Electroweak Precision Measurements at CMS

New measurement of $\sin^2\theta^{\ell}_{\text{eff}}$ *and* $A_{\text{FB}}(y,m)$ *at 13 TeV*

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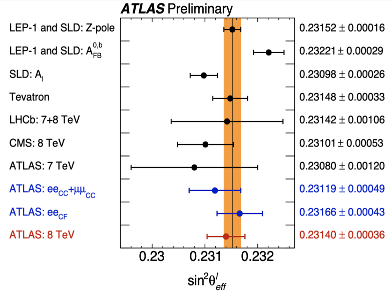
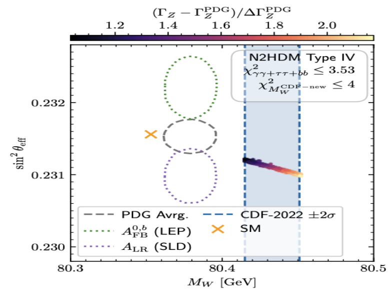
On behalf of the CMS Collaboration

Moriond EW, March 25, 2024

- Precision Standard Model measurements = indirect search for new physics
- Key electroweak parameters: m_W and $\sin^2\theta^\ell_{\text{eff}} = (1 - m^2_{\text{W}}/m^2_{\text{Z}})\kappa^\ell$ can be calculated in SM using other precise experimental inputs: $\sin^2\theta^\ell_{\text{eff}} = 0.23155 \pm 0.00004$ (SM)
- Two most precise $\sin^2\theta^\ell_{\text{eff}}$ results from LEP and SLD differ by $\sim 3\sigma$
- Measurements at hadron colliders are now also competitive

ATLAS-CONF-2018-037 | Eur. Phys. J. C 83, 450 (2023)





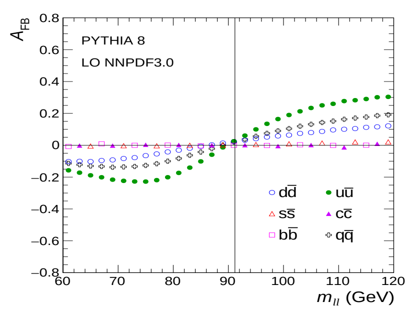
- Latest CDF m_{W} measurement disagrees with previous results and SM
- Models that describe CDF m_{W} prefer lower (SLD) value of $\sin^2\theta^\ell_{\text{eff}}$

→ New CMS measurement of $\sin^2\theta^\ell_{\text{eff}}$ at 13 TeV is the main topic of this talk

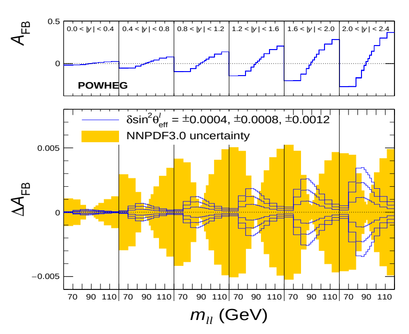
- Use $Z/\gamma \to \ell\ell$ events
- Asymmetry in lepton decay angle:

  $1+\cos^2\theta+0.5A_0(1-3\cos^2\theta)+A_4\cos\theta$

  $\to A_{\rm FB} = 3/8A_4$
- $m_{\ell\ell}$ dependence from γ-Z interference
- Colins-Sopper frame – reduced theoretical and experimental unc.



Eur. Phys. J. C 78, 701 (2018)



1) Near m_Z, $A_{\rm FB}$ depends on $\sin^2\theta^\ell_{\rm eff}$

- In pp, definition of positive z direction relies on $\ell\ell$ boost (sign of $y_{\ell\ell}$)

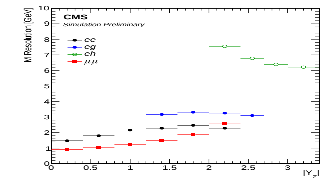
  $\to$ only valence quarks contribute

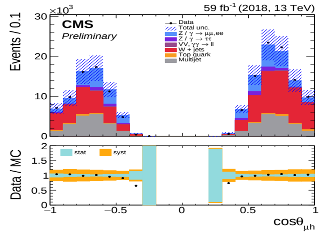
  $\to$ significant $y_{\ell\ell}$-dependent dilution

