Rencontre de Vietnam 2018 - windows on the universe -

Standard Model Physics at LHC

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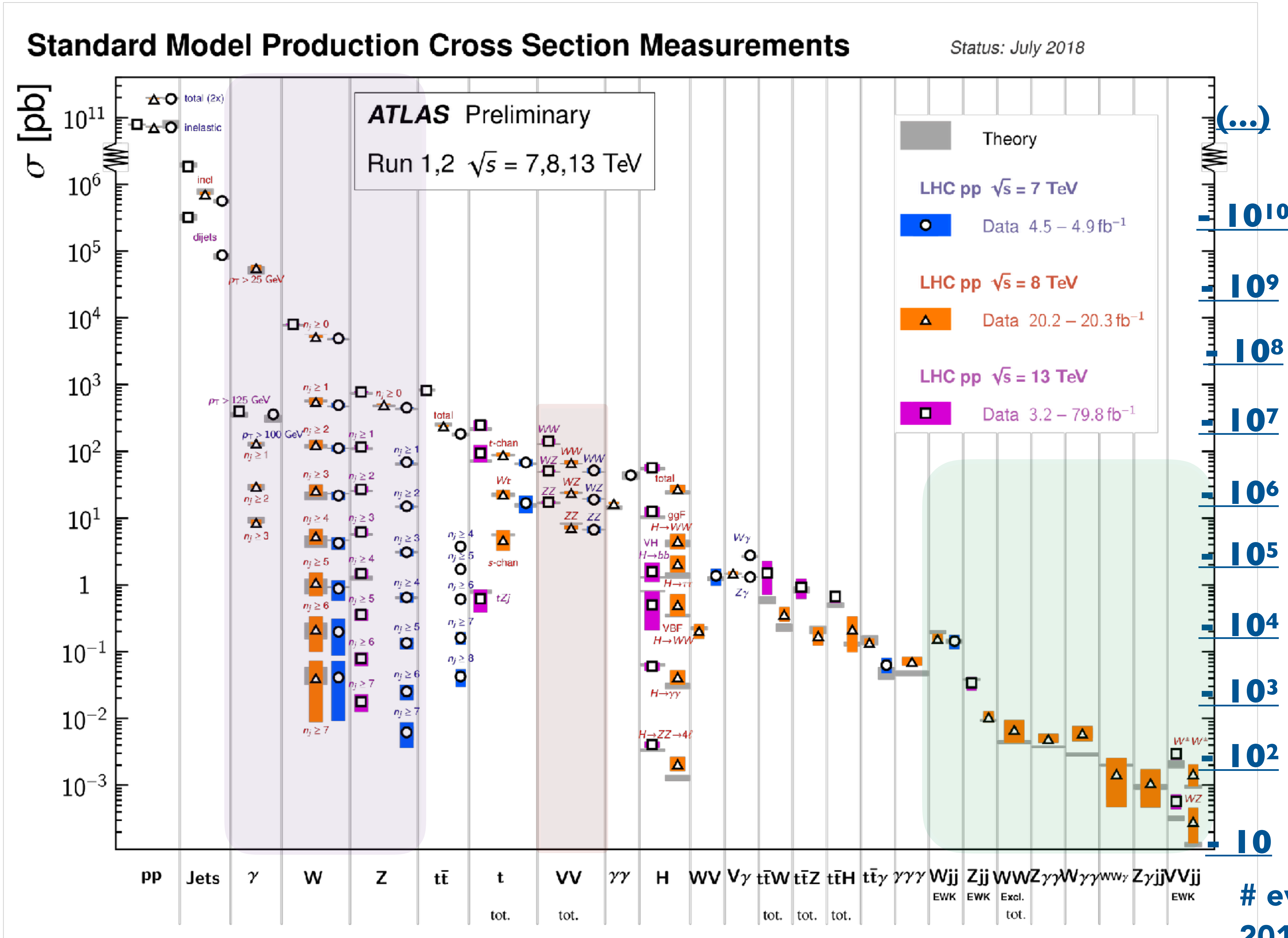
on behalf of ATLAS CMS and LHCb experiments

SM Physics Measurement

SM measurements play essential roles in testing our current understanding of the laws that govern the universe.

1. Measurements of the SM at LHC are looking at unexplored territory
   - Testing the validity of SM in challenging & previously unaccessible regions
     - High energy, rare processes
     - Difficult modelling: high-order/EW corrections
   - Tune MC generators, constraints PDFs, ...
2. Constrain, or observe, new physics contributions
   - Rare production processes
   - Processes sensitive to anomalous couplings
3. Background to all direct searches & Higgs measurements

SM measurements validity range



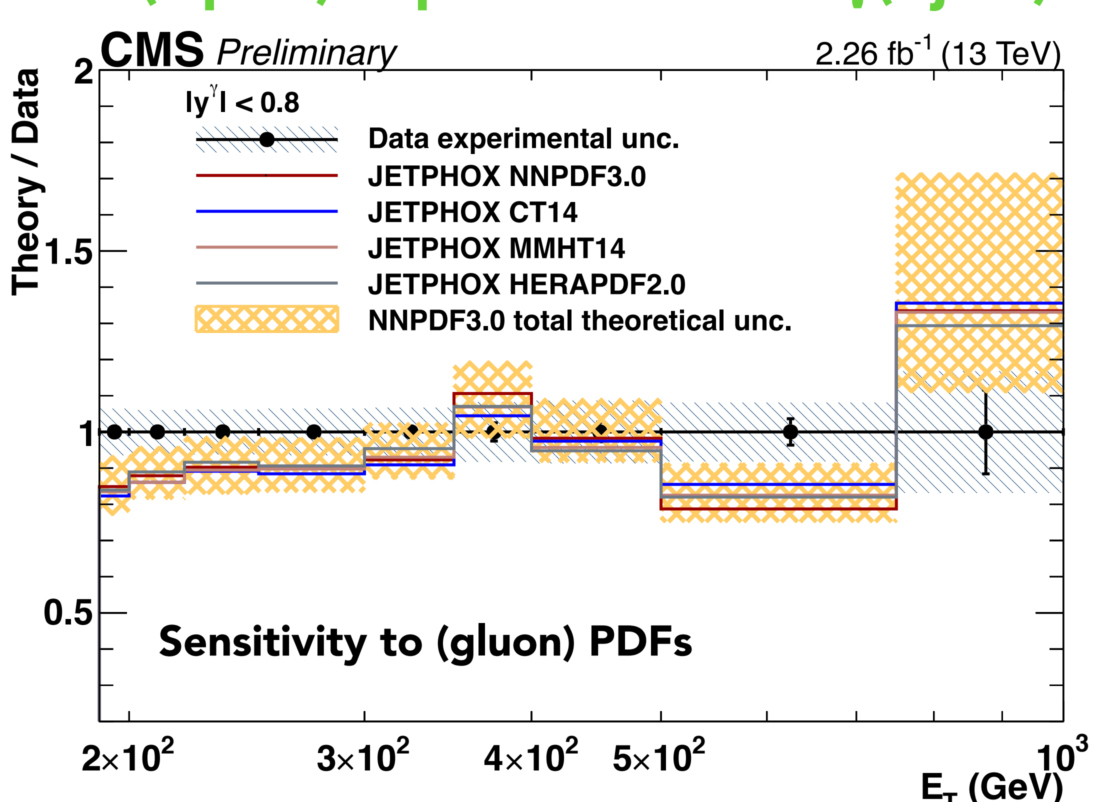
events in 2016 dataset

Single boson + jets

Precision measurements of [differential] V+Jets production cross sections stringent tests of SM predictions

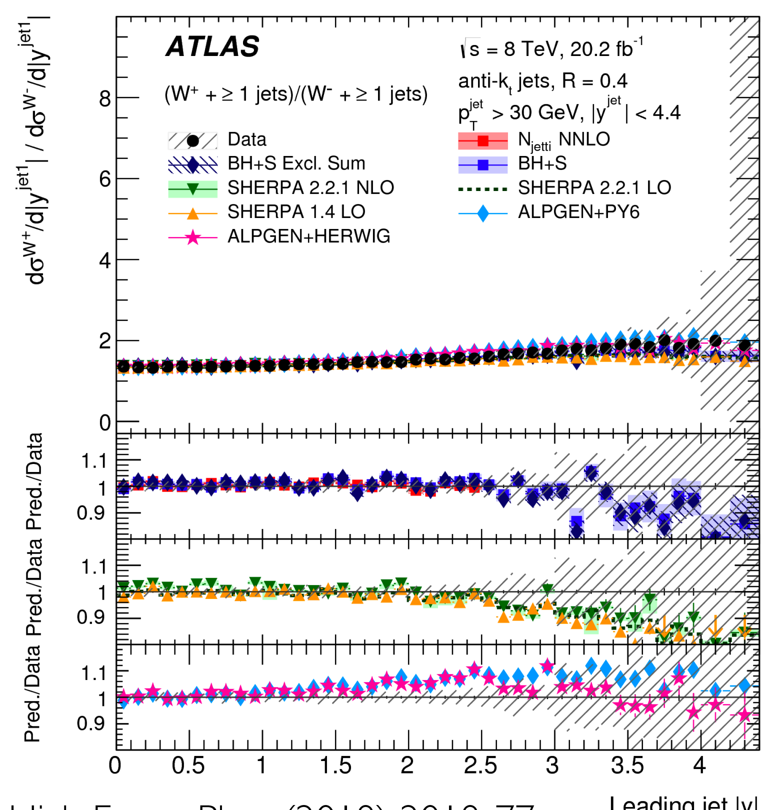
- Comparison of the measurements with predictions motivates additional Monte Carlo (MC) generator development and improves our understanding of the prediction uncertainties.
  - sensitive to *higher order (QCD and EWK effects)*
  - sensitive to *non perturbative effects* (e.g. particle emission, parton shower)
  - also explicitly EWK production mode (VBF, soft QCD modelling)

(Up to) triple differential γ(+jets)



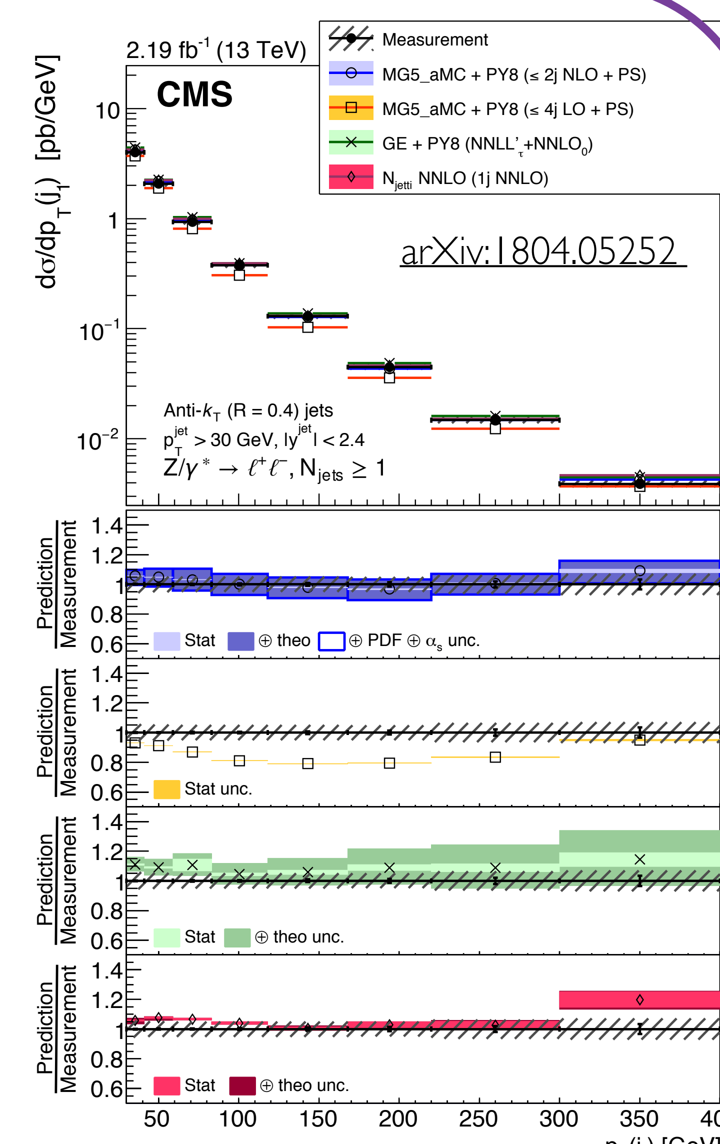
submitted to EPJC

W/Z + (jets)



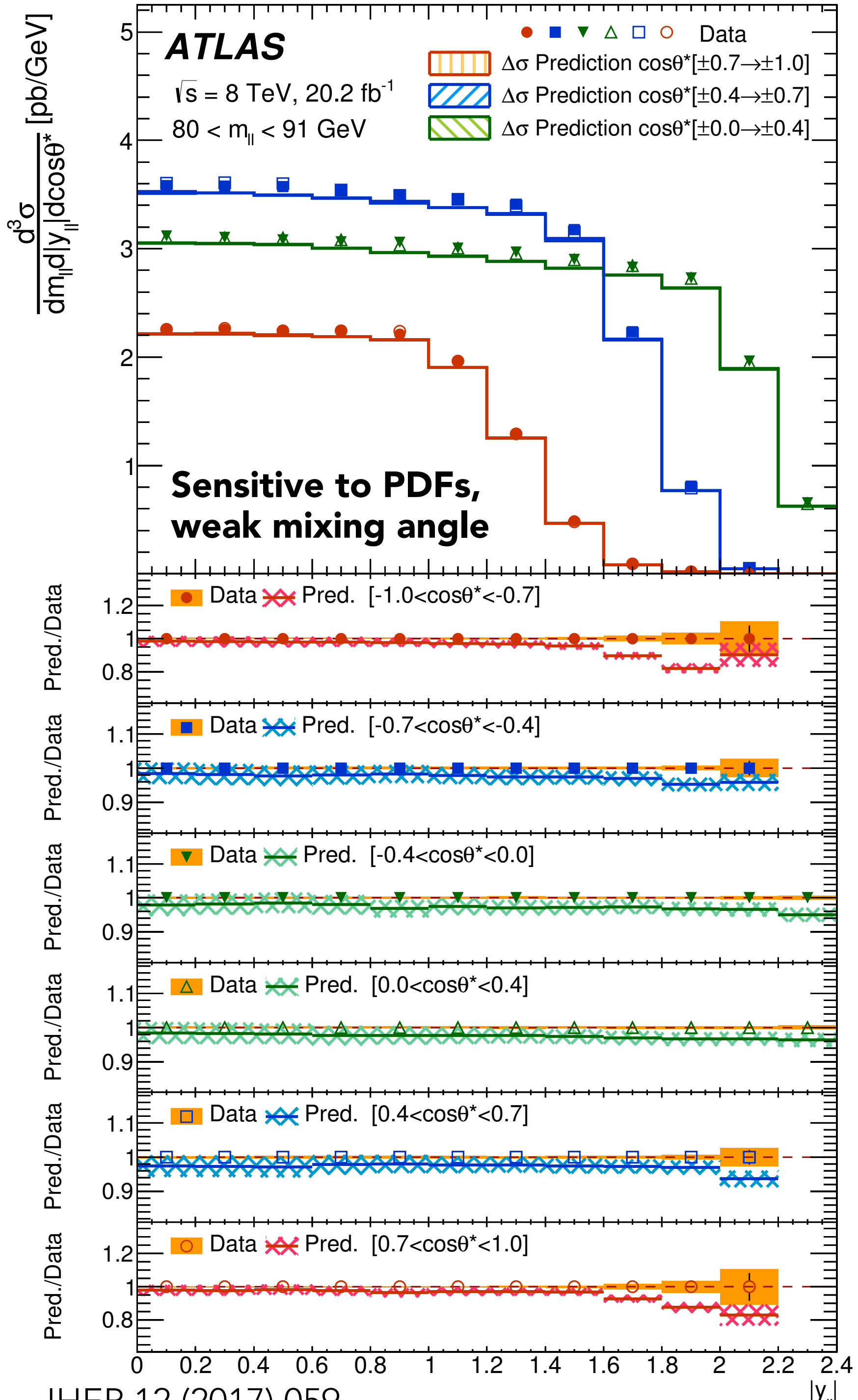
High Energ. Phys. (2018) 2018: 77

Sensitive to valence quark and gluon PDFs at high x



Triple differential Drell-Yan cross-section

Triple differential Drell-Yan



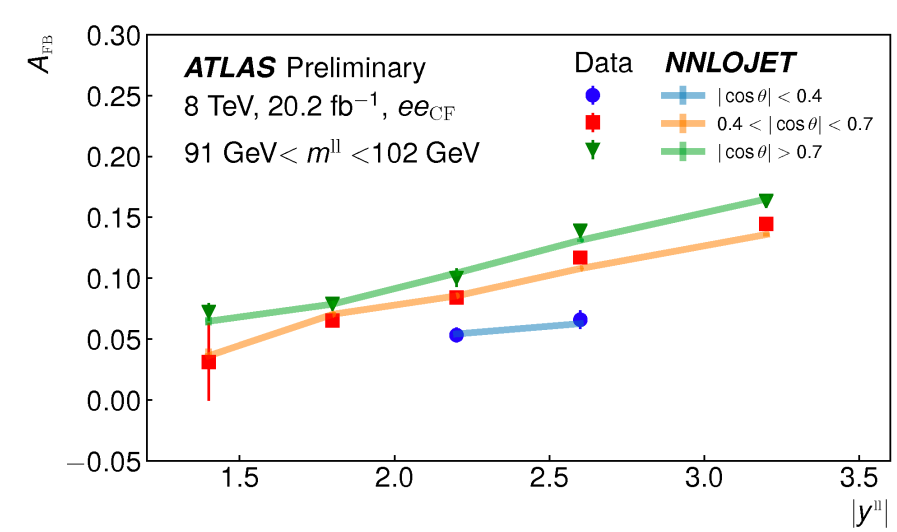
JHEP 12 (2017) 059

Unique measurement of the triple differential cross section:

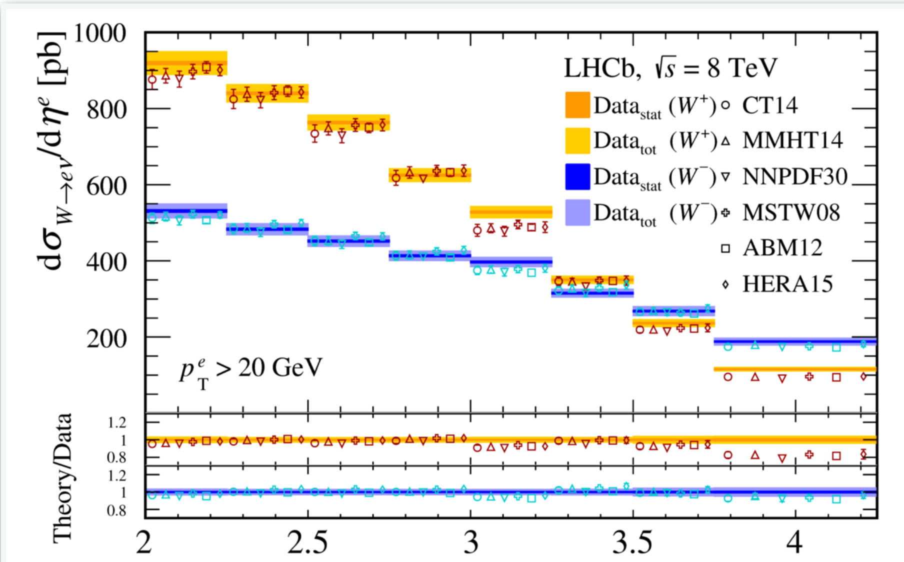
$d^3\sigma/dy_{ll}dm_{ll}d\cos\theta_{CS}$ in a wide kinematic range, mll [46,200] GeV and $y_{ll} < 3.6$, using $\sqrt{s} = 8$ TeV ATLAS data.

