Precision Electroweak Measurement in ATLAS

Louis Helary (CERN)
on behalf of the
ATLAS collaboration

Moriond Electroweak – March 12th 2018

Electron Microscope Picture of an Influenza Virus
http://www.biology-pages.info/I/Influenza.html

Precision Electroweak Measurement in ATLAS

Matthias Schott (Uni. Mainz)

on behalf of the

Louis Helary (CERN)

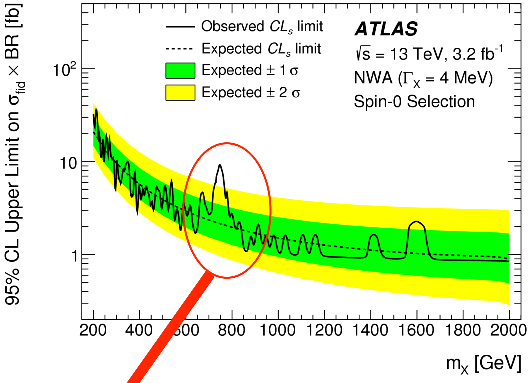
on behalf of the

ATLAS collaboration

Moriond Electroweak – March 12th 2018

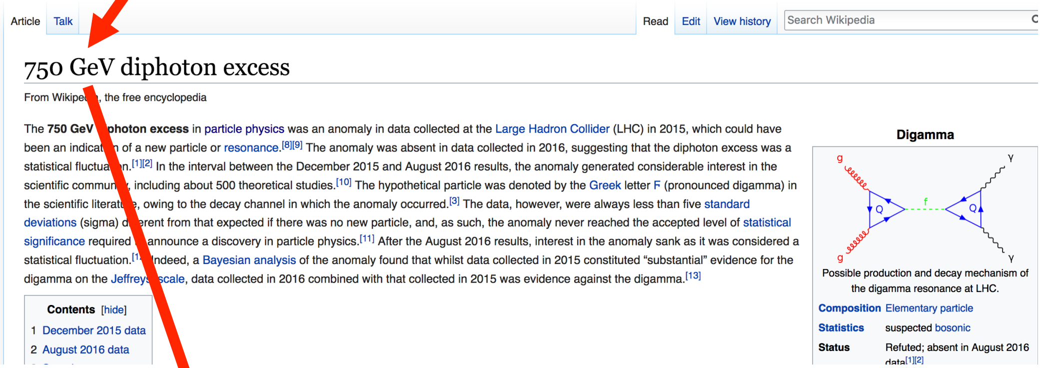
Introduction

Why precision measurements?



***2015:**1606.03833*

Large expectation to find new physics early-on with direct searches at the LHC. But so far everything looks very consistent with the SM.



750 GeV diphoton excess

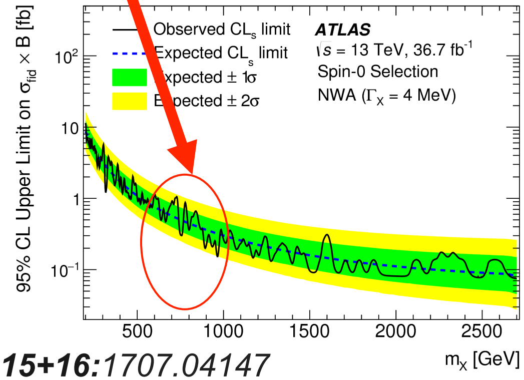
From Wikipe , the free encyclopedia

The **750 GeV photon excess** in particle physics was an anomaly in data collected at the Large Hadron Collider (LHC) in 2015, which could have been an indicat n of a new particle or resonance.[8][9] The anomaly was absent in data collected in 2016, suggesting that the diphoton excess was a statistical fluctua n.[1][2] In the interval between the December 2015 and August 2016 results, the anomaly generated considerable interest in the scientific commun , including about 500 theoretical studies.[10] The hypothetical particle was denoted by the Greek letter Ϝ (pronounced digamma) in the scientific literat e, owing to the decay channel in which the anomaly occurred.[3] The data, however, were always less than five standard deviations (sigma) d erent from that expected if there was no new particle, and, as such, the anomaly never reached the accepted level of statistical significance required announce a discovery in particle physics.[11] After the August 2016 results, interest in the anomaly sank as it was considered a statistical fluctuation.[1 Indeed, a Bayesian analysis of the anomaly found that whilst data collected in 2015 constituted “substantial” evidence for the digamma on the Jeffreys scale, data collected in 2016 combined with that collected in 2015 was evidence against the digamma.[13]

Digamma

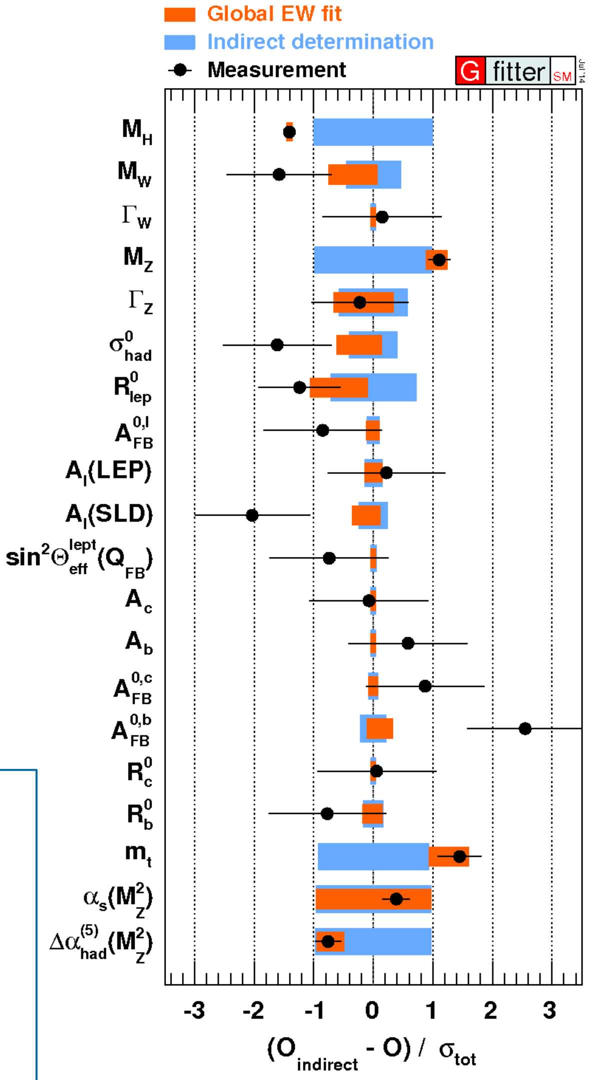
Possible production and decay mechanism of the digamma resonance at LHC.

Composition	Elementary particle
Statistics	suspected bosonic
Status	Refuted; absent in August 2016 data[1][2]

