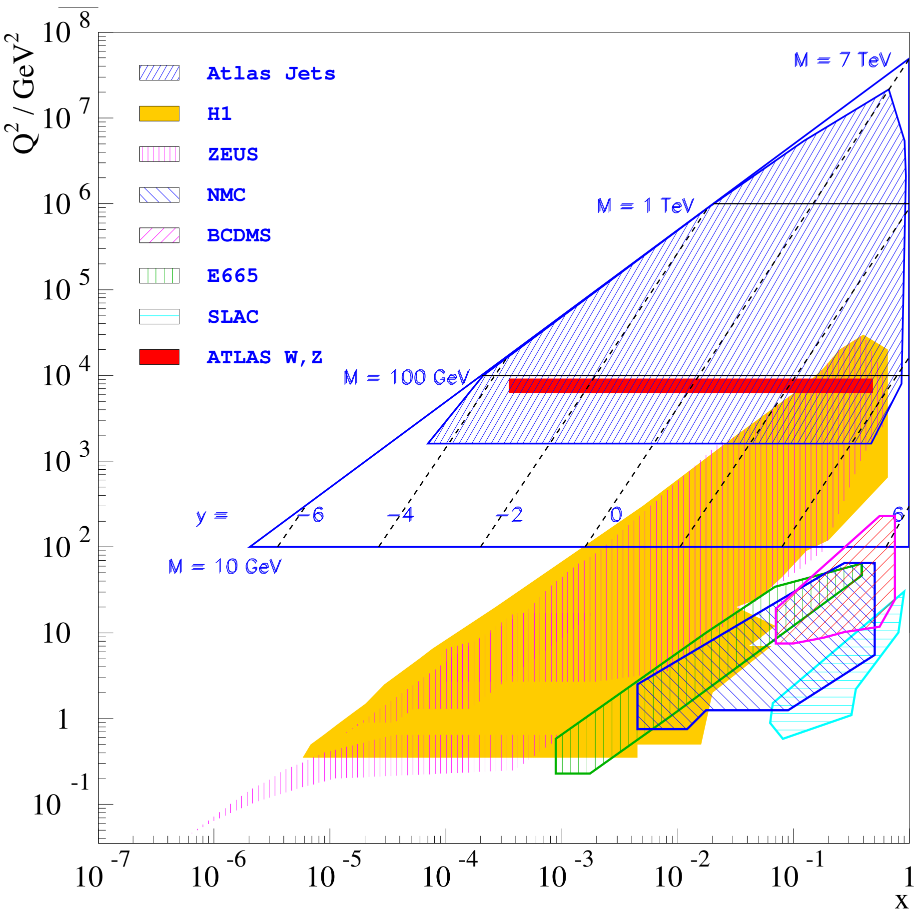
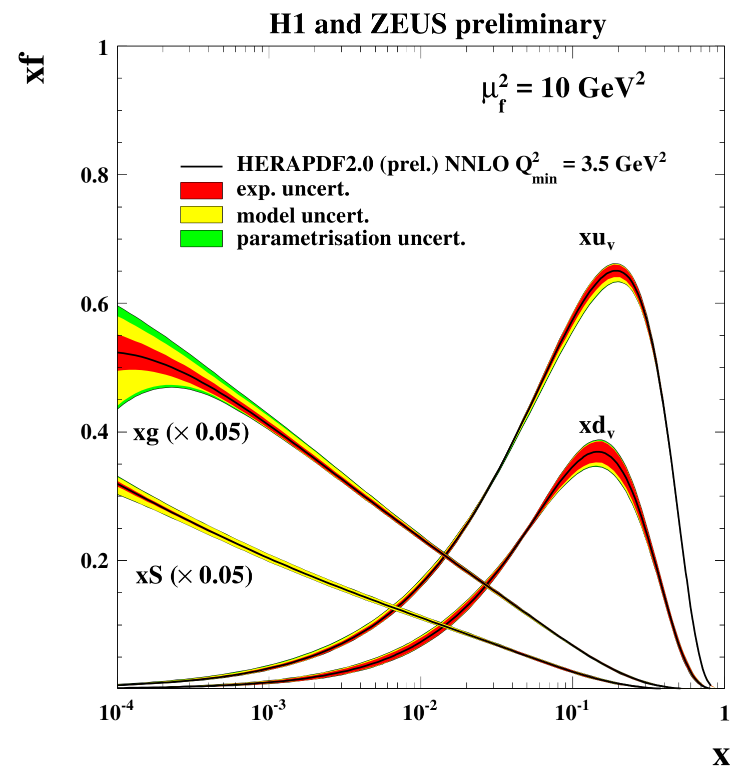
Precision Drell-Yan measurements at ATLAS

S. Glazov, Minsk, 27 Feb 2018

The LHC: parton-parton collider

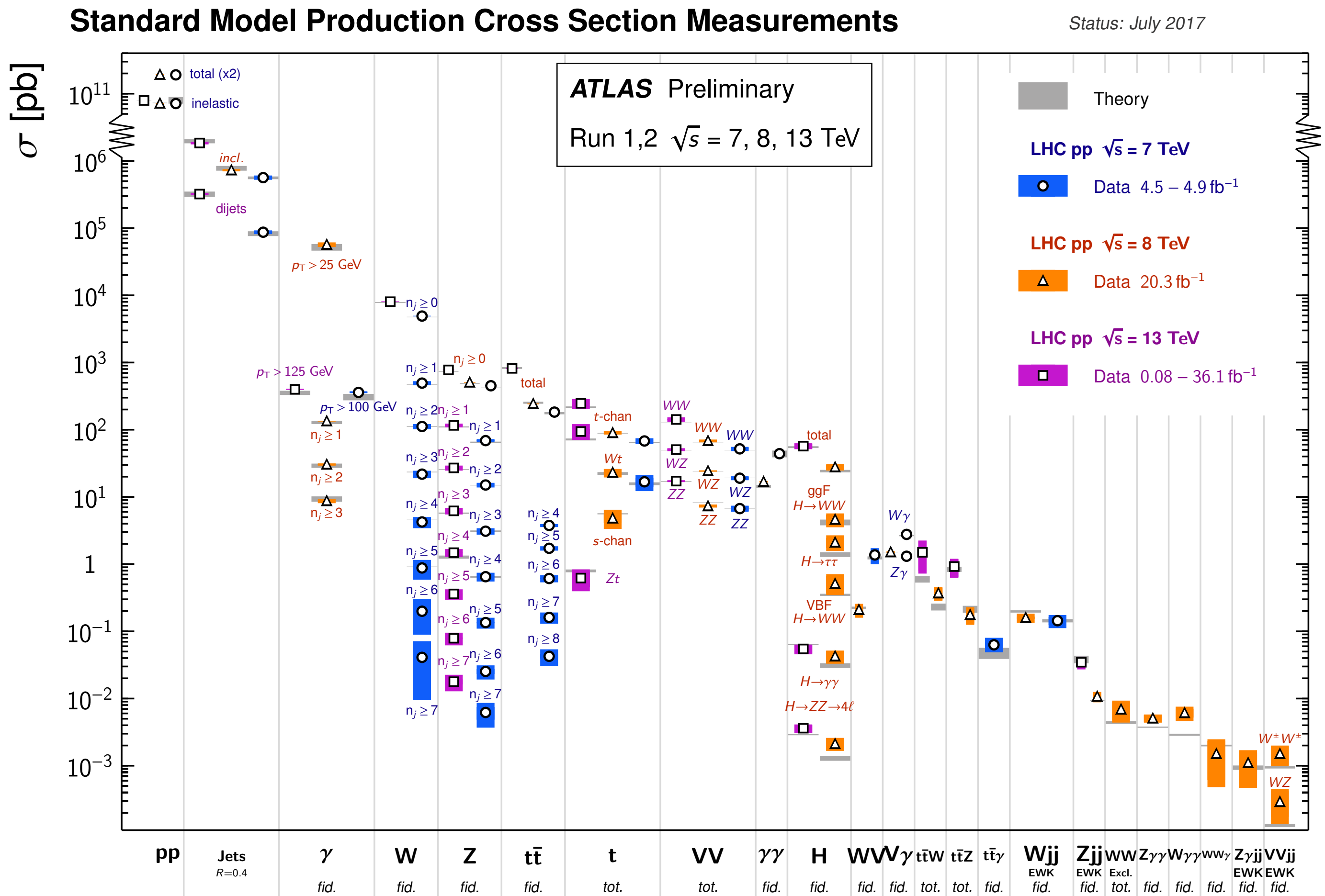




Protons are not elementary, "hard collisions" involve partons carrying fraction of the beam energy, $x_1 P$ and $x_2 P$. The effective centre of mass energy is $\sqrt{\hat{s}} = 2P\sqrt{x_1 x_2}$.

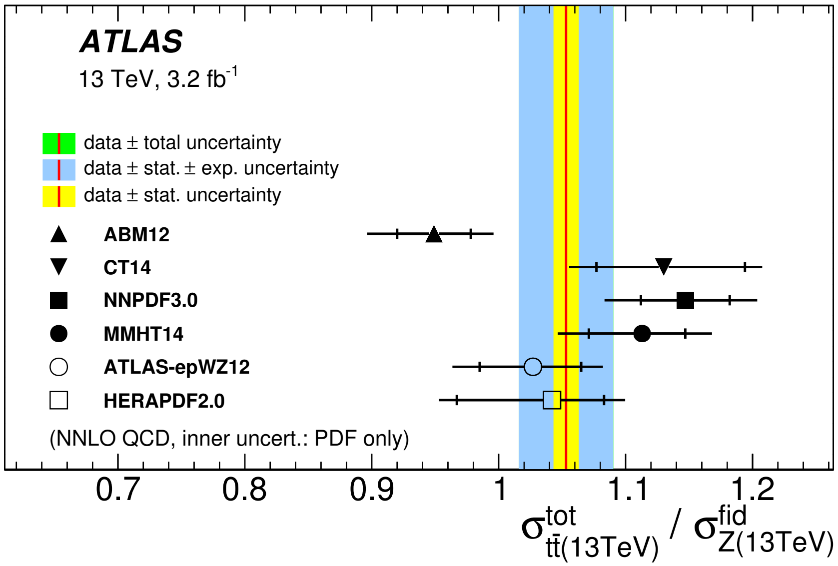
At large $x > 0.1$, valence u_v and d_v quarks play dominant role. For low x, LHC is the gluon-gluon and gluon-(anti)quark collider.

