Measurements of W and Z bosons in CMS

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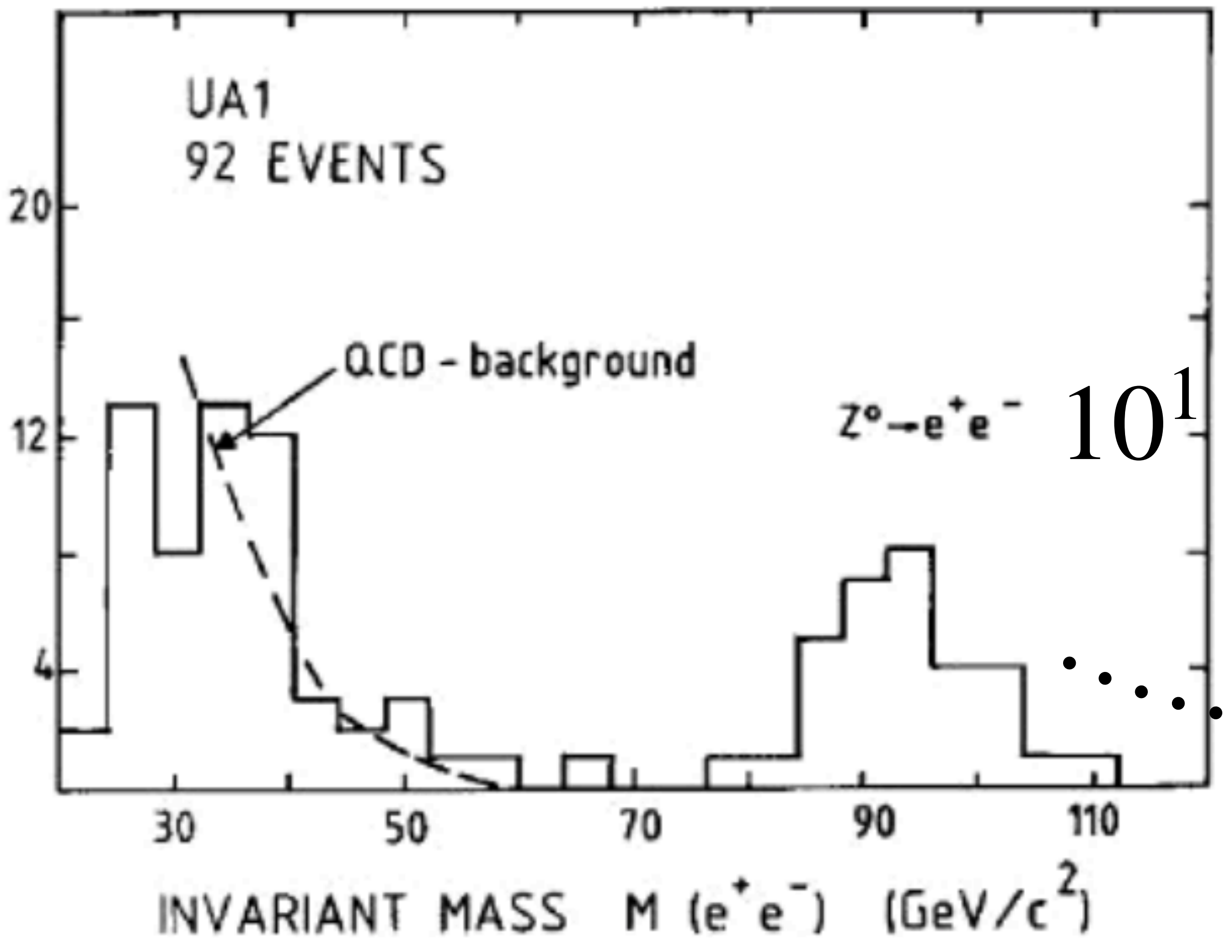
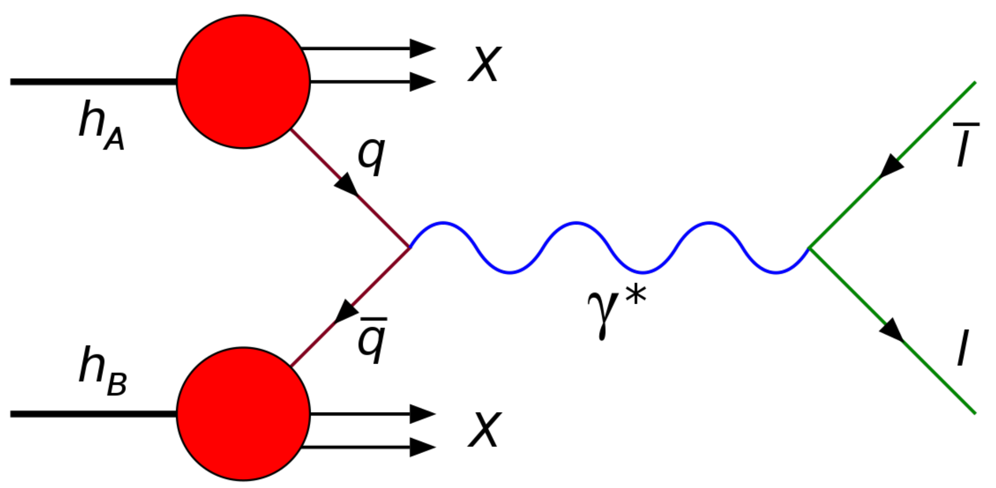
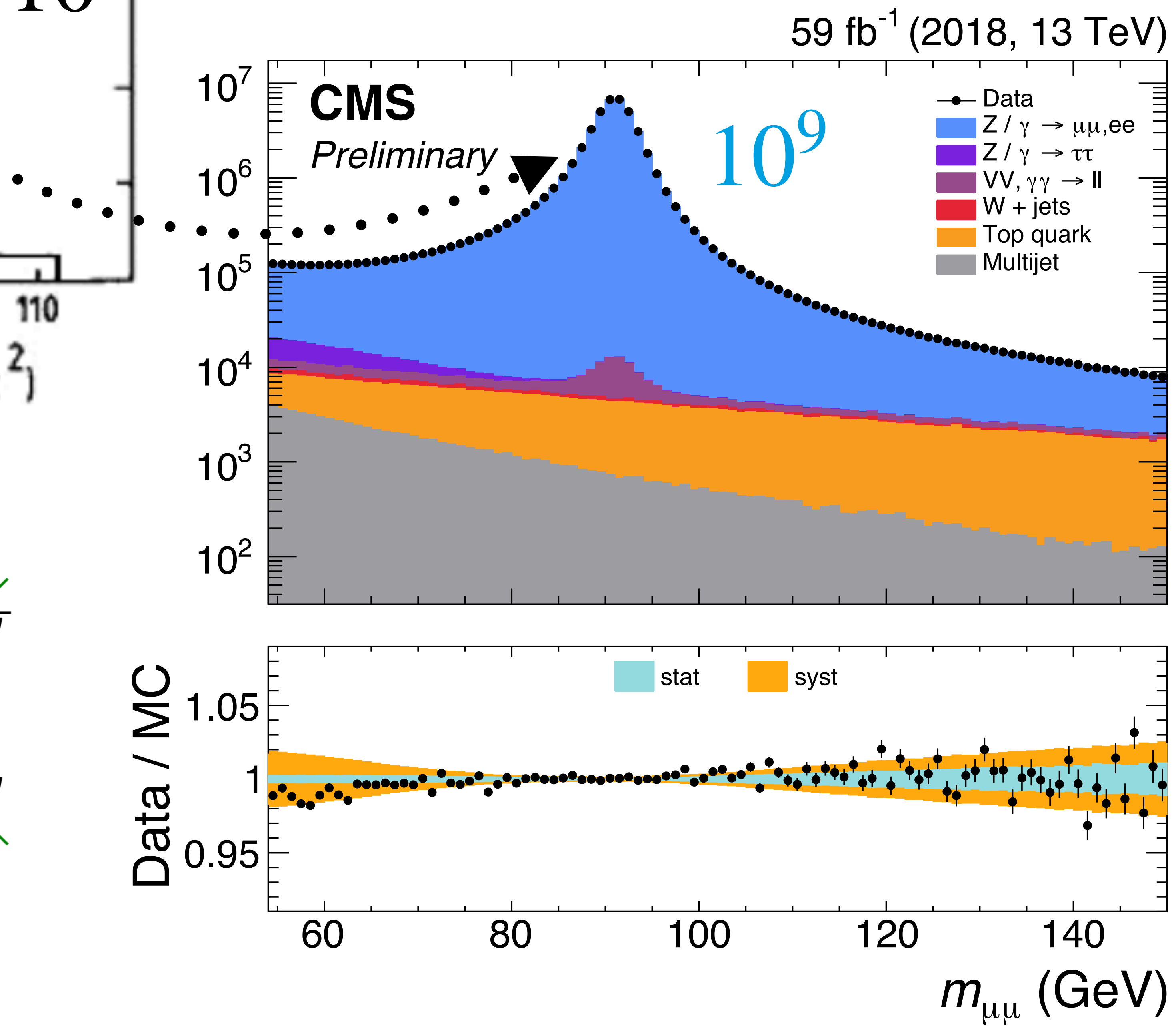
PHENOMENOLOGIST POINT OF VIEW

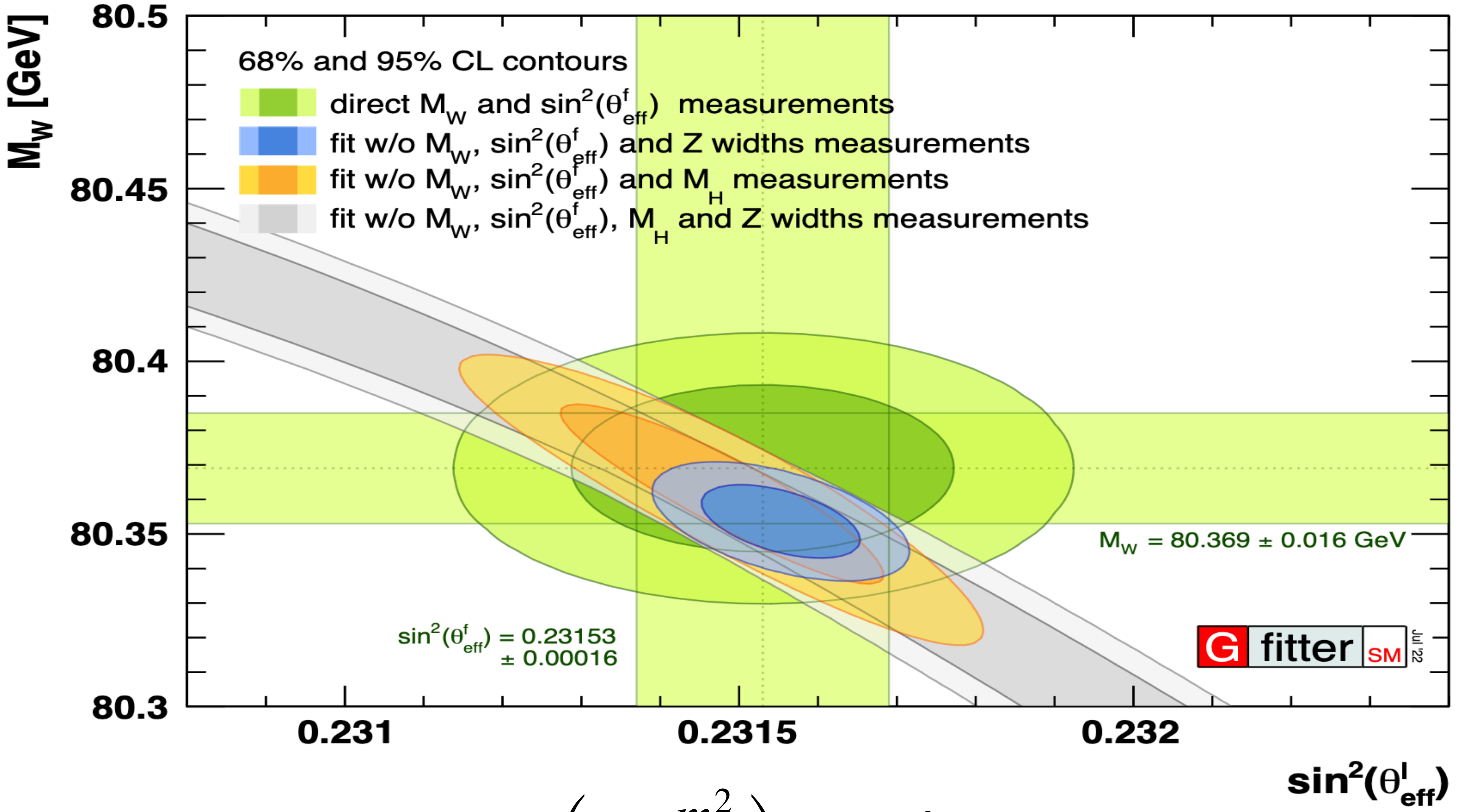
BUILDING BLOCK OF THE SM

- 1983: discovered at CERN SPS in $p\bar{p}$ collisions
- Today: CERN LHC is practically a vector boson factory









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

POWERFUL THEORETICAL PROBE

- Test theoretical (QCD, EW) predictions + determination of SM fundamental parameters
- Probe PDFs: increased data/prediction accuracy
- Constraint New Physics: **extremely tiny** deviations (could be) visible from **extremely precise** measurements

Experimentalist point of view

Clean experimental signature

- Leptonic decays to $e/\mu \rightarrow$ ID eff. ~1%
- E/p_T res. ~1%, scale res. ~0.1%