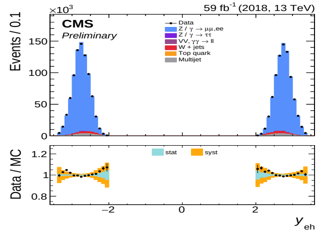
2) Strong dependence on PDFs

$\to$ Fit $A_{\rm FB}$ floating $\sin^2\theta^\ell_{\rm eff}$ and PDFs

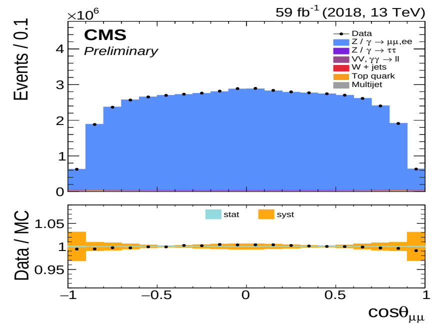
- **What we measure**:
  - → $\sin^2\theta^{\ell}_{\text{eff}}$ using $A^{\text{wgt}}_{\text{FB}}$
    (small systematics, used in Run 1)
  - → Unfolded $A_4(y, m)$
    (can be used in future reinterpretation)
- **Four $\ell\ell$ channels**: $\mu\mu$, ee, eg, eh
  - μ – muon: $|\eta| < 2.40$
  - e – central electron: $|\eta| < 2.50$
  - g – EF electron: $2.50 < |\eta| < 2.87$
  - h – HF electron: $3.14 < |\eta| < 4.36$
- **Backgrounds**:
  - – Multijet from data sidebands
    cross-checked in same-sign samples
  - – W+jets from simulation
    in eg & eh corrected by fake-lepton SFs
  - – Other EW and top bkg from simulation
    top and $\tau\tau$ checked in μe samples
- **Signal sample**:
  Powheg MiNNLO + Pythia8 + Photos
  (with various corrections)



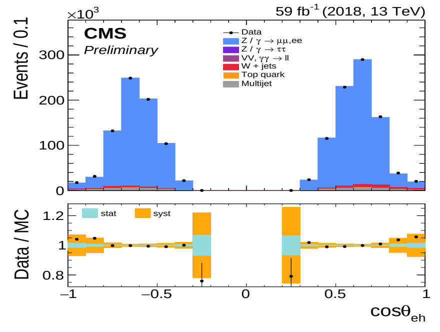




- **Experimental**
  - MC statistical
  - Efficiencies
  - Momentum calibration
  - Backgrounds
  - Other
    - Trigger prefiring
    - z_{vtx} position
    - Charge misID
    - Pileup
    - Luminosity

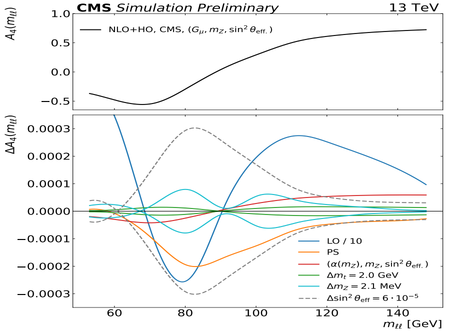


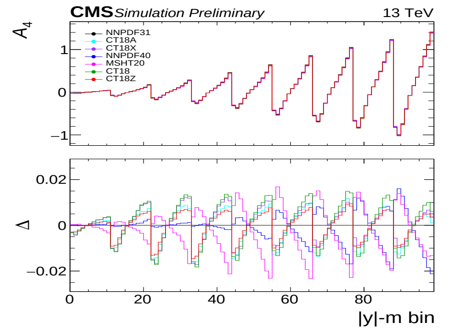
- **Theory**
  - μ_R, μ_F scales
  - $p_T^{\ell\ell}$ model
  - FSR
  - EW input schemes
  - EW input parameters
- **PDF**



