A CMS measurement of the effective leptonic weak mixing angle in pp collisions at $\sqrt{s} = 13$ TeV

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EW precision measurements

- With the Higgs mass m_h known, the EW sector of the SM is overconstrained
- The three best measured parameters ($\alpha(0)$ scheme) are related through:

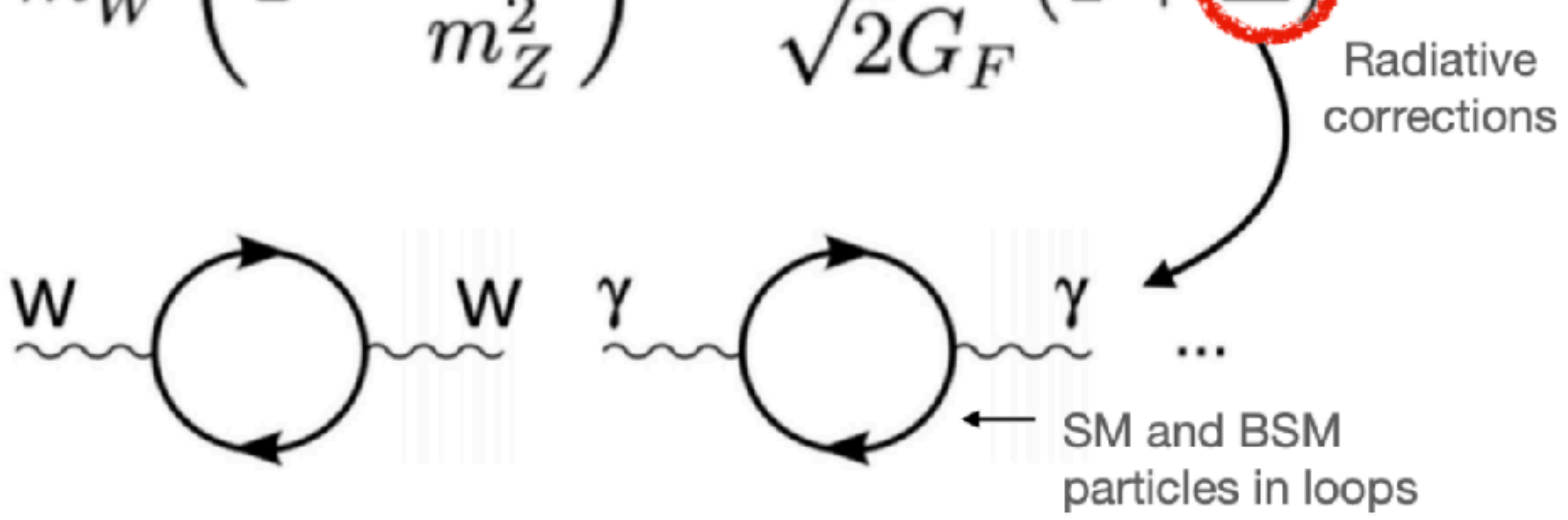
$$\begin{aligned} \alpha &= 1/137.035999139(31) \\ G_F &= 1.1663787(6) \times 10^{-5}\ \mathrm{GeV}^{-2} \\ m_Z &= 91.1876(21)\ \mathrm{GeV} \end{aligned}$$

→ at leading order

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha(0)}{\sqrt{2}G_F}$$

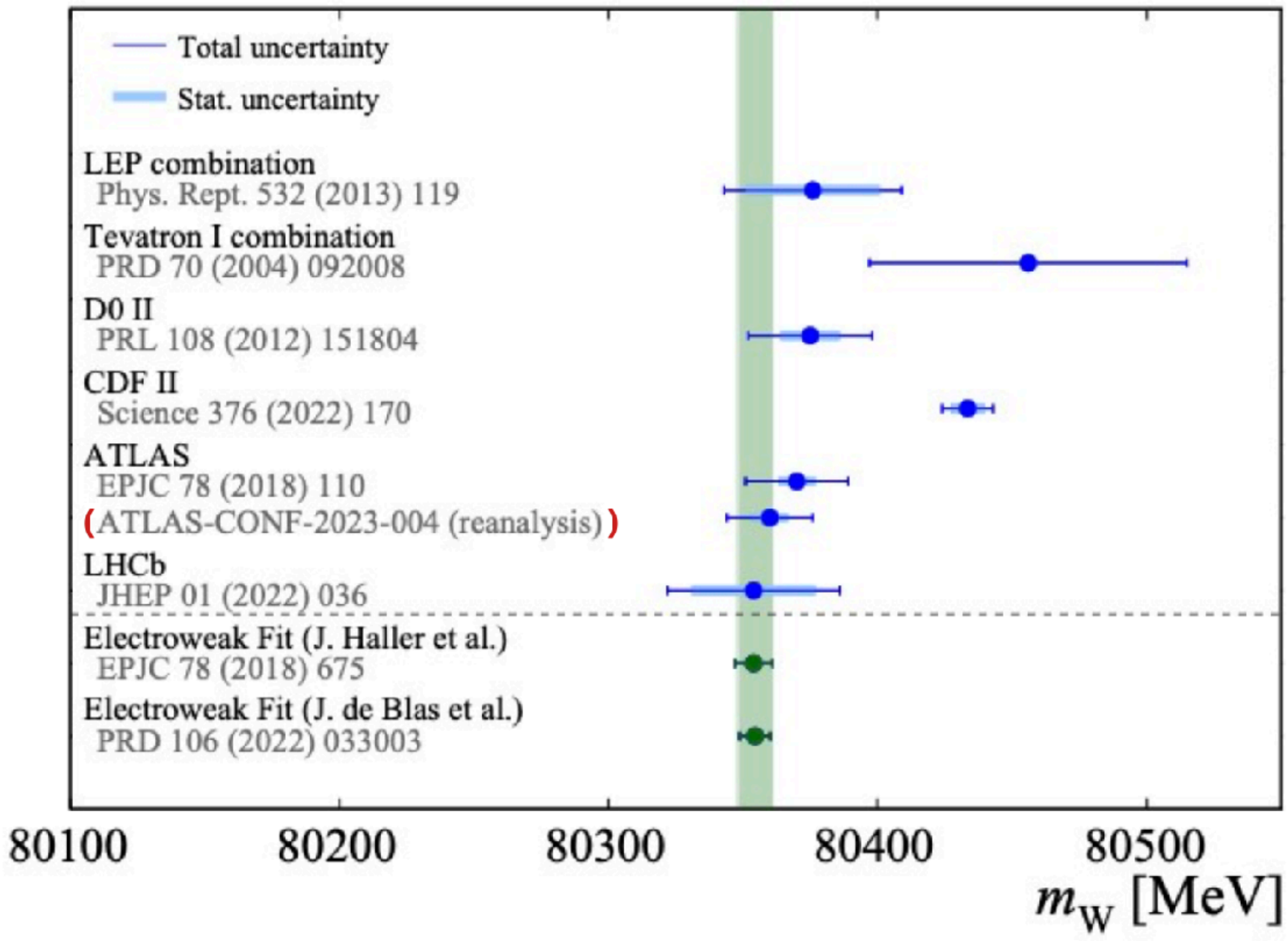
- Higher order corrections modify these relations:

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



- Measuring one observable one can predict another
- Measuring more allows internal consistency checks of the SM
- Test new physics in EW loops

EW precision measurements - M_W



- Extremely challenging at hadron colliders
- New CDF measurement achieves 9 MeV uncertainty
  - in tension with other experiments and the SM
- ATLAS 7 TeV re-analysis reaches 16 MeV uncertainty

The electroweak mixing angle

For bare quantities:

$$\sin\theta_w = \frac{e}{g_2} = \frac{g_1}{\sqrt{g_1^2 + g_2^2}}$$

MSbar (running)

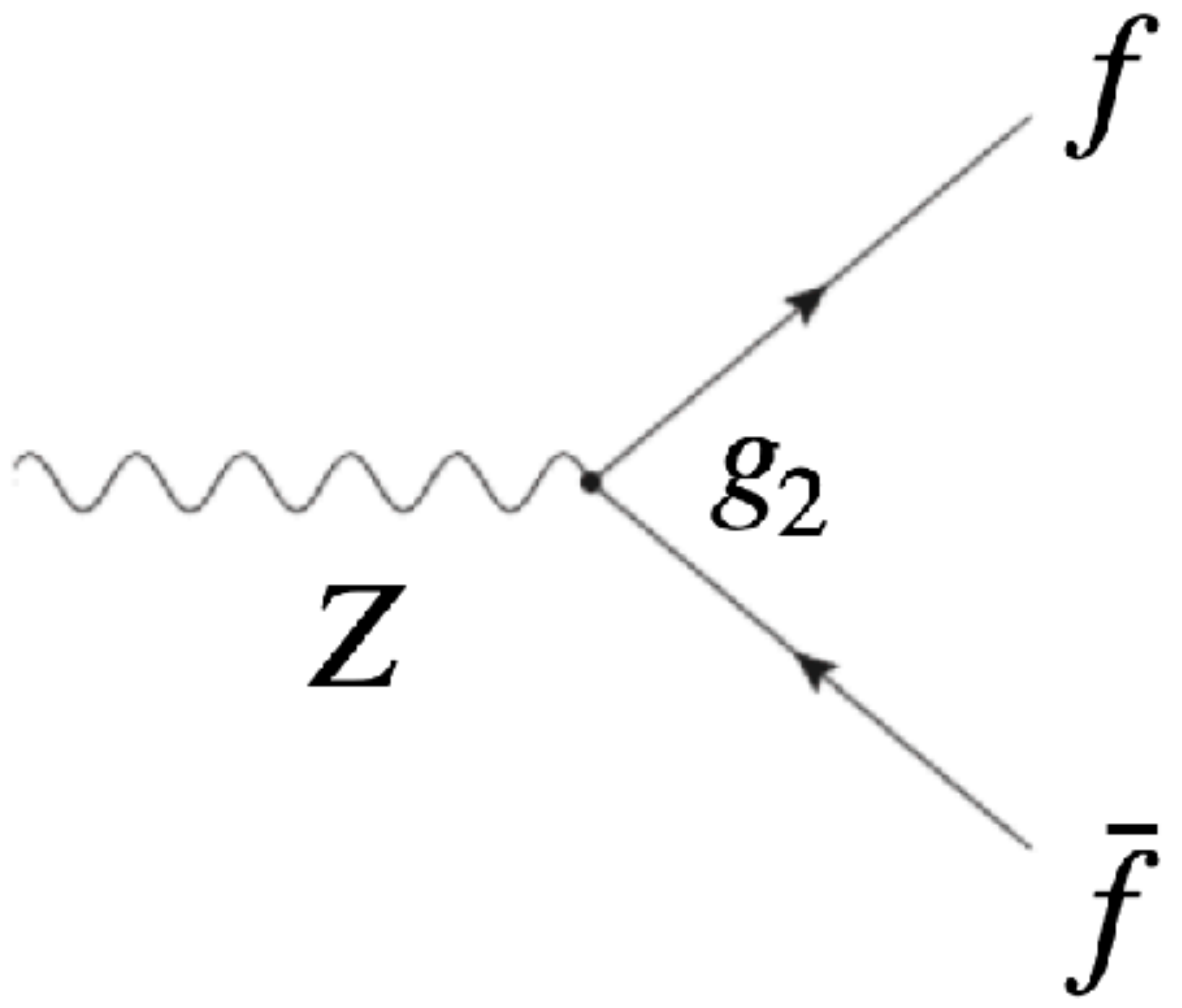
$$\sin\theta_w^{\overline{MS}}(\mu) = \frac{e^{\overline{MS}}(\mu)}{g_2^{\overline{MS}}(\mu)}$$

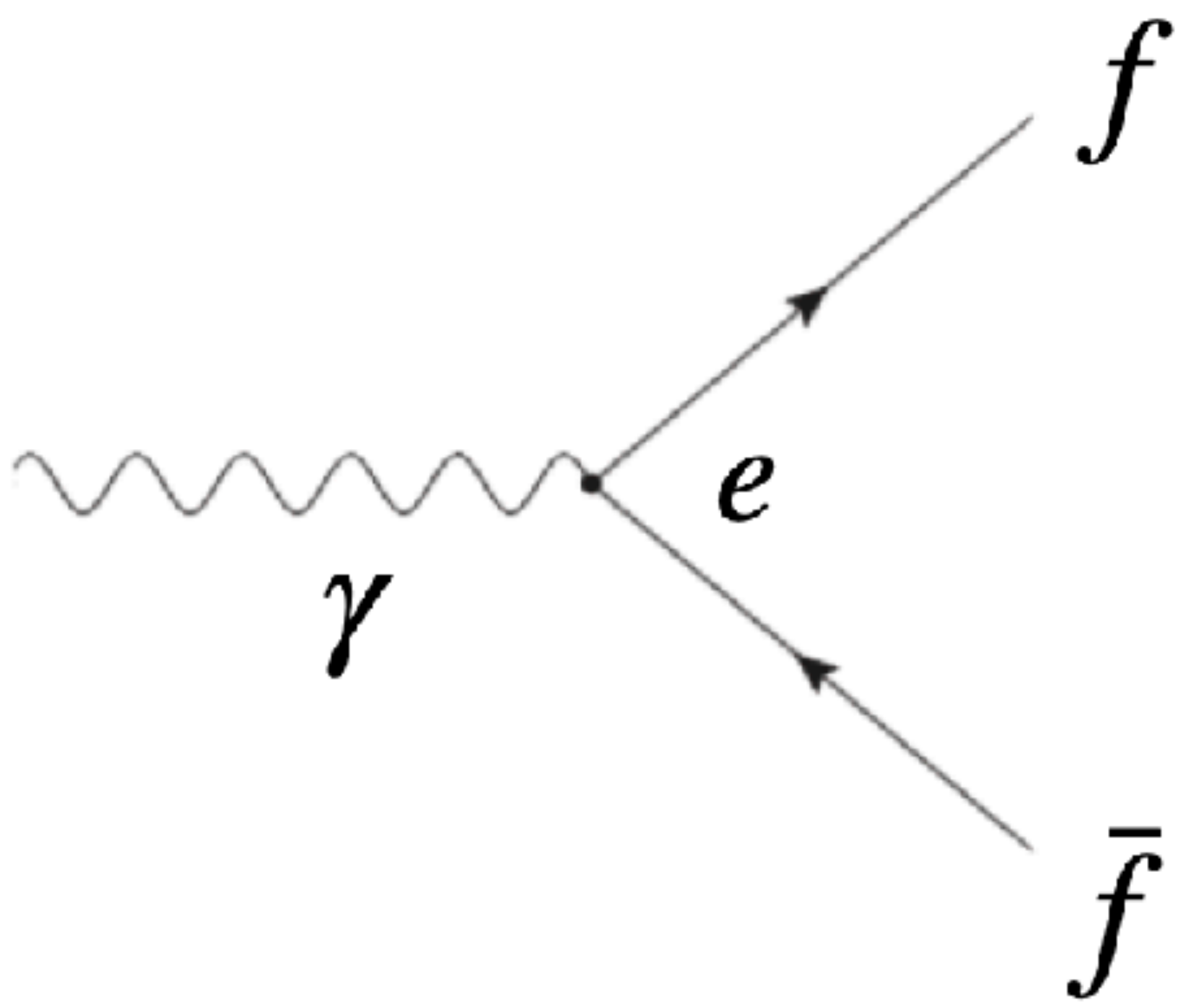
On-shell

$$\sin^2\theta_{OS} = 1 - \frac{M_W^2}{M_Z^2}$$

Effective weak mixing angle

$$\sin^2\theta_{eff} = \frac{1}{4|Q|}\left(1 - \frac{g_V}{g_A}\right)$$

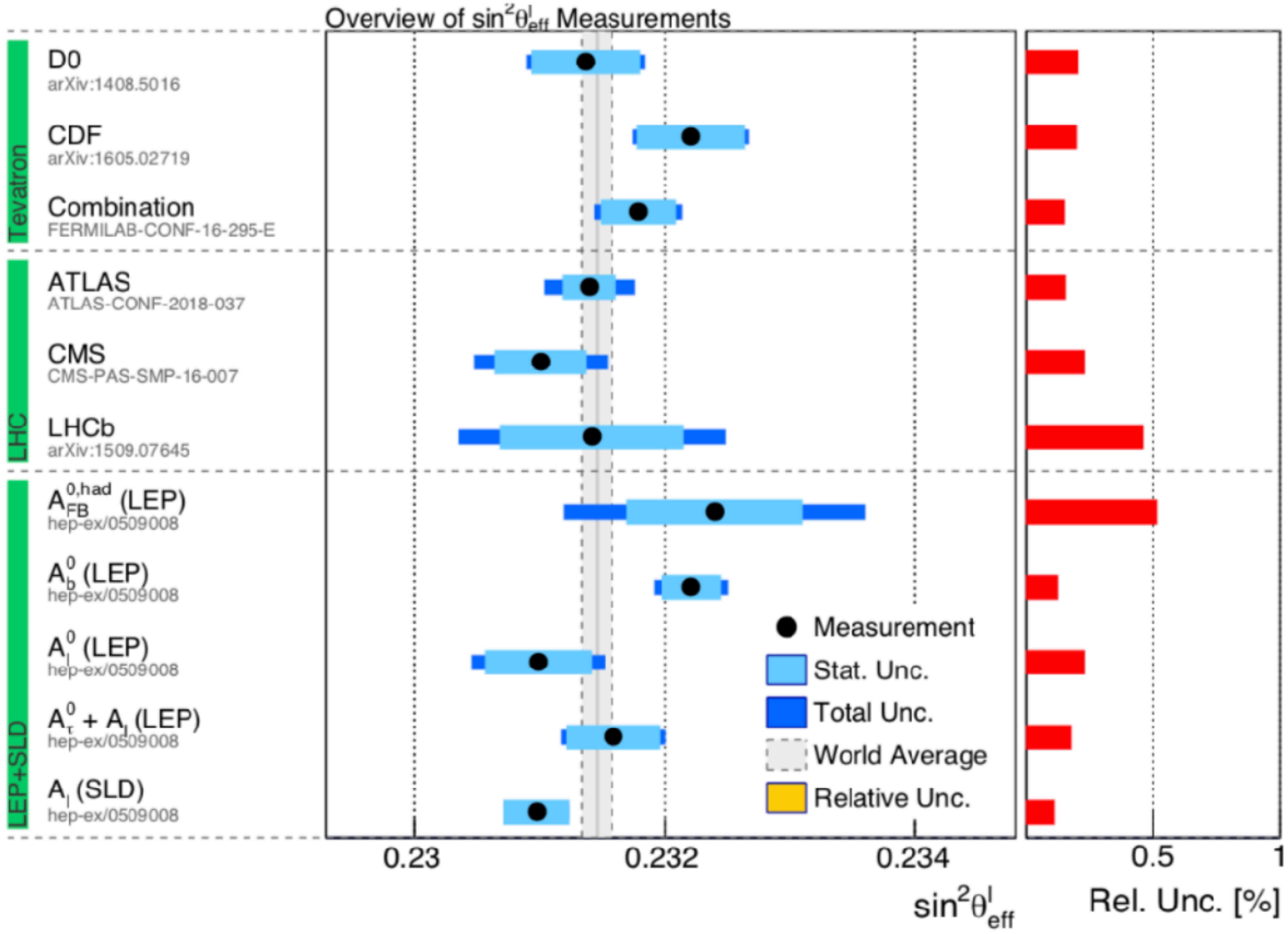




Scheme	Notation	Value	Uncertainty
On-shell	s_W^2	0.22339	±0.00010
$\overline{\text{MS}}$ Z pole	$\hat{s}_Z^2$	0.23122	±0.00004
$\overline{\text{MS}}$ $Q^2 = 0$	$\hat{s}_0^2$	0.23863	±0.00005
Effective angle	$\bar{s}_\ell^2$	0.23155	±0.00004

PDG 2022

EW precision measurements - $\sin^2\theta^l_{\rm eff}$



- World average precision of $\delta \sin^2\theta^l_{\rm eff} = 16 \cdot 10^{-5}$, still dominated by lepton colliders
- Discrepancy between LEP A_b^0 and SLD A_l source of much speculation in the past
- Results from the LHC Run-1 reached Tevatron precision

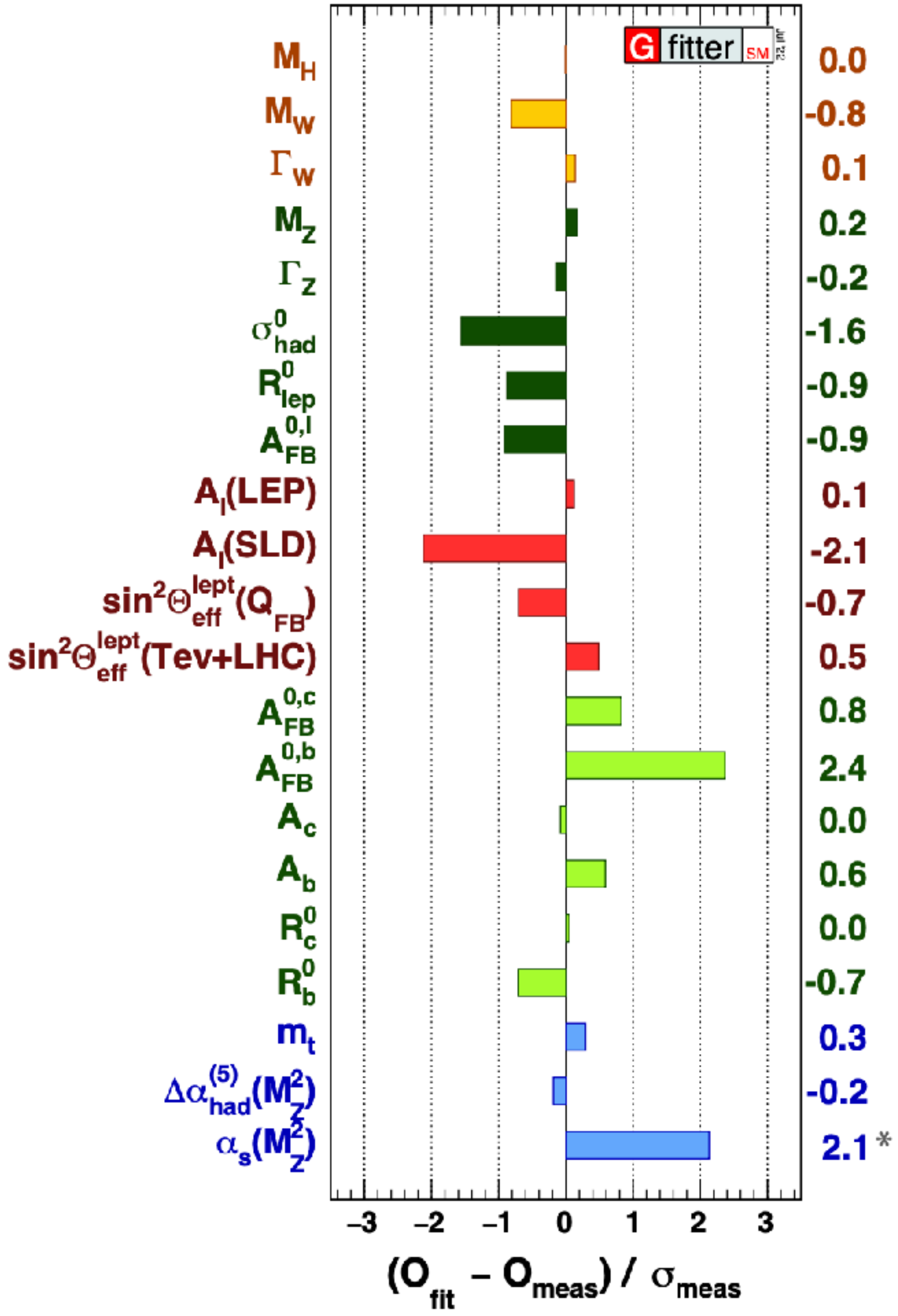
The global EW fit

- In the recent past, the global electroweak fit was used to predict the masses of the top quark and Higgs boson before their discovery
- Now, perform stringent test of the self consistency of the SM
- Relations between electroweak observables can be predicted now at 2-loop level
- A very good consistency observed

$$\chi^2_{min} / \mathrm{ndf} = 16.62 / 15$$

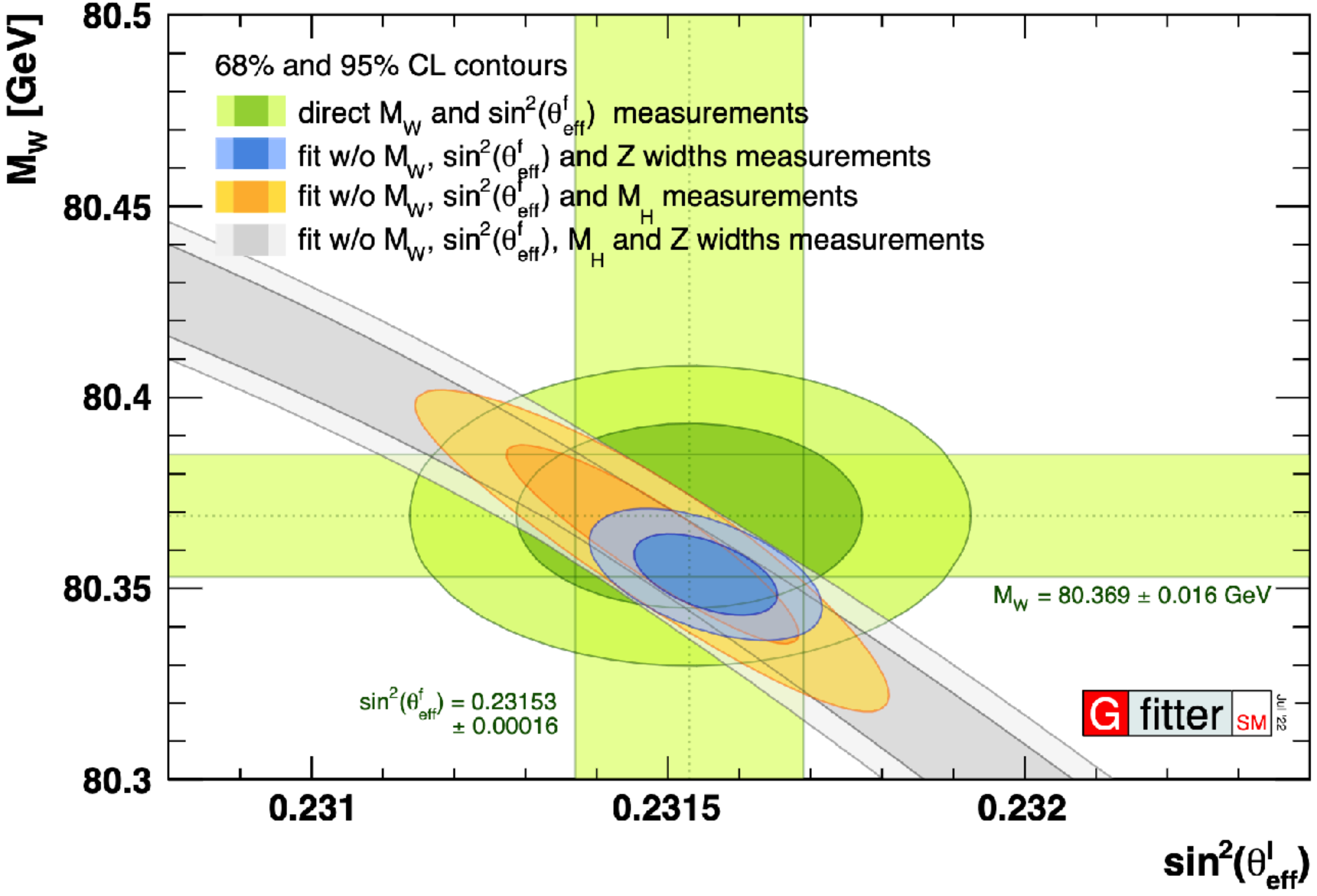
$$p \text{ value} = 0.34$$

Discarding the new CDF mW measurement



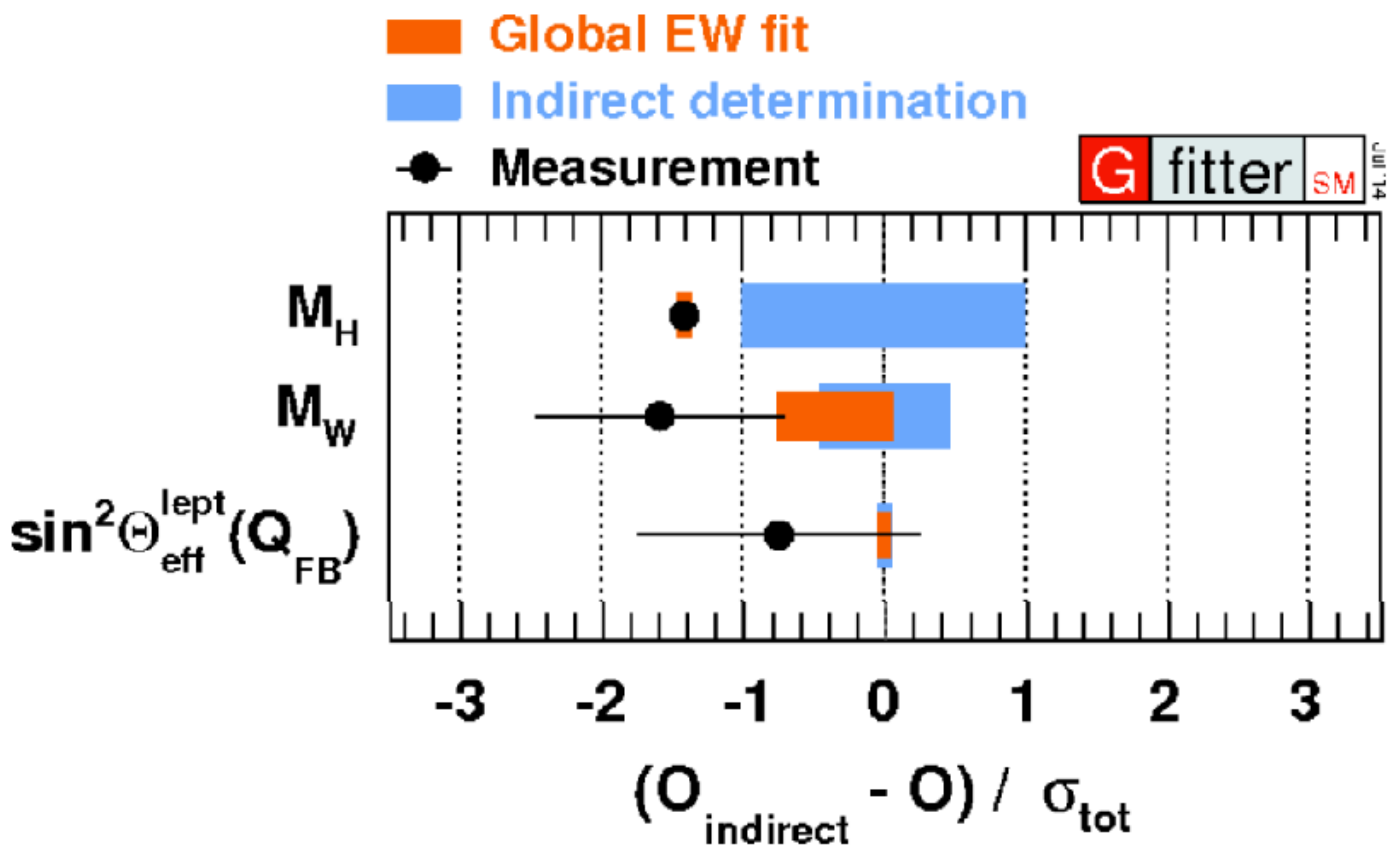
(*) comparison to PDG value, not included in fit as input parameter

The global EW fit



Precision targets

- Indirect determinations of m_W and $\sin^2\theta^l_{\text{eff}}$ are more precise than current experimental measurements