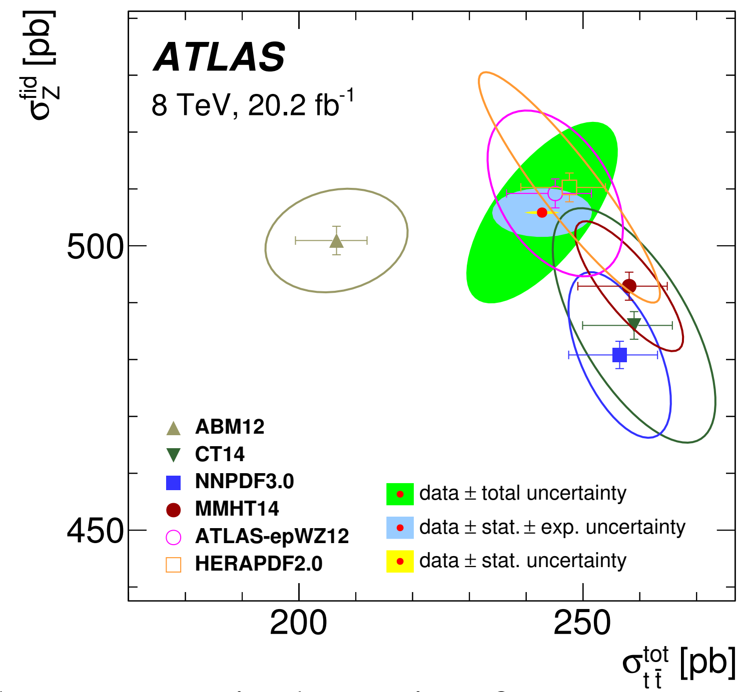
The measured processes



- Many new measurements from the LHC experiments.
- From first results at $\sqrt{s} = 13$ TeV to precision analyses of run I data.

$\sigma_{t\bar{t}}/\sigma_Z$ ratio measurement





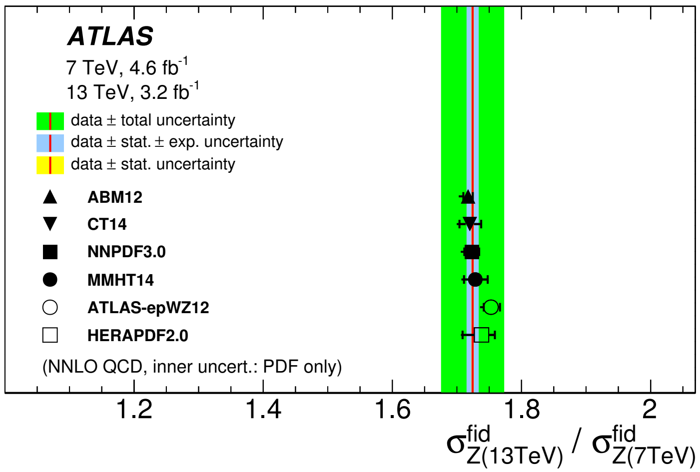
- Production of $t\bar{t}$ and Z dominated by gg and $q\bar{q}$, respectively: ratio of cross sections is sensitive to gluon/sea at $x \sim 0.1$.
- Dedicated measurement of σ_Z^{fid} at $\sqrt{s} = 13$ GeV for

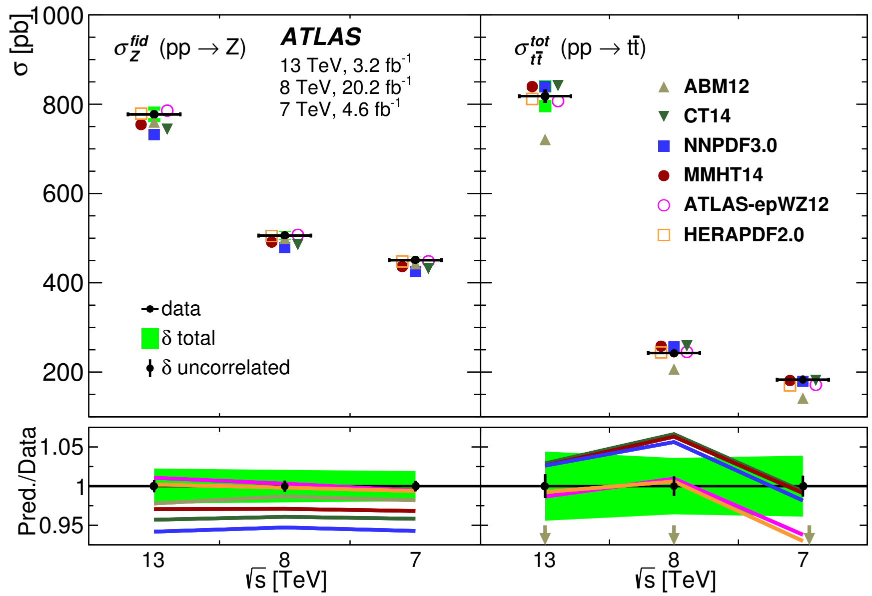
$$\frac{\sigma_{t\bar{t}}^{\text{tot}}}{\sigma_Z^{\text{fid}}} = \frac{2\sigma_{t\bar{t}\to X+e\mu}^{\text{tot}}}{\sigma_{Z\to ee}^{\text{fid}} + \sigma_{Z\to\mu\mu}^{\text{fid}}}$$

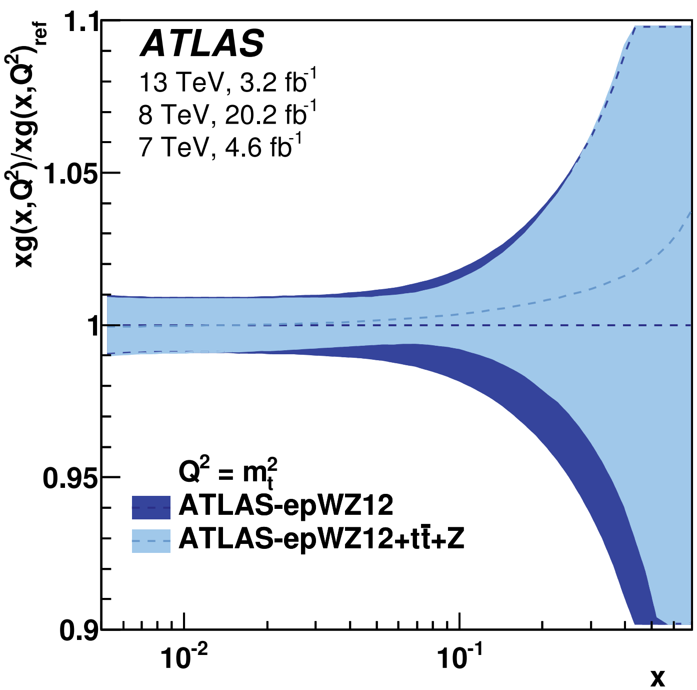
- Evaluation of correlations for existing 7, 8 TeV measurements.