Backgrounds for other analyses

- Higgs boson analyses
- Searches for New Physics

ACHIEVING PERCENT-LEVEL MEASUREMENTS TAKES TIME AND EFFORT

Run 2 dataset

- Large and diverse: still a lot to learn
- Multidifferential measurements with negligible stat. unc.
- Low PU data, better control of p_T^{miss} systematics

Run 3 dataset

- Test the SM at different energy (or combine with Run 2 data)
- Deploy new strategies in view of HL-LHC
- Monitor detector performances

W and Z cross sections at low Pile-up and higher energies

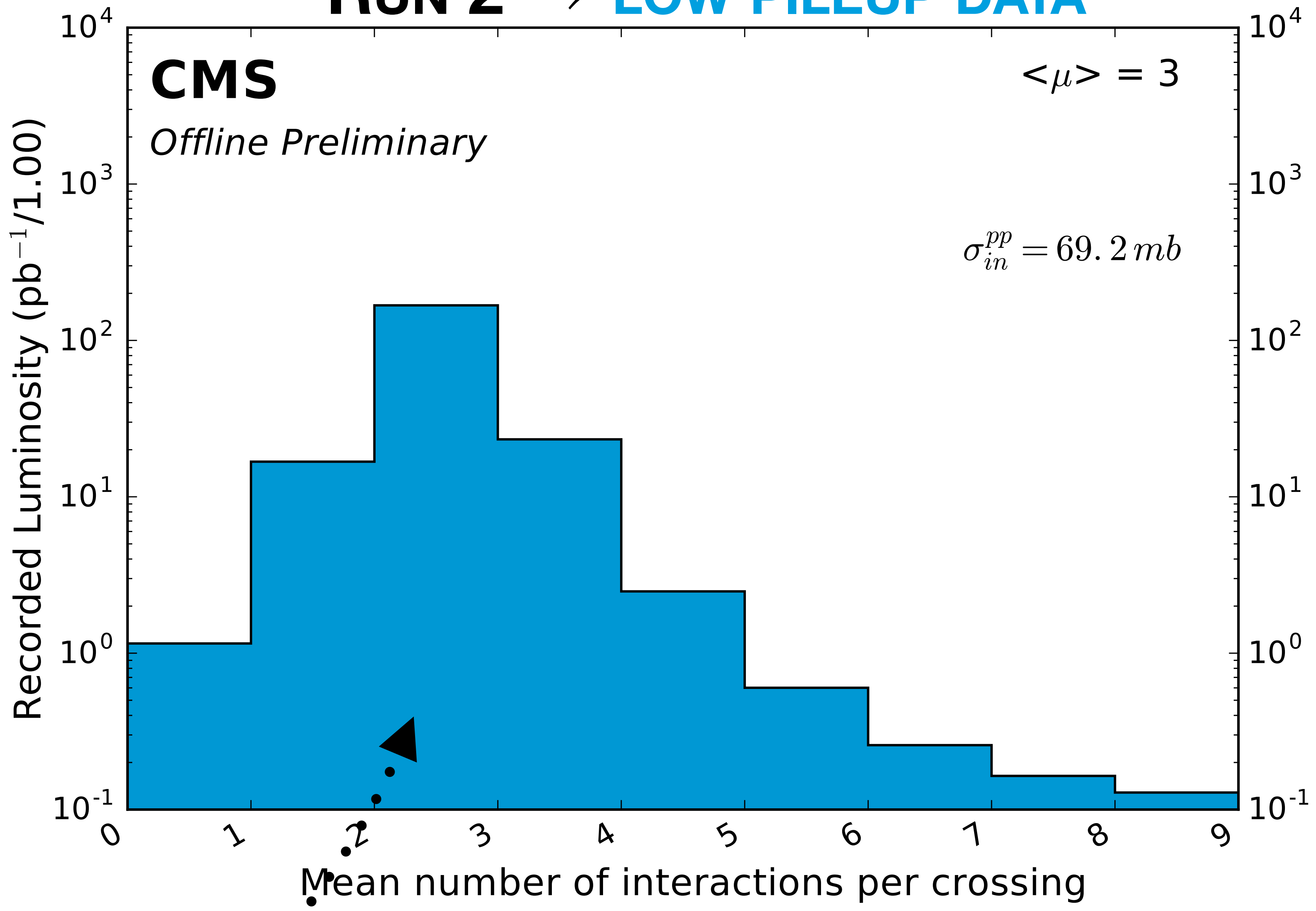
Understand modelling of EWK boson production

- Available calculations up to N^3LO (QCD) + NLO (EW)
- Sources of experimental uncertainties:
  - **luminosity**
  - **momentum** and **recoil resolution**
  - **lepton efficiencies**

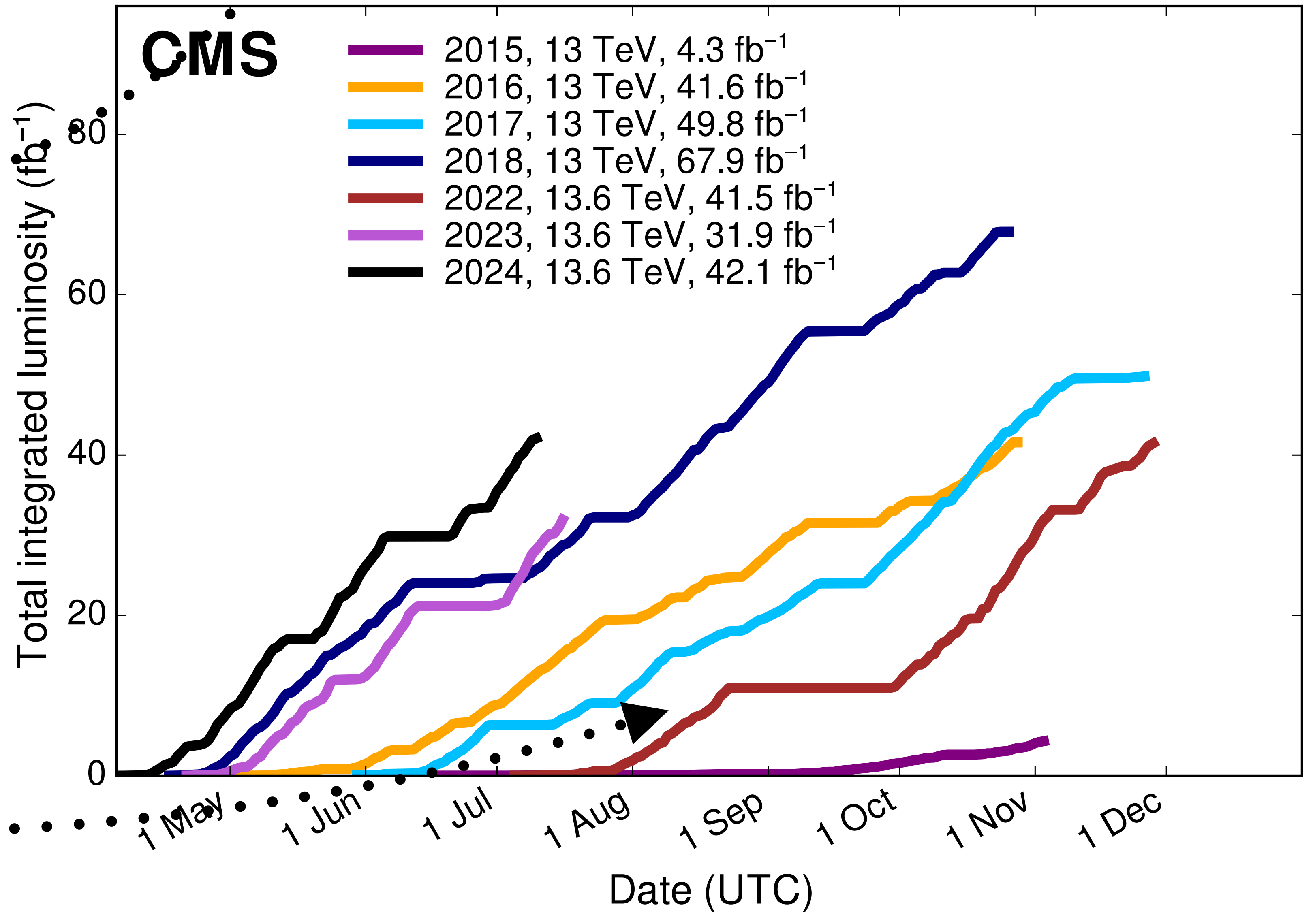
Available data

- Run 2 low pileup data at **5.02 TeV** (~300 pb^{-1}) and **13 TeV** (~200 pb^{-1}):
  - Better recoil resolution
  - Lower QCD multijet background
- Run 3 data at **13.6 TeV** (partial dataset, ~5.04 pb^{-1})
  - Unprecedented energy regime to be tested