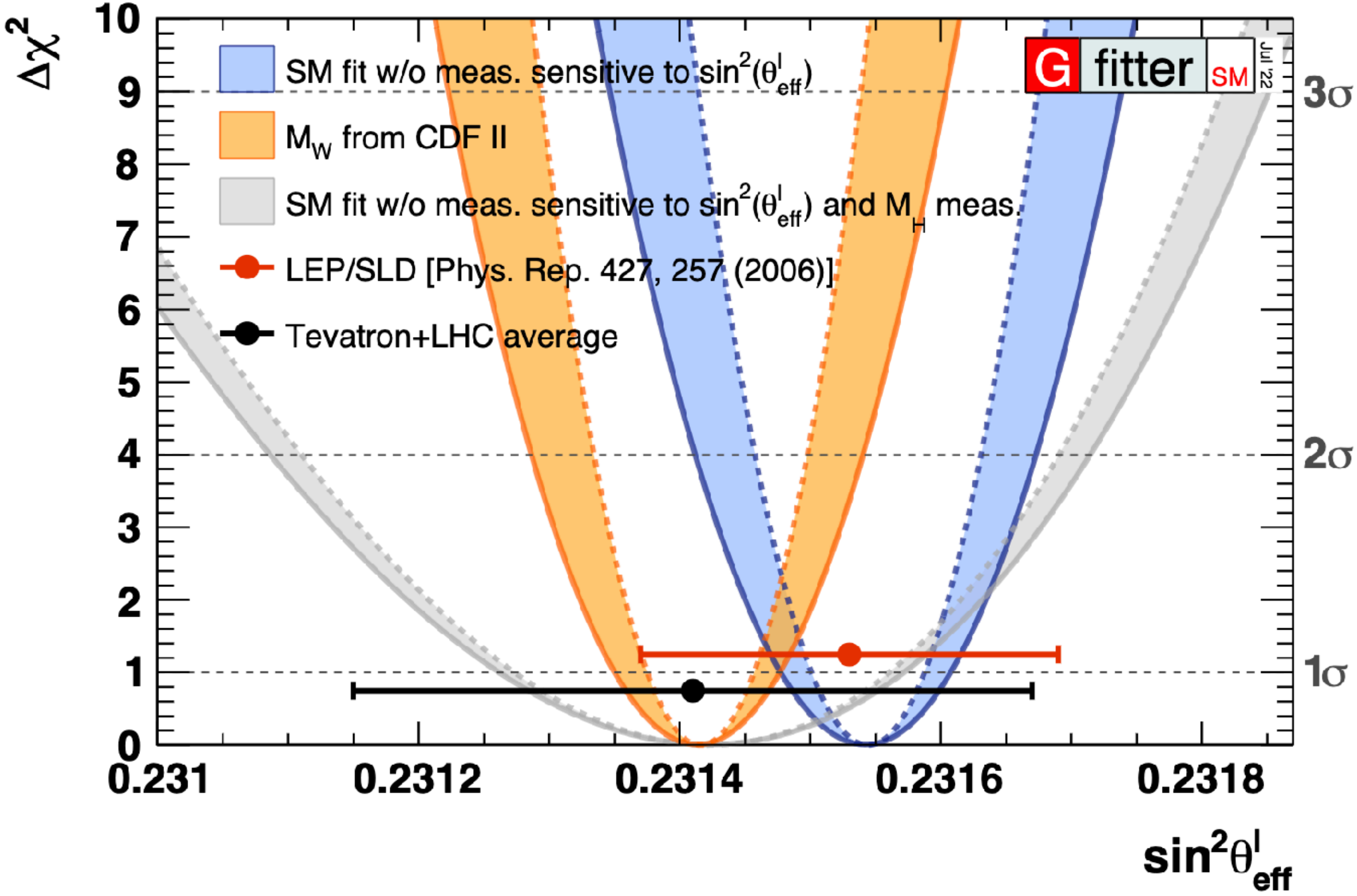
Indirect precision on:

$\delta m_W = 8$ MeV → Calls for measuring m_W with < 10 MeV precision

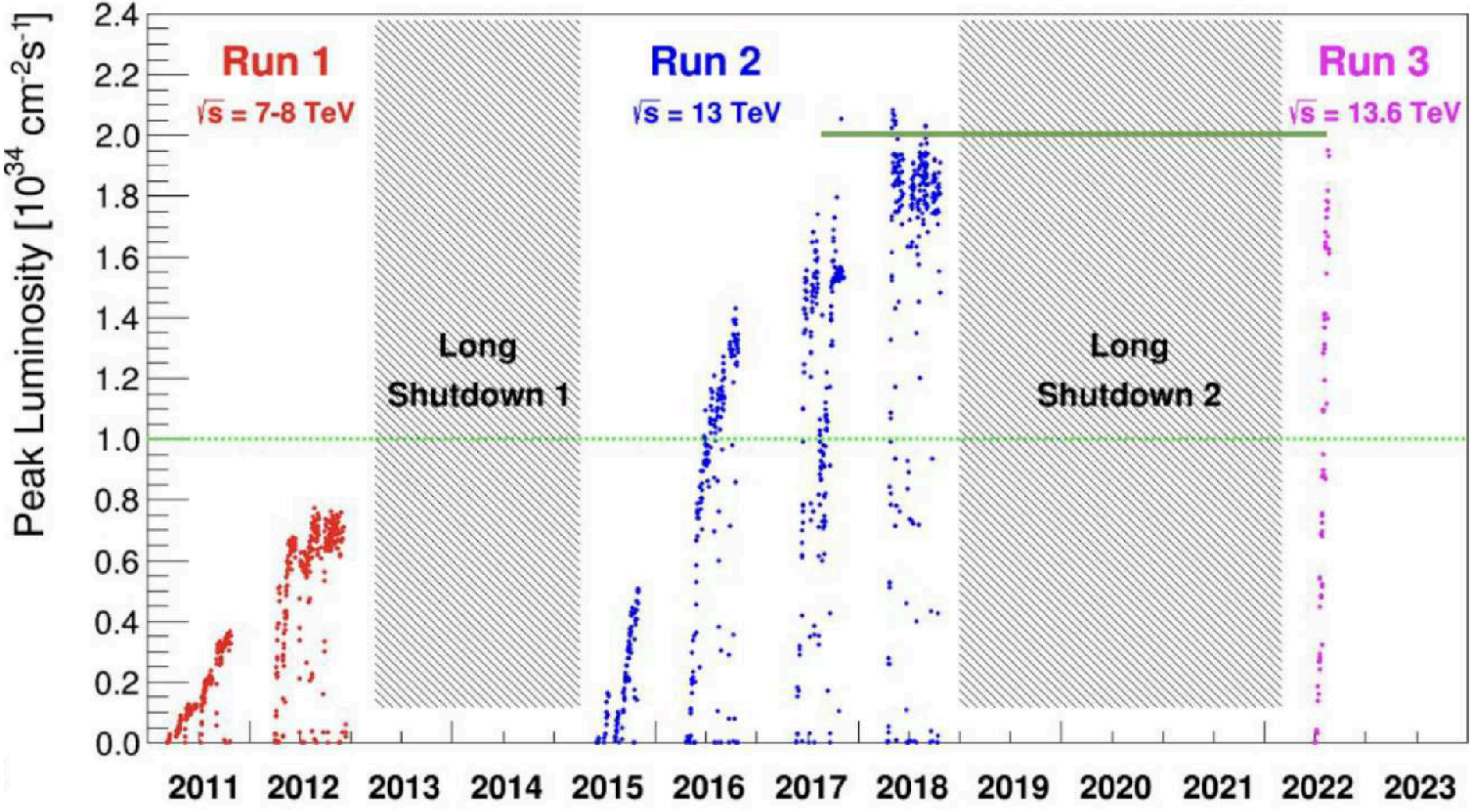
$\delta \sin^2\theta^l_{\text{eff}} = 6 \cdot 10^{-5}$ → $20 \cdot 10^{-5}$ precision on $\sin^2\theta^l_{\text{eff}}$ corresponds 10 MeV uncertainty in m_W

Can we achieve these level of precision at the LHC ?

$\sin^2\theta^l_{\rm eff}$ and the new CDF M_W



STATUS OF THE LHC

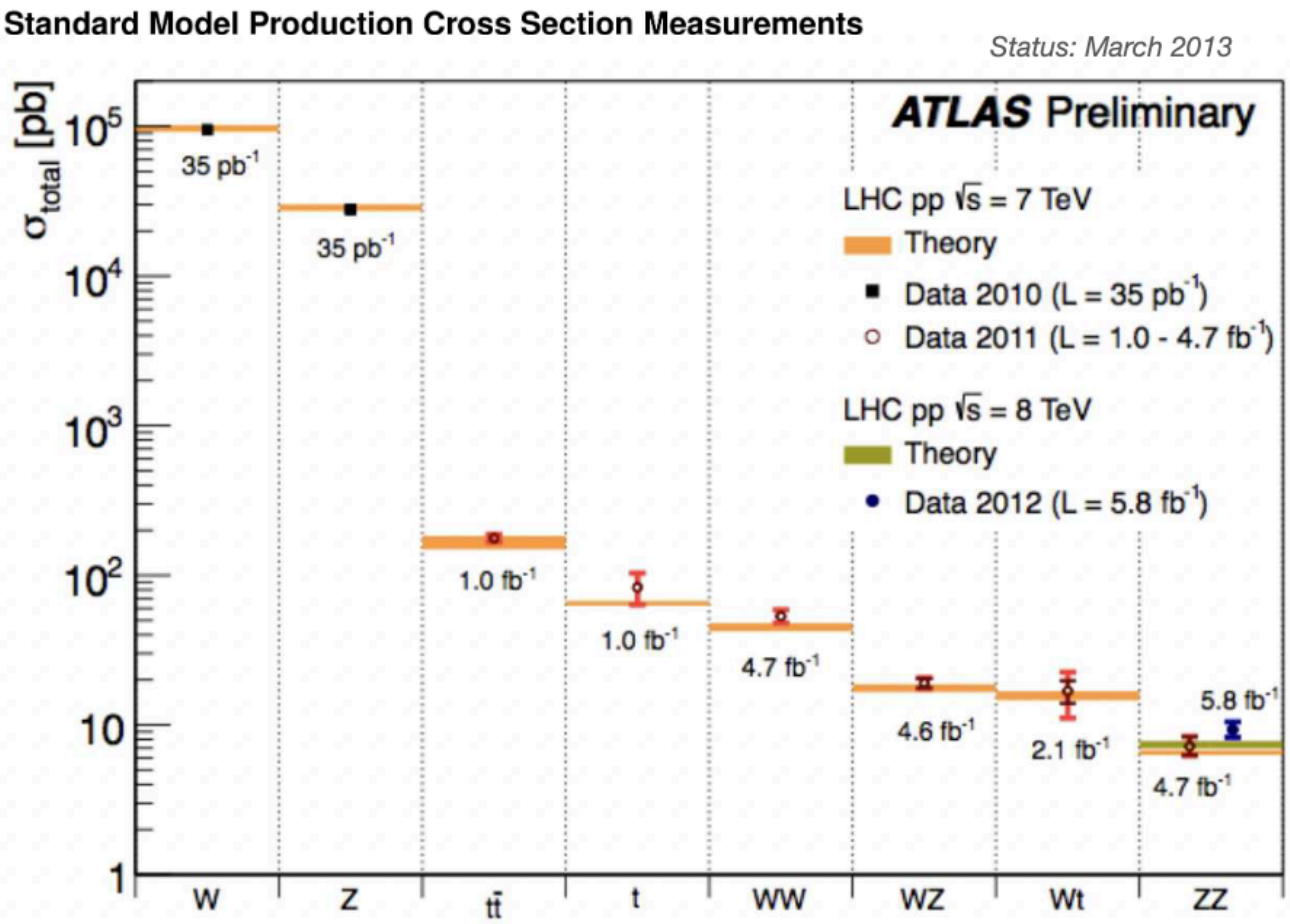


The LHC is an "everything factory"

Particle	Produced in 139 fb^{-1} at $\sqrt{s}$ = 13 TeV	
Higgs boson	7.7 millions	
Top quark	275 millions	
Single top quark	50 millions	
Z boson	2.8 billions	290 millions leptonic
W boson	12 billions	3.7 billions leptonic
Bottom quark	~40 trillions	

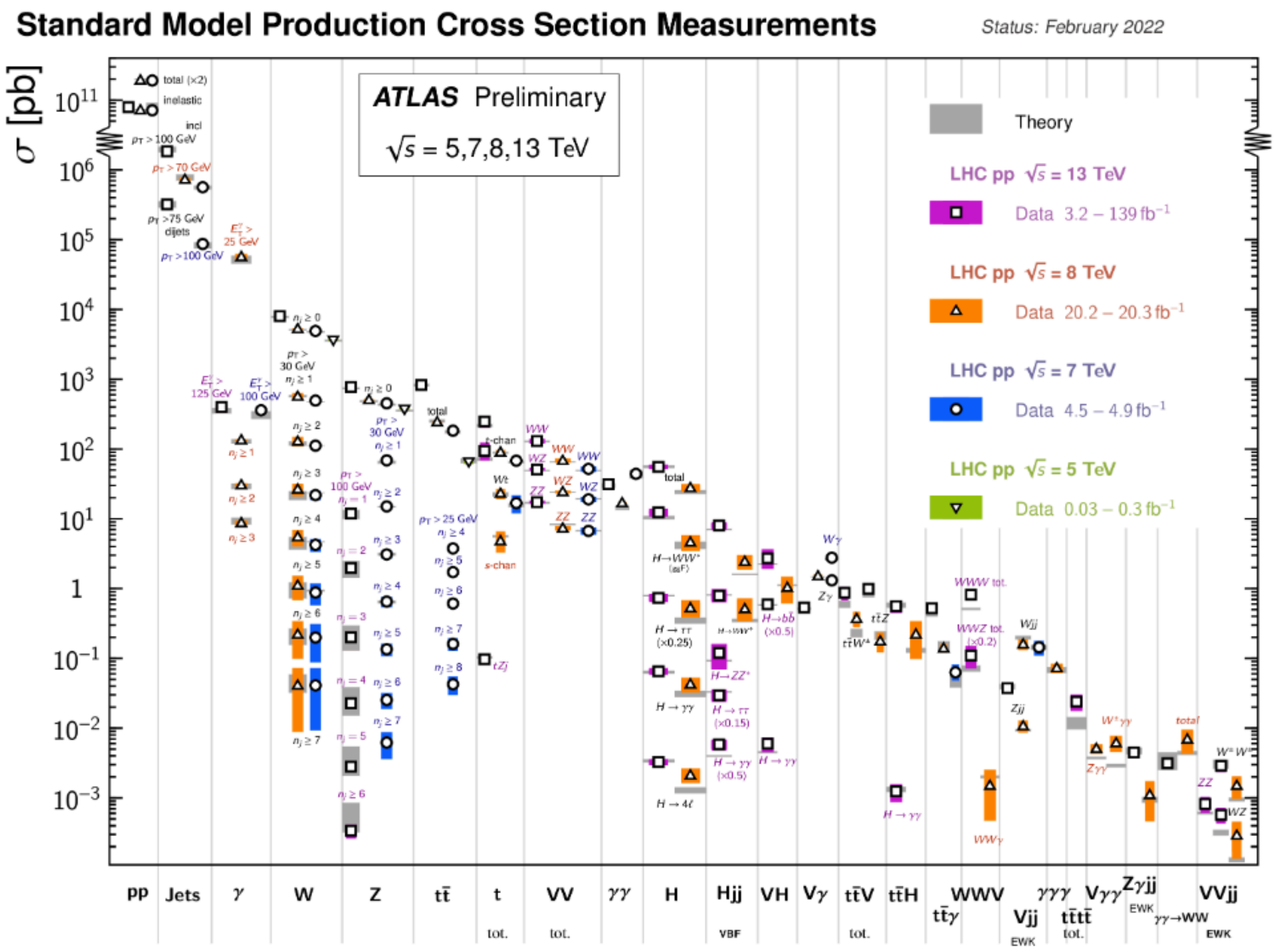
From A. Hoecker

Standard Model at the LHC



- **Discovery of the Higgs**
- **Precision measurements** of QCD and EW processes
- Exploration of **BSM physics** via direct and indirect searches

Standard Model at the LHC

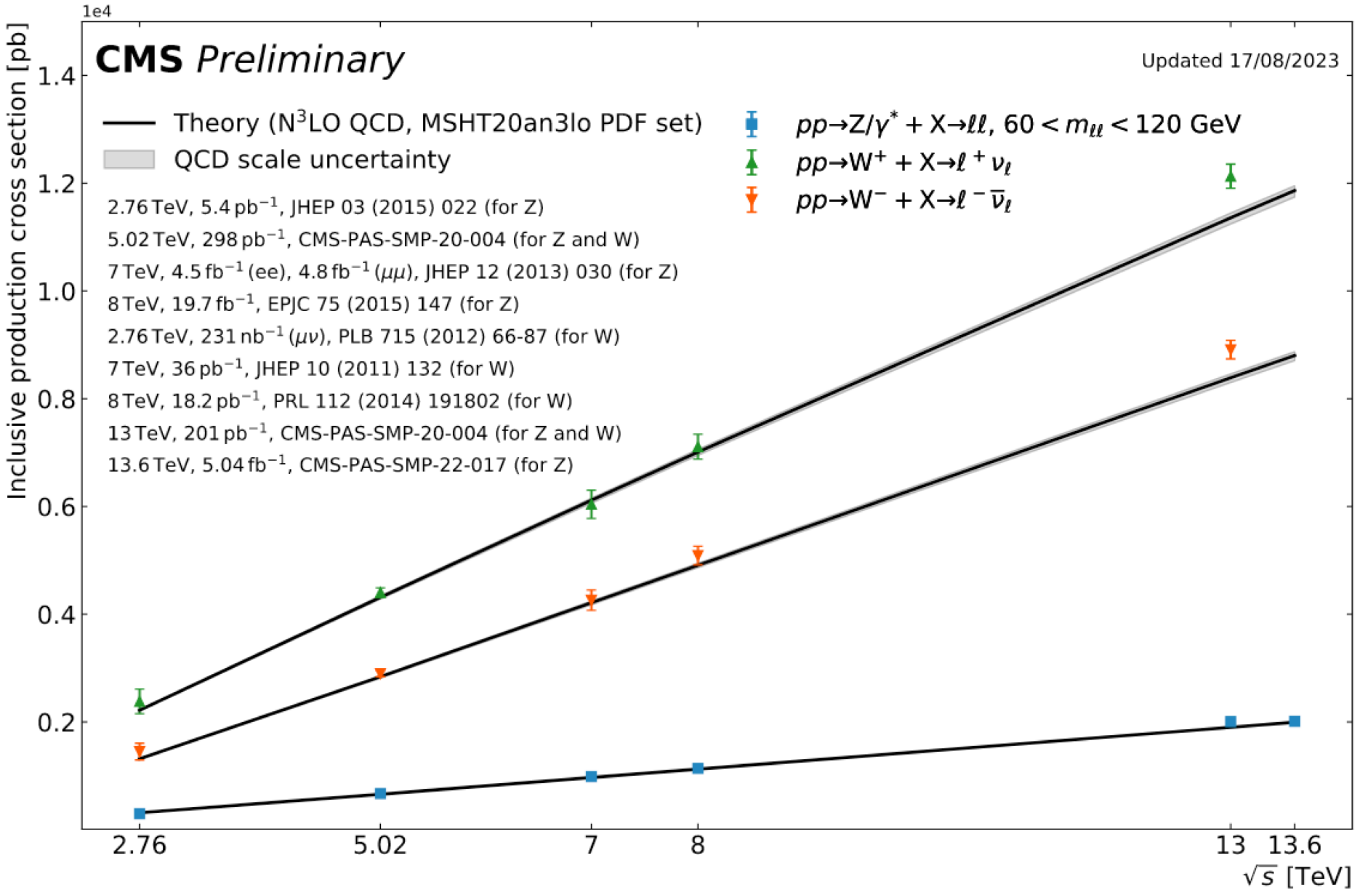


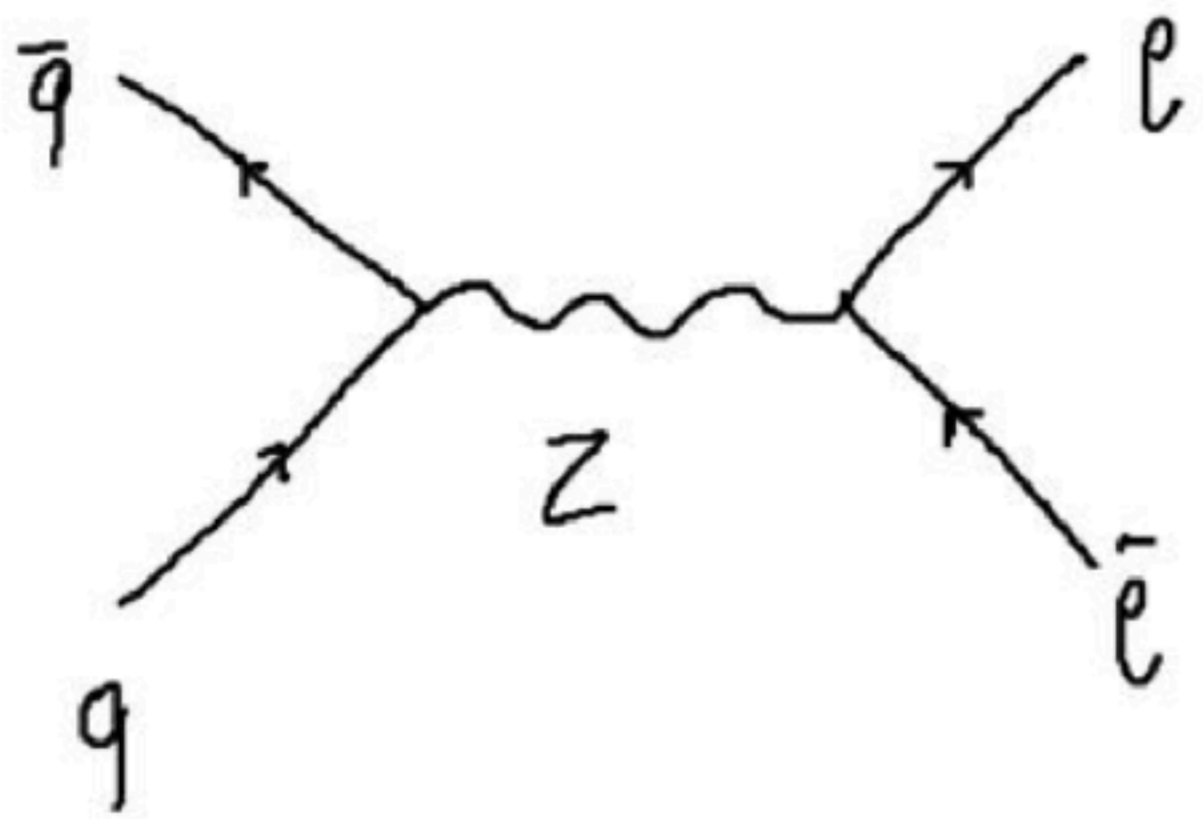
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-009/

- **Precision measurements** of Higgs and Standard Model processes
- Observation of very **rare SM processes**
- Direct BSM searches
- Indirect BSM searches through precision measurements

Drell-Yan measurements at the LHC

- Drell-Yan events are copiously produced at the LHC

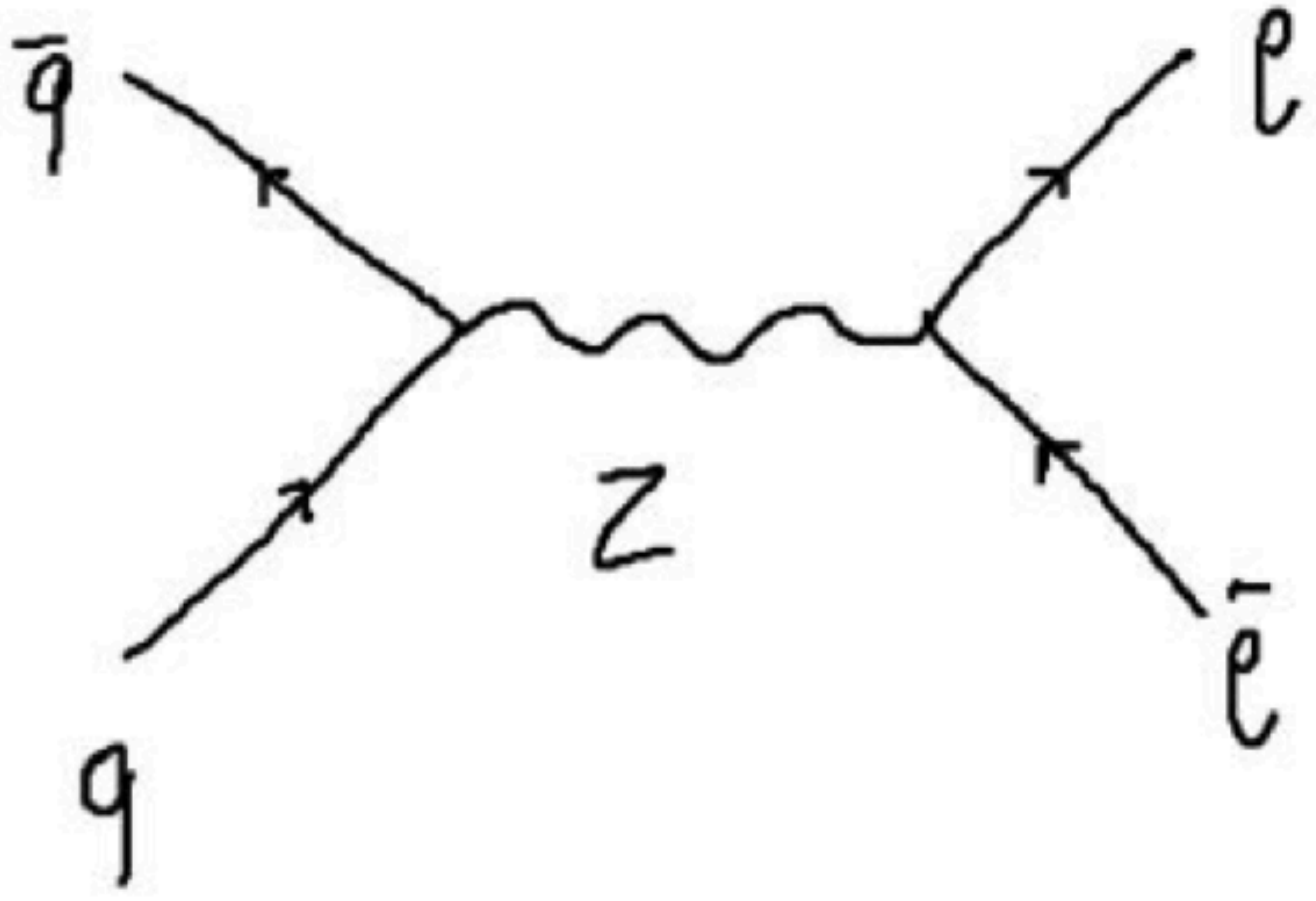




- Provide plenty of statistics for precise lepton calibrations
- Measured inclusively and differentially over a wide phase-space and at different collision energies
- Can now be predicted up to N^{3}LO in QCD and NLO in EW

Measuring the effective angle at the LHC

- At hadron colliders $\sin^2\theta^l_{\text{eff}}$ can be measured from leptonic asymmetries in Drell-Yan:



At leading order in QCD the cross-section is

$$\sim 1 + \cos^2\theta_{\ell\bar{\ell}} + A_4 \cos\theta_{\ell\bar{\ell}}$$

where A_4 is parity-violating and sensitive to $\sin^2\theta^l_{\text{eff}}$

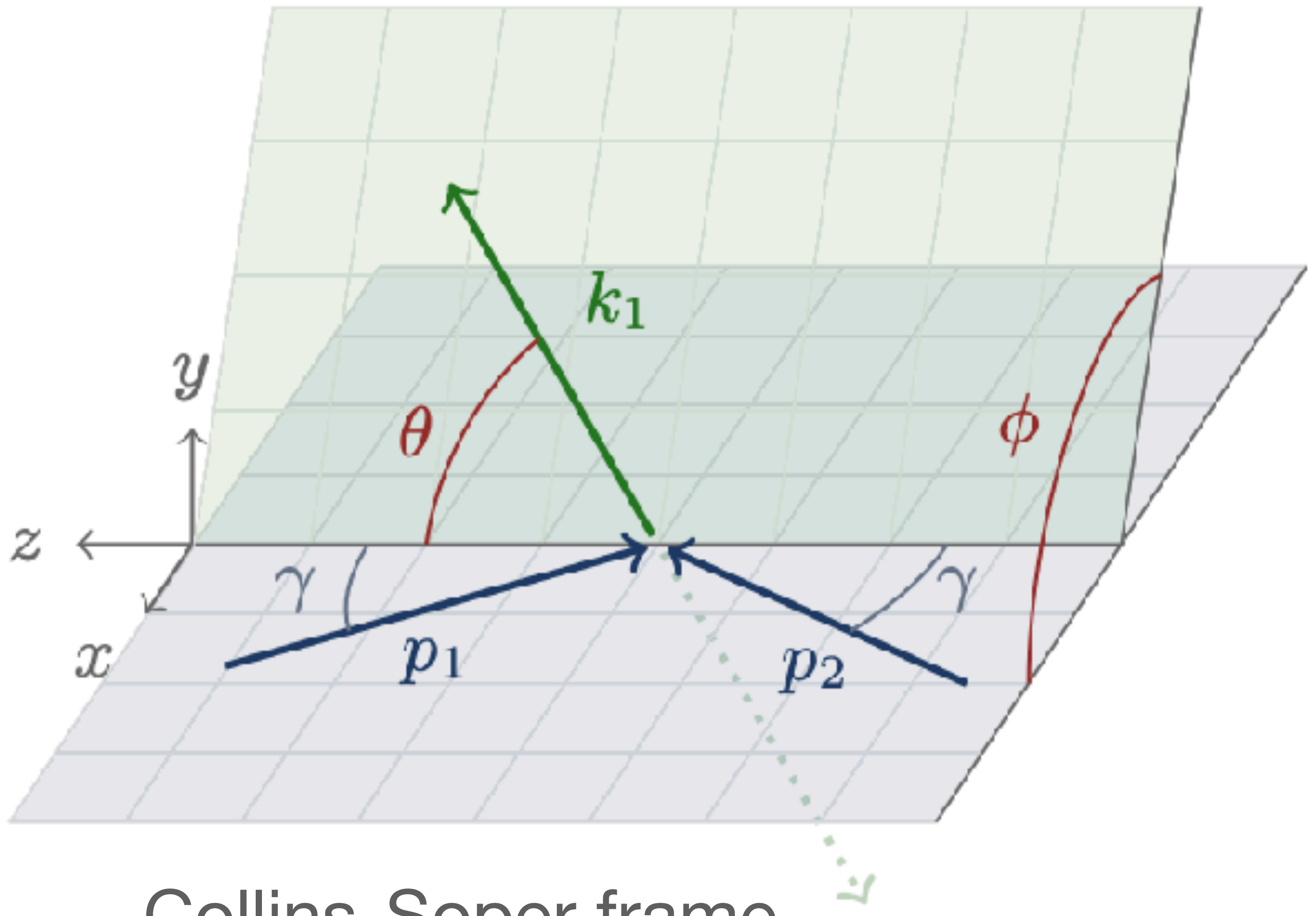
In full phase-space of the decay leptons:

$$A_4 = \frac{3}{8} A_{FB} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$

$\sin^2\theta^l_{\text{eff}}$ from template fits to A_{FB}/A_4:

$A_{FB}(m_{ll}, |y_{ll}|)$ data $\longrightarrow$ MC samples with different values of $\sin^2\theta^f_{\text{eff}}$ $\longrightarrow$ Measured value = MC sample which best fit the data

