Inclusive and differential W and Z at CMS and ATLAS

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on behalf of the ATLAS and CMS Collaborations

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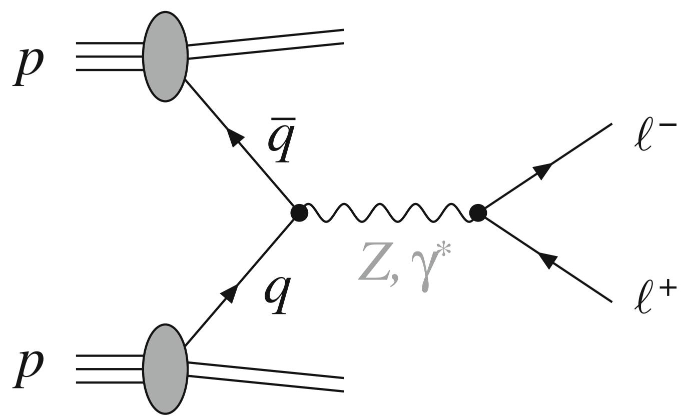
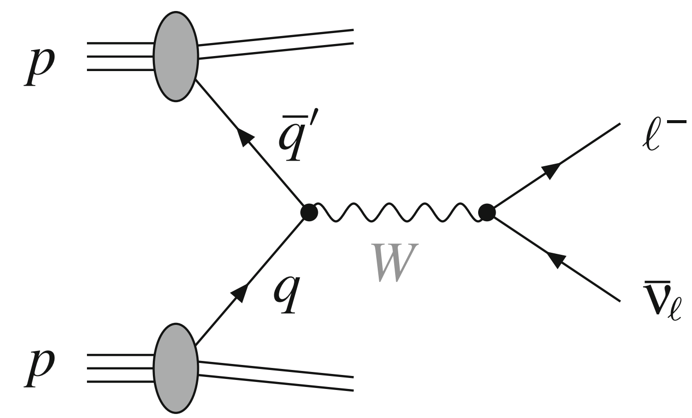
W and Z production

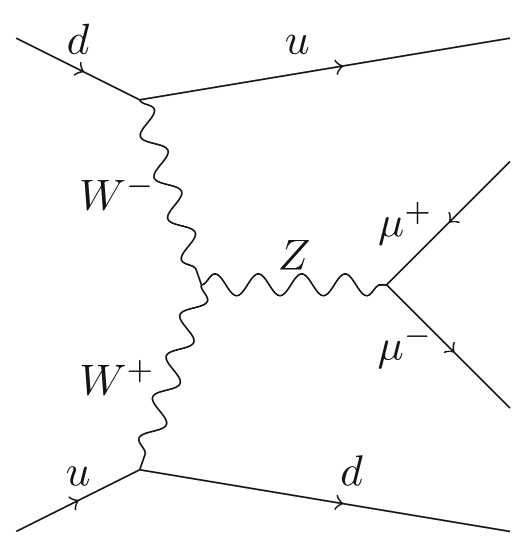
- Production of Z/γ* and W via Drell-Yan process

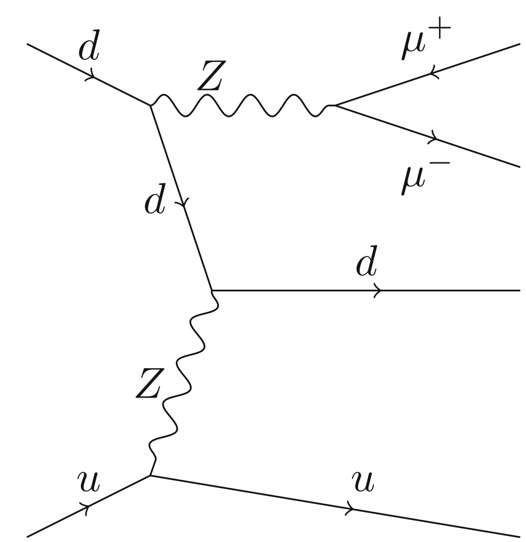




  - purely leptonic decays are a very clean experimental signature
  - observables sensitive to both QCD and EW sectors of the Standard Model
    - theory cross sections computed up to NNLO in QCD and NLO in EW
  - total and differential cross-sections (absolute or normalized) are sensitive to the proton structure (PDFs)

- EW production of Z and W bosons
  - vector boson fusion, bremsstrahlung-like and other diagrams
  - sensitive to triple gauge boson couplings
    - possible new physics contributions





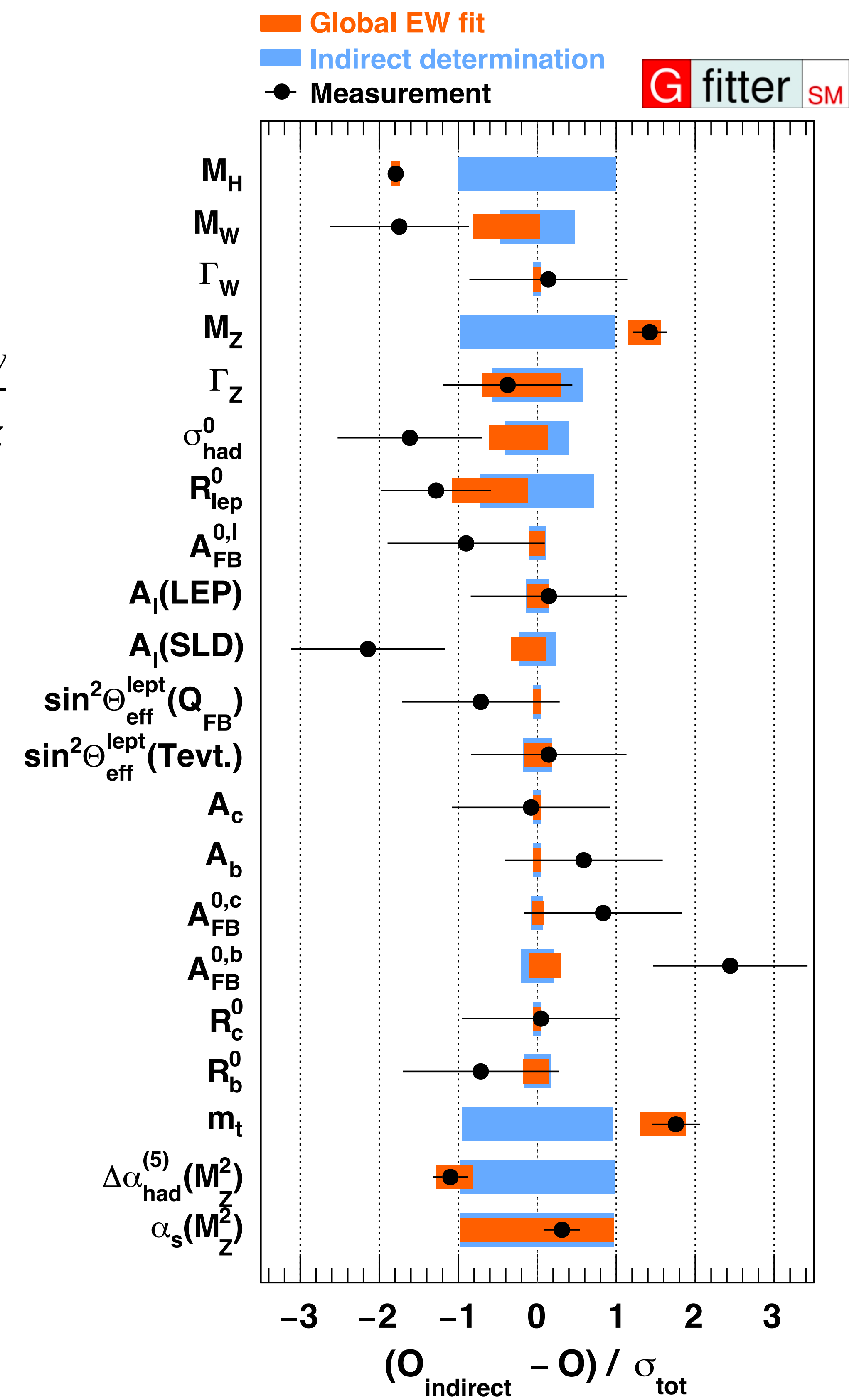
EW tests of the Standard Model

- In the SM, 3 parameters defines the EW sector
  - U(1), SU(2) couplings and VEV: (g, g', v) can be connected to observables
    - e.g. at tree level:

$$M_W = \frac{v|g|}{2}, \qquad M_Z = \frac{v\sqrt{g^2 + g'^2}}{2}, \qquad cos\theta_W = \frac{m_W}{m_Z}$$

  - mass of the W (Z) measured at LHC and Tevatron (LEP) with millions of events
  - weak mixing angle θ_W from precision Z measurements

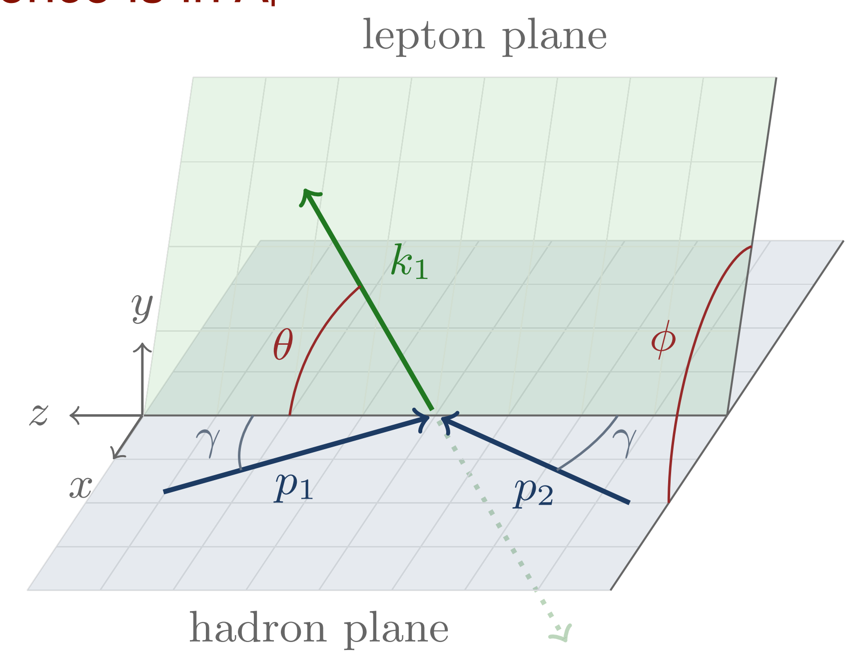
- The same 3 parameters regulate triple-/ quartic-couplings, but are measured with lower precision
  - sensitive to new physics
- Higgs boson and top enter the EW picture through radiative corrections
- Stringent consistency tests can be done via a global EW fit (e.g. M_W - M_{top} - m_H)



Drell-Yan angular analysis

- The 5D differential cross section can be decomposed as 1+8 harmonic polynomials $P_i(\cos\theta^*, \phi^*)$, multiplied by dimensionless angular coefficients $A_i(p_T^Z, y_Z, m_Z)$
  - all hadronic dynamics and EW fundamental parameters dependence is in A_i

$$\frac{d\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta\, d\phi} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z} \times \Big\{ (1+\cos^2\theta) + \frac{1}{2} A_0 (1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi + \frac{1}{2} A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta \cos\phi + A_4 \cos\theta + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi \Big\}. \quad (1.1)$$



  - ATLAS has a measurement of A_0—A_7 [*JHEP 08 (2016) 159*]. CMS reported A_0—A_4 [*PLB750 (2015) 154*]

- The path to full 5D is step-by-step in increasing number of variables

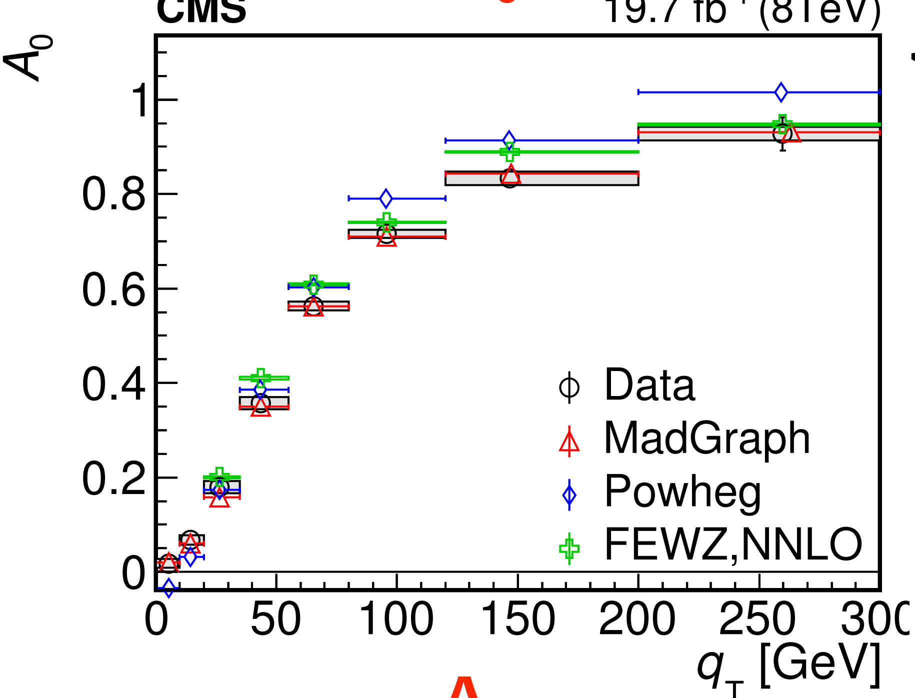
differential in:	sensitive to:
di-lepton mass $m_{\ell\ell}$ di-lepton rapidity $y_{\ell\ell}$	proton PDFs
dilepton $p_{T\ell\ell}$	higher order QCD predictions
angular distributions ($\cos\theta^*$,$\sin\phi^*$)	weak mixing angle θ_W (and PDFs)

Angular coefficients results

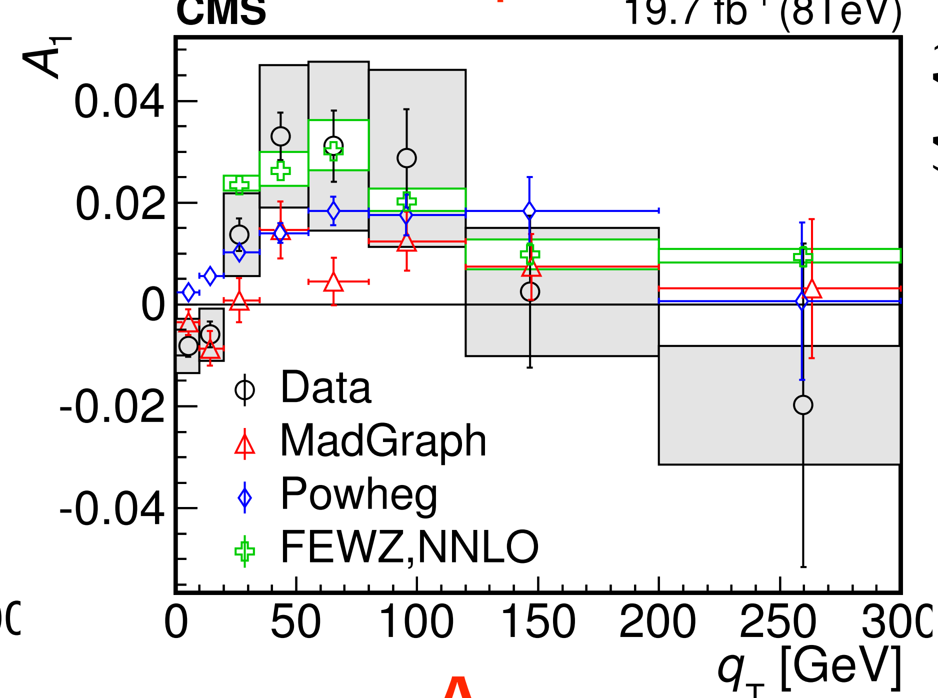
- Measurement with 8 TeV data from ATLAS and CMS are more precise than the calculations
  - violation of Lam-Tum relation $A_0 = A_2$ by higher order QCD corrections