ATLAS, JHEP 02 (2017), 117

Correlated Z and $t\bar{t}$ cross sections

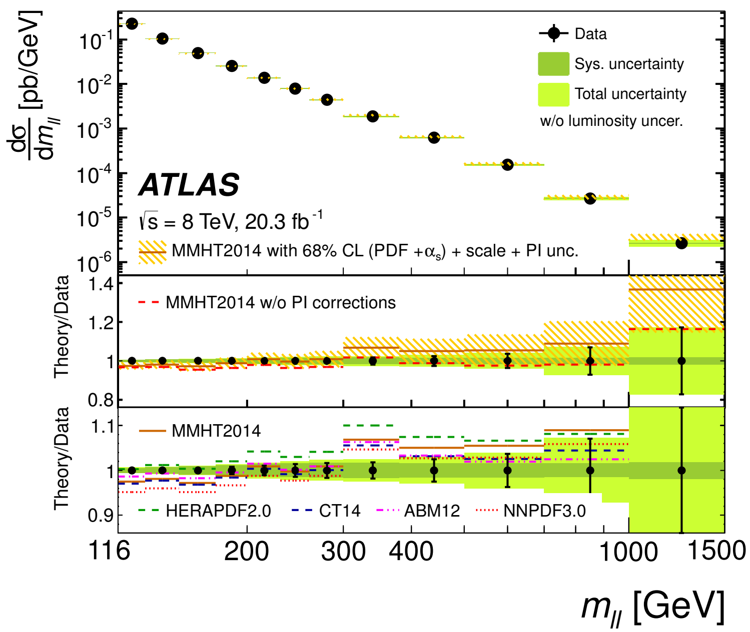


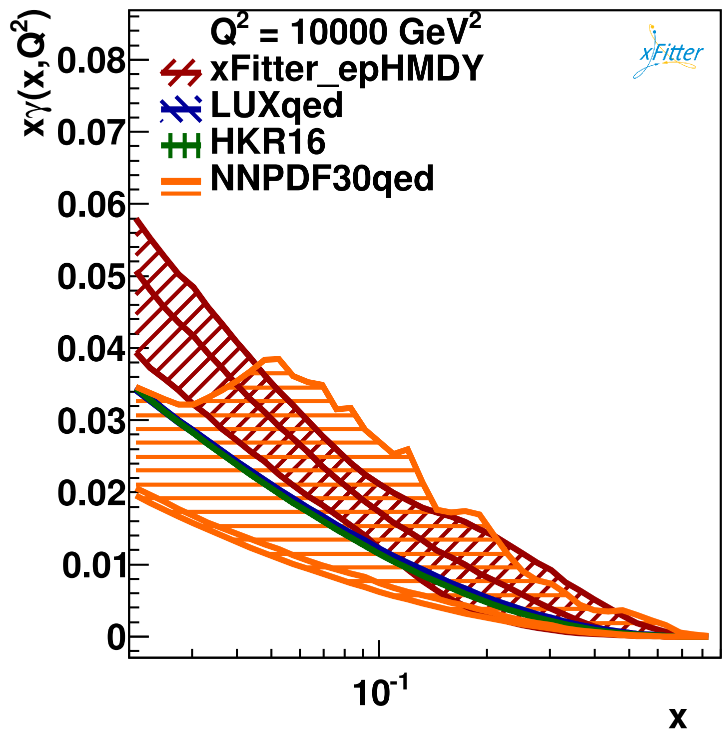




- Ratio of σ_Z^{fid} at different $\sqrt{s}$ has small PDF uncertainty, smaller vs lumi error.
- ATLAS data agree best with HERAPDF2.0 and ATLAS-epWZ12 PDFs.
- Profile ATLAS-epWZ12 PDF using correlated fiducial cross sections; sizable impact on the gluon uncertainty (and almost no pull on central value).

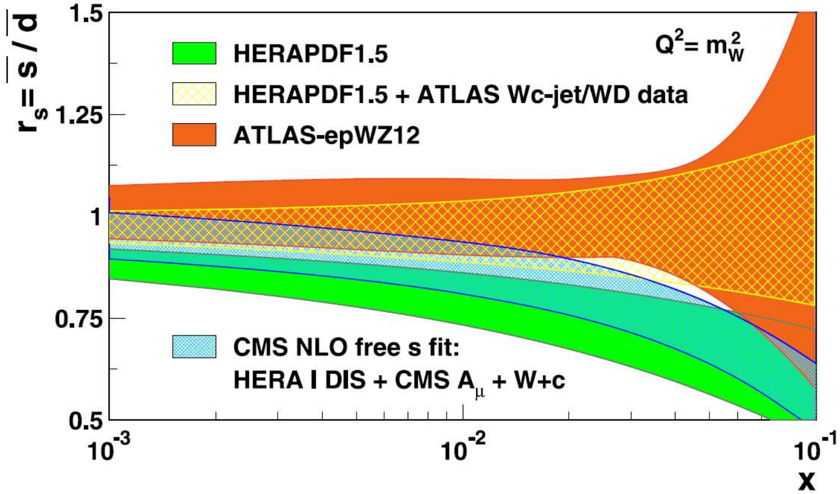
High mass DY measurement at $\sqrt{s} = 8$ TeV





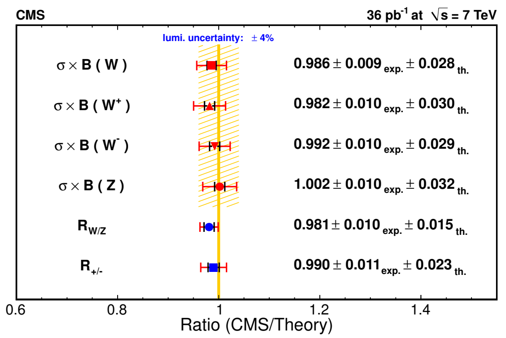
- Measurement in e and μ channels with combined experimental precision better than 1% for low $M_{\ell\ell}$ (plus 1.9% lumi), double differential in $M_{\ell\ell}$ and $y_{\ell\ell}$ and $\delta\eta_{\ell\ell}$.
- Sensitive to $\gamma\gamma \to \ell\ell$ with significant constraining power vs NNPDF3.0, as shown by xFitter-team analysis
  ATLAS, JHEP 08 (2016) 009; xFitter, EPJC 77 (2017) 400

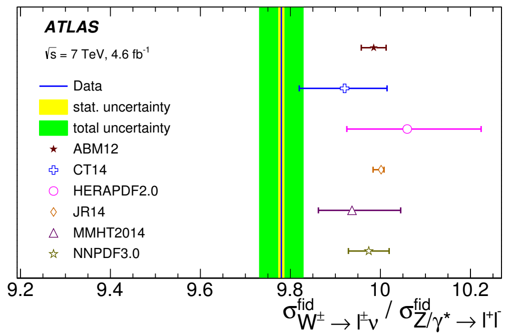
Strange-quark distribution

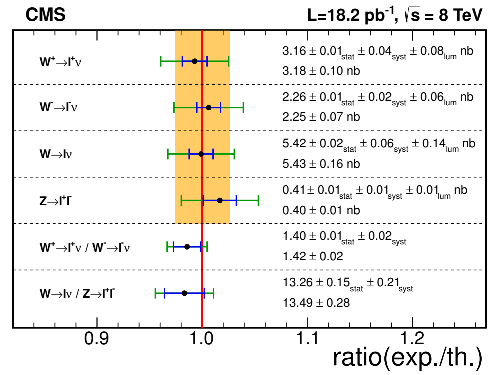


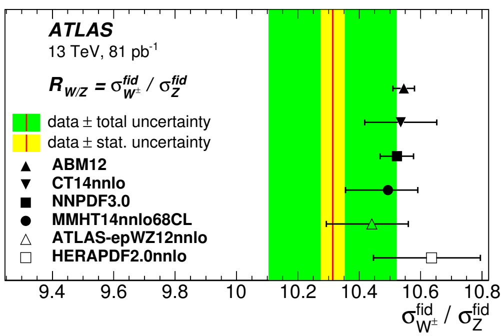
- Light-quark sea is likely to be symmetric for *u*- and *d*-quarks for small *x*. For the strange-quark distribution it might be different.
- Fixed-target neutrino data on $\nu_\mu s \to \mu^\pm c^\mp \to \mu^- \mu^x X$ scattering suggests suppression.
- LHC data are sensitive to the strange-quark distribution via:
  - *Z*-boson rapidity distribution (more central for $s\bar{s}$)
  - σ_W/σ_Z cross section ration (affects more *Z* vs *W*)
  - $gs \to W^\pm c^\mp \to \ell^\pm \nu c^\mp$ production of *W*-boson with tagged charm.

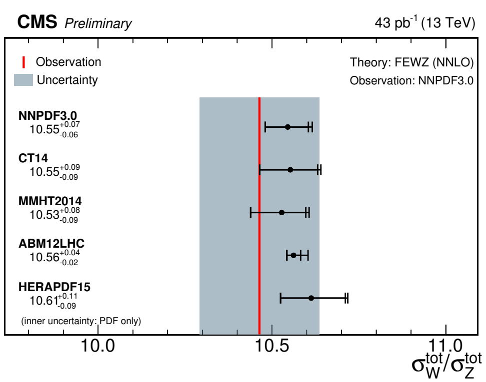
W/Z cross section ratios









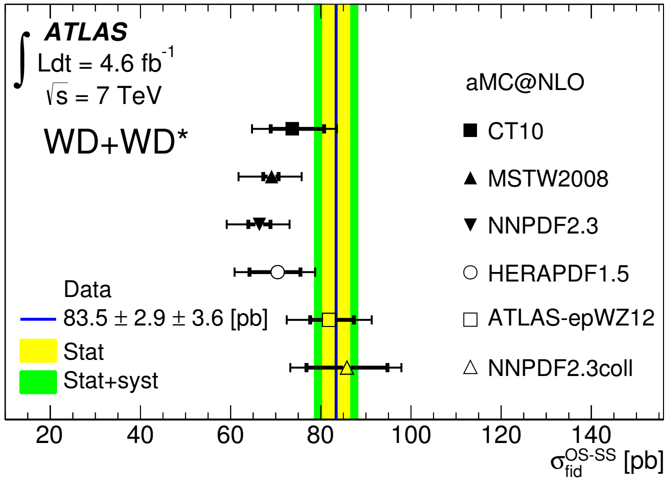


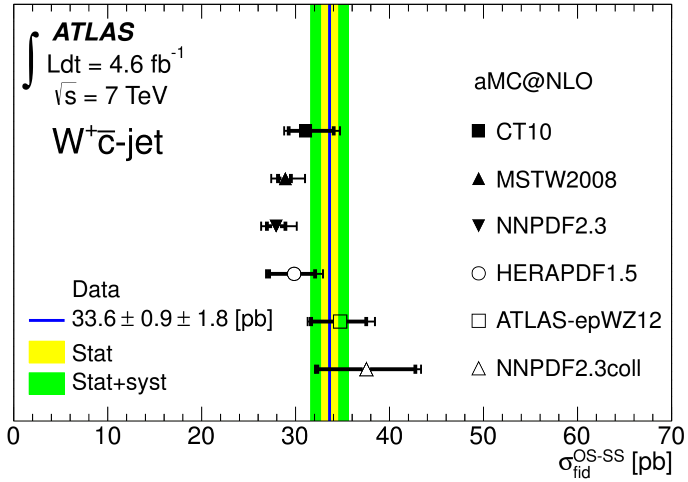
- All measured ratios σ_W/σ_Z tend to be below predictions for PDFs with suppressed strangeness.
- Further more accurate measurements required; best exp. accuracy is for fiducial cross sections.
- Additional uncertainty for fiducial predictions: difference between FEWZ vs DYNNLO NNLO predictions for the ratio (at 0.5% level).

