SM Measurements at ATLAS and CMS

Michael Schmitt (Northwestern University)
for the **ATLAS** and **CMS** collaborations

CORFU 2018

September 2, 2018

Selected topics:

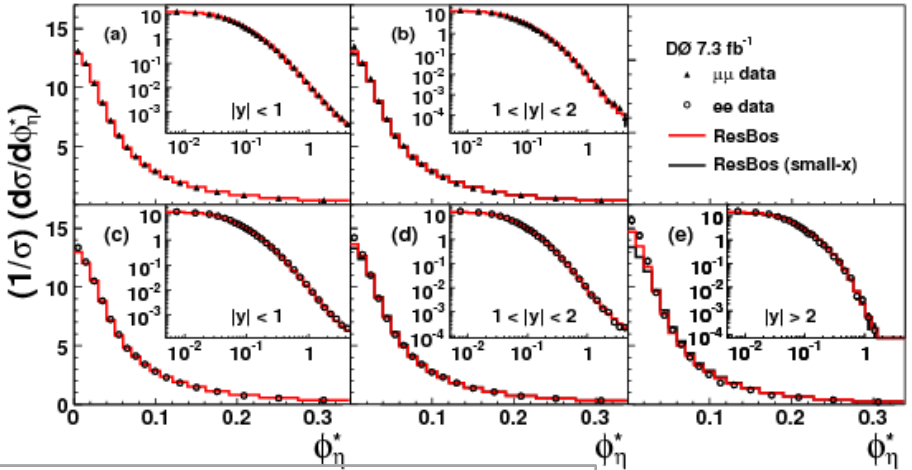
1. Drell-Yan differential cross section: $d\sigma/d\phi^*$
2. $\sin^2\theta_W$
3. M_W
4. Angular decorrelation of jets
5. Same-sign WW

Differential cross section $d\sigma/d\phi^*$:

- ϕ^* is closely related to q_T (dilepton transverse momentum). (Banfi et al.)
- It is based on angles, so resolution is very good.
- First explored by D0 at the Tevatron.
- Analysis is fairly straight forward:
  - Dilepton pairs
  - Small backgrounds
  - Very minor resolution effects
  - Normalize to total fiducial cross section – reduce systematic uncertainties.
  - Study ϕ^* distributions for various kinematic regions.
- ATLAS published 2016, CMS in 2018.

Primary goal: Check models at the level of event generators.

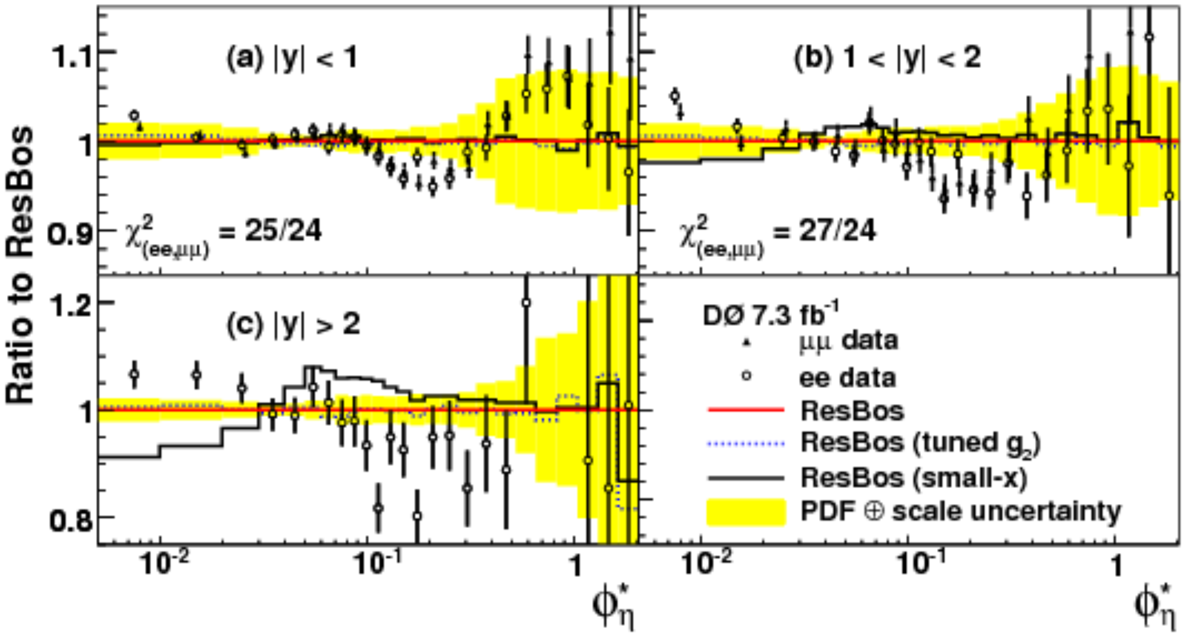
1. Does ResBos match the data?
2. Check as a function of rapidity *y*.



D0 Collab, PRL 106 (2011) 122001

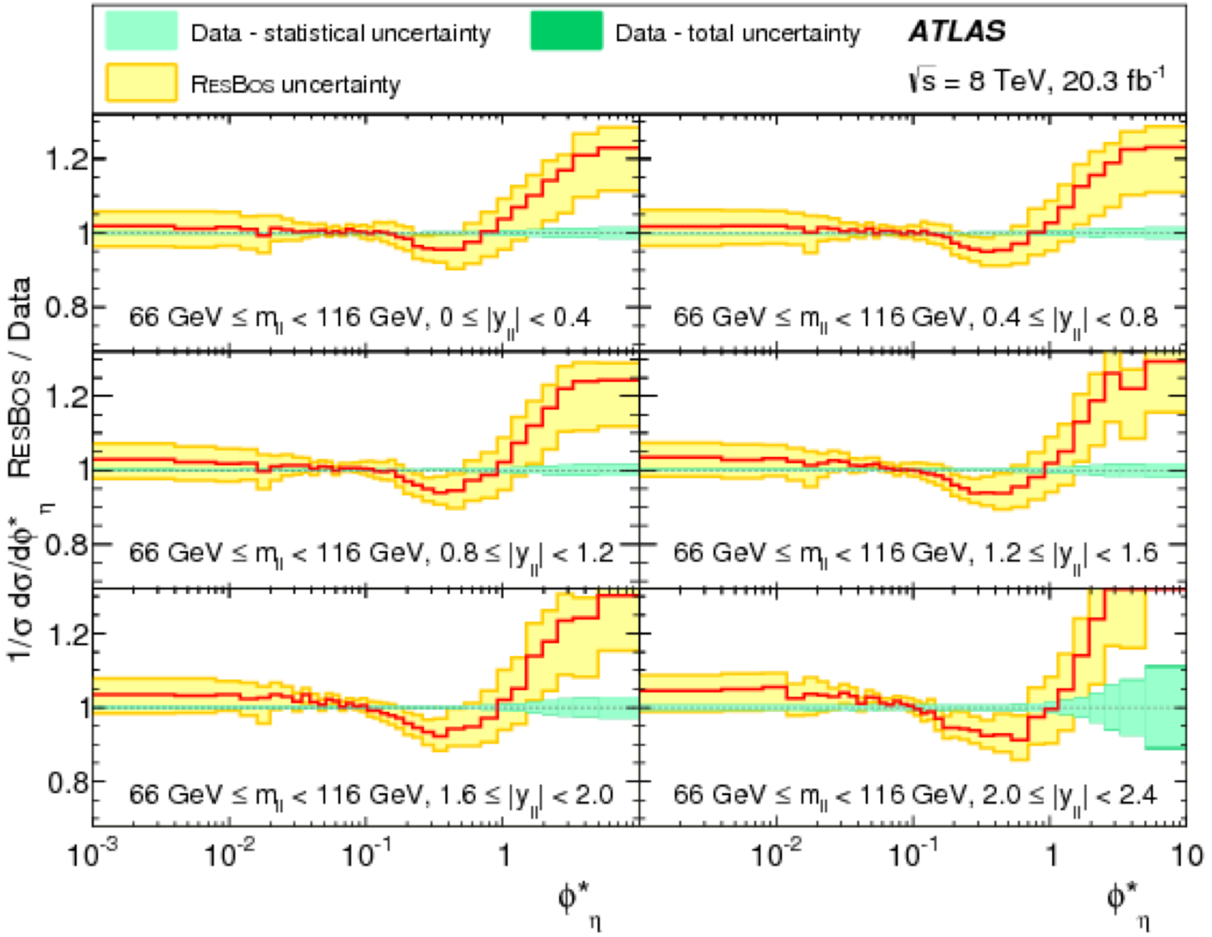
D0

Data/ResBos



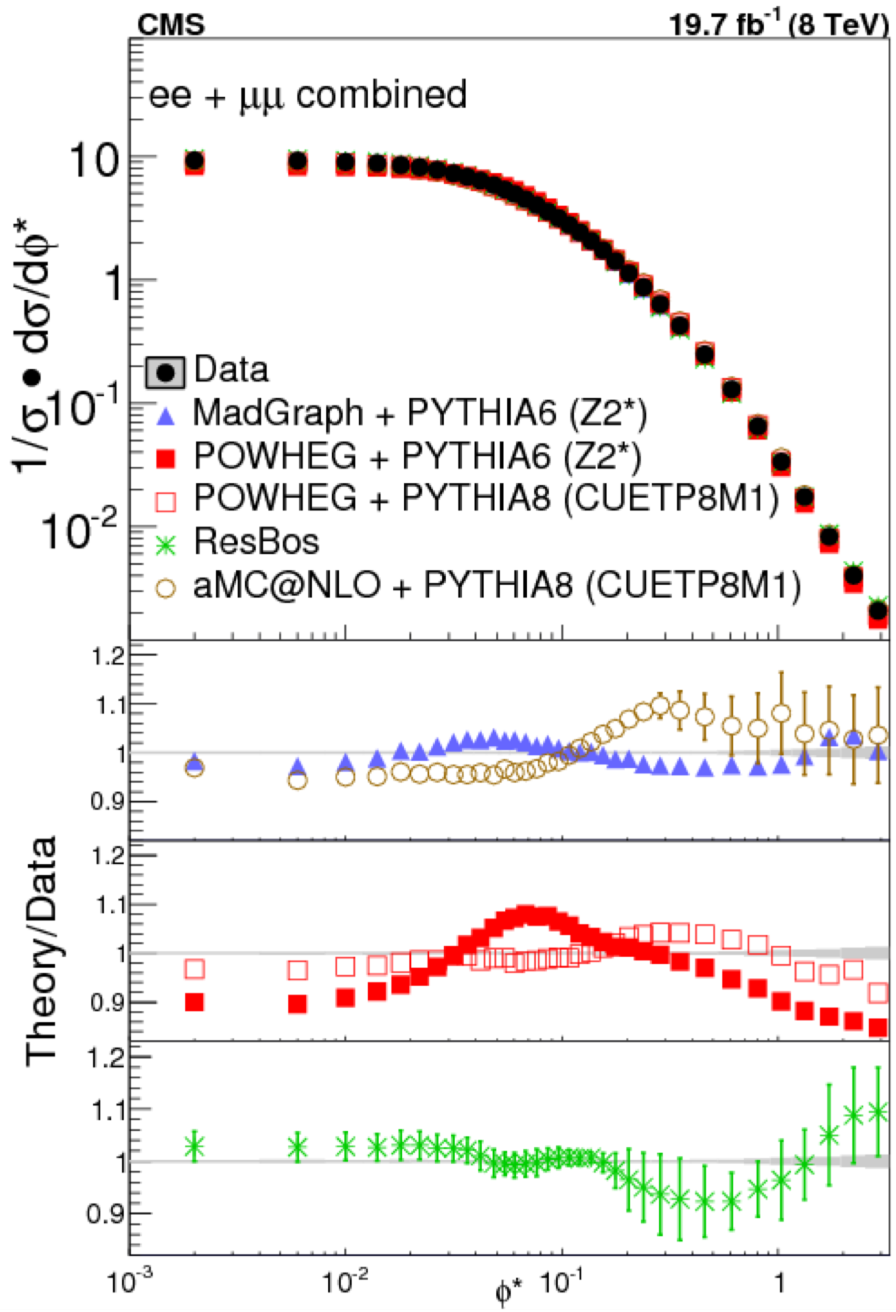
ATLAS, EPJC 76 (2016) 291

ResBos/Data

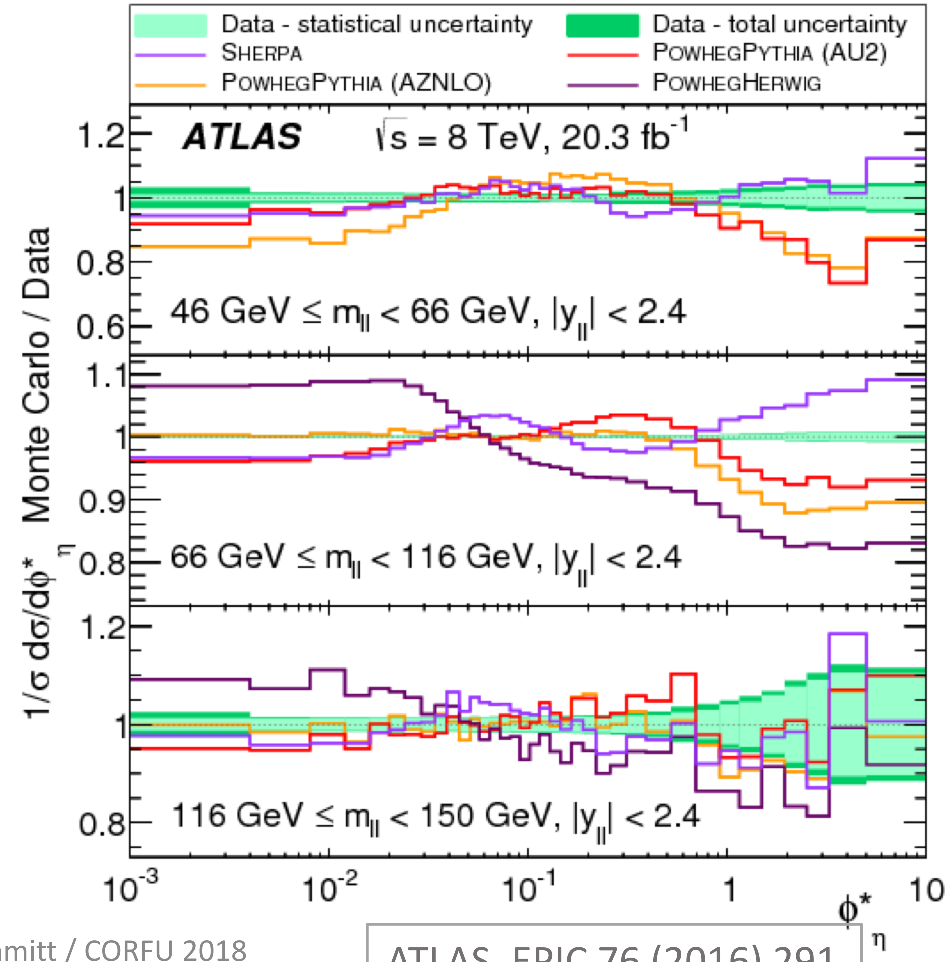


- Compare to other models:
  MadGraph, POWHEG, aMC@NLO, SHERPA

- None is successful at this level.

