Electroweak precision measurements with the CMS detector

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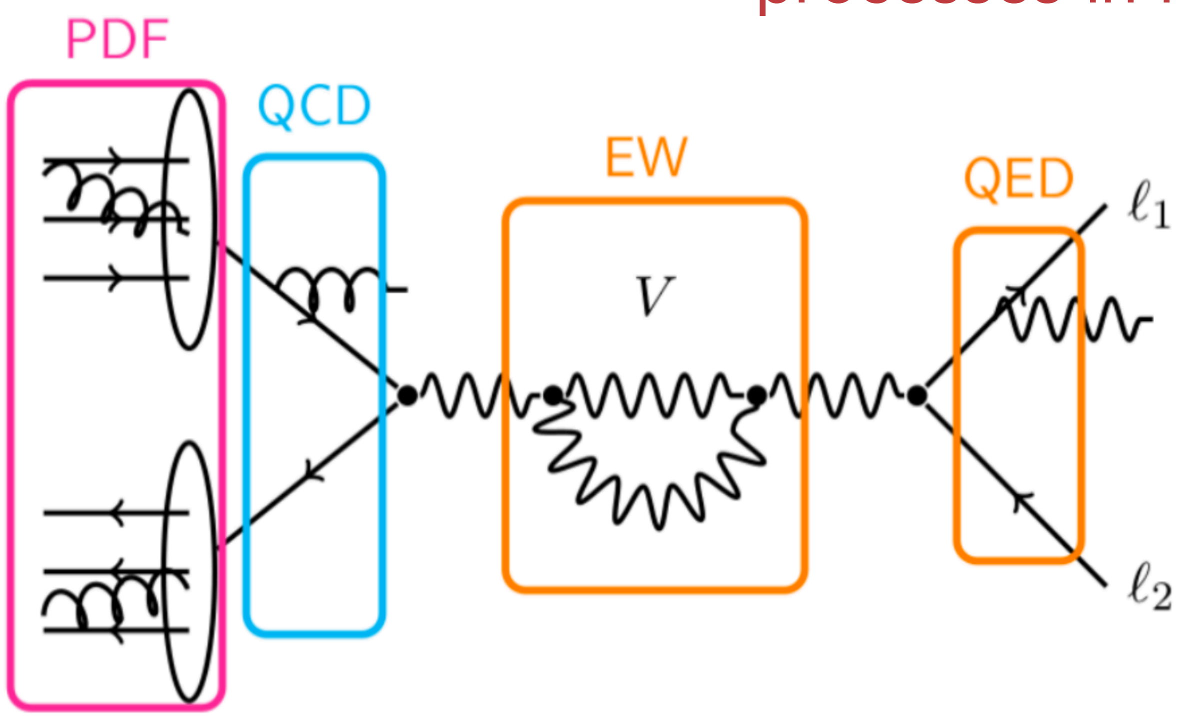
Electroweak processes at hadron colliders

One of the most studied and precisely measured processes in hadron colliders

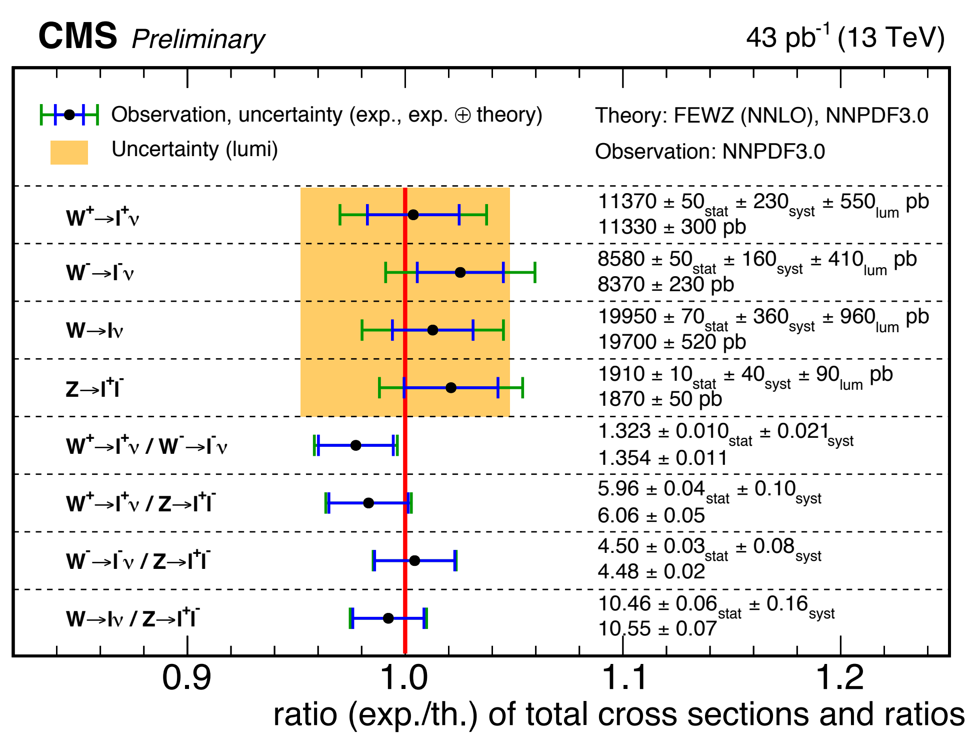


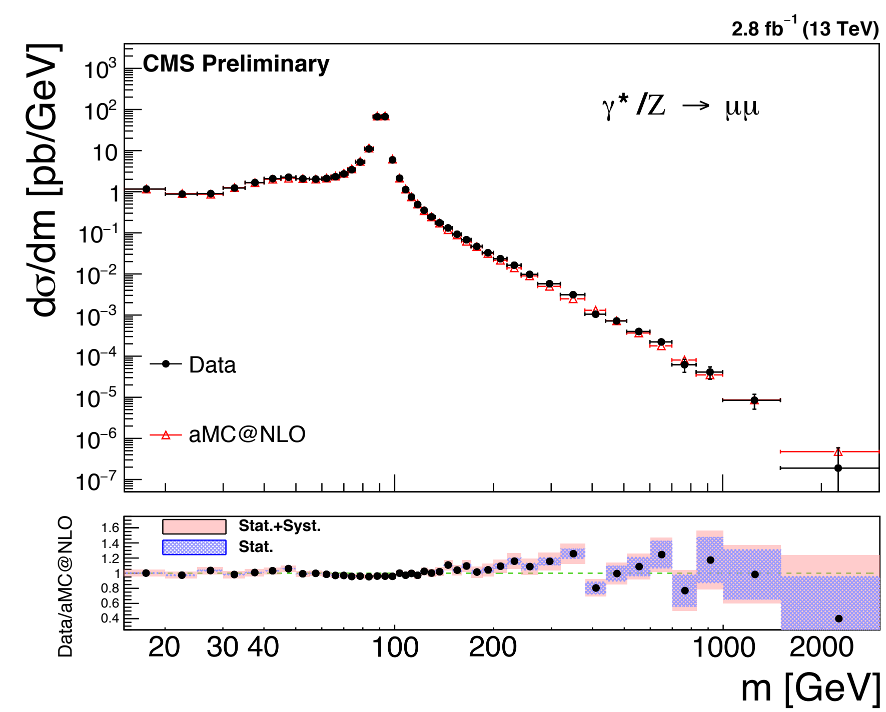
Several aspects only partially understood:

- Resummation at low p_T
- Higher-order QED correction
- Effect of heavy quarks in the initial state
- Power corrections

Can very precise measurements help understand these issues?

- Several cross section measurements (total, fiducial and differential) performed at CMS — see talk by Jay Lawhorn.
- Focus here on very precise measurements of Z and W boson production and decay.





Precision measurements

- Measurement of ratios of production cross sections

$$\left(\frac{1}{\sigma_{\mathrm{W}}}\frac{d\sigma}{dp_{\mathrm{T}}^{\mathrm{W}}}\right)\Big/\left(\frac{1}{\sigma_{\mathrm{Z}}}\frac{d\sigma}{dp_{\mathrm{T}}^{\mathrm{Z}}}\right),\ \left(\frac{1}{\sigma_{\mathrm{W}^+}}\frac{d\sigma}{dp_{\mathrm{T}}^{\mathrm{W}^+}}\right)\Big/\left(\frac{1}{\sigma_{\mathrm{W}^-}}\frac{d\sigma}{dp_{\mathrm{T}}^{\mathrm{W}^-}}\right)$$

- Differential cross sections of high-resolution observables

$$\phi^* = \tan\left(\frac{\phi_{\mathrm{acop}}}{2}\right)\sin(\theta^*_\eta) \qquad \phi_{\mathrm{acop}} = \phi - \Delta\phi \qquad \theta^*_\eta = \tanh[(\eta_- - \eta_+)/2]$$

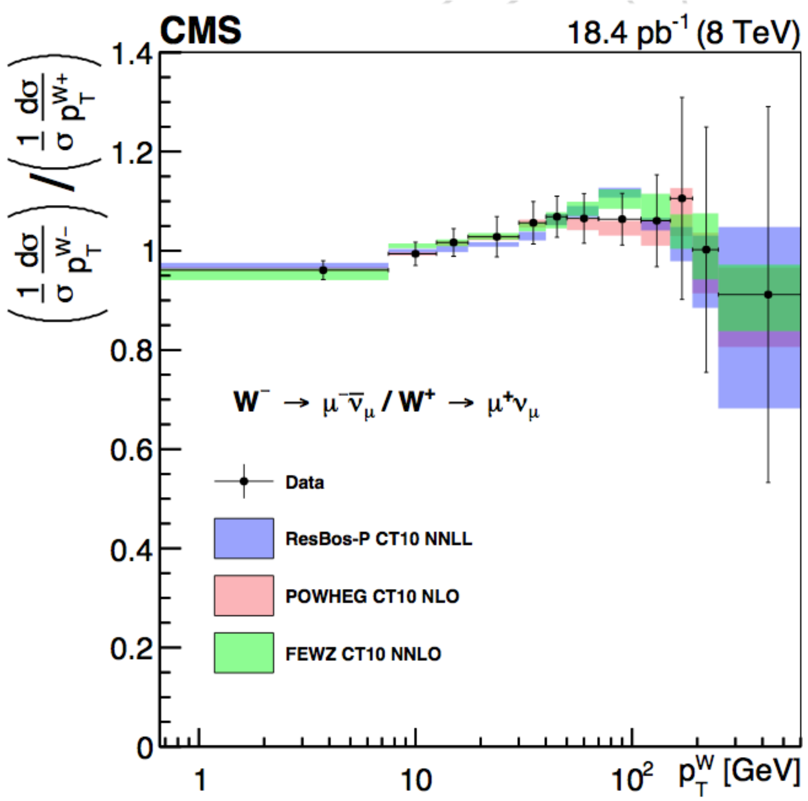
- Effective weak mixing angle $\sin(\theta^\ell_{\mathrm{eff}})$

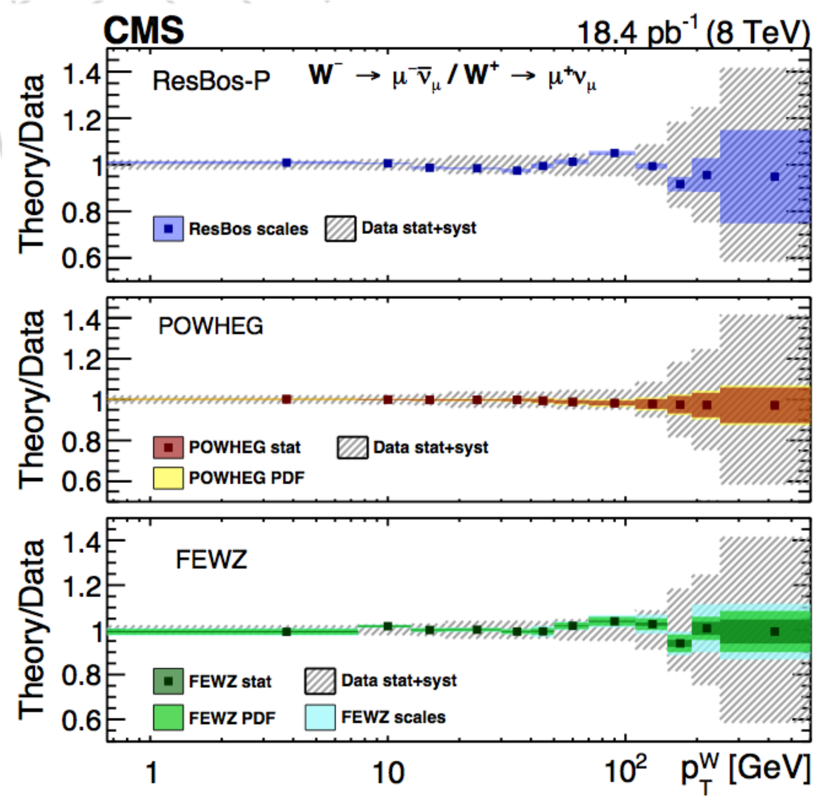
NEW

First presented at EPS-HEP this year!

