Measurement of the forward-backward asymmetry and effective leptonic weak mixing angle at $\sqrt{s} = 13$ TeV

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The CMS $sin^2\theta^{\ell}_{eff}$ analysis group

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Hwidong Yoo (YONSEI-UNIV)
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The forward-backward asymmetry in Drell–Yan production and the effective leptonic weak mixing angle are measured using a sample of proton-proton collisions at $\sqrt{s}$=13 TeV collected by the CMS experiment and corresponding to an integrated luminosity of $137 fb^{-1}$. The measurement uses both dimuon and dielectron events, and is performed as a function of the dilepton's mass and rapidity. The measured value agrees with the standard model prediction. The total uncertainty using the CT18Z PDF is 0.00031. This is the most precise measurement at a hadron collider, with a precision comparable to the results obtained at LEP and SLD.

A new era of Precision EW Measurements at the LHC

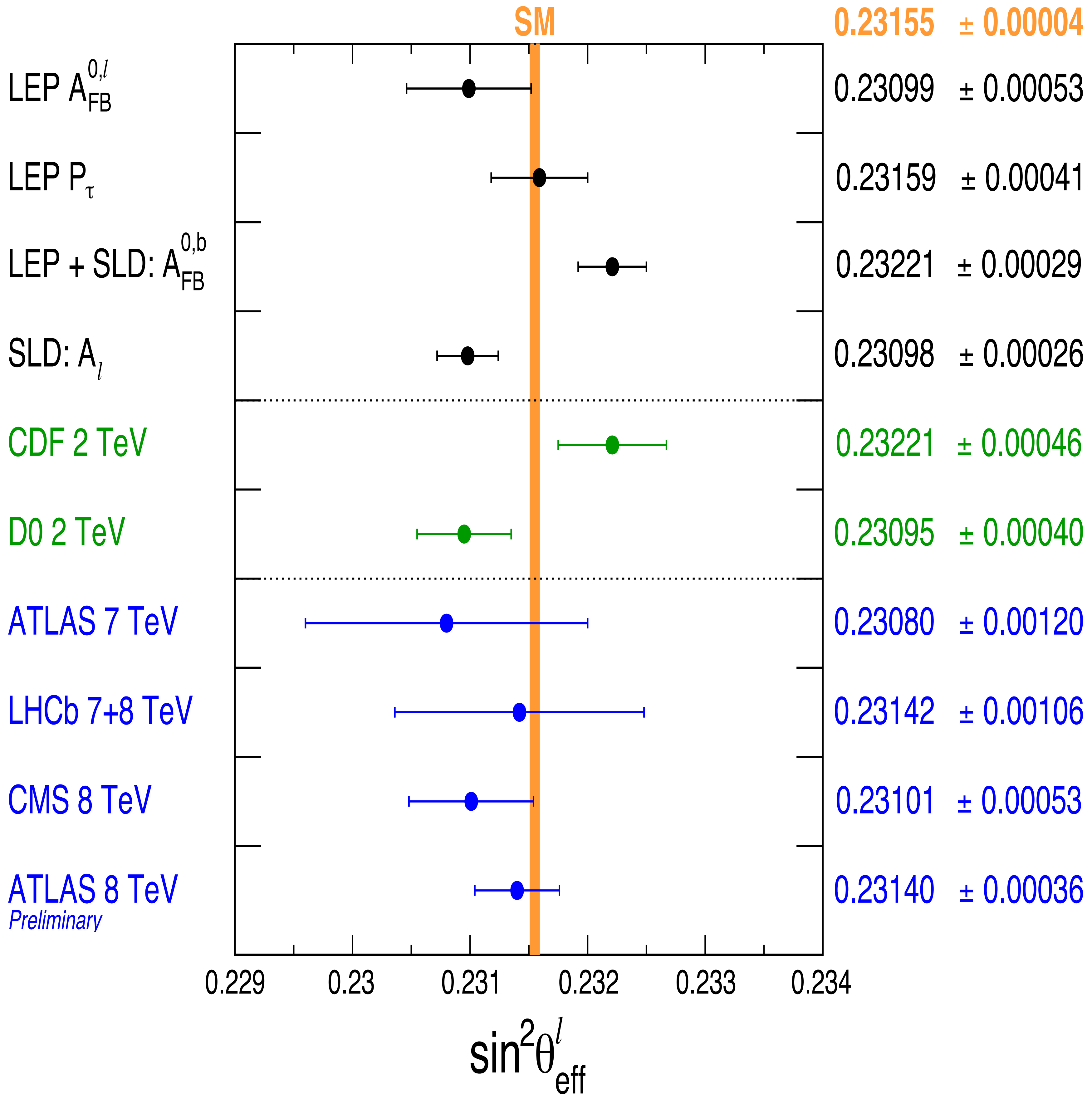
Precision Standard Model measurements are indirect searches for new physics

Key electroweak parameters: m_W and $sin^2\theta^\ell_{eff} = k^\ell(1 - m_W^2/m_Z^2)$ can be calculated from SM using precise experimental inputs: $sin^2\theta^\ell_{eff} = 0.23155 \pm 0.00004(SM)$

Electroweak radiative corrections in k^ℓ are accurately calculated in standard model

The two most precise measurements of $sin^2\theta^\ell_{eff}$ from LEP and SLD differ by ~3σ

Measurements at hadron colliders are now becoming competitive



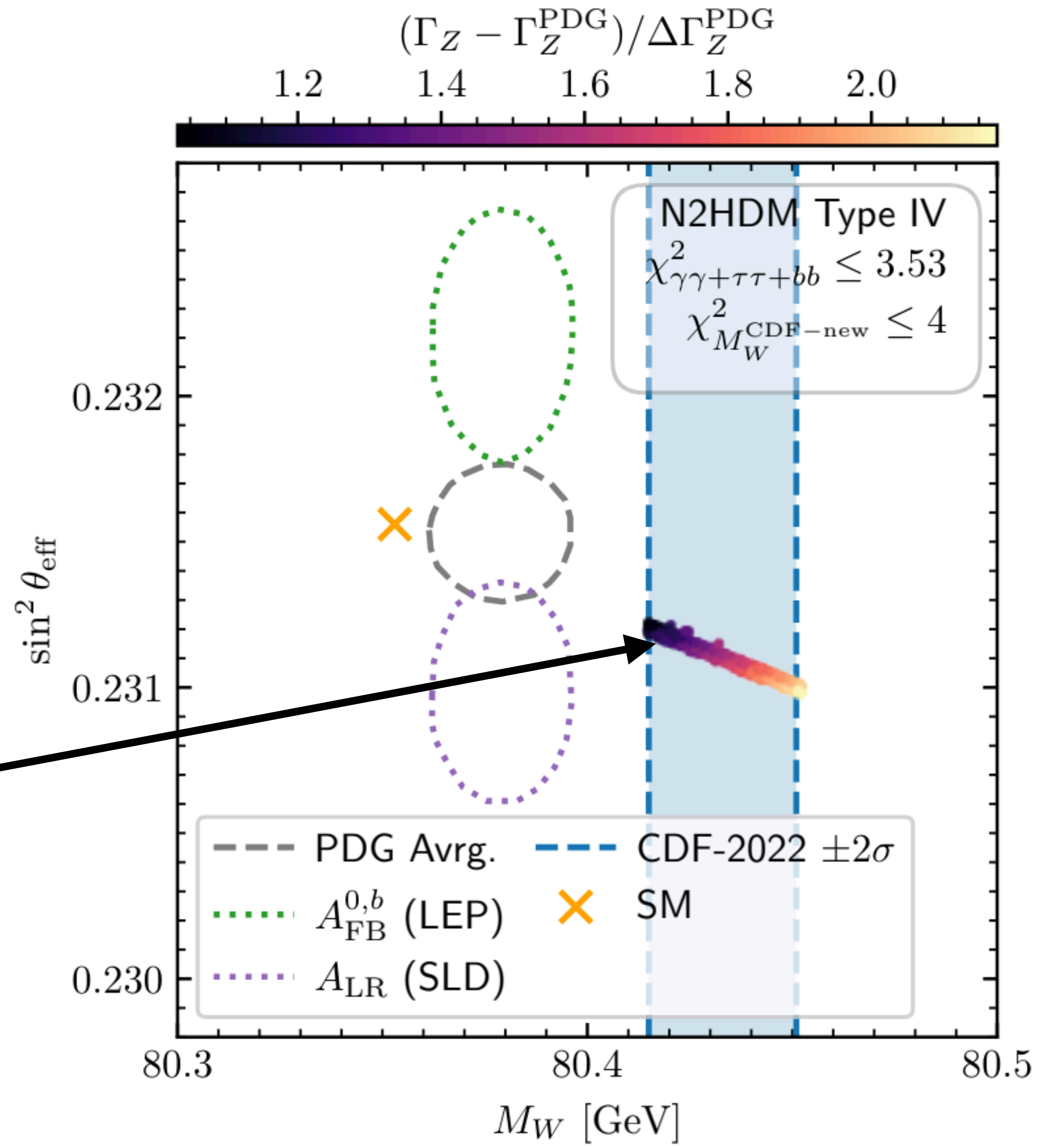
A new era of Precision EW Measurements at the LHC

The latest m_W measurement from CDF disagrees with previous results and SM

Models of new physics that agree with the CDF m_W prefer a lower (SLD) value of $sin^2\theta^{\ell}_{eff}$

2 Higgs doublet Model that agrees with CDF m_W predicts

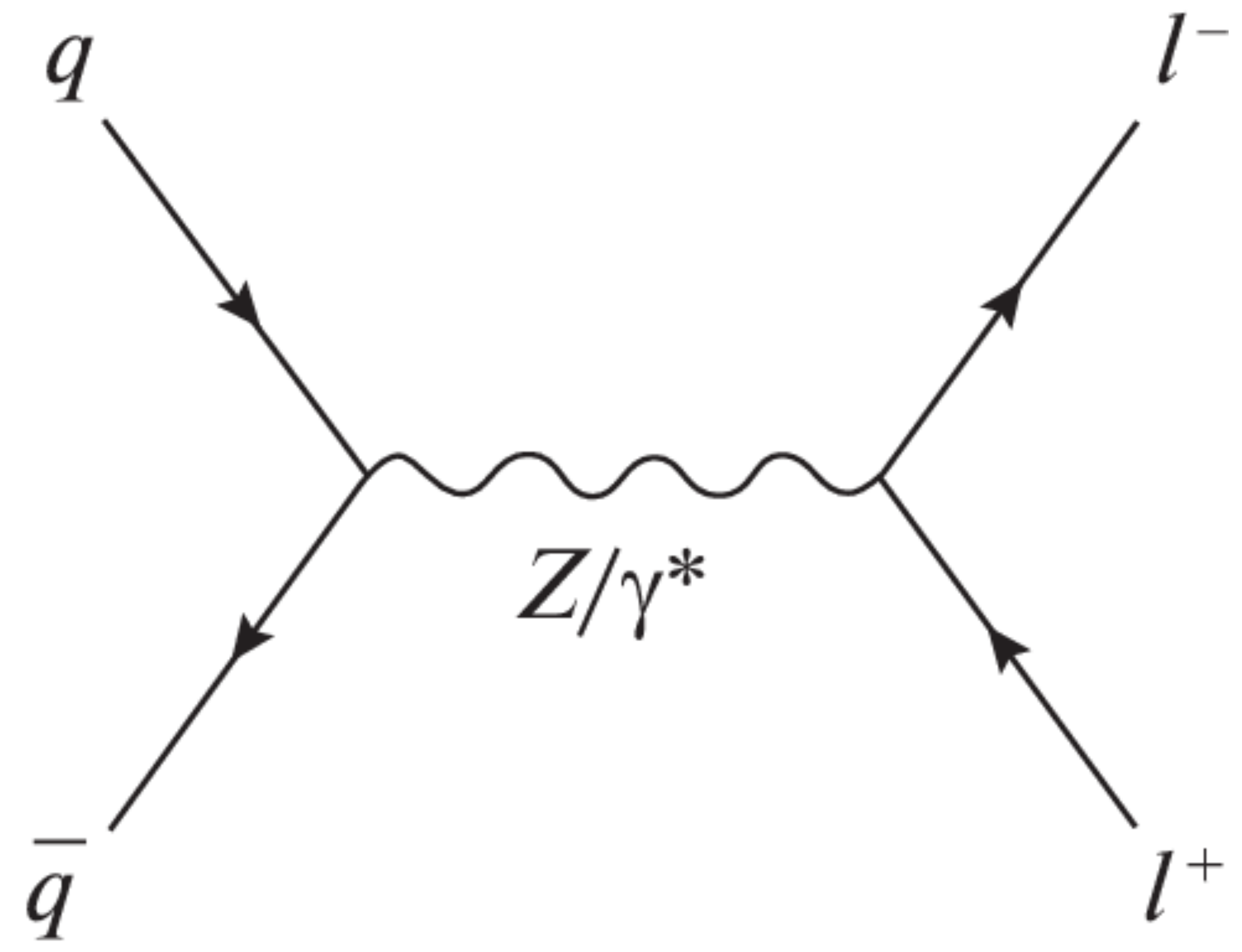
$$sin^2\theta^{\ell}_{eff} = 0.23110 \pm .00010$$



T. Biekötter et al, Eur.Phys.J.C 83 (2023) 5, 450

Measuring $sin^2\theta^{\ell}_{eff}$ at the LHC

The axial and vector neutral currents interfere



Weak neutral current strength related to $sin^2\theta^{\ell}_{eff}$

$$sin^2\theta_W = sin^2\theta_W^{on-shell} = 1 - m_W^2/m_Z^2$$

What we measure with dilepton events is an effective leptonic mixing angle

$$sin^2\theta^{\ell}_{eff} = Re[k^{\ell}(m_Z^2, sin^2\theta_W)]sin^2\theta_W$$

≈ 1.037

Precision EW measurements at LHC are now possible because of three innovative techniques

1. Precise lepton momentum/energy scale and resolution modeling
   — Reduces contribution to $\Delta sin^2\theta_{eff}$ to ± 0.00008
   A. Bodek, Eur. Phys. J. C72 , 2194 (2012)

2. Angular Event weighting method for A_{FB} analyses: Most systematic errors in acceptance and efficiency cancel
   A. Bodek. Eur. Phys. J. C67 , 321 (2010)