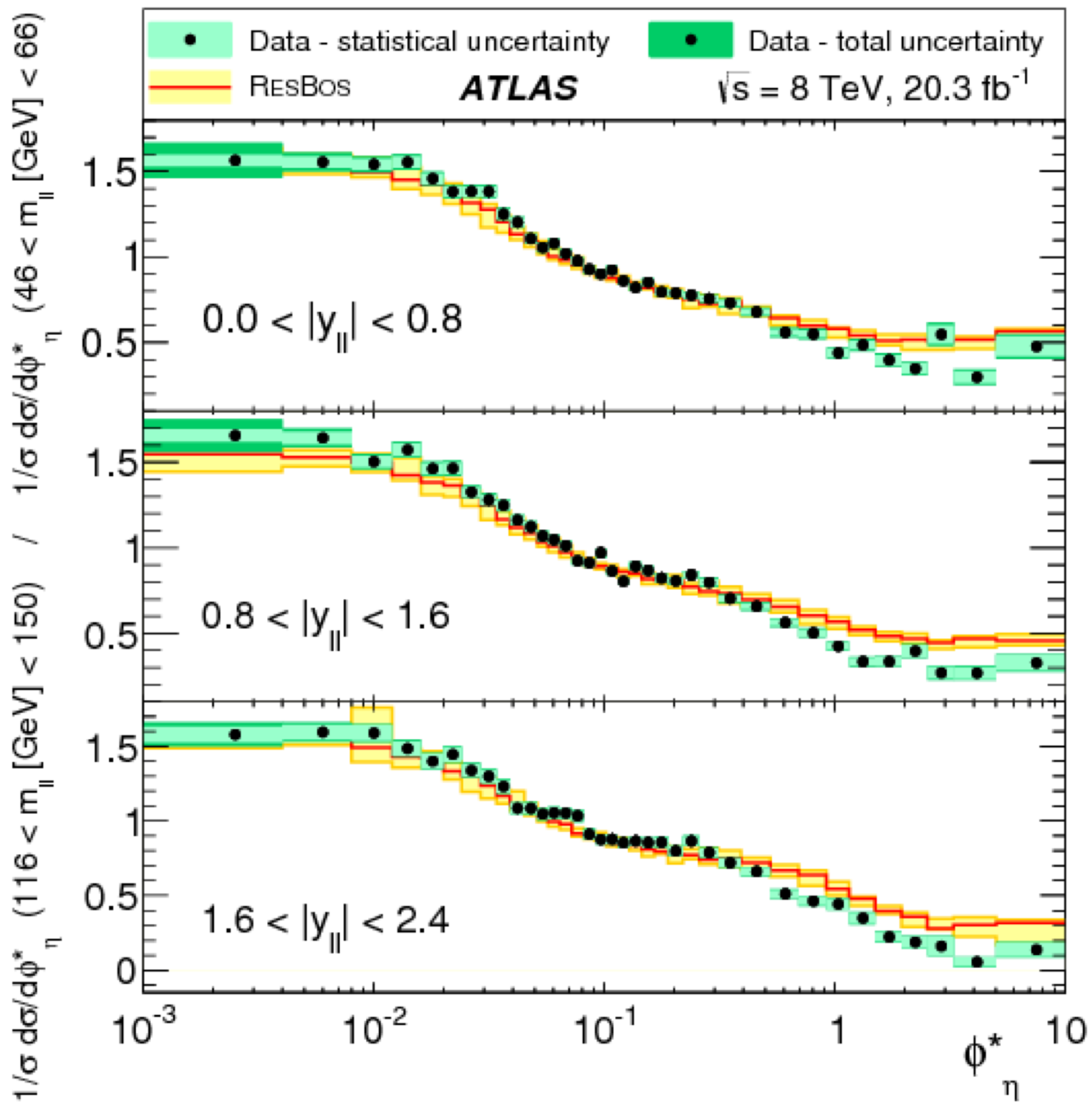


CMS, JHEP03(2018)172



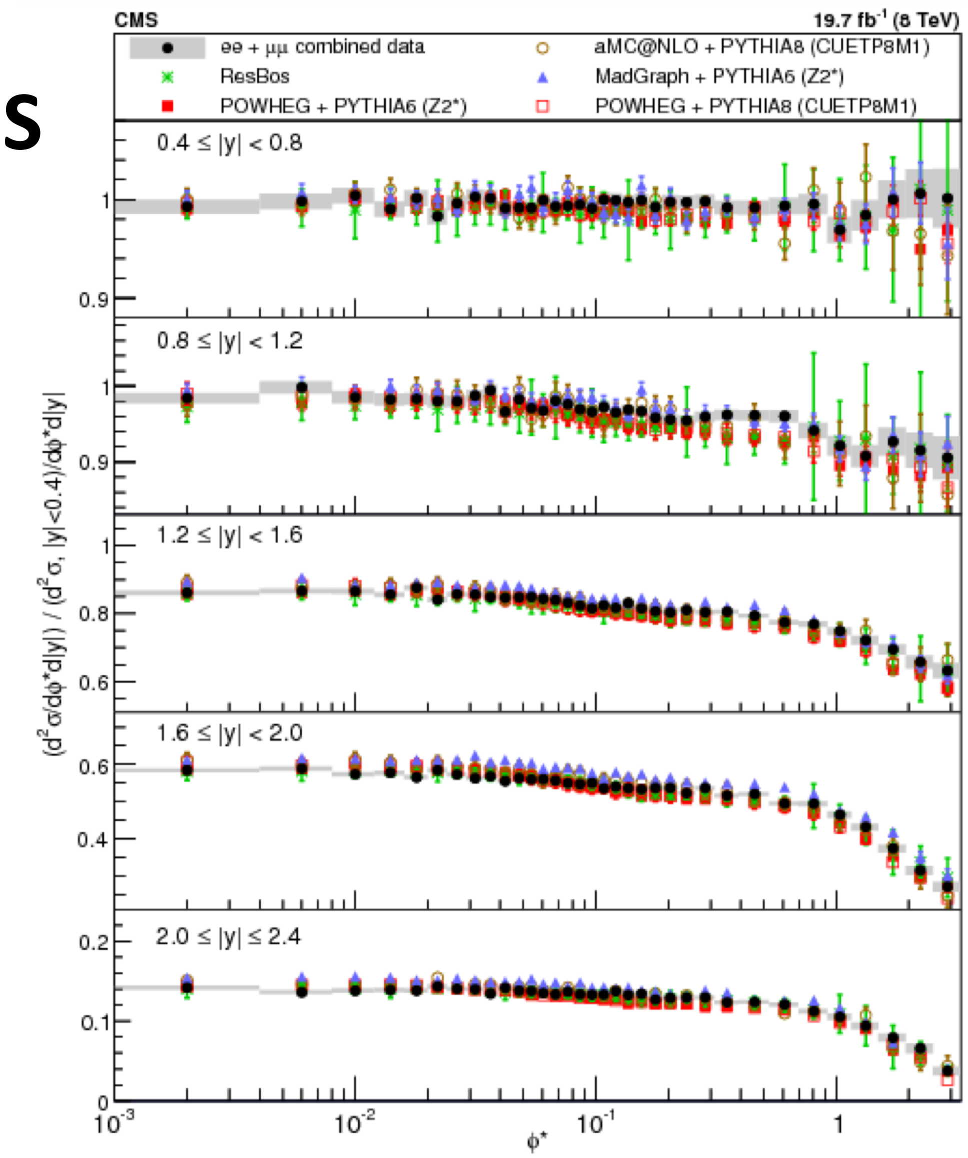
ATLAS, EPJC 76 (2016) 291

- ATLAS made unique measurements below and above the Z resonance.
- Use the low-mass data to normalize the Z resonance data (and still look as a function of rapidity).
- Precise!
- ResBos is generally successful; some tension at higher ϕ^*.

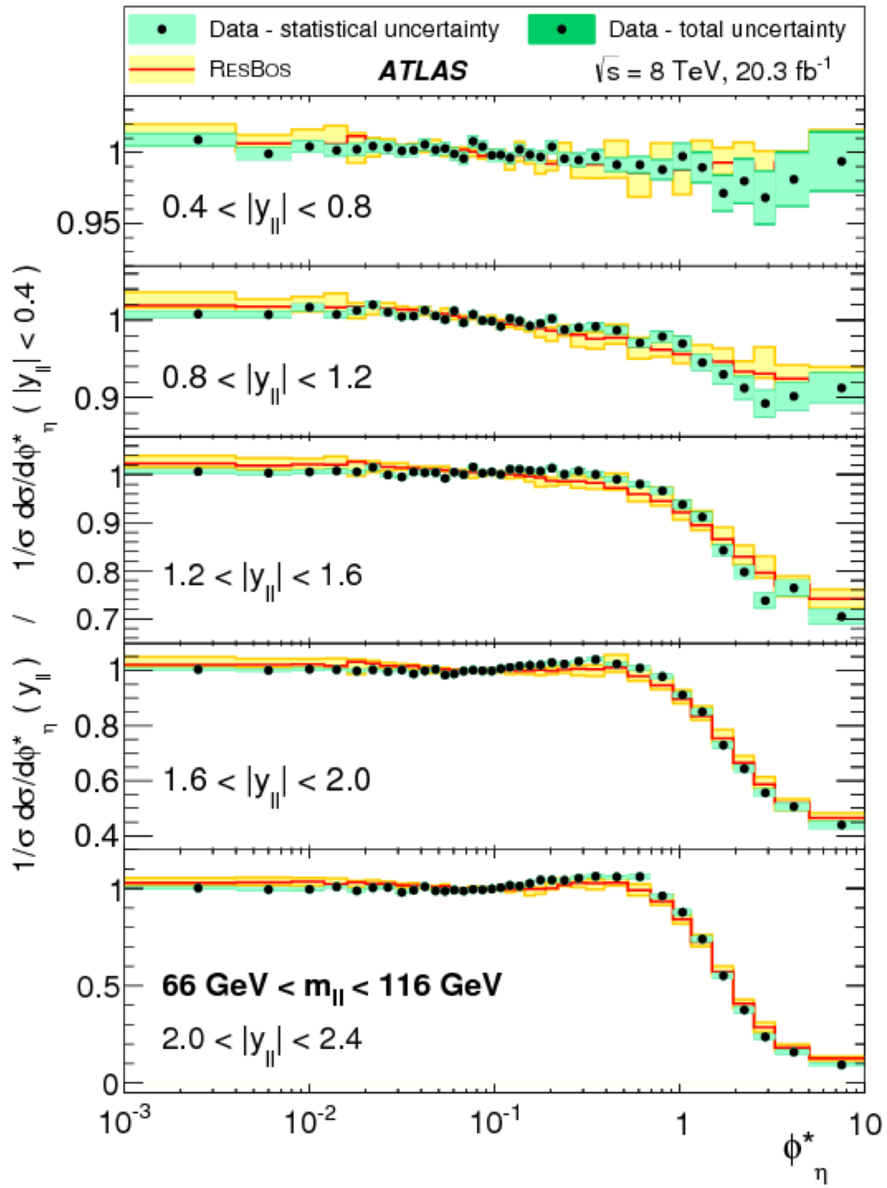


Similar: normalize to central Z production: |y| < 0.4

CMS



ATLAS

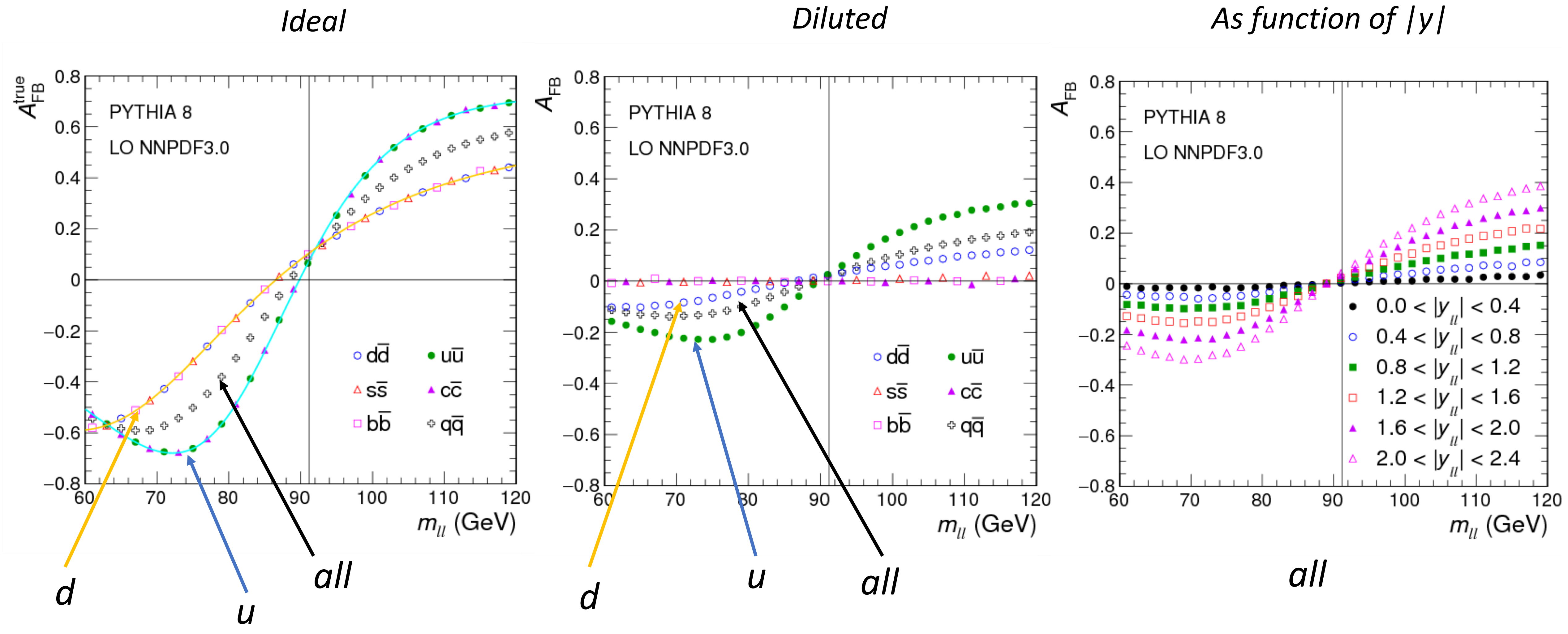


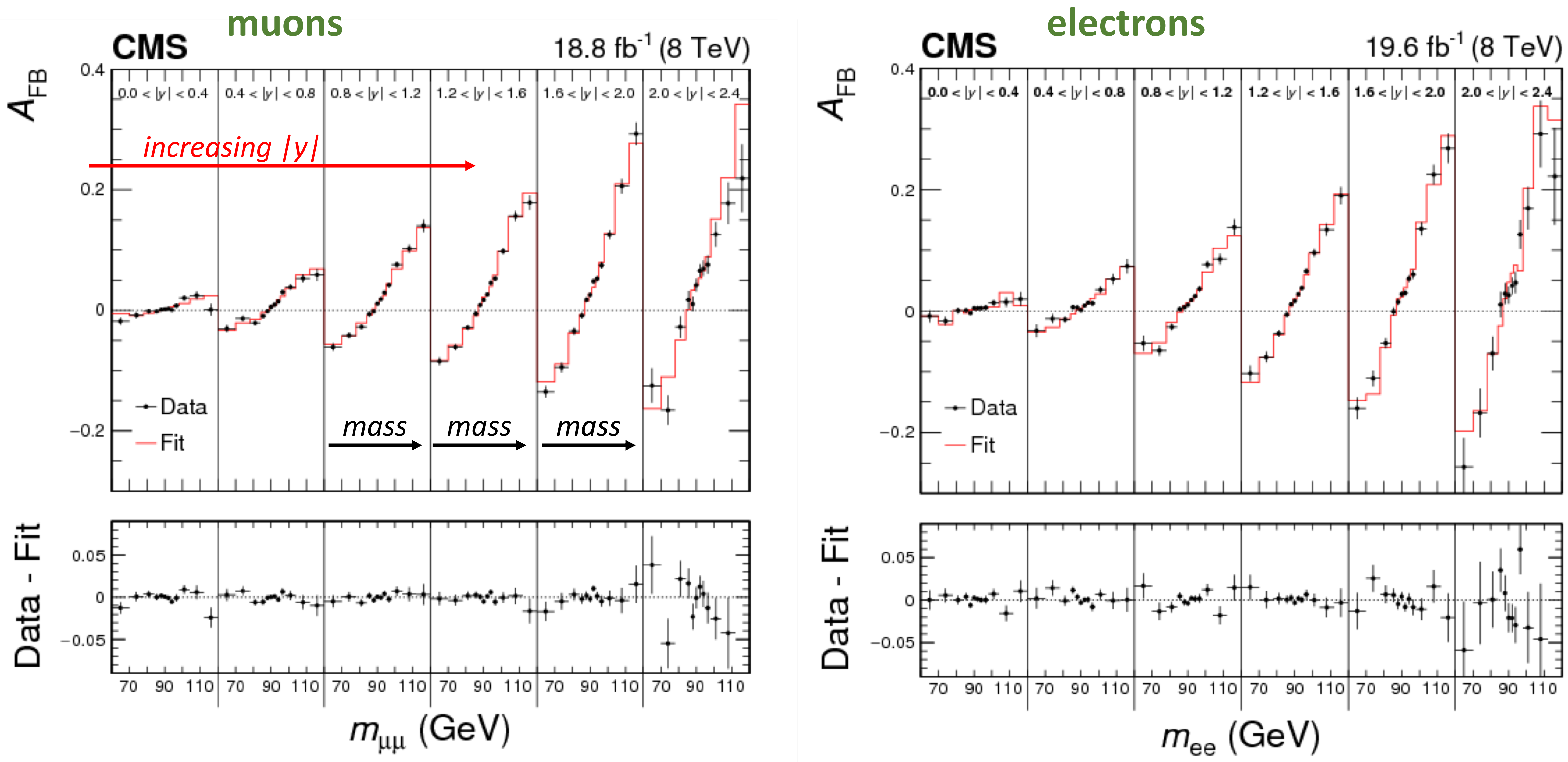
$\sin^2\theta_W$:

- $\sin^2\theta_W$ is a fundamental parameter of the SM.
- There is a long-standing tension between certain values from LEP & SLD.
- Hadron colliders provide huge samples of Z bosons.
- $\sin^2\theta_W$ determines the interference of axial and vector couplings near the Z pole
- Extract $\sin^2\theta_W$ by analyzing decay distributions $Z \rightarrow l^+l^-$ e.g. A_{FB} asymmetries.
- Entangled with PDFs (axial and vector couplings are different for *u, d* quarks).
  - PDF uncertainties are the large component of the uncertainty.
- "Dilution" of asymmetries makes the job much harder, especially at the LHC.
- CMS posted in June 2018, ATLAS has conference note from July 2018.
  - Methodology is quite different.

Primary goal: Measure a fundamental parameter of the SM.