- **Default EW configuration:**
  - NLO weak + universal HO corrections
  - input scheme: $(\sin^2\theta^{\ell}_{\text{eff}}, m_Z, G_\mu)$
  - width: complex-mass scheme (CMS)

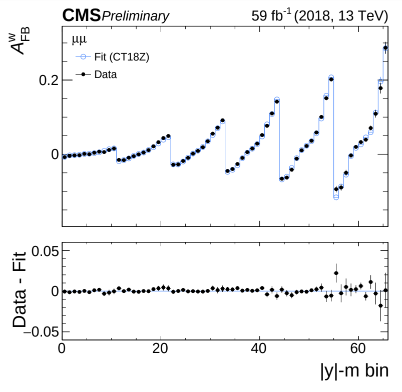
- **Systematic variations:**
  - input scheme: $(\sin^2\theta^{\ell}_{\text{eff}}, m_Z, \alpha)$
  - width: pole scheme (PS)
  - parameters: $(\Delta m_Z, \Delta m_t, \Delta G_\mu)$

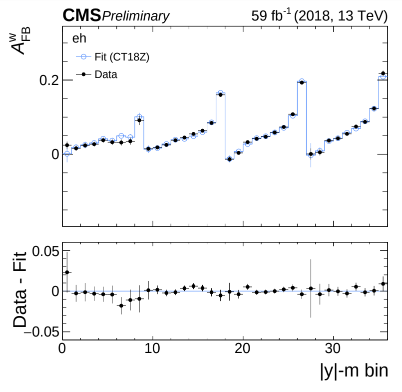




- Various NNLO PDFs considered
- **By default we chose CT18Z** (before unblinding) since its uncertainty covers best others' central values (→ next)

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

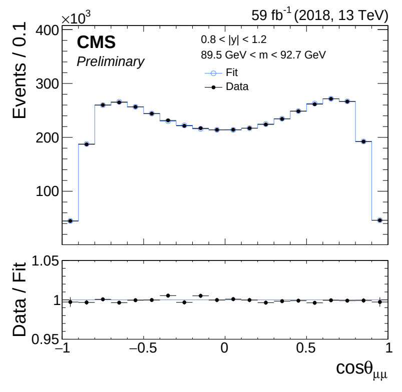


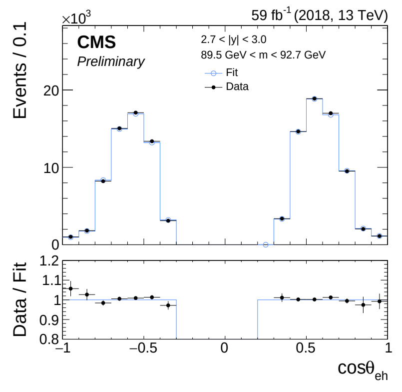


- Here and in next slides, $\sin^2\theta^{\ell}_{\mathrm{eff}}$ values and its uncertainties are in units of 10^{-5}

ch	χ^2	nbin	p(%)	$\sin^2\theta^{\ell}_{\mathrm{eff}}$	$\pm$	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

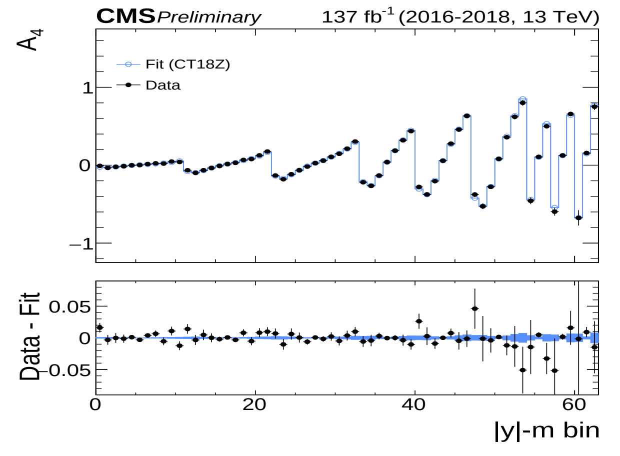
- $A_4(y,m)$ is measured by fitting reconstructed $\cos\theta_{CS}$ distributions in y and m bins simultaneously in all runs and channels





