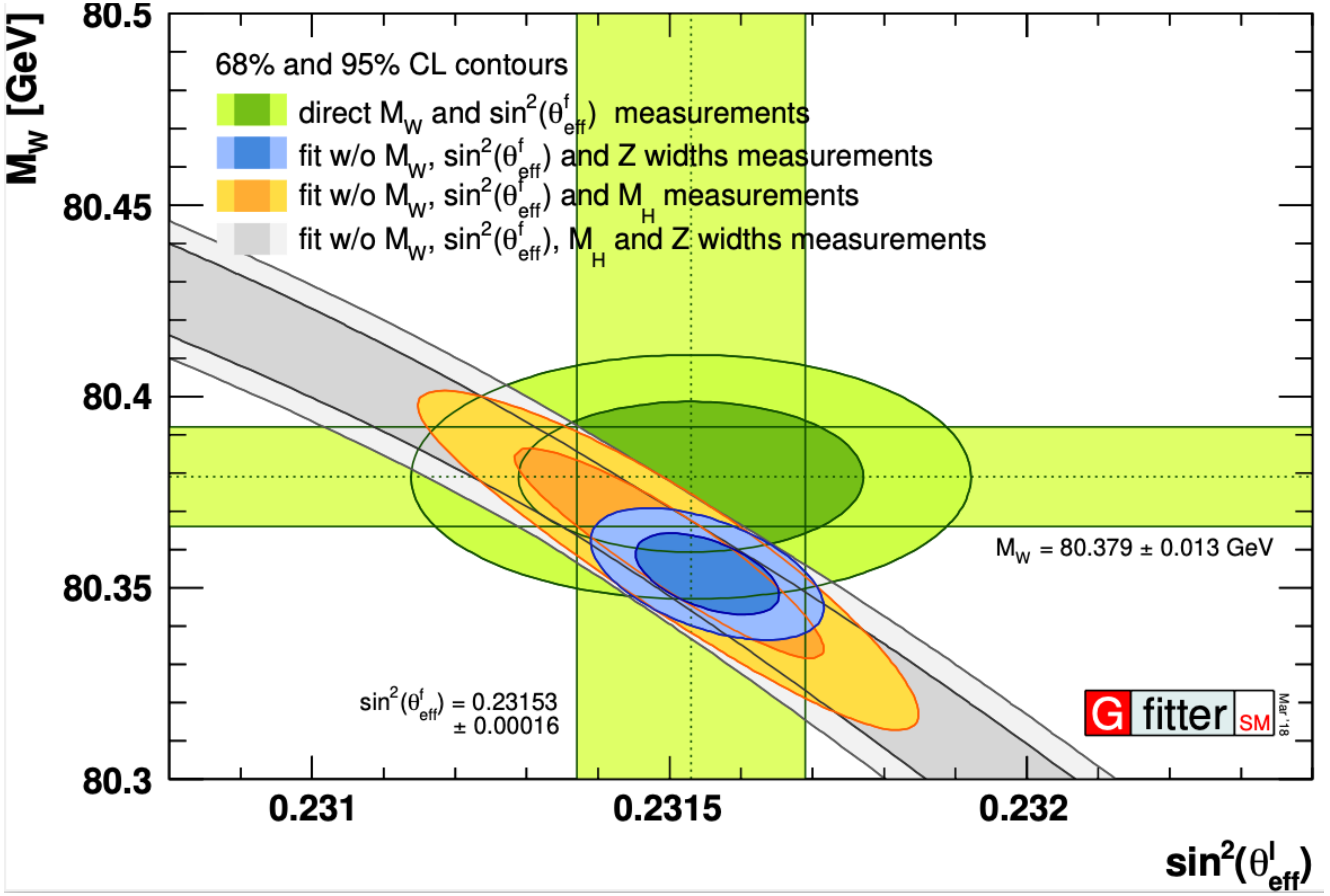
Precision Electroweak and top quark measurements

Andrew Gilbert
on behalf of the ATLAS, CMS and LHCb Collaborations

LHCP 2024 Boston | 5 June 2024

Motivation for precision EW & top measurements at the LHC

- Test the self-consistency of the SM
  - Electroweak sector over-constrained ⇒ identify tension between direct & indirect constraints on observables
  - Deviations may be due to new physics in higher order virtual corrections



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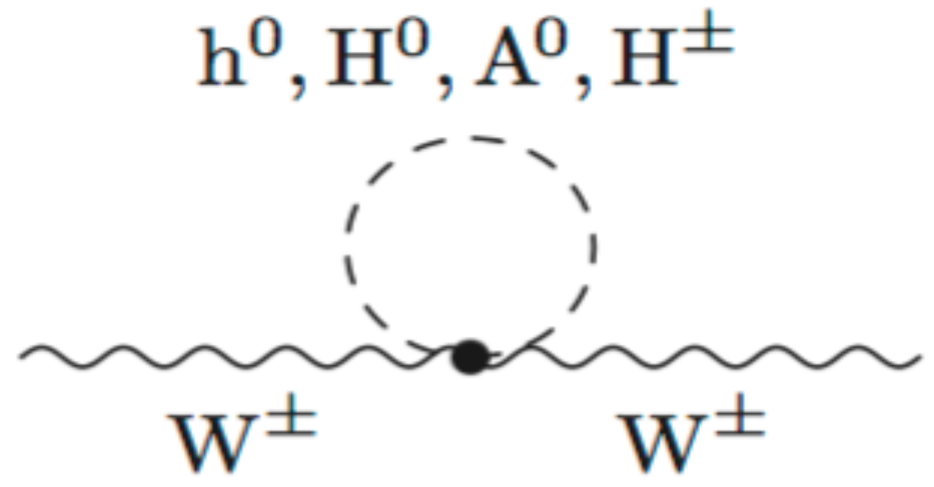


E.g. predict $\mathbf{M_W}$ and $\mathbf{\sin^2\theta_{eff}}$:

$$M_W = \frac{M_Z^2}{2}\left(1 + \sqrt{1 - \frac{\sqrt{8}\pi\alpha(1+\Delta r)}{G_F M_Z^2}}\right)$$

$$\sin^2\theta_{\text{eff}} = \sin^2\theta_W(1+\Delta\kappa)$$
$$= (1 - M_W^2/M_Z^2)(1+\Delta\kappa)$$

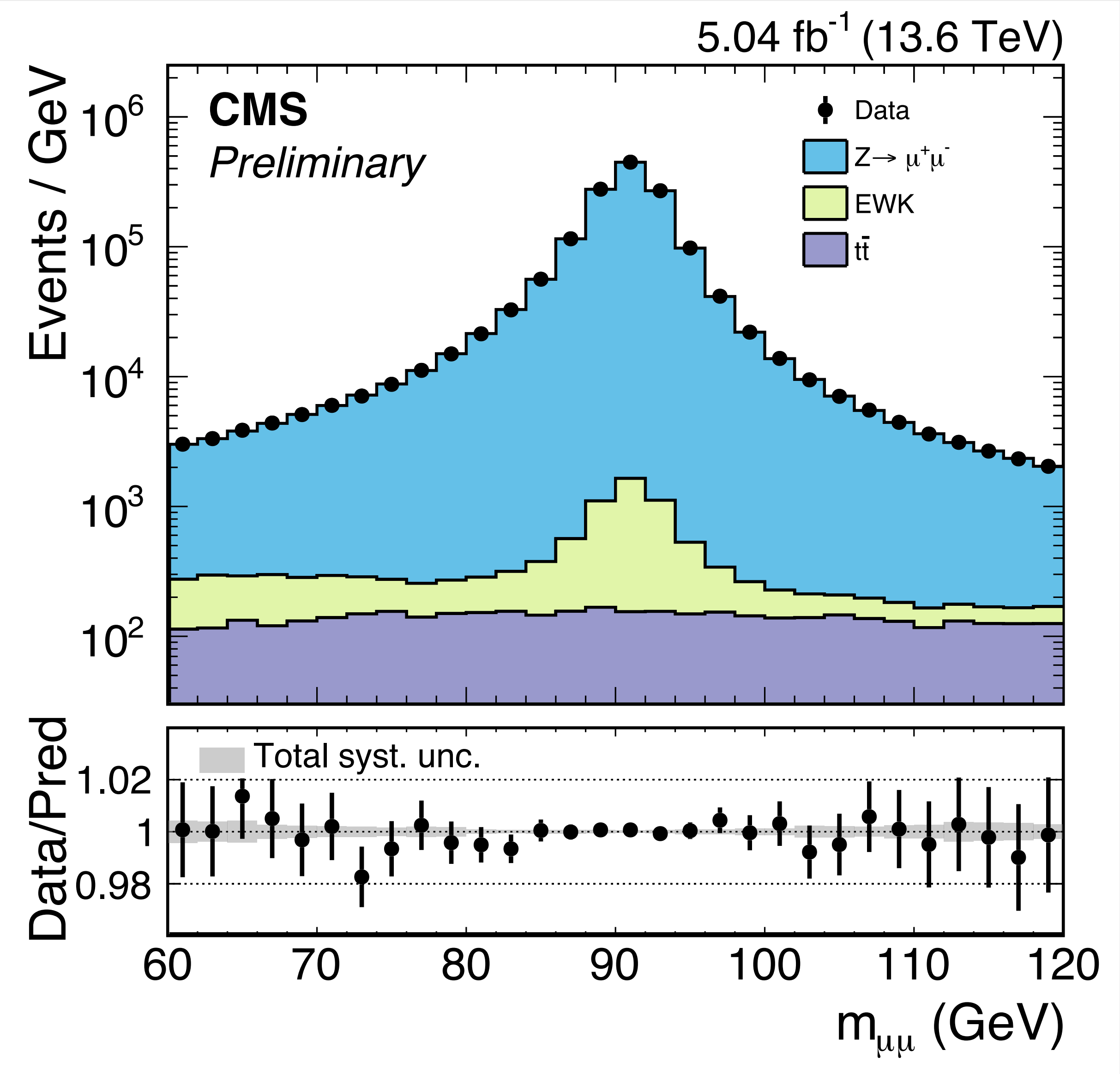
← and compare to measurements

W and Z measurements

W and Z cross sections measurements

- Fundamental measurements and crucial validation of **Run 3** data
- Recent measurement of σ_W and σ_Z (and their ratio) from ATLAS
  - Extracted from simultaneous fit to W/Z/$t\bar{t}$ regions
  - For absolute σ, lumi uncertainty dominates, for ratios: nonprompt & lepton eff.

arXiv:2403.12902 (submitted to PLB)

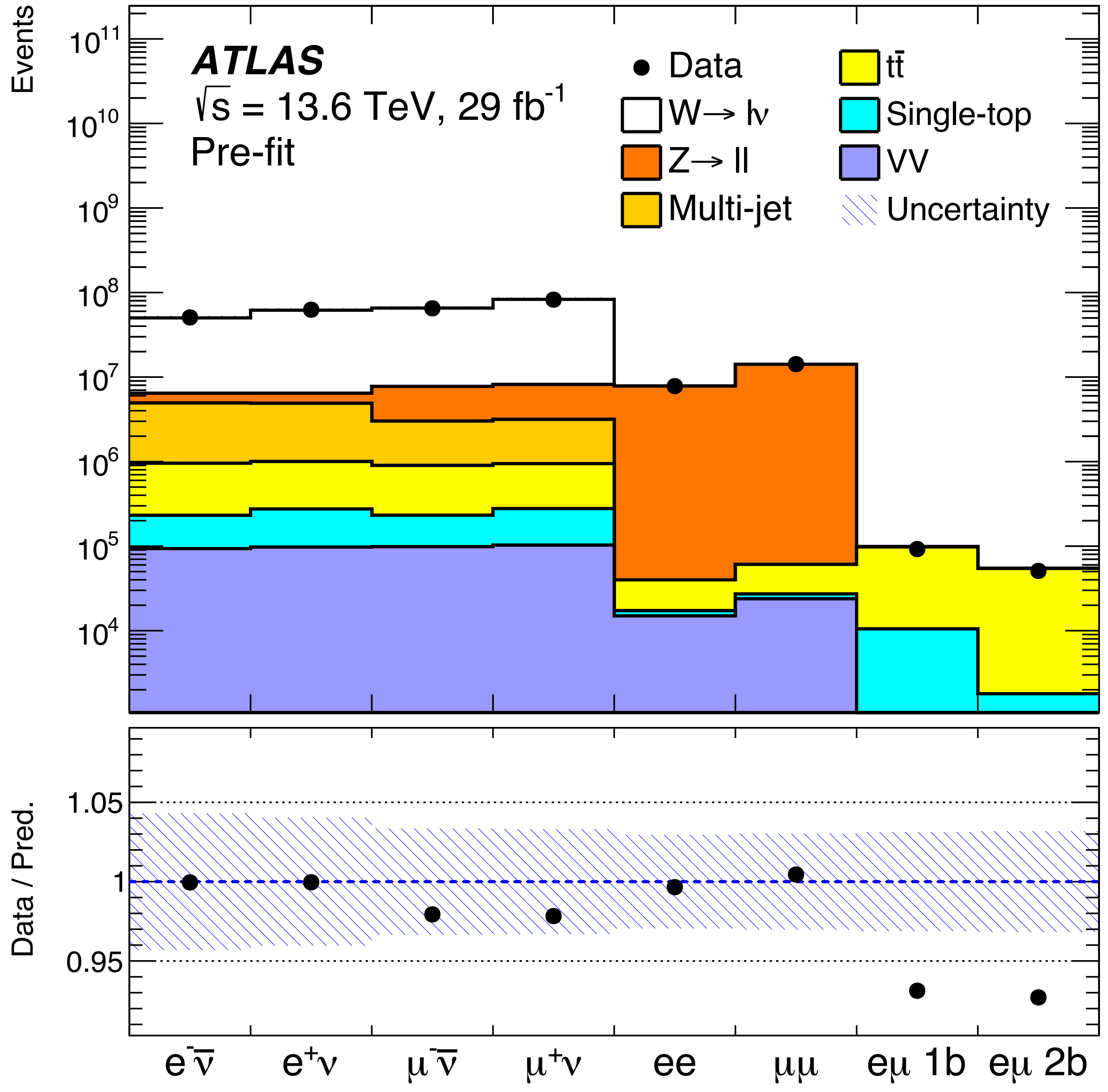


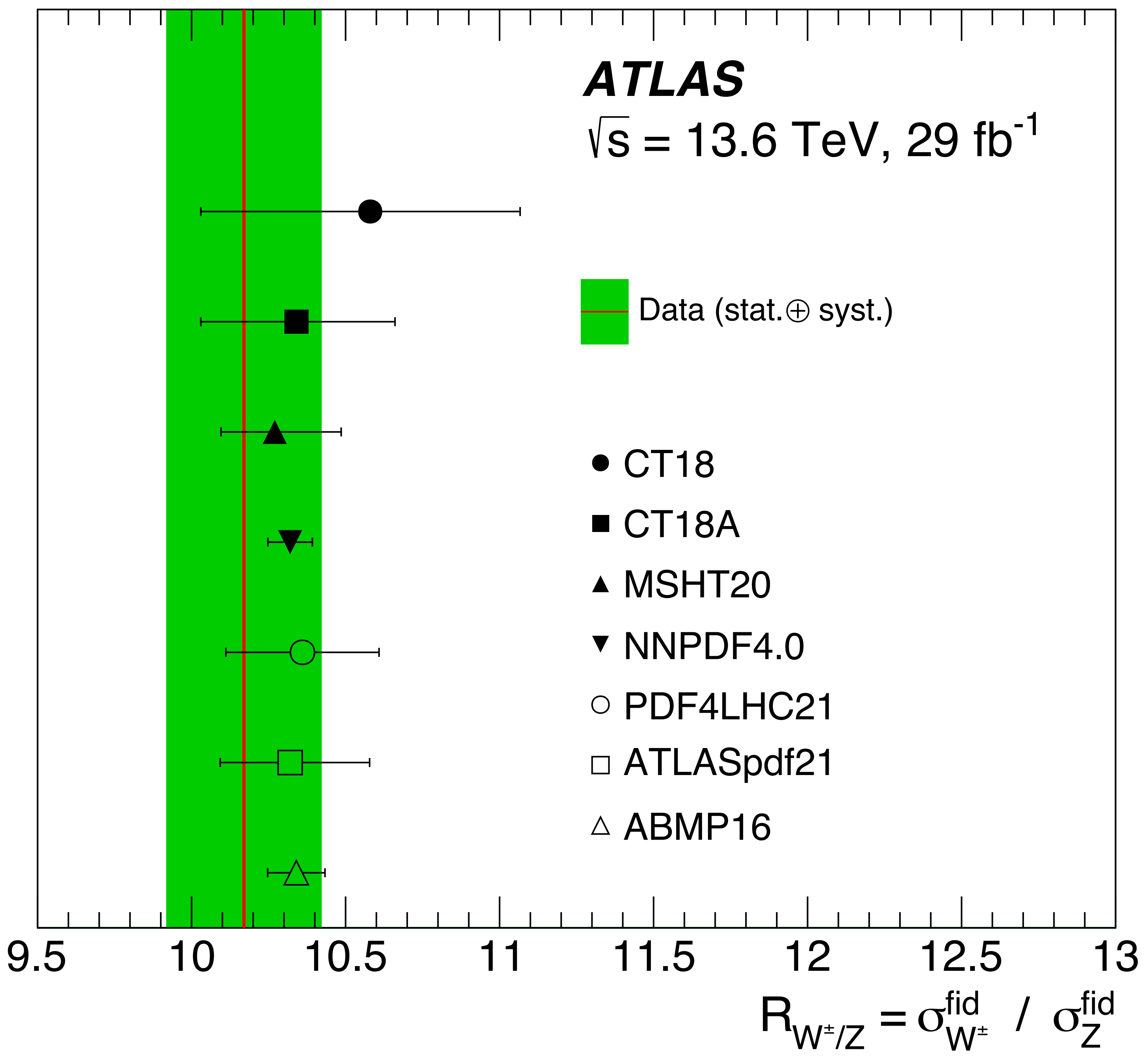
Z cross section @ 13.6 TeV

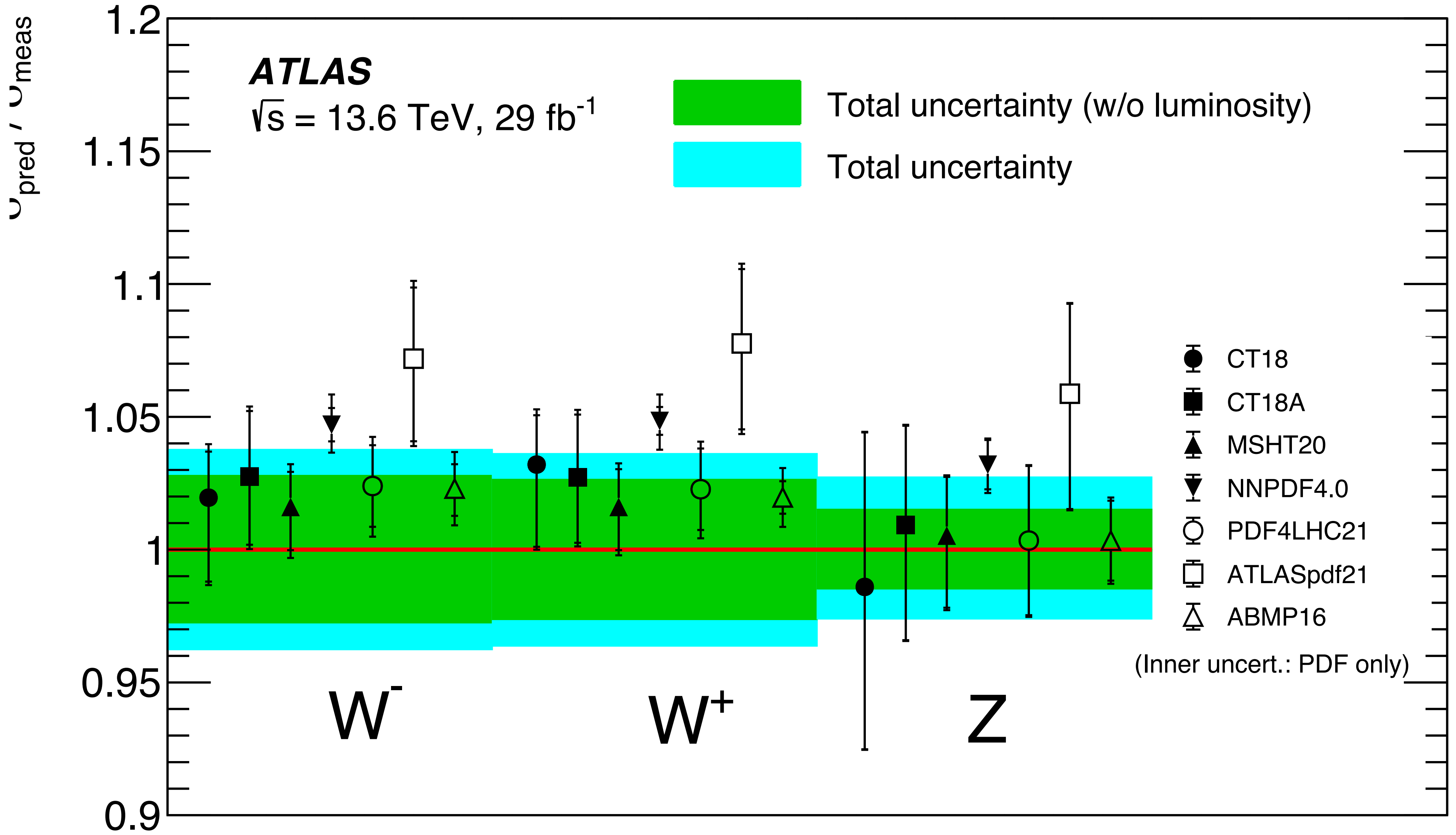
CMS-PAS-SMP-22-017

$$(\sigma_{\text{fid}}\mathcal{B})_{\text{measured}} = (0.7635 \pm 0.0004(\text{stat}) \pm 0.0069(\text{syst}) \pm 0.0176(\text{lumi}))\ \text{nb},$$

$$(\sigma_{\text{fid}}\mathcal{B})_{\text{predicted}} = (0.7666 \pm 0.0065(\text{PDF})^{+0.0021}_{-0.0045}(\text{scale}))\ \text{nb},$$