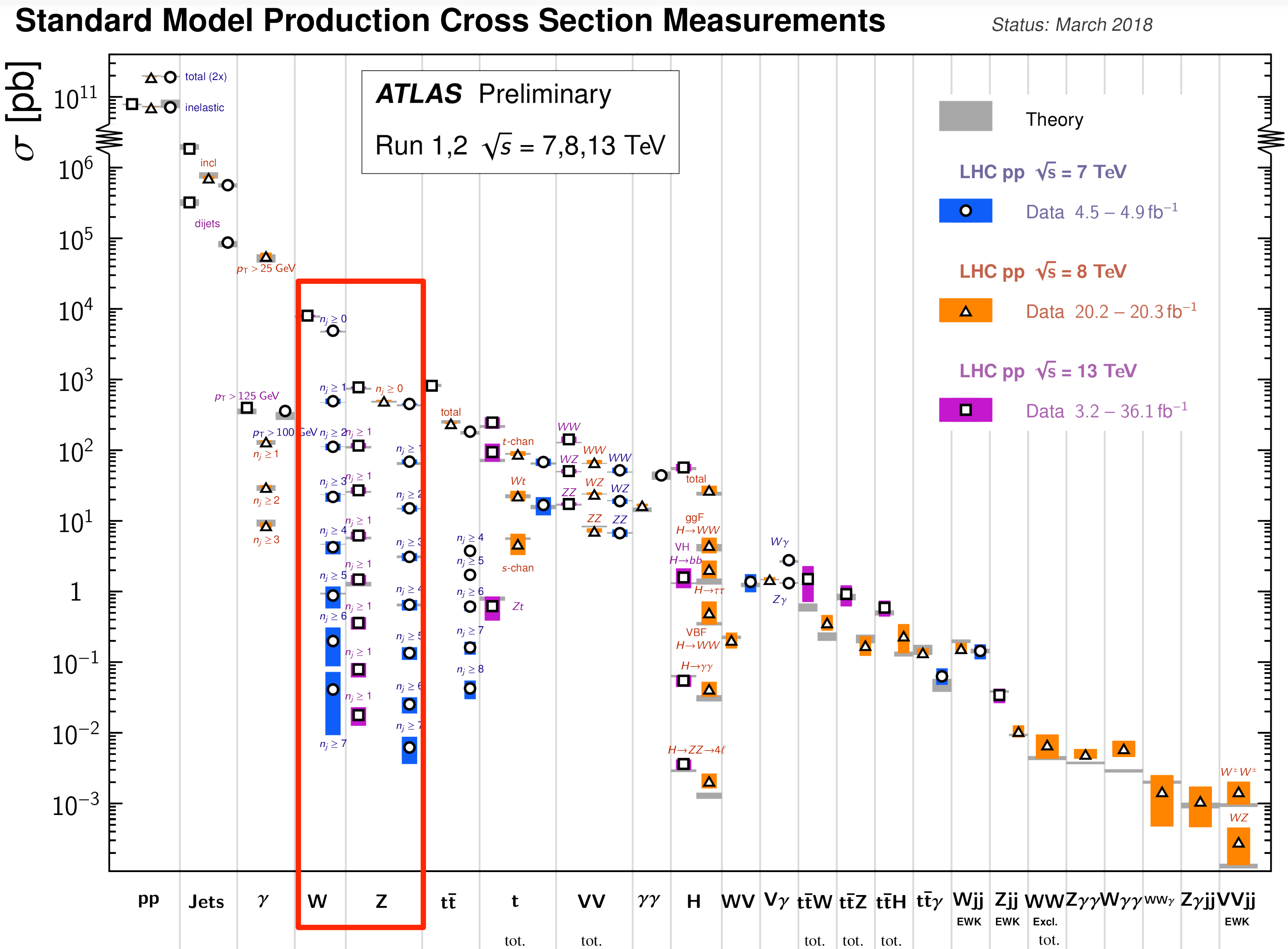


***2015+16:**1707.04147*

Alternative approach:
Find new physics by improving measurement precision of EWK parameters and probe the SM.
Up to now: STU; in the future EFTs?



SM measurements in ATLAS

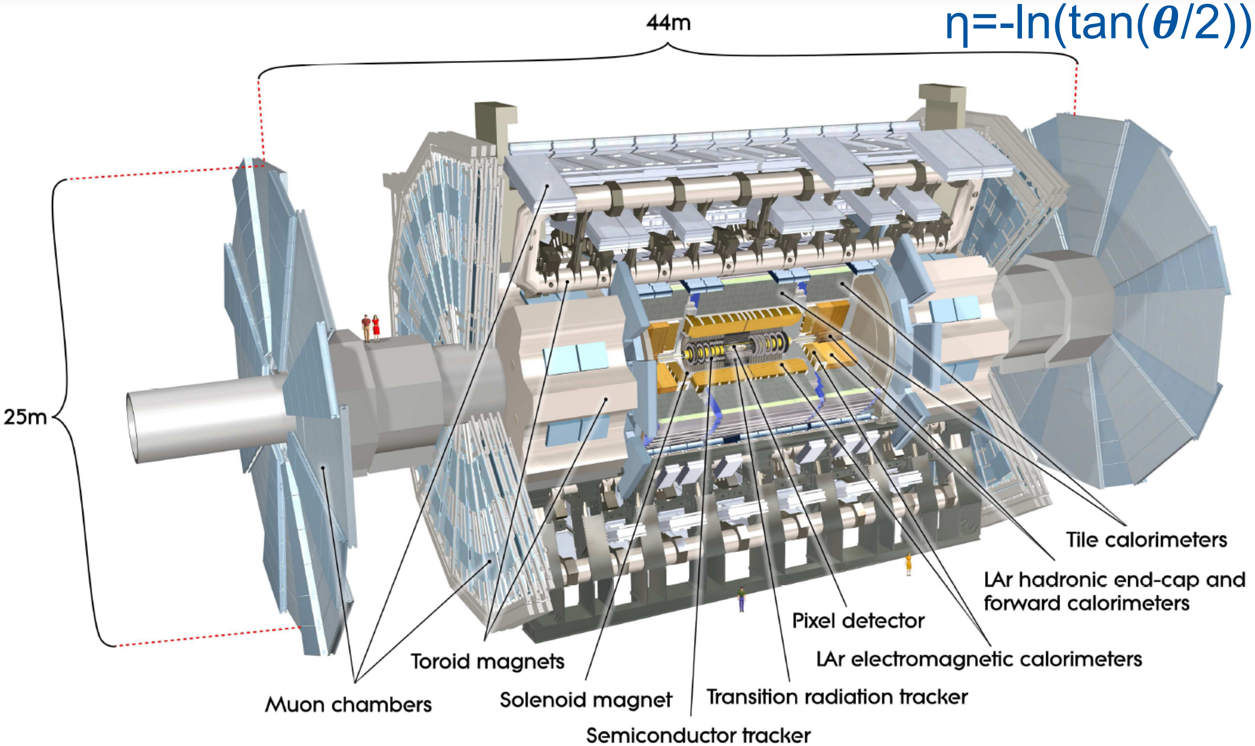


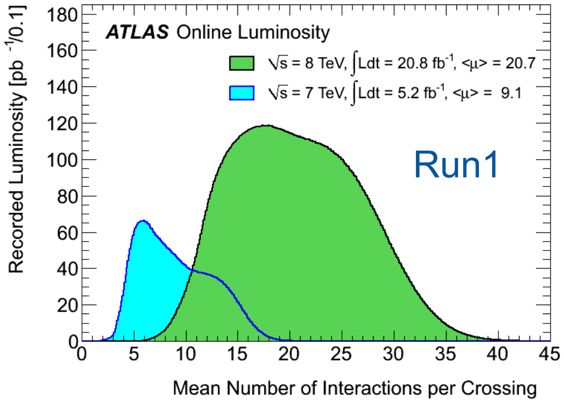
ATLAS has performed a large number of measurements.

Here will focus on electroweak boson measurements properties.

ATLAS and data collected

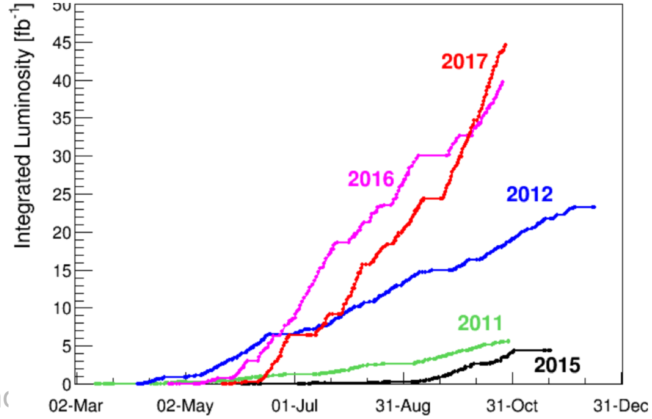
η=-ln(tan(*θ*/2))

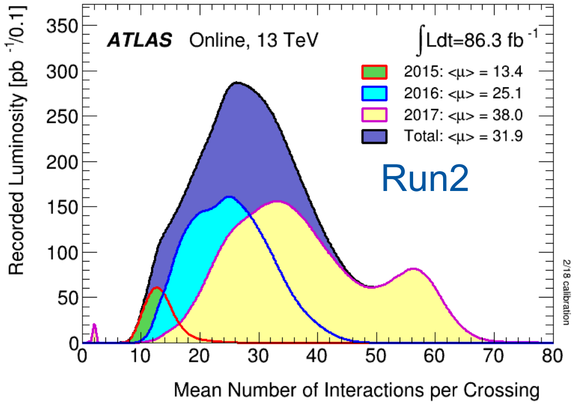




Precision analyses at the LHC still use Run1 data.