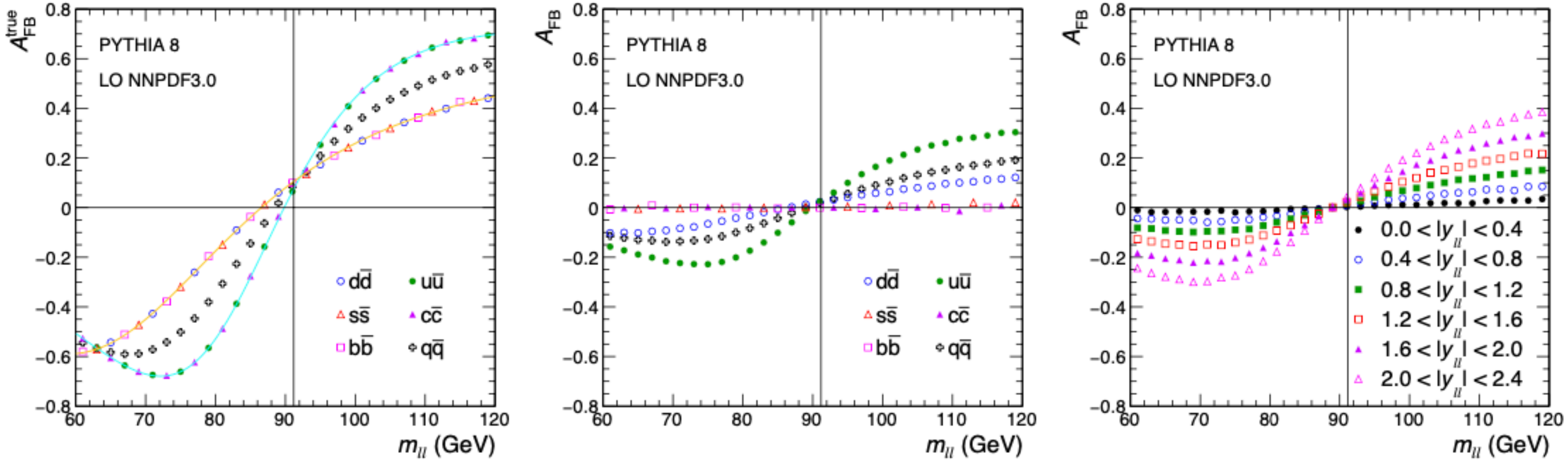
3. Most important In situ reduction of PDF errors by PDF reweighting/profiling
   A.Bodek et al, Eur. Phys. J. C76 , 3 (2016)

Extracting $sin^2\theta^{\ell}_{eff}$ from the forward backward asymmetry of Drell-Yan dilepton events at the Z mass pole

The forward backward asymmetry, A_{FB} increases with the Z boson rapidity, Y_Z

Only valence quarks contribute to the A_{FB}

At high Y_Z the high X parton is likely to be the valence quark and the low X parton is likely to be the antiquark — less dilution when quark direction is better known



CMS, arxiv: 1806.00863

Event Weighted A_{FB}
In situ cancellation of experimental systematic errors

Use Collins-Soper frame (CS-frame) - Z axis defined by quark direction

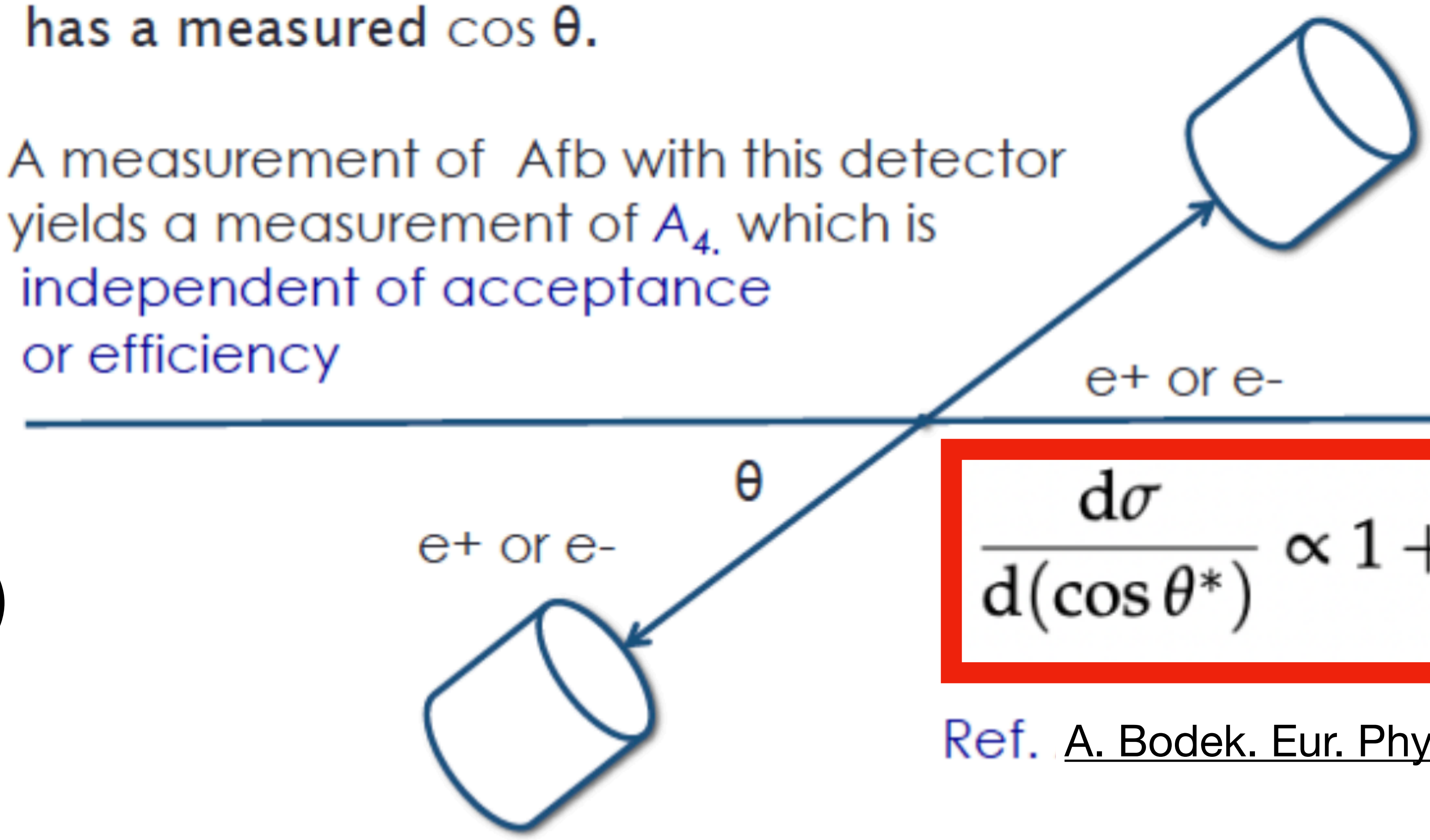
Event weighted A_{FB}^{W} is the same as A_{FB} for full acceptance (i.e. A_4 but smeared by experimental resolution and final state radiation)

With this technique most systematic errors in acceptance and efficiency cancel

$$A_{FB} = \frac{3}{8} A_4 = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

Imagine a detector with acceptance for only one value of cos θ. **Each event has a measured** cos θ.

A measurement of Afb with this detector yields a measurement of A_4, which is independent of acceptance or efficiency



$$\frac{d\sigma}{d(\cos\theta^*)} \propto 1 + \cos^2\theta^* + A_4 \cos\theta^*$$

Ref. A. Bodek. Eur. Phys. J. C67 , 321 (2010)

cos **θ=1 yields best** measurement of A_4. cos **θ=0 yields no measurement of** A_4

We can combine measurements of A_4 with different detectors at different values of by weighting events. Events with cos **θ=0 have zero weight.** Events with cos **θ=1 have maximum weight. → obtain smaller statistical error.** **Afb (all** cos **θ) = (3/8)** A_4 → **No acceptance corrections needed.**

In situ reduction of PDF errors with PDF reweighting/profiling

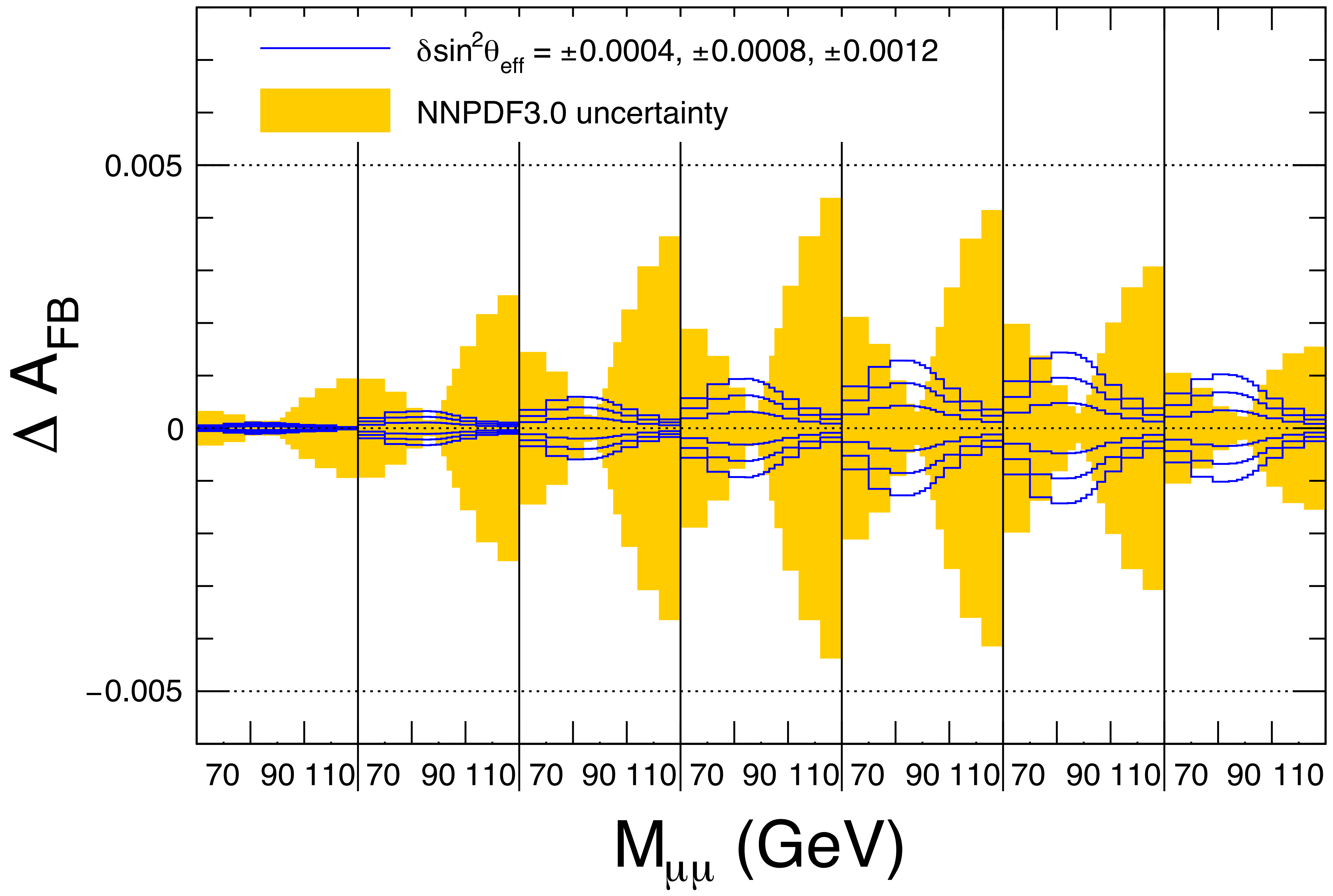
Reducing PDF uncertainties in the measurement of $sin^2\theta^{\ell}_{eff}$

At the Z peak, A_{FB} yields a measurement of $sin^2\theta^{\ell}_{eff}$. Here, A_{FB} is sensitive to both $sin^2\theta^{\ell}_{eff}$ and PDFs.

Above and below Z peak the axial coupling known. Here A_{FB} is not very sensitive to $sin^2\theta^{\ell}_{eff}$ but it is very sensitive to PDFs.

In this region, measurements of A_{FB} provide constraints on PDF using the same Drell Yan sample (but above and below the Z peak).

A.Bodek et al, Eur. Phys. J. C76 , 3 (2016)



PDF reweighting/profiling

The constraints on PDF are statistically limited

Therefore, the errors are reduced with larger statistical samples (e.g. larger integrated luminosity, and/or by combing data from the three LHC experiments)

With 13 TeV data ($138fb^{-1}$) PDF uncertainties in $sin^2\theta^{\ell}_{eff}$ measurement are reduced by factor of 2 compared to 8 TeV ($19fb^{-1}$)

Reducing PDF errors in the measurements of both $sin^2\theta^{\ell}_{eff}$ and m_W

Future plans:

Further reduction of PDF uncertainties by including kinematic distribution of W bosons, e.g., W boson asymmetry and other distributions not sensitive to m_W.

