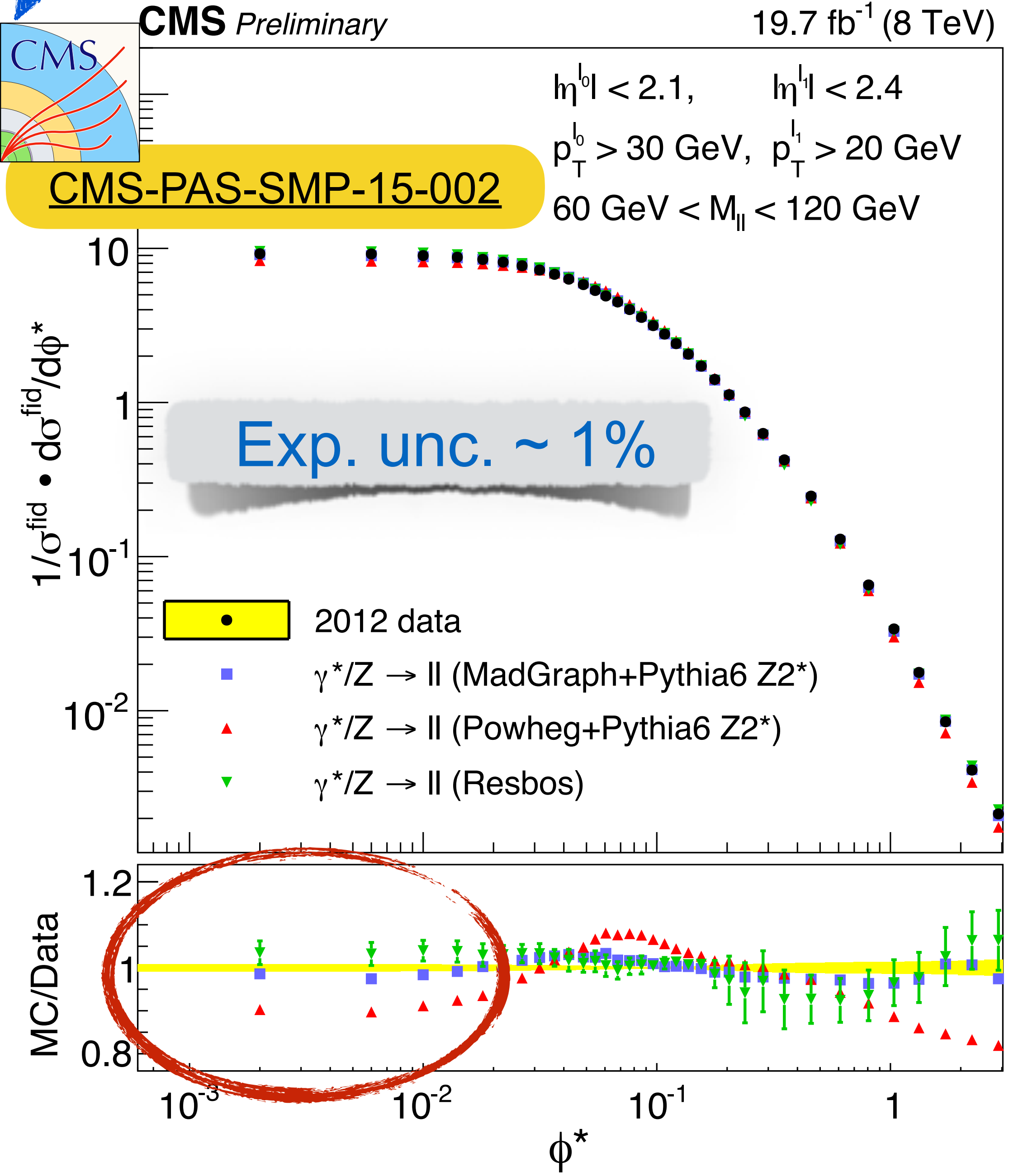
Z pT spectrum - Φ* Measurement

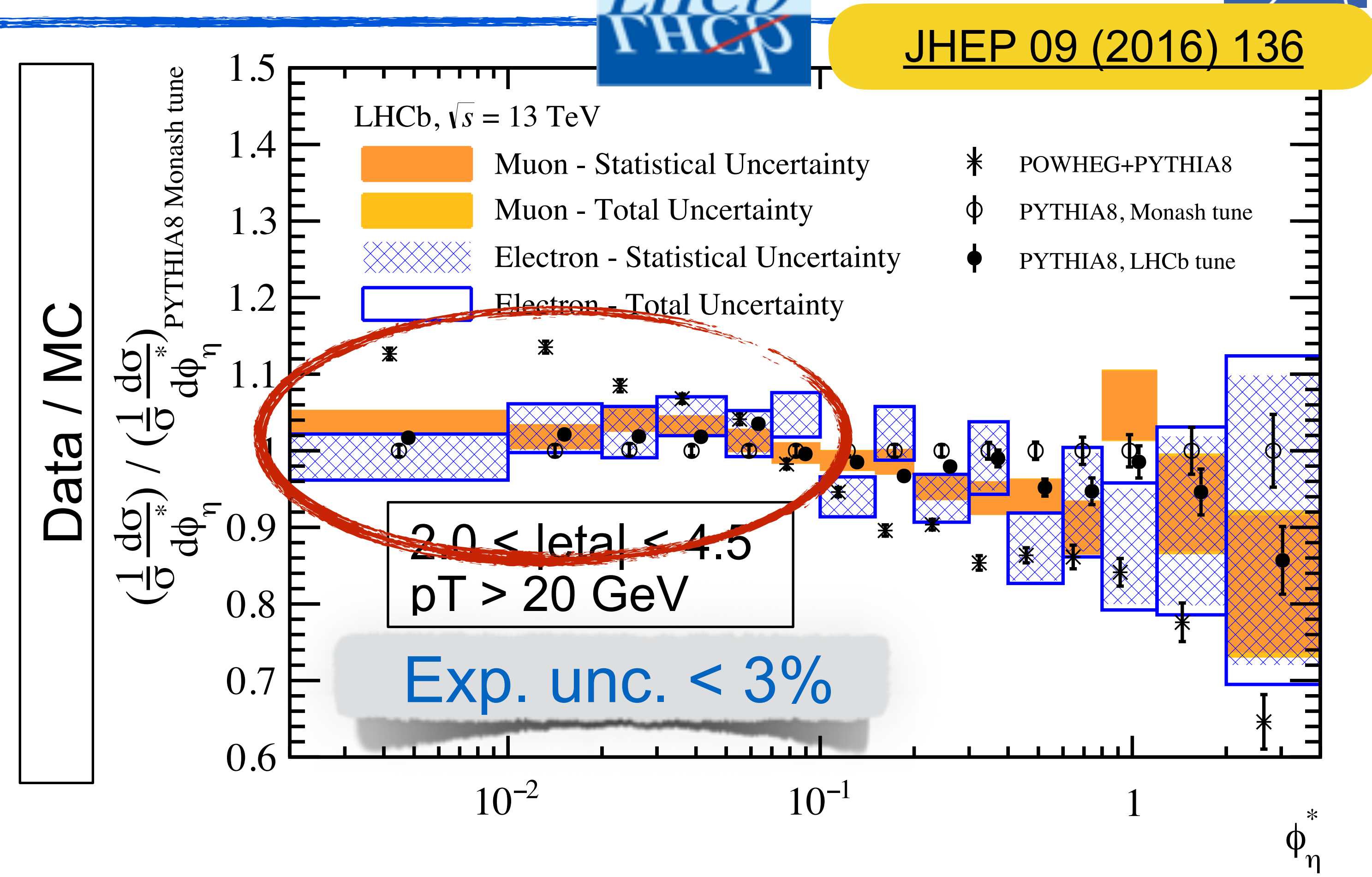




- Low range dominated by:
  - Non perturbative effects
  - Parton shower
- High range dominated by:
  - Hard parton emission
  - Matrix element generator
- Good agreement: Pythia8 & MG w.r.t data

Z pT spectrum - Φ* Measurement





PowHeg + Pythia prediction below measurement for low Φ* values

- Low range dominated by:
  - Non perturbative effects
  - Parton shower
- High range dominated by:
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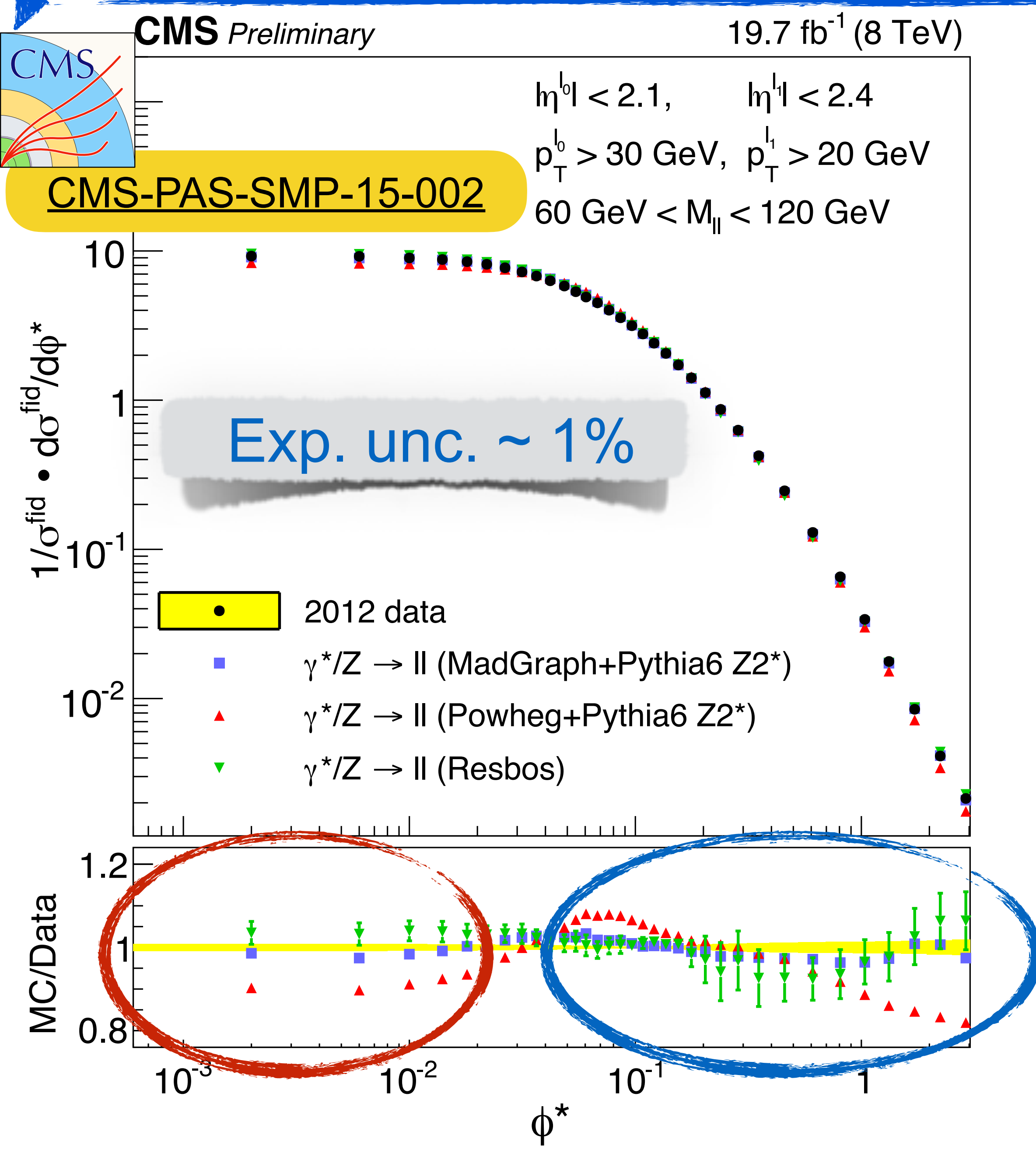
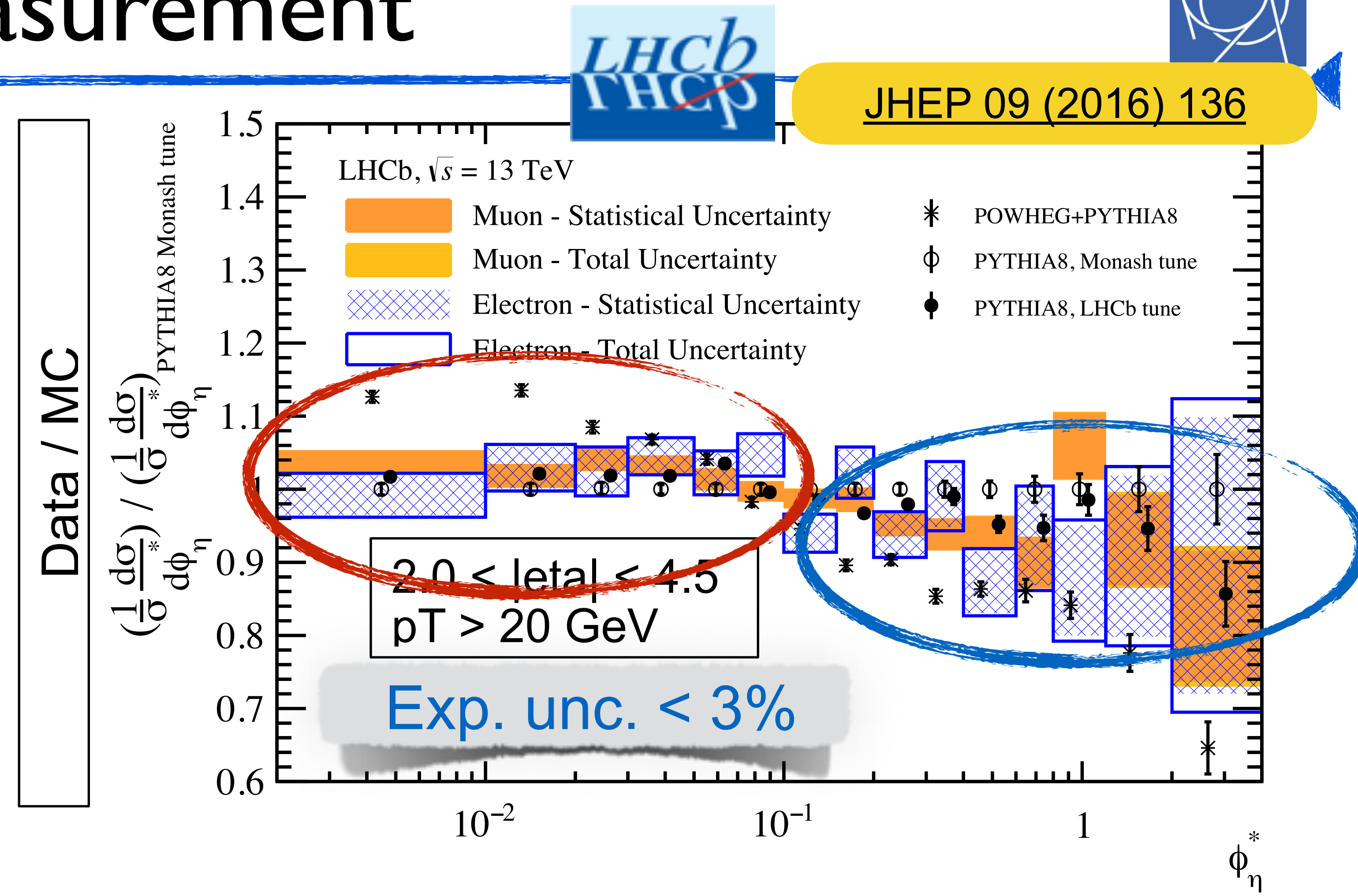
  - Matrix element generator
- Good agreement: Pythia8 & MG w.r.t data

Z pT spectrum - Φ^* Measurement





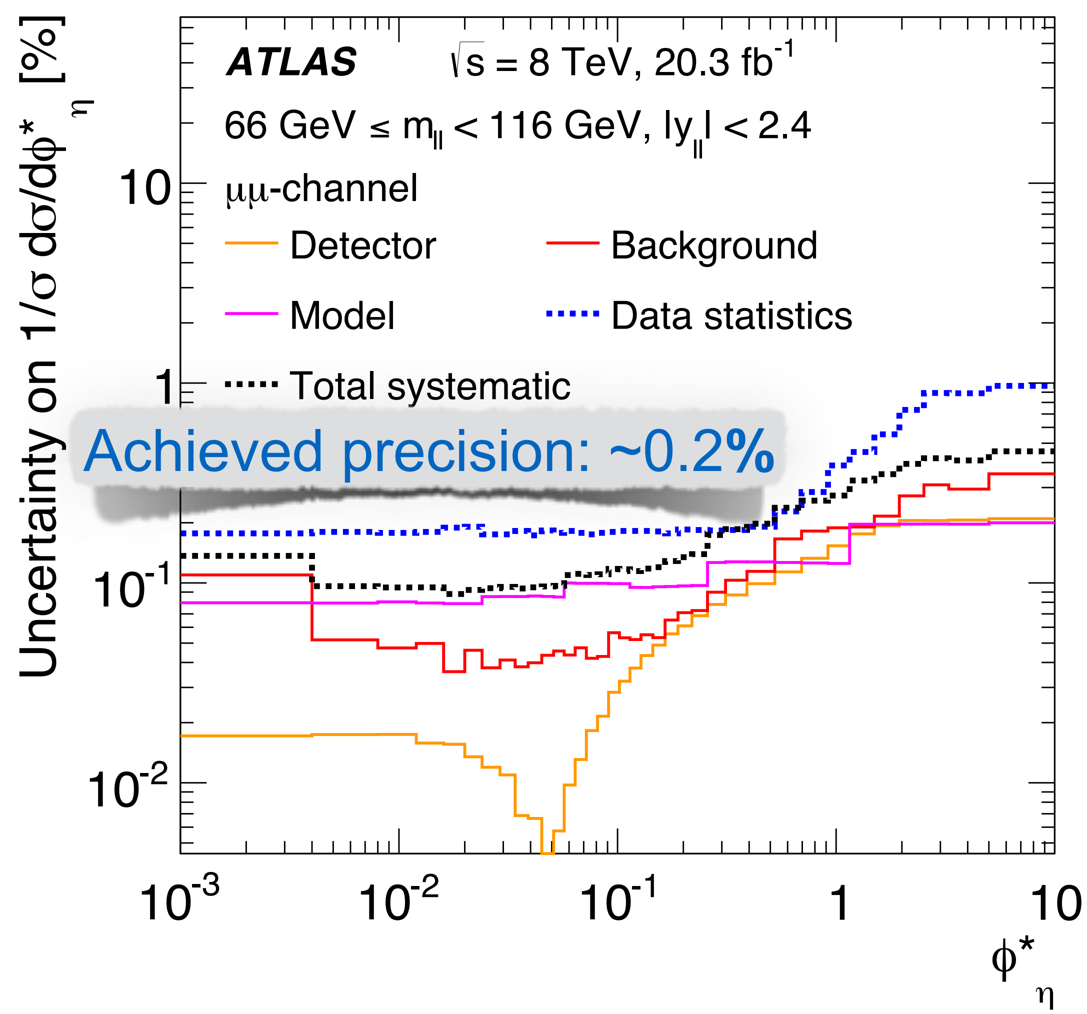
PowHeg + Pythia prediction below measurement for low Φ^* values

P&P: Different behavior in high Φ^* region

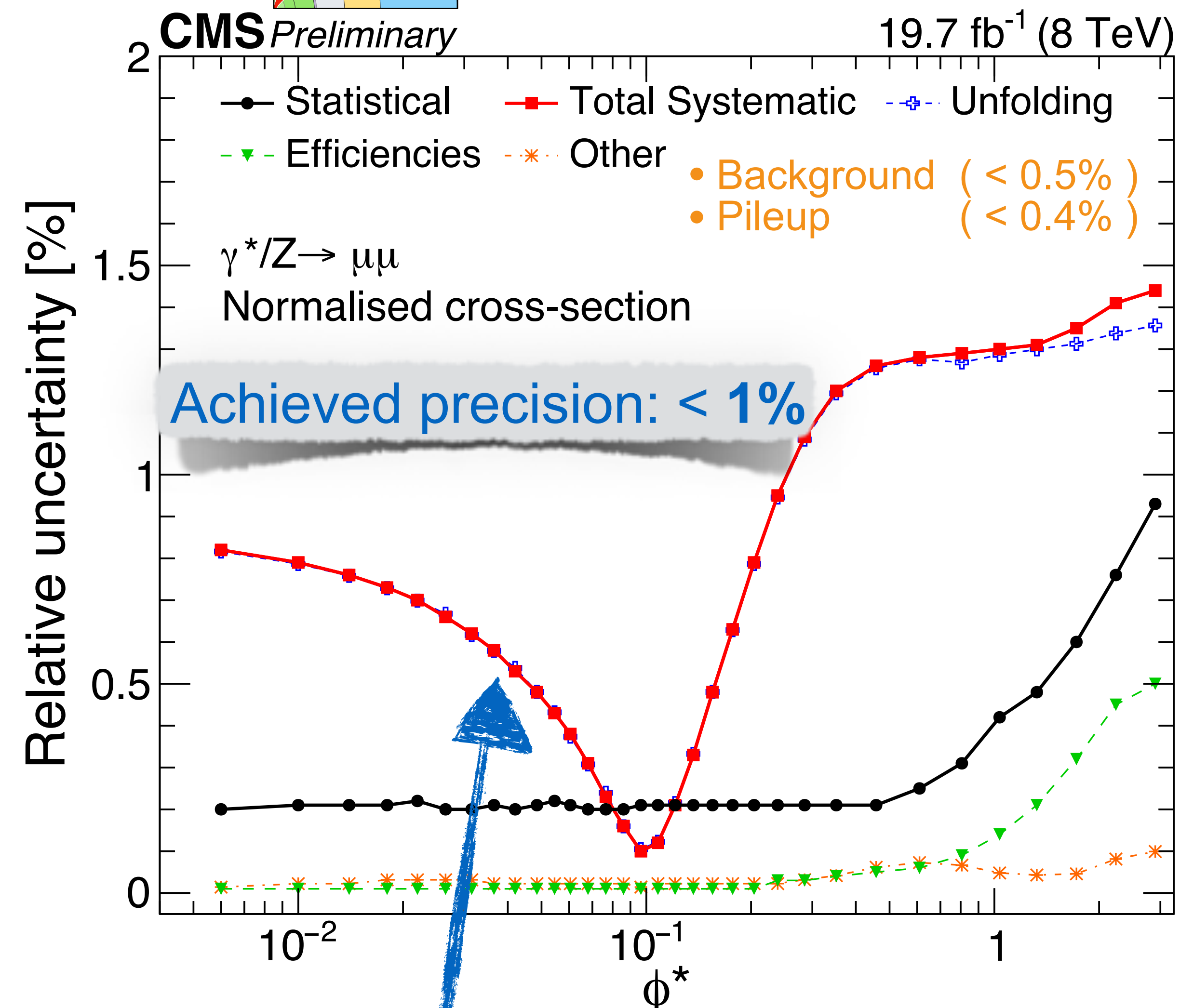
- Low range dominated by:
  - Non perturbative effects
  - Parton shower
- High range dominated by:
  - Hard parton emission
  - Matrix element generator
- Good agreement: Pythia8 & MG w.r.t data