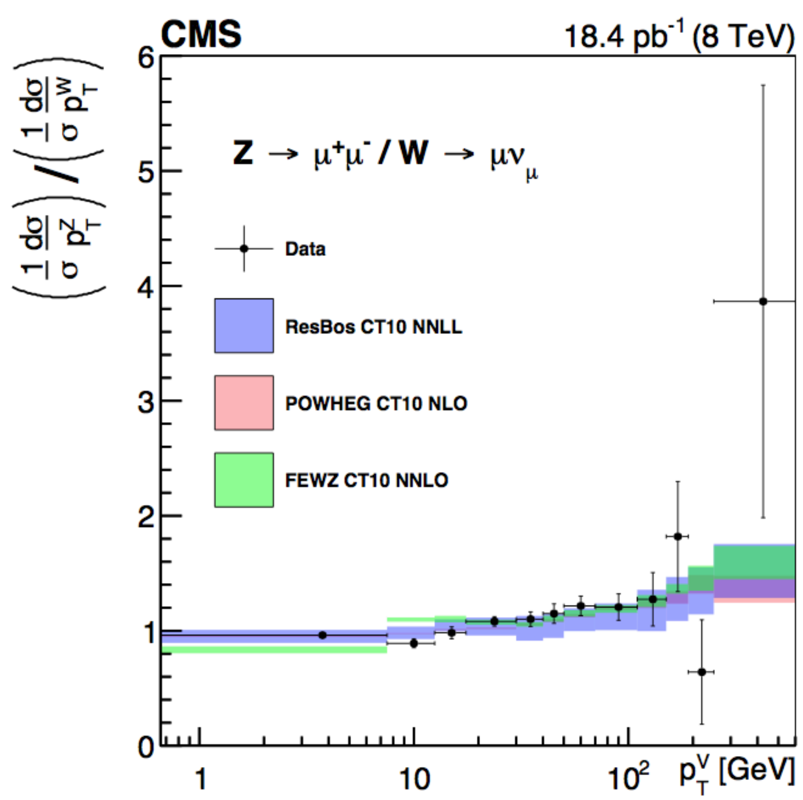
- W-like Z boson mass

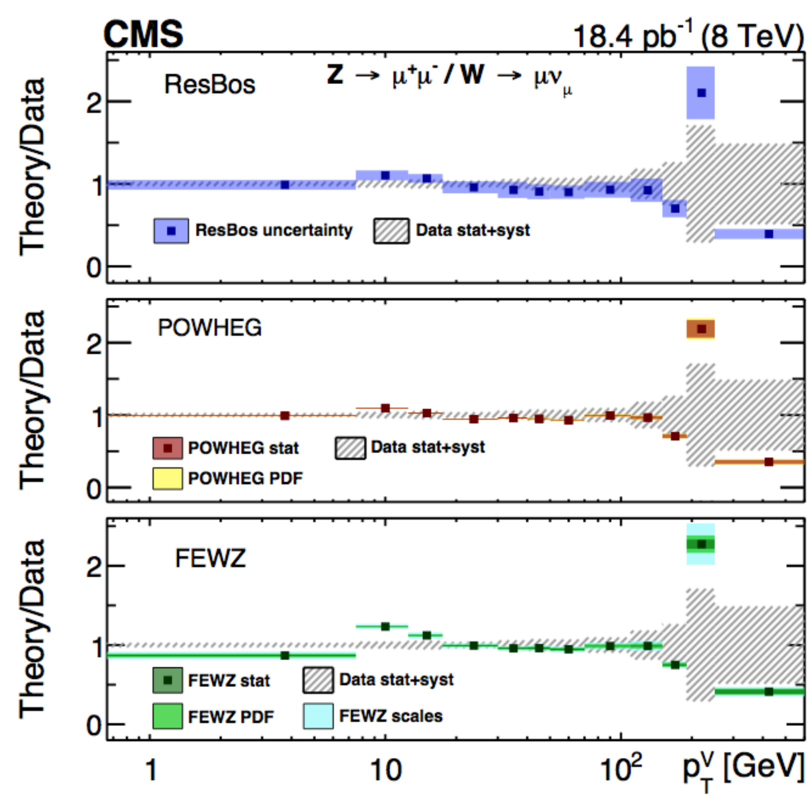
Production cross section ratios





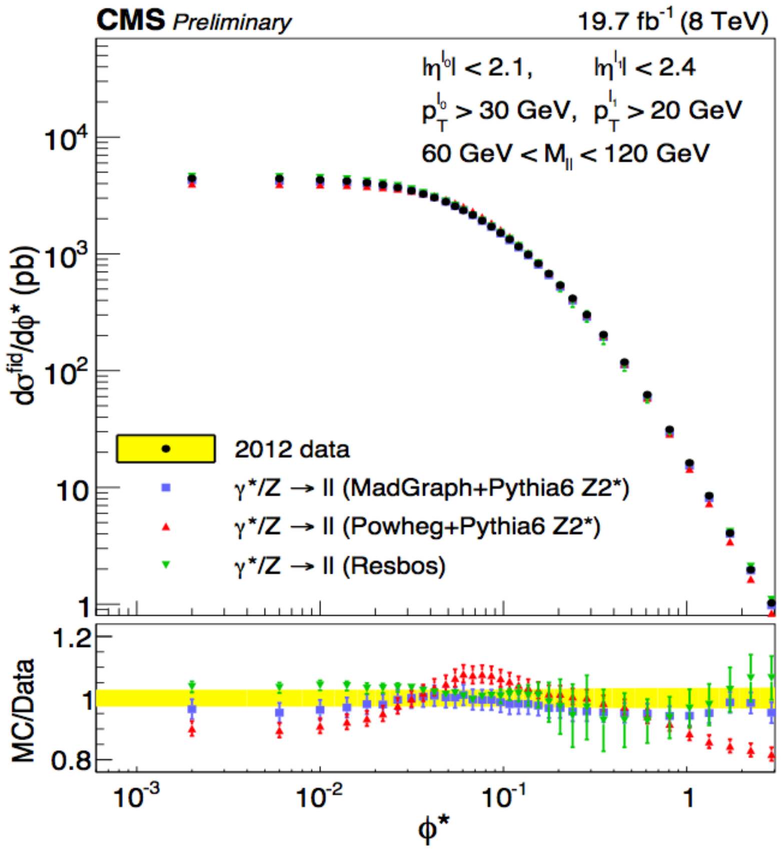
CMS SMP-14-012
8TeV, 18.4 pb^{-1}

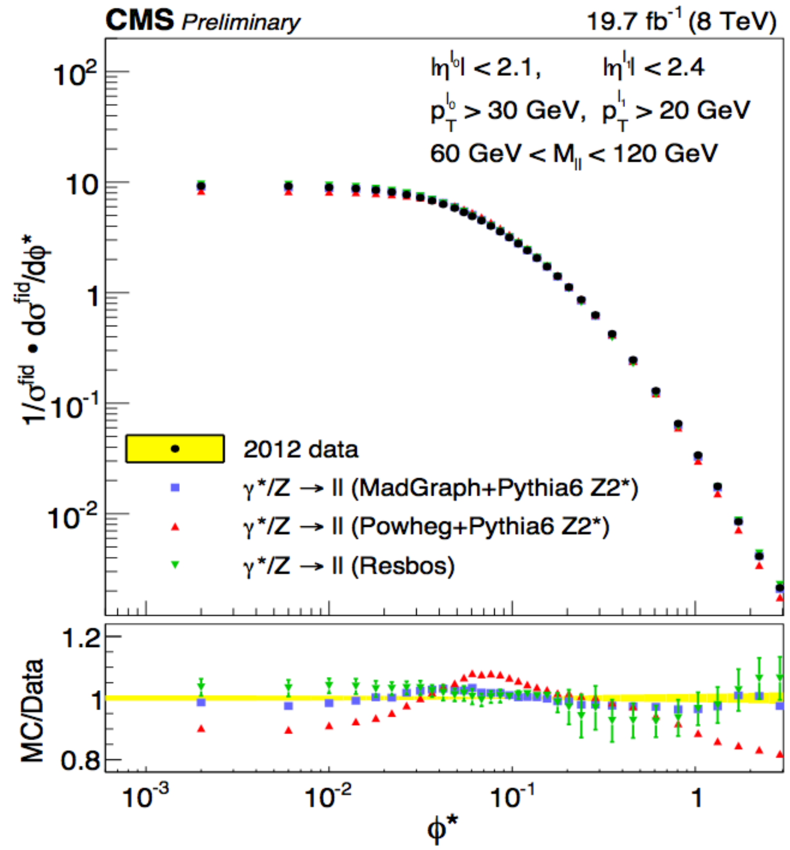




- Some tension in the $(d\sigma/dp_T^W)/(d\sigma/dp_T^Z)$ cross section measurement
- First bin is too large to resolve Sudakov peaks
- The limitation is the poor resolution at low W p_T