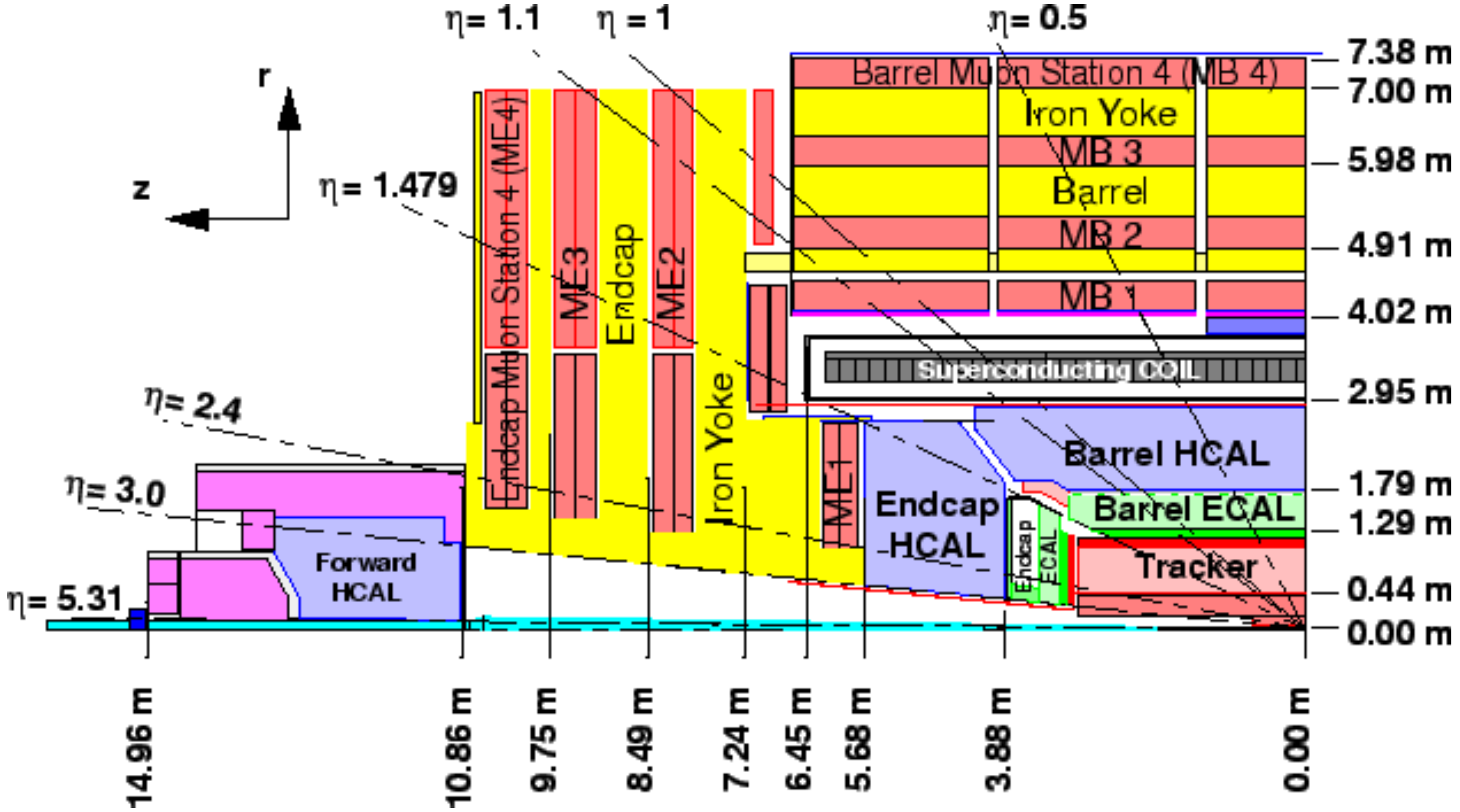
Run-2 Analysis

What we measure

- $sin^2\theta^{\ell}_{eff}$ from angular weighted A_{FB} - small systematics, used in Run-1
- Unfolded $A_4(y_Z, m_Z)$ at born level in the pre-FSR dilepton system $y - m$ bins - can be used in future reinterpretation

In 4 dilepton channels: $\mu\mu, ee, eg, eh$

μ - muon $|\eta| < 2.4$
e - central electron $|\eta| < 2.5$
g - ECAL electron past tracker $2.5 < |\eta| < 2.87$
h - forward HCAL electron $3.14 < |\eta| < 4.36$



POWHEG Z_ew bug

This analysis uses POWHEG Z_ew program to:
-Correct the MiNNLOPs predictions to NLO EW
-Estimate impact of weak corrections

POWHEG Z_ew predictions were obtained from svn3964 revision (2022-01-13)

arXiv: 1302.4606 [hep-ph]

A bug in POWHEG was found by the authors which affect the complex mass scheme (CMS) predictions for EW input schemes such as $(G_\mu, m_Z, \sin^2\theta^\ell_{eff})$

The bug impacts the analysis in two aspects:
-The central value obtained with the CMS is expected to be shifted
-The difference between the CMS and Pole Scheme (PS) (largest theoretical uncertainty in the fit) is reduced

F. Vazzoler

POWHEG Z_ew bug

The bug has been fixed in the POWHEG Z_ew svn4049 revision (2024-03-08)

arXiv: 2402.14659 [hep-ph]

POWHEG Z_ew predictions rederived with svn4049 to check impact on A_4 and the extracted $sin^2\theta^{\ell}_{eff}$

The effect of the bug fix is only studied on the unfolded A_4 data and theoretical model

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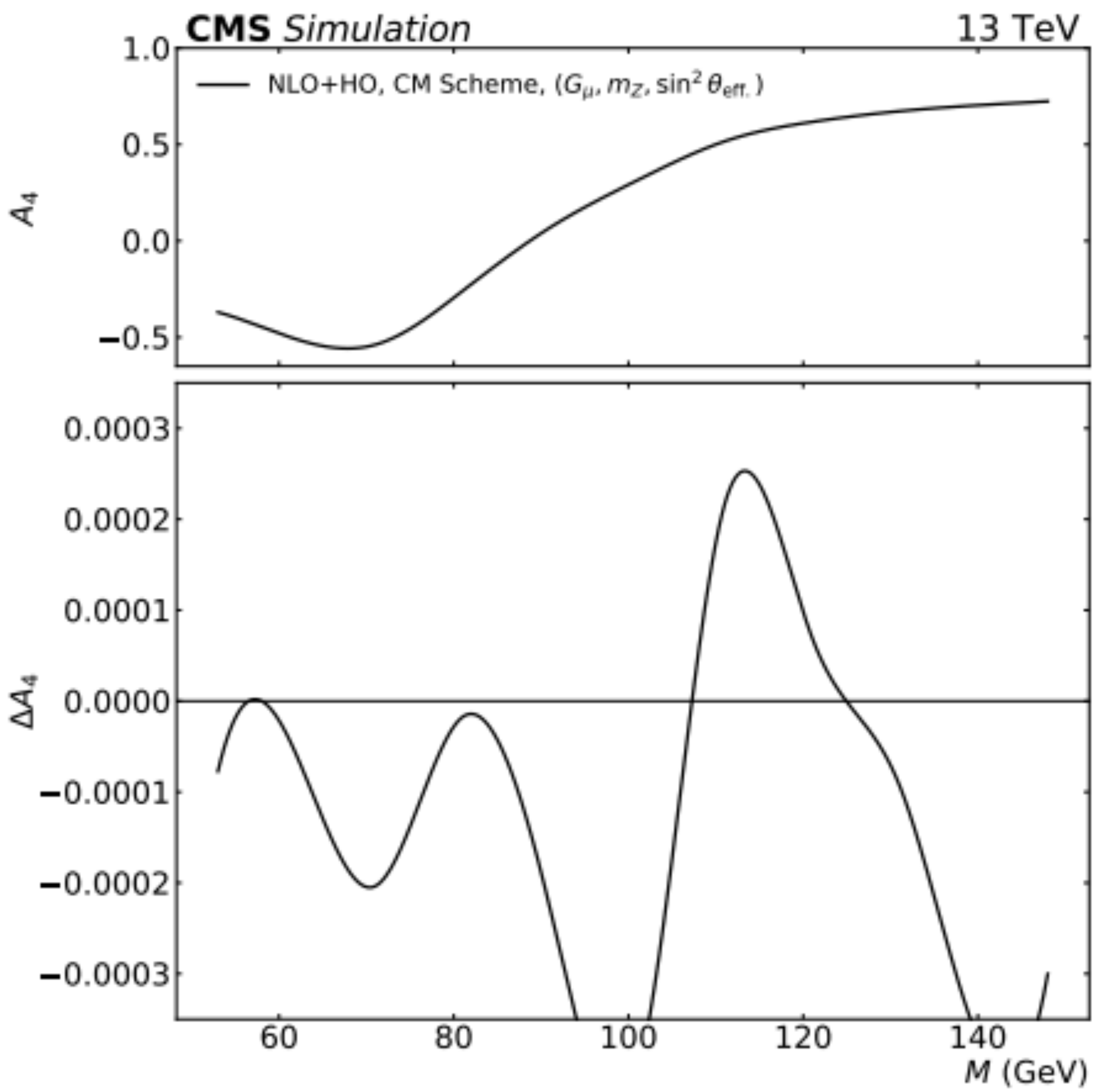
Impact on theoretical model

Comparison between the new $A_4(m_{\ell\ell})$ nominal values (svn4049) and the former (bugged) ones (svn3964).

The difference between the two predictions is almost contained within the (former) weak uncertainties but the $m_{\ell\ell} = m_Z$ region where ΔA_4 is a factor of two larger than the ΔA_4 difference between the CMS and PS scheme



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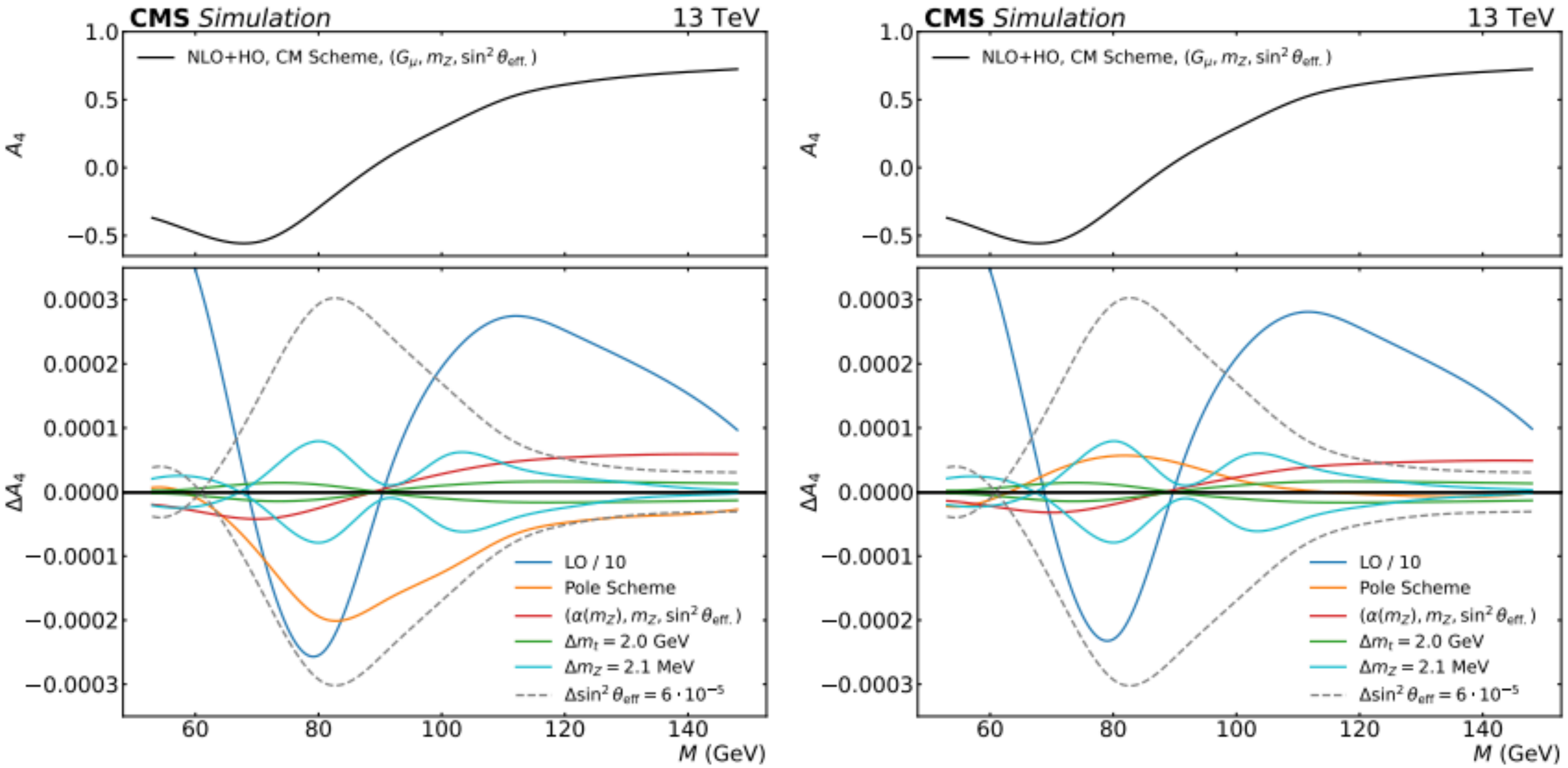
Impact on the theoretical model uncertainties