W,Z p_T spectrum - Φ^* Measurement Uncertainties

Eur. Phys. J. C (2016) 76



CMS-PAS-SMP-15-002



JHEP 09 (2016) 136

- Dominating **experimental uncertainty**:
  - Reconstruction efficiency

  (2.4% on total cross section)

- Unfolding dominated by:
  - MC generator modeling
    - (MG vs PowHeg)

Impact on theory developments

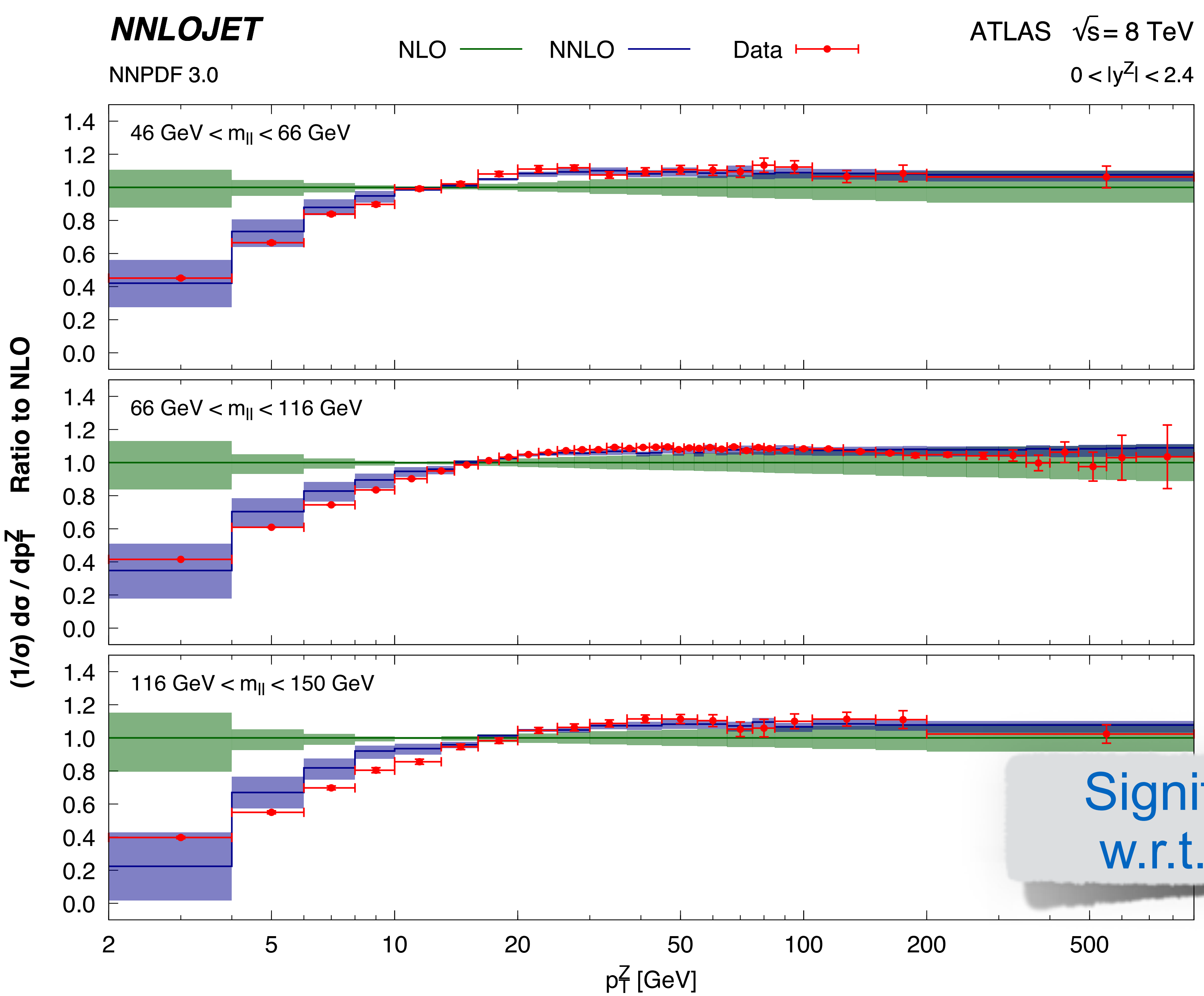
- Tuning of NNLOJET to describe LHC data
  - Nov. 2016

A. Gehrmann-De Ridder, T. Gehrmann, E.W.N. Glover, A. Huss and T.A. Morgan

JHEP11(2016)094

- Latest LHC results included from **May 2016:**

- Fast feedback into MC :-)



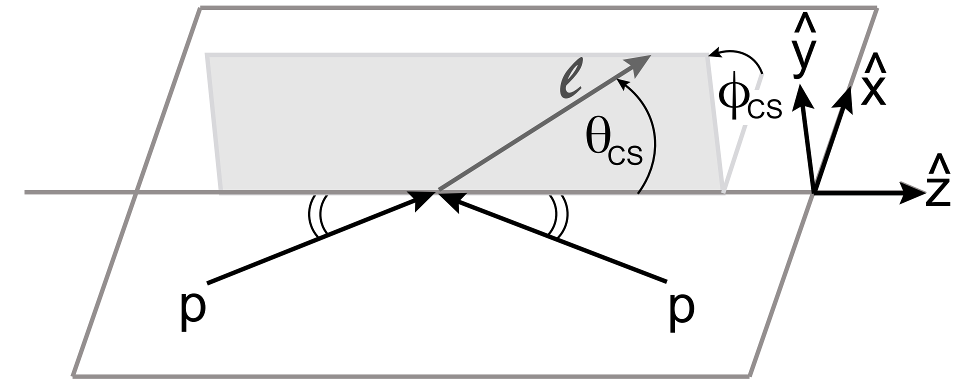
Significant improvement w.r.t. NLO predictions!

Z-Boson:
Forward Backward asymmetry, angular distributions & weak mixing angle

Intro

- Polarization of Z Bosons:
  - Accessible via angular distributions of decay leptons
  - Difficult to model in Monte Carlo simulation
    - ME & Spin correlations of FS particles
- Weak mixing angle accessible
  - Fundamental parameter of EWK standard model sector
- Several Measurements at colliders:
  - Forward Backward asymmetry (A_{FB})
    - Weak mixing angle
  - Angular coefficients → Z polarisation
    - Input to m(W) measurement
    - Not well modeled by several MC generators

Angles in **Collins-Soper** Frame:



- Rest frame of di-lepton system
- Z-axis bisecting directions of incoming proton momenta
- Direction of z-axis defined by longitudinal boost of di-lepton system

Angular coefficients:

Orthogonal polynomials used to parametrize angular distribution:

$$\langle P(\cos\theta,\phi)\rangle = \frac{\int P(\cos\theta,\phi)\,d\sigma(\cos\theta,\phi)\,d\cos\theta\,d\phi}{\int d\sigma(\cos\theta,\phi)\,d\cos\theta\,d\phi}$$

Differential cross section

$$pp \to Z/\gamma^* + X \to l^+l^- + X$$

$< 1 + \cos^2\theta >$ — normalization of unpolarized cross section, also applied to all other P

$< \frac{1}{2}(1-3\cos^2\theta) >= \frac{3}{20}(A_0 - \frac{2}{3})$ — longitudinal polarization

$< \sin 2\theta \cos\phi >= \frac{1}{5}A_1$ — interference term: longitudinal / transverse

$< \sin^2\theta \cos 2\phi >= \frac{1}{10}A_2$ — transverse polarization

$< \sin\theta \cos\phi >= \frac{1}{4}A_3$ — product of v-a couplings, sensitive to Weinberg angle

$< \cos\theta >= \frac{1}{4}A_4$ — 8/3 * forward backward asymmetry A_{FB}, sensitive to **Weinberg angle**; non-zero already at LO $q\bar{q} \to Z/\gamma^* \to l^+l^-$

$< \sin^2\theta \sin 2\phi >= \frac{1}{5}A_5$

$< \sin 2\theta \sin\phi >= \frac{1}{5}A_6$

$< \sin\theta \sin\phi >= \frac{1}{4}A_7$

Predicted to be 0 @ NLO
Non zero contributions @ NNLO for large $p_T(Z)$

Angular coefficients:

Orthogonal polynomials used to parametrize angular distribution:

$$\langle P(\cos\theta,\phi)\rangle = \frac{\int P(\cos\theta,\phi)\, d\sigma(\cos\theta,\phi)\, d\cos\theta\, d\phi}{\int d\sigma(\cos\theta,\phi)\, d\cos\theta\, d\phi}$$

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non-zero already at LO $q\bar{q} \to Z/\gamma^* \to l^+l^-$

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$< \sin 2\theta \sin\phi >= \frac{1}{5}A_6$

$< \sin\theta \sin\phi >= \frac{1}{4}A_7$

Predicted to be 0 @ NLO
Non zero contributions @ NNLO for large $p_T(Z)$

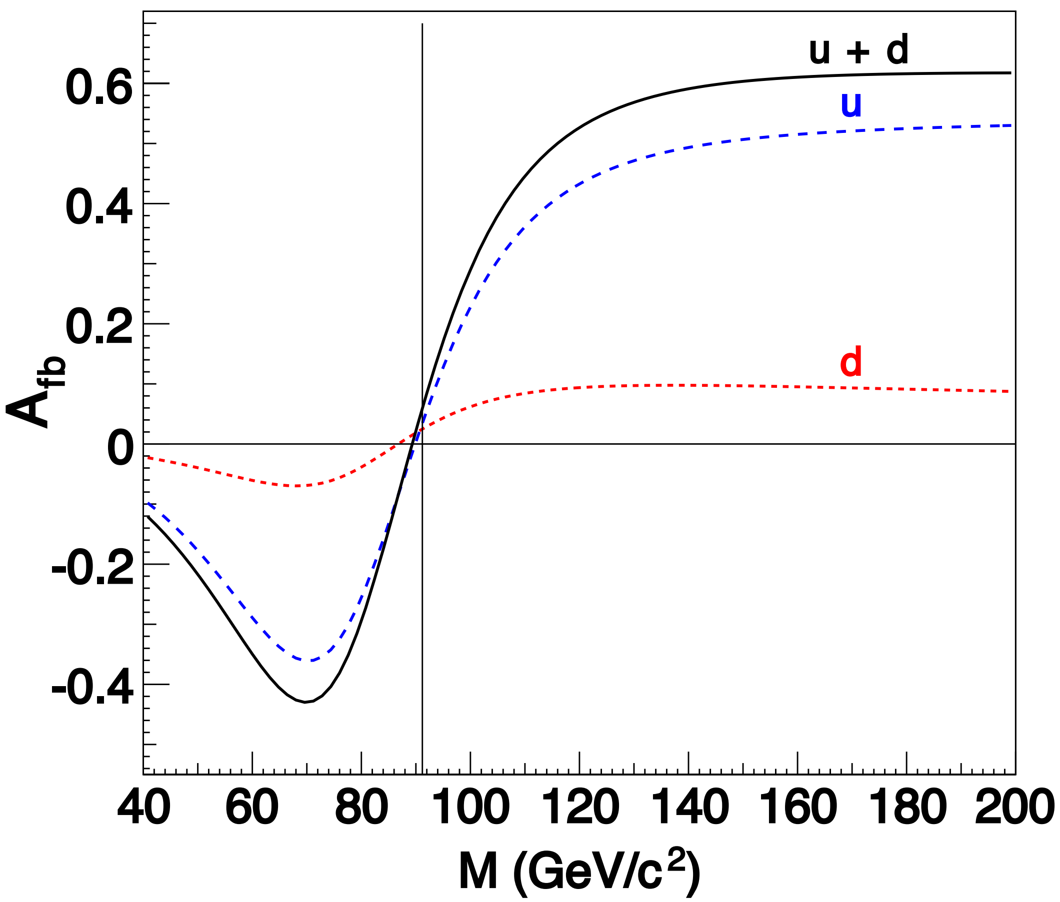
A_i are neither input to theory calculations, nor simulations!

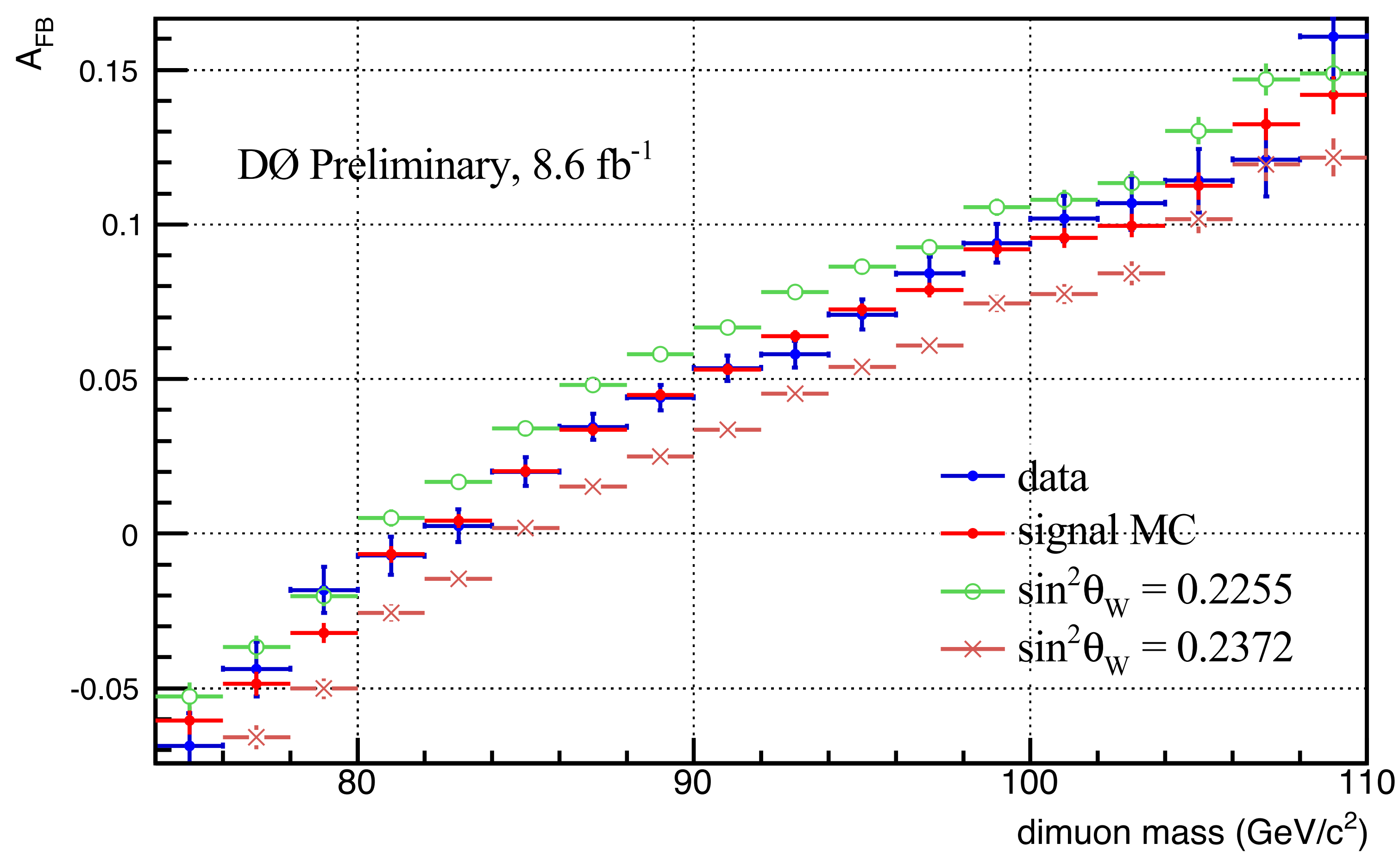
Z boson Forward Backward Asymmetry (A_{FB})