- ***The measurement is designed to be sensitive to both PDFs and $\sin^2\theta_W$***
- In the Z-peak region, the data accuracy is better than 0.5% in a wide region of $|y_{ll}| < 1.4$.
- The measurement is used to compute single- and double-differential $d\sigma/dm_{ll}$ and $d^2\sigma/dm_{ll}dy_{ll}$ cross sections
  - The results are well described by modified Powheg predictions.
- as well as ***forward-backward asymmetry (A_{FB})***:

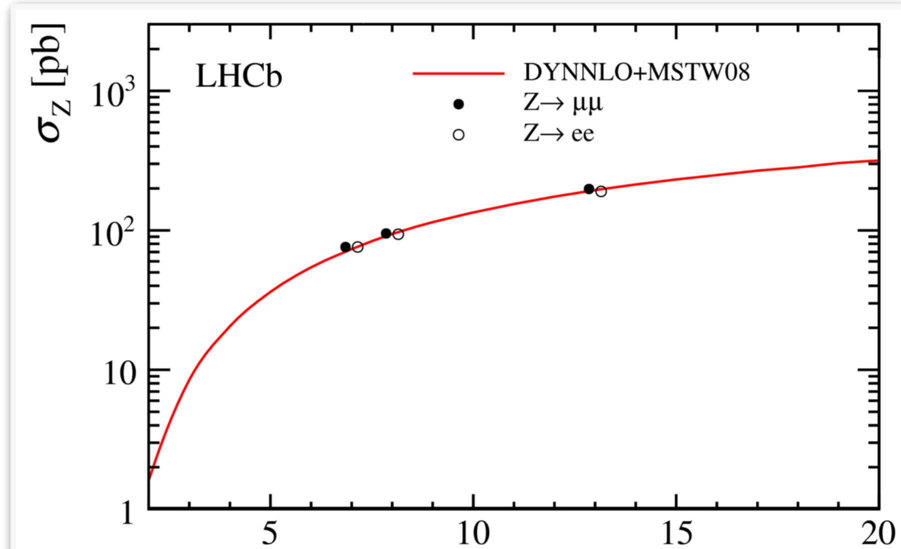
Triple-differential distributions of the forward-backward asymmetry, A_{FB}, compare with the predictions from the inclusive NNLOJET calculations using the MMHT14 PDF set for $\sin^2\theta_W$ = 0.23148.



LHCb single boson measurement



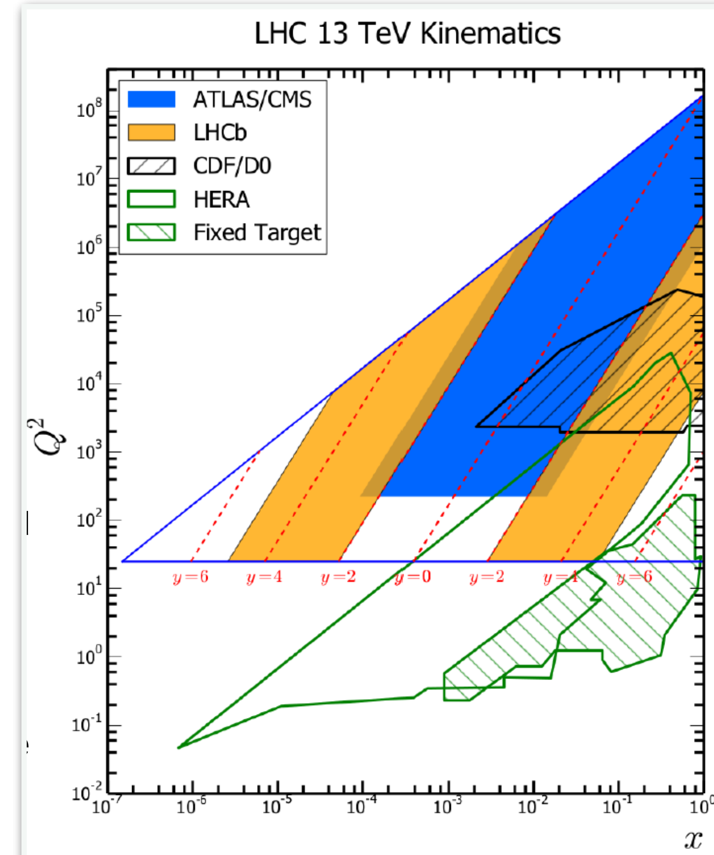
JHEP 10 (2016) 030

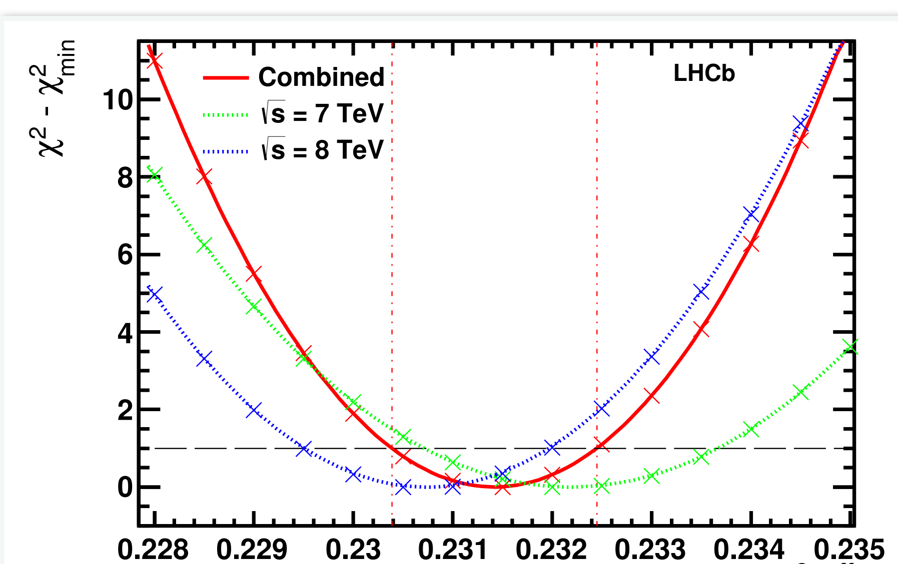


JHEP 09 (2016) 136

Differential cross-section measurements of W and Z production in the forward acceptance.

Access to PDFs in regions of known high-*x* and unexplored low-*x* partons.





J.High Energ. Phys. (2015) 2015: 190

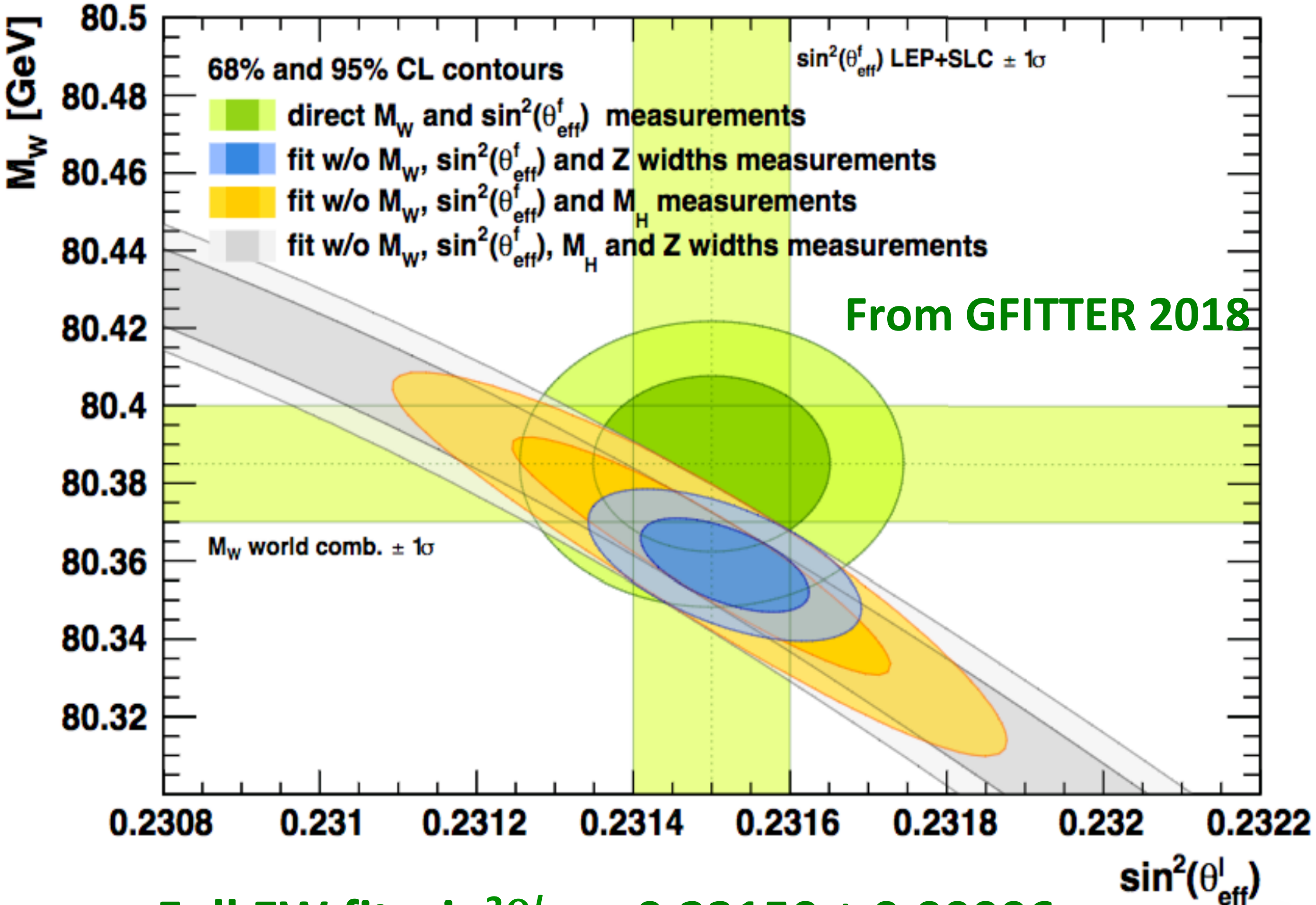
LHCb offers a **complementary phase space** region with respect to ATLAS and CMS for Standard Model tests **in electroweak sector**

$\sin^2\theta_W$ measurement with $\sqrt{s}$ = 7, 8 TeV $Z\to\mu\mu$ events

$$\sin^2\theta_W^{eff} = 0.23142 \pm 0.00073 \pm 0.00052 \pm 0.00056,$$

stat. **sys.** **PDF**

Precision physics



Full EW fit: $\sin^2\theta^l_{eff}$ = 0.23150 ± 0.00006

Indirect determination from EW fit: $\sin^2\theta^l_{eff}$ = 0.23149 ± 0.00007

Lepton collider average (LEP/SLC): $\sin^2\theta^l_{eff}$ = 0.23152 ± 0.00016

Tests of the consistency of the EW sector in the SM through higher precision measurements of its fundamental parameters (**$\sin^2\theta_W$** and **m_W**) it is one of the goal of LHC physics program.

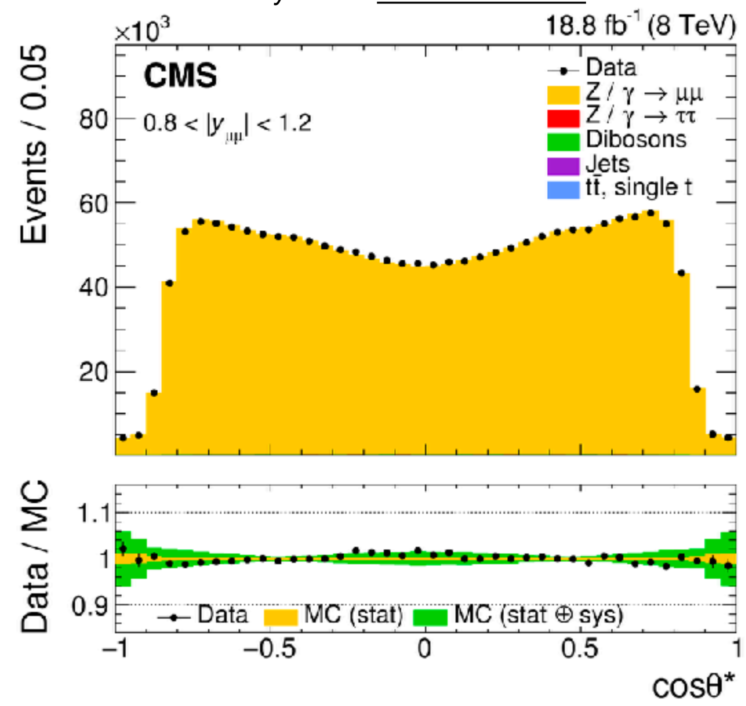
- This requires specific efforts in the experimental community and the theory community
  - using high $|y^{ll}|$ events to enhance sensitivity to weak mixing angle
  - validate use of improved Born approximation at the LHC for precision Z physics.
  - precision DY measurements require ultimate performance of detector for electrons/muons and hadronic recoil
  - low-μ runs in 2017/2018 to measure precisely p_T^W
  - improve theoretical predictions and uncertainty estimates for p_T^W/p_T^Z

CMS effective mixing angle extraction

$\sin^2\theta_{eff}^{lept}$ -- key SM parameter

- Exploit forward-backward asymmetry (A_{FB}) in Drell-Yan ee/μμ events
  - Fit mass (Tevatron) or mass & rapidity (CMS) dependence of observed A_{FB} to SM predictions as function of $\sin^2\theta_{eff}^{lept}$
  - Extract from angular coefficient A_4 (ATLAS) in mass/rapidity bins

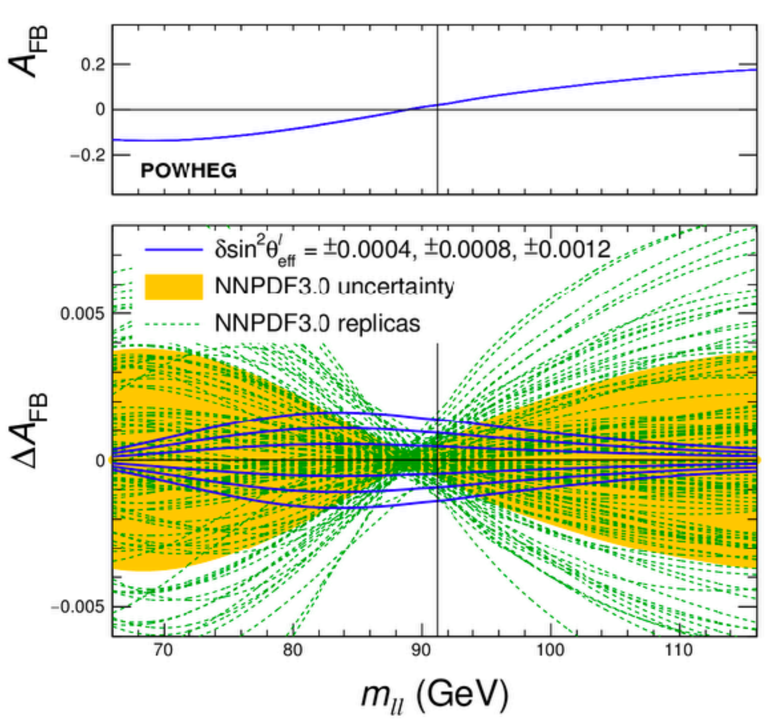
Submitted to Eur. Phys. J. C arXiv:1806.00863

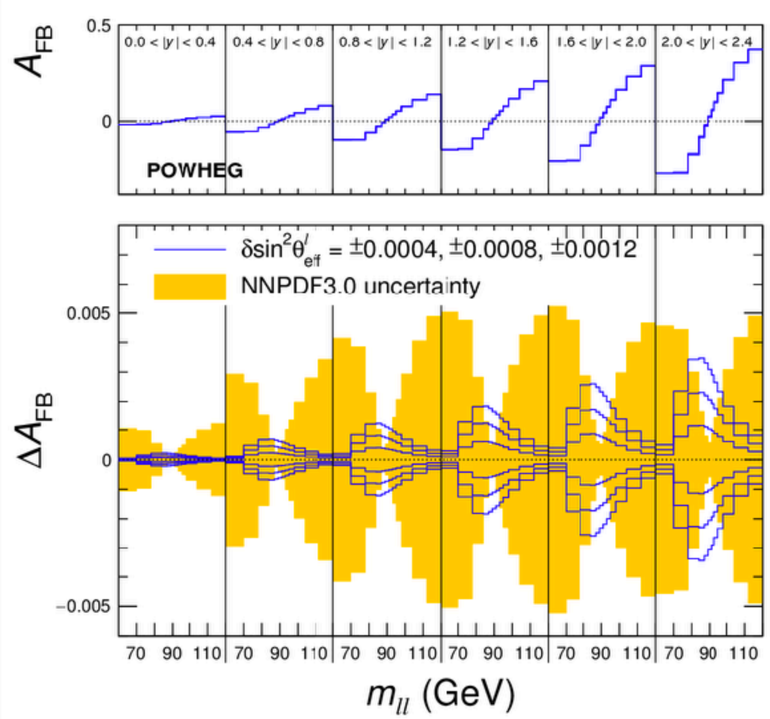


CMS data correspond to 18.8 and 19.6 fb^{-1} collected @$\sqrt{8}$ TeV

- Events weights based on cosθ*
  - Less sensitive to acceptance!
  - Smaller statistical uncertainty

$$\sin^2\theta^{\ell}_{\text{eff}} = 0.23101 \pm 0.00036\,(\text{stat}) \pm 0.00018\,(\text{syst}) \pm 0.00016\,(\text{theo}) \pm 0.00031\,(\text{PDF})$$





Using Bayesian Reweighting used for equiprobable NNPDF replicas from the measured forward-backward asymmetry.