Most searches presented in the following days are using Run2 data.

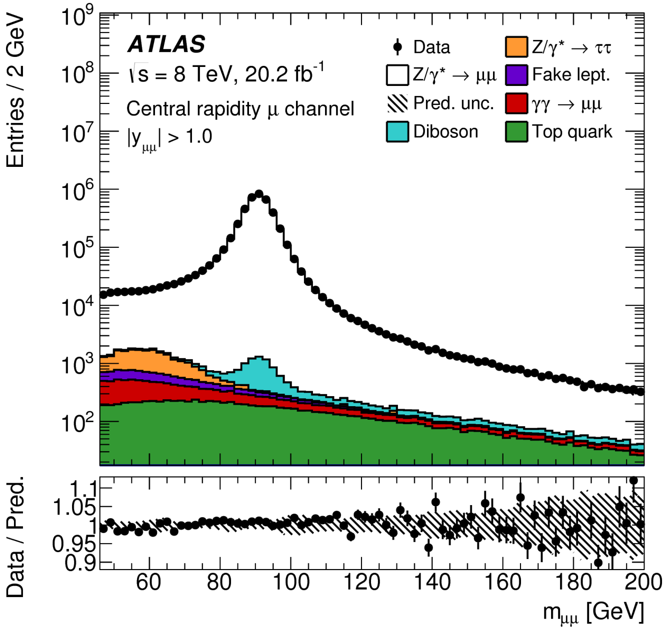




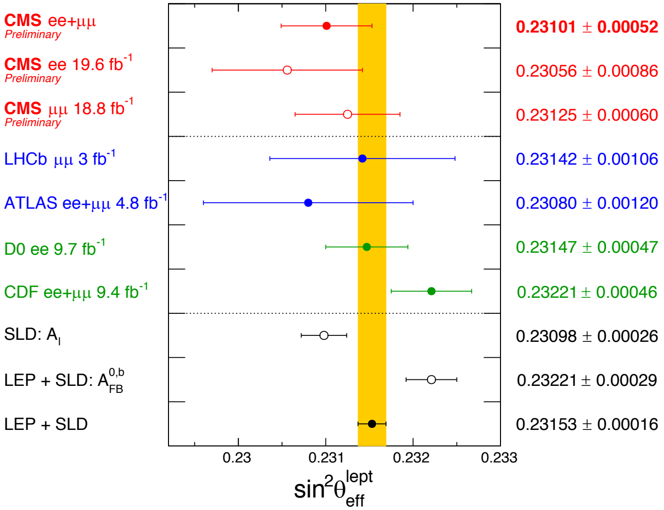
JHEP 12 (2017) 059

$$\frac{d^3\sigma Z/\gamma^*}{dm_{\ell\ell}dY_{\ell\ell}dcos\theta^*}$$

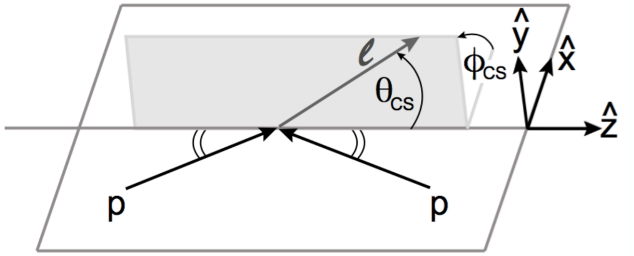
Z differential – AFB – Weak mixing angle



Motivation for Z-3D unfolding



CMS_PAS_SMP_16_007



- Previous ATLAS weak mixing angle (*JHEP09(2015)049*) measurement obtained with 4.6 fb^{-1} at 7 TeV.
  - Result sys. dominated (large PDF uncertainties):
  - $\sin^2\theta_W$=0.23080±0.0005(stat)±0.0006(syst)±0.0009(PDF)

- Design new measurement to be sensitive to both PDFs and $\sin^2\theta_W$.

$$\frac{d^3\sigma}{dm_{\ell\ell}dY_{\ell\ell}dcos\theta^*} = \frac{\pi\alpha^2}{3m_{\ell\ell}s}\sum_q \boxed{P_q}[\boxed{f_q(x1,Q^2)f_{\bar{q}}(x2,Q^2)} + (q \leftrightarrow \bar{q})]$$

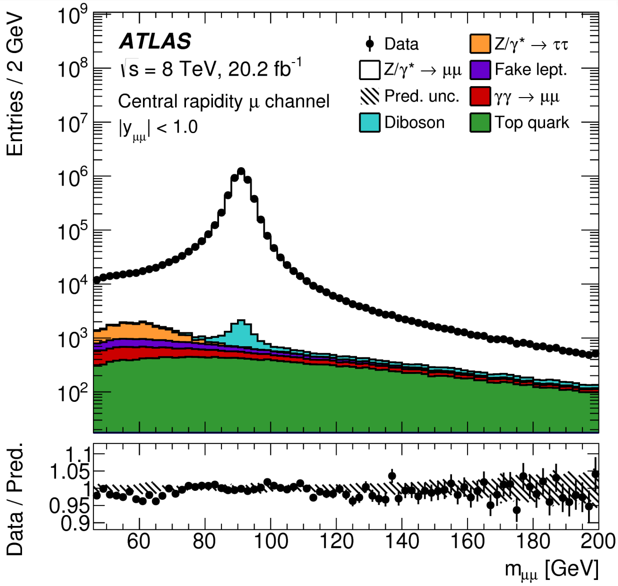
- Differential measurement proportional to the product of propagator and PDFs .
  - Production mode sensitive to $m_{\ell\ell}$ and $y_{\ell\ell}$: →sensitivity to PDF.
  - Interference Z/ɣ* responsible for asymmetry in $\cos\theta^*_{CS}$, which generate A_{FB}:

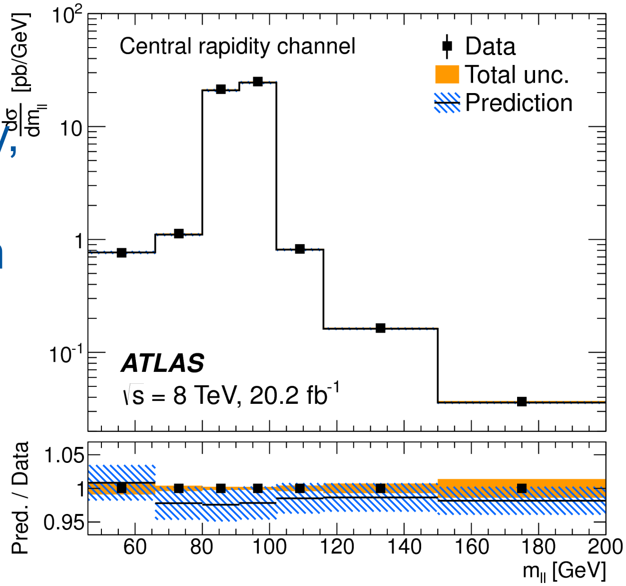
$$A_{FB} = \frac{d^3\sigma(cos\theta^* > 0) - d^3\sigma(cos\theta^* < 0)}{d^3\sigma(cos\theta^* > 0) + d^3\sigma(cos\theta^* < 0)}$$

