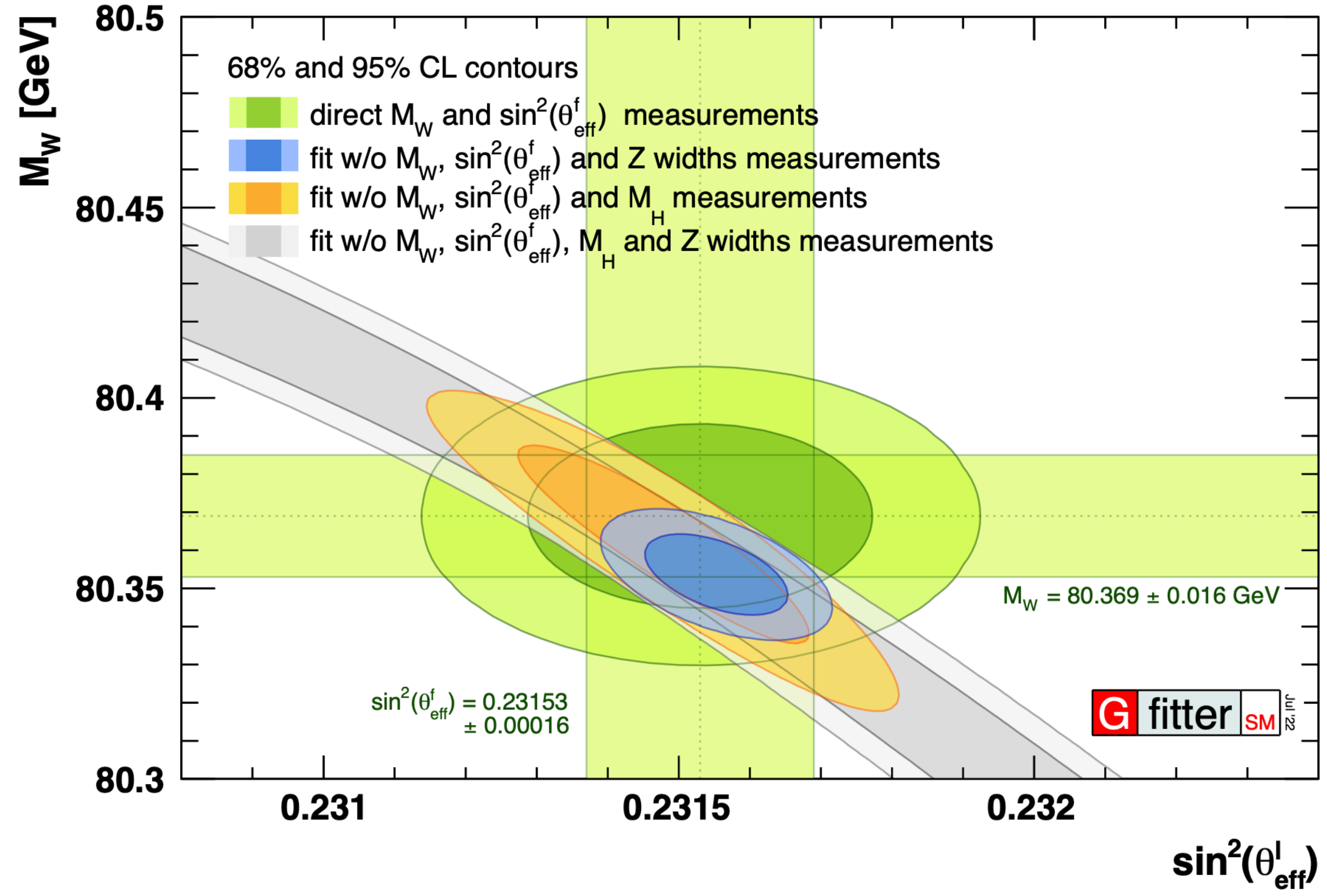
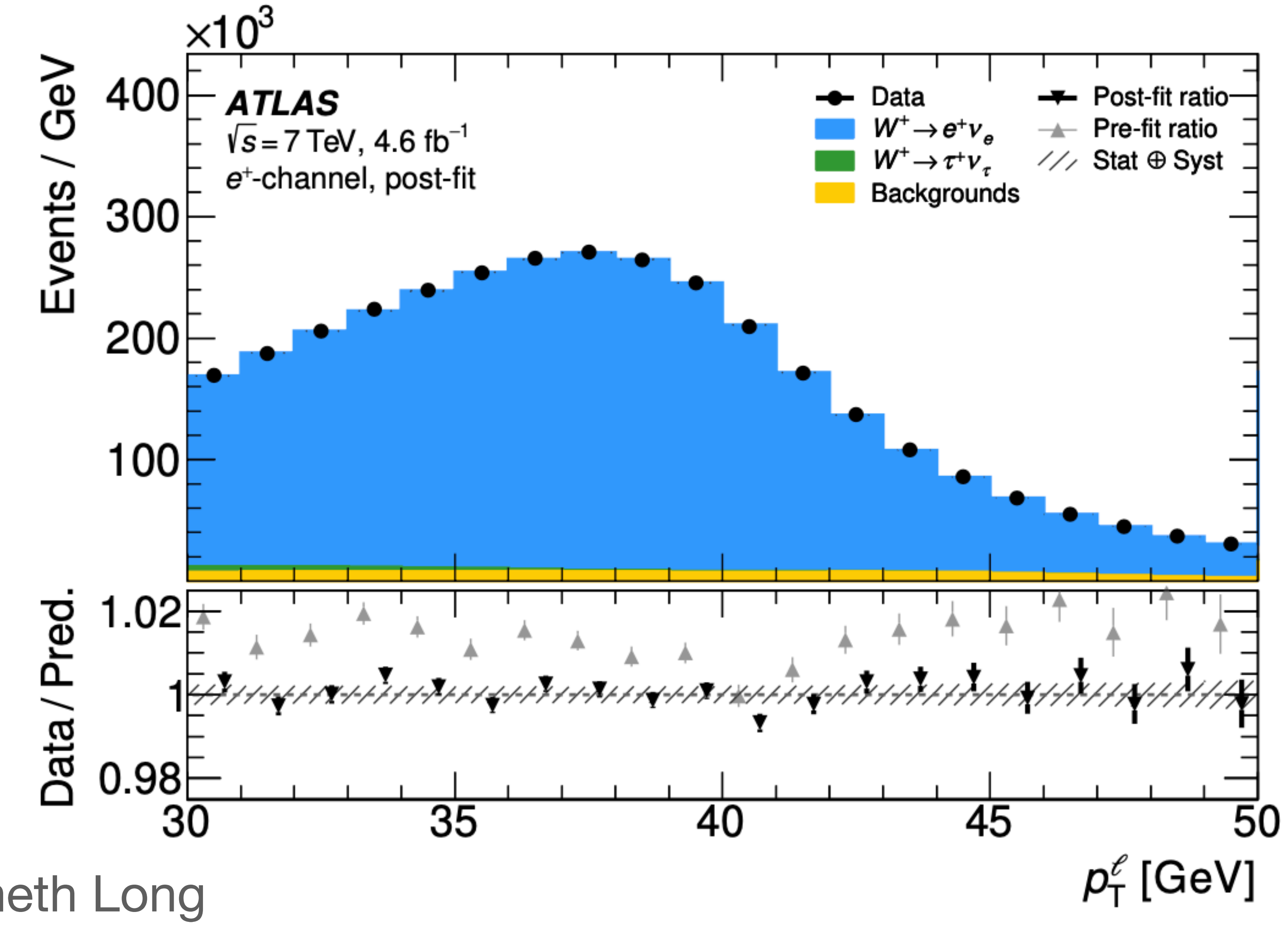
Recent electroweak single boson (W/Z) results from ATLAS and CMS

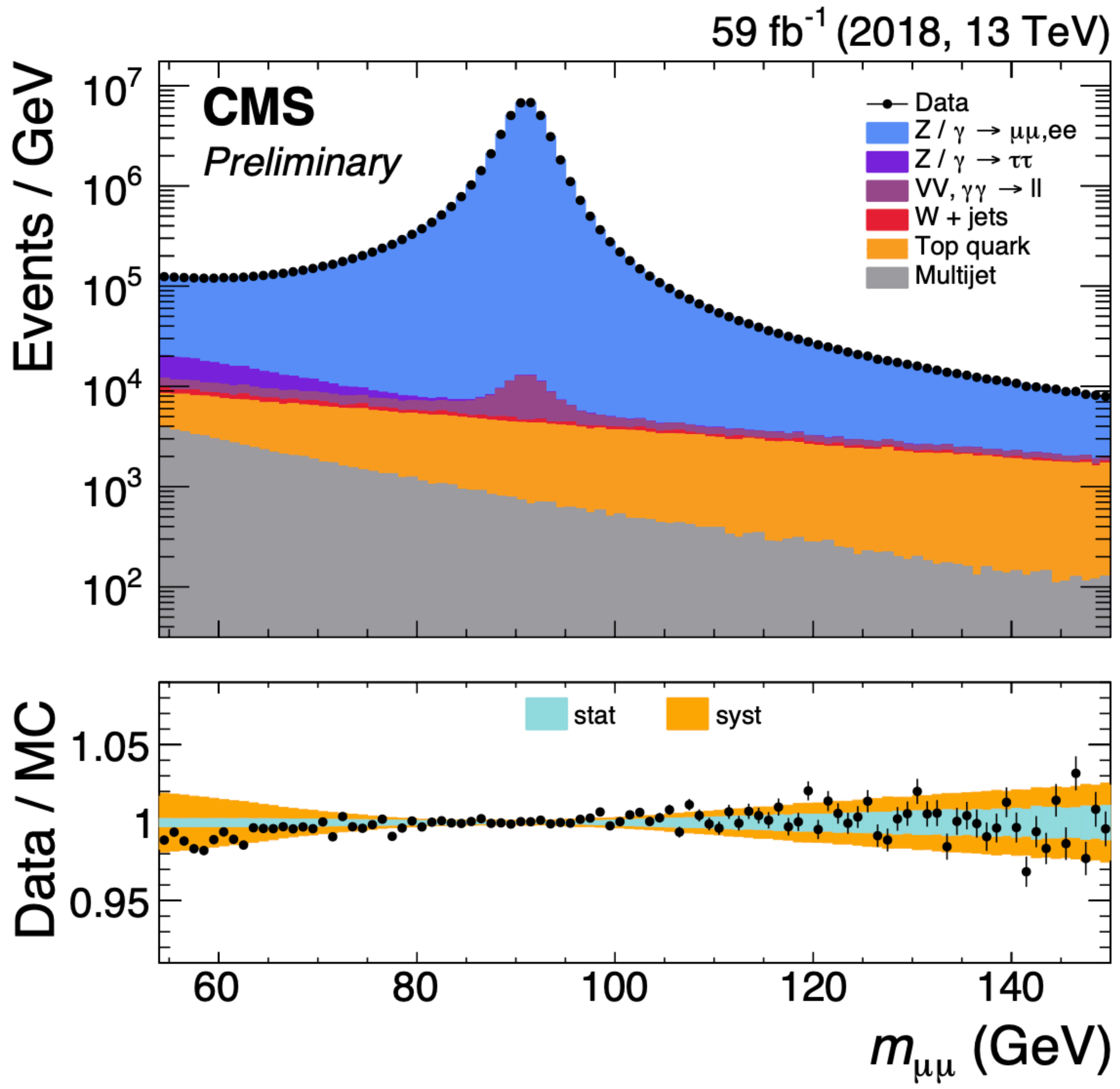
Kenneth Long for the ATLAS and CMS Collaborations

Introduction

- Electroweak theory **extremely successful** over vast scales
- Some parameters are fundamentally experimental
  - but precise **relationships predicted by SM**
- Huge samples of W and Z boson production at LHC enable studies of SM self consistency, tests of pQCD: *O*(billion) event data sets
- Building **percent-level measurements** takes time
  - Still a lot to learn from Run 2 (or 1) data
  - New measurements in Run 3 are arriving
  - Huge value in special runs (low pileup)







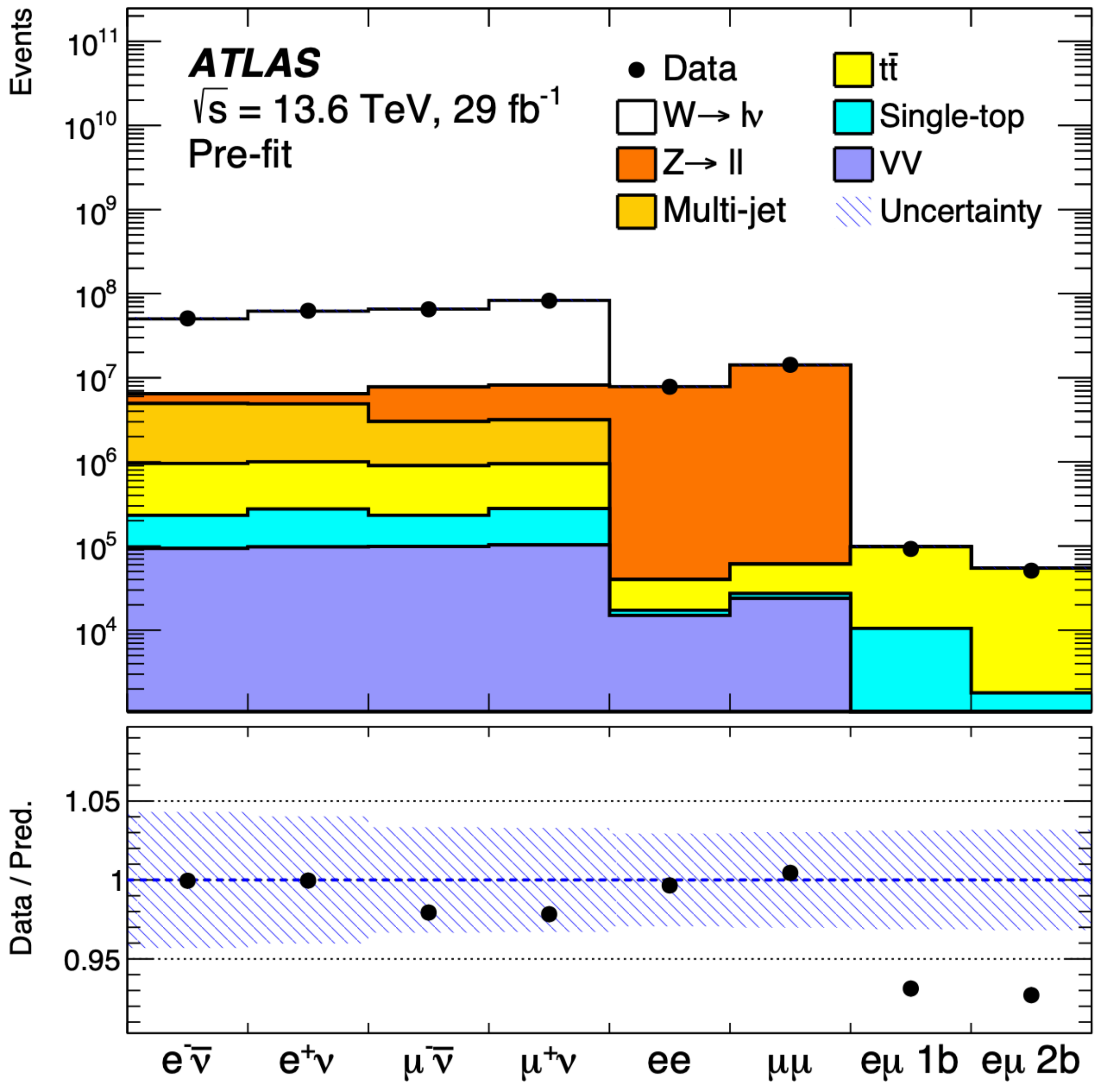
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r)$$

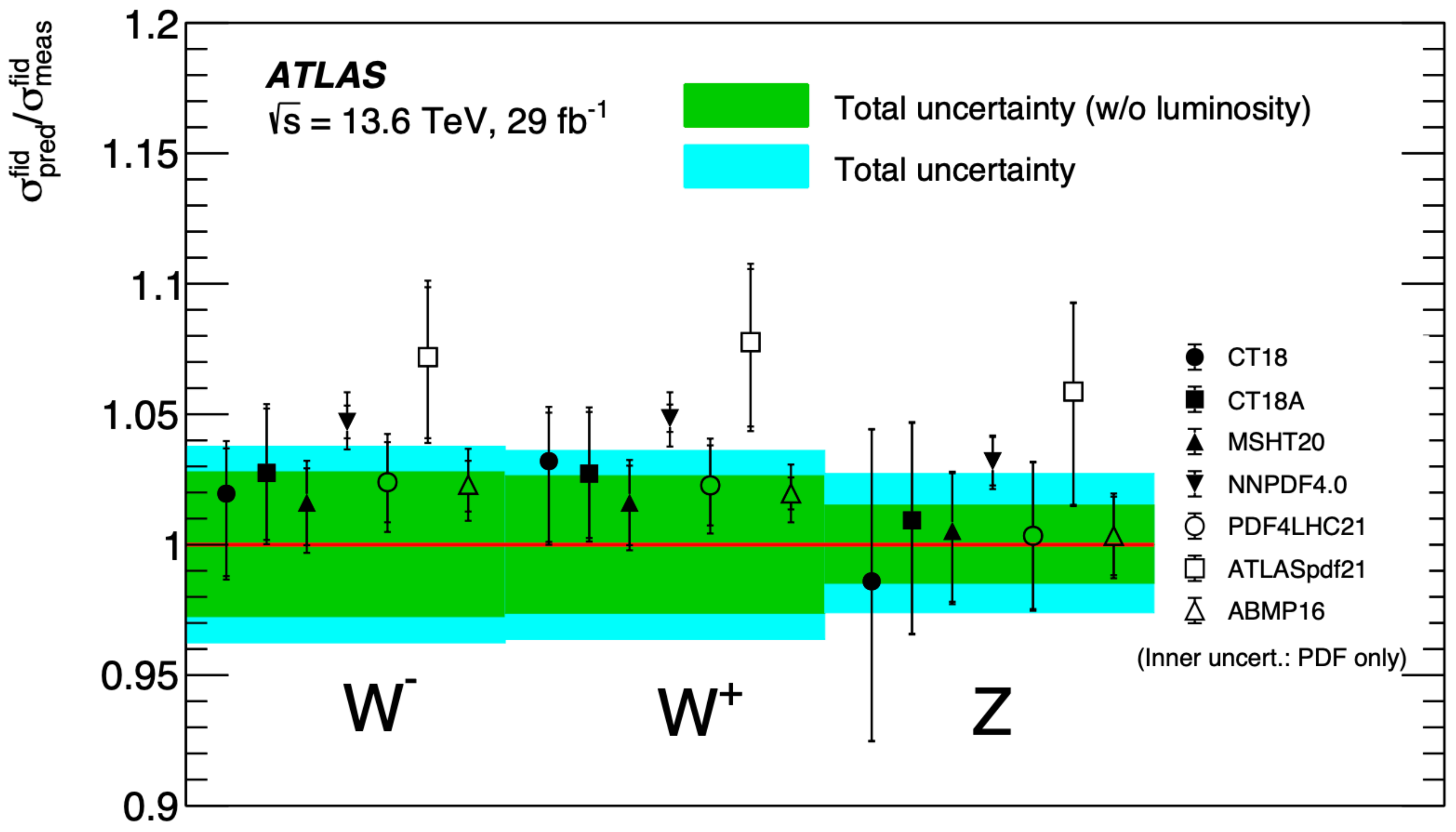
Higher-order corrections (Δr) depend on m_t, m_H, … m_{BSM}?