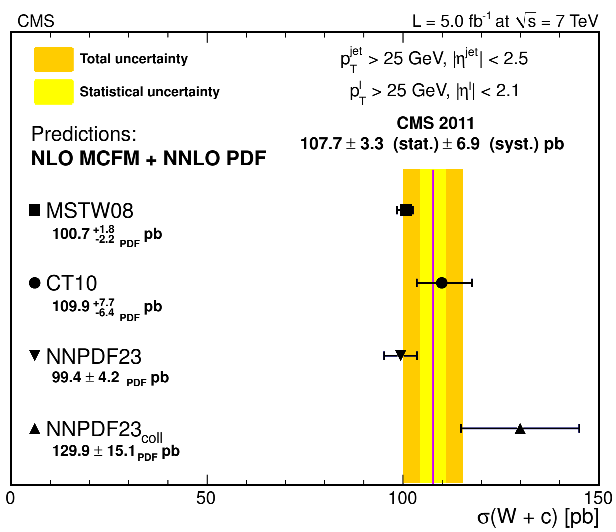
→ N3LO ?

CMS JHEP 10 (2011) 132, PRL 112 (2014) 191802, CMS-PAS-SMP-15-004, ATLAS PLB 759 (2016) 601, EPJ C77 (2017) 367

Measurements of $W+c$ from ATLAS and CMS



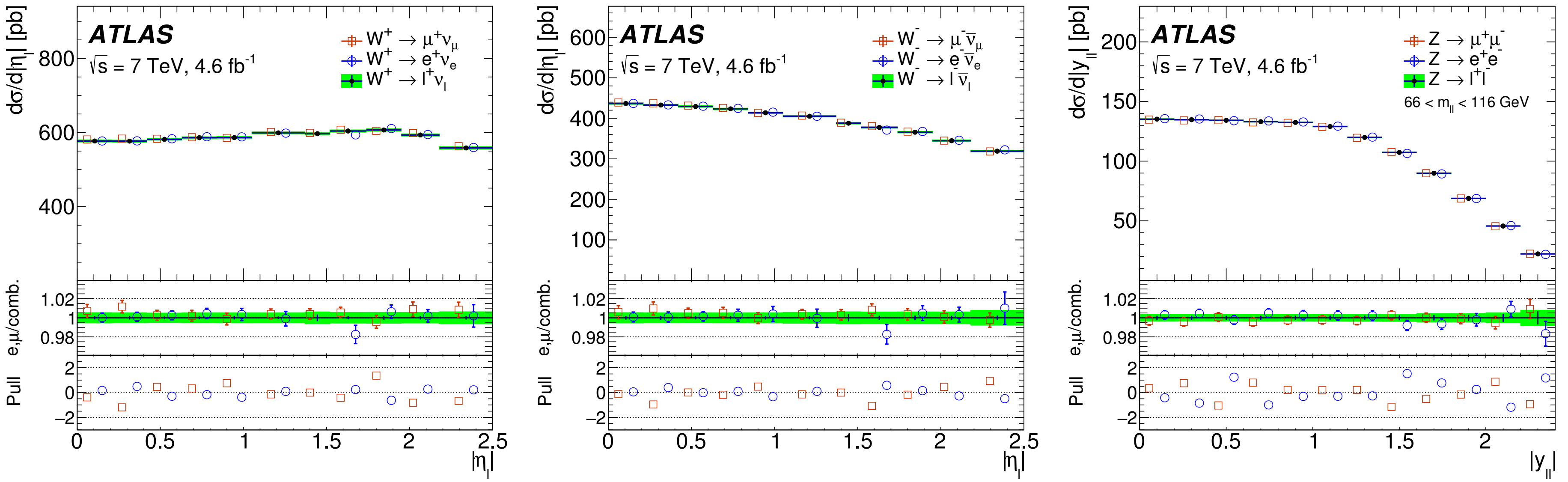




- Measurements of $\sigma(W^\pm c^\mp) - \sigma(W^\pm c^\pm)$ from ATLAS and CMS (JHEP 02 (2014) 013, arXiv:1402.6263), using c-jets tagged by soft muons and $D^{(*)}$ mesons, to probe strange-sea PDF using $gs \to Wc$ process.
- Large NLO scale uncertainties. For $W + c$-jet ($p_T > 20$ GeV), can use NNLO for W+jet.

$\to$ NNLO for $W + D$

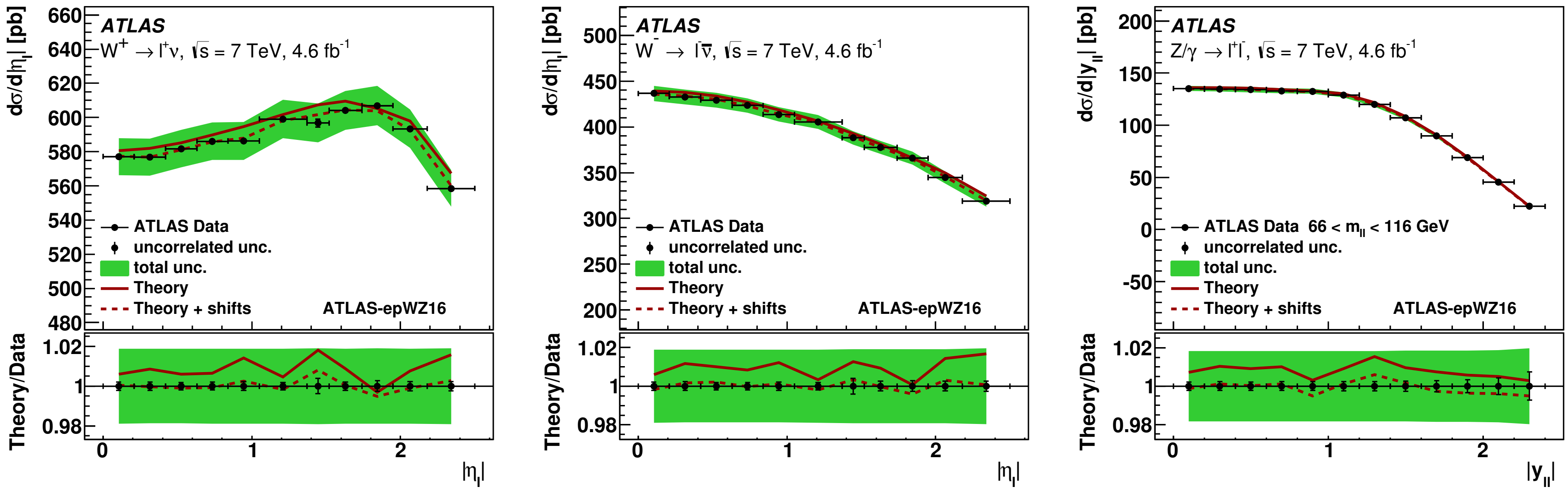
W and Z cross sections at $\sqrt{s} = 7$ TeV



- Differential measurements of $W^{\pm}$, Z/γ^{*} production (including off-peak) using electron and muon decays, with sub-percent accuracy, and full correlated errors treatment.
- Good compatibility of the two channels, $\chi^2/\mathrm{dof} = 59.5/53$, combined result has better than 0.5% accuracy.

ATLAS EPJ C77 (2017) 367.

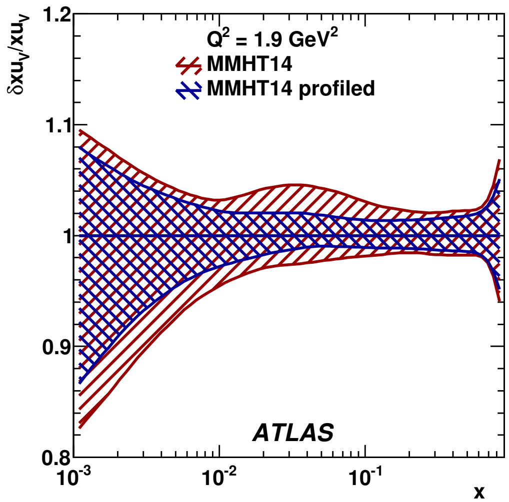
W and Z cross sections at $\sqrt{s} = 7$ TeV

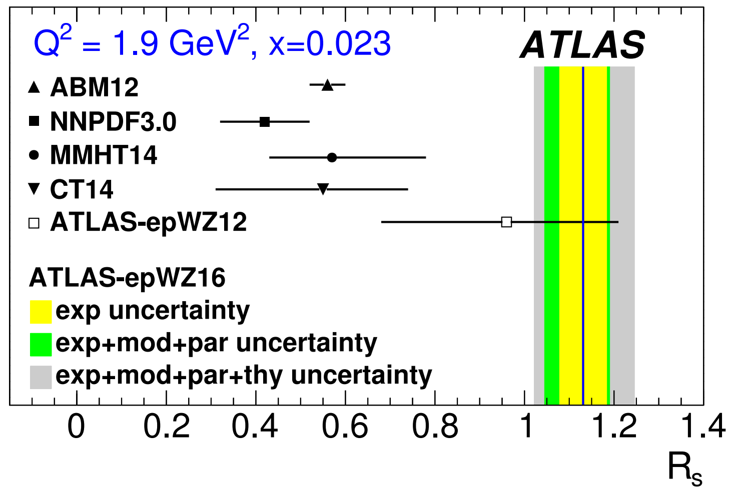


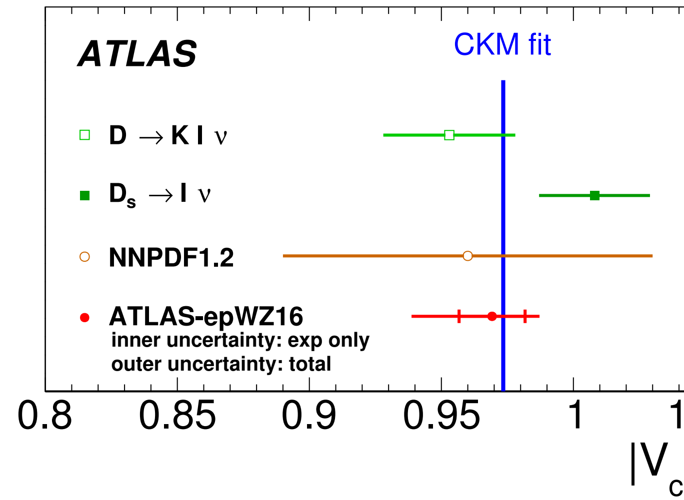
- ATLAS $W, Z/\gamma^*$ data together with the inclusive HERA-II data included in a QCD analysis at NNLO QCD + NLO EWK using xFitter program.