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

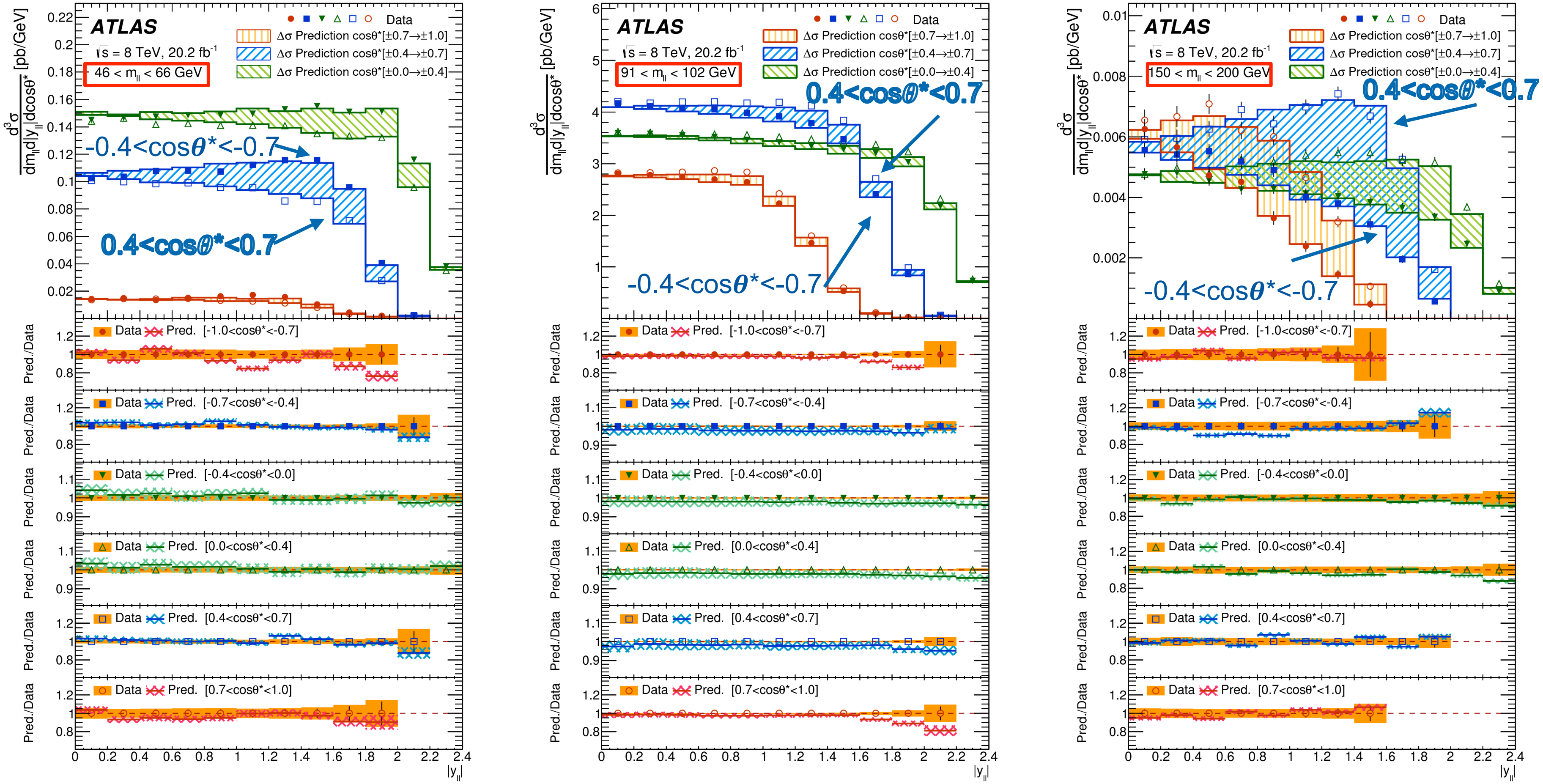
Selection and 1D measurement

- **Central-Central (CC) selection:**
  - electrons and muons with $|\eta_\ell|<2.4$, $p_{T\ell}>20$ GeV
  - 7 bins in $46<m_{\ell\ell}<200$ GeV+ 12 bins in $|y_{\ell\ell}|<2.4$+ 6 bins in $\cos\theta^*_{CS}$ → 504 bins
- **Central-Forward (CF) Selection:**
  - 1 central ($p_{Te}>25$ GeV) and 1 forward ($|\eta_e|>2.5$ and $p_{Te}>20$ GeV) electron
  - 5 bins in $66<m_{ee}<150$+ 5 bins in $1.2|y_{ee}|<3.6$+ 6 bins in $\cos\theta^*_{CS}$ →150 bins.
- **Signal MC:** with PowhegPythia8 (CT10NLO, UA2 tune) from DYNNLO.
  - 3D cross-section integrated in 1D zo test consistency, show good agreement with PHP8 (here for $m_{\ell\ell}$).
- **Z peak:** reco+trigger+id eff. (<0.5%), scale and resolution (~1%), muon momentum (weak alignment mode ~1%).
- **Off peak:** Background (~15% low m_{ll} CC, ~10% CF),
- **Data accuracy**~2%(1.9% lumi +0.5% syst. + 0.5% stat.)





3D distribution



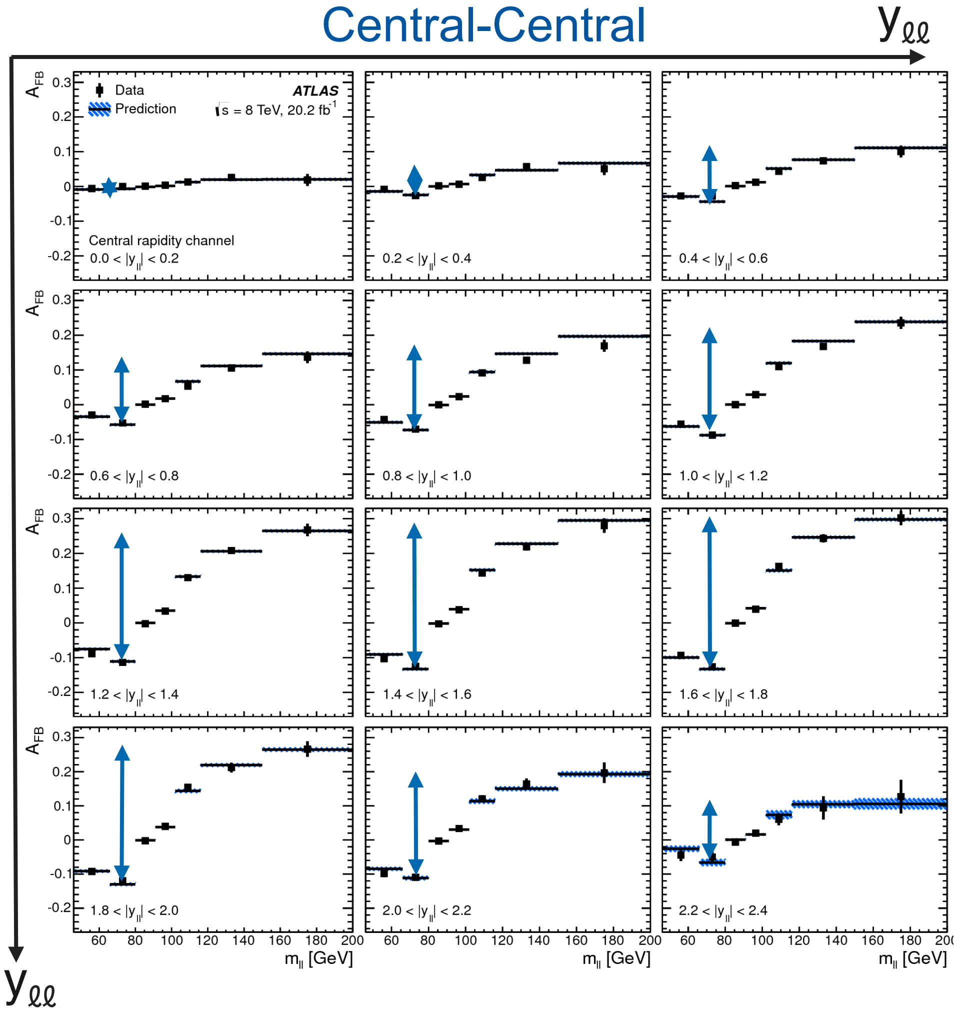
- Evolution of asymmetry: Negative below Z-pole, null at Z-pole, positive above it.
- Data accuracy is better than 0.5% in the Z-peak region for $|y_{\ell\ell}| < 1.4$.
- Good agreement between data and Powheg-based predictions.