ATLAS effective mixing angle extraction

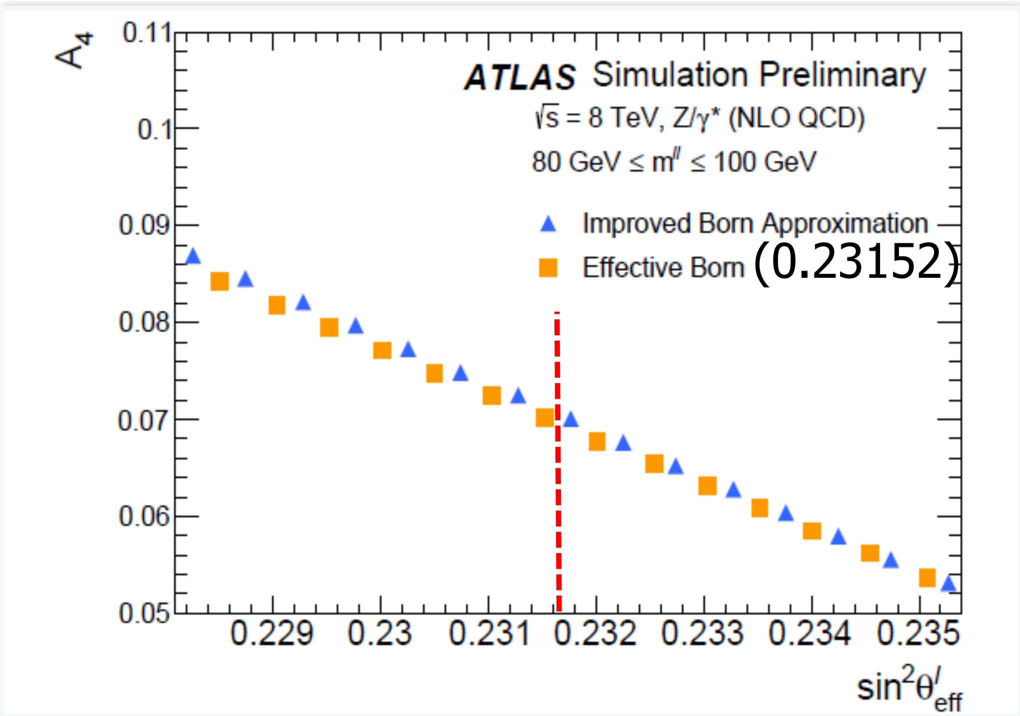
$\sin^2\theta_{eff}^{lept}$ -- key SM parameter

- Exploit forward-backward asymmetry (A_{FB}) in Drell-Yan ee/μμ events
  - Fit mass (Tevatron) or mass & rapidity (CMS) dependence of observed A_{FB} to SM predictions as function of $\sin^2\theta_{eff}^{lept}$
  - Extract from angular coefficient A_4 (ATLAS) in mass/rapidity bins

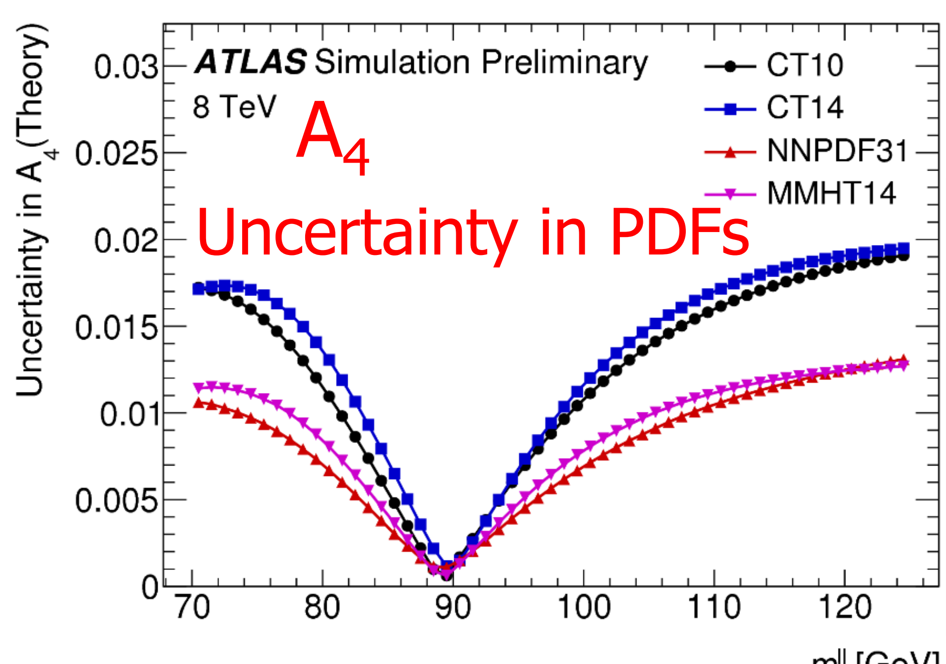
ATLAS-CONF-2018-037

$$\frac{d^5\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d^3\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z}$$
$$\{(1+\cos^2\theta) + 1/2\, A_0(1-3\cos^2\theta) + A_1\, \sin 2\theta\, \cos\phi$$
$$+1/2\, A_2\, \sin^2\theta\, \cos 2\phi + A_3\, \sin\theta\, \cos\phi + A_4\, \cos\theta$$
$$+A_5\, \sin^2\theta\, \sin 2\phi + A_6\, \sin 2\theta\, \sin\phi + A_7\, \sin\theta\, \sin\phi\}.$$

- ATLAS extraction is using **angular coefficient (A_i)** (3 channels: **μμ, ee, ee_{CF}** at 8TeV) is technically more challenging than AFB, but some advantages
- Measurements in full phase space via analytical extrapolation of the spherical harmonics.
  - Reduced theory uncertainties
  - Constrain experimental/theory systematics trough angular decomposition
  - Possibly more sensitive to NLO EW effects that can break harmonic decomposition compared to AFB (but can be accounted for with corrections)



$$\sin^2\theta^{\ell}_{\rm eff} = 0.23140 \pm 0.00021\,(\text{stat.}) \pm 0.00024\,(\text{PDF}) \pm 0.00016\,(\text{syst.}),$$



Measurement of the Angular coefficient in m_{ll} and Y_{ll} bins simultaneously reduce considerably the dominant source of experimental systematic uncertainties and theory unc. arising from PDF

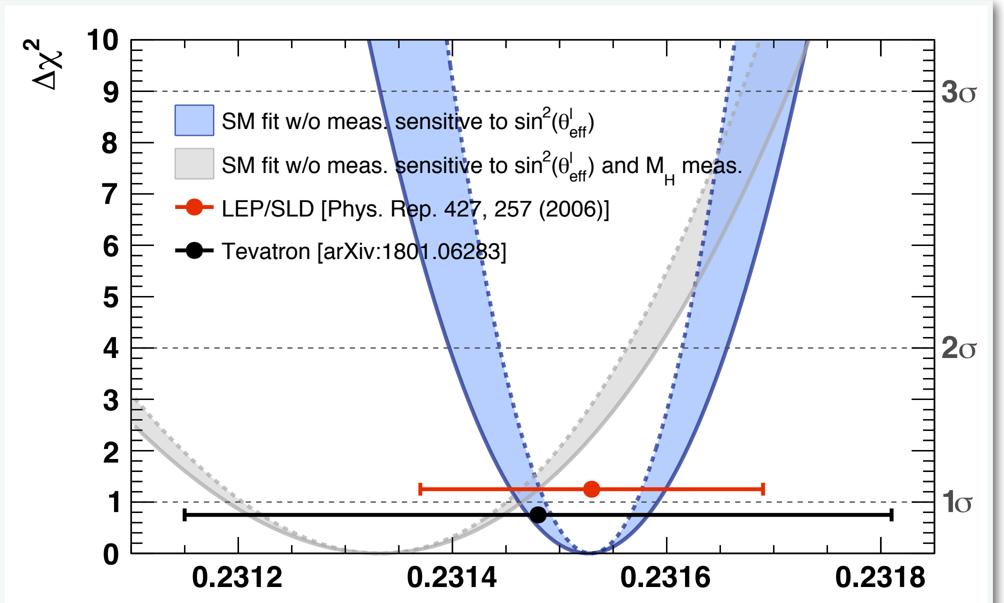
ATLAS uncertainty breakdown of WMA

Channel	ee_{CC}	$\mu\mu_{CC}$	ee_{CF}	$ee_{CC} + \mu\mu_{CC}$	$ee_{CC} + \mu\mu_{CC} + ee_{CF}$
Central value	0.23148	0.23123	0.23166	0.23119	0.23140
	Uncertainties				
Total	68	59	43	49	36
Stat.	48	40	29	31	21
Syst.	48	44	32	38	29
	Uncertainties in measurements				
PDF (meas.)	8	9	7	6	4
p_{T}^{Z} modelling	0	0	7	0	5
Lepton scale	4	4	4	4	3
Lepton resolution	6	1	2	2	1
Lepton efficiency	11	3	3	2	4
Electron charge misidentification	2	0	1	1	< 1
Muon sagitta bias	0	5	0	1	2
Background	1	2	1	1	2
MC. stat.	25	22	18	16	12
	Uncertainties in predictions				
(MMHT) PDF (predictions)	37	35	22	33	24
QCD scales	6	8	9	5	6
EW corrections	3	3	3	3	3

x 10^{-5}

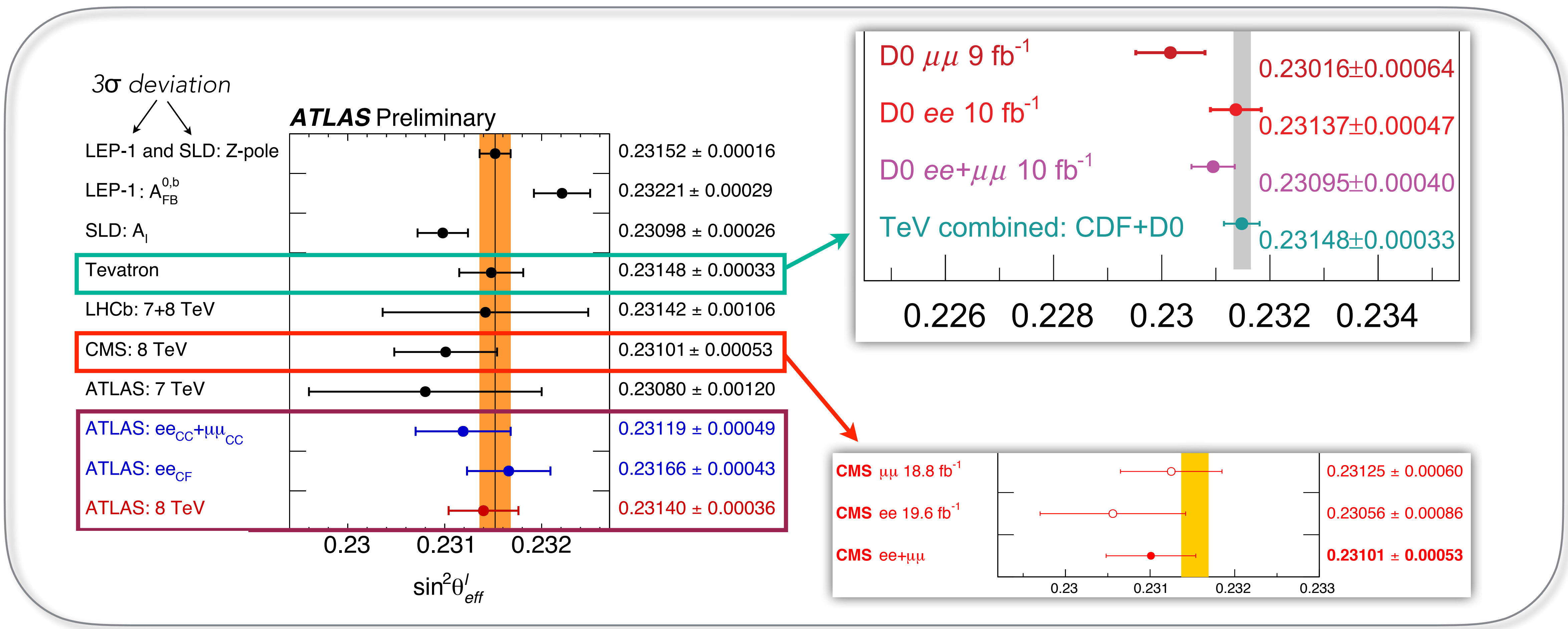
ee_{CF} is most precise channel [1.5 M of events (13.5M ee+μμ)
measurement uncertainty 36 x 10^{-5}

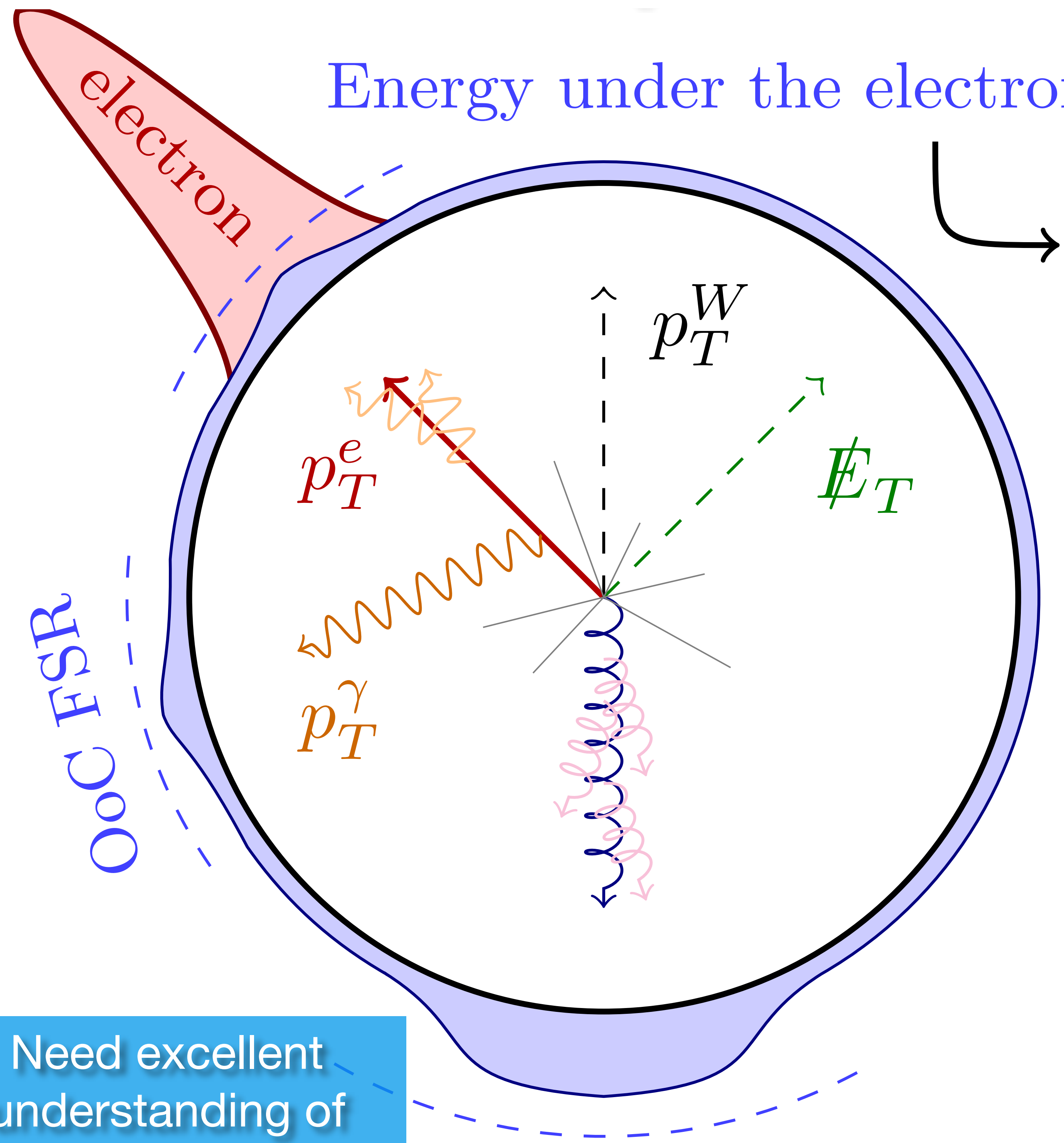
weak mixing angle extraction summary



G-fitter 1803.01853

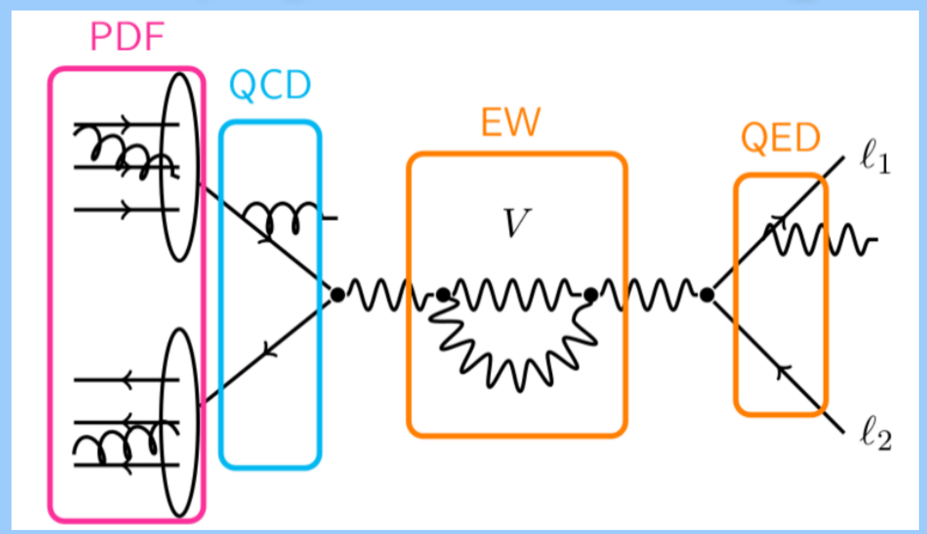
New analysis techniques, including in-situ PDF profiling and categorisation statistical and systematic uncertainties are significantly reduced relative to previous CMS and ATLAS measurements.





Need excellent understanding of detector and MC simulation

physics modelling



W mass @ATLAS strategy

- At LO p_{Tl} has a Jacobian peak at $m_W/2$, m_T has an endpoint at m_W
- Method:
  Fit the distribution of p_{Tl} and m_T using MC templates generated with different m_W in 16 category.
  - m_T less sensitive to W boson p_T, but more sensitive to hadronic recoil resolution
  - p_{Tl} not directly dependent on recoil, but more sensitive to p_T^W
- Different effects modify the reconstructed p_{Tl} and m_T distributions:
  - Initial and final state radiation (QED);
  - The W boson p_TW distribution (QCD);
  - Detector response.

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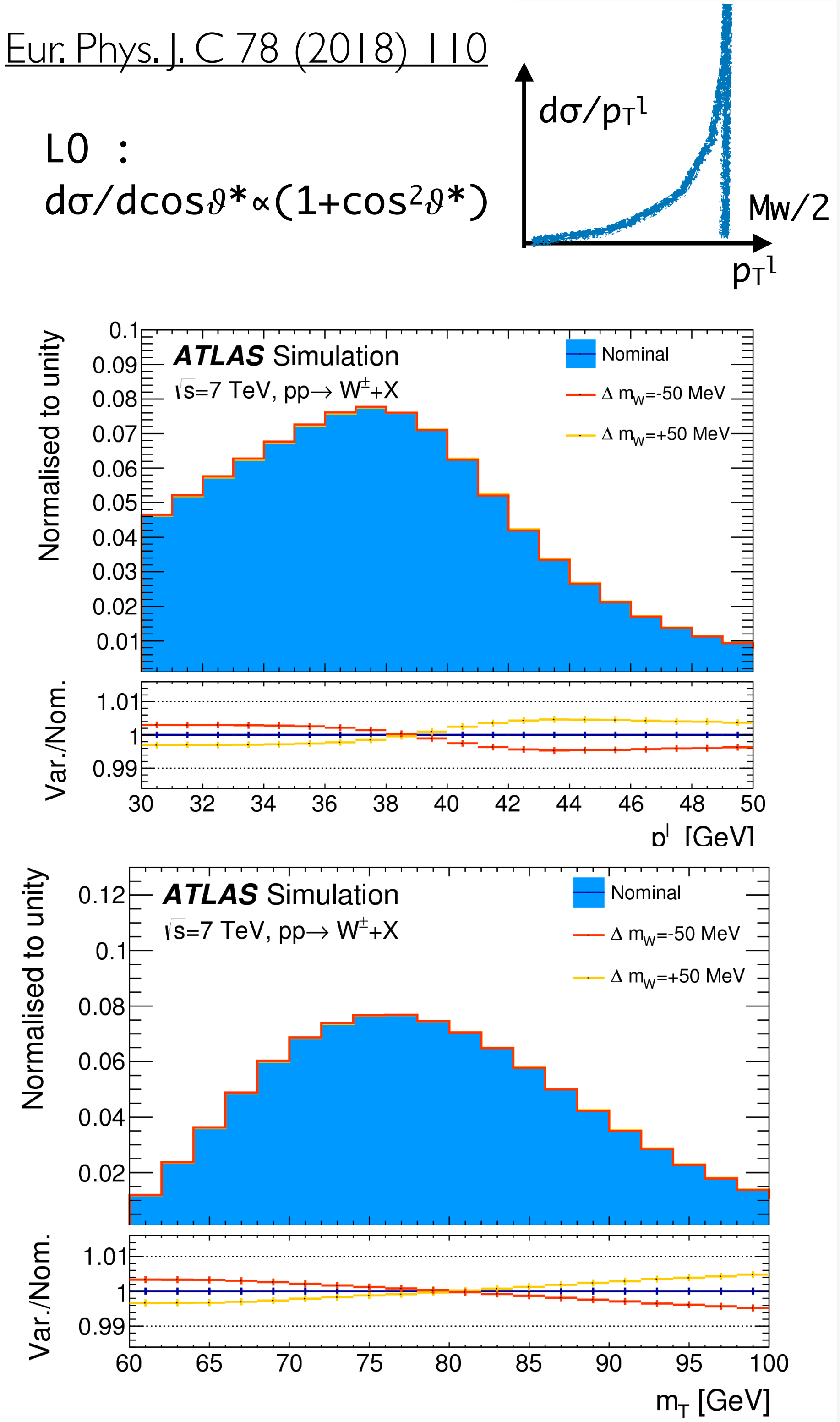
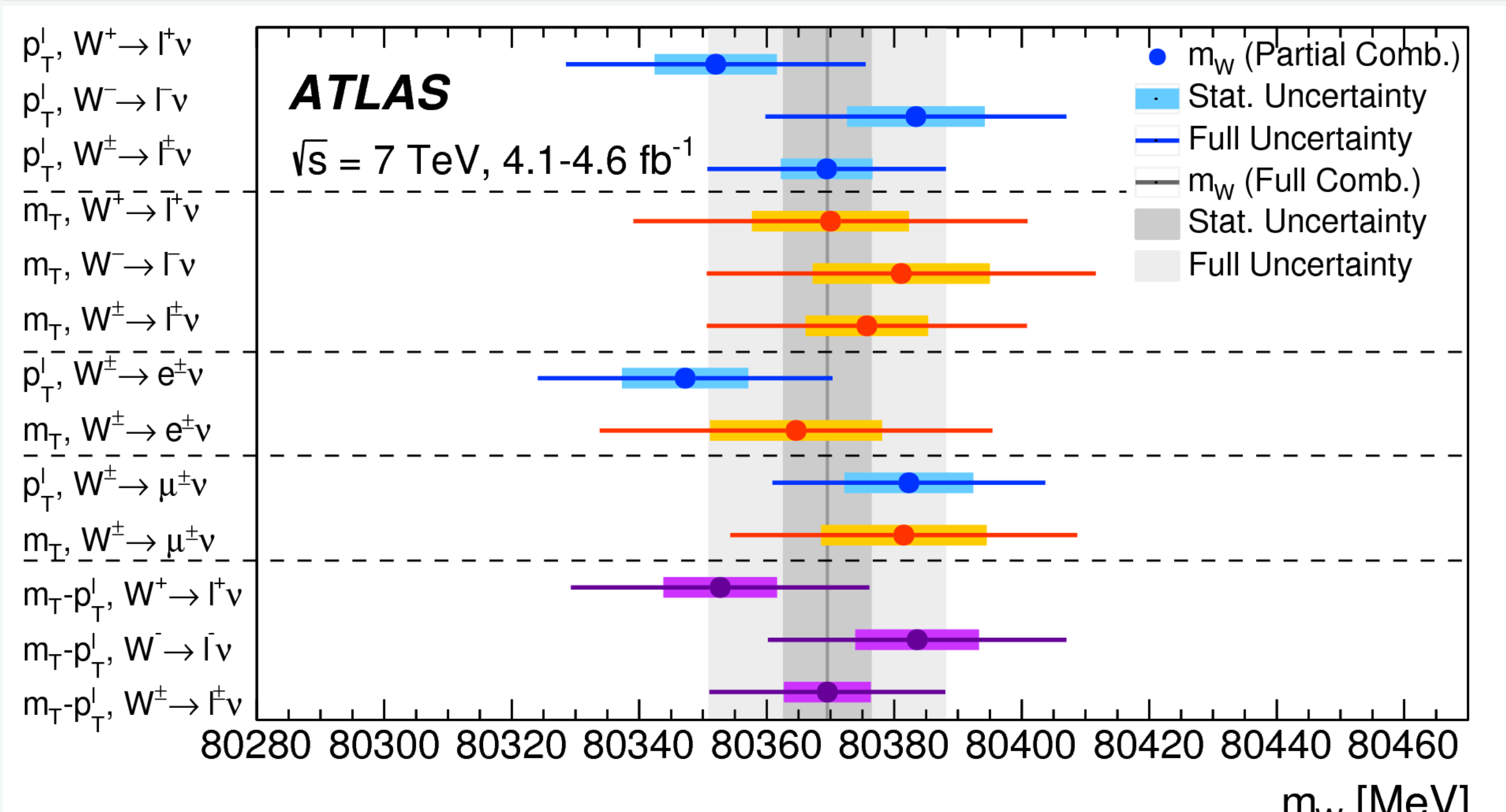
LO : $d\sigma/d\cos\vartheta^* \propto (1+\cos^2\vartheta^*)$