CMS, arXiv:1806.00863



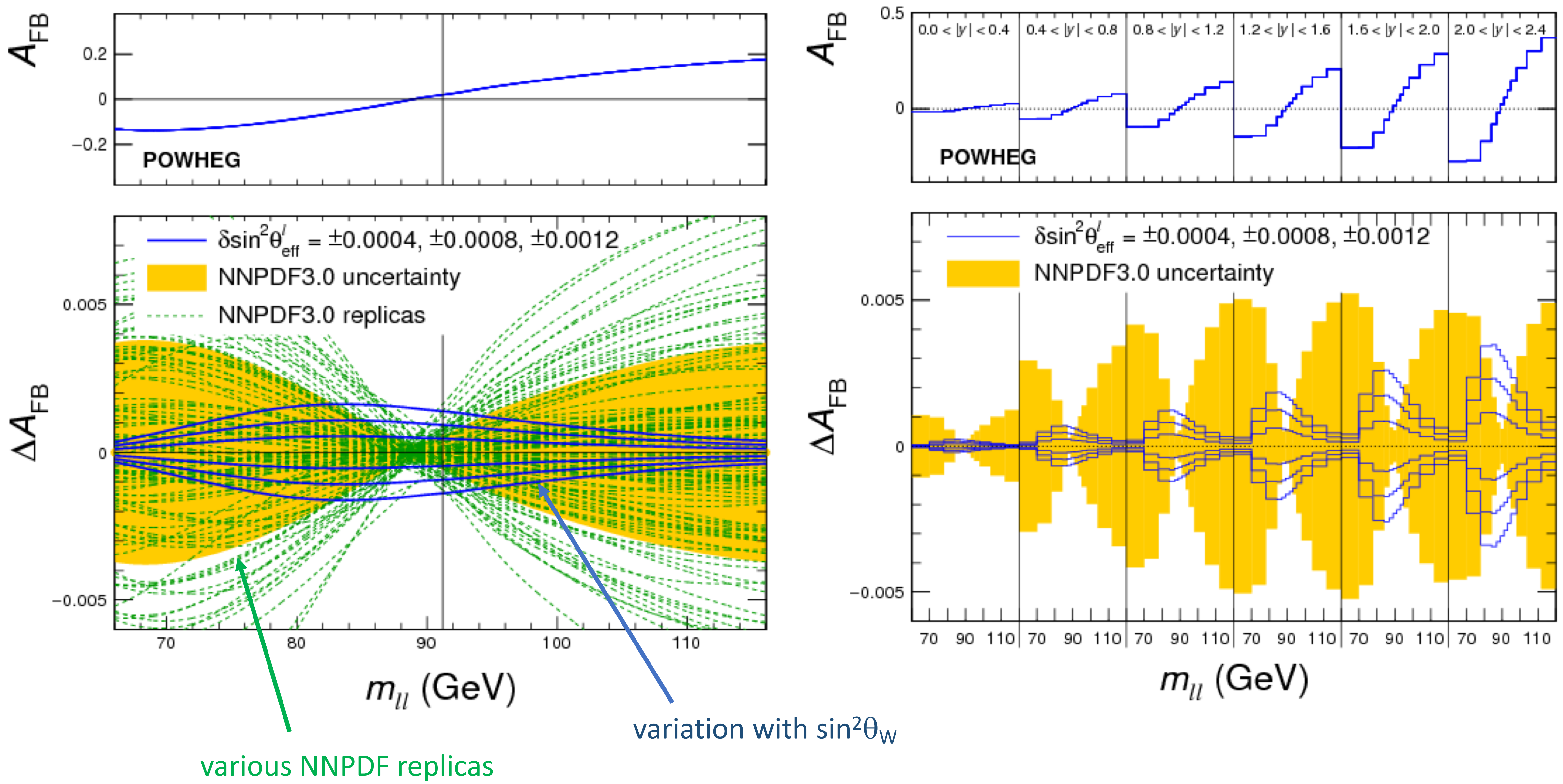


CMS, arXiv:1806.00863

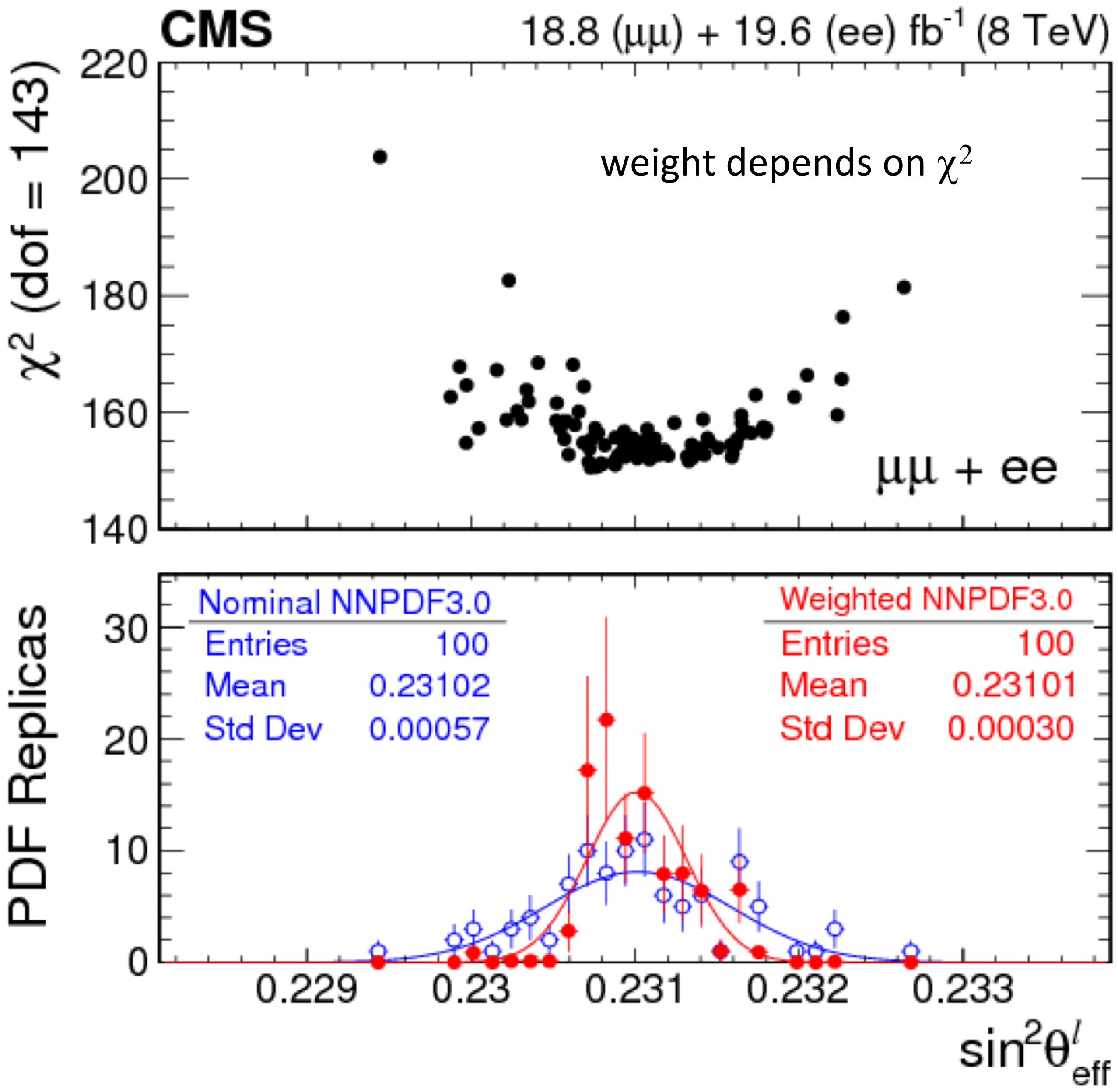
($\sin^2\theta_W$ is proportional to the slope at $M_{ll} = M_Z$.)

The PDF variations are vaguely orthogonal to the dependence on $\sin^2\theta_W$

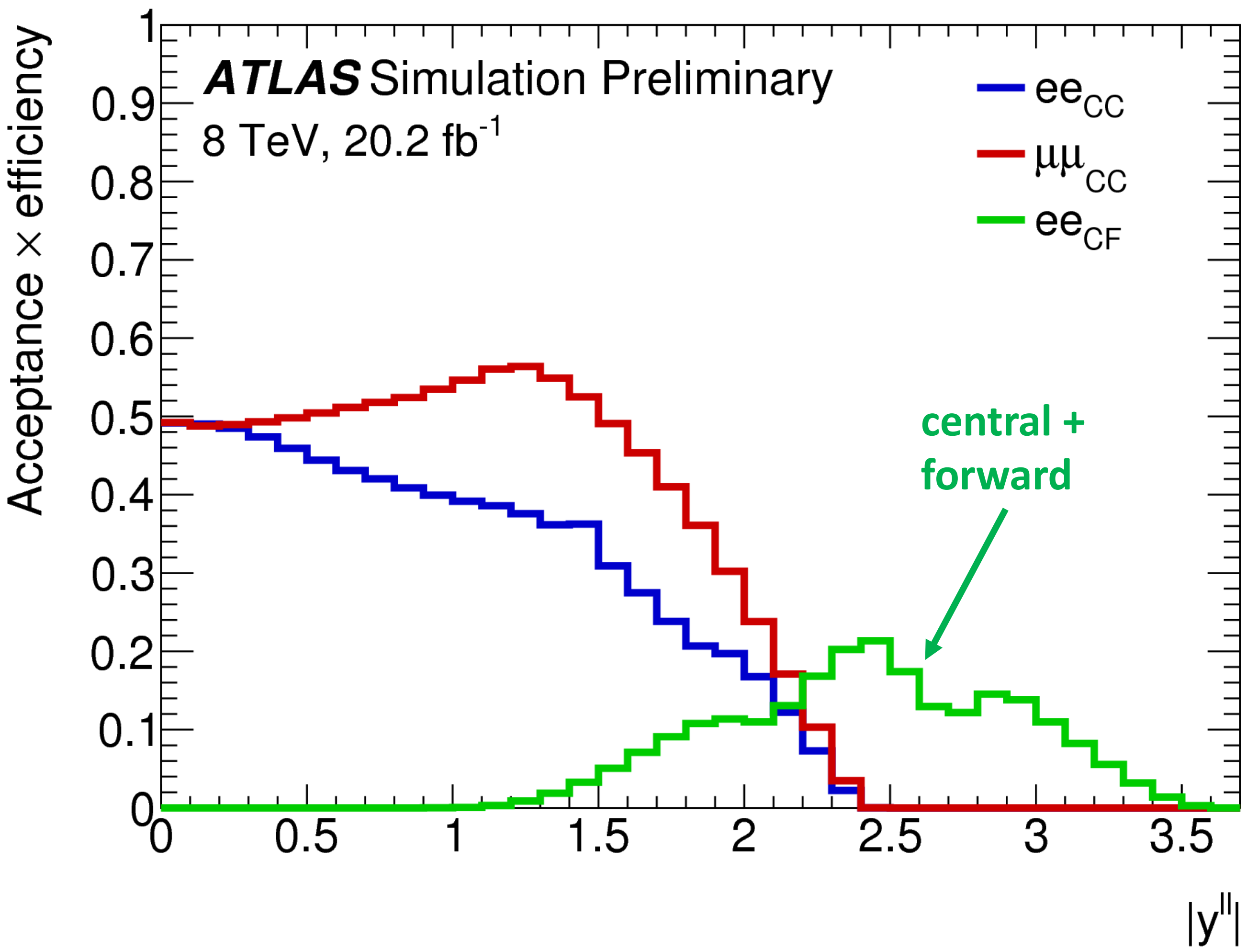
CMS, arXiv:1806.00863



- A_{FB} versus M_{ll} provides an in situ constraint on PDFs.
- Assign weights according to how well a given PDF reproduces the A_{FB} versus M_{ll} data.
- Reduces PDF uncertainties by 30% with no bias in $\sin^2\theta_W$.



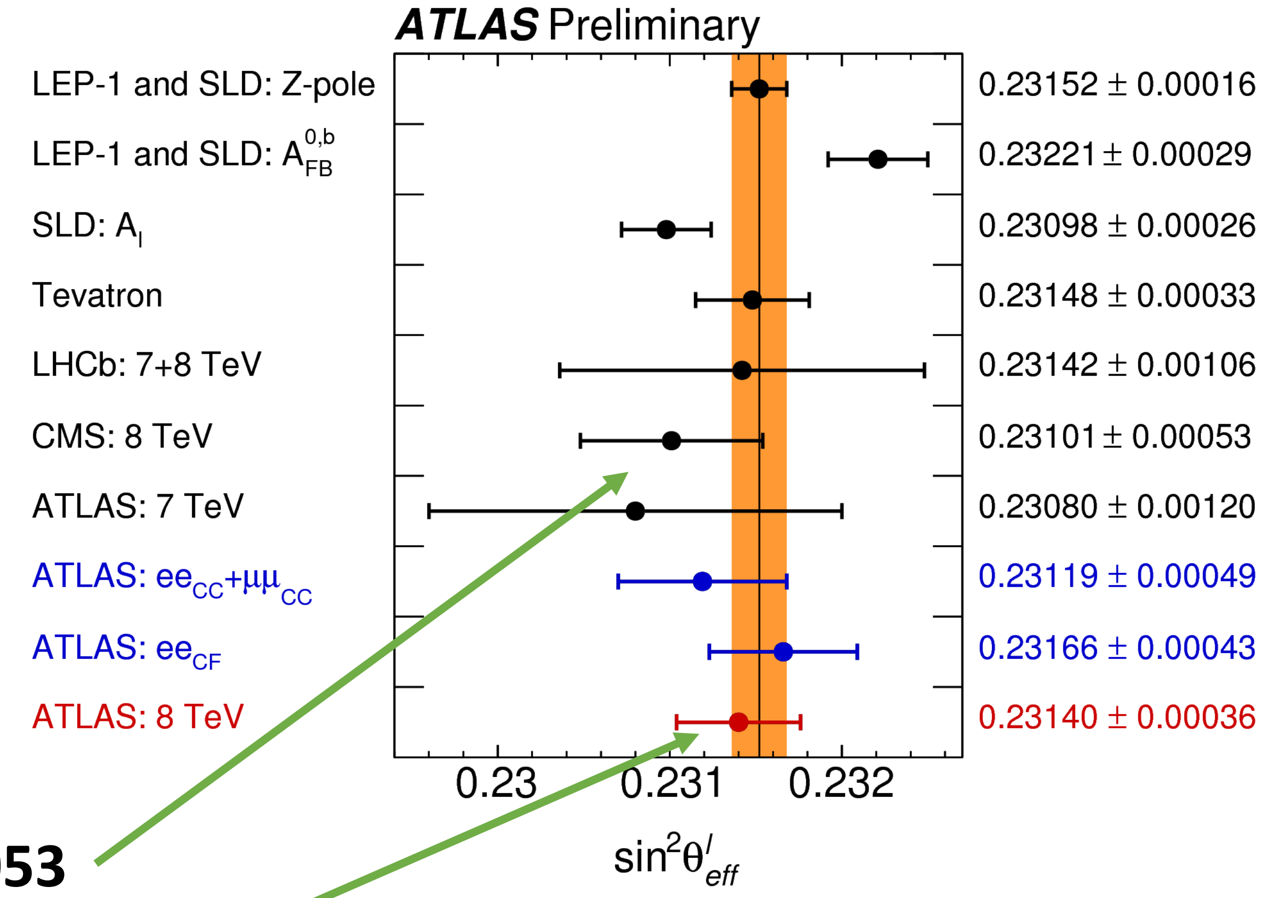
CMS, arXiv:1806.00863



- ATLAS determine all eight of the coefficients governing the lepton kinematic distributions.
- Sophisticated template fits.
- Utilize the full phase space (m_{ll} and *y but integrate over* p_T)
- Key feature: use forward electrons

- CMS & ATLAS approach Tevatron, maybe LEP/SLD

- Central values lower than but consistent with earlier measurements.



CMS: $\sin^2\theta_W = 0.23101 +/- 0.00053$

ATLAS: $\sin^2\theta_W = 0.23140 +/- 0.00036$

		statistical	*exp. syst.*	*theory syst.*	*PDFs*
CMS:	$\sin^2\theta_W$ = **0.23101**	**+/- 0.00036**	**+/- 0.00017**	**+/- 0.00016**	**+/- 0.00031**
ATLAS:	$\sin^2\theta_W$ = **0.23140**	**+/- 0.00021**	**+/-**	**0.00016**	**+/- 0.00024**

Extra statistical power from forward electrons

Theory uncertainties
come out smaller.