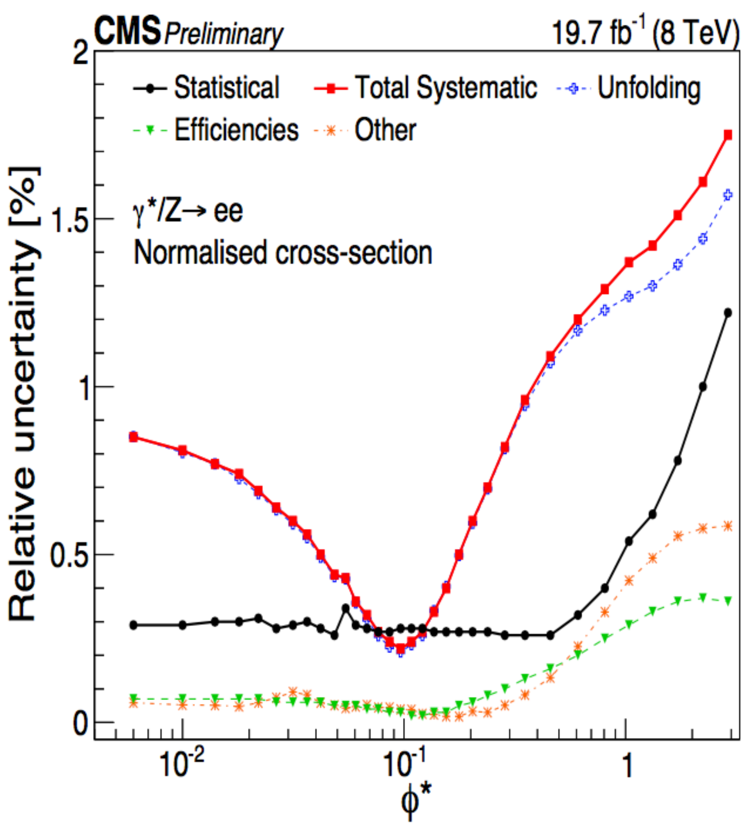
ϕ* differential cross section at 8 TeV

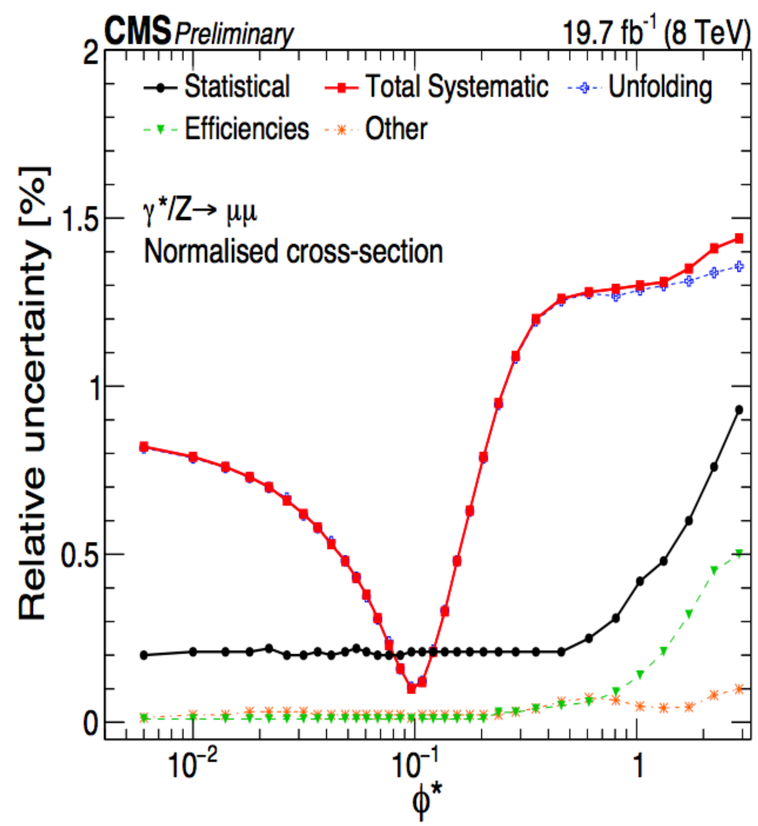




CMS SMP-15-002
8TeV, 19.7 fb^{-1}

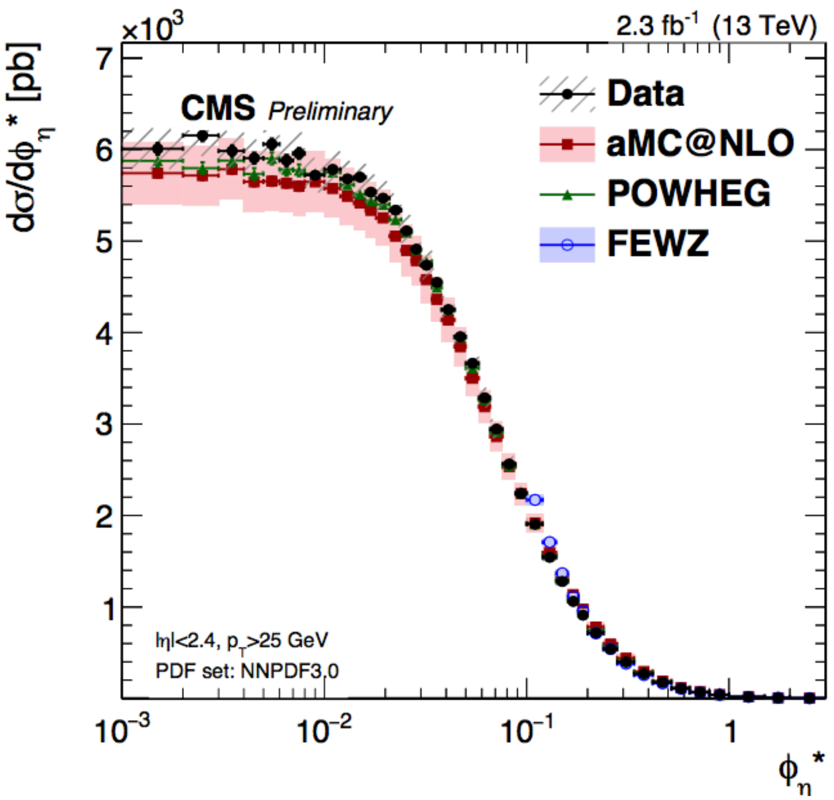
CMS SMP-15-011
13TeV, 2.3 fb^{-1}

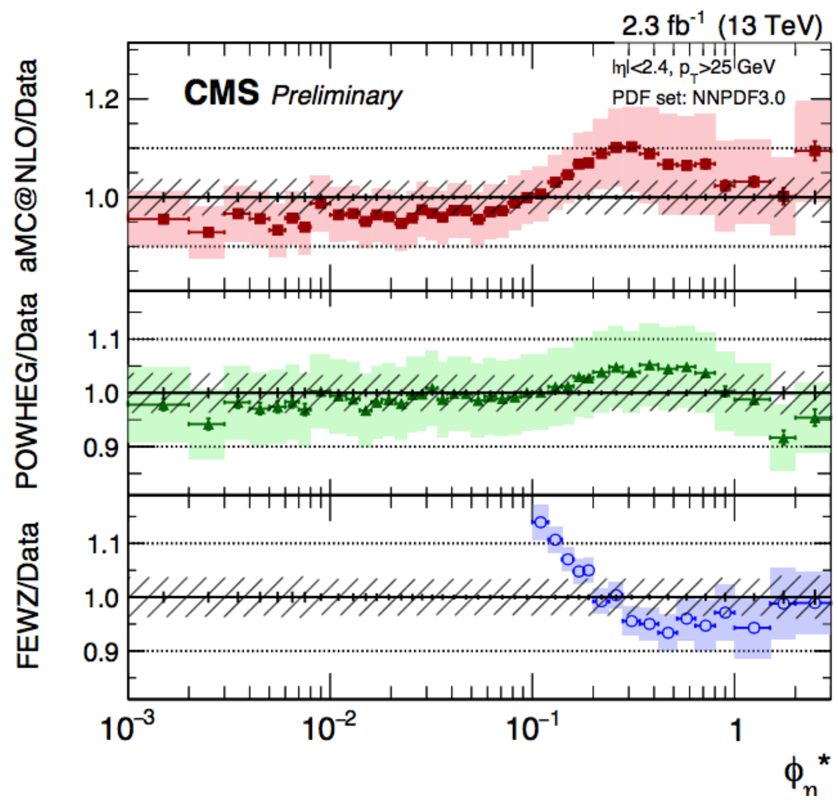


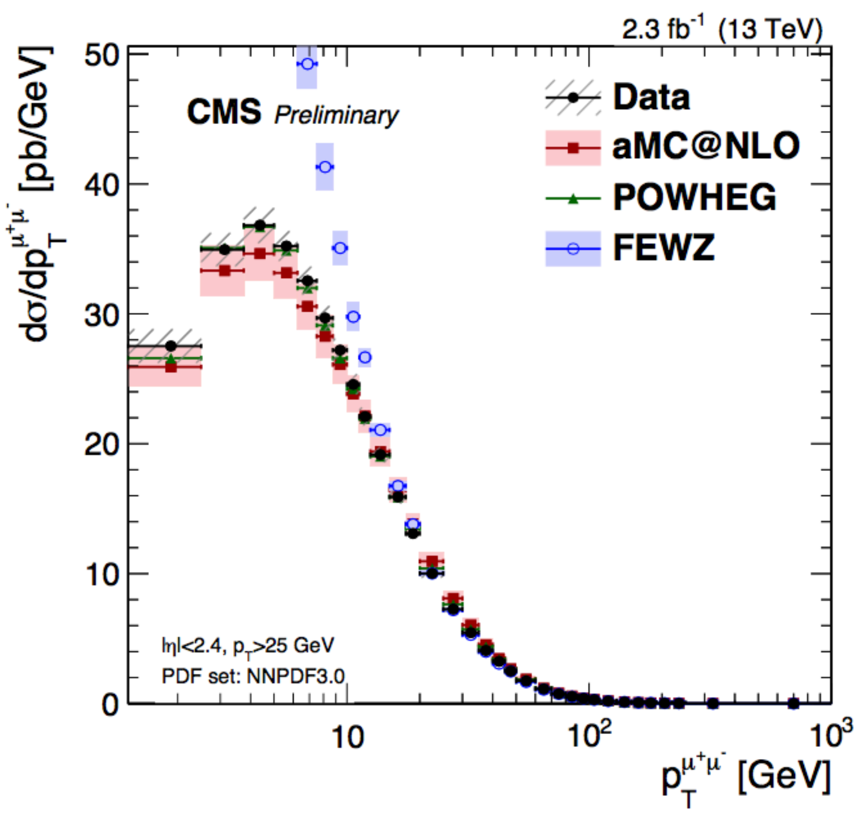


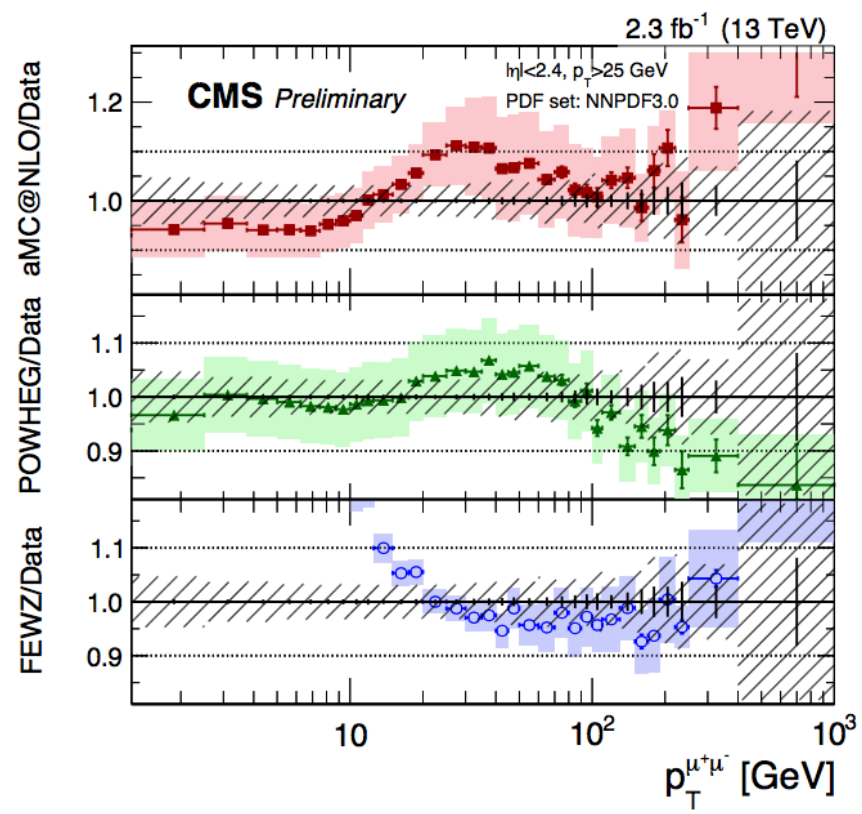
- For Z p_T < 100 GeV, $\phi^* \sim p_T$
- Much better resolution at low ϕ^* (low Z p_T) since only the tracker is used
- Similar disagreement observed in Z p_T differential cross section measurements.

ϕ* differential cross section at 13 TeV









CMS SMP-15-002
8TeV, 19.7 fb^{-1}

CMS SMP-15-011
13TeV, 2.3 fb^{-1}

- Similar behavior observed in events with $\sqrt{s}$ = 13TeV
- The result here uses only 2.3fb^{-1} of integrated luminosity collected in 2015.
- Much more data already in CMS tapes!

Weak mixing angle measurement

CMS SMP-16-007
8TeV, 19.6 fb^{-1}

- The mixing angle is measured using the forward-backward asymmetry in Z events.

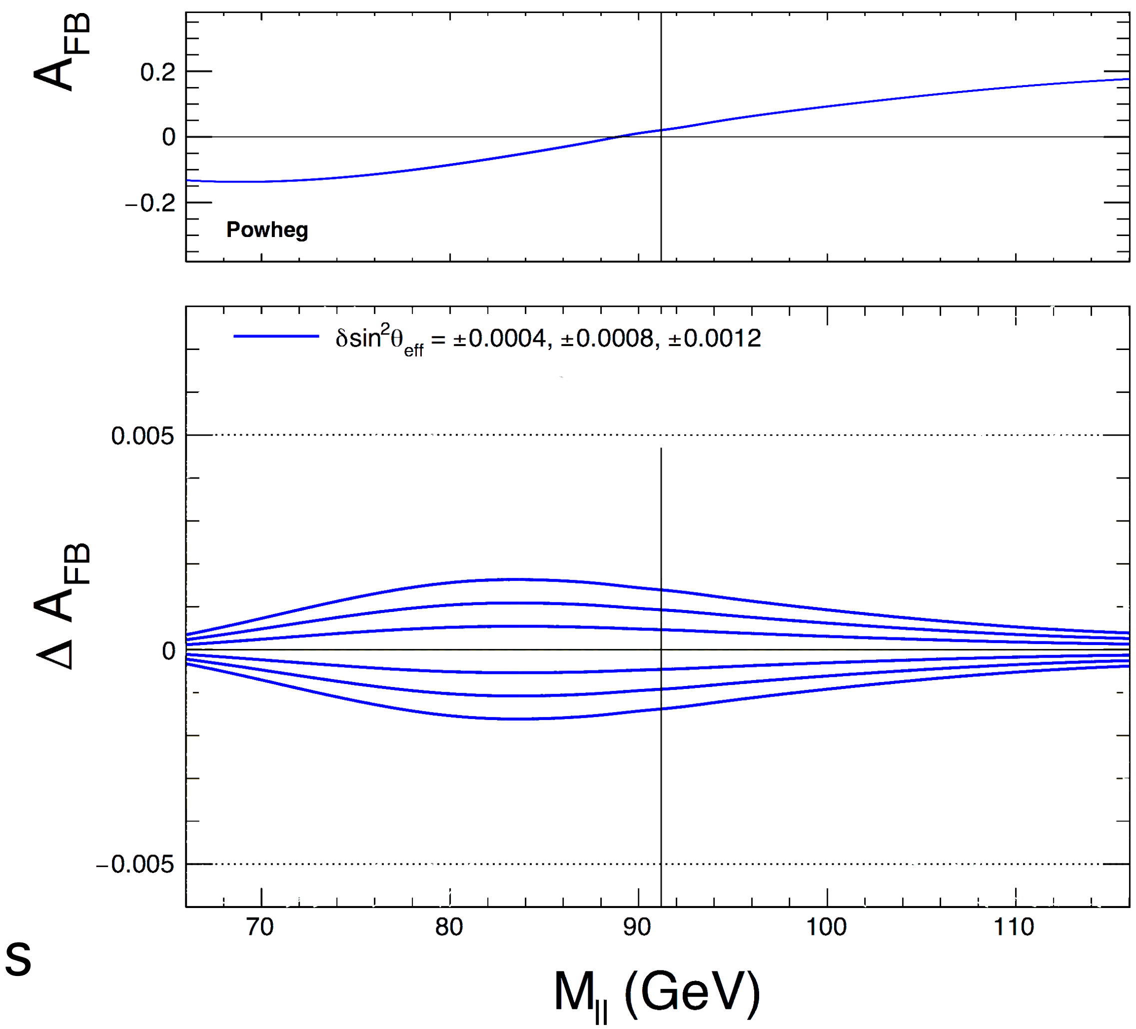
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

- Whether an event is forward or backward is defined by the angle of the negatively charged lepton in the Collins-Soper frame

$$\cos\theta^* = \frac{2(p_1^+ p_2^- - p_1^- p_2^+)}{\sqrt{M^2(M^2 + P_T^2)}} \times \frac{P_z}{|P_z|}$$