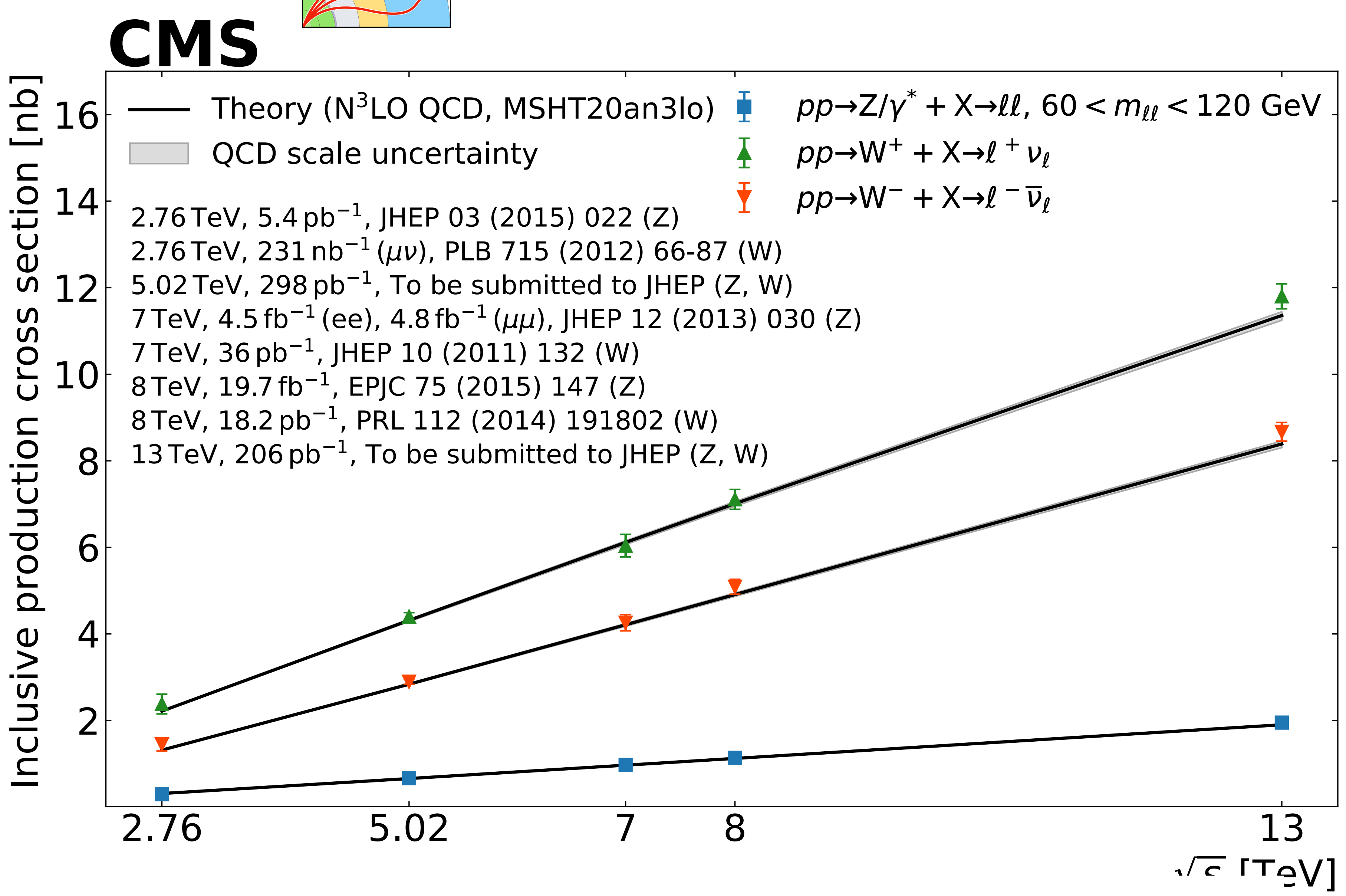


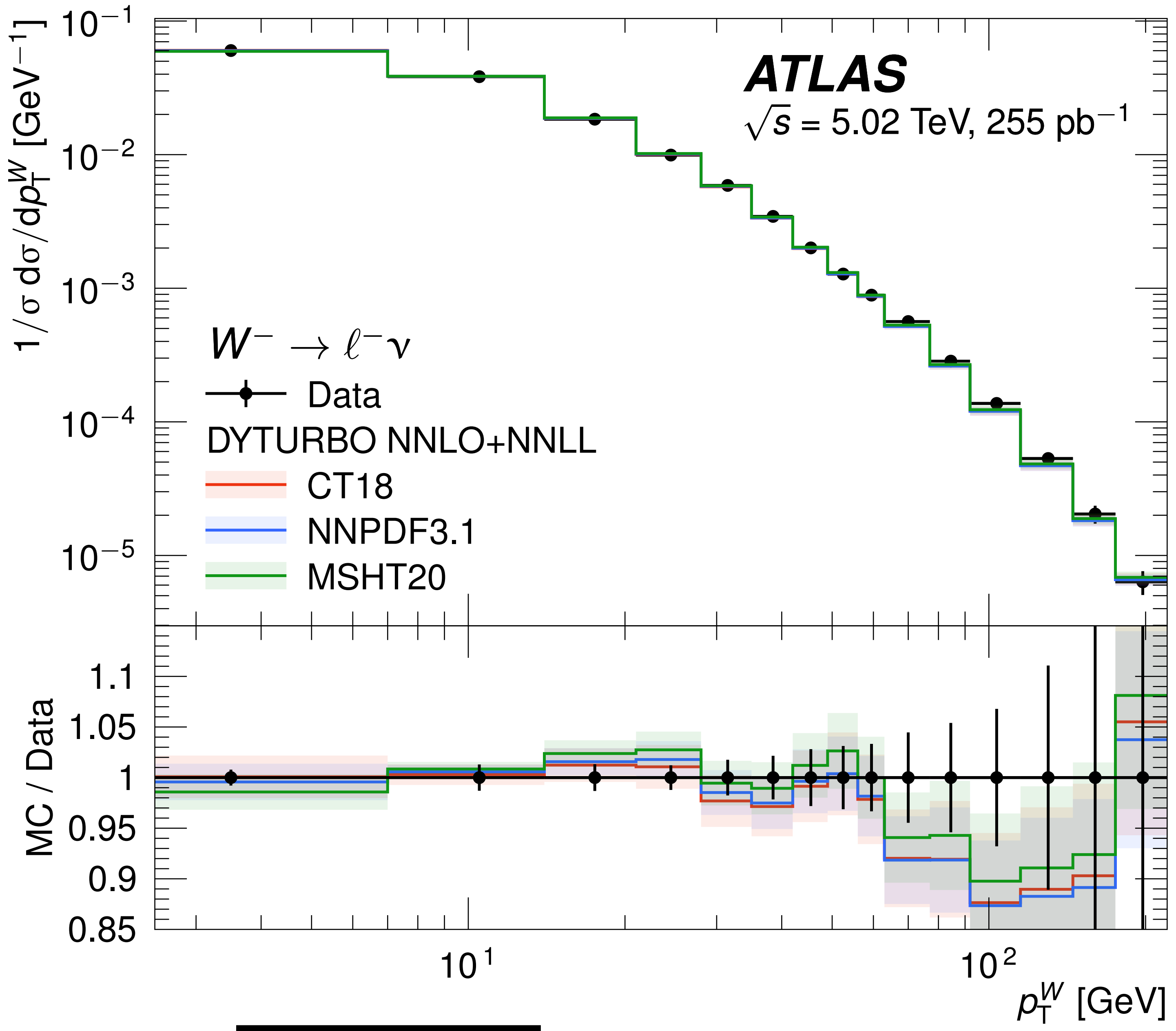


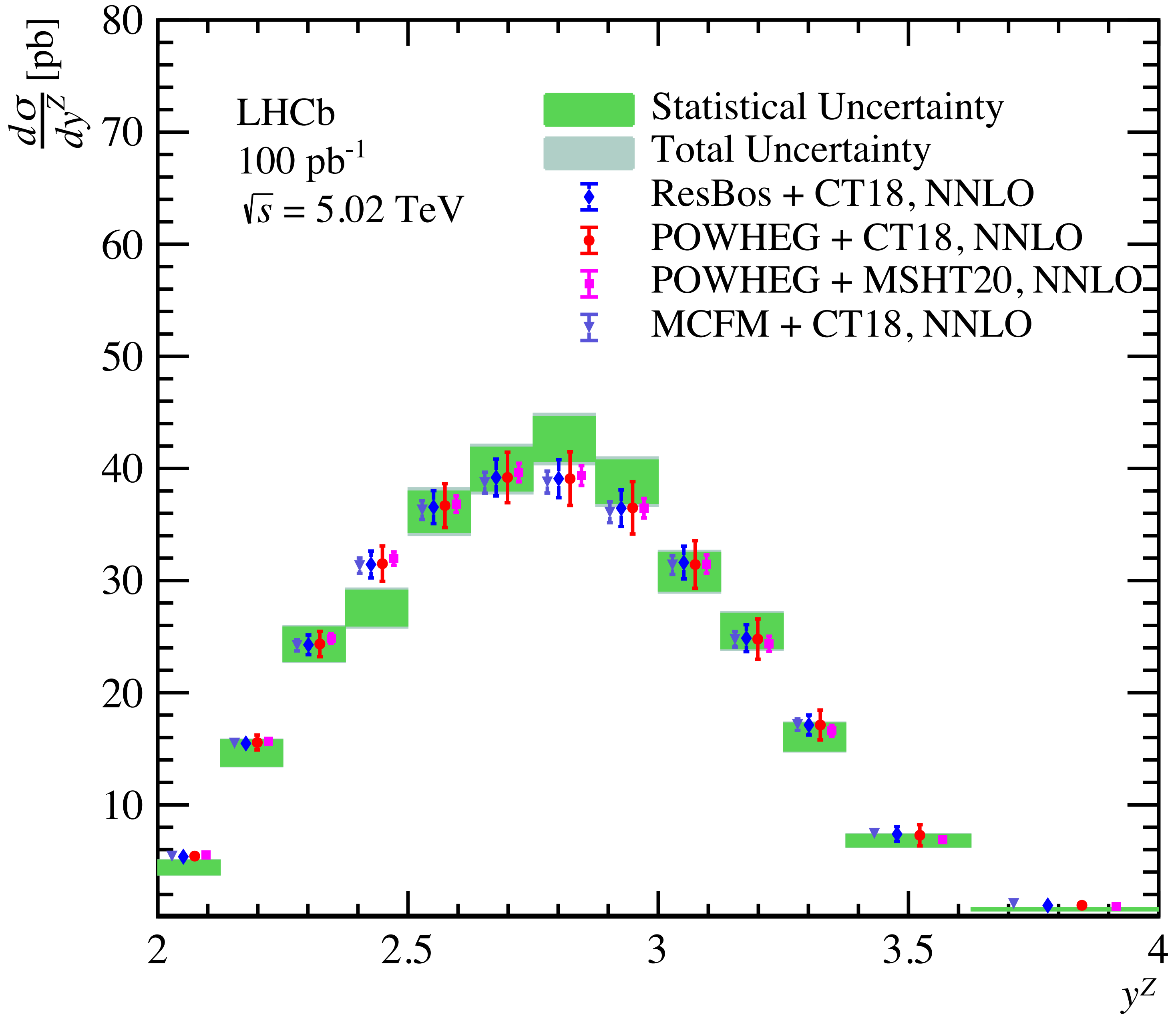
W and Z cross sections measurements

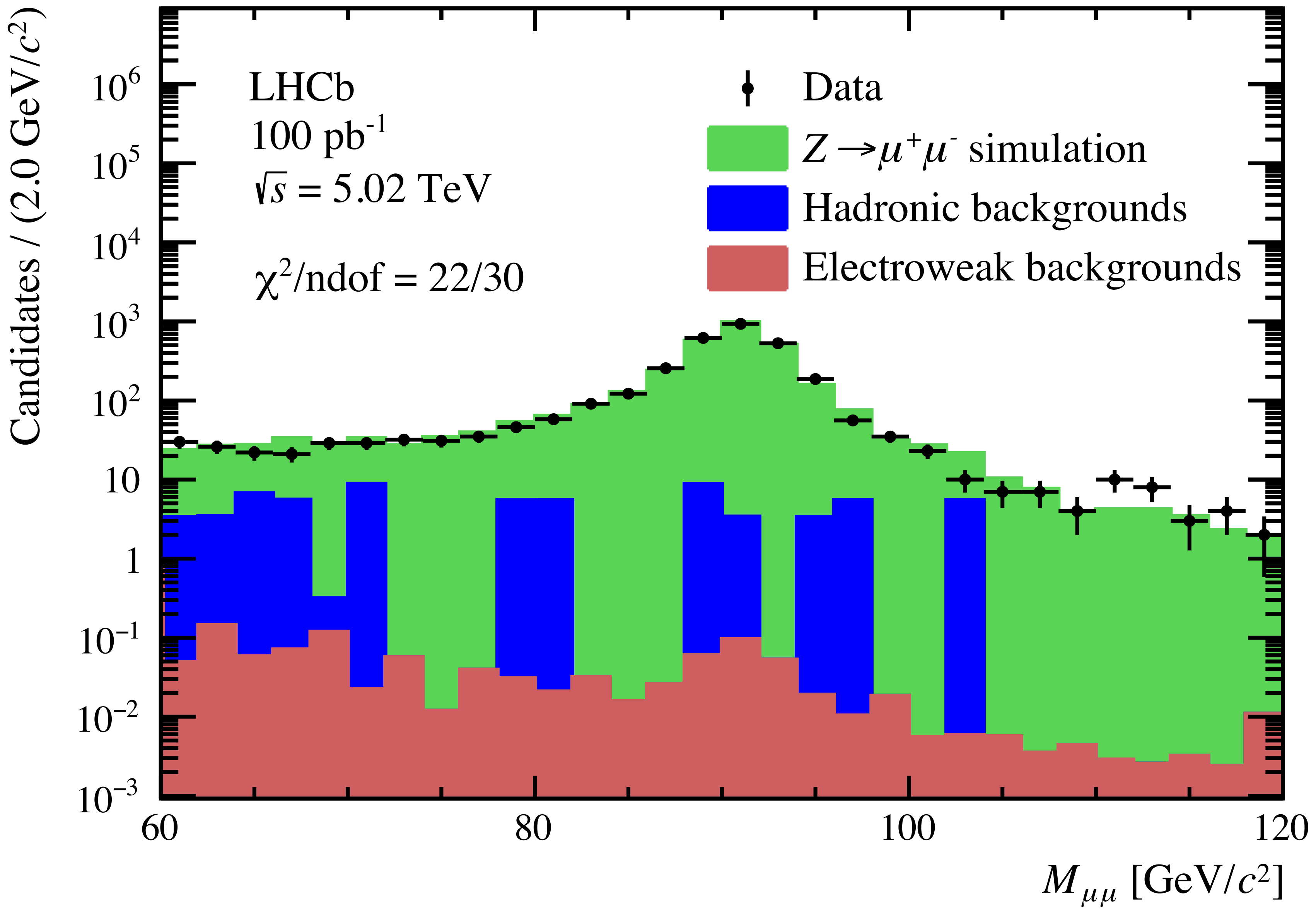
arXiv:2405.18661

- Also measured in special LHC runs
  - 200-350 pb^{-1} at 5 and 13 TeV for ATLAS + CMS, 100 pb^{-1} for LHCb at 5 TeV
- Lower pileup mitigates degradation of certain observables
  - E.g. variables dependent on p_T^{miss}: $\mathbf{p_T^W}$, $\mathbf{m_T^W}$
- Precise measurements of cross sections, ratios and differential distributions
  - Validation of theory $\mathbf{p_T^W}$ especially important for m_W









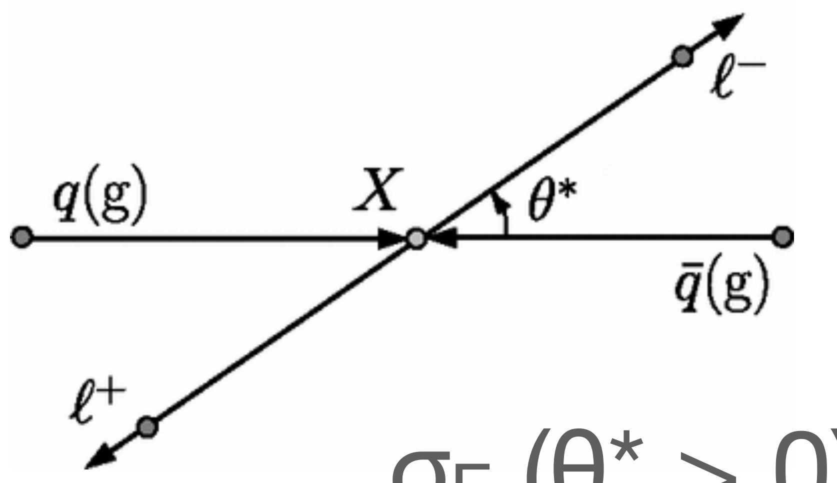
$$\sigma_{Z\to\mu^+\mu^-} = 39.6 \pm 0.7\,(\mathrm{stat}) \pm 0.6\,(\mathrm{syst}) \pm 0.8\,(\mathrm{lumi})\ \mathrm{pb}$$

arXiv:2404.06204 (sub. to EPJC)

JHEP 02 (2024) 070

Measurement of $\sin^2\theta^{\ell}_{\rm eff}$

CMS-PAS-SMP-22-010



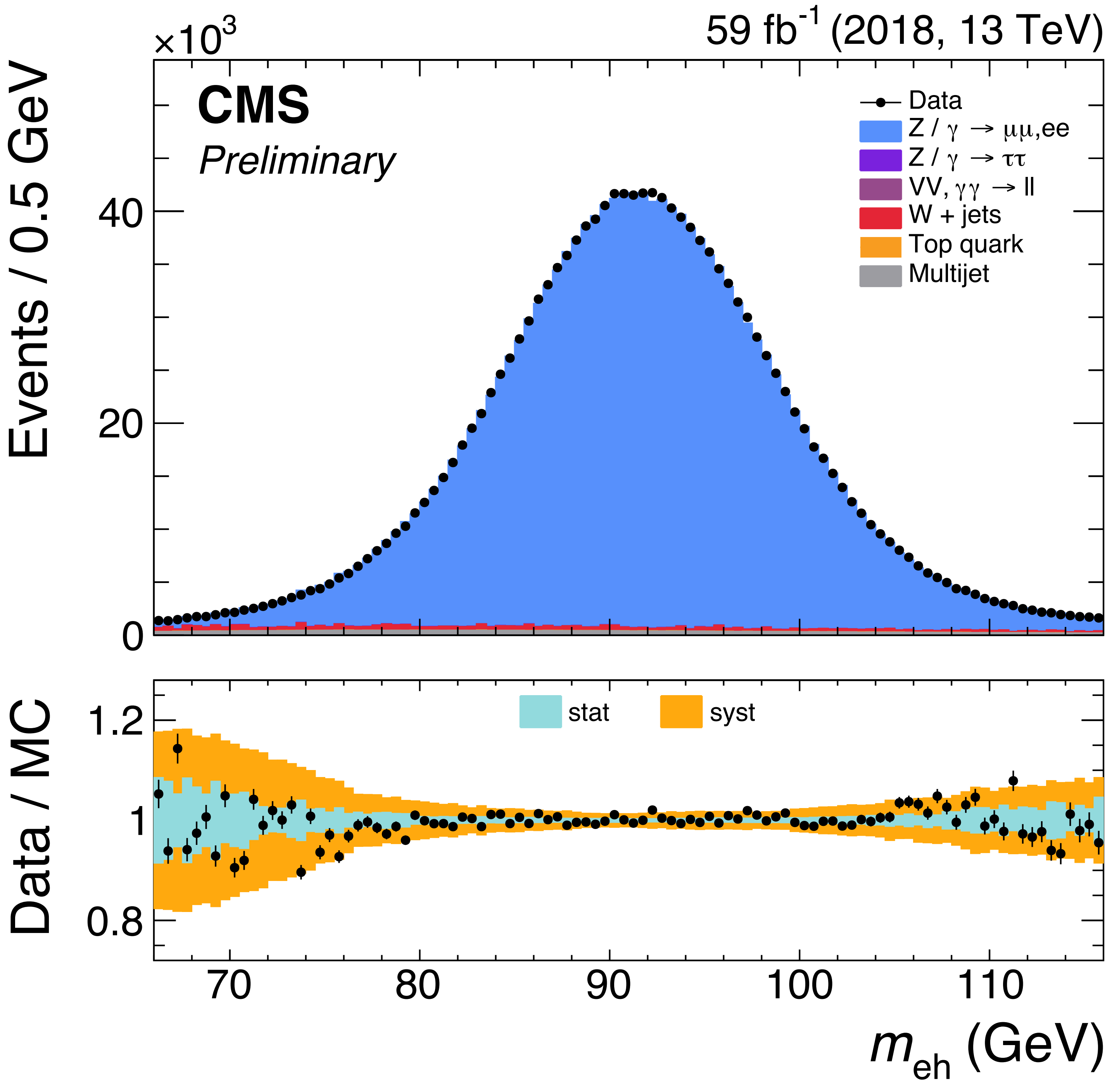
σ_F ($\theta^* > 0$)
σ_B ($\theta^* < 0$)

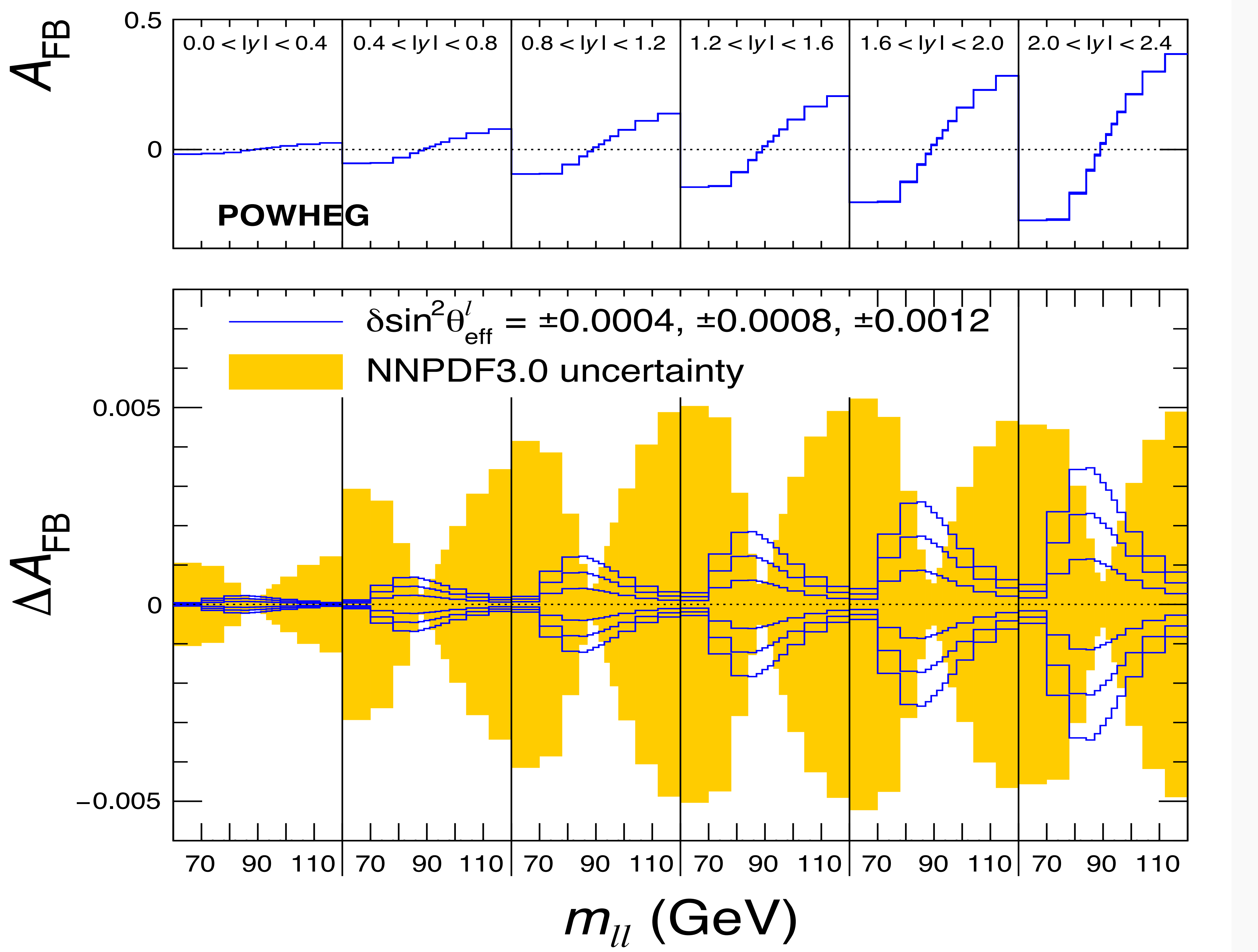
- Fundamental EW parameter: $\sin^2\theta^{\ell}_{\rm eff} = (1 - m_W^2/m_Z^2)\kappa^{\ell}$
  - Measured via Z/γ*→ll, asymmetry in lepton decay angle: $1+\cos^2\theta+0.5A_0(1-3\cos^2\theta)+A_4\cos\theta$

$\rightarrow A_{\rm FB} = 3/8 A_4$

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

- Recent CMS measurement at 13 TeV
  - $\sin^2\theta^{\ell}_{\rm eff}$ measured via $A_{\rm FB}$ (similar to previous Run 1 approach)
  - New: unfolded A4 (for future reinterpretation)
- Strong dependence on PDFs
  - Profile in $\sin^2\theta^{\ell}_{\rm eff}$ fits
- Adds reconstruction of electrons outside tracker acceptance for increased $A_{\rm FB}$ sensitivity
  - e: |η| < 2.5
  - g: 2.5 < |η| < 2.87 (fwd. ECAL)
  - h: 3.14 < |η| < 4.36 (fwd. HCAL)

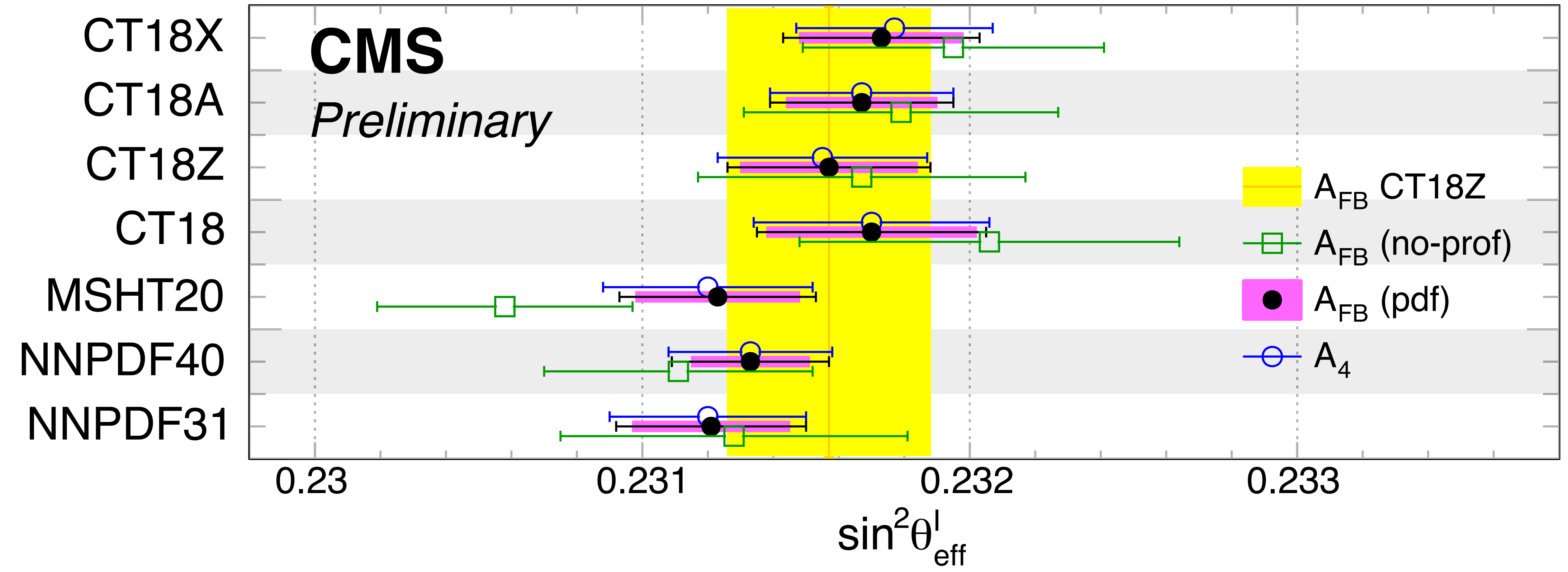


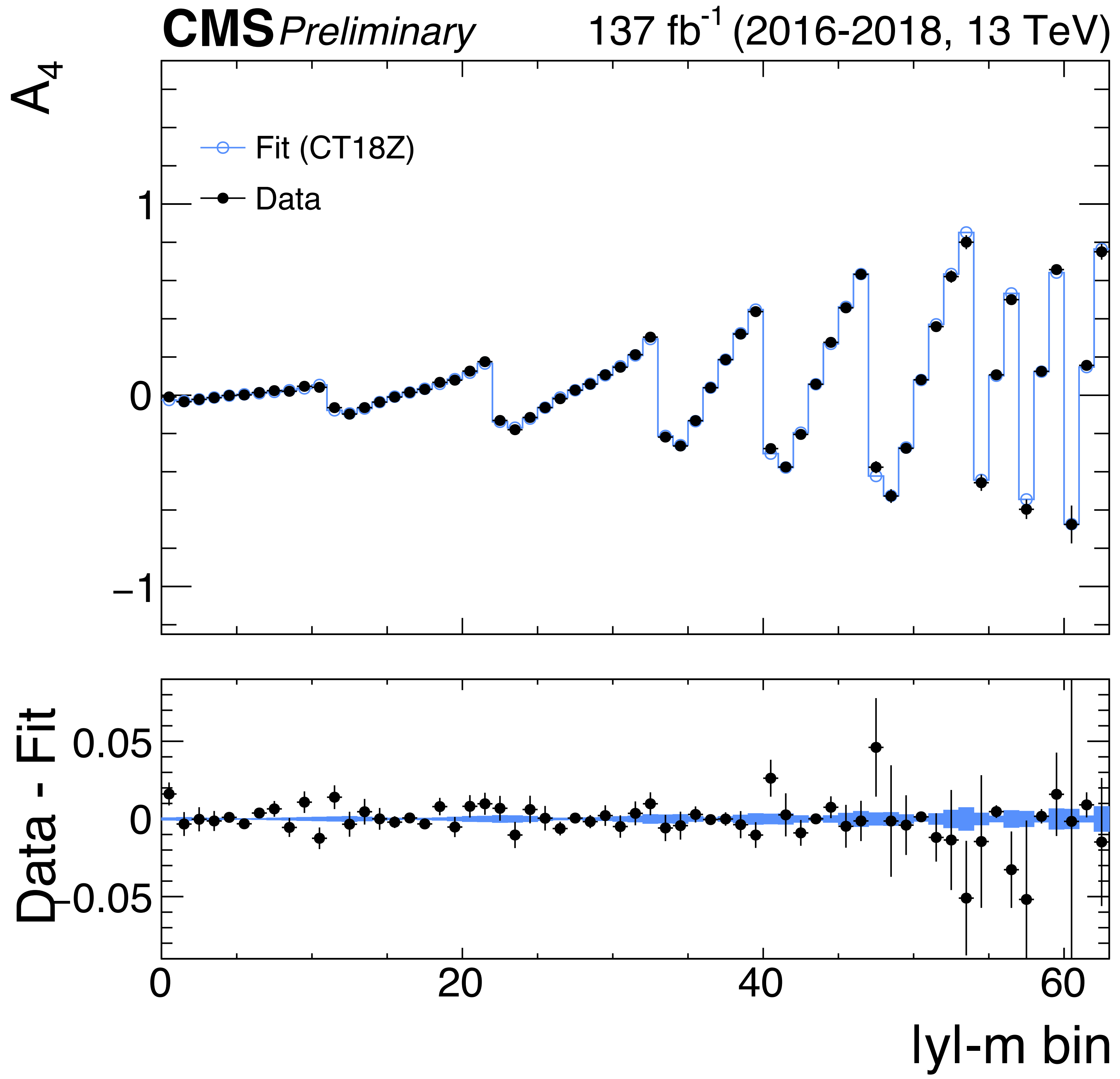


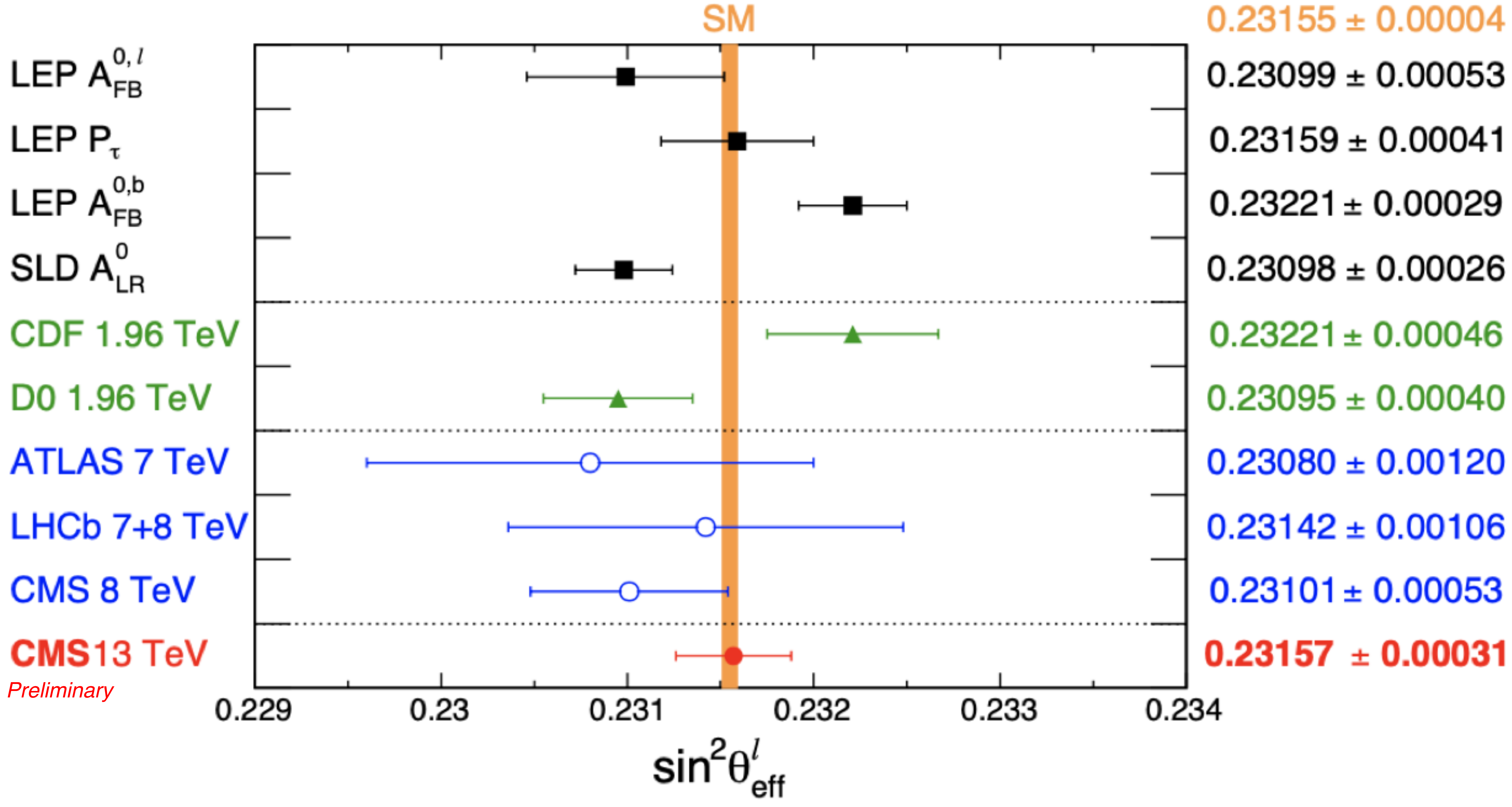
Measurement of $\sin^2\theta^{\ell}_{\text{eff}}$

CMS-PAS-SMP-22-010

- Consistent results for A_{FB}, A_4 and direct cosθ fits
  - PDF profiling reduces differences between PDF sets
  - CT18Z chosen (pre-unblinding) for nominal result - best coverage of other PDF central values







See also: ATLAS 8 TeV [ATLAS-CONF-2018-037]

$\sin^2\theta^{\ell}_{\text{eff}}$ = **0.23140 ± 0.00036**

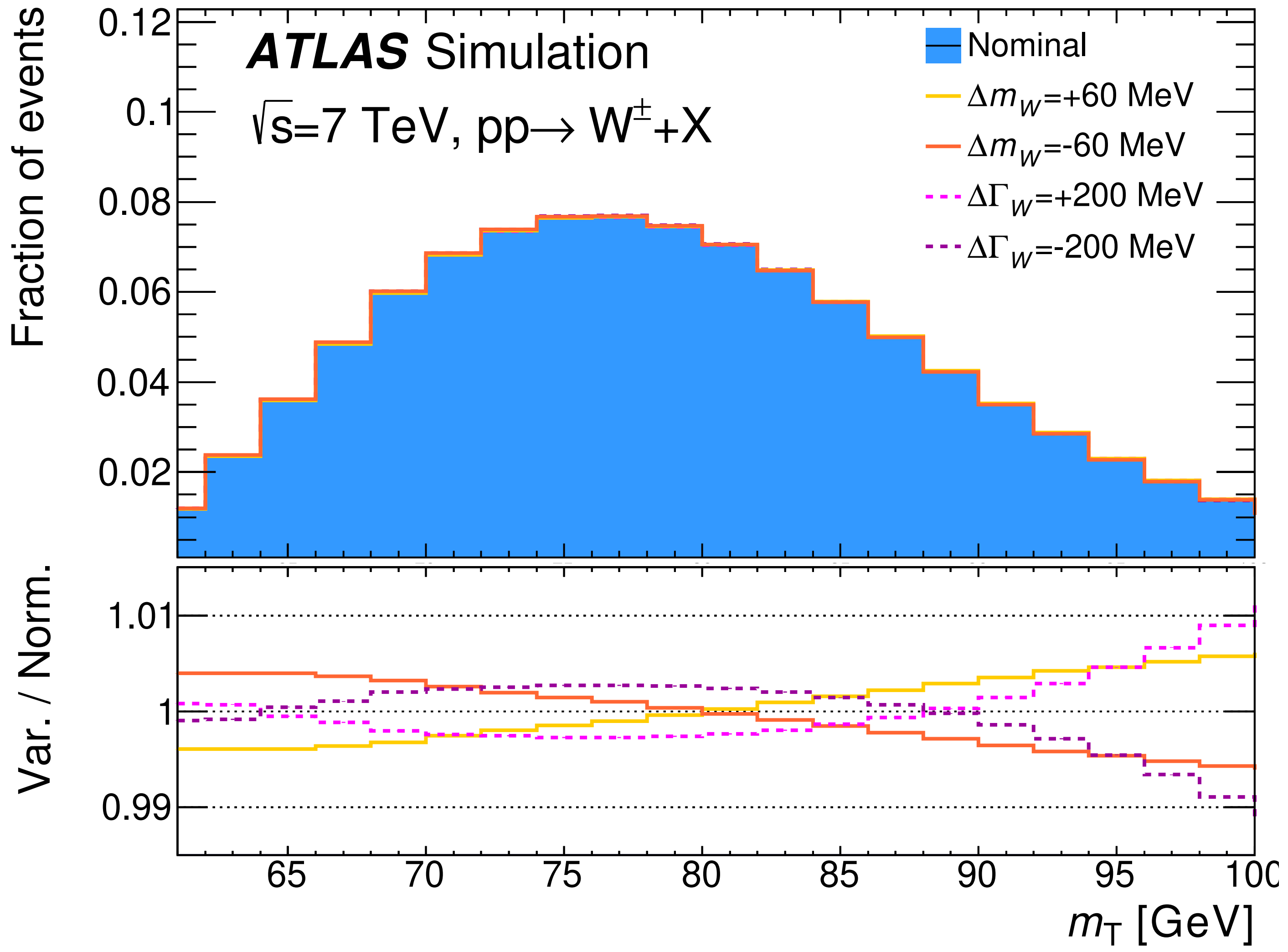
Best hadron collider measurement, approaching LEP and SLD:

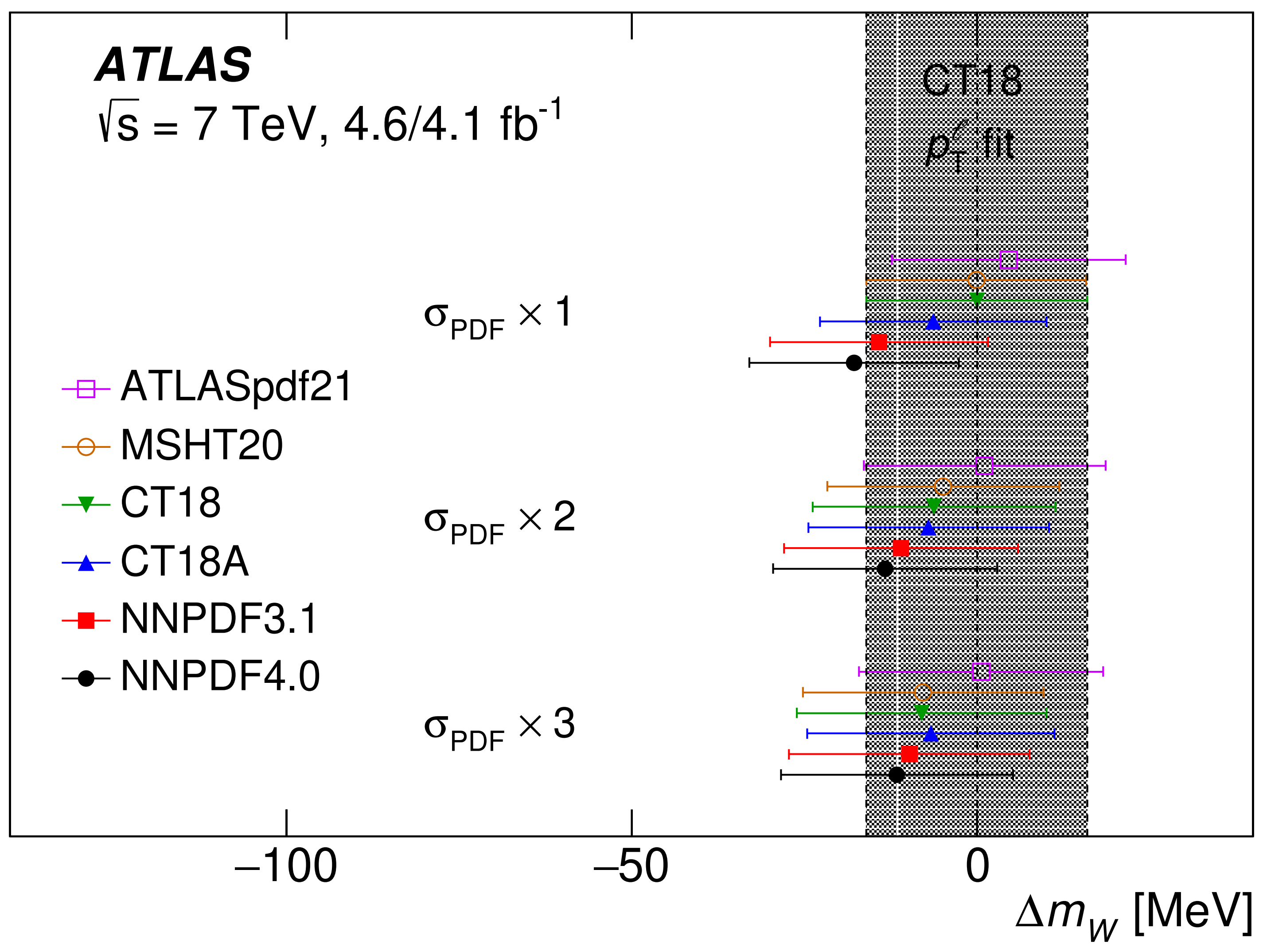
$$\sin^2\theta^{\ell}_{\text{eff}} = 0.23157 \pm 0.00010(\text{stat}) \pm 0.00015(\text{syst}) \pm 0.00009(\text{theo}) \pm 0.00027(\text{pdf})$$

W boson mass

arXiv:2403.15085 (submitted to EPJC)

- m_W precision of $\Delta m_W = 6$ MeV from global EW fits
- Challenging measurement at hadron colliders
  - Most precise CDF measurement in significant tension with SM prediction and other experimental results
- Update to the ATLAS analysis (wrt. preliminary 2023):
  - Γ_W assumed SM with EW fit uncertainty (+6.5 MeV shift)
  - New PDF approach: inflate external uncertainties
  - ⇒ reduced tension between PDF sets
- Profile likelihood fits to p_T^ℓ and m_T ⇒ also sensitive to Γ_W

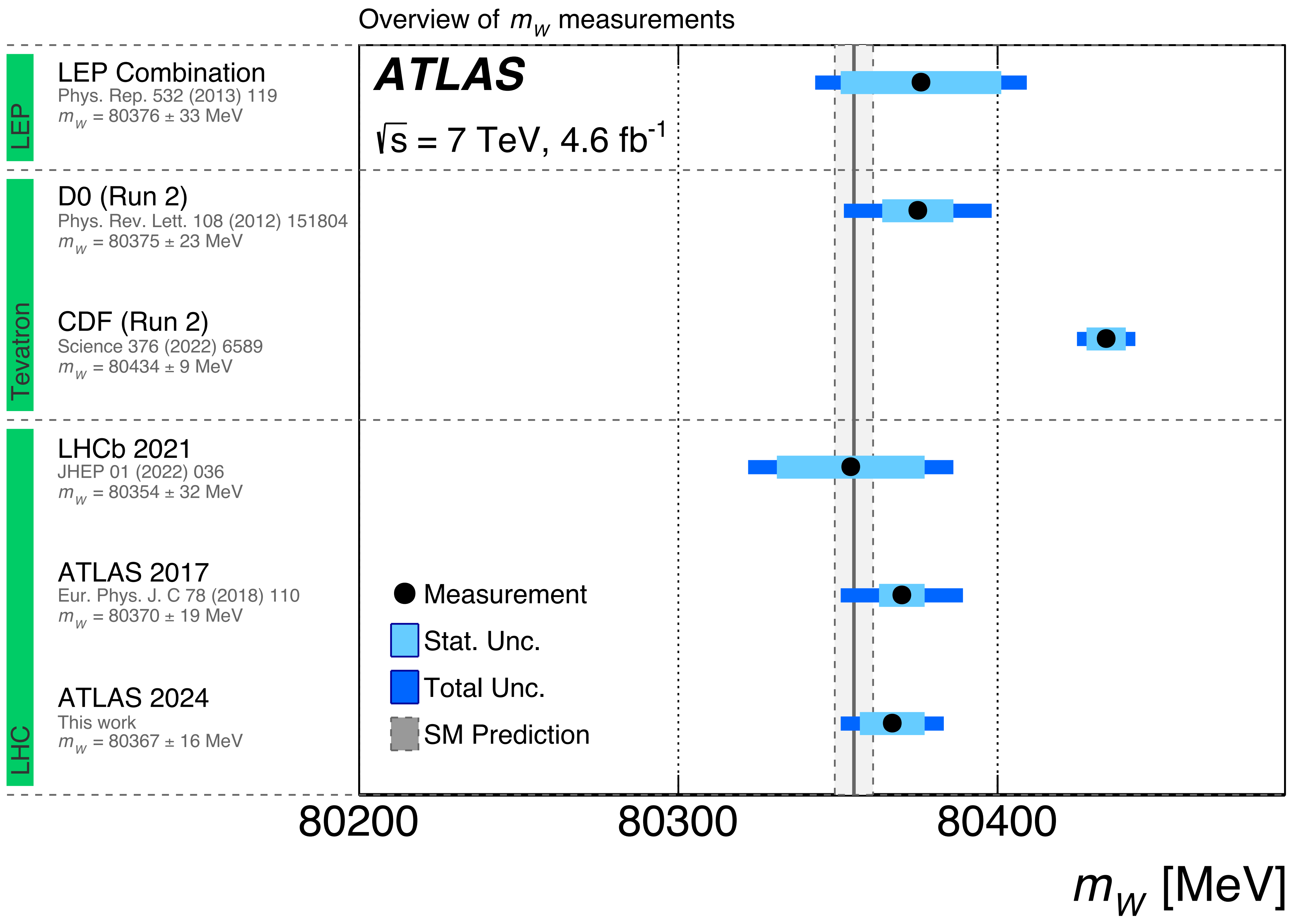




m_W uncertainties

Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	Γ_W	PS
p_T^ℓ	16.2	11.1	11.8	4.9	3.5	1.7	5.6	5.9	5.4	0.9	1.1	0.1	1.5
m_T	24.4	11.4	21.6	11.7	4.7	4.1	4.9	6.7	6.0	11.4	2.5	0.2	7.0
Combined	15.9	9.8	12.5	5.7	3.7	2.0	5.4	6.0	5.4	2.3	1.3	0.1	2.3

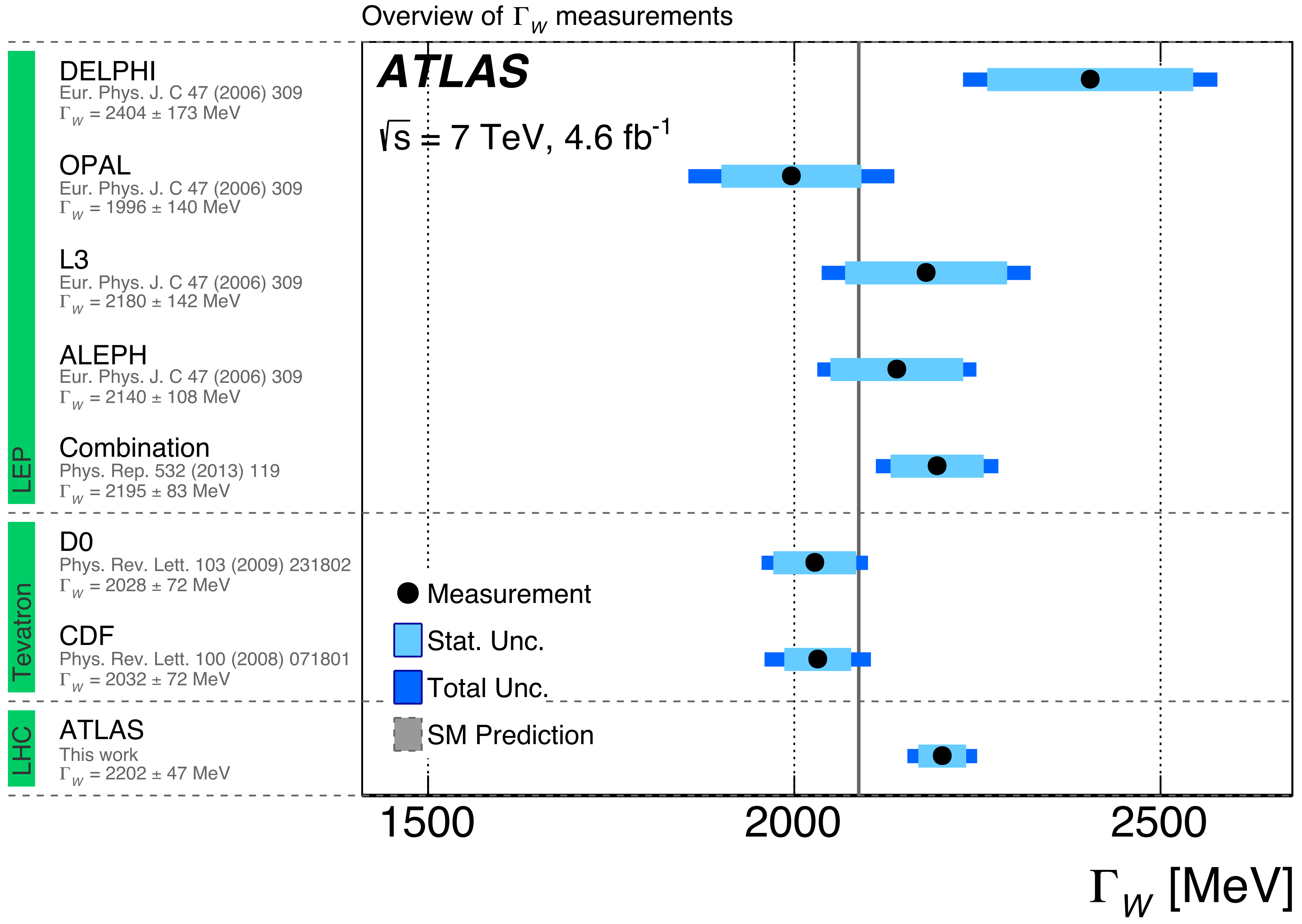
$$m_W = 80366.5 \pm 9.8\ (\text{stat.}) \pm 12.5\ (\text{syst.})\ \text{MeV} = 80366.5 \pm 15.9\ \text{MeV}$$

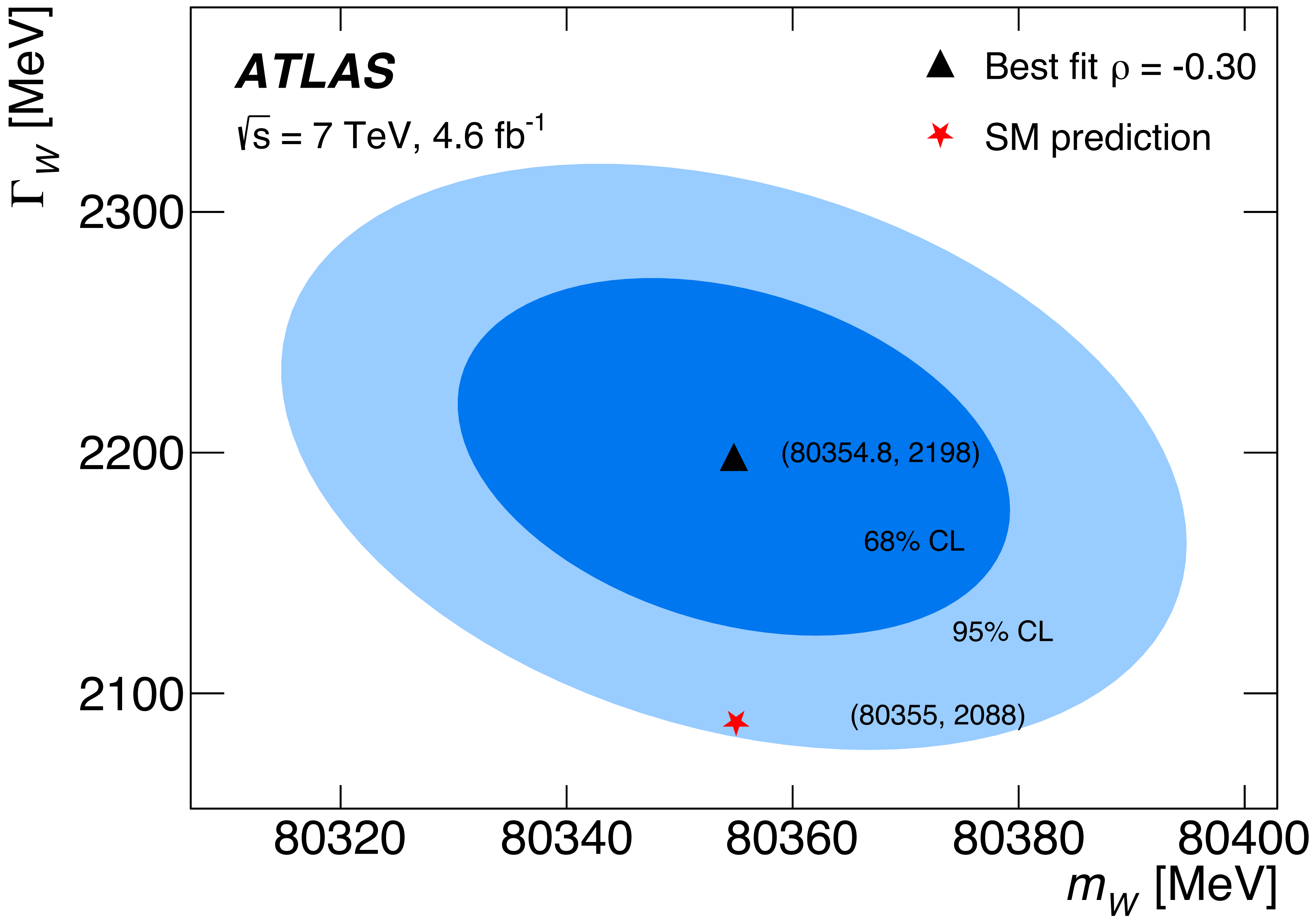


arXiv:2403.15085 (submitted to EPJC)

W boson width

- First Γ_W measurement at the LHC and most precise single measurement to date (w/ m_W constrained to prediction)
  - Similar strategy to m_W: fit to p_T^ℓ and m_T (more sensitive)
- Modelling (shower tune variations) and recoil dominate uncertainty
- Simultaneous fit for m_W and Γ_W reveals interplay:





Γ_W uncertainties

Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	m_W	PS
p_T^ℓ	72	27	66	21	14	10	5	13	12	12	10	6	55
m_T	48	36	32	5	7	10	3	13	9	18	9	6	12
Combined	47	32	34	7	8	9	3	13	9	17	9	6	18

	1 param. fits	2 param. fit	
m_W	80366.5 ± 15.9	80354.8 ± 16.1	↓12 MeV
Γ_W	2202 ± 47	2198 ± 49	↓4 MeV

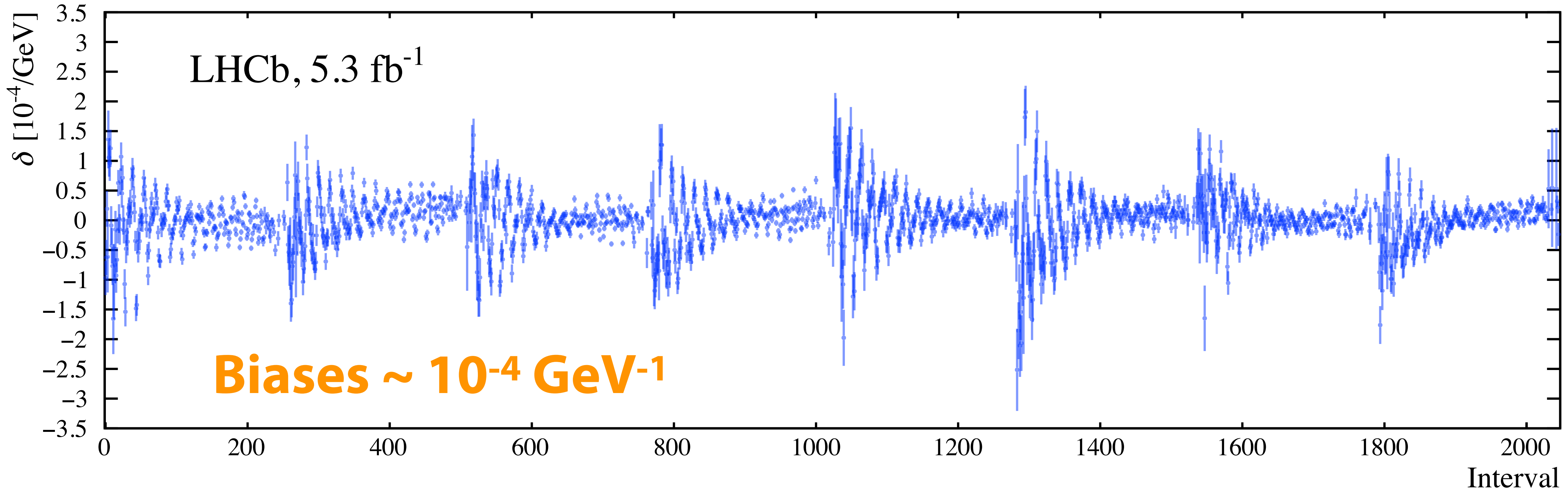
Small impact on uncertainties

Momentum calibration

JINST 19 (2024) P03010

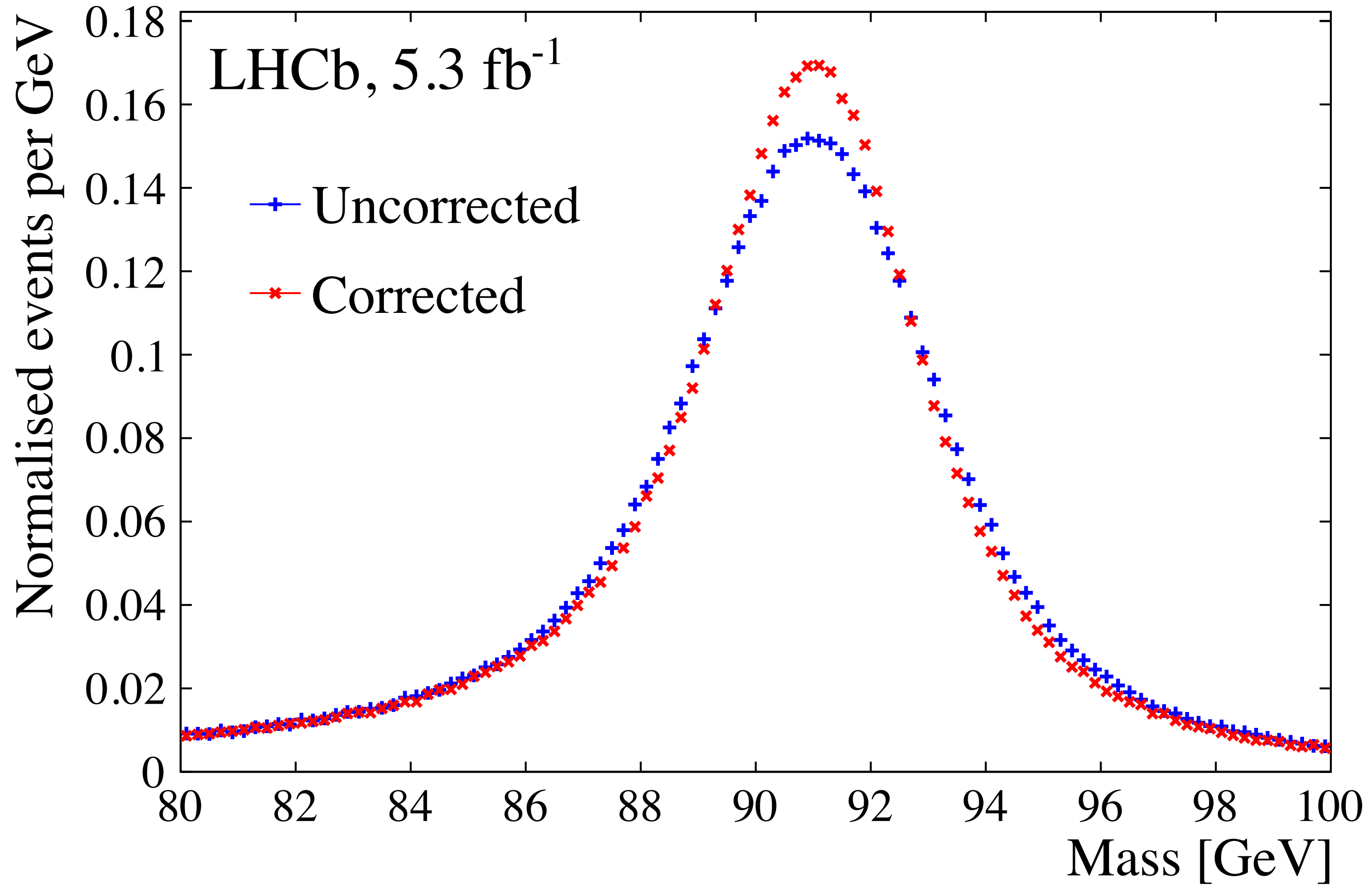
- Crucial to control muon momentum scale to high precision for m_W and other precision EW measurements
- New calibration from LHCb to correct for charge-dependent curvature biases: $$\frac{q}{p} \rightarrow \frac{q}{p'} = \frac{q}{\alpha p} + \delta,$$
- Method: measure "pseudomass" variable
  - Extract via asymmetry in peak positions

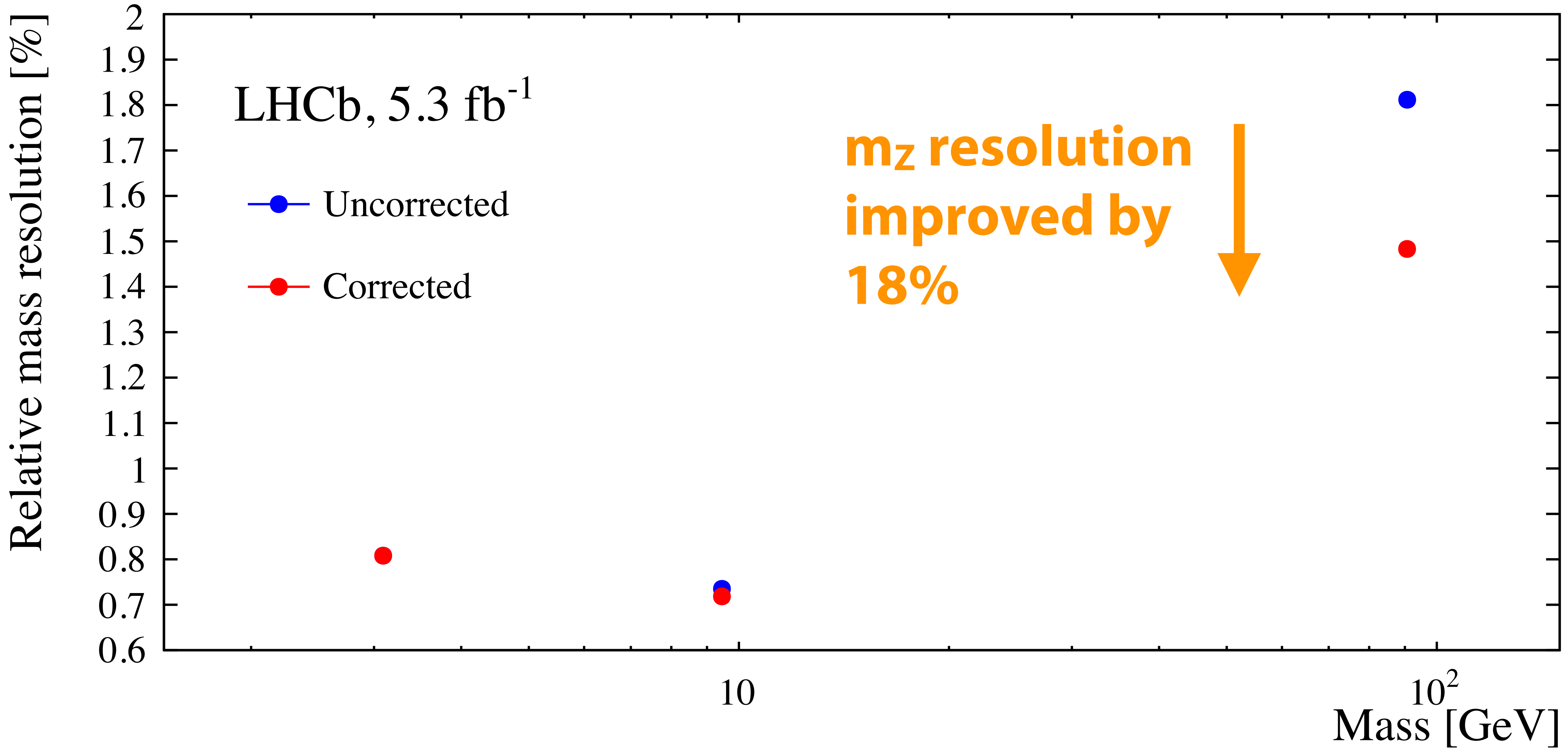
$$\mathcal{M}^{\pm} \equiv \sqrt{\frac{p_T^{\pm}}{p_T^{\mp}}} M = \sqrt{2p^+p^- \frac{p_T^{\pm}}{p_T^{\mp}}(1-\cos\theta)} = \sqrt{2p^{\pm}p_T^{\pm}\frac{p^{\mp}}{p_T^{\mp}}(1-\cos\theta)},$$



Data biases vs time, φ, η, polarity

$$\delta \approx -\frac{\mathcal{A}}{2} \times \left(\left\langle\frac{1}{p^+}\right\rangle + \left\langle\frac{1}{p^-}\right\rangle\right)$$