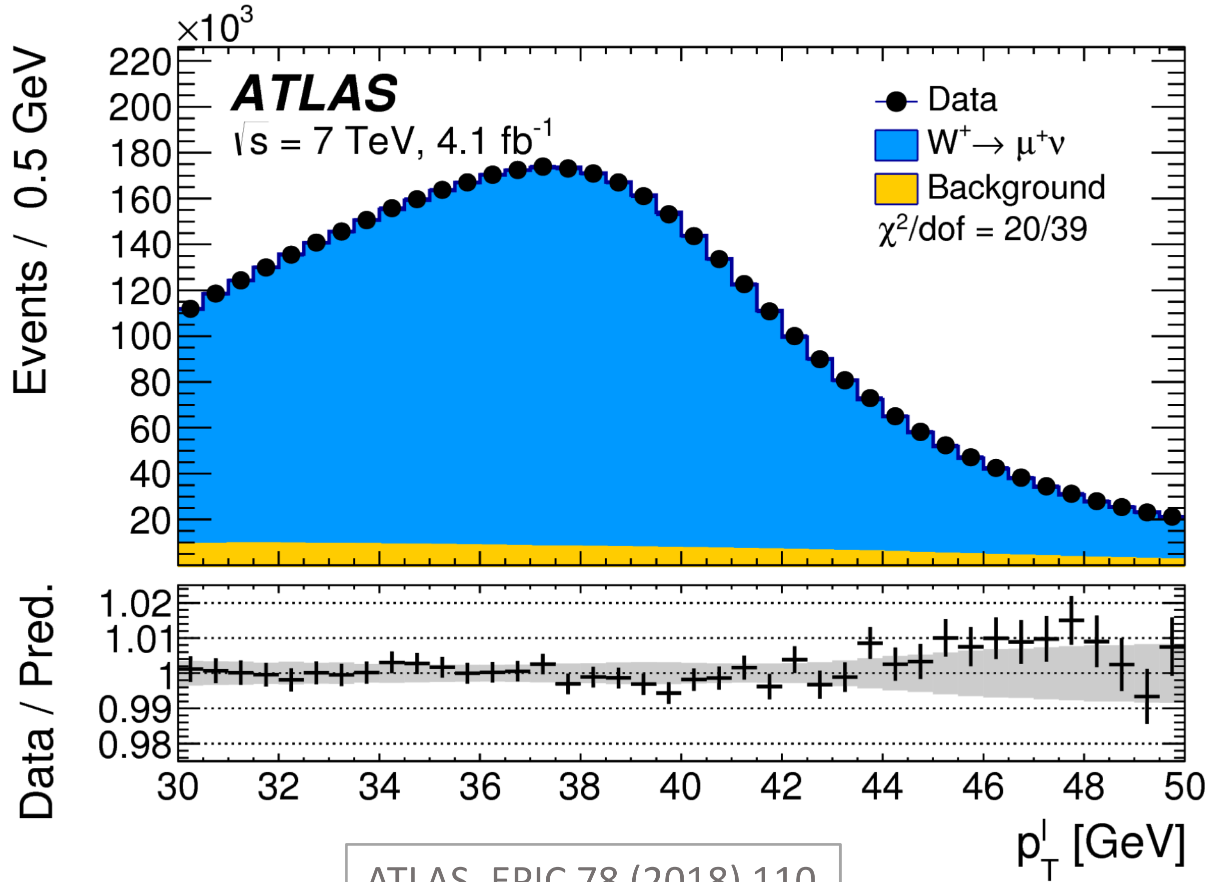
Difficult to understand given
CMS weighting approach.

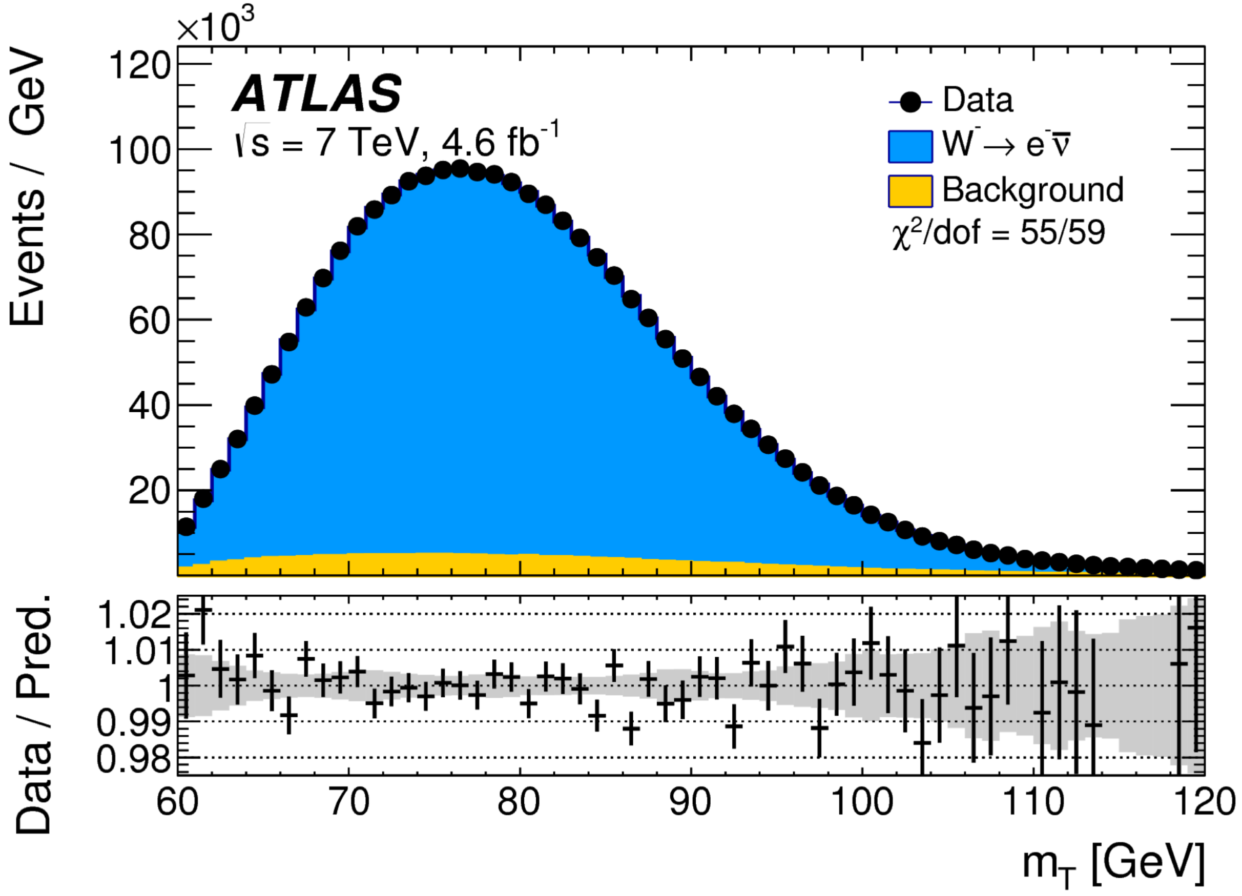
M_W:

- One of the big prizes of a high luminosity hadron collider.
- Provides crucial test of the standard model
    - Global electroweak fits provide a precision of about 8 MeV which sets the goal for direct measurements of M_W.
- One of the very most challenging analyses at a hadron collider
    - lepton calibration, hadronic recoil calibration, background estimation, modeling of kinematics, PDFs, etc. etc.
    - Progress make by working on all fronts – no single key to the 8 MeV goal.
- ATLAS published early in 2018 (public in early 2017). CMS is working.

Primary goal: Measure a fundamental parameter of the SM.

- **Technique is similar to Tevatron measurements: fit lepton p_T and transverse mass m_T**
- **Calculate full χ^2 for a set of templates – vary assumed M_W for each template.**
- **Quadrative behavior gives best M_W and the uncertainty.**
- **Obtain M_W for several cases/channels and combine them taking correlations into account.**

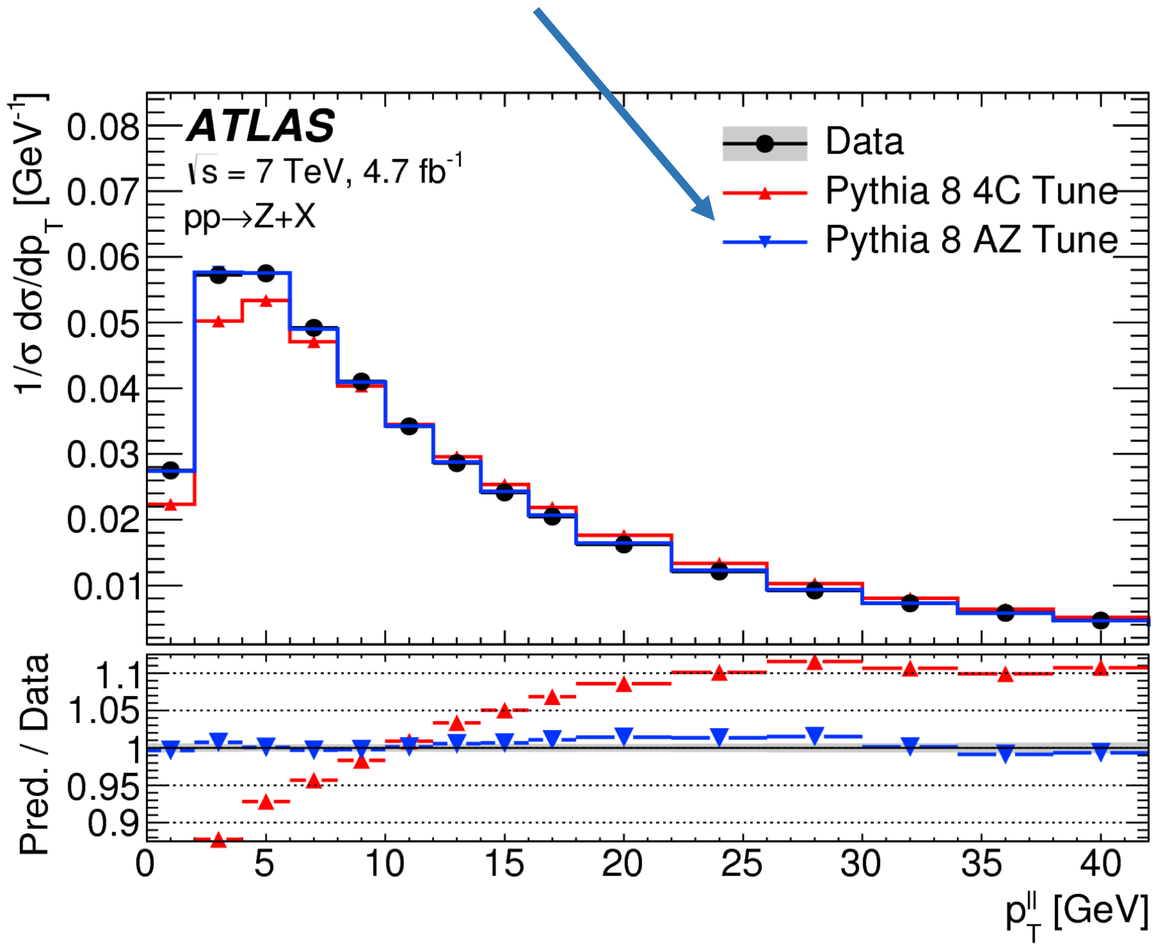


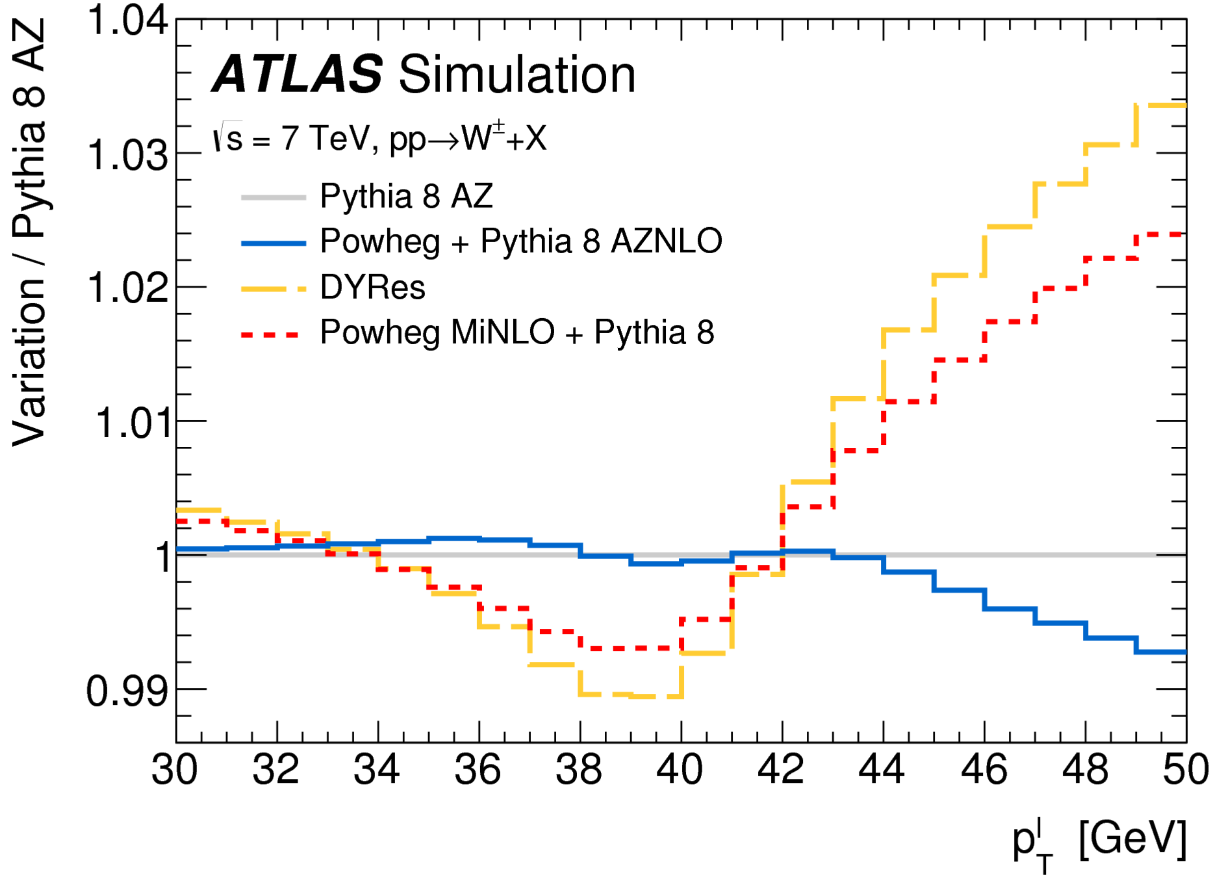


ATLAS, EPJC 78 (2018) 110

ATLAS developed a careful “AZ” tune of POWHEG+PYTHIA8 that matches several key measurements.

ATLAS, EPJC 78 (2018) 110



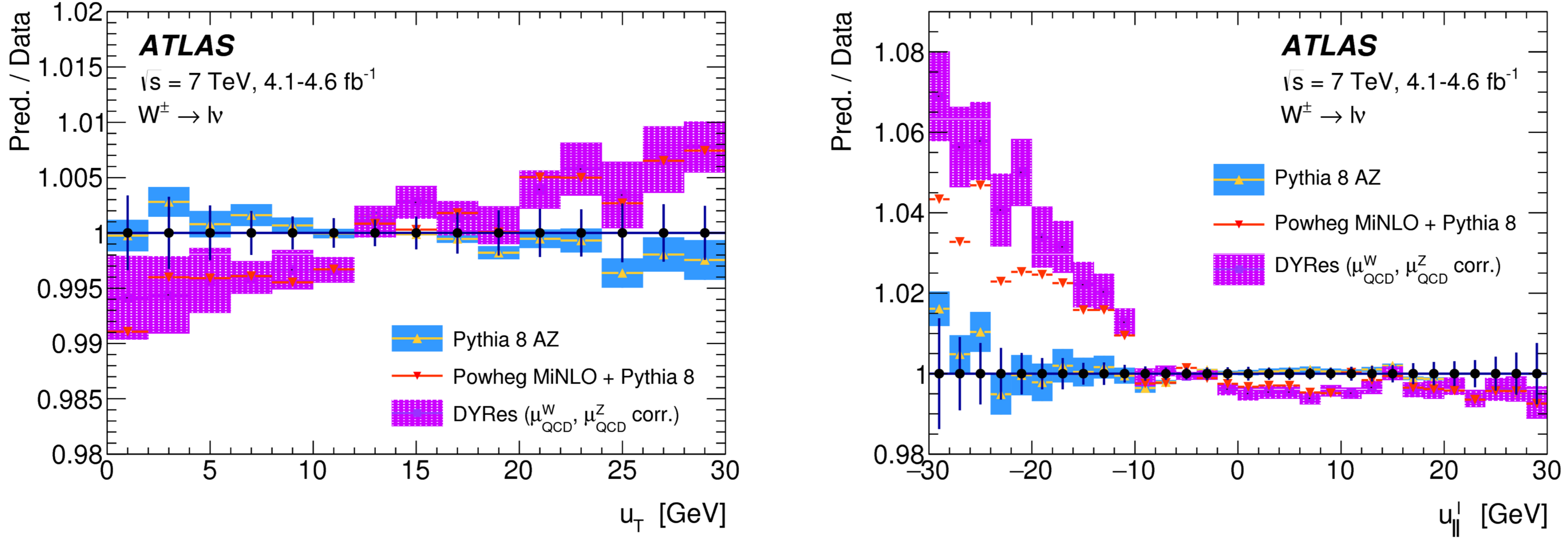


Other advanced programs (DYRes, POWHEG MiNLO) match the data poorly.
If considered as part of the kinematic model, would lead to large (30 MeV) uncertainties.
ATLAS decided to simply reject these programs…

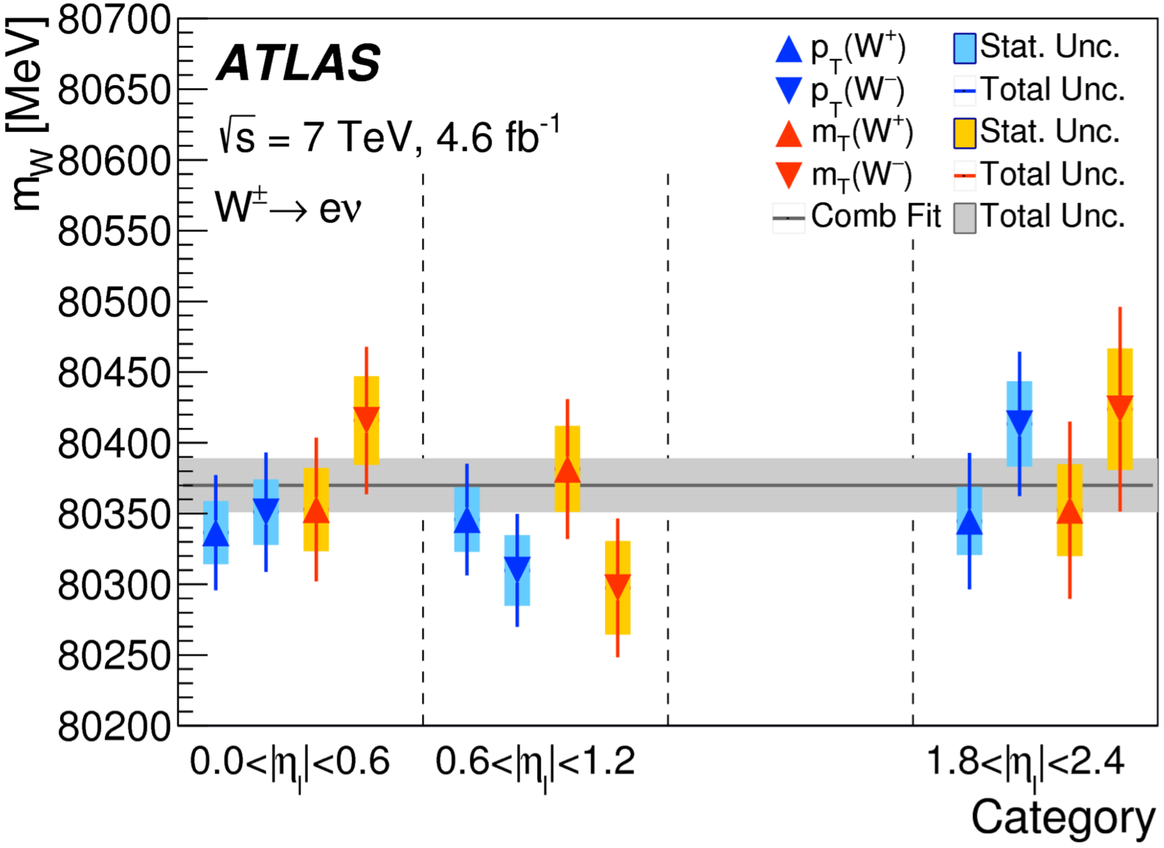
The discrepancies would be very evident in the hadronic recoil modeling.