- Total $\chi^2_{min} = 14839$ for total of 14205 measurement bins and 101 free POIs
- Minimized with L-BFGS method using analytic gradient input
- Resulting covariance matrix also evaluated analytically with inverse Hessian

- Fit measured $A_4(y, m)$ with $\sin^2\theta^{\ell}_{\text{eff}}$ (s) and PDF-nuisance templates

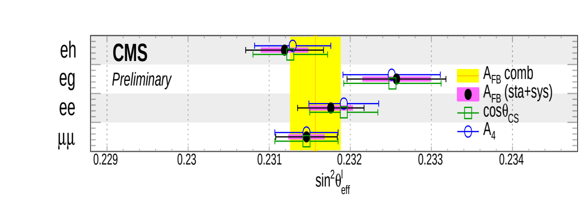


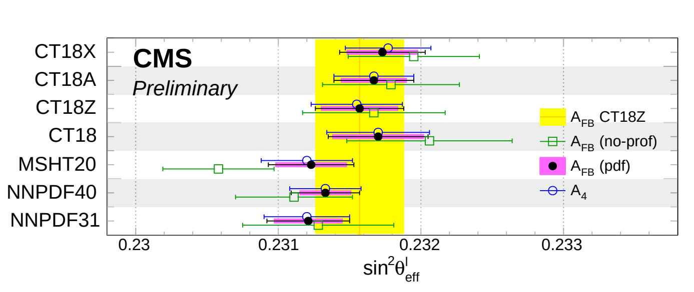
Channel	n(bins)	χ^2_{min}	p(%)	$\sin^2\theta^{\ell}_{\text{eff}}$	$\pm$	σ
$\mu\mu$	54	59.7	24.6	23146	$\pm$	39
ee	54	47.0	70.7	23192	$\pm$	43
eg	12	11.1	43.6	23251	$\pm$	60
eh	12	8.4	67.3	23129	$\pm$	47
$\ell\ell$	63	61.3	50.3	23155	$\pm$	32

Compared results for:

- A_{FB}, A_4, & $\cos\theta_{\mathrm{CS}}$ fits
- Different channels
- Different runs (backup)
- Different PDFs

  (with & without profiling)

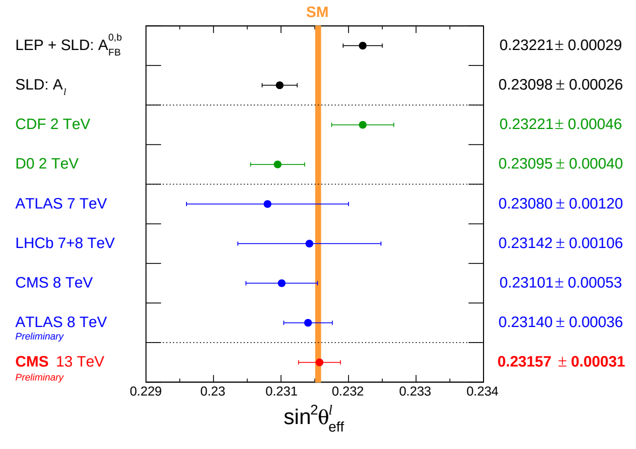




- Results in good agreement within corresponding uncertainties

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

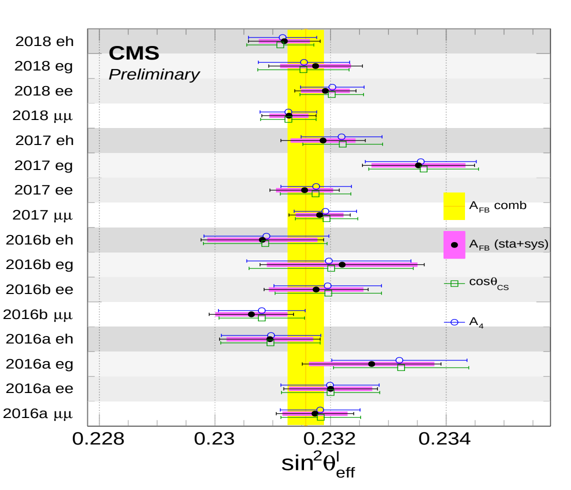
$$\sin^2\theta^\ell_{\text{eff}} = 0.23157 \pm 0.00031$$