- Sensitive to PDFs at low / high masses
  - up - down quark distributions

DØ note 6497-CONF

- Sensitive to weak mixing angle around the Z-pole





Forward - Backward asymmetry

- Latest measurement at LHC
  - Binned in Boson Rapidity

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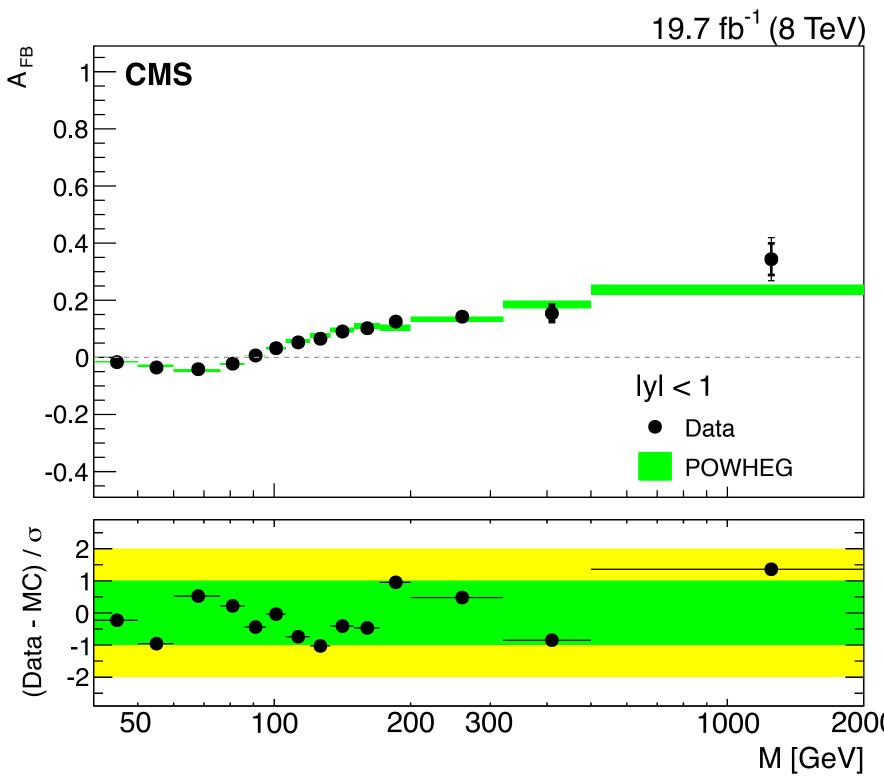
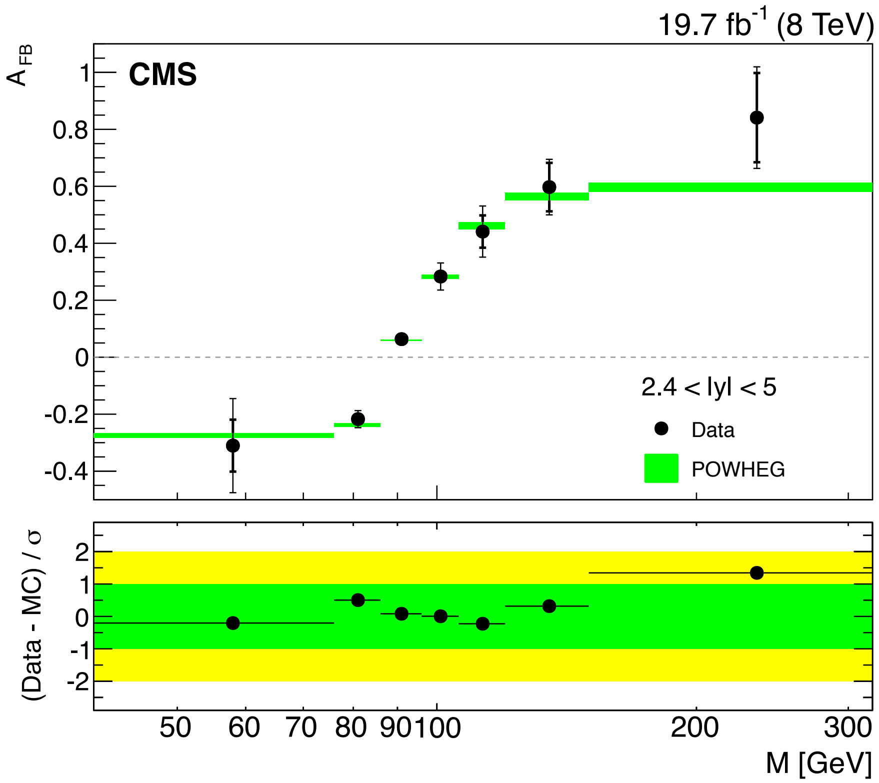
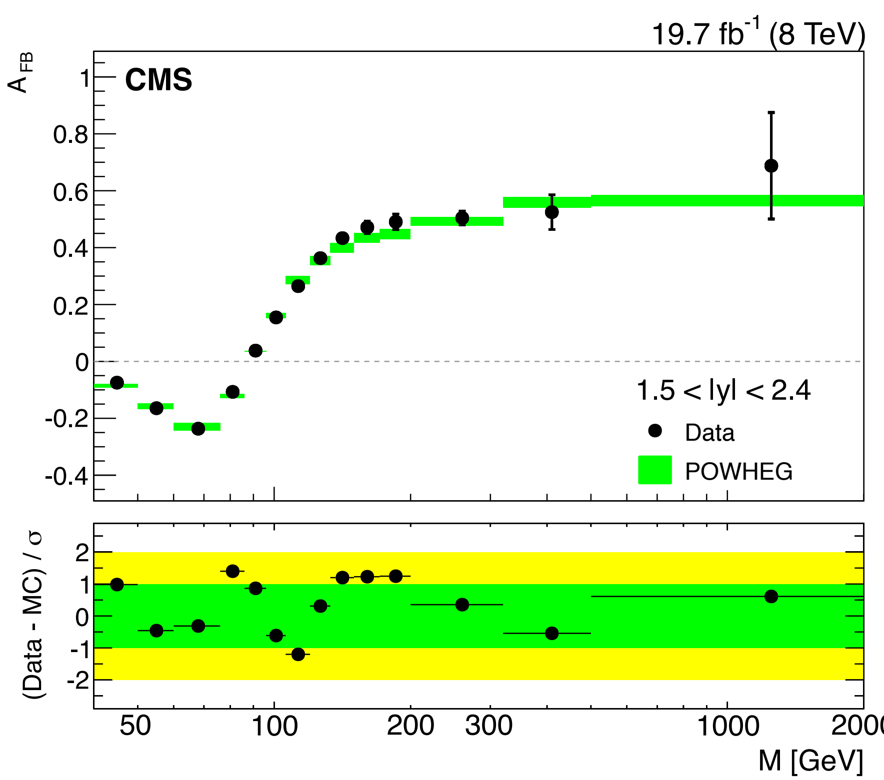
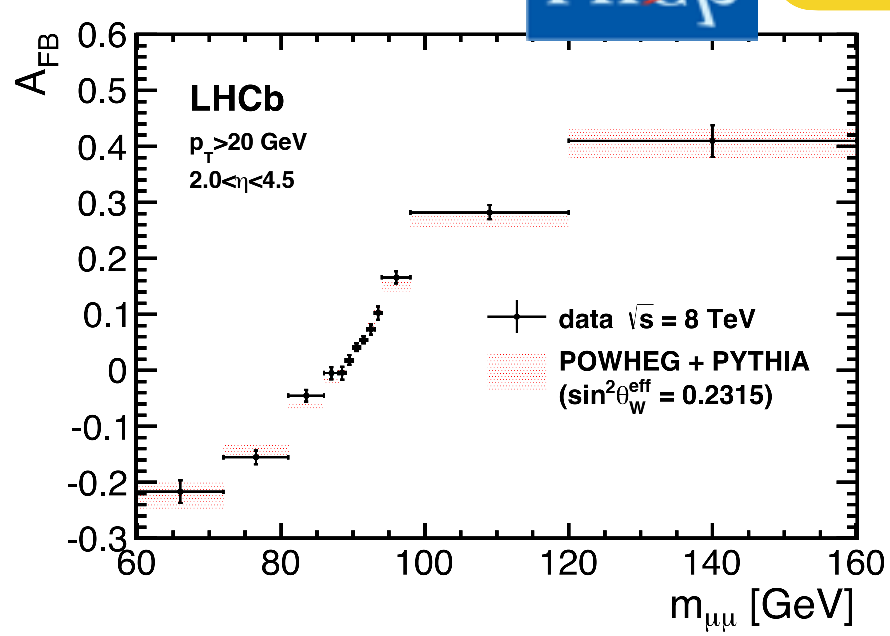




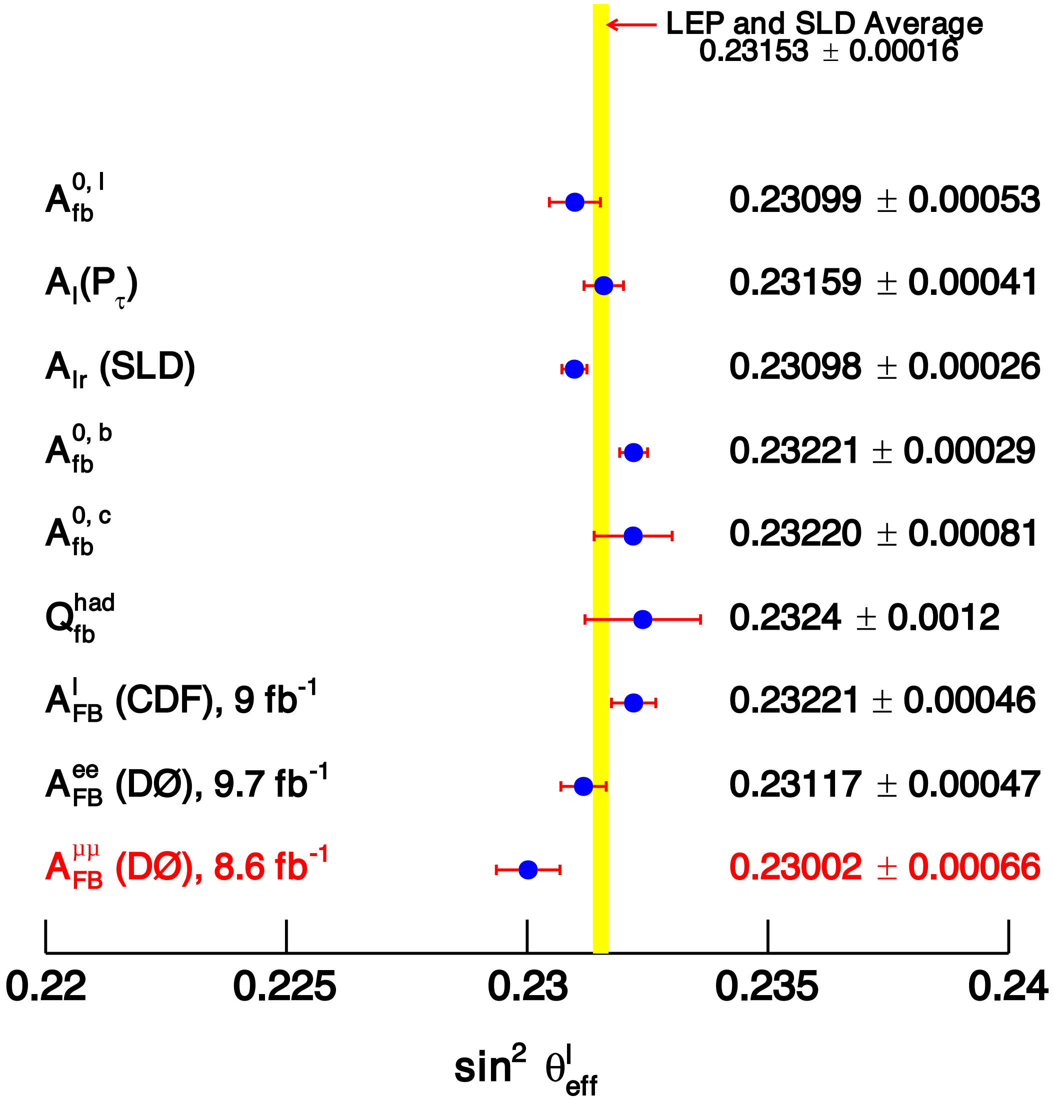


JHEP 1511(2015) 190



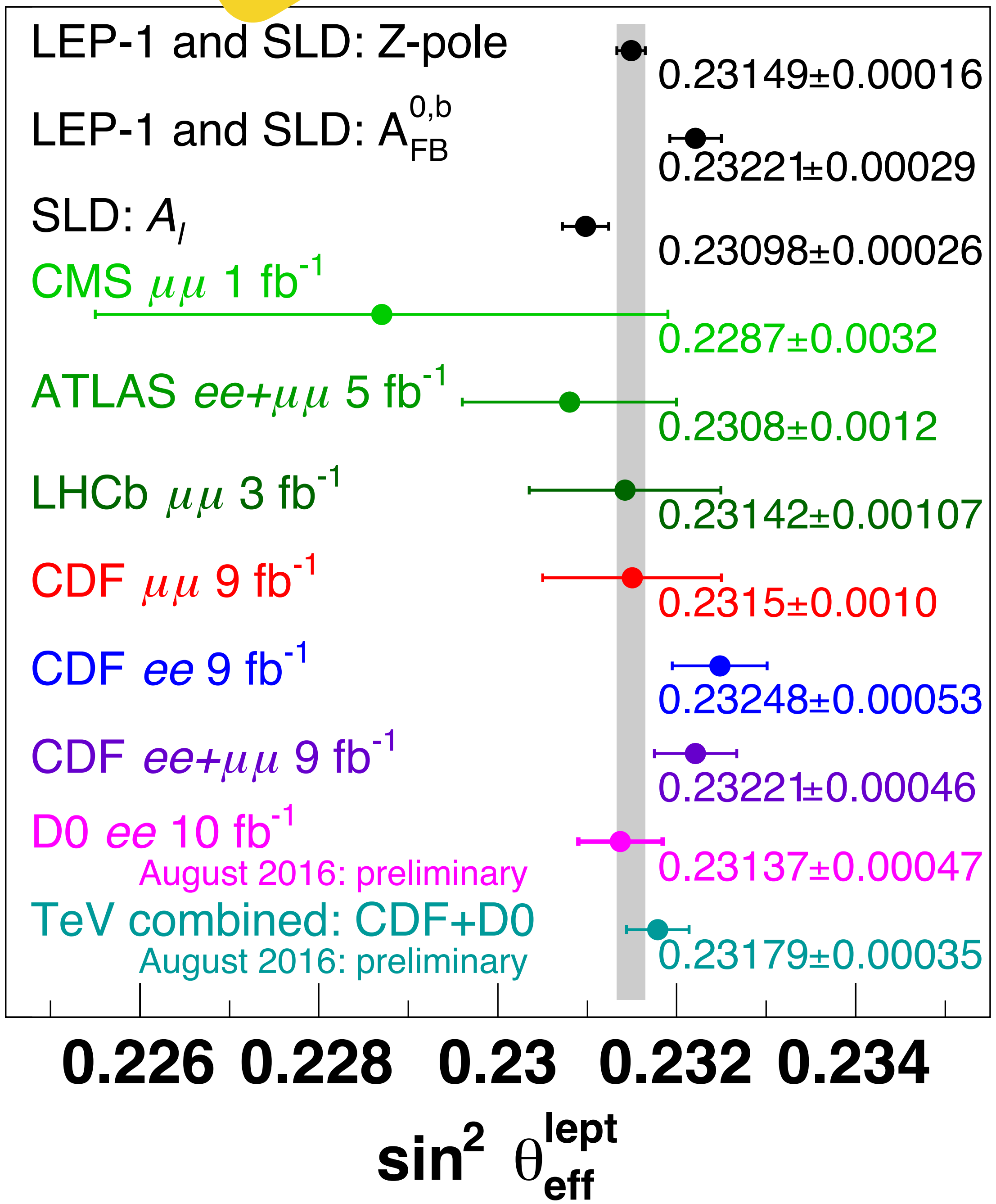
Weak mixing angle

DØ note 6497-CONF



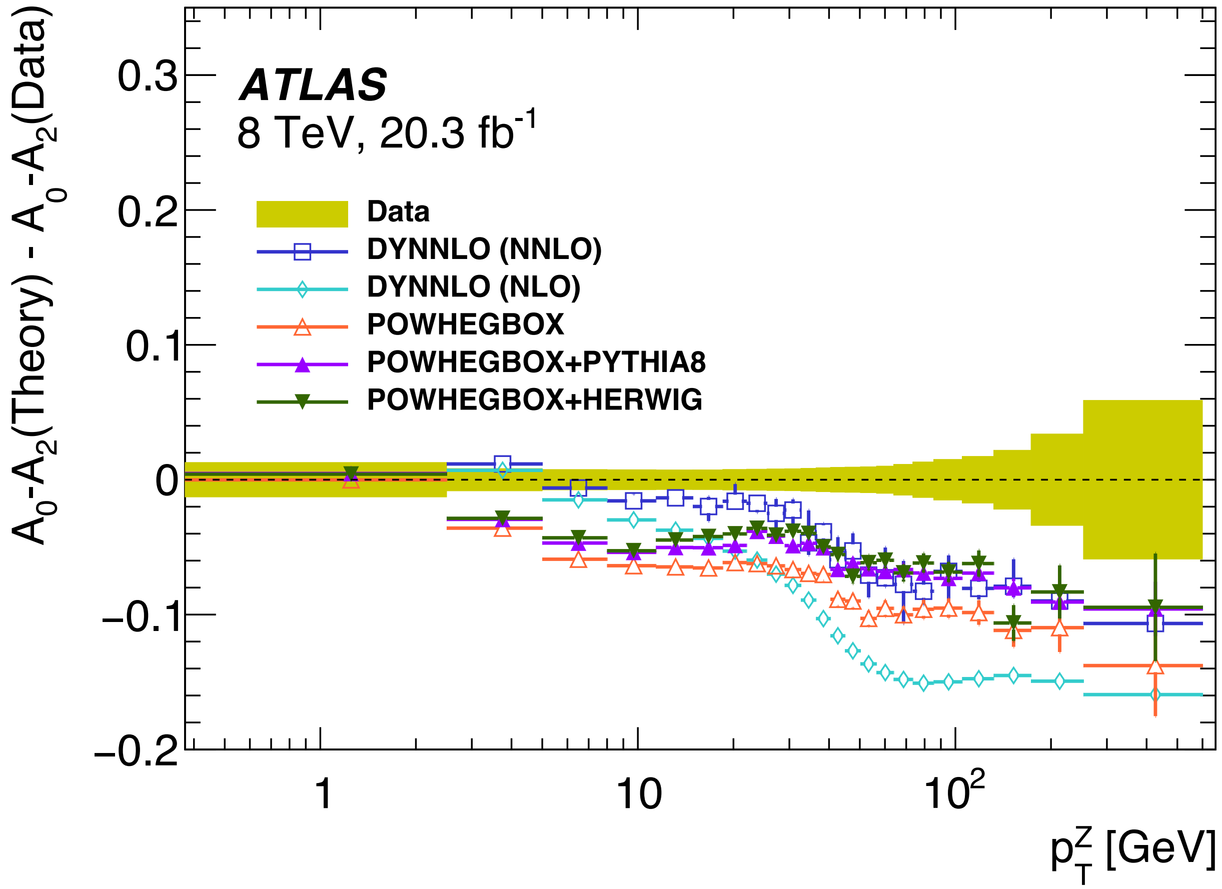
JHEP 1511(2015) 190

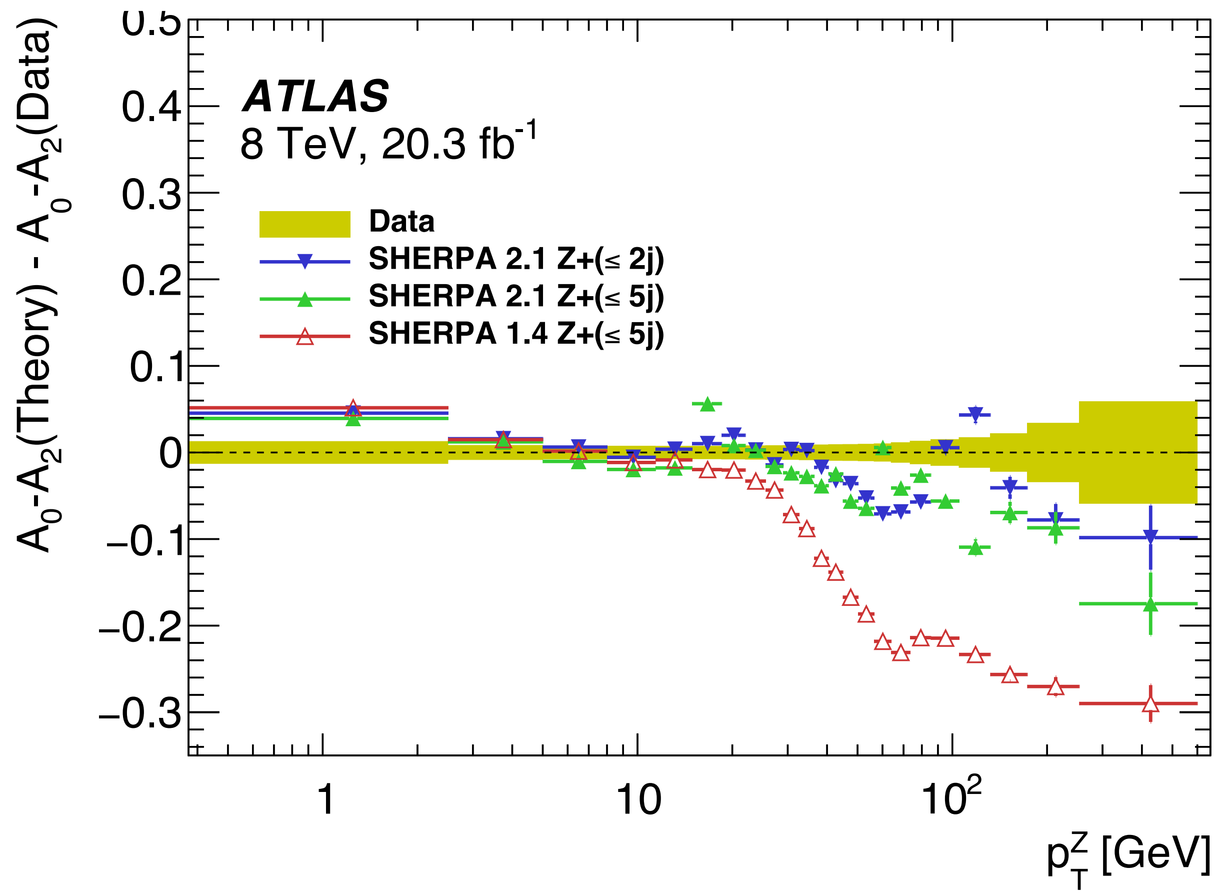
Fermilab-Conf-16-295-E



Z Boson Polarisation

JHEP08(2016)159





- Significant differences between simulations!
- Sherpa & PowHegBox show statistical unc. only
- DYNNLO gives best description of measured A_0
- No generator describes A0-A2
  - (Best: Sherpa 2.1)
- Improvement from Sherpa 1.4 to 2.1
  - Included feedback from this Measurement

Summary

Summary

- Rich physics program using W & Z Bosons at hadron colliders
- Experimental precision achieved:
  - **~ % or better** on many inclusive & differential observables!
  - Largest uncertainties:
    - Reconstruction efficiencies
    - Momentum Scales
    - Model uncertainties

Can be further reduced

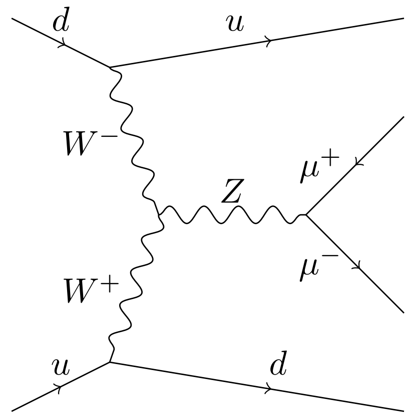
Need improved calculations

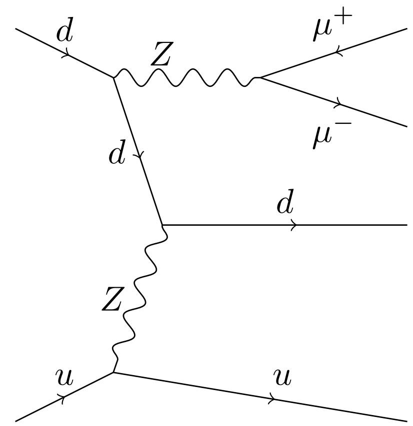
- More precise than current theory calculations for several observables
  - Tensions with several theory calculations observed
  - Interesting development expected!
- Adding constrains to PDFs
  - Dominant uncertainty for many collider measurements

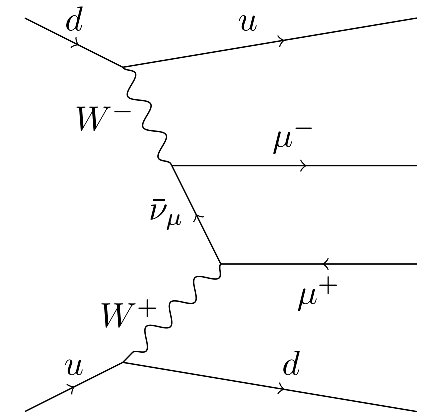
Results on standard model EWK sector passing LEP precision!