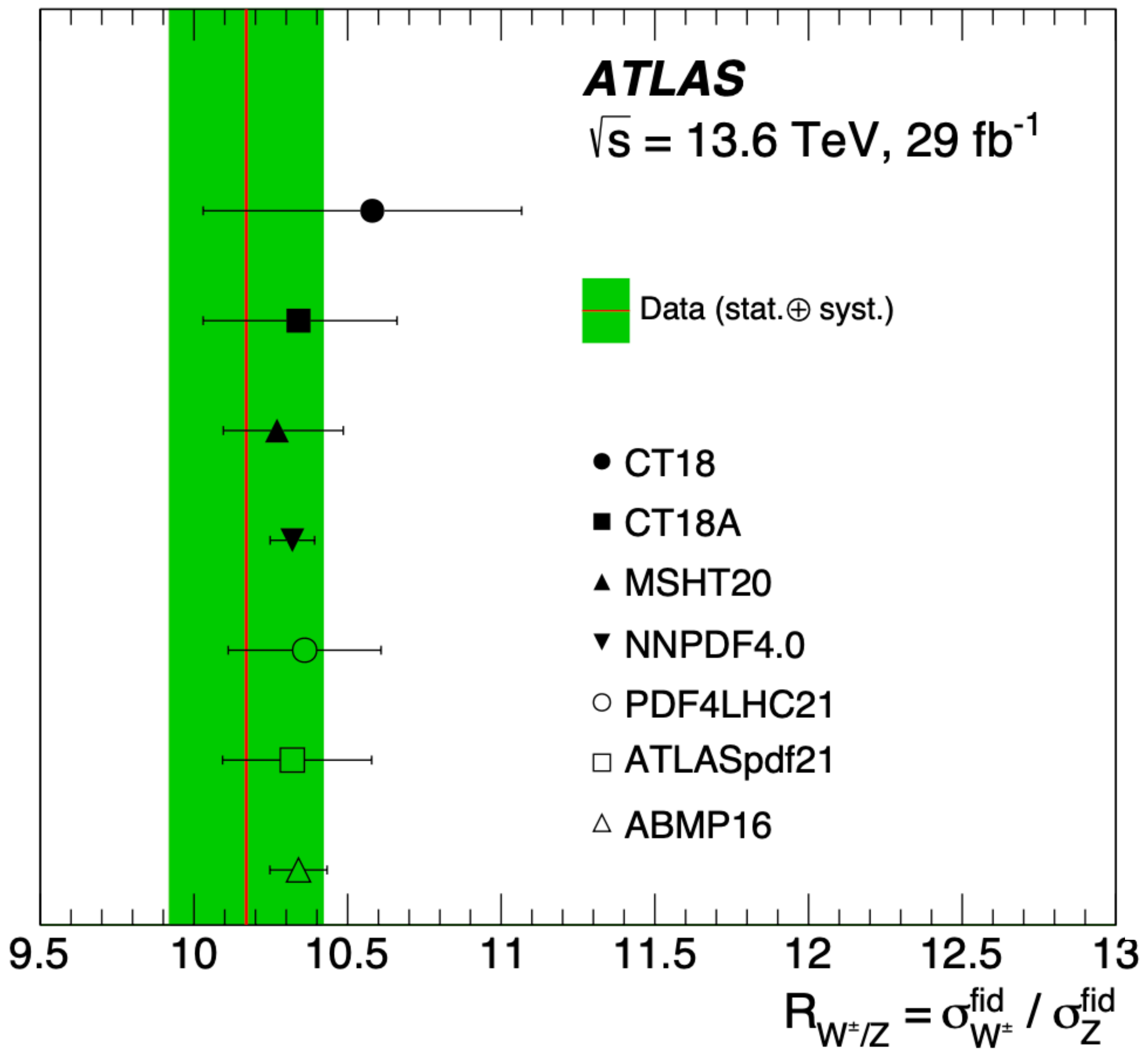
W and Z cross section measurements: 13.6 TeV (*New*)

arxiv:403.12902

- Cornerstone of experimental program. **New opportunities at 13.6 TeV**
  - Test of perturbative calculations, important input for PDFs
  - *Experimentally challenging!* e.g., estimation of non-prompt backgrounds for W
- New **measurement of σ_W and σ_Z and ratio at 13.6 TeV** from ATLAS
  - Prod. ratios directly extracted from simultaneous fit to W/Z/tt
  - Nonprompt estimated by extrapolating track isolation in m_T and p_T^{miss}
  - Lumi dominates absolute σ, nonprompt and lepton reco. for ratio
  - **Dedicated talk by M. Marinescu tomorrow**
- Measurement of **σ_Z at 13.6 TeV also performed at CMS** (CMS-SMP-22-017)







Channel	$\sigma^{\text{fid}} \pm \delta\sigma_{\text{stat}\oplus\text{syst}}$ [pb]
$Z \rightarrow e^+e^-$	740 ± 22
$Z \rightarrow \mu^+\mu^-$	747 ± 23
$Z \rightarrow \ell^+\ell^-$	744 ± 20

ATLAS

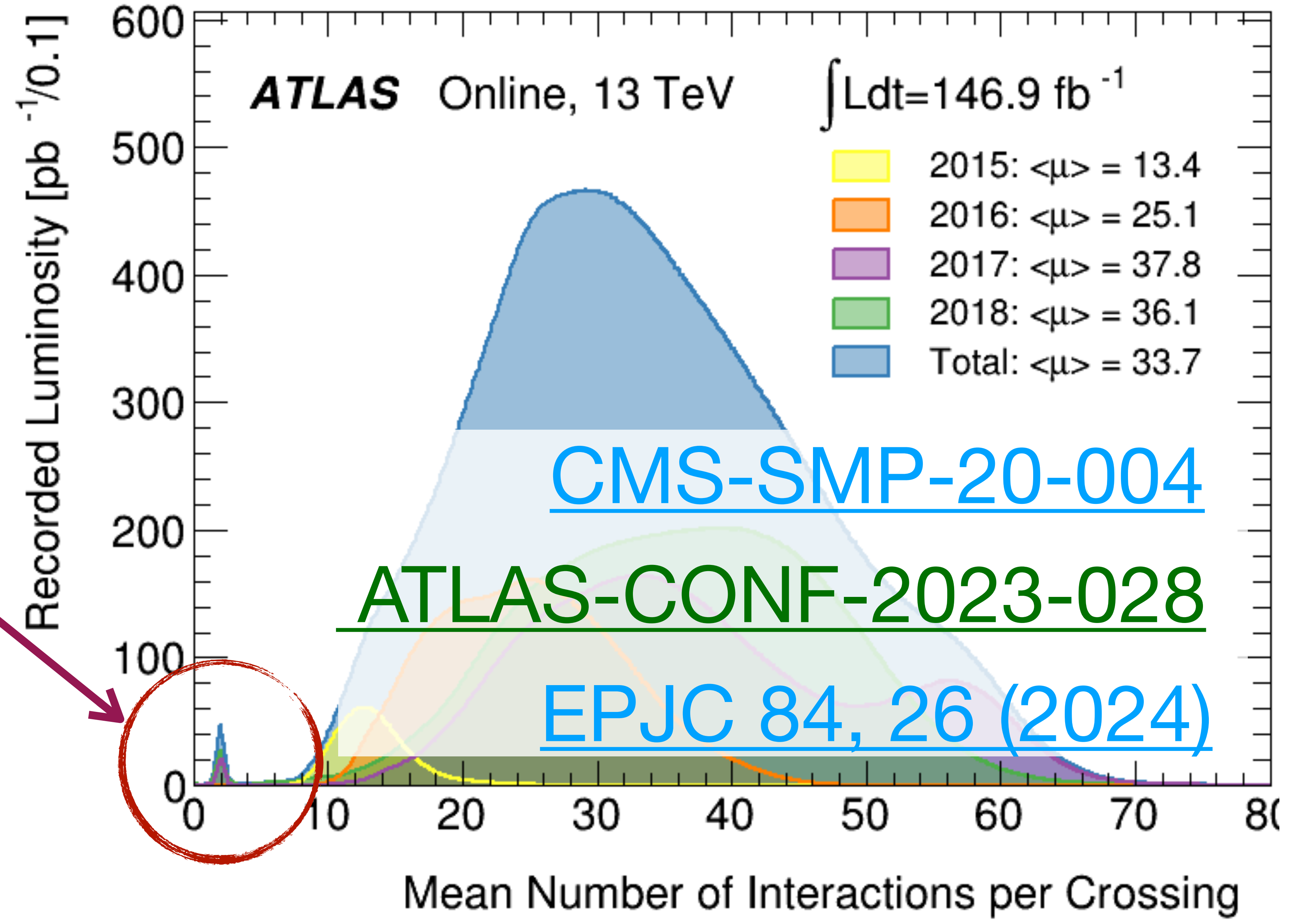
$$\sigma_{\text{pred.}} = \frac{\sigma^{\text{fid}} \pm \delta\sigma_{\text{stat}} \pm \delta\sigma_{\text{scale}} \pm \delta\sigma_{\text{PDF}}\ [\text{pb}]}{746.1^{+0.1\%\,+0.4\%\,+2.8\%}_{-0.1\%\,-0.6\%\,-2.8\%}}$$

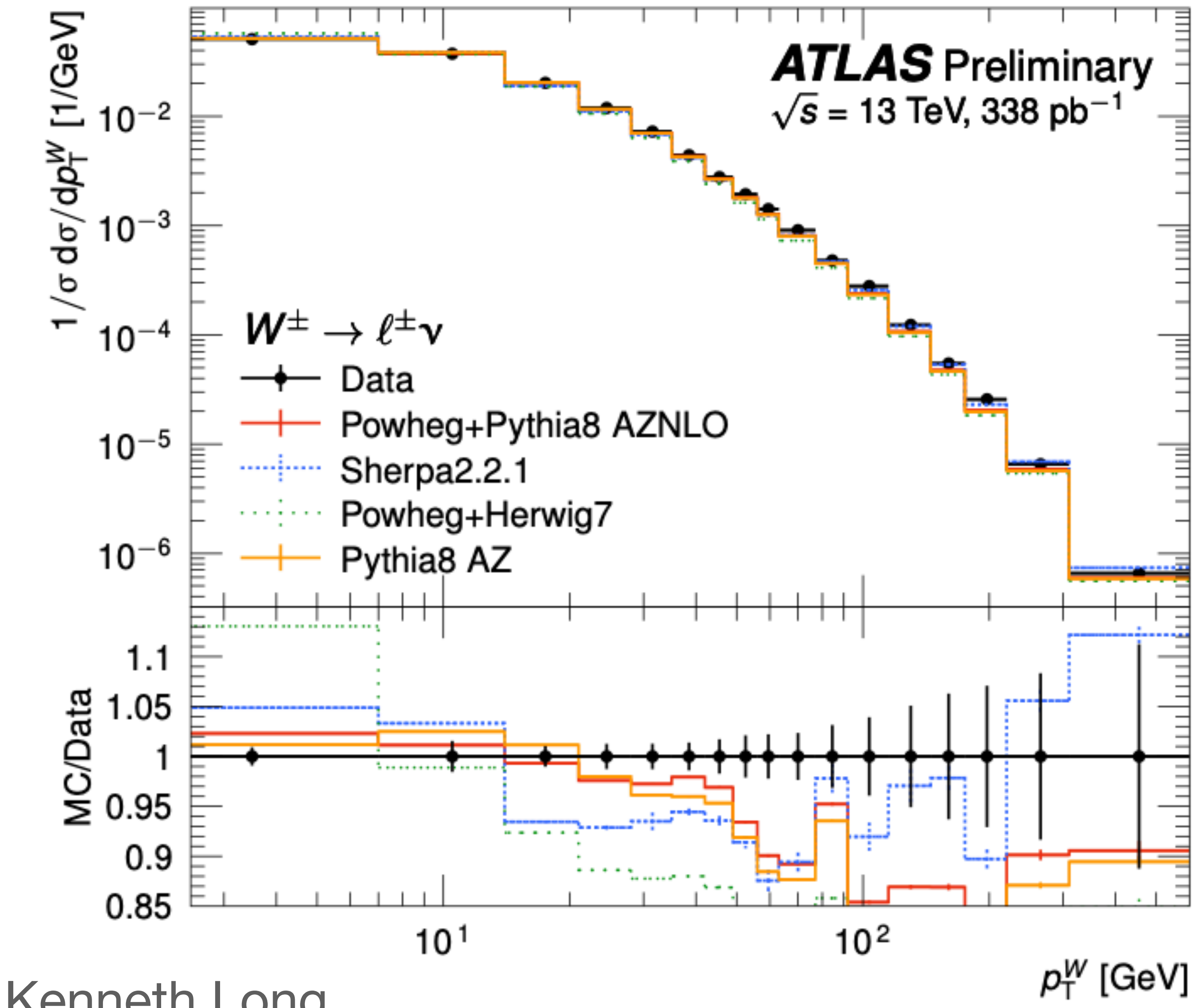
$$(\sigma_{\text{fid}}\mathcal{B})_{\text{measured}} = (0.7635 \pm 0.0004(\text{stat}) \pm 0.0069(\text{syst}) \pm 0.0176(\text{lumi}))\ \text{nb},$$
$$(\sigma_{\text{fid}}\mathcal{B})_{\text{predicted}} = (0.7666 \pm 0.0065(\text{PDF})^{+0.0021}_{-0.0045}(\text{scale}))\ \text{nb},$$

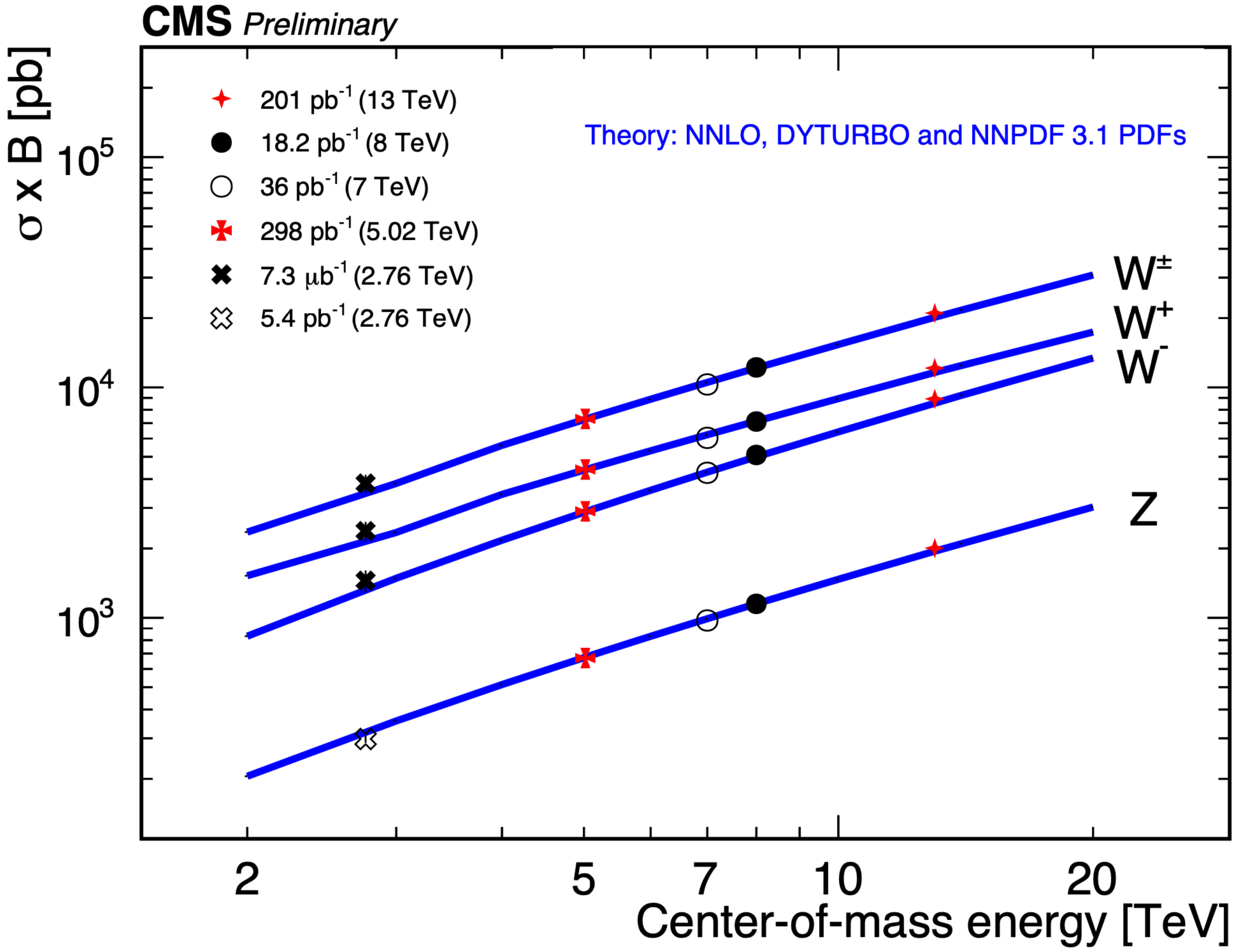
CMS

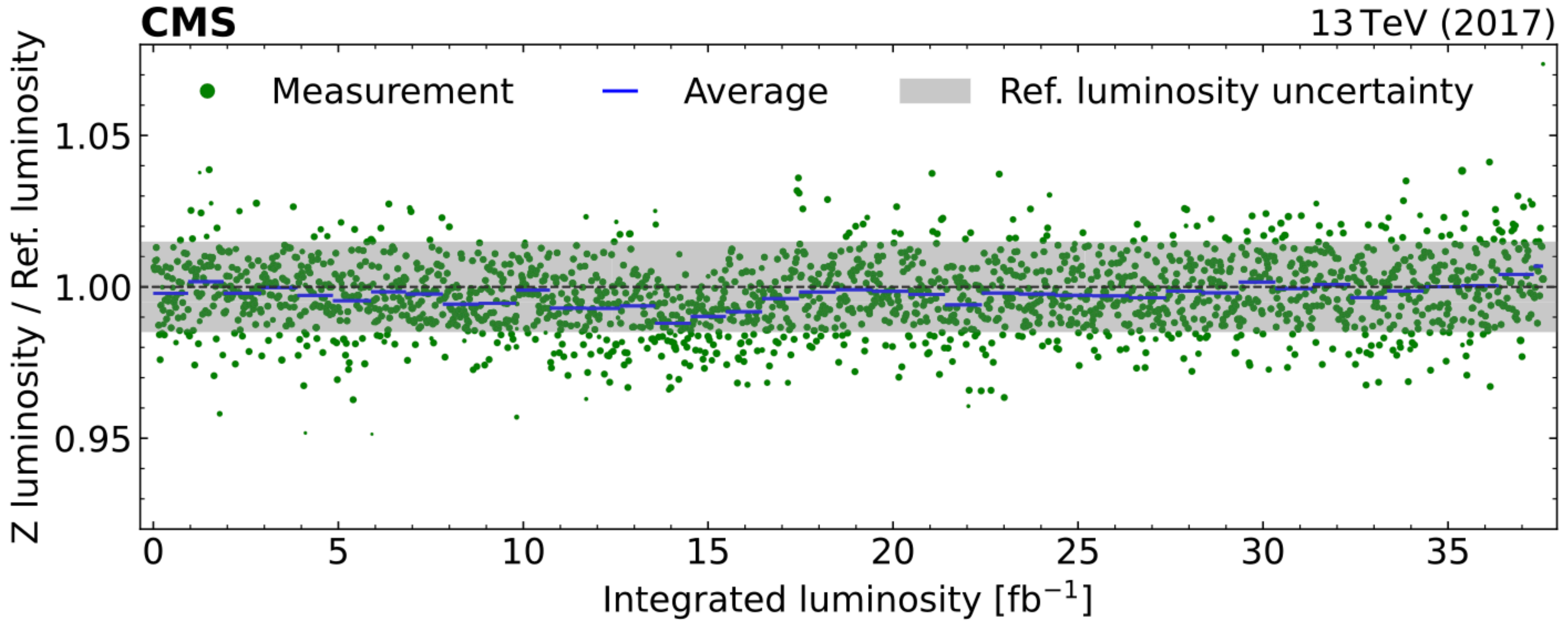
W and Z measurement in special LHC runs: 5 and 13 TeV