PLB750 (2015) 154

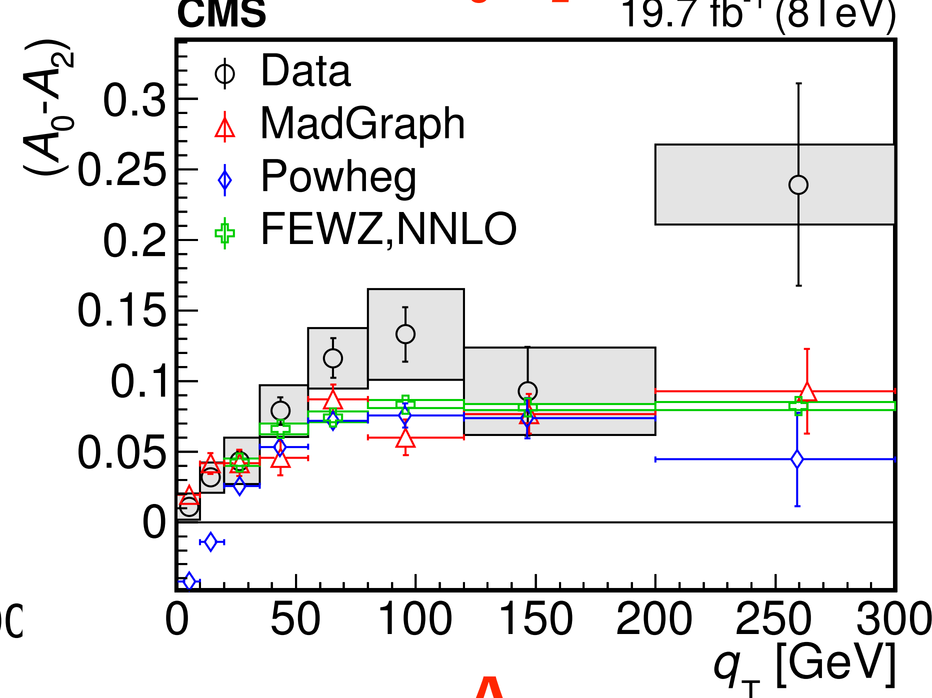
A_0



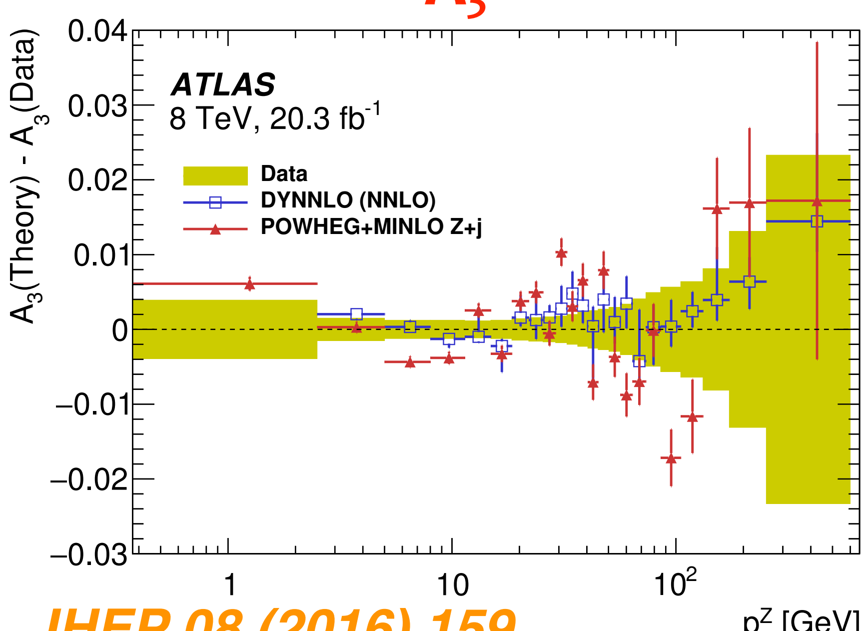
A_1



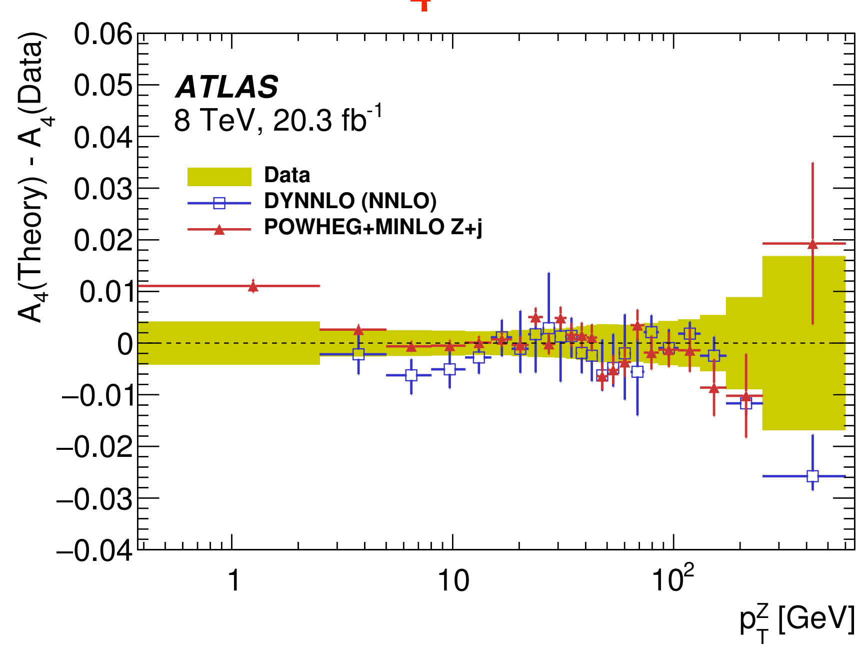
A_0-A_2



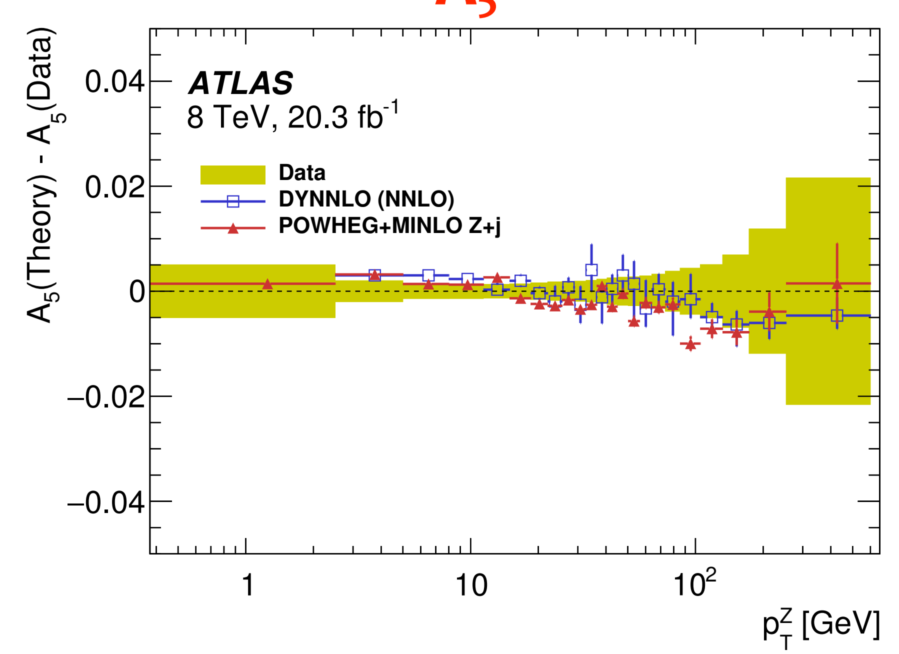
A_3



A_4



A_5



JHEP 08 (2016) 159

Triple differential DY cross-section

JHEP 12 (2017) 059

- ATLAS measures DY production w.r.t. 3 kinematic variables

$$\frac{d^3}{dm_{\ell\ell} \quad d|y_{\ell\ell}| \quad d\cos\theta^*}$$

$dm_{\ell\ell}$: improves both θ_W and PDF sensitivities

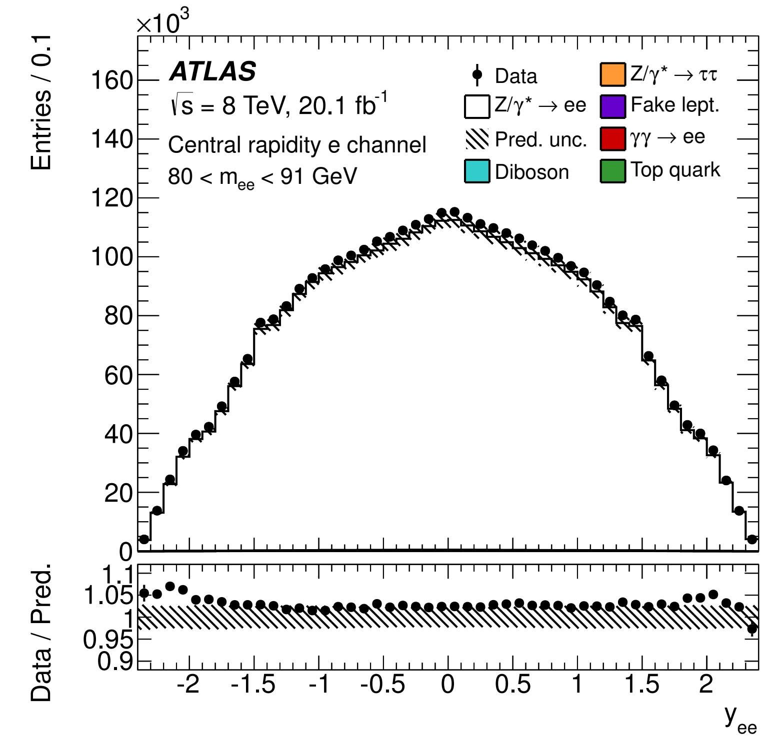
$d|y_{\ell\ell}|$: sensitivity to proton PDFs

$d\cos\theta^*$: sensitivity to θ_W

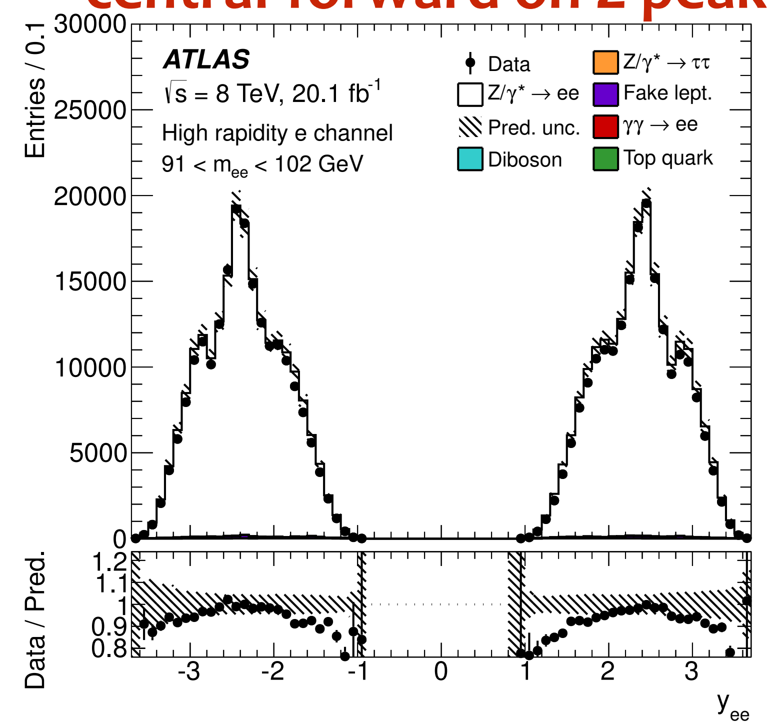
  - the θ_W measurements at colliders typically limited by the PDFs
  - this measurement is designed to be simultaneously sensitive to θ_W and PDFs
    - limiting the leading systematic uncertainties

- $d^3\sigma$ measured in fiducial region, unfolded to Born-level
  - phase space defined by lepton p_T, η, and $m_{\ell\ell}$ ranges
  - $d^3\sigma$ up to $|y_{\ell\ell}| < 2.4$ with $ee+\mu\mu$ and up to 3.6 with *ee*