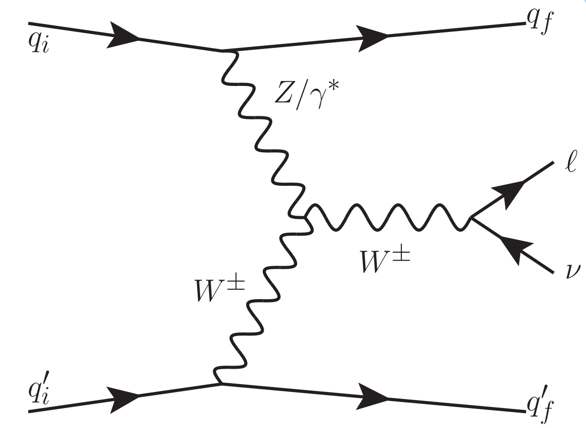
BACKUP

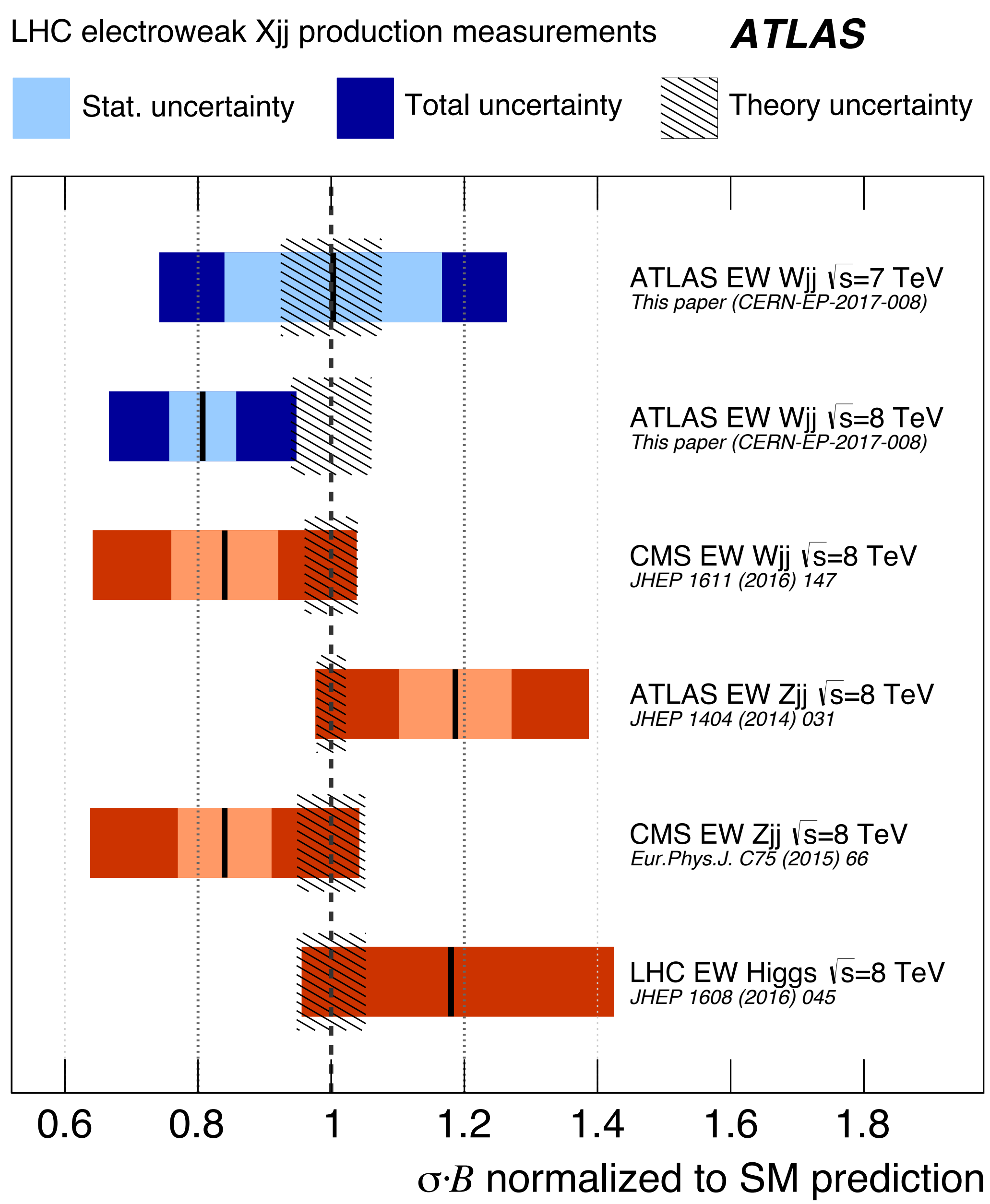
VBF W,Z production

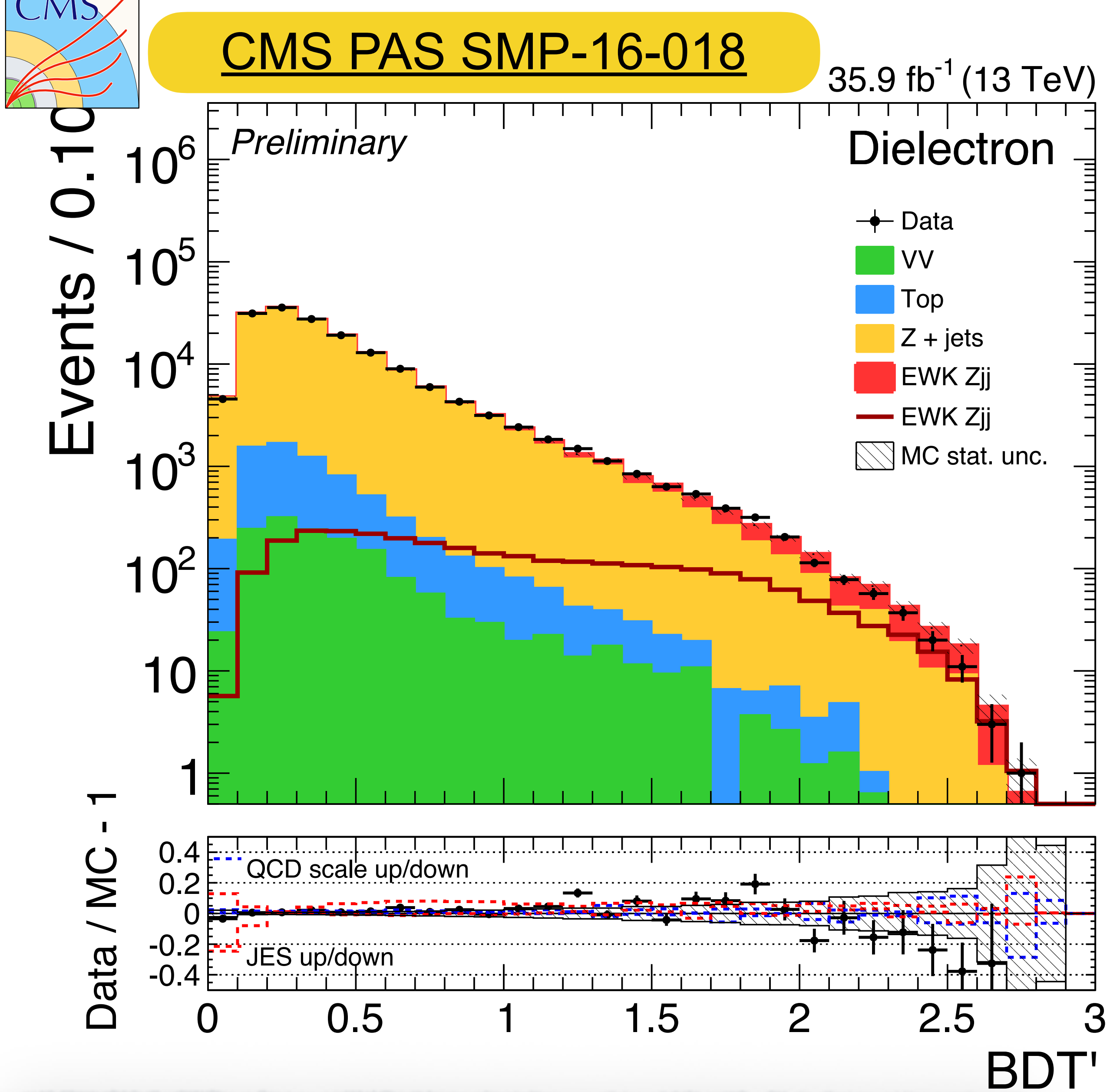












$$\sigma_{EW}(lljj) = 552 \pm 19(stat) \pm 55(syst)\ fb$$

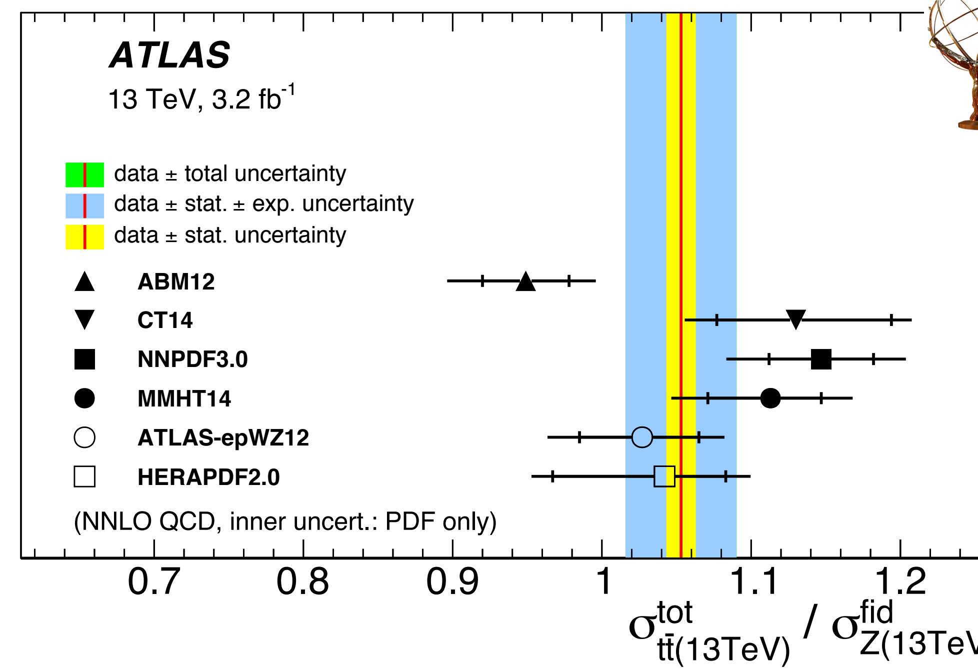
Ratio of cross sections:
ttbar / Z
at $\sqrt{s}$ of 7,8 and 13 TeV

Ratio of ttbar / Z production cross sections

JHEP 02 (2017) 117

- Many experimental systematics cancel in ratio measurements
  - ttbar and Z analyses harmonized to maximize cancellation of uncertainties!

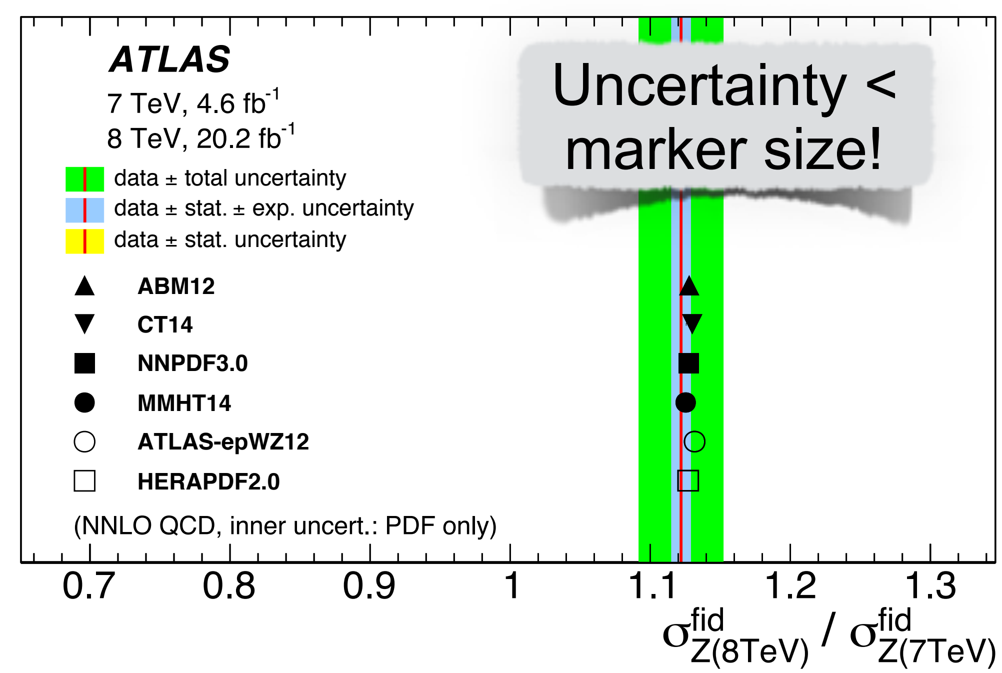
- Ratio ttbar / Z:
  - Luminosity cancels
- Ratio same processes at different √s
  - Reco & selection efficiencies, ….



- Allows precise comparisons to predictions
  - ABM12 disfavored by measurement

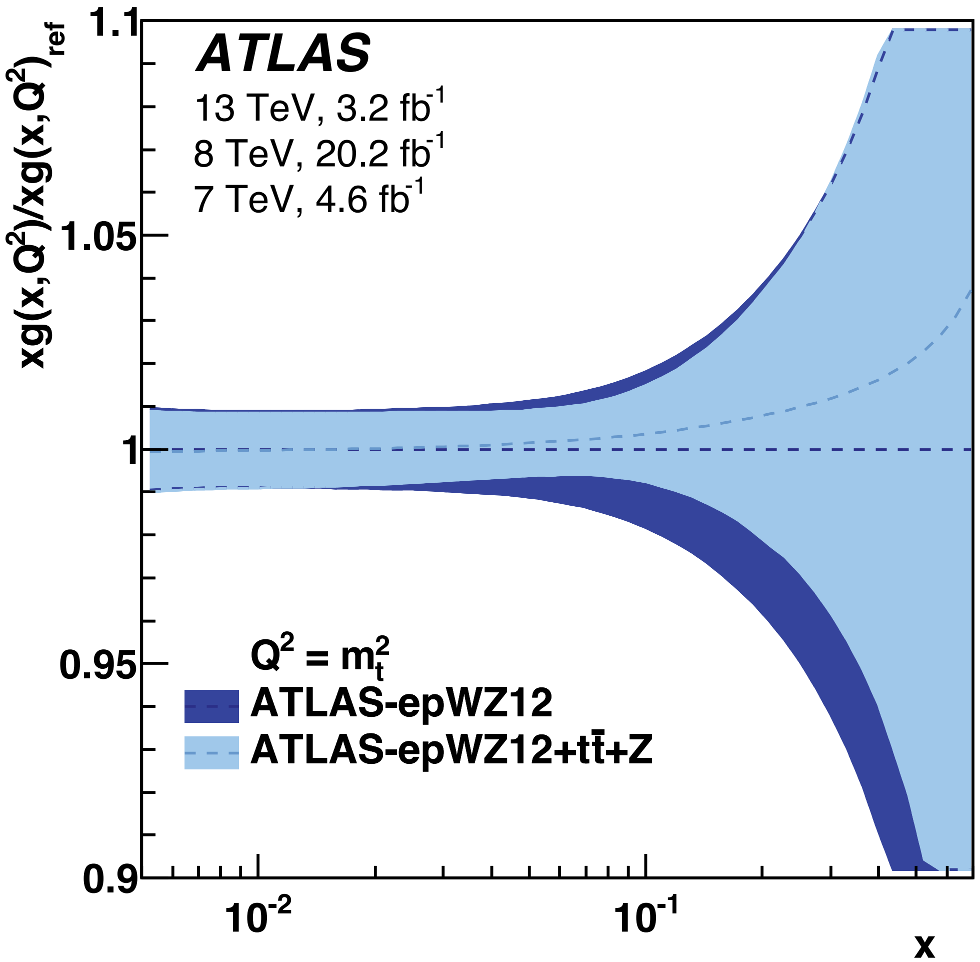
- ttbar / Z ratio sensitive to PDFs
  - Contribution of **Gluons**

- Eventually: **double ratios**

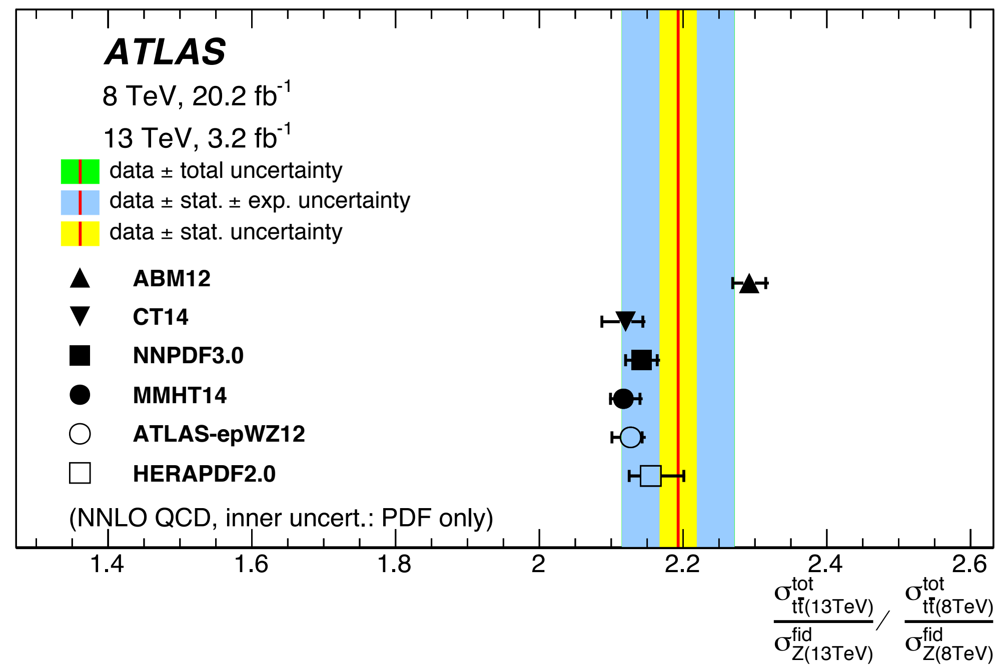


Ratio of ttbar / Z production cross sections

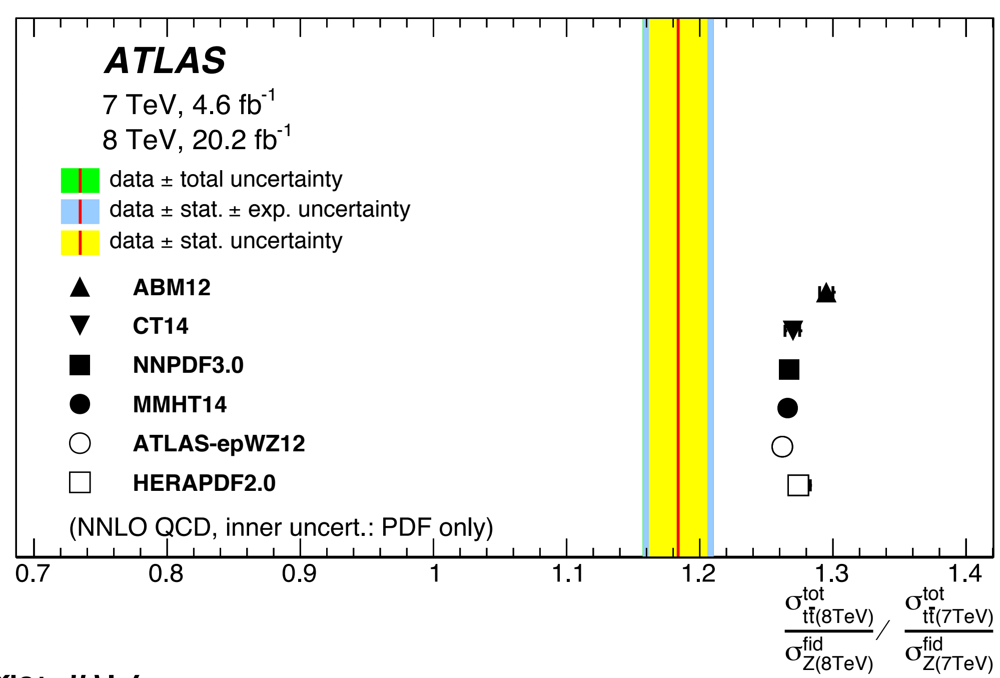
- Double ratios are very sensitive probe
  - Significant impact on **gluon PDF** uncertainty



Good agreement, predictions with ABM12 differs w.r.t. other PDFs



Significant discrepancy between data & prediction. Origin lies in 7 TeV measurement / prediction.