- Challenge for the theory to match the data accuracy, $\chi^2/\mathrm{N_{data}} = 108/61$ (ATLAS only) for the nominal scale settings $\mu_F = \mu_R = M_Z$, improving to $\chi^2/\mathrm{N_{data}} = 85/61$ for $\mu_F = \mu_R = 1/2M_Z$

W and Z cross sections at $\sqrt{s} = 7$ TeV

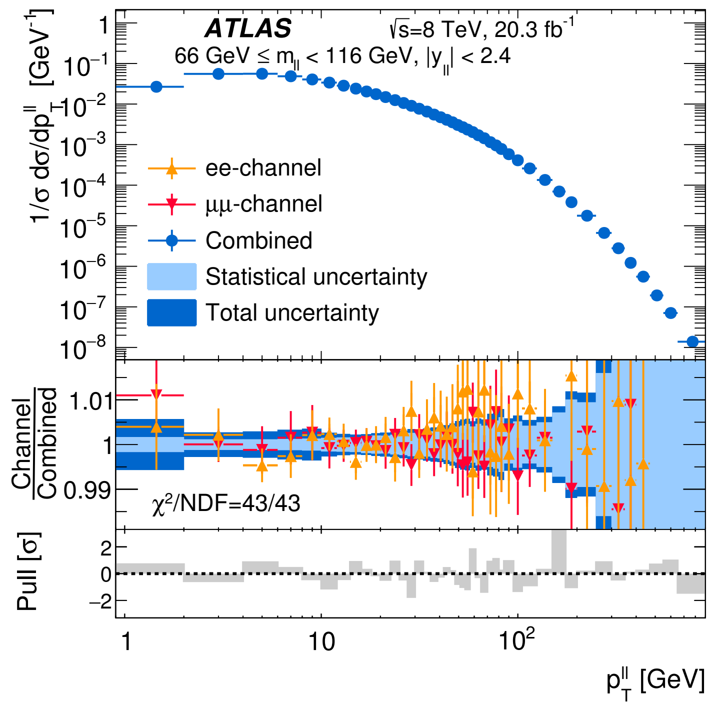


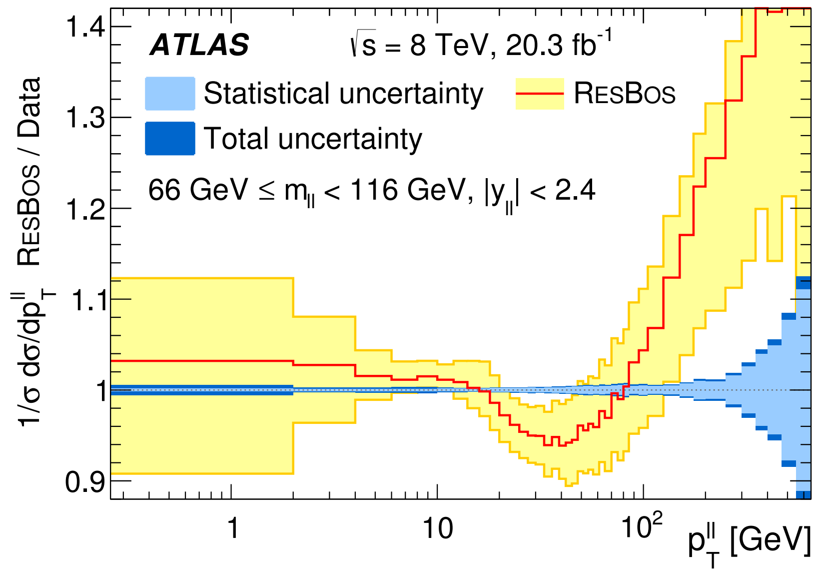




- Significant impact on valence-quark distributions (estimated using PDF profiling vs modern MMHT14 set), as well on the light sea-quark decomposition, $R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}}$, determined from the QCD fit for the x-value of maximal sensitivity.
- Sensitivity of the W cross-section data to production from $c\bar{s}$ ($s\bar{c}$) initial quarks allows to determine CKM matrix element V_{cs}, with an accuracy comparable to dedicated determinations from D-meson decays.

Measurement of Z_{p_T}

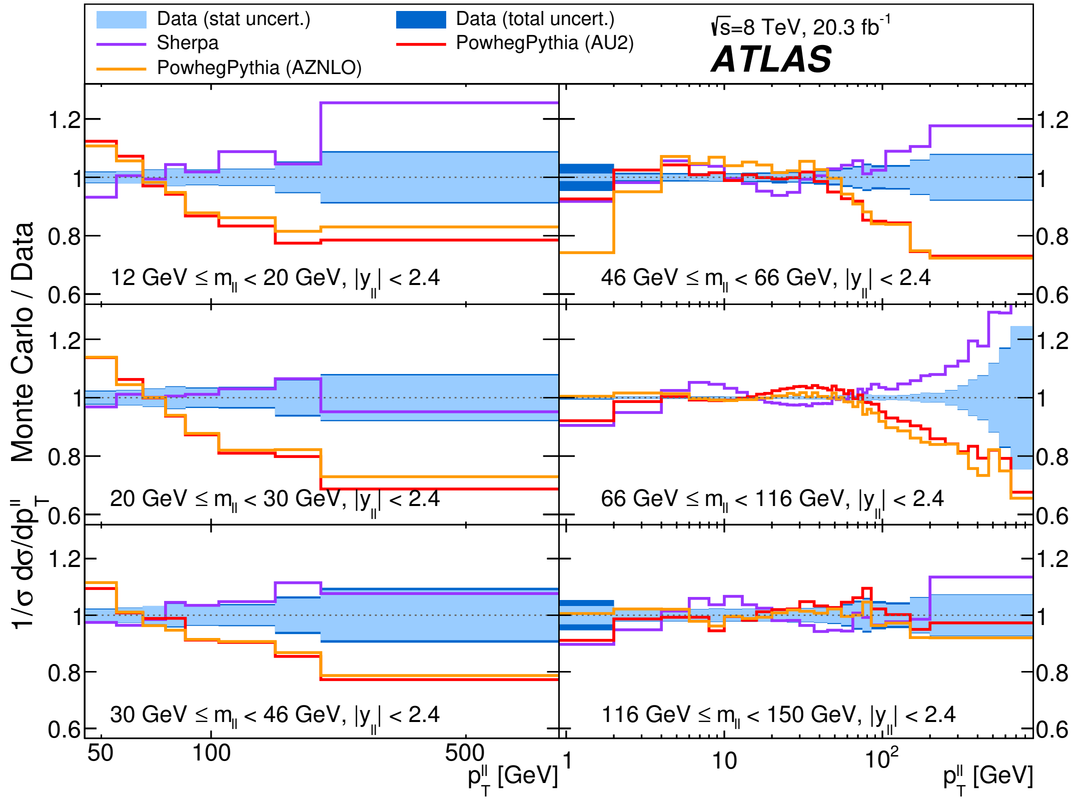




- Several measurements of Z_{p_T} at $\sqrt{s} = 7$ and 8 TeV by ATLAS and CMS.
- ATLAS measurements use both $Z \to ee$ and $Z \to \mu\mu$ channels, which have comparable accuracy. The combined result is accurate to better than 0.5% for $P_T < 100$ GeV range.

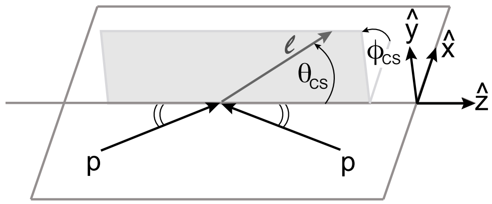
ATLAS, EPJ C76 (2016) 12

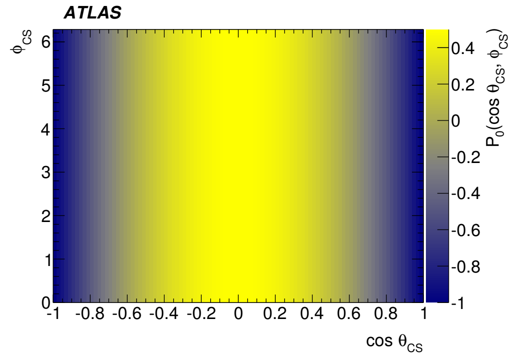
Off-peak p_T measurements

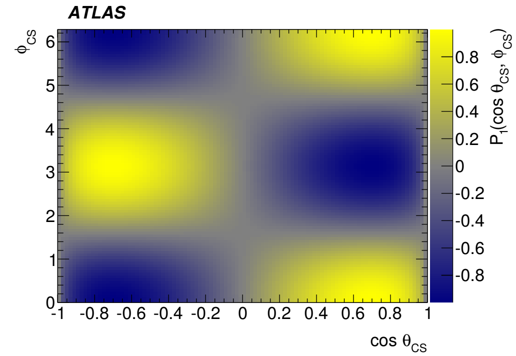


- Large $\sqrt{s} = 8$ TeV samples can be used to probe distributions double differentially. Studying dependence in mass can probe different PDF decomposition, scale dependence, electroweak effects.
- Dedicated Powheg+Pythia tune AZNLO, developed using Z_{p_T} $\sqrt{s} = 7$ TeV data, works very well for the peak range but deviates at low masses.