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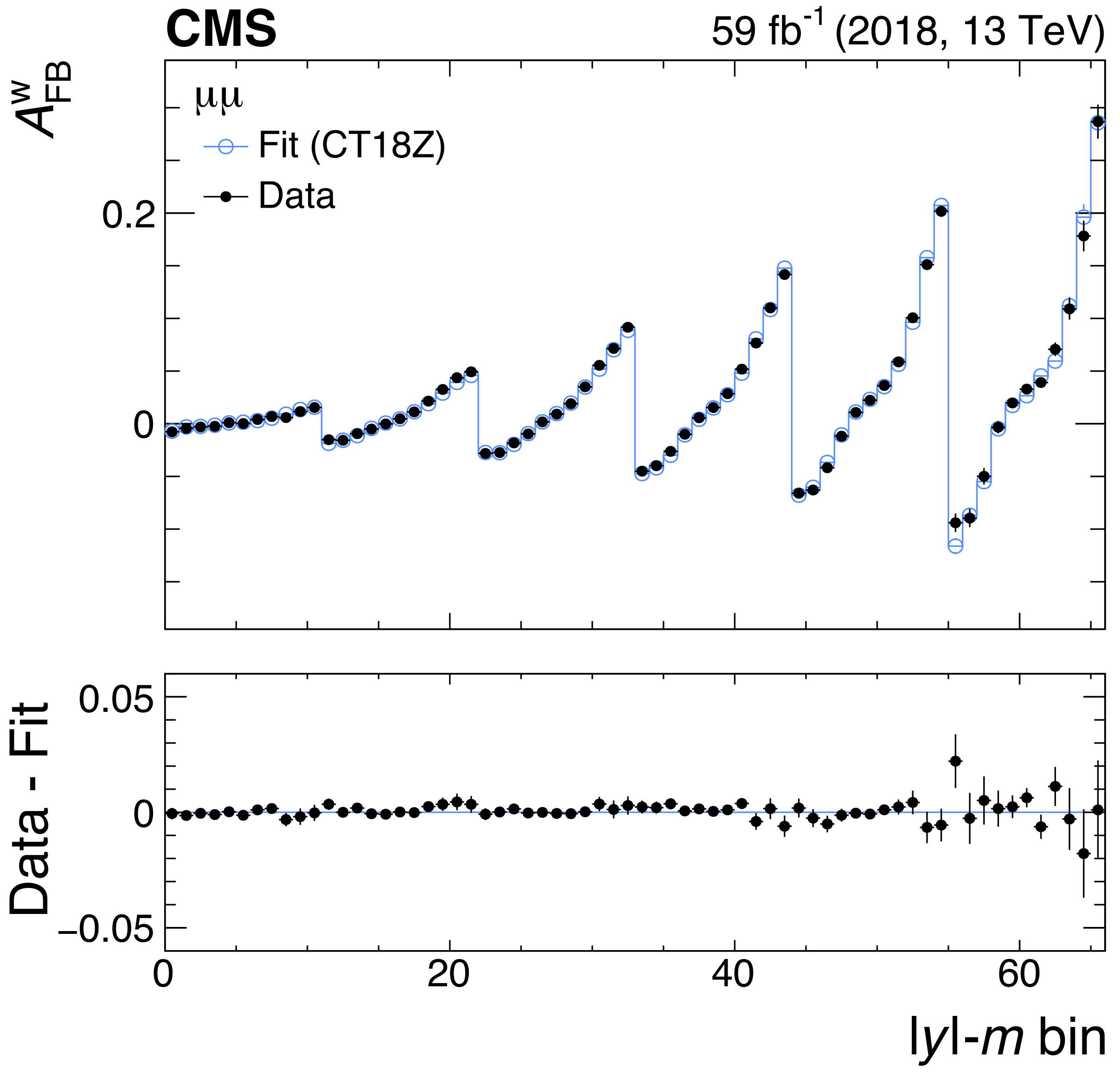
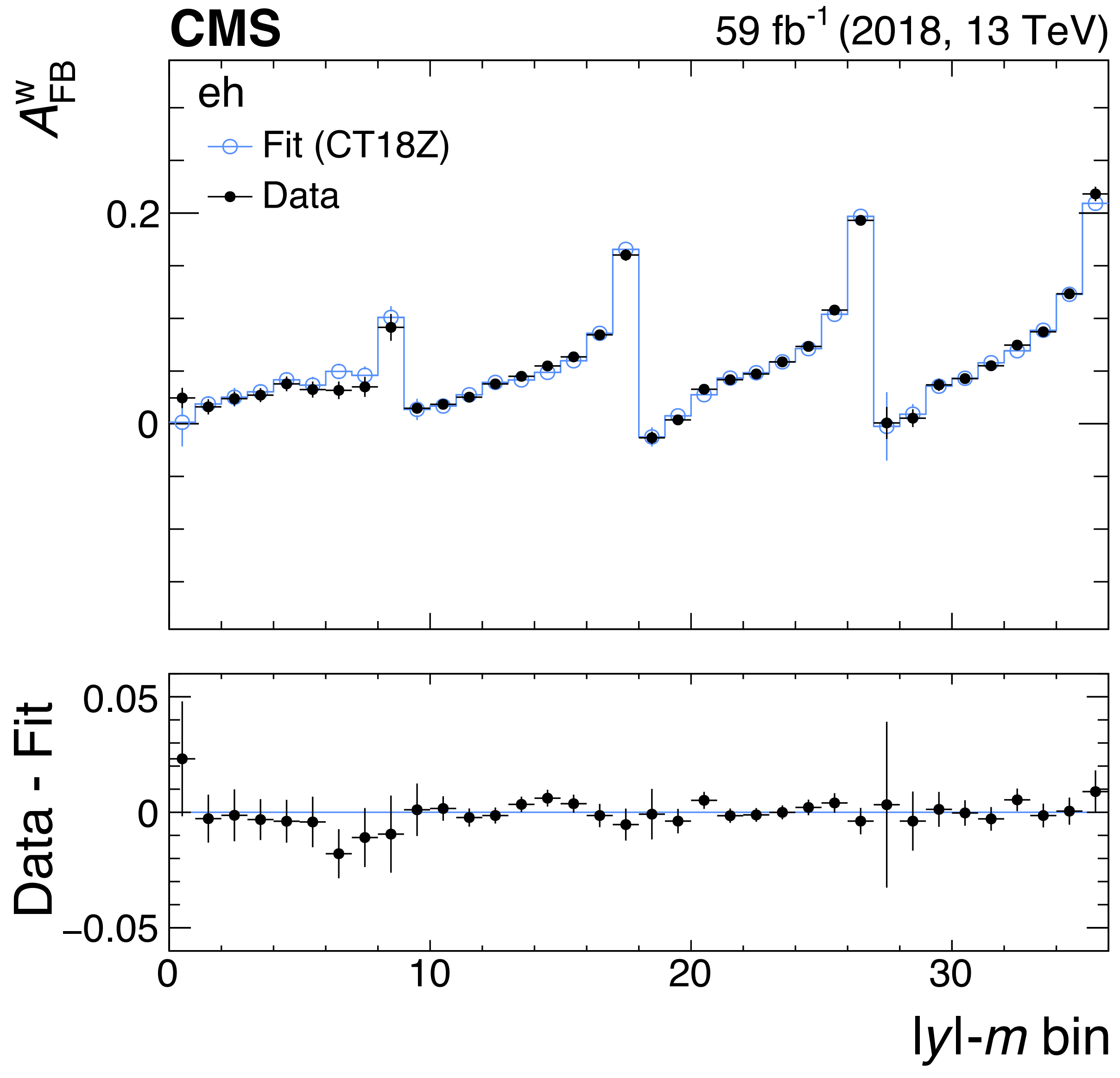
The only sizable difference, as expected, is on the ΔA_4 distribution obtained by comparing the CMS and the PS which changes sign and has a reduced impact by a factor ≈ 1/2.

Angular Weighted $A_{FB} - A_{FB}^{W}$

A_{FB}^{W} is equivalent to experimental full acceptance A_{FB} but includes FSR and detector resolution smearing — equivalent to measuring A_4





$sin^2\theta^{\ell}_{eff}$ is extracted by simultaneous χ^2 fit of $A_{FB}^{W}(y, m)$ in all runs and channels

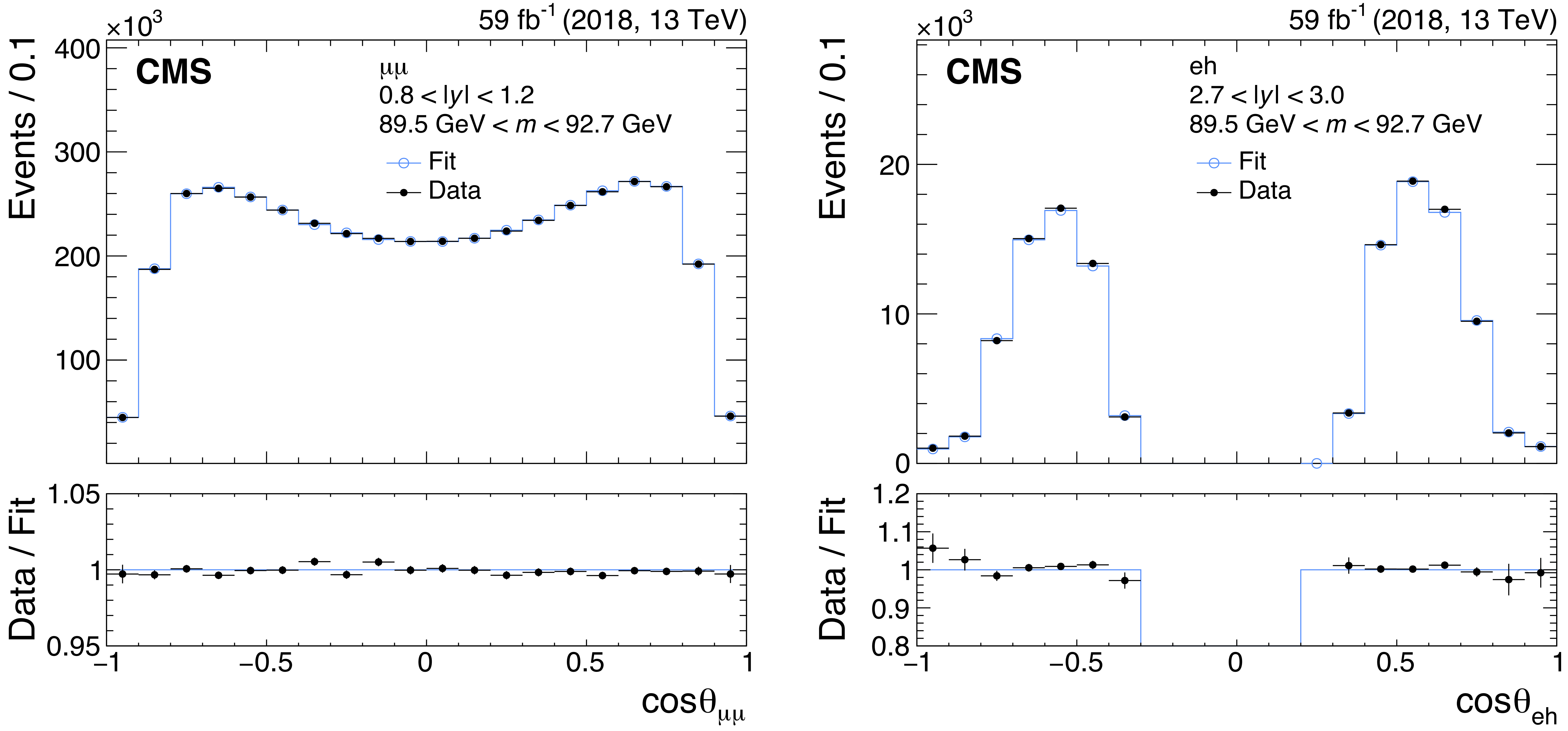
In detector level angular weighted A_{FB} most experimental systematic uncertainties cancel

Shown in units 10^{-5}

ch	χ^2	nbin	p(%)	$\sin^2\theta^{\ell}_{\text{eff}}$	$\pm$	σ	stat	exp	theo	pdf	mc	bkg	eff	calib	other
$\mu\mu$	241.3	264	82.7	23146	$\pm$	38	17	17	7	30	13	3	2	5	4
ee	256.7	264	59.8	23176	$\pm$	41	22	18	7	30	14	4	5	3	7
eg	119.1	144	92.8	23257	$\pm$	61	30	40	5	44	23	11	12	19	9
eh	104.6	144	99.3	23119	$\pm$	48	18	33	9	37	14	10	16	18	6
$\ell\ell$	730.7	816	98.4	23157	$\pm$	31	10	15	9	27	8	4	6	6	3

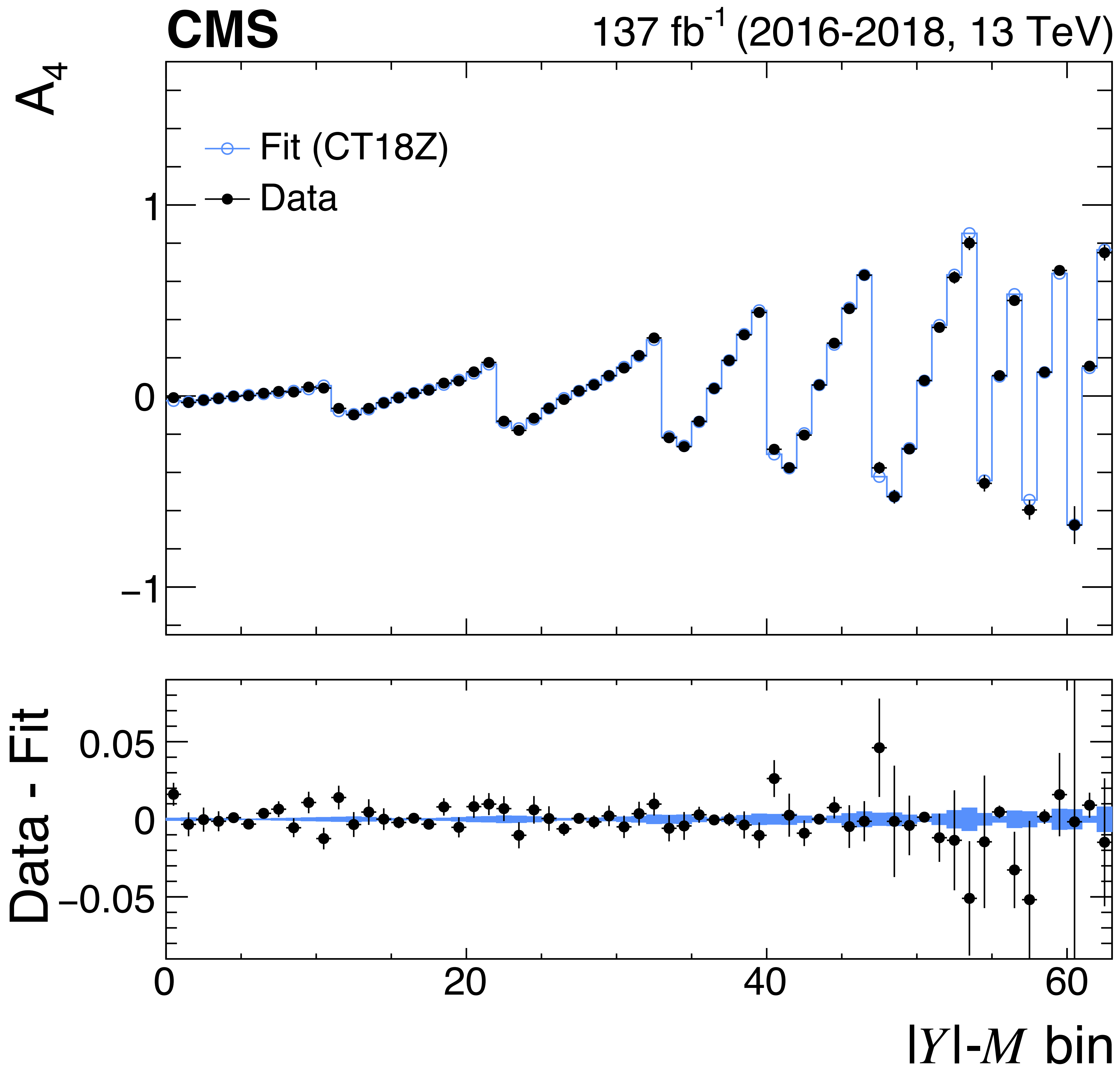
Measurement of $A_4(y, m)$

$A_4(y_Z, m_Z)$ is measured by fitting reconstructed $cos\theta_{CS}$ distributions in y and m bins simultaneously in all runs and channels



Total $\chi^2_{min} = 14839$ for total of 14205 measurement bins and 101 free POIs