Run 2 → low pileup data

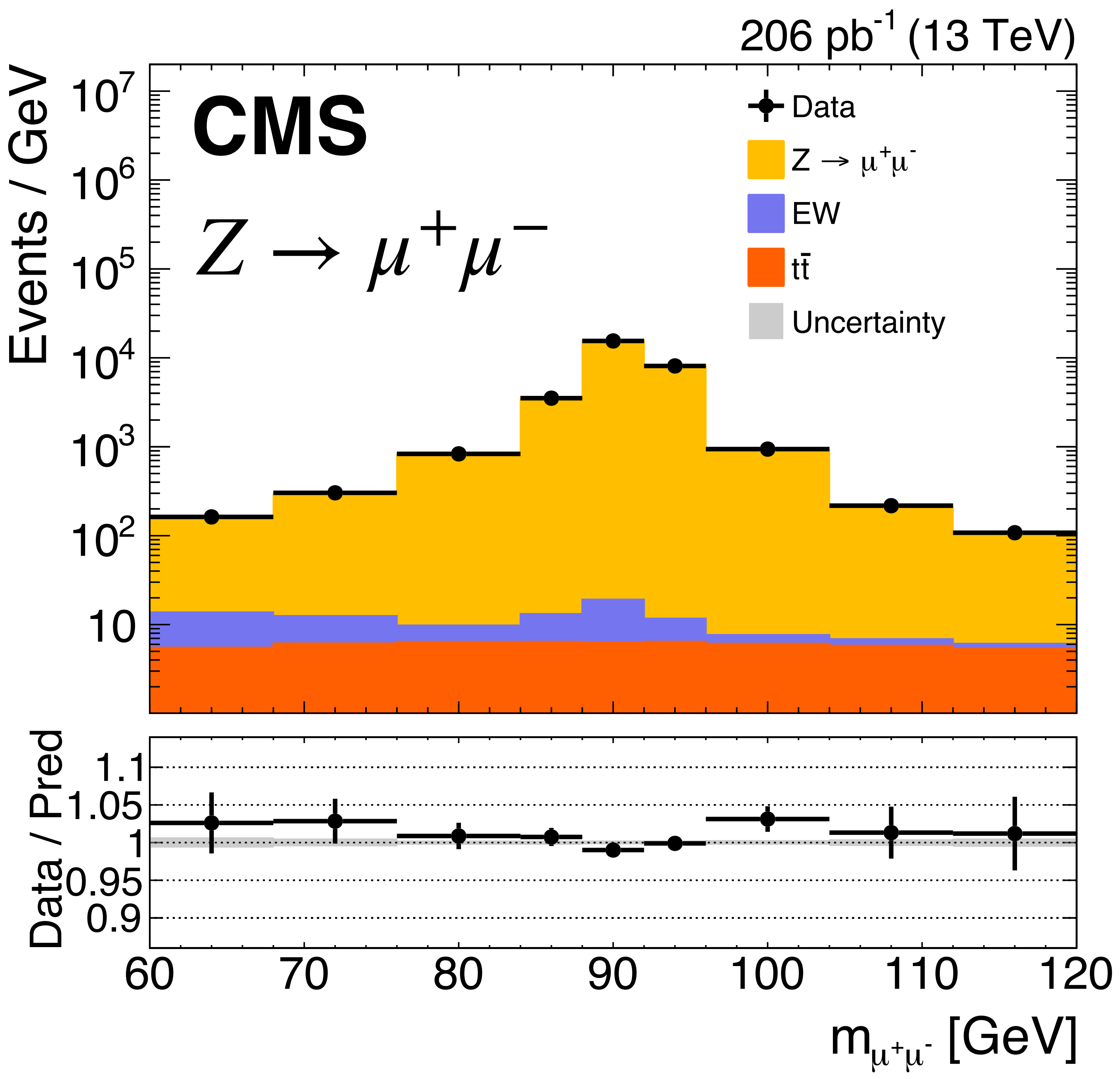


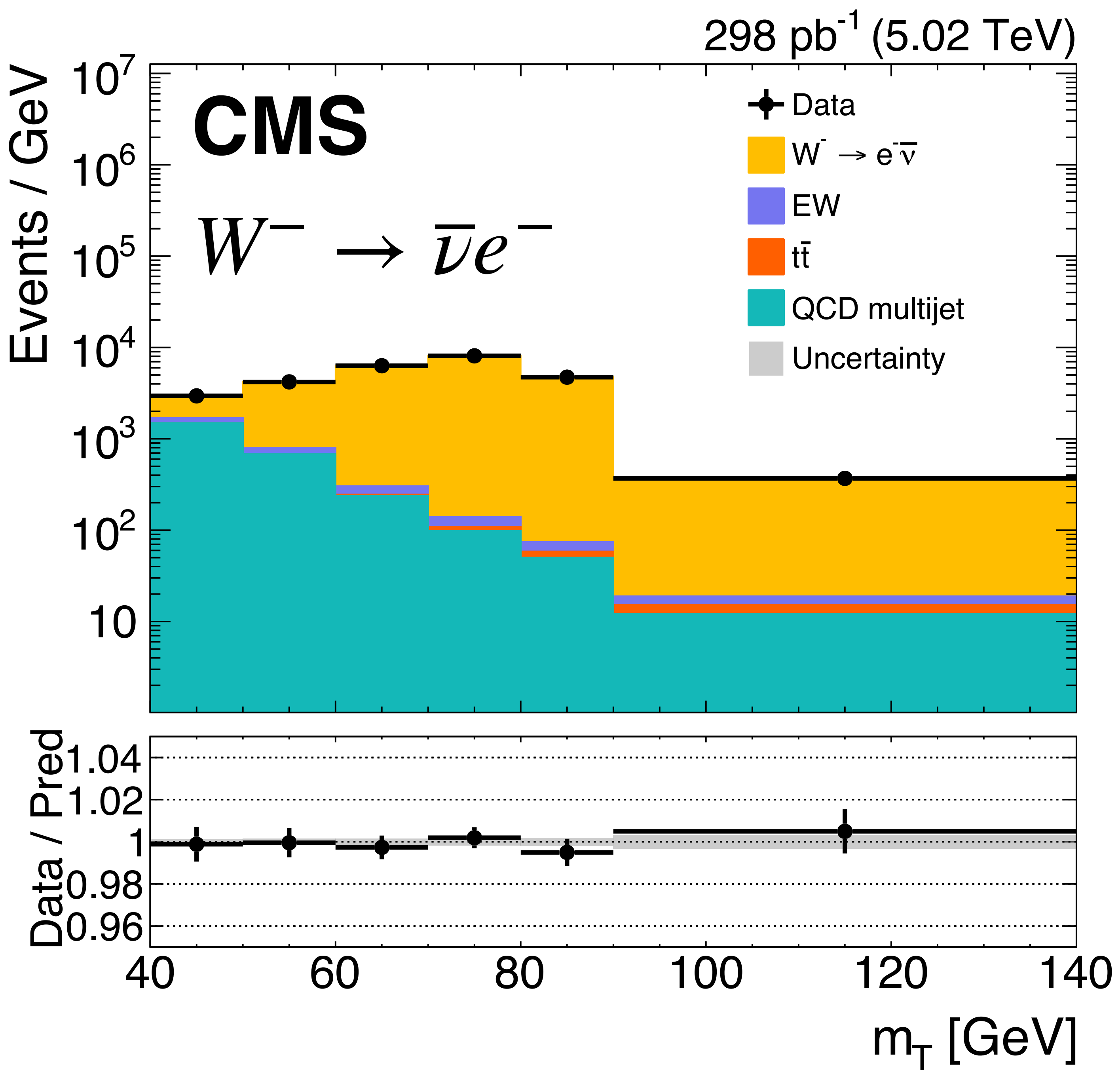
Run 3 → 13.6 TeV data

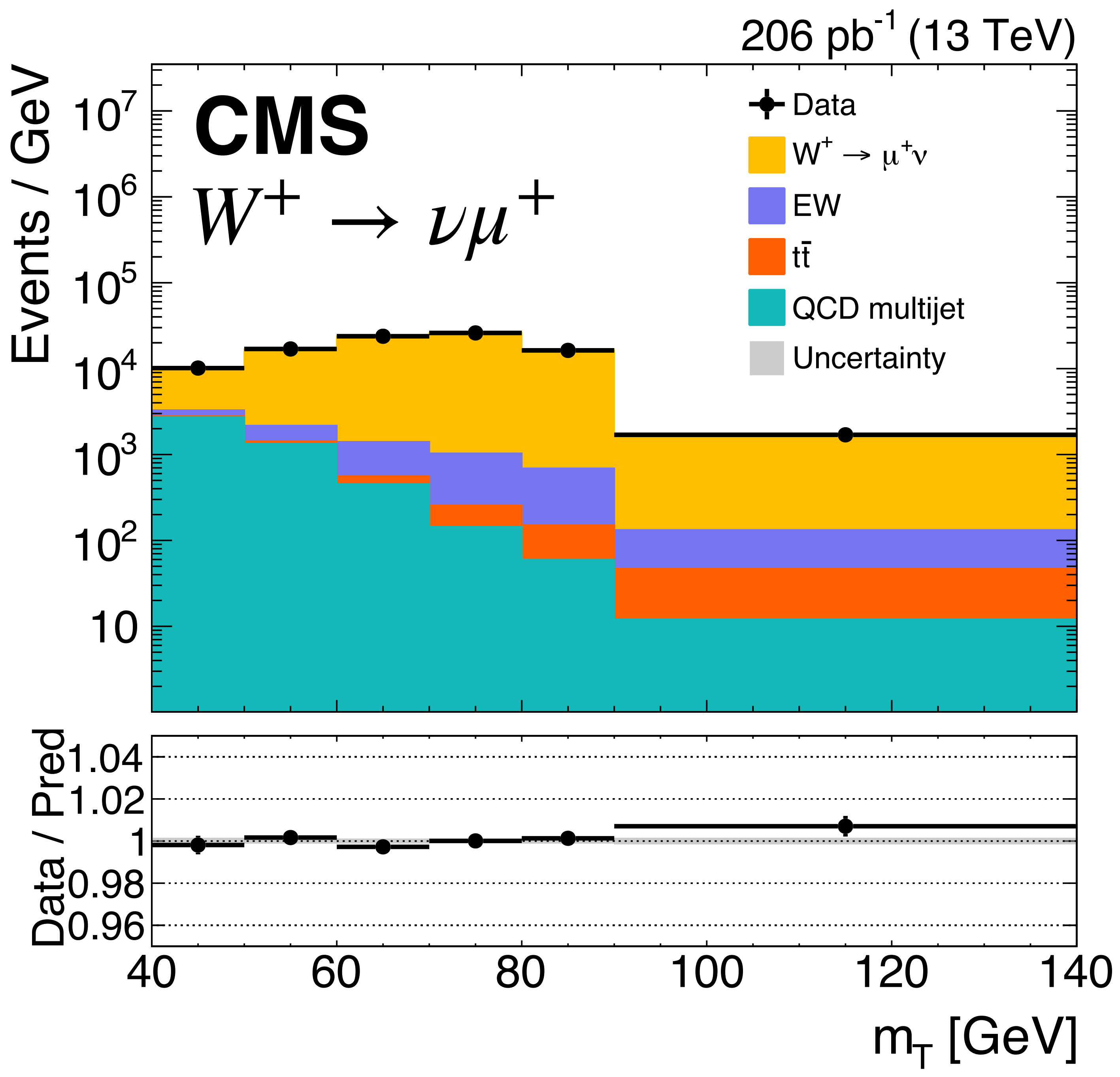


W and Z cross-sections at 5.02 TeV and 13 TeV

SMP-20-004







Event selection & backgrounds

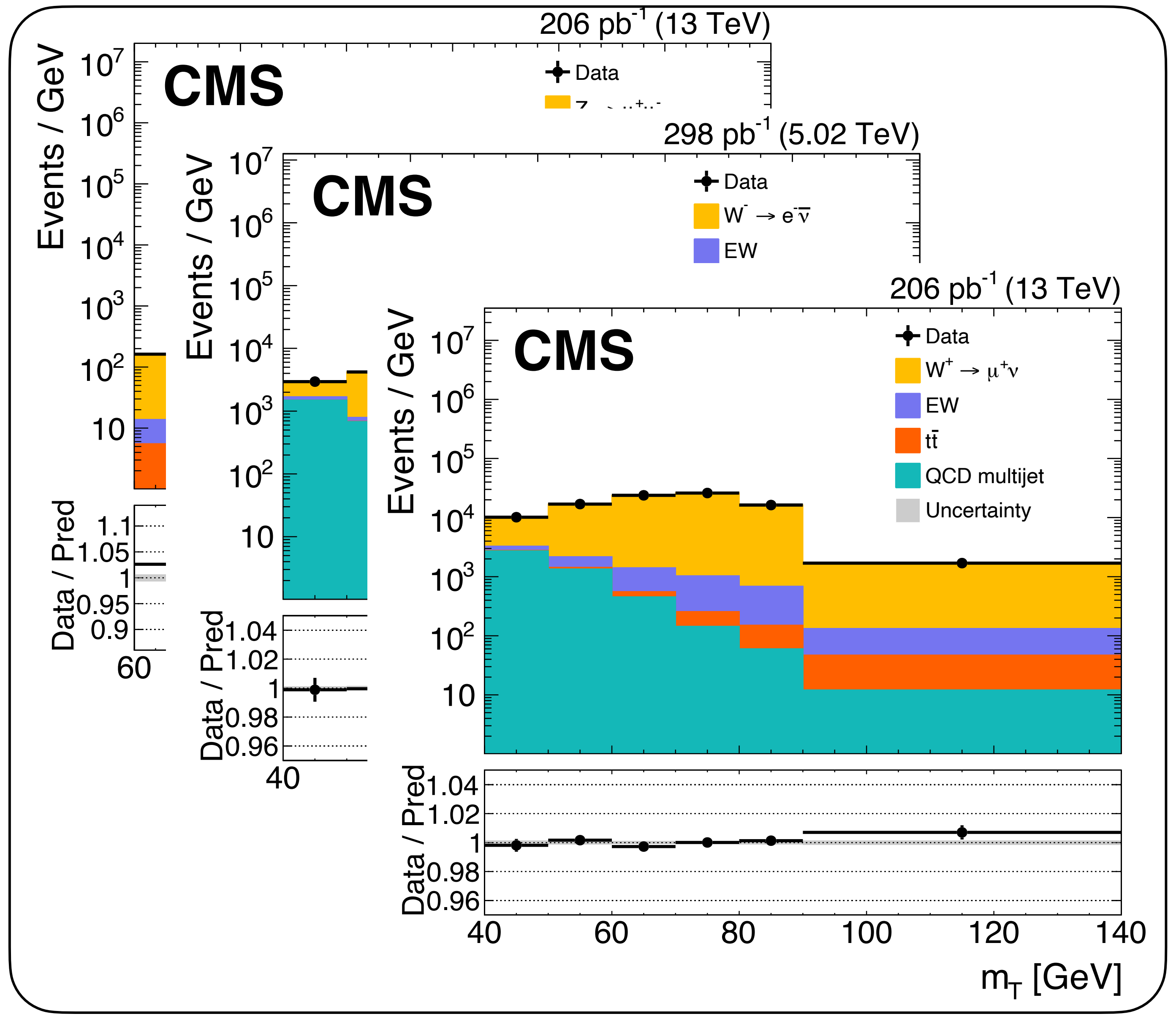
- Object selection: identify one (two) prompt, energetic and isolated lepton(s)
- EW and $t\bar{t}$ backgrounds from simulation
- For the W case, QCD multijets background from control region in data (invert m_T cut)

	$W^+ \to e^+\nu$	$W^- \to e^-\bar{\nu}$	$Z \to e^+e^-$	$W^+ \to \mu^+\nu$	$W^- \to \mu^-\bar{\nu}$	$Z \to \mu^+\mu^-$
Observed	689131	561870	72040	1016318	796731	128889
Signal	591760 ± 770	467820 ± 680	71520 ± 270	923620 ± 960	708680 ± 840	128390 ± 360
EW	12150 ± 110	11450 ± 110	159 ± 13	38200 ± 200	33710 ± 180	271 ± 16
$t\bar{t}$	4768 ± 69	4780 ± 69	216 ± 15	6326 ± 80	6345 ± 80	360 ± 19
QCD multijet	80750 ± 280	77980 ± 280	-	47910 ± 220	47930 ± 220	-