Z-boson polarisation



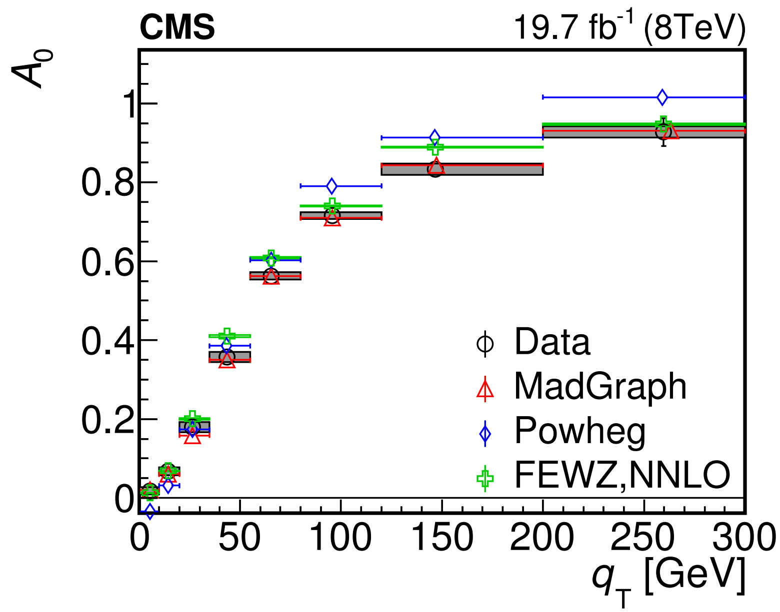


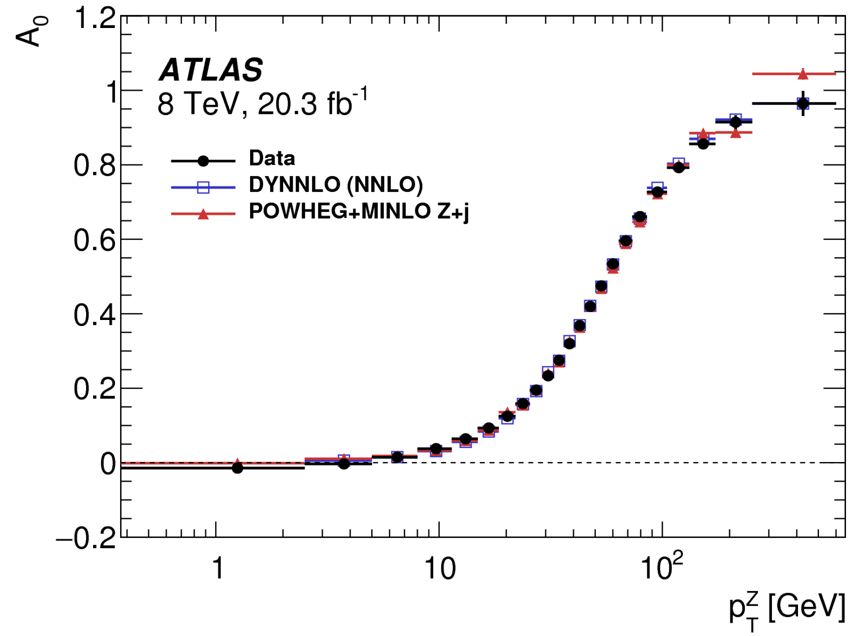


$$\frac{d\sigma}{d\cos\theta d\phi} = (1+\cos^2\theta) + A_0\frac{1}{2}(1-3\cos^2\theta) + A_1\sin 2\theta + \frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi$$
$$+A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\,.$$

- W, Z bosons are vector particles and are produced polarised. Decay distributions can be described by spherical harmonics with eight parameters.
- At leading order QCD, only A_4, corresponding to forward-backward asymmetry is present
- At NLO, due to new gq and $g\bar{q}$ diagrams, $A_0 - A_4$ are not zero.
- All coefficients are not zero at NNLO.

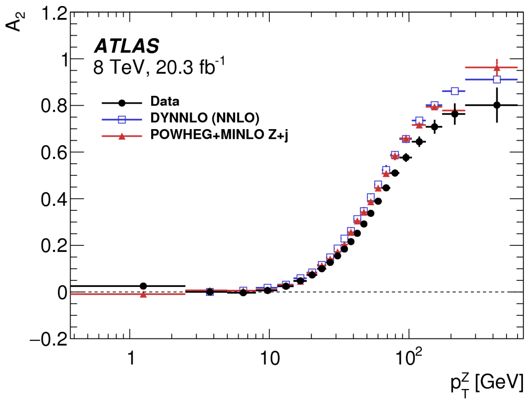
Z polarisation results

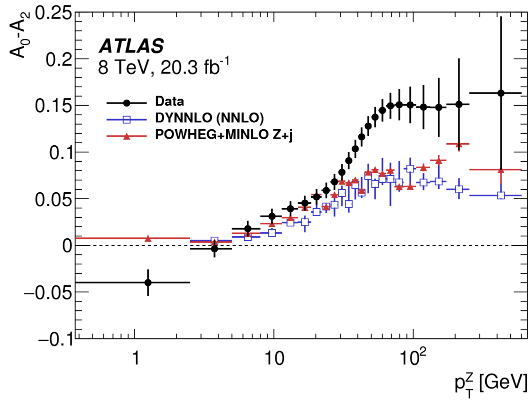


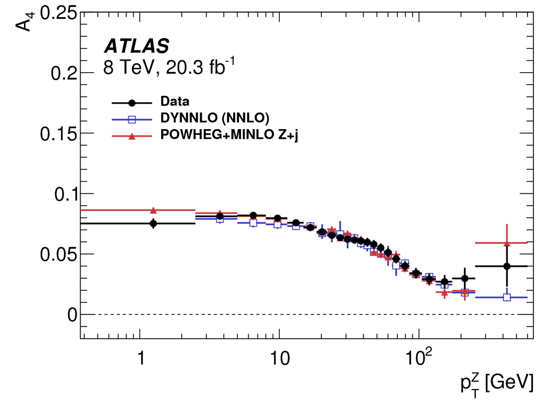


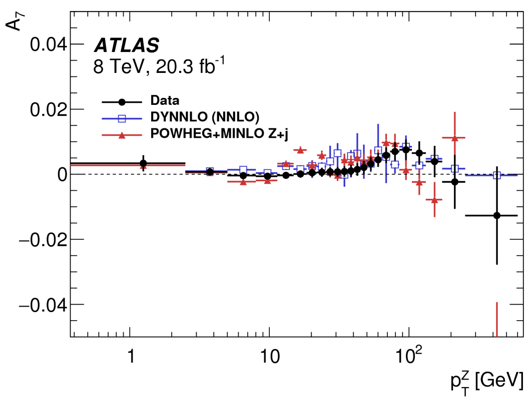
- Measurement of Z polarisation coefficients from ATLAS and CMS.
- ATLAS measures all $A_0 - A_8$ polynomials using data from both electron and muon channel and their combination.
- Excellent agreement for A_0 with NNLO QCD.
  CMS, PLB 750 (2015) 154, ATLAS JHEP 08 (2016) 159.

Z angular coefficients





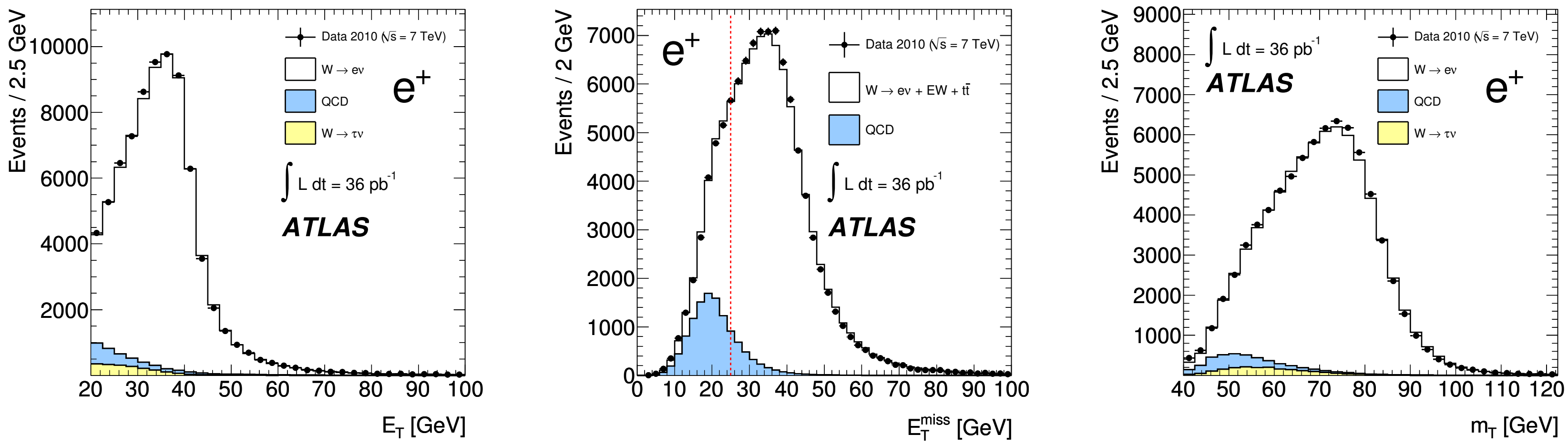




- $A_0 - A_0$ is expected to become non-zero at NNLO, data confirms that
- Data deviates from NNLO expectations for A_2 (and $A_0 - A_2$) at high p_T.
- A_4 measures forward-backward asymmetry, can be used to extract $\sin^2\theta_W$
- Higher order coefficients appear from NNLO, evidence of them in data.