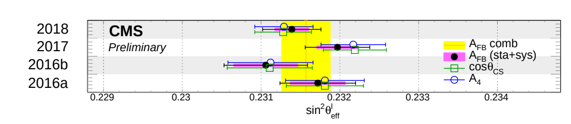


- Good agreement with previous measurements and SM
- PDF uncertainties (which are correlated with others) dominate

- Most precise hadron-collider measurement: $\sin^2\theta^{\ell}_{\text{eff}} = 0.23157 \pm 0.00031$
  $\rightarrow$ precision also comparable with LEP and SLD results
- PDF is already the dominant uncertainty in Run-2
  $\rightarrow$ main challenge for future $\sin^2\theta^{\ell}_{\text{eff}}$ measurements at the LHC
- Also measured unfolded $A_4(y, m)$
  $\rightarrow$ simple reinterpretation and combination with other measurements

Backup


CMS
Preliminary
2018 eh
2018 eg
2018 ee
2018 μμ
2017 eh
2017 eg
2017 ee
2017 μμ
2016b eh
2016b eg
2016b ee
2016b μμ
2016a eh
2016a eg
2016a ee
2016a μμ
A_{FB} comb
A_{FB} (sta+sys)
$\cos\theta_{CS}$
A_4
0.228
0.23
0.232
0.234
$\sin^2\theta^l_{eff}$


CMS
Preliminary
2018
2017
2016b
2016a
A_{FB} comb
A_{FB} (sta+sys)
$\cos\theta_{CS}$
A_4
0.229
0.23
0.231
0.232
0.233
0.234
$\sin^2\theta^l_{eff}$

Event selections

$\mu\mu$,ee: single- & double-ℓ triggers
standard ID, opposite charges

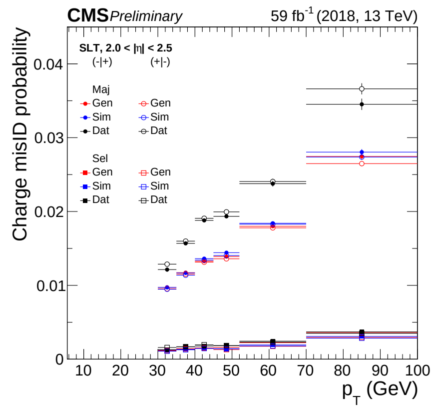
eg,eh: single-e triggers
dedicated IDs for g & h
tight (selective) charge-ID for e

Signal sample

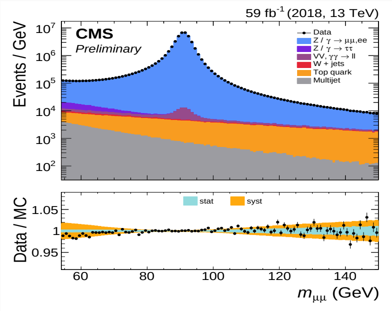
Powheg MiNNLO + Pythia8 + Photos

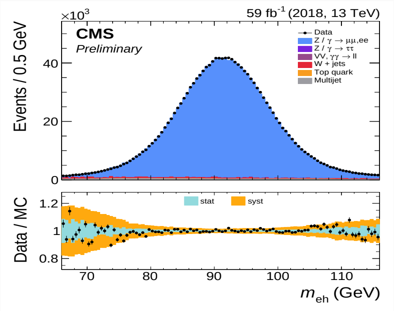
corrections:

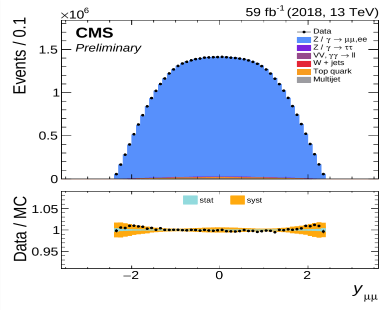
- NLO weak corrections (Powheg-EW)
- Pileup weighting
- Trigger prefiring weighting
- Efficiency SFs
- **Electron charge MisID SFs** →
- Lepton momentum corrections
- Dilepton p_T weighting