Ratio of ttbar / Z production cross sections

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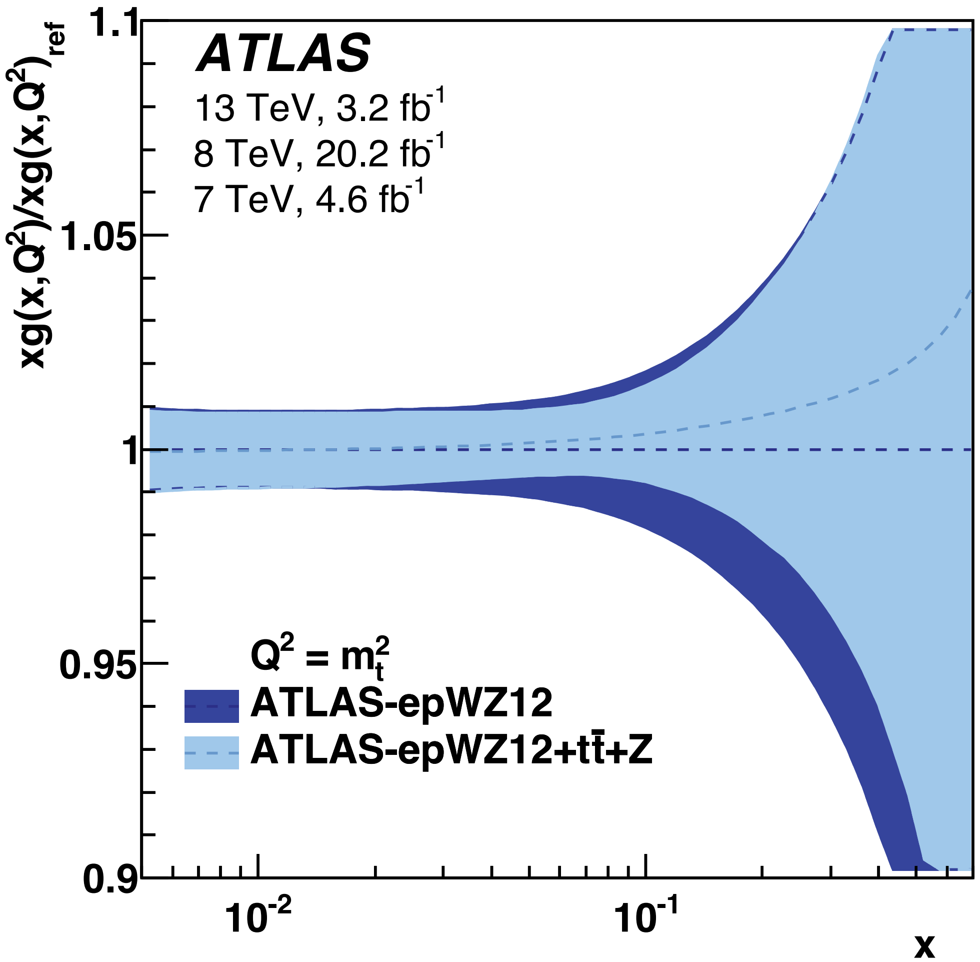
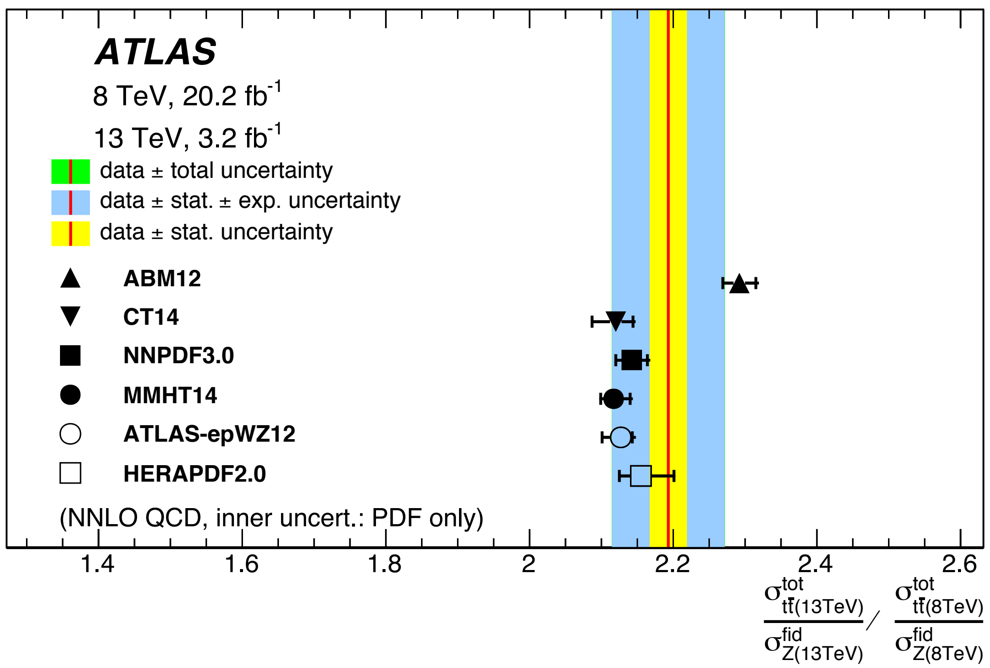


- Discrepancy not explainable with PDF effects
- Correlation model excluded as source.
- Origin most likely in the ttbar data.

Good agreement, predictions with ABM12 differs w.r.t. other PDFs



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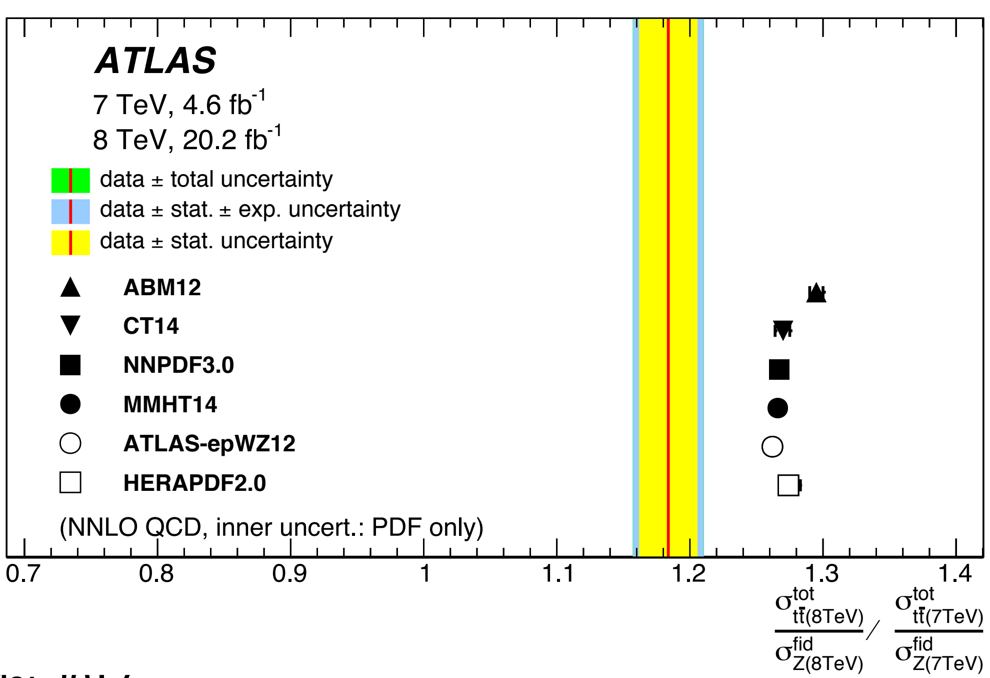
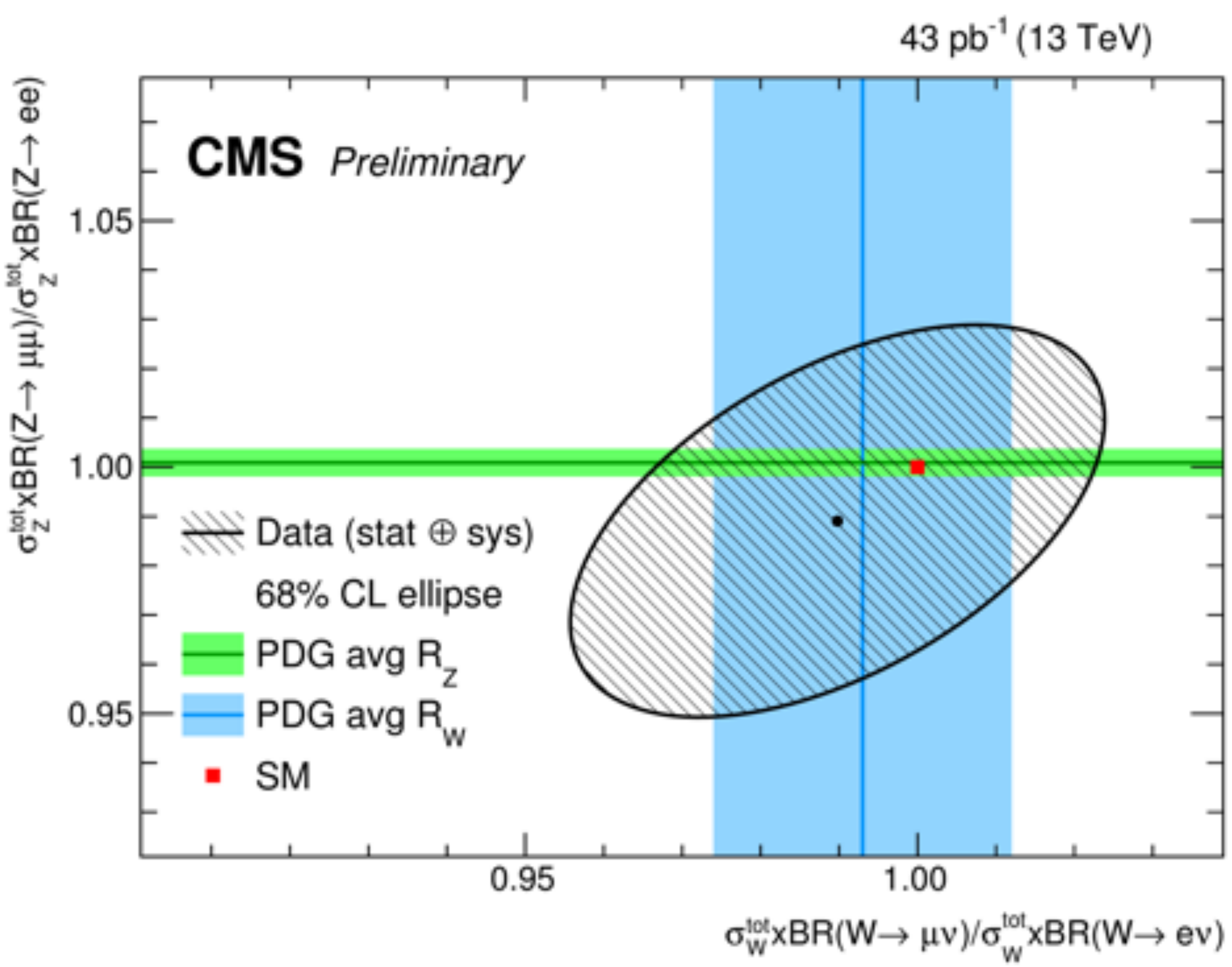
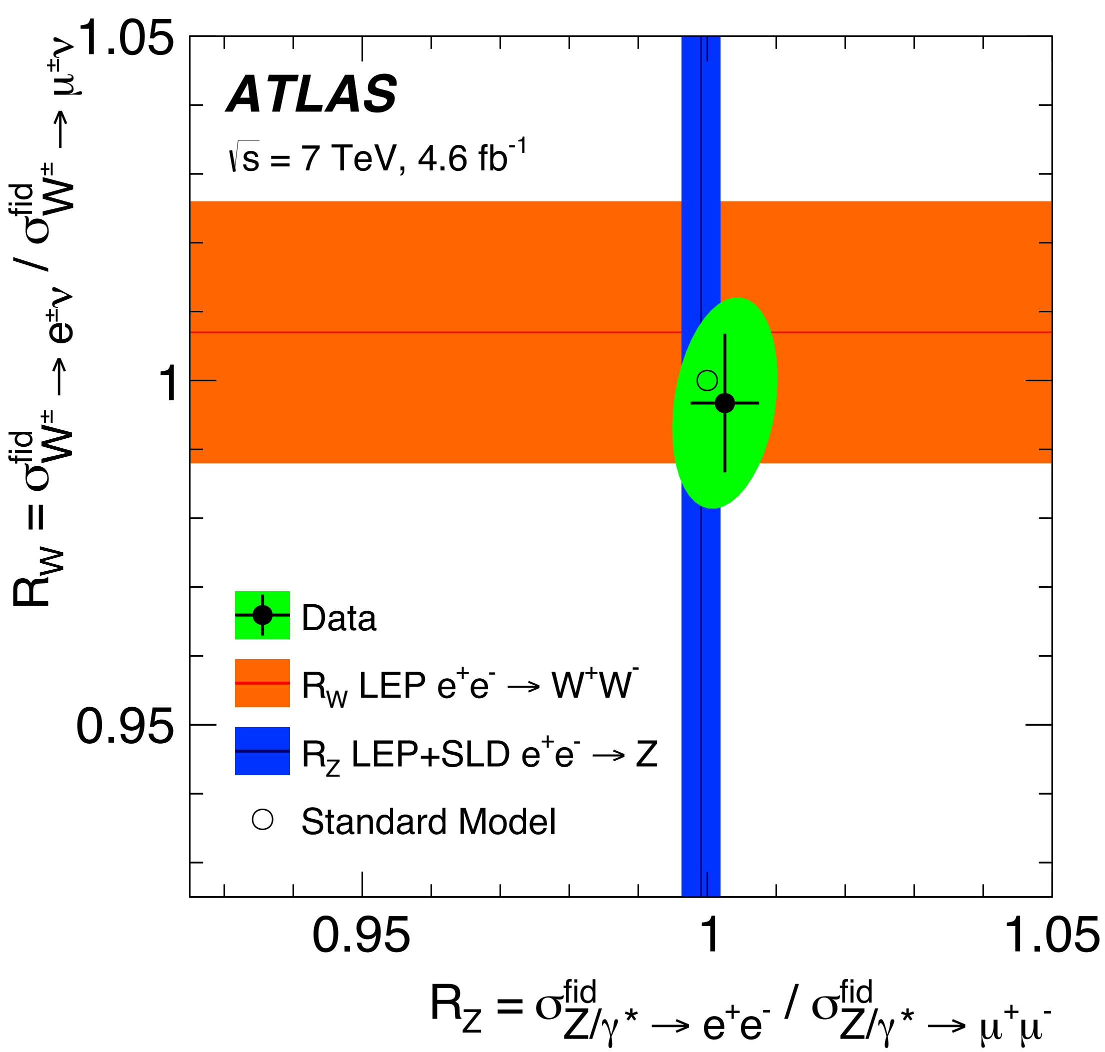


W,Z - Boson Inclusive Cross-Section

CMS-PAS-SMP-15-004

arXiv:1612.03016





W,Z @ 7 TeV - Uncertainties

- Electron channel

	$\delta\sigma_{W+}$ [%]	$\delta\sigma_{W-}$ [%]	$\delta\sigma_{Z}$ [%]	$\delta\sigma_{\text{forward } Z}$ [%]
Trigger efficiency	0.03	0.03	0.05	0.05
Reconstruction efficiency	0.12	0.12	0.20	0.13
Identification efficiency	0.09	0.09	0.16	0.12
Forward identification efficiency	–	–	–	1.51
Isolation efficiency	0.03	0.03	–	0.04
Charge misidentification	0.04	0.06	–	–
Electron p_{T} resolution	0.02	0.03	0.01	0.01
Electron p_{T} scale	0.22	0.18	0.08	0.12
Forward electron p_{T} scale + resolution	–	–	–	0.18
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft term scale	0.14	0.13	–	–
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft term resolution	0.06	0.04	–	–
Jet energy scale	0.04	0.02	–	–
Jet energy resolution	0.11	0.15	–	–
Signal modelling (matrix-element generator)	0.57	0.64	0.03	1.12
Signal modelling (parton shower and hadronization)	0.24	0.25	0.18	1.25
PDF	0.10	0.12	0.09	0.06
Boson p_{T}	0.22	0.19	0.01	0.04
Multijet background	0.55	0.72	0.03	0.05
Electroweak+top background	0.17	0.19	0.02	0.14
Background statistical uncertainty	0.02	0.03	<0.01	0.04
Unfolding statistical uncertainty	0.03	0.04	0.04	0.13
Data statistical uncertainty	0.04	0.05	0.10	0.18
Total experimental uncertainty	0.94	1.08	0.35	2.29
Luminosity			1.8	

- Muon channel

	$\delta\sigma_{W+}$ [%]	$\delta\sigma_{W-}$ [%]	$\delta\sigma_{Z}$ [%]
Trigger efficiency	0.08	0.07	0.05
Reconstruction efficiency	0.19	0.17	0.30
Isolation efficiency	0.10	0.09	0.15
Muon p_{T} resolution	0.01	0.01	<0.01
Muon p_{T} scale	0.18	0.17	0.03
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft term scale	0.19	0.19	–
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft term resolution	0.10	0.09	–
Jet energy scale	0.09	0.12	–
Jet energy resolution	0.11	0.16	–
Signal modelling (matrix-element generator)	0.12	0.06	0.04
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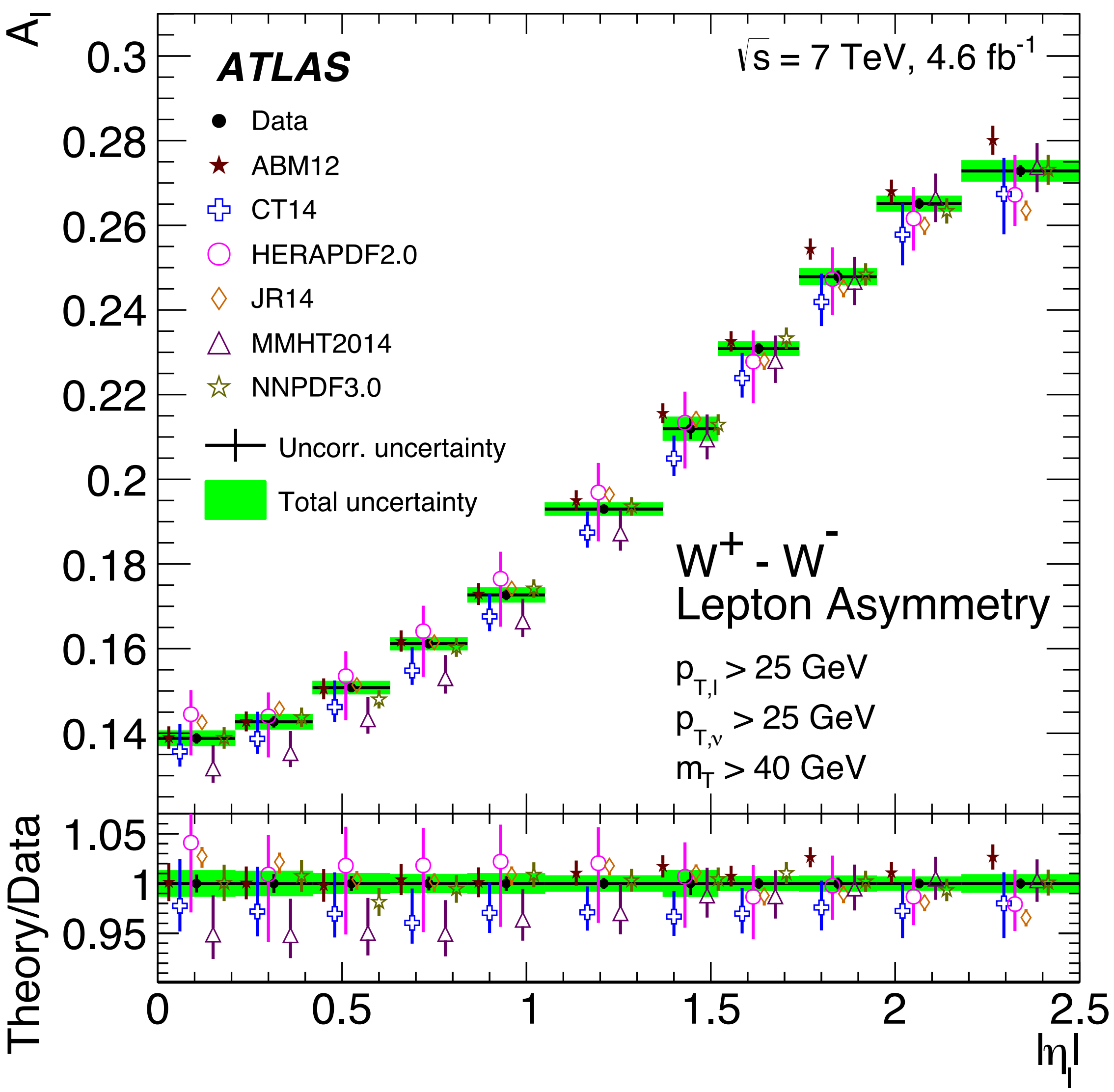
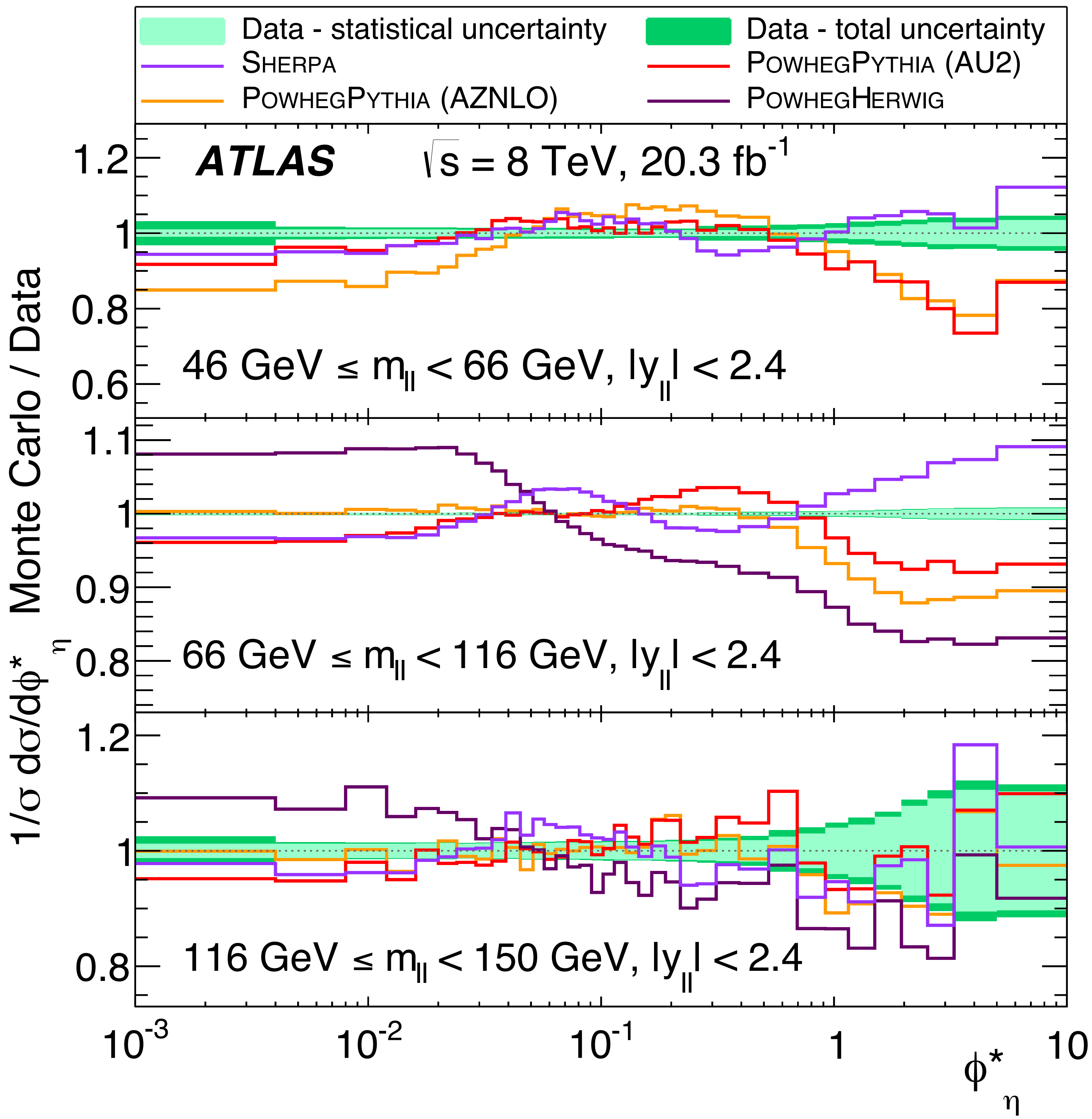
Multijet background	0.33	0.27	0.07
Electroweak+top background	0.19	0.24	0.02
Background statistical uncertainty	0.03	0.04	0.01
Unfolding statistical uncertainty	0.03	0.03	0.02
Data statistical uncertainty	0.04	0.04	0.08
Total experimental uncertainty	0.61	0.59	0.43
Luminosity		1.8	