central on Z peak



central-forward on Z peak

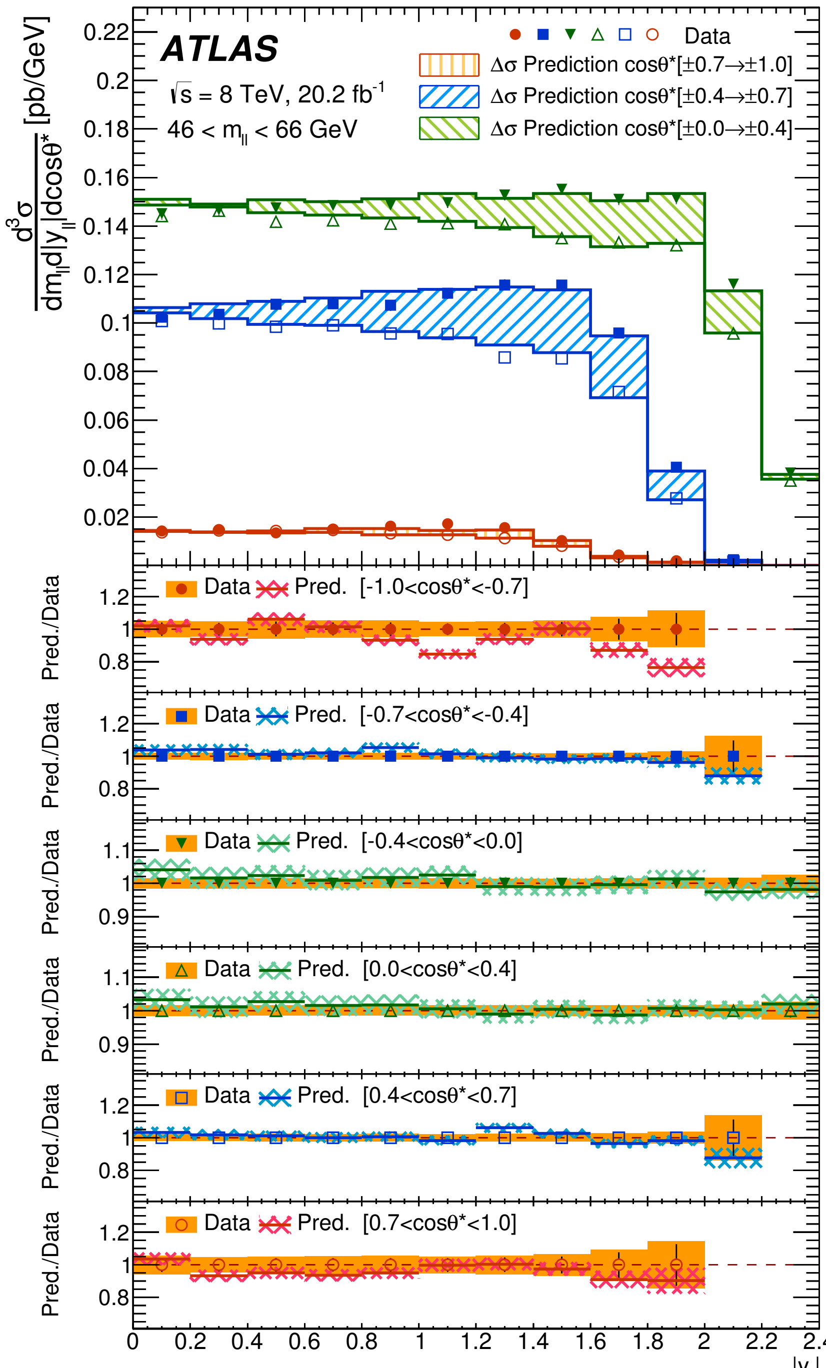


primary result of 3D Drell-Yan

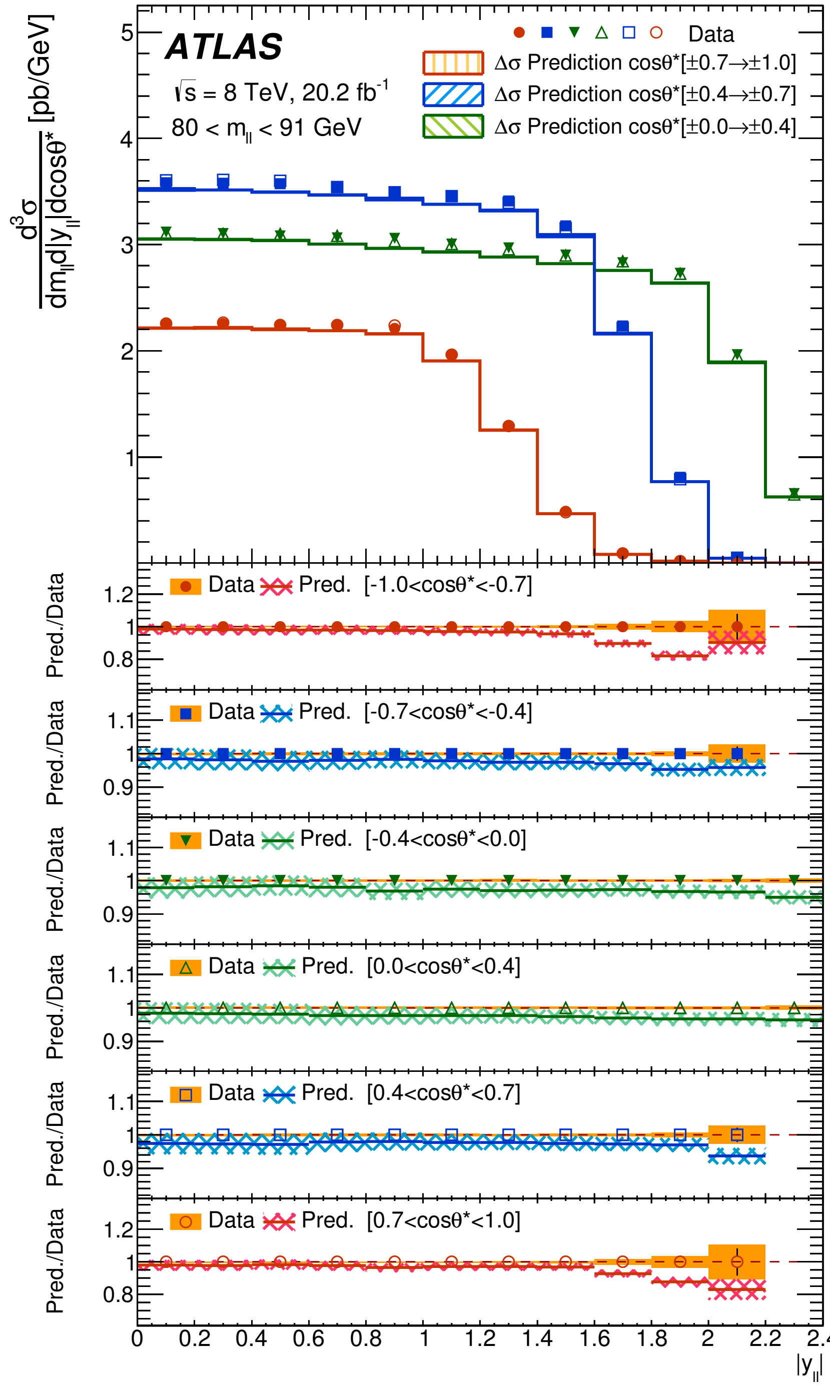
- 3 of 7 mass ranges shown
- asymmetry between ± cosθ* (filled region) reflects parity violation in Z-boson decays
  - asymmetry is zero and flips sign at $m_{\ell\ell} \sim M_Z$

JHEP 12 (2017) 059

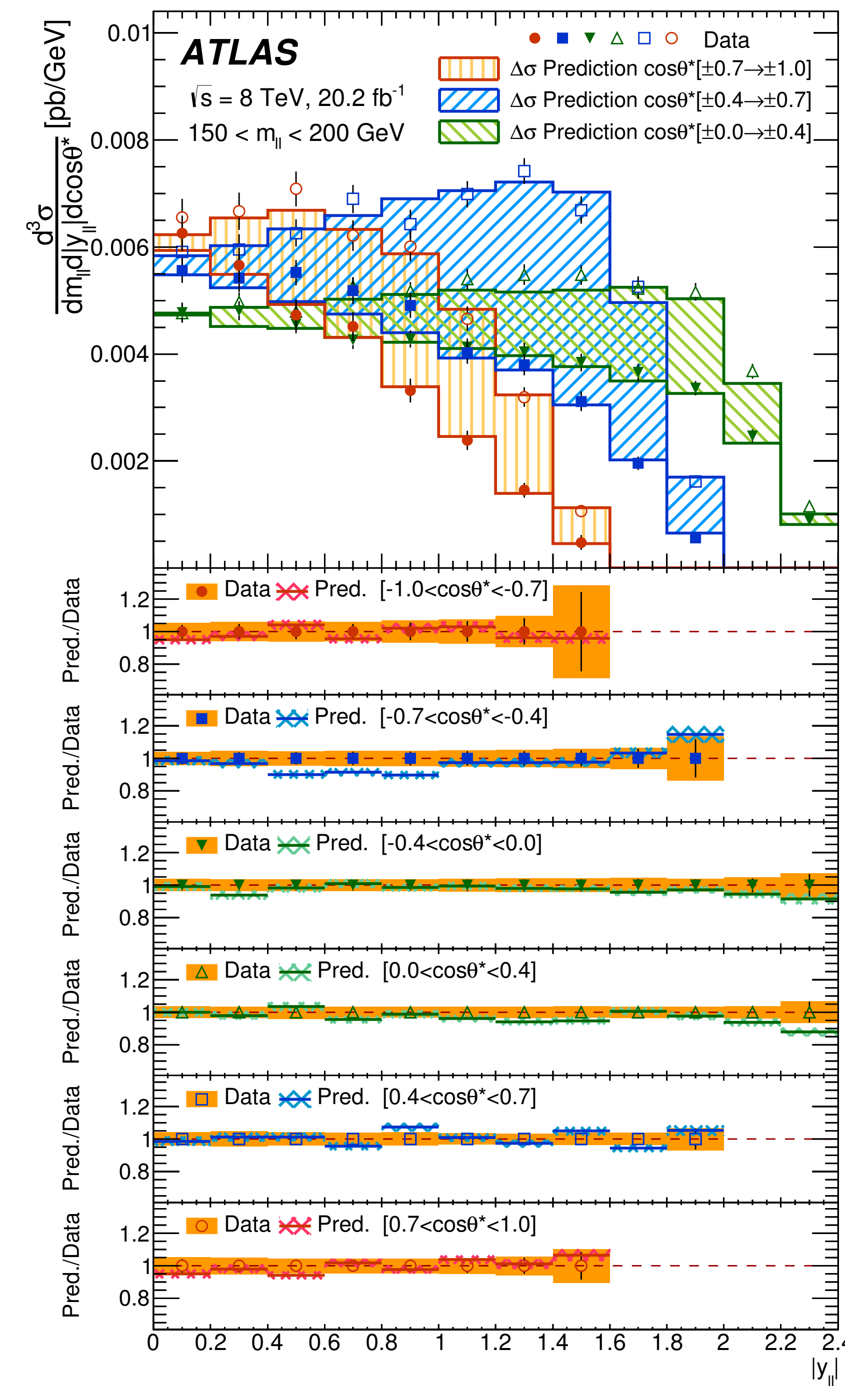
$M_{\ell\ell} < M_Z$



$M_{\ell\ell} \sim M_Z$



$M_{\ell\ell} > M_Z$

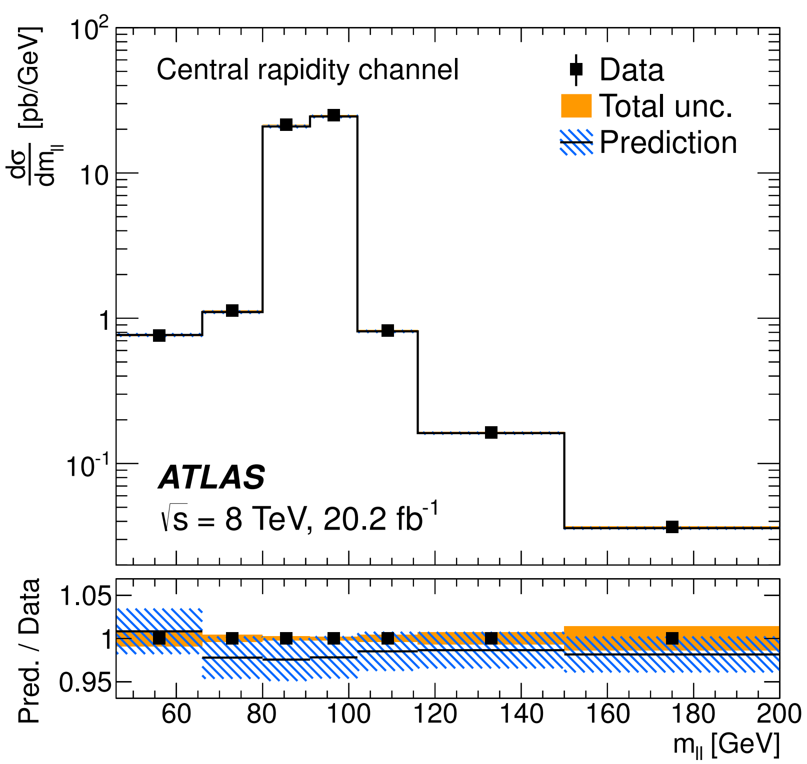


Forward-backward asymmetry

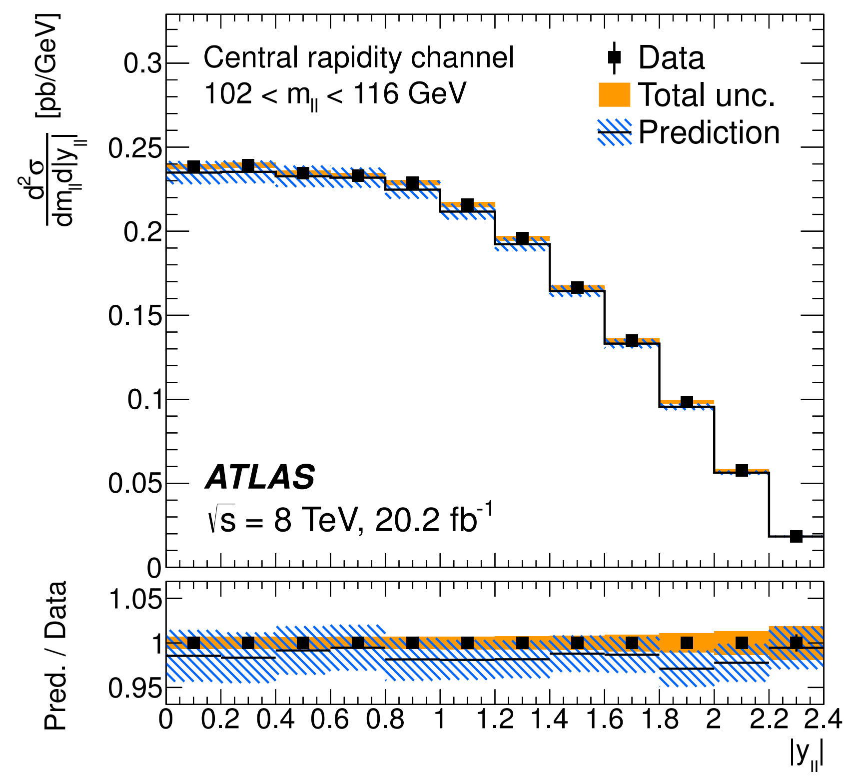
- From 3D differential x-s, derive 2D, 1D integrated results: JHEP 12 (2017) 059
  - $d\sigma/dm_{\ell\ell}$, $d^2\sigma / d\, m_{\ell\ell}\, d\,|y_{\ell\ell}|$
  - A_{FB}, which makes more clear the parity violation effects:

$$A_{FB}(m_{\ell\ell}, |y_{\ell\ell}|) = \frac{\int d\sigma(\cos\theta^* > 0) - \int d\sigma(\cos\theta^* < 0)}{\int d\sigma(\cos\theta^* > 0) + \int d\sigma(\cos\theta^* < 0)}$$

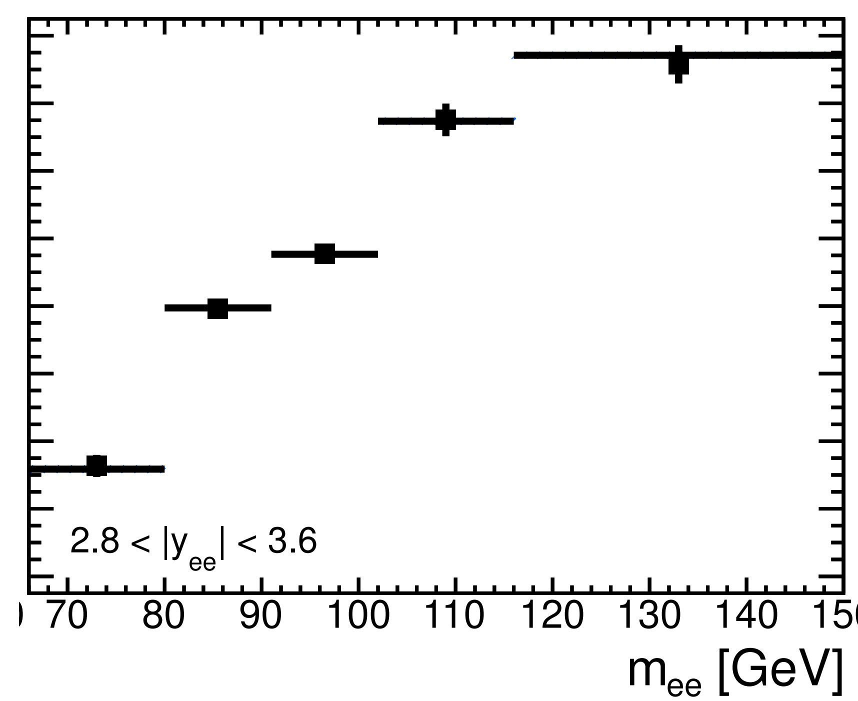
$d\sigma/dm_{\ell\ell}$



$d^2\sigma / d\, m_{\ell\ell}\, d\,|y_{\ell\ell}|$



A_{FB} (one lepton central, one forward)