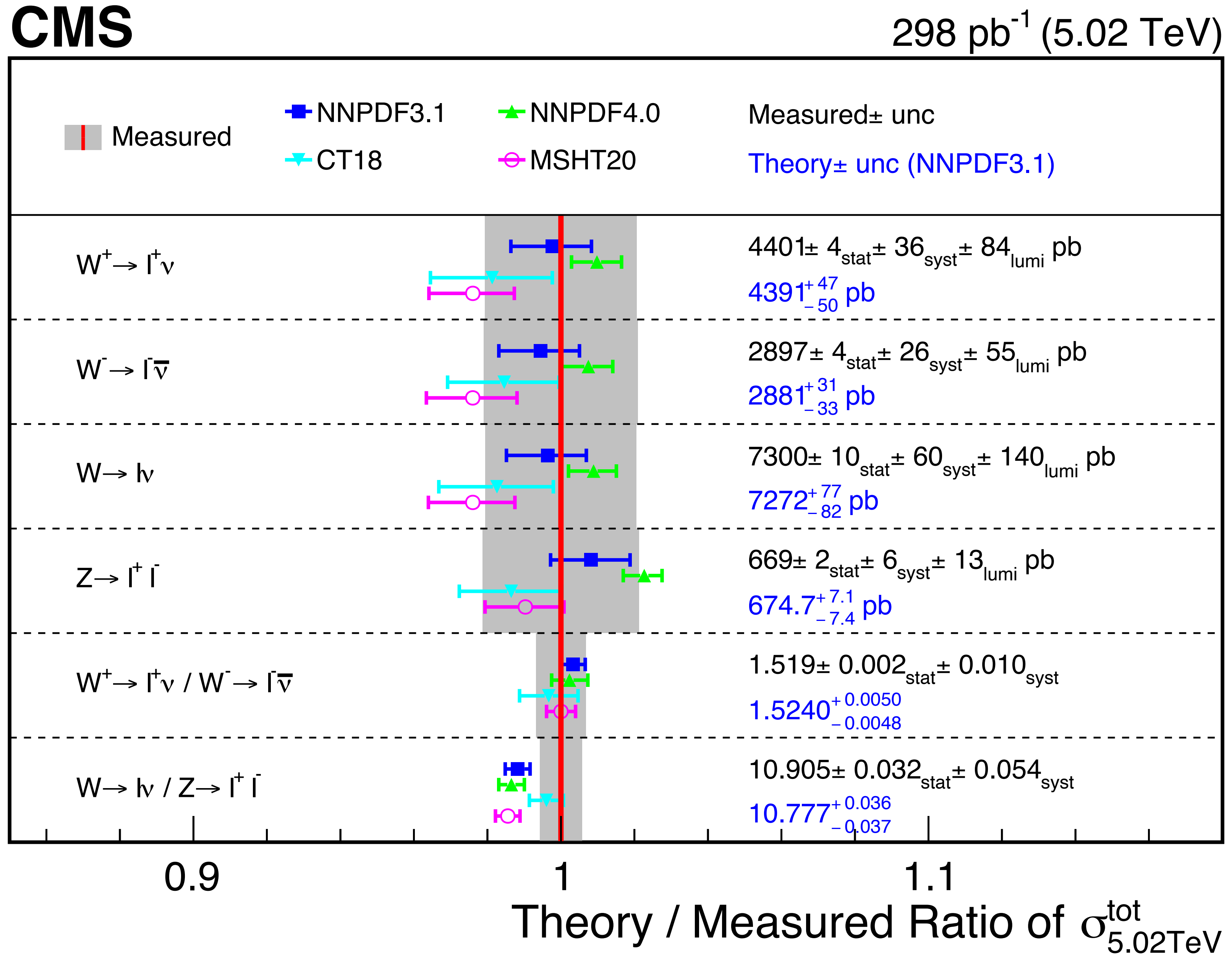
Post-fit event yields @ 13 TeV

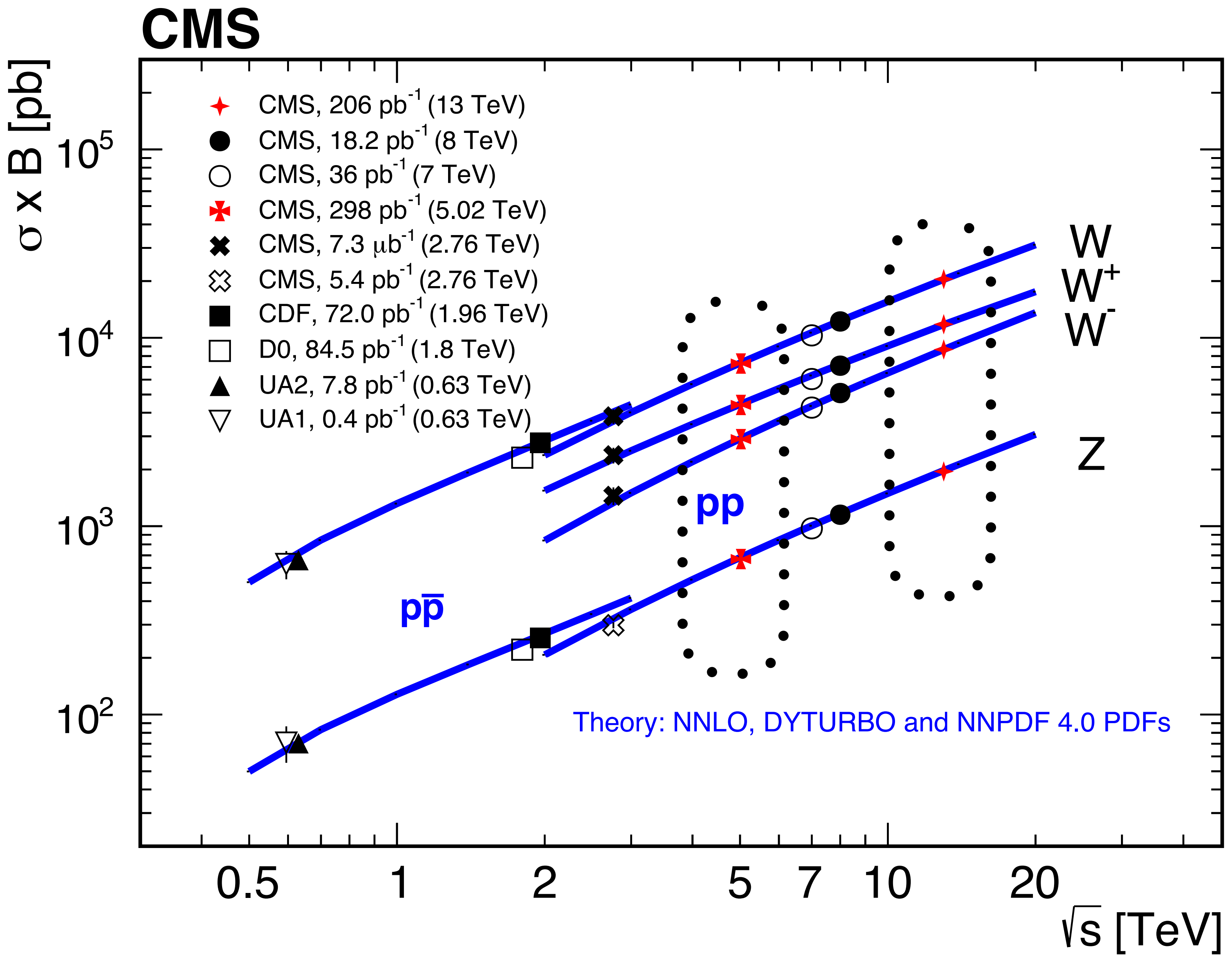
W AND Z CROSS-SECTIONS AT 5.02 TEV AND 13 TEV

[SMP-20-004](SMP-20-004)



FIT TOGETHER





SIGNAL EXTRACTION

- Fit $m_{\ell\ell}$ and m_T distribution for Z and W
  → extract cross-section and cross-section ratios
- Luminosity unc. at 5.02 TeV (13 TeV) 1.9% (2.3%), other experimental unc. ~0.3%
- Good agreement with NNLOpredictions at different energies

	$W^+ \to \ell^+\nu$	$W^- \to \ell^-\bar{\nu}$	$Z \to \ell^+\ell^-$	$W^\pm \to \ell^\pm\nu$	$W^\pm/Z$	W^+/W^-
Total	0.32	0.34	0.37	0.26	0.25	0.40
Efficiency (stat)	0.23	0.21	0.26	0.17	0.11	0.30
Trigger prefire correction	0.14	0.13	0.22	0.14	0.08	0.01
QCD multijet (syst)	0.11	0.15	0.12	0.09	0.15	0.19
MC sim. stat	0.10	0.12	0.11	0.08	0.13	0.15
EWK+tt̄ cross section	0.08	0.10	0.02	0.09	0.07	0.03
PDF + α_S	0.05	0.07	0.03	0.05	0.05	0.07
Efficiency (syst)	0.04	0.05	0.09	0.04	0.06	0.01
QCD multijet (stat)	0.04	0.04	0.03	0.03	0.04	0.06
Hadronic recoil calibration	0.02	0.02	0.02	0.02	0.03	0.01
μ_R and μ_F scales	0.01	0.01	0.01	0.01	0.01	0.00

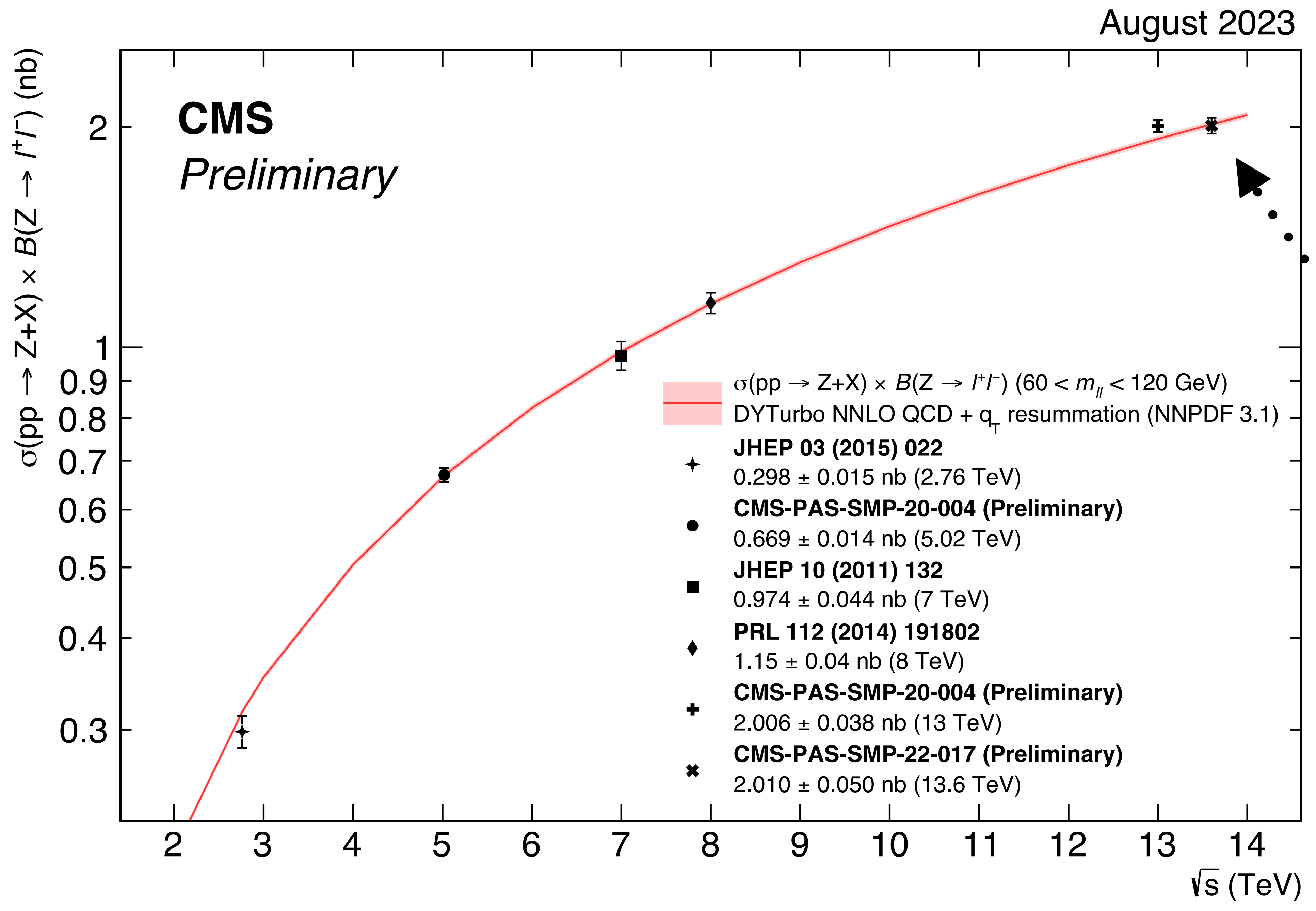
Post-fit uncertainties @ 5.02 TeV

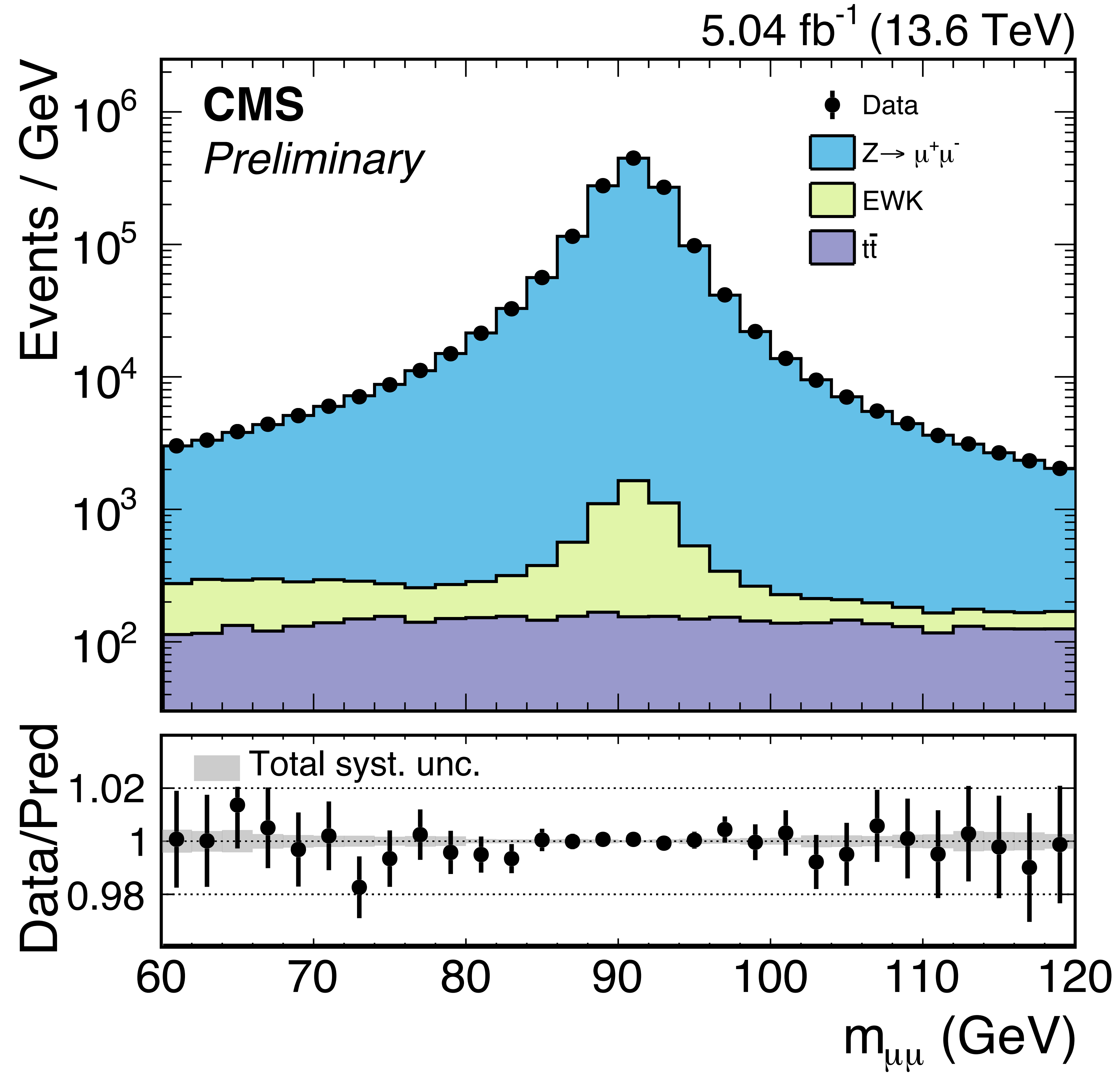
Z cross-section at 13.6 TeV

SMP-22-017

Event selection & corrections

- Object selection: two prompt, energetic and isolated muons
- Object corrections: delicate for early stage analyses
  → **Muon efficiency**
  → **Scale** and **energy resolution**
  → Trigger
  → Pileup