- “**Special” LHC runs** have strong value for W/Z measurements
- Lower pileup allows lower trigger and reco thresholds and lower degradation of pileup-impacted variables (**especially W recoil, m_T^W**)
- Measurements performed by ATLAS and CMS using ~2-350 pb^{-1} of low PU 13 TeV data + ~300 pb^{-1} of 5 TeV data (HI reference runs)
  - Precise measurements of σ, ratios, and energy scaling
  - Differential **measurements validate p_T^W modeling** (for m_W)
- Could play **important role in LHC precision SM program** in future









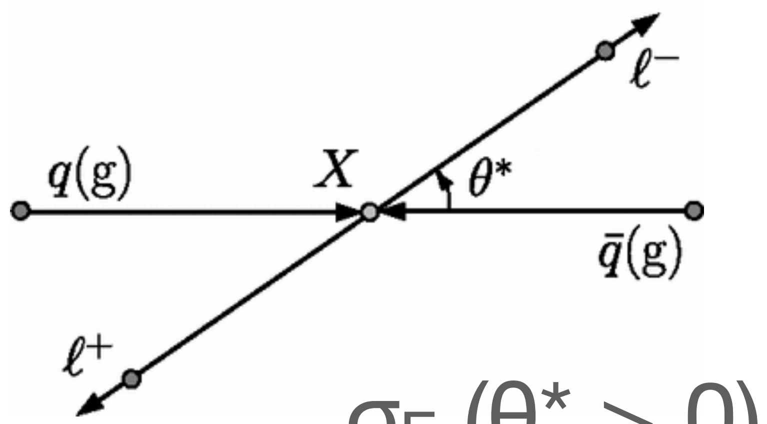
- CMS Z counting lumi monitoring uses low pileup as reference
- High precision, valuable feedback to measurement

Electroweak precision: Measurement of $\sin\theta^{\ell}_{eff}$ at CMS (***NEW***)

- Drell-Yan angular properties, non-zero A_{FB} arise from different Z/γ* vector/axial couplings, interference
  - $\sin^2\theta^{\ell}_{eff} := \kappa_F(1 - m^2_W/m^2_Z)$
    - Modification impacts A_{FB}, angular distributions
  - **New CMS measurement**: reconstructed A_{FB}, $\cos\theta^*$; unfolded A_4
- Extreme experimental challenge
  - include electrons outside of tracking/only in forward calor. (h)
  - **|η| acceptance up to 4.36**, increase sensitivity to A_{FB}
- **Best hadron collider measurement**, approaching LEP and SLD sensitivity
  - PDF unc. dominates (nom. CT18Z)
- **In-depth look will be presented in wildcard talk** by A. Khukhunaishvili later today

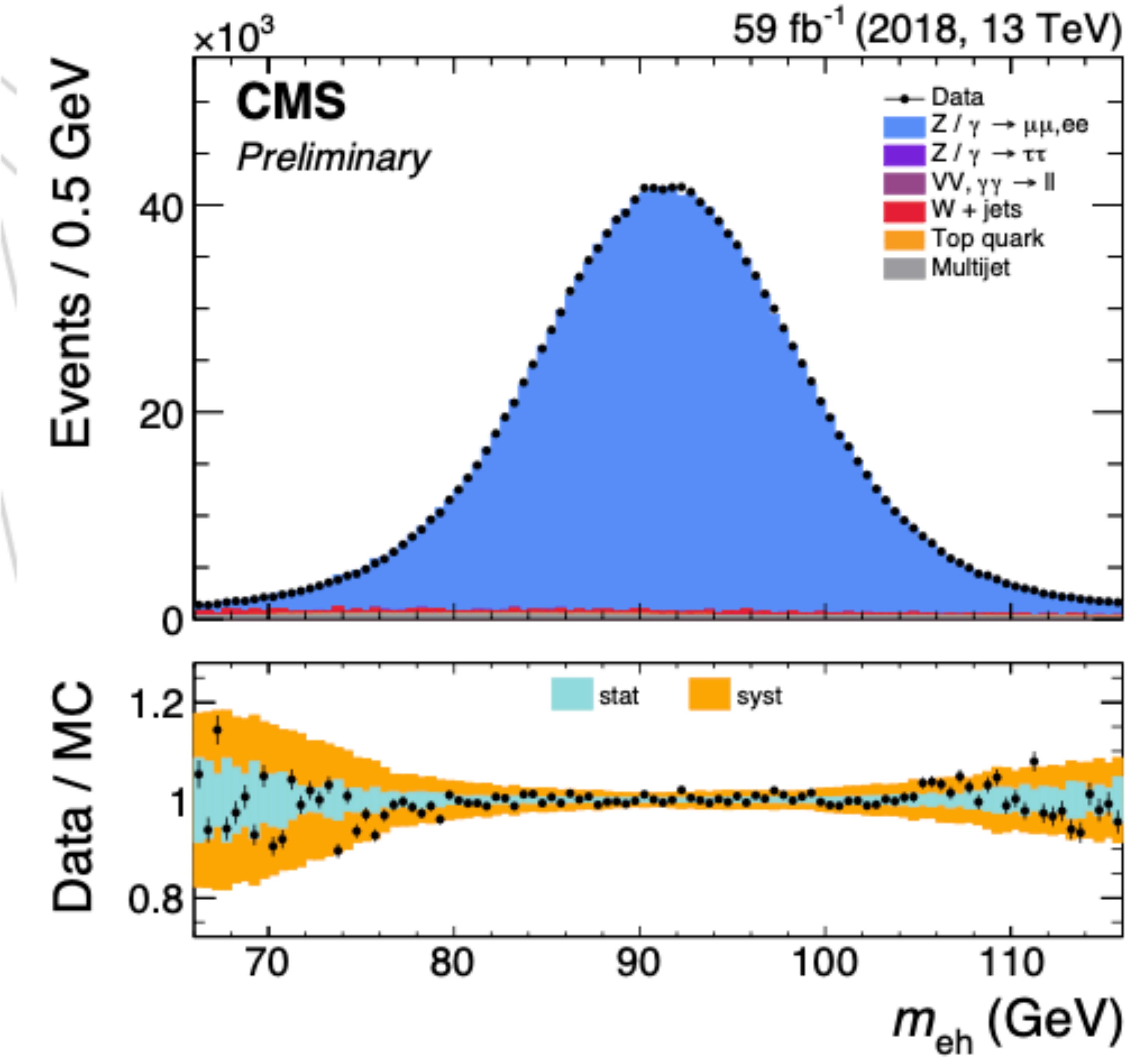
$$\frac{d\sigma}{d\cos\theta^*} = C\left[\frac{3}{8}\left(1+\cos^2\theta^*\right) + A_{FB}\cos\theta^*\right]$$

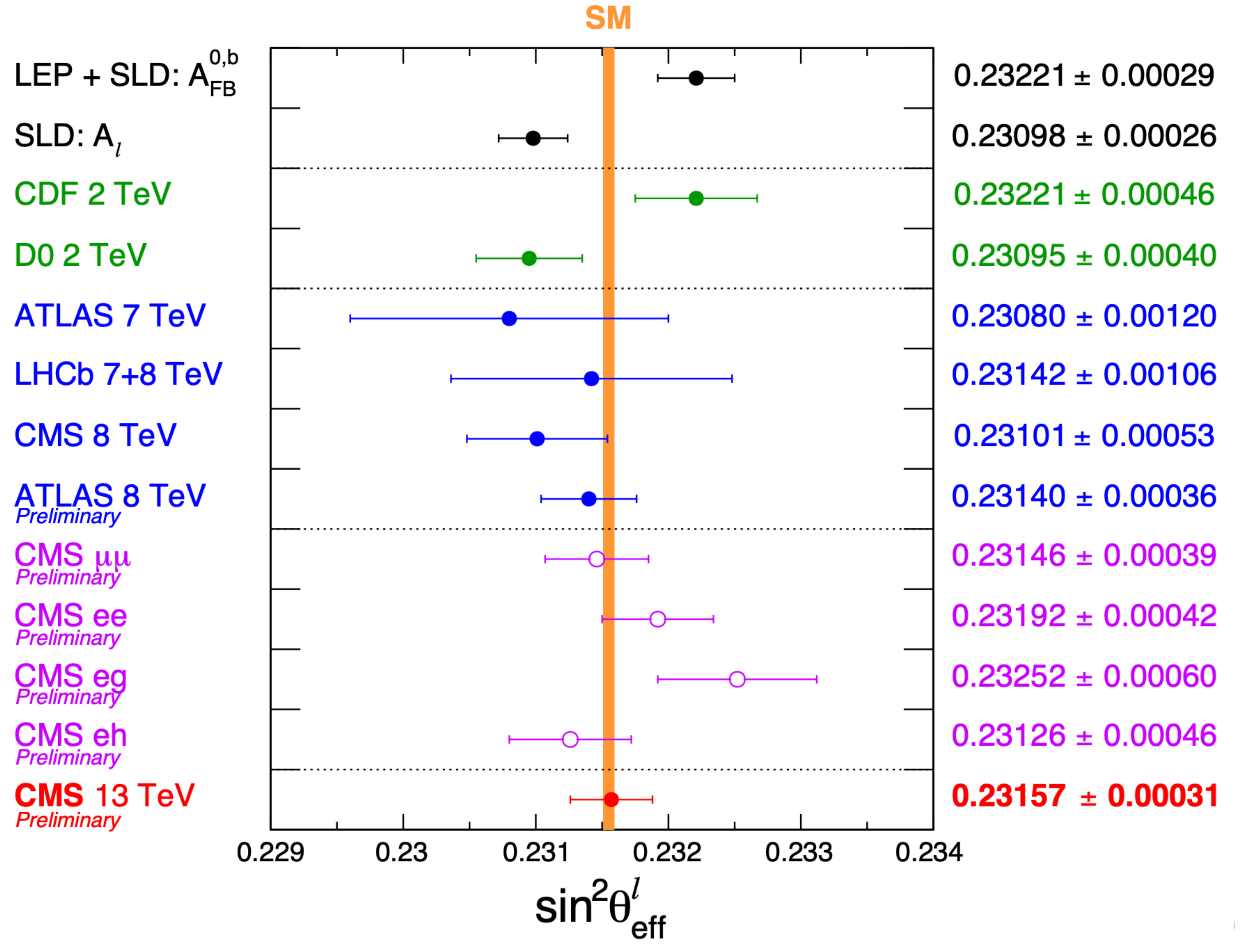
Axial vector/ vector interf.



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

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





$$\sin^2\theta^{\ell}_{\rm eff} = 0.23157 \pm 0.00031$$ (0.00027 from PDF)

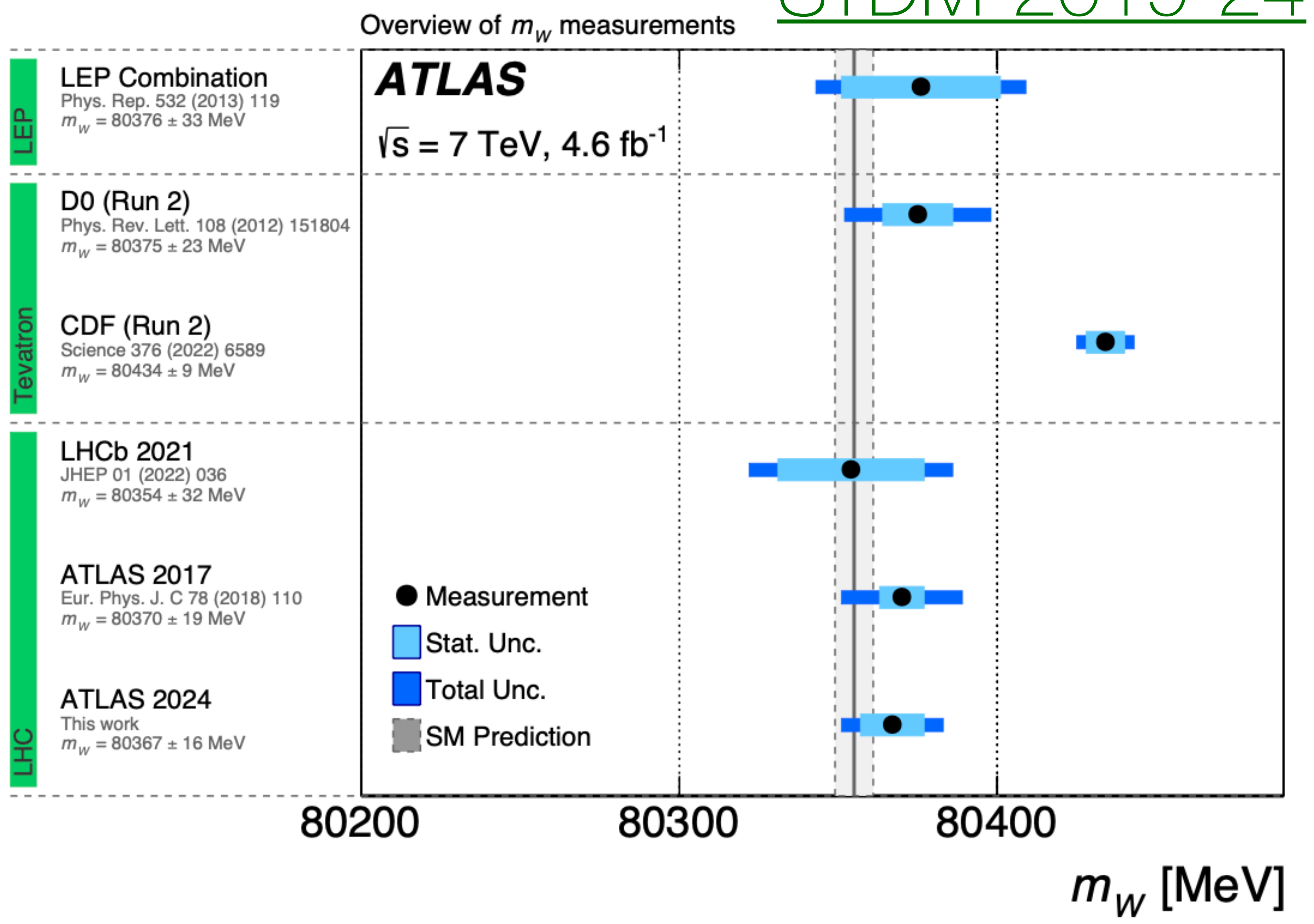
0.23155 ± 0.00004 (EW fit expectation)

CMS-SMP-22-010

Electroweak precision: m_W and Γ_W at ATLAS (***New***)

STDM-2019-24

- Measuring m_W **is a major challenge at hadron colliders**
  - Most precise measurement from CDF is in strong tension with EW fit and other experimental results
- Update of ATLAS m_W analysis shown 1 year ago, in agreement with SM
  - Updated for publication with **extended studies of PDF**
  - +6.5 MeV shift in m_W wrt preliminary due to Γ_W constraint (EW fit unc.)
  - Impact of PDF profiling demonstrated by inflating pre-fit unc.
    - Increased PDF priors lead to less PDF-model-dependence