Louis Helary (represented by M. Schott)

A_{FB} extraction

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

Central-Central

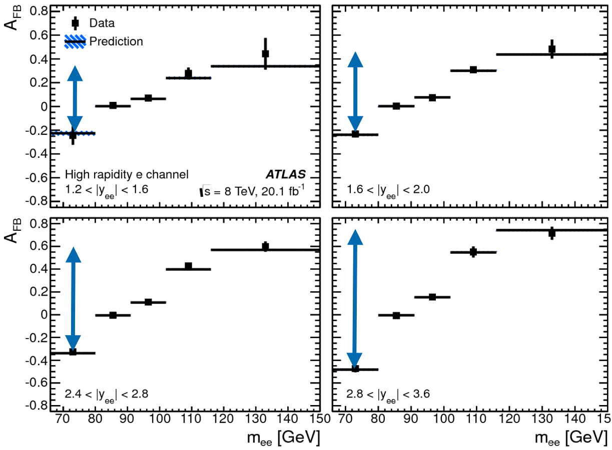


- Symmetric uncertainties in $\cos\theta^*_{cs}$ (scale, resolution) cancel

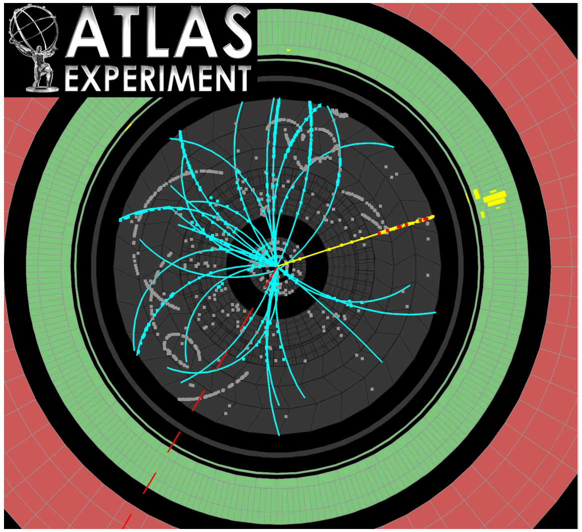
- A_{FB} increases in $y_{\ell\ell}$ for CC, and drops for last bins due to fiducial acceptance.
- A_{FB} even larger for CF due to reduced dilution.

- Large $|y_{\ell\ell}|$ corresponds to important x values, where valence quarks carry a larger momentum with a longitudinal boost.

- Good agreement observed with predictions.
- Use these measurement to constrain PDFs and extract $\sin^2\theta_W$.

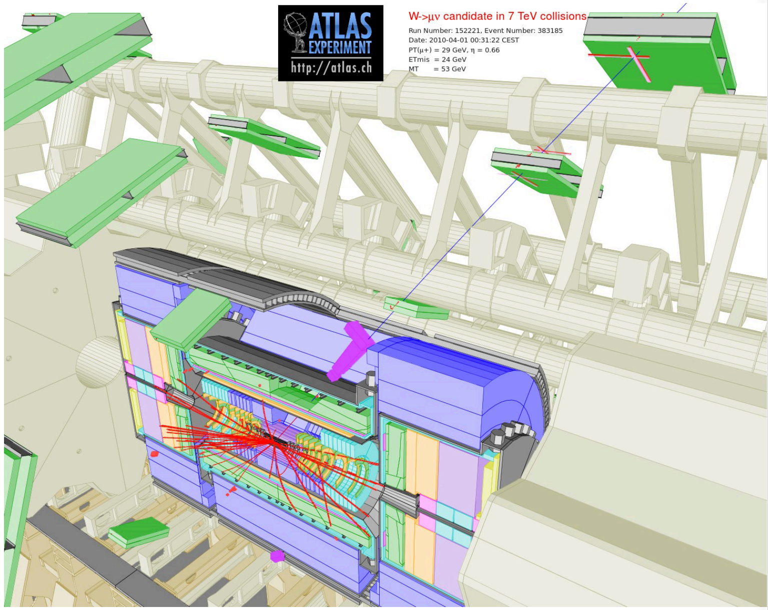


Central-Forward



W mass measurement

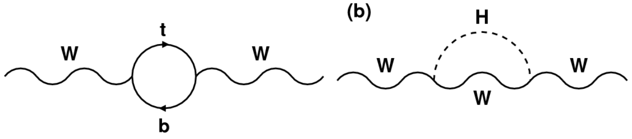
EPJC 78 (2018) 110



Motivation and challenges for m_W measurement

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

  Where Δr radiative corrections mostly dominated by top quarks and Higgs loops **→Δr ∝ m_t^2 and ln(m_H)**
- Relation between m_W, m_t and m_H provides stringent test to SM consistency.

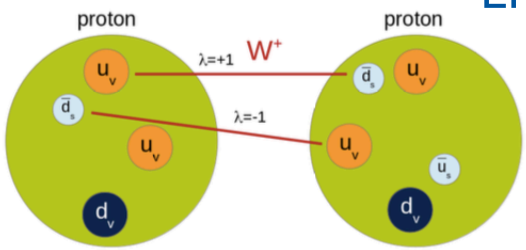


	Measurement (GeV)	**Prediction (GeV)**
m_H	125.09±0.24	102.8±26.3
m_t	172.84±0.70	176.6±2.5
m_W	80.385±0.015	80.360±0.008

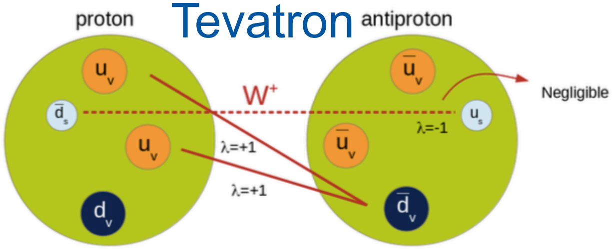
- Measured m_H and m_t better than theory, Δm_W~8 MeV target for precision of future m_W.
  →Potential to constrain NP!

- LHC environment more challenging than Tevatron:
  - pp (@7TeV): 25% of W's induced by s and c.
    → implication on y_W and p_{TW} .
  - pp (@1.96 TeV): only ~5% of the events.
  - But larger Z and W samples available at the LHC.
    →Calibrate theoretical predictions and experimental measurement on the Z and transfer the knowledge to the W!

LHC



Tevatron



Physics Modelling

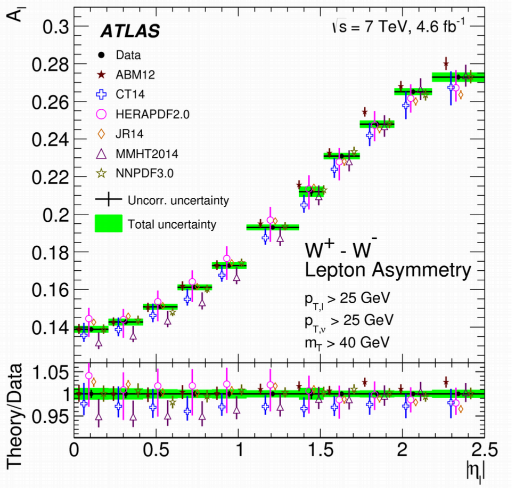
- Build physics modelling to get the best predictions using older ATLAS measurements, or from the state of the art theoretical predictions.
- Factorize Drell-Yan in:

$$\frac{d\sigma}{dp_1\,dp_2} = \underbrace{\left[\frac{d\sigma(m)}{dm}\right]}_{\text{Breit-Wigner}} \overbrace{\left[\frac{d\sigma(y)}{dy}\right]}^{\text{NNLO pQCD}} \underbrace{\left[\frac{d\sigma(p_T, y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]}_{\text{Parton Shower}} \overbrace{\left[(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T, y) P_i(\cos\theta, \phi)\right]}^{\text{NNLO pQCD}}$$

- Reweight or check predictions for each of these aspects:

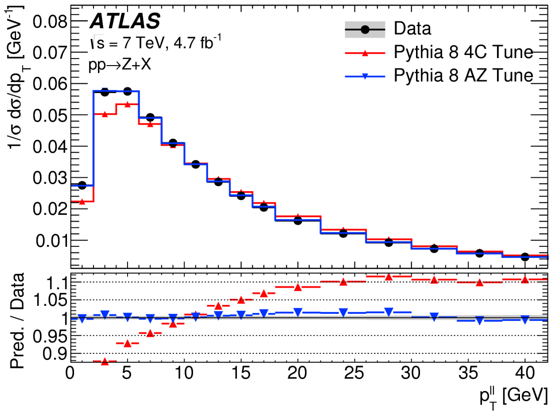
1) Reweight DYNNLO dσ/dy, (checked with W/Z measurements @ 7 TeV)
2) Use 7 TeV p_{TZ}, tune Pythia 8 PS model (UAZ) , transfer p_{TZ} to p_{TW} distribution.
3) Reweight polarization coefficients (Ai) and compare to measurements @8TeV