- The weak mixing angle is extracted using $m_{\ell\ell}$ templates where the vector couplings of leptons to the Z boson are varied:

$$v_f = T_3^f - 2Q_f \sin^2\theta_W,$$
$$a_f = T_3^f,$$

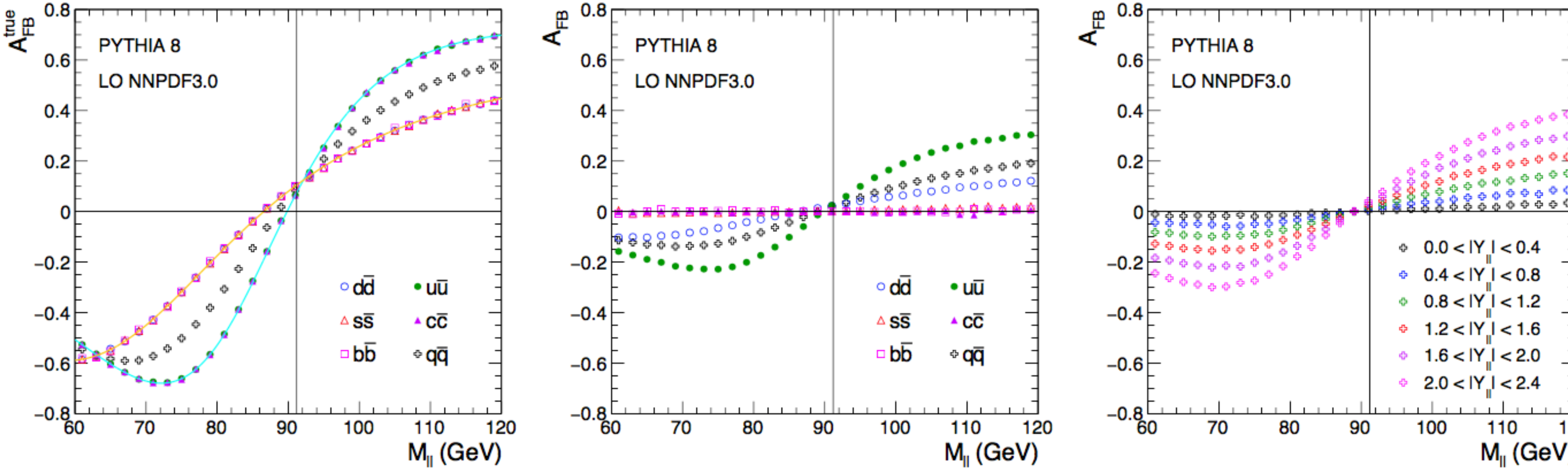


This is the tree level relation. After renormalization, the angle is called the effective mixing angle θ^ℓ_{eff}

Weak mixing angle and PDF

CMS SMP-16-007
8TeV, 19.6 fb^{-1}

- The forward-backward asymmetry depends strongly on the initial state quarks and on the dilepton rapidity

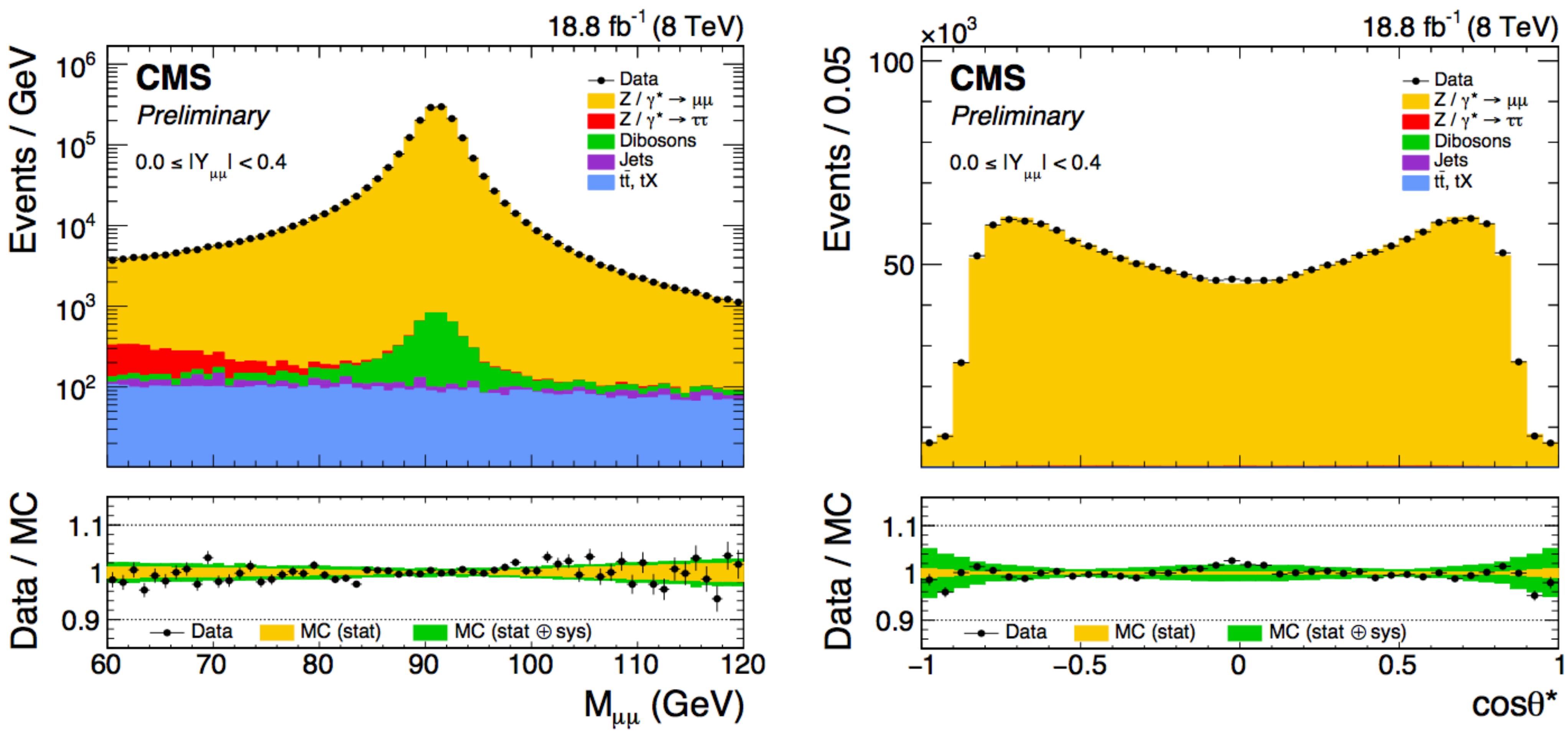


- Therefore, the CMS measurement uses $m_{\ell\ell}$ templates in six different dilepton rapidity $|y_{\ell\ell}|$ bins.
- Similarly, NNPDF3.0 MC replicas are used to reweight the templates and reduce the PDF uncertainty in the measurement.

Event selection

CMS SMP-16-007
8TeV, 19.6 fb^{-1}

- The measurement uses events with two electrons or two muons selected by single leptons triggers.
- In the muon channel, the leading and sub-leading muons are required to satisfy $p_T > 20$ and 15 GeV respectively. In the electron channel, the leading and sub-leading electrons are required to satisfy $p_T > 30$ and 20 GeV respectively.
- Z boson decays are selected with $|y_{\ell\ell}| < 2.4$ and $60 < m_{\ell\ell} < 120$ GeV. The $m_{\ell\ell}$ distribution is used to calibrate the electron and muon energy scale and resolution.



Not all events are born equal

CMS SMP-16-007
8TeV, 19.6 fb^{-1}

- Events with different cos(θ*) have different sensitivity to the weak mixing angle.
- CMS weighs each selected event with a weight proportional to their sensitivity to the forward-backward asymmetry

$$w_{\mathrm{D}} = \frac{1}{2}\frac{c^2}{(1+c^2+h)^3},$$

Denominator (normalization) weight

$$w_{\mathrm{N}} = \frac{1}{2}\frac{|c|}{(1+c^2+h)^2},$$

Numerator (asymmetry) weight

$$h = 0.5A_0(1-3c^2)$$

$A_0 = A_0(m_{\ell\ell}, p_{\mathrm{T}}^{\ell\ell}, y_{\ell\ell})$ from the angular decomposition of the Z decay cross section

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*} = \frac{3}{8}\left(1+\cos^2\theta^* + \frac{A_0}{2}(1-3\cos^2\theta^*) + A_4\cos\theta^*\right).$$

Source of forward-backward asymmetry

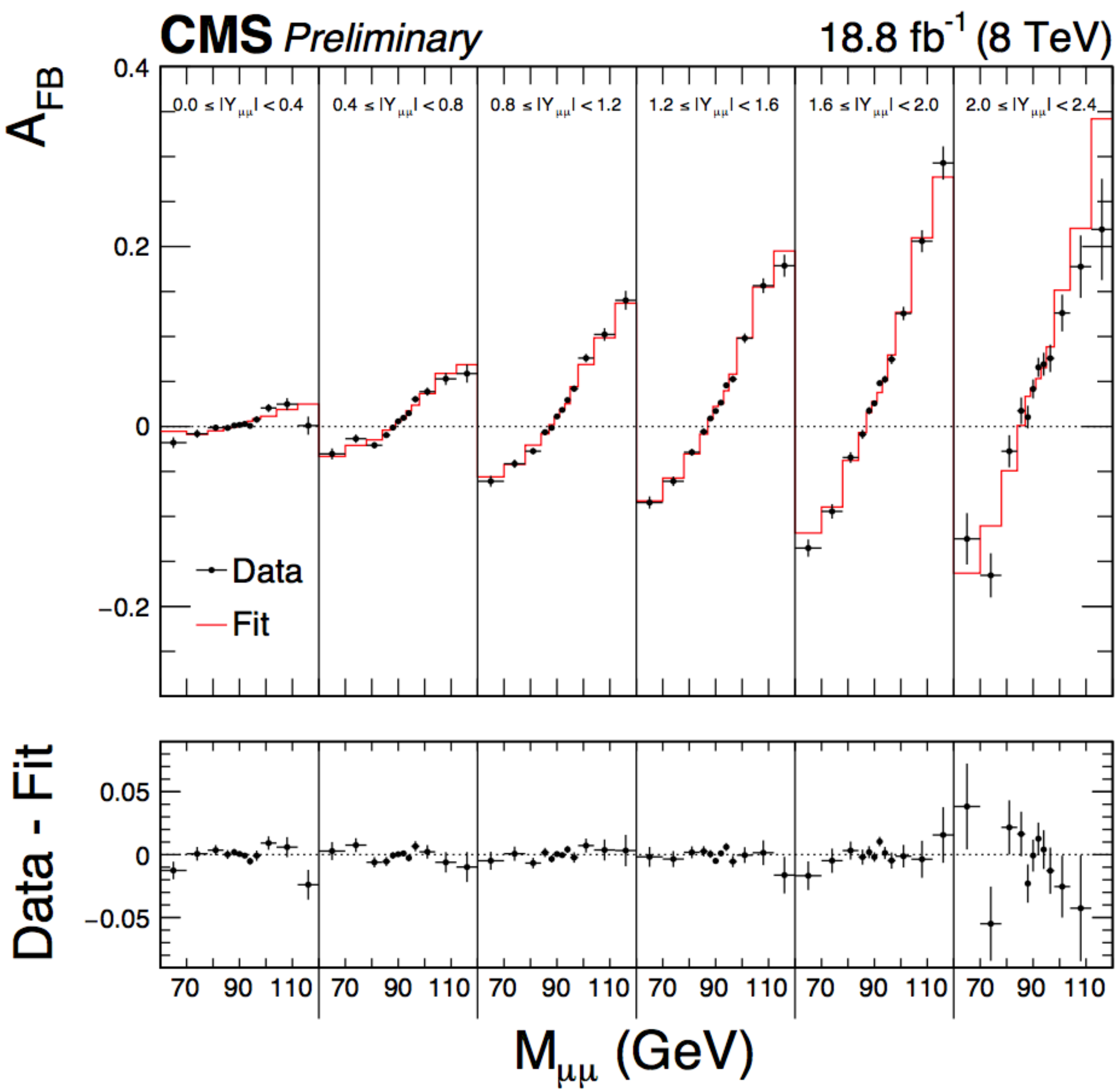
$$D_{\mathrm{F}} = \sum_{c>0} w_{\mathrm{D}}, D_{\mathrm{B}} = \sum_{c<0} w_{\mathrm{D}},$$
$$N_{\mathrm{F}} = \sum_{c>0} w_{\mathrm{N}}, N_{\mathrm{B}} = \sum_{c<0} w_{\mathrm{N}},$$