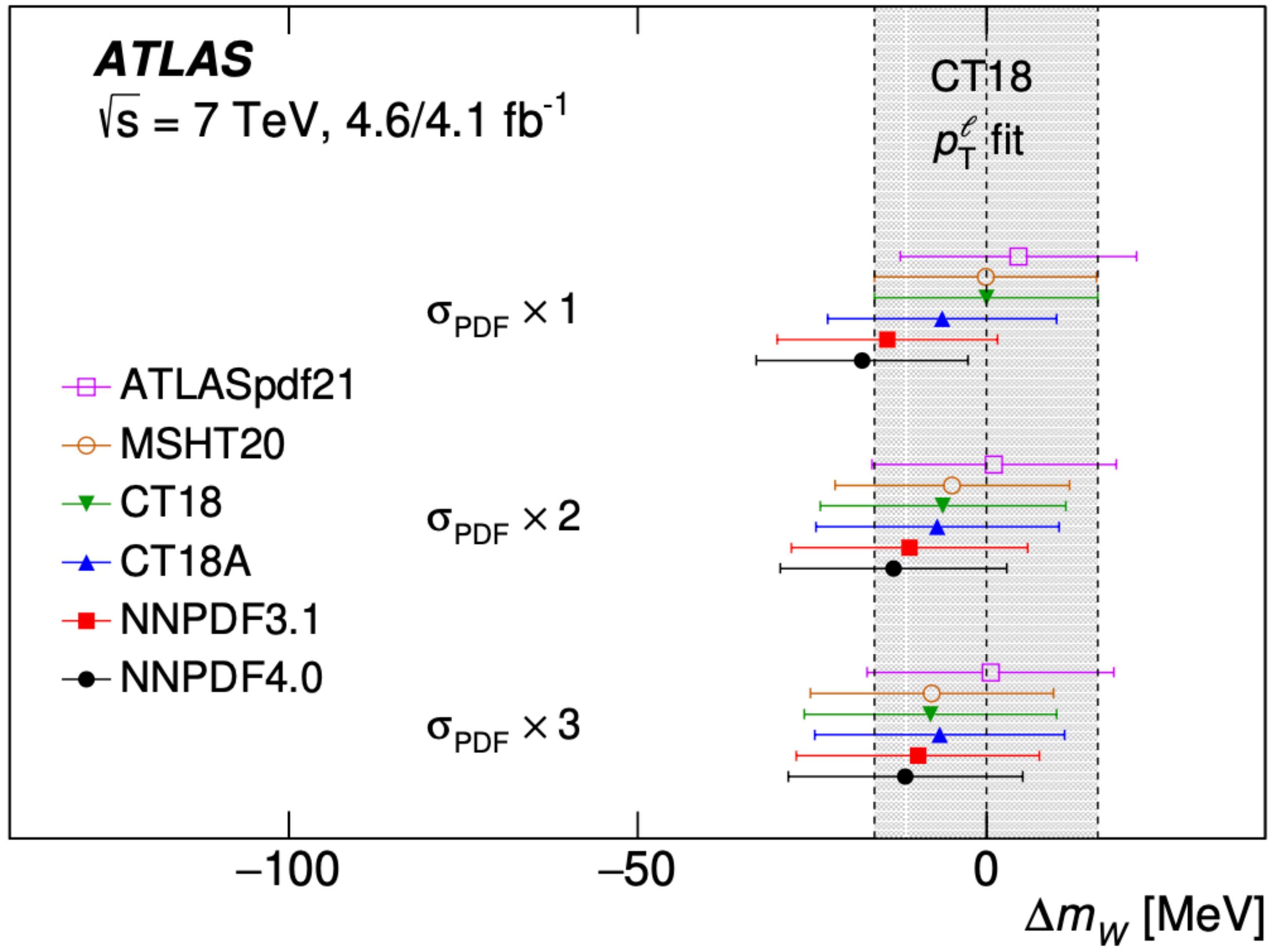


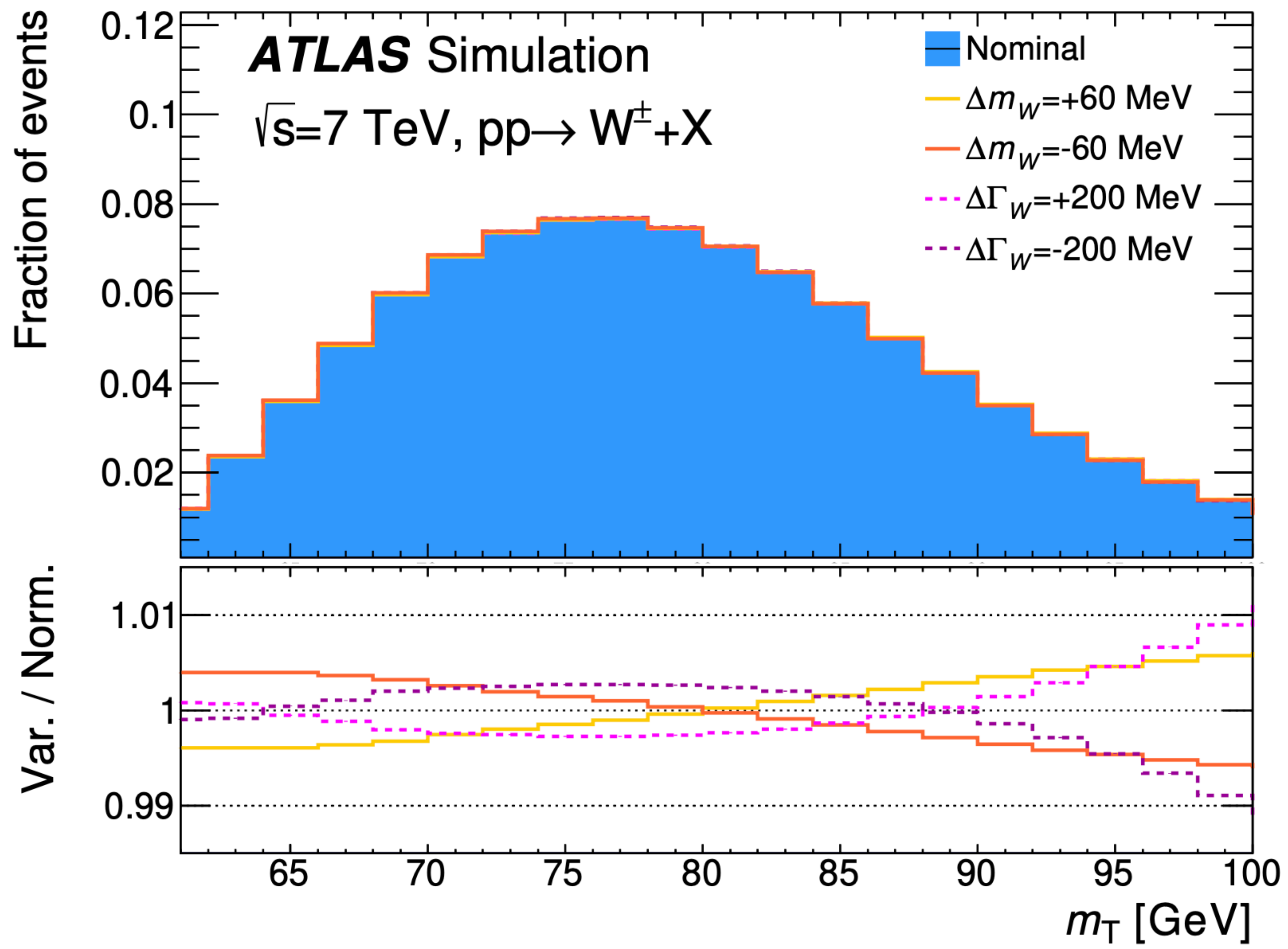
m_W = 80366.5 ± 15.9 MeV

- m_W measured from m_T^W, p_T^W; also sensitive to Γ_W

➡**New measurement Γ_W is first at LHC**

- Study Interplay of m_W and Γ_W



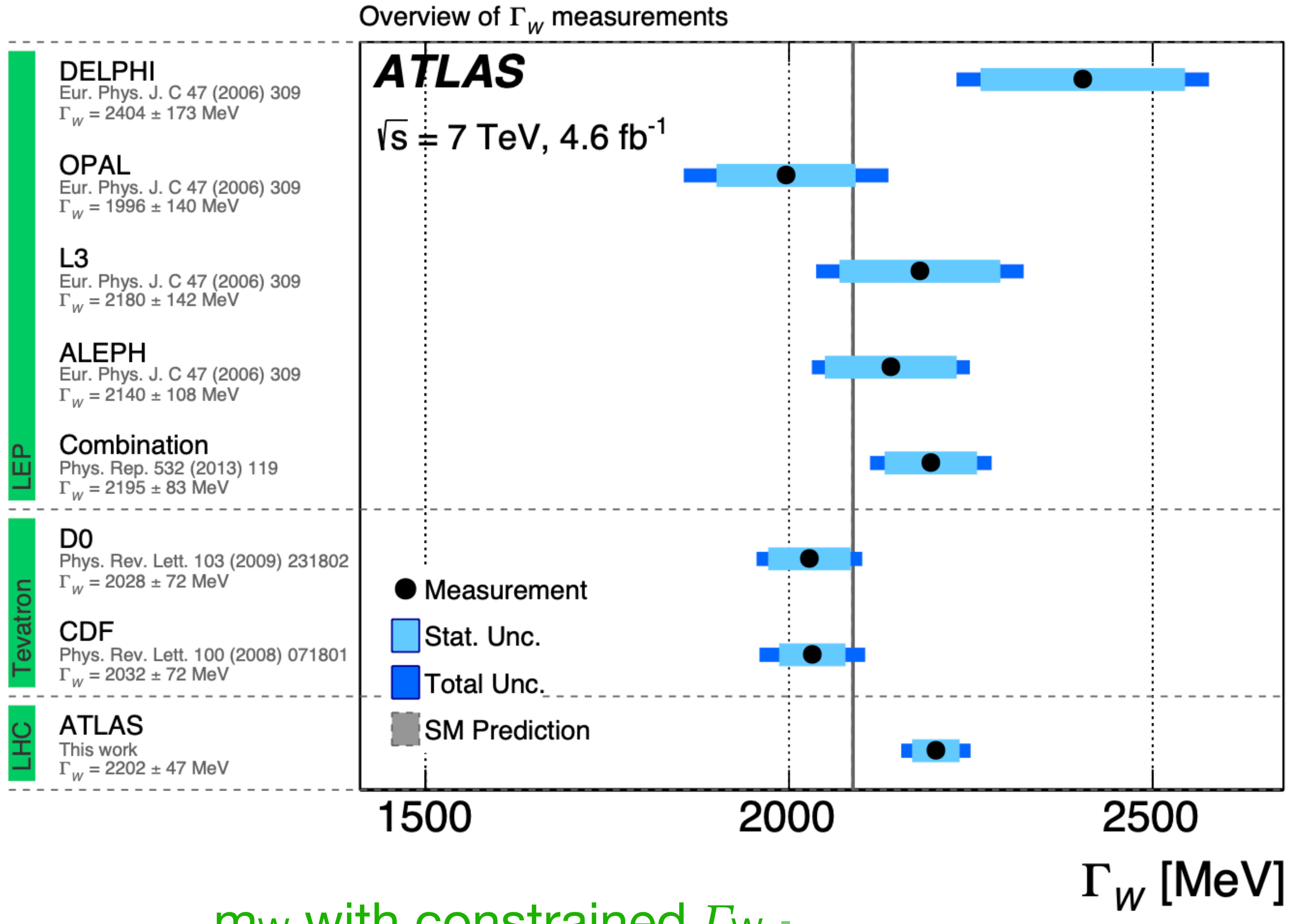


Electroweak precision: m_W and Γ_W at ATLAS (***New***)

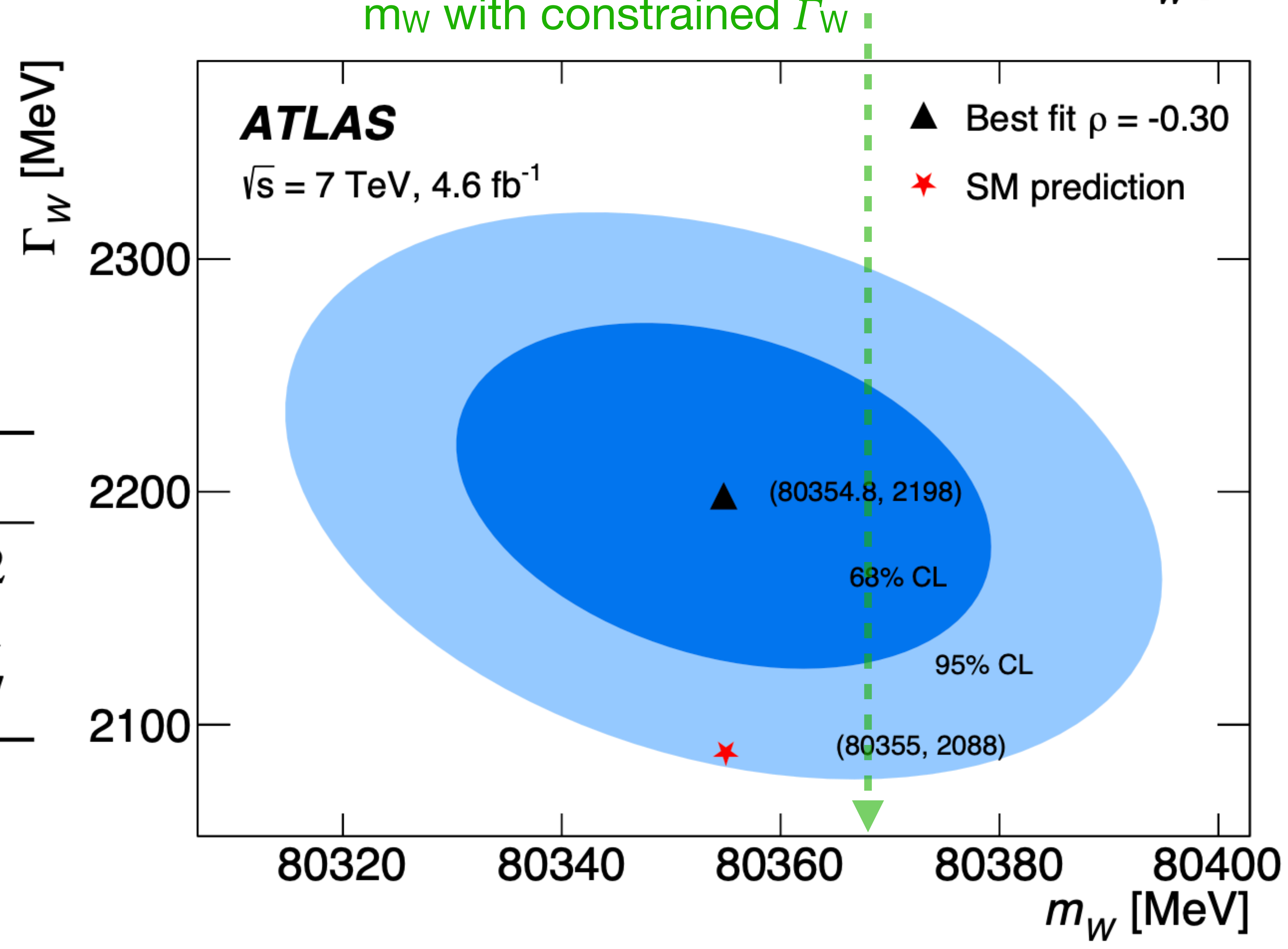
STDM-2019-24

- Γ_W (m_W) measurement with m_W (Γ_W) constrained **and simultaneously**
- Measurement w/ m_W constrained: **most precise from single experiment**
  - Modeling (shower tune variations) and recoil unc. dominate
  - m_T^W significantly more sensitive channel (opposite of m_W)

$$\Gamma_W = 2202 \pm 32\ (\text{stat.}) \pm 34\ (\text{syst.})\ \text{MeV} = 2202 \pm 47\ \text{MeV}$$



- Central value in m_W differs by -12 MeV in simultaneous fit vs. fixed Γ_W fit
  - Uncertainty ~1% increase
- Width unc. increases by ~4% in simultaneous measurement with very small shift in central value



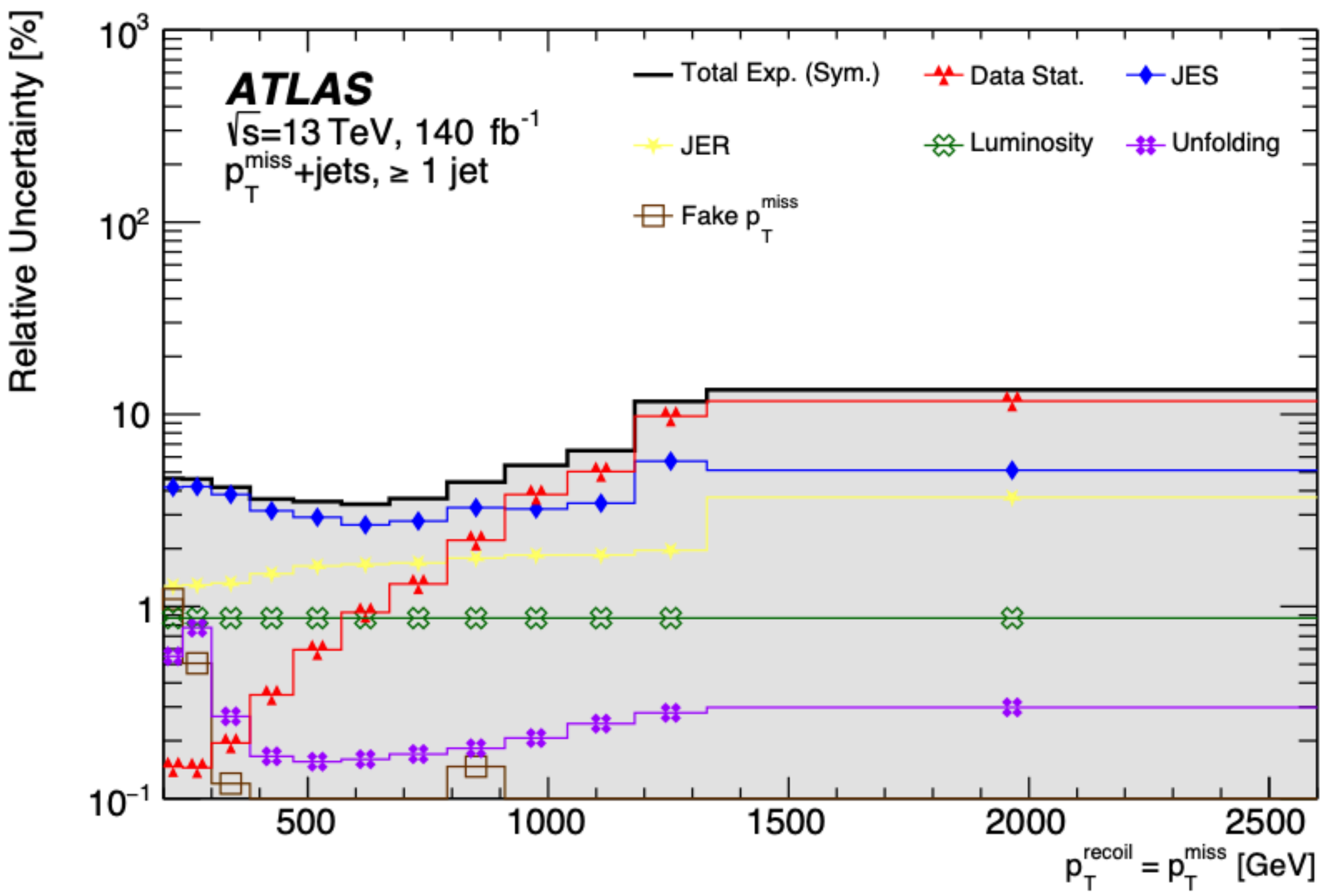
Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	m_W	PS
p_T^ℓ	71.8	27.3	66.4	21.2	13.9	10.4	4.9	13.2	11.5	12.0	9.6	6.3	55.2
m_T	47.5	35.5	31.6	4.9	6.6	9.6	3.3	13.2	9.2	17.6	9.1	5.5	12.1
Combined	46.8	32.0	34.1	6.7	7.5	9.4	3.3	13.1	9.4	16.7	9.1	5.6	17.7

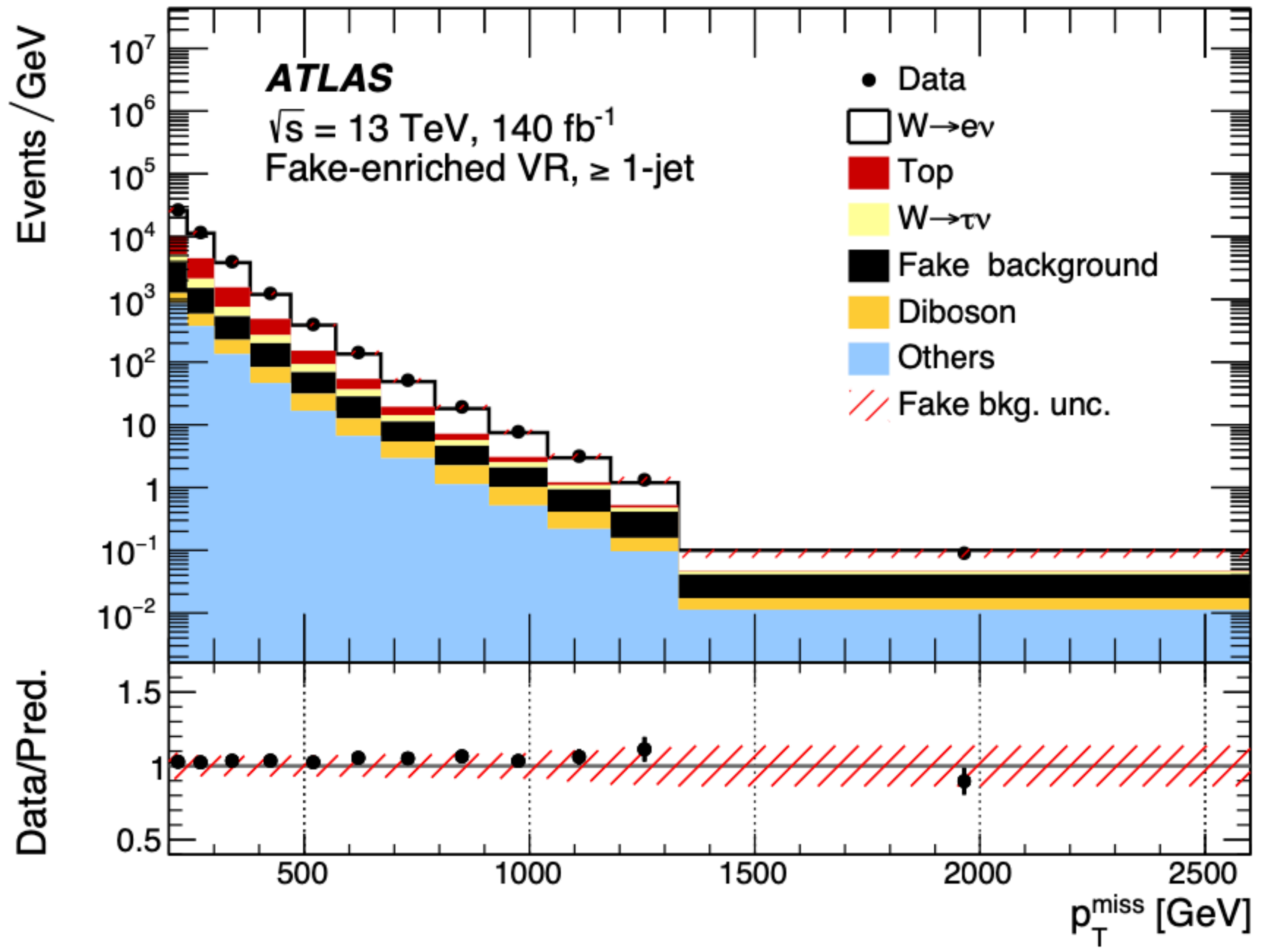
Differential study of p_T^{miss}+jets (***NEW***)