W,Z - Boson Differential Measurements @ 7 TeV

- Differential measurements in (pseudo-) rapidity
    - Sensitive to PDF
    - Impact on PDF evaluated using profiling



Comparison to parton-shower Simulations



- Comparison in 3 regions of m_{ll}
- 2 individual Pythia tunes:
  - AZNLO done on 7 TeV data at Z-peak
  - AU2
- Significant disagreement between simulation & data in peak region
- Also significant disagreement between PowHeg and Sherpa
  - Particularly for large φ^* values

Ratio of ttbar / Z production cross sections

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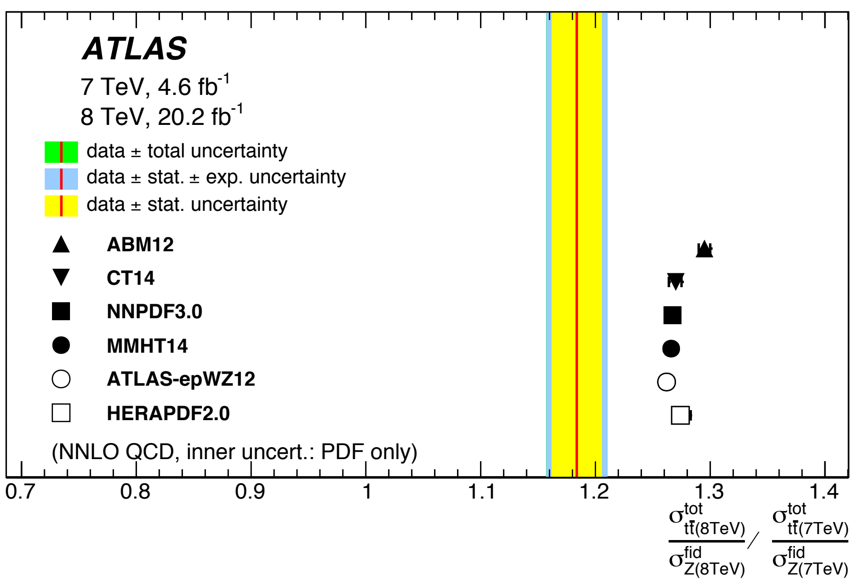
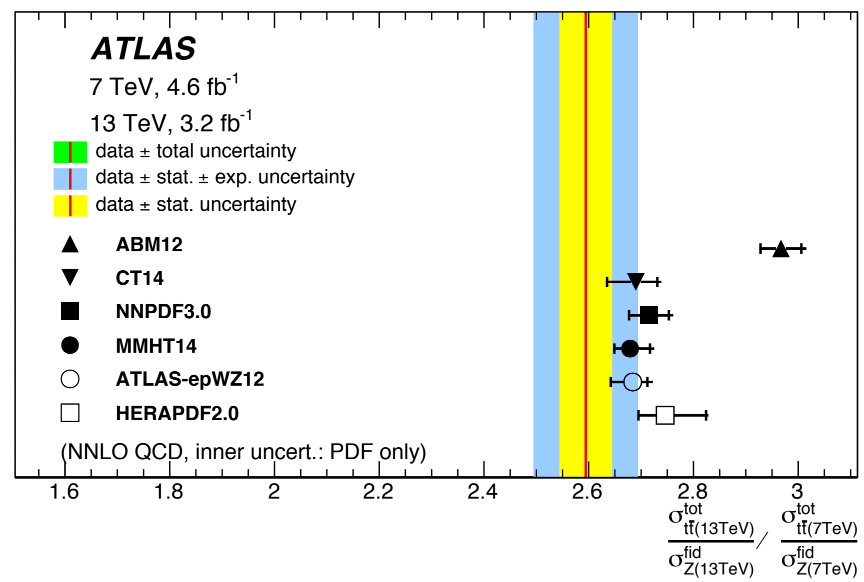
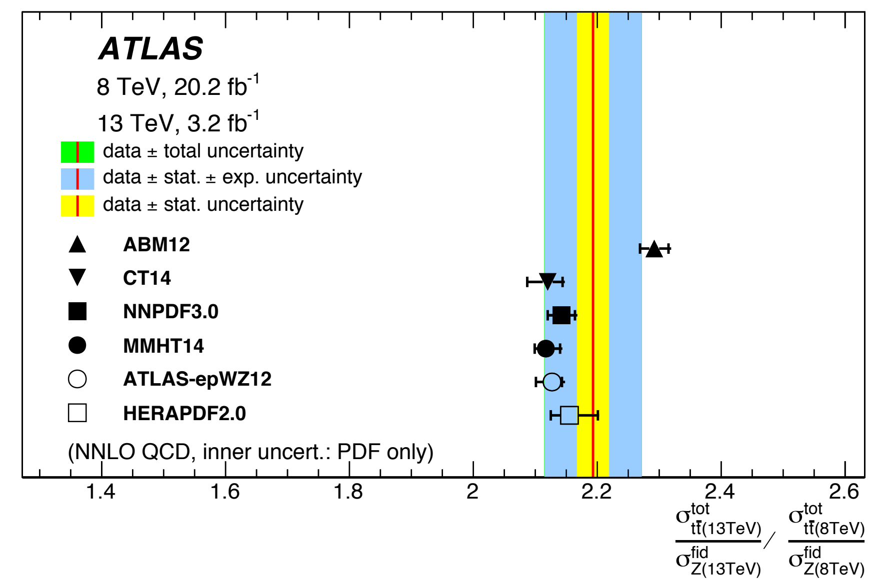
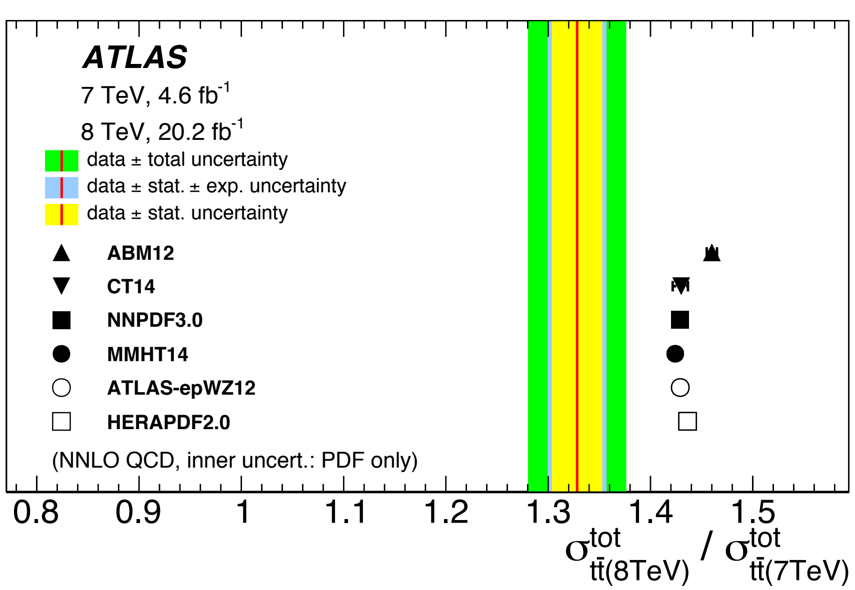
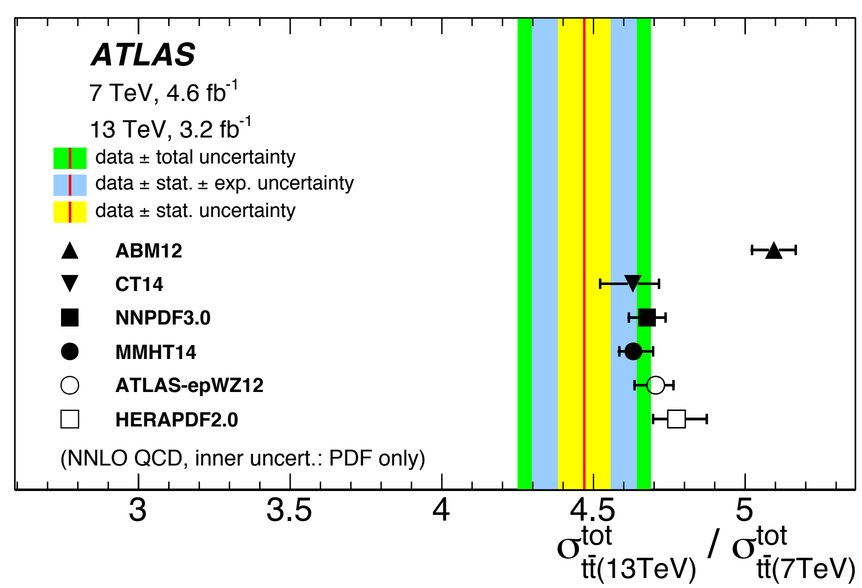
- Discrepancy observed in super-ratio including 7TeV data:
  - Origin in ttbar(8 TeV) / ttbar(7 TeV) ratio
  - Suspected to lie in 7 TeV ttbar measurement