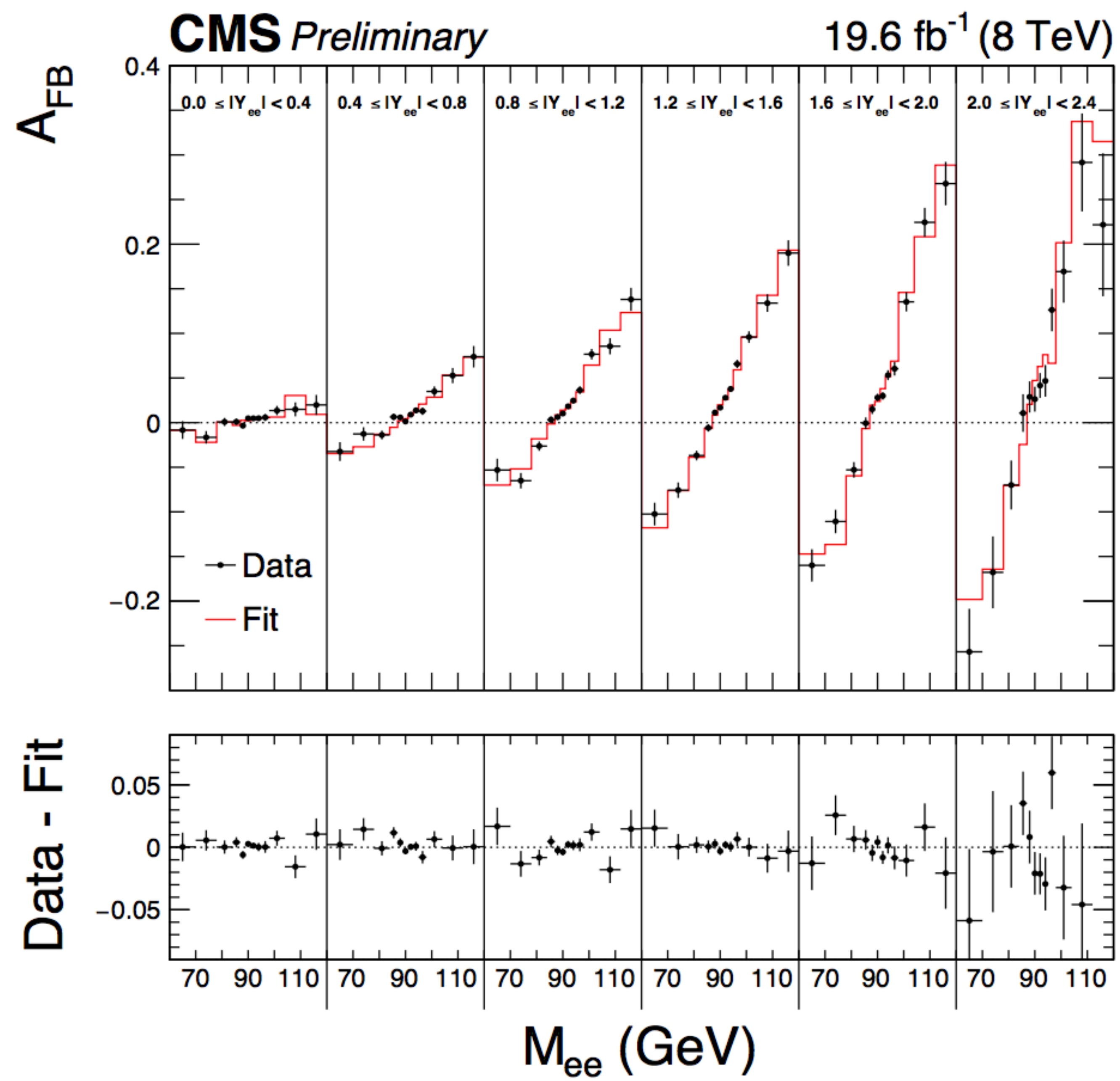
$$\boxed{A_{\mathrm{FB}} = \frac{3}{8}\frac{N_{\mathrm{F}}-N_{\mathrm{B}}}{D_{\mathrm{F}}+D_{\mathrm{B}}}.}$$

Observed distributions

CMS SMP-16-007
8TeV, 19.6 fb^{-1}

- Data-MC comparison of $m_{\ell\ell}$ templates with best fit $\sin(\theta^{\ell}_{\mathrm{eff}})$ in $|y_{\ell\ell}|$ bins after PDF reweighting.

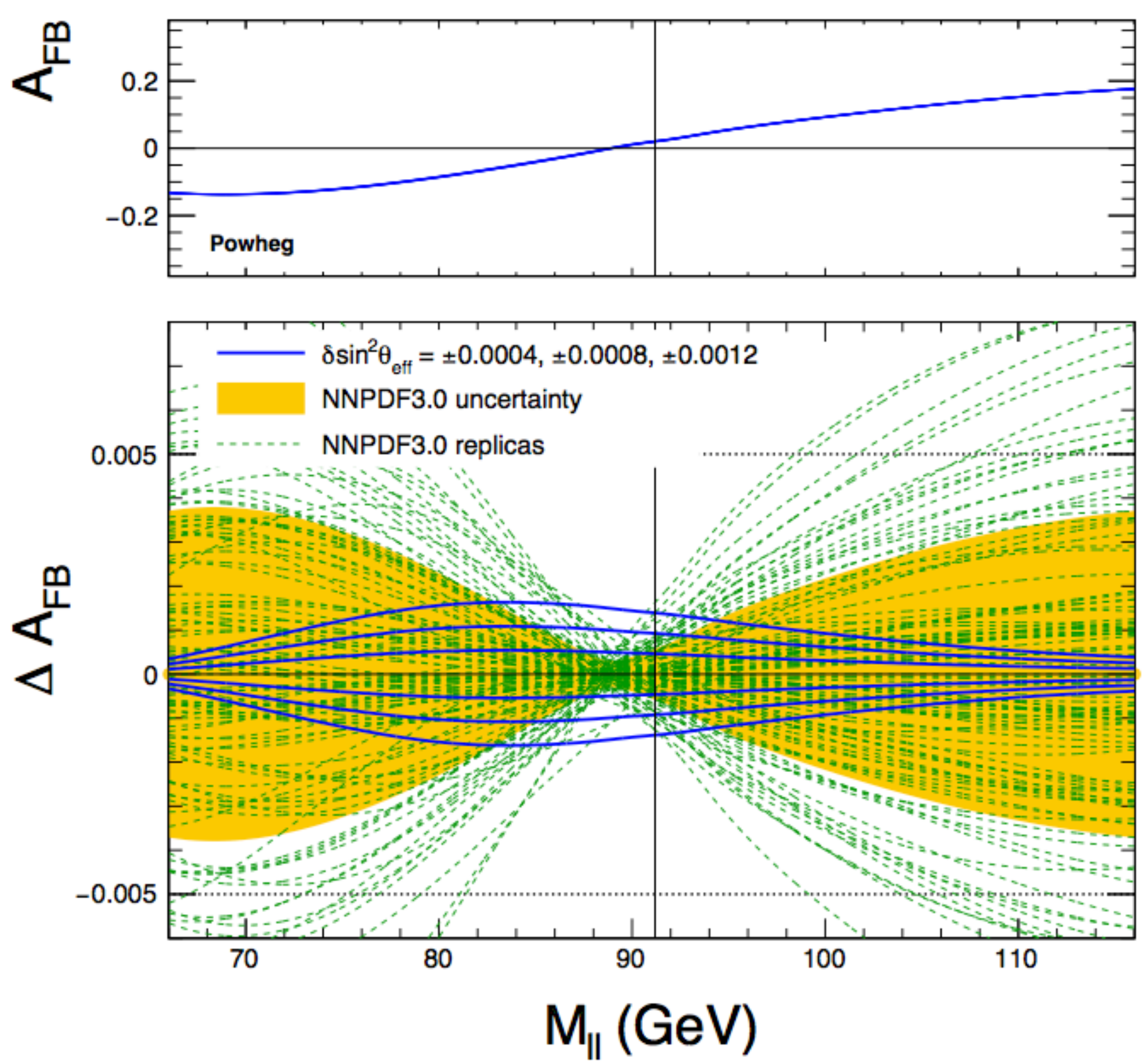


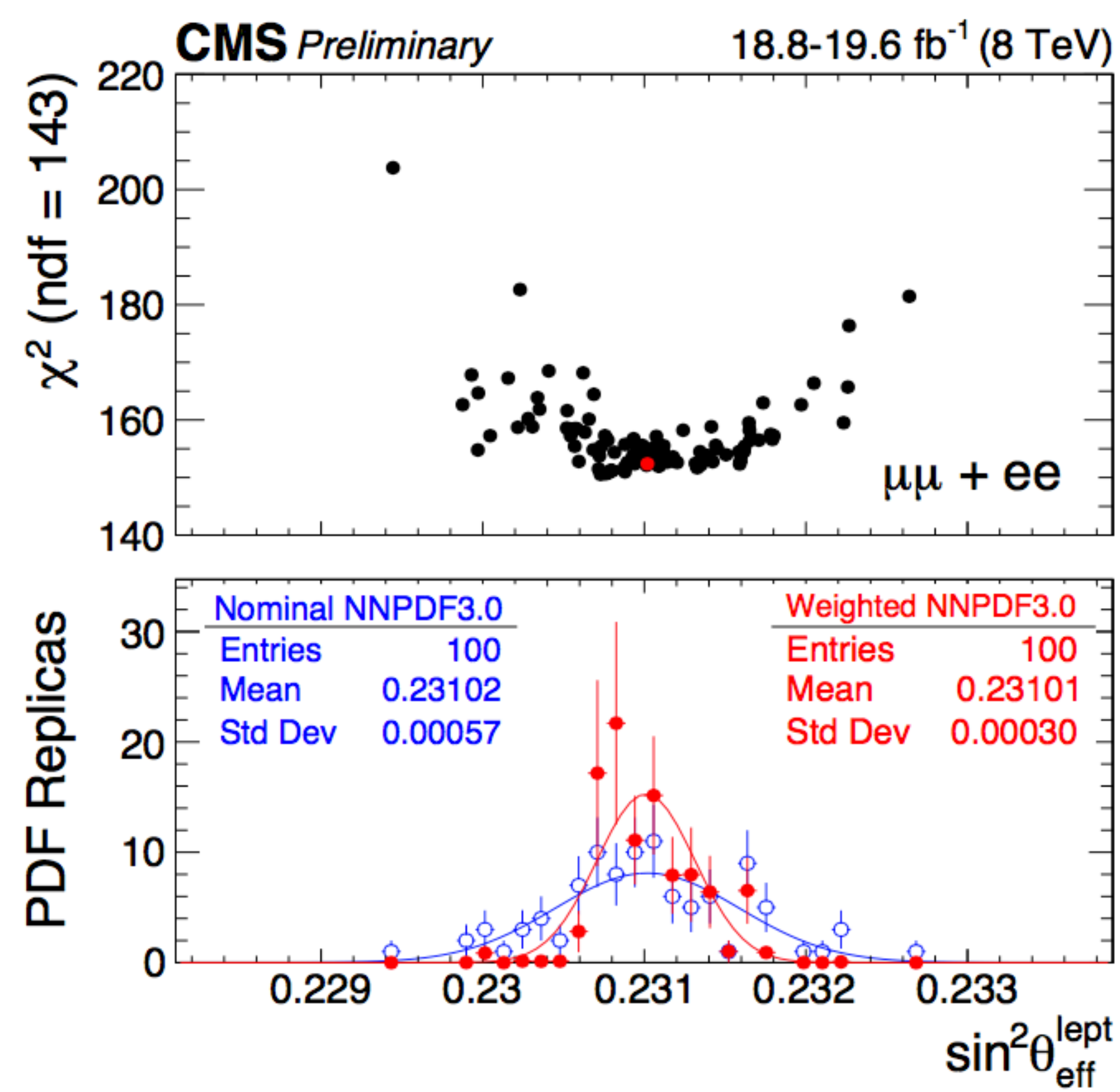


Impact of PDF reweighting

CMS SMP-16-007
8TeV, 19.6 fb^{-1}

- PDF reweighting using MC replicas was first proposed in Nucl. Phys. B849 (2011) 112-143 [arXiv:1012.0836].
- Each MC replica of the NNPDF3.0 ensemble is weighted with a probability density determined by comparing the A_{FB} values between data and MC.





Weak mixing angle results

CMS SMP-16-007
8TeV, 19.6 fb^{-1}

Combined results

$$\sin^2\theta_{\rm eff}^{\rm lept} = 0.23101 \pm 0.00036({\rm stat}) \pm 0.00018({\rm syst}) \pm 0.00016({\rm theory}) \pm 0.00030({\rm pdf})$$

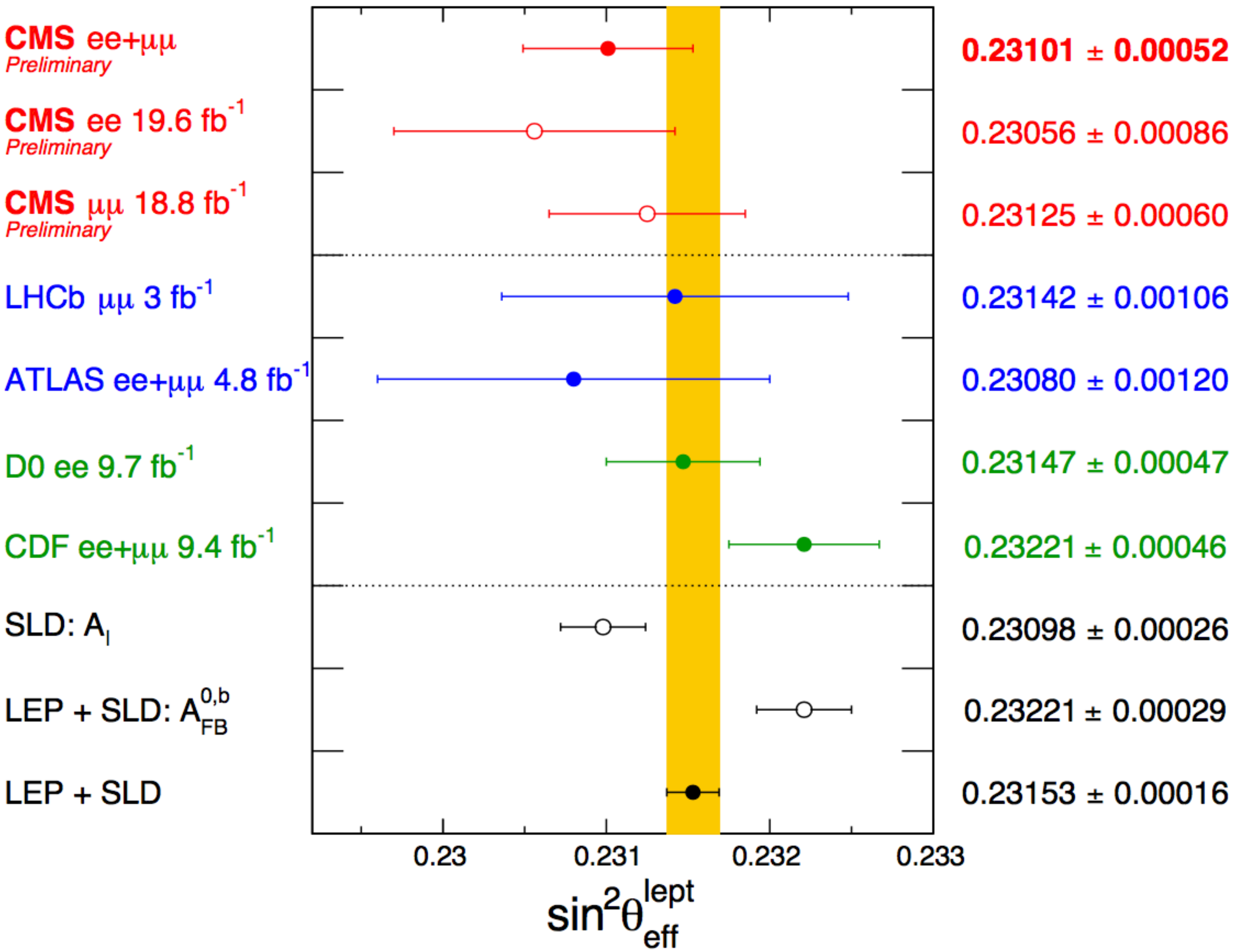
$$\sin^2\theta_{\rm eff}^{\rm lept} = 0.23101 \pm 0.00052.$$