A_{FB} and the Collins-Soper frame

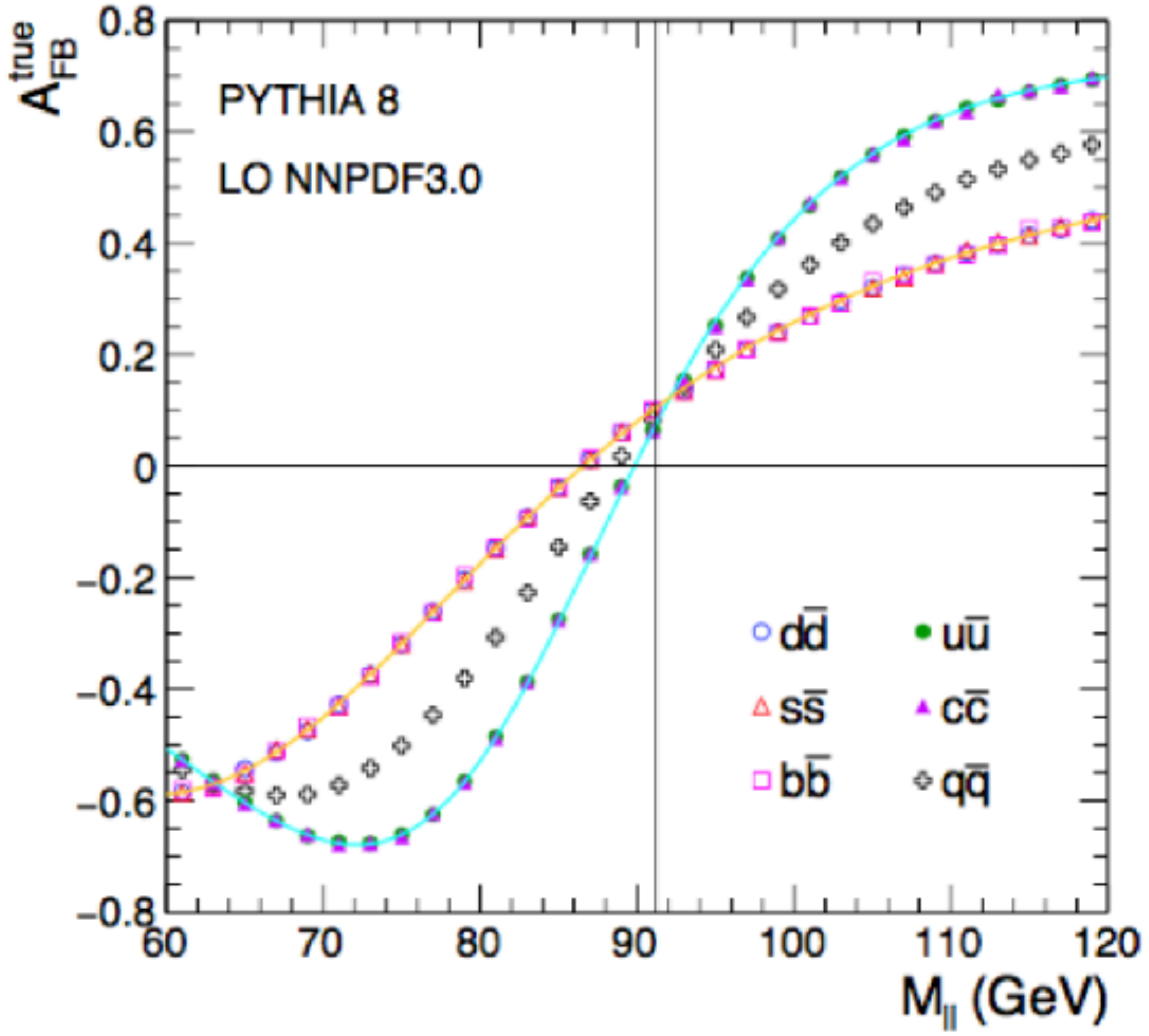


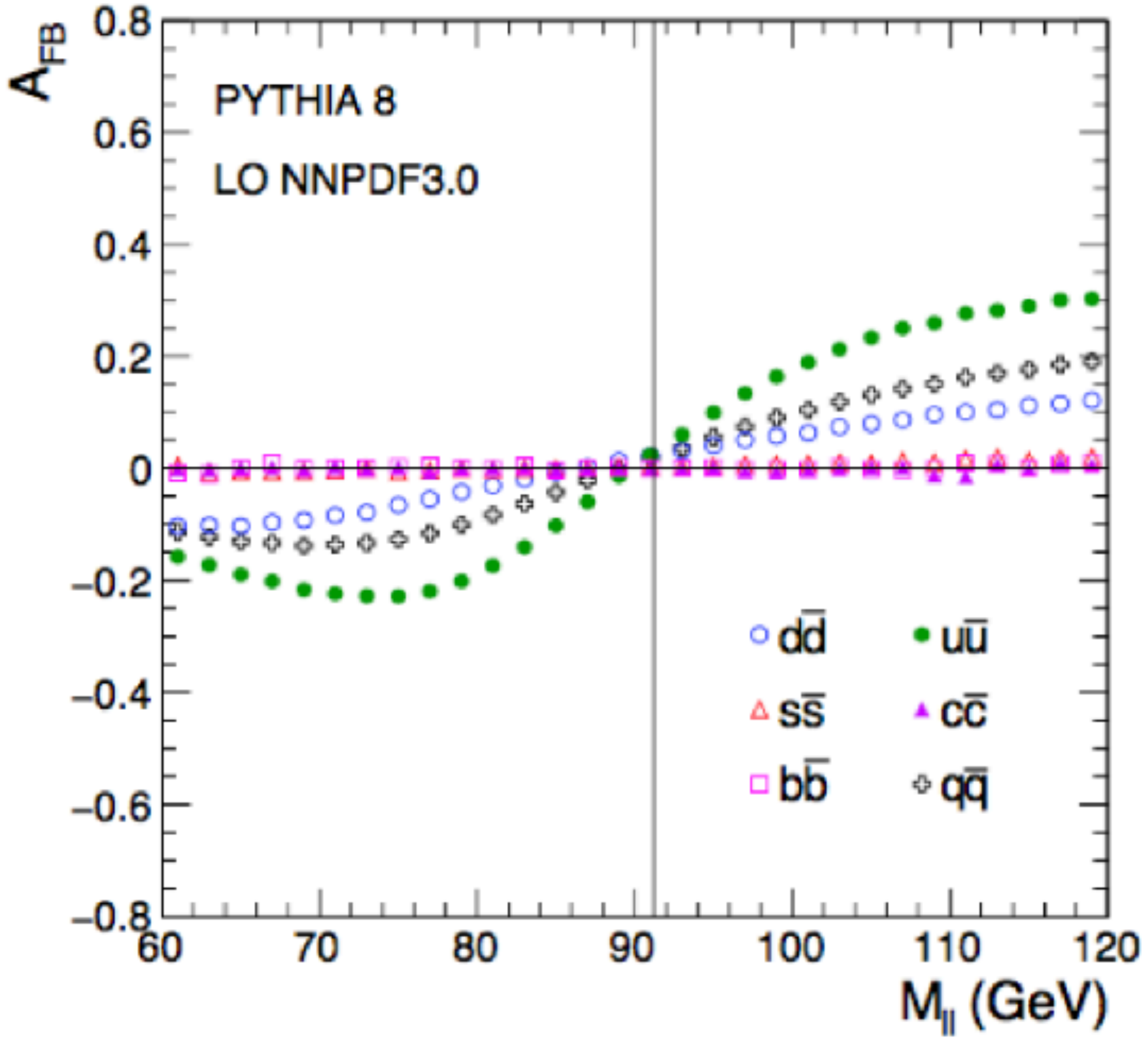
Collins-Soper frame

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

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

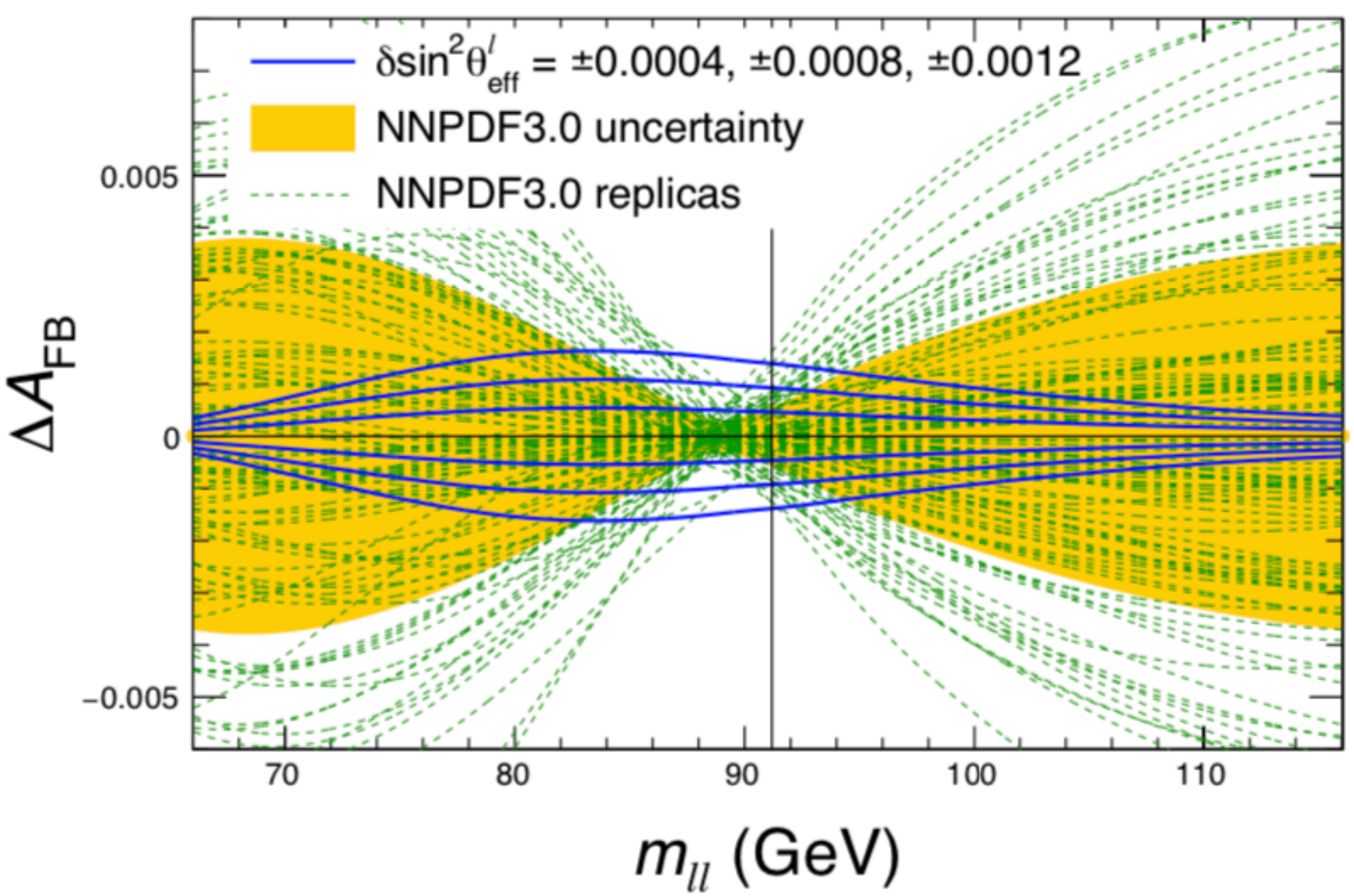
- The quark direction is unknown, inferred from Z-boson direction
  - valence quarks have on average larger Bjorken-x than antiquarks
  - Dilutes the measured asymmetry
- Parton-level asymmetry measured at particle-level, **large sensitivity to proton structure (PDFs)**

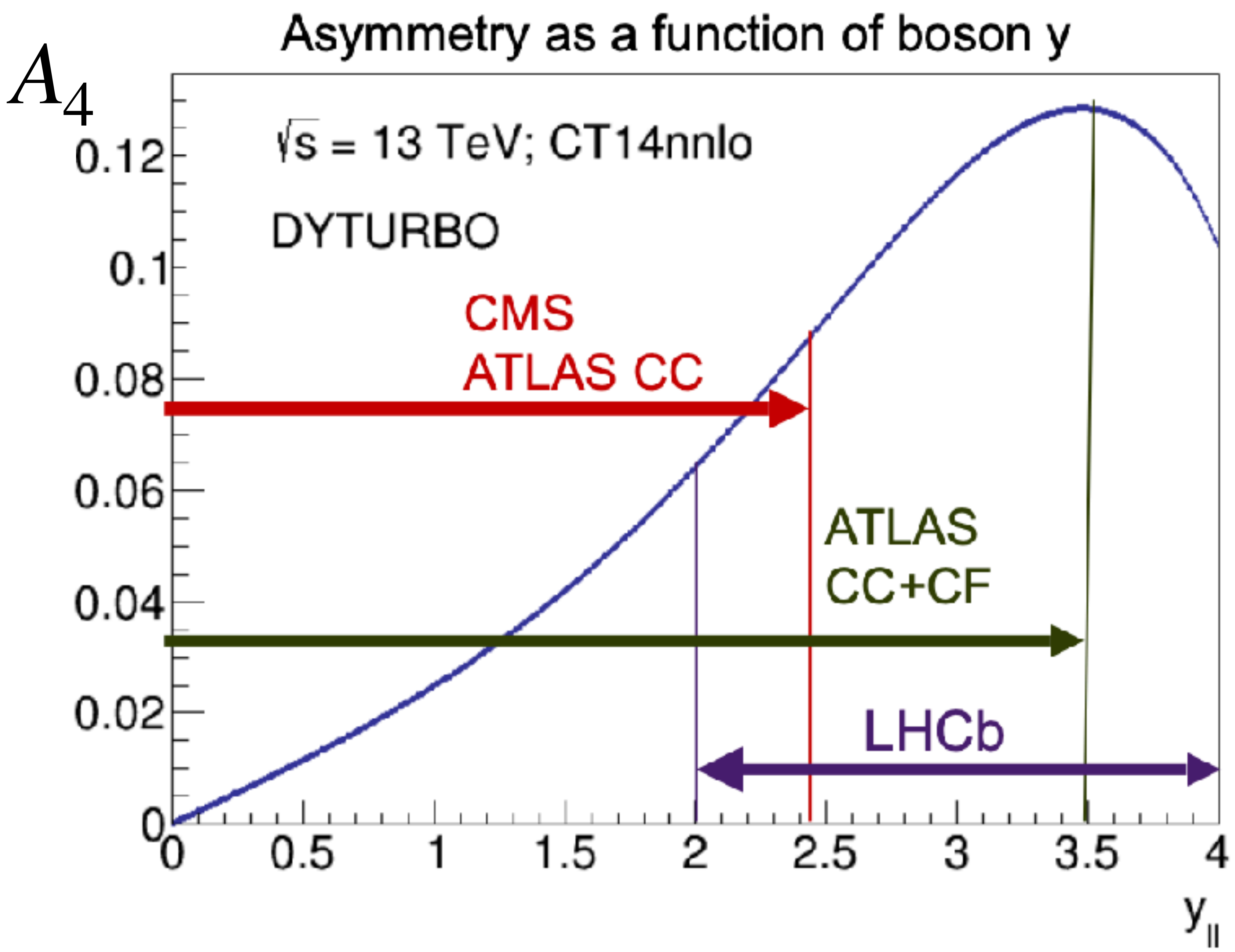




A_4/A_{FB} and PDFs

- The forward-backward asymmetry and A4 depend strongly on the initial state quarks and on the dilepton rapidity and mass
- At large rapidities the asymmetry is larger as is the sensitivity to $\sin^2\theta^l_{\rm eff}$
- Can exploit the different dependence on y, m to disentangle PDF effects





Not all events are the same: event-weighted A_{FB}

- Events with different $\cos\theta_{CS}$ have different sensitivities to the weak mixing angle
- Can gain by weighting each selected event depending on their $\cos\theta_{CS}$

$$w_D = \frac{1}{2}\frac{c^2}{(1+c^2+h)^3}$$ ← Denominator (normalization) weight

$$w_N = \frac{1}{2}\frac{|c|}{(1+c^2+h)^2}$$ ← Numerator (asymmetry) weight

$$h = 0.5A_0(1-3c^2)$$ ← $A_0 = A_0(m, y, p_T)$ from angular coefficients decomposition of the Z cross-section

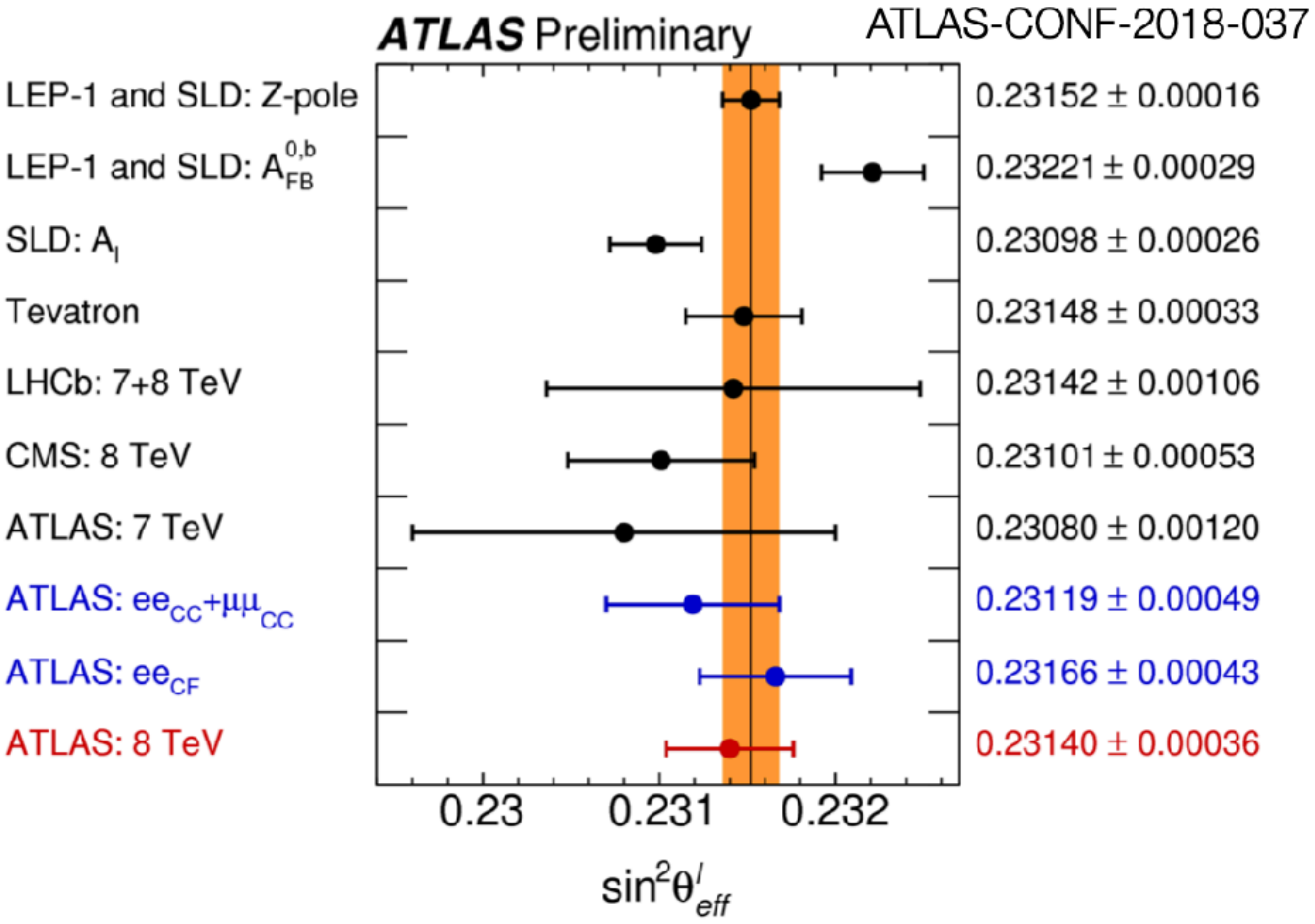
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{8}\left(1+\cos^2\theta^* + \frac{A_0}{2}(1-3\cos^2\theta^*) + A_4\cos\theta^*\right)$$

$$D_F = \sum_{c>0} w_D, D_B = \sum_{c<0} w_D$$

$$N_F = \sum_{c>0} w_N, N_B = \sum_{c<0} w_N$$

$$A_{FB} = \frac{3}{8}\frac{N_F - N_B}{D_F + D_B}$$

Present LHC determinations of $\sin^2\theta^l_{\rm eff}$



- ATLAS from a fit to $A_4(y,m)$
- CMS from a fit to $A_{FB}{}^{w}(y,m)$
- Comparable precision but ATLAS adds electrons reconstructed in the forward calorimeter
- PDF uncertainties constrained in the interpretations but remain very large

- Measurements dominated by statistical and PDFs uncertainties

CMS: 0.23101 ± 0.00036 (stat) ± 0.00018 (syst) ± 0.00016 (th) ± 0.00031 (PDF)

ATLAS: 0.23140 ± 0.00021 (stat) ± 0.00016 (syst) ± 0.00024 (PDF)

The new CMS measurement

- New CMS measurement of the $\sin^2\theta^{l}_{\text{eff}}$ dileptonic (electron and muon) events

- Use 137 fb^{-1} of *pp* collision data collected in Run2 at $\sqrt{s} =$ 13 TeV

- Fit **weighted A_{FB}** in mass and rapidity, but additionally **unfold A_4(y,m)** in full phase-space for future reinterpretations and combinations

- Extended to higher dilepton rapidities with **new central-forward channel** including electrons reconstructed in the forward calorimeters

- **Improve the interpretation** model using modern PDF sets and incorporating latest advances in theoretical calculations (QCD and EW)

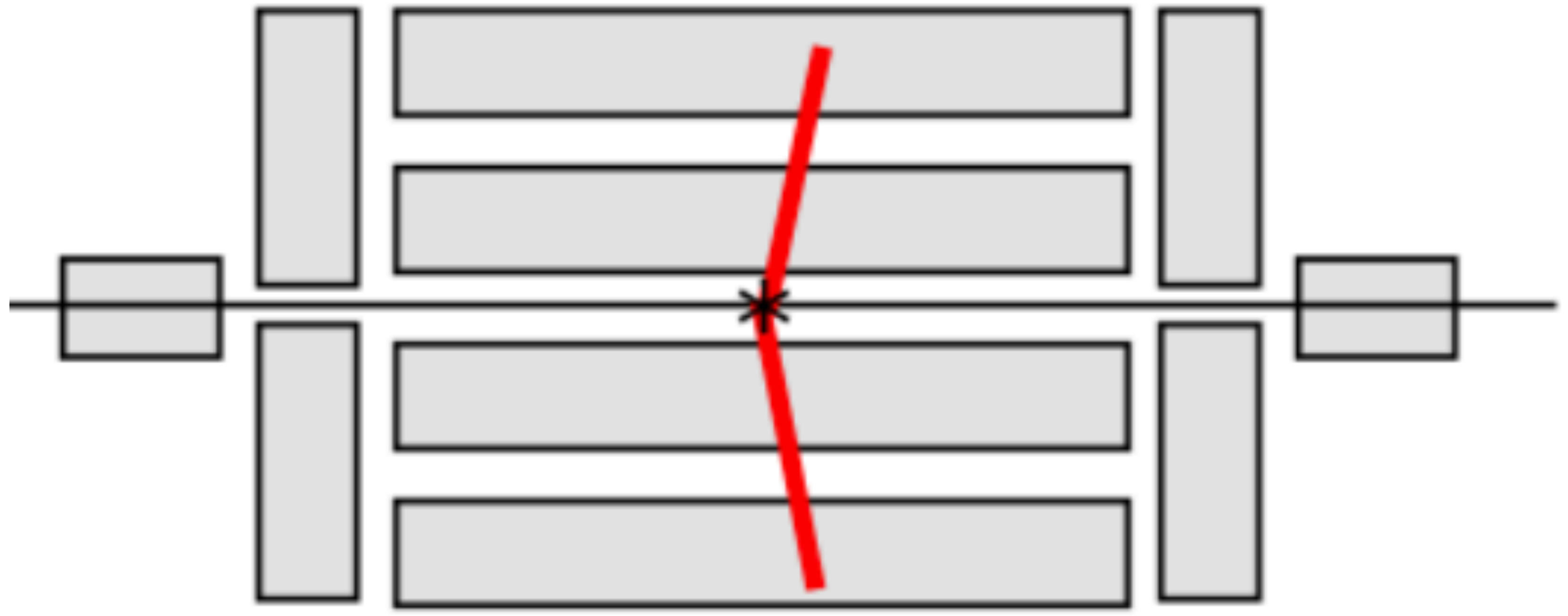
Event selection

- Events are selected using single- and double-lepton triggers to maximize the data sample
- Several dilepton categories are defined:
  - $\mu\mu, ee$: at least two good central leptons with opposite charges passing the medium identification (criteria
  - eg, eh: at least one central electron passing tight identification and one medium forward electron

Channel	$\lvert\eta\rvert$		min p_T^{lead} (GeV)	min p_T^{trail} (GeV)
$\mu\mu$	0.00–2.40		20	10
ee	0.00–2.50		25	15
	$\lvert\eta_e\rvert$	$\lvert\eta_{g,h}\rvert$	min p_T^{e} (GeV)	min $p_T^{g,h}$ (GeV)
eg	0.00–2.50	2.50–2.87	30	20
eh	1.57–2.50	3.14–4.36	30	20

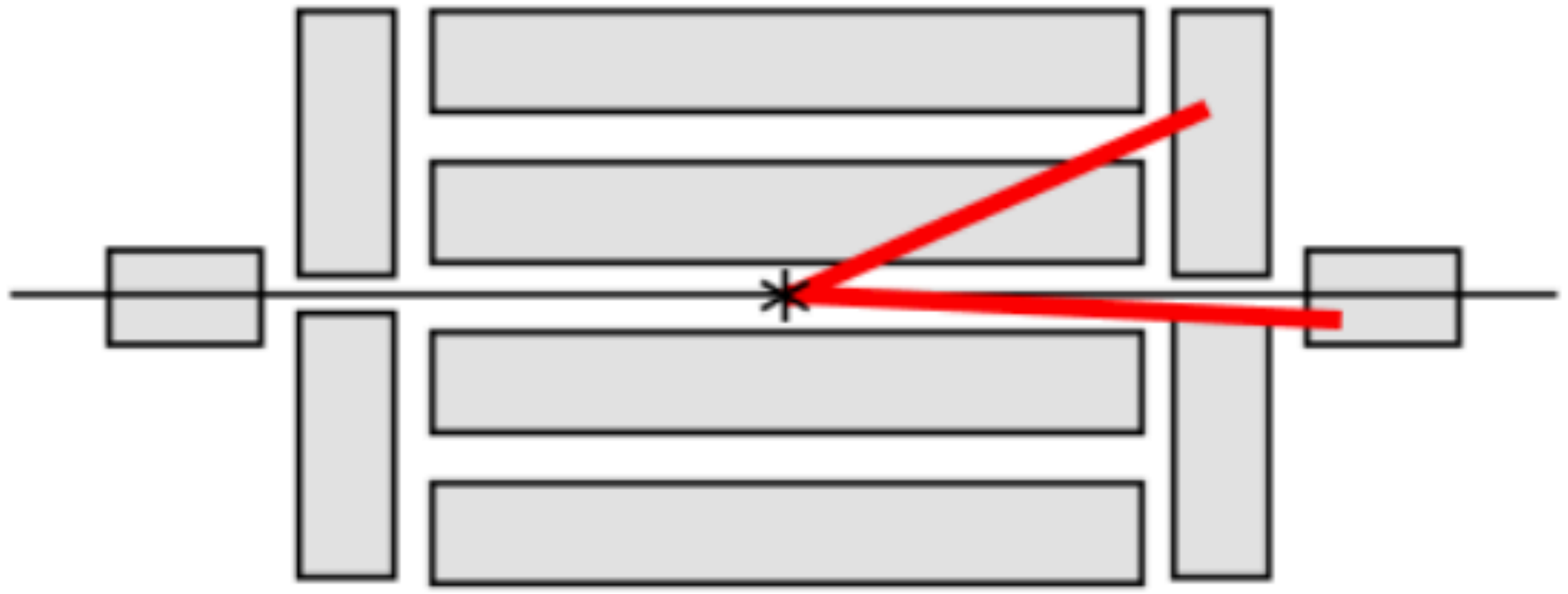
- Dedicated ID developed for forward electrons reconstruction using either shower shapes information or jet constituents

Central-Central:



$\mu\mu, ee$

Central-Forward:



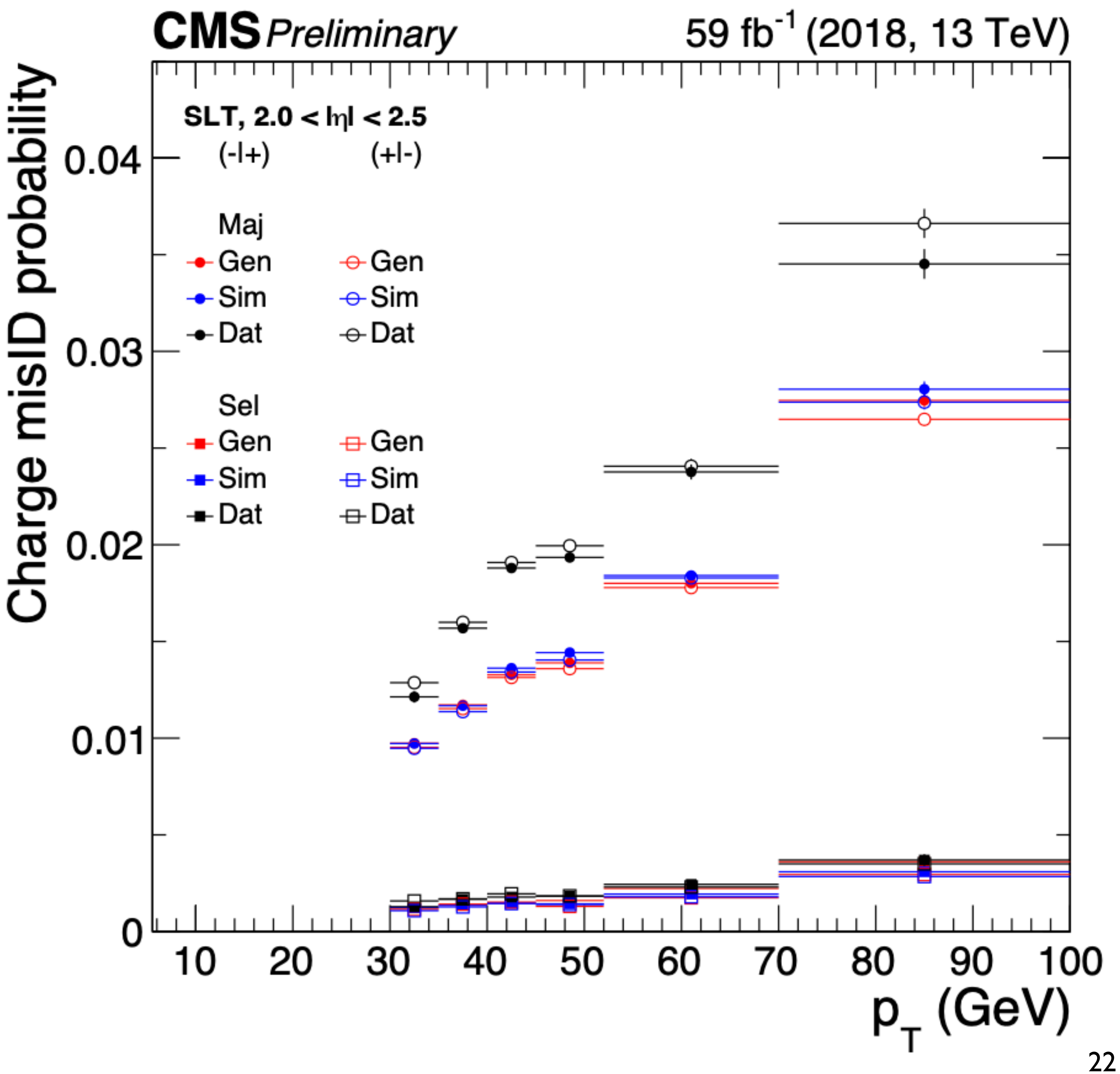
eg, eh

Forward EM calo　Forward HAD calo

Lepton efficiencies and charge mis-ID

- Lepton selection efficiencies are evaluated with tag-and-probe (T&P) method using Z events.
  - Measured separately for reconstruction, identification, and trigger selection

- The (small) electron charge misidentification rates are measured as a function of the electron's p_T and η
  - In a sample of same-sign and opposite-sign dielectrons with a maximum-likelihood fit.