W mass measurement with ATLAS



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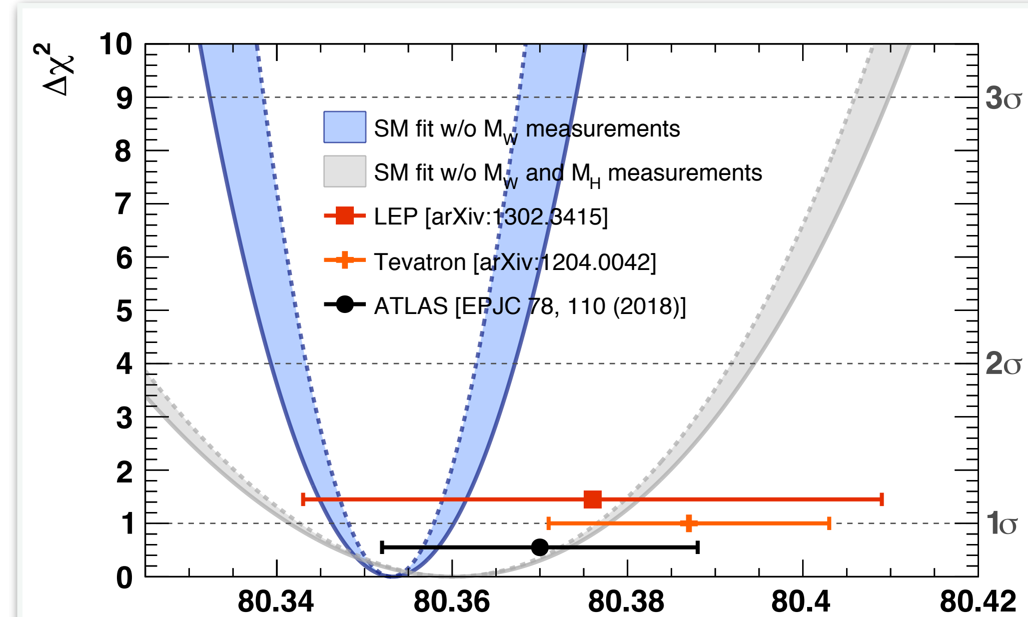


G-fitter 1803.01853

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.
80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

stat. = 6.8 MeV exp. syst = 10.6 MeV mod. syst =13.6 MeV

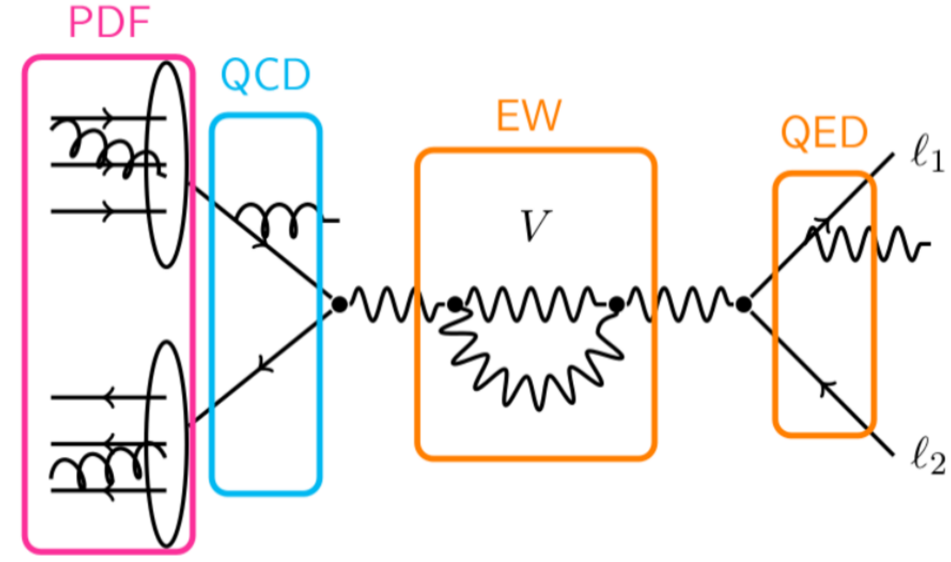
m_W = 80370 +- 19 MeV

W mass physics modelling

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.
80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

stat. = 6.8 MeV exp. syst = 10.6 MeV mod. syst =13.6 MeV

m_W = 80370 +- 19 MeV

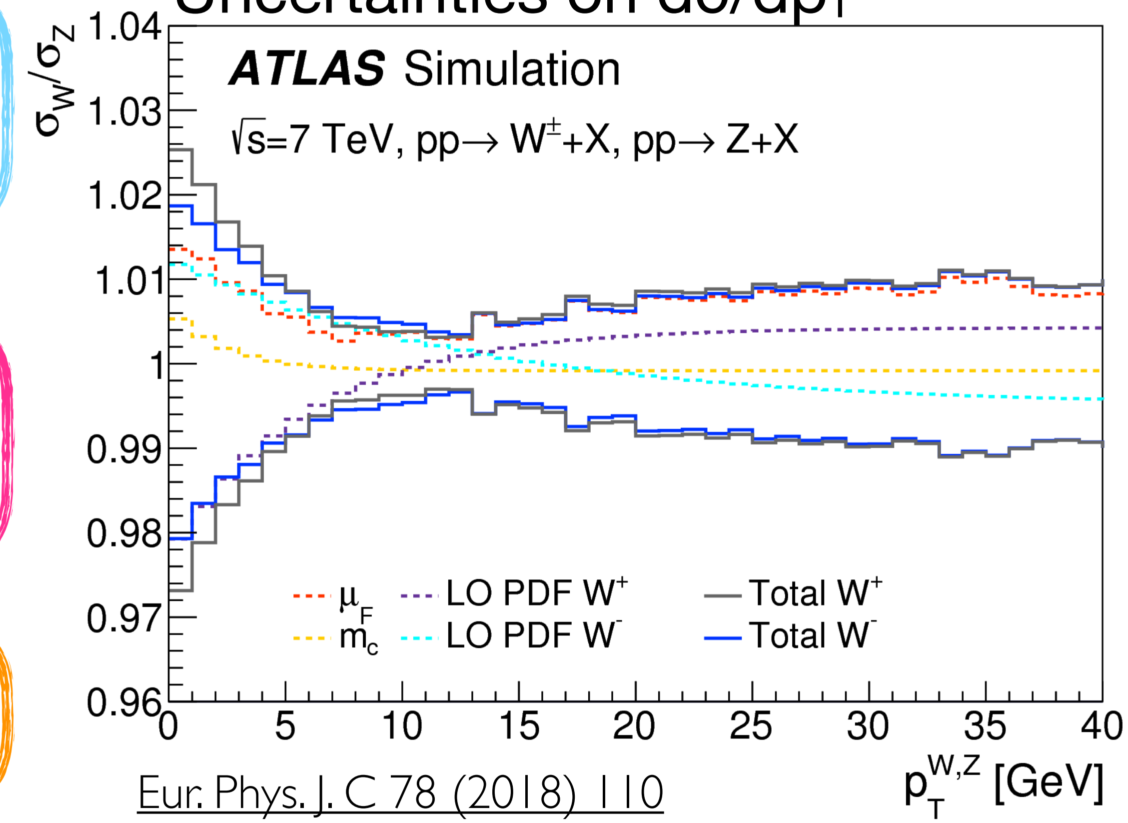


$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T,y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta)+\sum_{i=0}^{7}A_i(p_T,y)P_i(\cos\theta,\phi)\right]$$

Breit-Wigner NNLO pQCD Parton Shower

- QCD uncertainties are evaluated by varying parameters of Pythia-8 AZ tune and of the NNLO calculation.
- Largest uncertainties on m_W from PDF variations in NNLO calculation: 13-15 MeV, largely anti-correlated between W^+ and W^-
- Uncertainties from missing higher-order electroweak corrections are small.

Uncertainties on $d\sigma/dp_T$



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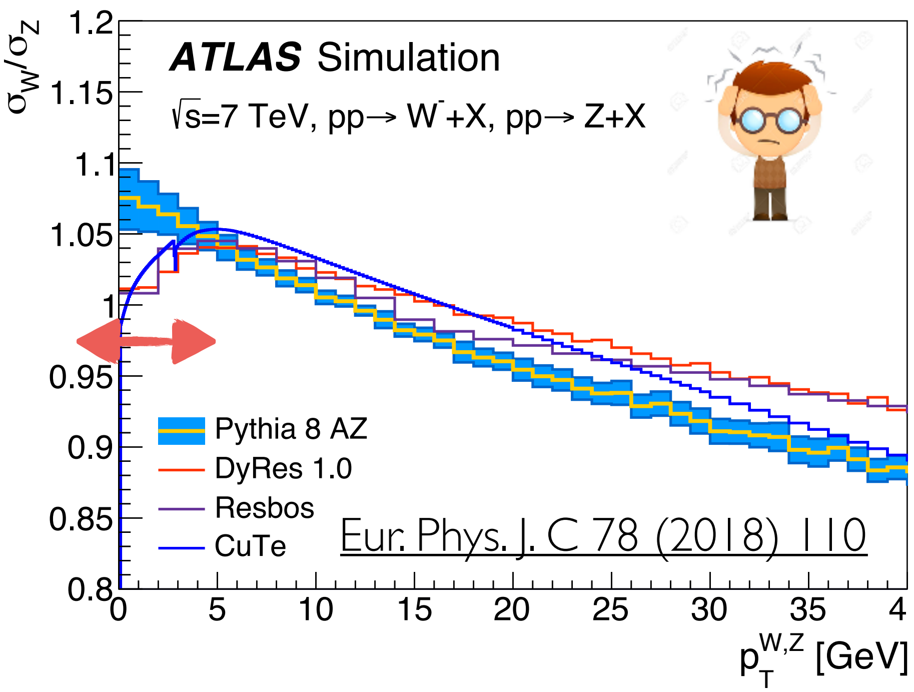
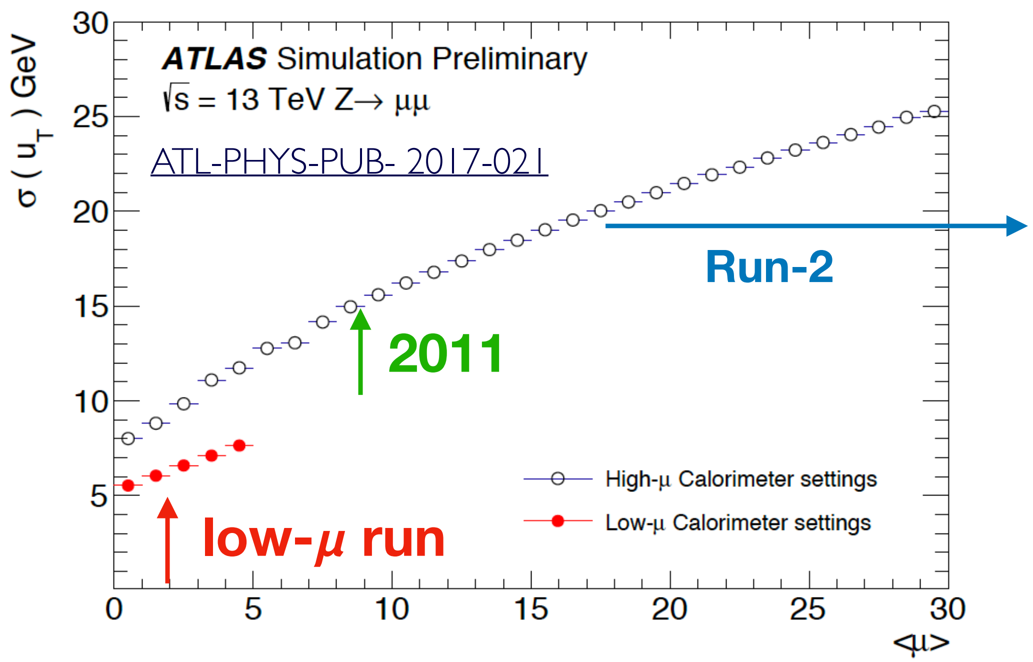
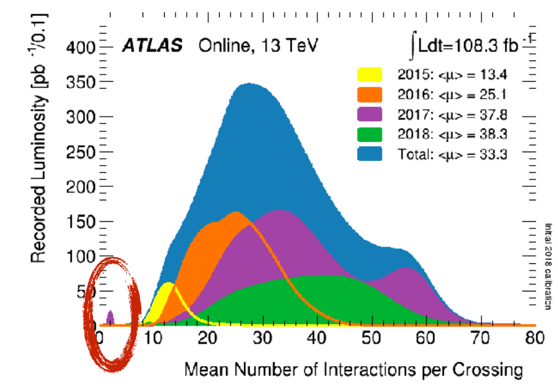
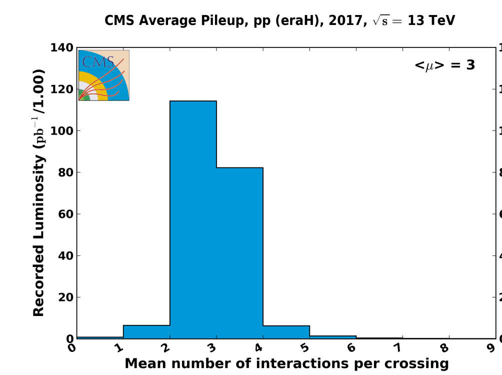
W-boson transverse momentum measurement in low-mu environment









The modelling of the W/Z p_T ratio in pp collisions is an open issue in QCD: Only (N)LL parton shower predictions are in agreement with the data, all other higher order predictions fail to describe the observed distributions

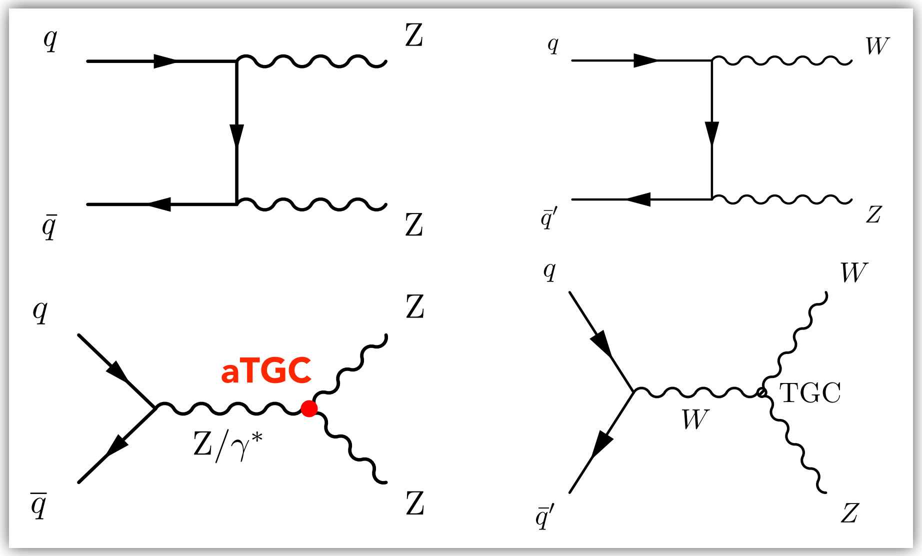
➡A measurement able to resolve W p_T in bins of 5 GeV with **1% uncertainty** would provide a direct probe of the W/Z p_T ratio and a crucial experimental input to understand this issue
In order to resolve W p_T at 5 GeV we need to achieve a experimental resolution of the Hadronic recoil of the same order.

Both ATLAS and CMS collected @500 pb⁻¹ of data collected with low Pileup! fantastic opportunity for W boson transverse momentum measurement!