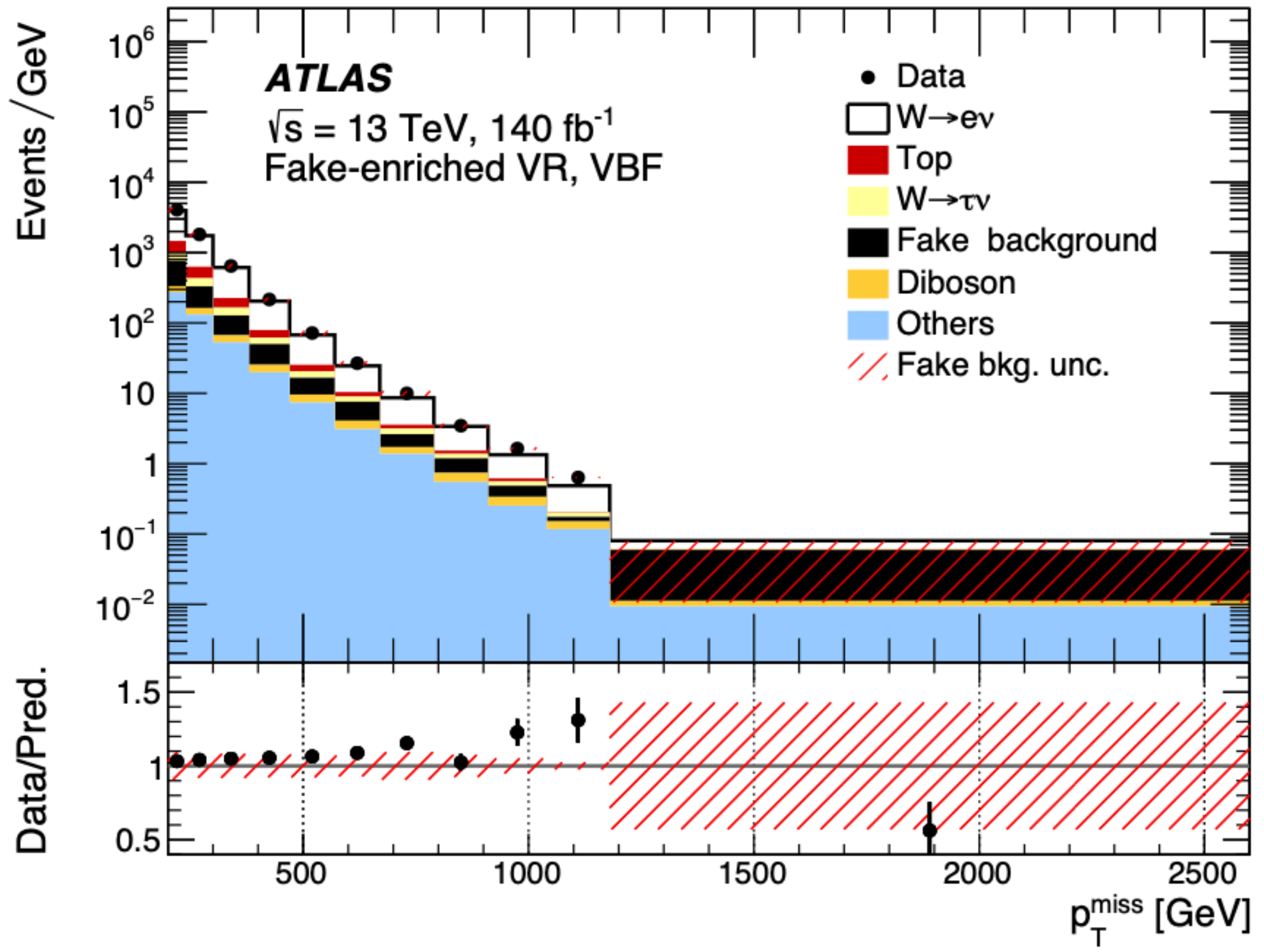
- New ATLAS studies of W/Z production with ν decays
  - Backgrounds for searches (e.g., mono-jet), VBF H(νν)
  - Sensitivity to high p_T^V spectrum wrt Z(ℓℓ) channel
  - Sensitive to BSM (limits in EFT and specific models)
- **Very comprehensive result**, with W, Z, γ dominated selections and unfolded results
- Nonprompt background estimated by smearing jets in selected data events to produce pseudodata with p_T^{miss}

arxiv:2403.02793

	Final-state event selection					
Production process	p_T^{miss}+jets	$2e$+jets	2μ+jets	e+jets	μ+jets	γ+jets
$Z \to \nu\nu$ + jets	55%	–	–	–	–	–
$Z \to ee$ + jets	–	94%	–	–	–	–
$Z \to \mu\mu$ + jets	–	–	95%	–	2%	–
$W \to e\nu$ + jets	6%	–	–	68%	–	–
$W \to \mu\nu$ + jets	9%	–	–	–	67%	–
$W \to \tau\nu$ + jets	20%	–	–	5%	7%	–
γ + jets	–	–	–	–	–	>99%
Top	7%	3%	2%	25%	21%	–
Multi-boson	3%	3%	3%	2%	3%	<1%



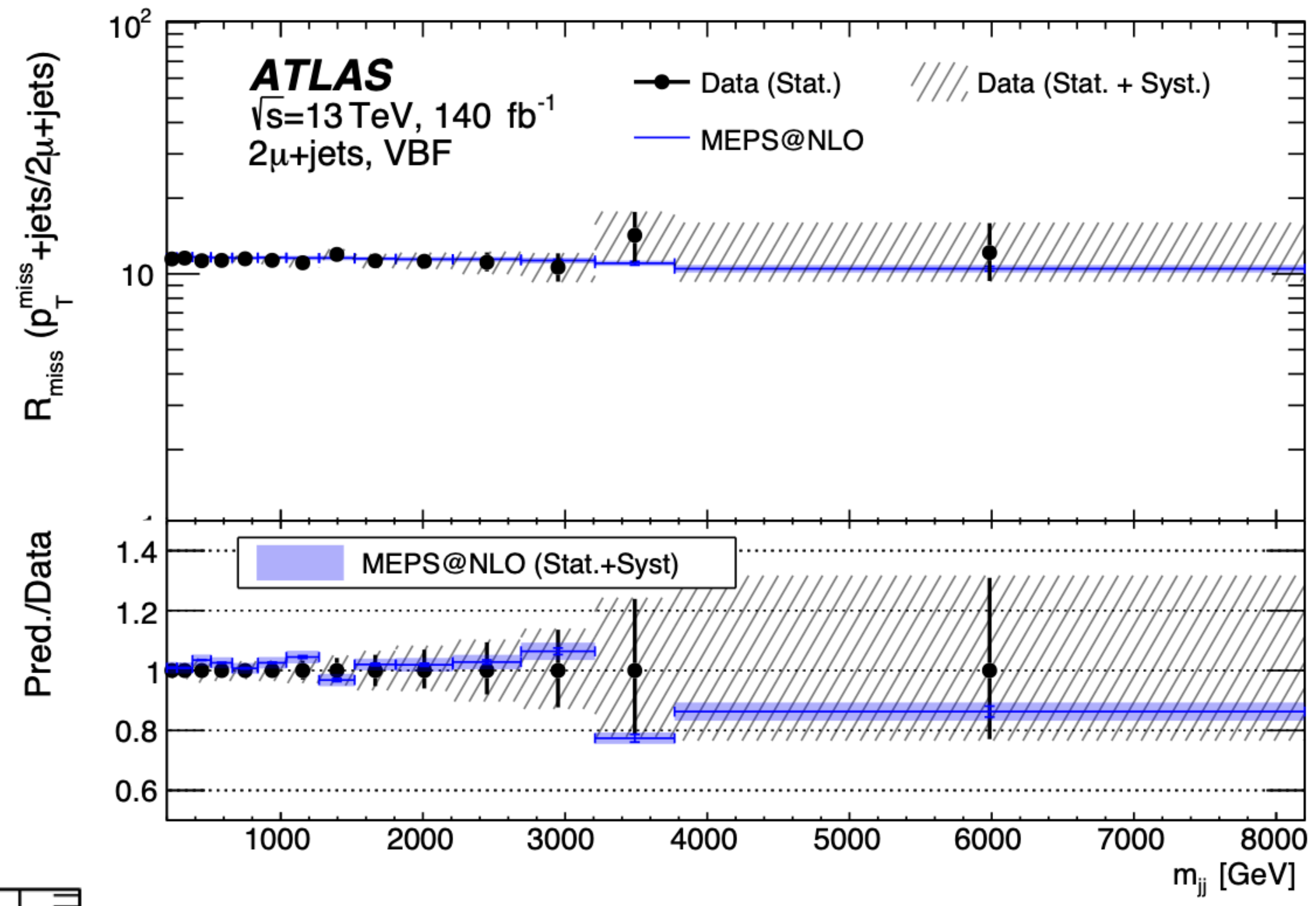


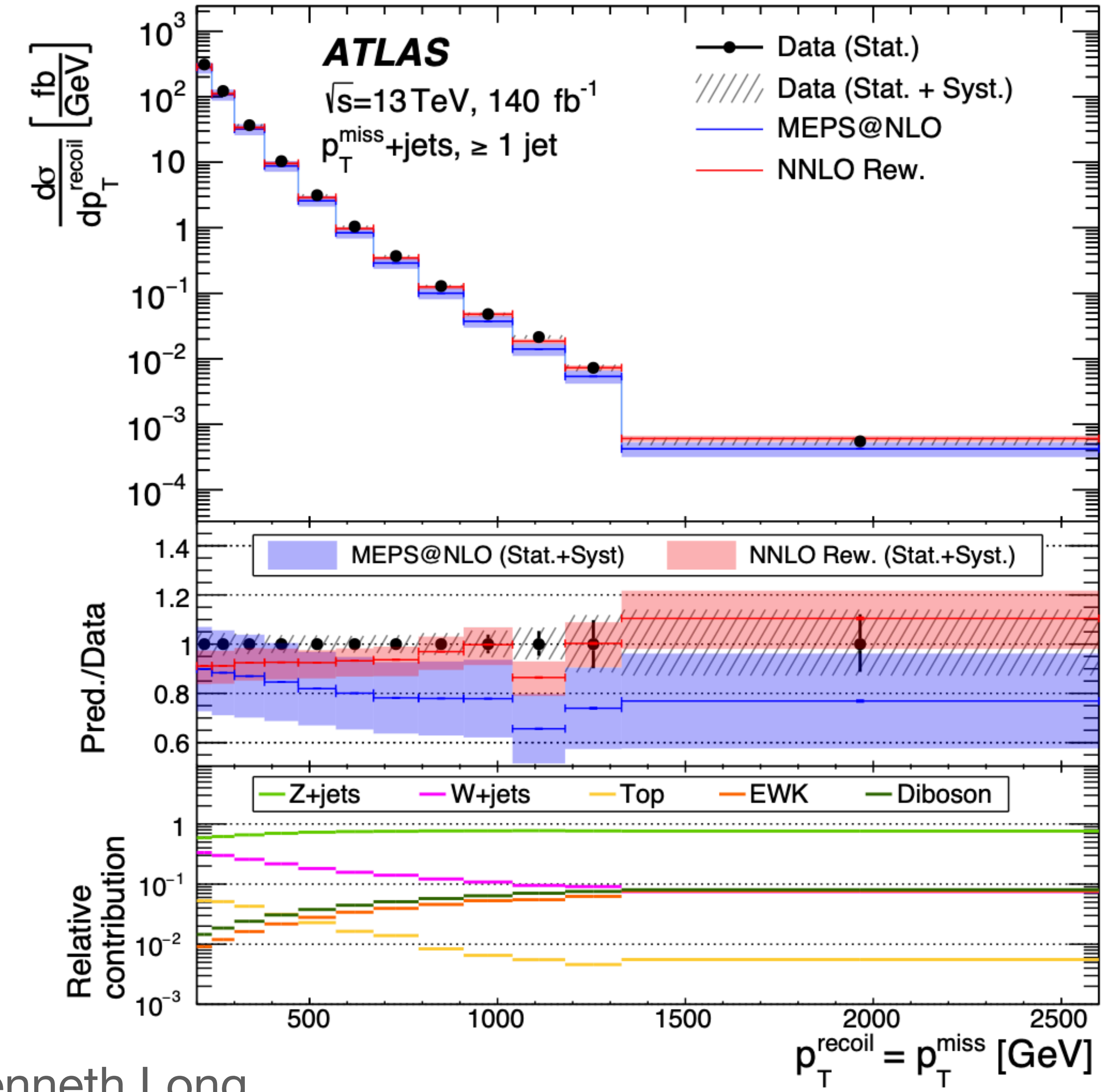


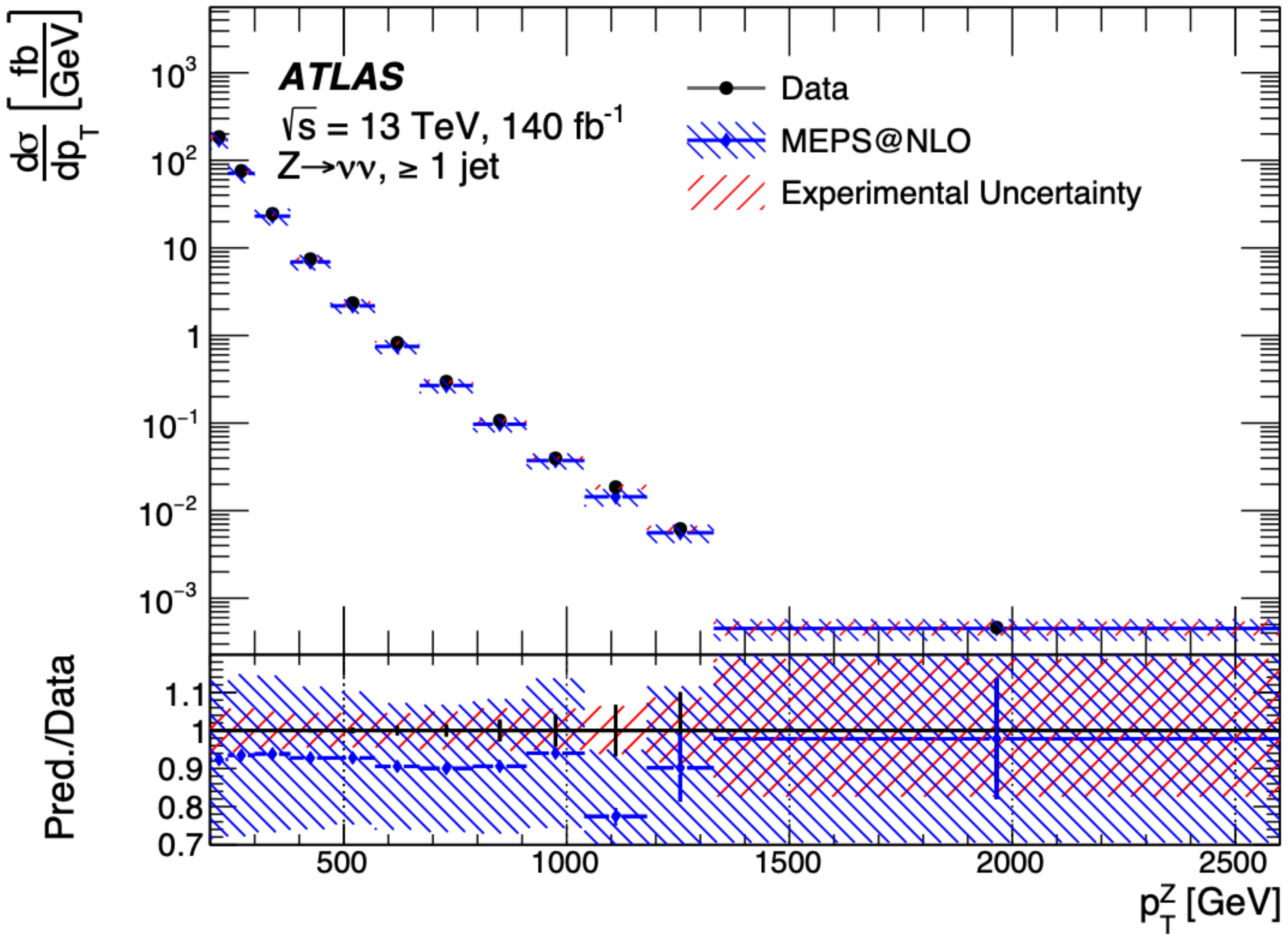
Differential study of p_T^{miss}+jets (***NEW***)

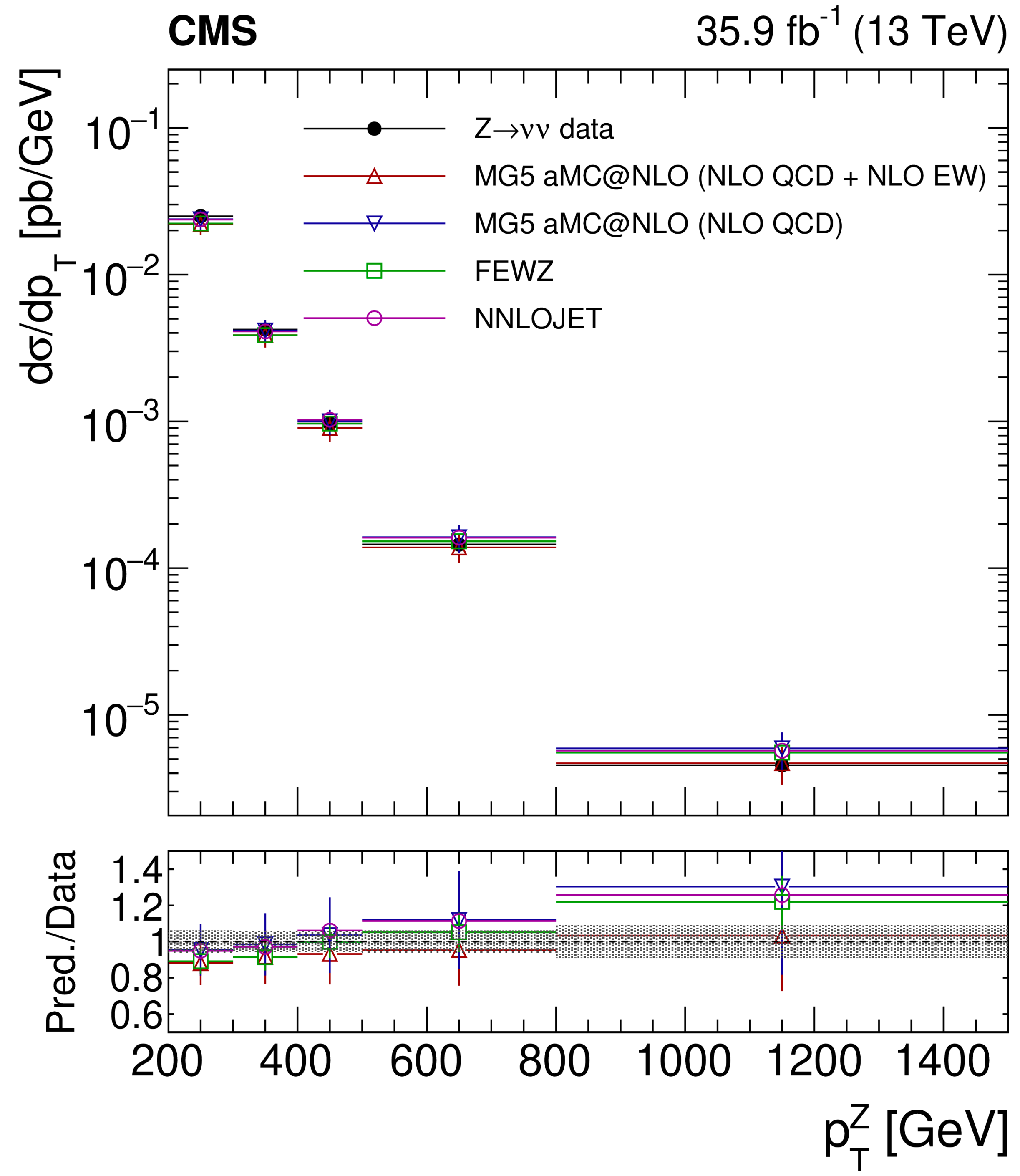
arxiv:2403.02793

- **Incredibly comprehensive study**, impossible to do justice to the breadth of results presented
  - **Unfolded results for combined EW processes and single-process only**
  - $Z\rightarrow\nu\nu$ measurement directly comparable to CMS: JHEP 05 (2021) 205
    - Interesting for validation of predictions up to high p_T^V
  - **R^{miss} = ratio of $p_T^{miss}/p_T^{\ell\ell}$** also measured
    - Important for data-driven NP searches