Interpretation of A_4 fit

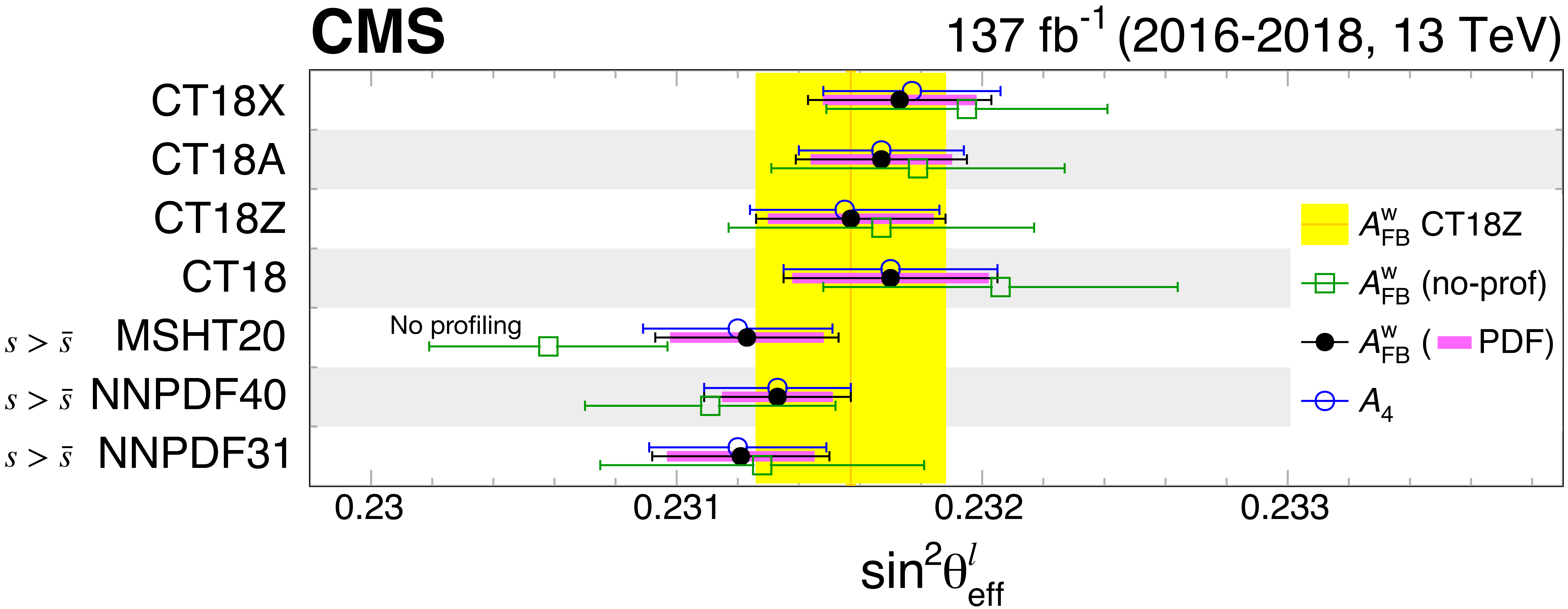


Measured and best fit $A_4(Y_Z, M_Z)$ distributions for the Run 2 fit with the CT18Z PDF set. The shaded band represents the post-fit PDF uncertainty.

Channel	n(bins)	χ^2_{min}	p(%)	$\sin^2\theta^\ell_{eff}$	$\pm$	σ
$\mu\mu$	54	59.7	24.6	23146	$\pm$	39
ee	54	47.0	70.7	23192	$\pm$	43
eg	12	11.1	43.6	23251	$\pm$	60
eh	12	8.4	67.3	23129	$\pm$	47
$\ell\ell$	63	61.3	50.3	23155	$\pm$	32

Results for different PDF sets

CT18Z chosen as 'default' pdf set before unblinding



1. PDF reweighting/profiling reduces PDF error by a factor of 2, and results in better agreement between different PDF sets.

2. A_{FB} and A_4 analysis yield the same value of $sin^2\theta^{\ell}_{eff}$ (A^W_{FB} is a check on unfolded A_4)

Results for different PDF sets

PDF	A_{FB} (816 bins)		A_4 (63 bins)	
	χ^2_{min}	$\sin^2\theta^\ell_{eff}$	χ^2_{min}	$\sin^2\theta^\ell_{eff}$ $(1E-5)$
NNPDF31	724.7	$23\,121 \pm 29$	58.5	$23\,120 \pm 30$
NNPDF40	730.5	$23\,133 \pm 24$	62.6	$23\,133 \pm 25$
MSHT20	735.8	$23\,123 \pm 30$	71.0	$23\,120 \pm 32$
CT18	728.4	$23\,170 \pm 35$	62.2	$23\,170 \pm 36$
CT18Z	730.7	$23\,157 \pm 31$	61.3	$23\,155 \pm 32$
CT18A	730.3	$23\,167 \pm 28$	63.6	$23\,167 \pm 28$
CT18X	728.5	$23\,173 \pm 30$	61.8	$23\,177 \pm 30$

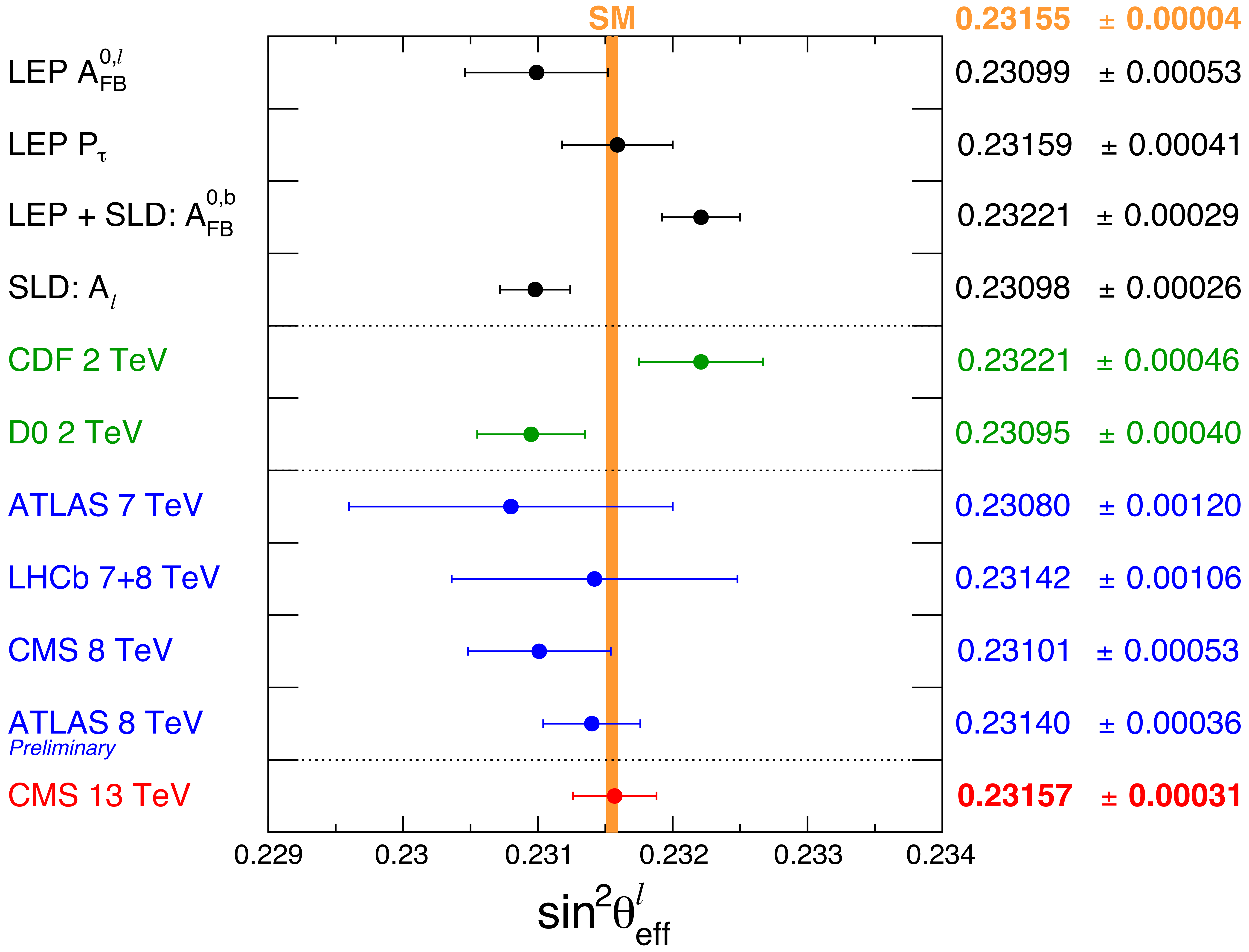
$$sin^2\theta^\ell_{eff} = 0.23157 \pm 0.00010(stat) \pm 0.00015(exper) \pm 0.00009(theo) \pm 0.00027(pdf)$$

Reduce PDF error by using the values of A_4 to extract $sin^2\theta^\ell_{eff}$ with PDF reweighting/profiling that also includes W boson asymmetry and other W boson distributions at 13 TeV.

Comparison of $sin^2\theta^{\ell}_{eff}$ with previous experiments

The new CMS measurement of $sin^2\theta^{\ell}_{eff}$ is now competitive with LEP/SLD

PDF uncertainties remain as the dominant systematic errors
Main challenge for future $sin^2\theta^{\ell}_{eff}$ measurements at the LHC



PDF Fit cross check

We performed the following cross check (with svn3964 POWHEG Z_ew model):

-Extract $sin^2\theta^{\ell}_{eff}$ by profiling the data from the analysis with the HERAPDF2.0 set

-Extract $sin^2\theta^{\ell}_{eff}$ by fitting the HERA and unfolded A_4 data with the HERAPDF2.0 parameterization

Configuration	Results
Profiling	23224 ± 21
Fit	23226 ± 20

We do not extract simultaneously $sin^2\theta^{\ell}_{eff}$ and the PDFs with the fit since no parametrization scan is performed

The central values of $sin^2\theta^{\ell}_{eff}$ are off with respect to modern PDFs but the HERAPDF parameterization is the easiest to be directly implemented in a PDF fit

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xFitter Profiling Results

NNPDF and MSHT assume $s > \bar{s}$

They give a smaller value of $sin^2\theta^\ell_{eff}$ by ~0.00024 and have a smaller uncertainty with respect to CT18Z

NNPDF does not use a tolerance

CT18As_LatNNLO assumes $s > \bar{s}$

Gives a larger error bar of 0.00044 and a smaller value of $sin^2\theta^\ell_{eff}$ by 0.00039

	PDF	χ^2_{min}	$\sin^2\theta^\ell_{eff}$
$s > \bar{s}$	NNPDF31_nnlo_as_0118_hessian	58.6	23120 ± 29
$s > \bar{s}$	NNPDF40_nnlo_as_01180_hessian	62.6	23133 ± 24
$s > \bar{s}$	MSHT20nnlo_as118	70.5	23119 ± 31
$s = \bar{s}$	CT18NNLO	62.2	23167 ± 37
$s = \bar{s}$	CT18ZNNLO	62.3	23153 ± 32
$s = \bar{s}$	CT18ANNLO	63.9	23166 ± 28
$s = \bar{s}$	CT18XNNLO	62.0	23174 ± 30
$s > \bar{s}$	NNPDF40_nnlo_as_01180_mhou	60.1	23114 ± 27
$s > \bar{s}$	NNPDF40_an3lo_as_01180_mhou	61.1	23123 ± 25
$s > \bar{s}$	MSHT20qed_an3lo	65.6	23140 ± 31
$s > \bar{s}$	NNPDF40_an3lo_as_01180	61.2	23136 ± 25
$s = \bar{s}$	HERAPDF20_NNLO_EIG	114.8	23218 ± 22
$s = \bar{s}$	ABMP16_5_nnlo	57.1	23084 ± 25
$s = \bar{s}$	PDF4LHC21_40	59.5	23135 ± 33
$s > \bar{s}$	CT18As_LatNNLO	61.5	23114 ± 44