Uncertainty sources

Source	muons	electrons
MC statistics	0.00015	0.00033
Lepton momentum calibration	0.00008	0.00019
Lepton selection efficiency	0.00005	0.00004
Background subtraction	0.00003	0.00005
Pileup modeling	0.00003	0.00002
Total	0.00018	0.00039

model variation	Muons	Electrons
Dilepton p_T reweighting	0.00003	0.00003
QCD $\mu_{R/F}$ scale	0.00011	0.00013
POWHEG MiNLO Z+j vs NLO Z model	0.00009	0.00009
FSR model (PHOTOS vs PYTHIA)	0.00003	0.00005
UE tune	0.00003	0.00004
Electroweak ($\sin^2\theta_{\rm eff}^{\rm lept} - \sin^2\theta_{\rm eff}^{\rm u,d}$)	0.00001	0.00001
Total	0.00015	0.00017

Comparison to other results



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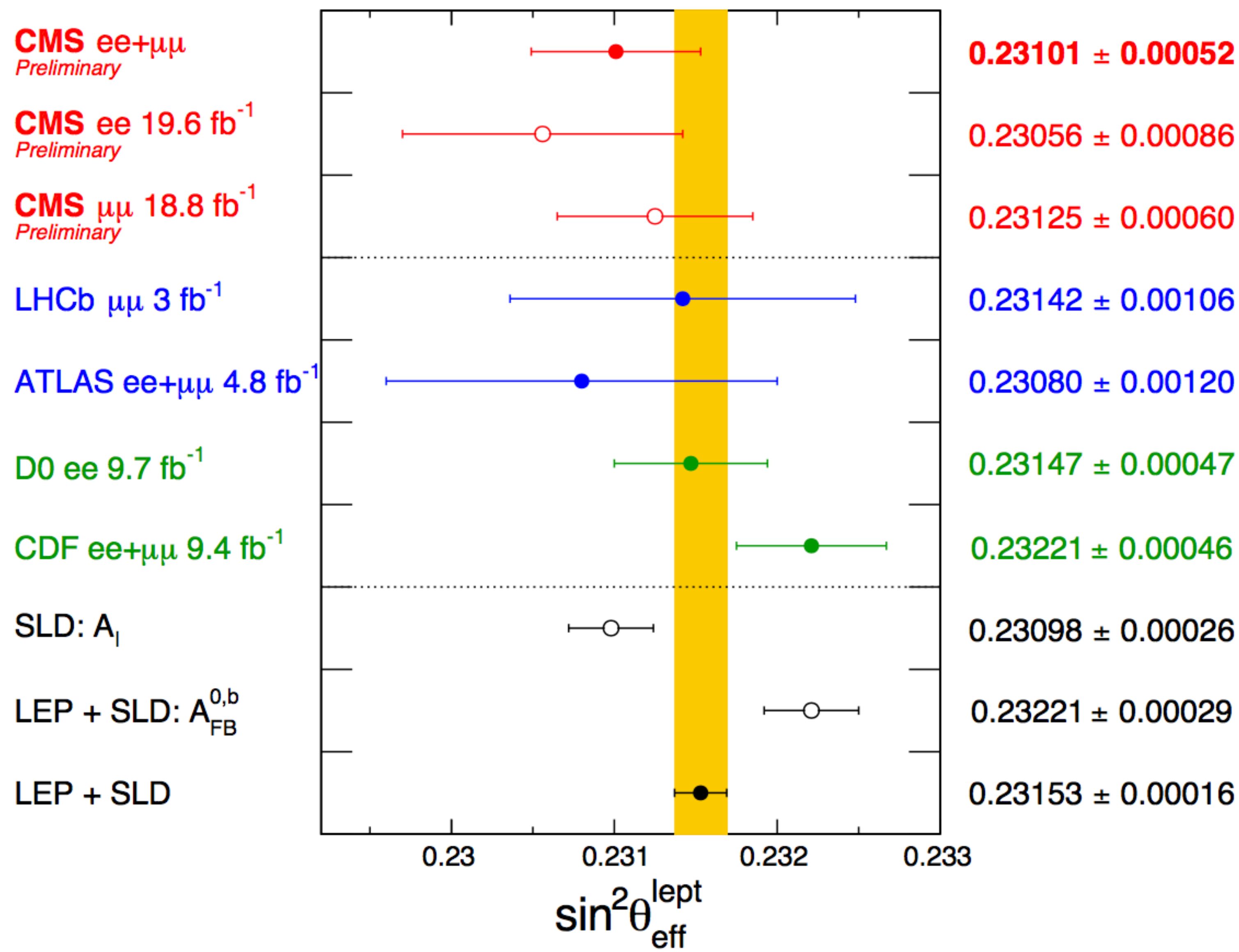

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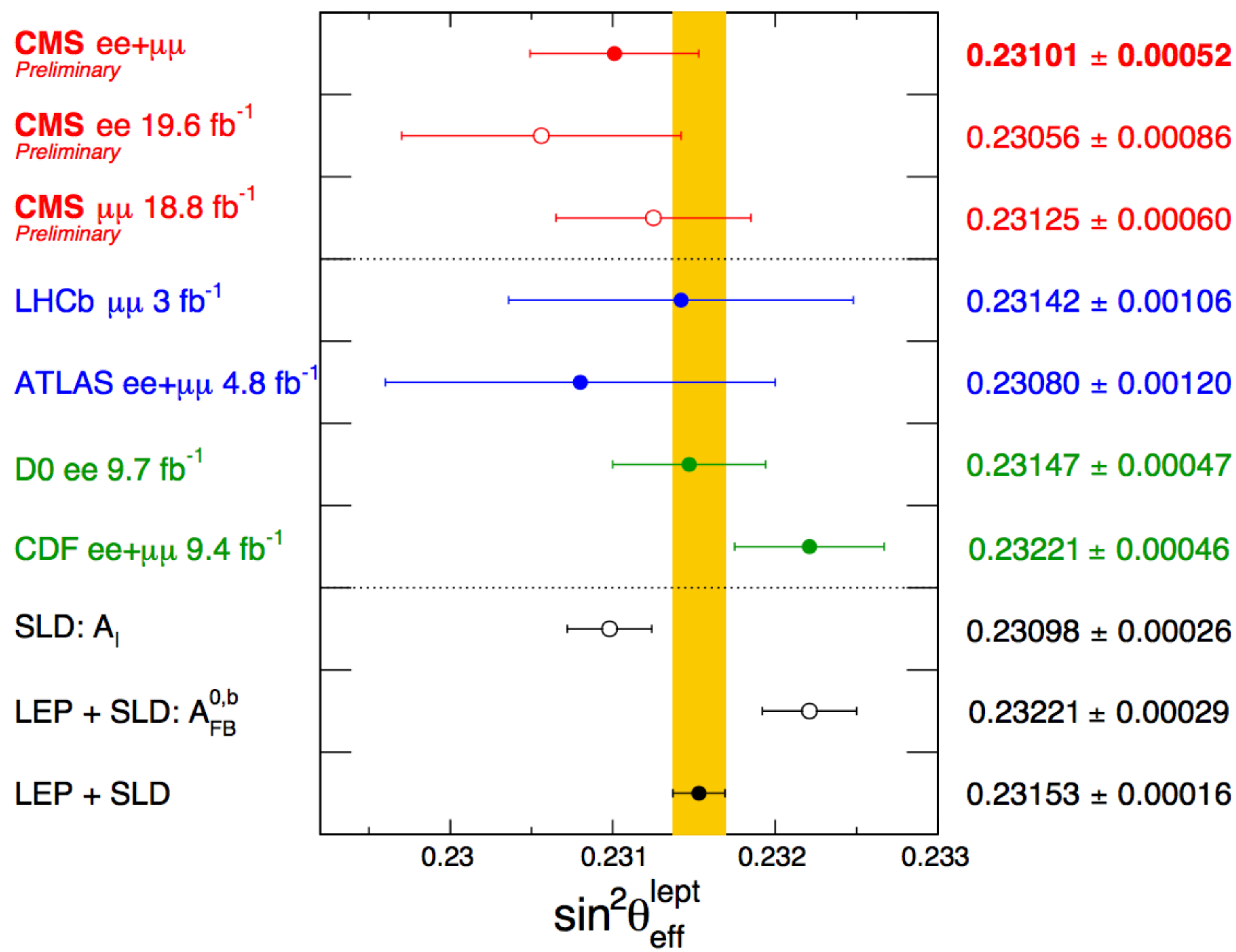

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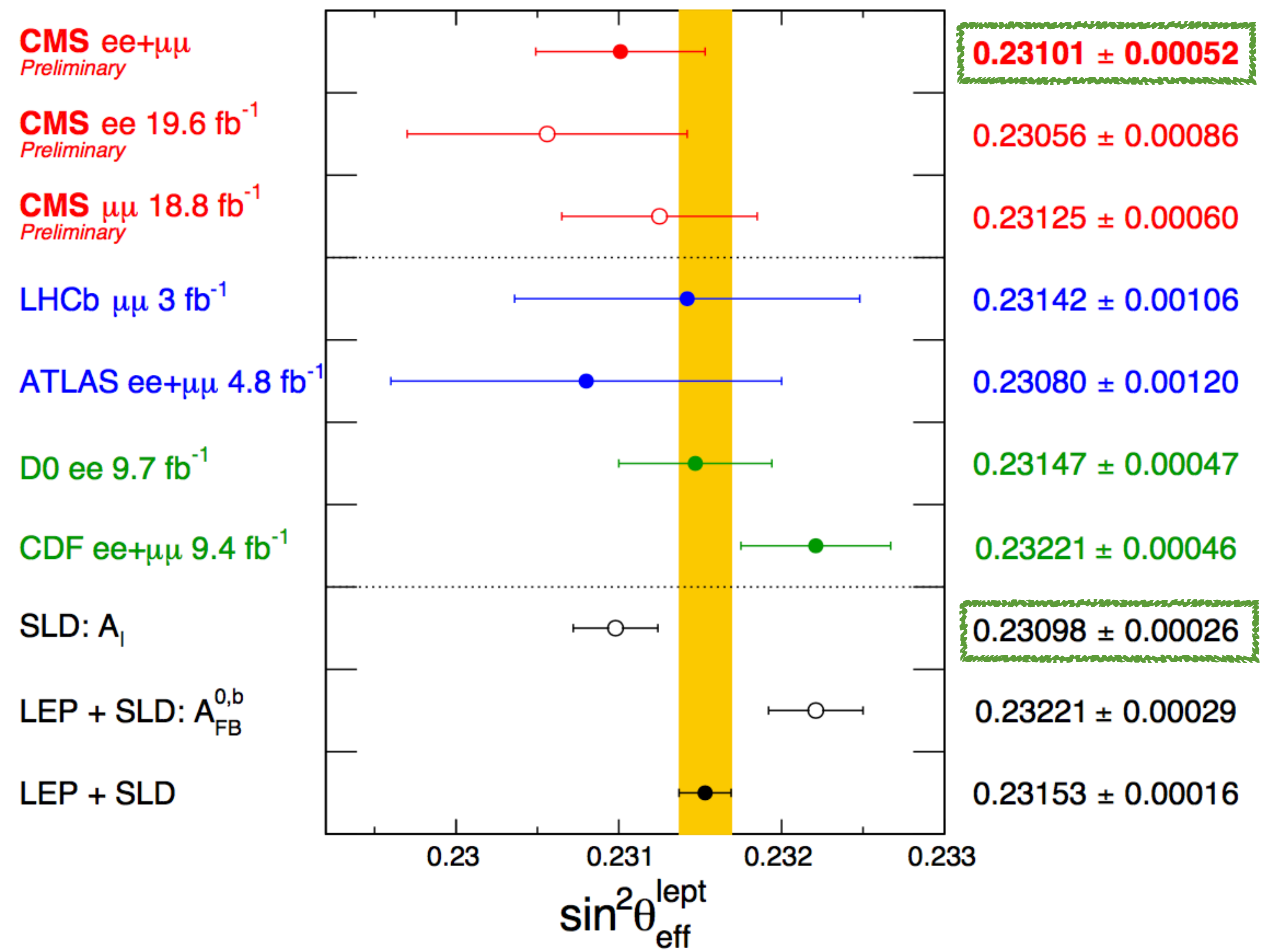