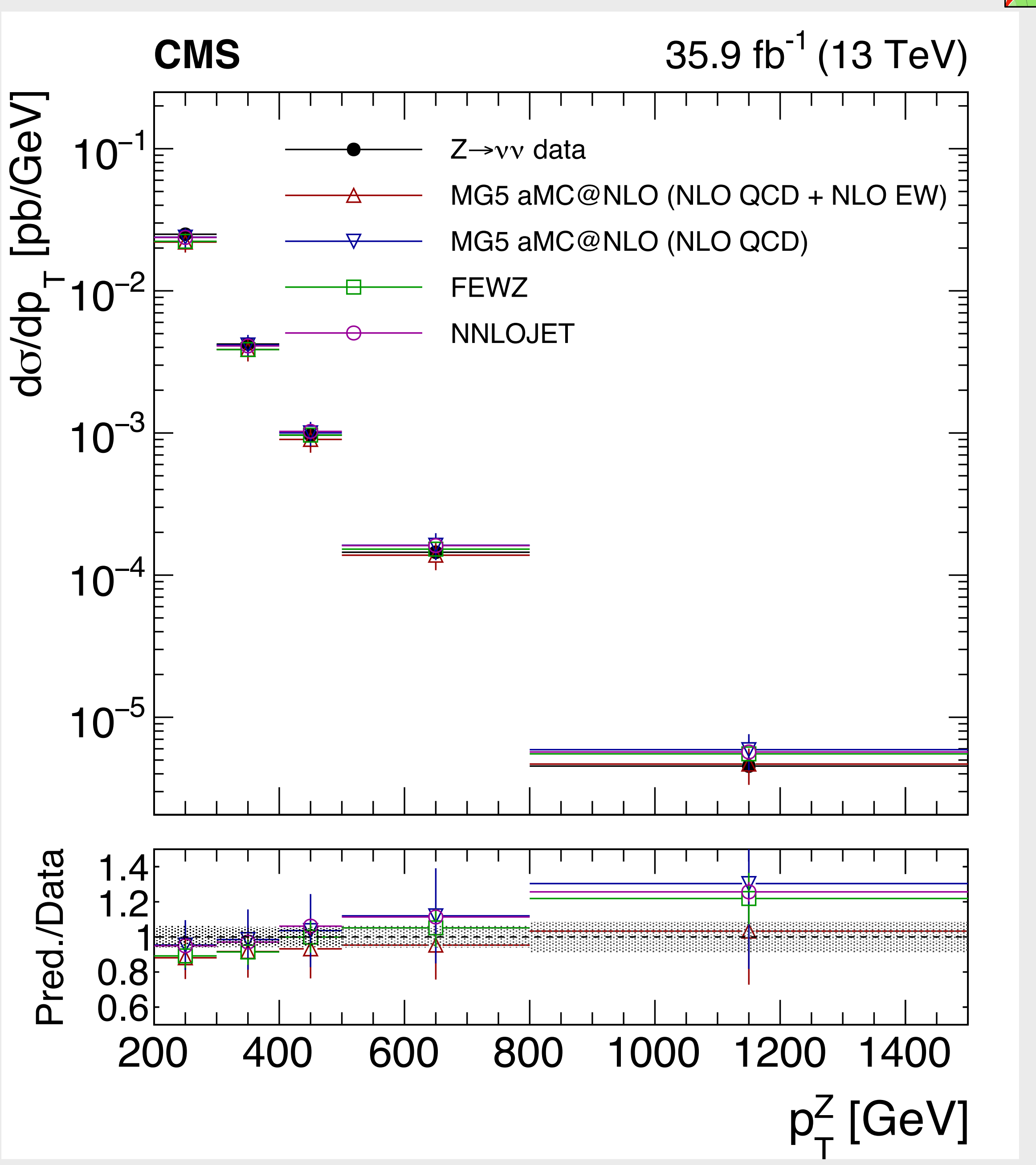


Differential p_T^{miss} + jets

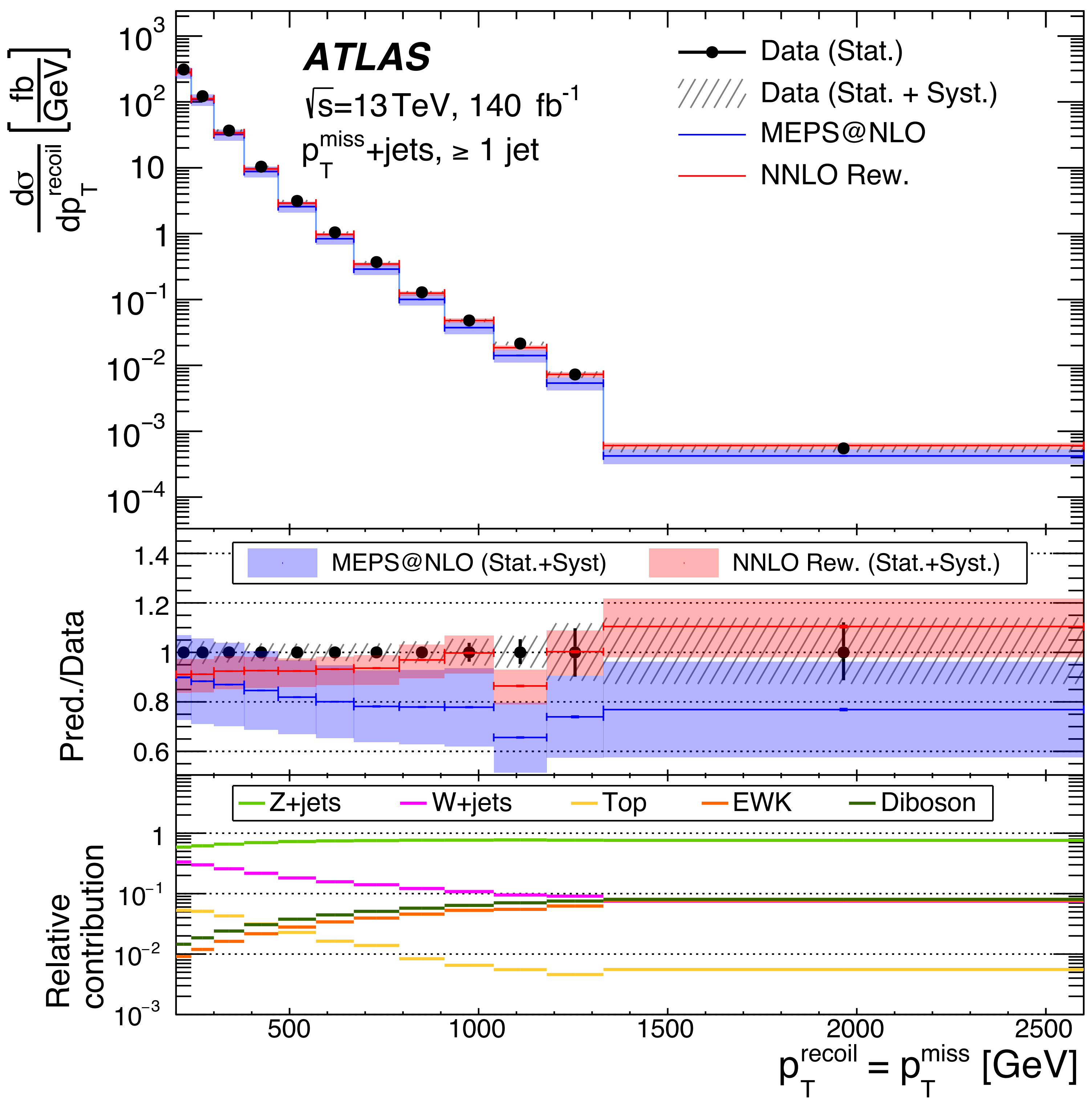
ATLAS EXPERIMENT

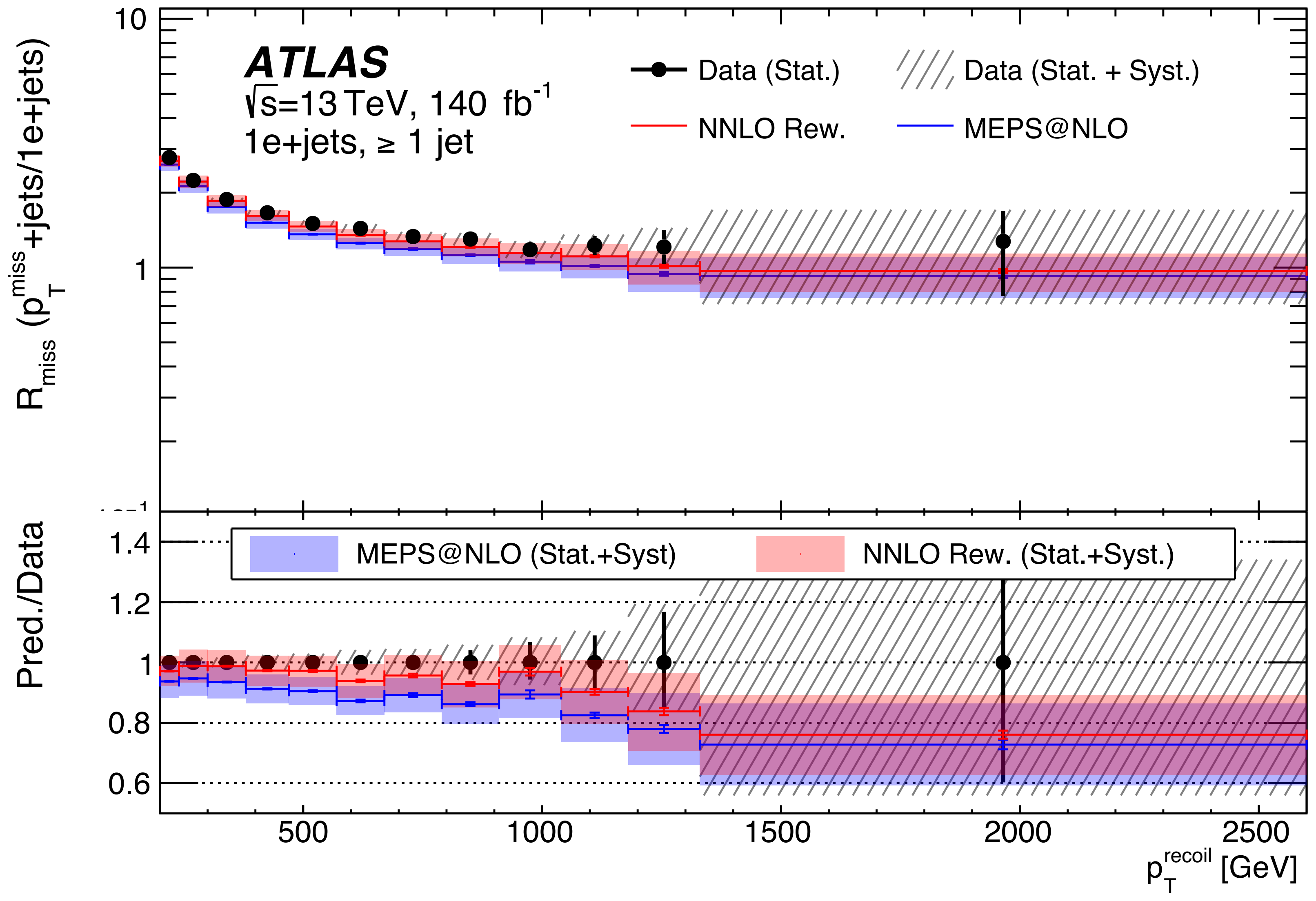
arXiv:2403.02793
Submitted to JHEP

See also: JHEP 05 (2021) 205



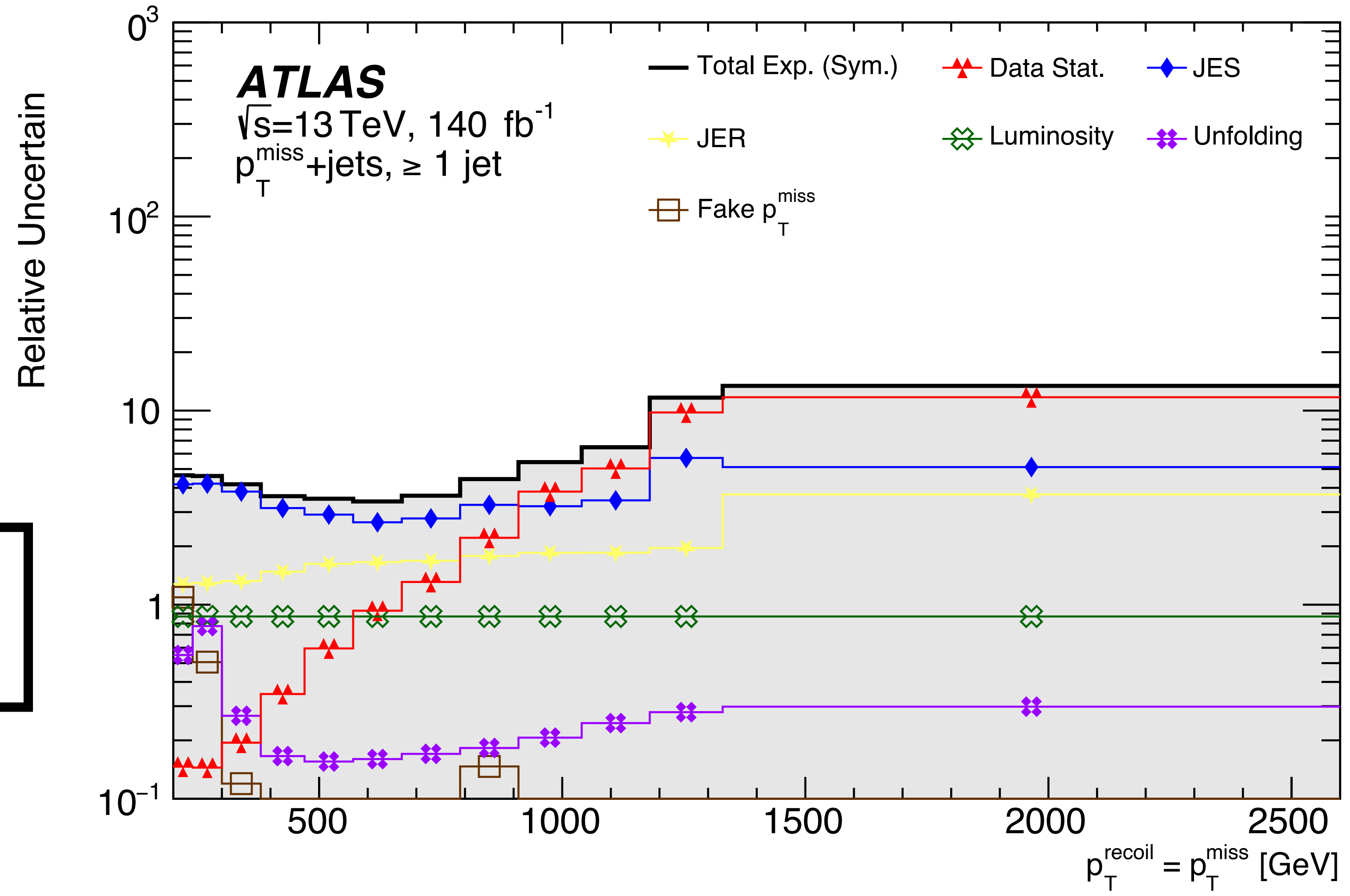
- **Aim**: precise detector-corrected p_T^{miss} + jet measurement
  - Inclusive, minimize model dependence
- Plus auxiliary p_T^{recoil} in ℓ + jet and γ + jet systems
  - Uncertainties cancel in ratios
  - BSM contributions (e.g. dark matter) would not cancel





All SM processes treated as "signal" for unfolding

Uncertainties: JES + stat. (at high p_T)



Z invisible width

PLB 854 (2024) 138705

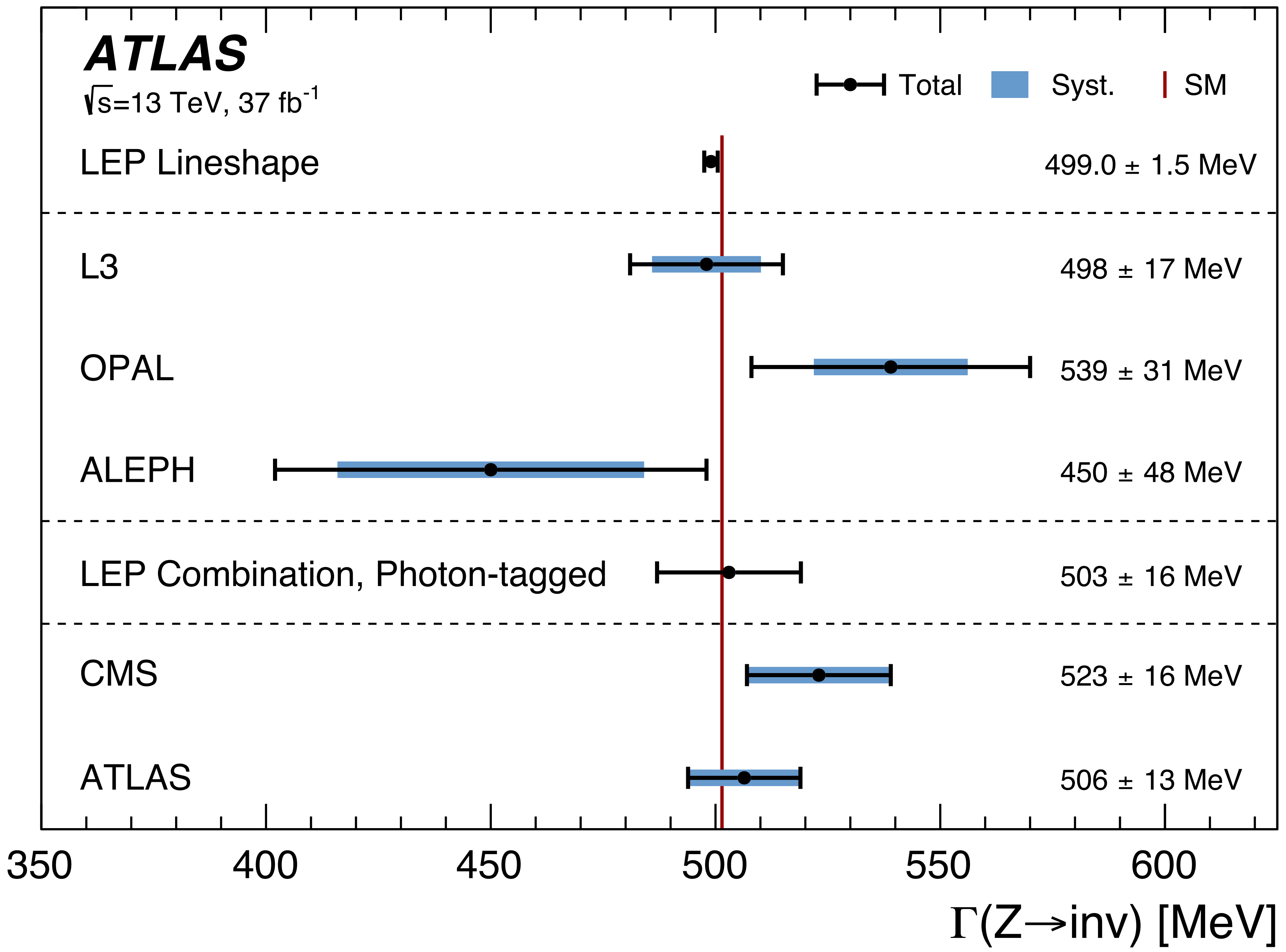
$$\Gamma^{\mathrm{SM}}_{\mathrm{inv}} = 501.3 \pm 0.6\,\mathrm{MeV}$$

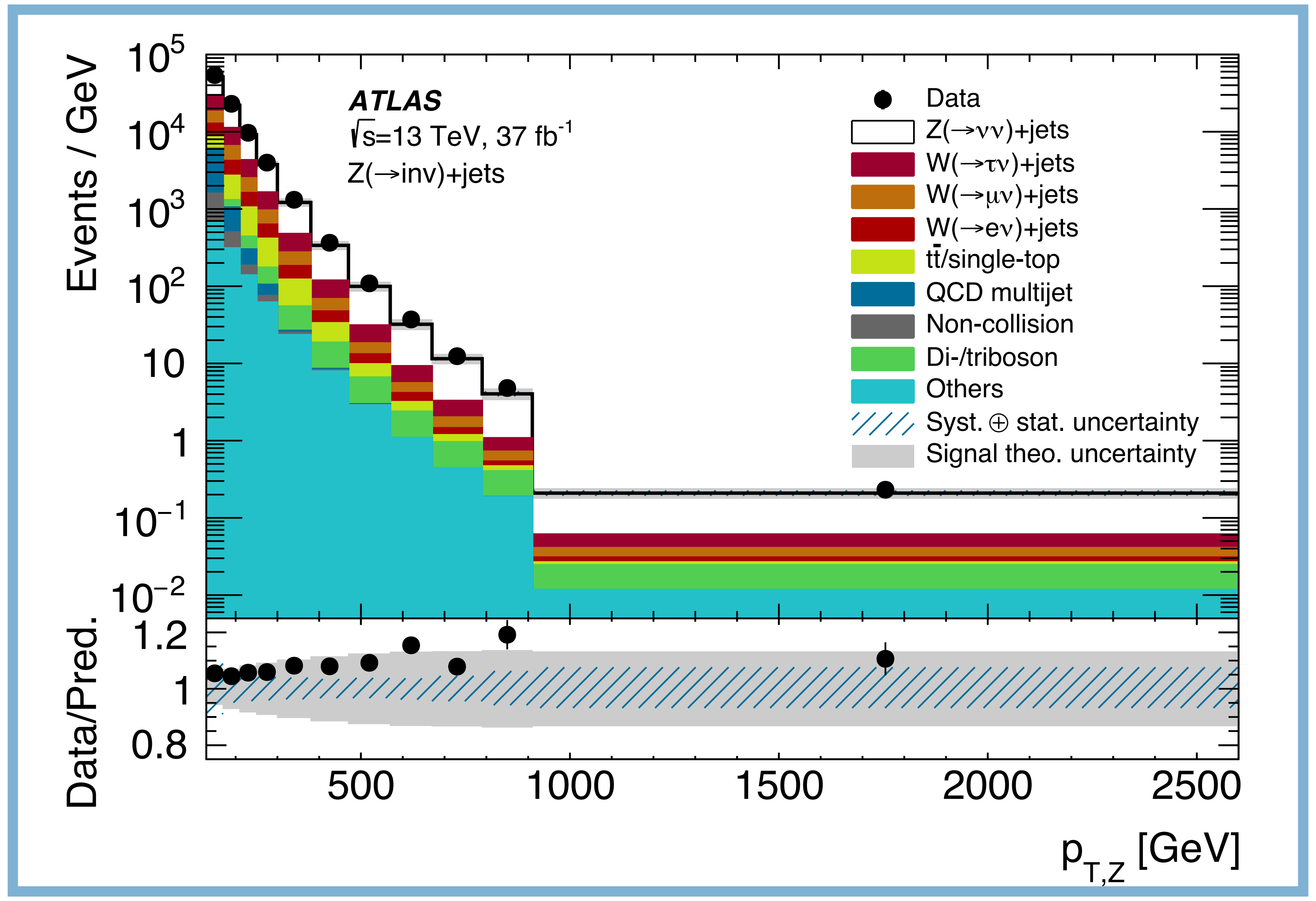
See also: PLB 842 (2023) 137563

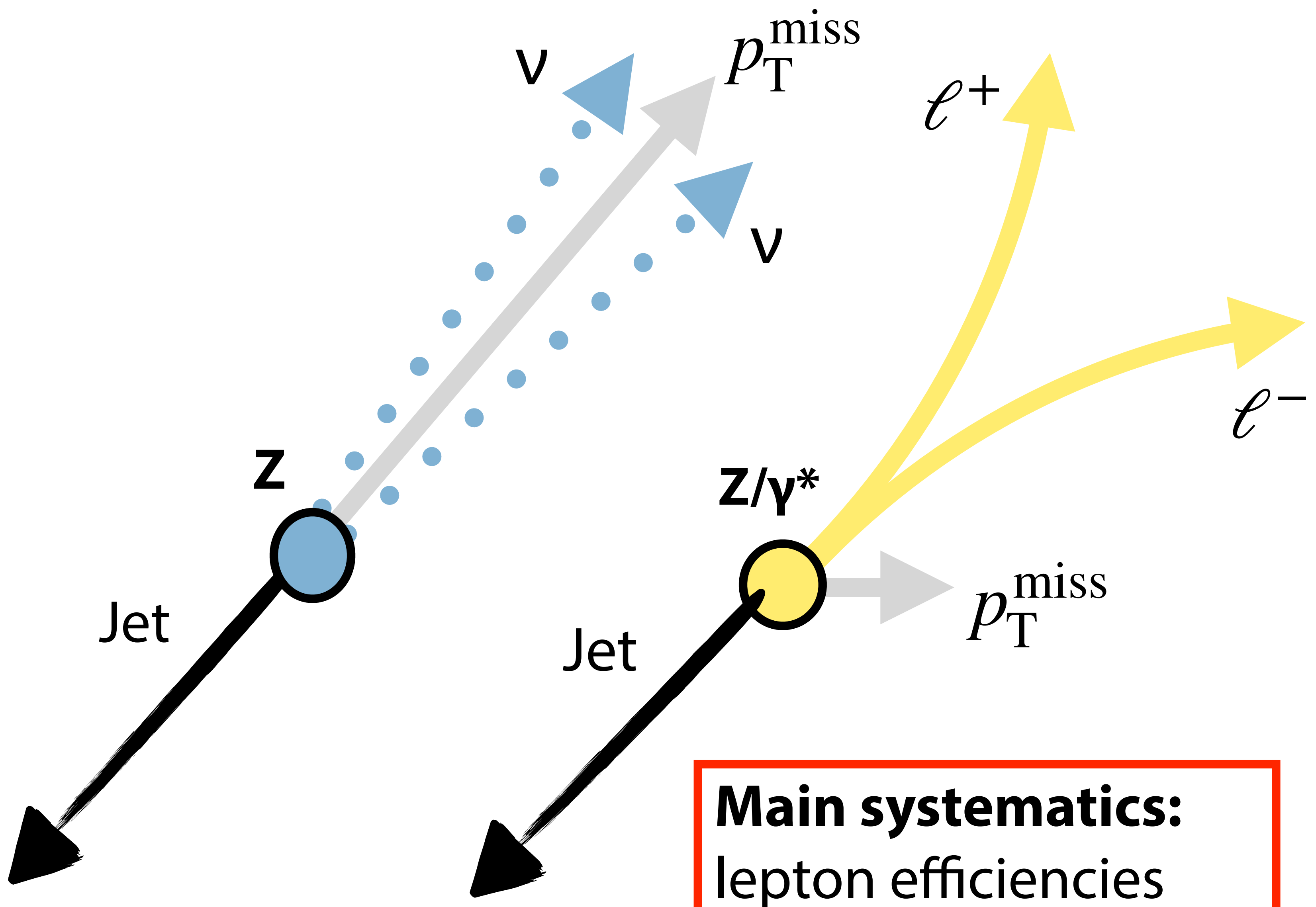
- **Indirect**: from Γ_{tot} - $\Gamma_{visible}$ using Z lineshape and m_Z: $\Gamma^{\mathrm{LEP}}_{\mathrm{inv}} = 499.0 \pm 1.5\,\mathrm{MeV}$
- **Direct**: from $e^+e^- \to \gamma$ + inv. cross section: $\Gamma^{\mathrm{LEP}}_{\mathrm{inv}} = 503 \pm 16\,\mathrm{MeV}$
- **LHC**: via ratio extracted from

$$\Gamma(Z \to \nu\bar{\nu}) = \frac{\sigma(Z\text{+jets})\mathcal{B}(Z \to \nu\bar{\nu})}{\sigma(Z\text{+jets})\mathcal{B}(Z \to \ell\ell)}\Gamma(Z \to \ell\ell)$$

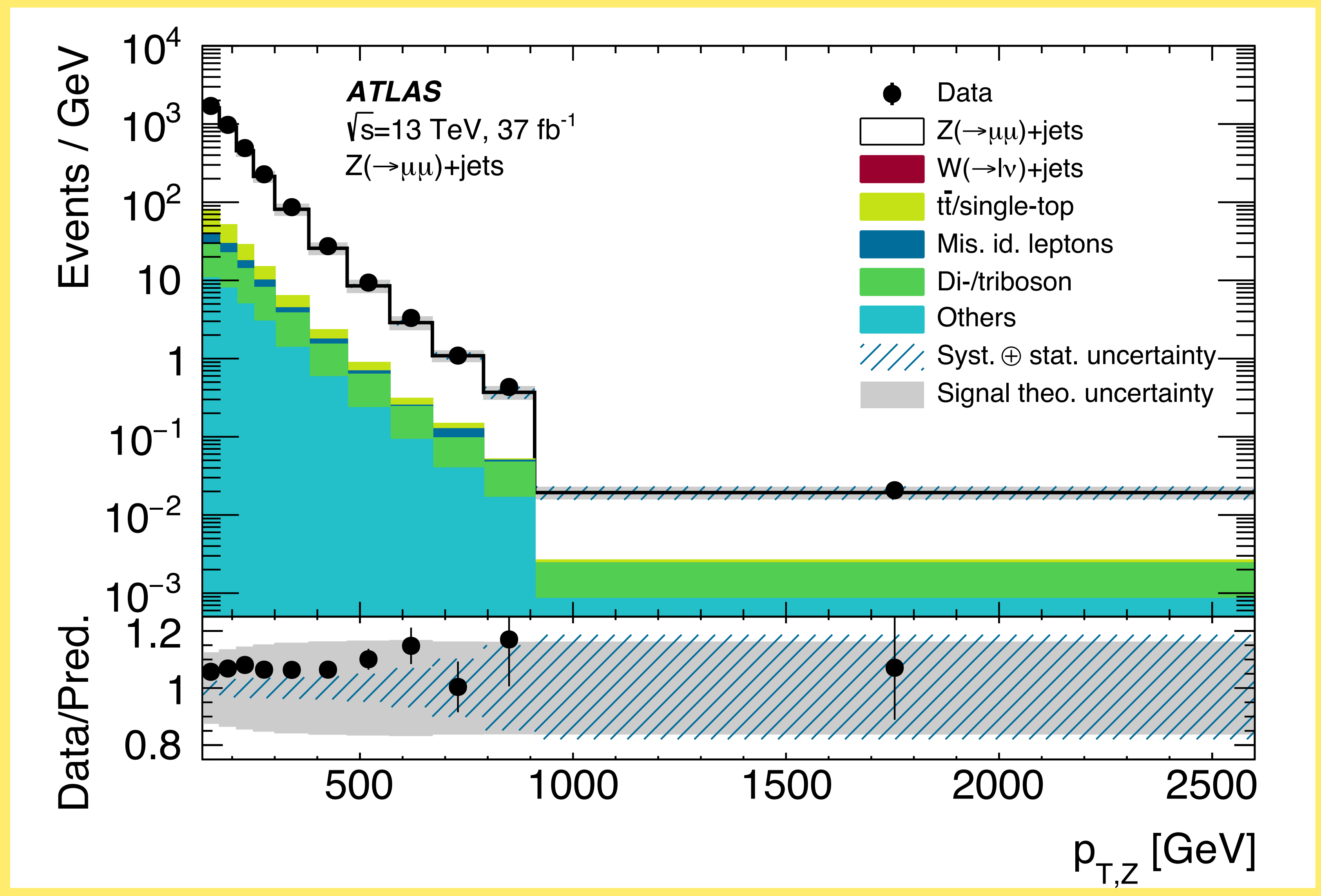
Recent ATLAS result most recoil-based measurement to date:
$\Gamma = 506 \pm 2(\mathrm{stat}) \pm 12(\mathrm{syst})$ MeV