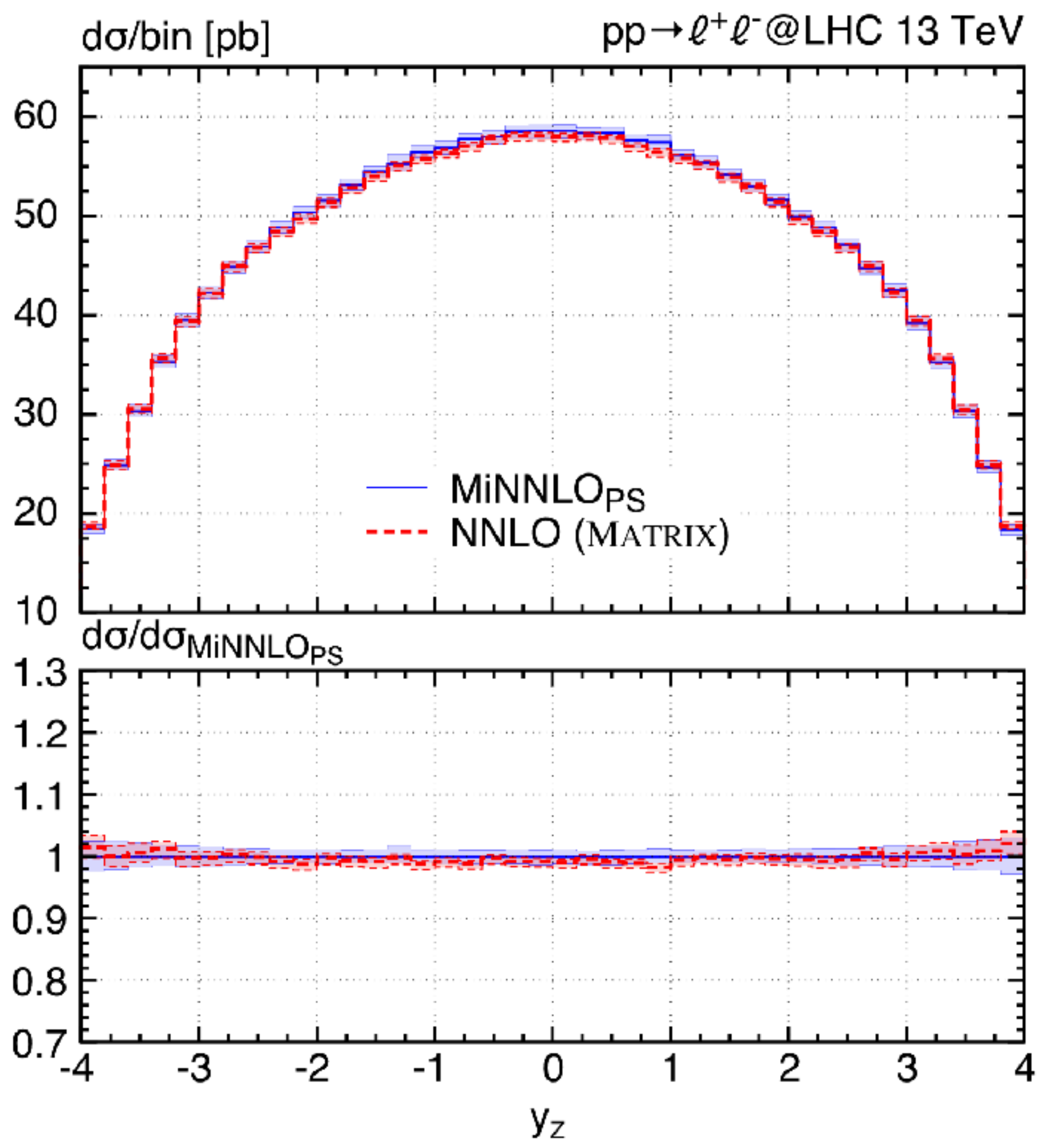


Signal Monte Carlo

- A large signal sample of 1.5B simulated Drell-Yan events is generated using the Zj-MiNNLOPS program in Powheg-Box

- State-of-the-art event generator at **NNLO QCD**
- Matched to Pythia8 for parton shower hadronisation as well as **initial-state photon radiation** (QED ISR)
- Further interfaced to PHOTOS++ for **final-state photon radiation** (QED FSR)

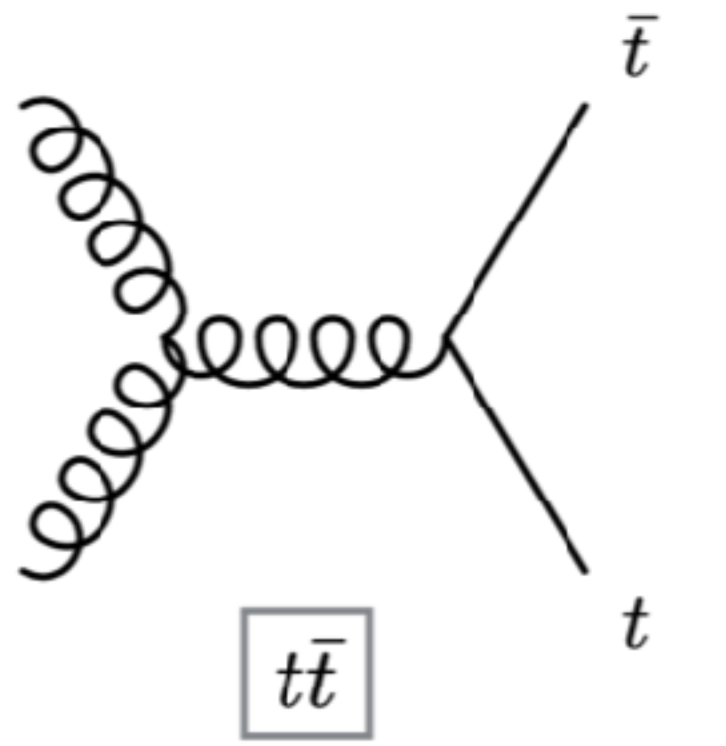
- Small mismodelling is observed in the description of the dilepton p_T distribution
- Corrected reweighing the MC to data in bins of dilepton rapidity

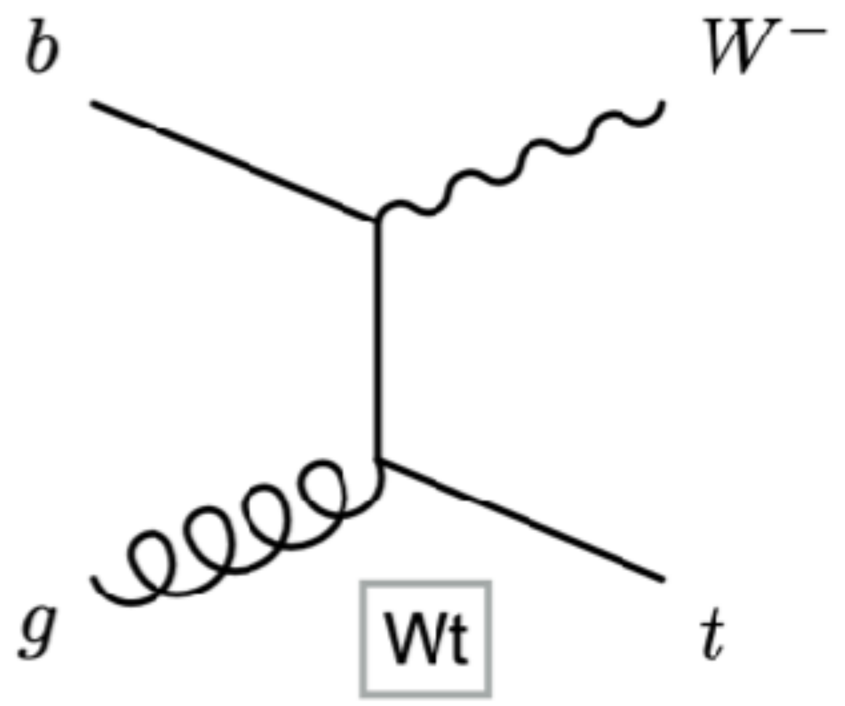


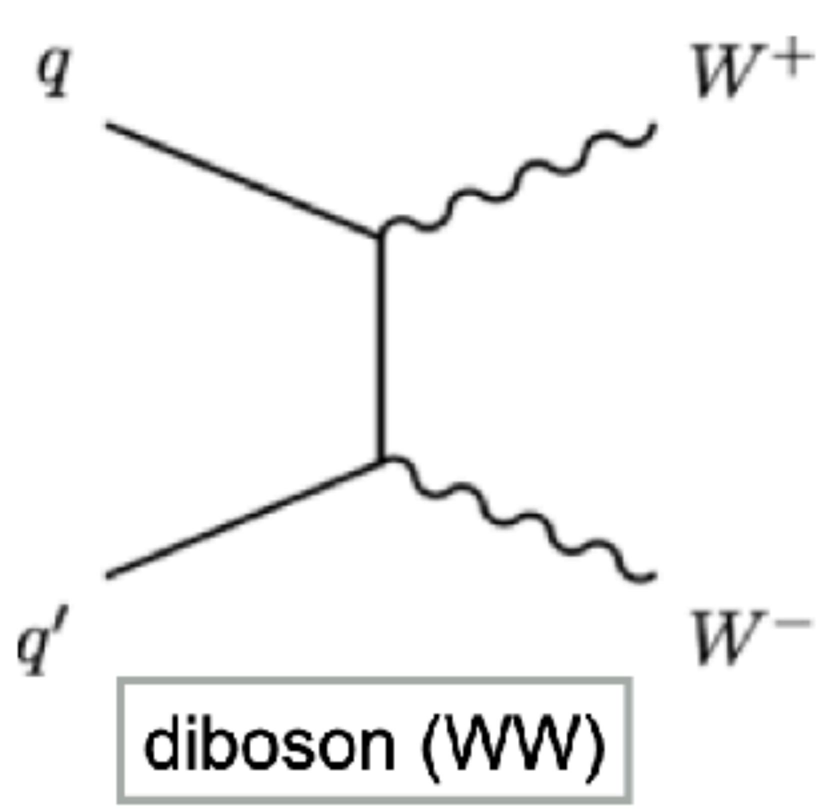
Backgrounds

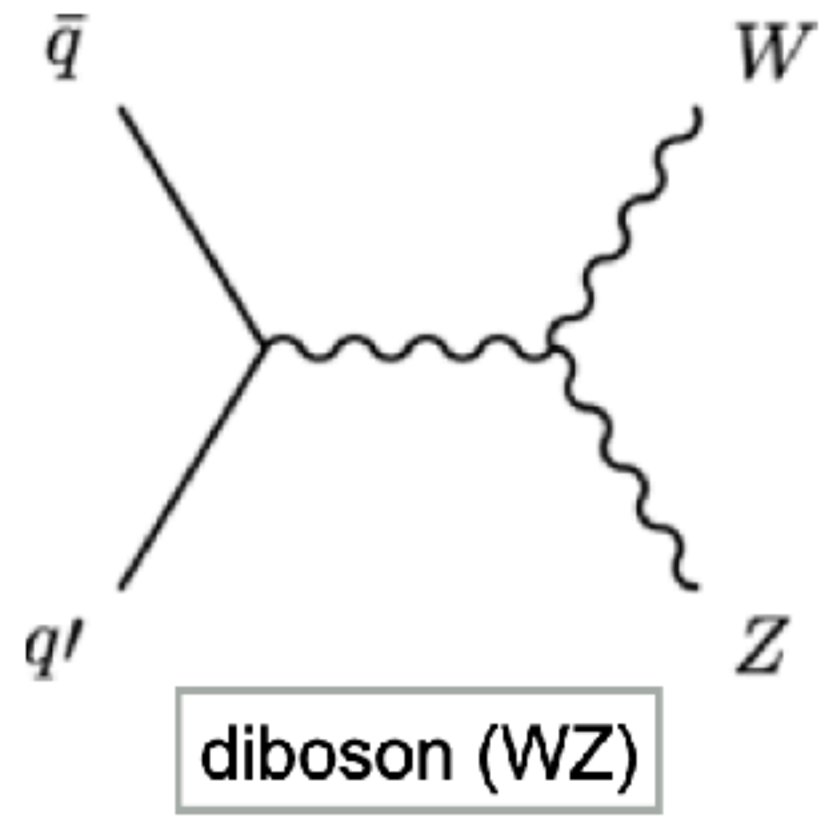
- Several sources of backgrounds to isolated lepton pairs

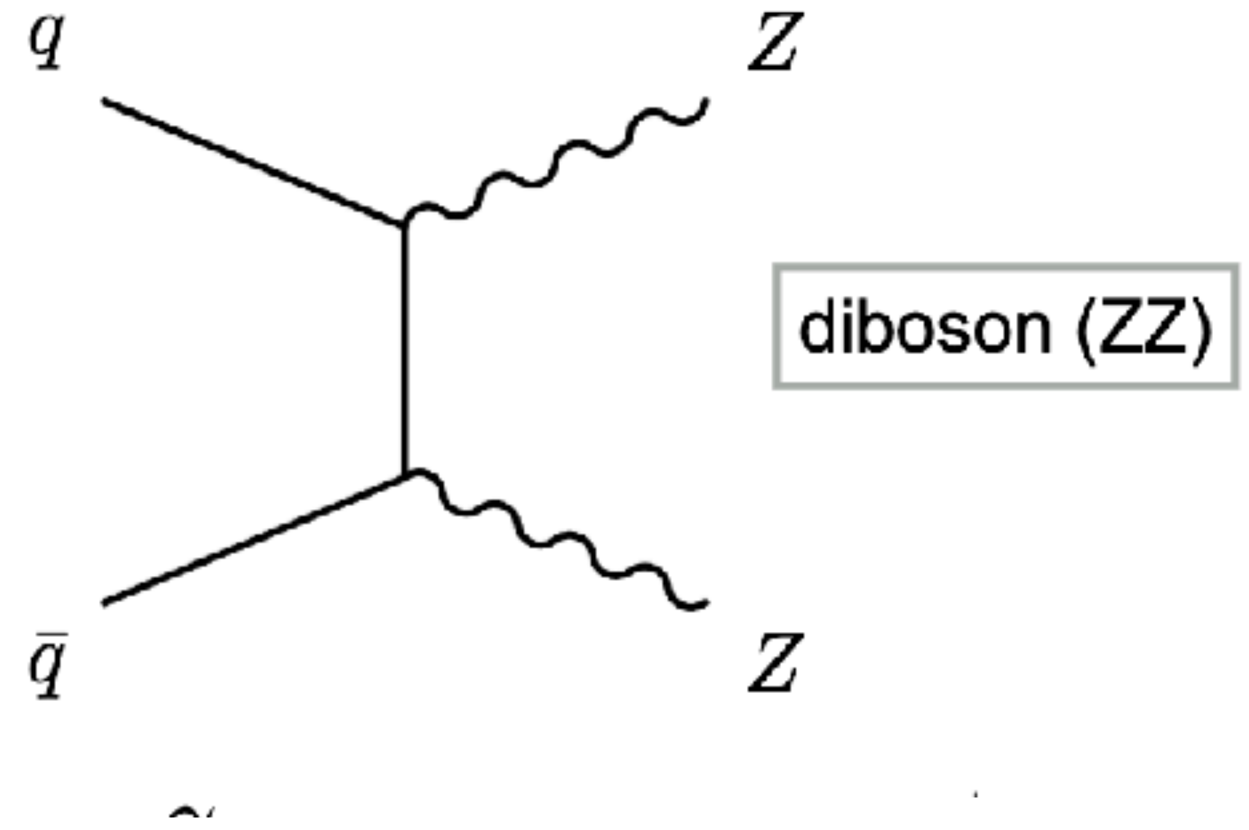
Top backgrounds
2-10% contribution
(largest at high $\cos\theta_{CS}$)





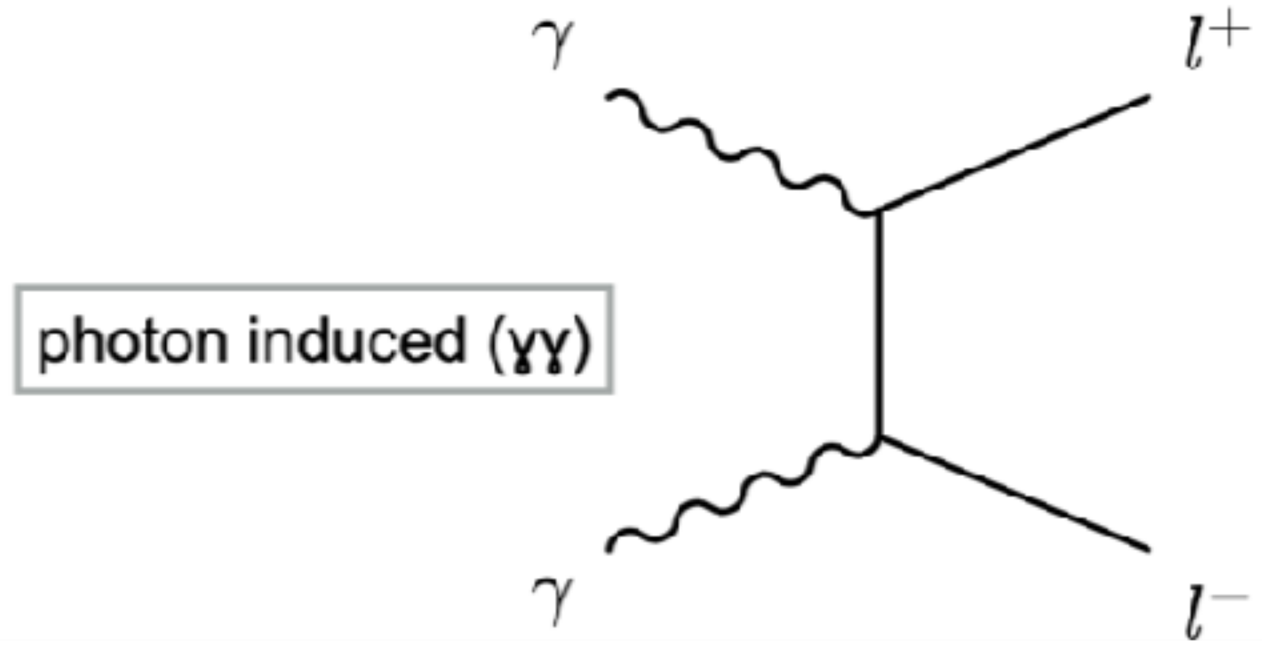






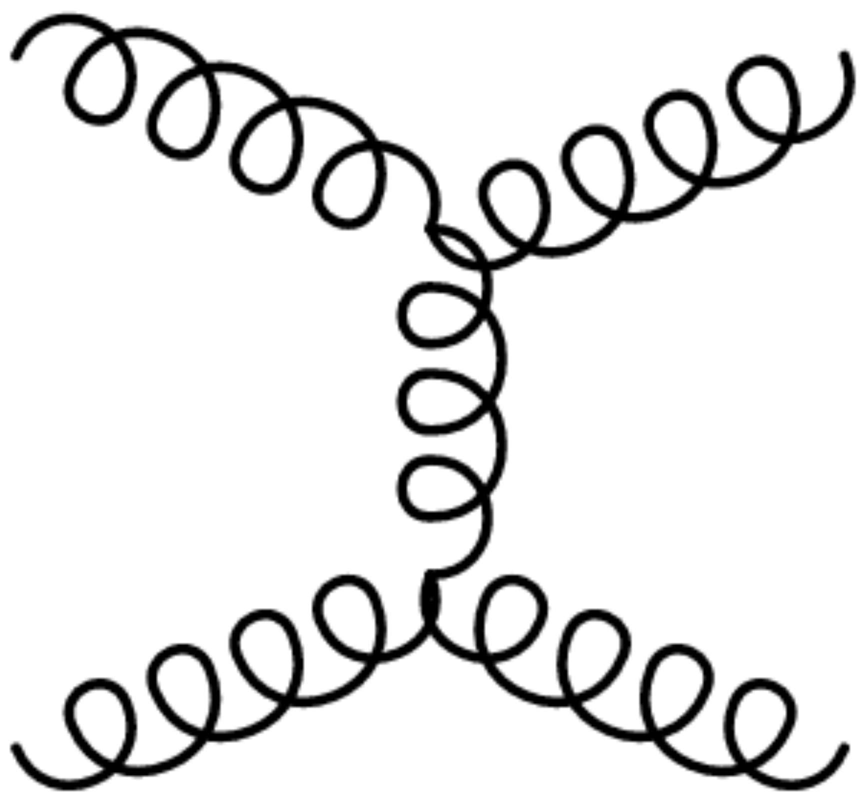
Multiboson production
3-6% contribution

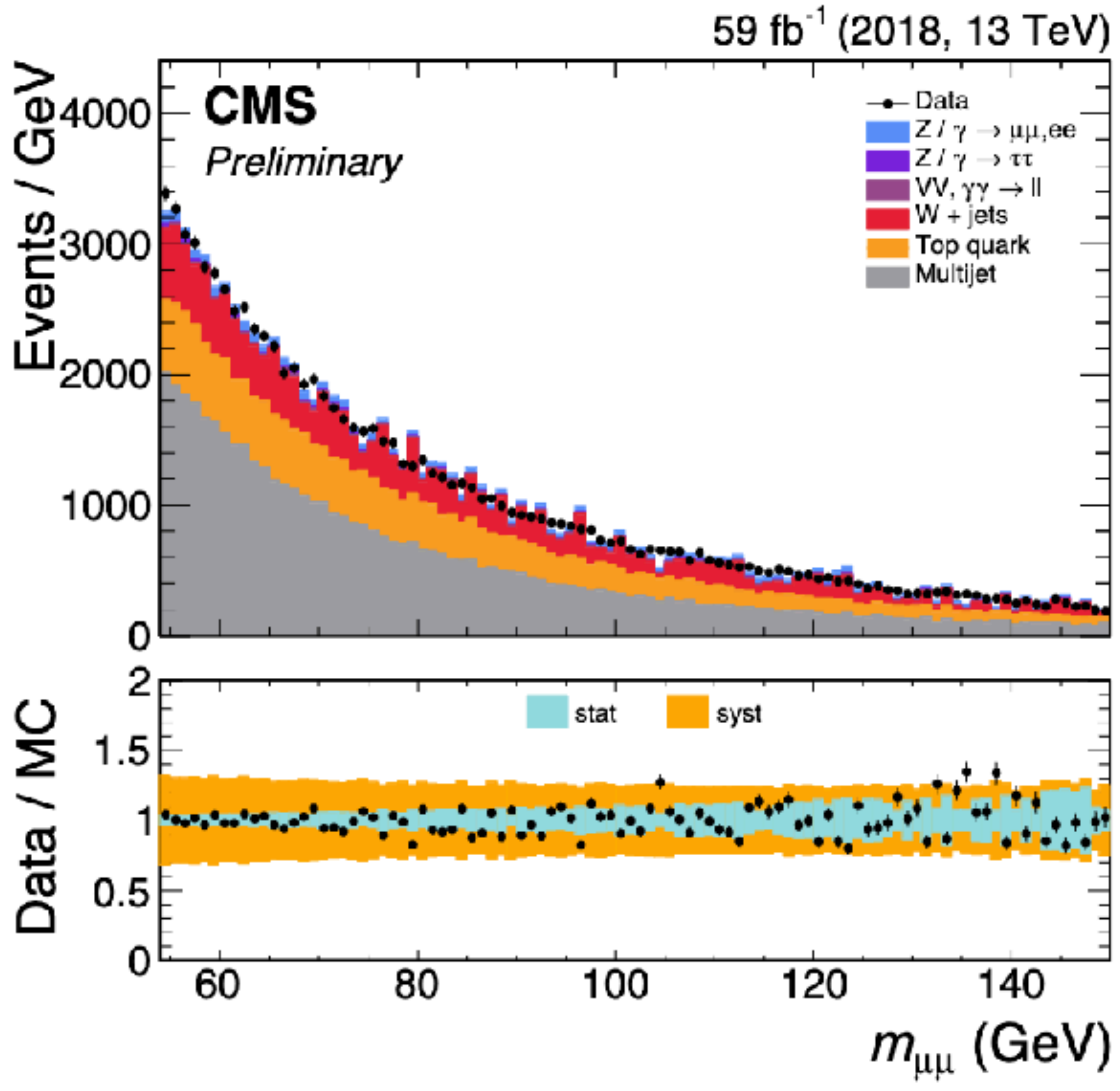
Photon induced production
(formally an NLO EW contribution)
2-5% contribution, largest at high mass

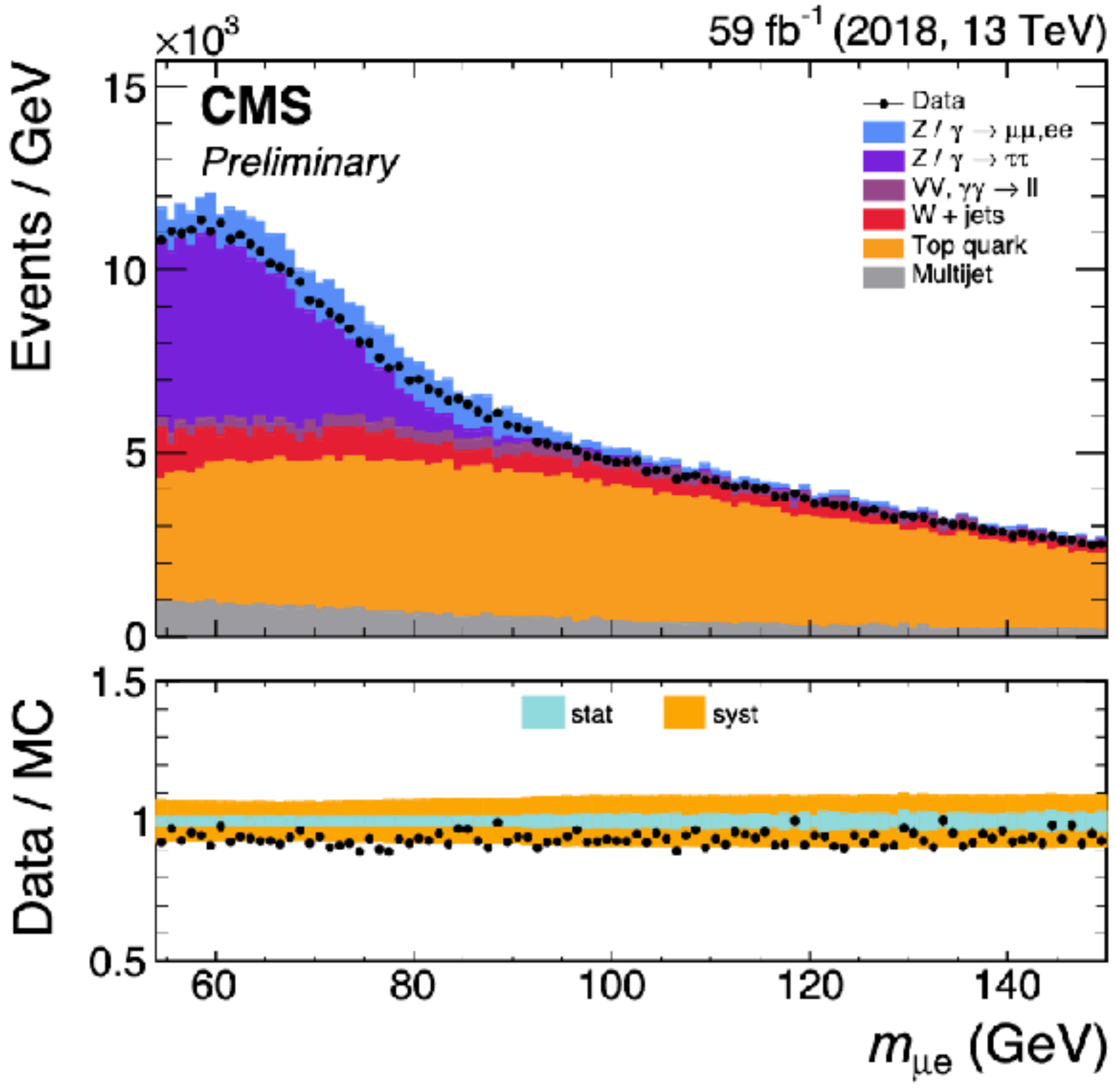


Multijet background

- QCD multijet production has very large cross-sections, contributes to background via
  - b-, c-quark with leptonic meson decays
  - Misidentification of hadron jets as electrons
- Complex to simulate, estimated using data



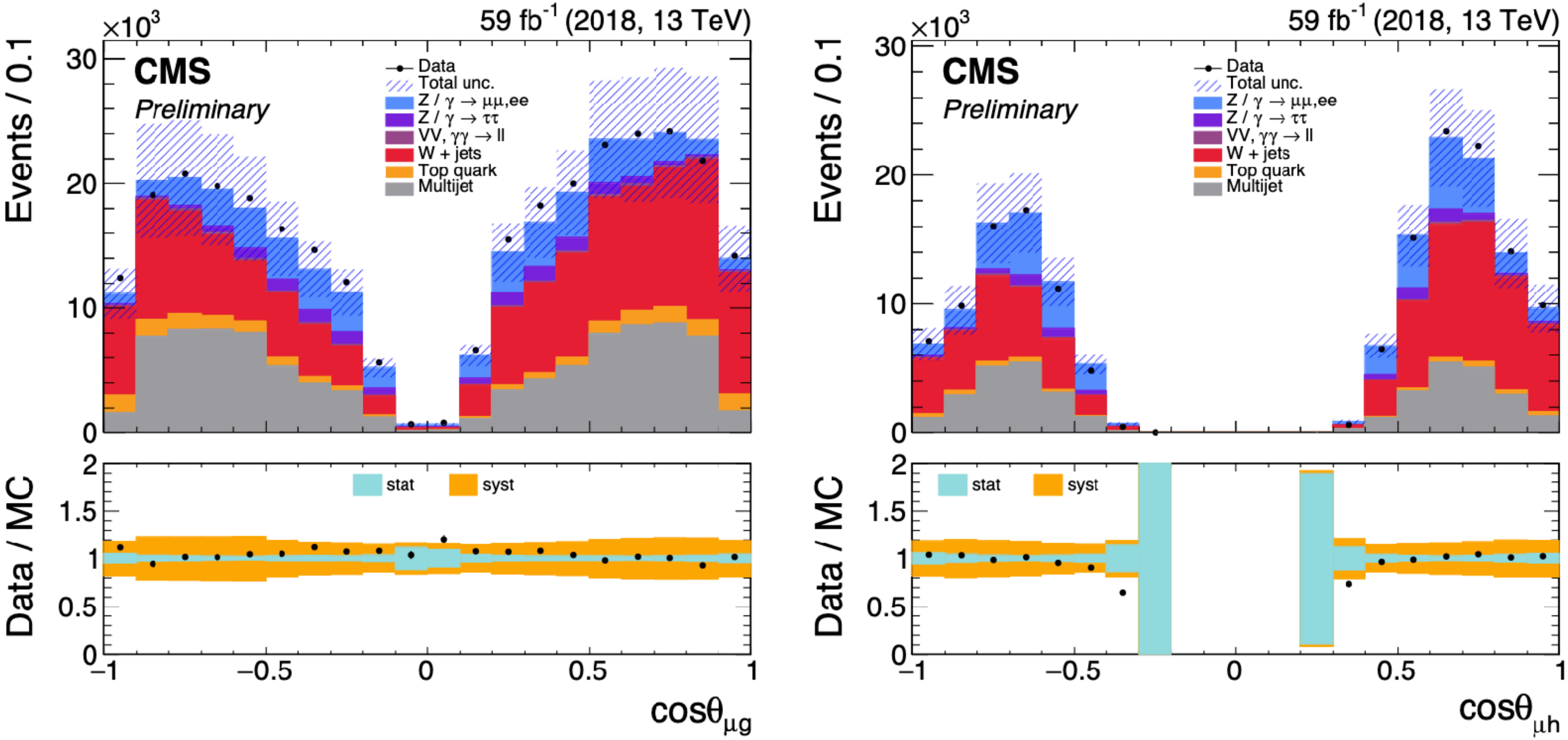




- Multijet enriched regions inverting ID/reco selection
- Transfer factor evaluated in samples of same-charge or different-flavor dileptons
- Good agreement seen in dedicated control regions

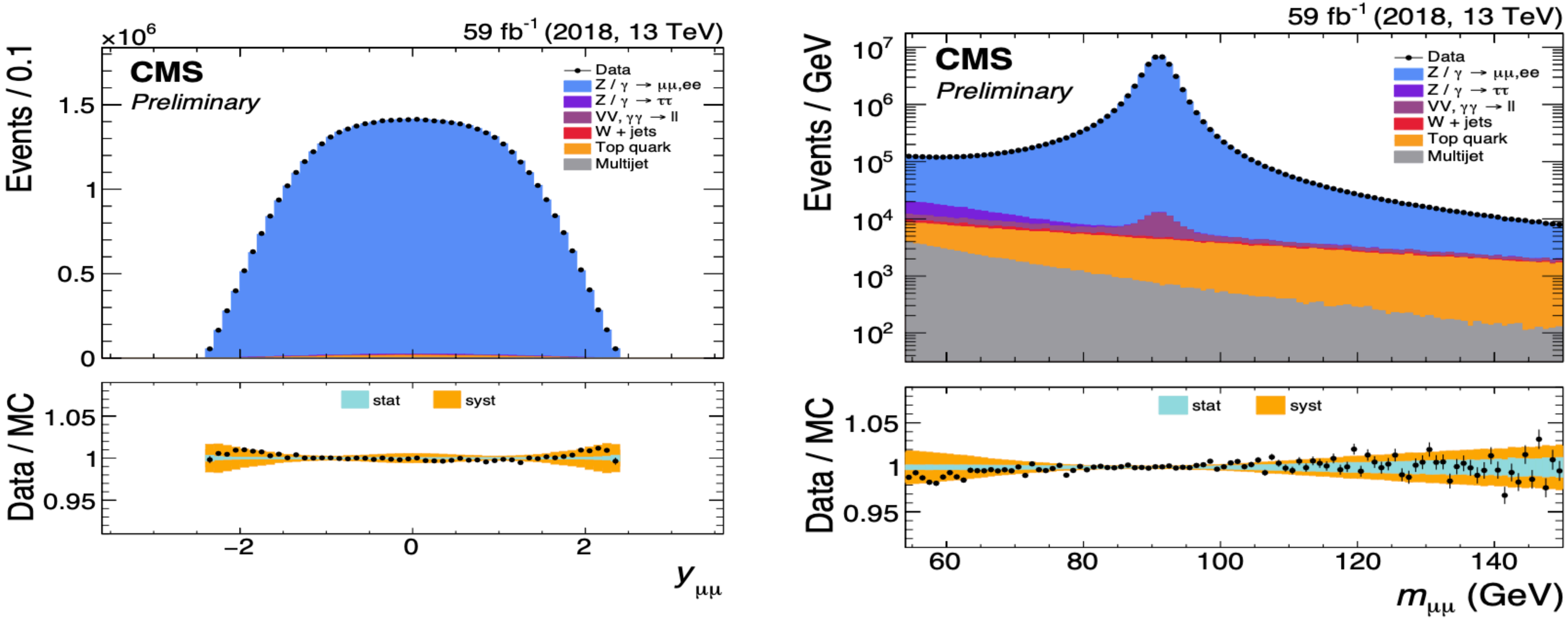
W+jets background

- W+jets background also taken from Monte Carlo, but in the forward channels corrected using scale factors derived in data control regions