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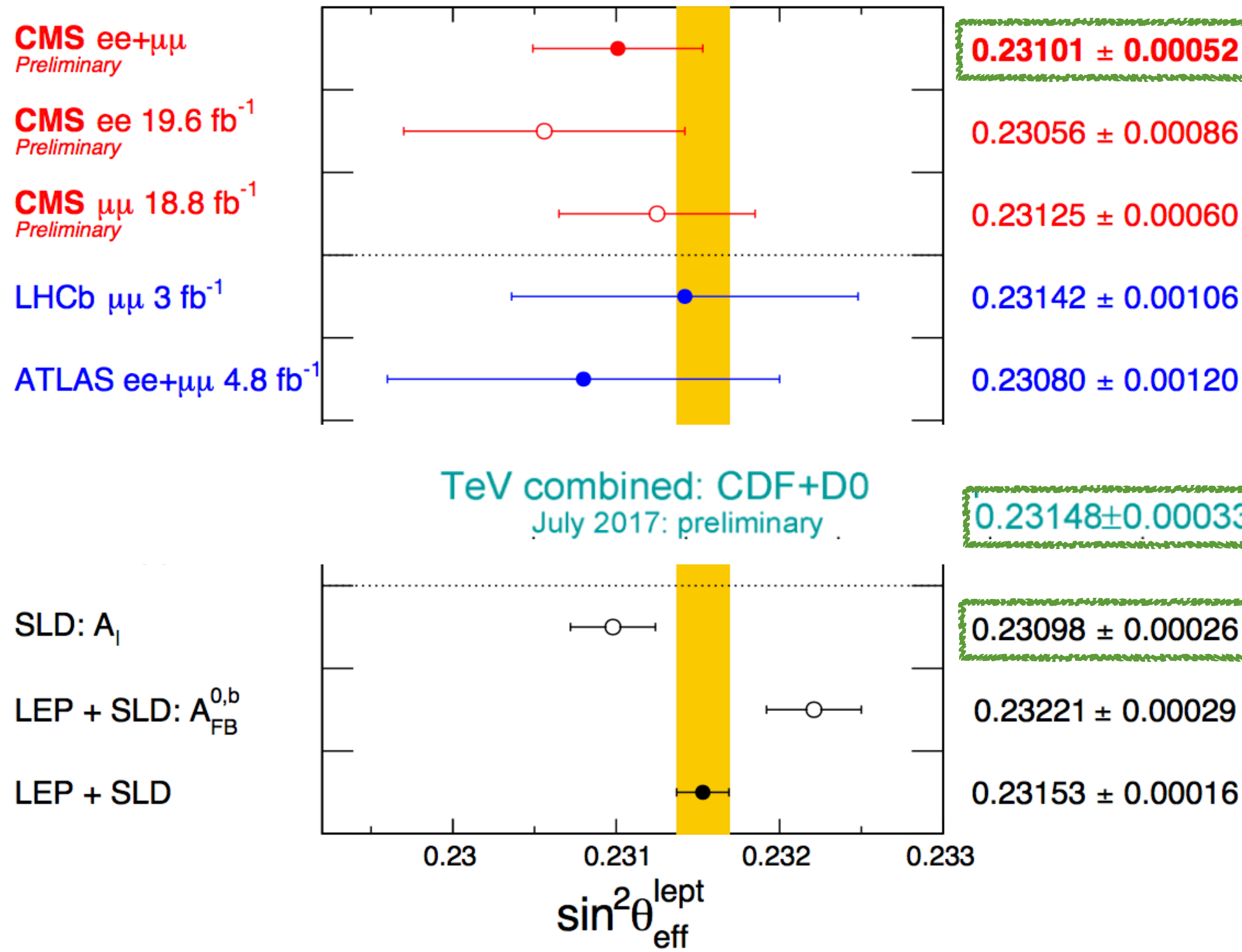
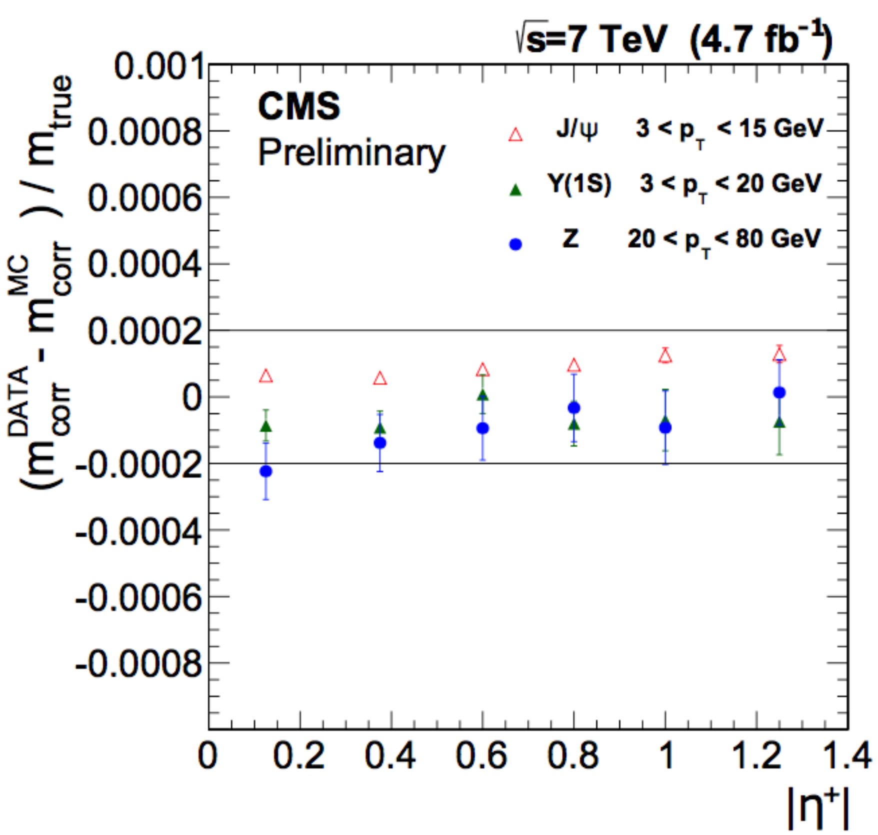
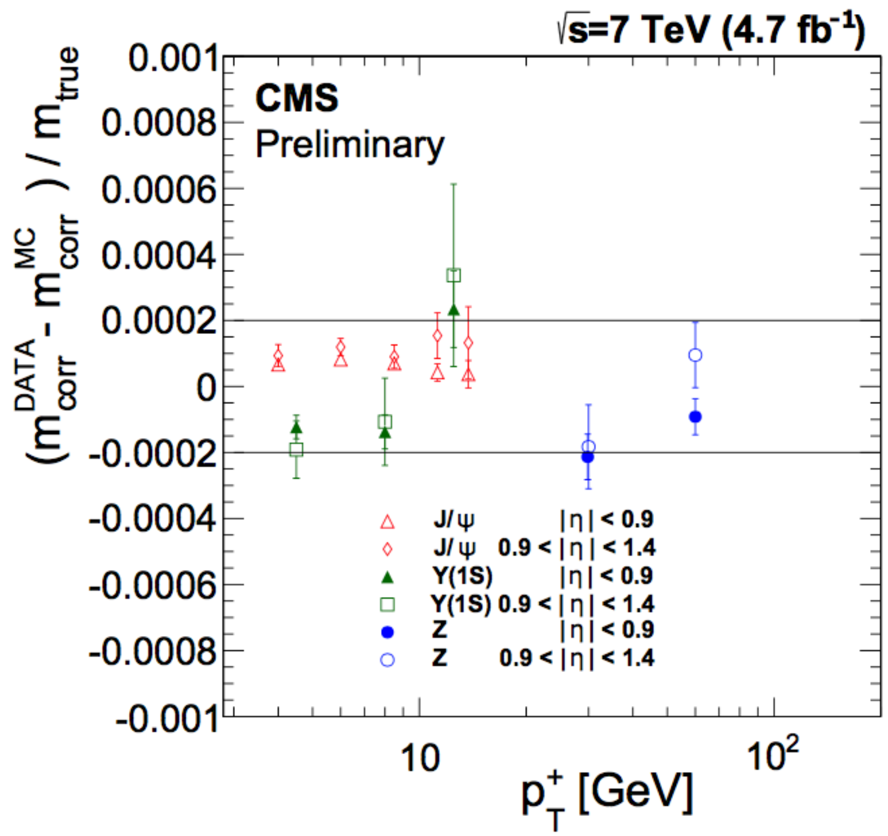


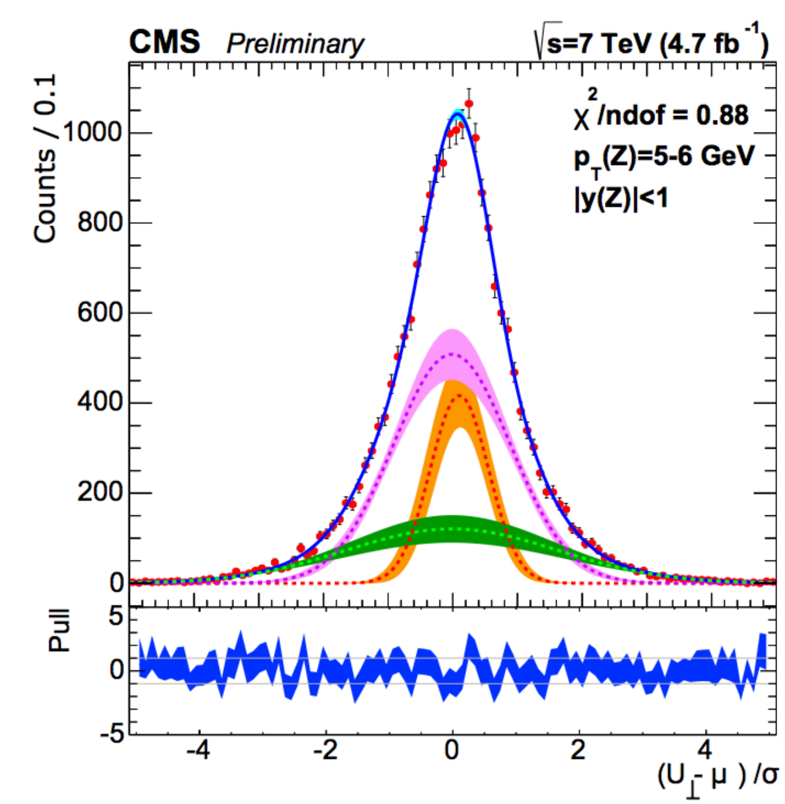
Studies towards a W mass measurement

CMS SMP-14-007
7TeV, 4.7 fb^{-1}

- CMS has performed a measurement of the Z boson mass using methods similar to those used for a W boson mass measurement.
- The measurement uses $Z \rightarrow \mu\mu$ decays where one of the muons is removed from the Z boson reconstruction. Muons are required to have $|\eta| < 0.9$ and $p_T > 30$ GeV.
- Half of the reconstructed Z bosons are used for recoil calibration. Muon momentum calibration is done with J/ψ and Υ decays.