ATLAS JHEP 08 (2016) 159.

Main experimental techniques to measure M_W

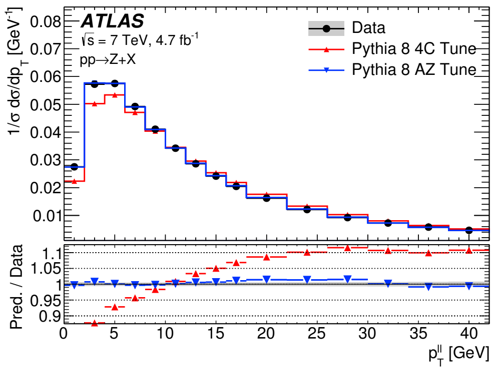


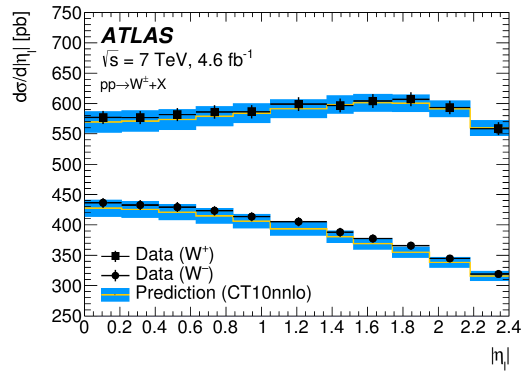
$$pp \to X + W^{\pm}, \quad W^{\pm} \to \ell^{\pm}\nu$$

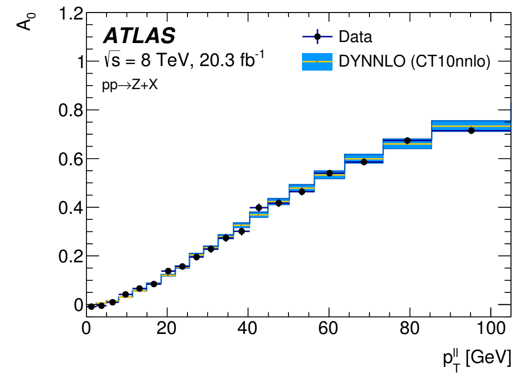
- Fit lepton ($e^{\pm}$ and $\mu^{\pm}$) p_T distribution around Jakobian peak. Most accurate experimentally, robust to pileup, most prone to W p_T modeling problems.
- Fit missing energy distribution E_T^{miss}. Requires modeling of hadron recoil. Hard in case of large pileup.
- Fit transverse mass M_T. Needs good E_T^{miss} reconstruction. Least prone to modeling issues.

Fits can be performed using binned in η-lepton, which can be useful to control PDF effects.

Theory inputs for W production modeling

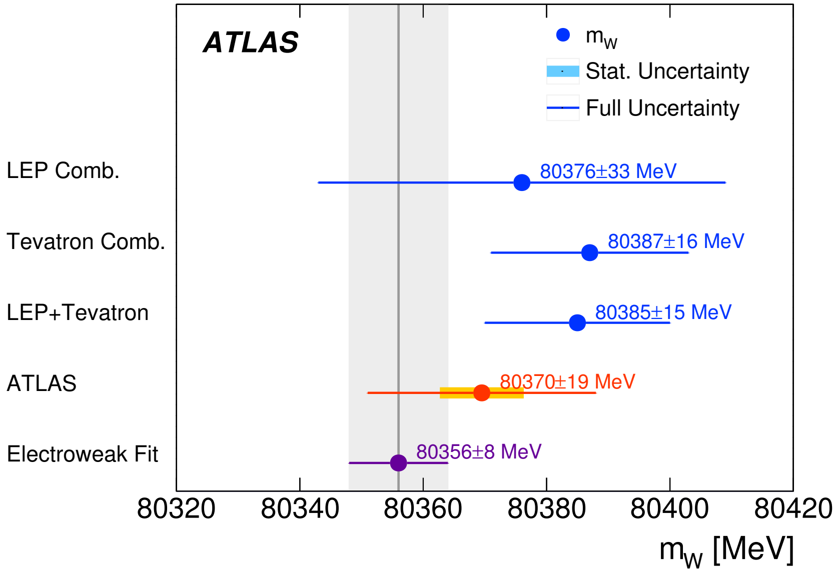


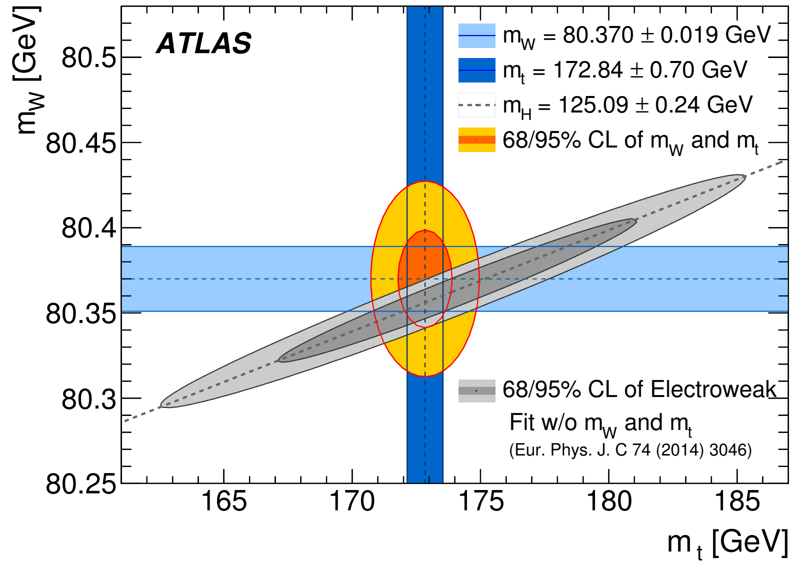




- Control over modeling of W production is essential for accurate W-boson mass measurement.
- Use data-driven methods as much as possible.
- Control W_{p_T} using measurements of Z_{p_T}. W_{p_T} can be measured directly → dedicated low pileup runs in 2017 at 5 TeV and 13 TeV.
- W rapidity is probed using lepton η distribution. Perform measurement in slices of η.
- W polarisation can be checked by the Z polarisation measurements.

m_W results





- Measurement accuracy is better than combined LEP, comparable to Tevatron individual best measurements.
- Modeling uncertainties dominate, but they can be reduced using additional measurements.
- ATLAS data are in perfect agreement with the expectations from the electroweak fit.