- Good agreement with POWHEG, with NNLO QCD and NLO EW *K*-factors
- Large sensitivity from the electron channel with one fwd electron
  - possible to simultaneosly extract $\sin^2\theta_{eff}$ and PDFs with improved precision

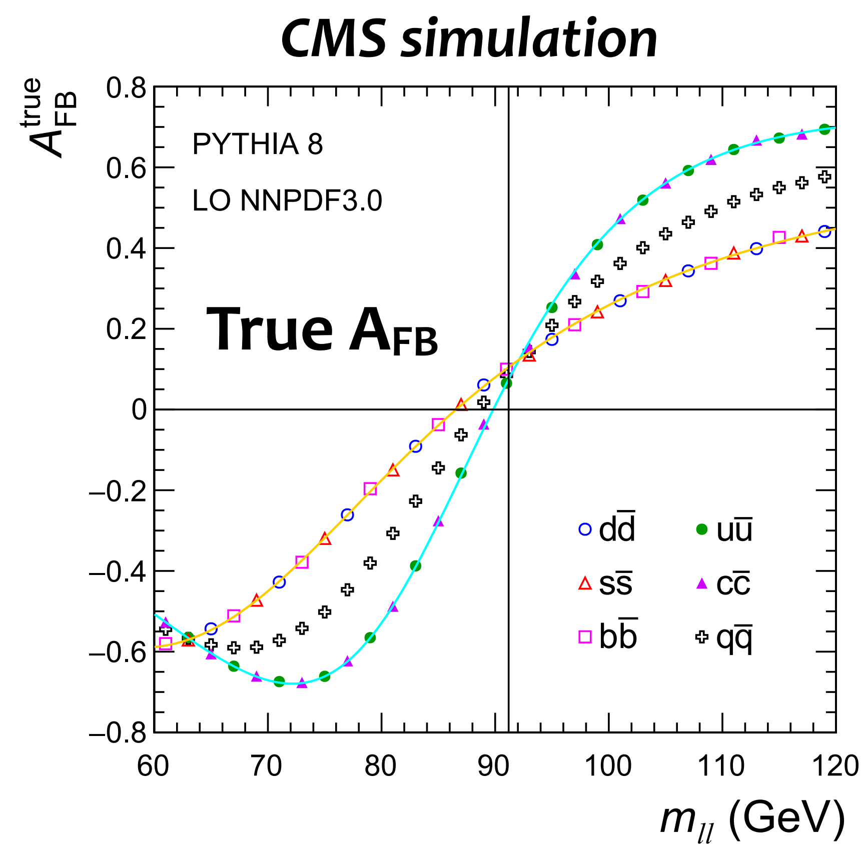
$\sin^2\vartheta_W$ measurements

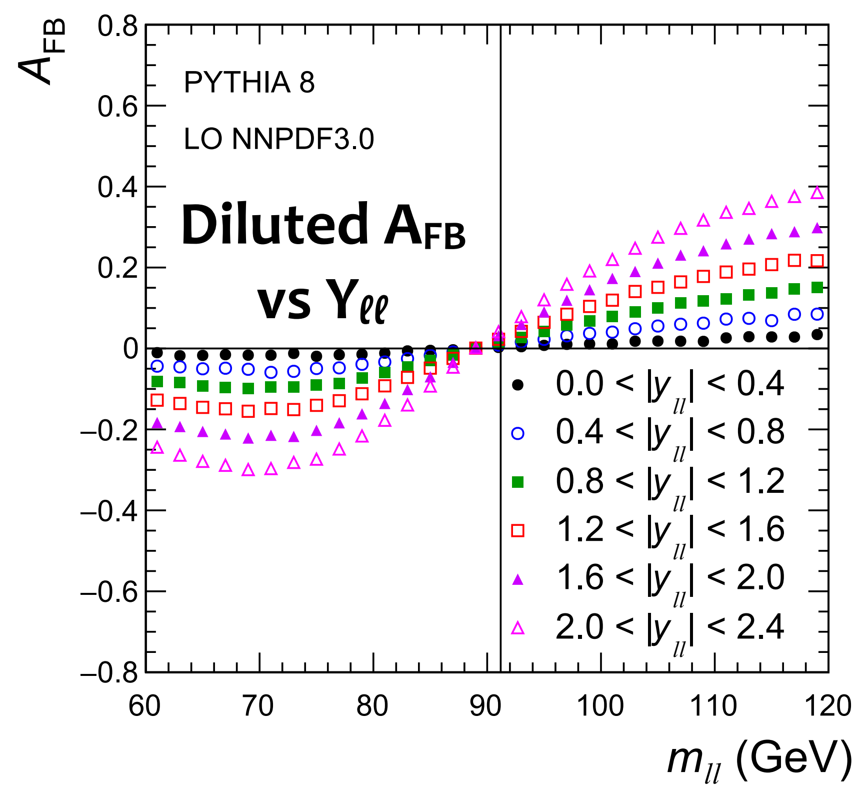
- A_{FB} depends on the interference of vector and axial currents
  - at LO EW, $\sin^2\theta_W = 1 - m_W/m_Z$.
  - beyond, tree level couplings are replaced by effective couplings, measuring:

$$\sin^2\theta^{\ell}_{\text{eff}} = k^{\ell}_{Z}\sin^2\theta_W$$

- A_{FB} depends on quark flavor ⇒ **sensitivity to PDFs**

- θ^* is the angle between the lepton and quark
  - at LHC (pp) use the direction of the di-lepton system in the laboratory frame as the positive axis
  - dilution of asymmetry when not true
  - quarks are mainly originated from valence and tend to have larger x than antiquarks
    - **dependence on PDFs** from large-x antiquarks

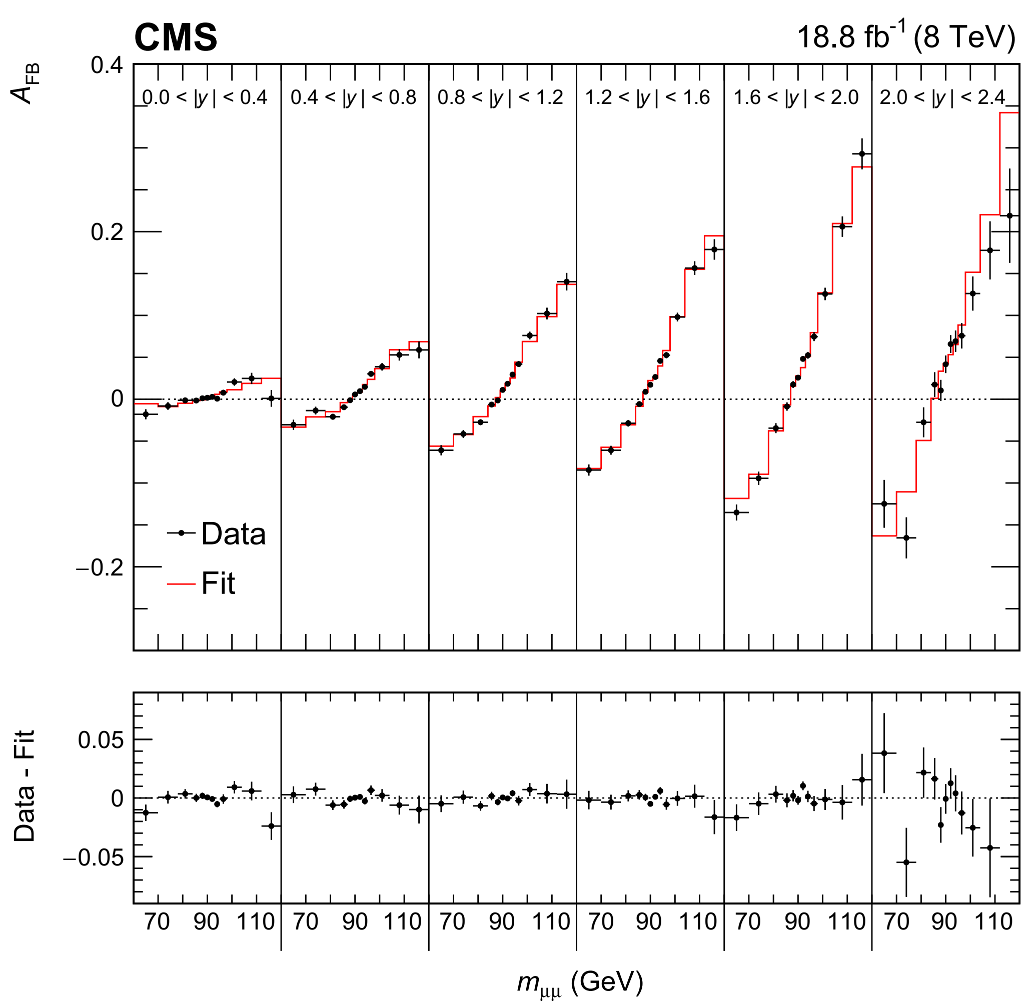


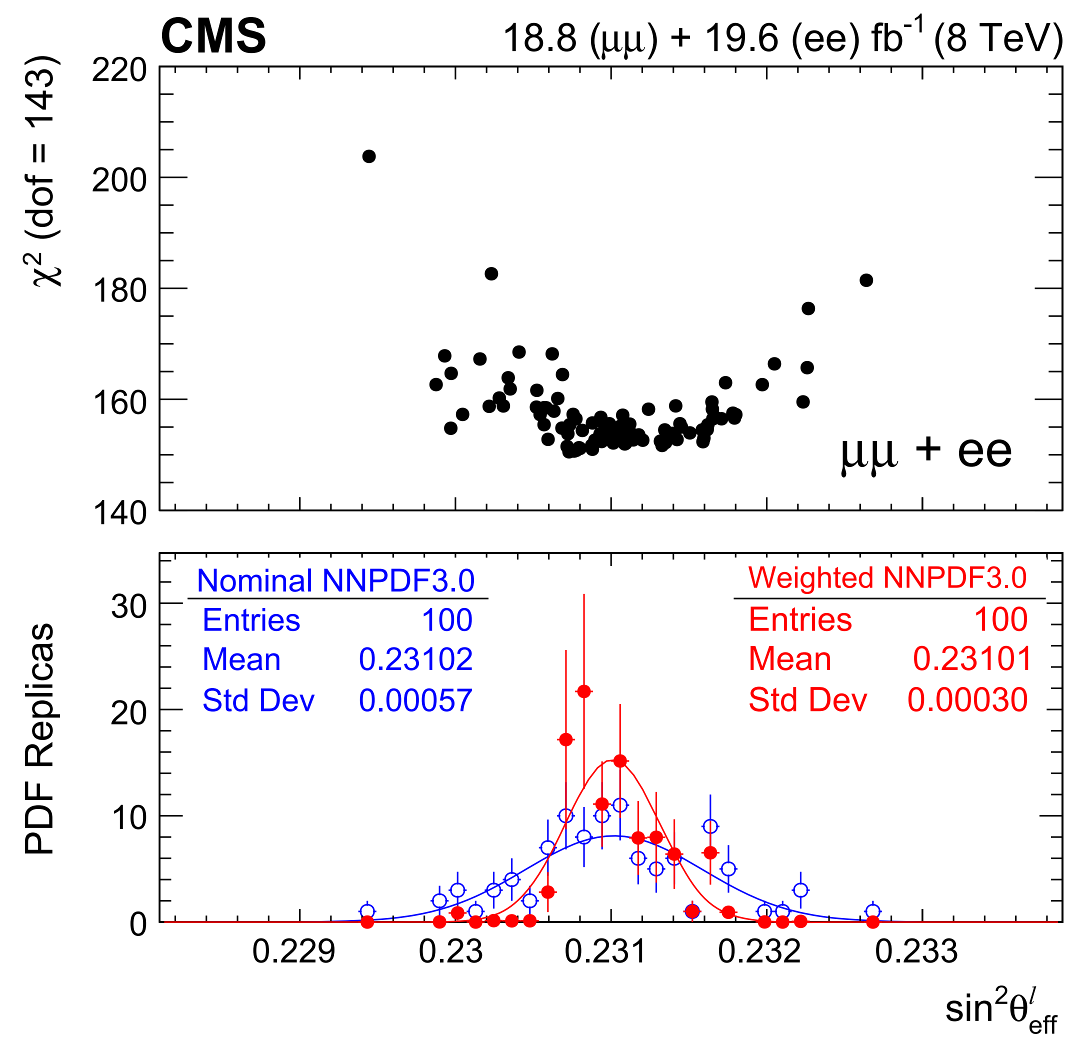


A_{FB} and $\sin^2\vartheta_W$

- CMS measures A_{FB} in 6 bins of rapidity and 12 bins of dilepton mass (8 TeV)
  - Extract $\sin^2\theta_{eff}$ by fitting the measured A_{FB} with different templates
- Using Bayesian weighting method with NNPDF3.0 replicas: $w \propto \exp\{\chi^2/2\}$
  - uncertainty related to PDFs reduces from 0.00057 to 0.00030 (factor ~2)