Control Distributions

- A very good agreement between data and simulation can be seen in the dilepton rapidity and mass distribution for the various channels and years



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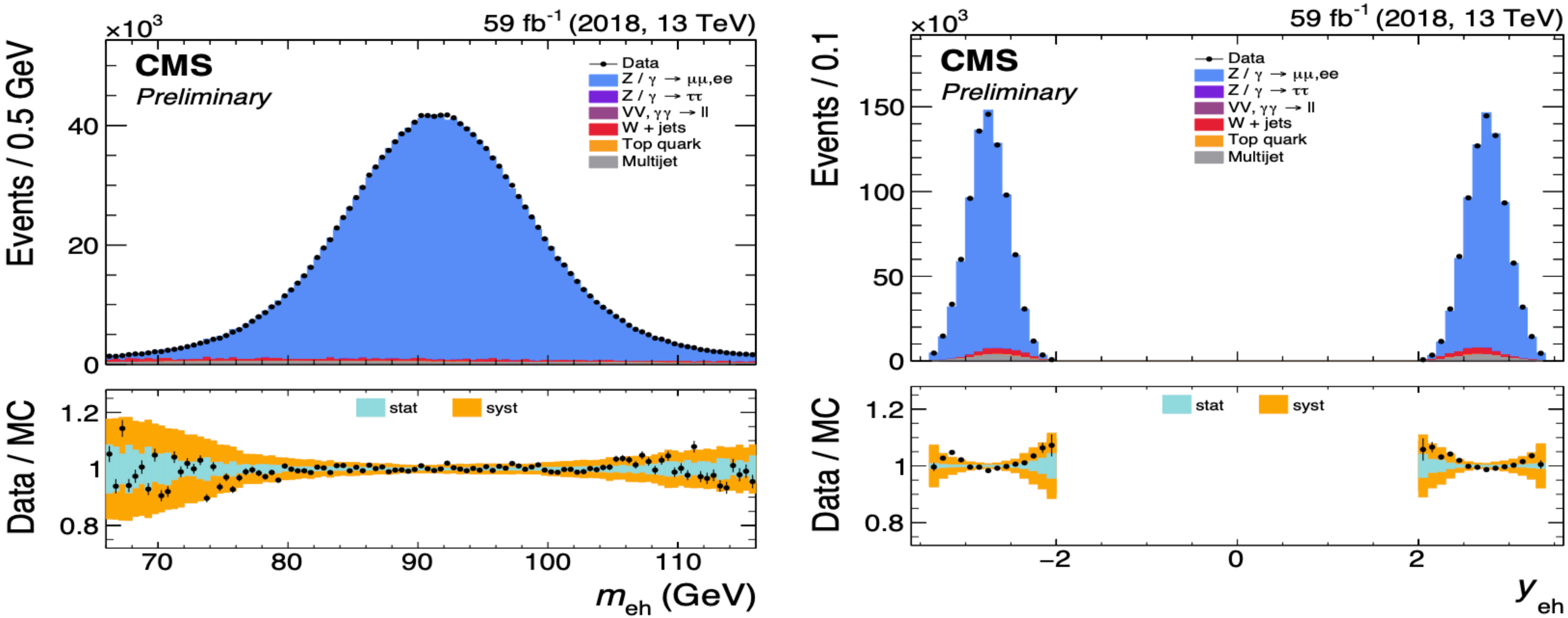

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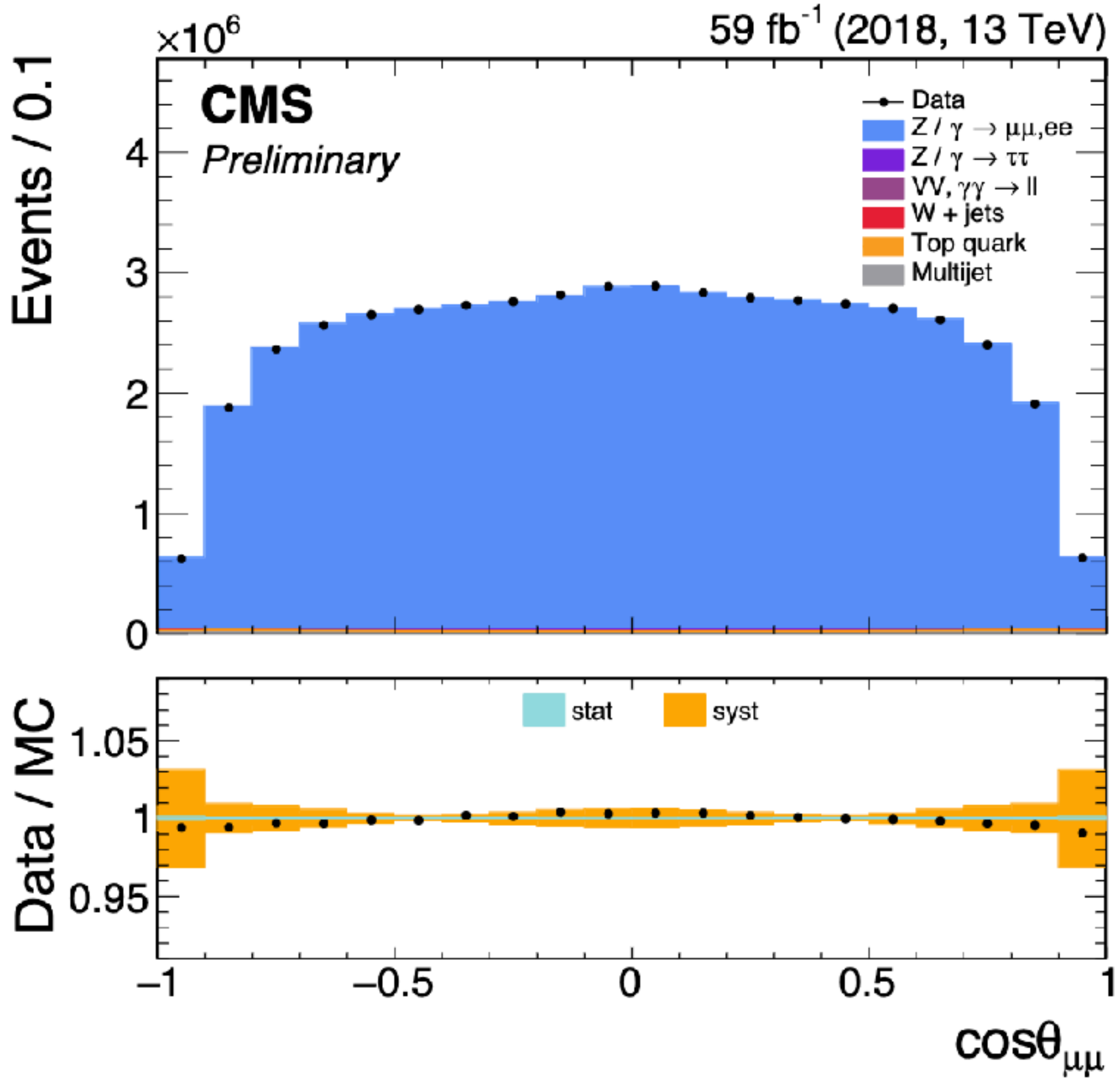
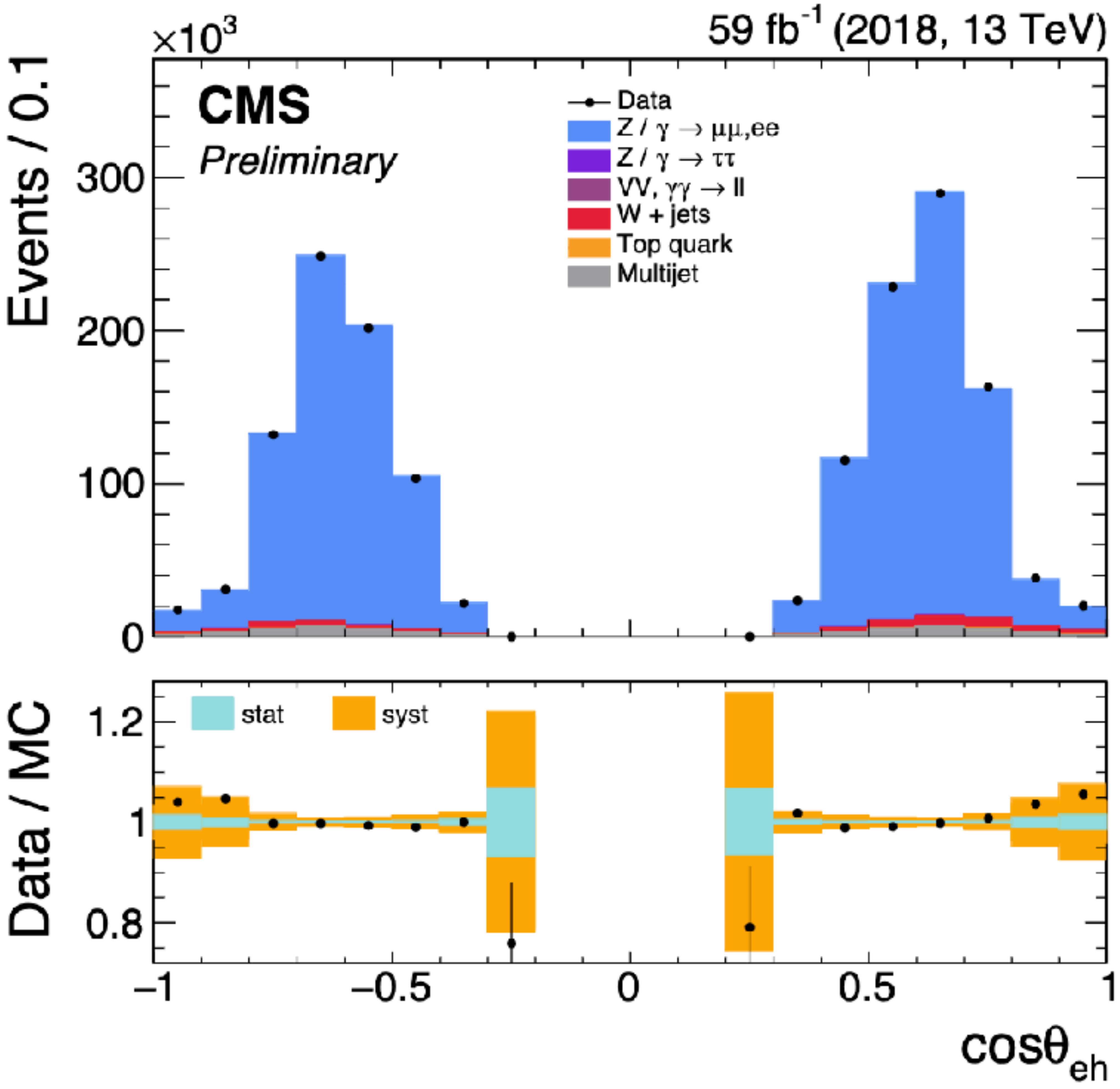


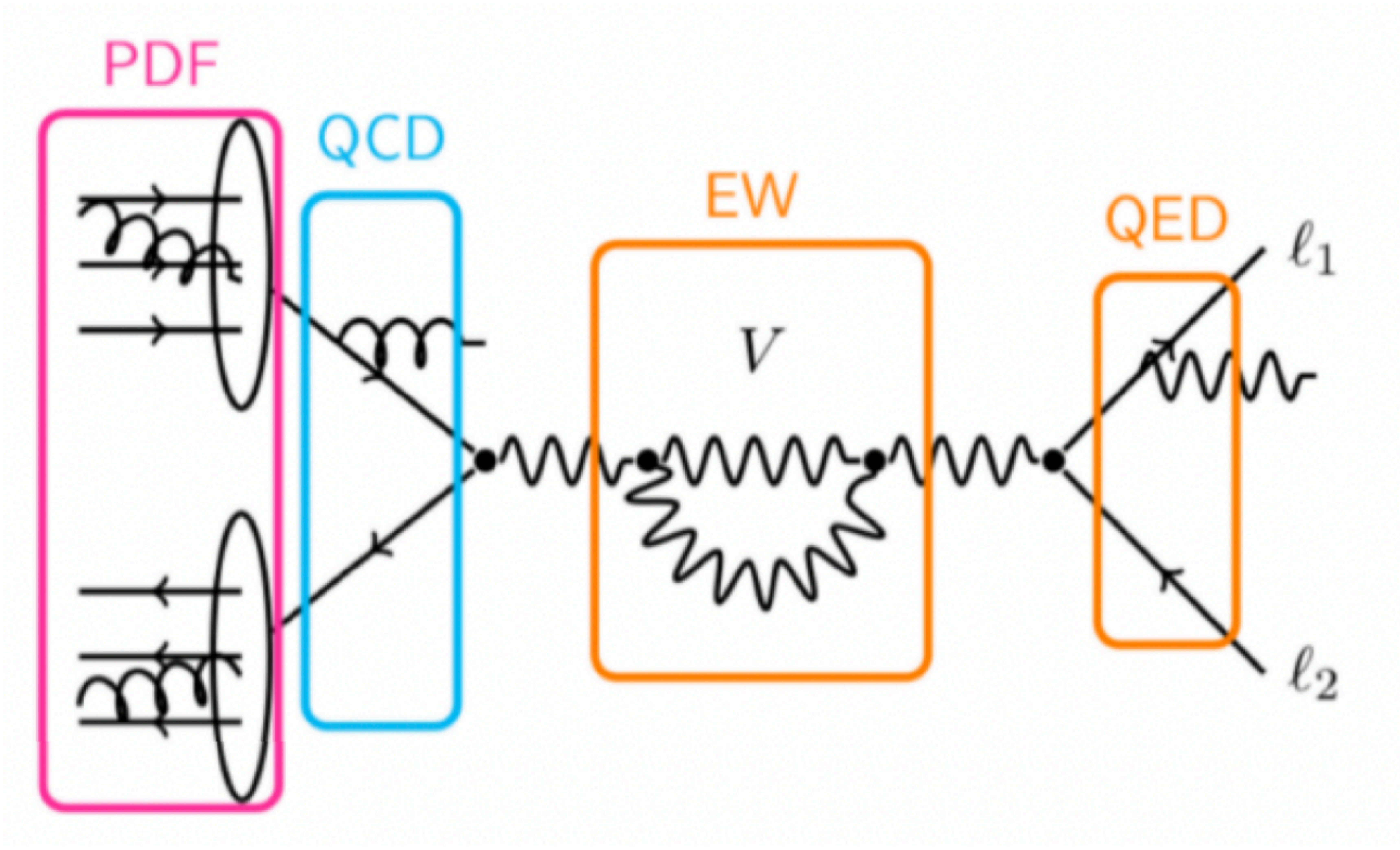


Measurement binning

- The observed reconstructed weighted $A_{\mathrm{FB}}(y, m)$ is used for the $\sin^2\theta^l_{\mathrm{eff}}$ extraction
- The measurement is performed in 9 bins of dilepton rapidity, with y up to 3.4 and in 11 bins of dilepton mass, with y between 54 GeV and 150 GeV
- A different binning is used to determine the unfolded $A_4(y, m)$, driven by the dilepton mass resolution

channel						bin boundaries							# of bins
$\lvert y_{\ell\ell}\rvert$	0.0	0.4	0.8	1.2	1.6	2.0	2.4	2.7	3.0	3.4			9
$\mu\mu, ee$	I	I	I	I	I	I	I						6
eg				I	I	I	I	I					4
eh						I	I	I	I	I			4
$m_{\ell\ell}$ (GeV)	54.0	66.0	76.0	82.0	86.0	89.5	92.7	96.0	100.0	106.0	116.0	150.0	11
						Observed $A^w_{\mathrm{FB}}(y, m)$ fit							
$\mu\mu, ee$	I	I	I	I	I	I	I	I	I	I	I	I	11 × 6
eg, eh		I	I	I	I	I	I	I	I	I	I		9 × 4
						$A_4(Y, M)$ unfolding and interpretation							
$0.0 < y < 1.2$	I	I	I	I	I	I	I	I	I	I	I	I	11 × 3
$1.2 < y < 2.4$	I	I	I		I			I		I	I	I	7 × 3
$2.4 < y < 3.4$		I			I			I			I		3 × 3

Interpretation model



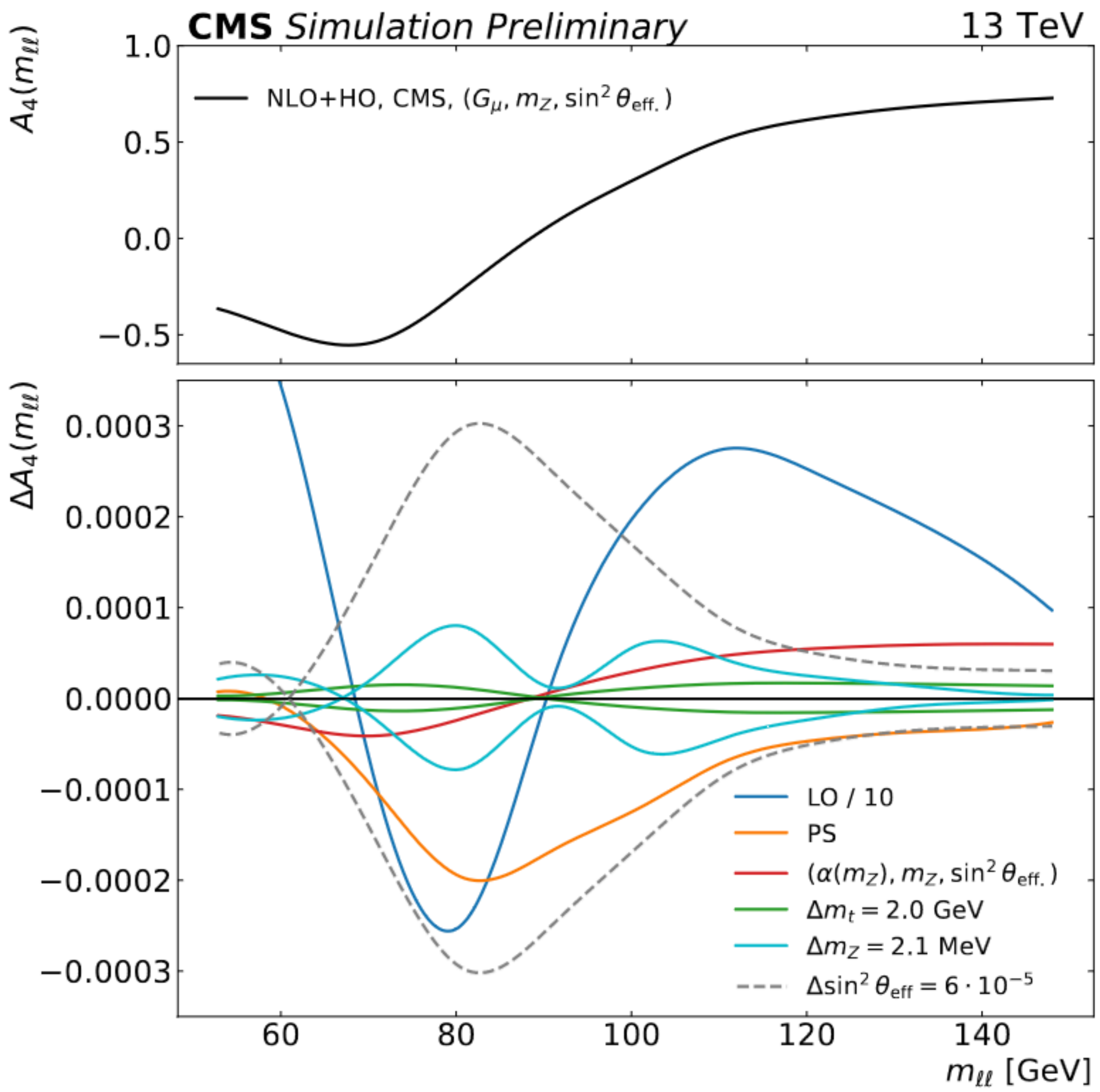
NLO weak corrections in Powheg-Box

- Remaining electroweak corrections from **virtual electroweak loops**
  - Can be estimated separately from photonic corrections in a gauge-invariant way

- Calculated at NLO with the Powheg **Z_EW-BMNNPV** Monte Carlo program
  - *renormalization scheme* with $(G_F, \sin^2\theta_w^{\overline{MS}}(\mu), m_Z)$ as inputs
  - Vary $\sin^2\theta_w^{\overline{MS}}(\mu)$ for a *consistent direct determination* with template fits
  - Universal two-loop *higher order corrections* to $\Delta\alpha$, $\Delta\rho$ included
  - Treatment of unstable resonance in the *Complex-Mass-Scheme*
  - Corrections benchmarked against many other codes in LHCEWWG activities

- Implemented as weights on top of NLO QCD + shower events, used to reweigh MiNNLOPS

NLO weak uncertainties



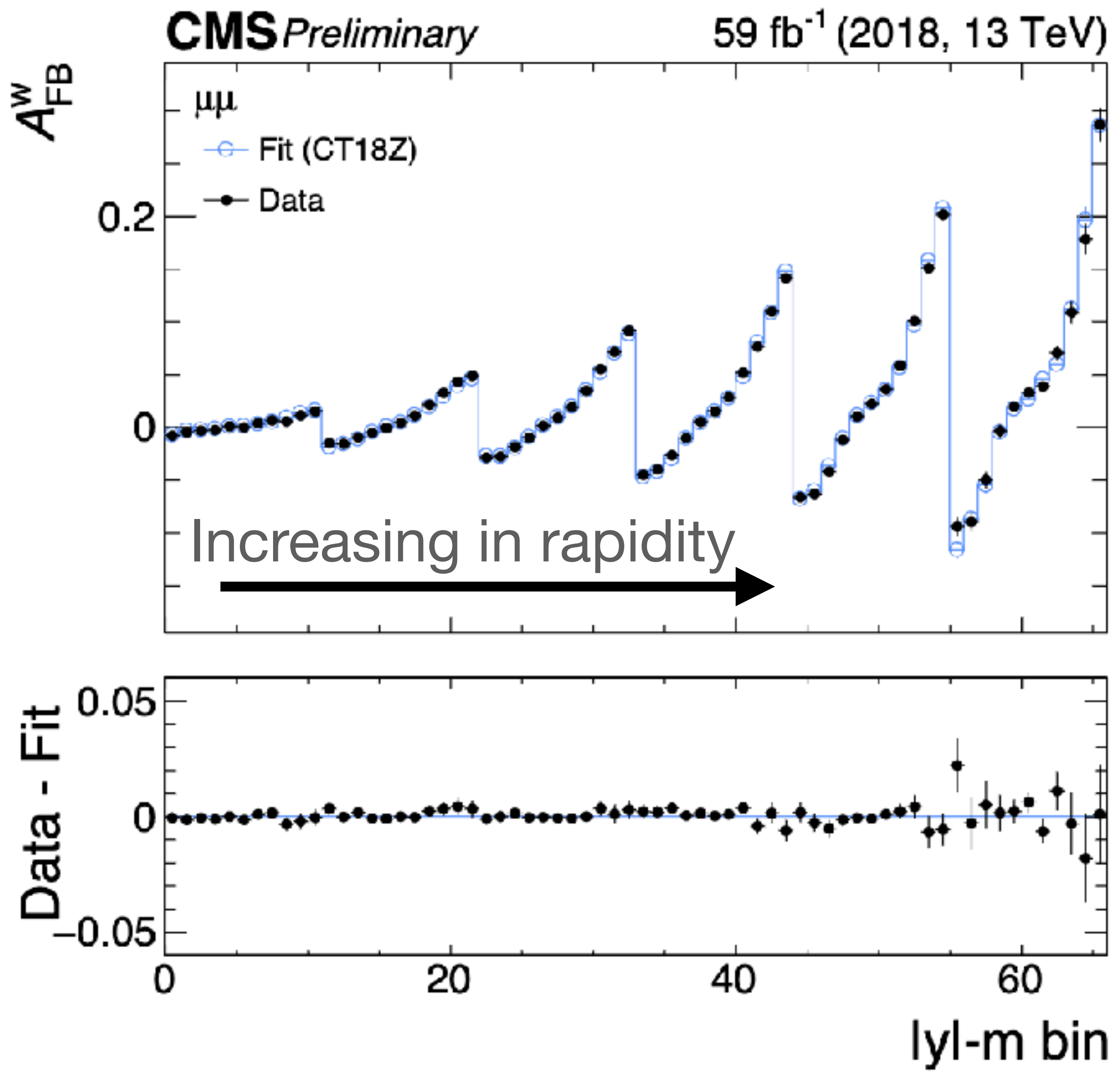
- Several sources of uncertainties are considered on the NLO weak corrections
- Comparison of the complex-mass and pole scheme for the treatment of the finite width
- Comparison between the $(G_F, m_Z, \sin^2\theta^l_{\text{eff}})$ and $(\alpha(m_Z), m_Z, \sin^2\theta^l_{\text{eff}})$ input EW schemes
- Parametric uncertainties on the measured values of m_t and m_Z (others negligible)

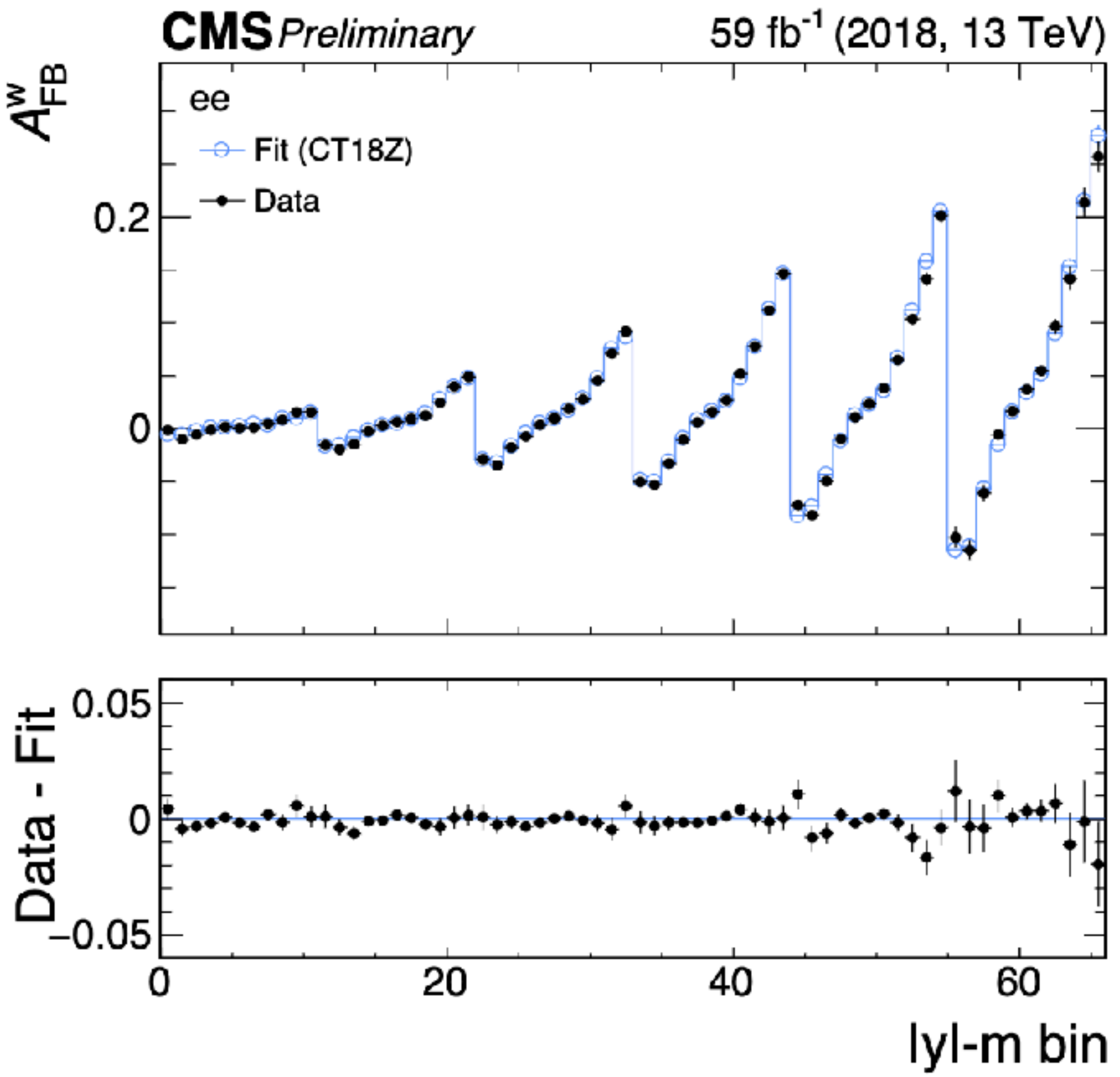
A_{FB} FIT

- $\sin^2\theta^{l}_{\text{eff}}$ extracted in a simultaneous fit to $A_{\text{FB}}(y, m)$ in all measurement bins and channels
- Minimising $$\chi^2(s,\vec{\theta}) = |\vec{\theta}|^2 + \sum_r \sum_c \left(D_{rc} - T_{rc}(s,\vec{\theta})\right)^T V_{rc}^{-1} \left(D_{rc} - T_{rc}(s,\vec{\theta})\right)$$

Covariance

Nuisances — runs, channels — Data — Theory prediction





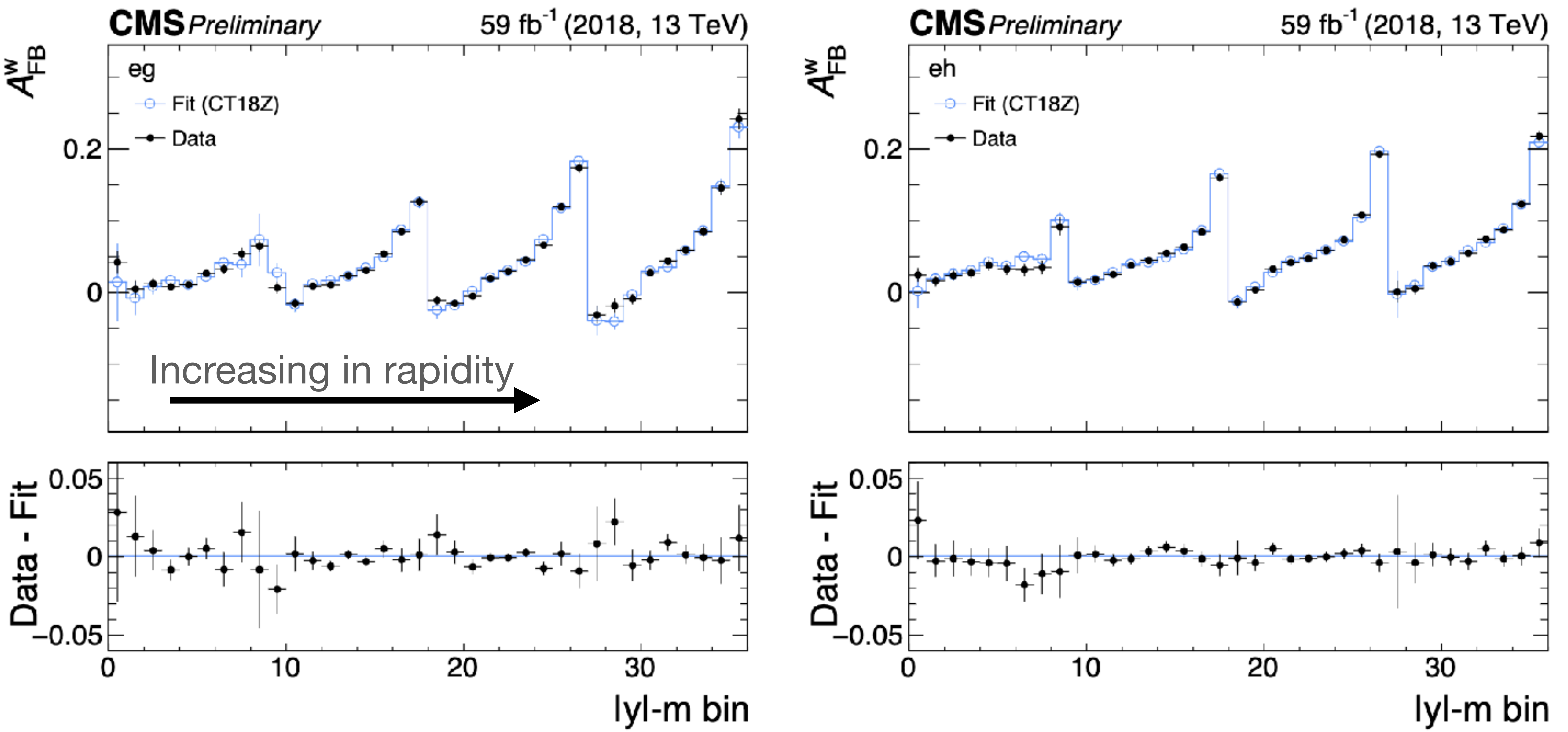
AFB fit

- $\sin^2\theta^l_{\rm eff}$ extracted in a simultaneous fit to $A_{\rm FB}(y,m)$ in all measurement bins and channels
- Minimising

$$\chi^2(s,\vec{\theta}) = |\vec{\theta}|^2 + \sum_r \sum_c \left(D_{rc} - T_{rc}(s,\vec{\theta})\right)^T V_{rc}^{-1} \left(D_{rc} - T_{rc}(s,\vec{\theta})\right)$$