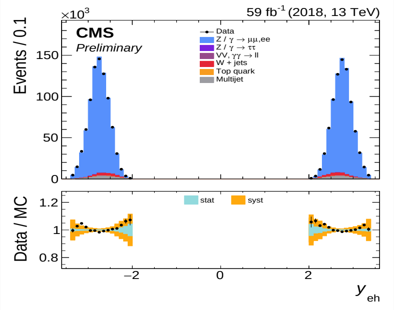


Dilepton mass and rapidity





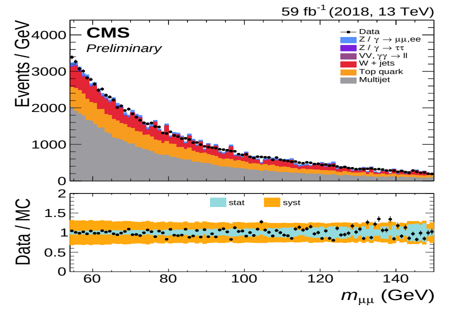


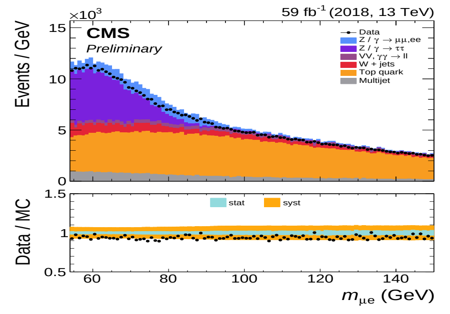


- Small multijet bkg estimated from data bkg-enriched regions using transfer-factors (TF)

- TFs evaluated using various μe and same-sign (SS) bkg-enriched regions

- Independent check in SS $\ell\ell$ samples



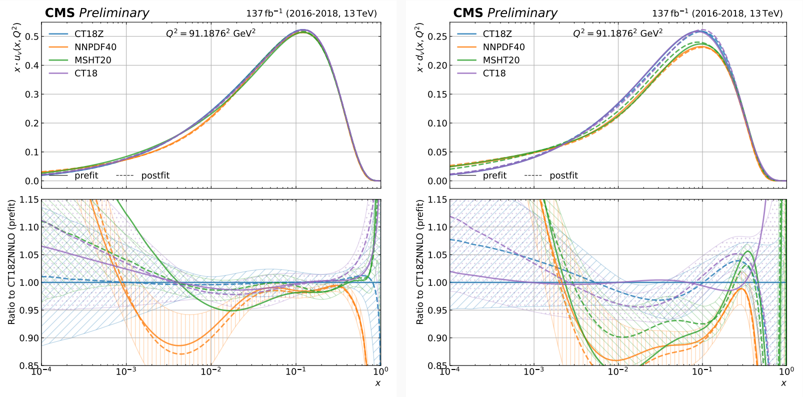


- Small EW & top bkg normalized to luminosity with NNLO x-sections

→ Checked in μe samples

- $\mu g, \mu h$ samples used to check multijet estimate & derive fake-lepton SFs for $W + jets$

- Comparison of pre and post-fit valence quark distributions (only post-fit error bands are shown)



- Moderate changes in individual distributions

- Rapidity and mass bins in different fits:

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

- Combined Run-2 fit configuration:

runs (r)	2016a, 2016b, 2017, 2018	4
channels (c)	$\mu\mu$, ee, eg, eh	4
$c \times y \times m$ bins	$6 \times 11 + 6 \times 11 + 4 \times 9 + 4 \times 9$	204
$\cos\theta_{\mathrm{CS}}$ bins		20
$r \times c \times y \times m \times \cos\theta_{\mathrm{CS}}$	with $n_{pred} > 10$	14205
$a_4(y, m)$	$3 \times 11 + 3 \times 7 + 3 \times 3$	63
$\mu(y, m)$	$6 \times 5 + 4 \times 1 + 4 \times 1$	38
nuisances	all systematic uncertainties	3361