μμ





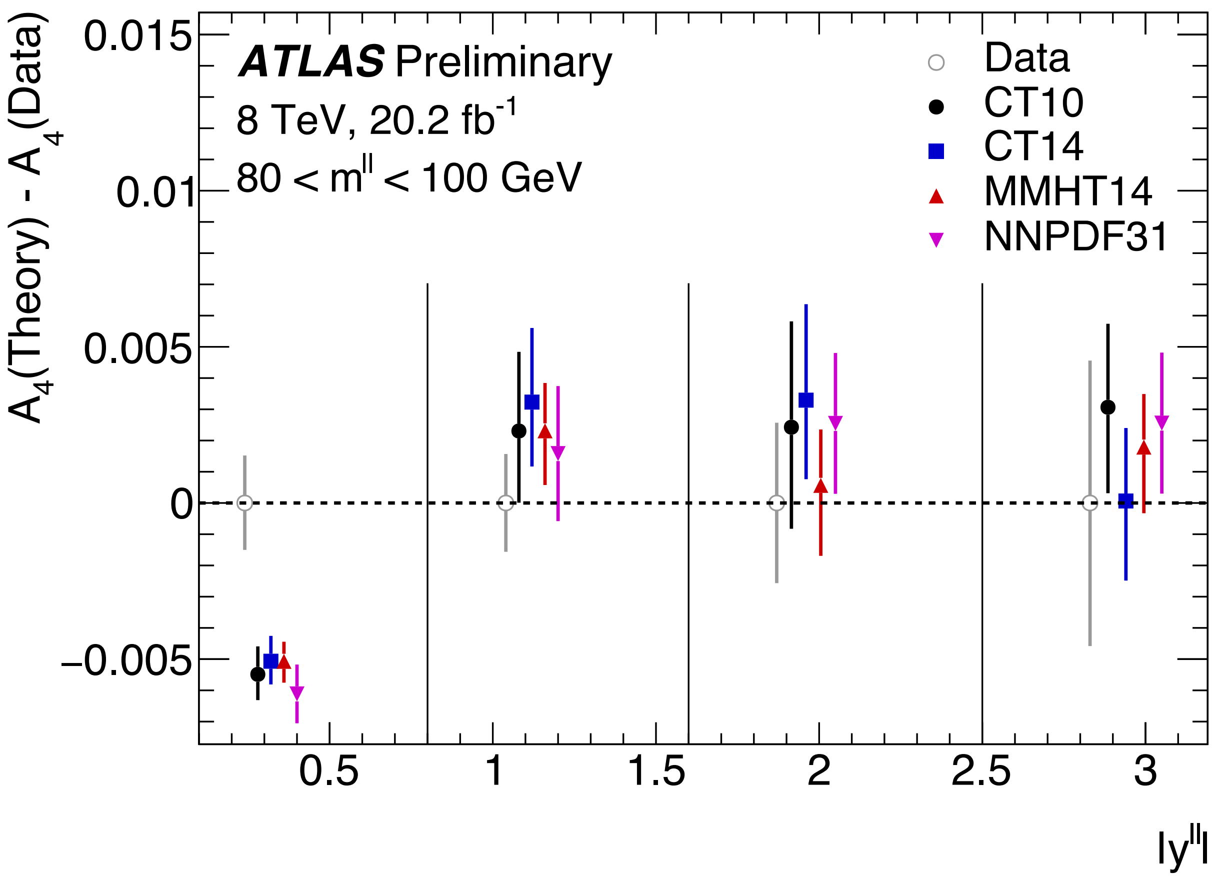
EPJ C (2018) 78:701

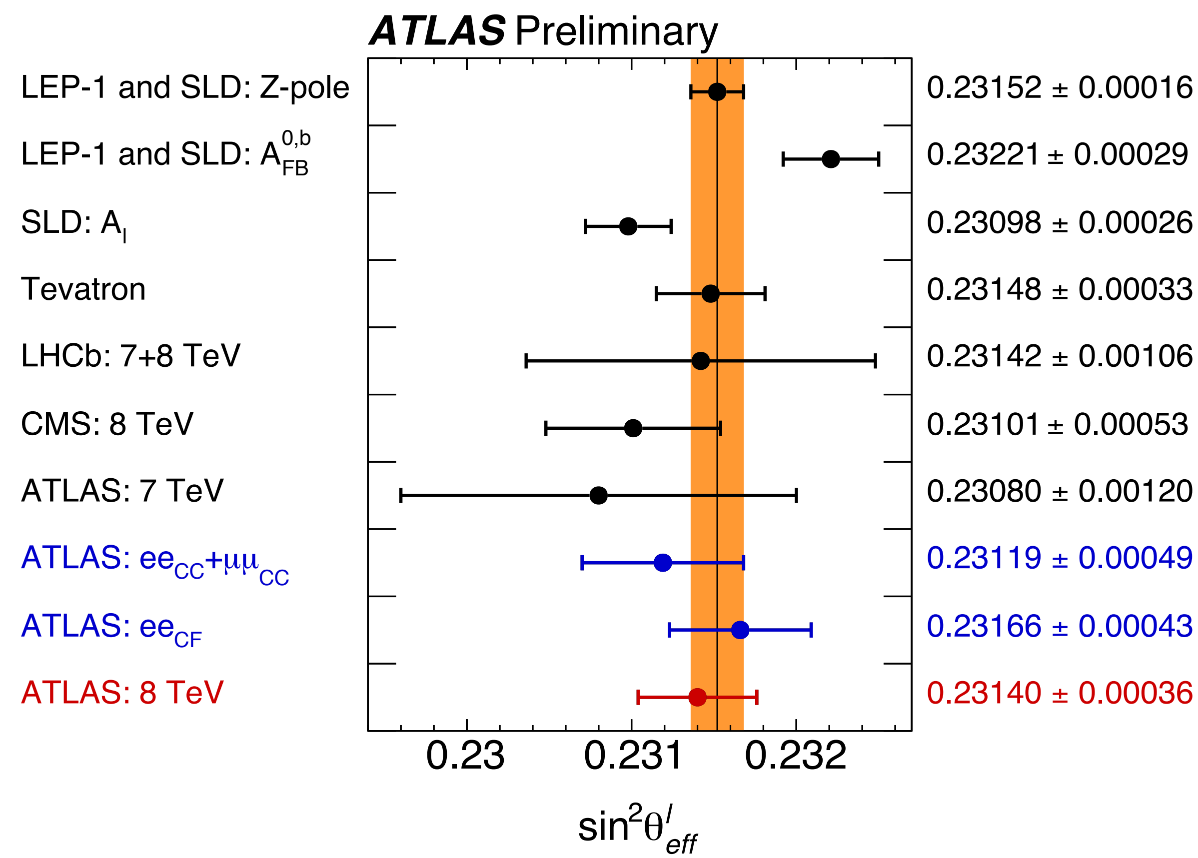
$\sin^2\theta_{eff} = 0.23101 \pm 0.00053$

$\sin^2\theta_{eff} = 0.23101 \pm 0.00036$ (stat) ± 0.00018 (syst) ± 0.00016 (theo) $\pm$ **0.00031 (PDF)**

ATLAS $\sin^2\vartheta_W$

- ATLAS measures as A_{FB}=3/8A_4, fitting the A_i with templates (8x8 bins in ($\cos\theta^*$,ϕ^*) for each $y_{\ell\ell}$, $m_{\ell\ell}$ bin
  - then **A_4= a x $\sin^2\theta_{eff}$ + b** in each bin. Sensitivity enhanced by using *central-forward ee*





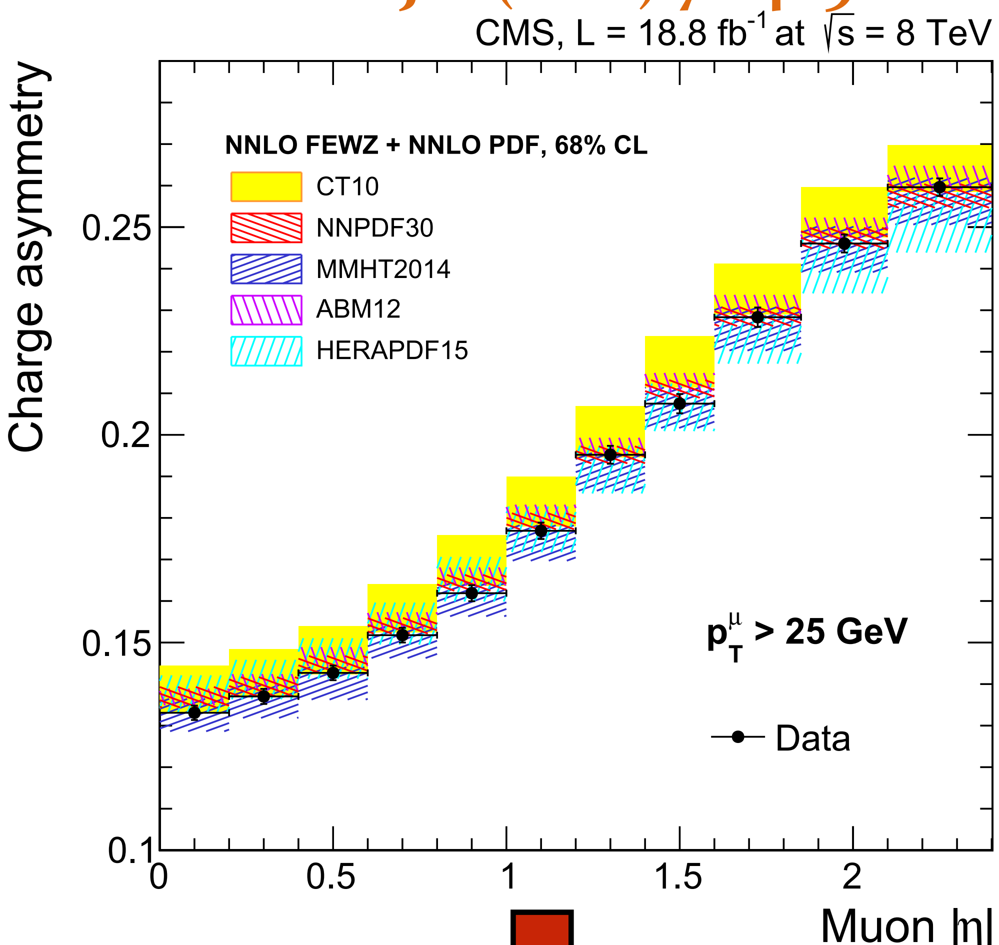
ATLAS-CONF-2018-037

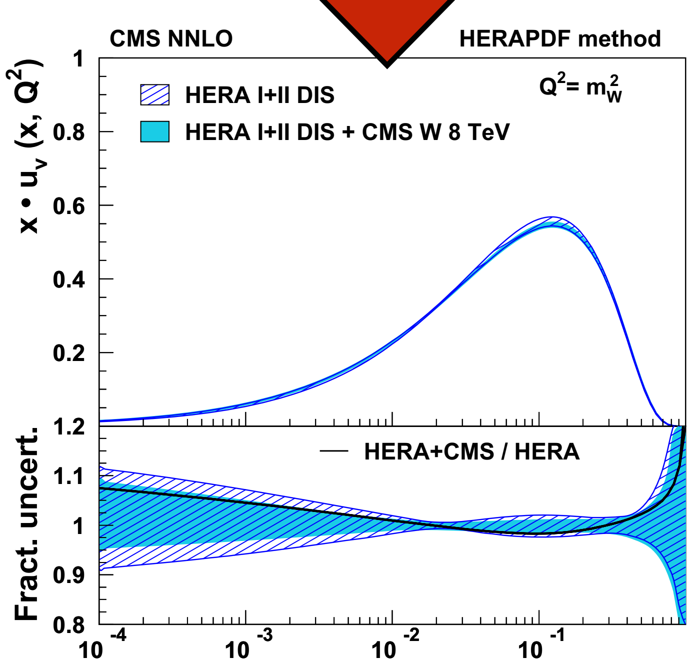
$$\sin^2\theta_{eff} = 0.23140 \pm 0.00036$$

$$\sin^2\theta_{eff} = 0.23101 \pm 0.00021\,(\text{stat}) \pm 0.00016\,(\text{syst}) \pm 0.00024\,(\text{PDF})$$