Signal extraction

- Maximum likelihood fit to the $m_{\mu\mu}$ distribution
- Luminosity unc. 2.3%, other experimental unc. 0.92% (muon efficiency dominated)
- Good agreement with theory predictions

EXTRACTION OF $\sin^2\theta^{\ell}_{\mathrm{eff}}$ AT 13 TEV

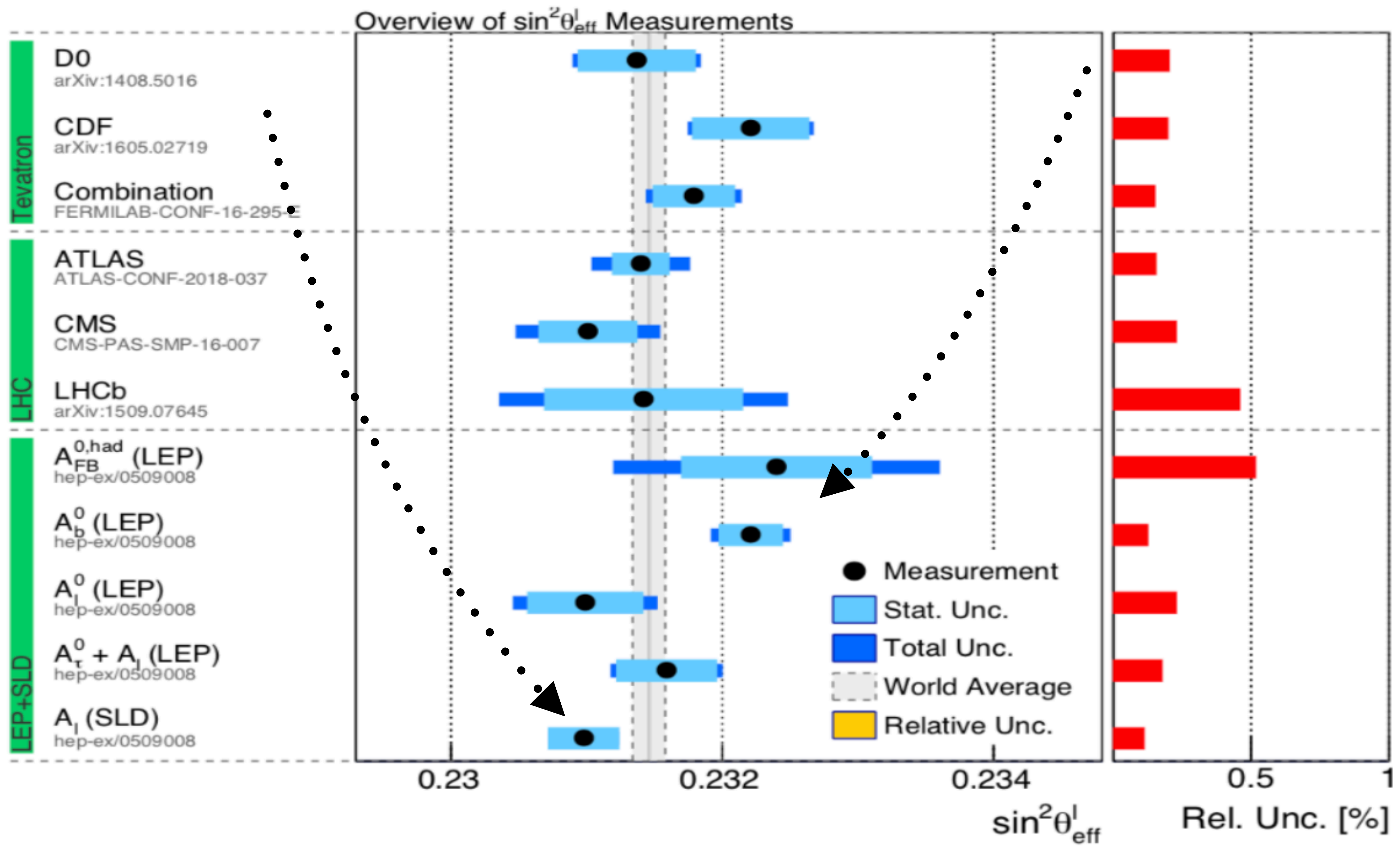
SMP-22-010

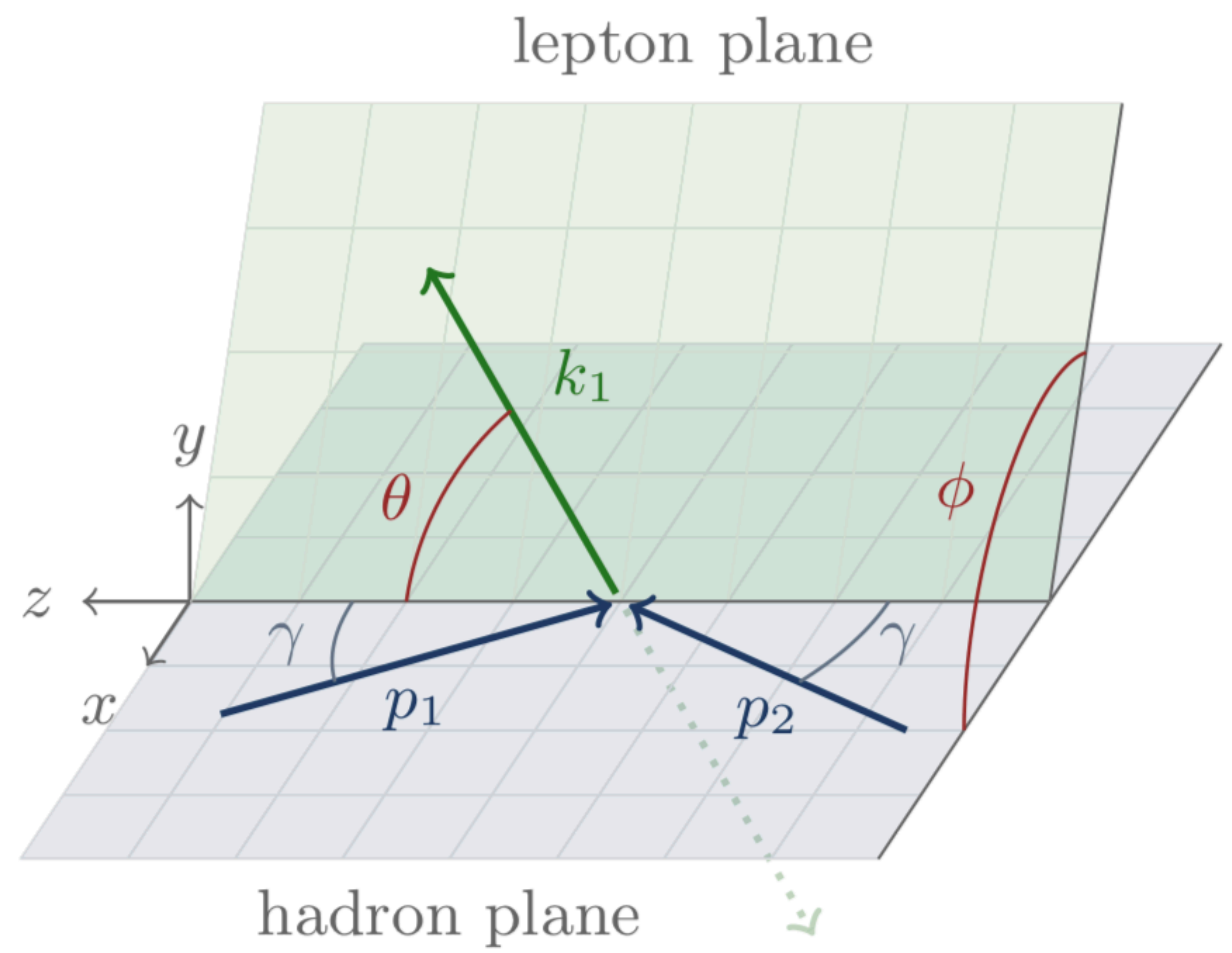
FUNDAMENTAL EW PARAMETER

- Relates masses of EW bosons + govern strength of EW interaction
- At all orders in EW: $\sin^2\theta^{\ell}_{\mathrm{eff.}} = \kappa_{\ell}(1 - m_W^2/m_Z^2)$
  - Precise calculation within SM
  - Two most precise exp. results from LEP/SLD differ by $\sim 3\,\sigma$

EXPERIMENTAL ASPECTS

- Study **final state leptons angular distribution** in NCDY events, using Collins-Soper frame
- Asymmetry in lepton decay angle $1 + \cos^2\theta + A_4\cos\theta$ $\rightarrow A_{FB} = 3/8A_4 \rightarrow$ near m_Z depends on $\sin^2\theta^{\ell}_{\mathrm{eff}}$
- Rely on $y_{\ell\ell} \rightarrow$ only valence quarks contribute + significant $y_{\ell\ell}$-dependent diluition $\rightarrow$ **strong PDFs dependence**





$$A_{FB} = \frac{N(\cos\theta_{CS} > 0) - N(\cos\theta_{CS} < 0)}{N(\cos\theta_{CS} > 0) + N(\cos\theta_{CS} < 0)}$$

Extraction of $\sin^2\theta^{\ell}_{\rm eff}$ at 13 TeV

SMP-22-010

Fundamental EW parameter

- Relates masses of EW bosons + govern strength of EW interaction
- At all orders in EW: $\sin^2\theta^{\ell}_{\rm eff.} = \kappa_{\ell}(1 - m_W^2/m_Z^2)$
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Experimental aspects

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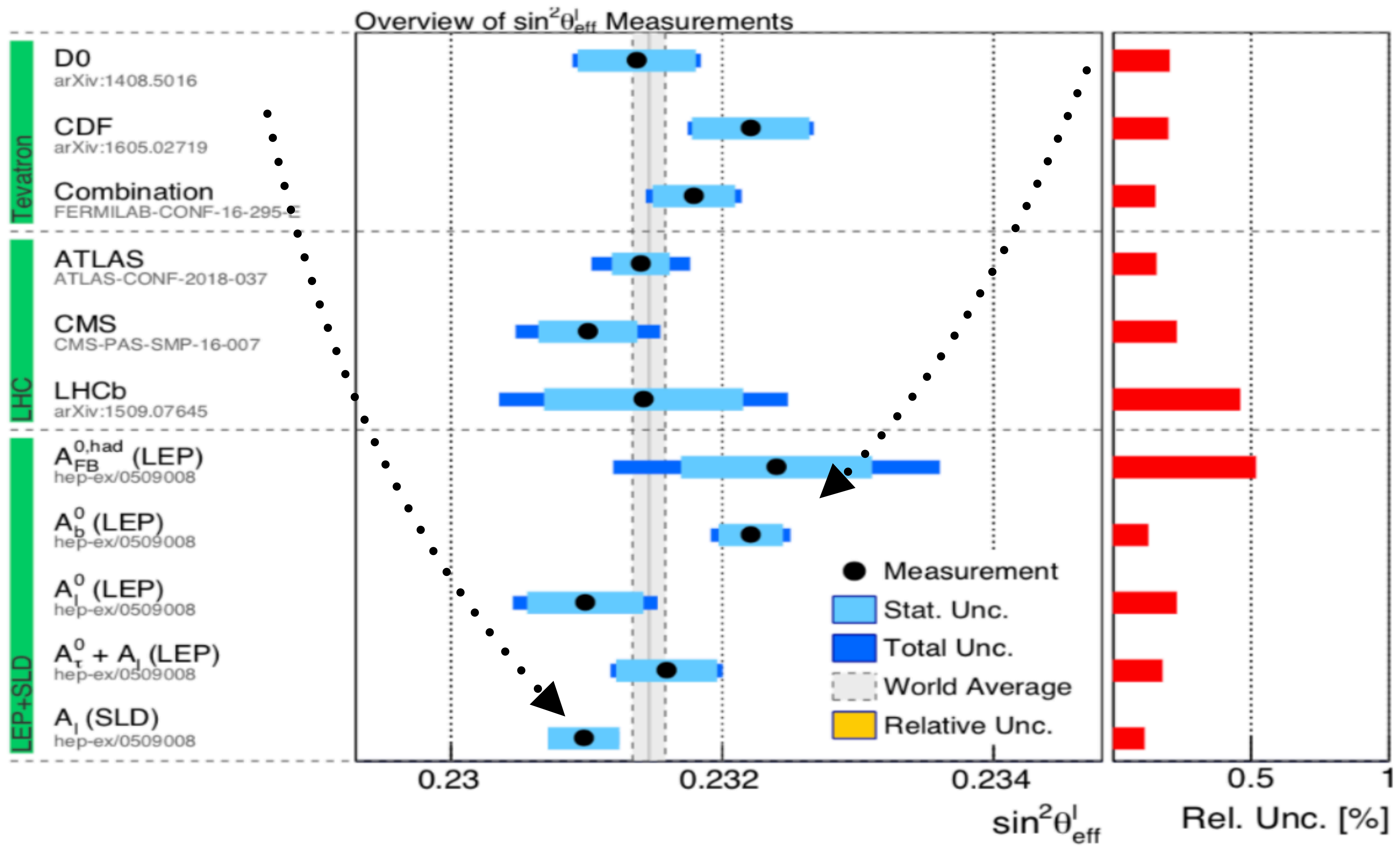