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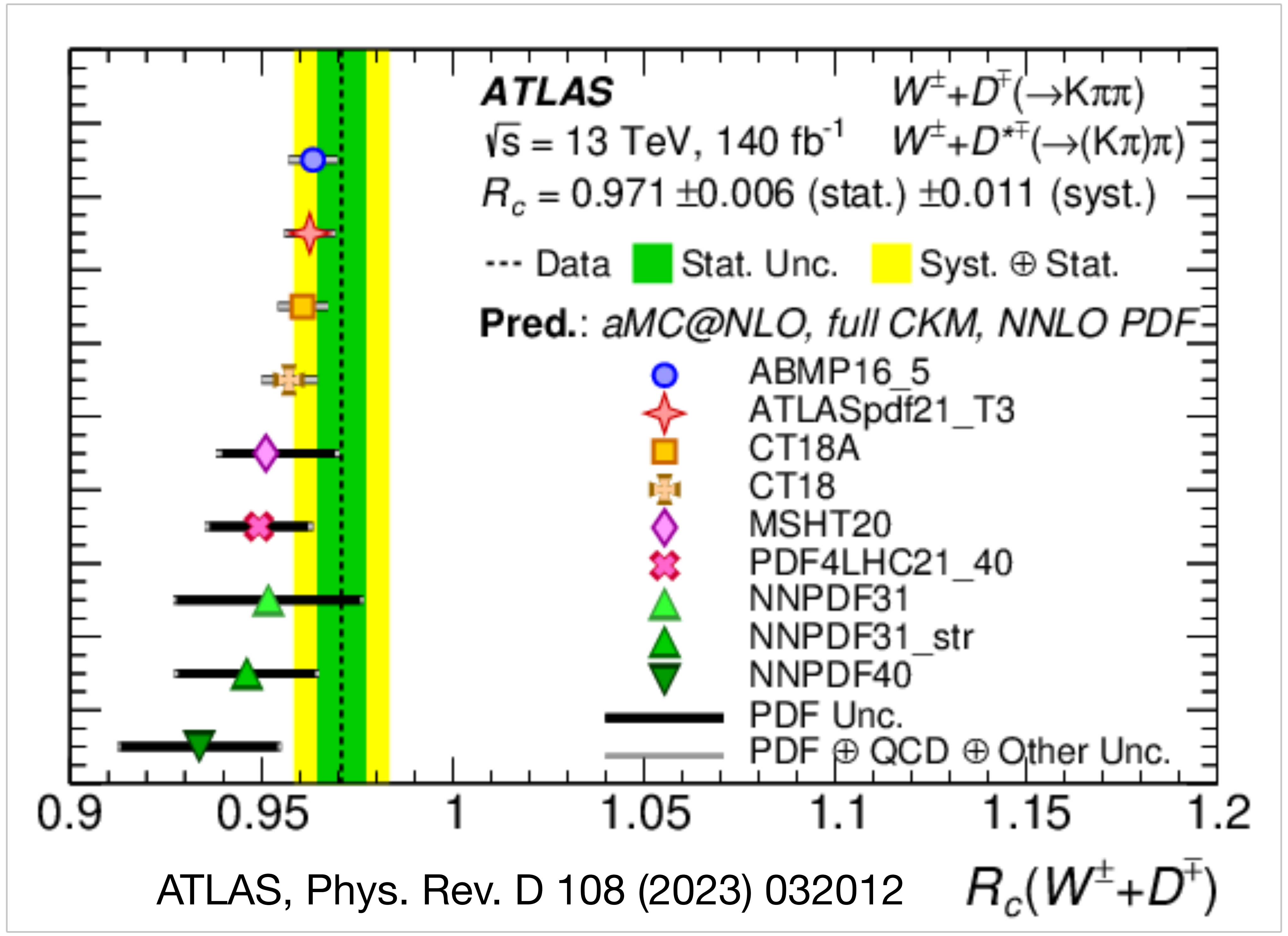
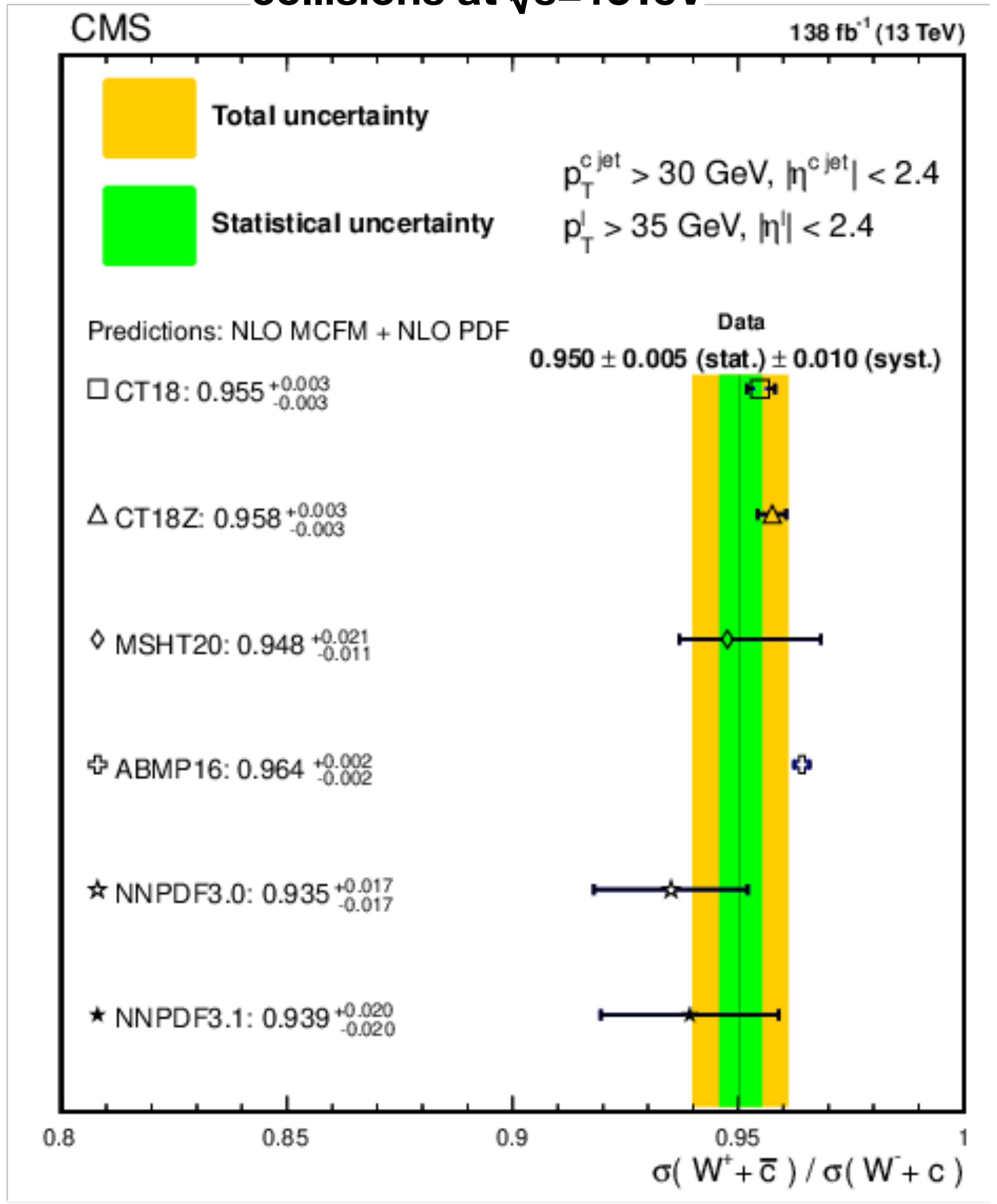
Ratio of s and $\bar{s}$ at LHC energies

Measurement of the production of a W boson in association with a charmed hadron in pp collisions at √s=13TeV with the ATLAS detector



ATLAS, Phys. Rev. D 108 (2023) 032012

Measurement of the production cross section for a W boson in association with a charm quark in proton–proton collisions at √s=13TeV



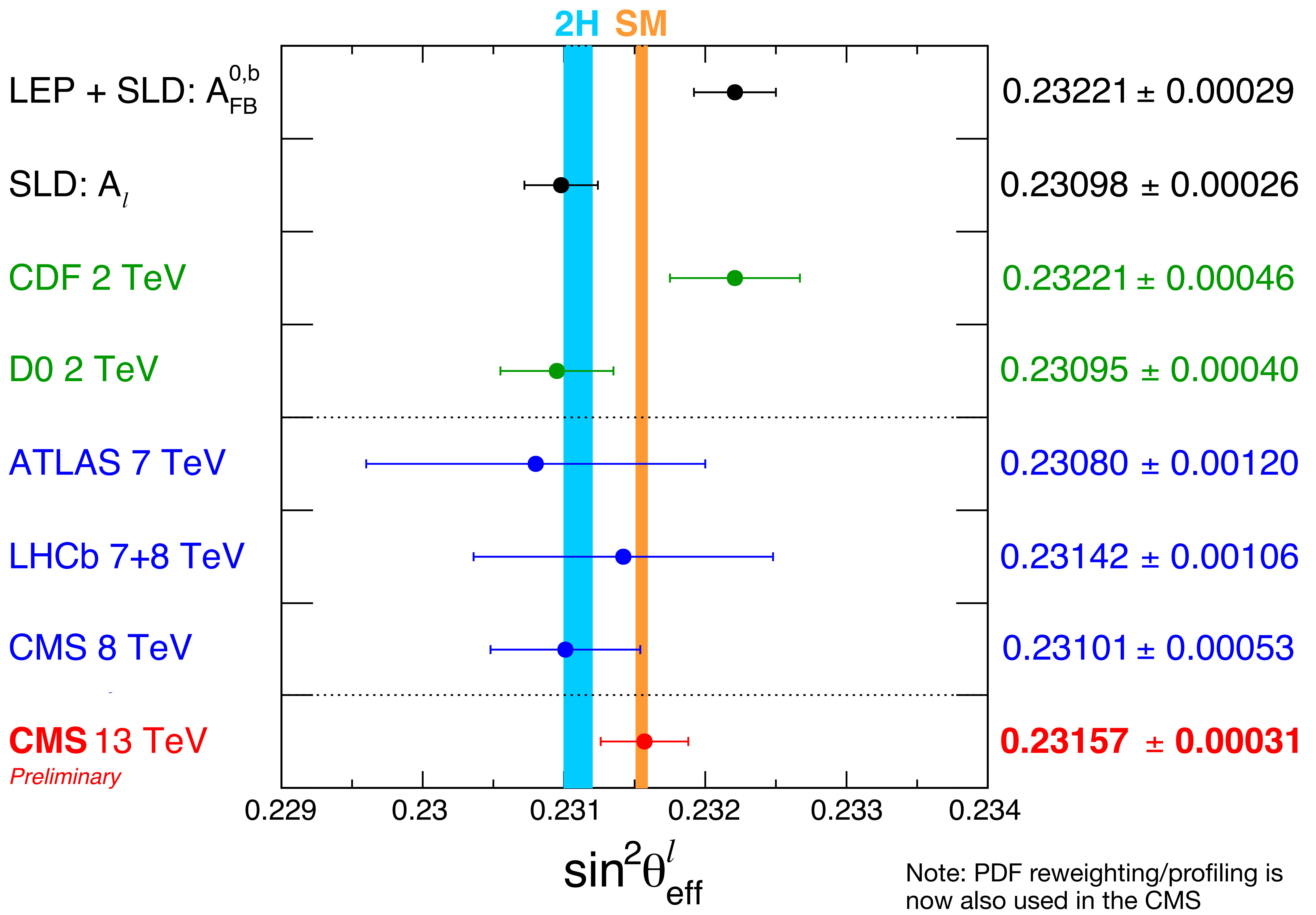
CMS, Eur. Phys. J. C 84 (2024) 27

Conclusion
A new era of Precision EW Measurements at the LHC

Further reduction in PDF errors is still needed to differentiate SM from the 2 Higgs Model

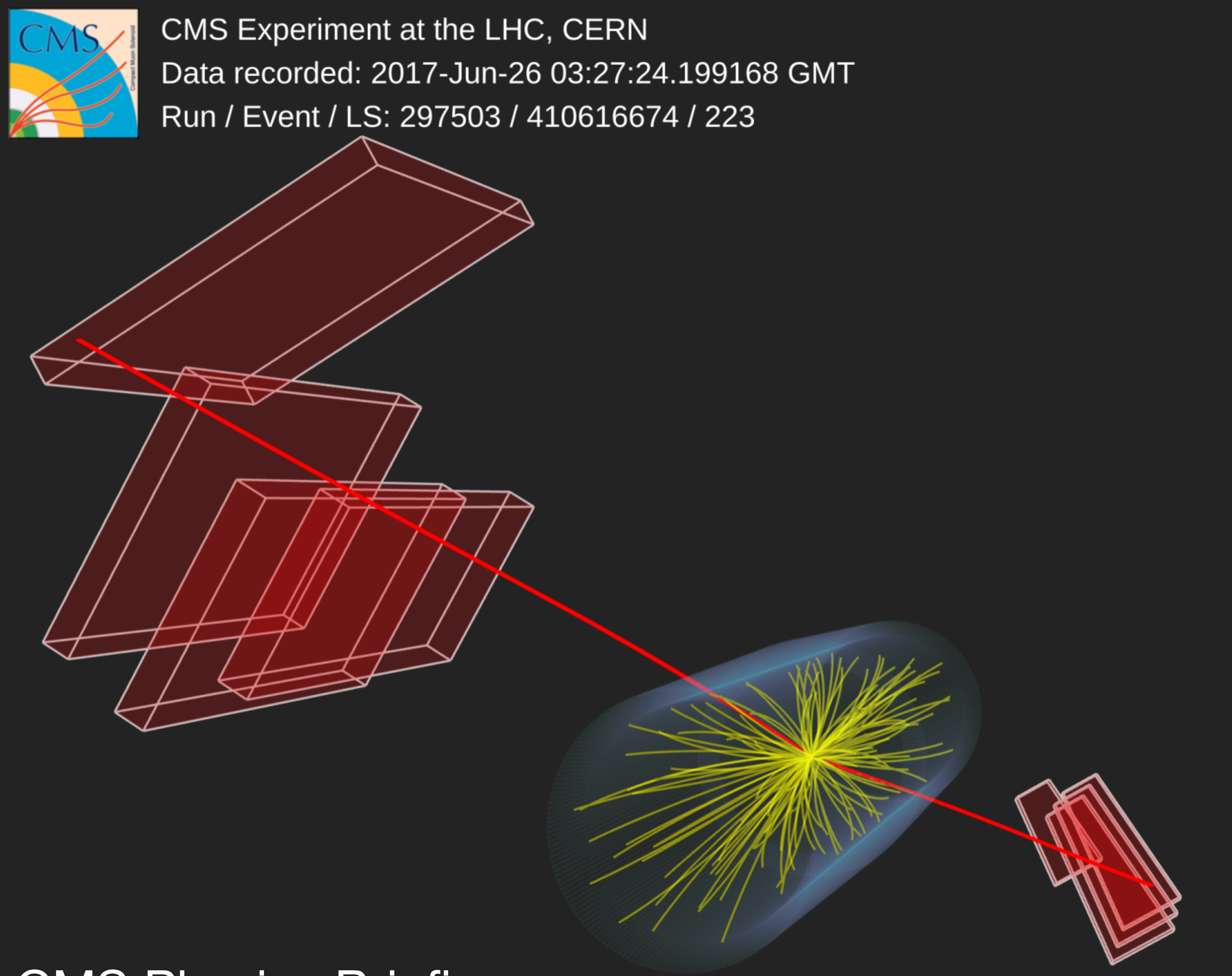
Future plans:
Using the unfolded A_4, an updated PDF reweighting/profiling analysis including W boson asymmetry will further reduce the PDF errors

PDF errors can also be reduced in a future combined analysis of A_4 measurements with ATLAS and LHCb



Note: PDF reweighting/profiling is now also used in the CMS measurement of m_W

Thank You



[CMS Physics Briefing]

Angular Coefficients

Full differential cross section

$$\frac{d\sigma}{dp_T^{\ell\ell}\, dy^{\ell\ell}\, dm^{\ell\ell}\, d\cos\theta\, d\phi} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_T^{\ell\ell}\, dy^{\ell\ell}\, dm^{\ell\ell}}$$

$$\Big\{(1+\cos^2\theta) + \frac{1}{2} A_0 (1 - 3\cos^2\theta) + A_1 \sin 2\theta \cos\phi$$

$$+ \frac{1}{2} A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta \cos\phi + A_4 \cos\theta$$

$$+ A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi \Big\}.$$

Integrating over ϕ

$$\frac{d\sigma}{d(\cos\theta^*)} \propto 1 + \cos^2\theta^* + A_4 \cos\theta^*,$$

PDF uncertainties

PDF groups provide a default (central) PDF set. There are two methods that are used for the determination of PDF uncertainties.