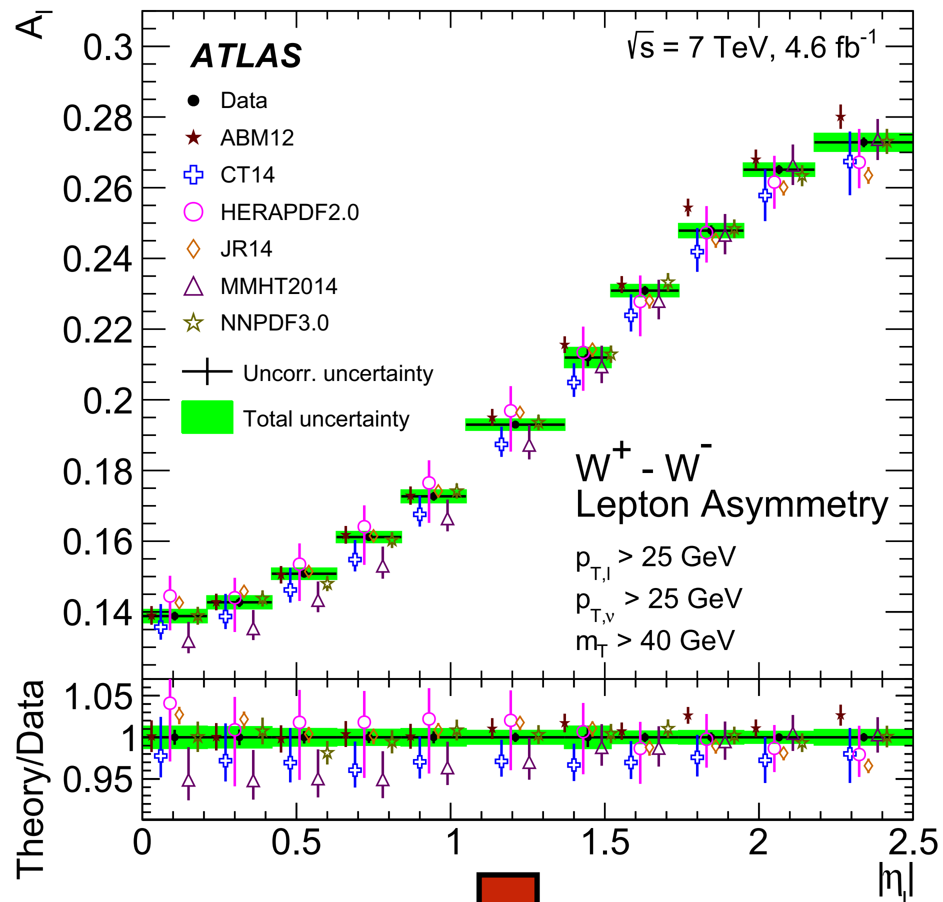
PDFs from W± charge asymmetry

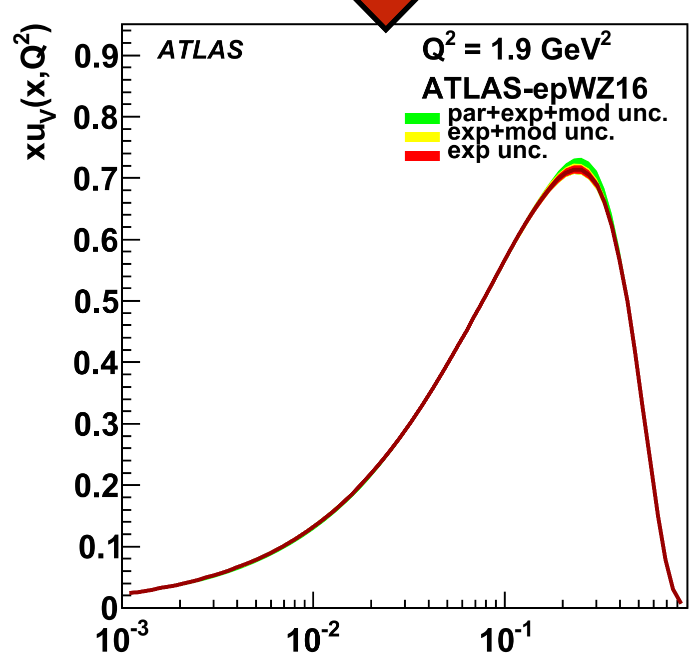
EPJ C (2016) 76:469



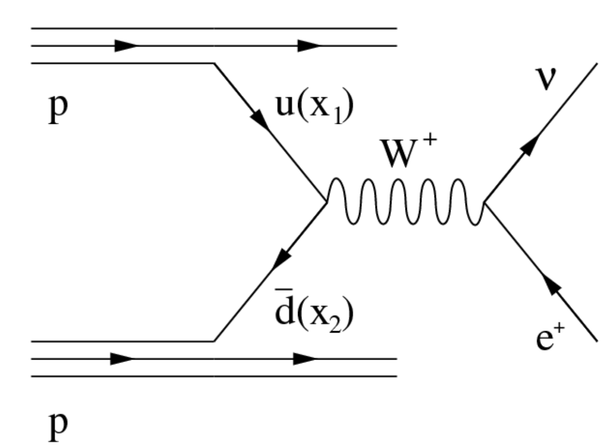


EPJ C (2017) 77:367





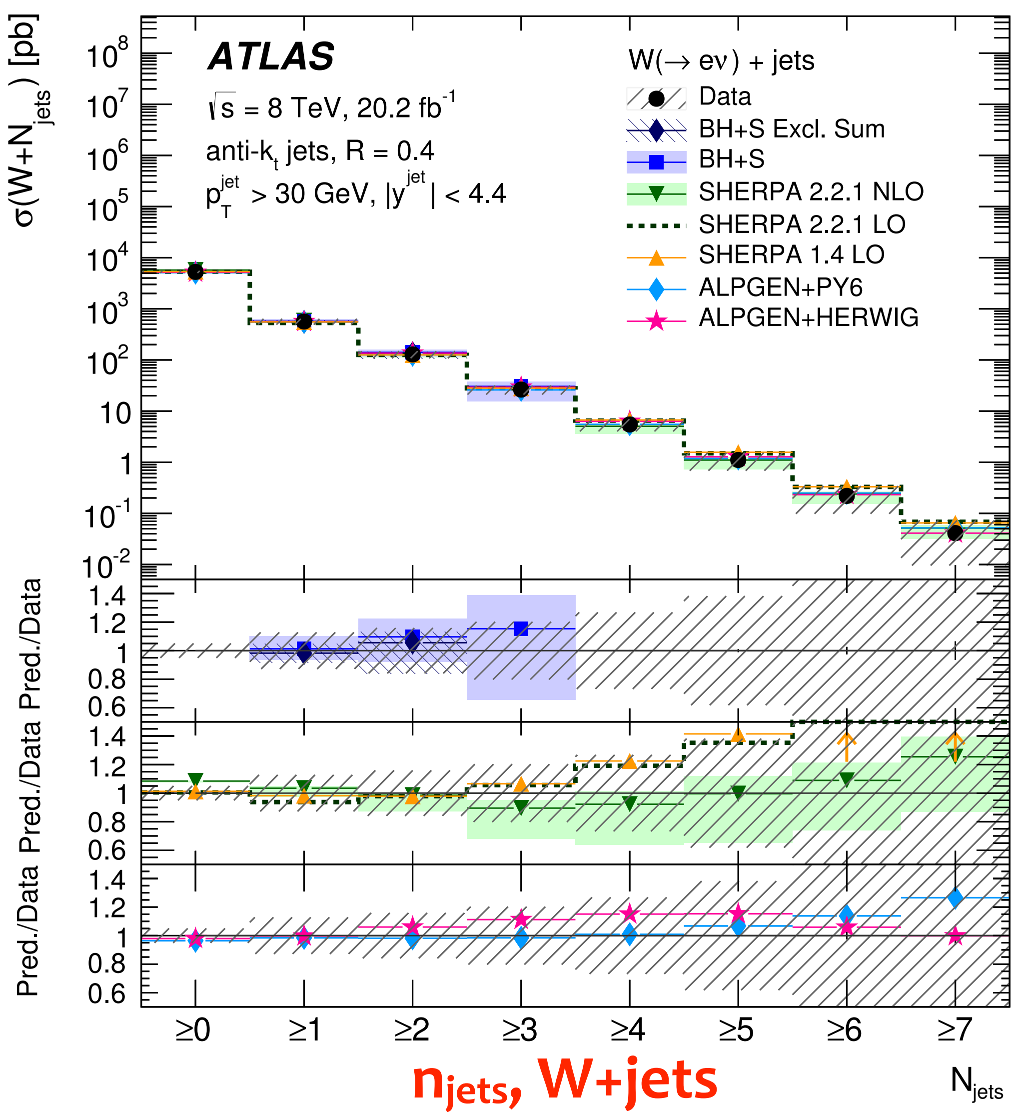
- Related to the larger number of valence u quarks than d quarks in the proton
- Rapidity distributions constrains quark and anti-quark PDFs
  - constraints from Run1, first ones at 13 TeV coming



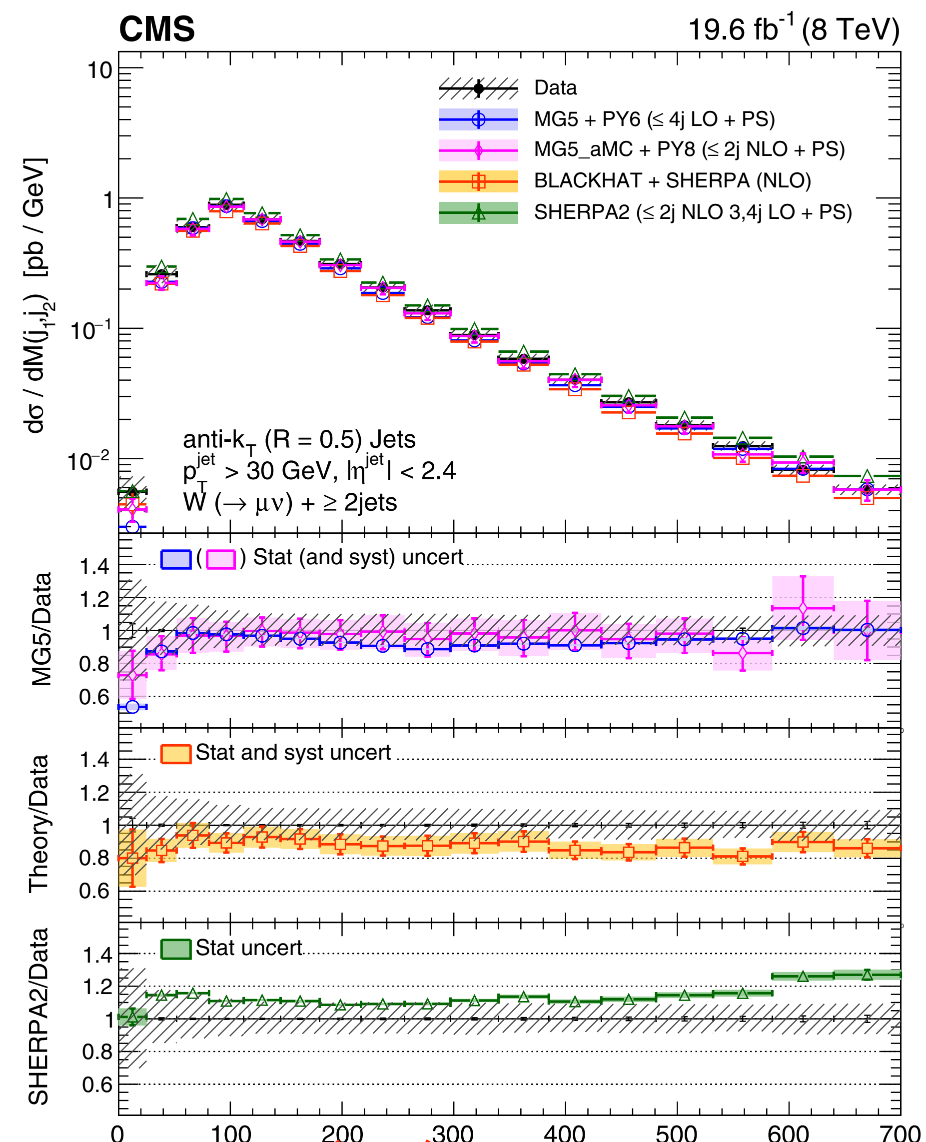
V + jets measurements

- QCD sector of the SM can be tested with associate V + jets production
  - NNLO in QCD, NLO in EWK: theory has O(1%) precision, experiment often sub-% level
- Z, W + light jets measured up to 7 jets, good agreement with NLO QCD
  - jet multiplicities test higher order terms, PDFs
  - also studied correlations (e.g. m_{jj}, $|\Delta Y_{jj}|$…) sensitive to ME/PS matching, non-perturbative effects modeled with PS, etc.

JHEP 05 (2018) 077



n_{jets}, W+jets

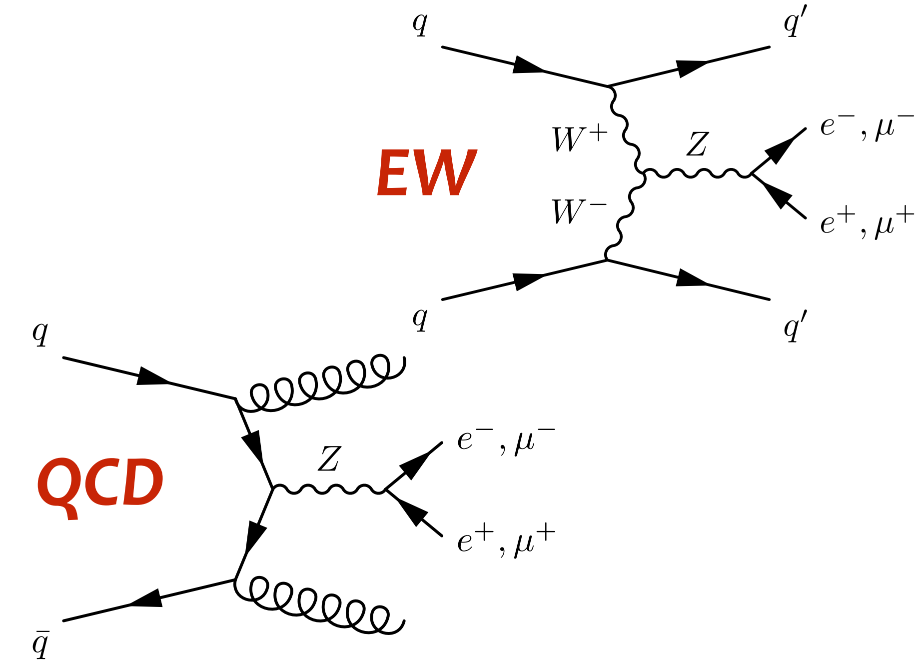


$m(j_1,j_2)$, W+ ≥ 2 jets

Phys. Rev. D 95 (2017) 052202

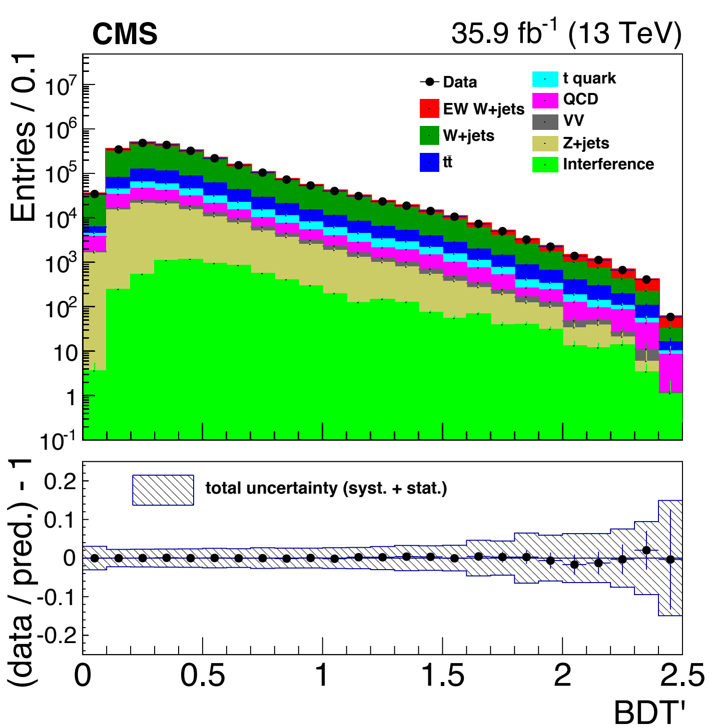
EW Z and W production

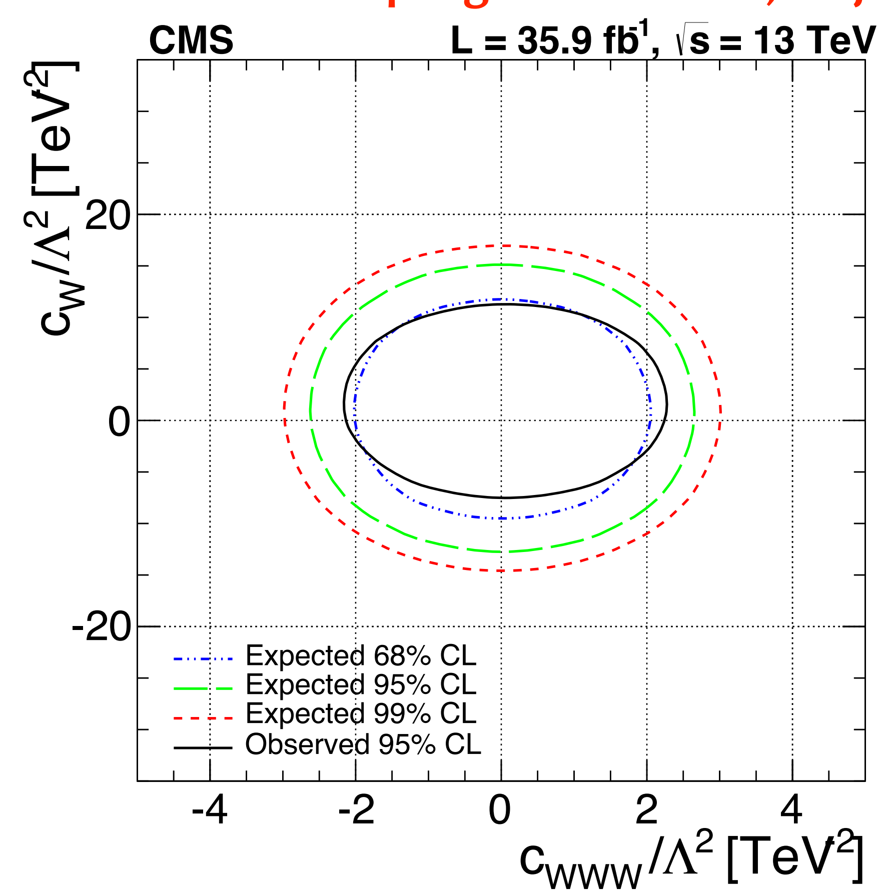
- EW W, Z production is one interesting mechanism
  - VBF understanding important for Higgs measurements and new physics searches
  - EW production << QCD one, but can be disentangled
    - typical handles: two forward jets with high di-jet mass
- ATLAS and CMS measure inclusive x-sec at 13 TeV
  - also used to constrain anomalous VVV couplings

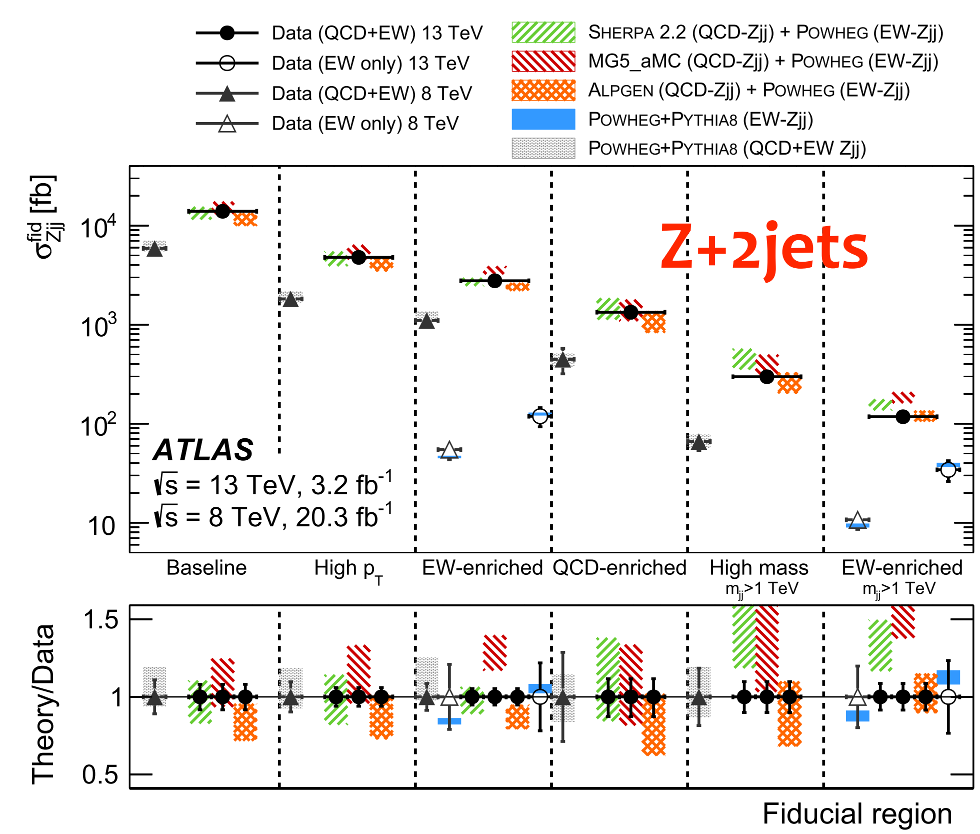


Anomalous couplings from EWK Z,V+2jets

W+2jets







σ_{EW} (Wjj) = 6.23 ± 0.12 (stat) ± 0.61 (syst) pb [submitted to EPJ C]