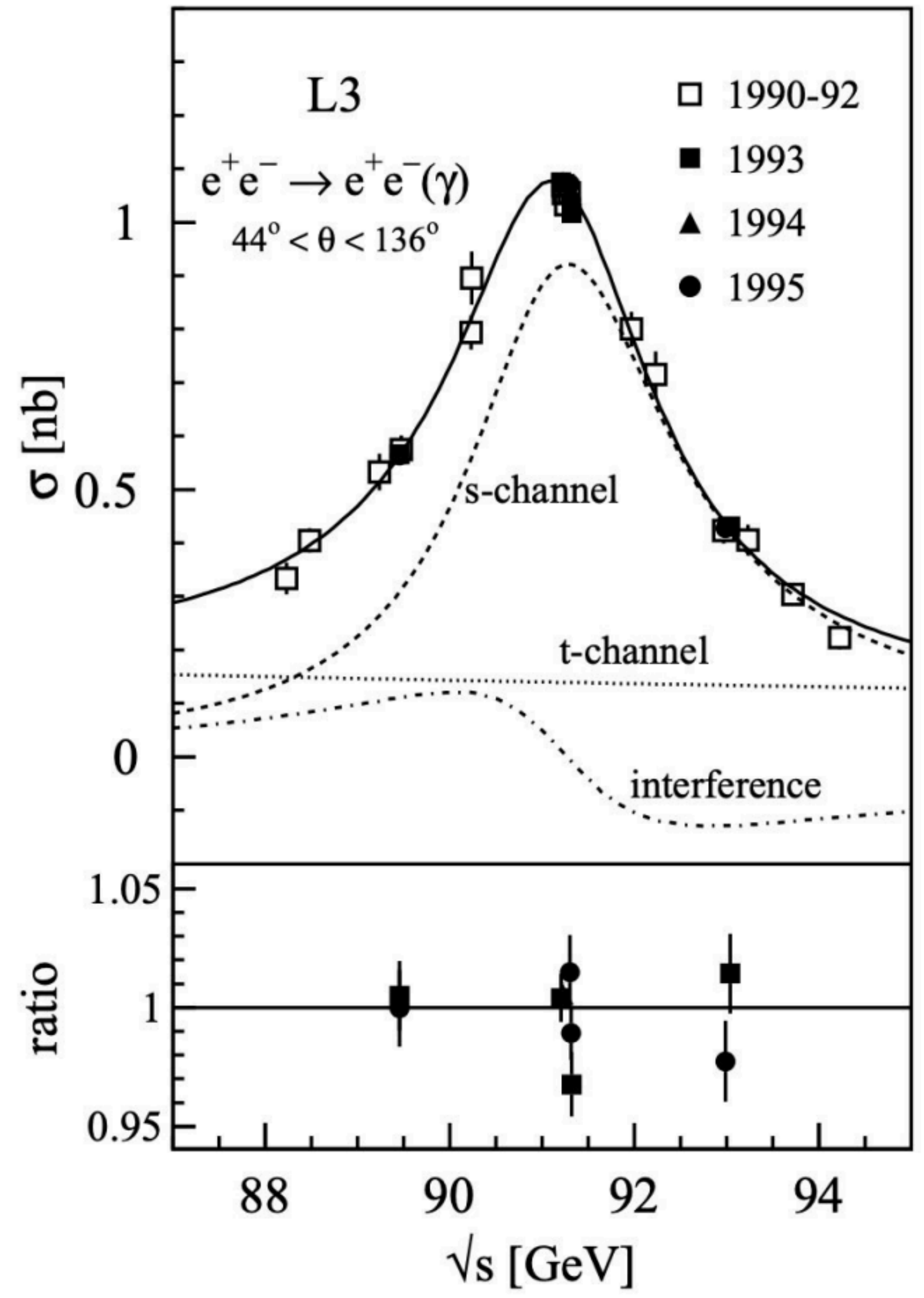






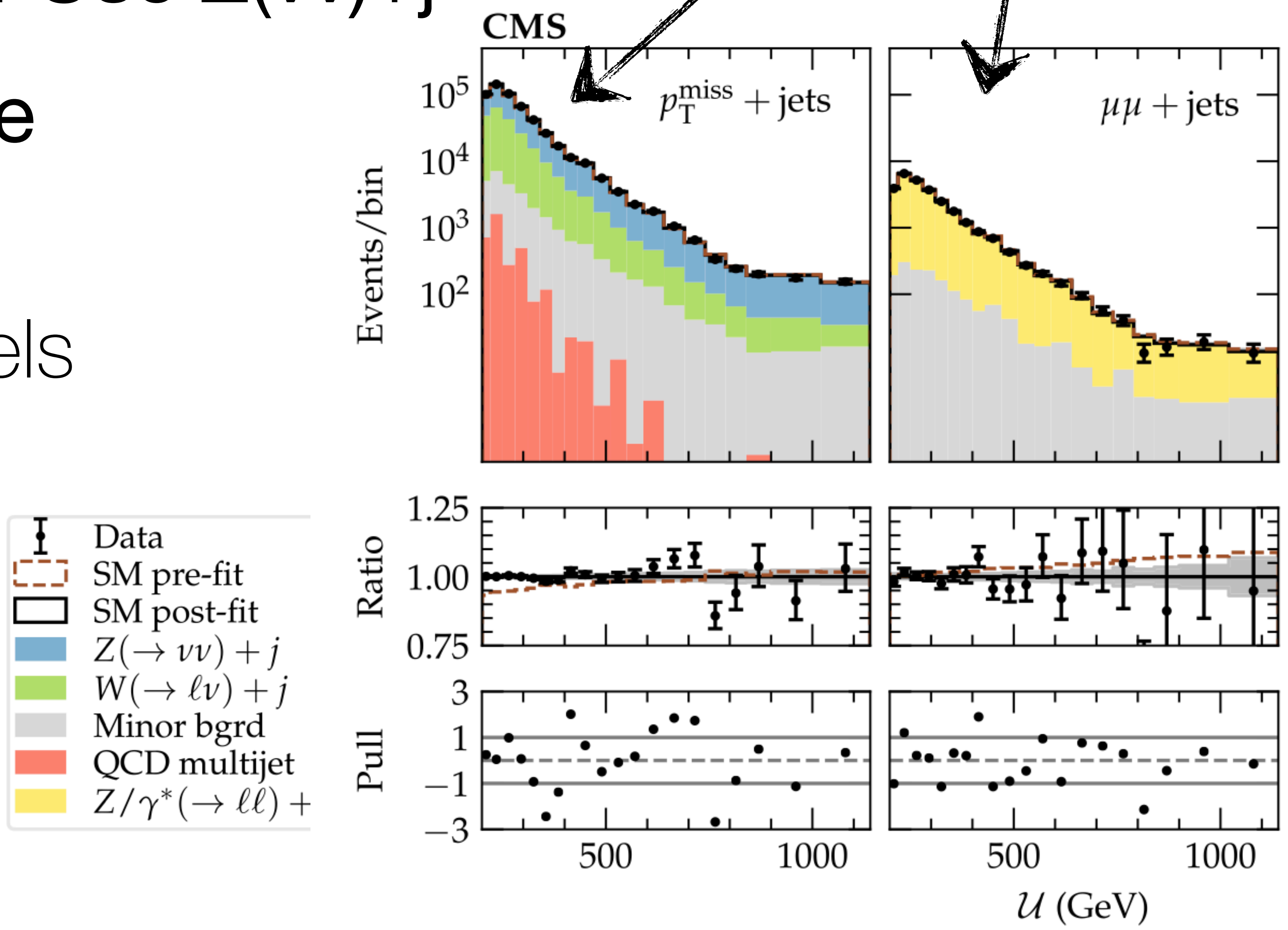
Electroweak precision: $\Gamma_{Z\to\nu\nu}$ at ATLAS

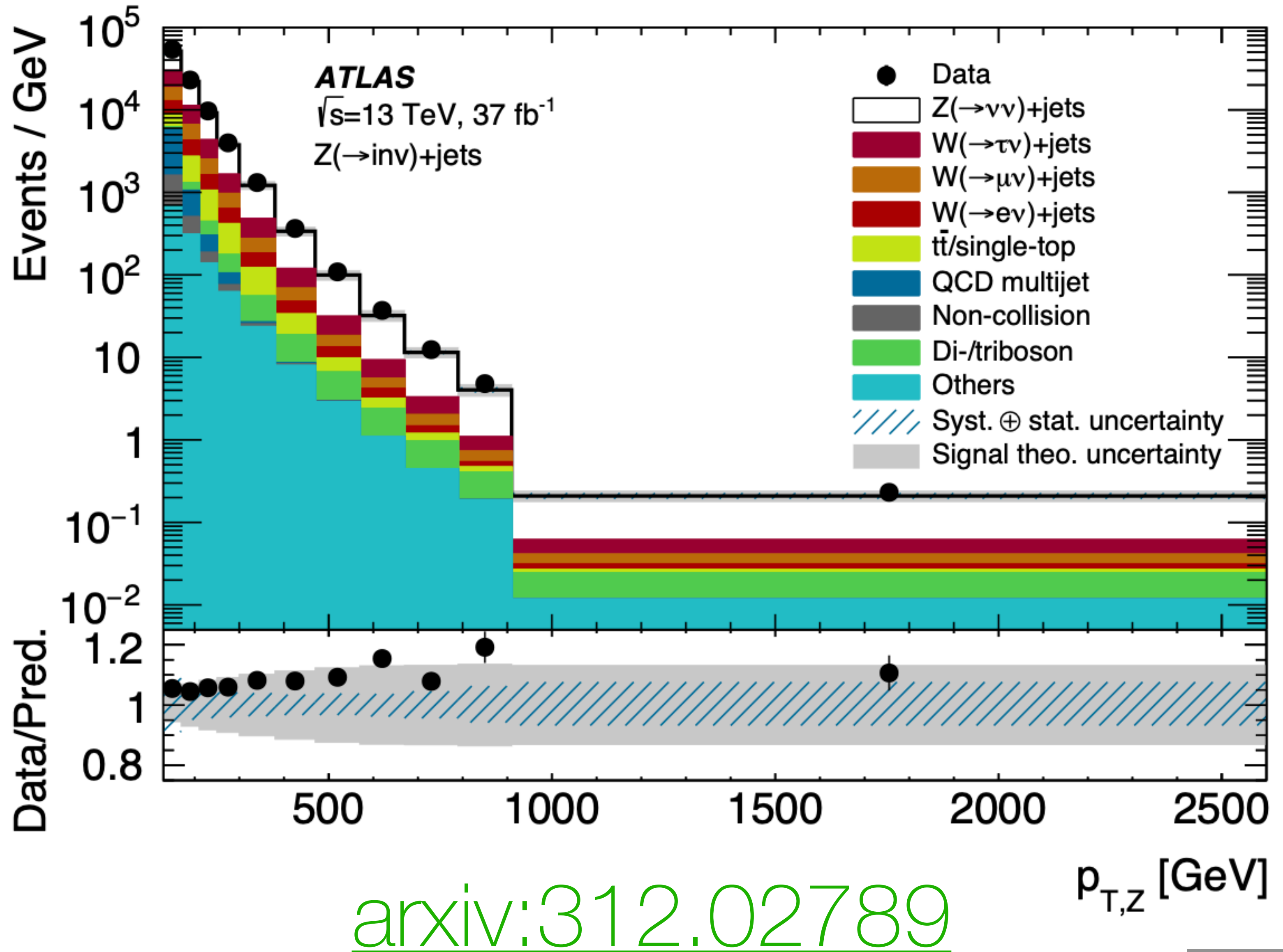
- Study of Z(νν) can be recast as partial width measurement
- Partial width is fundamental, **independent of production mechanism**
  - In practice, produce at collider, correct (hopefully small) assumptions
- Indirect Z(νν) measurement
  - At LEP (e^+e^-): **tot. width from energy scan.** subtract visible
  - ➡ Very accurate, this is the number in the PDG
- Direct measurement
  - At LEP: Z(νν)+γ. O(10x) less sensitive than indirect
  - At LHC: only indirect possible. **Use Z(νν)+j**



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

- **New ATLAS result most precise indirect measurement**
  - Measure Z in ee/μμ/νν channels
    - $u_T^Z > 130$ GeV
    - $p_T^j > 110$ GeV, $|\eta^j| < 2.4$
- Recently measured at CMS
  - PLB 842 (2023) 137563





arxiv:312.02789

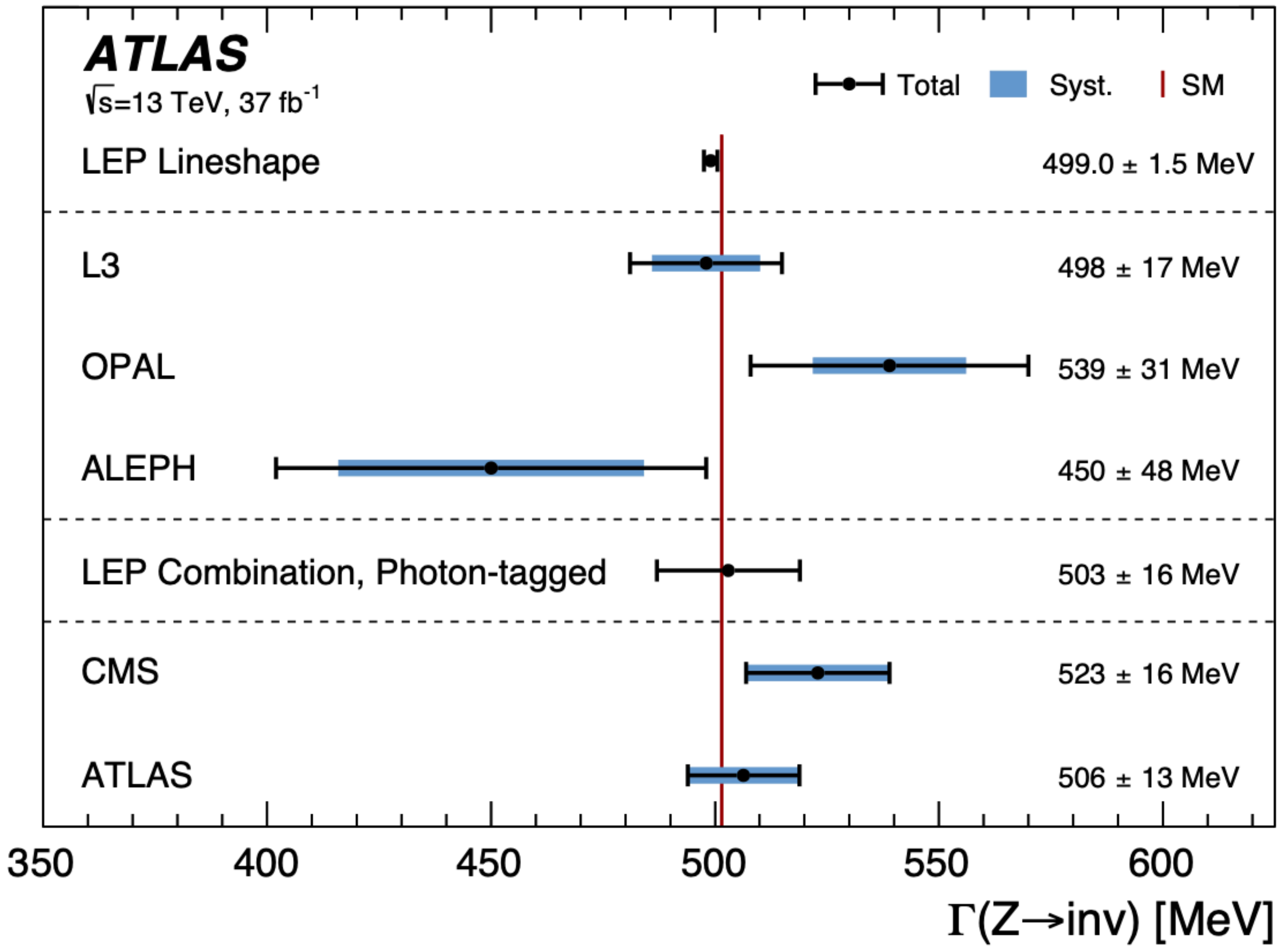
Electroweak precision: $\Gamma_{Z\to\nu\nu}$ results