W/Z: EPJC 77 (2017) 367

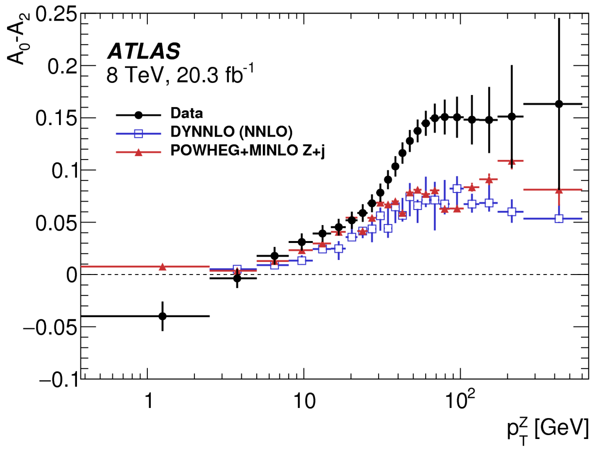


Schott)

$p_{T\,Z}$:JHEP09(2014)145

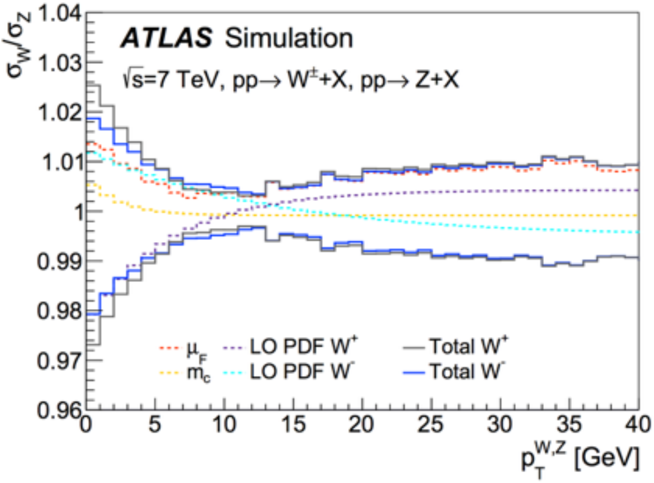


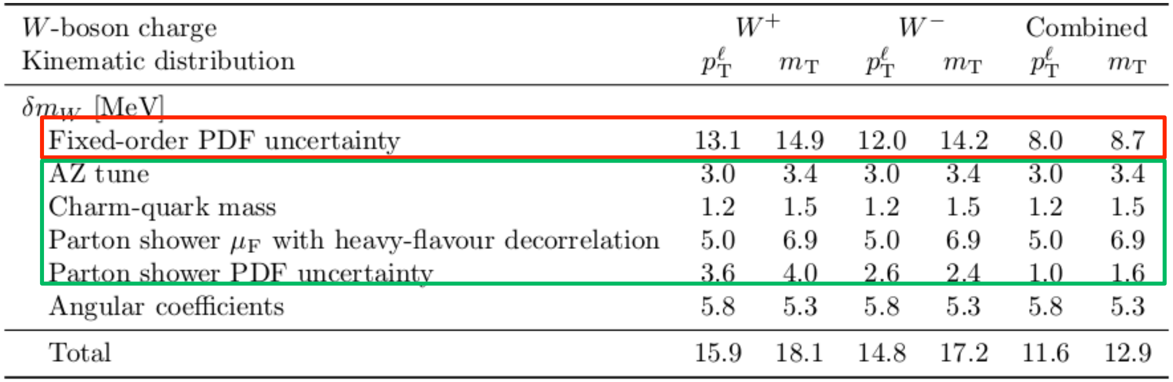
Ai: JHEP08(2016)159



Modelling uncertainties

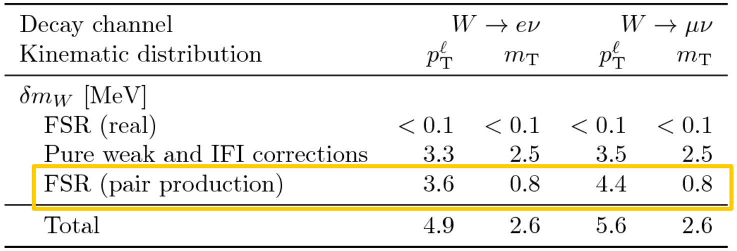
- For perturbative QCD modelling:
  - Largest uncertainties are due to PDF:
    - Anti-correlated between W+ W- →reduced in combination.
  - Use Pythia8 to transfer the tuned p_{TZ} to p_{TW} and to evaluate theory uncertainties on W/Z p_T ratio.
  - Large uncertainty on p_{TW} due heavy-quarks initial state.
    - Similar for m_W extracted from p_T lepton and from m_T.





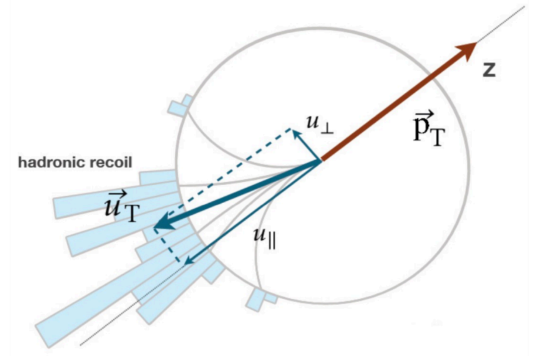
W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	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

- For EW corrections:
  - Dominant contribution from QED FSR.
    - Larger impact in p_{Tl} than in m_{TW}
    - Similar contributions in electron and muon channels.



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

Experimental model

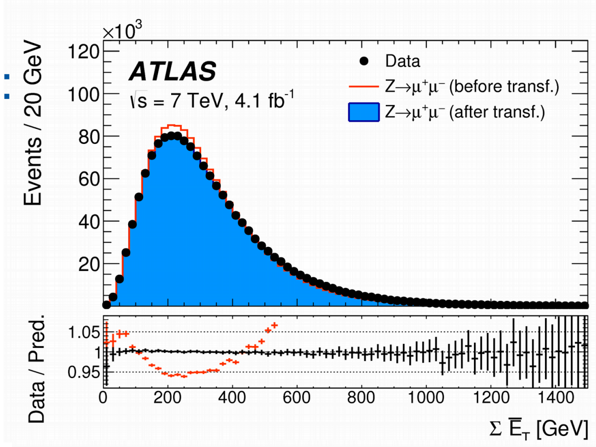


- Uses events with (e,μ) where p_{Tl}>30 GeV, $|\eta_l|$<2.4 , p_T^{miss}>30 GeV, m_T>60 GeV, u_T< 30 GeV.

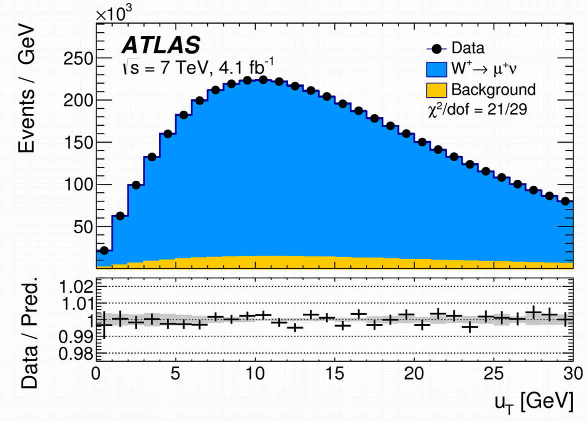
$$\vec{p}_T^{\,miss} = -\left(\vec{p}_T^{\,\ell} + \vec{u}_T\right) \quad m_T = \sqrt{2p_T^\ell p_T^{miss}(1-\cos\Delta\phi)} \quad \vec{u}_T = \sum_i \vec{E}_{T,i}$$

- Leptons are calibrated using the Z line shape.

- Hadronic recoil (u_T) is vector sum of E_T of all calo clusters: →u_T is a measure of p_{TW}
  - Calibration steps:
    - Correct pile-up profile in MC to match data
    - Correct for residual differences in SumET
    - Derive scale and resolution corrections from p_T balance in Z events.