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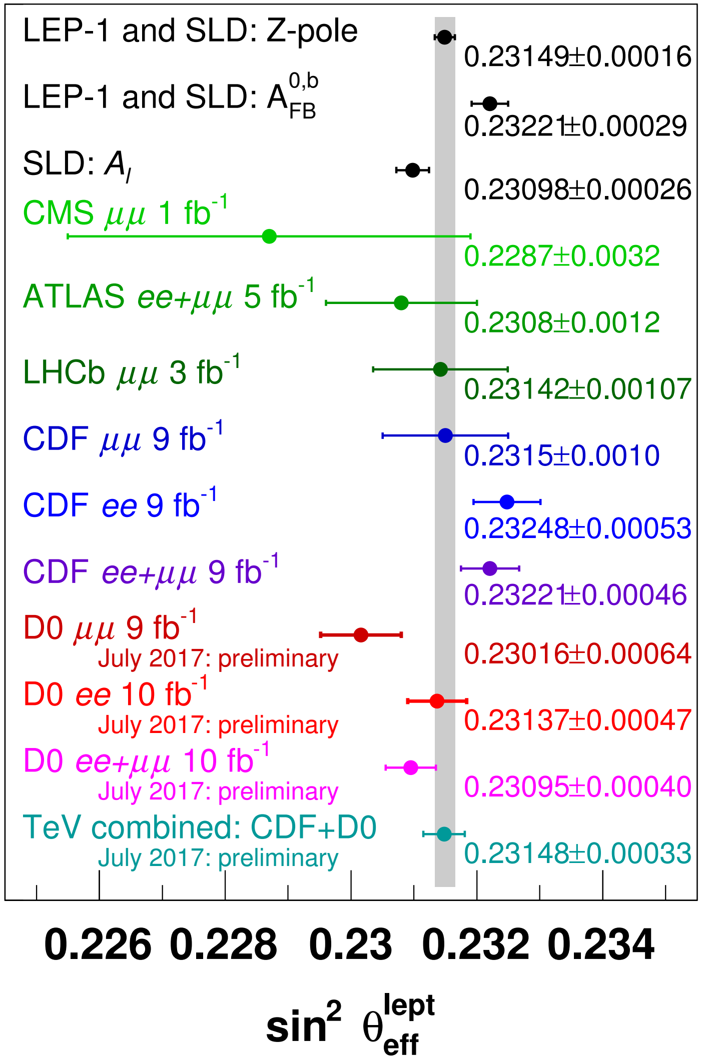
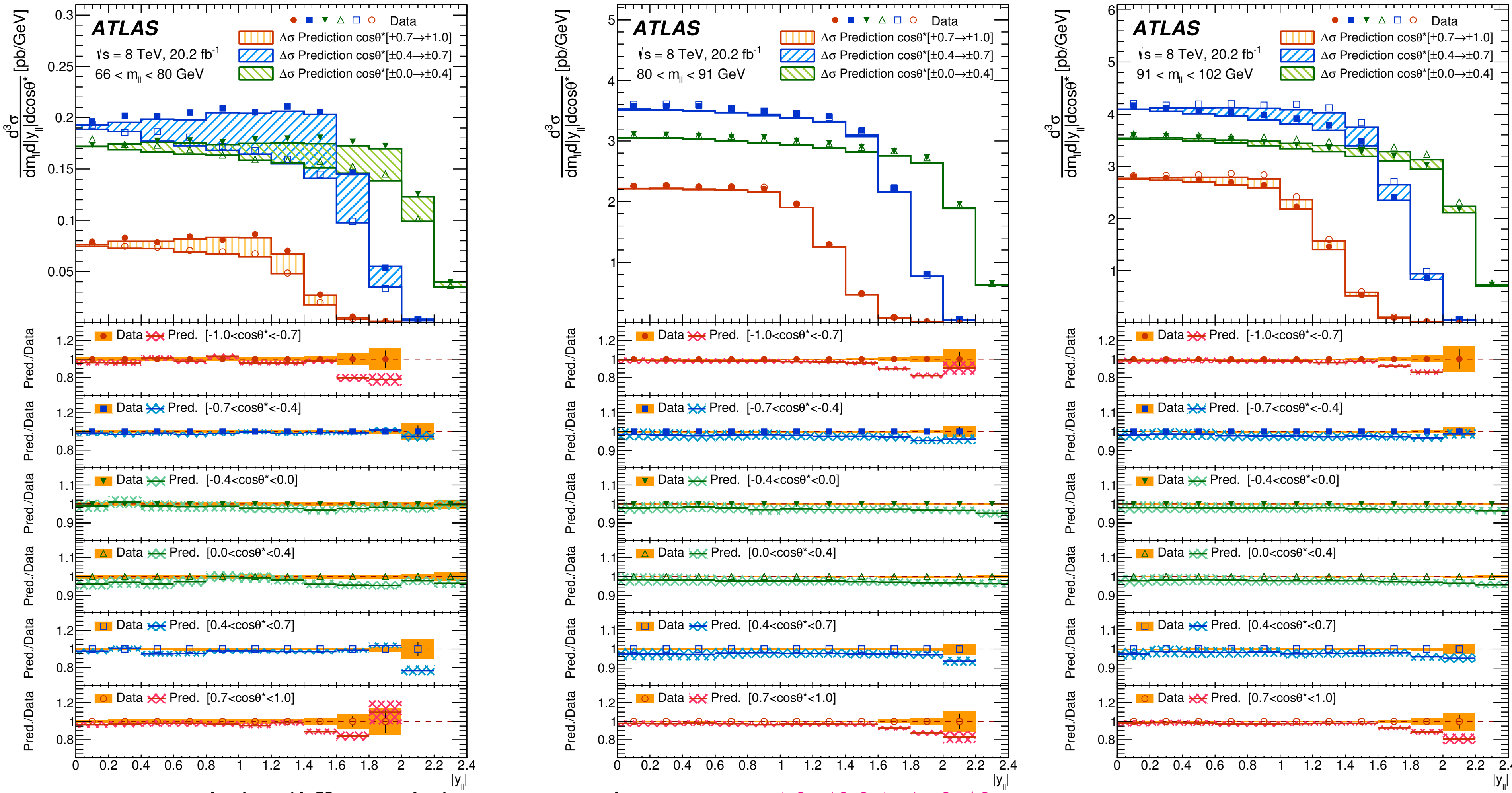
$\sin^2_{\rm eff}\,\theta_W$ experimental status



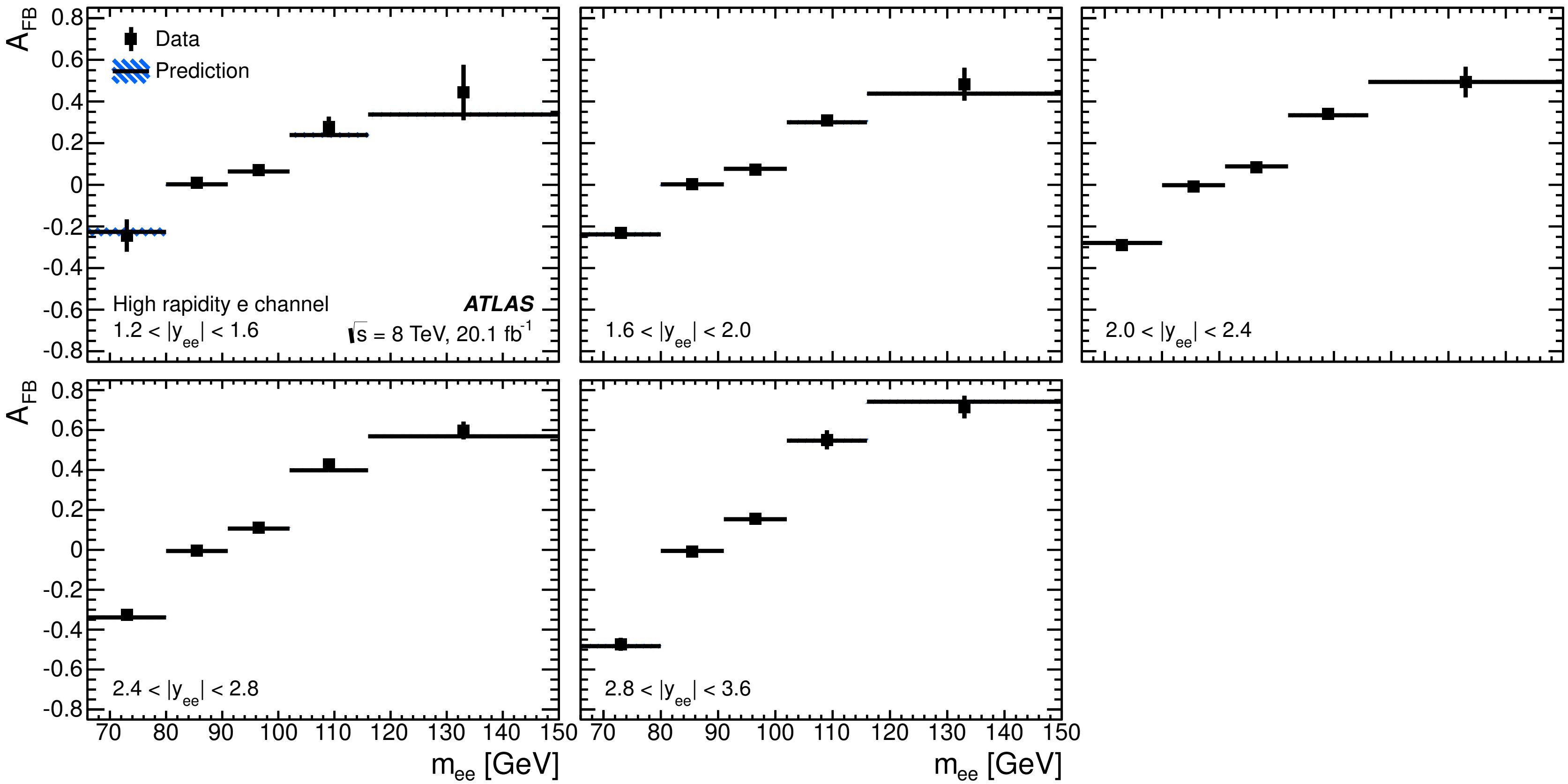
- Presented EPS combination of D0 and CDF results approaches in accuracy the individual LEP and SLD results.
- ATLAS $\sqrt{s} = 7$ TeV measurement is dominated by PDF uncertainties.
- CMS reports measurement at $\sqrt{s} = 8$ TeV using data to constraint PDFs which allows to reduce PDF uncertainties by factor 2, $\sin^2\theta^{\ell}_{eff,W} = 0.23101 \pm 0.00040$ (Exp) $\pm$ 0.00030 (PDF)

Triple differential cross section $d^3\sigma/dM_{\ell\ell}d|y_{\ell\ell}|d\cos\theta^*$



- Triple differential cross section JHEP 12 (2017) 059,
- Simultaneous sensitivity to PDFs and $\sin^2\theta_W$, interpreatations in terms of them as a next step.

Forward-backward asymmetry: Central Forward



- Cross-section measurements can be used to compute fiducial forward-backward asymmetry. It is large for central-forward channel.
- Measured A_{FB} ranges from -0.2 to +0.5 at the lowest and from -0.4 to +0.7 at the highest $y_{\ell\ell}$, in agreement with predictions.

Summary

- Precision Drell-Yan measurements start to challenge Standard Model predictions
- Measurements of cross-section ratios, $\sigma_{t\bar{t}}/\sigma_Z$, can be used to constrain gluon distribution function.
- Strange-quark distribution at low x remains to be a puzzle; further results and theory developments for $W + c$ production are needed.
- Measurements of Z-boson transverse momentum and polarisation provide precision tests of QCD and serve as calibration for the W-boson mass measurement.
- First W-mass measurement at the LHC is very accurate already, it is consistent with EWK fit.
- Precision determination of $\sin^2_{\theta_W}$ is on the way.