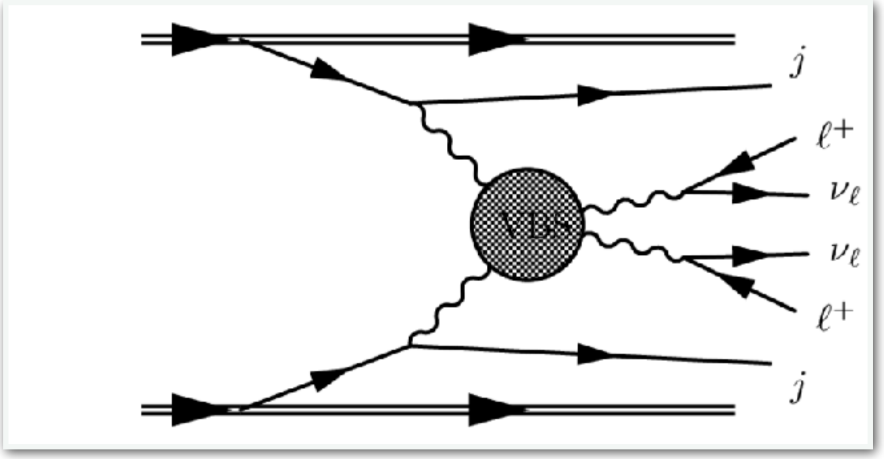
Test consistency of SM: Multi-bosons process

- Another fundamental goal of LHC physics program is to tests of the consistency of the SM through **direct exploration of the EW symmetry breaking mechanism using *diboson production***. This requires eventually very large datasets and specific efforts from the theory community

- Multi-bosons production at LHC:
  - Measure cross-section of process predicted by SM but never observed before
    - *EW and QCD higher order corrections are very important !*
  - Sensitive probe of BSM gauge iterations.
    - *Probe anomalous triple/quartic gauge couplings (aTGC,QGC)*

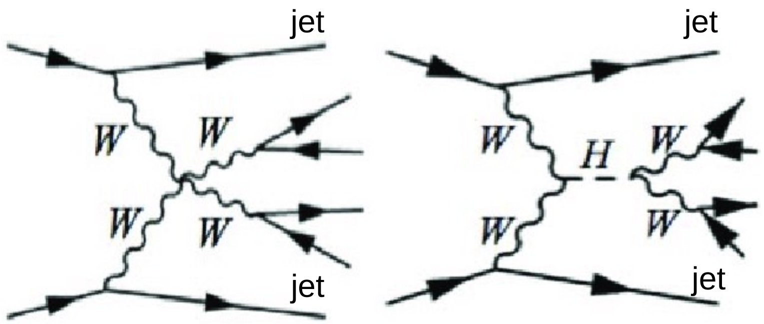


- Study vector-boson scattering (VBS) processes
  - Key test of EWSB
  - Sensitive to anomalous QGC
  - Enhanced in beyond-SM scenarios (e.g. modified Higgs sector or new resonances)



ssWW

- Higgs boson needed to restore unitarity of the WW scattering cross-section.
  - Higgs boson leads to strong suppression via gauge cancellation of individual EW diagrams. → **Fundamental piece of electroweak symmetry breaking studies.**
- pp → $W^{+/-}W^{+/-}jj$ process:
  Large electroweak cross-section fraction (σ_{EW}/σ_{QCD}) and a strong background suppression.



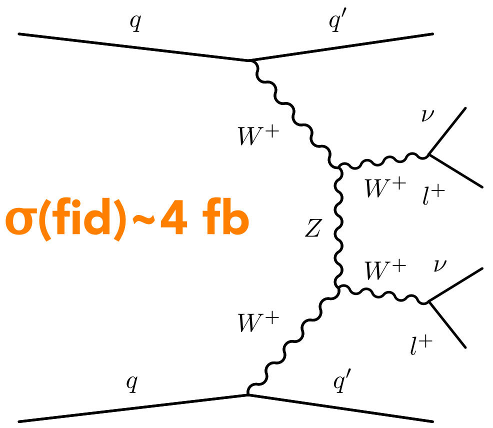
What about predictions?

Same-sign WW process is the only diboson process to-date for which NLO (EW and QCD) corrections have been computed. (PhysRevLett.118.261801)

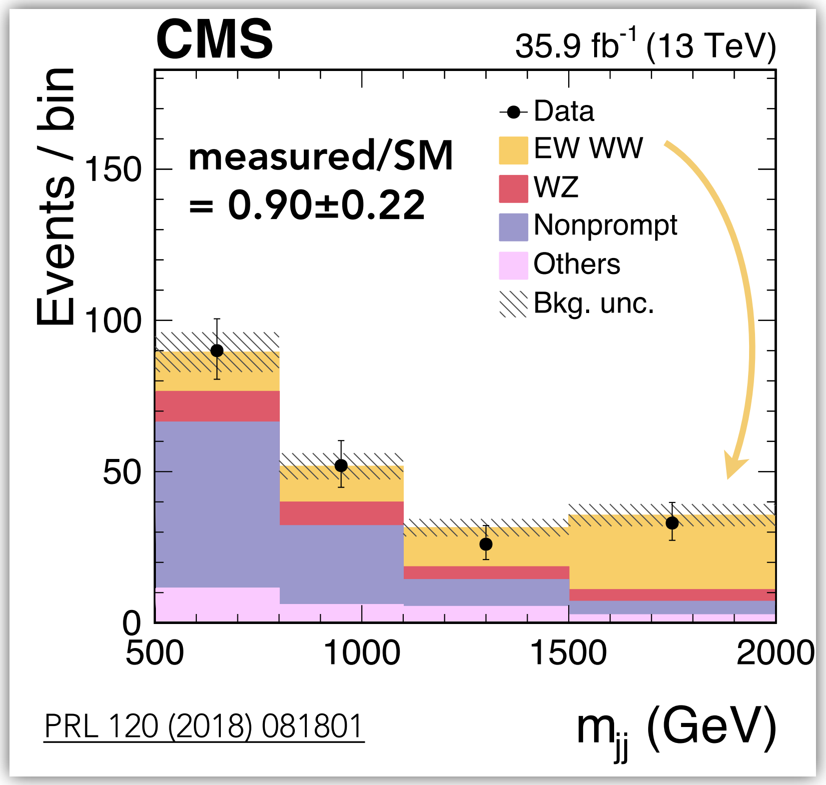
Main impact of improved calculation arises from NLO EW corrections which are negative and correspond to ≈ *20%* reduction of the fiducial cross section:

σ_{LO}^{fid} = 1.64 fb with ≈ 10% uncertainty

σ_{NLO}^{fid} = 1.36 fb with ≈ 2% uncertainty



σ(fid)~4 fb



Observation @CMS in 2017 (**5.5σ** observed, 5.7σ expected)

Measured fiducial cross section:

$$\sigma_{\text{fid}}(W^{\pm}W^{\pm}jj) = 3.83 \pm 0.66\,(\text{stat}) \pm 0.35\,(\text{syst})\ \text{fb}.$$

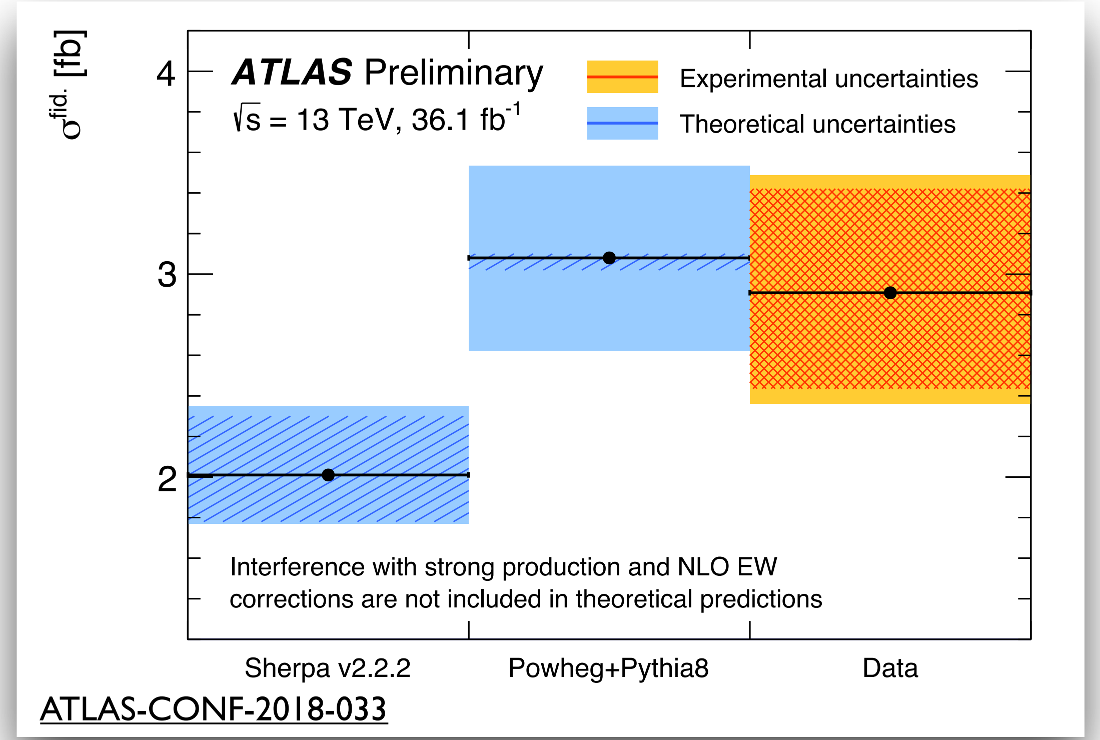
in agreement with LO prediction:
MADGRAPH5_aMC@NLO: 4.25 ± 0.27fb

Observation @ ATLAS (**6.9σ** observed, 4.6σ expected (Sherpa))

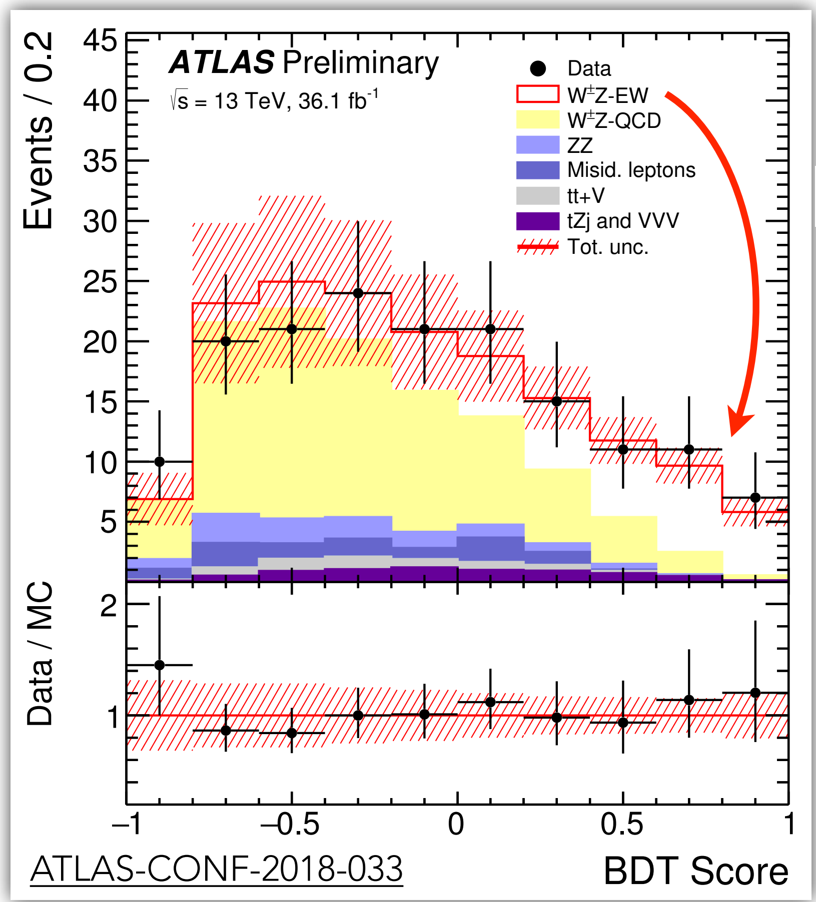
Same-sign WW : $\sigma^{\text{fid}} = 2.91^{+0.51}_{-0.47}\,(\text{stat.}) \pm 0.27\,(\text{sys.})$ fb.

Fiducial cross sections at LO for same-sign WWjj EW process:

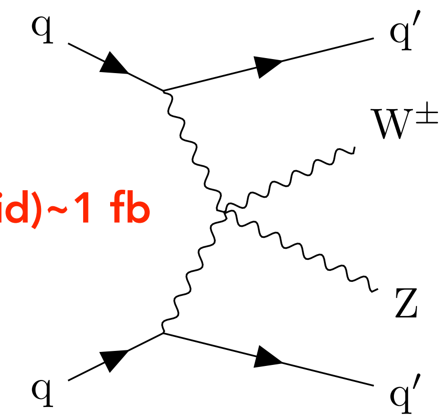
Sherpa v2.2.2: 2.0 ± 0.3 fb
Powheg+Pythia8: 3.1 ± 0.5 fb



VBS WZ final state



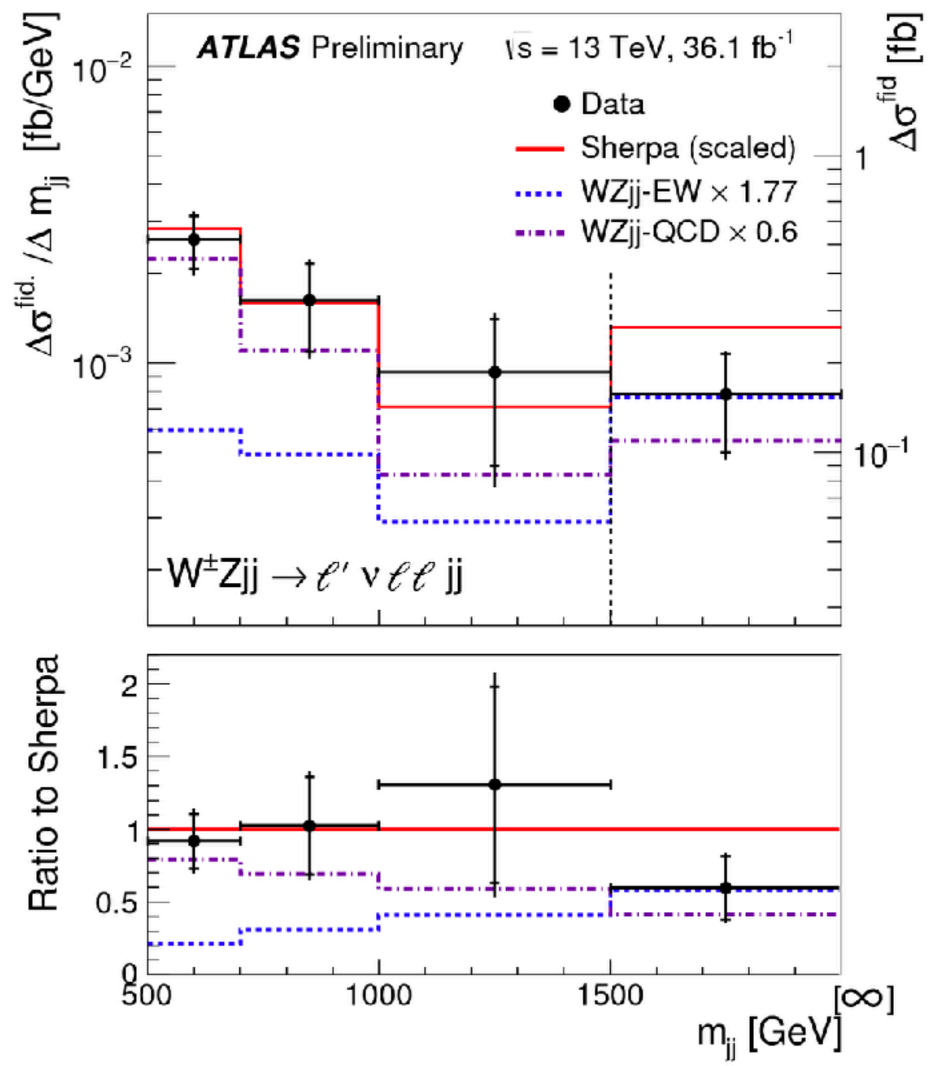
σ(fid)~1 fb



1st observation @ATLAS
EW WZ final state
(5.6σ observed, 3.3σ expected)

- *1st observation + differential measurements of EW processes in the WZ final state*

ATLAS-CONF-2018-033



WZjj EW σ_{fid}: 0.57±14(stat)±0.05(sys)± 0.04(th.) fb

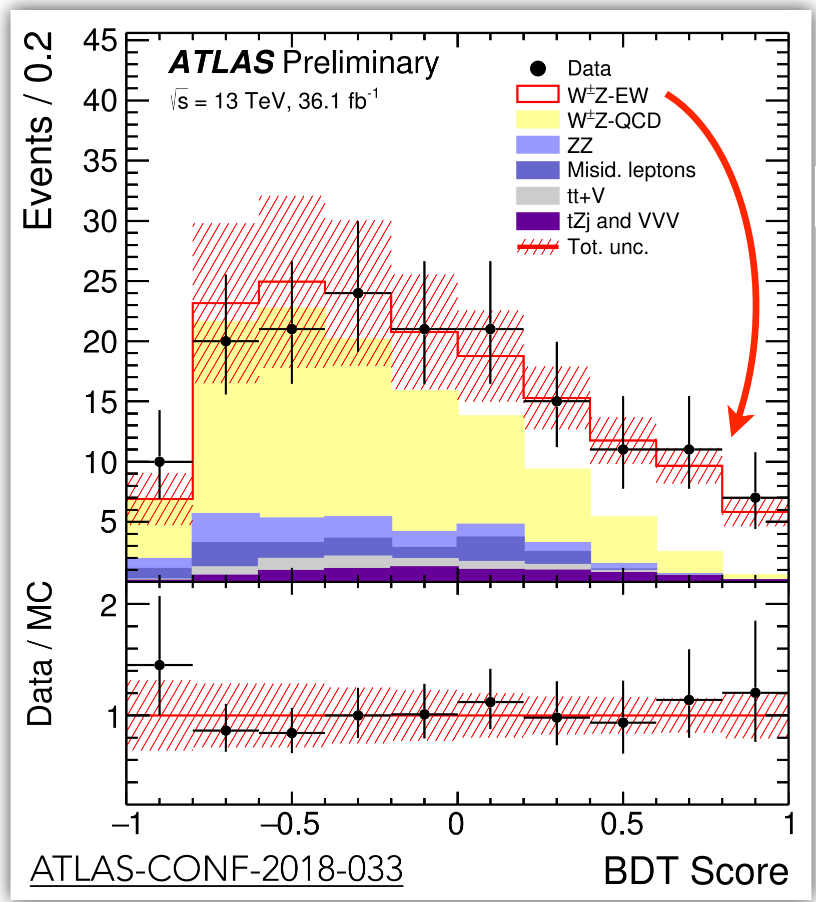
What about predictions?

Sherpa v2.2.2: 0.32 ± 0.03 fb

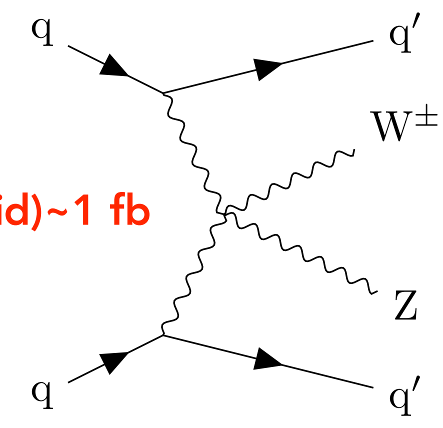
Only LO predictions exist for WZjj EW production.