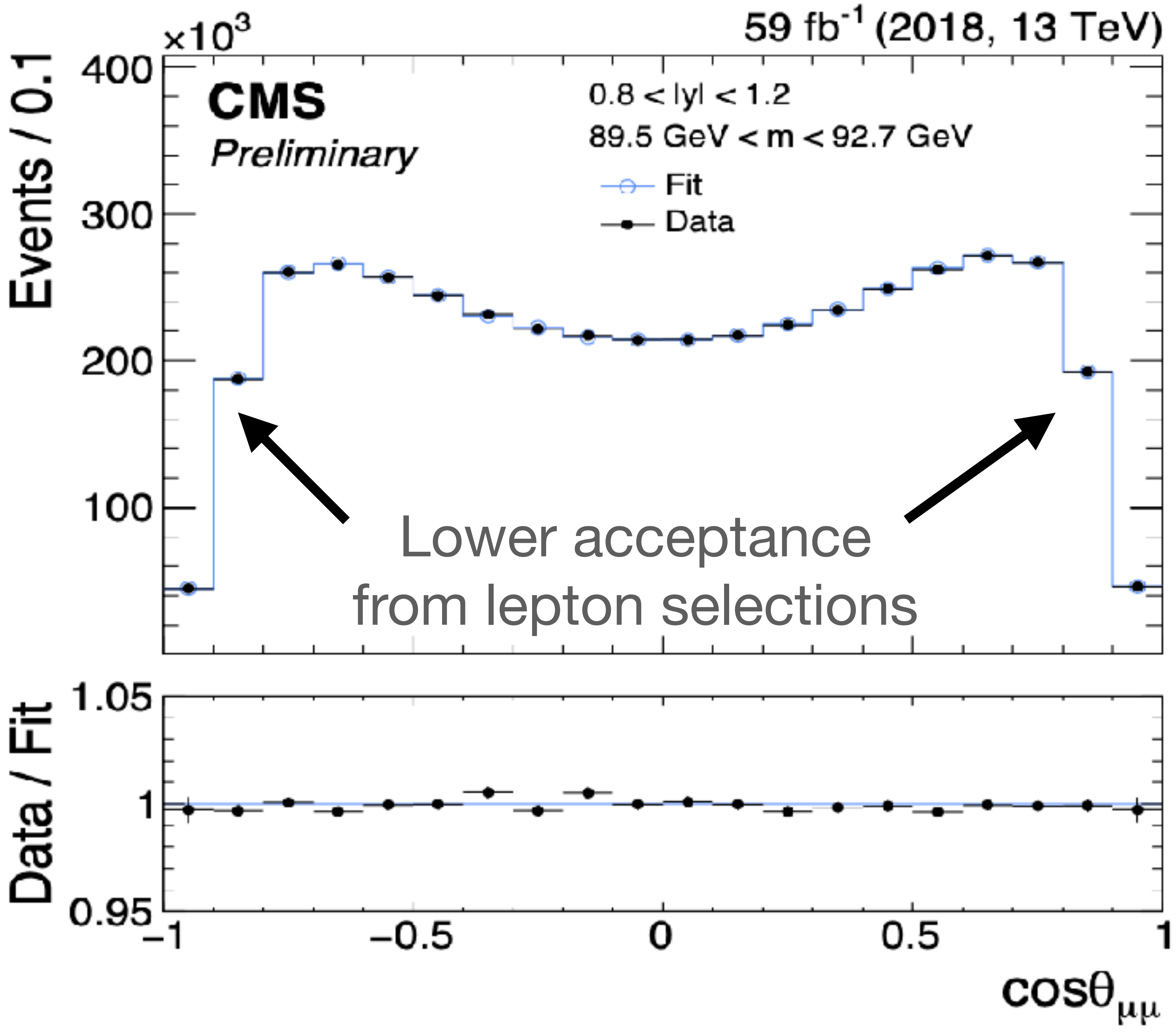
Covariance

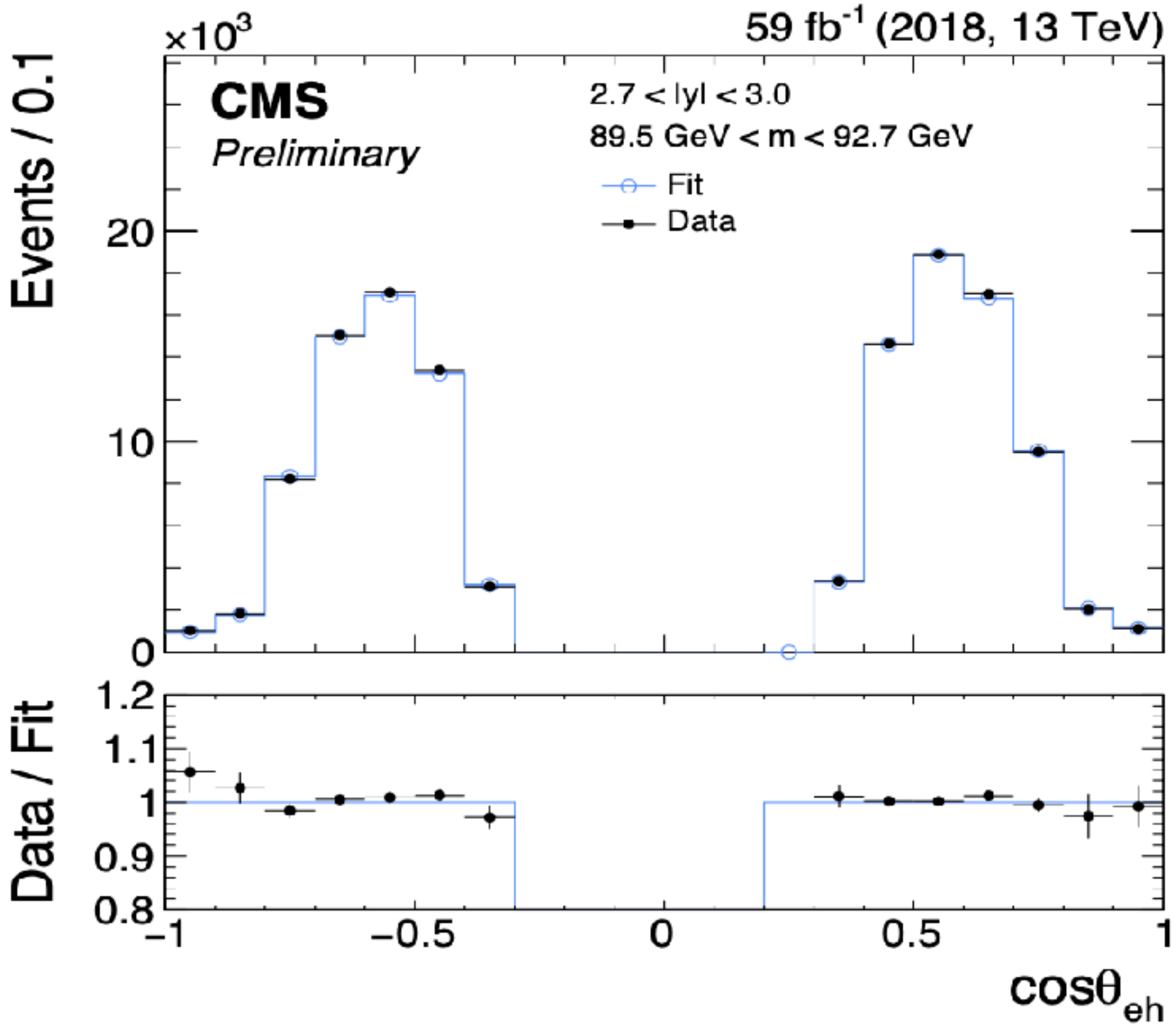
Nuisances — runs, channels — Data — Theory prediction



A4 measurement

- Additionally, $A_4(y, m)$ is measured from the reconstructed $\cos\theta_{CS}$ distribution
- Total fit χ^2= 14839 for total of 14205 measurement bins and 101 free parameters





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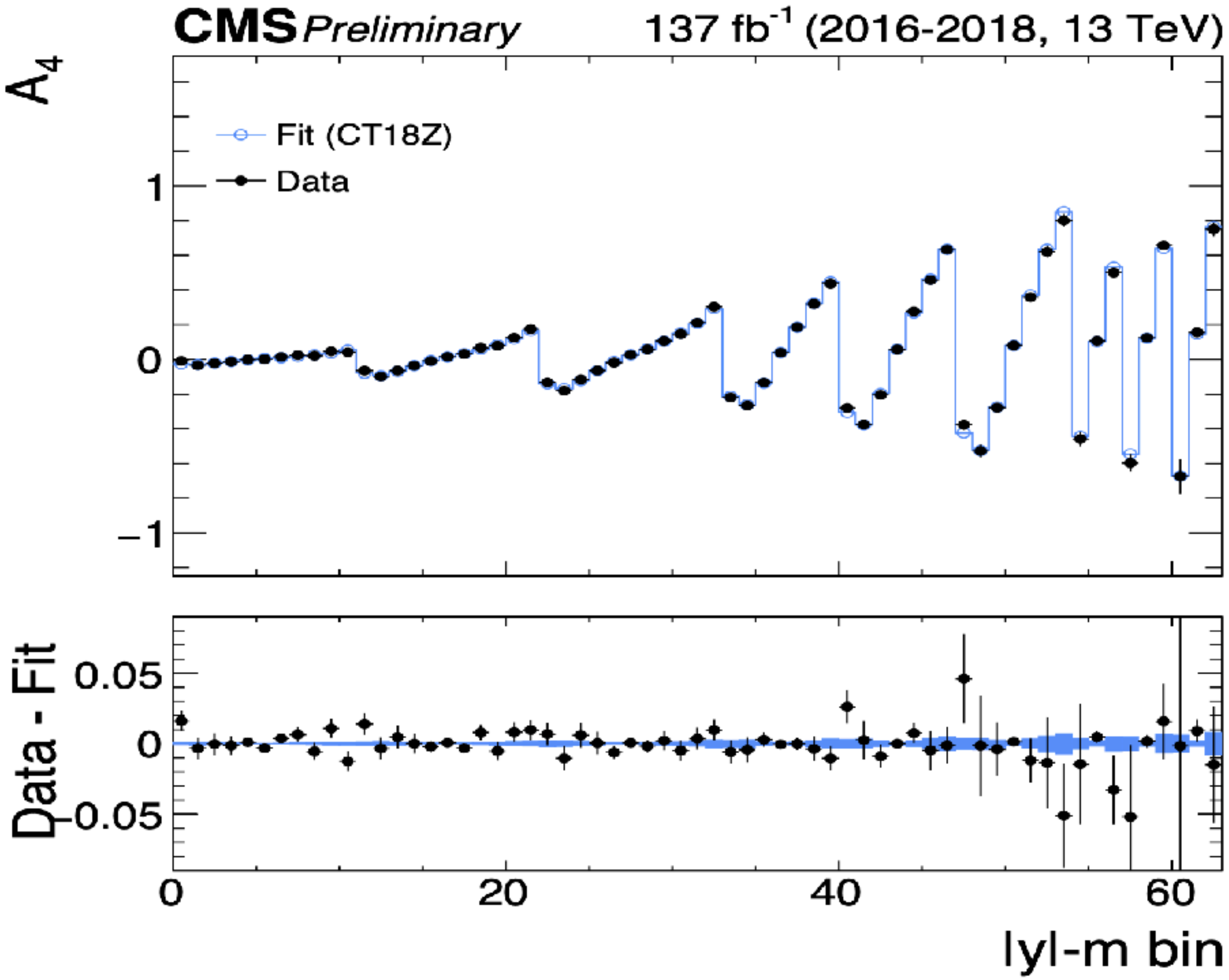
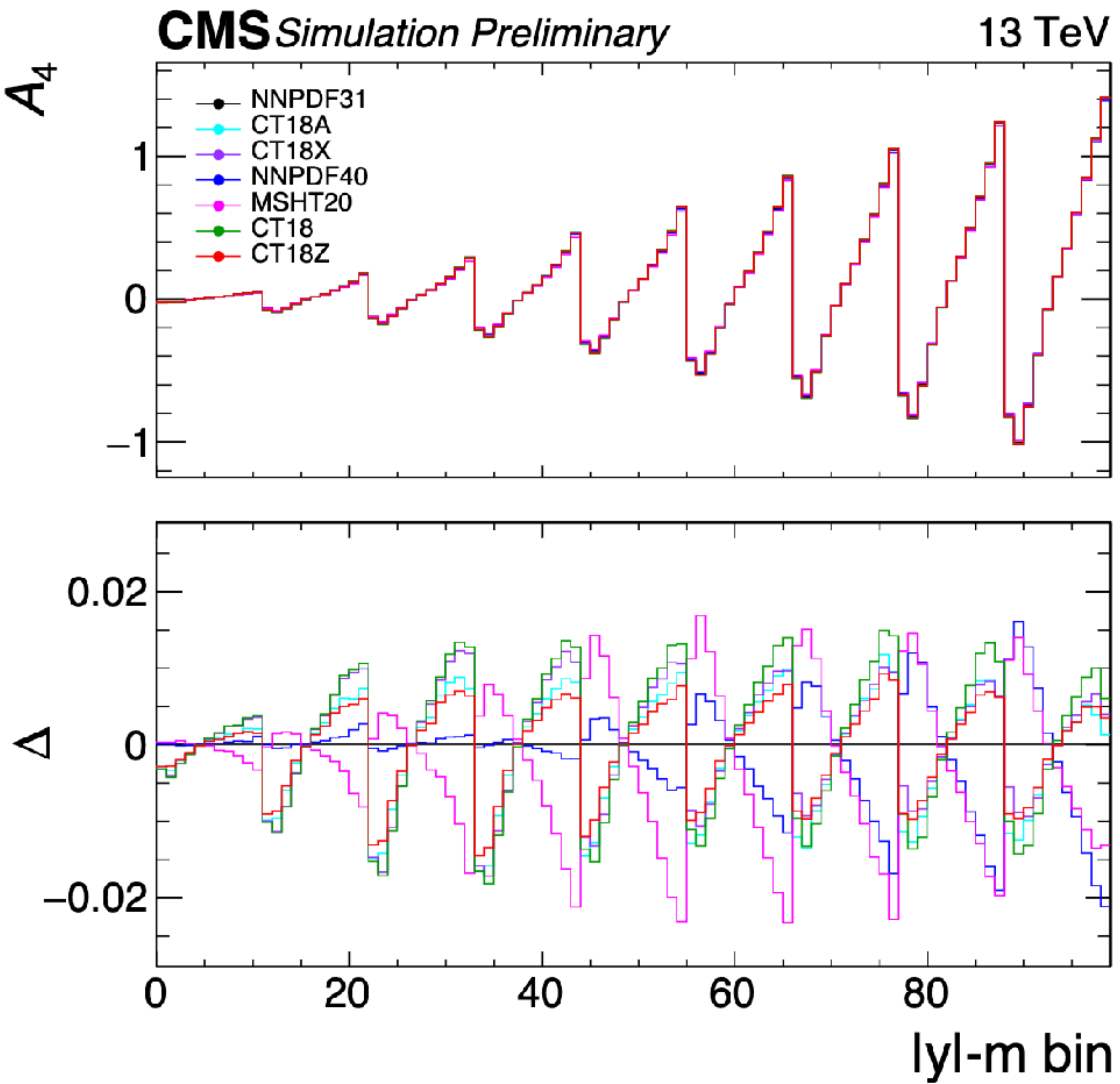


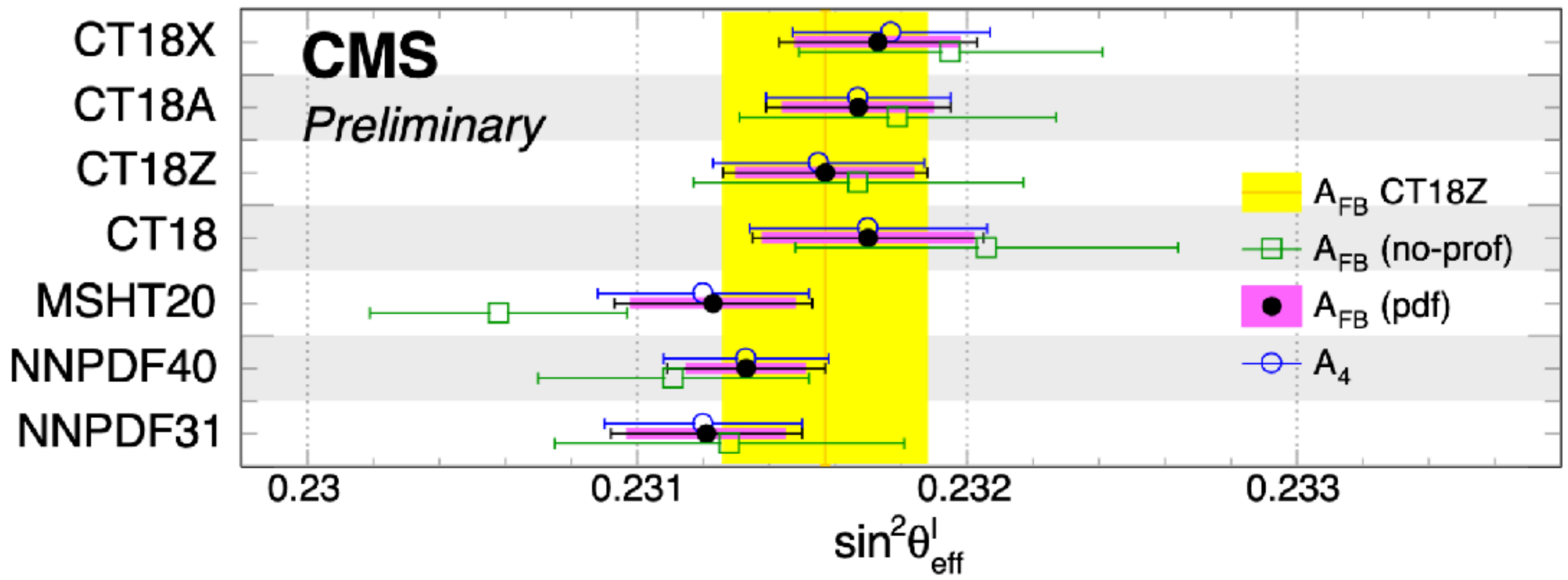
Parton distribution functions dependence of A_4



Choice of parton distribution functions

- All PDF sets provide an equally good description of the data
- PDF spread and uncertainties reduced in the fit

PDF	A_{FB} (816 bins)		A_4 (63 bins)	
	χ^2_{min}	$\sin^2\theta^\ell_{eff}$	χ^2_{min}	$\sin^2\theta^\ell_{eff}$
NNPDF31	724.7	23121 ± 29	58.5	23120 ± 30
NNPDF40	730.5	23133 ± 24	62.6	23133 ± 25
MSHT20	735.8	23123 ± 30	71.0	23120 ± 32
CT18	728.4	23170 ± 35	62.2	23170 ± 36
CT18Z	730.7	23157 ± 31	61.3	23155 ± 32
CT18A	730.3	23167 ± 28	63.6	23167 ± 28
CT18X	728.5	23173 ± 30	61.8	23177 ± 30



- But $\sin^2\theta^l_{eff}$ values with different PDFs are only consistent at the ~1 sigma level
- Use CT18Z as covering the central values obtained with the other sets

Hessian Profiling of PDFs

- Include the PDF eigenvectors in the χ^2/likelihood as covariance or nuisances

Data Theory

$$\chi^2(\mathbf{b}_{\mathrm{exp}}, \mathbf{b}_{\mathrm{th}}) = \sum_{i=1}^{N_{\mathrm{data}}} \frac{\left[D_i - T_i(1 - \sum_k \gamma_{ik}^{\mathrm{th}} b_{k,\mathrm{th}} - \sum_j \gamma_{ij}^{\mathrm{exp}} b_{j,\mathrm{exp}})\right]^2}{\delta_{i,\mathrm{uncor}}^2 T_i^2 + \delta_{i,\mathrm{stat}}^2 D_i T_i}$$

Nuisance parameter impacts

$$+ \sum_i \log \frac{\delta_{i,\mathrm{uncor}}^2 T_i^2 + \delta_{i,\mathrm{stat}}^2 D_i T_i}{\delta_{i,\mathrm{uncor}}^2 D_i^2 + \delta_{i,\mathrm{stat}}^2 D_i^2}$$

Uncorrelated and statistical uncertainties

Experimental nuisances

$$+ \sum_{j=1}^{N_{\mathrm{exp.sys}}} b_{j,\mathrm{exp}}^2 + \sum_{k=1}^{N_{\mathrm{th.sys}}} b_{k,\mathrm{th}}^2.$$

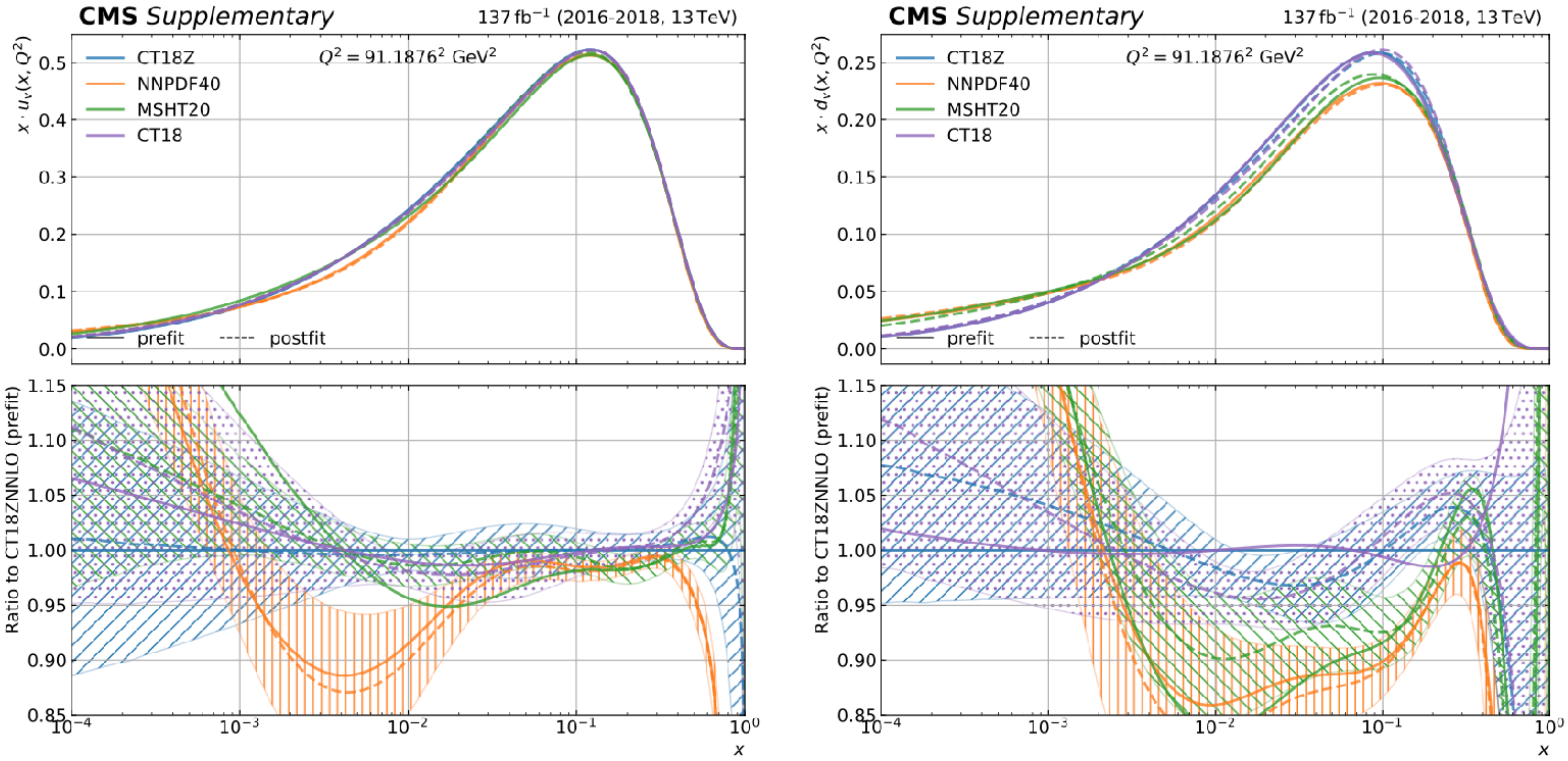
Theory nuisances

- Let the data shift and constrain (a linear combination of) them
- The values of the nuisance parameters at the minimum define a new profiled PDF with (generally) smaller uncertainties

$$f_0' = f_0 + \sum_k b_{k,\mathrm{th}}^{\mathrm{min}} \left(\frac{f_k^+ - f_k^-}{2} + b_{k,\mathrm{th}}^{\mathrm{min}} \frac{f_k^+ + f_k^- - 2f_0}{2} \right)$$

- This reduction in PDF uncertainties happens as long as their covariance is included in the fit, even if the nuisance parameters are not explicitly used

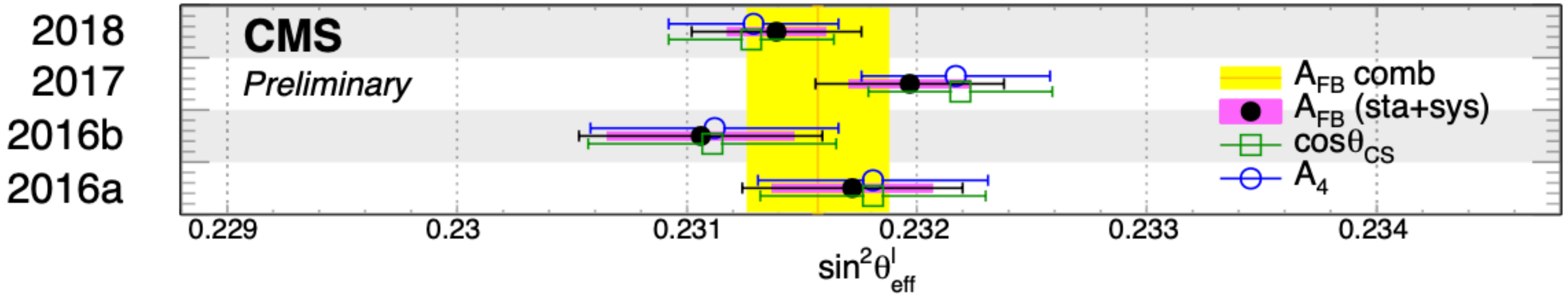
Pre- and Post-fit PDFs comparison

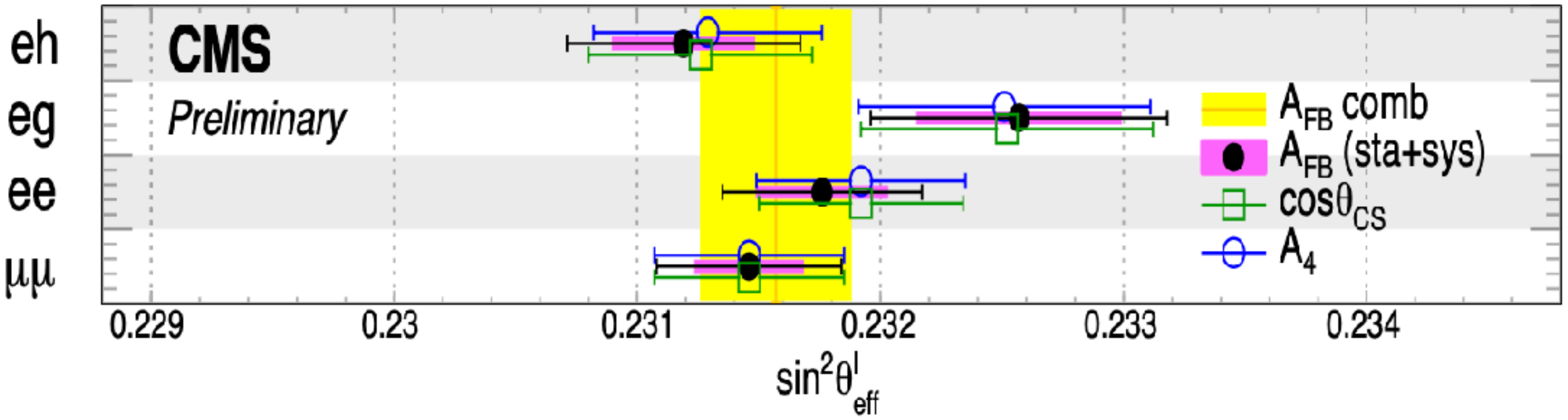


- The profiled PDFs are pulled by less than one sigma wrt the original ones
- CT18Z is the least pulled of the PDF sets considered (corroborating our choice)

Channels and years compatibility

- Many consistency checks performed before unblinding the central value of $\sin^2\theta^l_{\text{eff}}$
  - Channels consistency
  - Run consistency
  - Consistency between different fits: A_4, A_{FB}, $\cos\theta_{CS}$





- All tests found in agreement within their uncertainties

$\sin^2\theta^l_{\rm eff}$ CONSISTENCY AND ERROR BREAKDOWN

From weighted forward-backward asymmetry

ch	χ^2	nbin	p(%)	$\sin^2\theta^\ell_{\rm eff}$	$\pm$	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

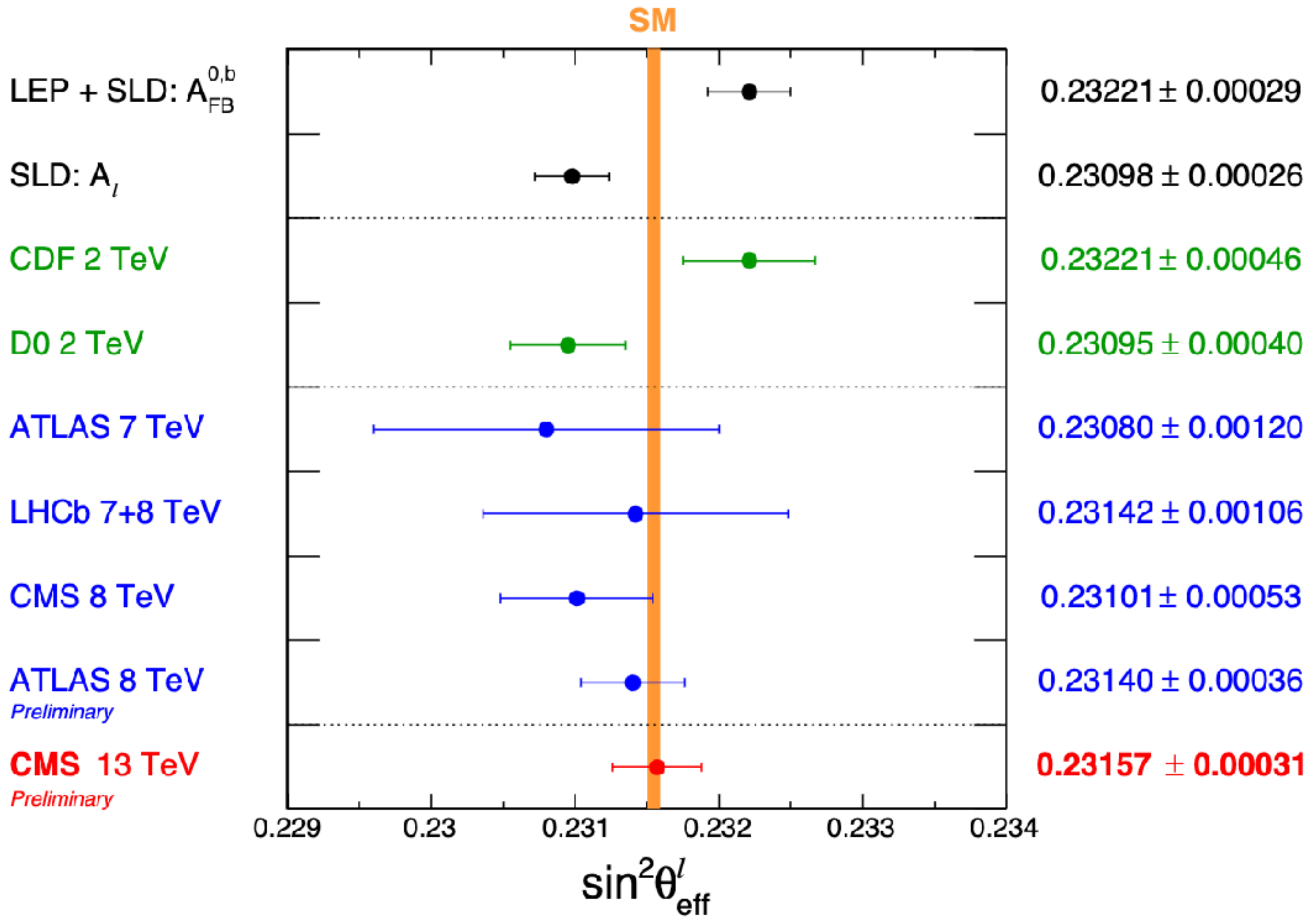
From differential unfolded A_4

Channel	n(bins)	$\chi^2_{\rm min}$	p(%)	$\sin^2\theta^\ell_{\rm eff}$	$\pm$	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