Main systematics:
lepton efficiencies



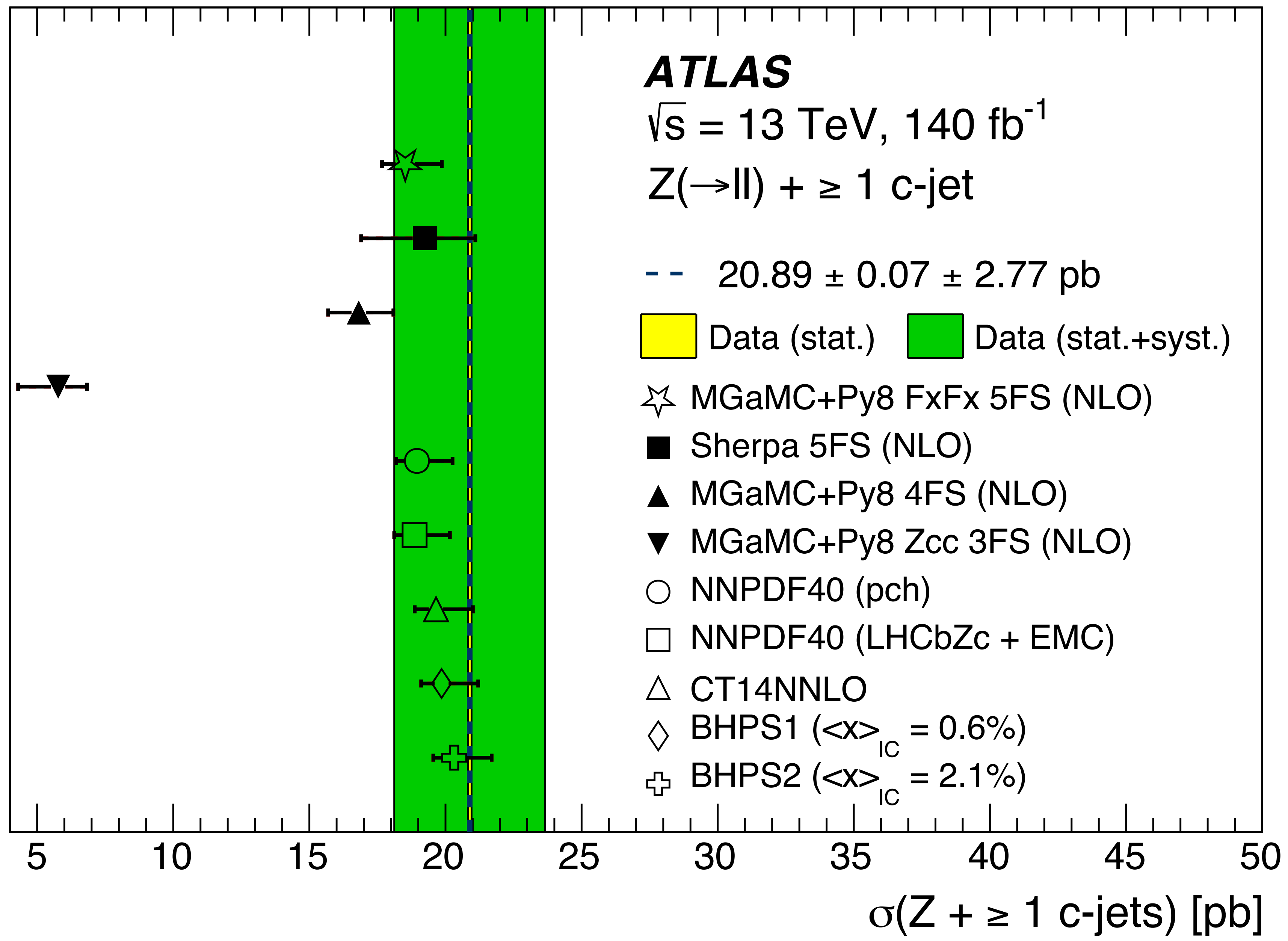
From vector bosons to quarks to leptons

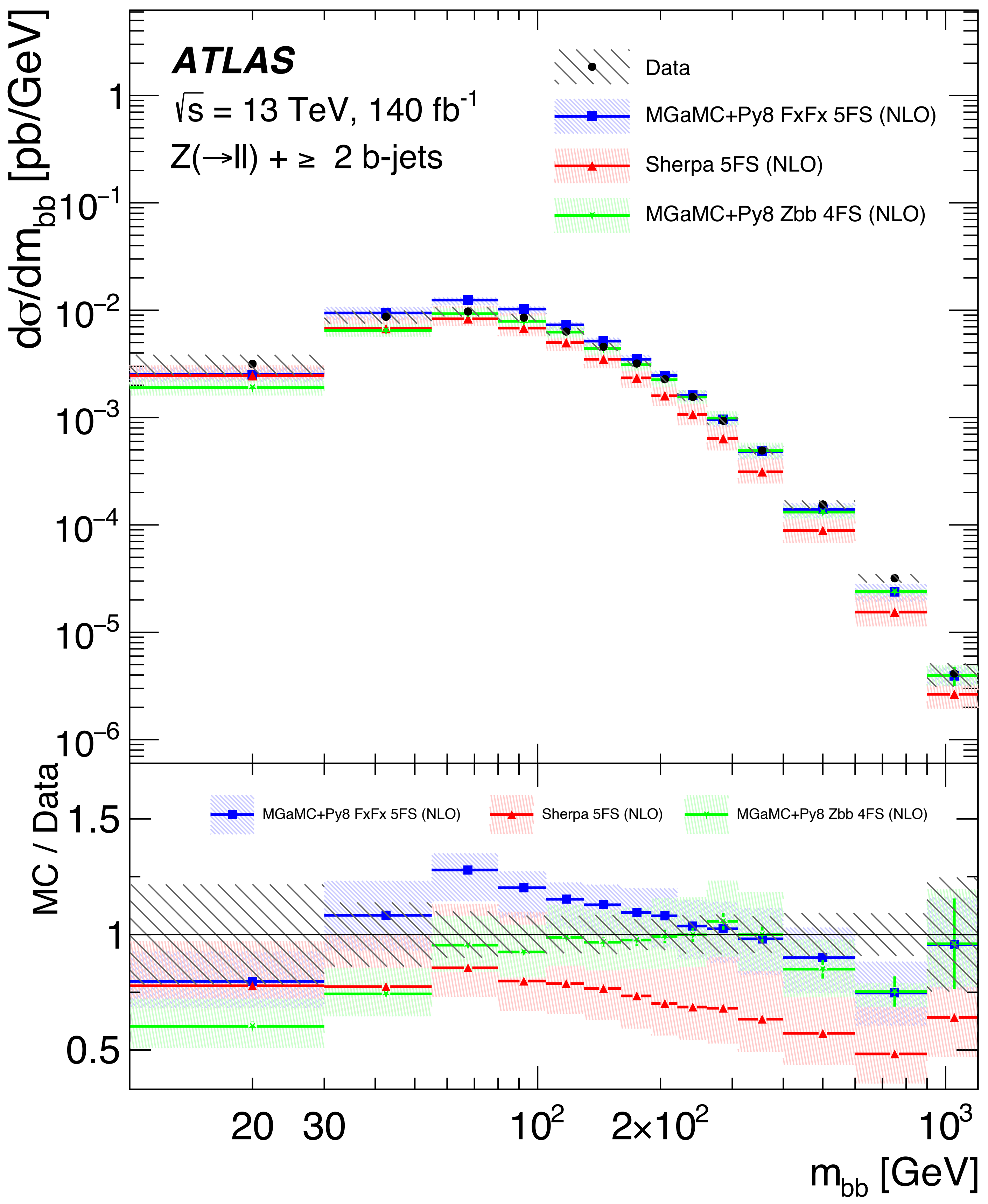
W/Z + heavy flavour

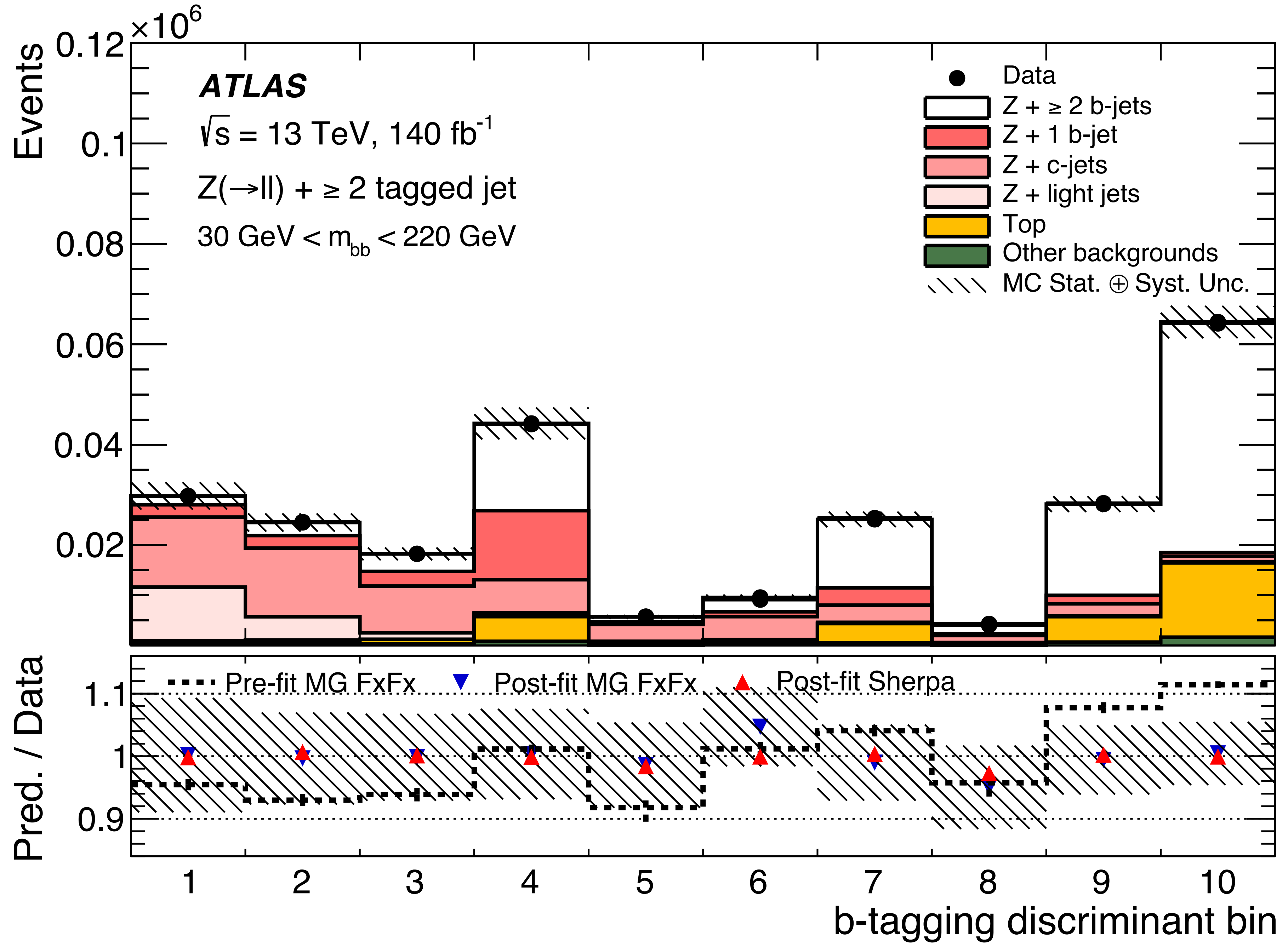
arXiv:2403.15093 (sub. to EPJC)

- ATLAS analysis studies Z + ≥1b, ≥1c, ≥2b jet topologies
- Wide range of differential distributions
  - E.g. m_{bb} useful input for MC modelling for H(bb)

- Study of intrinsic charm
  - 3FS significantly underestimates rate
  - Largest improvement with BHPS model (2.1% IC)

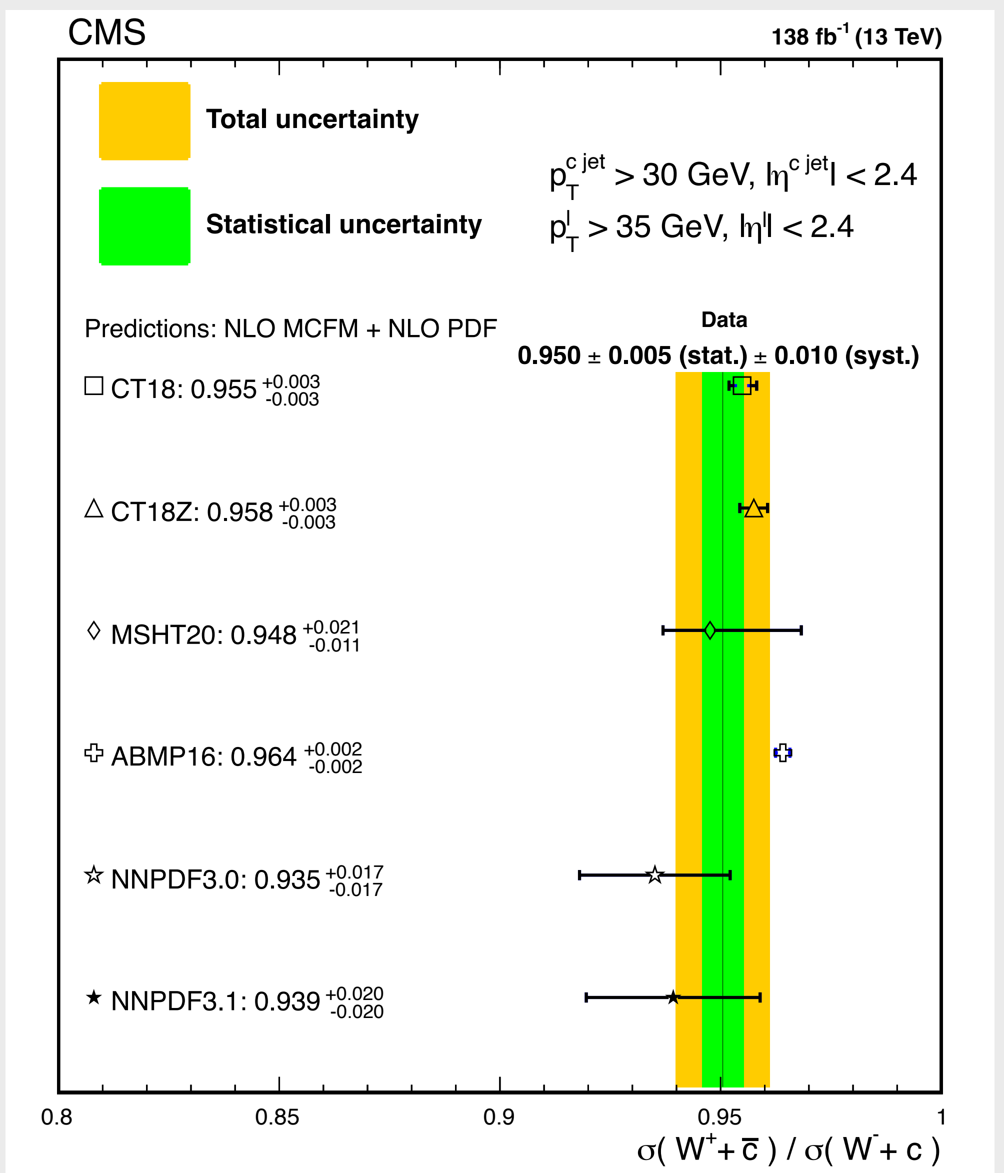






See also: W+c 13 TeV

EPJC 84 (2024) 27



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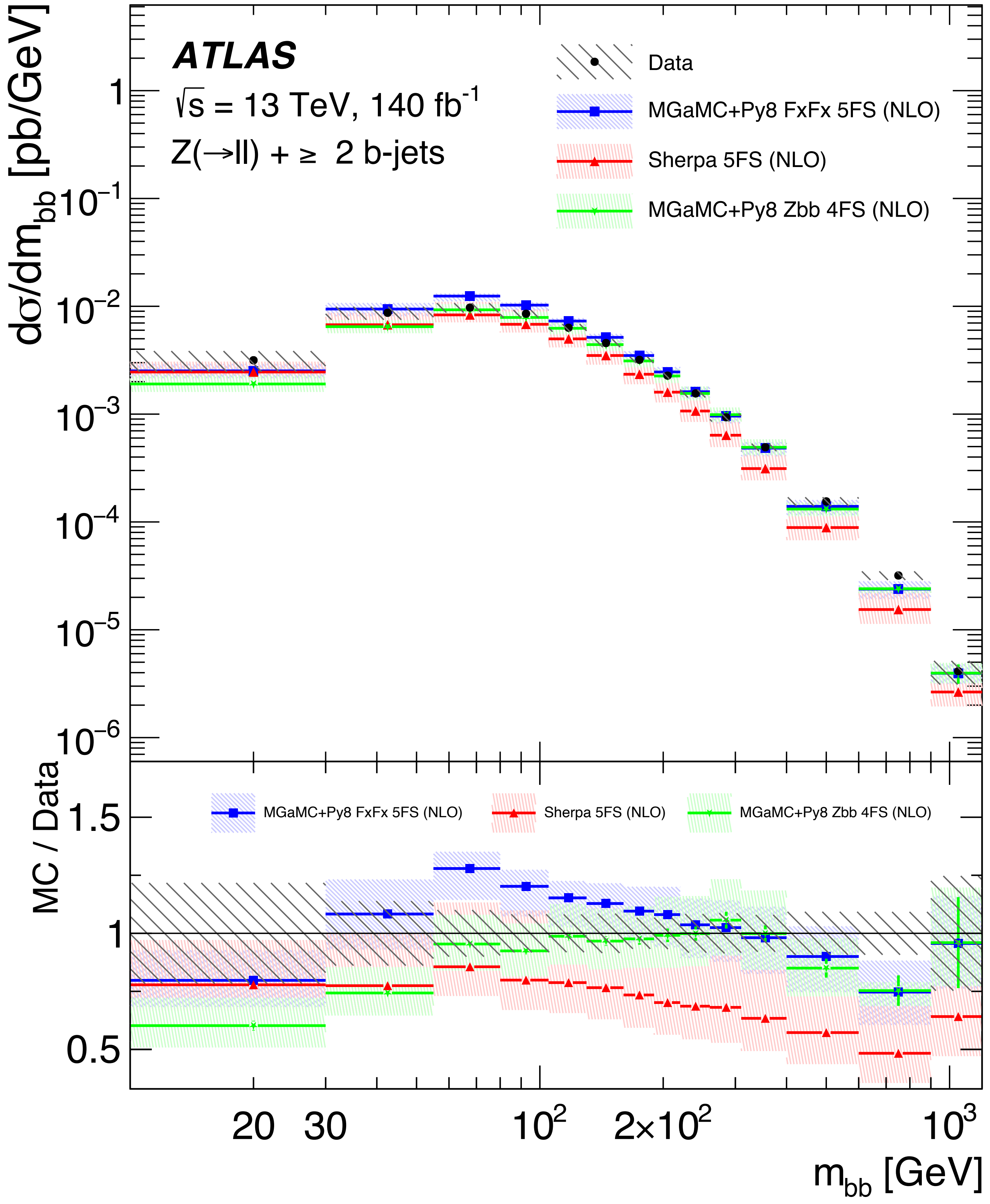

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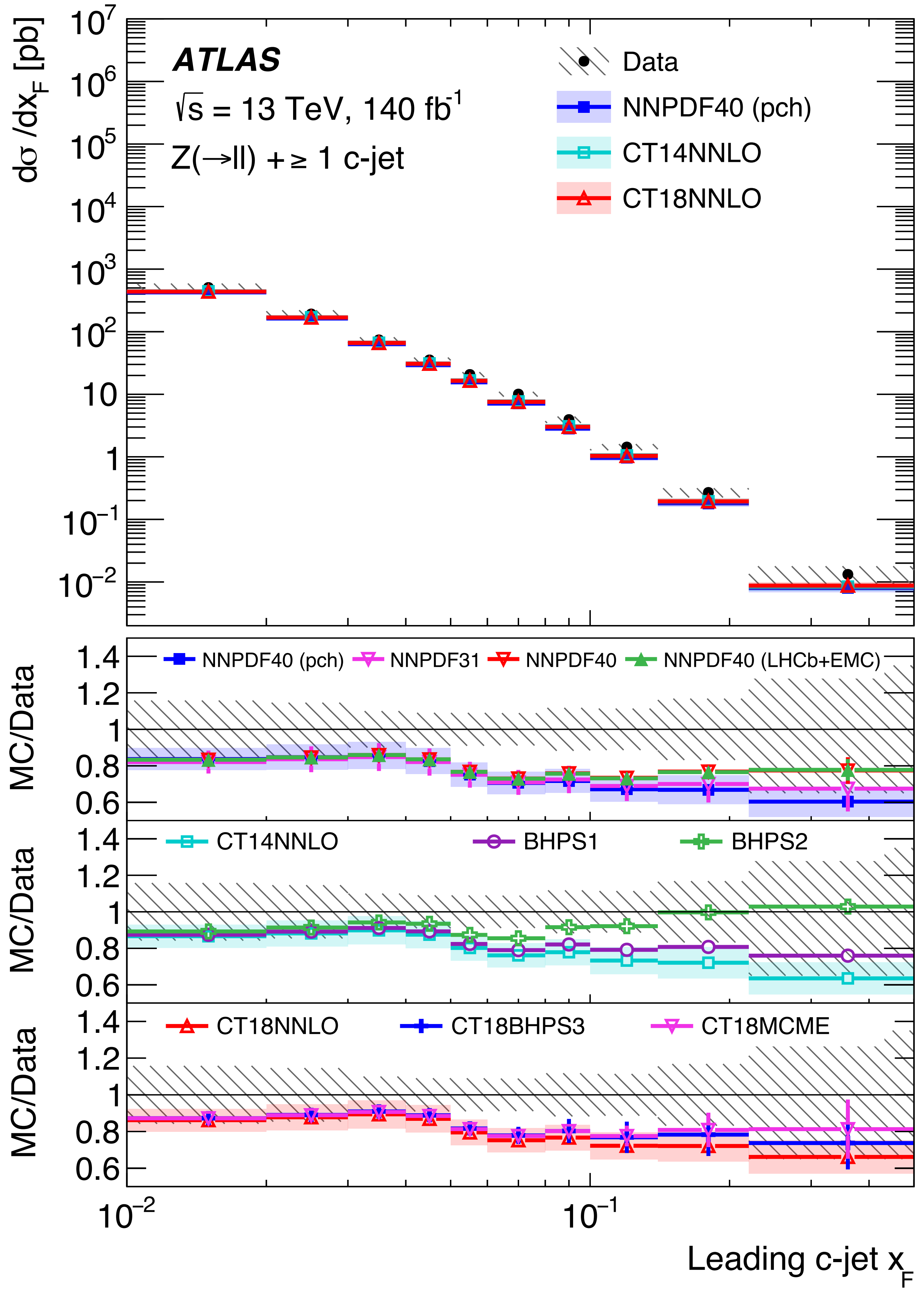
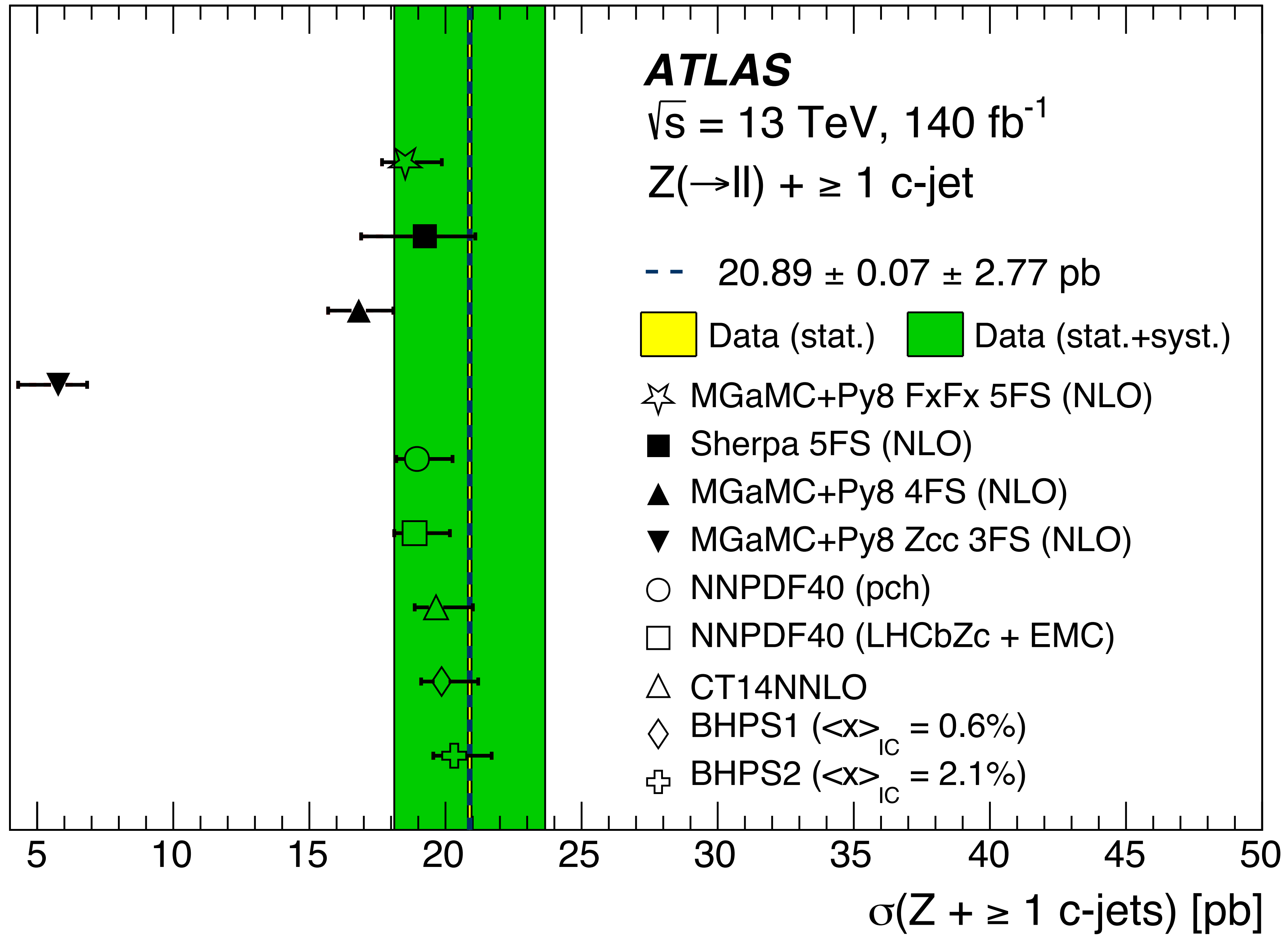
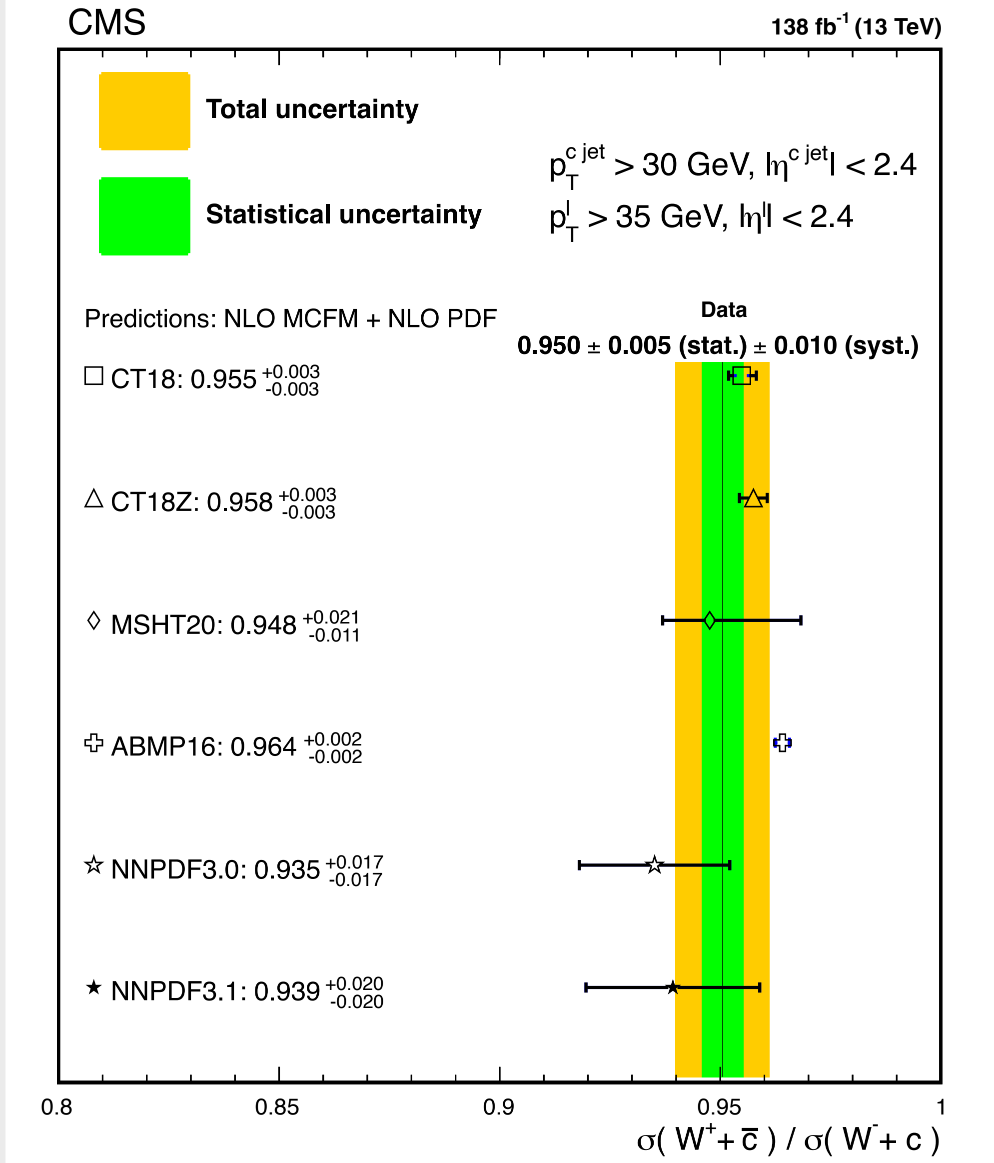