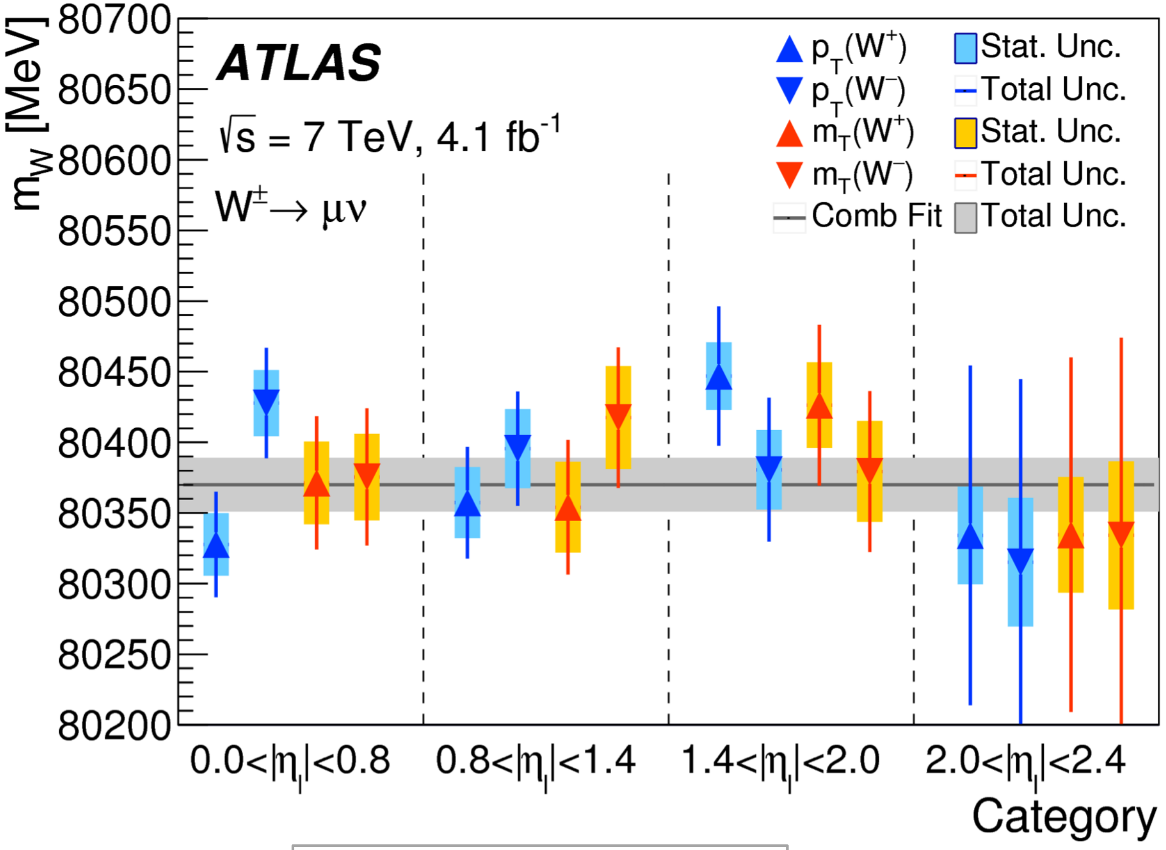
These plots show that the prediction would not be in line with the measurements.

ATLAS, EPJC 78 (2018) 110



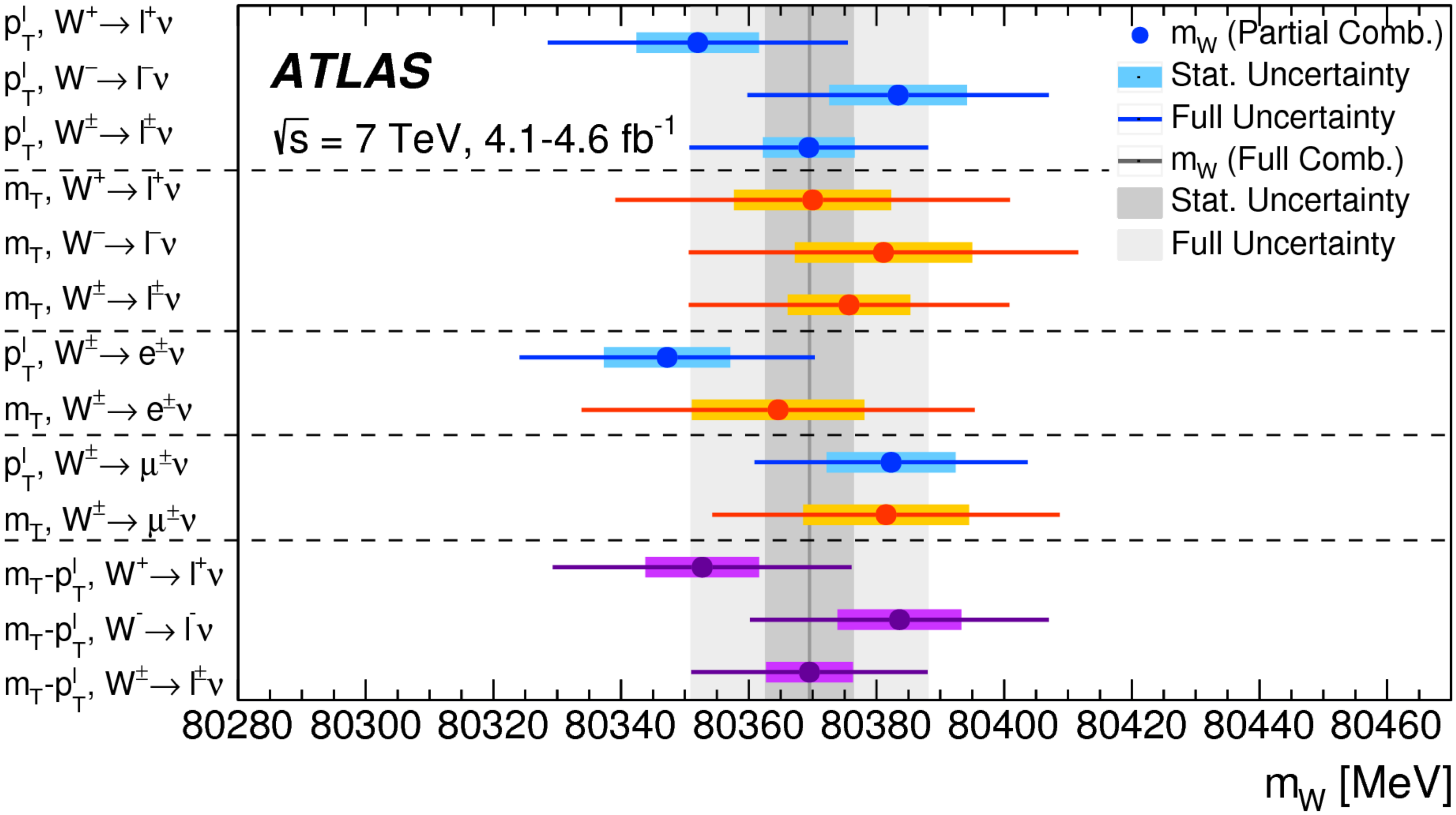
- **The ATLAS results are impressively consistent and stable.**
  - **positive and negative cancel PDF uncertainties**
  - **electron and muon channel have completely different (and challenging) lepton calibration issues**
  - ***M_T* is sensitive to hadronic recoil, *p_T* is not.**

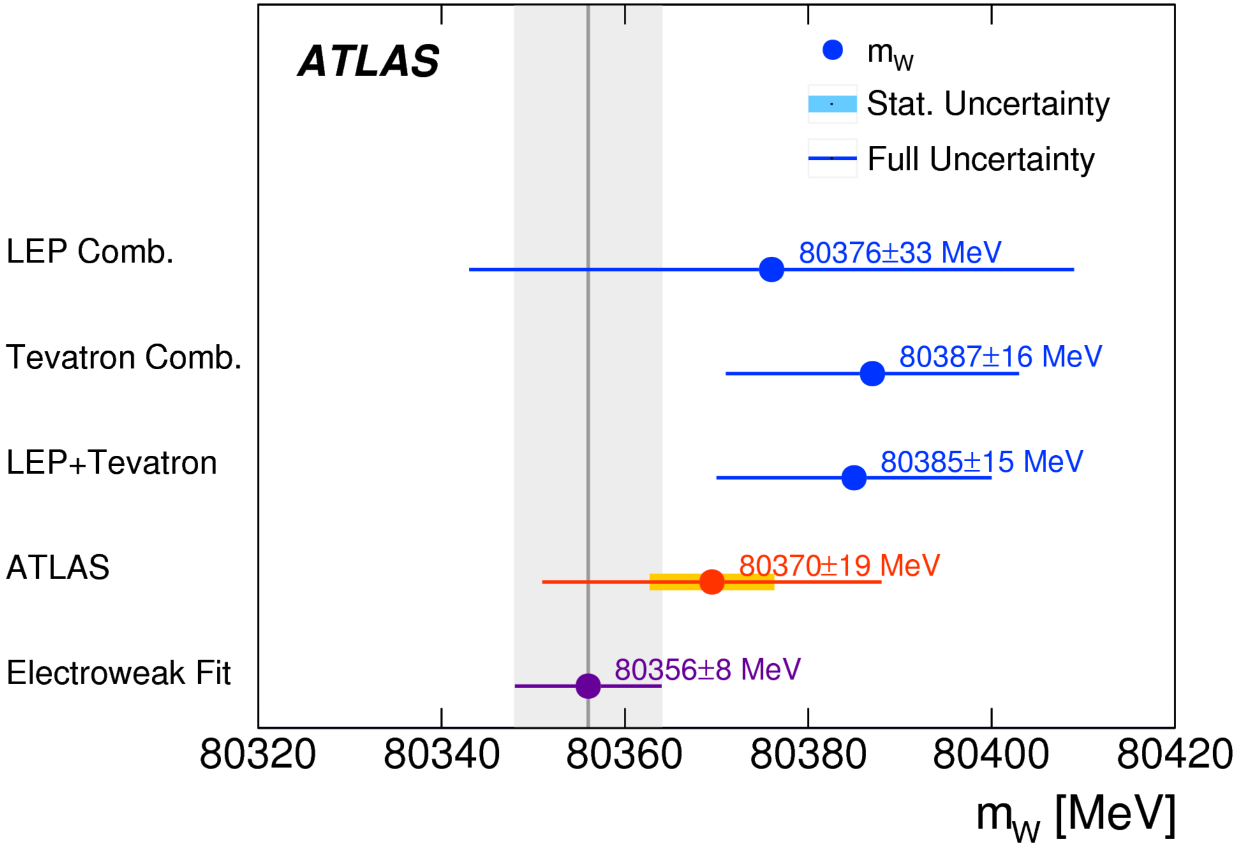


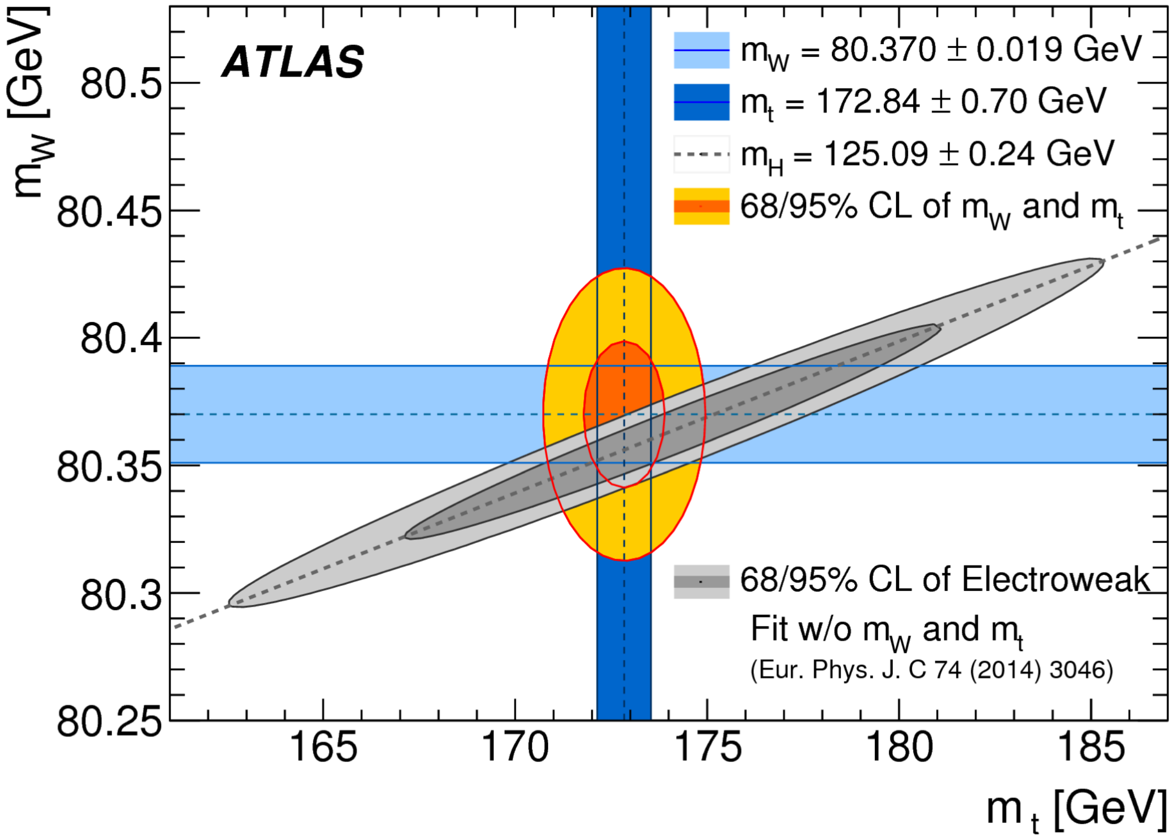


ATLAS, EPJC 78 (2018) 110

ATLAS, EPJC 78 (2018) 110




ATLAS
m_W
Stat. Uncertainty
Full Uncertainty
LEP Comb.
80376±33 MeV
Tevatron Comb.
80387±16 MeV
LEP+Tevatron
80385±15 MeV
ATLAS
80370±19 MeV
Electroweak Fit
80356±8 MeV
80320 80340 80360 80380 80400 80420
m_W [MeV]


ATLAS
m_W = 80.370 ± 0.019 GeV
m_t = 172.84 ± 0.70 GeV
m_H = 125.09 ± 0.24 GeV
68/95% CL of m_W and m_t
68/95% CL of Electroweak Fit w/o m_W and m_t
(Eur. Phys. J. C 74 (2014) 3046)
m_W [GeV]
80.25 80.3 80.35 80.4 80.45 80.5
165 170 175 180 185
m_t [GeV]