1. (Hessian method) Provide a set of eigenvector error PDFs. The PDF uncertainties in a measurement are determined by repeating the analysis for all of the error PDF sets, and adding in quadrature the difference in the results obtained with the error PDFs and the results obtained with the default PDF.

2. (replica PDFs methods) is to provide a set of N (e.g. 100 or 1000) replica PDFs. Each of the PDF replicas has equal probability of being correct. The central value of any observable is the average of the values extracted with each one of the N PDF replicas. The PDF uncertainty is the rms of the values extracted using all N replicas.

xFitter results plotted

PDF	χ^2_{min}	$\sin^2\theta^{\ell}_{eff}$	
NNPDF31_nnlo_as_0118_hessian	58.6	23120 ± 29	$s > \bar{s}$
NNPDF40_nnlo_as_01180_hessian	62.6	23133 ± 24	$s > \bar{s}$
MSHT20nnlo_as118	70.5	23119 ± 31	$s > \bar{s}$
CT18NNLO	62.2	23167 ± 37	$s = \bar{s}$
CT18ZNNLO	62.3	23153 ± 32	$s = \bar{s}$
CT18ANNLO	63.9	23166 ± 28	$s = \bar{s}$
CT18XNNLO	62.0	23174 ± 30	$s = \bar{s}$
NNPDF40_nnlo_as_01180_mhou	60.1	23114 ± 27	$s > \bar{s}$
NNPDF40_an3lo_as_01180_mhou	61.1	23123 ± 25	$s > \bar{s}$
MSHT20qed_an3lo	65.6	23140 ± 31	$s > \bar{s}$
NNPDF40_an3lo_as_01180	61.2	23136 ± 25	$s > \bar{s}$
HERAPDF20_NNLO_EIG	114.8	23218 ± 22	$s = \bar{s}$
ABMP16_5_nnlo	57.1	23084 ± 25	$s = \bar{s}$
PDF4LHC21_40	59.5	23135 ± 33	$s = \bar{s}$
CT18As_LatNNLO	61.5	23114 ± 44	$s > \bar{s}$

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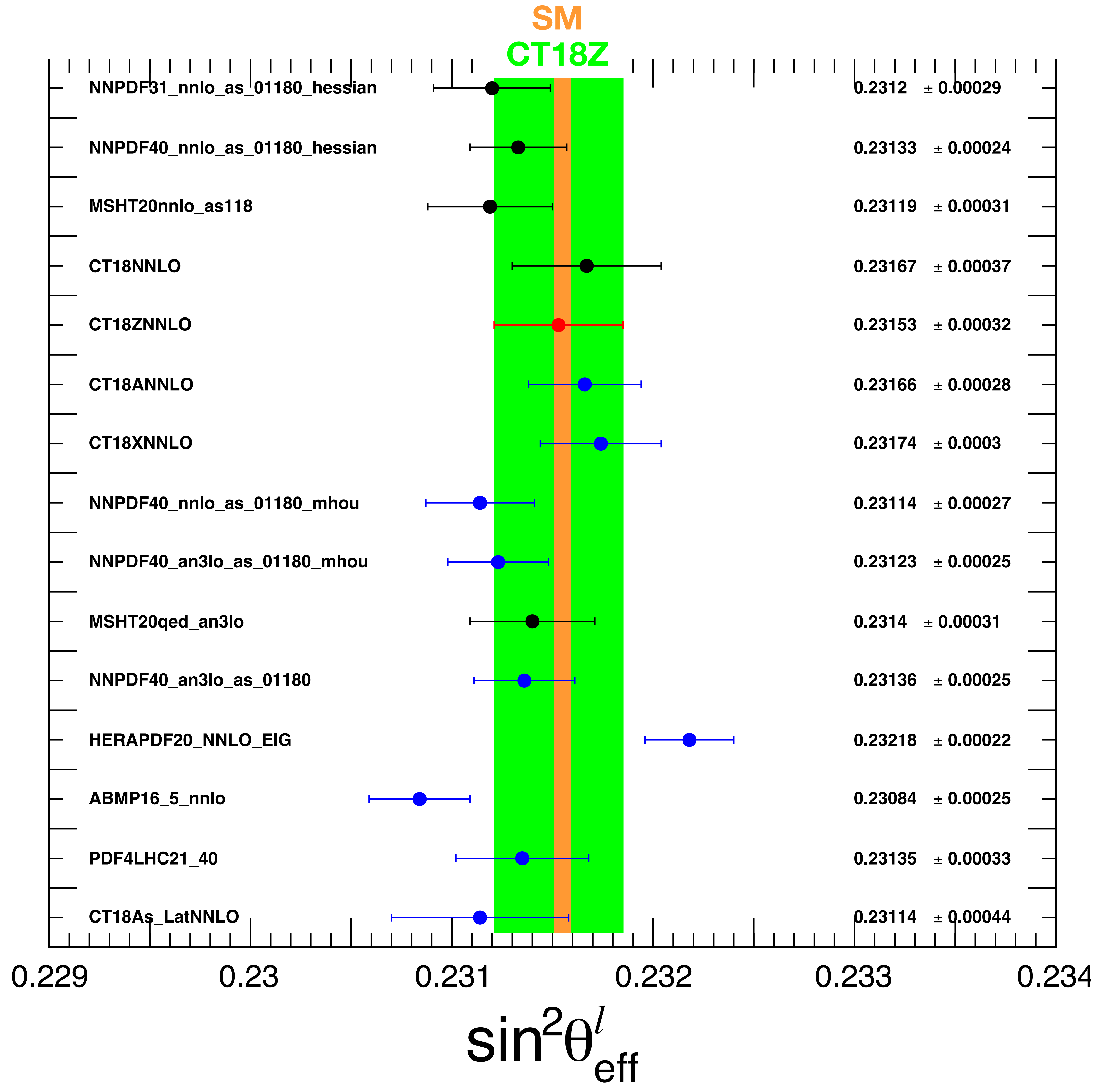
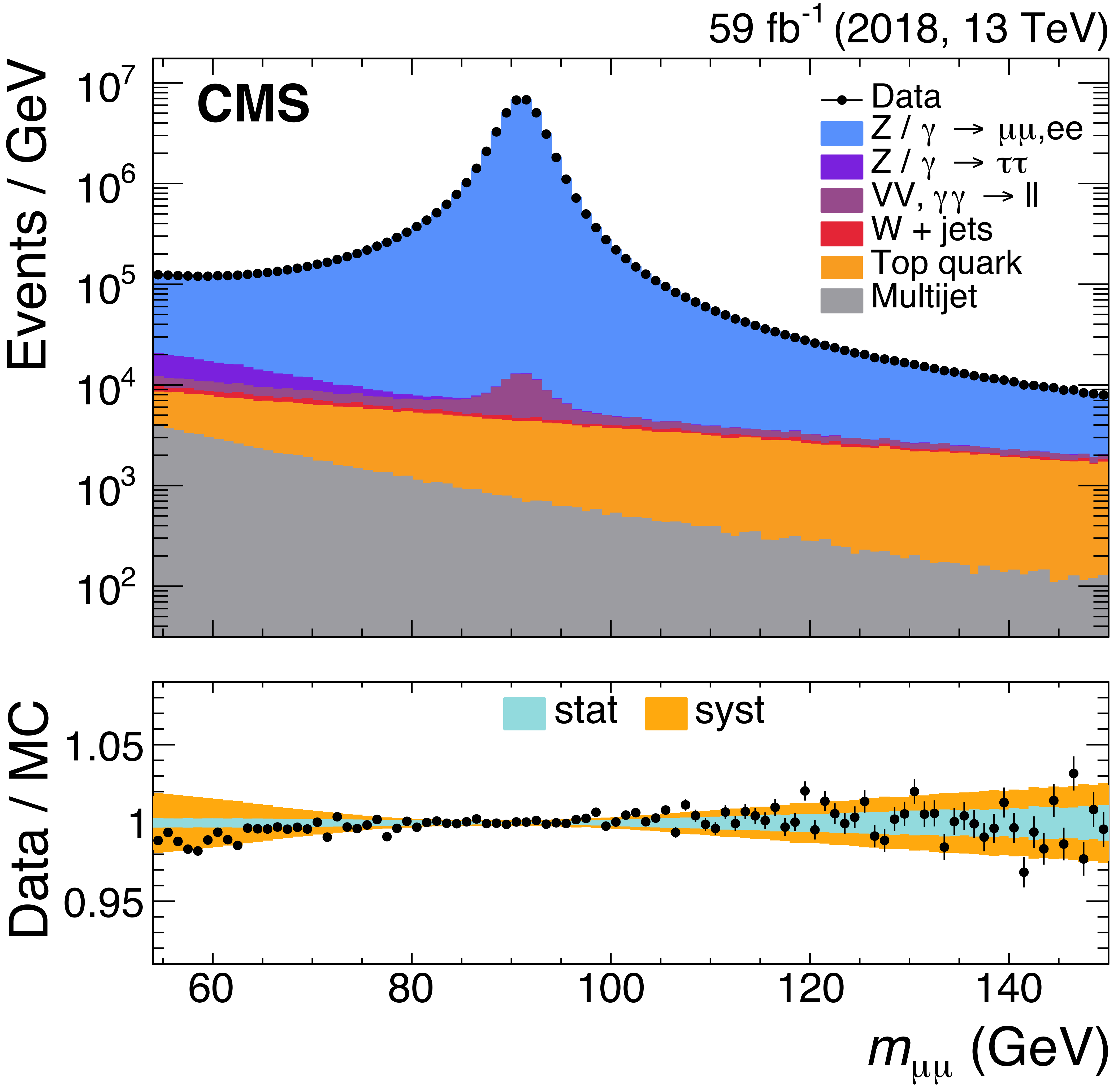
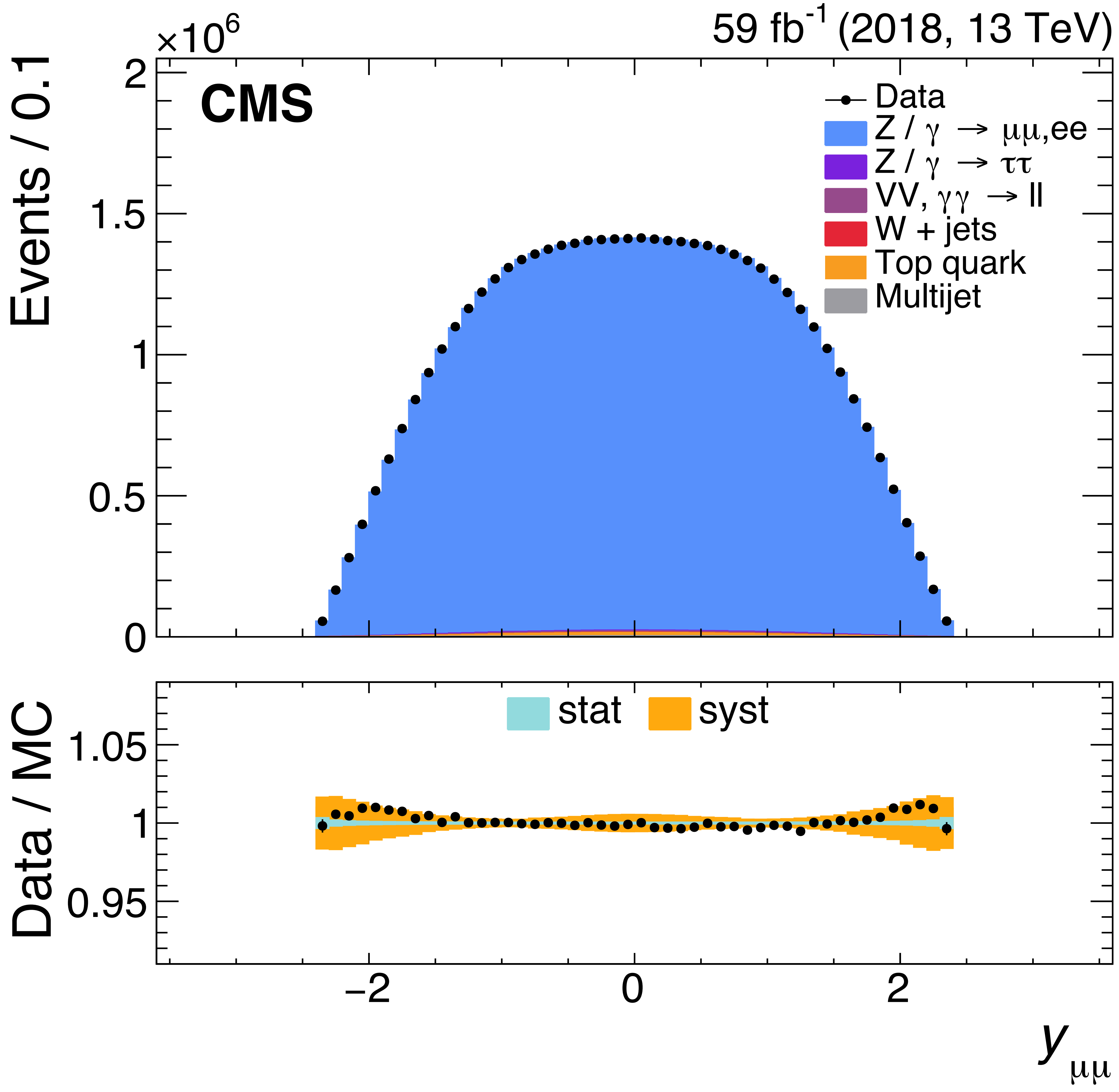
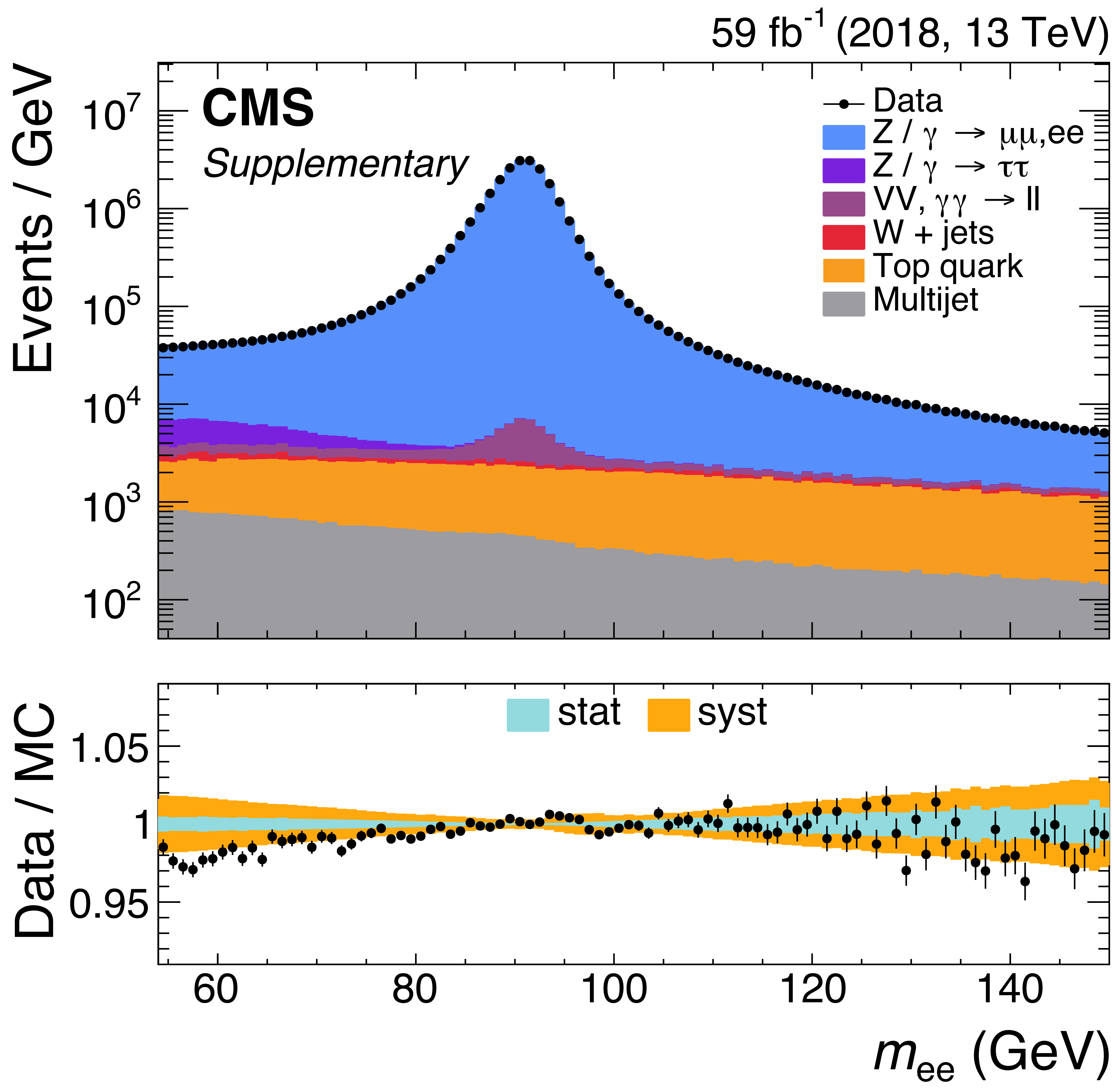