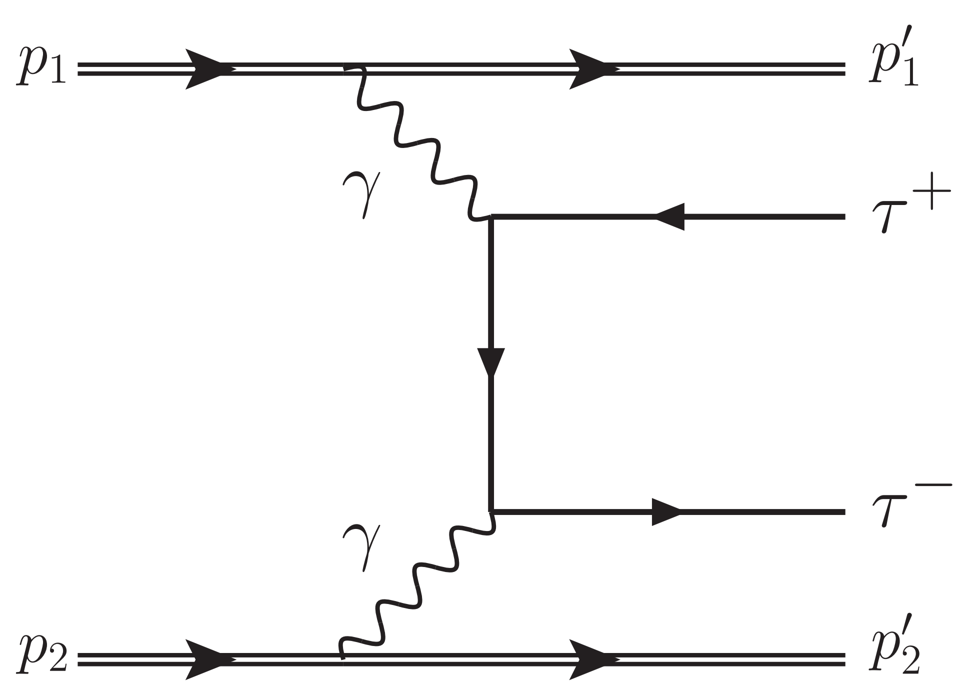
See also: W+c 13 TeV
EPJC 84 (2024) 27

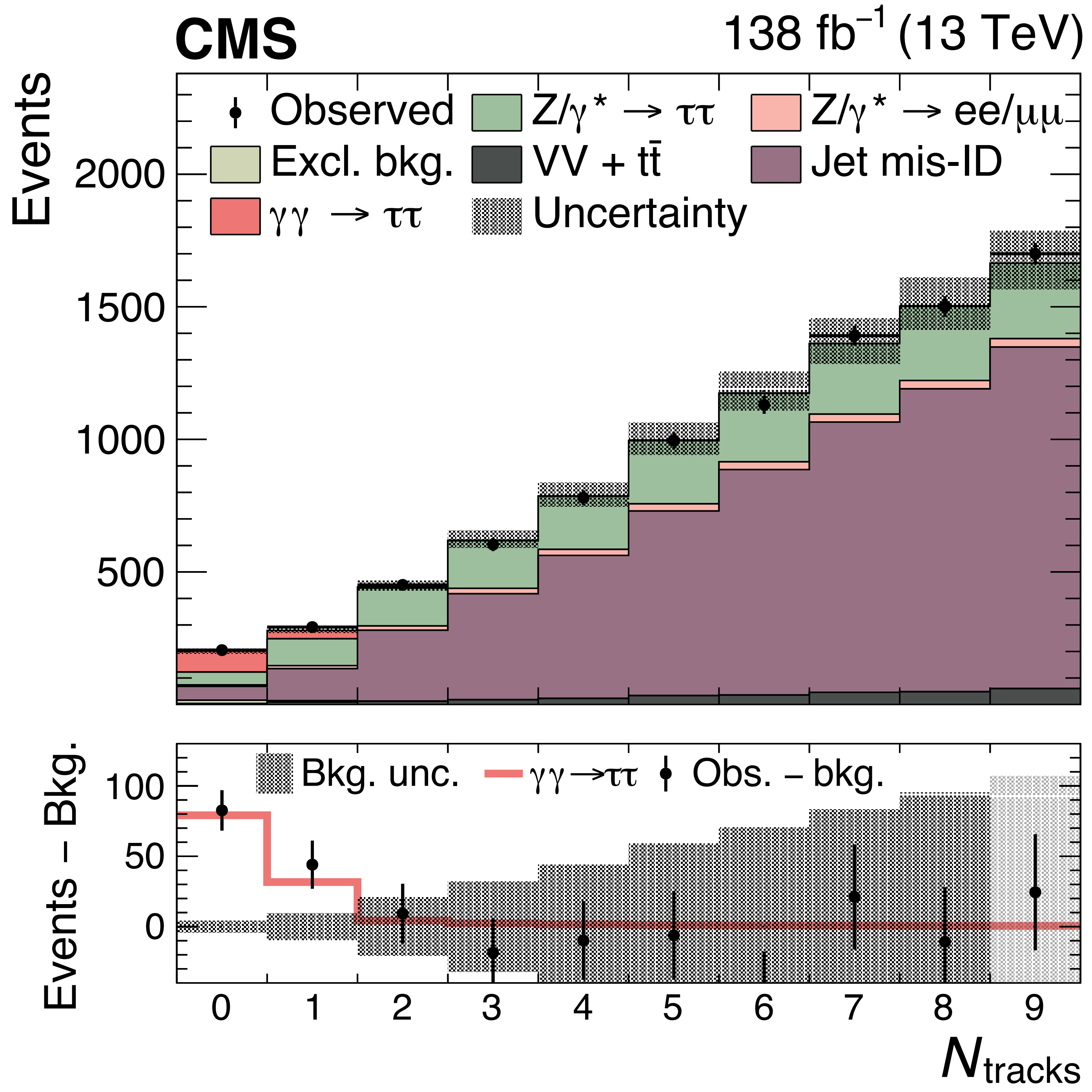


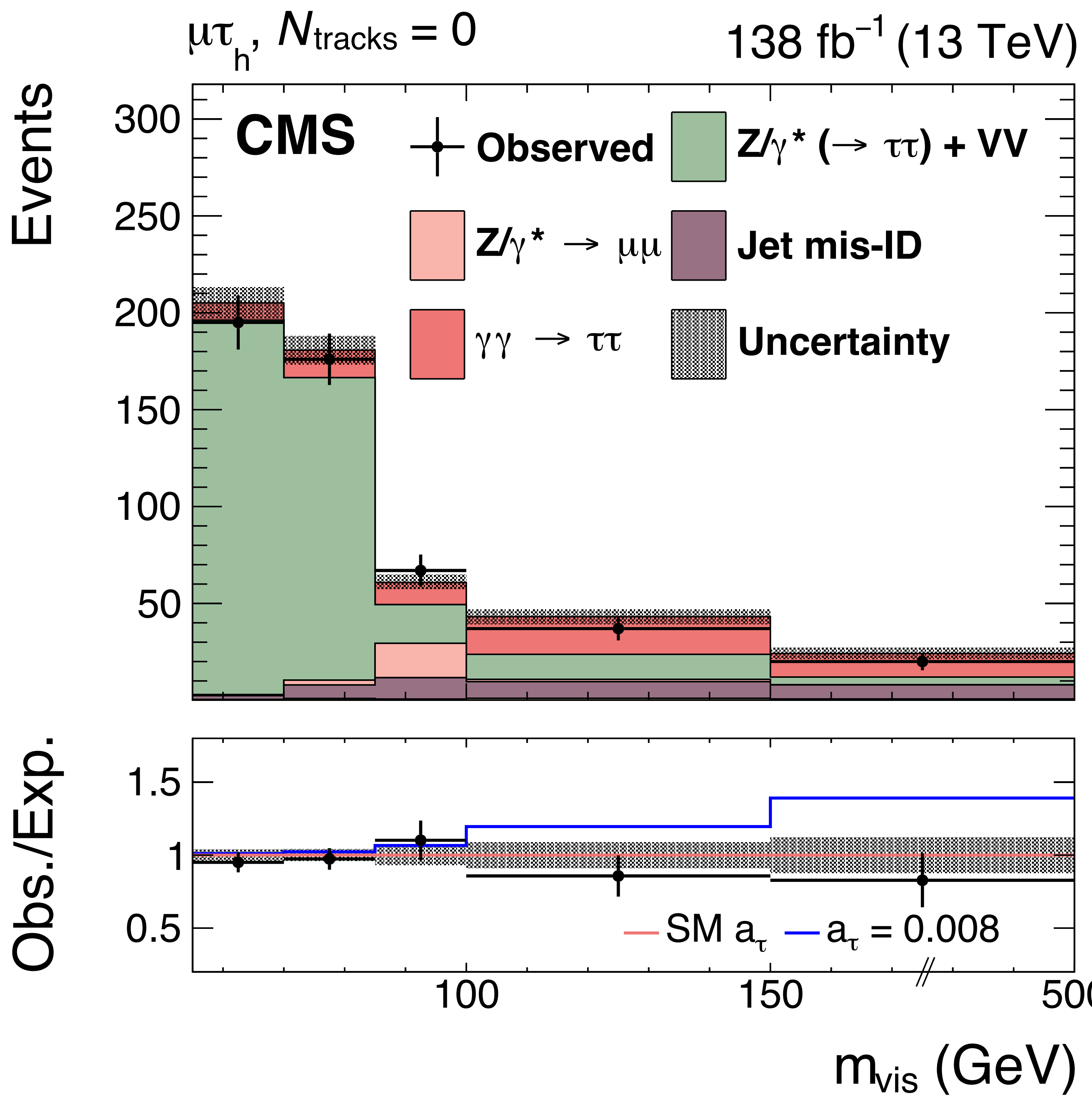
$\gamma\gamma\to\tau\tau$ and constraints on tau g-2

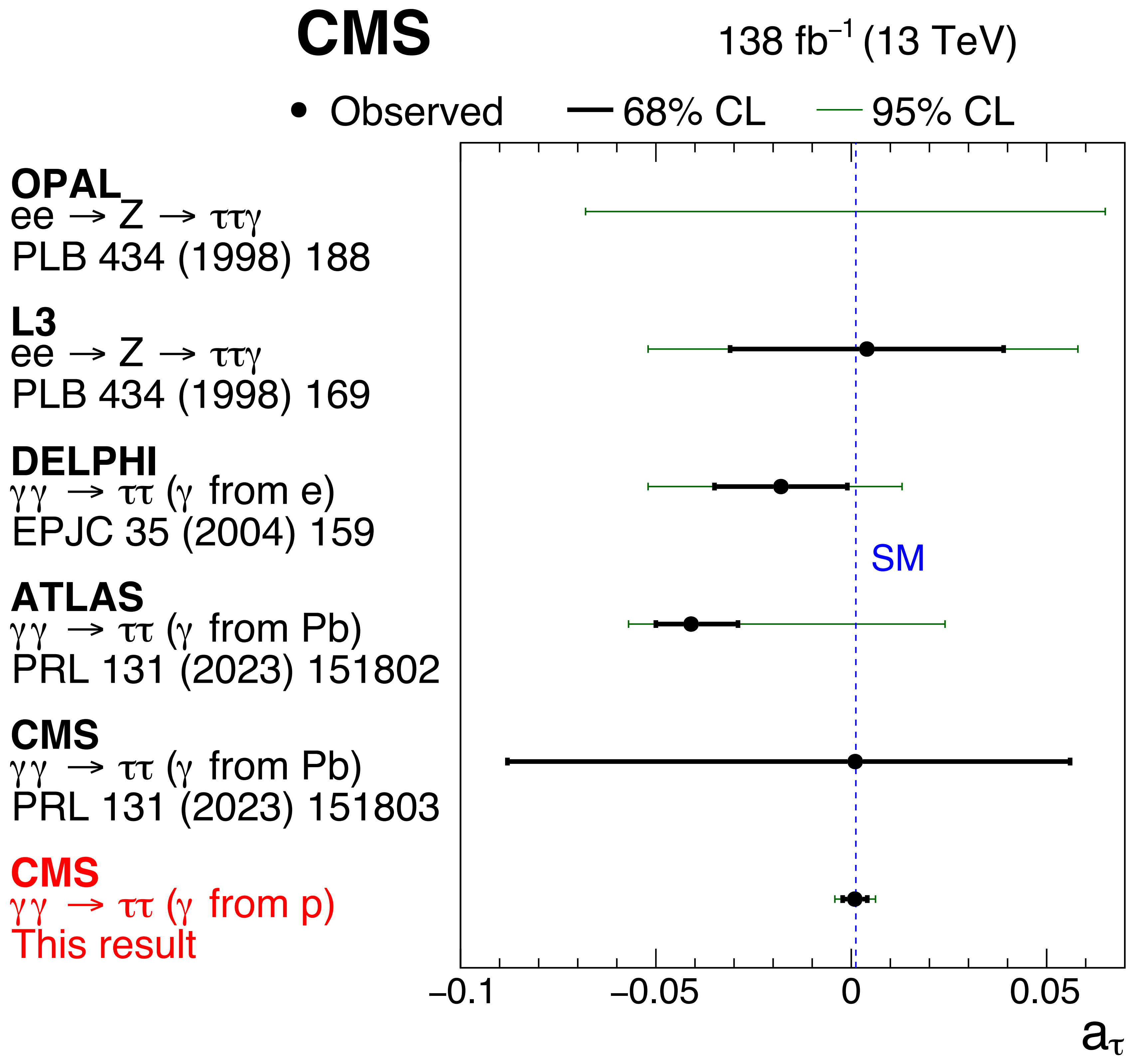
SMP-23-005
To be submitted to ROPP

- Select events with $N_{tracks} \leq 1$
  - Dedicated corrections for num. hard scatter & PU tracks in simulation
- First observation in pp collisions
  - 5.3σ observed (6.5 expected)
- Constraints on a_τ from m_{vis} enhancement









— Obs.: $a_\tau = 9^{+32}_{-31} \times 10^{-4}$ (68% CL)

···· Exp.: $a_\tau = 12^{+41}_{-43} \times 10^{-4}$ (68% CL)

See also: Observation of $\gamma\gamma\to WW$
Phys. Lett. B 816 (2021) 136190

γγ→ττ and constraints on tau g-2

SMP-23-005
To be submitted to ROPP

New

- Select events with $N_{tracks} \leq 1$
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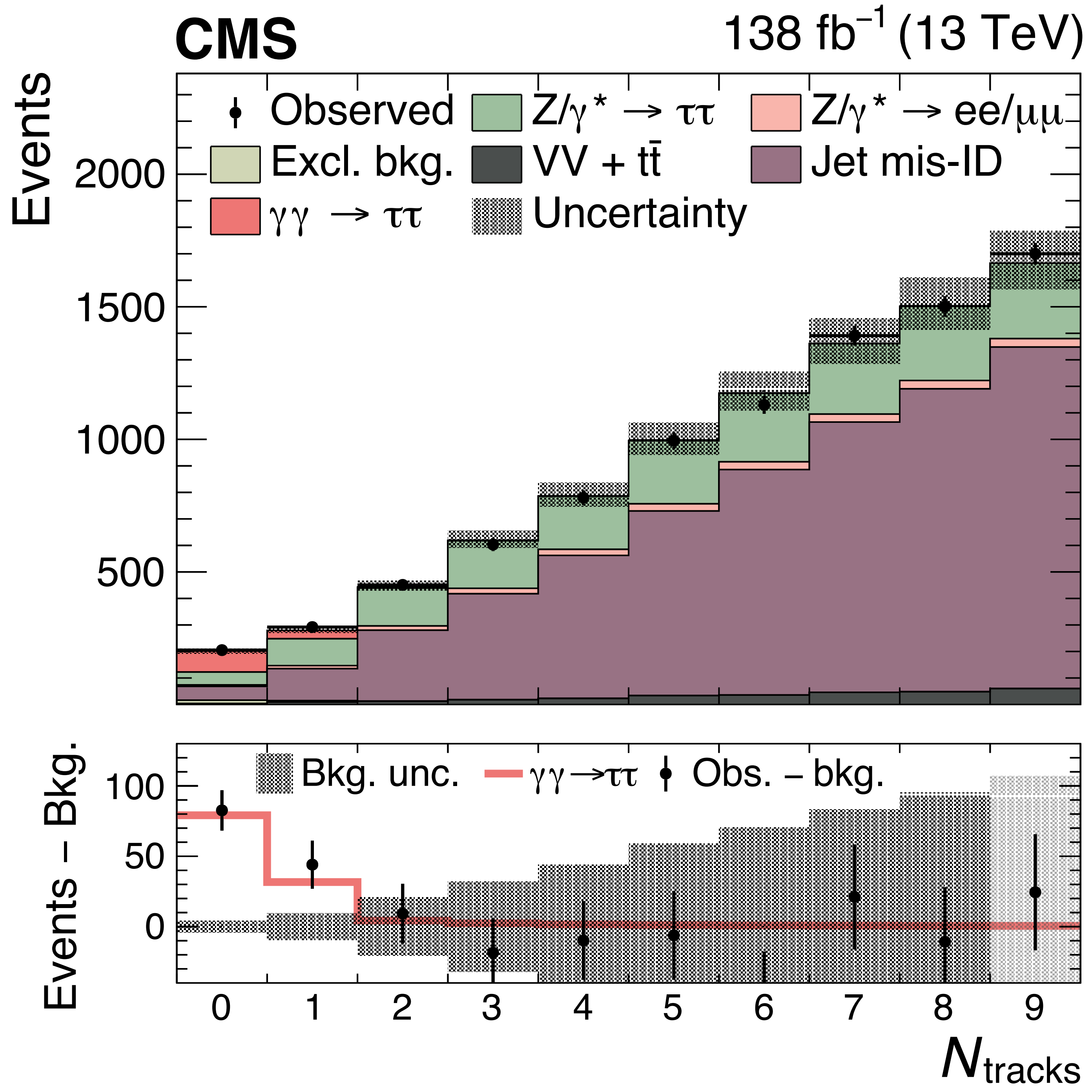


- Fiducial cross section
  - Matching closely expt. selection (N_{tracks} = 0 only)
- Prediction from gamma-UPC (elastic only) rescaled for dissociative using data CR

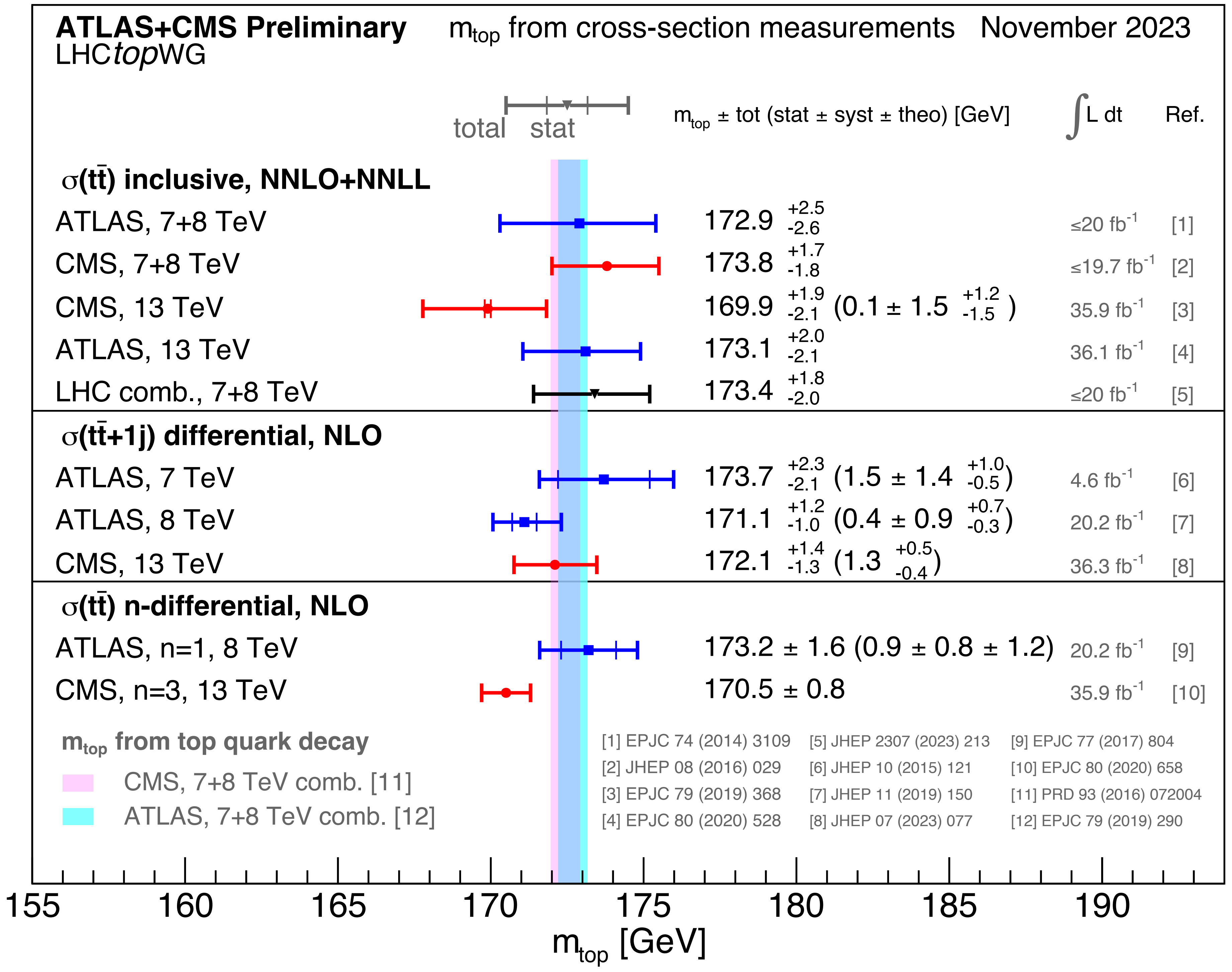
$$\sigma^{fid}_{obs} = 12.4^{+3.8}_{-3.1}\ \text{fb}$$

$$\sigma^{fid}_{pred} = 16.5 \pm 1.5\ \text{fb}$$

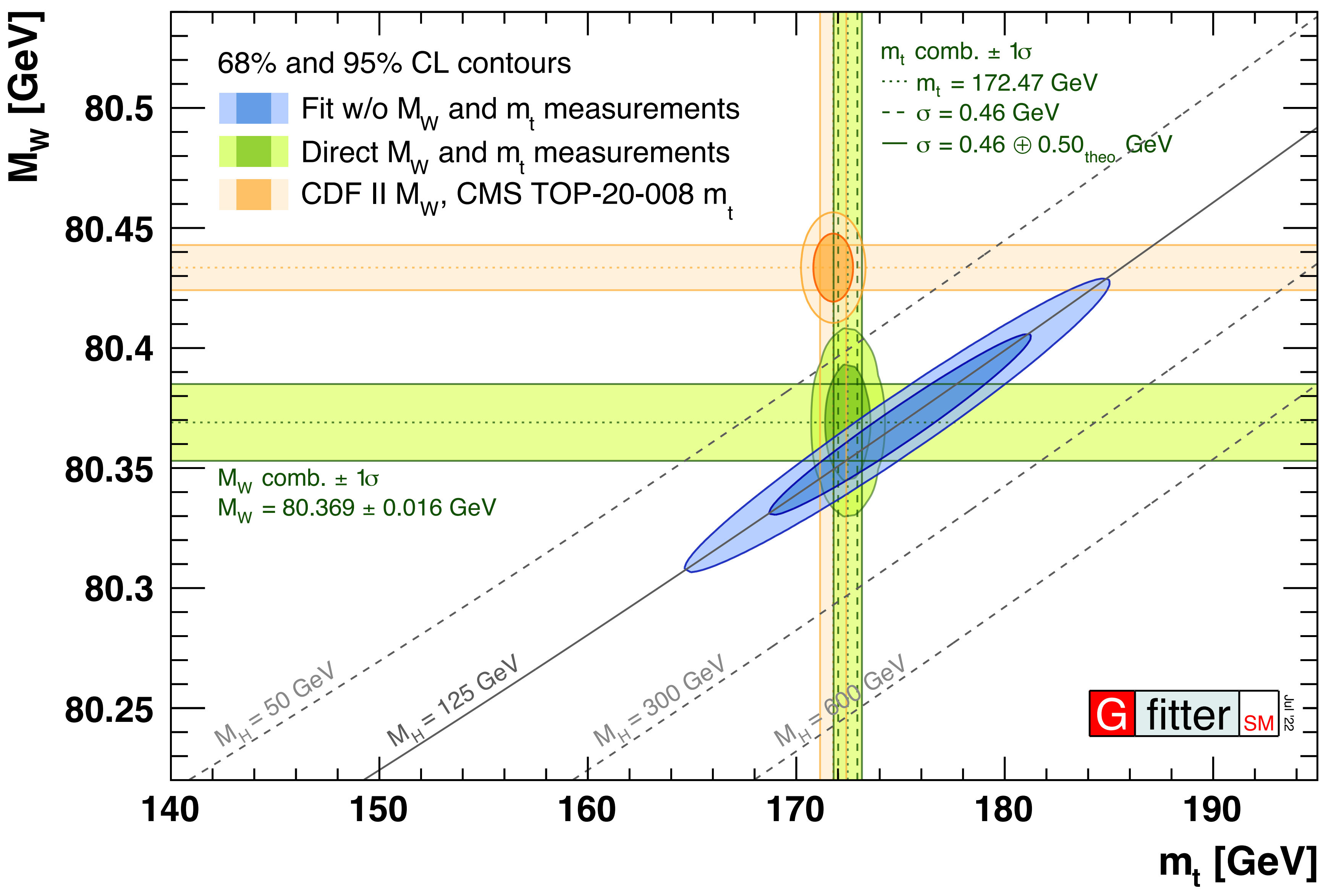
See also: Observation of γγ→WW
Phys. Lett. B 816 (2021) 136190

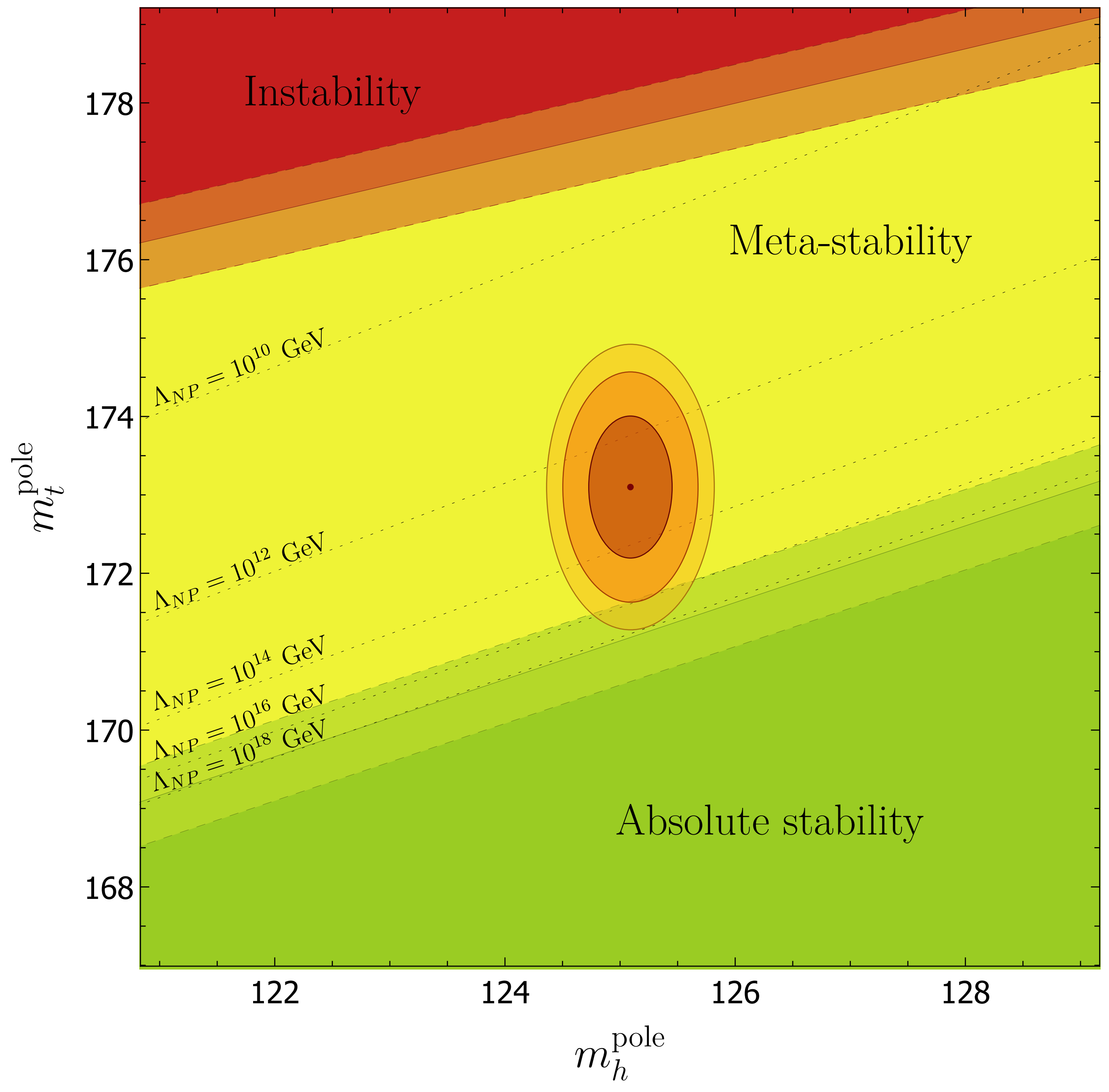
Top quark properties

- Deep connection to both EW and QCD sectors
- Large m_t ⇒ Higgs Yukawa ~ unity ⇒ key parameter for vacuum stability
  - Via loop corrections, uncertainty propagates to other EW parameters
- Measurement approaches:
  - **Indirect:** e.g. cross section dependence [not discussed today]
  - **Direct**: fit to mass (or correlated variable)



Phys. Rev. D 97, 056006 (2018)





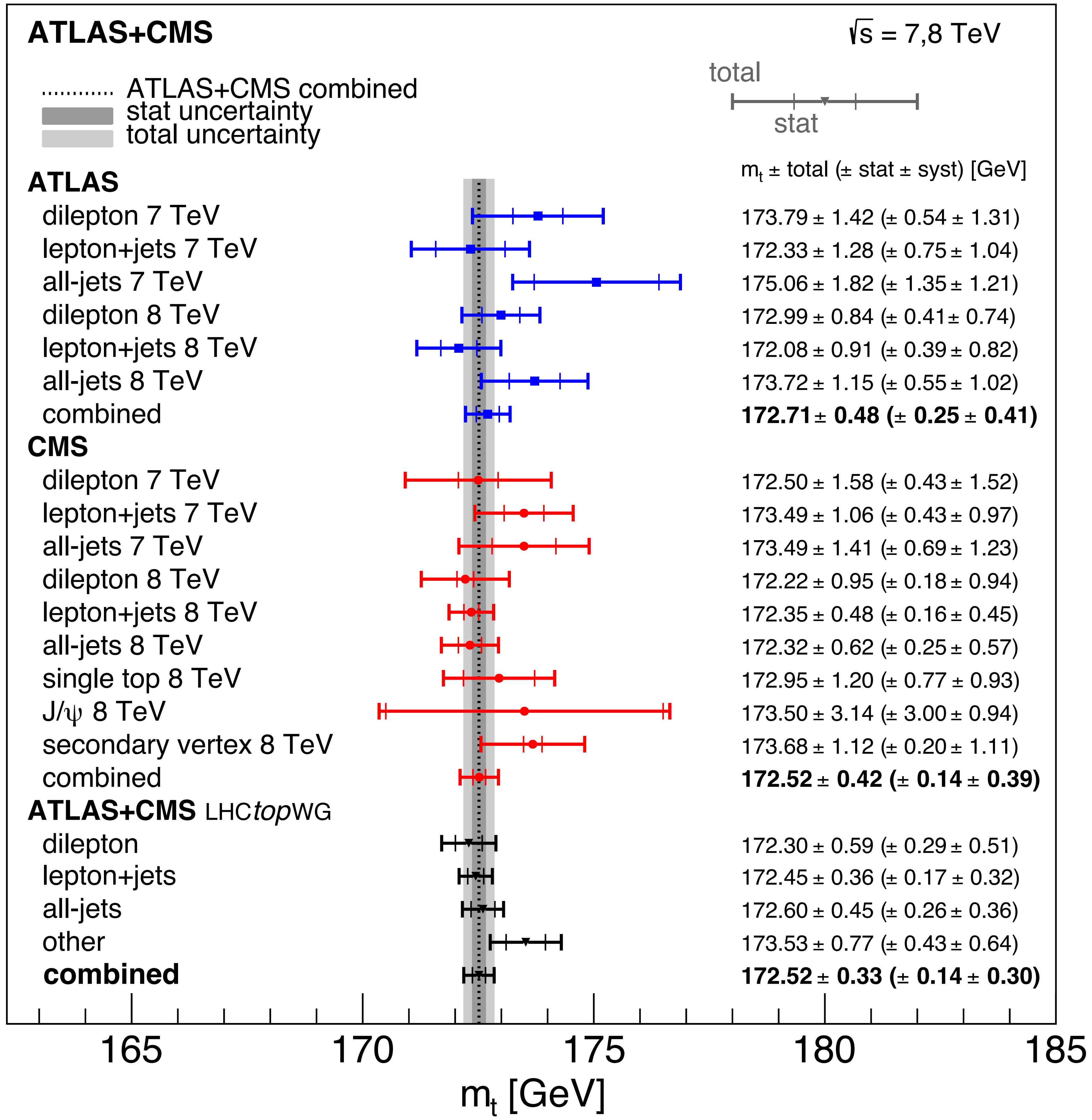
arXiv:2211.07665

Discussed in other plenary talks:
- Lepton flavor violation and rare heavy flavor decays - Monday evening
- Top cross-section measurements and rare ttX processes - tomorrow morning

ATLAS + CMS direct m_t combination

arXiv:2402.08713 (PRL accepted)

- Legacy combination of Run-1:
  - 6 (ATLAS) + 9 (CMS) measurements, detailed study of systematic correlations
- BLUE method: $m_t = \sum_i w^i m_t^i; \quad \sum_i w^i = 1$