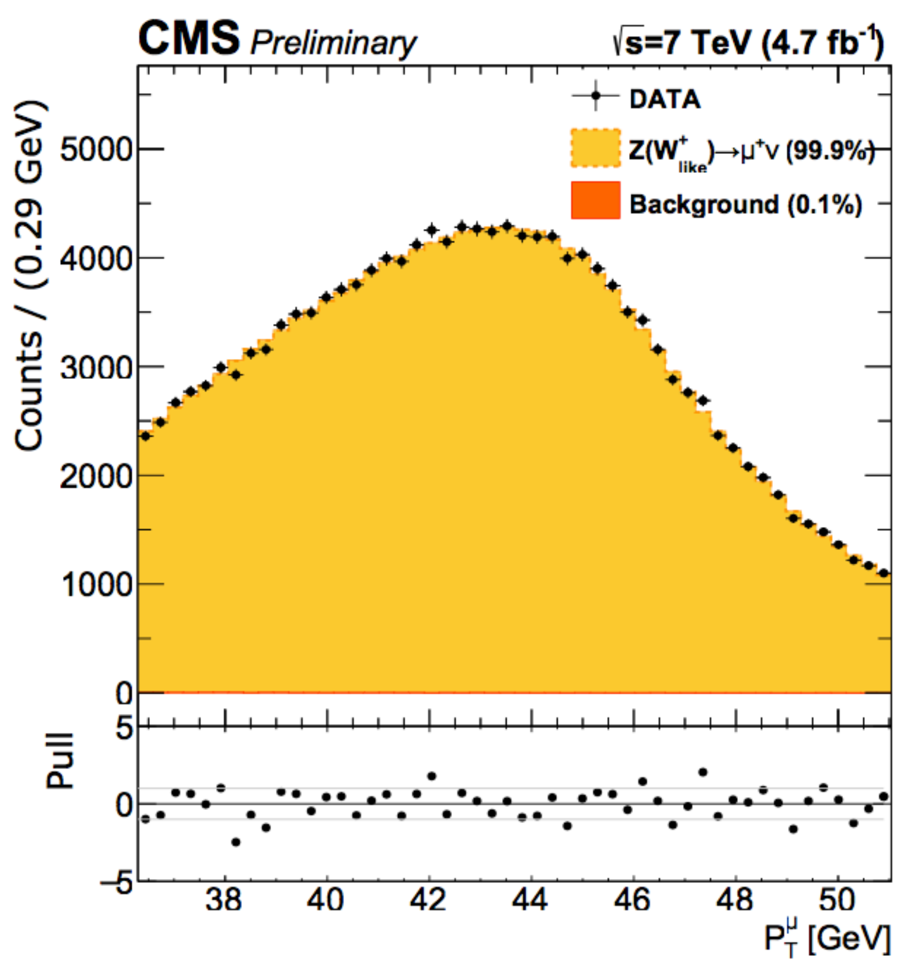


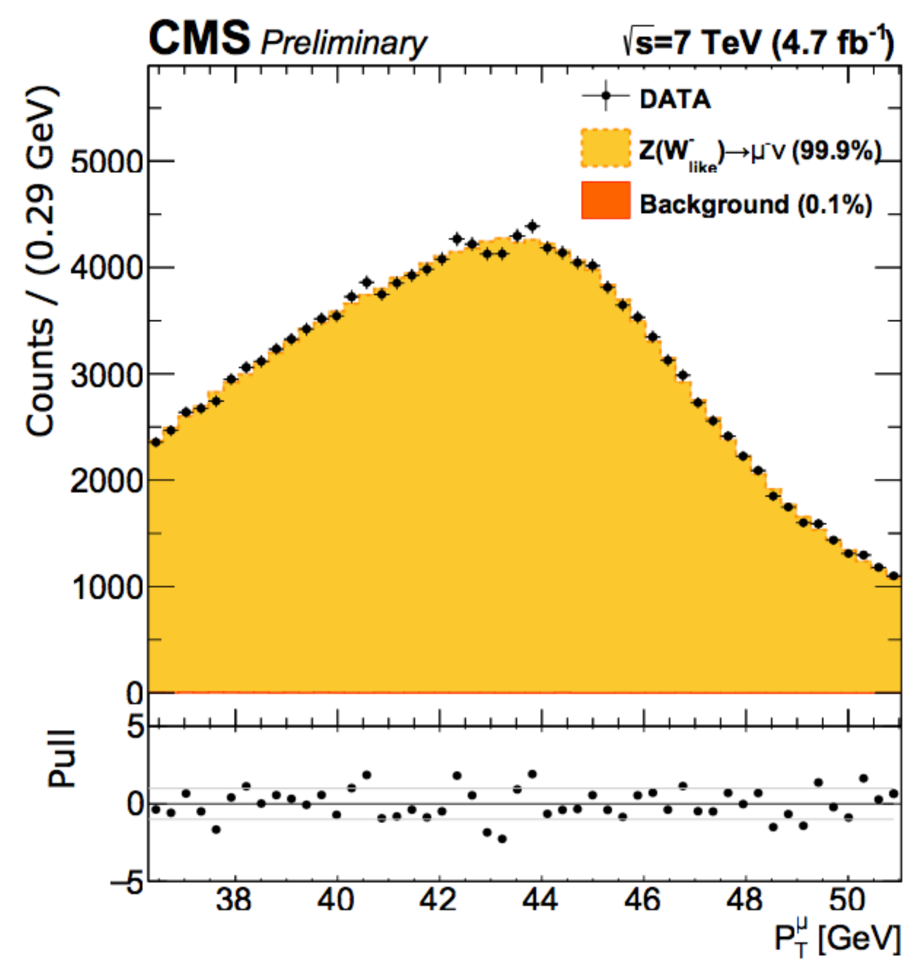


Observed distributions

CMS SMP-14-007
7TeV, 4.7 fb^{-1}

- The Z boson mass is measured using m_T, p_T, and E_T^{miss} templates with different Z boson mass.
- Templates are generated by reweighting the MC simulation using Breit-Wigner factors with different input masses.

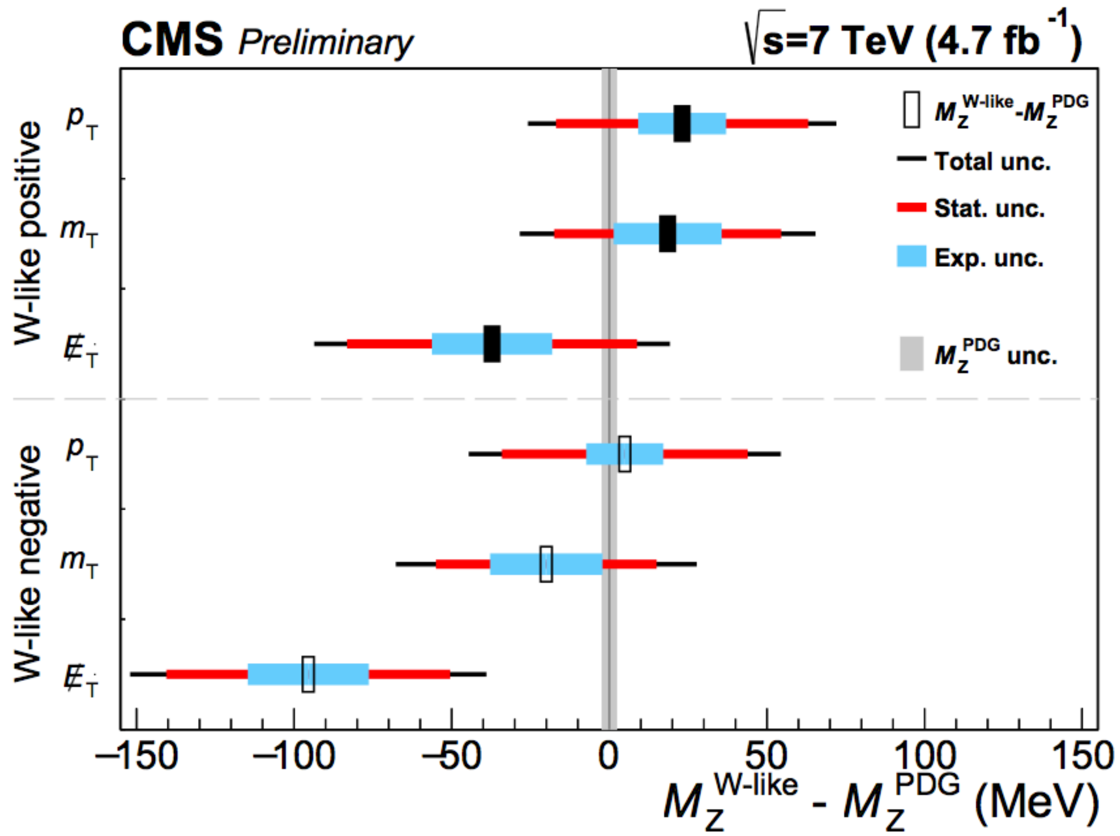




W-like Z boson mass result

CMS SMP-14-007
7TeV, 4.7 fb^{-1}

- Important first step towards a W mass measurement.
- Experimental methods for muon momentum and recoil scale calibrations are under control.
- The next step is to understand how to extrapolate this results to W boson events
- Need to understand well theoretical differences between W and Z production at the LHC



	$M_Z^{W\text{like}+}$			$M_Z^{W\text{like}-}$		
Sources of uncertainty	p_T	m_T	$\not{E}_T$	p_T	m_T	$\not{E}_T$
Lepton efficiencies	1	1	1	1	1	1
Lepton calibration	14	13	14	12	15	14
Recoil calibration	0	9	13	0	9	14
Total experimental syst. uncertainties	14	17	19	12	18	19
Alternative data reweightings	5	4	5	14	11	11
PDF uncertainties	6	5	5	6	5	5
QED radiation	22	23	24	23	23	24
Simulated sample size	7	6	8	7	6	8
Total other syst. uncertainties	24	25	27	28	27	28
Total systematic uncertainties	28	30	32	30	32	34
Statistics of the data sample	40	36	46	39	35	45
Total stat.+syst.	49	47	56	50	48	57

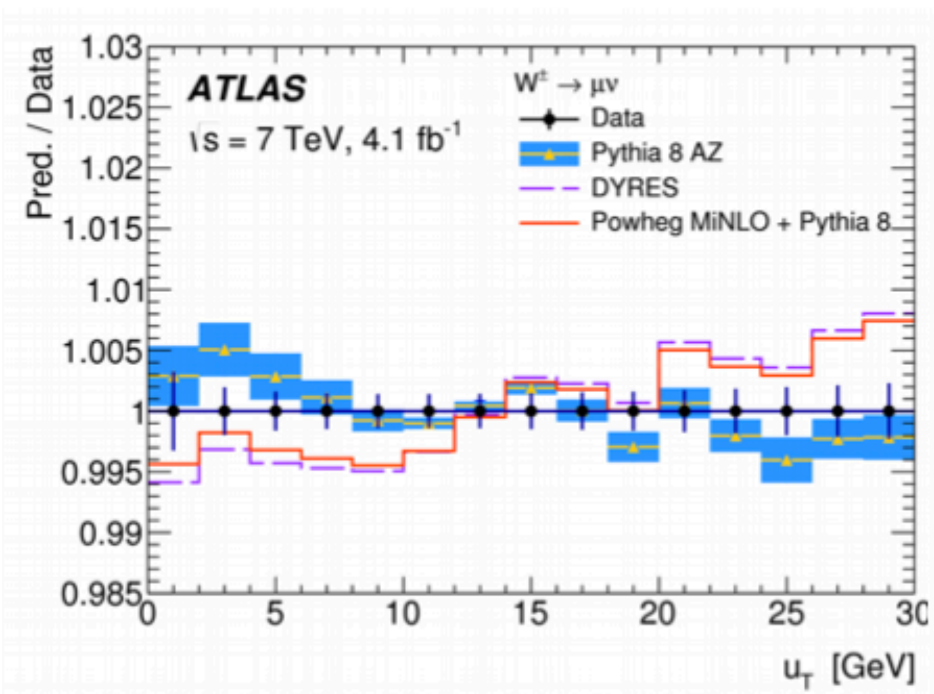
- Uncertainty dominated by statistical component.
- QED radiation uncertainty is very preliminary and will be re-evaluated for a final W mass measurement.
- No Z → W extrapolation uncertainties (experimental and theoretical)!

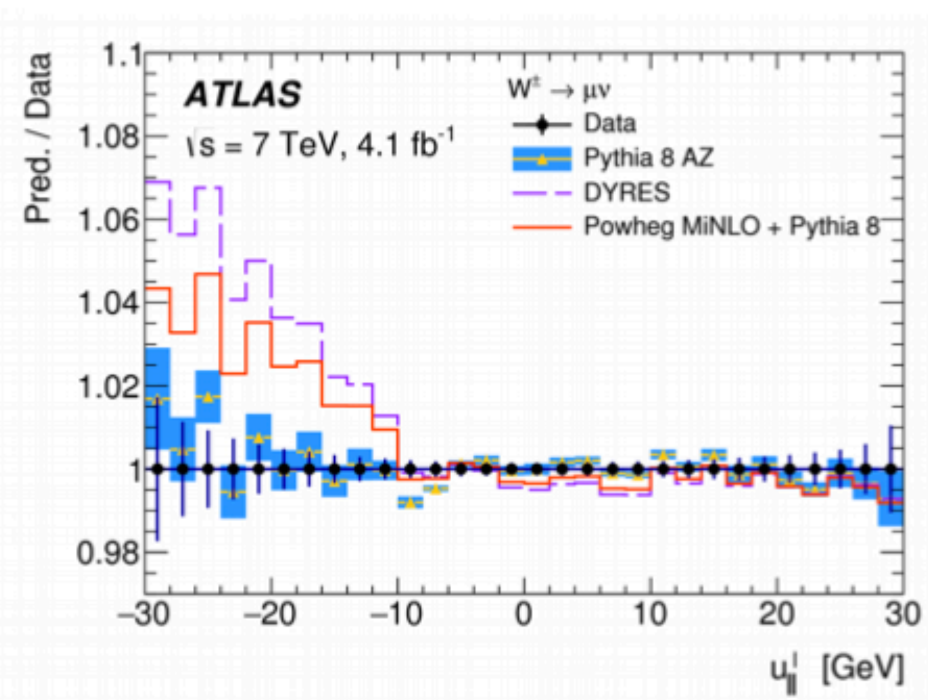
A quick look at other W mass efforts

Uncertainties in the recent ATLAS W mass measurement
[from S. Camarda @ W mass workshop at CERN, and arXiv:1701.07240]

Includes also Ai uncertainties

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.
p_T^ℓ, $W^\pm$, e	80347.2	9.9	0.0	14.8	2.6	5.7	8.2	5.3	8.9	23.1	4/5
m_T, $W^\pm$, e	80364.6	13.5	0.0	14.4	13.2	12.8	9.5	3.4	10.2	30.8	8/5
p_T^ℓ, $W^\pm$, μ	80382.3	10.1	10.7	0.0	2.5	3.9	8.4	6.0	10.7	21.4	7/7
m_T, $W^\pm$, μ	80381.5	13.0	11.6	0.0	13.0	6.0	9.6	3.4	11.2	27.2	3/7





Main theoretical uncertainties:

- QCD modeling of W and Z production in hadron collisions
- PDF modeling

ATLAS uses a dedicated Pythia tune to model W and Z production.

Conclusions

- CMS has a strong program of electroweak measurements. Several W and Z boson cross sections have been published at 7, 8, and 13 TeV.
- Some of these measurements can be performed with very high precision. Examples are cross section ratios, asymmetries, and differential cross sections of high-resolution observables.
- The $(d\sigma/dp_T^W)/(d\sigma/dp_T^Z)$ measurement performed at low instantaneous luminosity shows some tension with theoretical predictions, but the current precision is not sufficient to resolve the Sudakov peaks.
- The ϕ^* differential cross section measurement probes the same type of physics as the Z p_T differential measurement but with much higher precision. The measurements at 8 and 13 TeV show clear tension with theoretical predictions.
- The CMS measurement of the effective weak mixing angle $\sin\theta^{\ell}_{eff}$ with the complete 8 TeV dataset is presented. The uncertainty is twice as large as the world best single measurement, but most of the uncertainty is from the statistical component and will improve in the future.
- Finally, a future W mass measurement at CMS is discussed, highlighting the steps taken towards this measurement, what remains unknown about DY production at hadron colliders, and how high precision measurements can help improve our understanding.