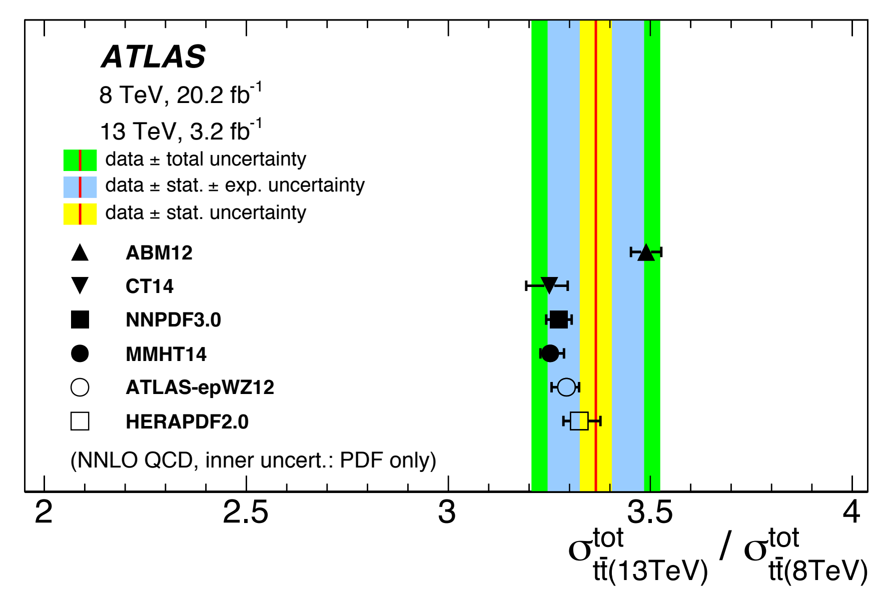










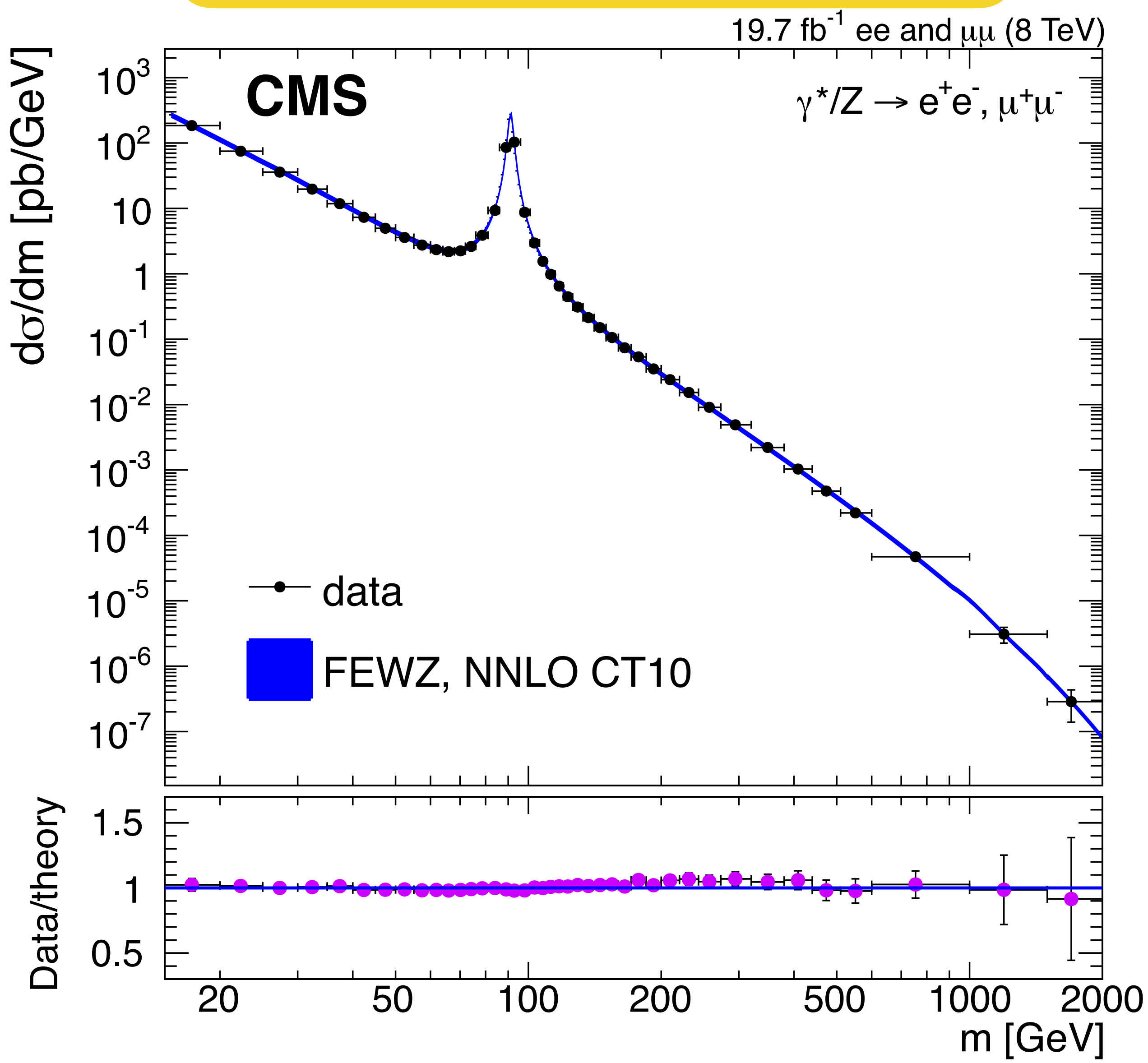


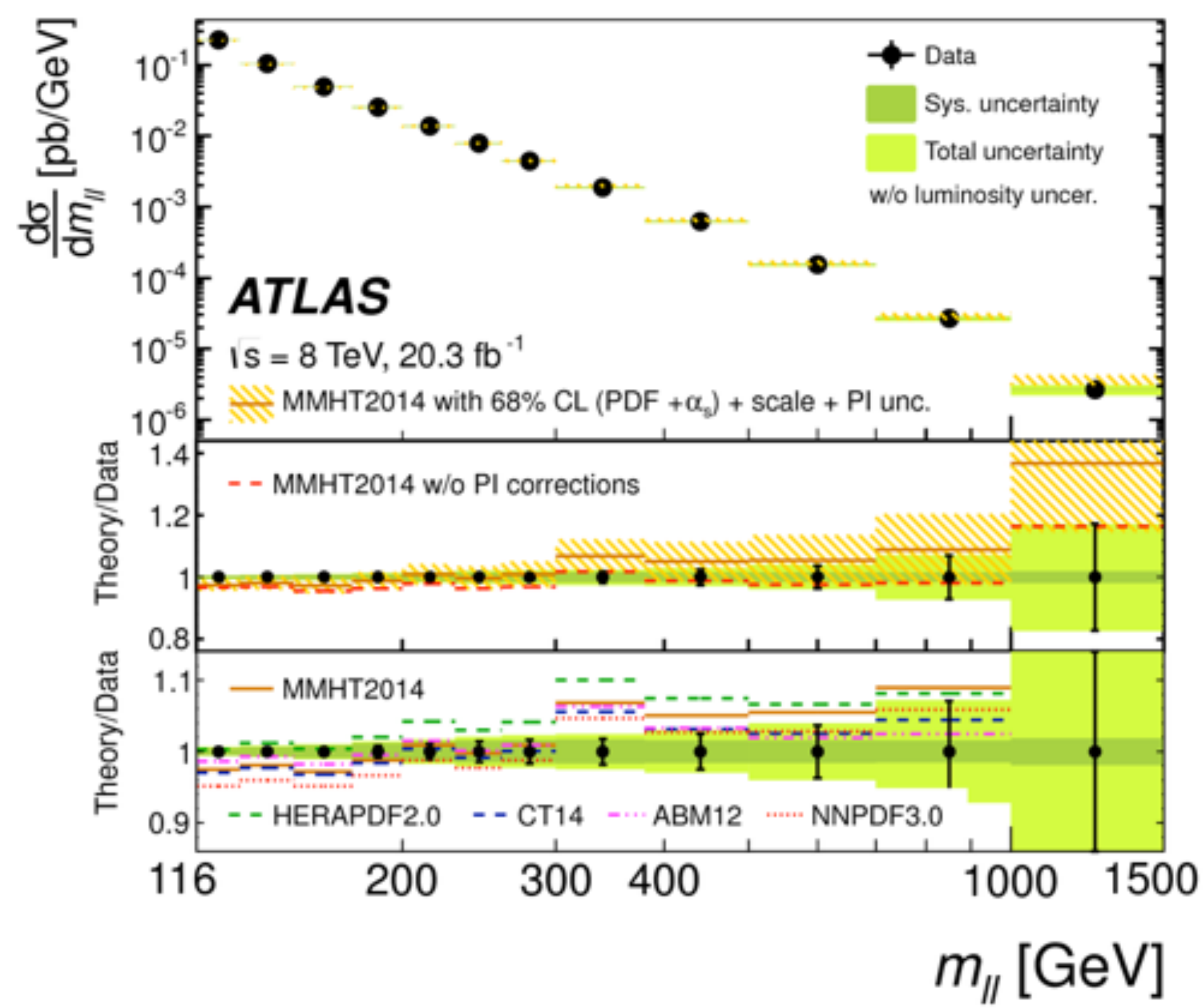
Drell-Yan measurements @ 8 TeV

Agreement with SM over 3 orders of magnitude in mass
9 order in cross section

- Uncertainties at few % level for m < 500 GeV

Eur. Phys. J. C 75 (2015) 147

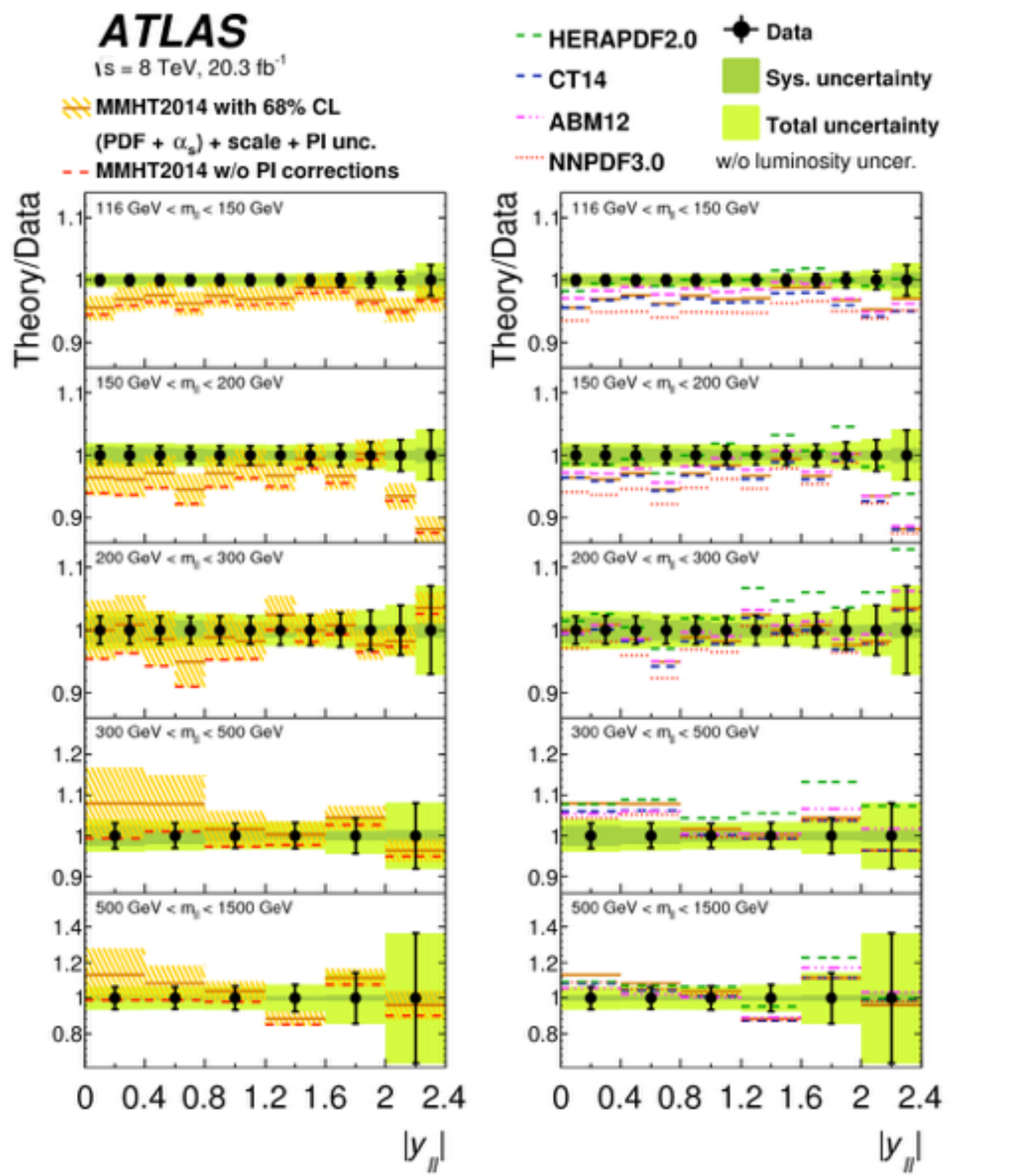




High mass DY measurement @ 8 TeV

JHEP 08 (2016) 009

- Only masses above Z-peak considered
  - Comparison to various PDFs
  - Rapidity distribution very sensitive
    - Significant deviations observed



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JHEP 08 (2016) 009

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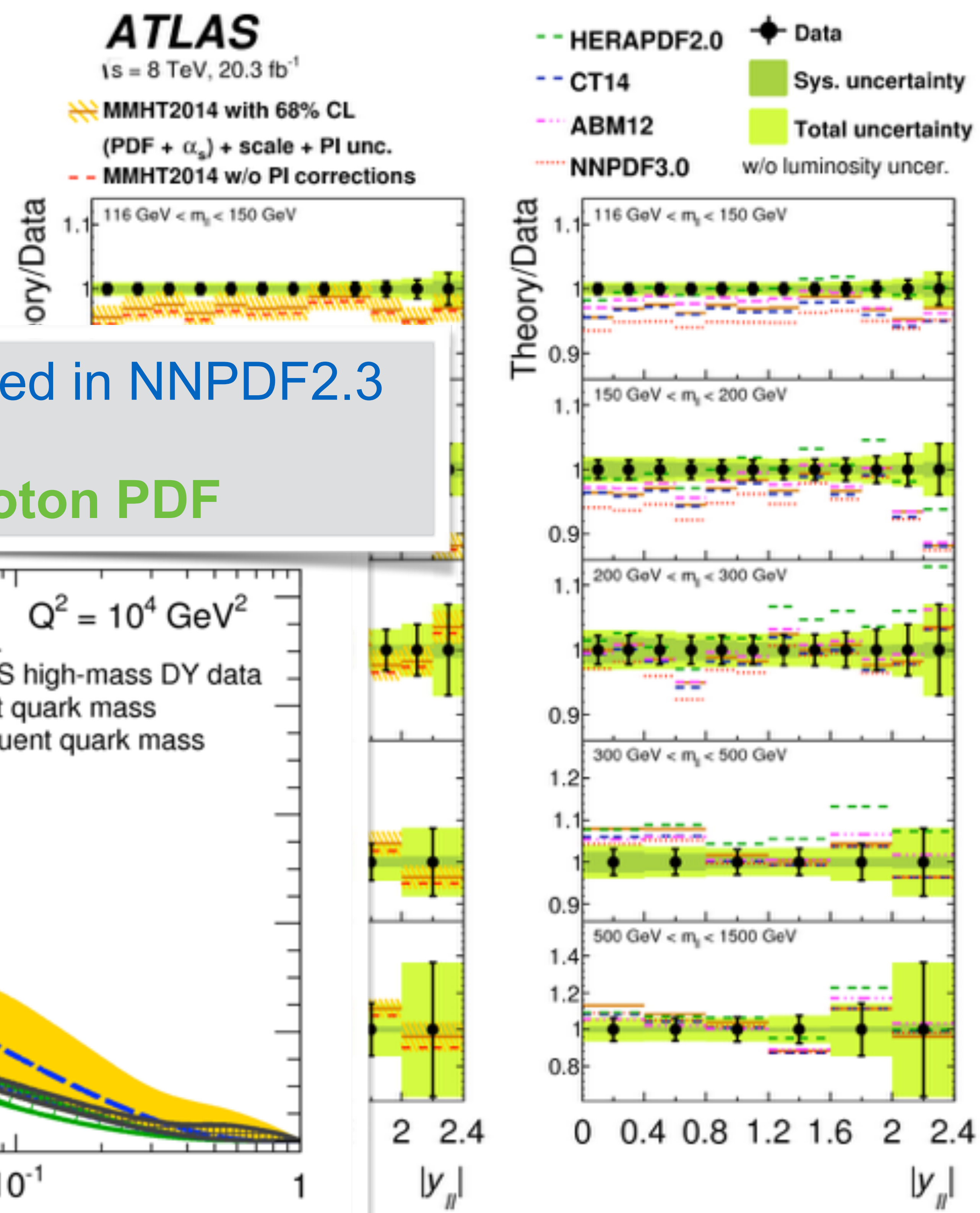
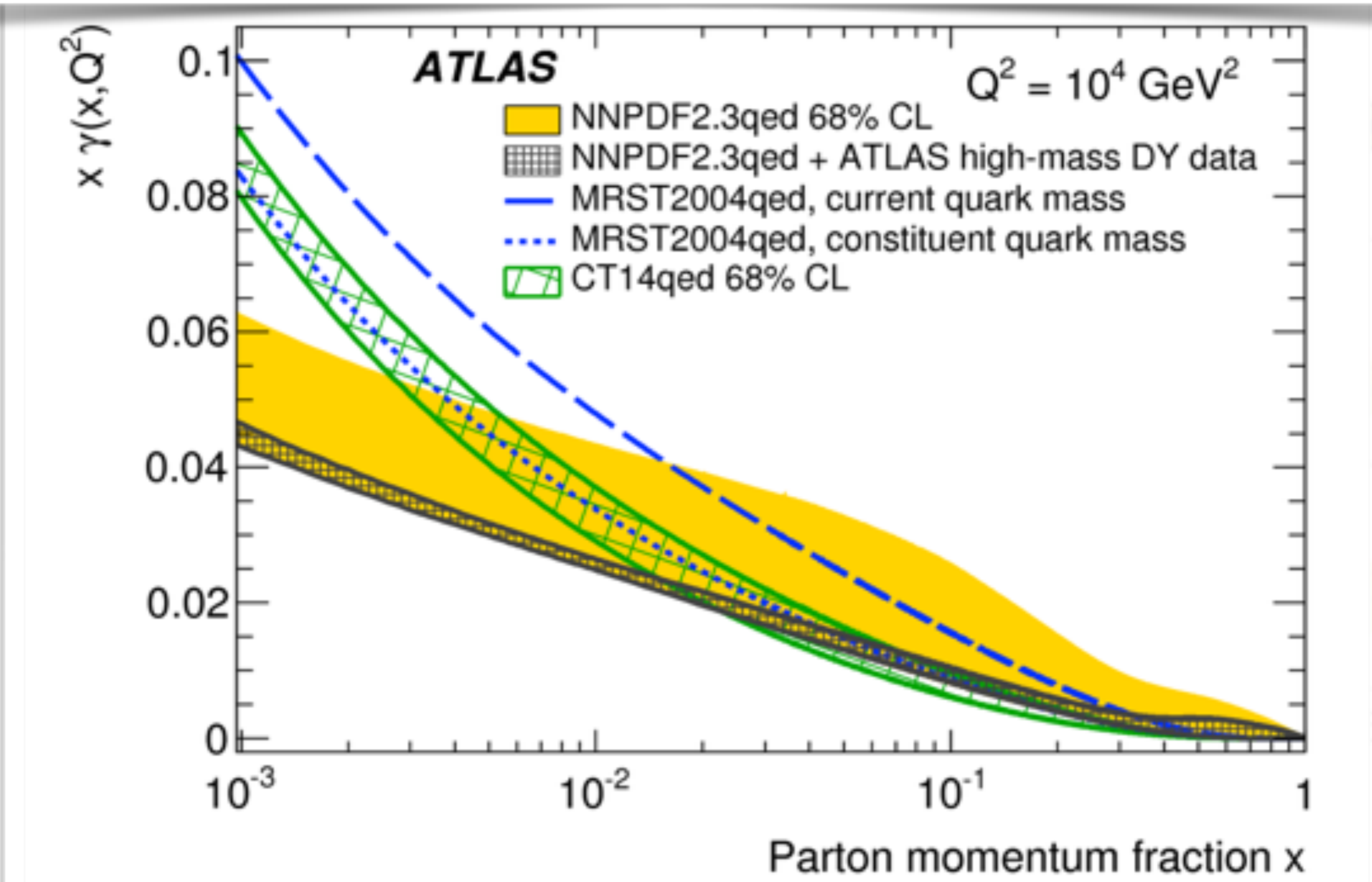


- High mass Drell-Yan data included in NNPDF2.3
  - Significant constraint of photon PDF



W mass @ 7 TeV - uncertainty details

Higher order EWK corrections

Decay channel	$W \to e\nu$		$W \to \mu\nu$	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]				
FSR (real)	< 0.1	< 0.1	< 0.1	< 0.1
Pure weak and IFI corrections	3.3	2.5	3.5	2.5
FSR (pair production)	3.6	0.8	4.4	0.8
Total	4.9	2.6	5.6	2.6

Recoil corrections

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
$\langle\mu\rangle$ scale factor	0.2	1.0	0.2	1.0	0.2	1.0
$\Sigma \bar{E}_T$ correction	0.9	12.2	1.1	10.2	1.0	11.2
Residual corrections (statistics)	2.0	2.7	2.0	2.7	2.0	2.7
Residual corrections (interpolation)	1.4	3.1	1.4	3.1	1.4	3.1
Residual corrections ($Z \to W$ extrapolation)	0.2	5.8	0.2	4.3	0.2	5.1
Total	2.6	14.2	2.7	11.8	2.6	13.0

Muons experimental

$\lvert\eta_\ell\rvert$ range	[0.0, 0.8]		[0.8, 1.4]		[1.4, 2.0]		[2.0, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]										
Momentum scale	8.9	9.3	14.2	15.6	27.4	29.2	111.0	115.4	8.4	8.8
Momentum resolution	1.8	2.0	1.9	1.7	1.5	2.2	3.4	3.8	1.0	1.2
Sagitta bias	0.7	0.8	1.7	1.7	3.1	3.1	4.5	4.3	0.6	0.6
Reconstruction and isolation efficiencies	4.0	3.6	5.1	3.7	4.7	3.5	6.4	5.5	2.7	2.2
Trigger efficiency	5.6	5.0	7.1	5.0	11.8	9.1	12.1	9.9	4.1	3.2
Total	11.4	11.4	16.9	17.0	30.4	31.0	112.0	116.1	9.8	9.7

Electrons experimental

$\lvert\eta_\ell\rvert$ range	[0.0, 0.6]		[0.6, 1.2]		[1.82, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]								
Energy scale	10.4	10.3	10.8	10.1	16.1	17.1	8.1	8.0
Energy resolution	5.0	6.0	7.3	6.7	10.4	15.5	3.5	5.5
Energy linearity	2.2	4.2	5.8	8.9	8.6	10.6	3.4	5.5
Energy tails	2.3	3.3	2.3	3.3	2.3	3.3	2.3	3.3
Reconstruction efficiency	10.5	8.8	9.9	7.8	14.5	11.0	7.2	6.0
Identification efficiency	10.4	7.7	11.7	8.8	16.7	12.1	7.3	5.6
Trigger and isolation efficiencies	0.2	0.5	0.3	0.5	2.0	2.2	0.8	0.9
Charge mismeasurement	0.2	0.2	0.2	0.2	1.5	1.5	0.1	0.1
Total	19.0	17.5	21.1	19.4	30.7	30.5	14.2	14.3

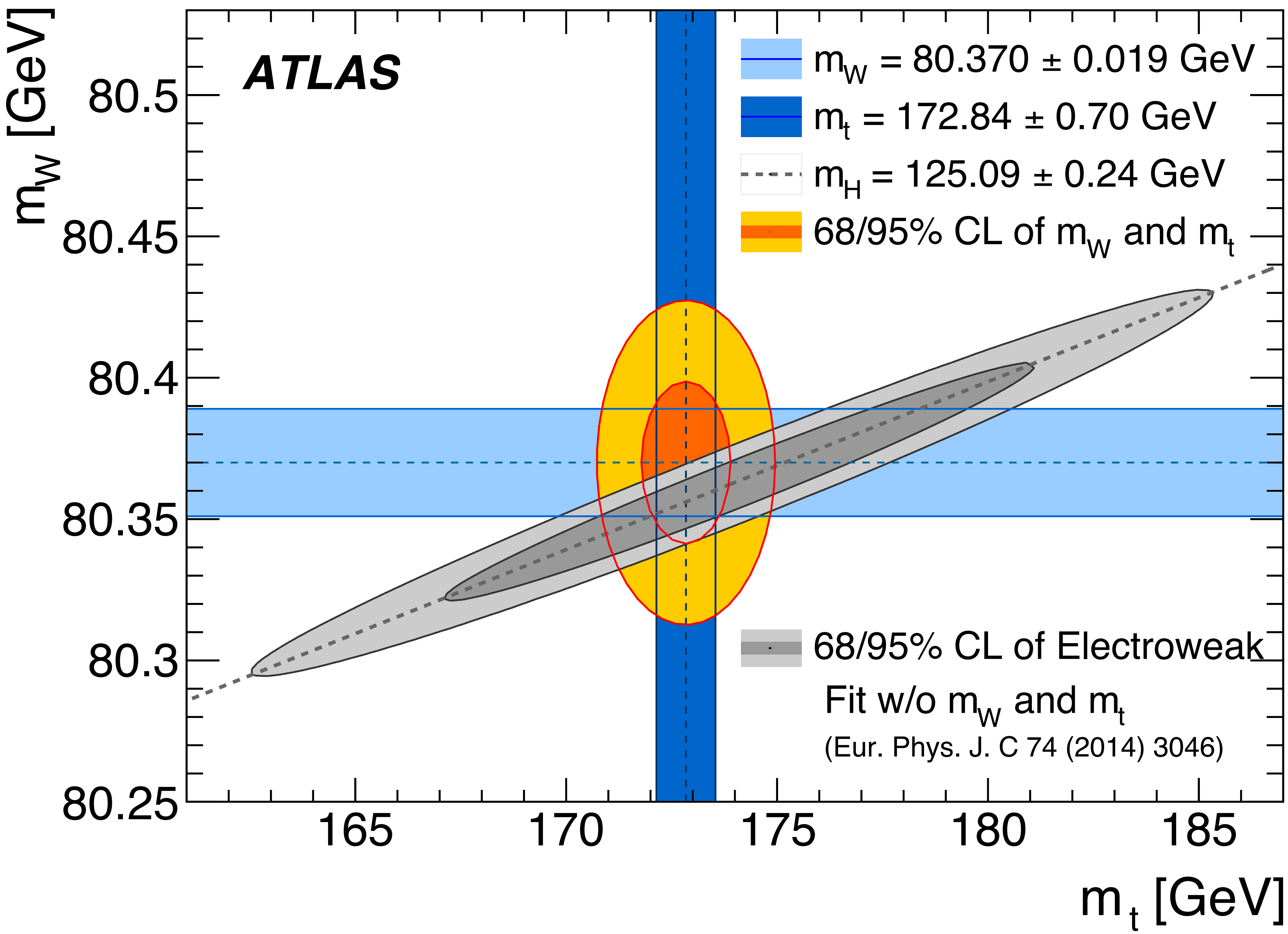
QCD modeling

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6
Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3
Total	15.9	18.1	14.8	17.2	11.6	12.9

W mass @ LHC - consistency of SM

- **Test for consistency of standard model:**

arXiv:1701.07240



W,Z inclusive @ 7 TeV => W mass

- Choosing the PDF to be used in simulations for W mass extraction
  - Best agreement with 7 TeV W,Z data: **CT PDF sets**