- The final combined result for $\sin^2\theta^{l}_{\text{eff}}$, using CT18Z parton densities is:

$$\sin^2\theta^{\ell}_{\text{eff}} = 0.23157 \pm 0.00010\,(\text{stat}) \pm 0.00015\,(\text{syst}) \pm 0.00009\,(\text{theo}) \pm 0.00027(\text{PDF})$$

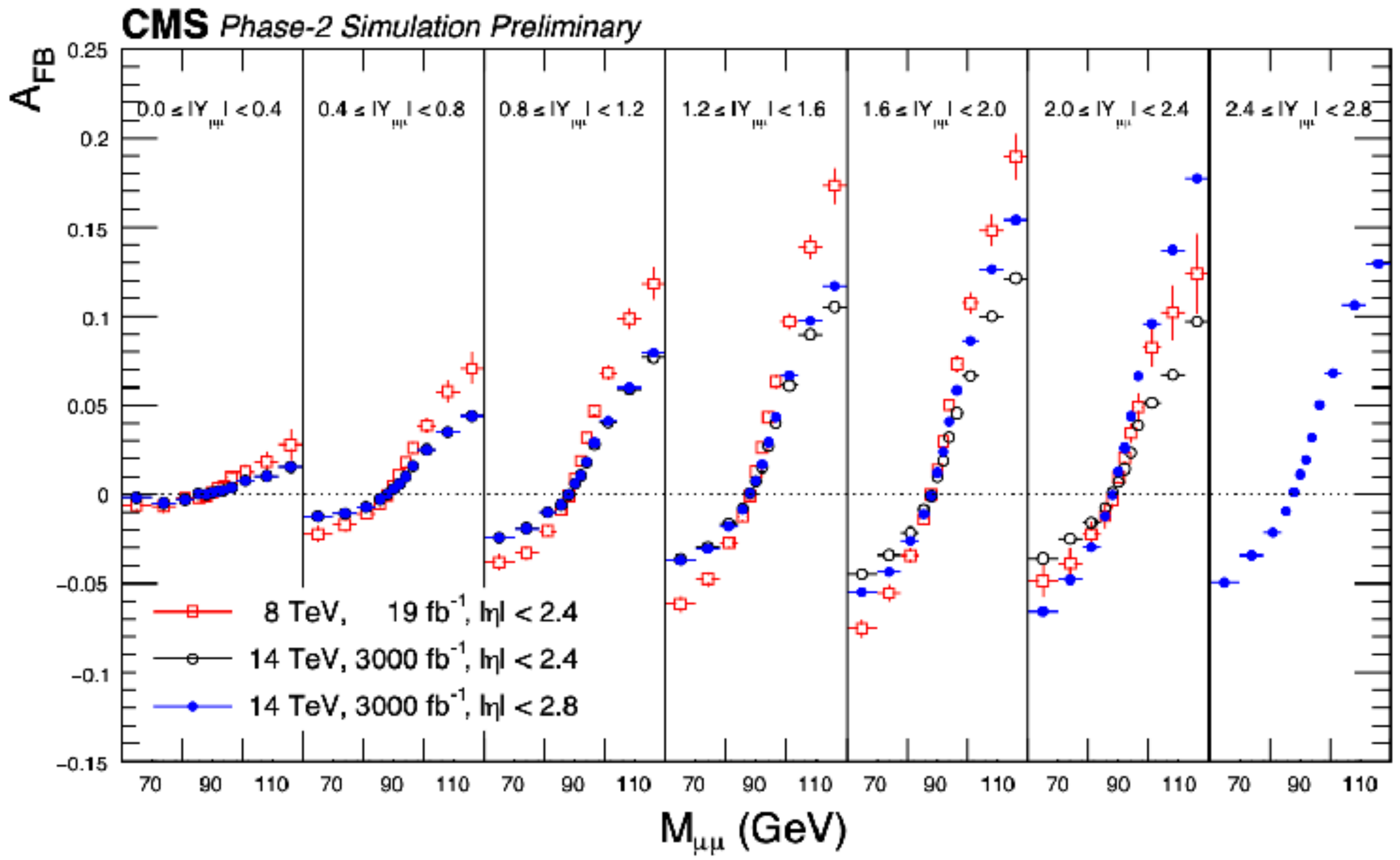


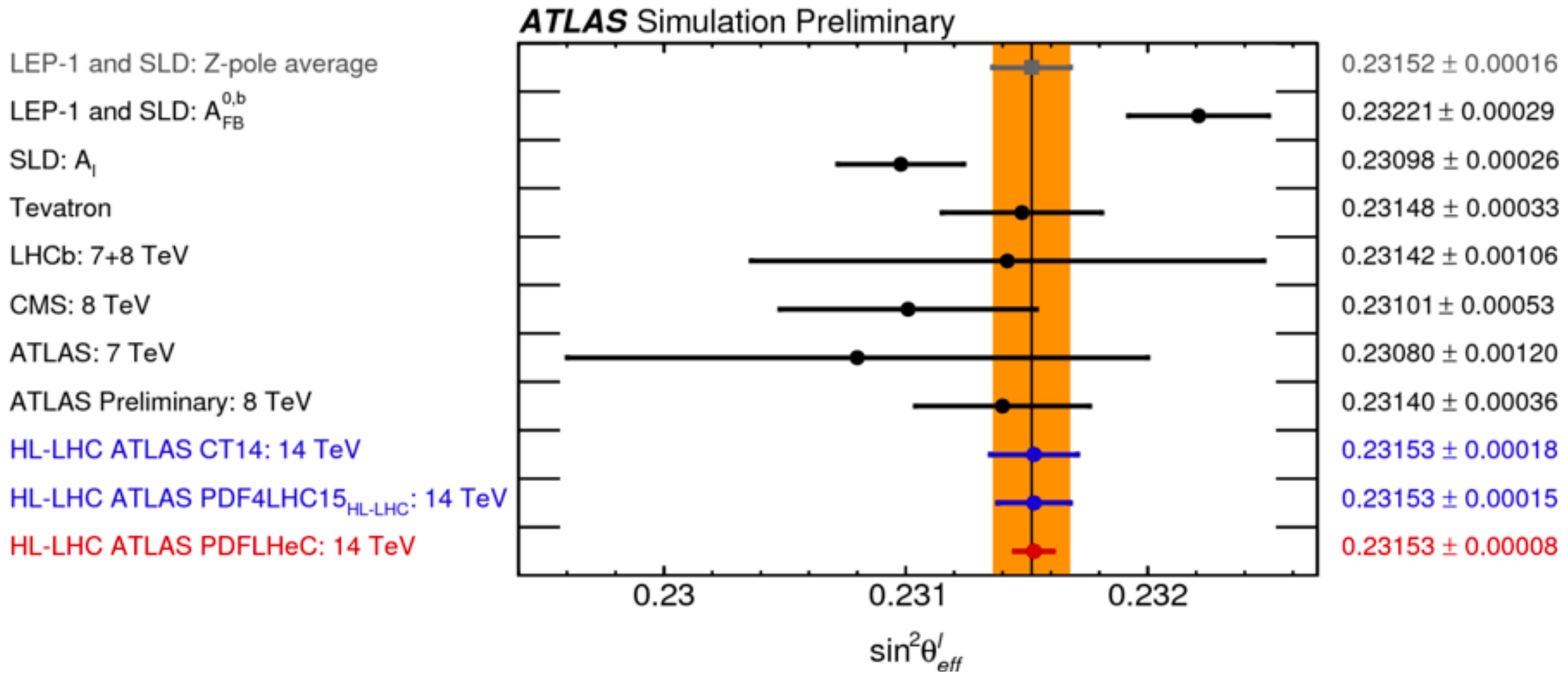
- Most precise extraction at hadron collider
- Excellent agreement with the world average and the SM prediction of 0.23155 ± 0.00004
- Precision comparable to LEP/SLD (26-29 10^{-5})

Prospects for High-Luminosity

- In the High-Luminosity phase of the LHC we expect to collect up to 3 ab^{-1} of integrated luminosity

https://arxiv.org/abs/1902.04070

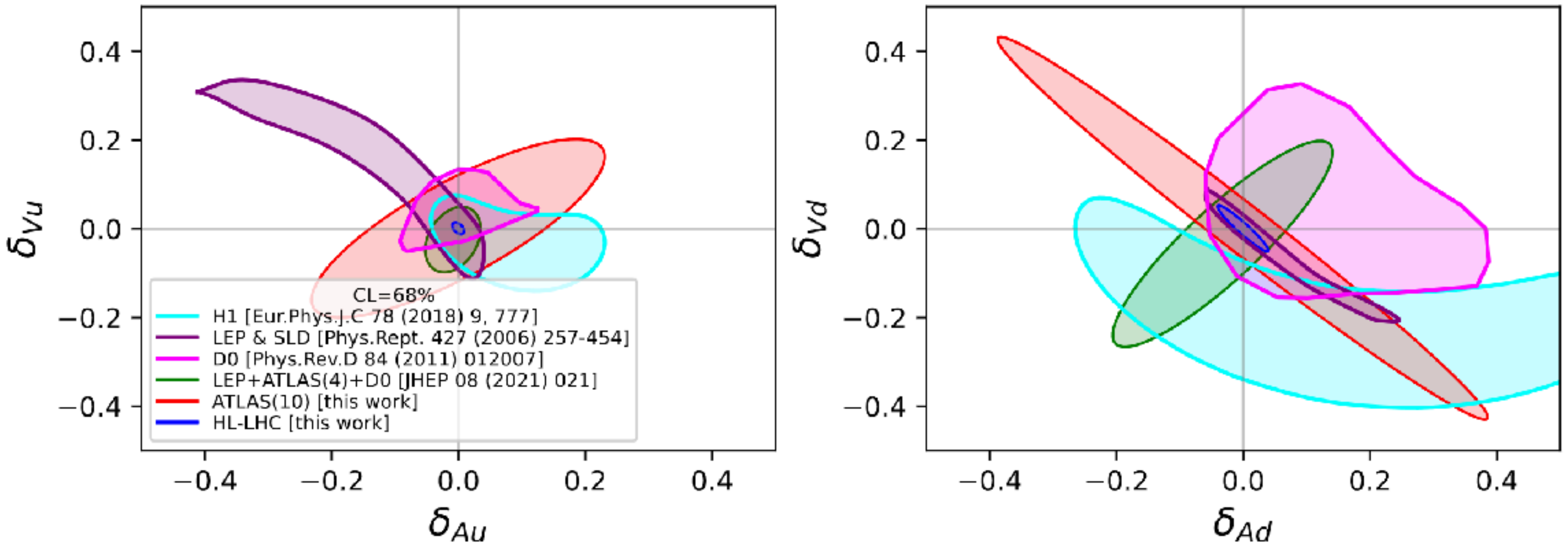




	ATLAS $\sqrt{s} = 8$ TeV	ATLAS $\sqrt{s} = 14$ TeV	ATLAS $\sqrt{s} = 14$ TeV
$\mathcal{L}$ [fb^{-1}]	20	3000	3000
PDF set	MMHT14	CT14	PDF4LHC15$_{HL-LHC}$
$\sin^2\theta^{lept}_{eff}$ [$\times 10^{-5}$]	23140	23153	23153
Stat.	± 21	± 4	± 4
PDFs	± 24	± 16	± 13
Experimental Syst.	± 9	± 8	± 6
Other Syst.	± 13	-	-
Total	± 36	± 18	± 15

- Thanks also to extended tracker coverage in the forward region expect to half the current uncertainties
- Another factor of two could possibly come from improved PDF determinations

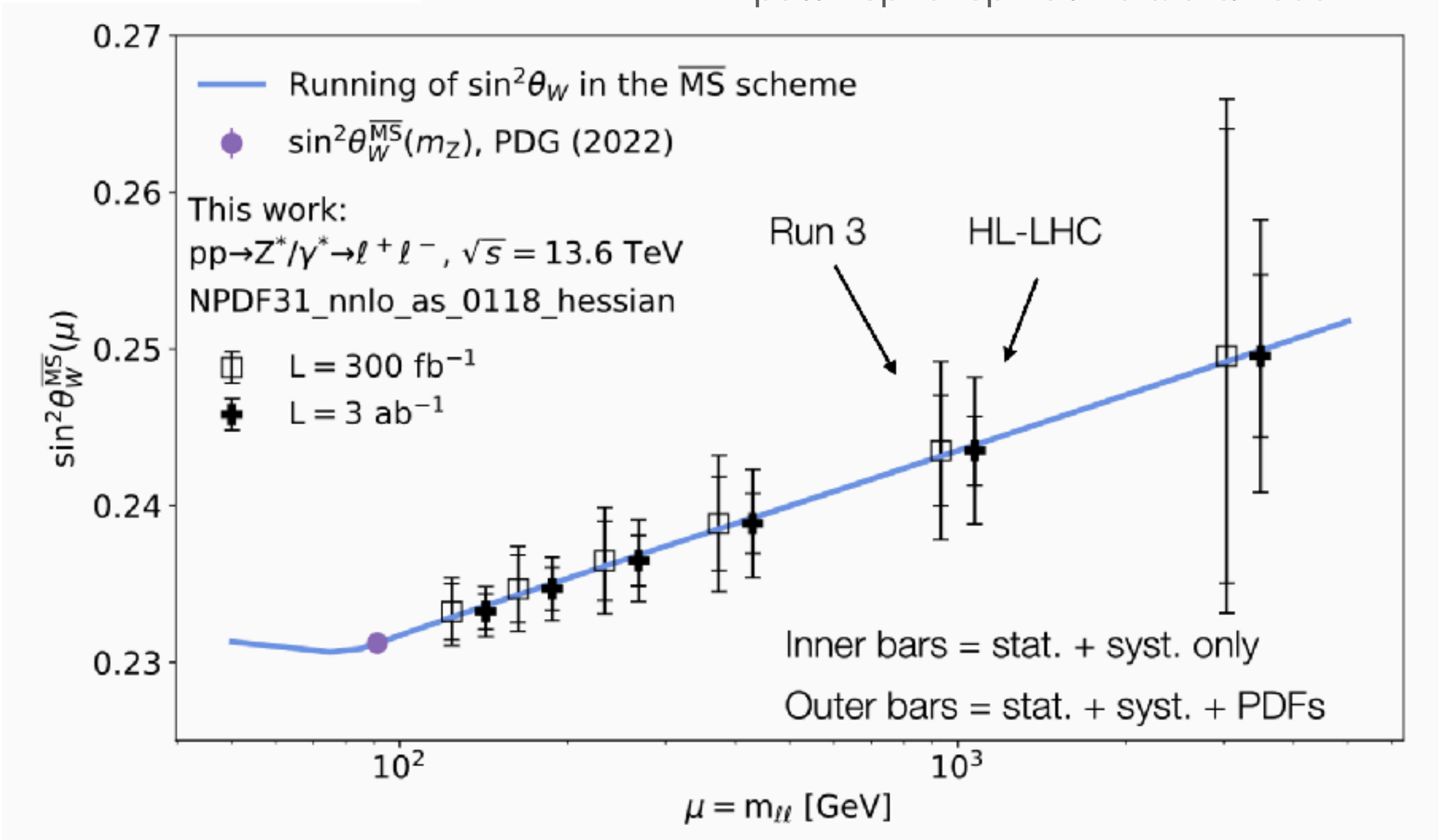
Further possibilities



https://inspirehep.net/literature/2715747

- Determine effective vector/axial couplings for each fermion type
- LHC can set the most stringent constraints for light-quarks

https://inspirehep.net/literature/2635122

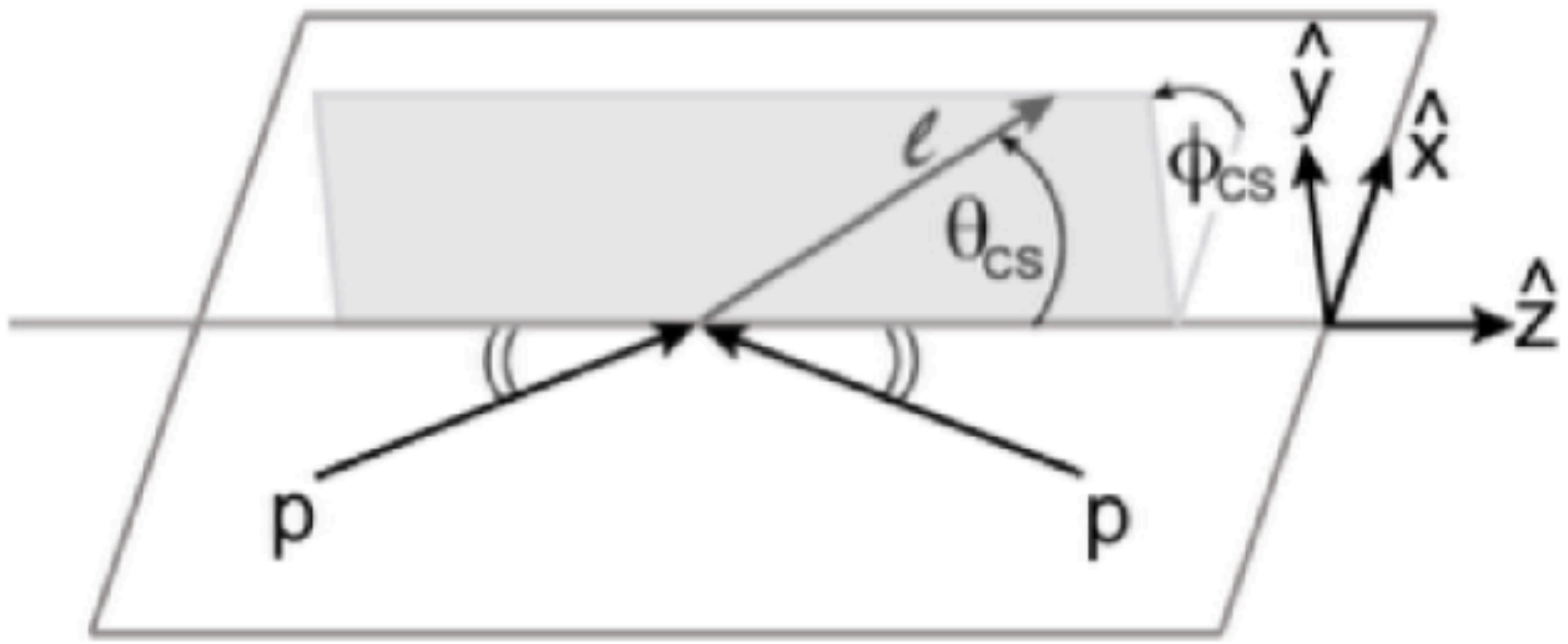


- Determine the weak mixing angle as a function of the scale in the MSbar (running) scheme
- Enhance sensitivity to high-energy loop effects

Summary

- New CMS measurement of differential $A_{\mathrm{FB}}(y, m)$ and A_4 using Run2 13 TeV data
- Results in the most precise measurement of $\sin^2\theta^l_{\mathrm{eff}}$ at a hadron collider
  $\sin^2\theta^l_{\mathrm{eff}} = 0.23157 \pm 0.00031$ (comparable precision to LEP/SLD)
- Central value in agreement with previous measurements and with SM prediction
- PDFs are now limiting both precision and accuracy of the measurement
- Potential for the High-Luminosity LHC to reach the SM precision of $6 \cdot 10^{-5}$ assuming some not too unreasonable improvements on the PDFs

Backup



Angular Coefficients

Complete 5d cross section can be decomposed into
9 harmonic polynomials & 9 coefficients $A_i(m,y,pT)$
Description is complete to all orders in QCD

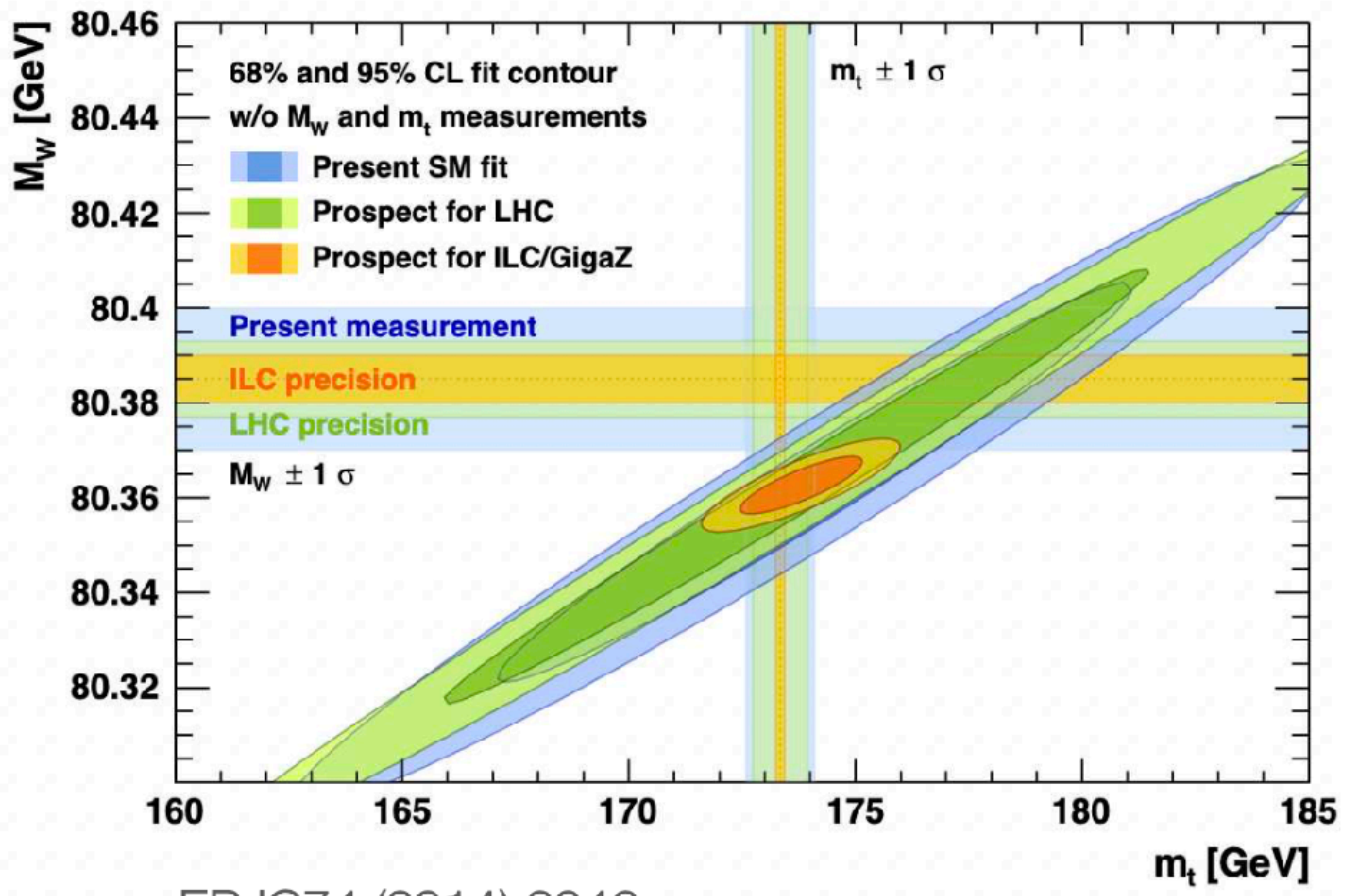
$$\frac{d\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta\, d\phi} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z} \Big\{(1+\cos^2\theta) + \frac{1}{2} A_0(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi + \frac{1}{2} A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta \cos\phi + A_4 \cos\theta + A_5 \sin^2\theta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

$$A_{FB} = \frac{8}{3} A_4$$

in full phase space

A_3 and A_4 related to $\sin^2\theta_{eff}$
(A_3 only contributes for $p_{T,Z}$ > 100 GeV)

HL-LHC projections



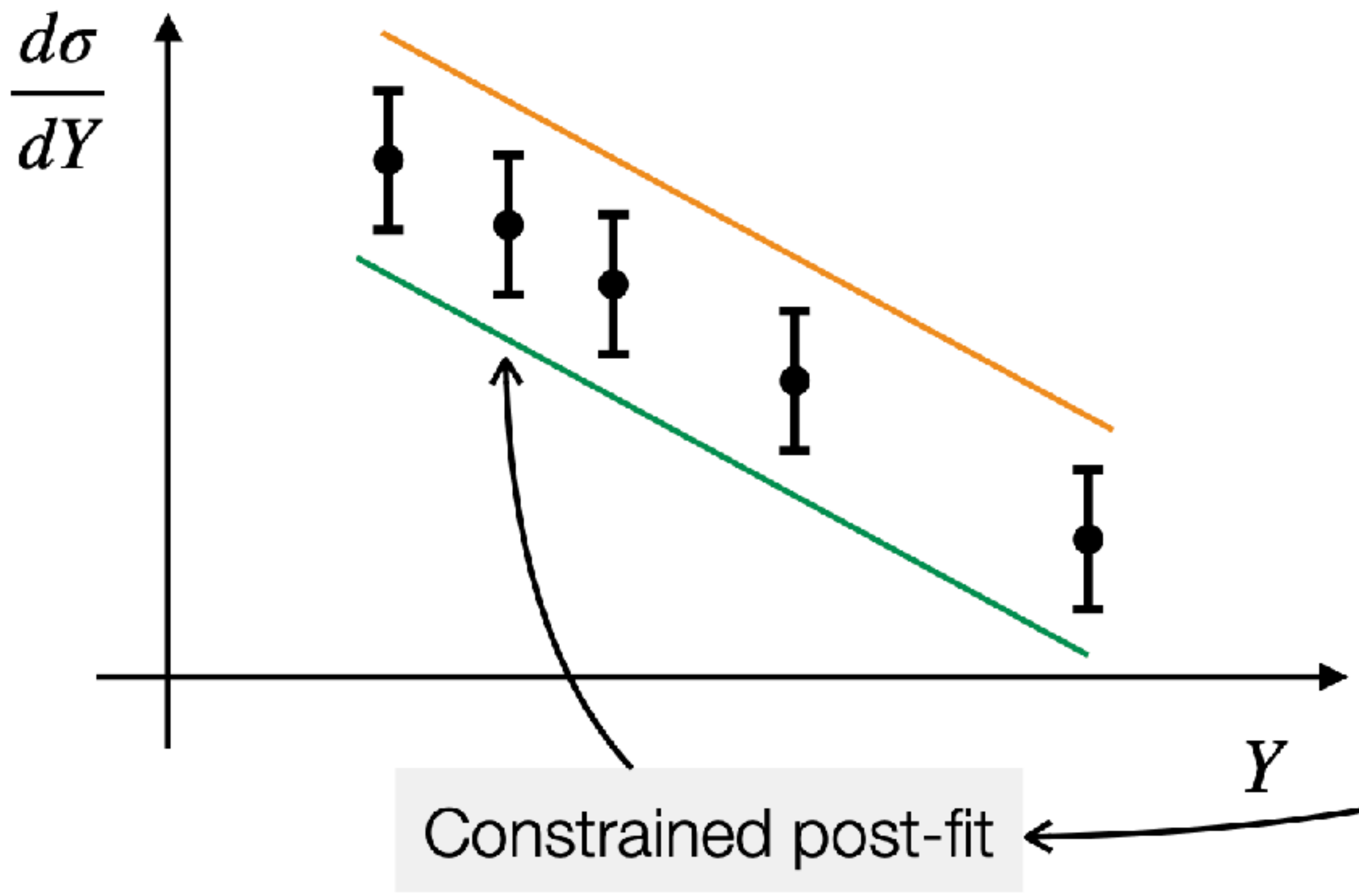
EPJC74 (2014) 3046

Parameter	Current precision	HL-LHC expected
m_H	170 MeV	10-20 MeV
$\sin^2\theta_{eff}$	50 10^{-5}	15 10^{-5}
m_W	20 MeV	4 MeV
m_t^{MC}	500 MeV	200 MeV
m_t^{pole}	~1 GeV	< 500 MeV
$\alpha_S(m_Z)$	~2%	~1%

Systematic uncertainties

- QCD scale variations and EW uncertainties are not included in the chi2 as nuisances but evaluated externally ("offset method")
- The statistical uncertainty of the obtained sin2 θ`eff also reflects, in addition to the data-fit covariance matrix, the covariance matrix of the MC samples, lepton calibrations, efficiencies, and prefiring weights.
- individual or grouped systematic uncertainties are calculated by fixing the corresponding nuisance parameter(s) to the best-fit values obtained in the combined fit and seeing by how much the uncertainty decreases: the quadratic difference from the nominal uncertainty is taken as the uncertainty under consideration

Template fit

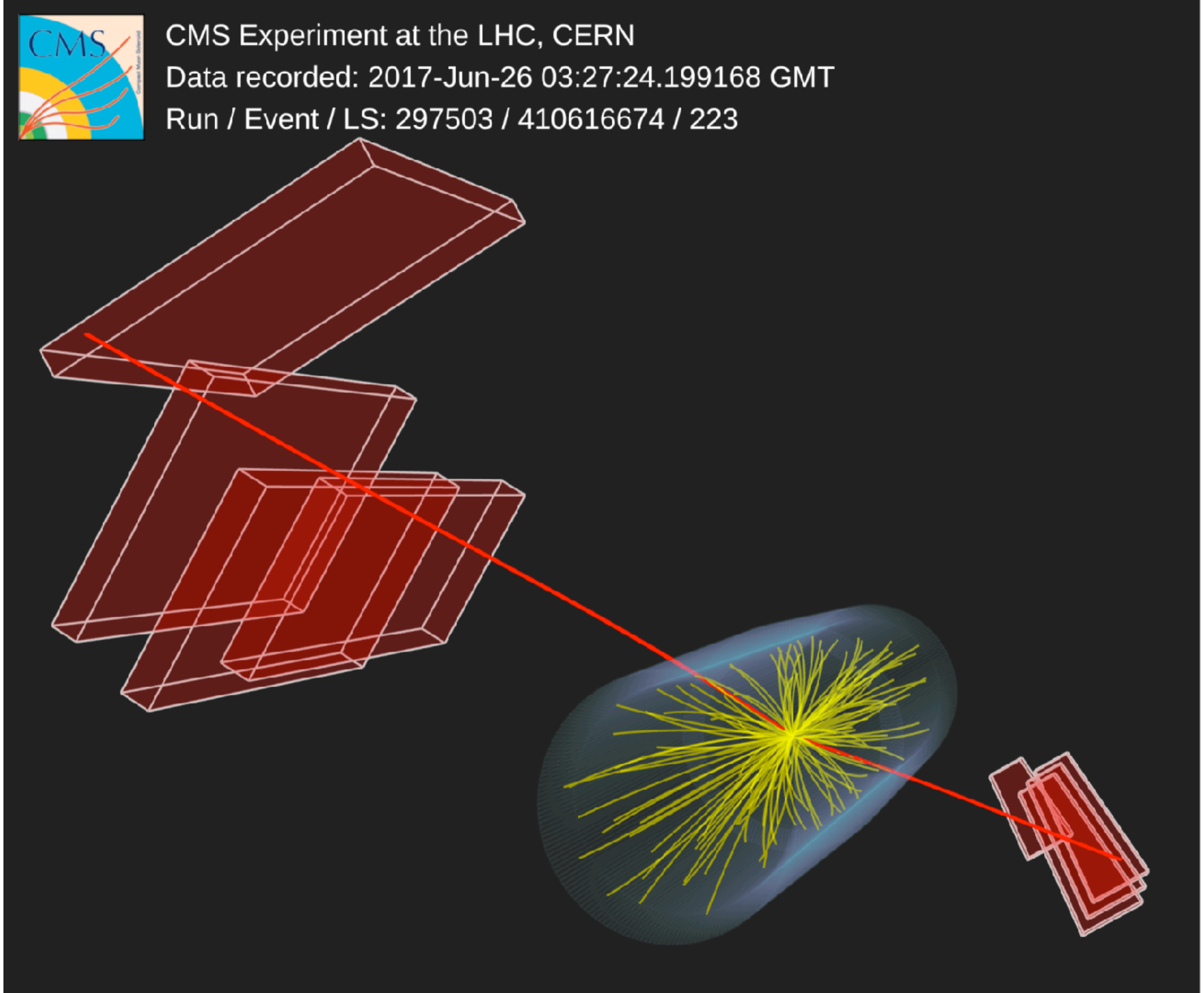


= pseudodata stat. + syst. unc.