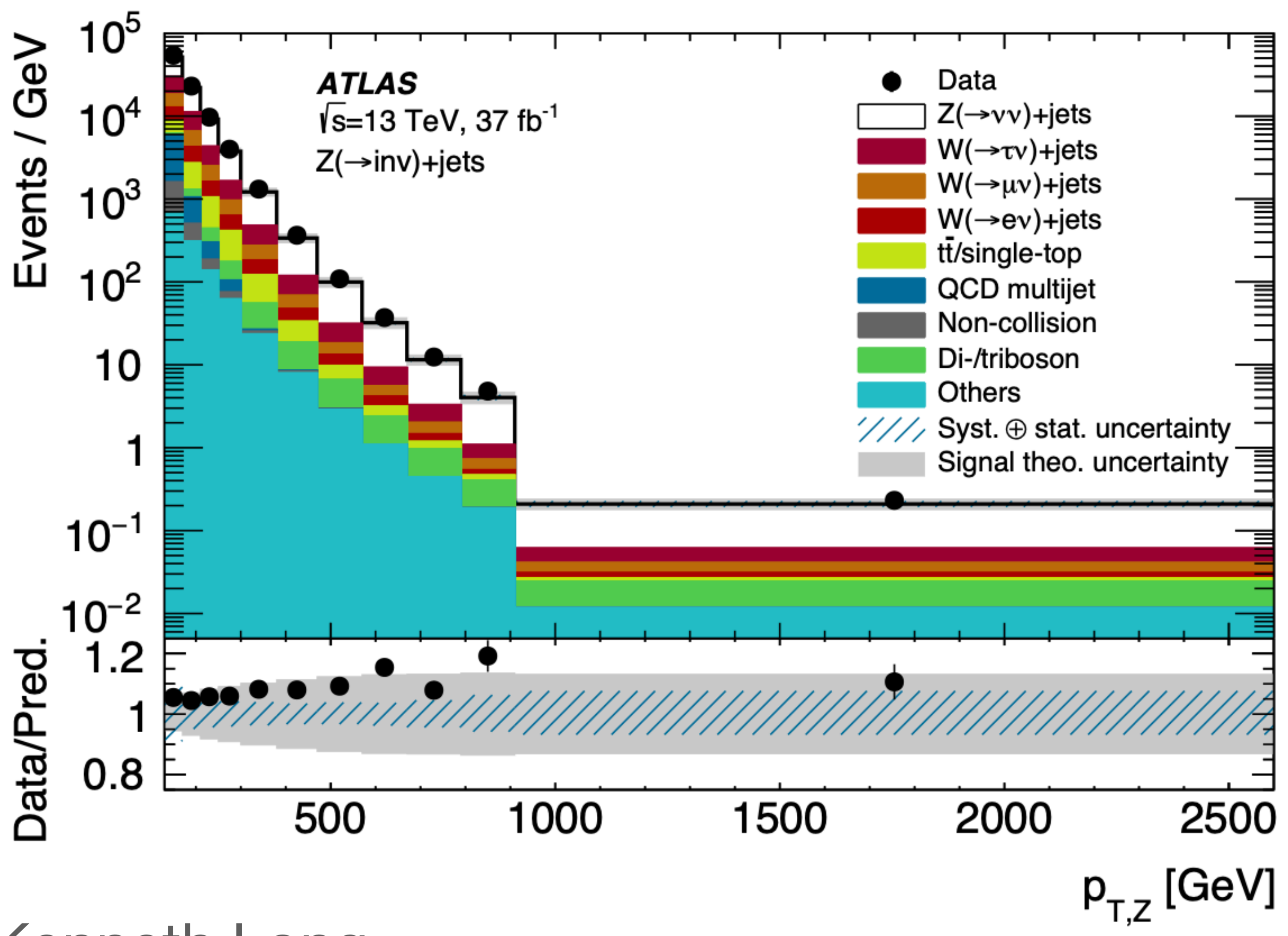
arxiv:312.02789

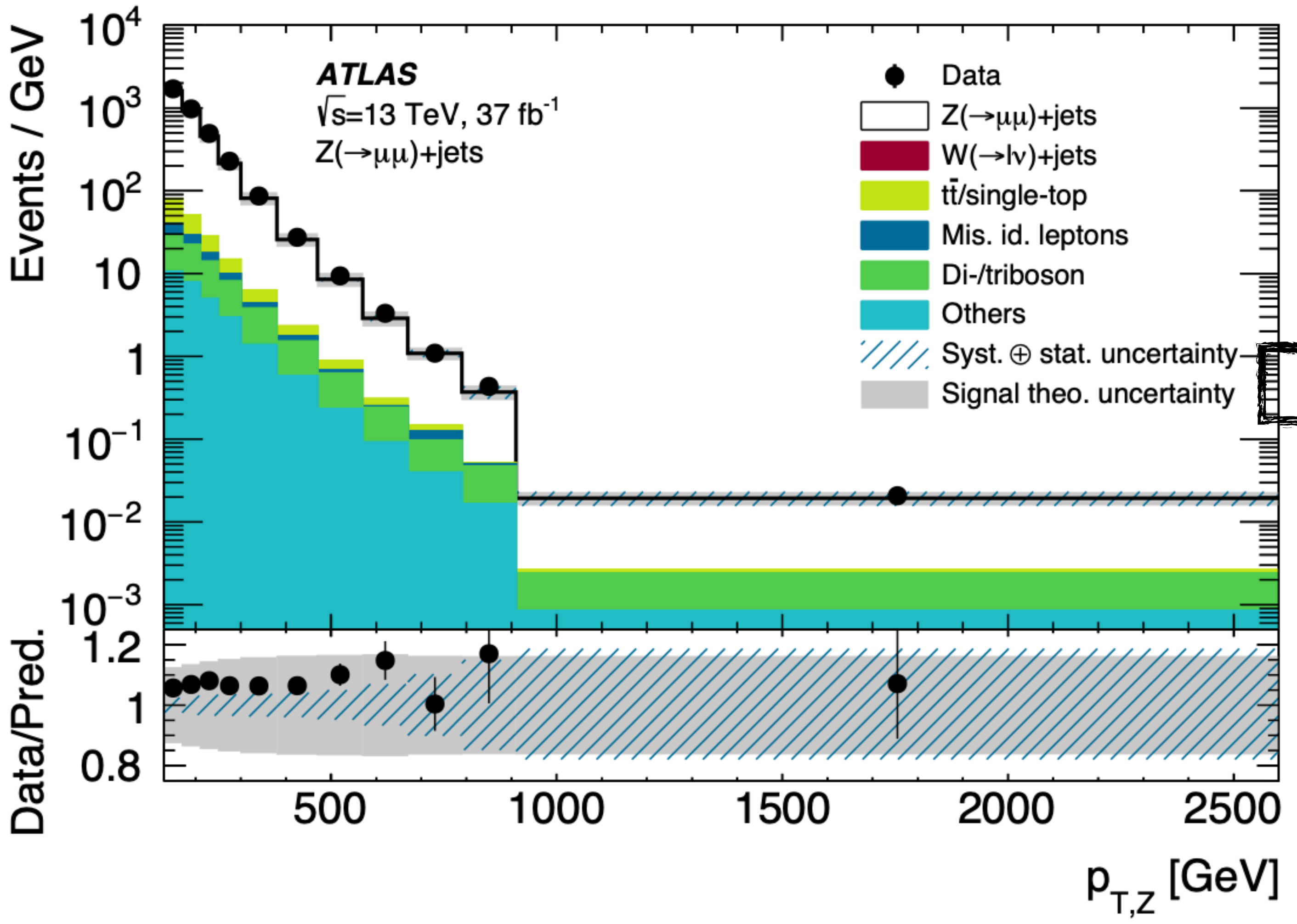
- W(ℓν) estimated from simulation corrected in single-lepton CRs
- True observable is ratio of Z(νν)/Z(ℓℓ) in fiducial (high p_T^Z) region
  - Rely on theory prediction for inclusive ratio (from fiducial)
  - Correct reco to gen level per bin
  - Derive single value for R = νν/μμ = νν/ee from corrected data

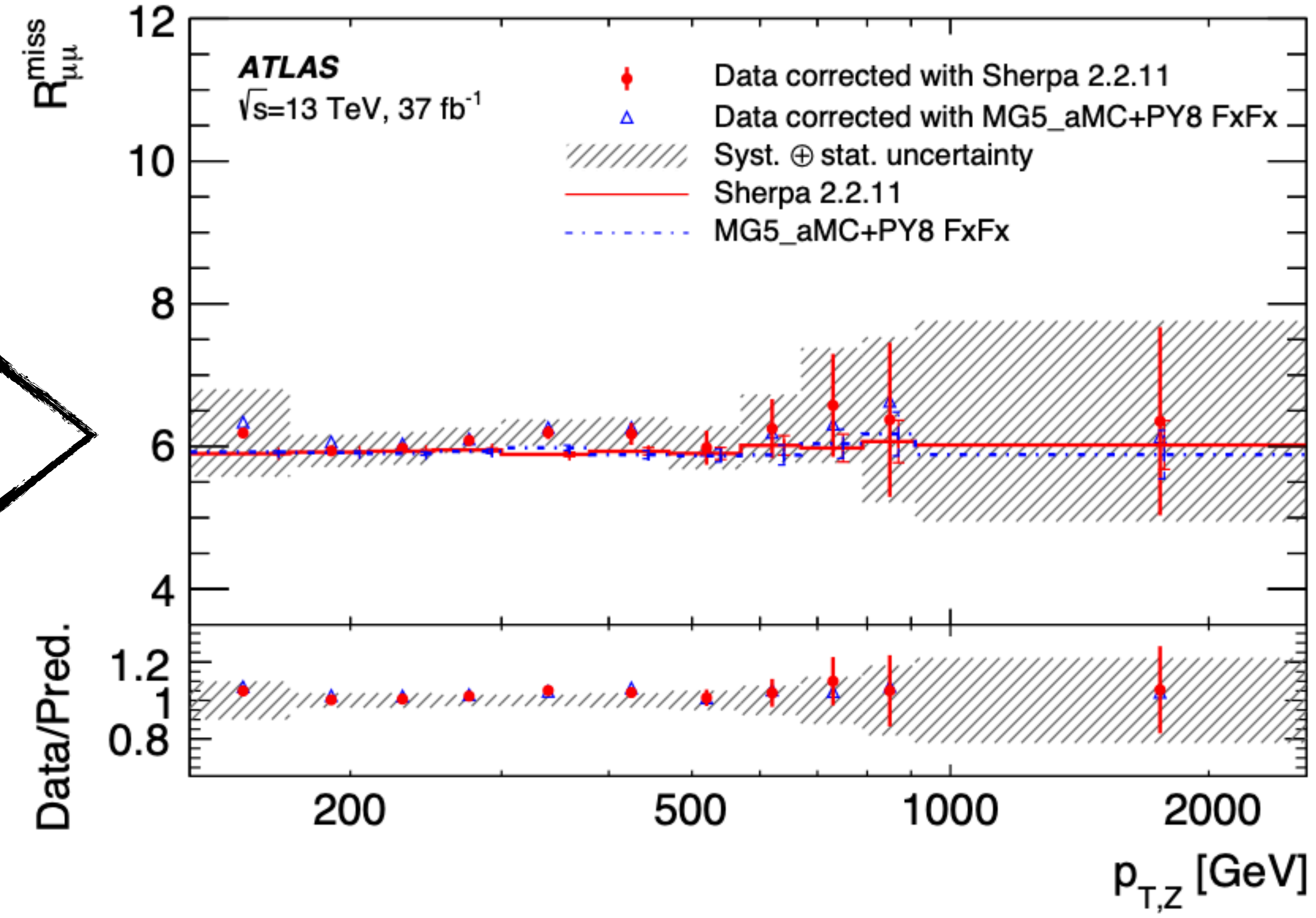
$$\Gamma_{Z\to\nu\nu} = 506 \pm 2\,(\text{stat.}) \pm 12\,(\text{syst.})\ \text{MeV}$$

- **Jet uncertainties strongly reduced** in ratio.
  - Dominant unc from lepton efficiency unc. (~1.5%)
  - Improvement wrt CMS driven by lepton eff. and jet scale





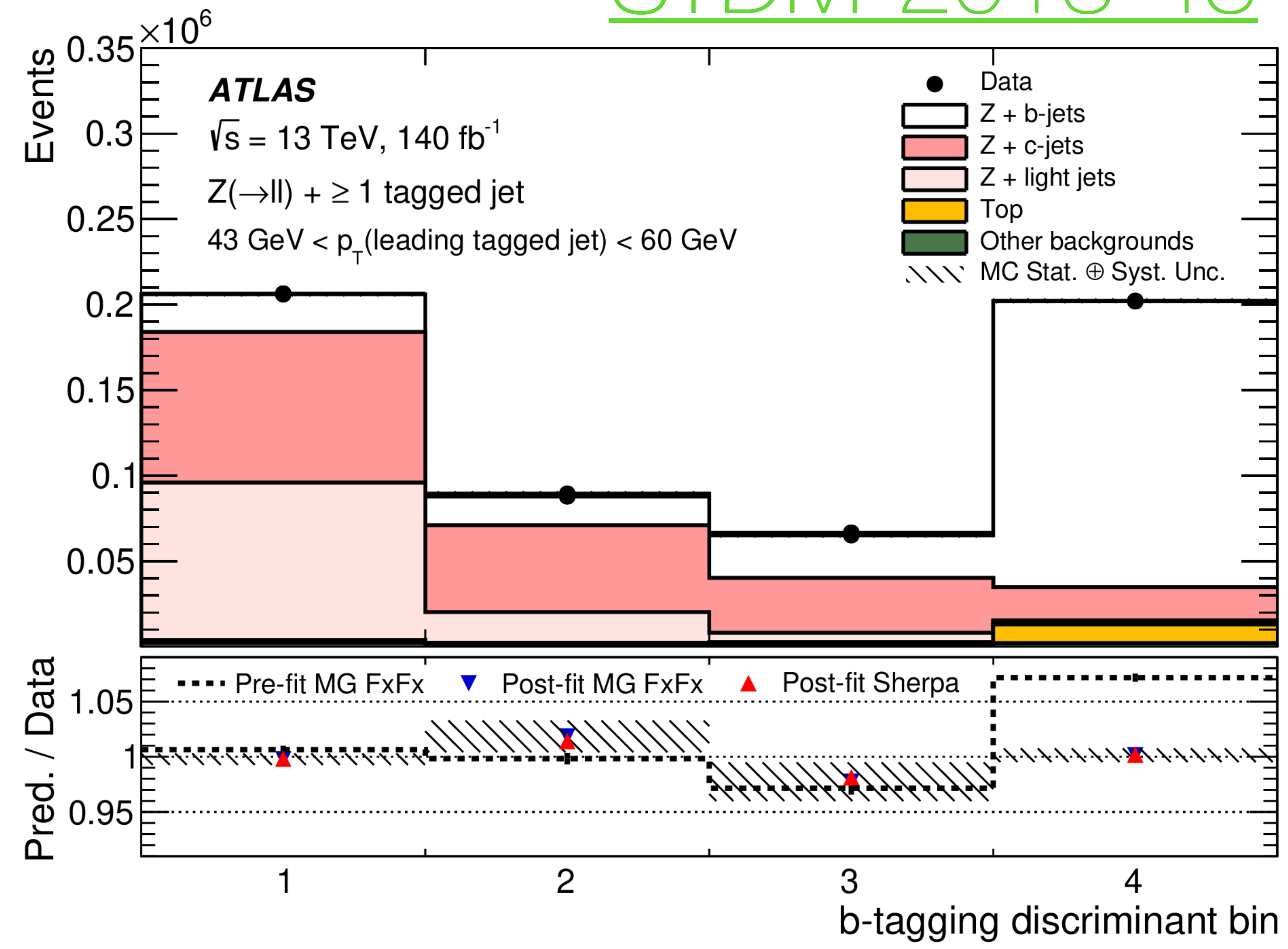


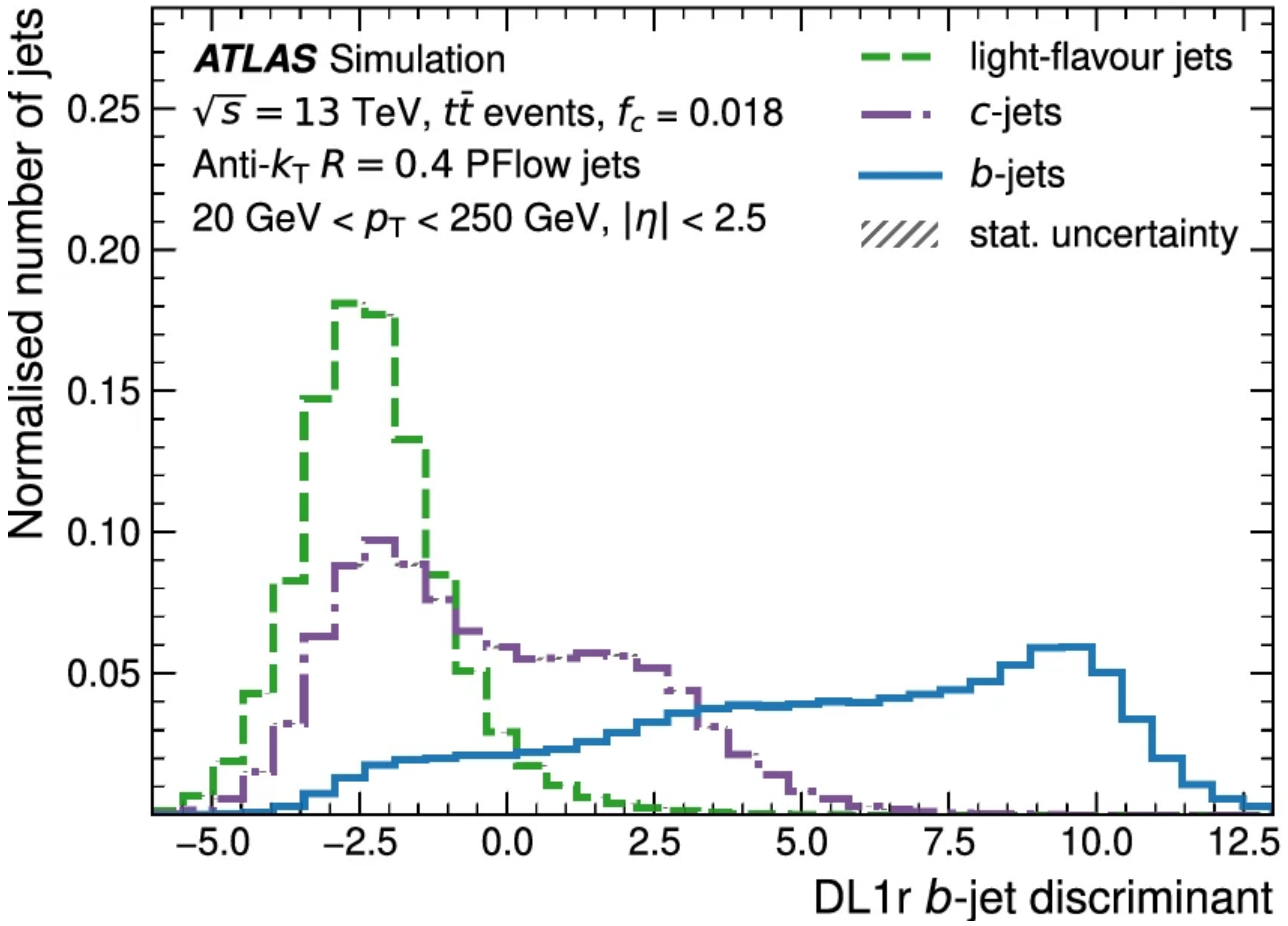


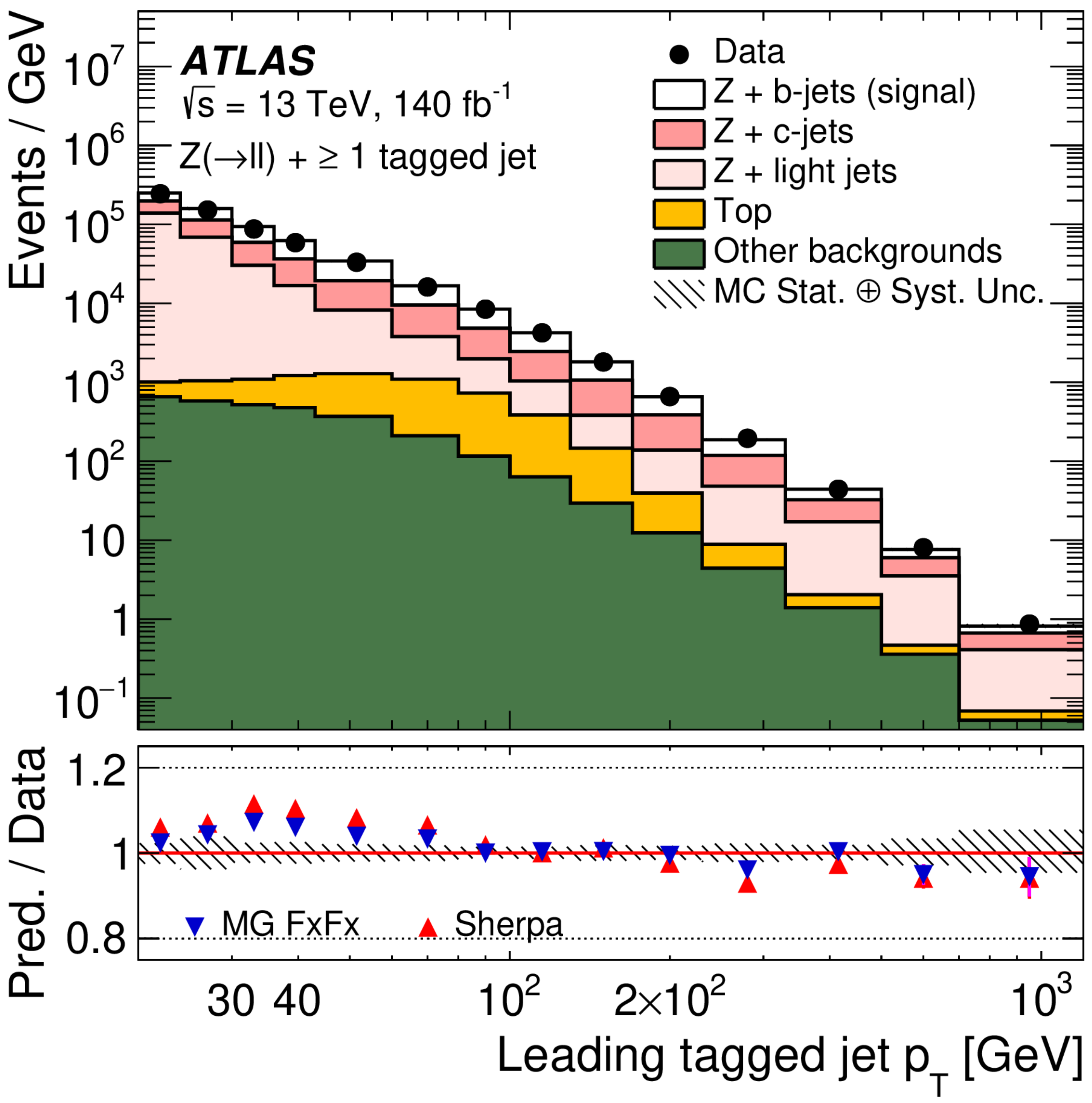
ATLAS Z+heavy flavour (***New***)

STDM-2018-43

- Z boson production in association with b and c quarks
  - **Important input to PDF fits**
  - Important background for Higgs measurements and searches
- Extensively studied in new ATLAS measurement
  - Categorize events into ≥1b, ≥1c, ≥2b jets, based on particle-level b/c-hadron matching in dR
  - Purity 34/28/46%, **other Z+b/c contributions and Z+ℓ majority of bkg**
  - Tagging of heavy flavour with DL1r algorithm, 85% WP
  - Top bkg from opposite flavour CRs
- Unfolding results with iterative Baysian (d'Agostini)
  - Signal model an important unc.
  - Jet tagging dominant exp unc.
- Comparable CMS analyses:
  - W+c: EPJC 84 (2024) 27
  - Z+b: PRD 105 (2022) 092014