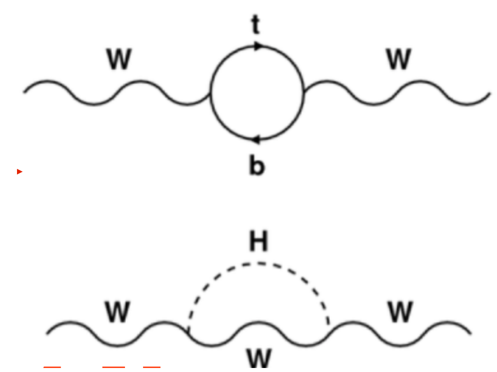
σ_{EW}(lljj)=534±20(stat)±57(syst)fb [EPJ C (2018) 78]

Phys. Lett. B 775 (2017) 206

W mass

- Valuable consistency check of the SM

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



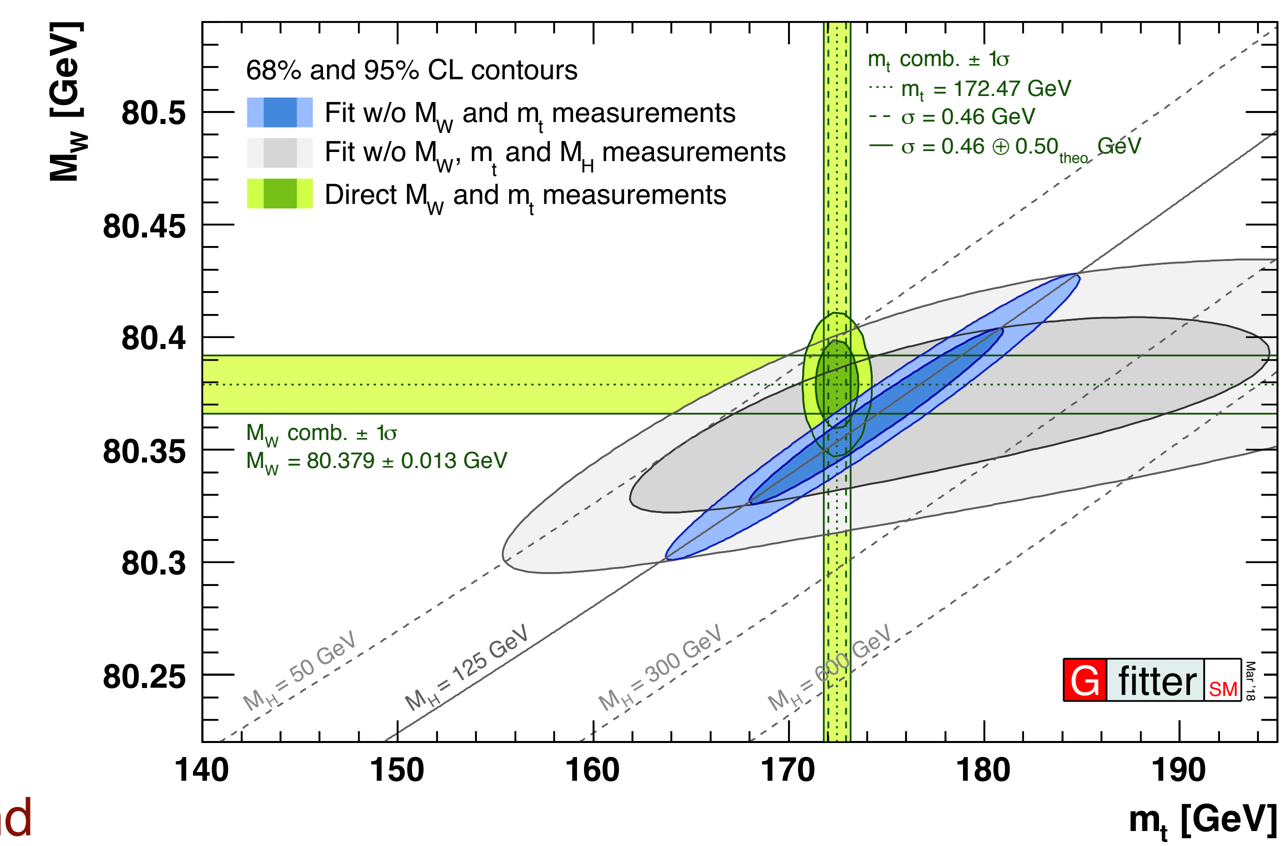
m_W particularly sensitive on M_{top} and M_{Higgs}

$$\Delta m_W^{theory}=8\ \text{MeV}<\Delta m_W^{exp}=15\ \text{MeV}$$

$$\Delta m_t^{theory}=2.1\ \text{GeV}>\Delta m_t^{exp}=0.76\ \text{MeV}$$

improve on m_W need $\Delta m_W/m_W \sim 10^{-4}$!

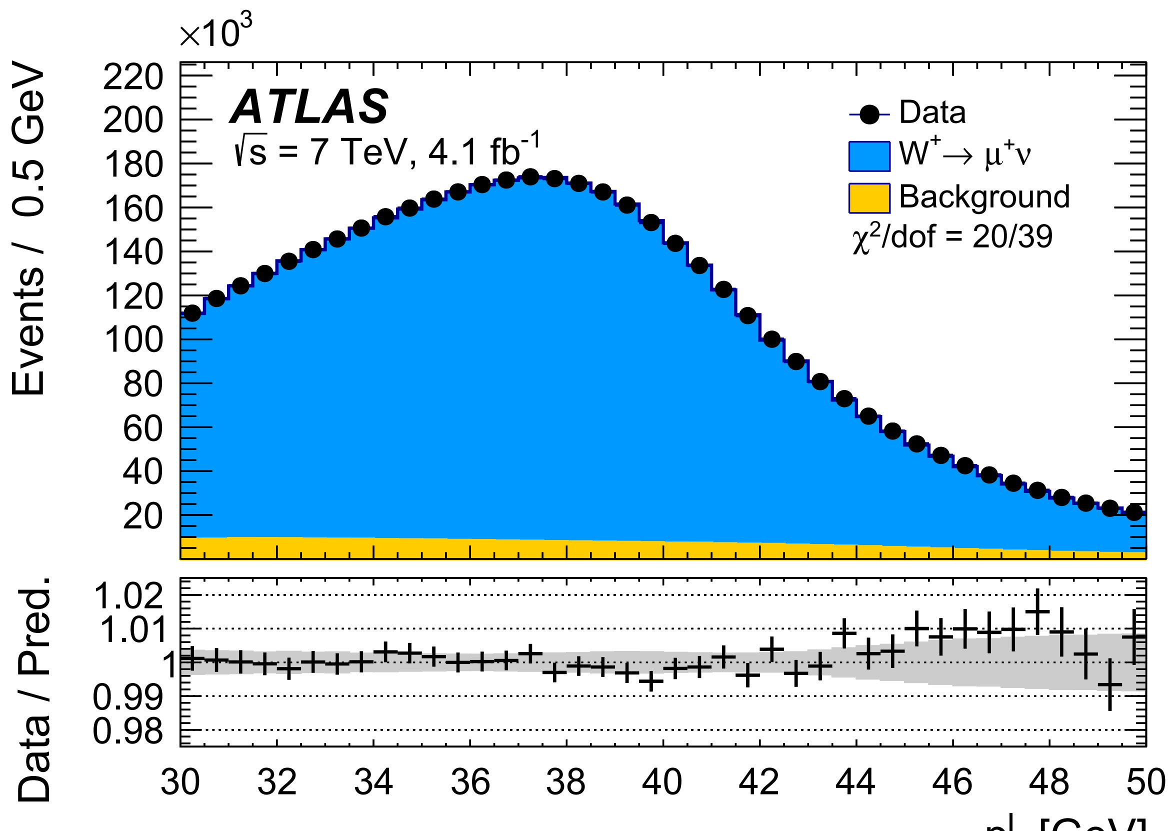
- Measurement at LHC affected by PDFs more than Tevatron (need sea quarks in pp vs pp̄ collisions)
  - 25% of W produced by *s* and *c* quarks (vs 5% at Tevatron)
  - reduction of PDF uncertainties vital !
- First and only m_W measurement at LHC so far from ATLAS
  - 2 template fit to $m_T(W)$, $p_T(lep)$
  - but none of the variables is Lorentz-invariant: **modelling uncertainties** of longitudinal (**PDFs**) and transverse (**q_T**) d.o.f. in W production



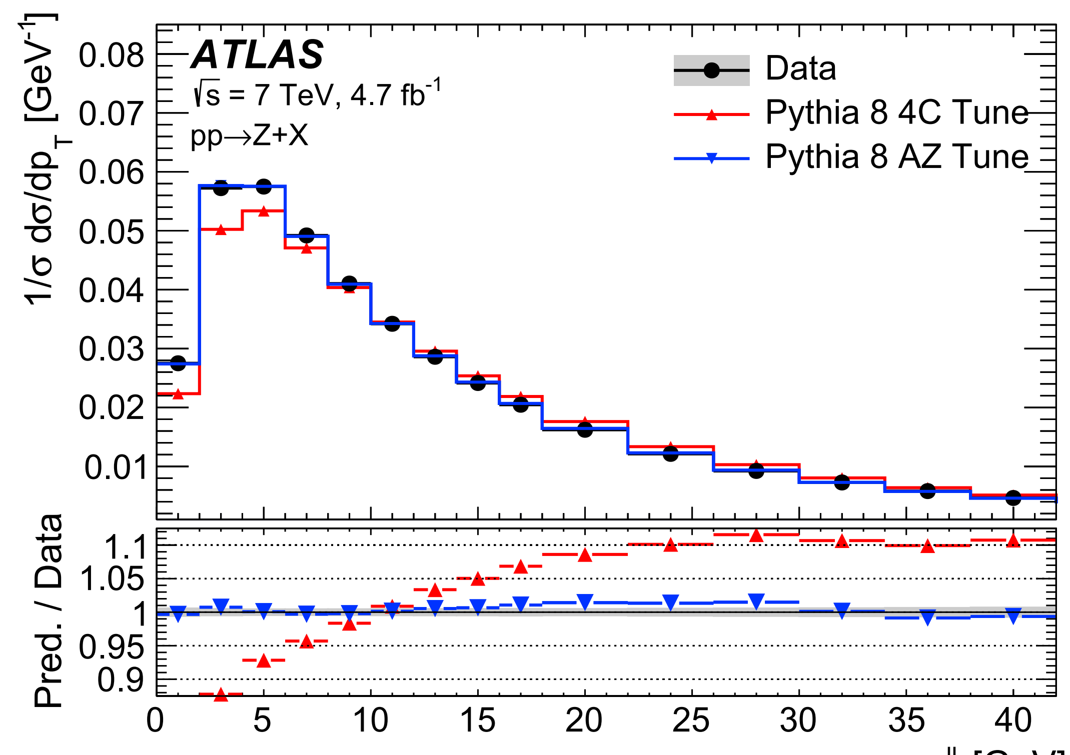
ATLAS W mass result

- precision **0.02%**, dominating uncertainty from theory: QCD, PDF — EPJ C (2018) 78
  - m_W = 80370 ± 7 (stat.) ± 11 (exp. syst.) ± 14 (mod. syst.) MeV = **80370 ± 19 MeV**
  - ATLAS measurement competes with Tevatron combination

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



p_T^μ in W^+ events



$p_T(Z)$ modelling

- Modelling uncertainties scenarios: if QCD scales are correlated among quark flavors, but uncorrelated between W and Z, **systematic on m_W ~ 30 MeV**
  - way forward under study at LHC EW WG: advisable a less model-dependent Z to W extrapolation
  - direct measurement of $p_T(W)$, W angular coefficients (e.g. low PU data taken in 2017)
  - e.g. PDF in-situ constraints from W data (e.g. JHEP12 (2017) 130). More finely grained W p_T in the low p_T region