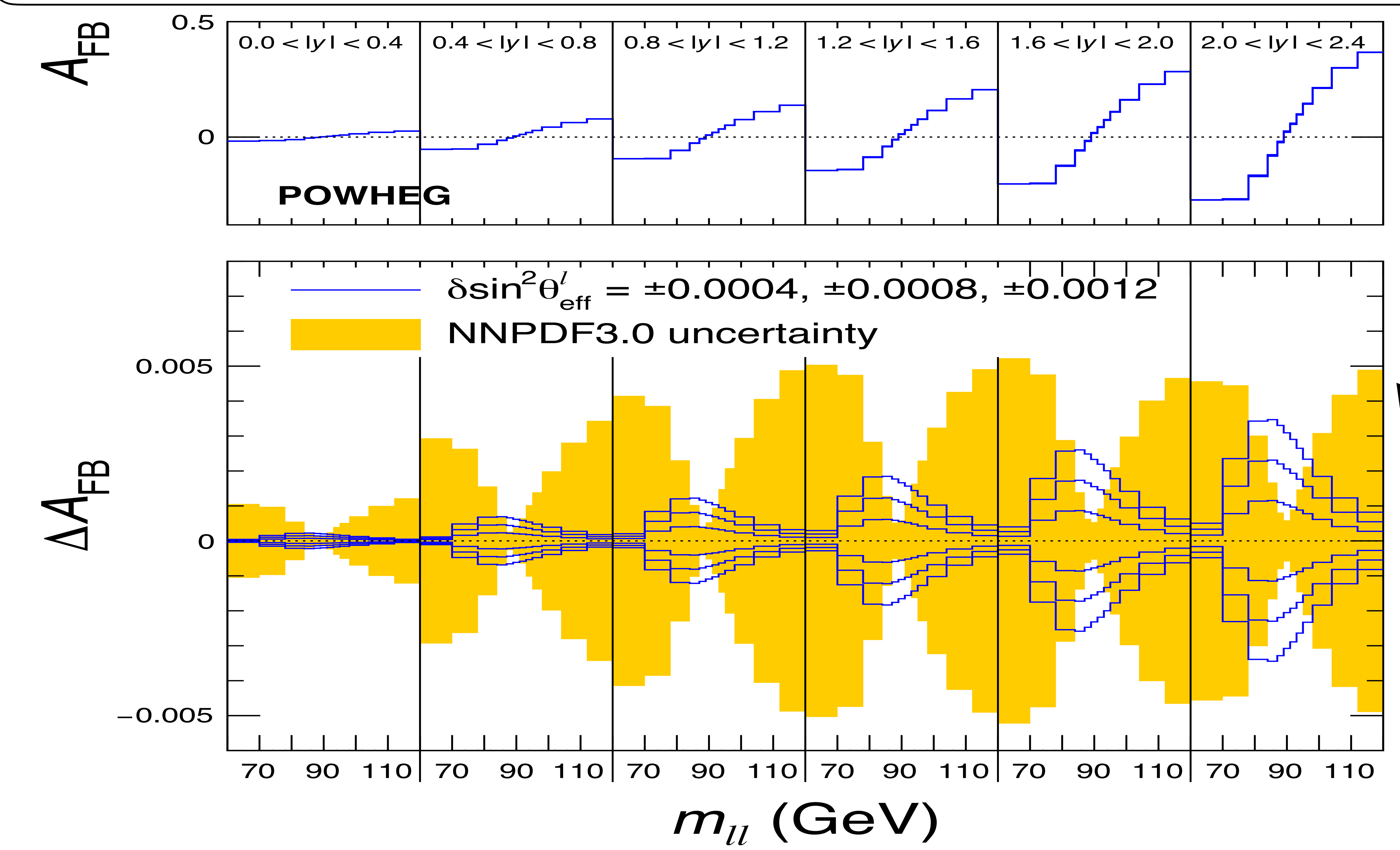

EXTRACTION OF $\sin^2\theta^{\ell}_{\text{eff}}$ AT 13 TEV

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ANALYSIS STRATEGY

- Full Run 2 dataset, pp collisions at 13 TeV
- Different dilepton final states → leverage dilution reduction at high $|y_{\ell\ell}|$

BACKGROUNDS & UNCERTAINTIES

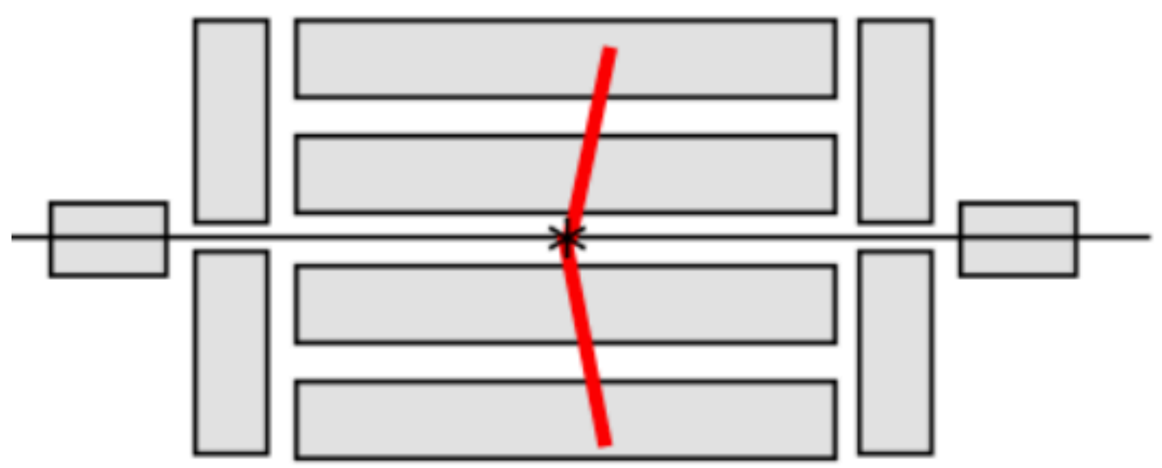
Main backgrounds

- QCD multijets: sideband in data
- W + jets: simulation corrected with FF from data
- Other EW + top: from simulation

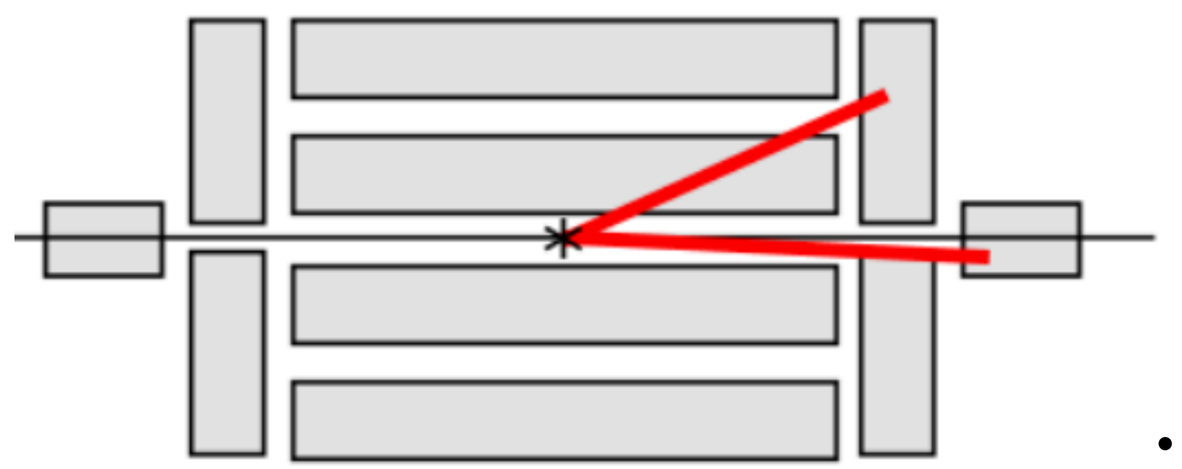
Systematic uncertainties

- Experimental: MC stat., efficiency, momentum calibration, backgrounds…
- Theory: QCD scales, $p_T^{\ell\ell}$ model, QED FSR, virtual EW, **PDFs**

Central-Central:



Central-Forward:

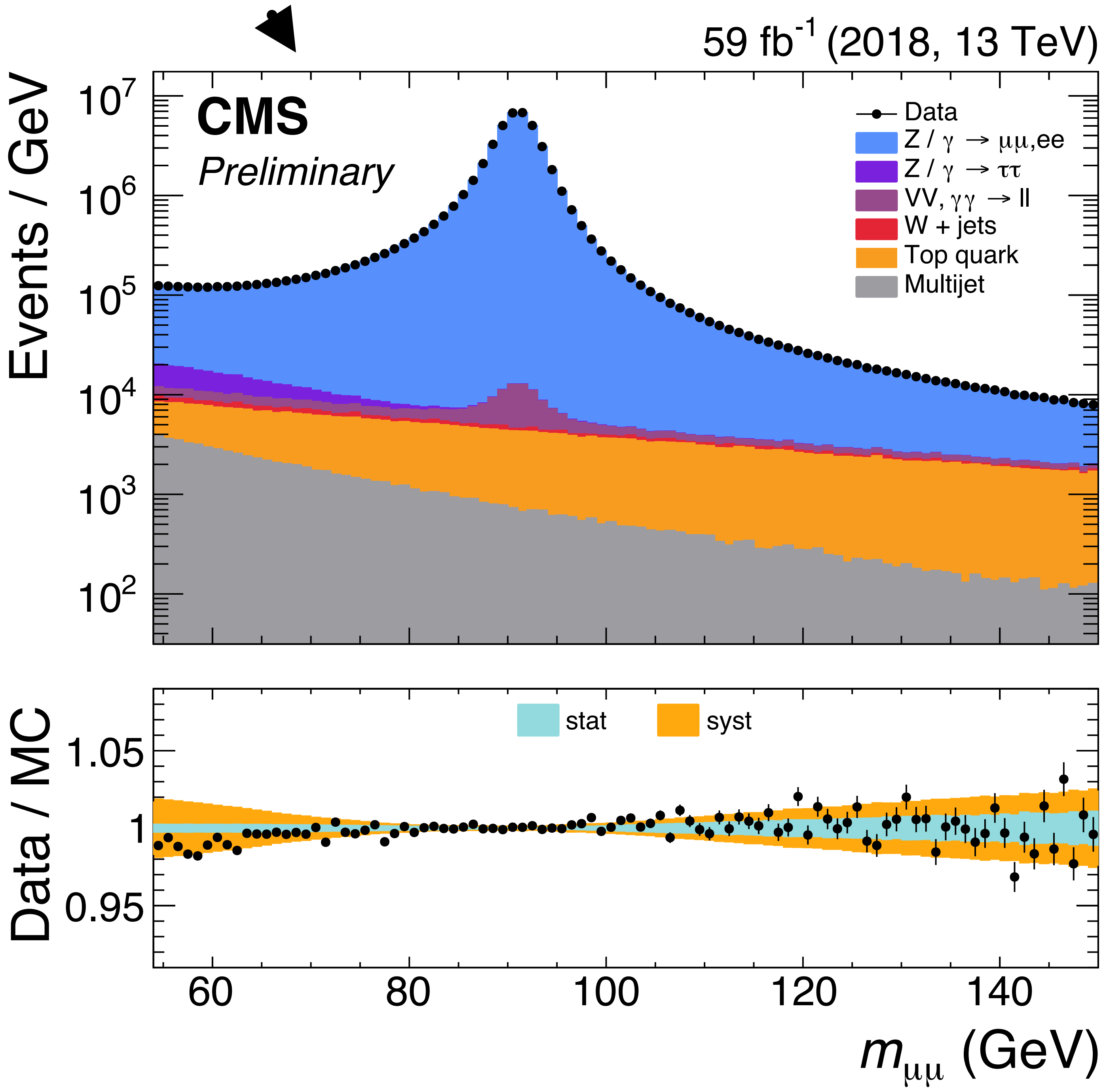


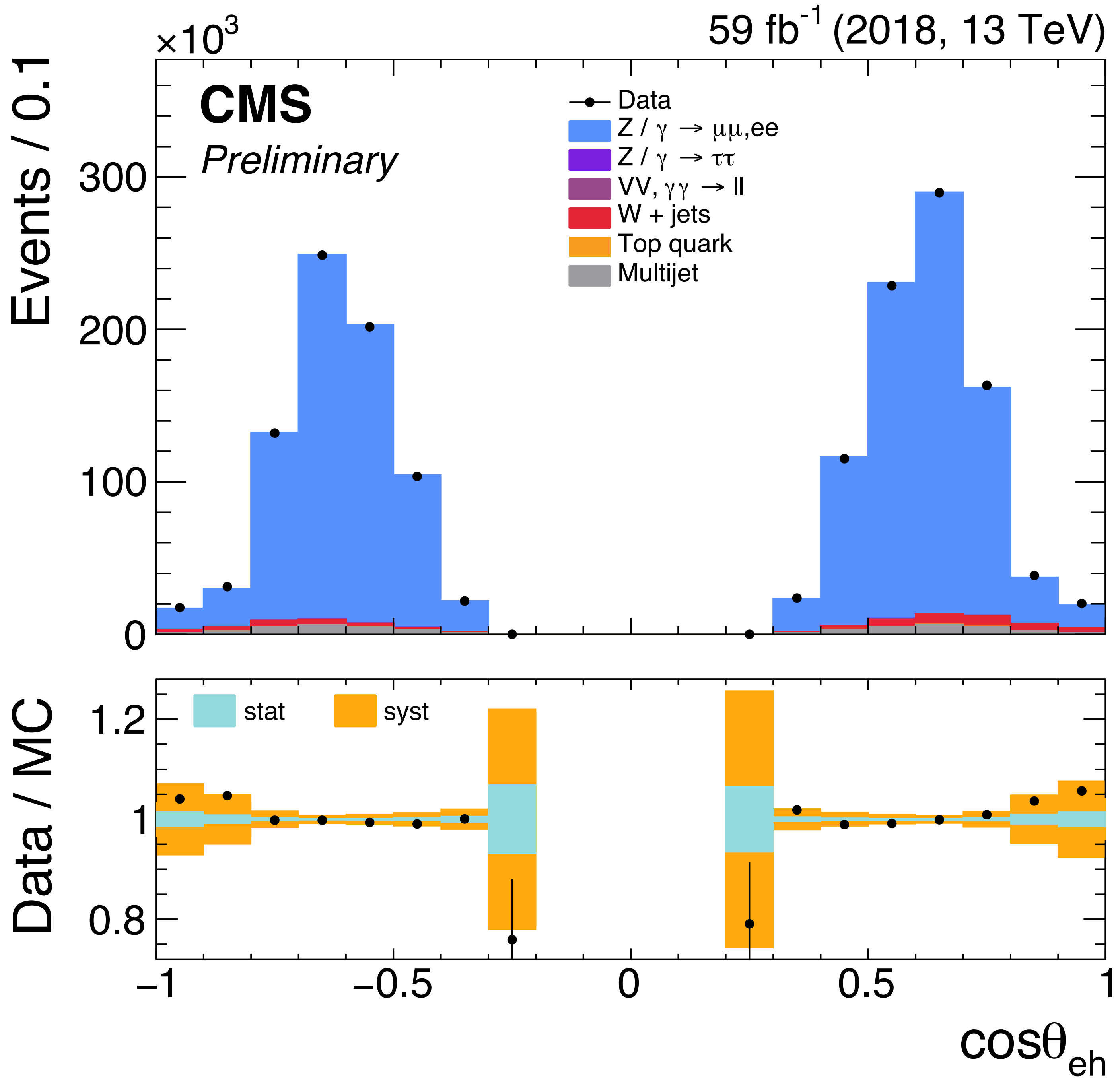
$\mu\mu$: $|\eta| < 2.4$

ee: $|\eta| < 2.5$

ee_g: $2.5 < |\eta| < 2.87$

ee_h: $3.14 < |\eta| < 4.36$





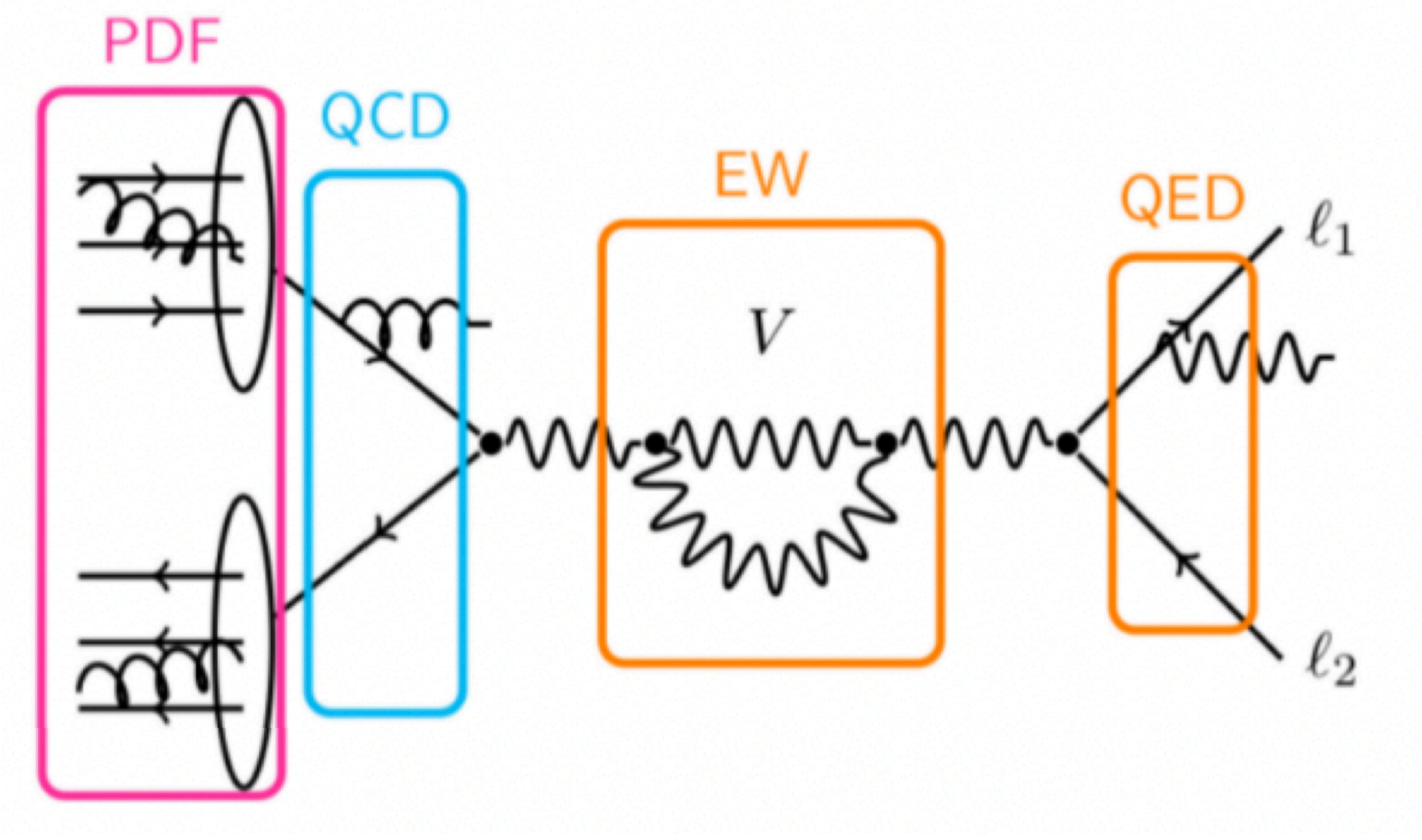
Notable data/MC agreement in all the phase-space

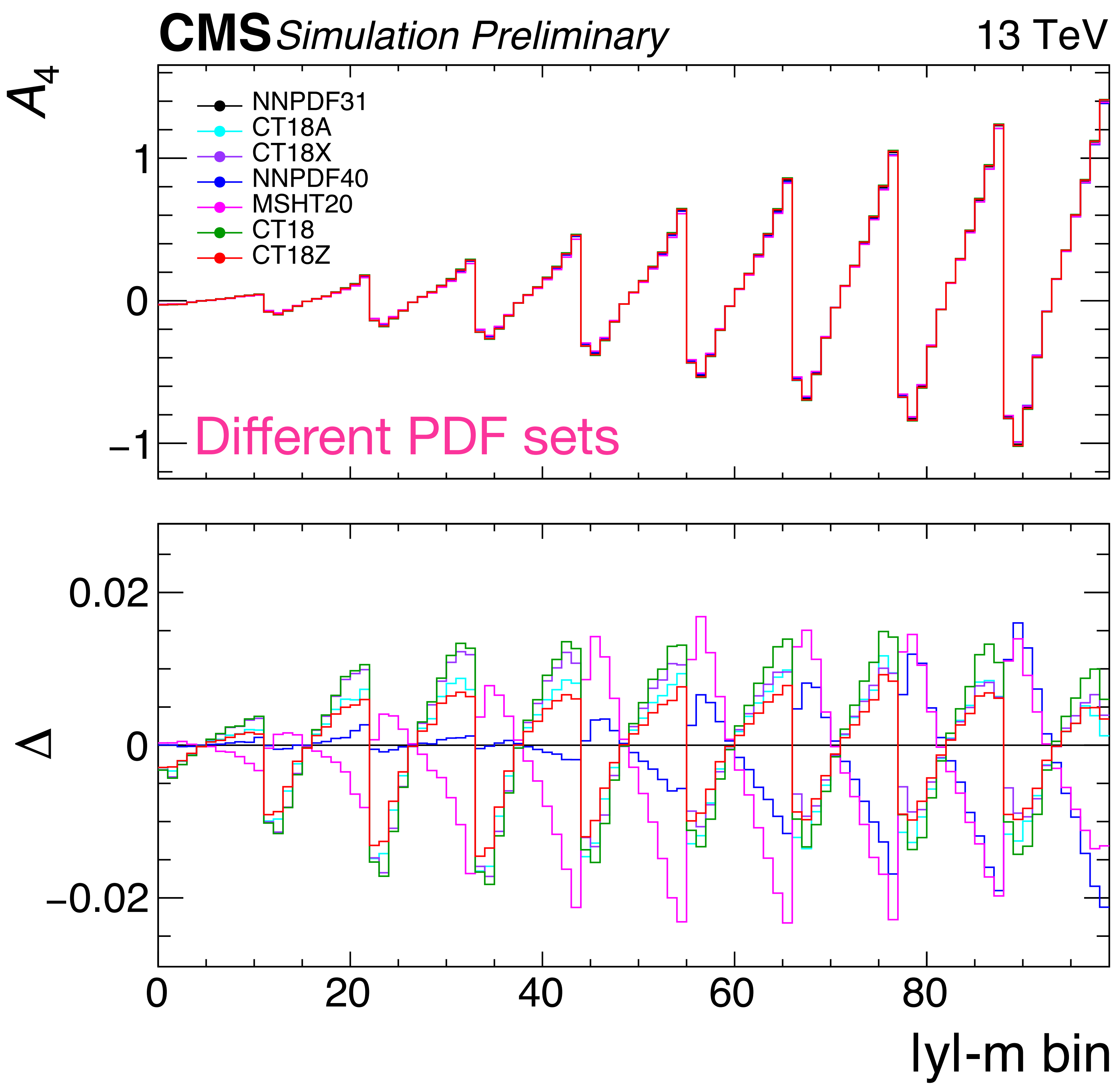
EXTRACTION OF $\sin^2\theta^{\ell}_{\text{eff}}$ AT 13 TEV

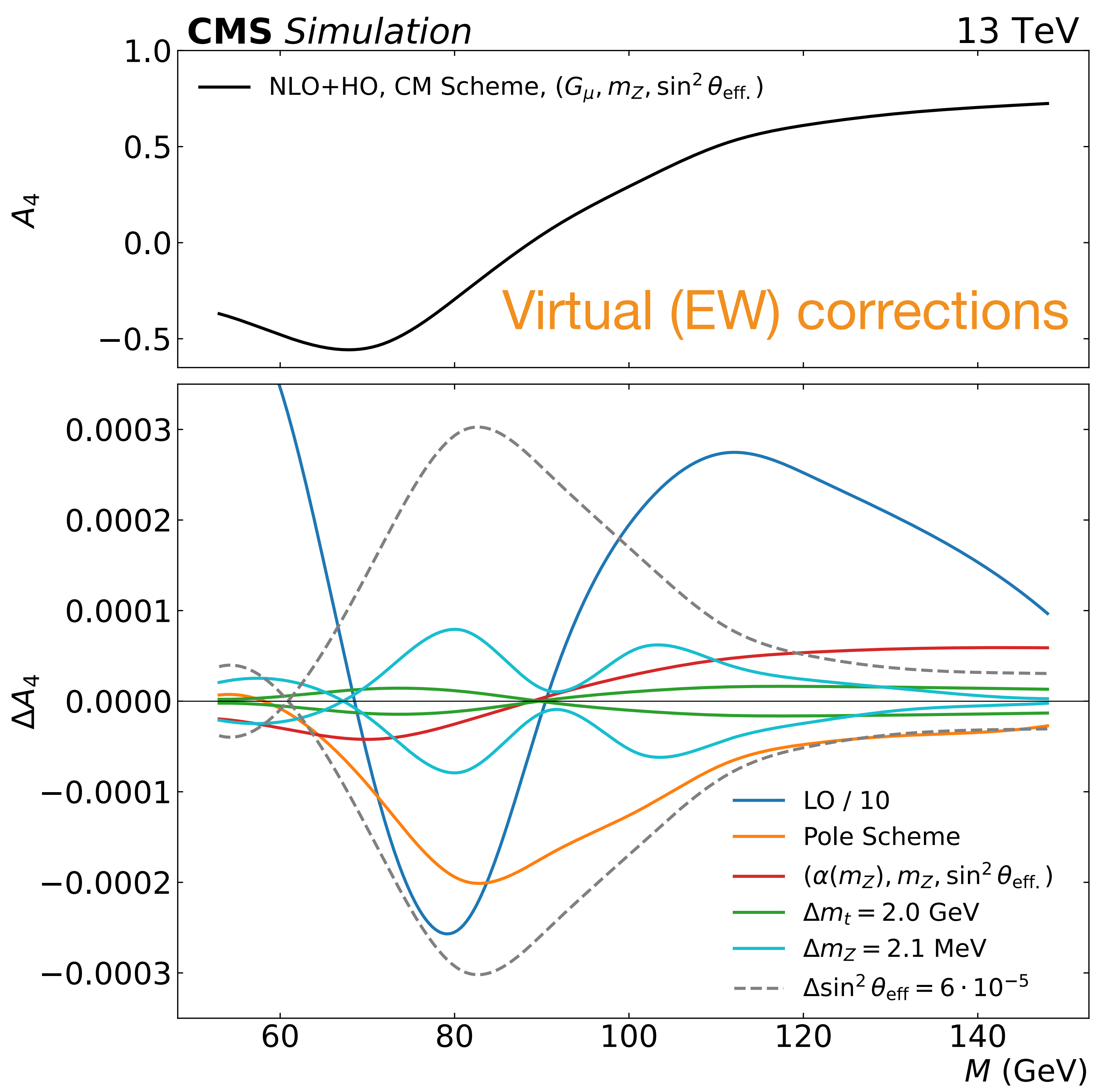
SMP-22-010

INTERPRETATION MODEL

- Baseline model: **POWHEG MiNNLO + Pythia8 + PHOTOS**
- **Virtual EW corrections included** with POWHEG Z_ew:
  - input renormalisation scheme $(G_\mu, m_Z, \sin^2\theta^{\ell}_{\text{eff}})$
  - NLO weak + universal HO corrections
  - Complex mass scheme width







IMPACT OF MODERN PDFs

- NNPDF
- CTEQ
- MSHT

IMPACT OF MISSING EW CORR.