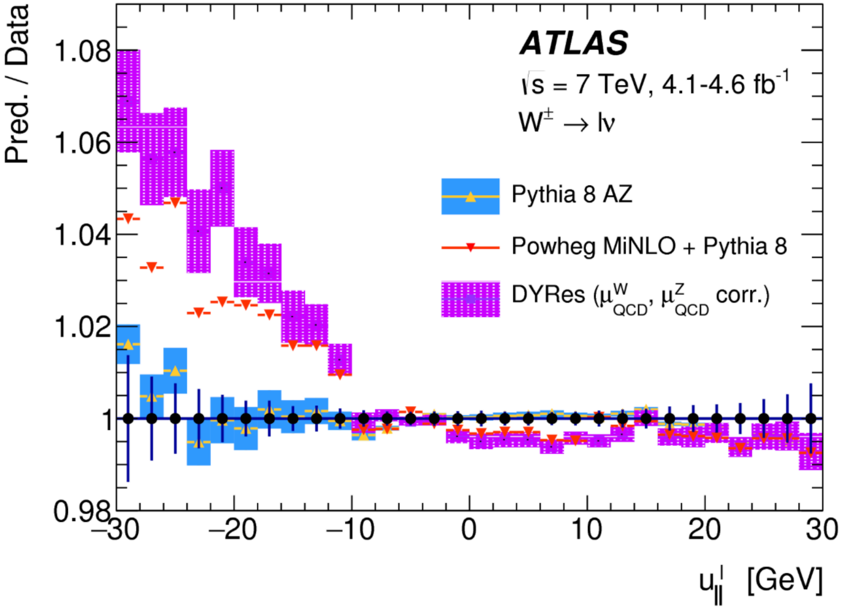


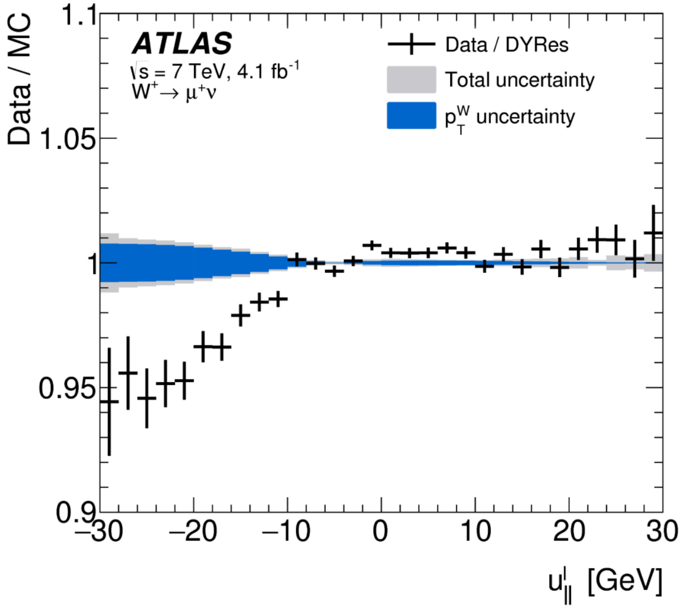
- Backgrounds are mostly determined using simulation, and normalized using NNLO predictions, or measurements.
- For multi-jet background:
  - Uses template fit of the lepton isolation variable.
  - Normalization and shape are extrapolated to the SR.



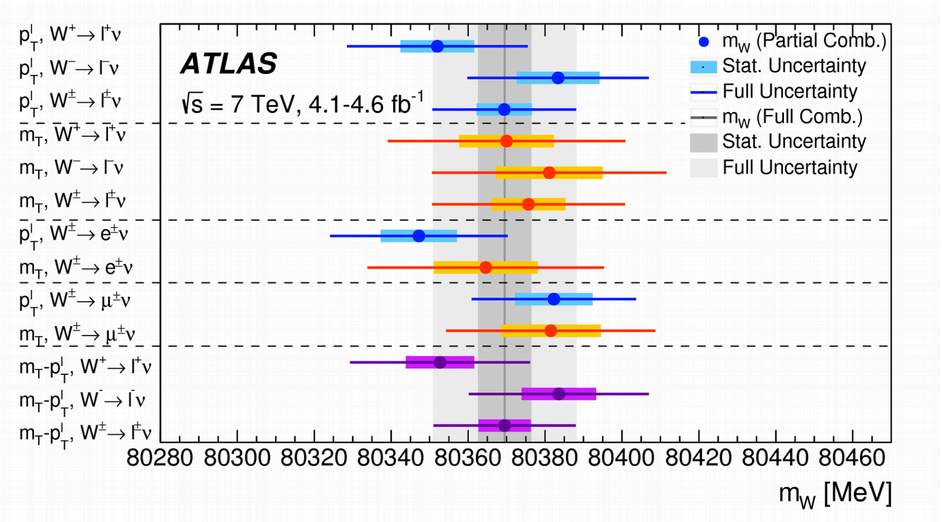
Why do we trust the $p_T(W)$ modeling?

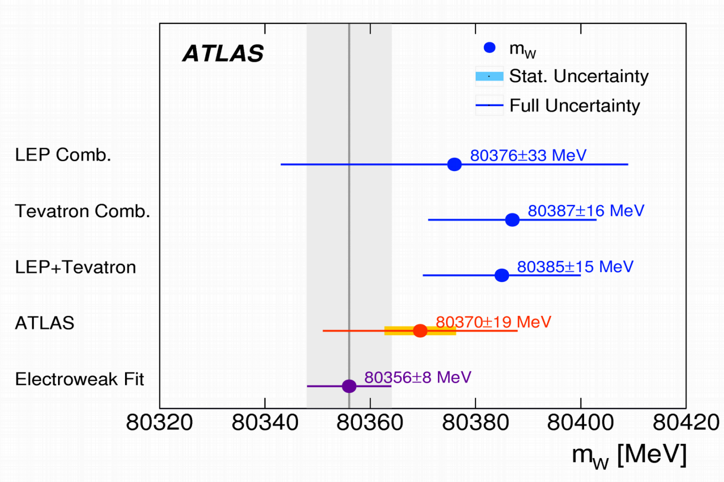
- Enormous amount of additional studies triggered during the review process
  - $u_{||}(l)$ distribution is indeed governed by the modeling of $p_T(W)$
    - Good observable to test modeling
  - PDF/Scale uncertainties in NNLO/NNLL predictions do not account for the observed difference seen in data
    - Current working hypothesis: The treatment of heavy flavors in those generators has to be improved