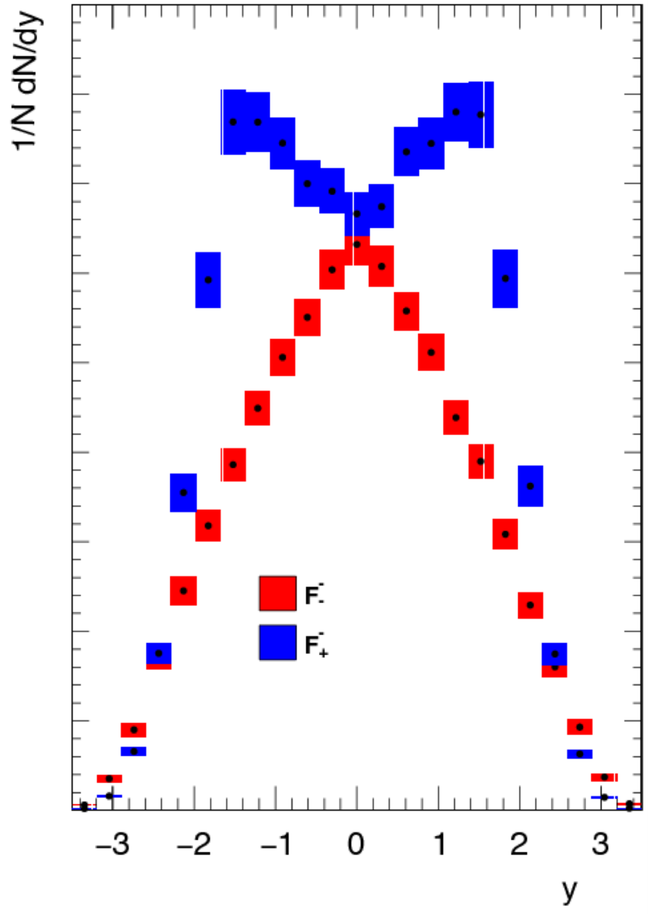
Manca et al. JHEP 12 (2017) 030

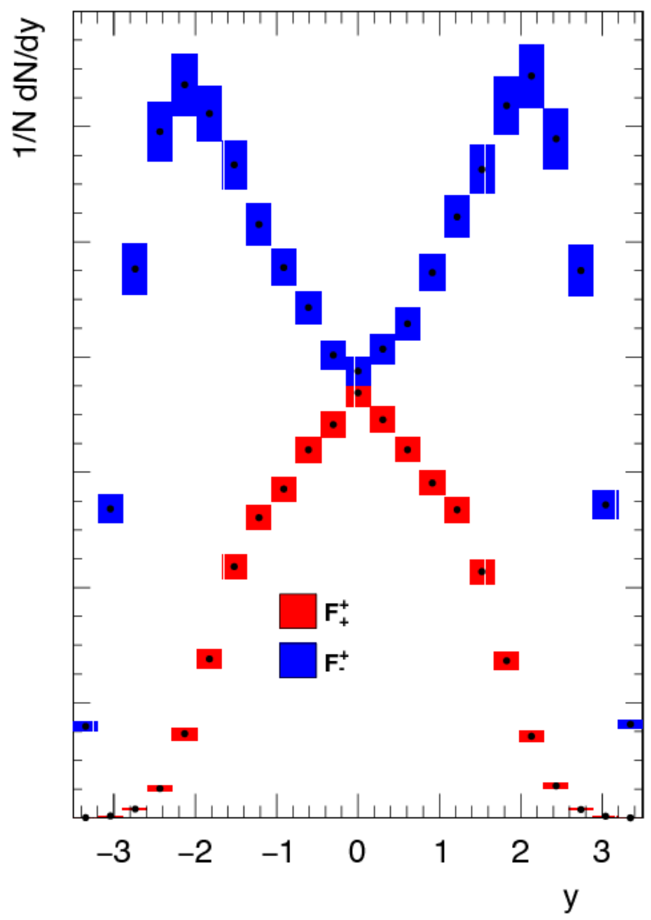
What's coming from CMS: W helicity measurements

Template fits not dissimilar to ATLAS Z angular coefficient analysis.
Not as straight forward due to neutrino – must rely on charged lepton alone.

negative W

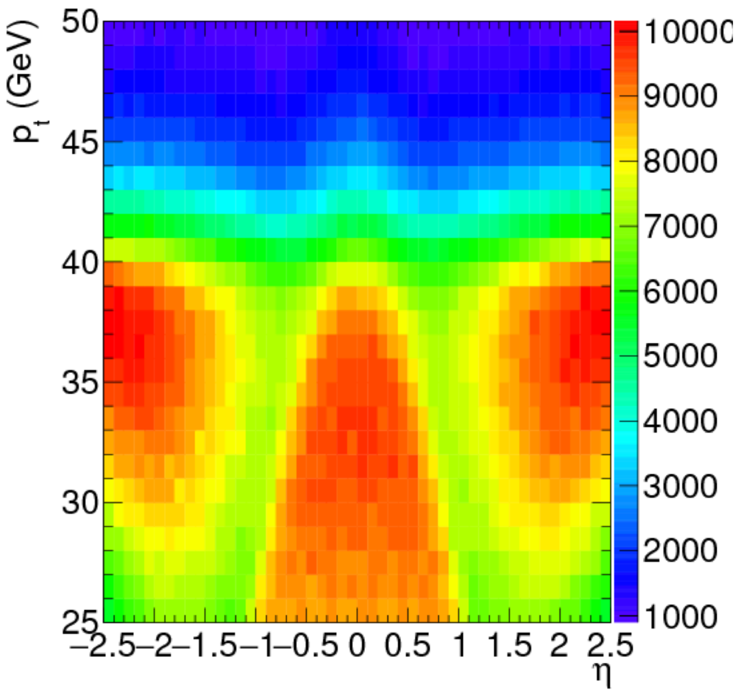
both helicities

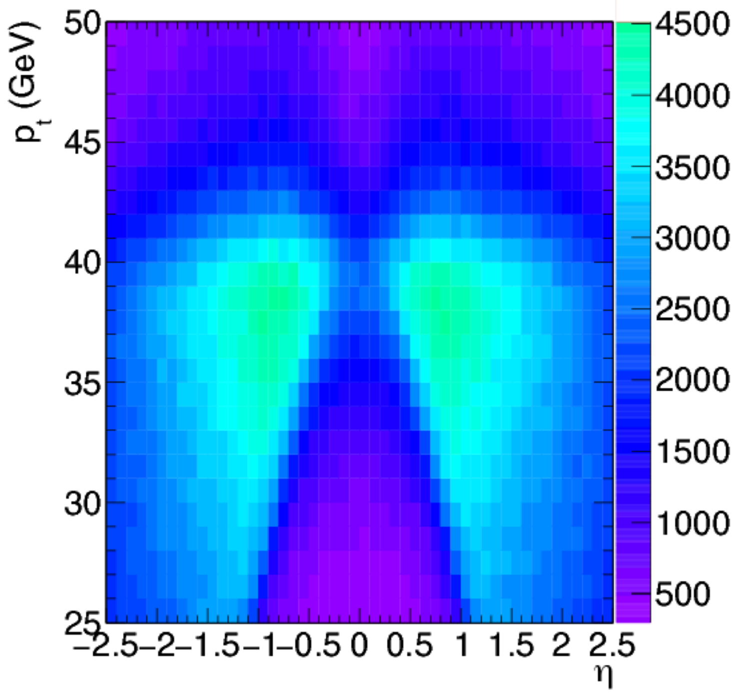




positive W

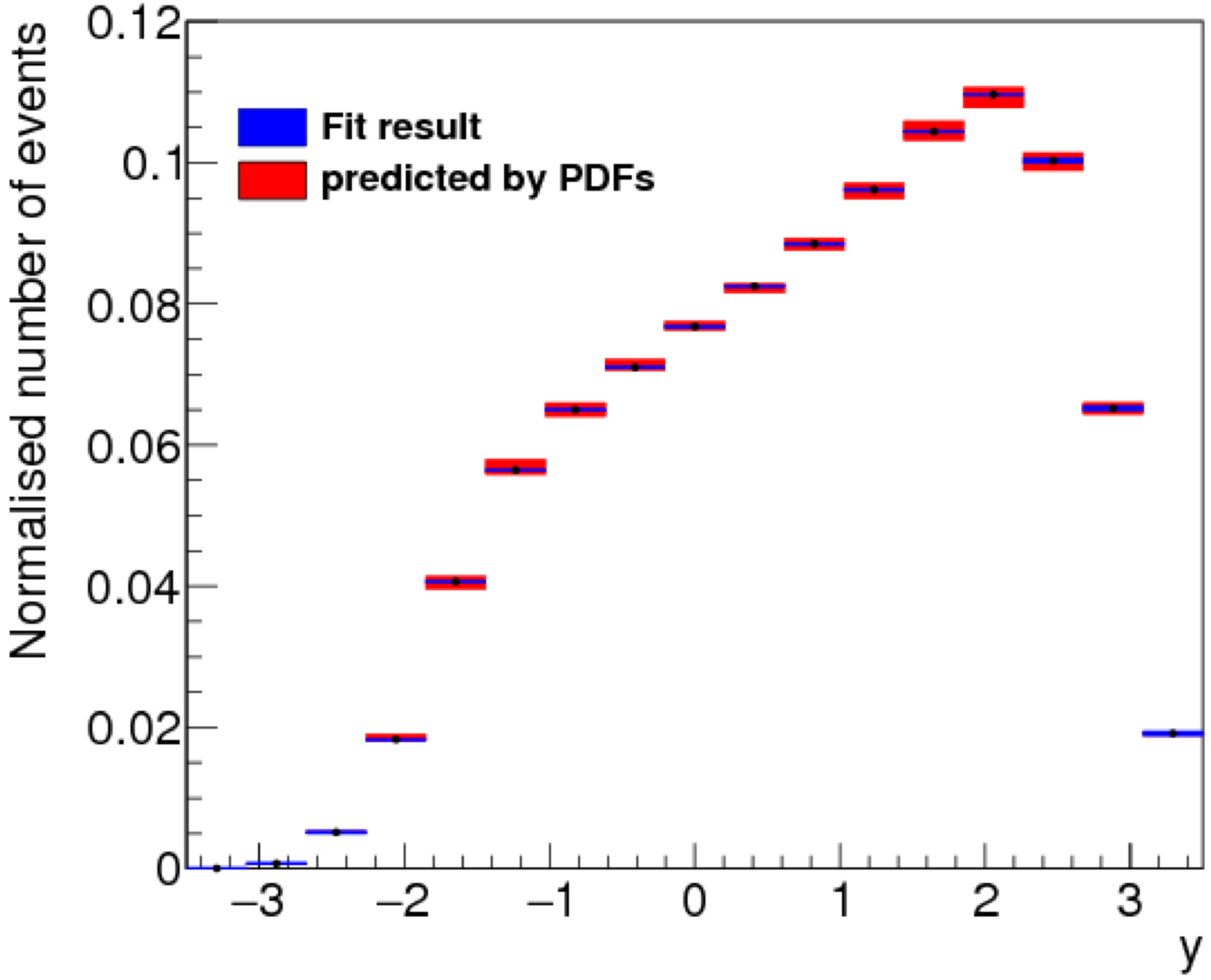
both helicities



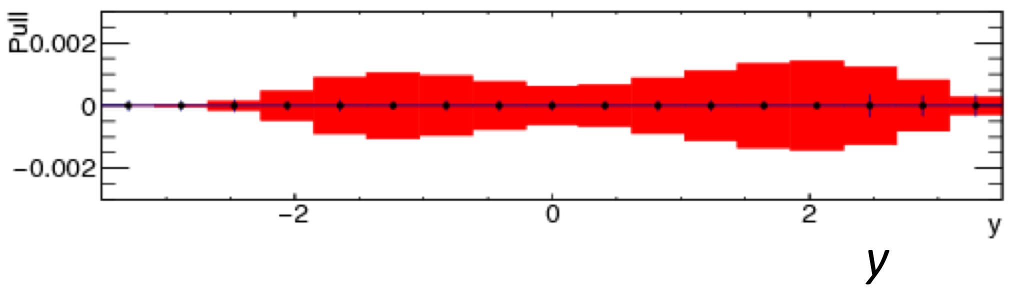


The parity violation in W decay helps out: the lepton (p_T,η) distribution is highly discriminating.

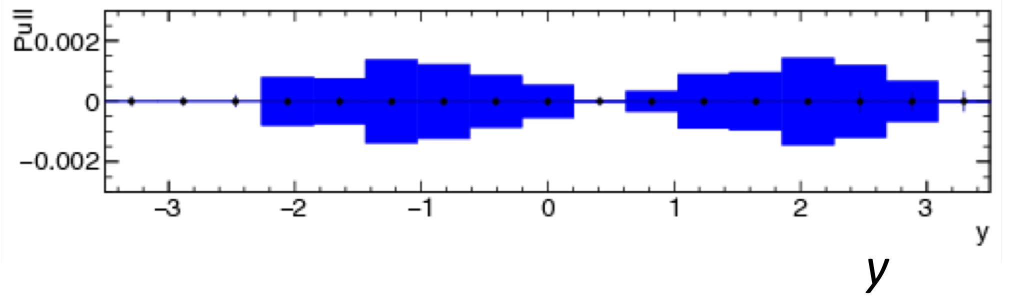
Fit templates like these to the data.