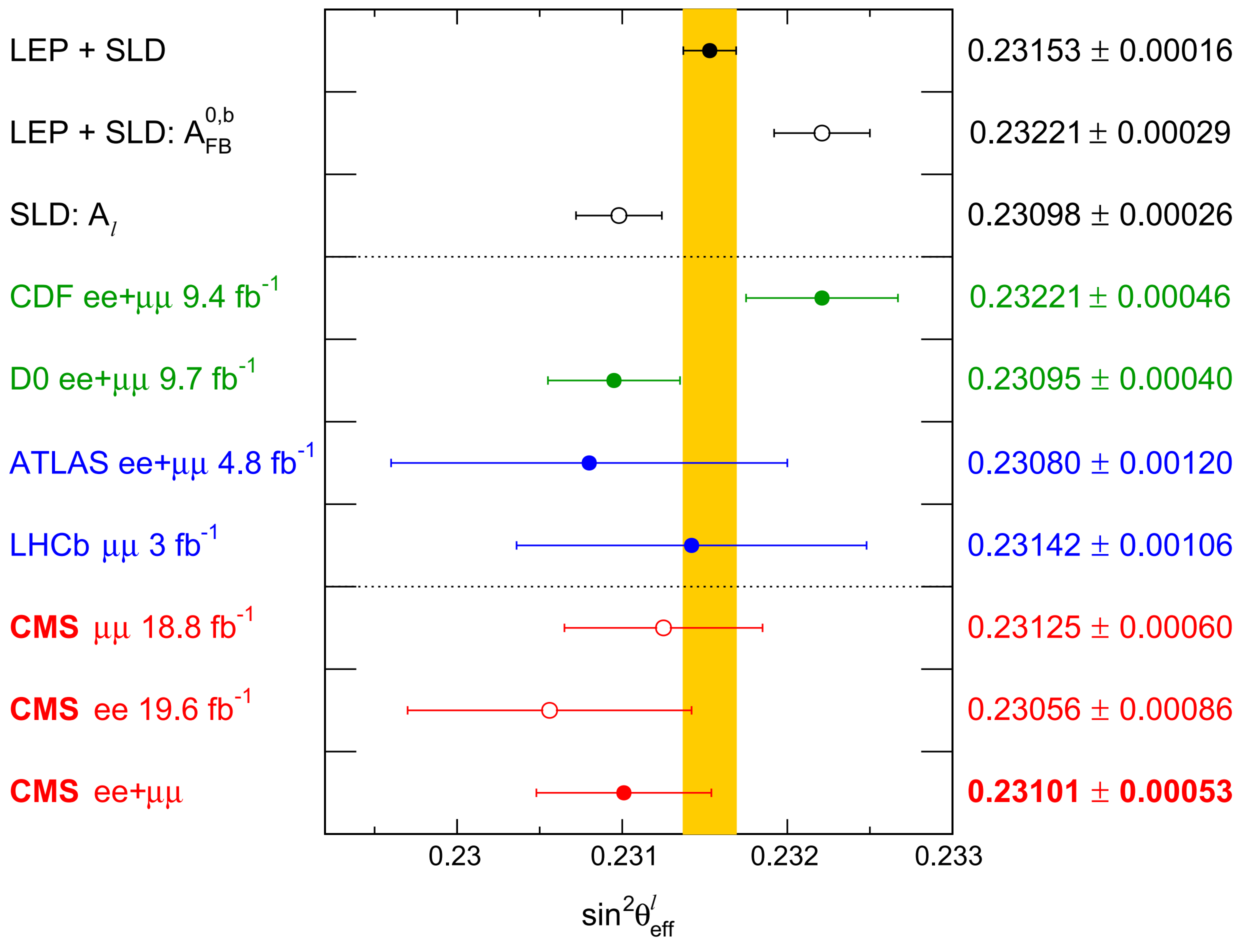
Conclusions

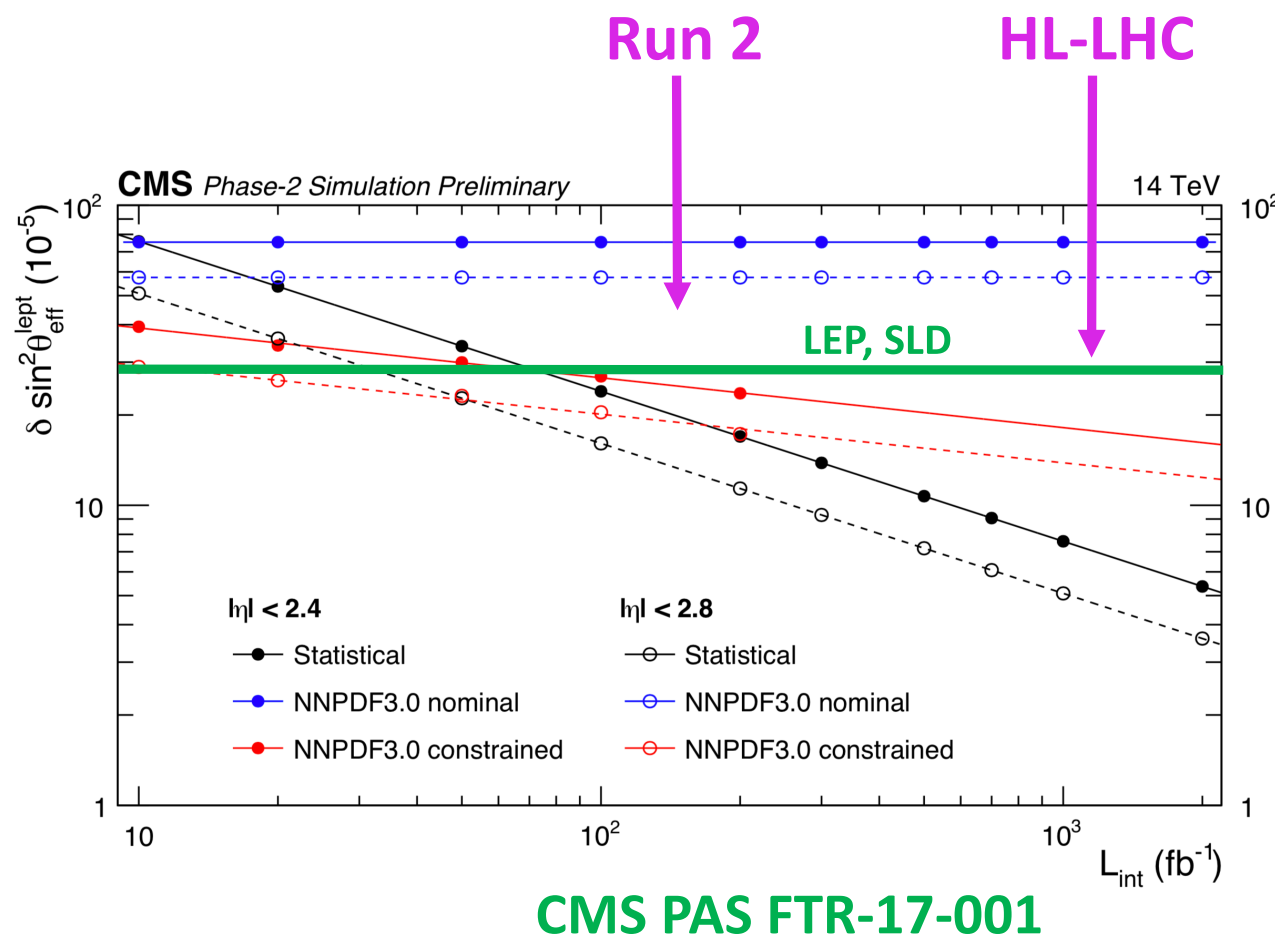
- A rich research program is being pursued at the LHC
- Given no direct indications of new physics, EW sector is the main area for tests of the Standard Model of particle physics
- LHC Run2 has just endend. Only a fraction of Run2 data has been used for EW measurements
  - expect a stream of precision measurements with 13 TeV during the LHC shutdown
- Several improved theoretical calculations exists
- Advanced experimental techniques aim in a reduced theory-dependent approach
  - a measurement becomes a full program of simultaneous measurements
  - sometimes it will require full Run2 statistics, **it always takes time**
- precision may be the path for discoveries

The End

Current $\sin^2\vartheta_W$ measurements

- CMS and ATLAS results consistent with the mean value of LEP and SLD and other available measurements
  - statistical uncertainties still dominate



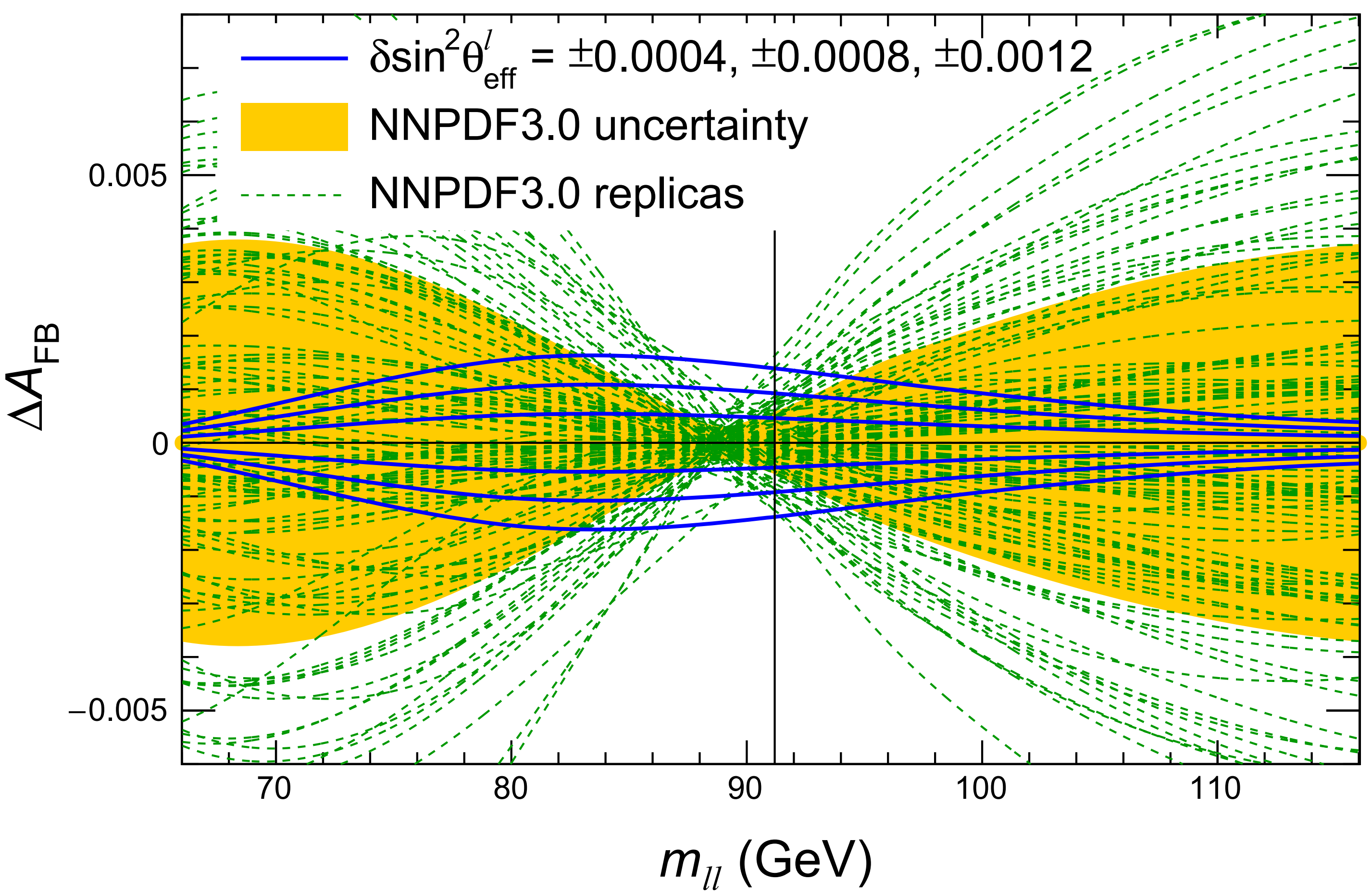


- Measurements at the LHC will improve with Run 2 data and beyond

- PDF uncertainties could be reduced including more recent LHC data and performing a global fit

PDF constraints

- PDFs affect A_{FB} mainly off the Z pole, with opposite sign below and above M_Z
- Max sensitivity for $\sin^2\theta_{eff}$ for $m_{\ell\ell} \sim M_Z$
- Using Bayesian weighting method with NNPDF3.0 replicas: $w \propto \exp\{\chi^2/2\}$
  - uncertainty related to PDFs reduces from 0.00057 to 0.00030 (factor ~2)
  - equivalent to ATLAS profiling of the PDF nuisances



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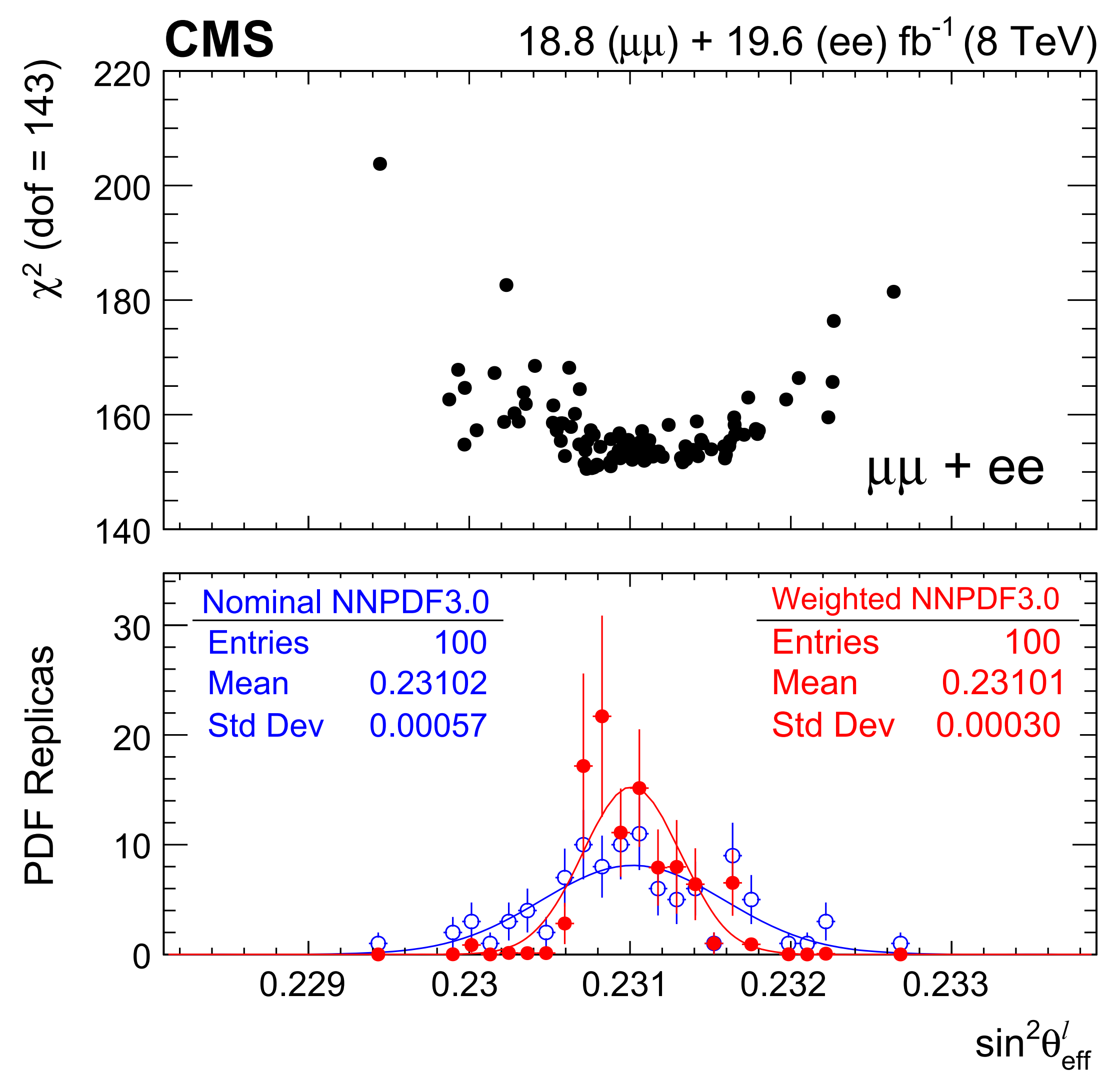
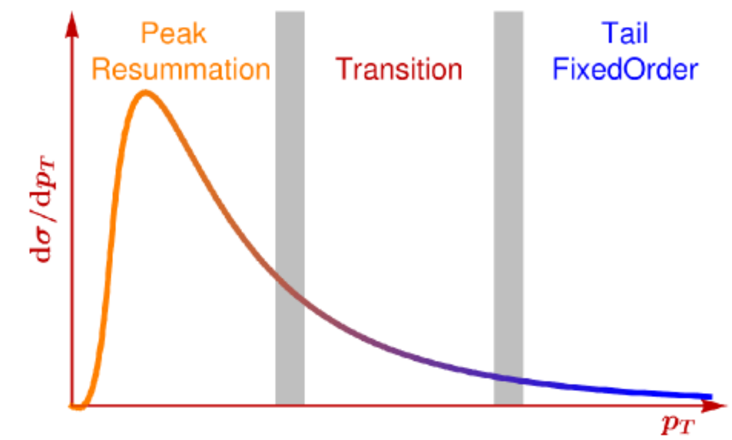


QCD sector of the Standard Model

- Z and W **+ jets** production can be used to test high-order QCD calculations
  - the DY process almost factorized wrt the strong interaction production
  - LO predicts W and Z at rest
  - the transverse boost of the V (=W,Z) can be modelled:
    - at small p_T needs soft gluon emission: resummation (non perturbative)
    - higher p_T, with perturbative QCD



- Many measurements of V+jets at LHC are compared with the most recent calculations:
  - NNLO in QCD, NLO in EWK: theory has O(1%) precision, experiment often sub-% level