- higher-order calculations of diboson EW production, existing to-date only for same-sign WW EW production

VBS ZZ and WZ final state

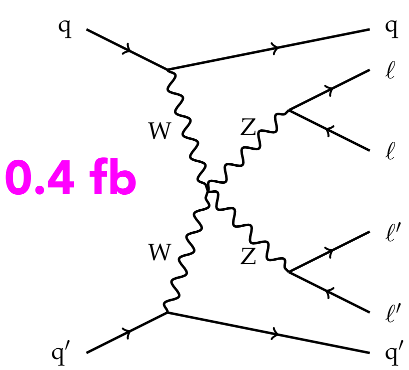


ATLAS-CONF-2018-033



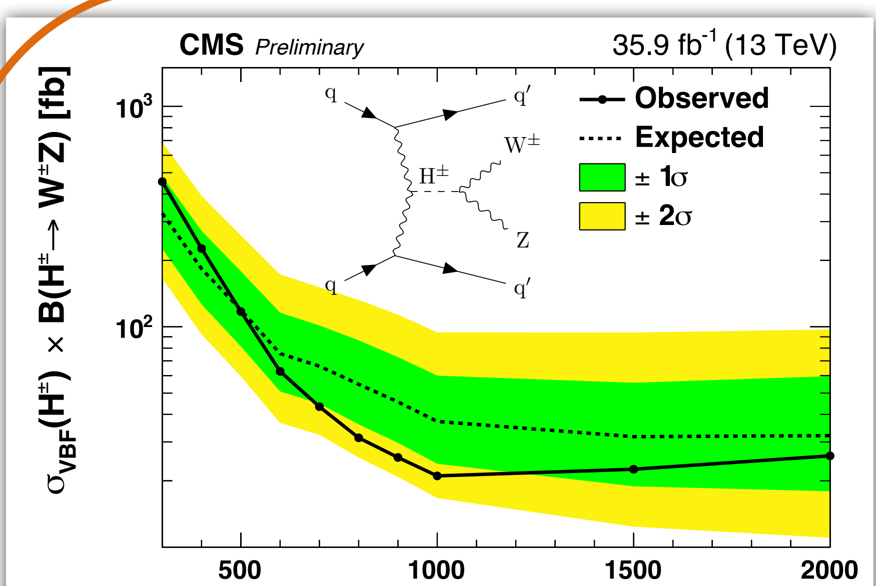
σ(fid)~1 fb

1st observation @ATLAS
EW WZ final state
(5.6σ observed, 3.3σ expected)



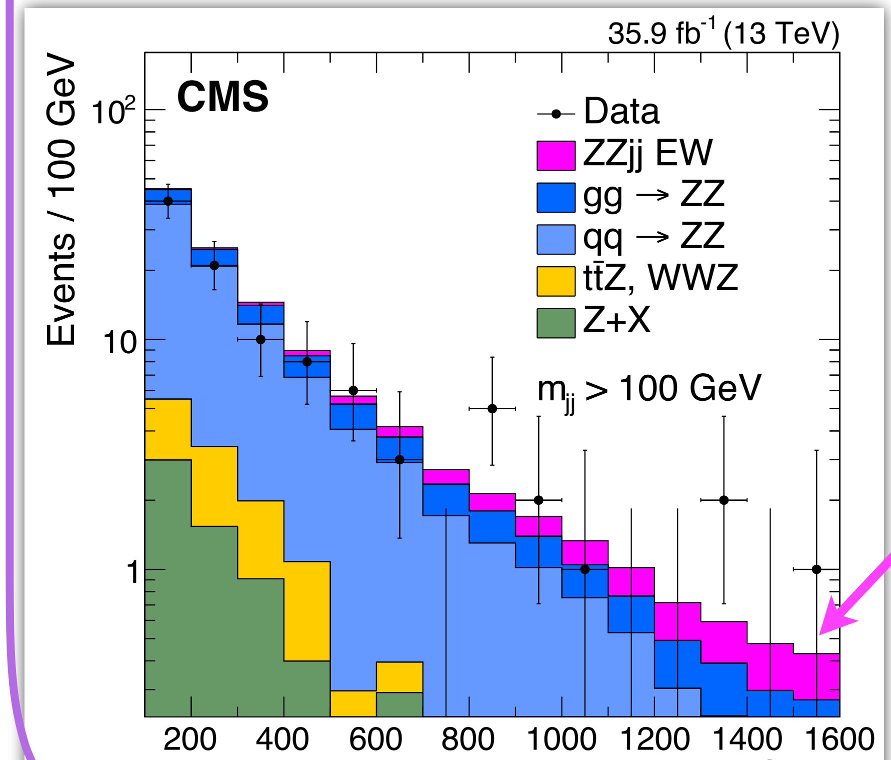
σ(fid)~0.4 fb

Approaching sensitivity to **EW ZZ** @ CMS
(2.7σ observed , 1.6σ expected)



CMS-PAS-SMP-18-001

@CMS
(1.9σ observed, 2.7σ expected)
Searches for aTGC & charged Higgs production @CMS

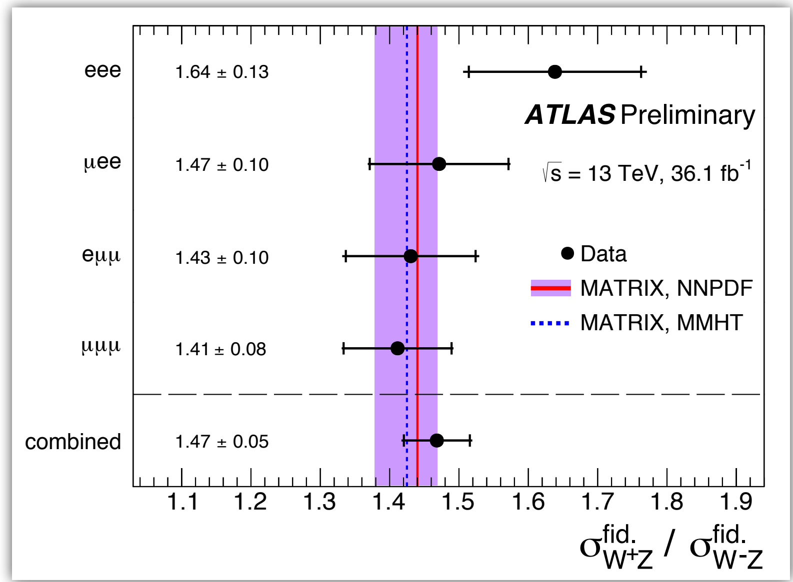


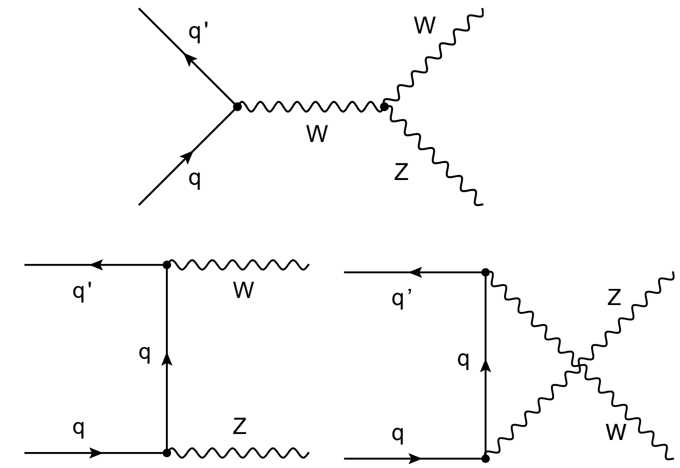
PLB 774 (2017) 682

latest WZ final state results

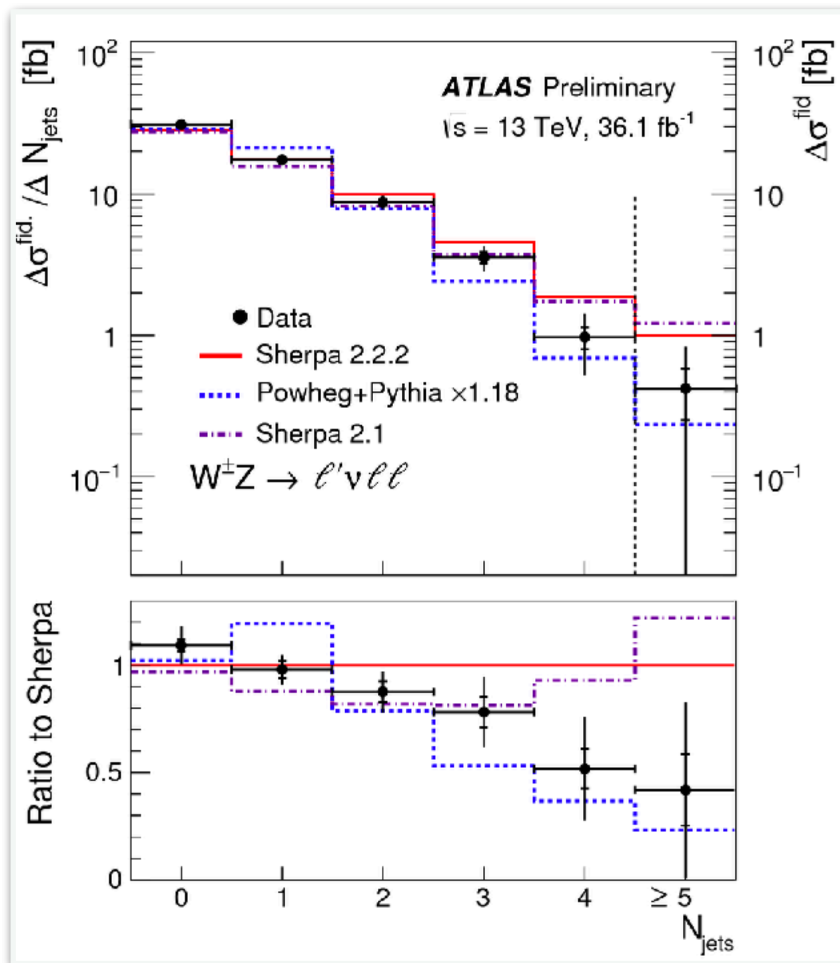
WZ Inclusive+differential cross section measurements from both ATLAS & CMS

Good agreement between data & predictions

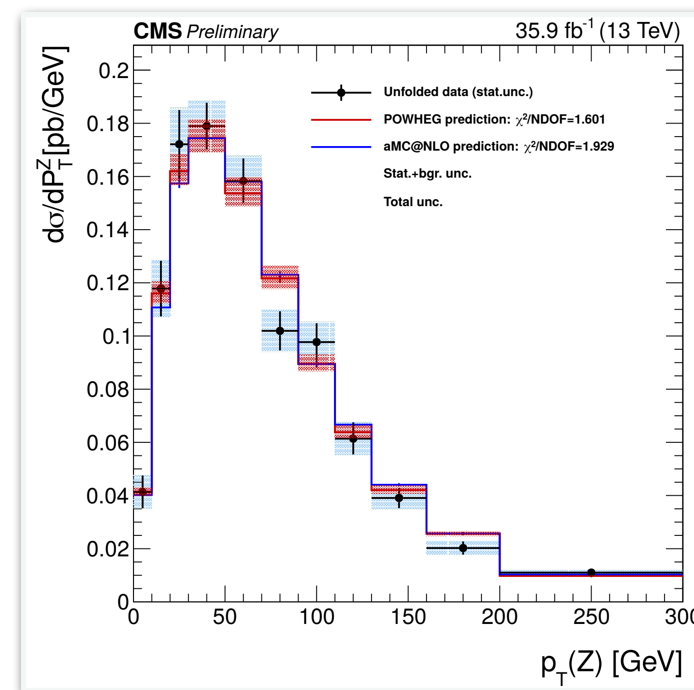




σ~50 pb



ATLAS-CONF-2018-0034, CMS-PAS-SMP-18-002

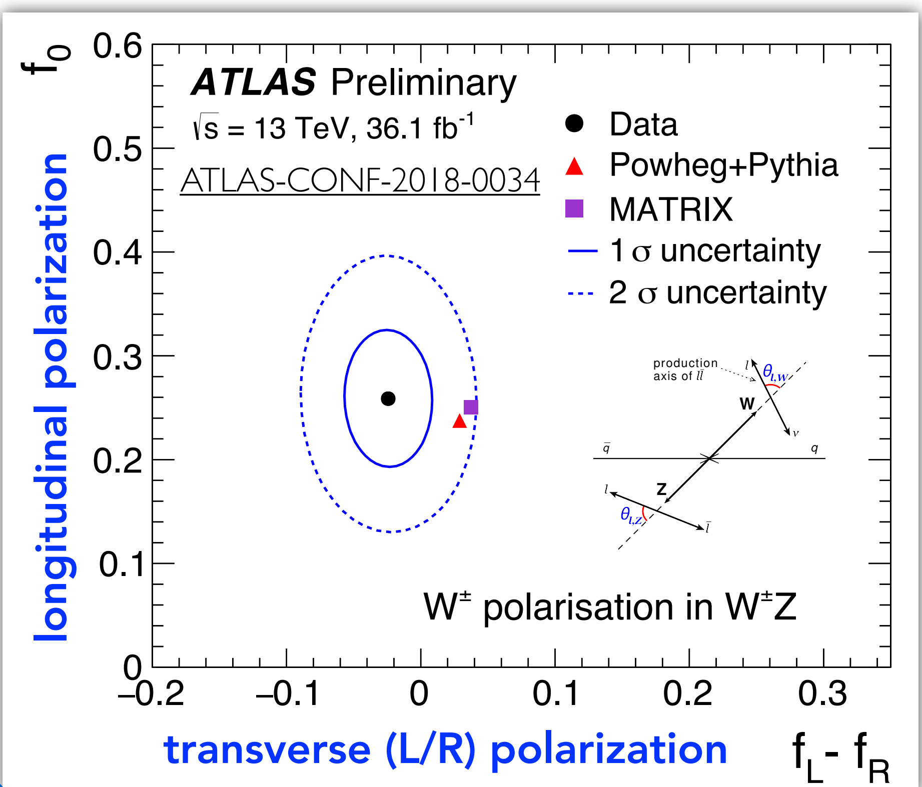


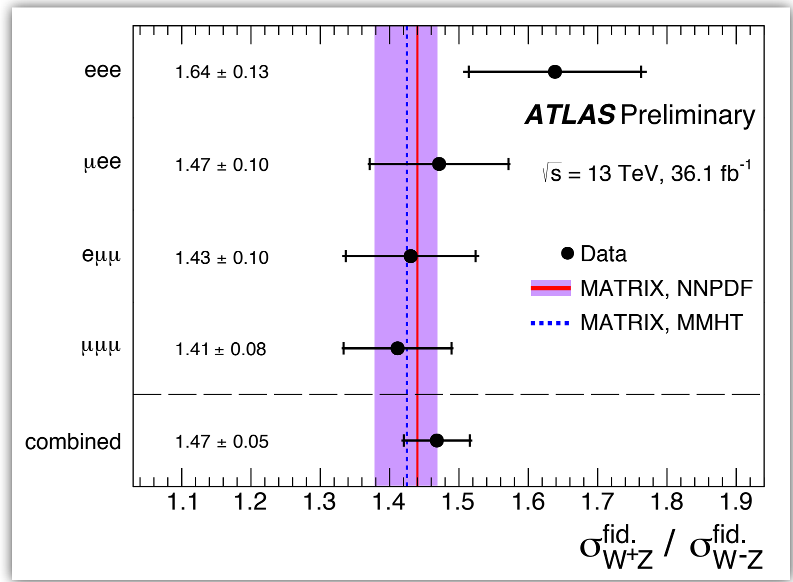
latest WZ final state results

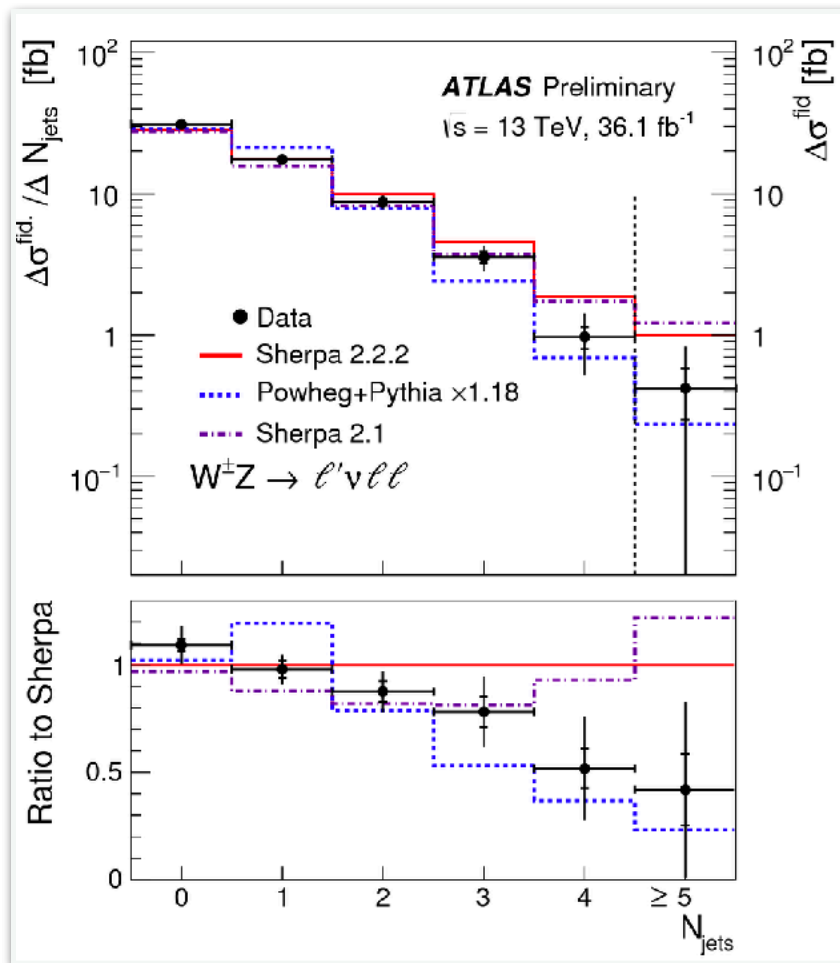
WZ Inclusive+differential cross section measurements from both ATLAS & CMS

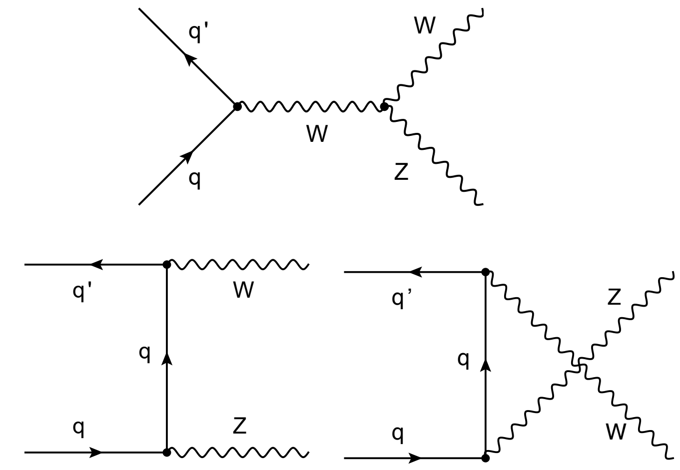
Good agreement between data & predictions

@ATLAS first measurement **measurement of WZ polarisation** use lepton angular distributions,
template fits to $(q_l \cdot)\cos\theta_{l,W}$