Envelope for PDFs



Envelope for W p_T spectrum

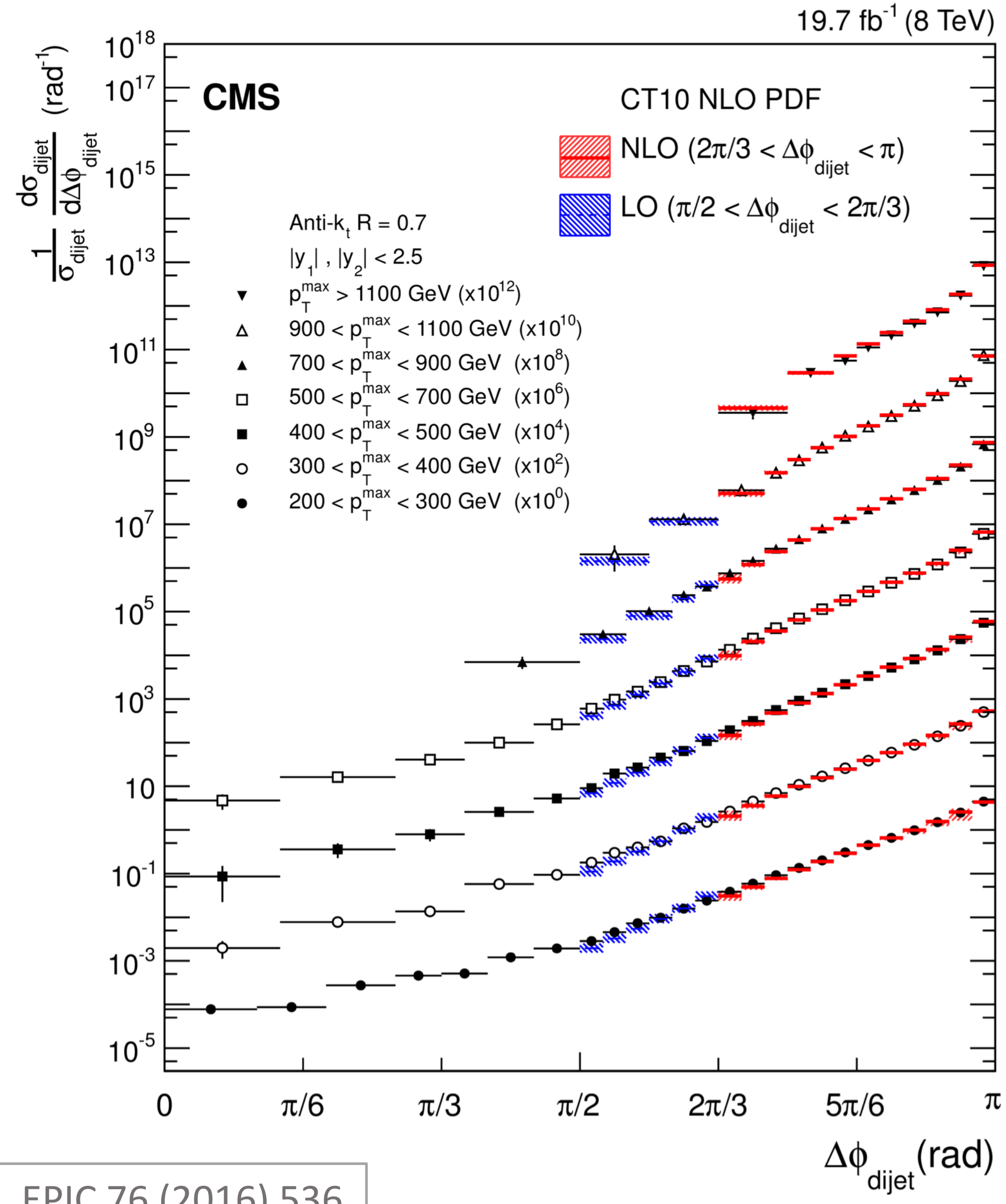


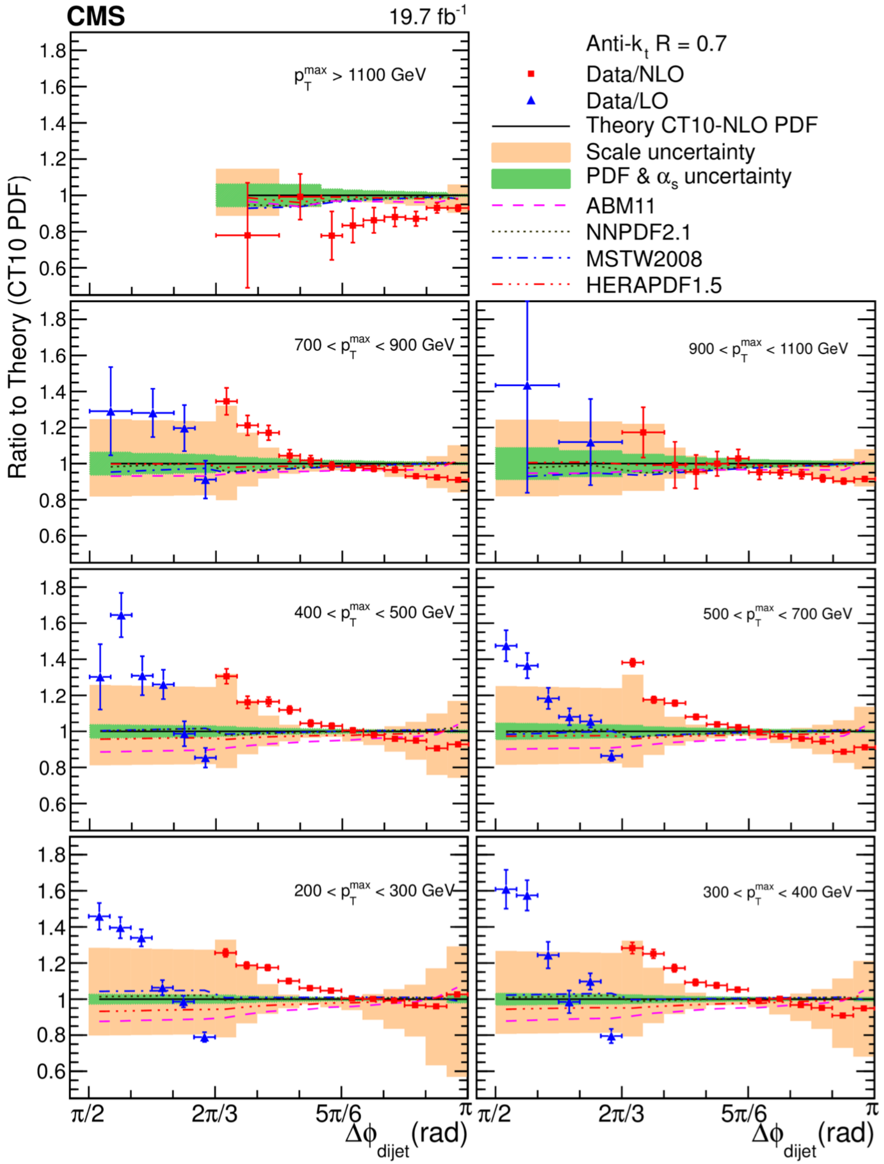
Azimuthal decorrelations:

- At LO, pp →2 jets must have $\Delta\phi = \pi$. ie, perfect correlation.
- At NLO, can have a 3rd jet; at NNLO, a 4th.
  This leads to $\Delta\phi < \pi$ ie, decorrelation
- How accurate are the NLO and NNLO calculations?
- CMS published in 2016, ATLAS has a paper on the arXiv out May 2018.
- These measurements probe the dynamics of multi-jet production.
  - Look as a function of the leading jet p_T and H_T.

Primary goal: Check predictions of pQCD.

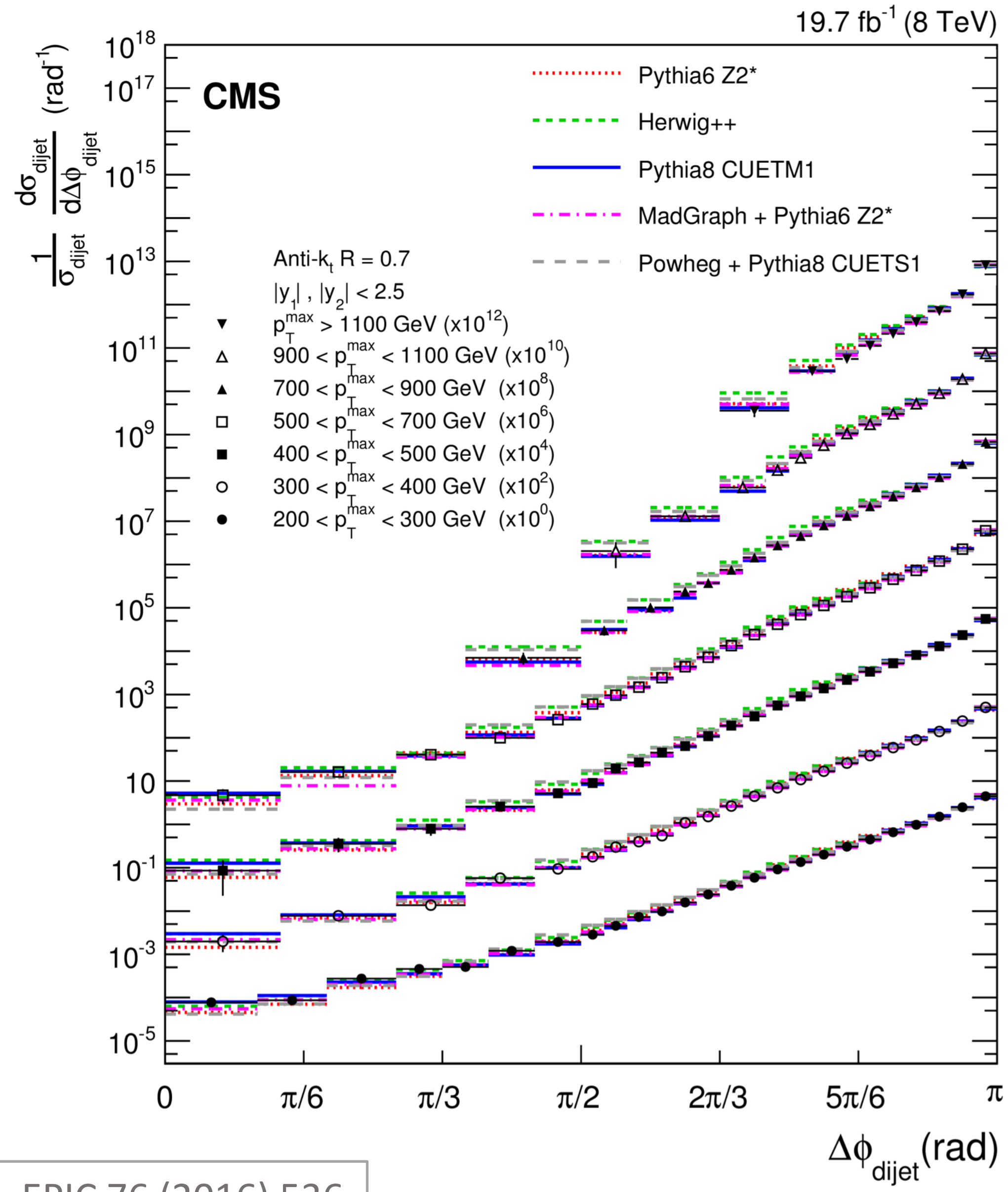
normalized differential cross sections

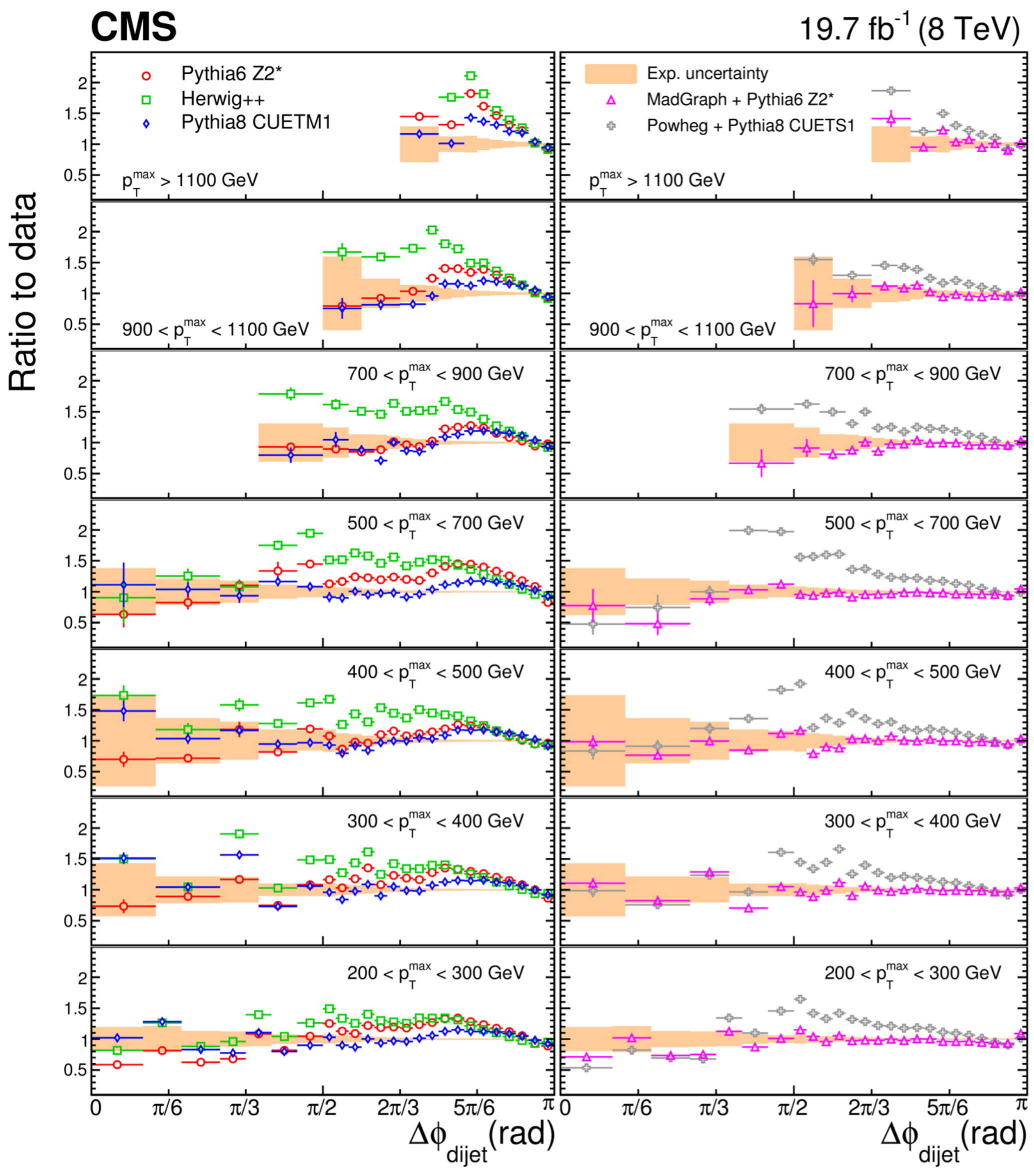




CMS, EPJC 76 (2016) 536

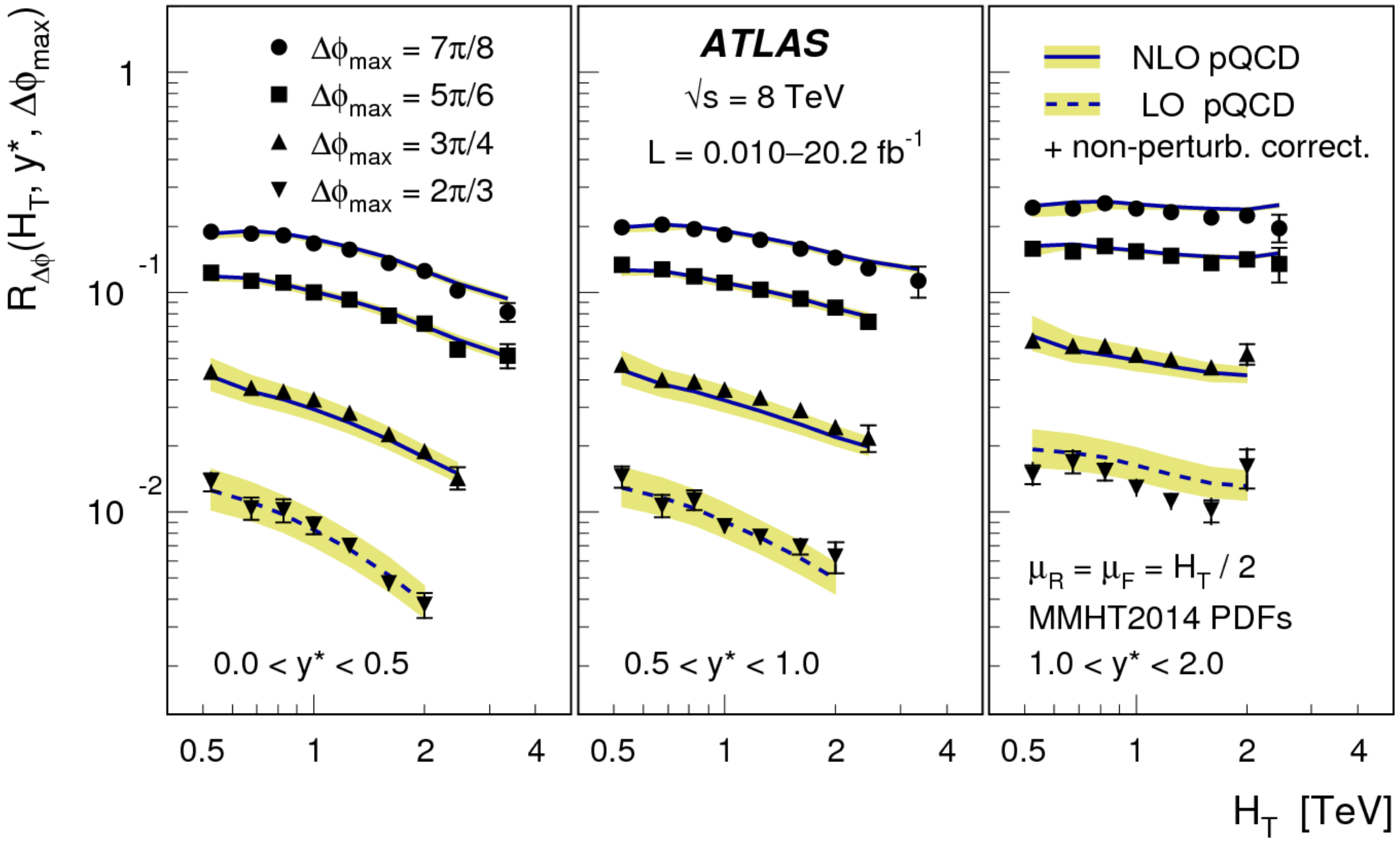
normalized differential cross sections





CMS, EPJC 76 (2016) 536

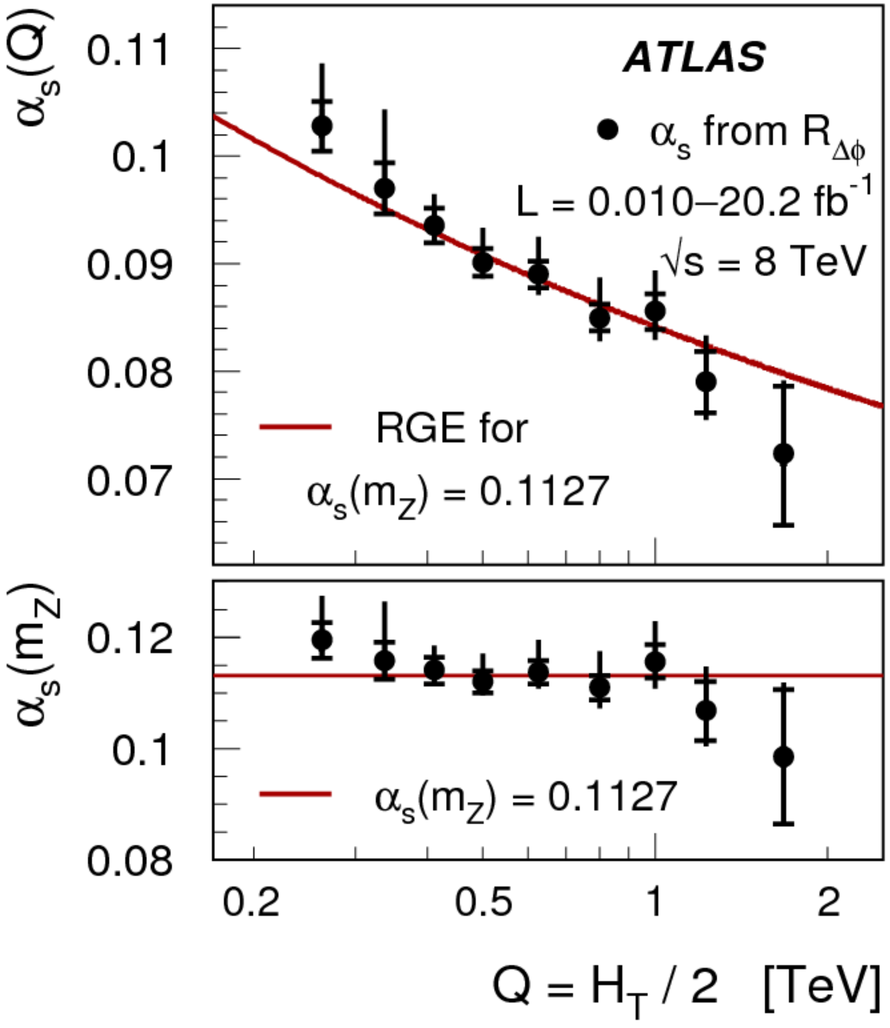
- **ATLAS took a completely different approach.**
- **Look at ratio of cross sections for $\Delta\phi < \Delta\phi_{max}$ to all $\Delta\phi$ as a function of H_T.**
- **Make slices in the relative different in rapidity.**