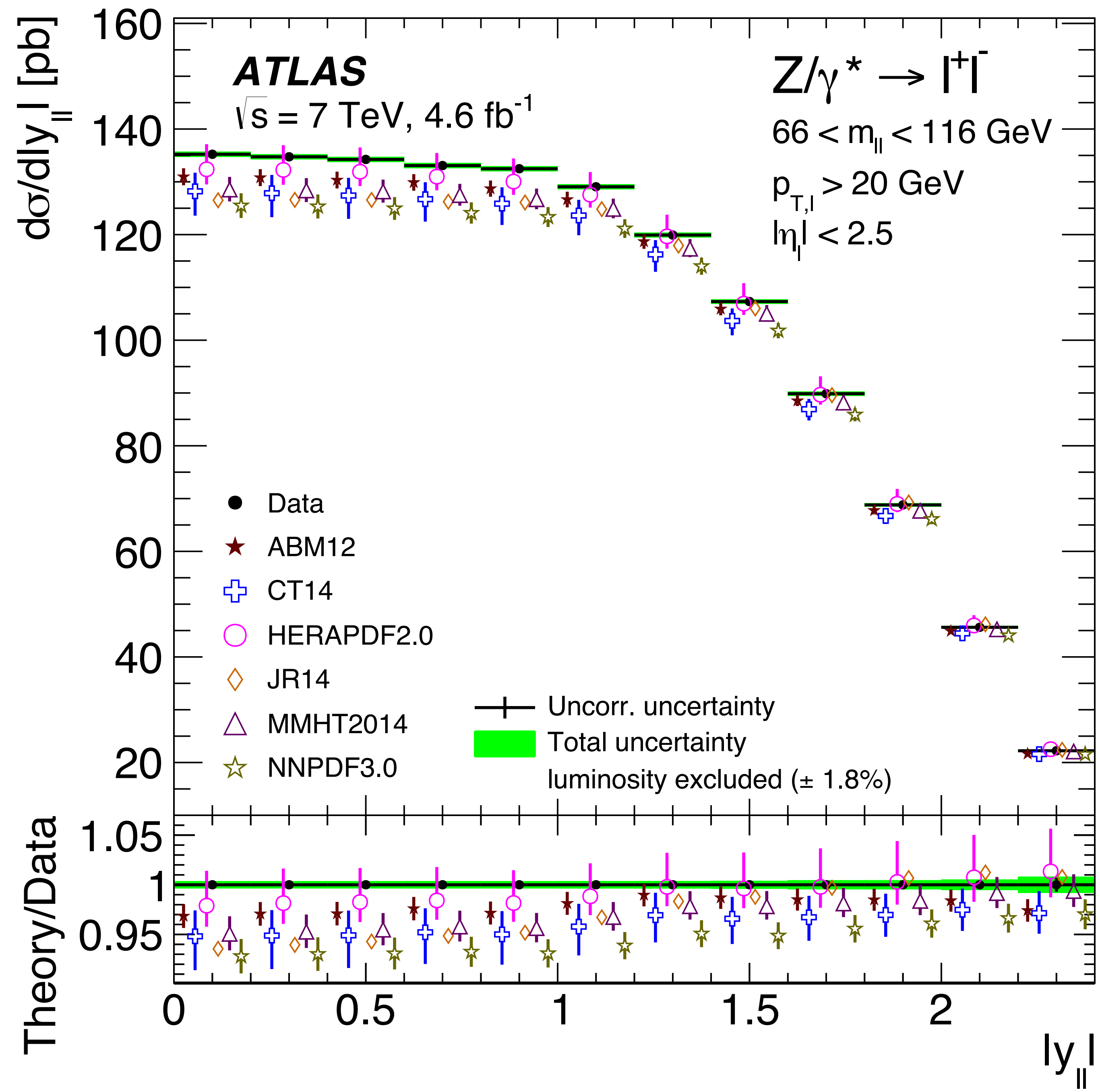
PDF uncertainties:
included | excluded

Data set	n.d.f.	ABM12	CT14	MMHT14	NNPDF3.0	ATLAS-epWZ12
$W^+ \to \ell^+ \nu$	11	11|21	10|26	11|37	11|18	12|15
$W^- \to \ell^- \bar{\nu}$	11	12|20	8.9|27	8.1|31	12|19	7.8|17
$Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} = 46 - 66$ GeV)	6	17|21	11|30	18|24	21|22	28|36
$Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} = 66 - 116$ GeV)	12	24|51	16|66	20|116	14|109	18|26
Forward $Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} = 66 - 116$ GeV)	9	7.3|9.3	10|12	12|13	14|18	6.8|7.5
$Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} = 116 - 150$ GeV)	6	6.1|6.6	6.3|6.1	5.9|6.6	6.1|8.8	6.7|6.6
Forward $Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} = 116 - 150$ GeV)	6	4.2|3.9	5.1|4.3	5.6|4.6	5.1|5.0	3.6|3.5
Correlated χ^2		57|90	39|123	43|167	69|157	31|48
Total χ^2	61	136|222	103|290	118|396	147|351	113|159

W,Z - Boson Differential Measurements @ 7 TeV

arXiv:1612.03016

- Predictions:
  - NNLO QCD using DYNNLO
  - NLO EWK corrections using
    - PHOTOS (QED FSR)
    - MCSANC (other)
  - Various PDFs
- Predicted cross section too low
  - (except HERA 2.0 PDF)
- Discrepancy in shape



Z - Boson Differential Measurements

- **LHCb**: forward spectrometer
  - Access to high rapidity regime!

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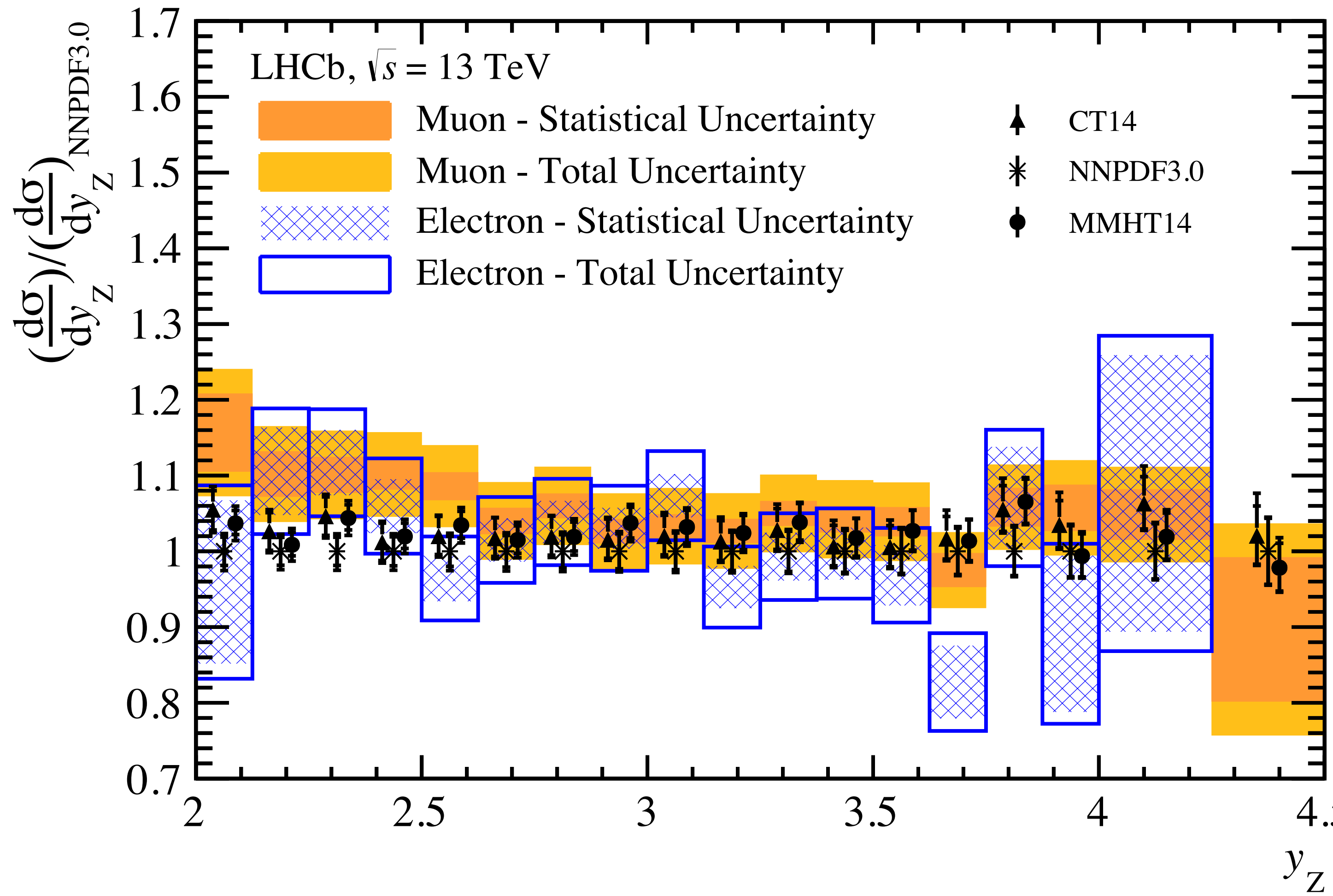
- Predictions:
  - NLO qQCD using FEWZ 3.1
  - LO EWK
  - Various PDFs



- Predicted cross section slightly below measurement for low rapidities
  - Consistent with other LHC measurements

Z p_T spectrum - Φ^* measurement

CMS-PAS-SMP-15-002

$$\phi^*_\eta = \tan\left(\frac{\pi - \Delta\phi}{2}\right) \cdot \sin(\theta^*_\eta)$$

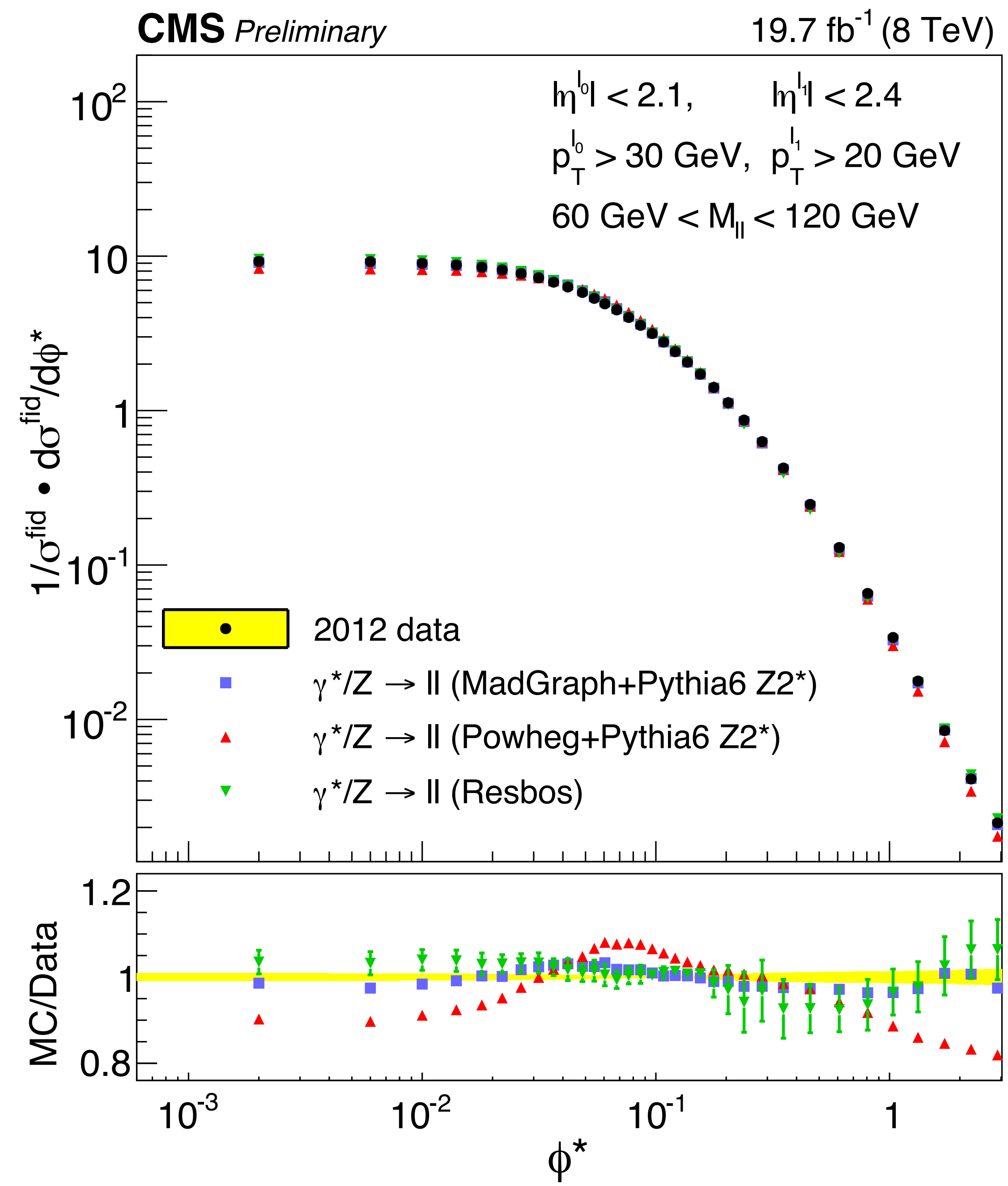
azimuthal angle between the two leptons

$$\theta^*_\eta = \arccos\left(\tanh\left(\frac{\eta^- - \eta^+}{2}\right)\right)$$

- Depends only on measured angles
  - Better resolution compared to momentum measurements

$$\sqrt{2} m_Z \phi^*_\eta \approx p_T^{ll}$$

- Significant deviations observed
  - MadGraph: best agreement
    - Deviations up to 5%
  - PowHeg + Pythia 6
    - Deviations up to 18%



Z pT spectrum - Φ* measurement

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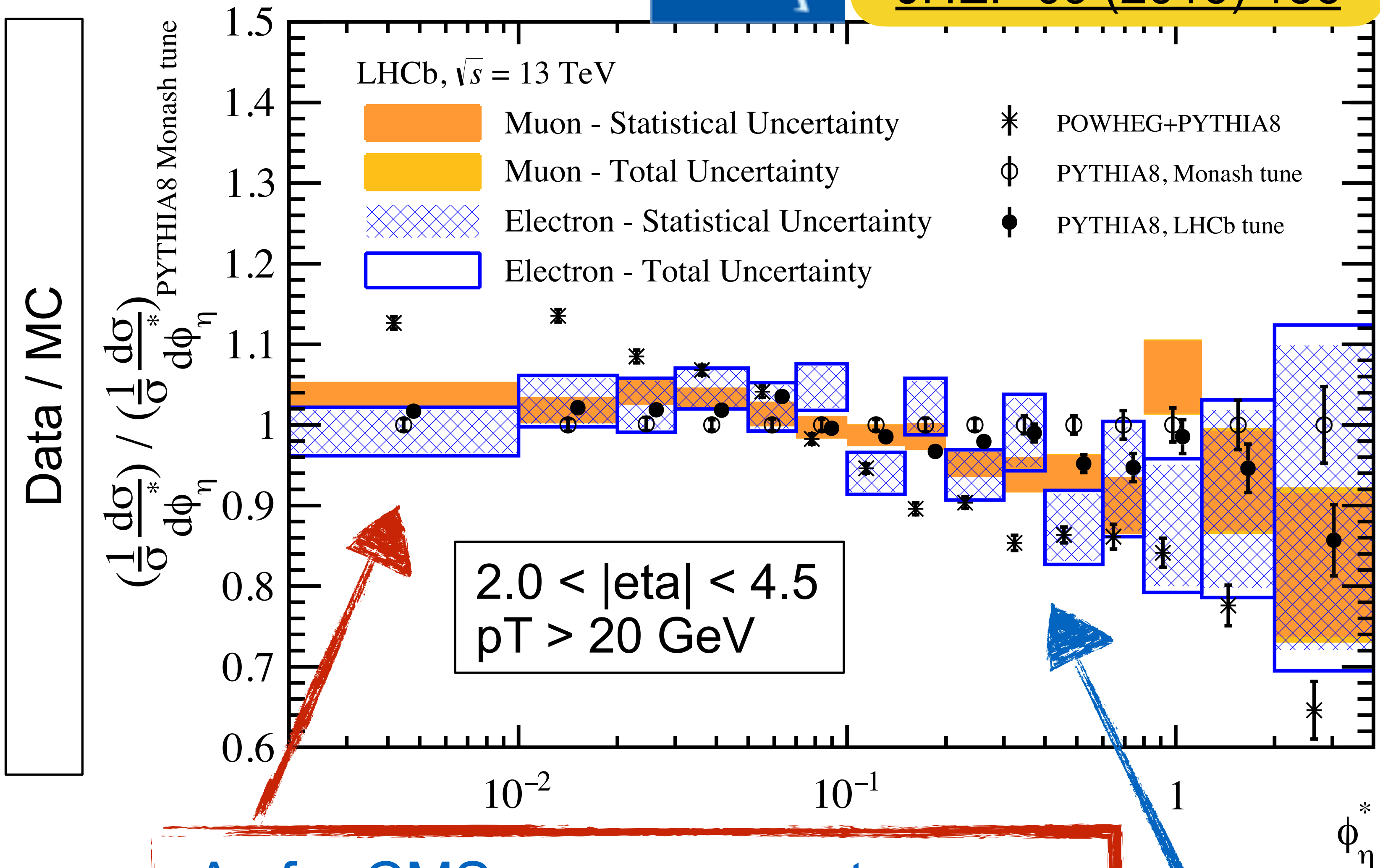
- Before: MC / Data!
- Low range dominated by:
  - Non perturbative effects
  - Parton shower
- High range dominated by hard parton emission
  - Matrix element generator
- Good agreement of Pythia 8 prediction with data



As for CMS measurement: PowHeg + Pythia prediction below measurement for low phi* values

Here different behavior w.r.t. data compared to previous results

Z pT spectrum - Φ^* measurement

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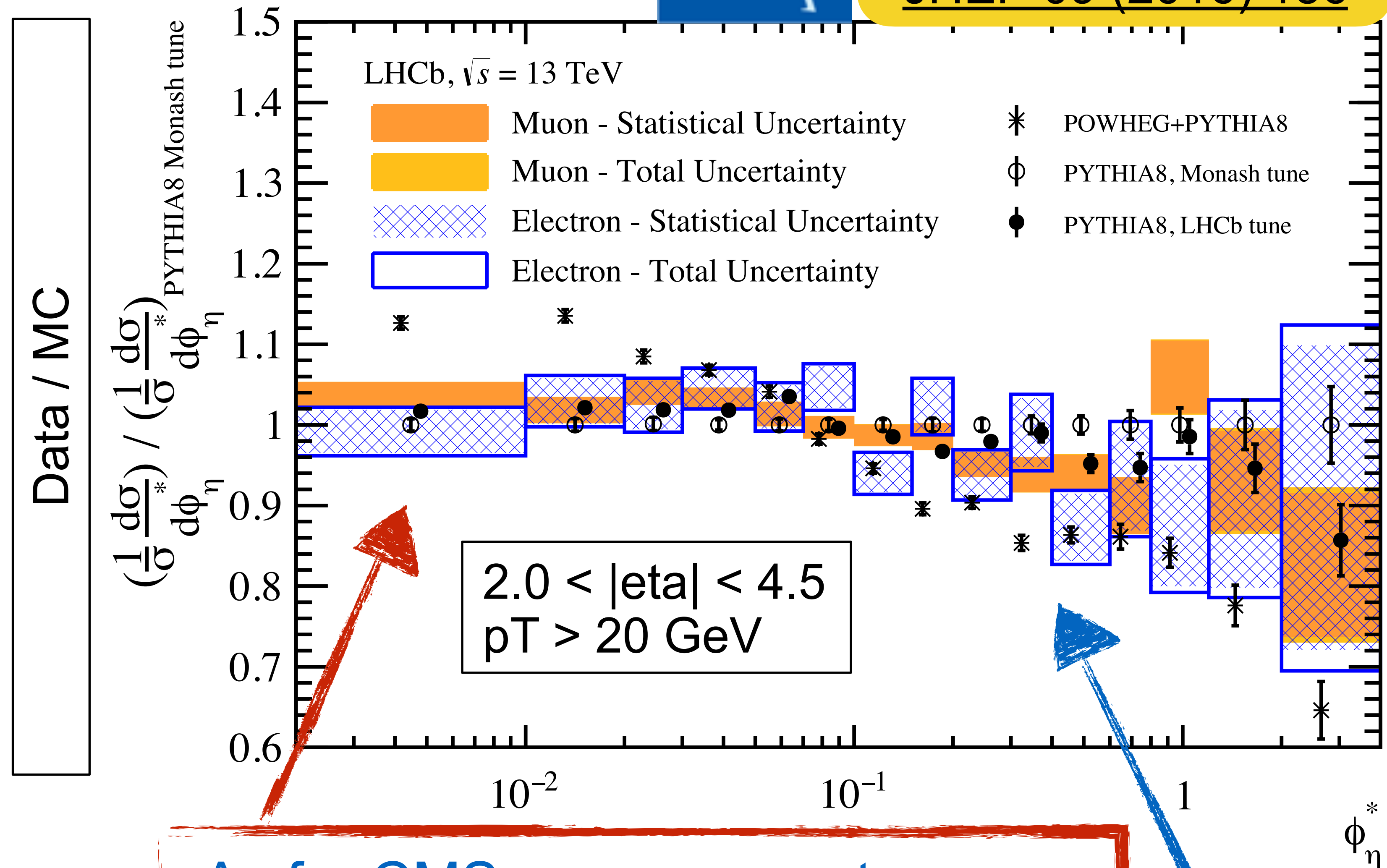

As for CMS measurement: PowHeg + Pythia prediction below measurement for low phi* values

Here different behavior w.r.t. data compared to previous results

- Dominating **experimental uncertainty**:
  - Reconstruction efficiency (2.4% on total cross section)

Z Boson - x-Section in forward region @ 13 TeV

LHCb

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- Acceptance in forward region:
  - $2.0 < |\eta_\ell| < 4.5$, $p_T > 20$ GeV
  - 60 GeV < $m_{\ell\ell}$ < 120 GeV

Source	$\Delta\sigma_Z^{\mu\mu}$ [%]	$\Delta\sigma_Z^{ee}$ [%]
Statistical	0.5	0.9
Reconstruction efficiencies	2.4	2.4
Purity	0.2	0.5
FSR	0.1	0.2
Total systematic (excl. lumi.)	2.4	2.5
Luminosity	3.9	3.9

- Achieved precision (combined):
  - **< 4.3% total uncertainty**
  - **1.7% experimental**
  - (3.9% luminosity)

stat. sys. lumi.

$$\sigma_Z^{\mu\mu} = 198.0 \pm 0.9 \pm 4.7 \pm 7.7\,\text{pb},$$
$$\sigma_Z^{ee} = 190.2 \pm 1.7 \pm 4.7 \pm 7.4\,\text{pb}.$$
$$\sigma_Z^{\ell\ell} = 194.3 \pm 0.9 \pm 3.3 \pm 7.6\,\text{pb}$$

total unc.:
4.5%
4.7%
4.3%