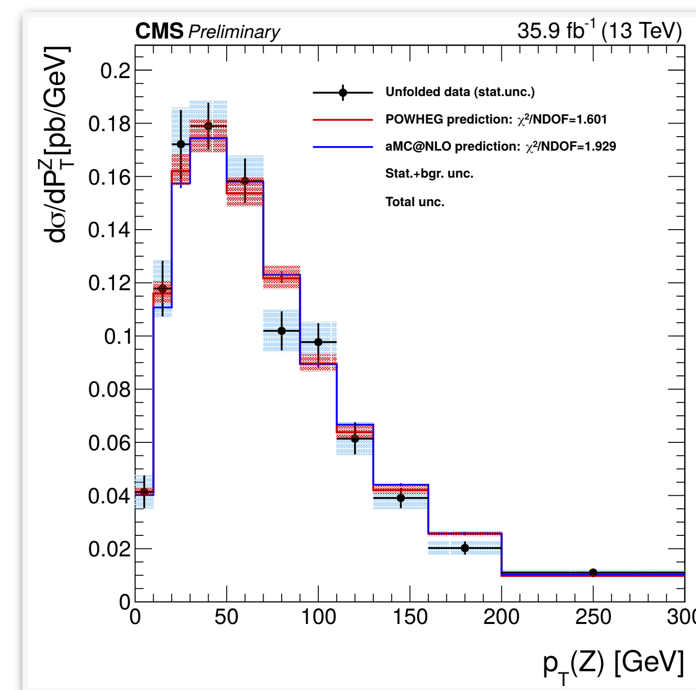






σ~50 pb

ATLAS-CONF-2018-0034,
CMS-PAS-SMP-18-002

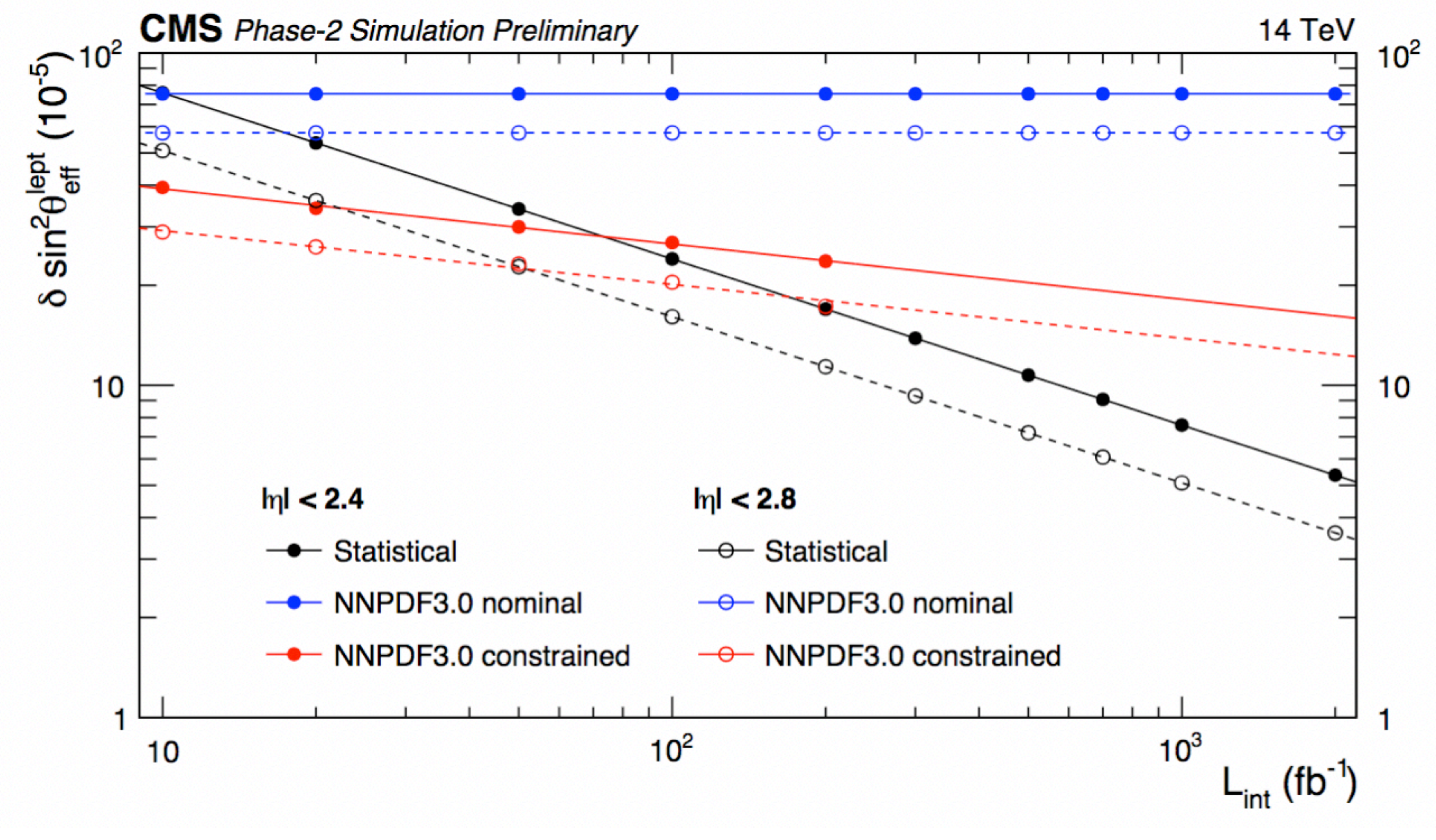


Summary

- **Measurements in EW sectors are keys in continuing testing the SM & searching for new physics.**
- Outstanding SM results using LHC Run1 data but vey impressing new results using LHC Run2 data @13TEV!
  - *Approaching LEP single experiment sensitivity for weak mixing angle measurement*
  - *First LHC measurement of W mass reach an accuracy of 20 MeV*
  - *On the road of detailed vector-boson scattering studies in different channel*
- Great potential in the future !

Backup

weak mixing angle extraction HL-LHC

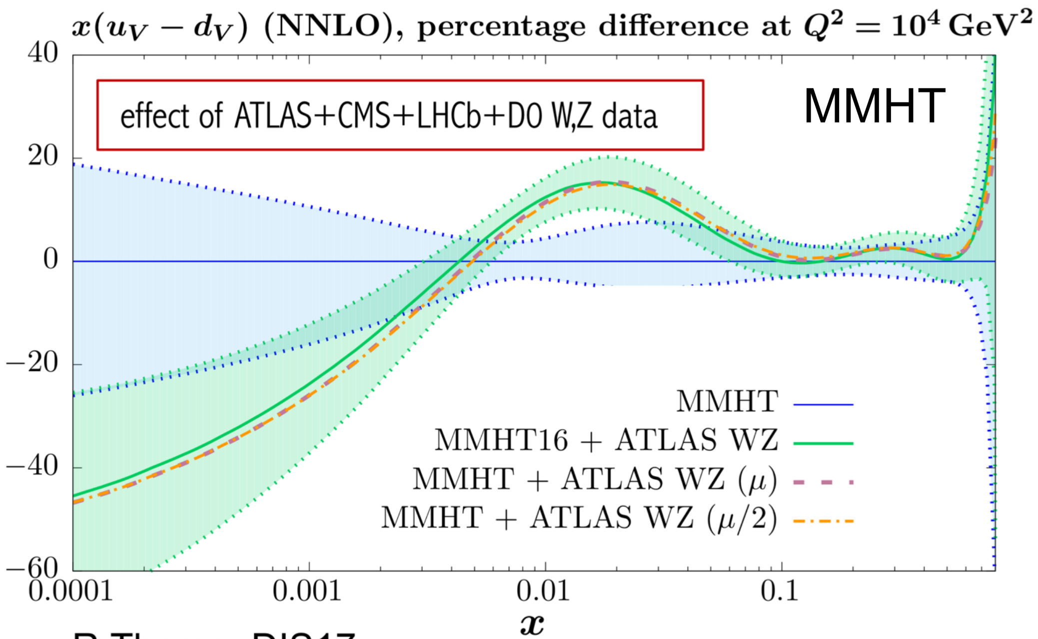


constraining PDFs with LHC data

LHC data has extensive and growing portfolio of pdf-sensitive measurements.

measurements of same process at different CM energies, and ratio measurements (EG. of different processes, or same process at different energies) with partially cancelling systematics can provide significant pdf constraints

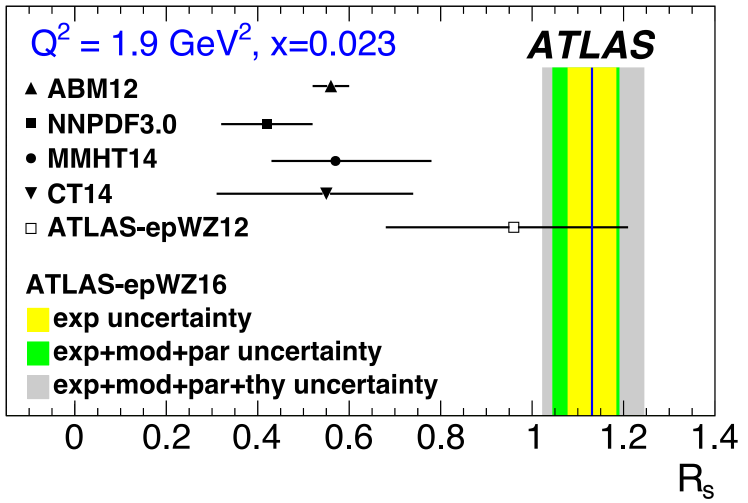
NNLO QCD calculations available for important physics processes – developments in grid technology (APPLfast) mean these data should be useable in rigorous NNLO pdf fits in the near future



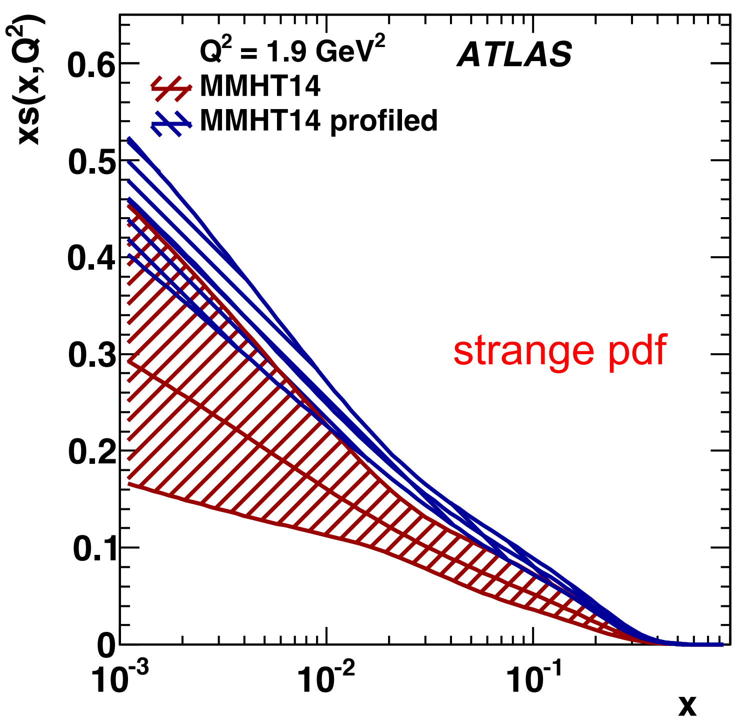
R.Thorne, DIS17

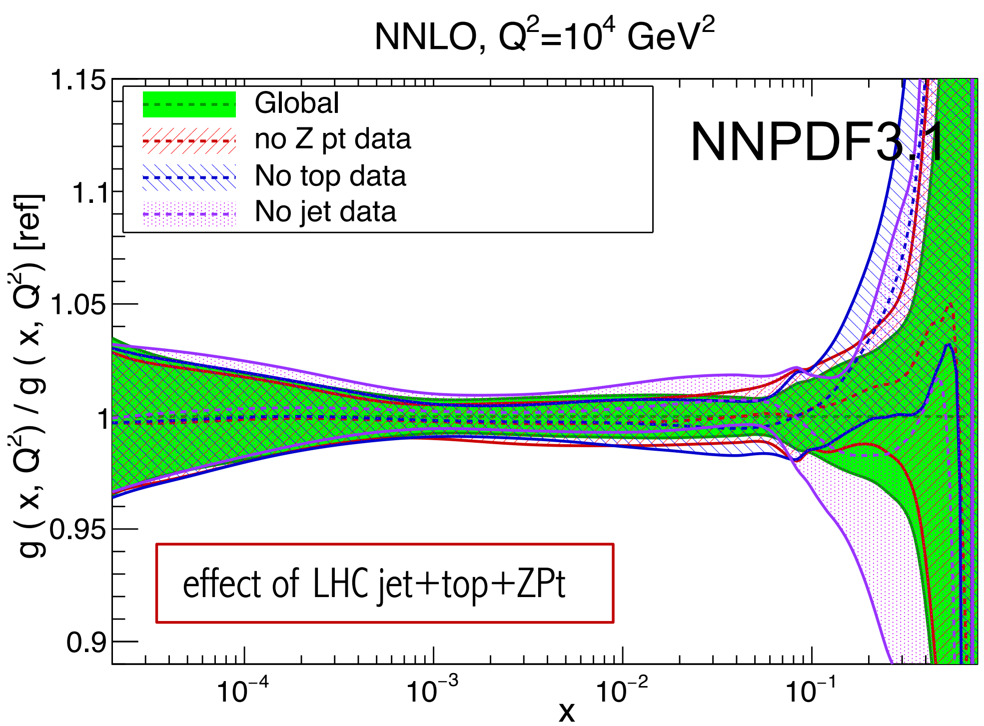
→ ATLAS-epWZ16 pdf (available on lhapdf)

$$R_s(x,Q^2) = \frac{s(x,Q^2)+\bar{s}(x,Q^2)}{\bar{u}(x,Q^2)+\bar{d}(x,Q^2)} \begin{cases} \approx 0.5 \text{ (from neutrino)} \\ \approx 1.0 \text{ (from ATLAS W,Z)} \end{cases}$$



EPJ C77 (2017) 367

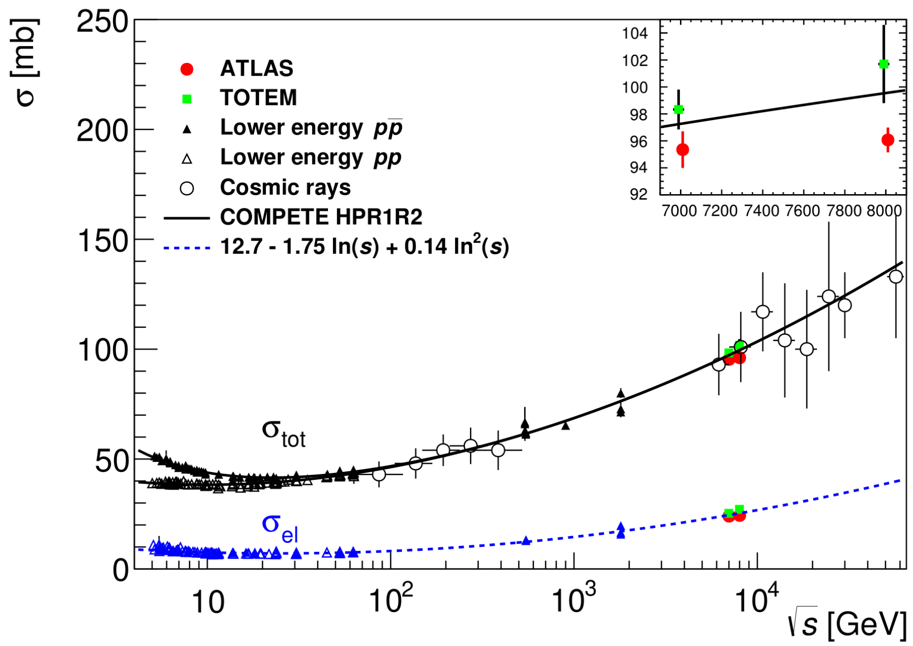




EPJ C77 (2017), 663

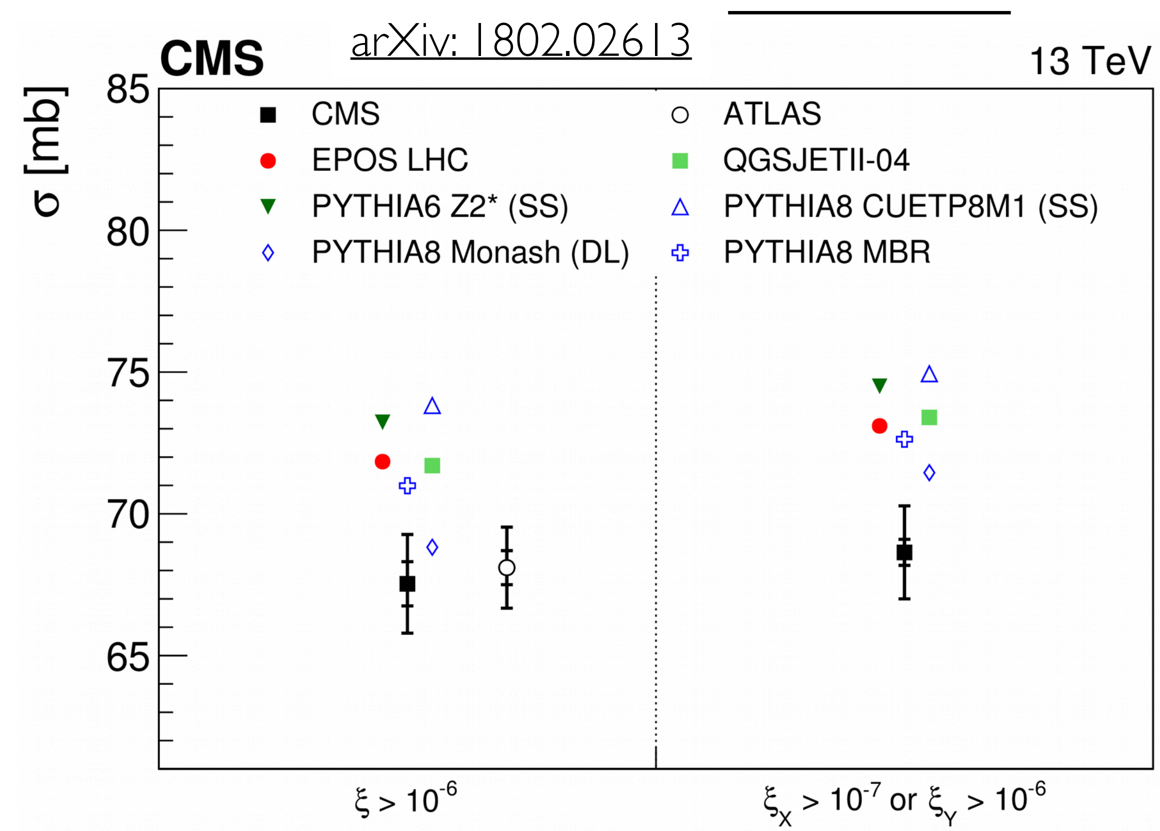
diffractive and inelastic cross-section

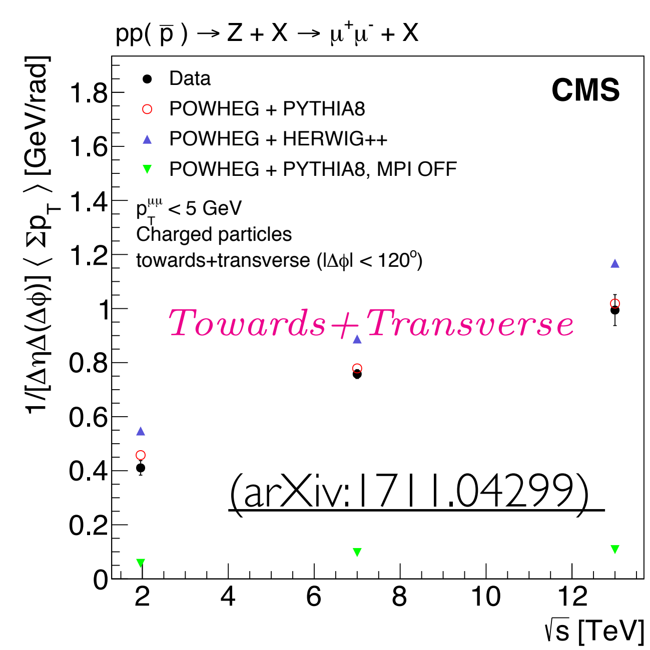
Phys. Lett. B 761 (2016) 158-17



(a)

- Energy evolution of $\sigma_{\rm tot}$ and $\sigma_{\rm el}$
- Elastic cross section from the nuclear part of the integrated fit function