- Uncertainty in b-jet JES dominates combination
- Requires detailed understanding of correlations

Uncertainty category	ρ	Scan range	$\Delta m_t/2$ [MeV]	$\Delta\sigma_{m_t}/2$ [MeV]
JES 1	0	—	—	—
JES 2	0	[−0.25, +0.25]	8	7
JES 3	0.5	[+0.25, +0.75]	1	<1
b-JES	0.85	[+0.5, +1]	26	5
g-JES	0.85	[+0.5, +1]	2	<1

mt = 172.52 ± 0.33 GeV (±0.14 stat) (±0.30 syst)

- Most precise to date: **< 2 per mille**

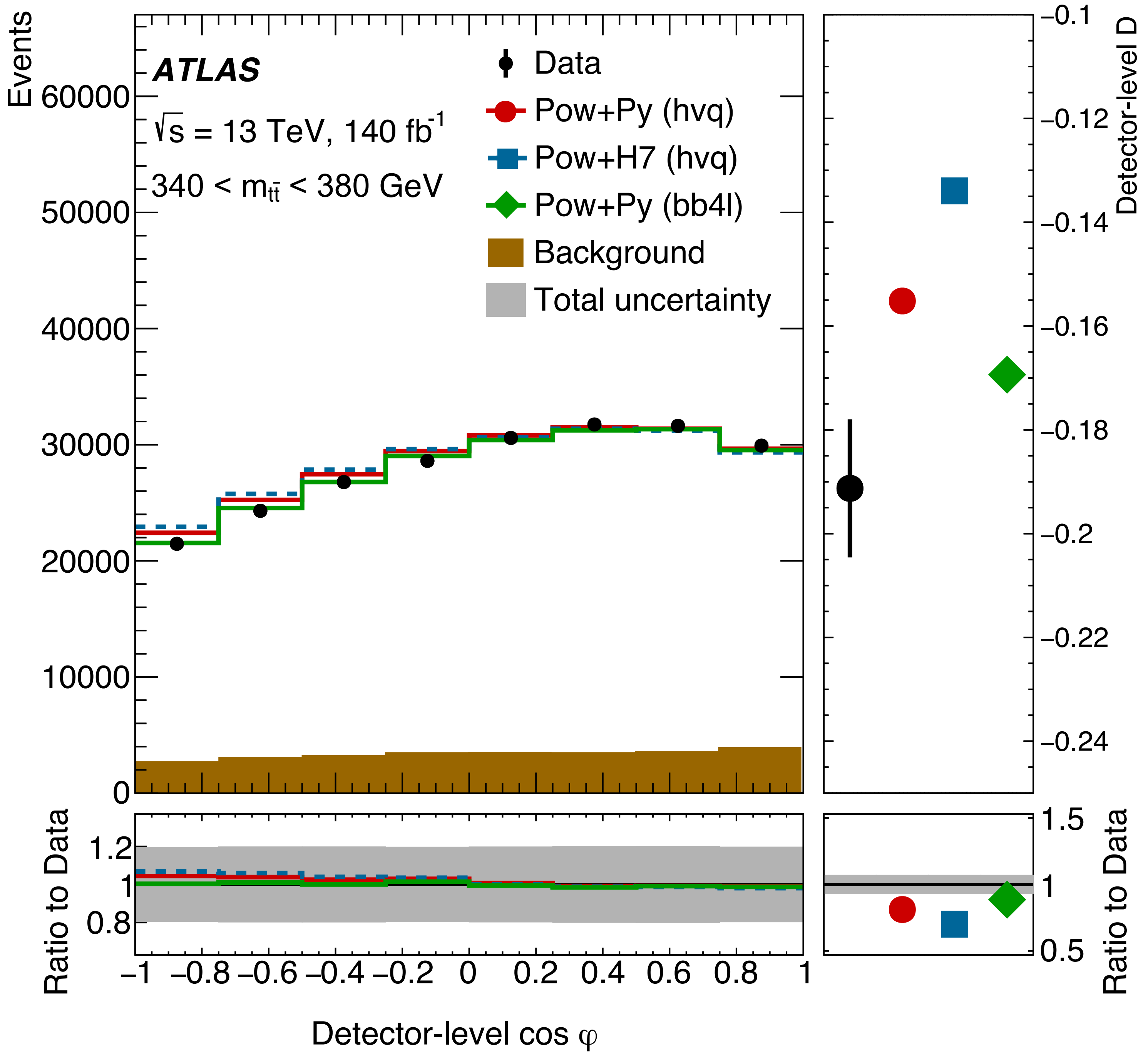
Uncertainty category	Uncertainty impact [GeV] LHC	ATLAS	CMS
b-JES	0.18	0.17	0.25
b tagging	0.09	0.16	0.03
ME generator	0.08	0.13	0.14
JES 1	0.08	0.18	0.06
JES 2	0.08	0.11	0.10
Method	0.07	0.06	0.09
CMS b hadron $\mathcal{B}$	0.07	—	0.12
QCD radiation	0.06	0.07	0.10
Leptons	0.05	0.08	0.07
JER	0.05	0.09	0.02
CMS top quark p_T	0.05	—	0.07
Background (data)	0.05	0.04	0.06
Color reconstruction	0.04	0.08	0.03
Underlying event	0.04	0.03	0.05
g-JES	0.03	0.02	0.04
Background (MC)	0.03	0.07	0.01
Other	0.03	0.06	0.01
l-JES	0.03	0.01	0.05
CMS JES 1	0.03	—	0.04
Pileup	0.03	0.07	0.03
JES 3	0.02	0.07	0.01
Hadronization	0.02	0.01	0.01
p_T^{miss}	0.02	0.04	0.01
PDF	0.02	0.06	<0.01
Trigger	0.01	0.01	0.01
Total systematic	0.30	0.41	0.39
Statistical	0.14	0.25	0.14
Total	0.33	0.48	0.42

Observation of $t\bar{t}$ entanglement

- Unique probe of entanglement via spin correlations
  - Both experiments analyses dilepton final state
  - $\Rightarrow$ measure angle between $\ell^{\pm}$ in $t\bar{t}$ rest frame

ATLAS: 2311.07288 (submitted to Nature)

CMS: CMS-PAS-TOP-23-001



- Focus on narrow range around $t\bar{t}$ production threshold
  - 80% cross section for spin-singlet state (rotational invariance needed for observation)

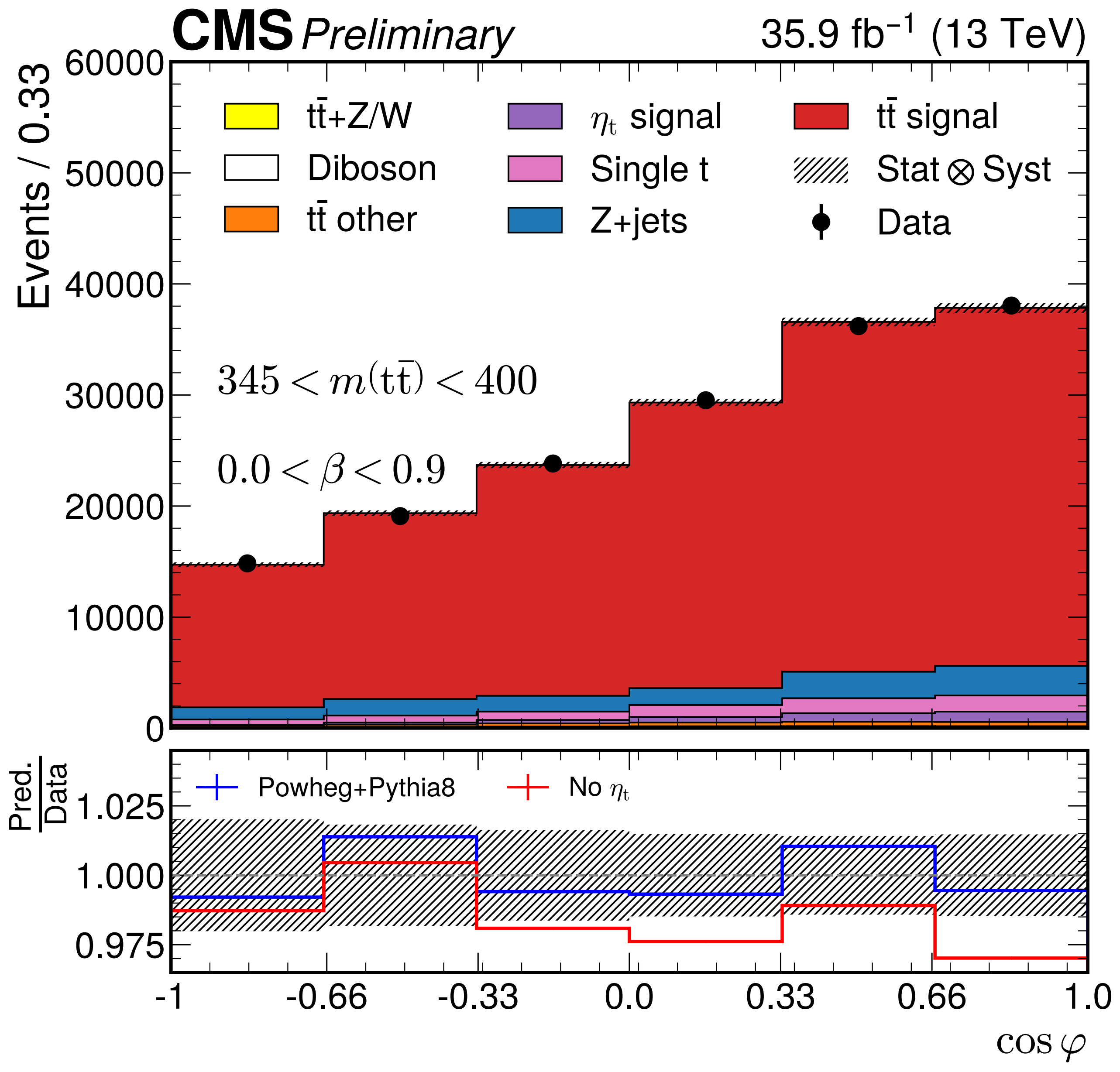
- Cross section:

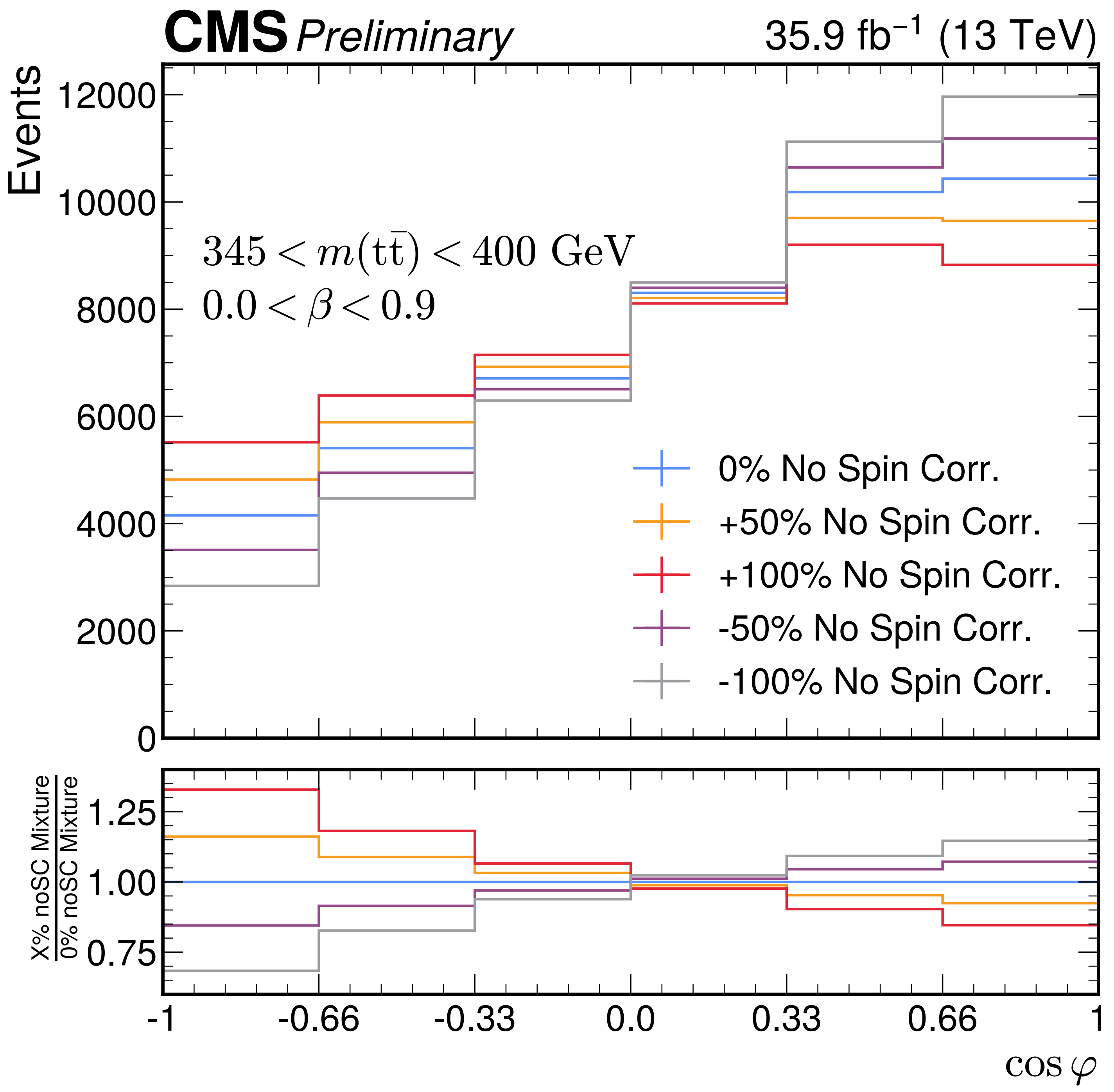
$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+ d\Omega_-} = \frac{1 + \mathbf{B}^+ \cdot \hat{\mathbf{q}}_+ - \mathbf{B}^- \cdot \hat{\mathbf{q}}_- - \hat{\mathbf{q}}_+ \cdot \mathbf{C} \cdot \hat{\mathbf{q}}_-}{(4\pi)^2}$$

$$D = \mathrm{tr}[\mathbf{C}]/3 = -3 \cdot \langle \cos\varphi \rangle$$

- **D < -1/3** implies entanglement

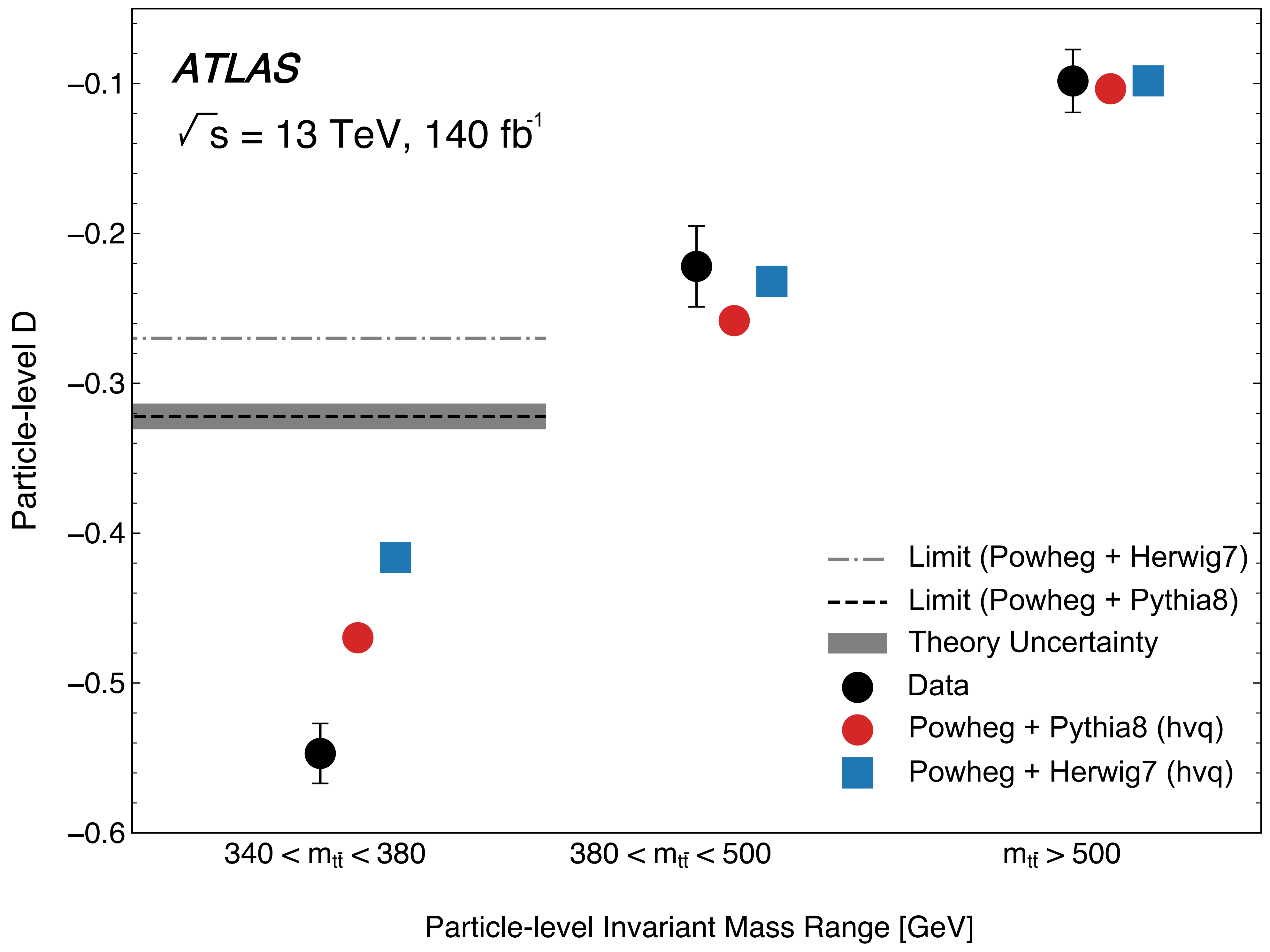
- CMS includes Toponium effects
  - Maximally entangled particles
  - Via a colour singlet single pseudoscalar [PRD 104 (2021) 034023]

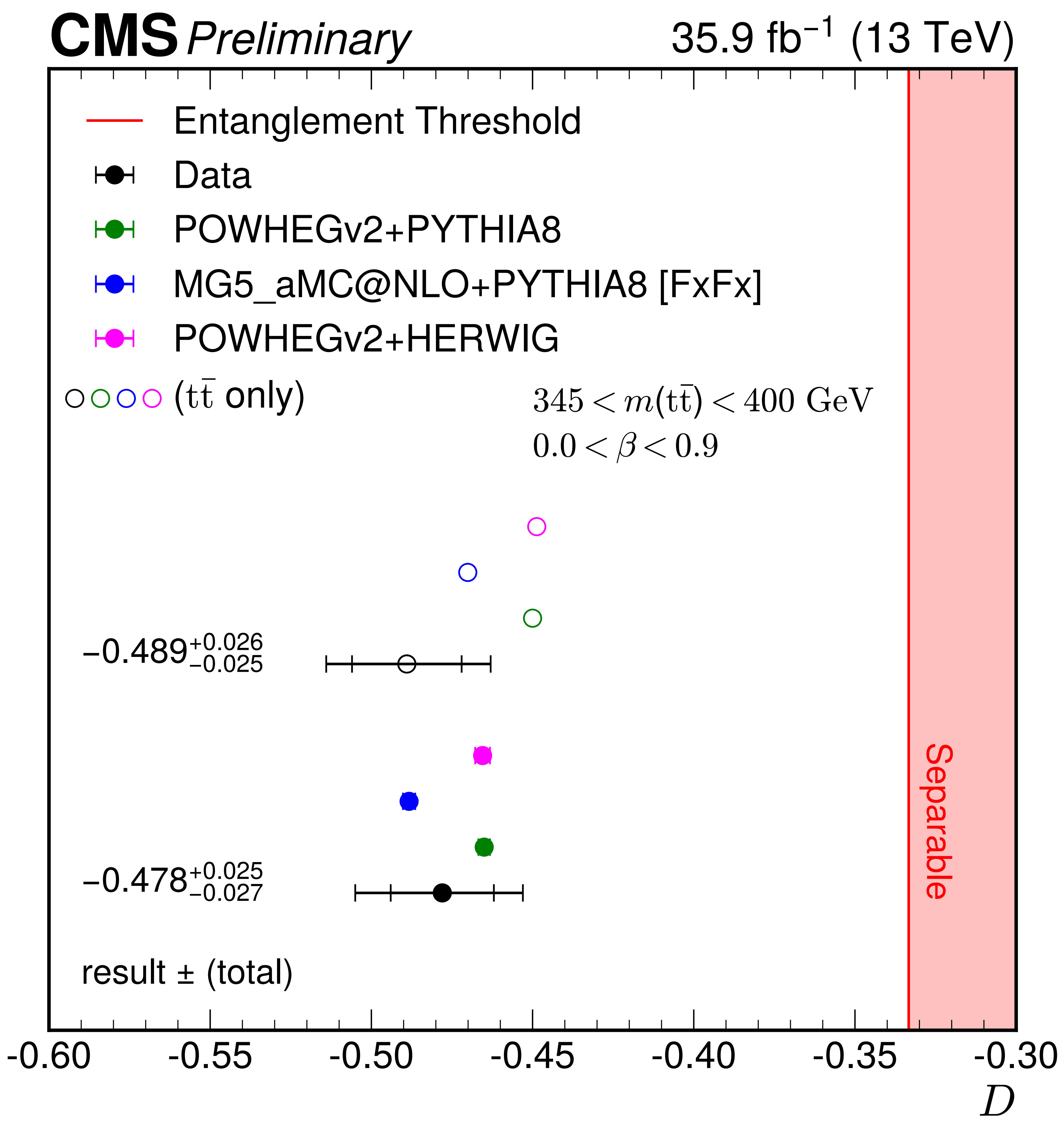




Observation of $t\bar{t}$ entanglement

- Both experiments observe entanglement with > 5σ significance
  - Good agreement with theory predictions
  - Systematics limited with full Run 2 data set





$$D = -0.547 \pm 0.002(\text{stat.}) \pm 0.021(\text{syst.})$$

$$D = -0.478 \pm 0.017(\text{stat.})^{+0.018}_{-0.021}(\text{syst.})$$

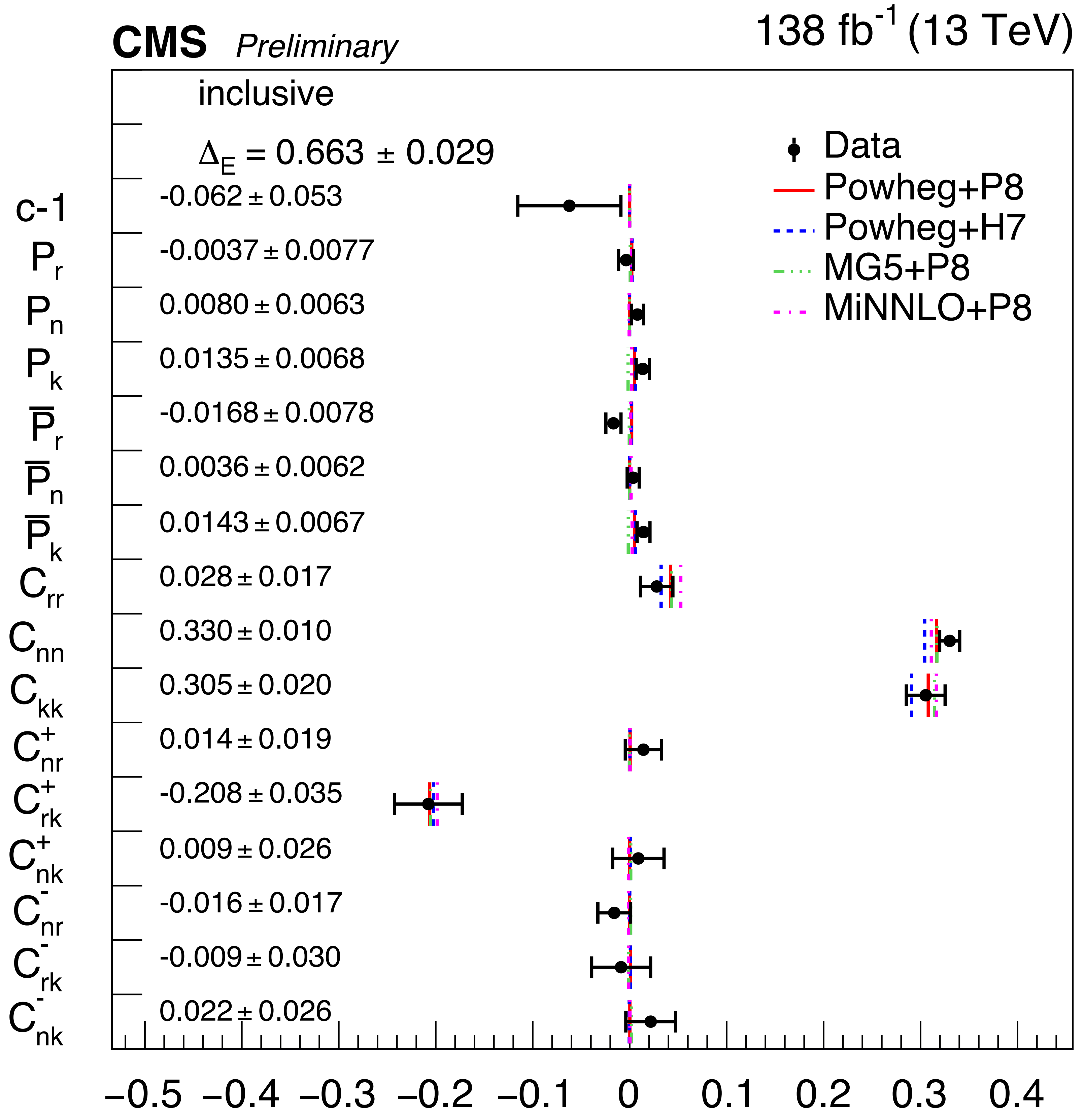
$t\bar{t}$ spin correlation and entanglement in ℓ+jets

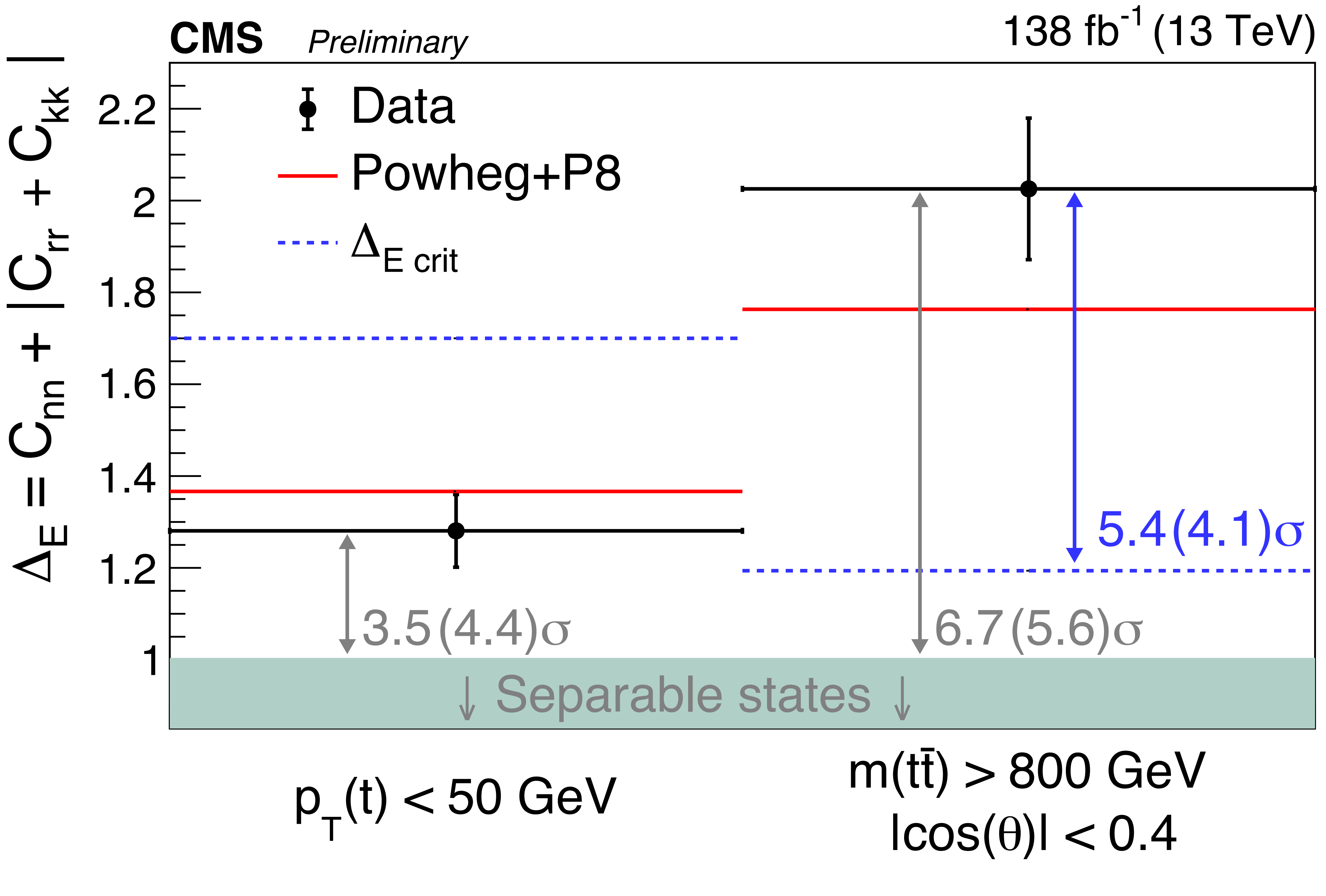
New

CMS-PAS-TOP-23-007

- All polarization vector & spin correlation matrix coefficients extracted simultaneously
  - In bins of $m_{t\bar{t}}$, $p_T(t)$, and $|\cos\theta|$
- Entanglement observed for the first time at high $m_{t\bar{t}}$
  - Addition criterion based on classical information exchange at v ≤ c