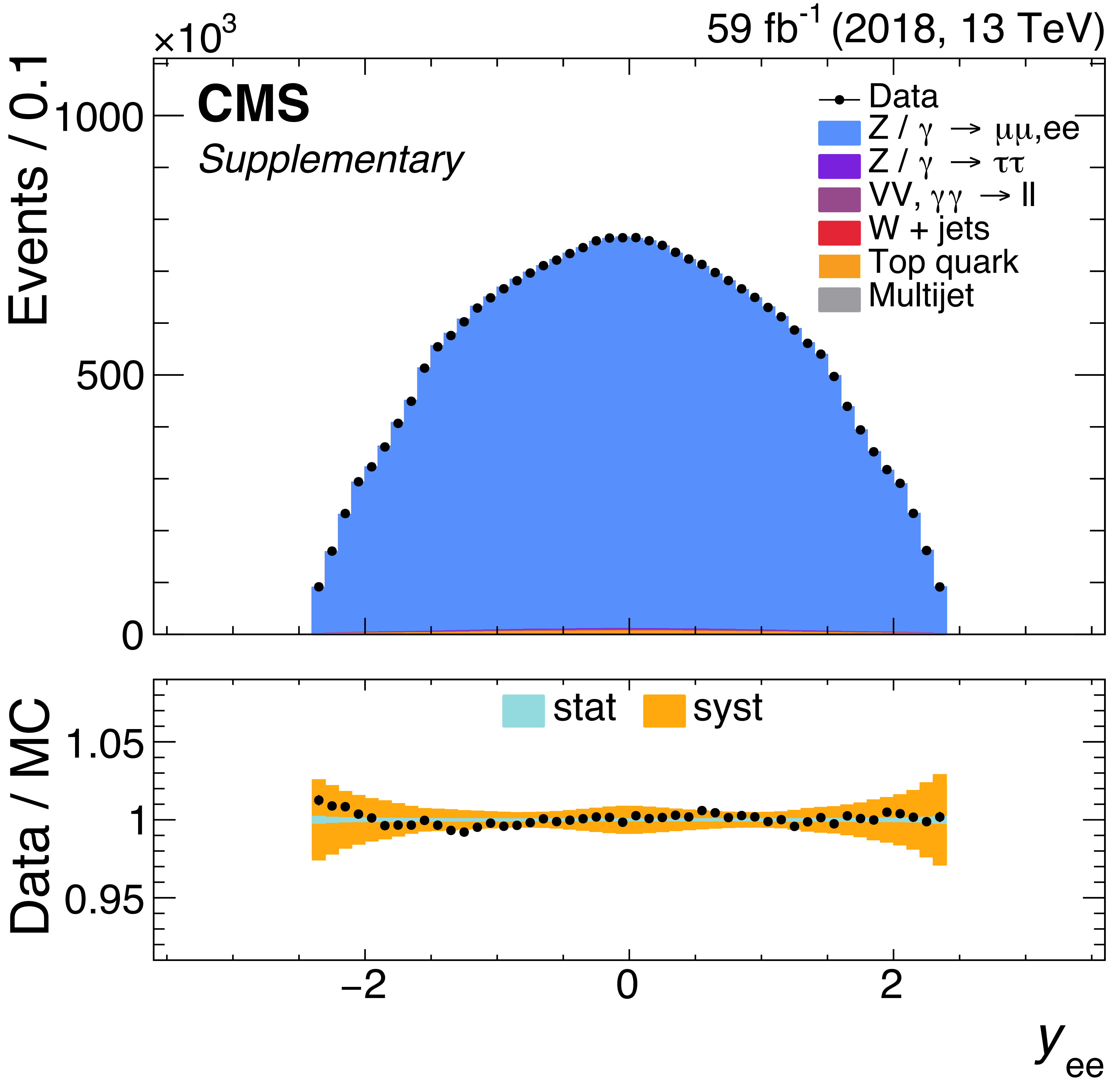
$\mu\mu$ mass and rapidity



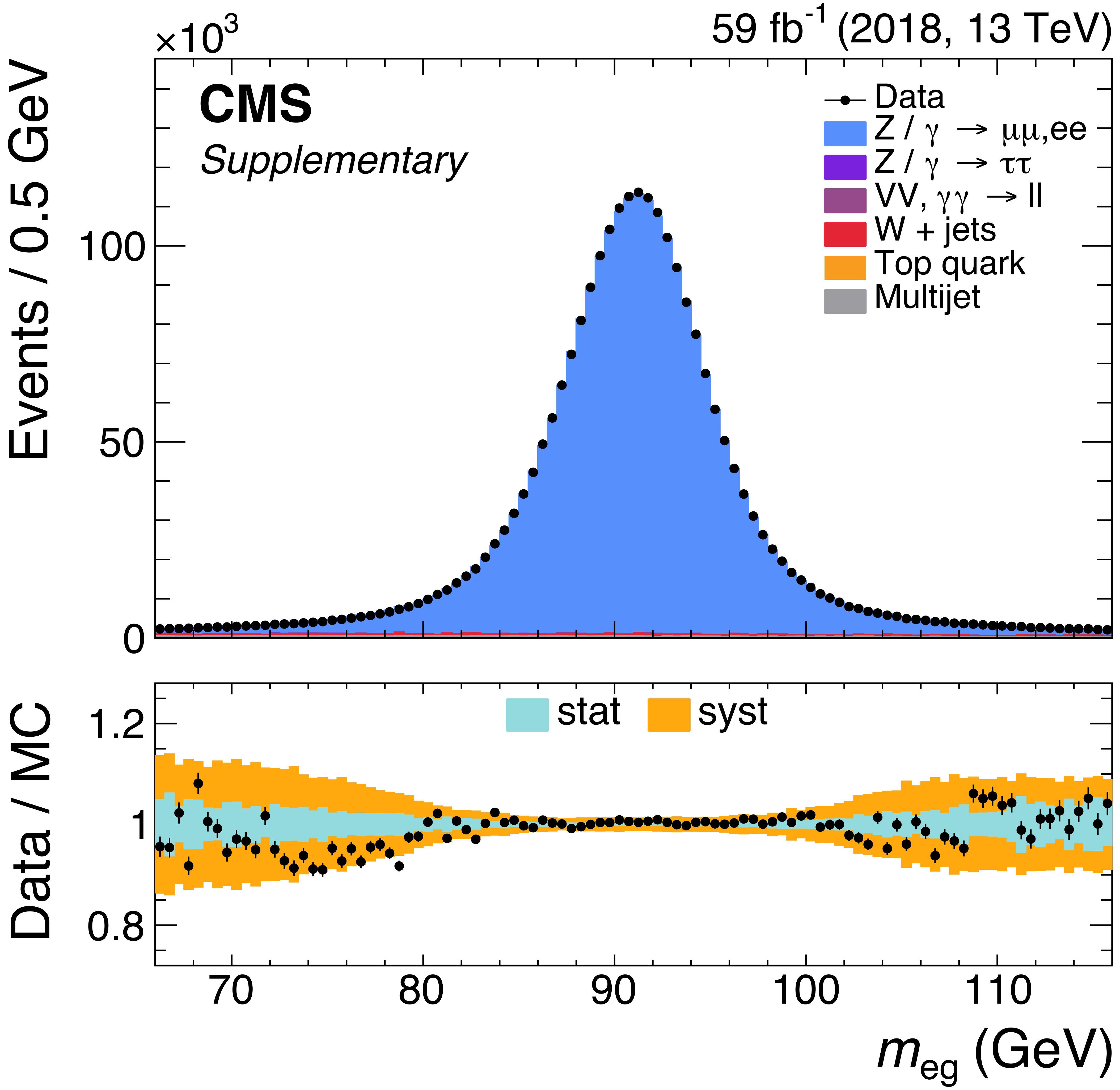


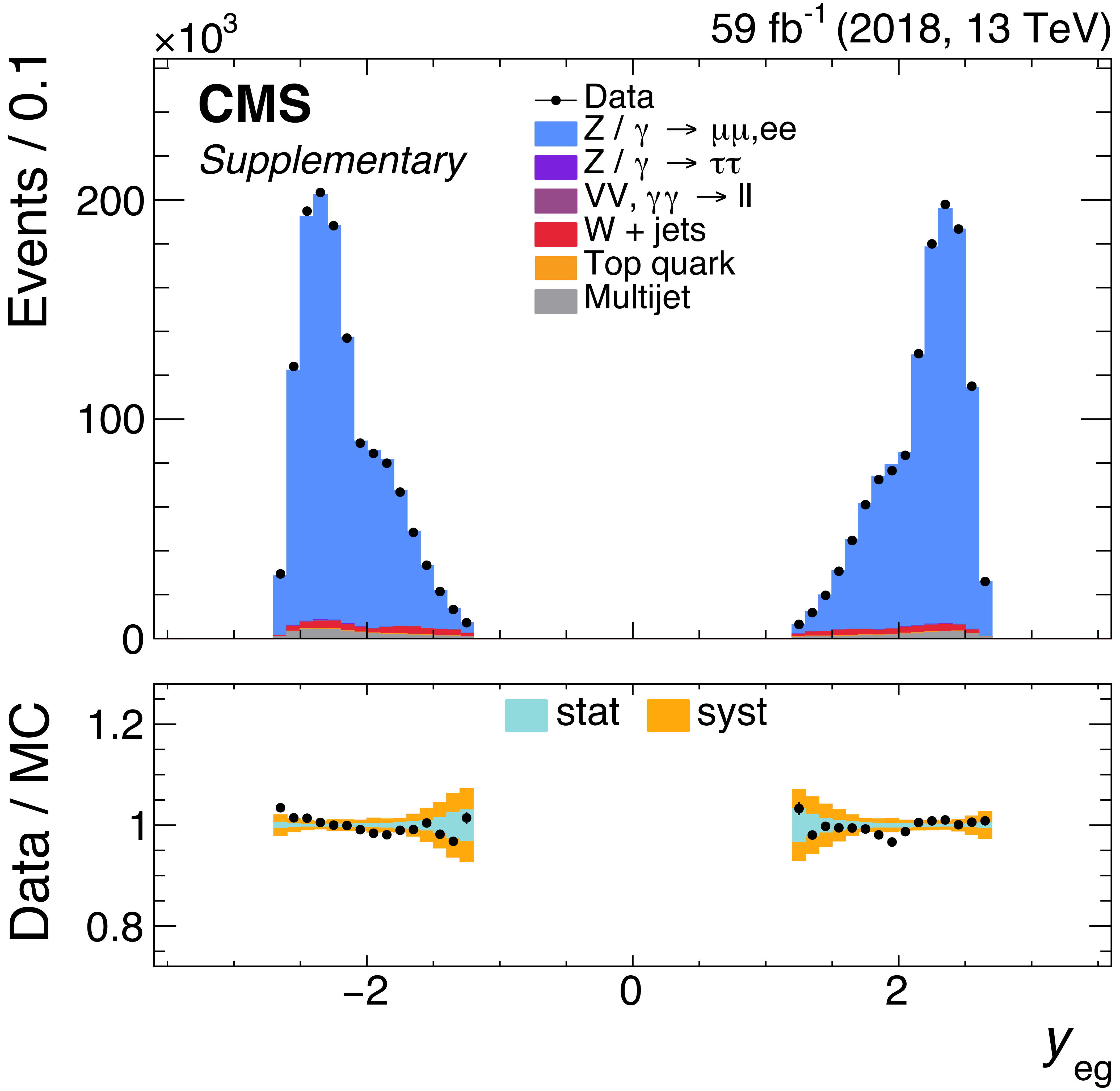
ee mass and rapidity





eg mass and rapidity





eh mass and rapidity