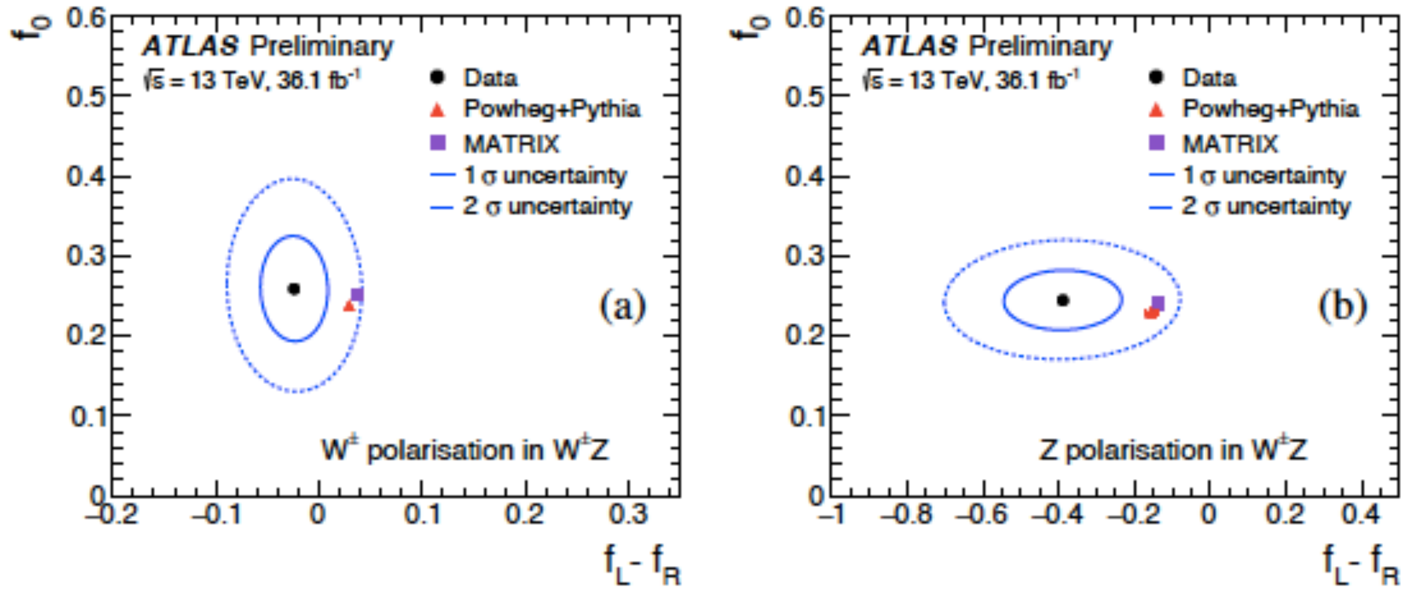




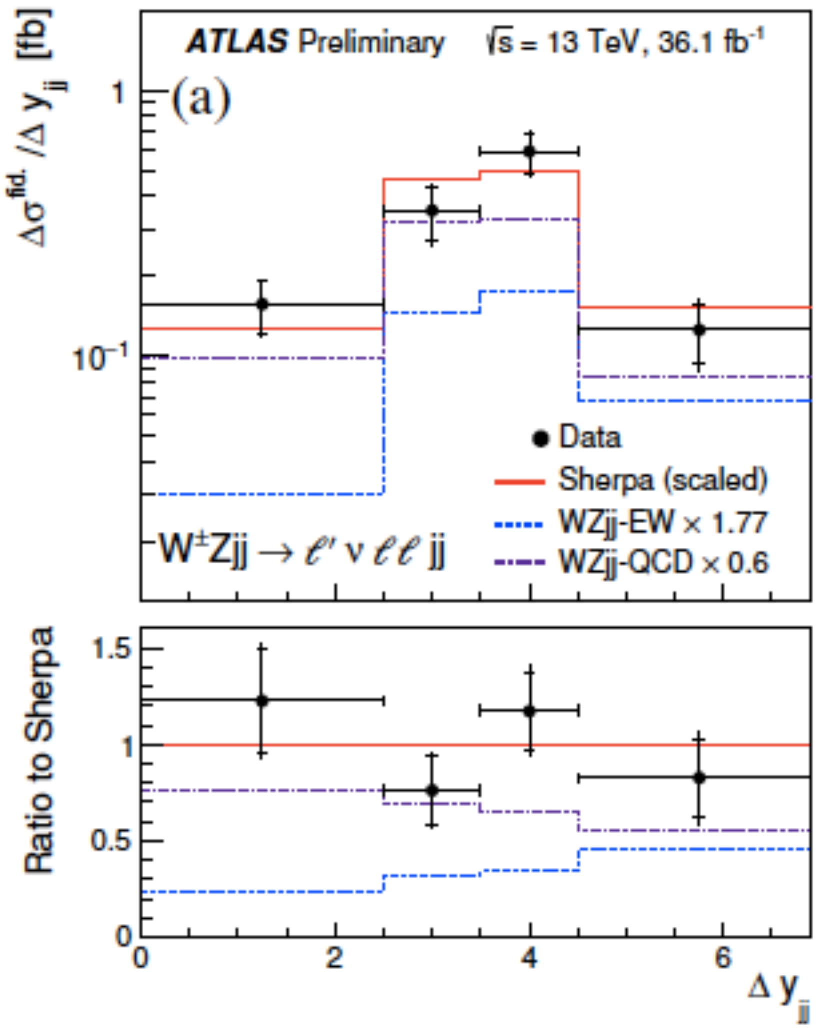
First measurement of W/Z polarisation in diboson processes

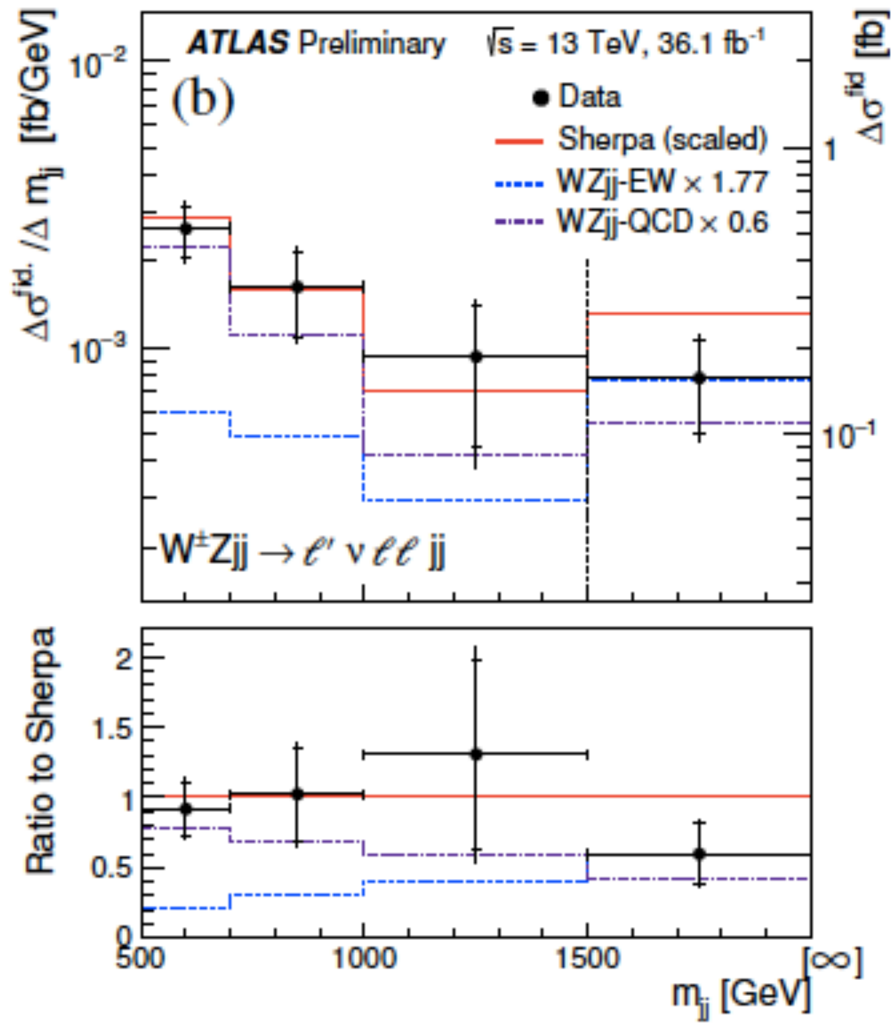
- **Helicity fractions f_0 (longitudinal polarisation) and f_L/f_R (transverse polarisation)**
- **Evidence for longitudinally polarised Ws at 4.2σ (3.8σ expected)**
- **Theory predictions are LO EW with $\sin^2\theta_W = 0.23152$ (PDG 2016)**

$$\frac{1}{\sigma_{W^\pm Z}}\frac{d\sigma_{W^\pm Z}}{d\cos\theta_{\ell,W}} = \frac{3}{8}f_L(1\mp\cos\theta_{\ell,W})^2 + \frac{3}{8}f_R(1\pm\cos\theta_{\ell,W})^2 + \frac{3}{4}f_0\sin^2\theta_{\ell,W}$$



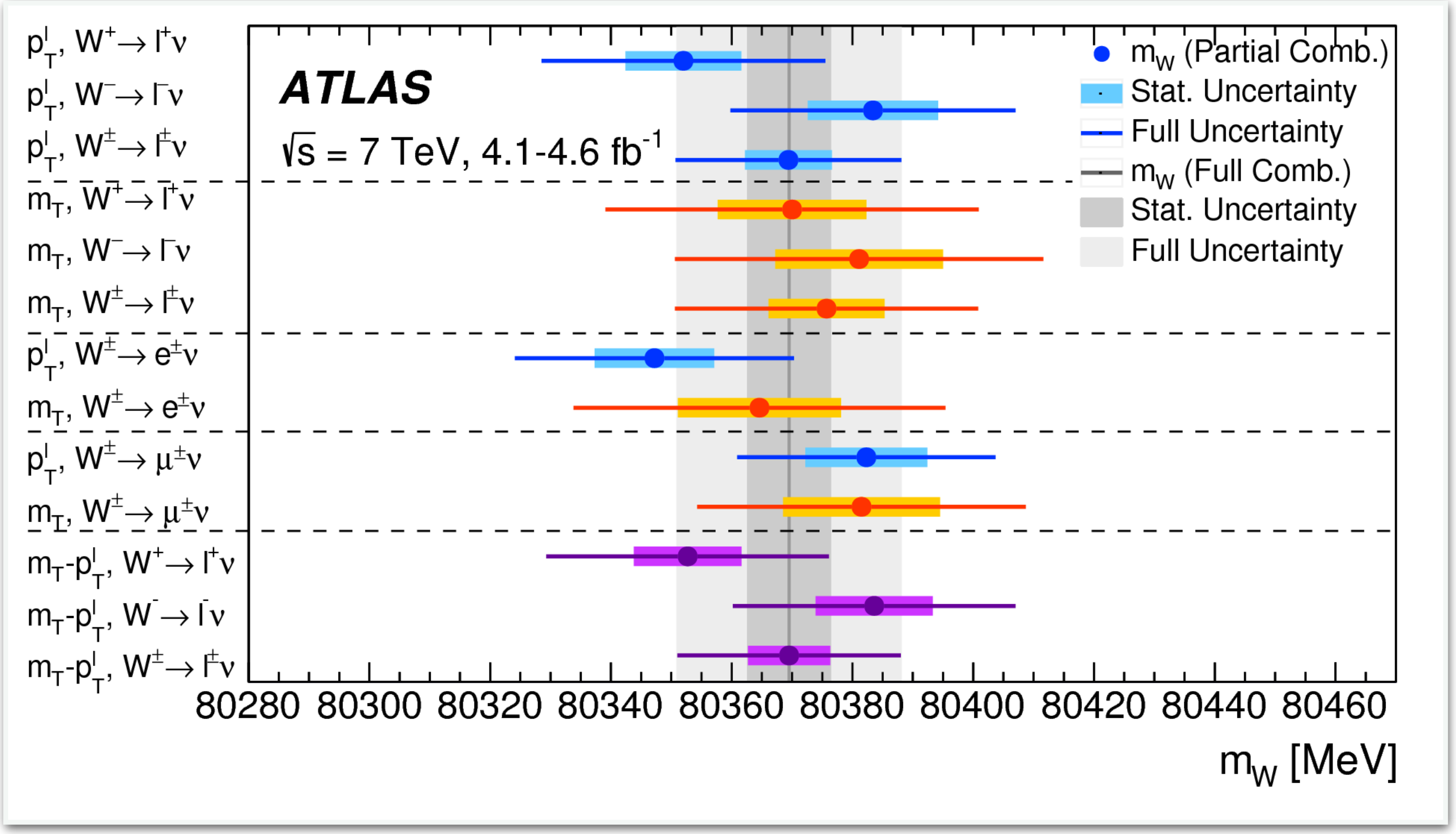
- **Examples of differential distributions for WZ EW signal region: Δy_{jj} (left) and m_{jj} (right), compared to Sherpa predictions rescaled to their post-fit values.**

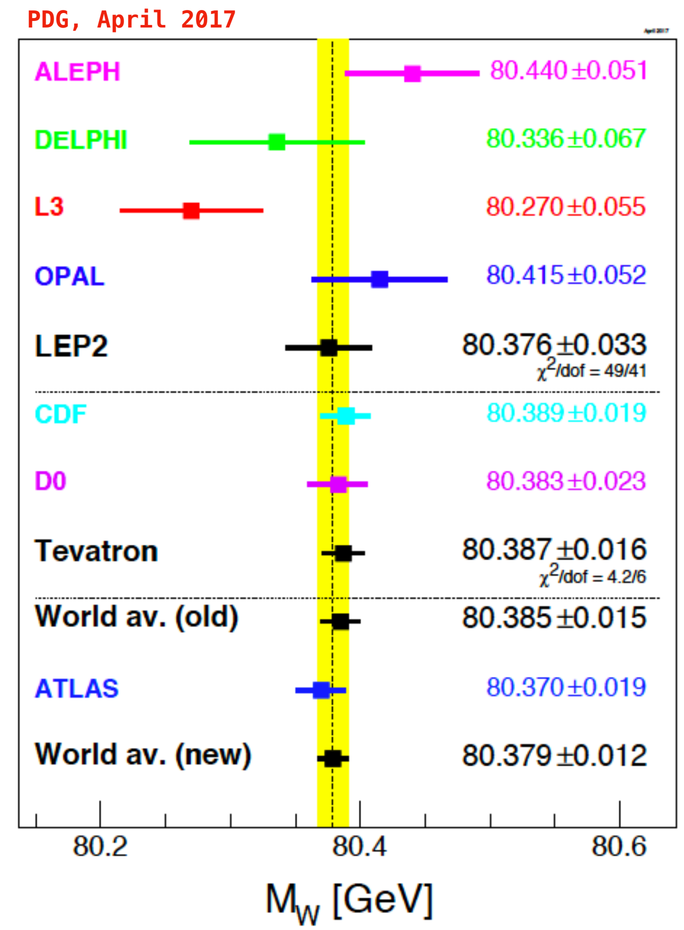




D. Froideval

W mass measurement with ATLAS





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.
80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

stat. = 6.8 MeV   exp. syst = 10.6 MeV   mod. syst =13.6 MeV

m_W = 80370 +- 19 MeV

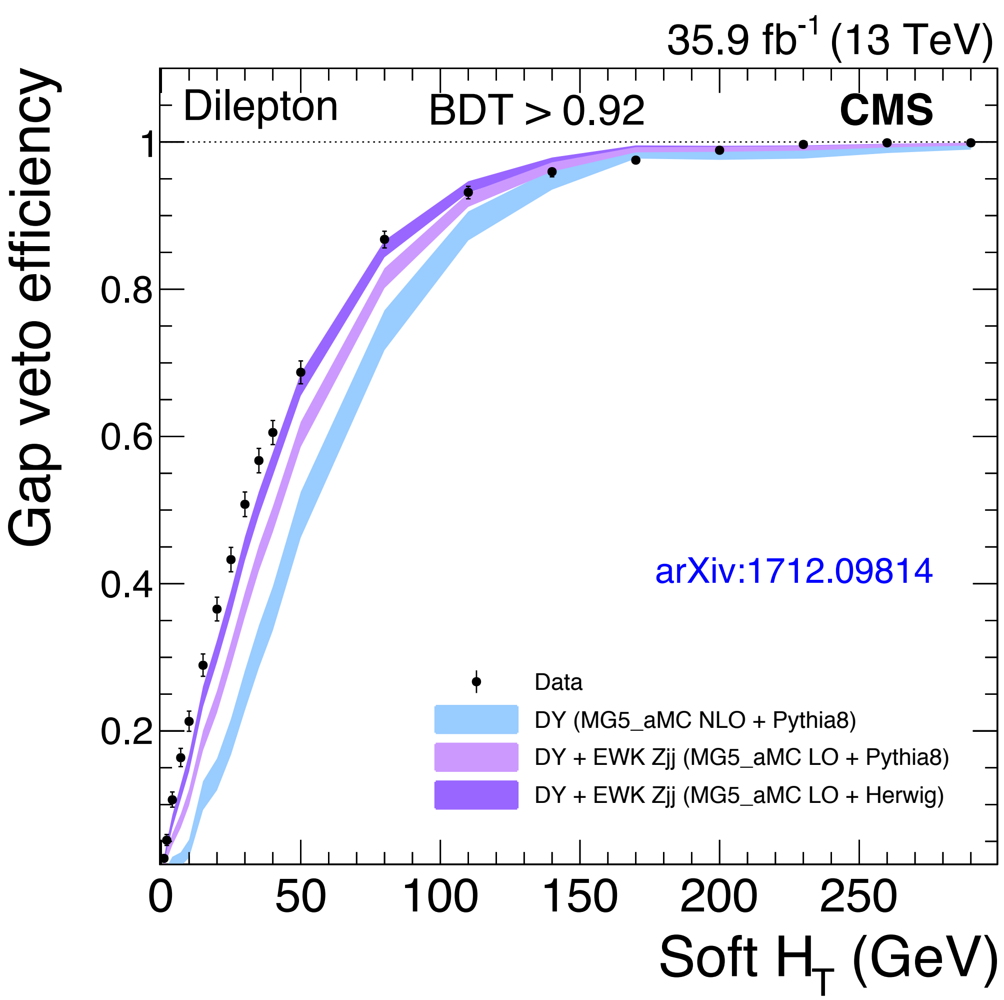
ATLAS EXPERIMENT CMS LHCb

Z VBF

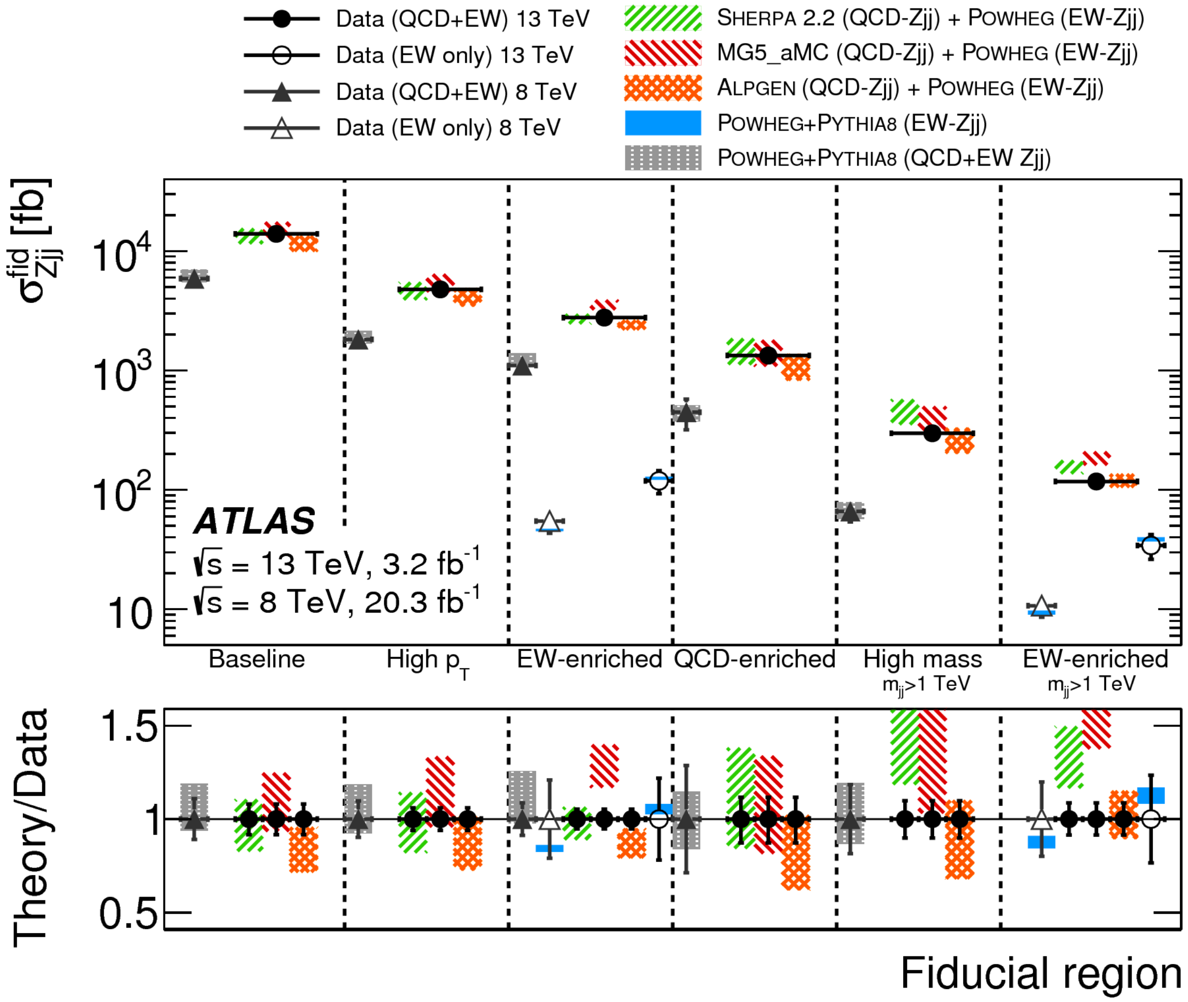
Properties of EW Zjj signal events:

well-separated jets in rapidity with large mjj, and central decay of Z boson

suppressed color flow in the region between the two jets (low hadronic activity in the rapidity interval)



Physics Letters B 775 (2017) 206



Simultaneous fit of EW and QCD component in the signal and control regions