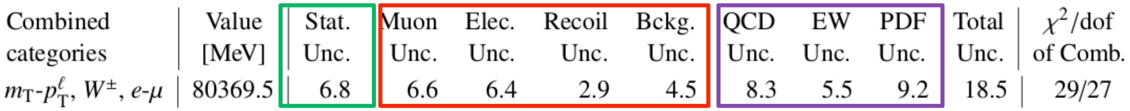


Measurement

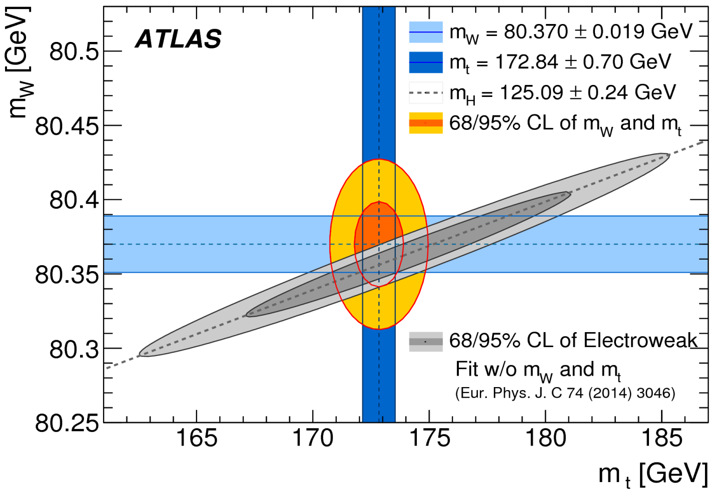




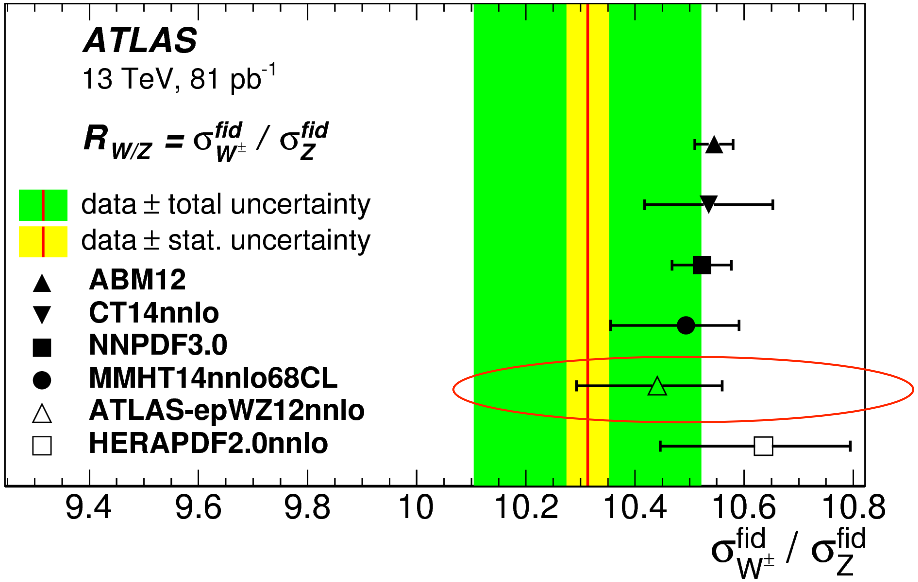
$$M_W = 80370 \pm 7\ (\text{stat}) \pm 11\ (\text{exp. syst.}) \pm 14\ (\text{model. syst.})\ \text{MeV} = 80370 \pm 18.5\ \text{MeV}$$



Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27



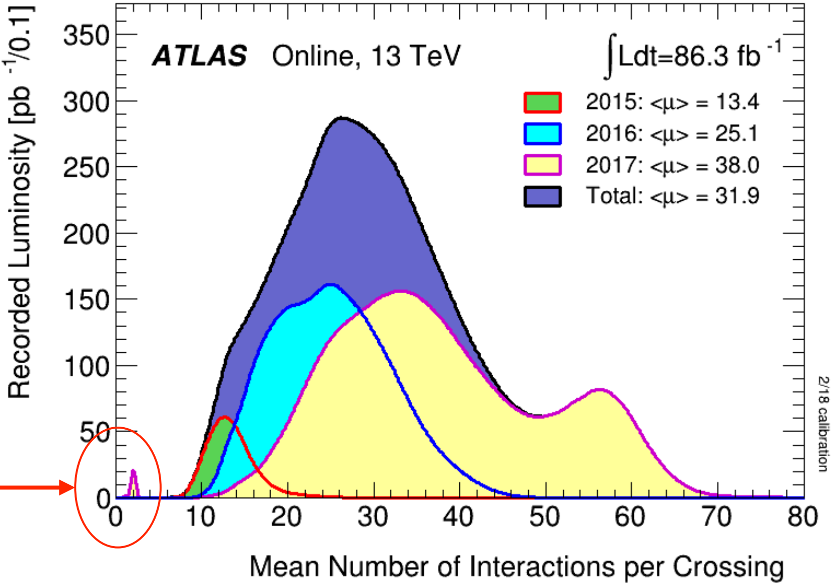
- Measurement consistent:
  - Between the different categories!
  - With previous LEP+Tevatron measurement!
  - Similar sensitivity as Tevatron!
- Measurement sys. dominated, with large uncertainty on the model (PDF & p_{TW}).



Extract and use new PDF sets from the data.

Future

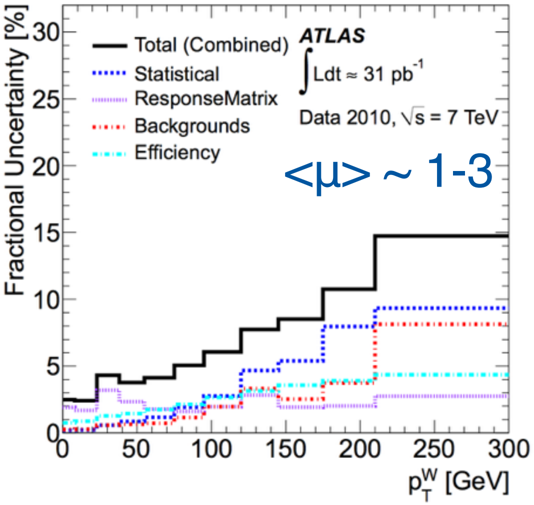
ATL-PHYS-PUB-2017-021

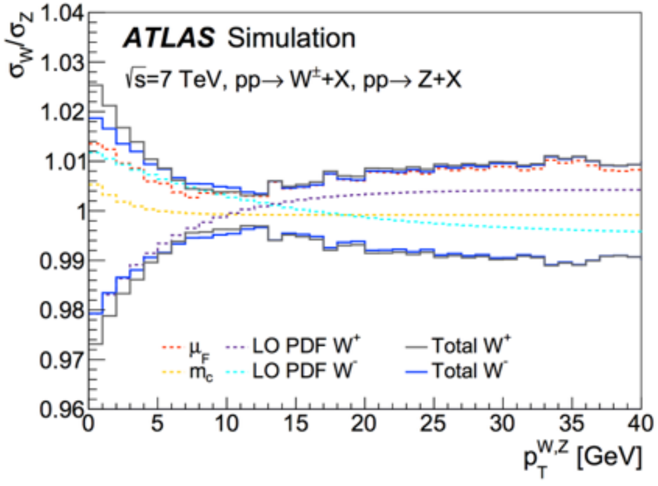


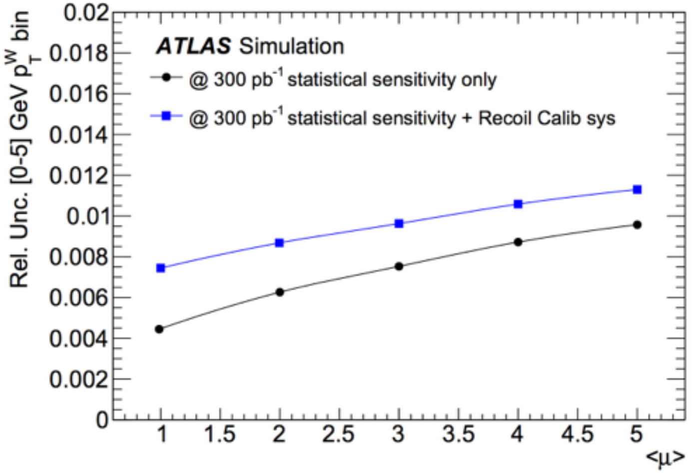
Level luminosity to low pileup values

Reduce W mass uncertainty using low-μ (pileup) runs

p_{TW} 7 TeV: *PRD 85 (2012) 012005*







- ATLAS p_{TW} measurement $31 pb^{-1}$ at 7 TeV from 2010 with error >2.5% on coarse bins.

- Recent low-μ runs taken by ATLAS:
  ~150/pb at 13 TeV: 1.75M W, 220k Z
  ~270/pb at 5 TeV: 1.3M W, 150k Z

- Possibility to measure directly p_{TW}/p_{TZ} at low p_{TW} which is crucial to improve Δm_W!
  - Measurement of p_{TW} ~ 1% uncertainty & 5 GeV binning at low p_{TW}, with low-μ data.

- Low-μ necessary for good recoil resolution.

Conclusions

Conclusions

- Publication of the Z cross-section measurement as a function of 3 variables: $m_{\ell\ell}$,$y_{\ell\ell}$, $\cos\theta^*_{cs}$.
  - Accuracy of the measurement better than 0.5% under the Z peak.
  - Measurement in agreement with the predictions.
  - Differential measurement of A_{FB} that can be used to extract $\sin^2\theta_W$.

- Publication of the first W mass measurement at the LHC using 4.5 fb^{-1} at 7 TeV
  - One year review process helped a lot to sharpen our arguments
  - Measurement compatible with current WA and competitive with Tevatron results.
  - Future measurements can be improved using:
    - Low-<μ> data might allow for a direct precision p_{TW} measurement!
    - Improved PDF modeling and theoretical models

- Many discussions ongoing at the LPCC (LHC Physics Centre at CERN) Electroweak Working group: https://lpcc.web.cern.ch/electroweak-precision-measurements-lhc-wg
  - How to improve the modeling of vector boson production at the LHC?
  - How to combine electroweak precision measurements?
  - How to interpret precision measurements in an EFT approach?
  - …