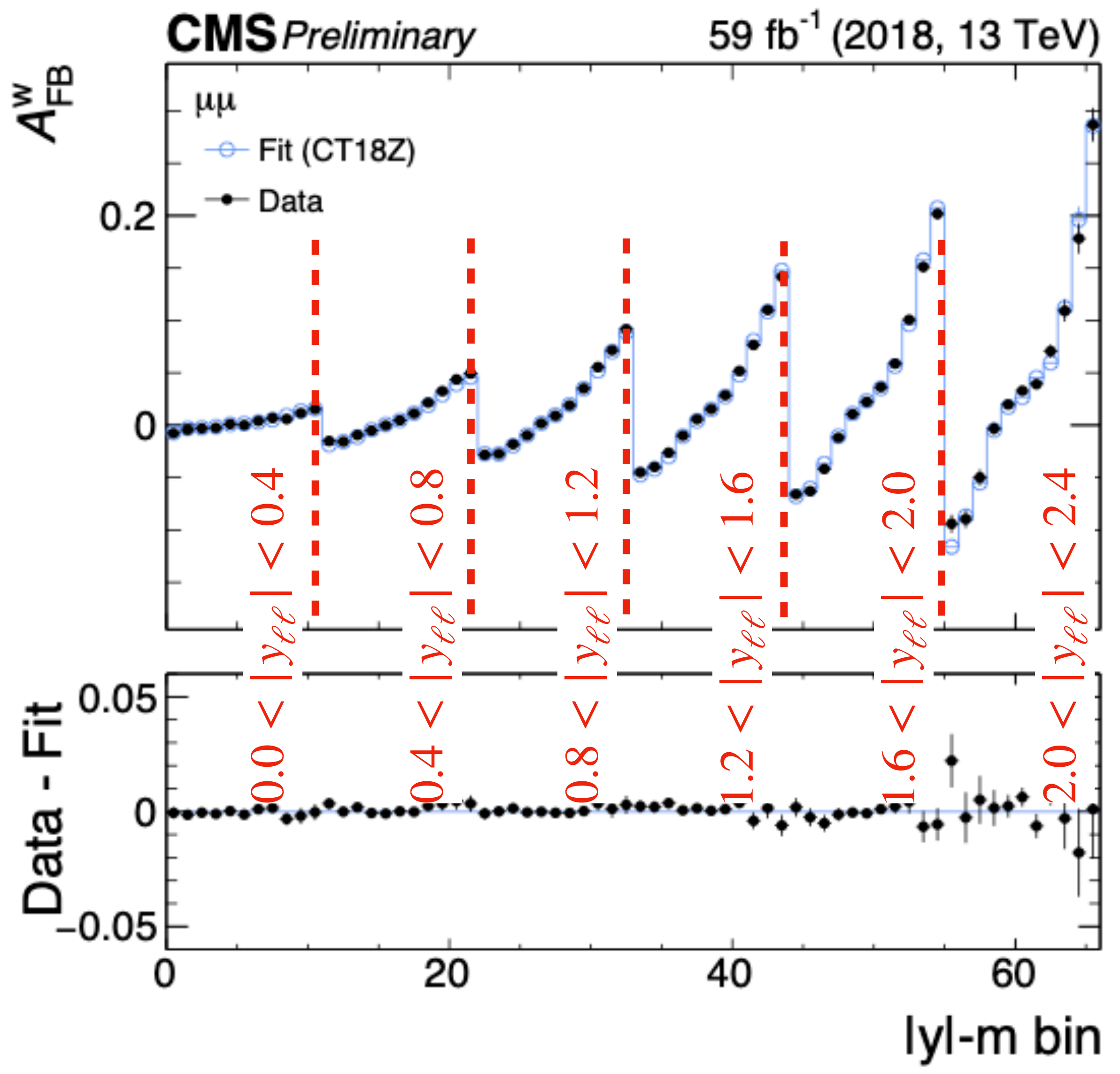
- Different renormalisation and propagator scheme
- Change input values for Δm_Z, $\Delta\alpha$, Δm_t

EXTRACTION OF $\sin^2\theta^{\ell}_{\text{eff}}$ AT 13 TEV

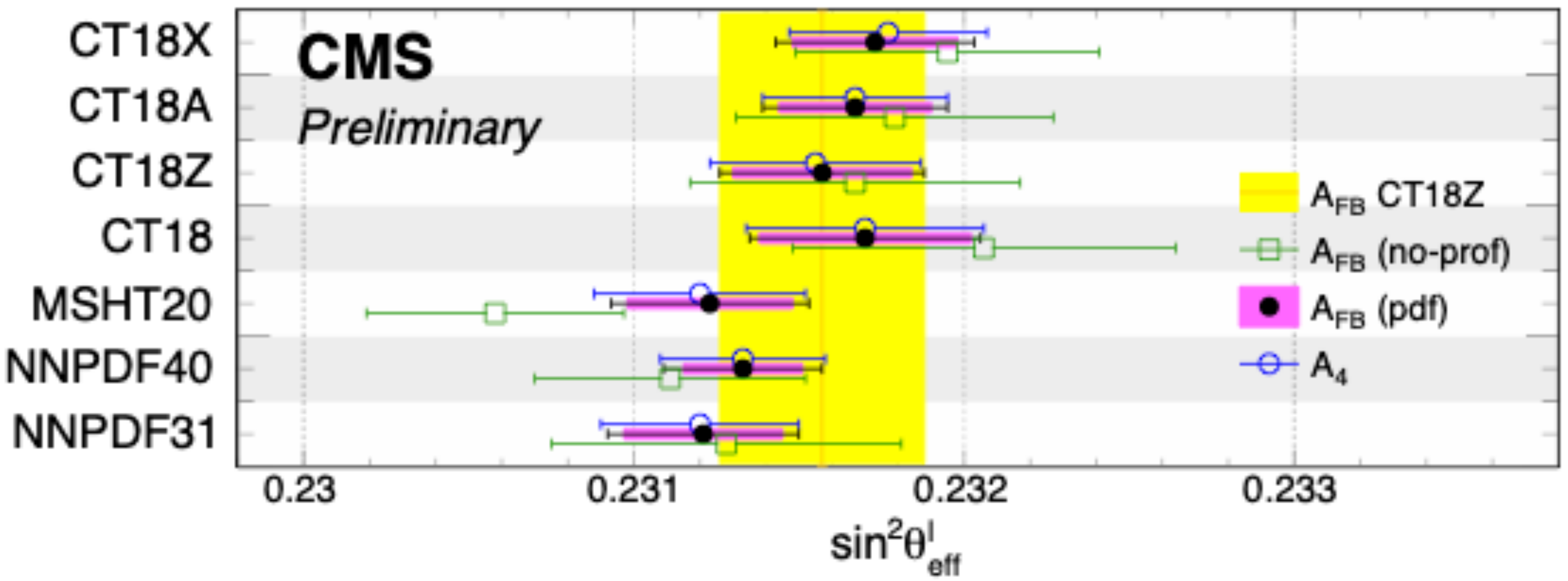
[SMP-22-010]

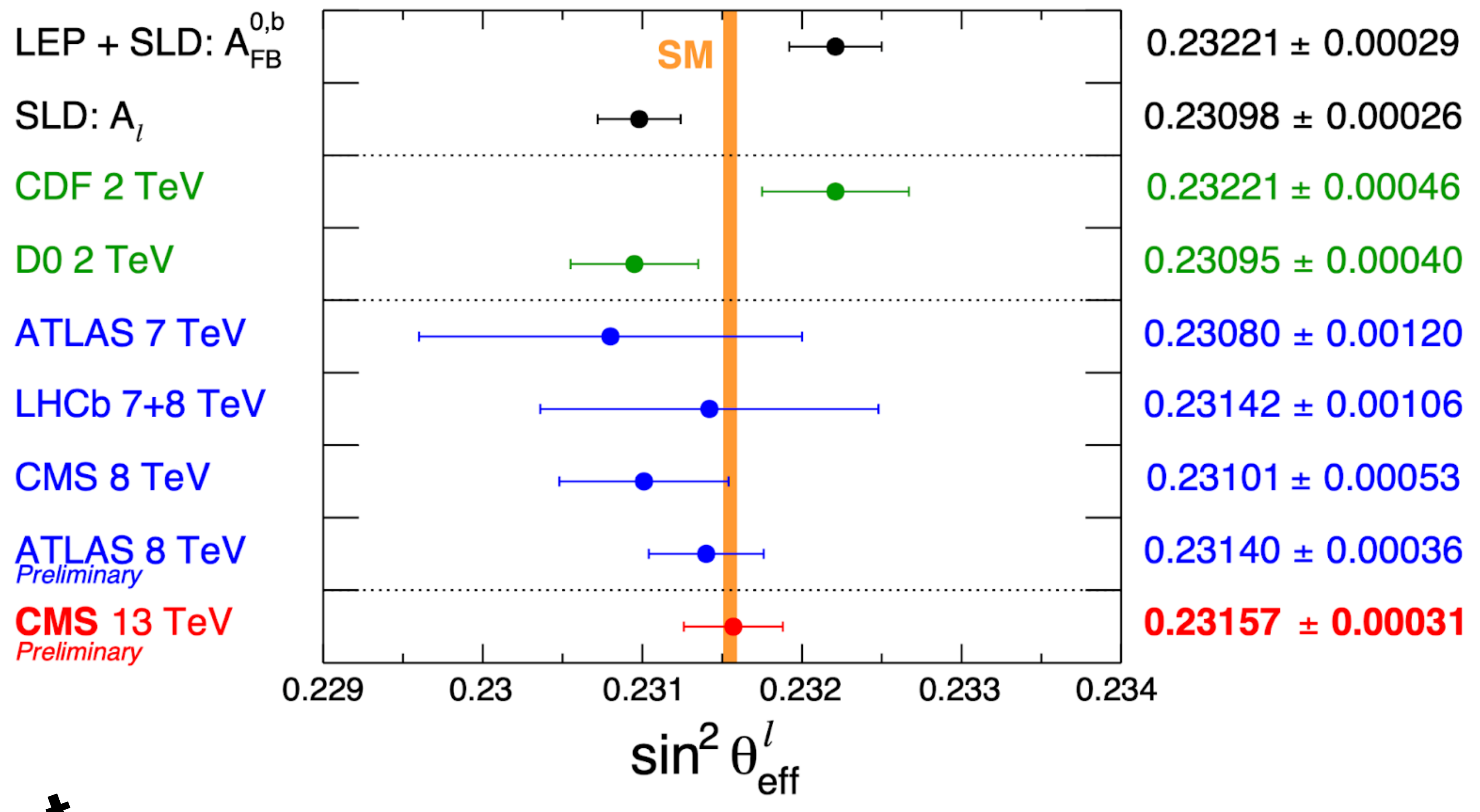
TEMPLATE FIT RESULTS

- Extract $\sin^2\theta^{\ell}_{\text{eff}}$ from **template fits** of (fiducial) A_{FB} and (unfolded) A_4
  → can be used for **possible reinterpretations**
  - All years and channels combined
  - Good sensitivity from forward topologies
- Uncertainties **dominated by PDF**
  → **CT18Z** as **default** result, its **uncertainty covers best** other central values



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





Best hadron collider measurement

$$\sin^2\theta^{\ell}_{\text{eff}} = 23157 \pm 10\,(\text{stat.}) \pm 15\,(\text{syst.}) \pm 9\,(\text{theo.}) \pm 27\,(\text{PDF}) \times 10^{-5}$$

SUMMARY

PHENOMENOLOGIST POINT OF VIEW

- **Feedback** experiment ↔ theory **fundamental**
- Entered the **N^{3}LO era** for both ME calculations and PDF determinations
- **Precise PDFs determination** becoming more and more **important**

EXPERIMENTALIST POINT OF VIEW

- Many recent measurements already **reached** (**surpassed**) the **LEP** precision era
- **Refine techniques** and **understand** of **detector** at high level
- Many **new results** in the **pipeline**: stay tuned!

DRELL-YAN MEASUREMENTS IMPORTANT ASSETS FOR THE LHC PHYSICS PROGRAM