= Theory up/down template (prefit)

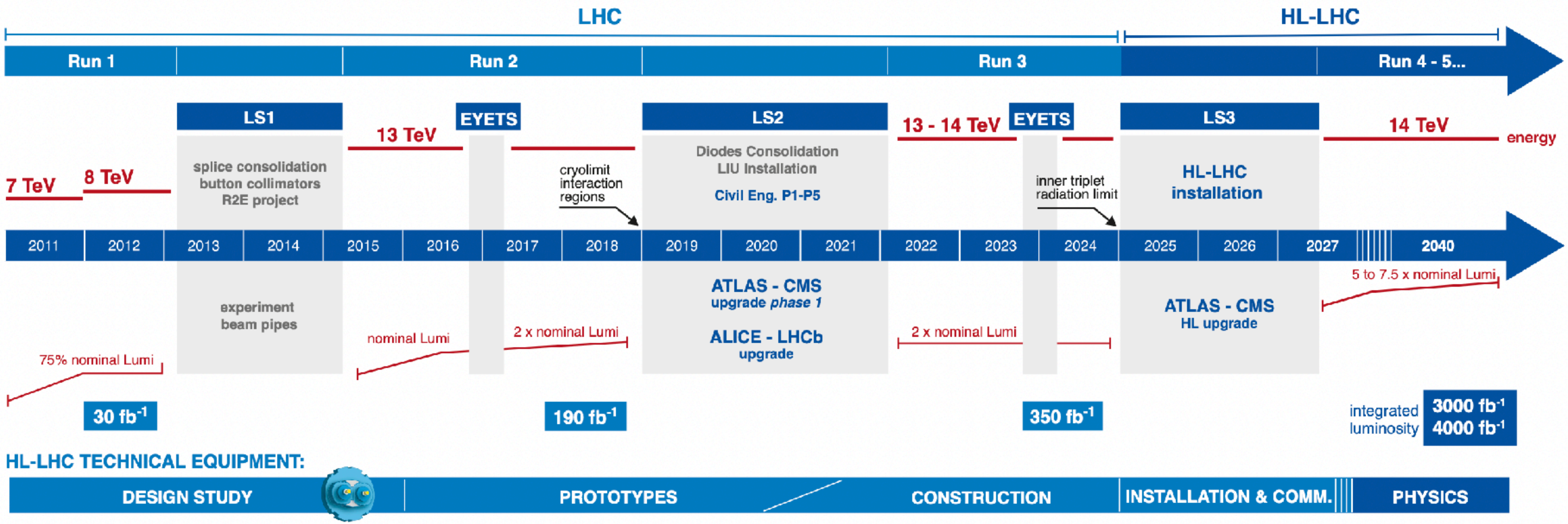
Include experimental $\beta_{j,\text{exp}}$ and PDF unc. β_{th} in the fit:

$$\chi^2(\beta_{\text{exp}}, \beta_{\text{th}}) = \sum_{i=1}^{N_{\text{data}}} \frac{(\sigma_i^{\text{exp}} + \sum_j \Gamma_{ij}^{\text{exp}} \beta_{j,\text{exp}} - \sigma_i^{\text{th}} - \sum_k \Gamma_{ik}^{\text{th}} \beta_{k,\text{th}})^2}{\Delta_i^2} + \sum_j \beta_{j,\text{exp}}^2 + \sum_k \beta_{k,\text{th}}^2$$

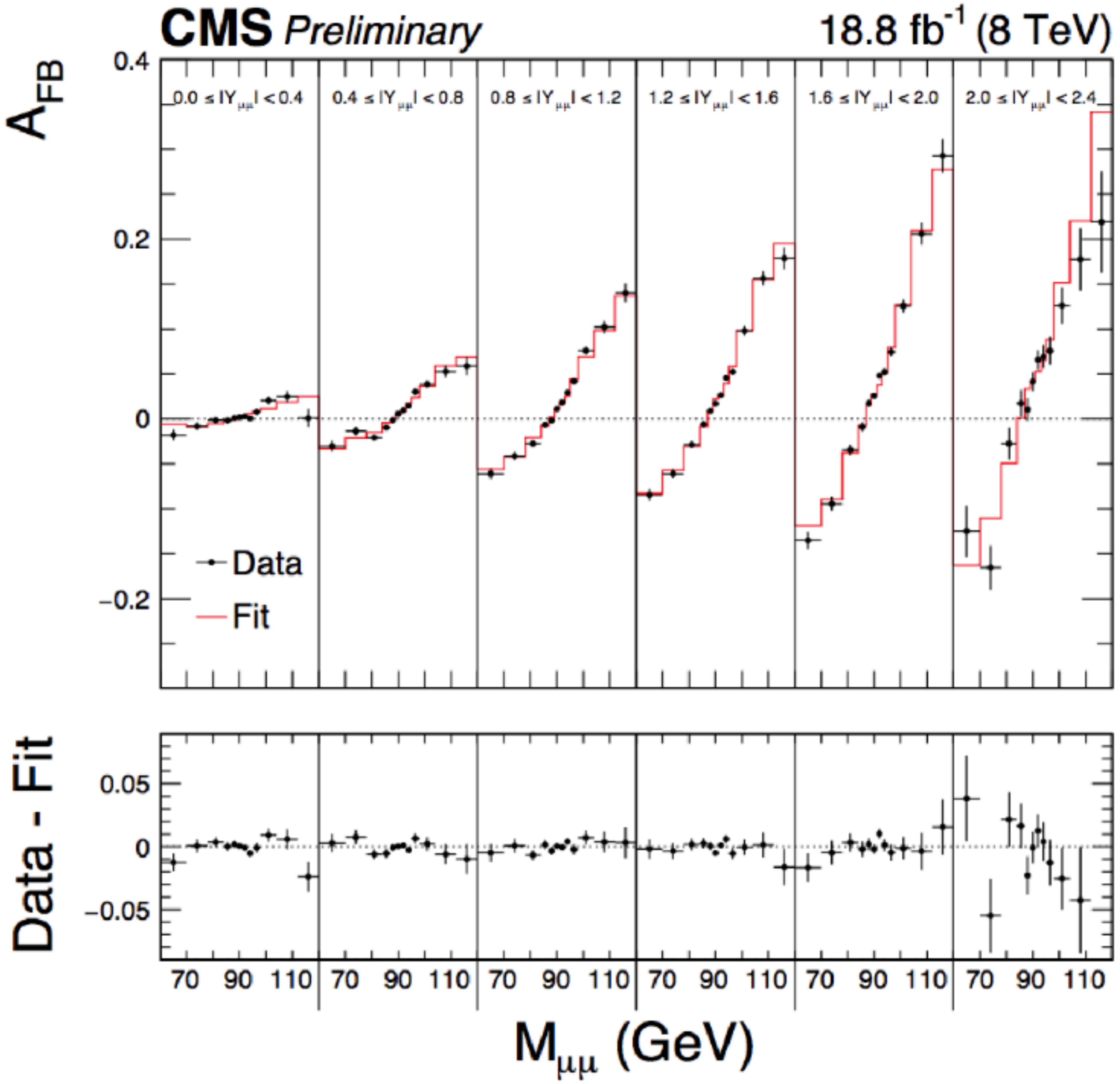

CMS Experiment at the LHC, CERN
Data recorded: 2017-Jun-26 03:27:24.199168 GMT
Run / Event / LS: 297503 / 410616674 / 223

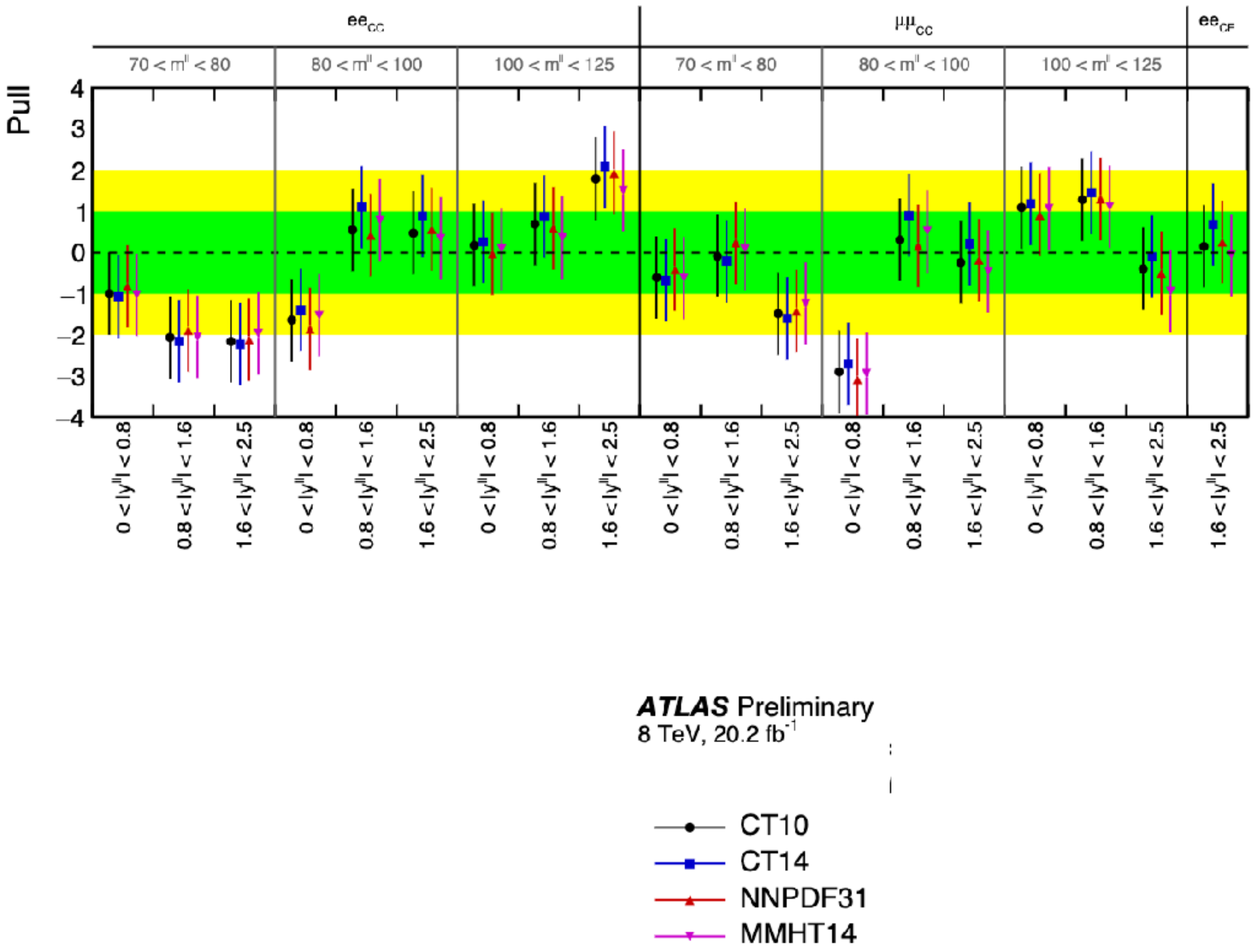
High-Luminosity (HL) - LHC

- Fully approved in 2016, technology available, construction well underway!
  - Expected 3-4 ab^{-1} at $\sqrt{s}$ =14 TeV at luminosities up to 7.5 10^{34} cm^{-2} s^{-1}
  - Pileup: $\langle \mu \rangle$ = 140—200, tougher conditions, detector upgrades to keep physics performance



Present LHC determinations of $\sin^2\theta^l_{\mathrm{eff}}$

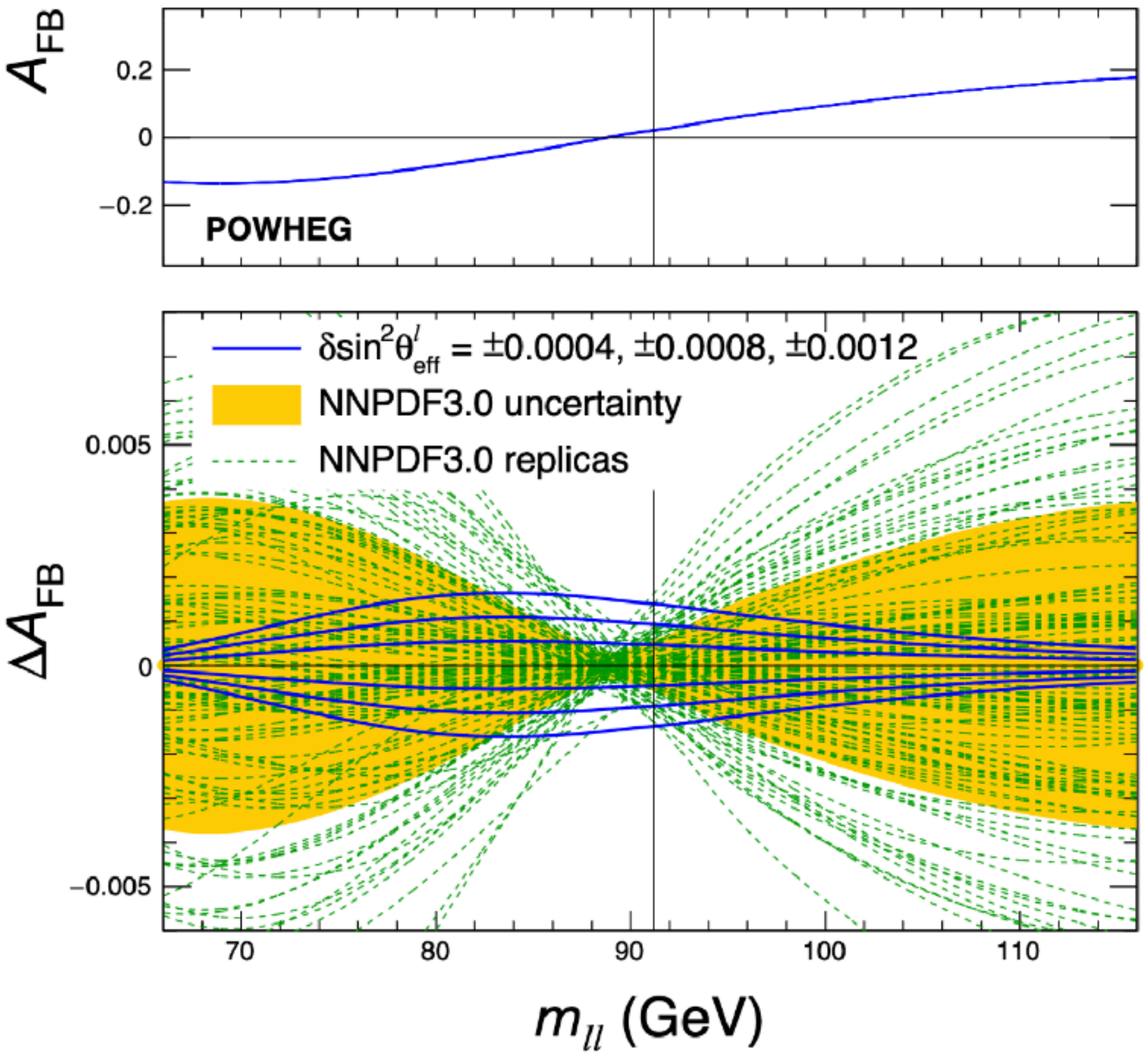


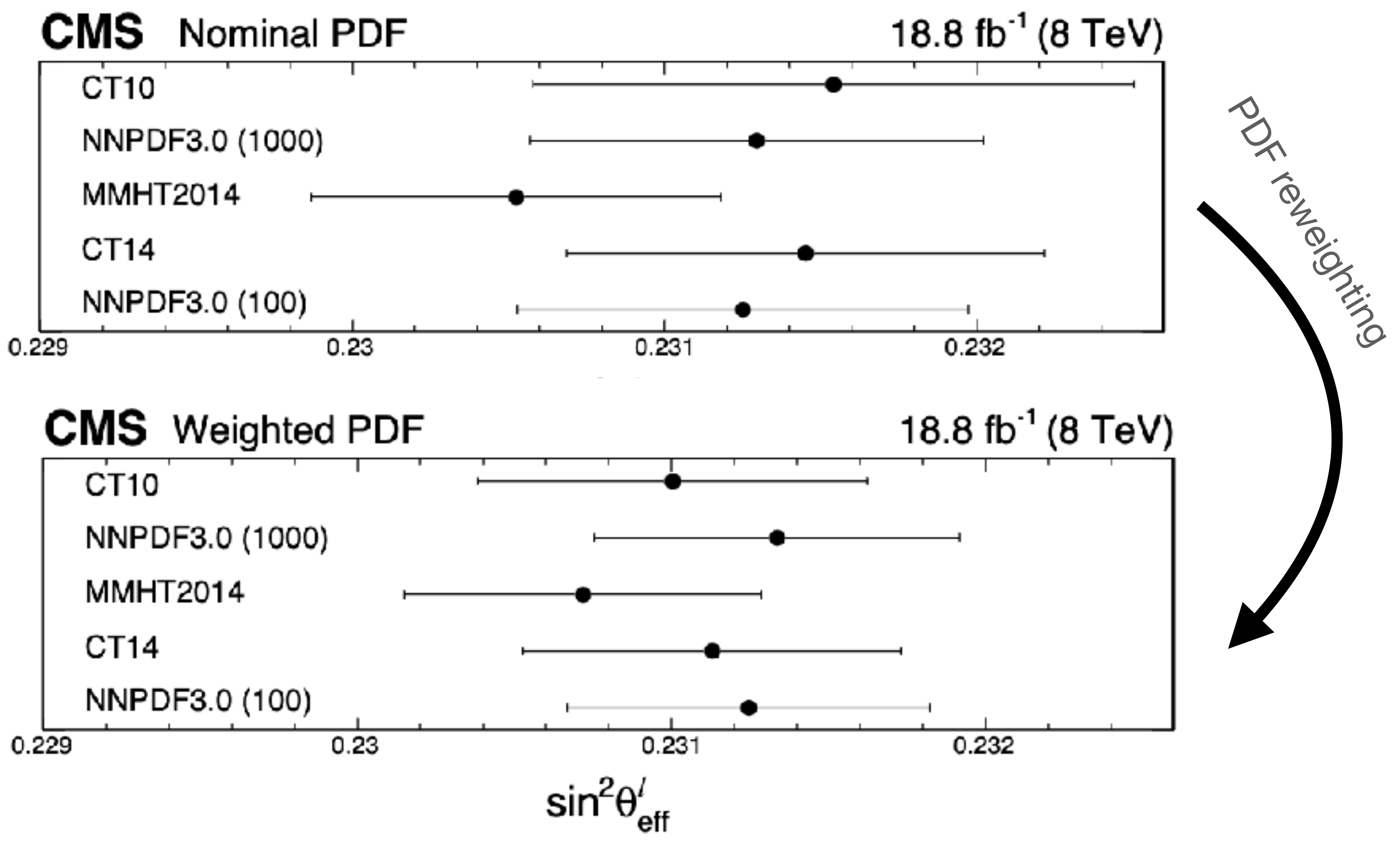


PDFs in $\sin^2\theta^l_{\rm eff}$ - CMS

- LHC measurements rely on the correlation pattern in the PDFs to reduce their impact on the weak mixing angle

$$\sin^2\theta^\ell_{\rm eff} = 0.23101 \pm 0.00036\,({\rm stat}) \pm 0.00018\,({\rm syst}) \pm 0.00016\,({\rm theo}) \pm 0.00031\,({\rm PDF})$$

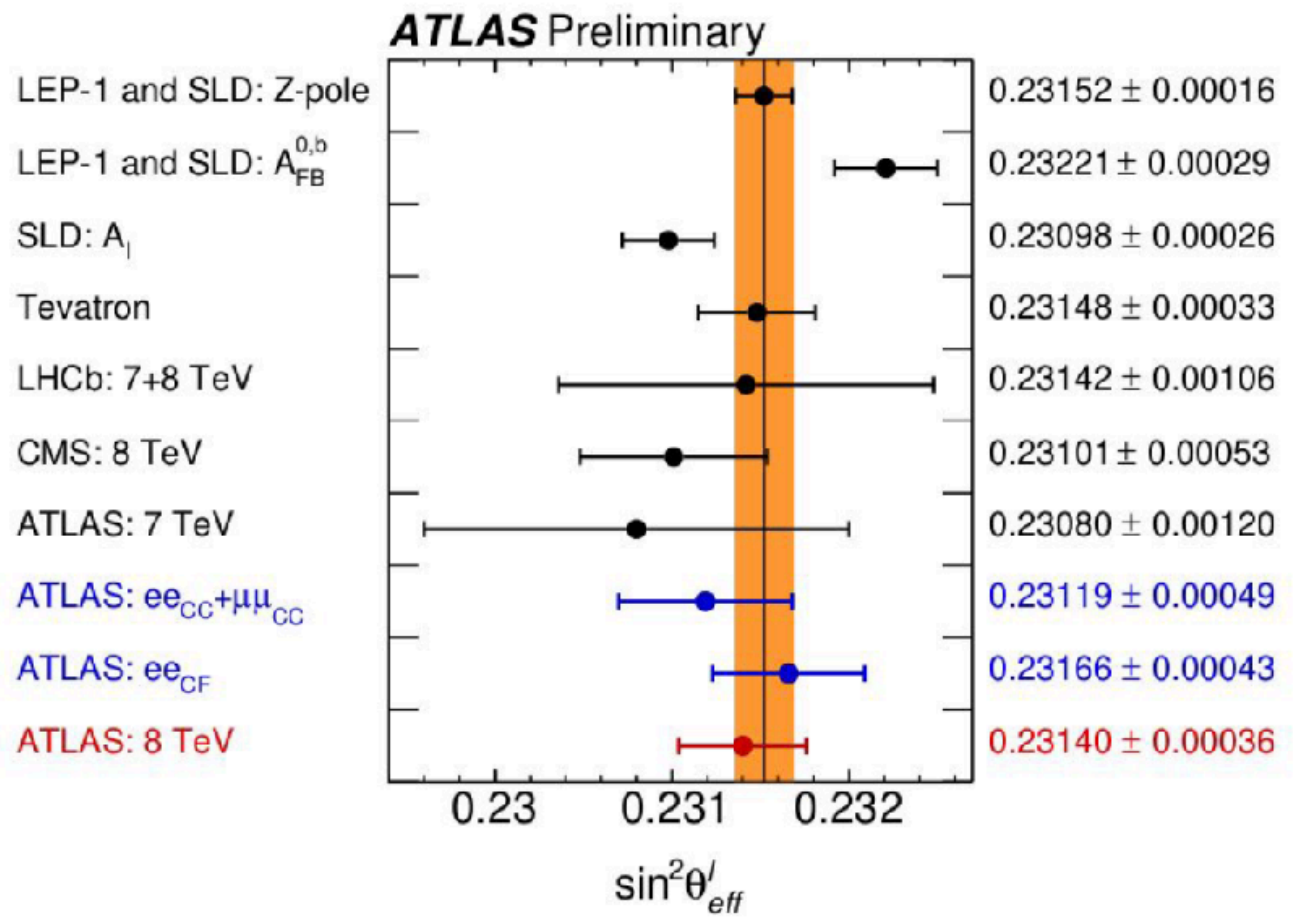




- PDF uncertainty of $3 \cdot 10^{-4}$ vs MSHT14/NNPDF30 spread of $6 \cdot 10^{-4}$

PDFs in $\sin^2\theta^l_{\text{eff}}$ - ATLAS

$$0.23140 \pm 0.00021\ (\text{stat.}) \pm 0.00024\ (\text{PDF}) \pm 0.00016\ (\text{syst.})$$



	CT10	CT14	MMHT14	NNPDF31
$\sin^2\theta^\ell_{\text{eff}}$	0.23118	0.23141	0.23140	0.23146
	Uncertainties in measurements			
Total	39	37	36	38
Stat.	21	21	21	21
Syst.	32	31	29	31

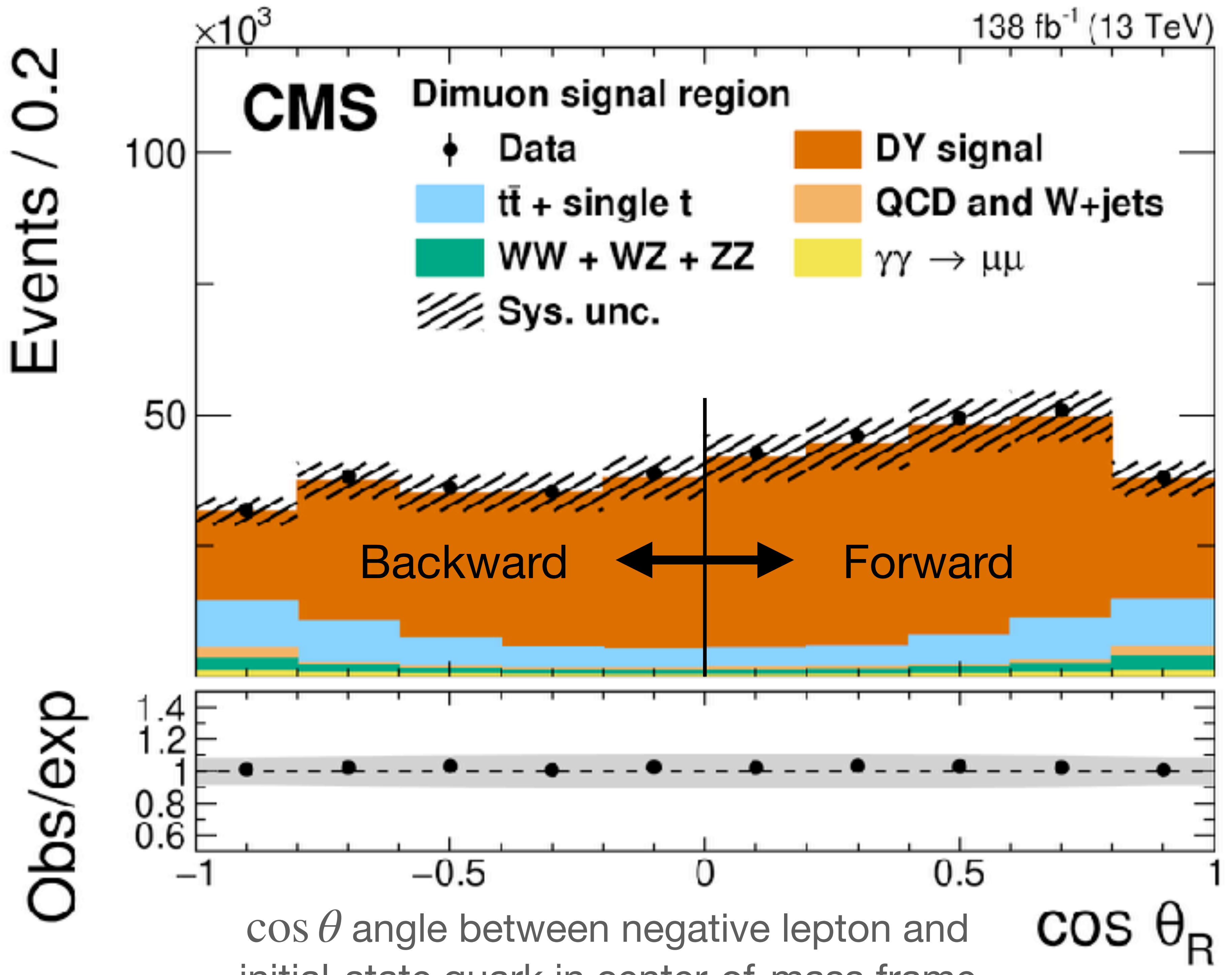
- Large uncertainty from envelope of PDFs, $3 \cdot 10^{-3}$, but using old PDF sets

HIGH-MASS AFB IN $Z \to l^+l^-$

- Forward-backward asymmetry in Drell-Yan probe of the V-A structure of weak interactions
  - At high-masses, probe extra massive gauge bosons

Forward-Backward asymmetry:

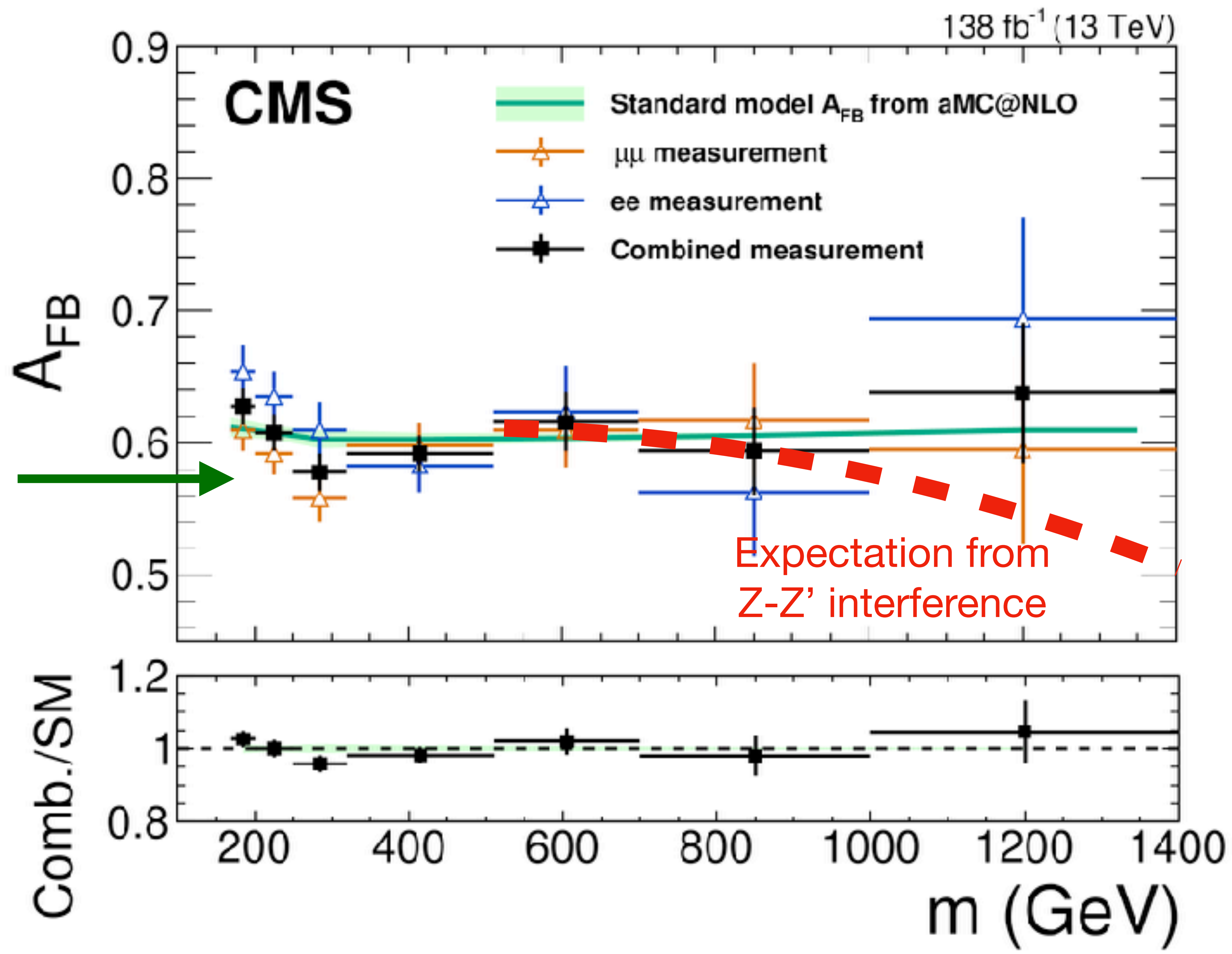
$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$



$\cos\theta$ angle between negative lepton and initial-state quark in center-of-mass frame

Submitted to J. High Energy Phys.

AFB positive at high-mass due to γ^*/Z interference



- Measurement in agreement with NLO QCD
- Derive limits on Z' in the Sequential SM
  - Excludes $m_{Z'} < 4.4$ TeV at 95% CL
  - Comparable with ~ 5 TeV from direct searches