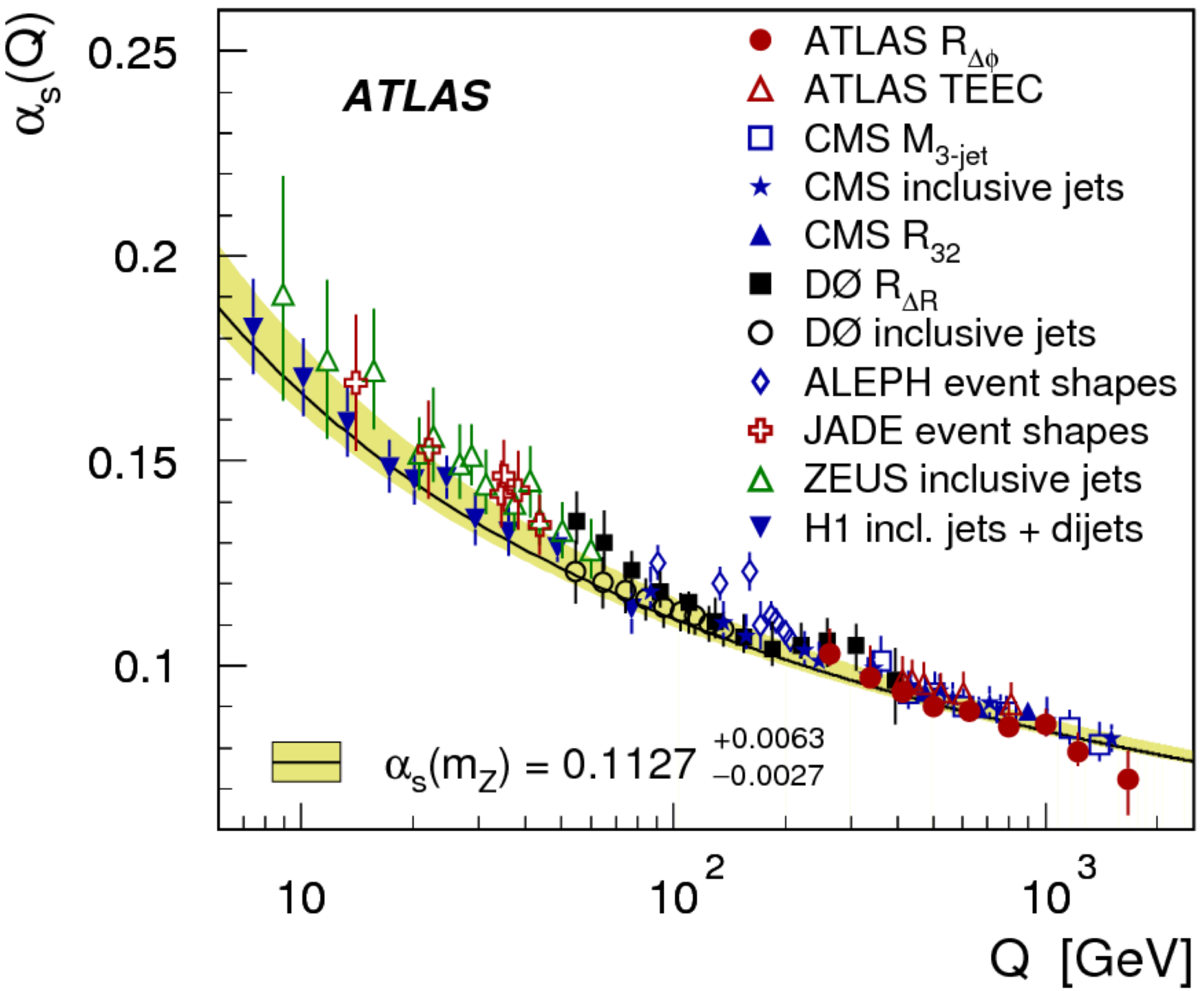


ATLAS, arXiv:1805.04691

- **ATLAS recognized an opportunity to measure α_S .**
- **Not the most precise values, but they do occur for high *Q*.**

ATLAS, arXiv:1805.04691





Same-sign WW production:

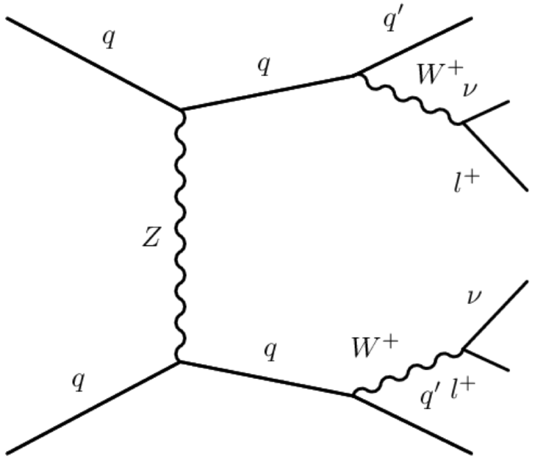
- Same-sign WW production probes vector-boson fusion.
- It is a very rare process, with distinctive features.
  - Two charged leptons of same sign. Missing energy.
  - Two energetic jets widely separated in rapidity.
- Both CMS and ATLAS have observed this process
  - CMS published in 2018, ATLAS has a conference note from July 2018.

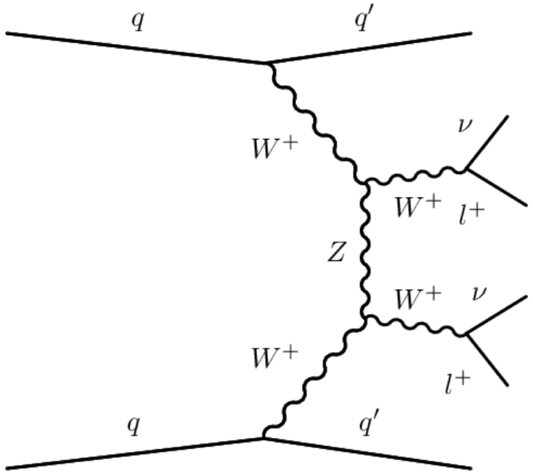
Primary goal: Observe rare process and check for anomalous production.

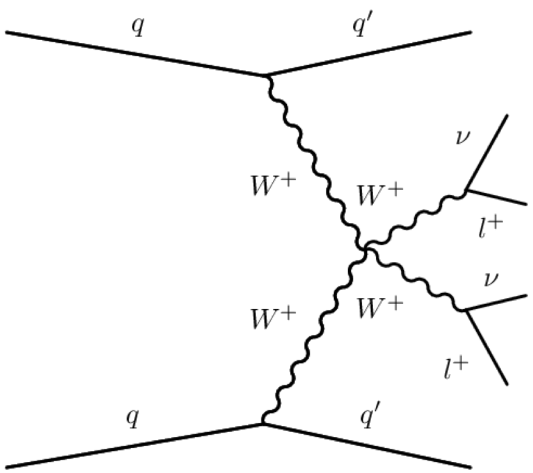
Feynman diagrams for same-sign WW production:

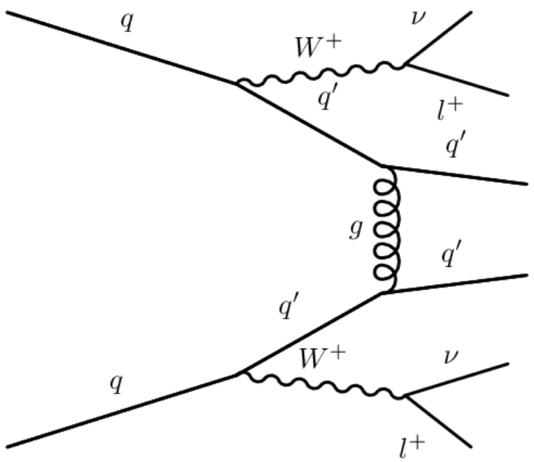
Weak

Strong







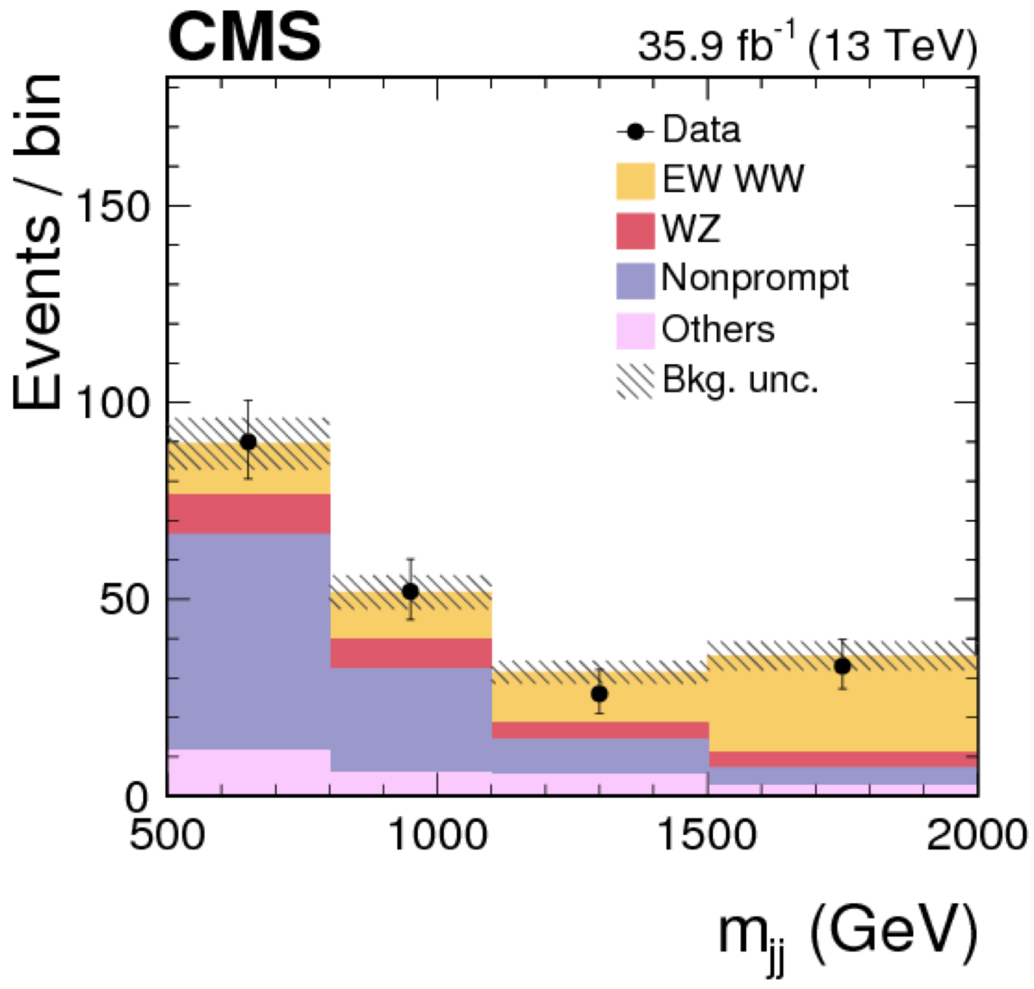


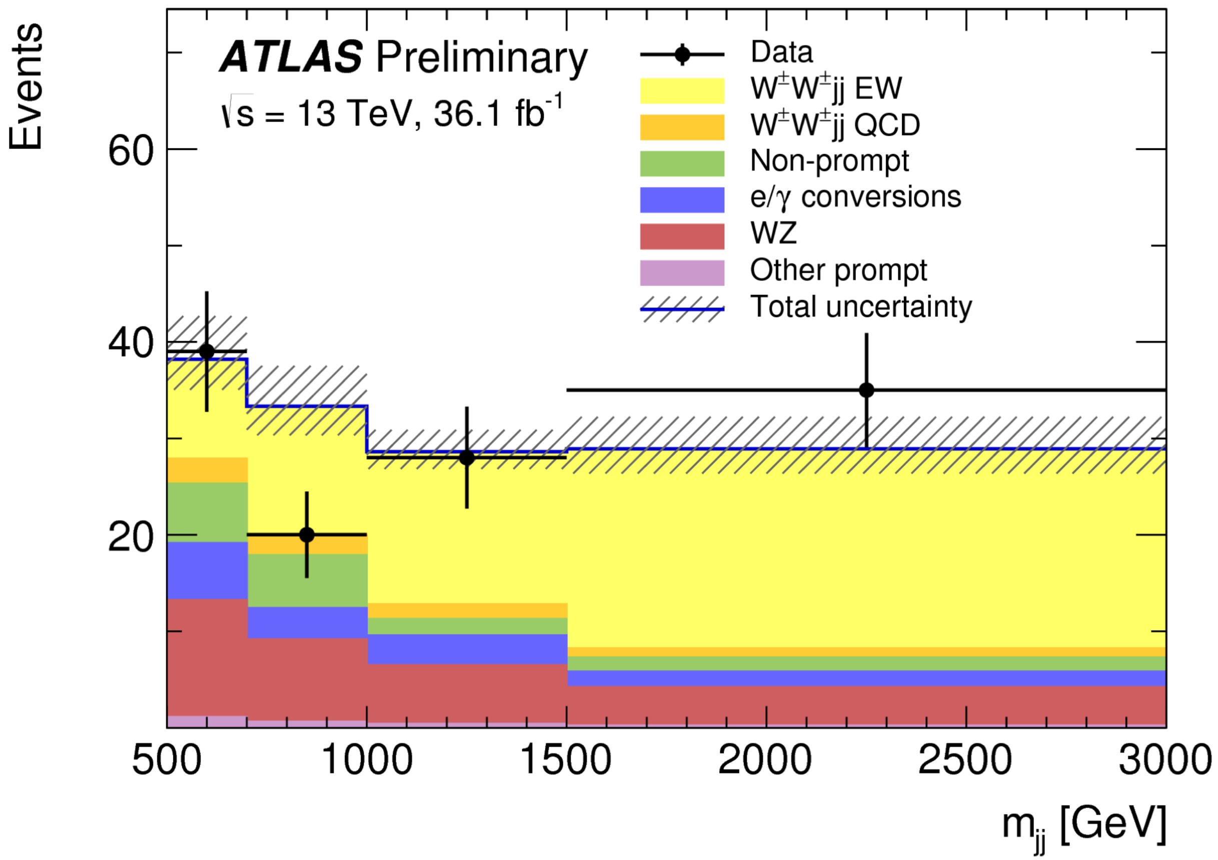
No gauge couplings.

Triple-gauge couplings.

Quartic-gauge couplings.

(Background)





5.5 st. dev. observed

5.7 st. dev. expected

6.9 st. dev. observed

4.6 st. dev. expected

CMS, PRL 120 (2018) 081801

ATLAS-CONF-2018-030

- **No anomalous production observed.**
- **CMS derived bounds on quartic anomalous couplings (assuming no anomalous TGCs).**
- **Sensitivity is very good and led to major improvements for some coefficients.**

	Observed limits (TeV^{-4})	Expected limits (TeV^{-4})	Previously observed limits (TeV^{-4})
f_{S0}/Λ^4	[−7.7, 7.7]	[−7.0, 7.2]	[−38, 40] , [11]
f_{S1}/Λ^4	[−21.6, 21.8]	[−19.9, 20.2]	[−118, 120] , [11]
f_{M0}/Λ^4	[−6.0, 5.9]	[−5.6, 5.5]	[−4.6, 4.6] , [36]
f_{M1}/Λ^4	[−8.7, 9.1]	[−7.9, 8.5]	[−17, 17] , [36]
f_{M6}/Λ^4	[−11.9, 11.8]	[−11.1, 11.0]	[−65, 63] , [11]
f_{M7}/Λ^4	[−13.3, 12.9]	[−12.4, 11.8]	[−70, 66] , [11]
f_{T0}/Λ^4	[−0.62, 0.65]	[−0.58, 0.61]	[−0.46, 0.44] , [37]
f_{T1}/Λ^4	[−0.28, 0.31]	[−0.26, 0.29]	[−0.61, 0.61] , [37]
f_{T2}/Λ^4	[−0.89, 1.02]	[−0.80, 0.95]	[−1.2, 1.2] , [37]

CMS, PRL 120 (2018) 081801

Summary and Conclusion:

- This presentation could not include many, many interesting analyses.
- Those that were presented could not be investigated in any depth.
- Some experiments left out: LHCb, Tevatron…
- Nonetheless, SM studies at the LHC are entering deep territory and quality and probative power surpasses past experiments by far.
- SM studies are multifaceted and rich.
- I predict major growth in the years to come.
- We **still** need better theory calculations!