Covered in R. Demina's talk in top parallel session today





Reviews

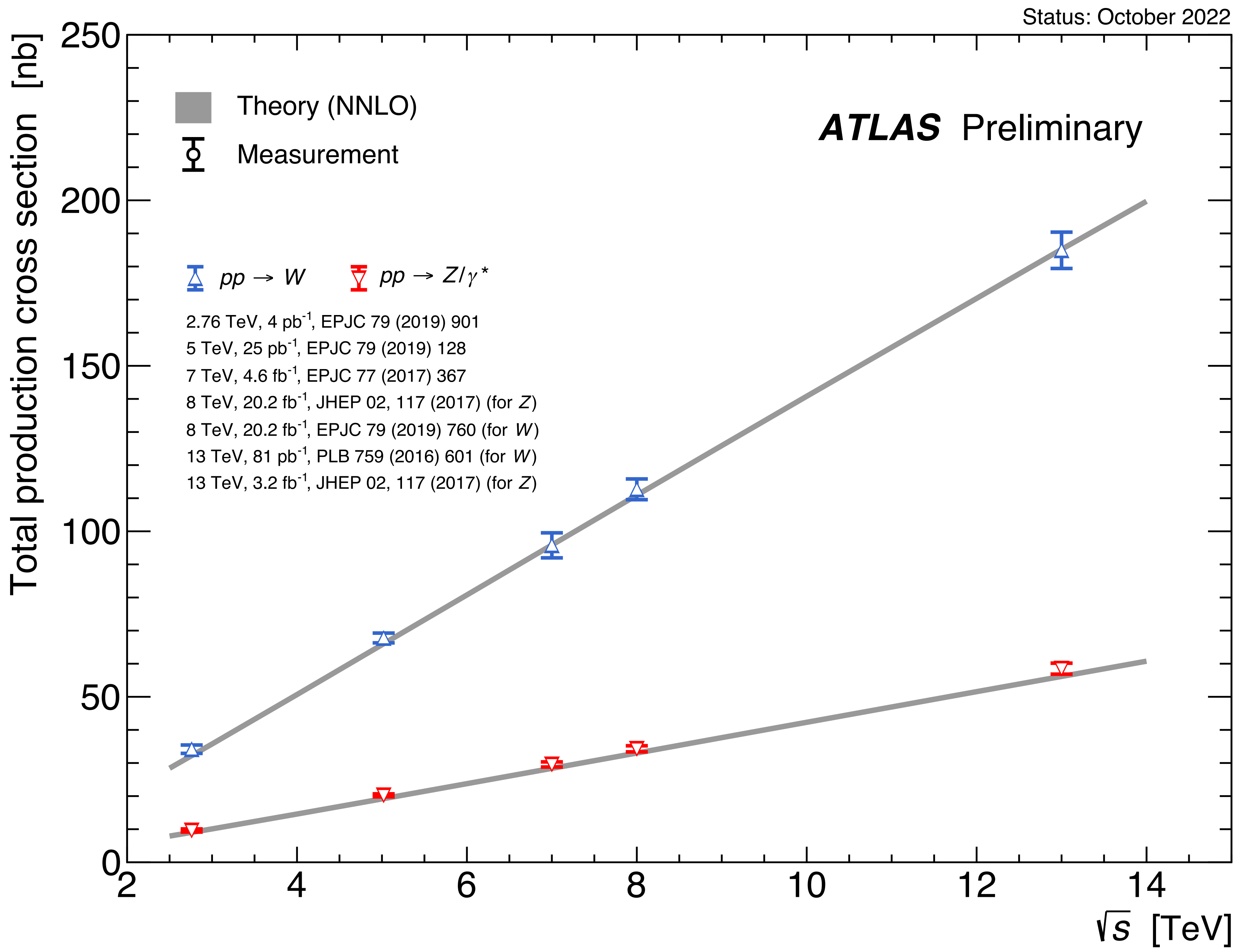
arXiv:2404.06829 (submitted Phys Rept)

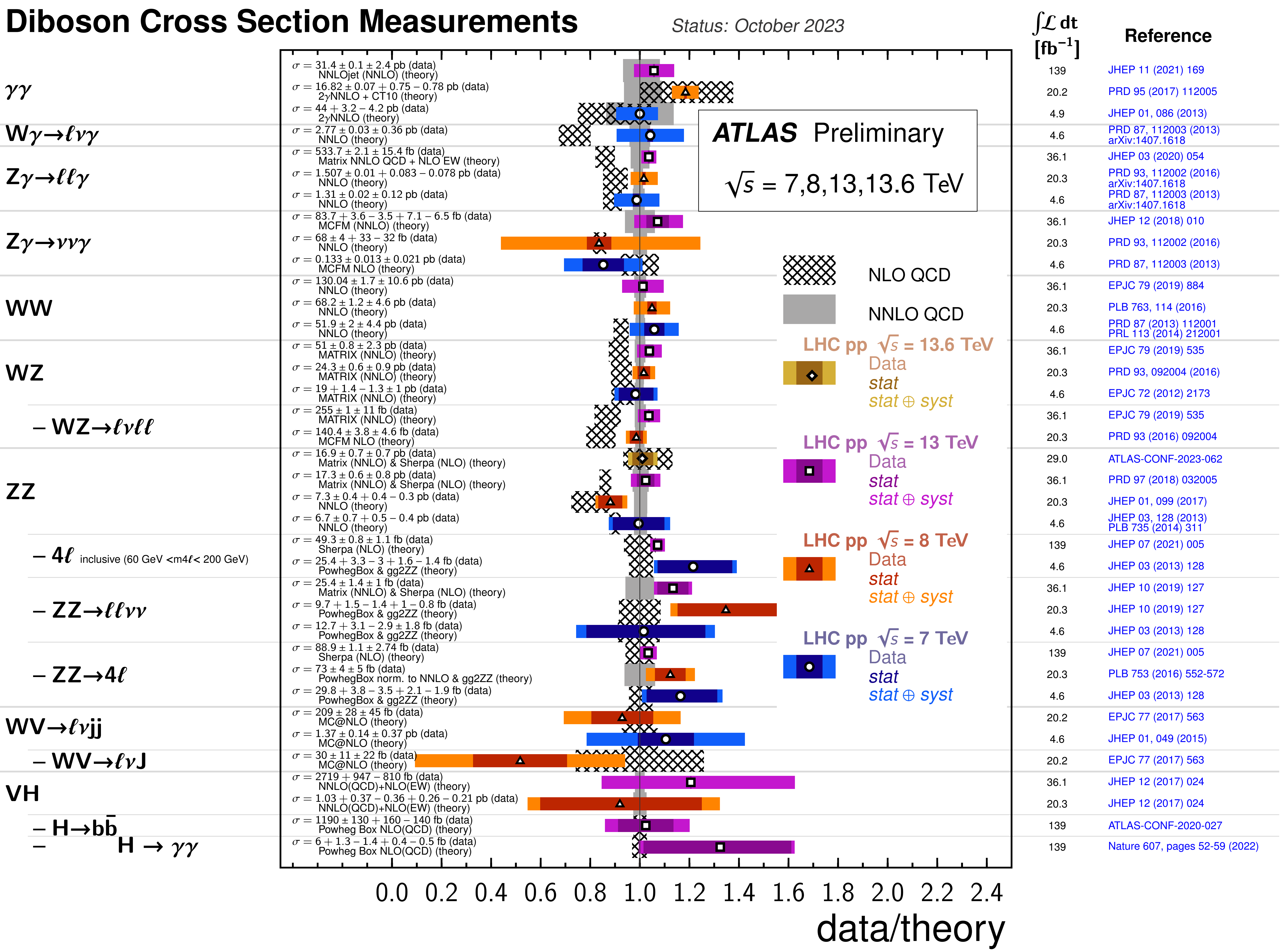
ATLAS: EW, QCD & flavour

- Extensive summary of precision single & mutiboson measurements using Run 2 13 TeV data
- Also covers:
  - Low energy strong particle production
  - High pT jet & QCD studies
  - EFT constraints on new physics
  - + more

Electroweak, QCD and flavour physics studies with ATLAS data from Run 2 of the LHC

The ATLAS Collaboration





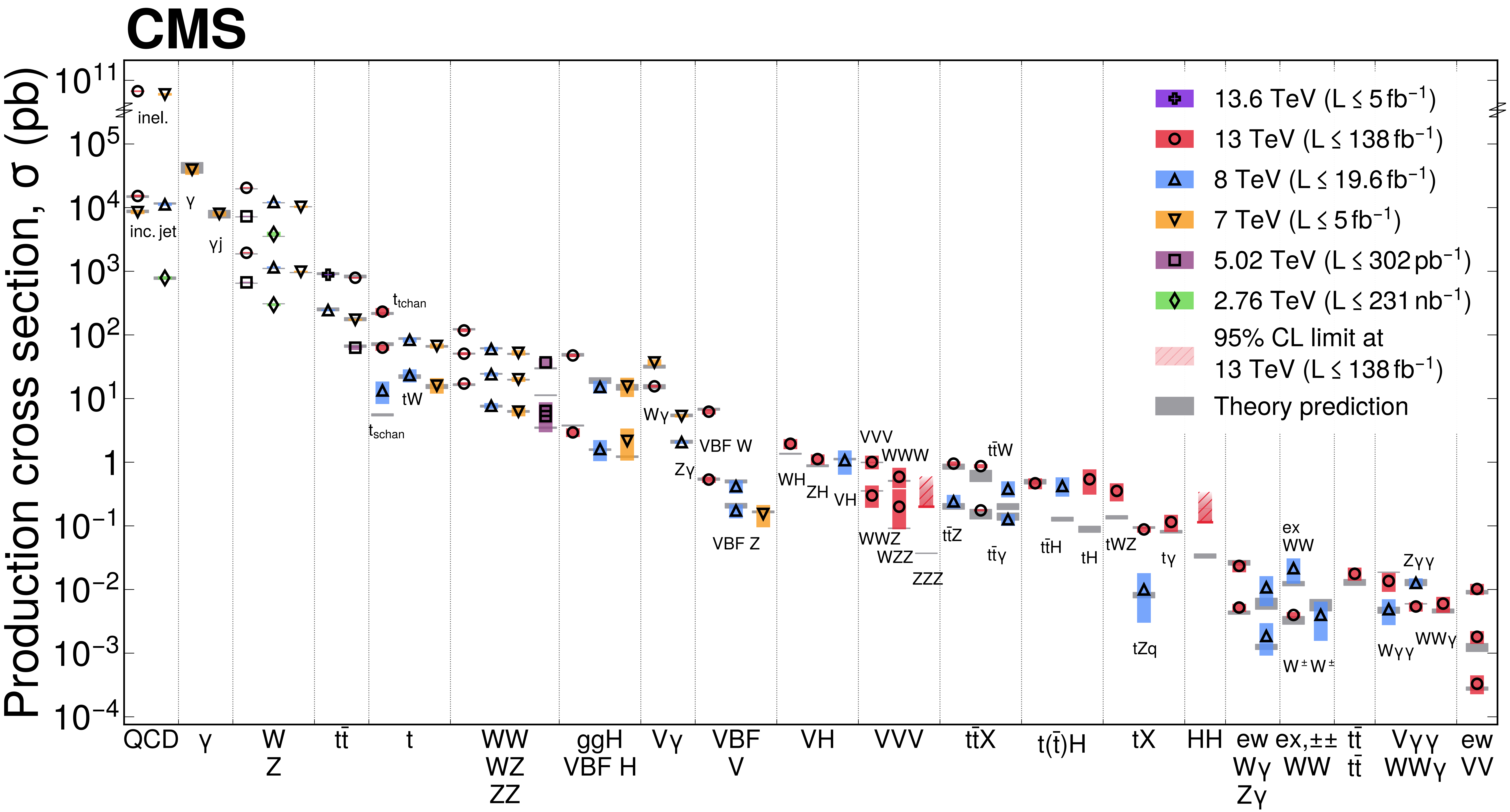
CMS cross section measurements

Stairway to discovery: a report on the CMS programme of cross section measurements from millibarns to femtobarns

The CMS Collaboration[a]

[a]CERN, Geneva, Switzerland

- Review of hadronic, EW, top and Higgs sector cross section measurements



ATLAS top quark review

arXiv:2404.10674 (submitted Phys Rept)

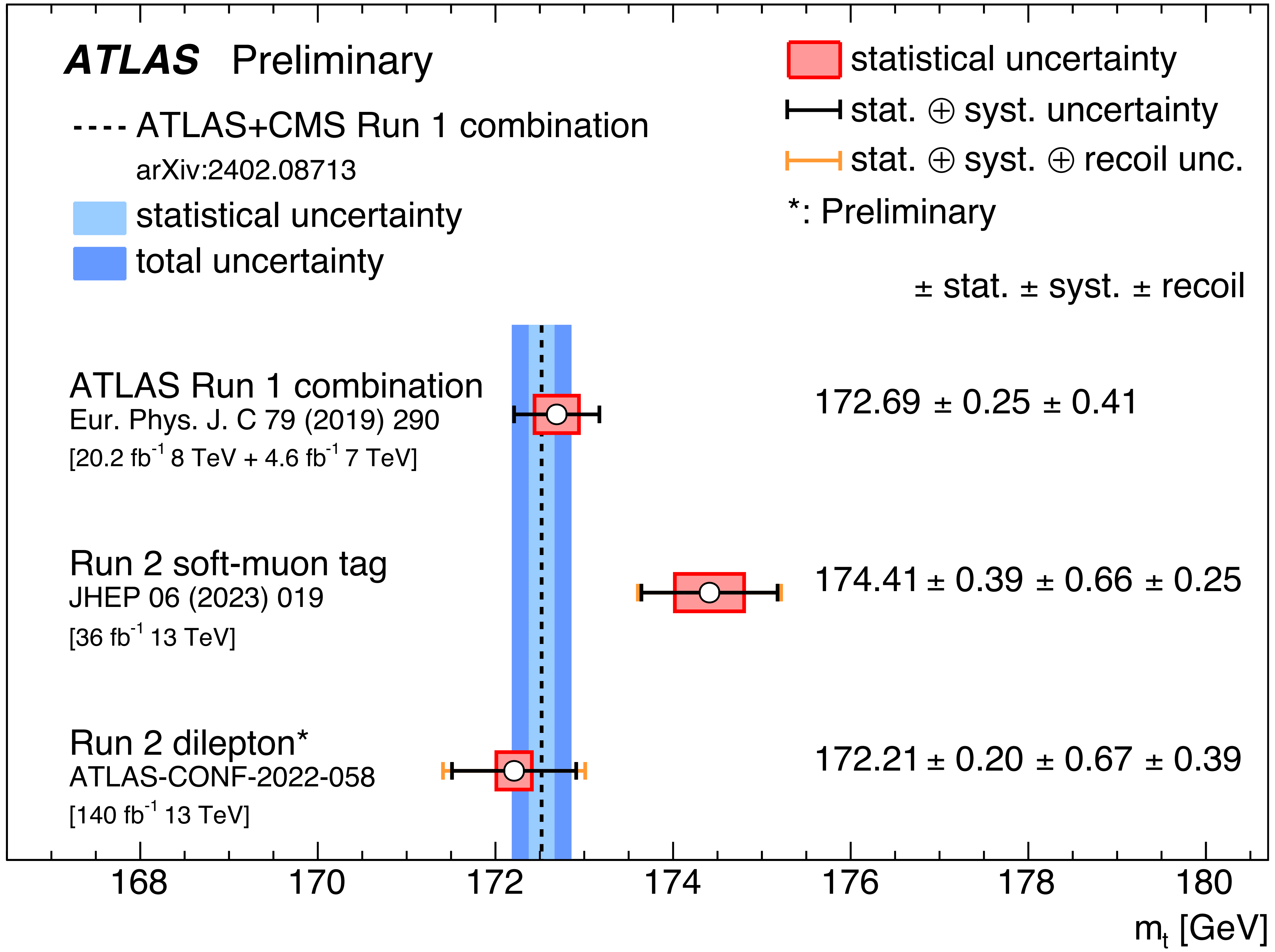
Climbing to the Top of the ATLAS 13 TeV data

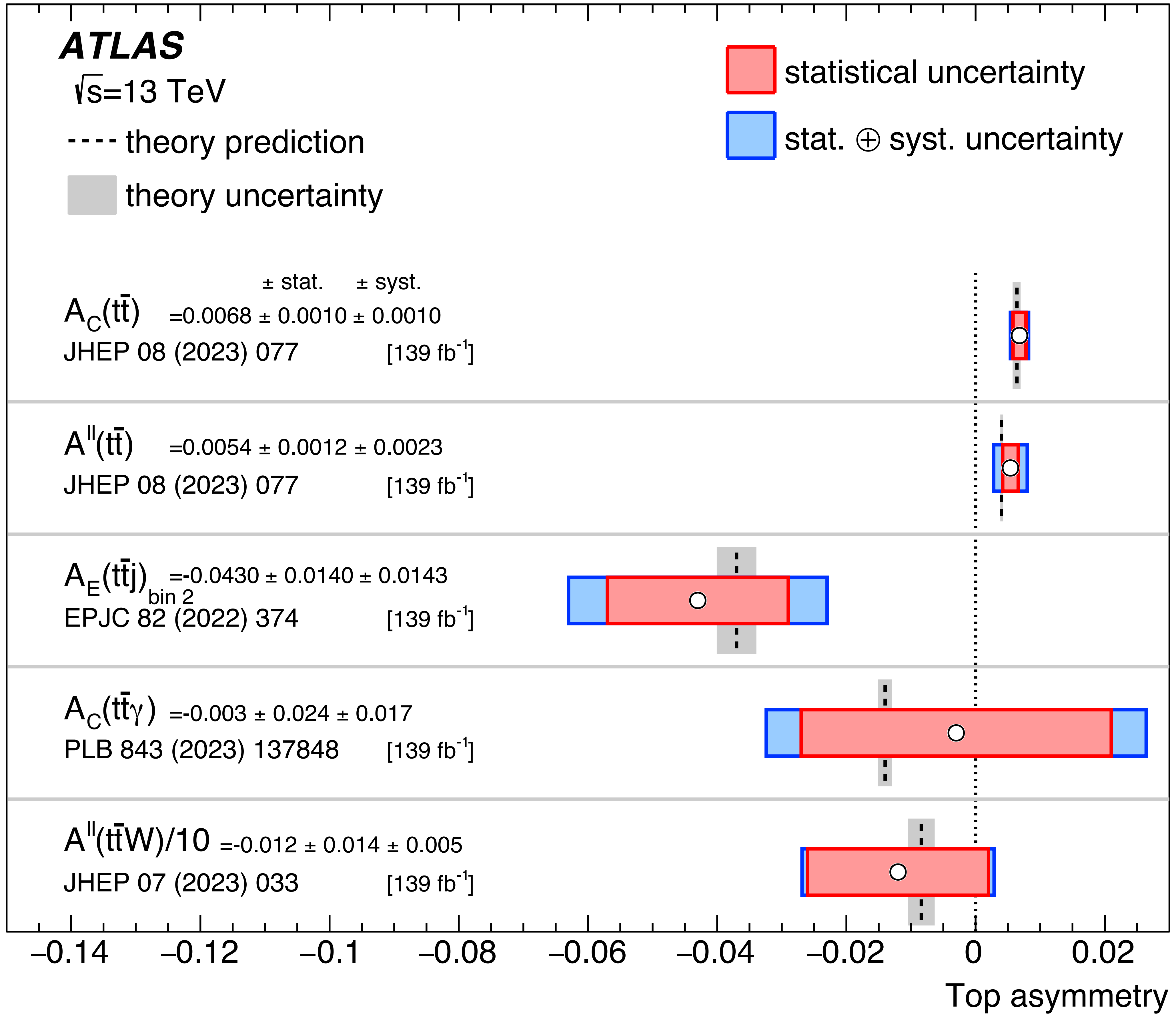
The ATLAS Collaboration

- Extensive review of top (+X) cross section, m_t measurements, entanglement, LFU tests, and more

Top asymmetry summary

Top mass summary





CMS top quark mass review

arXiv:2403.01313 (submitted Phys Rept)

Review of top quark mass measurements in CMS

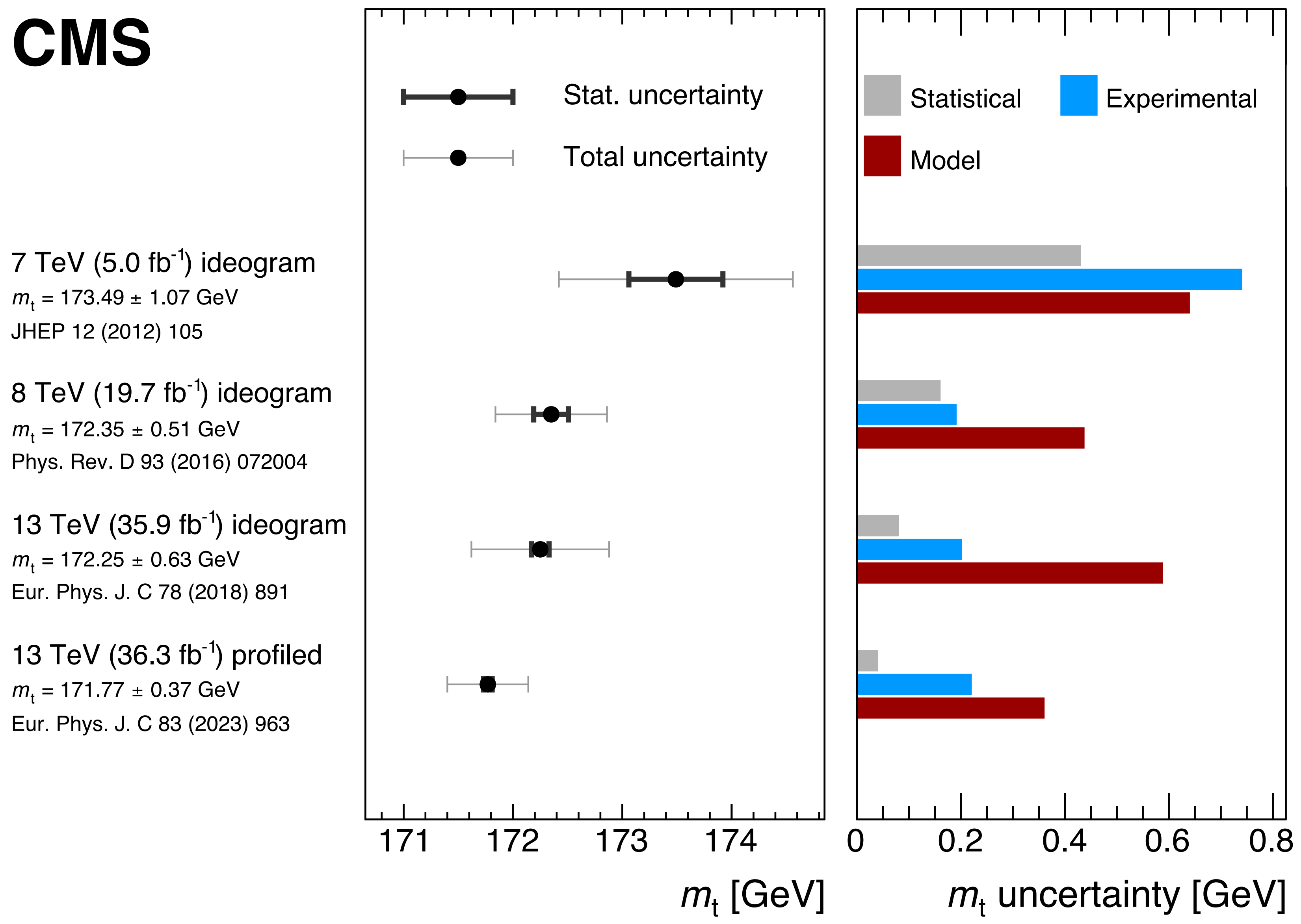
The CMS Collaboration*

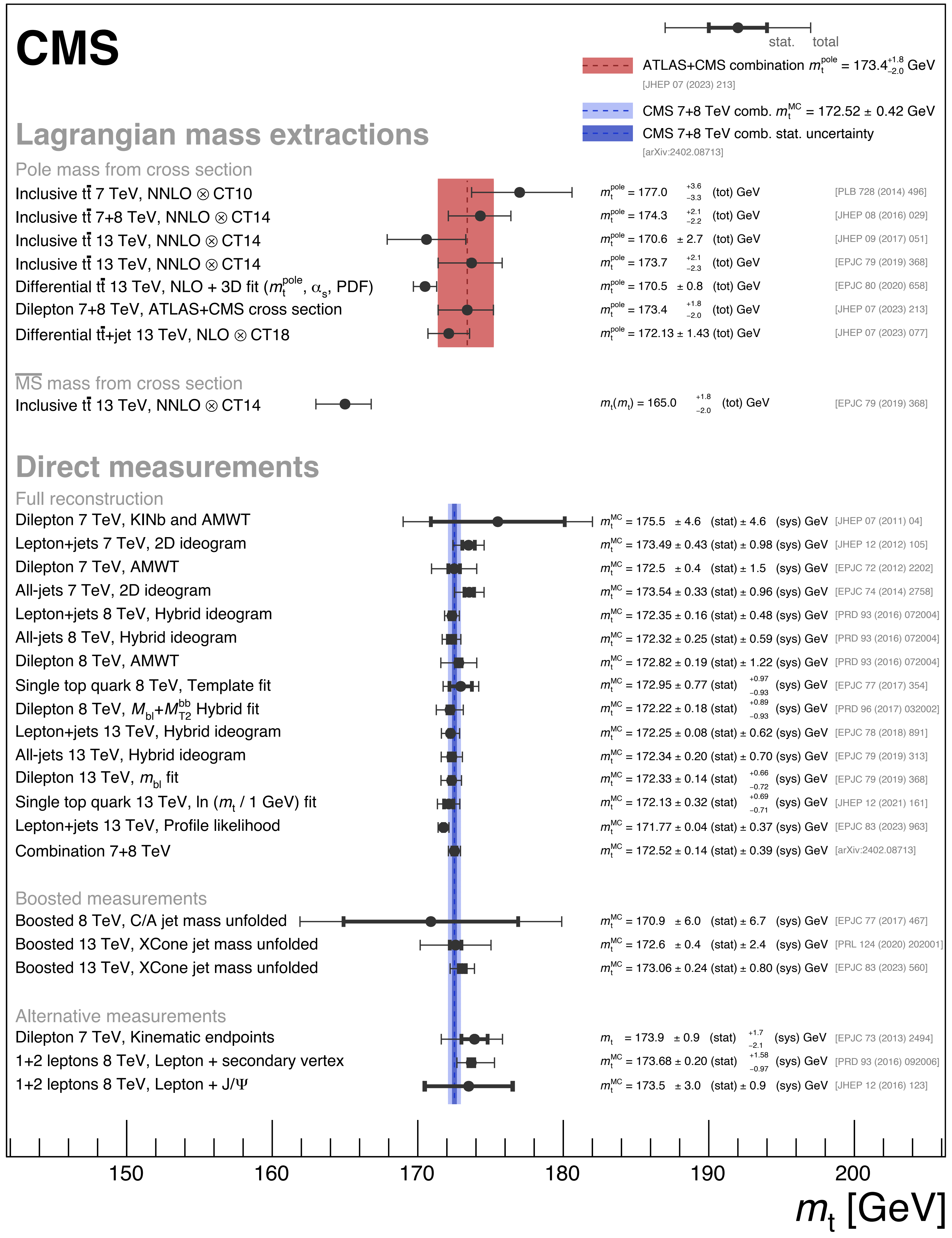
Current status

Overview of all measurement approaches

Past improvements

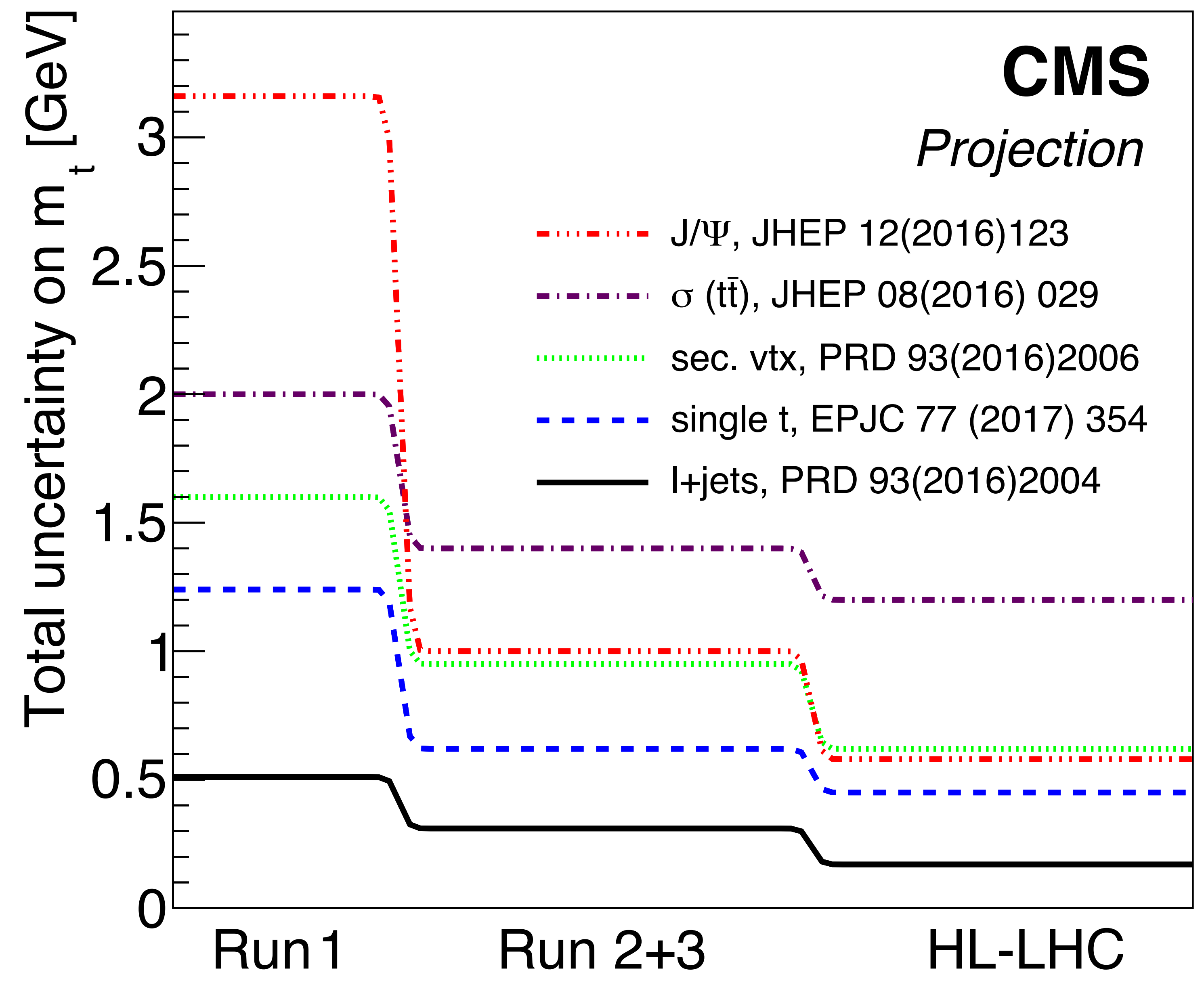
Consistent reduction in both statistical and systematic uncertainties





Review of projection studies

NB: not always taking into account detector improvements!



Summary

- The LHC has proved more than capable as a precision physics machine
  - In many cases challenging or exceeding e^+e^- collider constraints

- Future improvements may come from:
  - Better understanding / in-situ constraint of PDFs
  - Improved signal & background modelling
  - Refined detector calibrations
  - Dedicated low pileup LHC runs
  - Inter-experiment combinations

See parallel talks for more detail on these expt. topics:

Precision electroweak measurements in CMS	Yongbin Feng	Tuesday AM
Precision electroweak measurements in ATLAS	Alexander Bachiu	Tuesday AM
Recent electroweak precision measurements in LHCb	Miguel Ramos Pernas	Tuesday AM
Rare decays of electroweak bosons at CMS and ATLAS	Keith Ulmer	Tuesday PM
ATLAS results on top spin and entanglement	Baptiste Ravina	Wednesday AM
CMS results on top spin correlations and entanglement	Regina Demina	Wednesday AM
ATLAS top quark mass measurements	Thomas Mclachlan	Friday PM