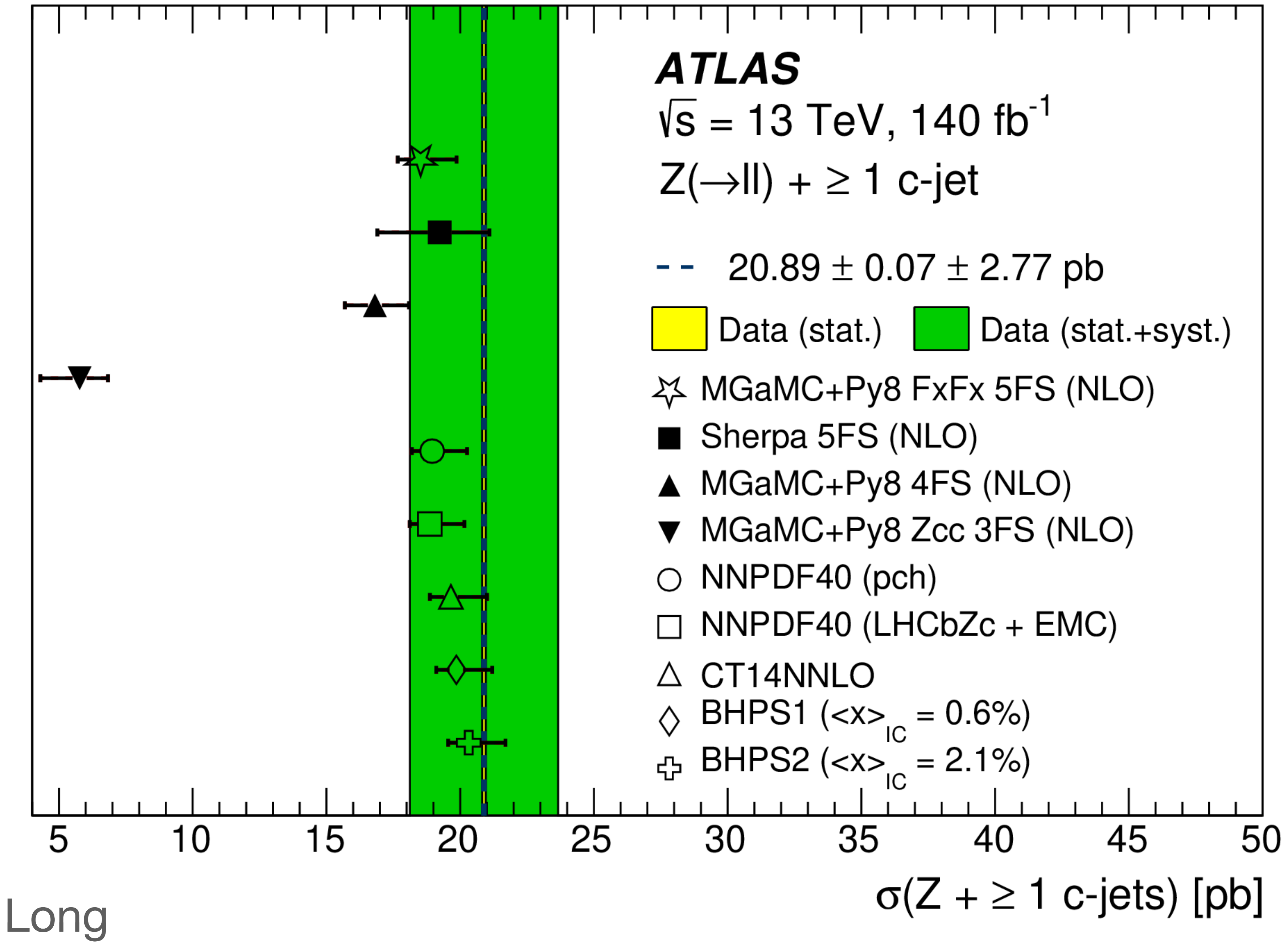


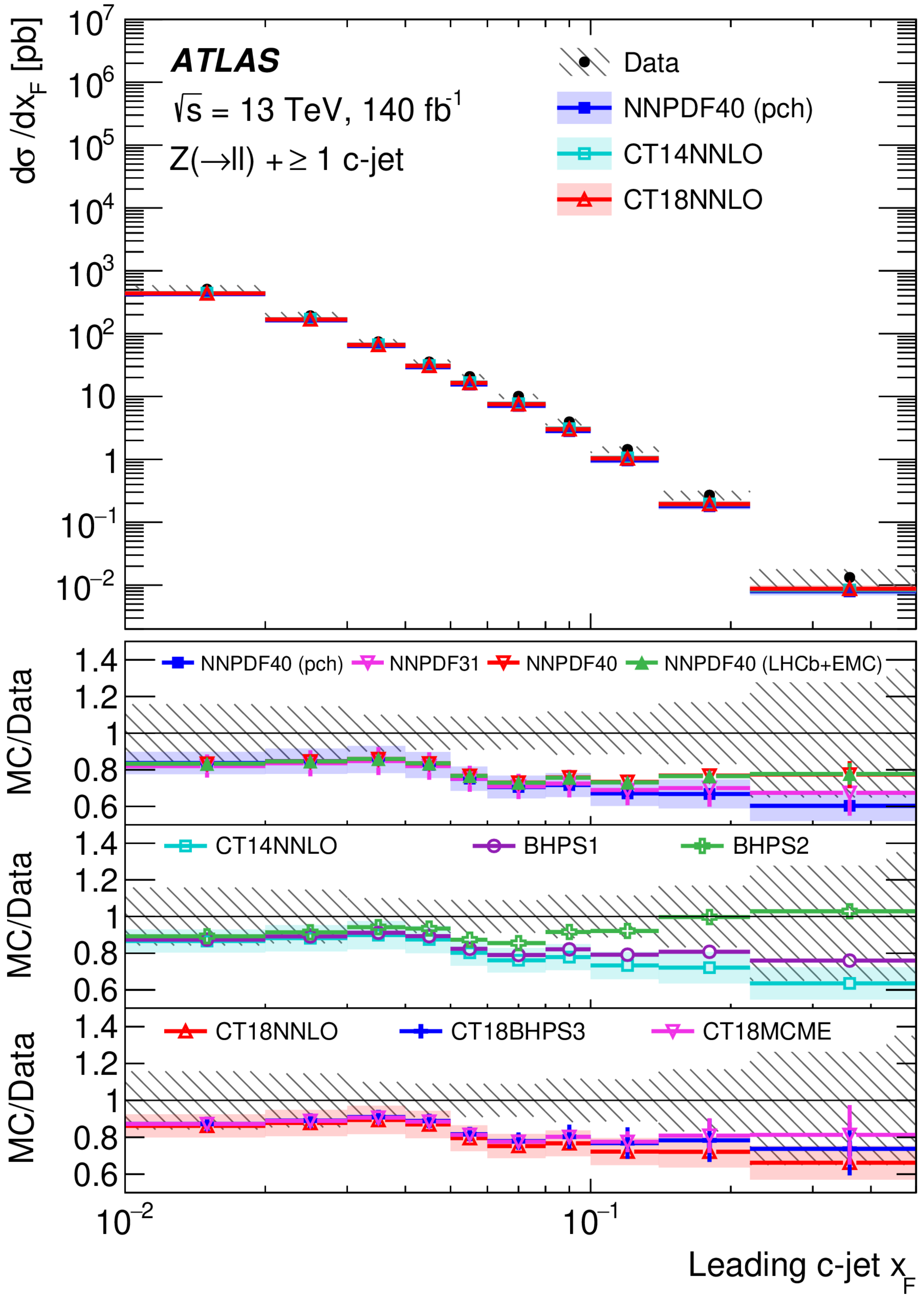


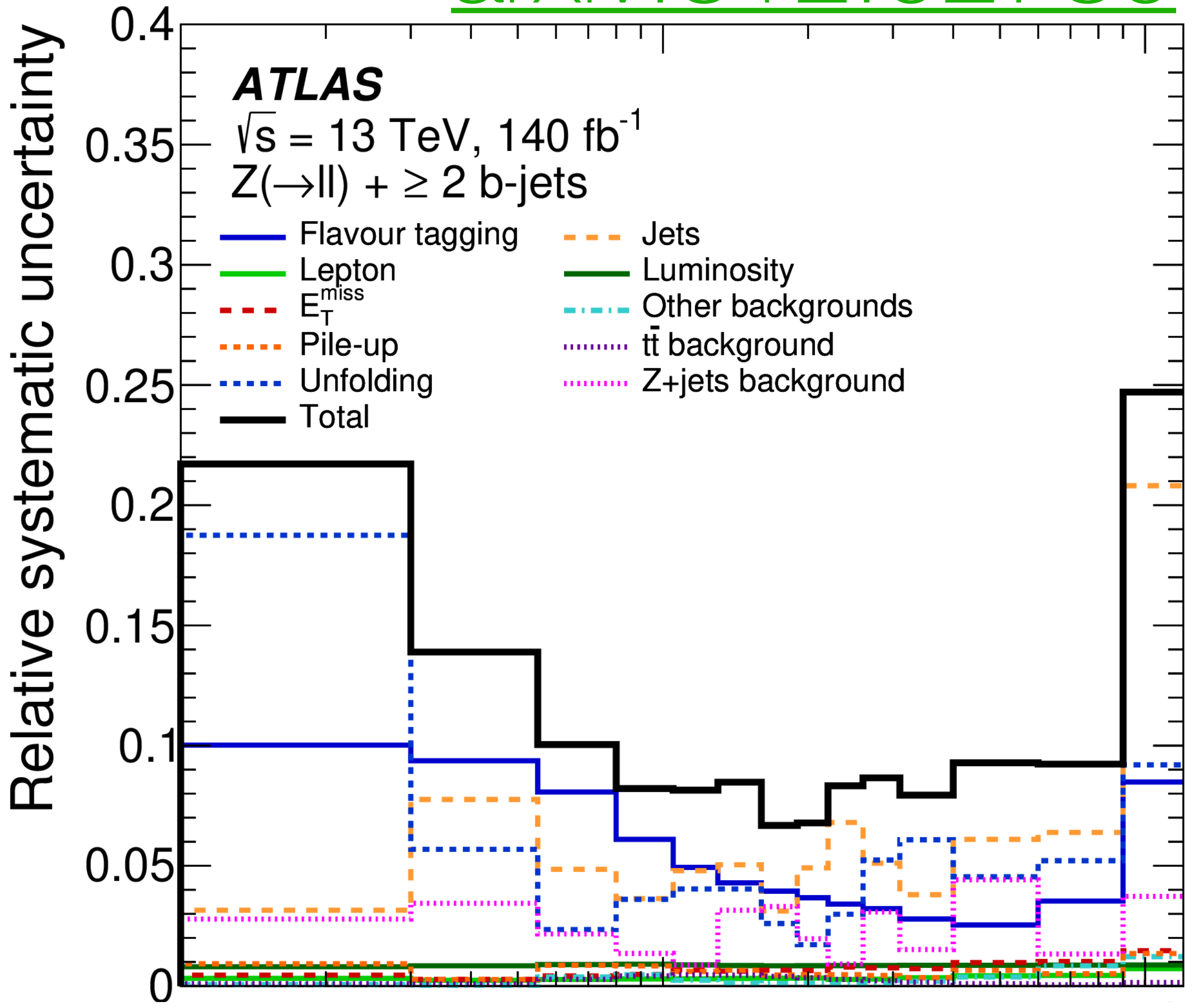
ATLAS Z+heavy flavour: Z+charm (***New***)

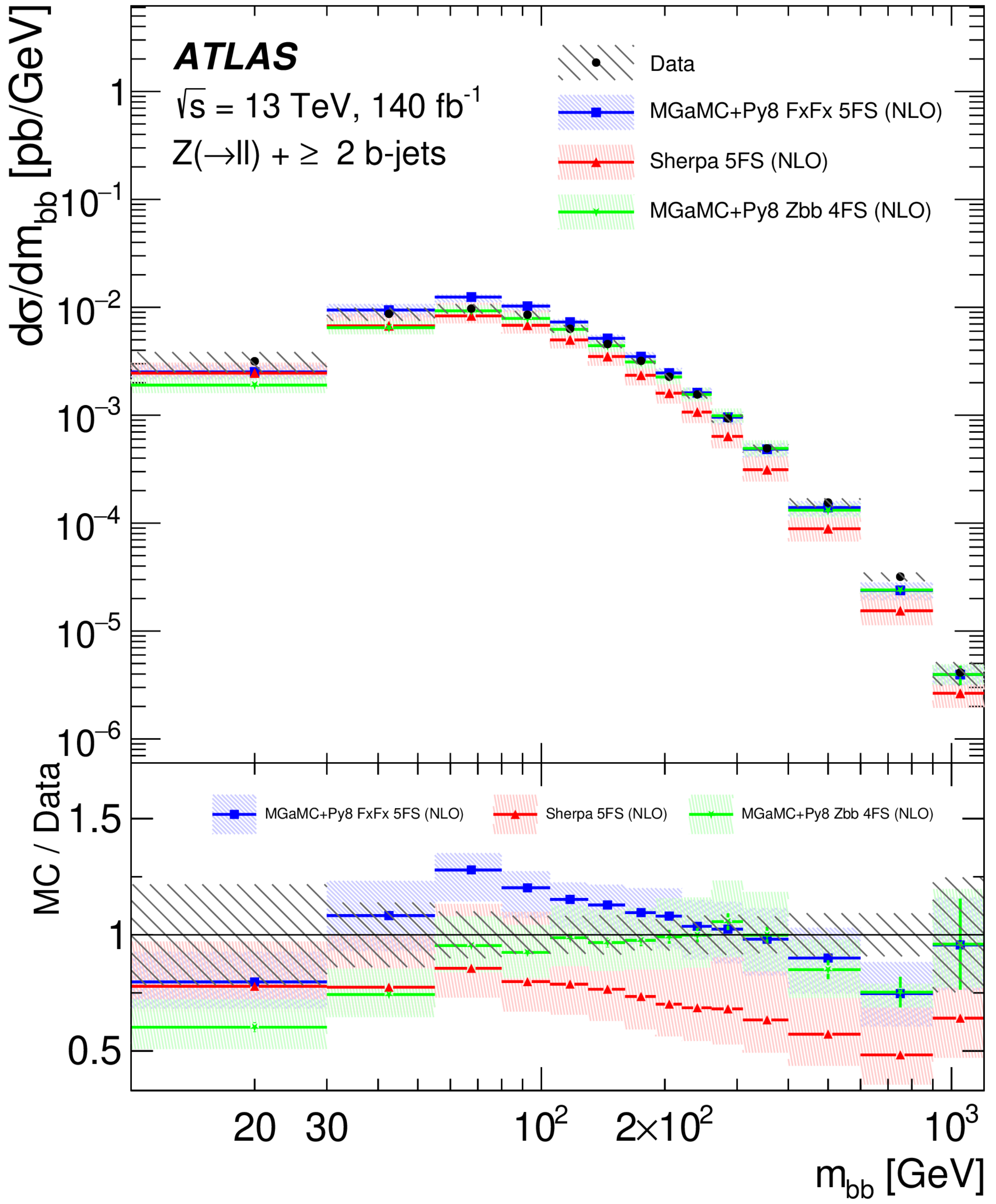
arxiv:312.02789

- Modeling of m_{bb} important for H(bb), **valuable input to MC generators**
  - Best described by 4FS MG5aMC@NLO
- Dedicated studies of **impact of intrinsic charm (IC)**
  - 3 FS significantly underestimates rate
  - Sensitivity limited by Bjorken-x probed
  - **Largest impact seen with <u>Brodsky-Hoyer-Peterson-Sakai model</u>** fit 2 in CT14NNLO (2.1% IC, <u>https://arxiv.org/abs/1707.00657</u>)









Summary and conclusions

- The LHC and its experiments have **proven to be precision tools**, competitive with measurements of fundamental parameters at purpose-designed colliders such as LEP and SLD

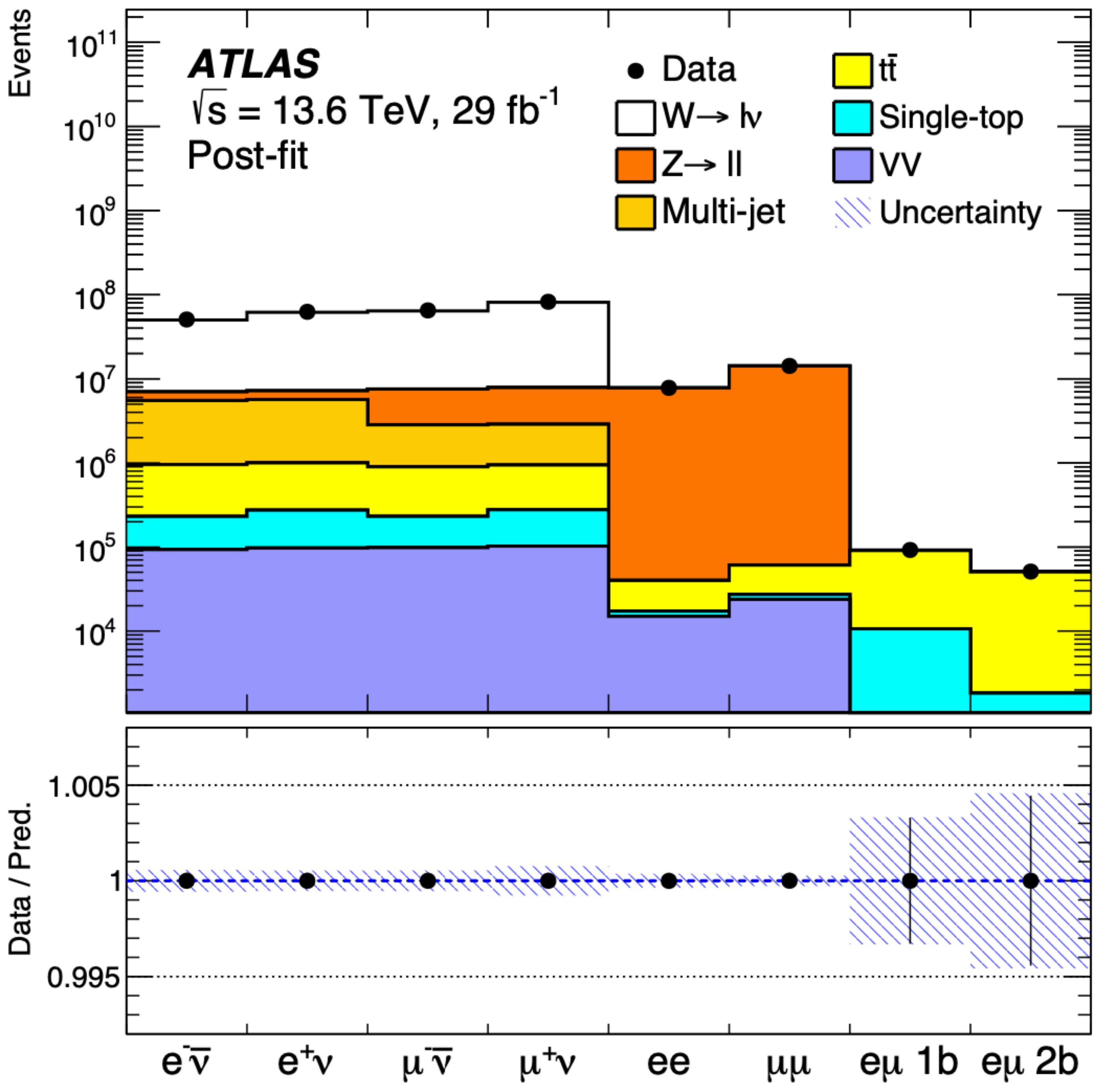
➡Thanks to years of collecting very high quality data, developing understanding of detector, and **incredible performance of theoretical tools**

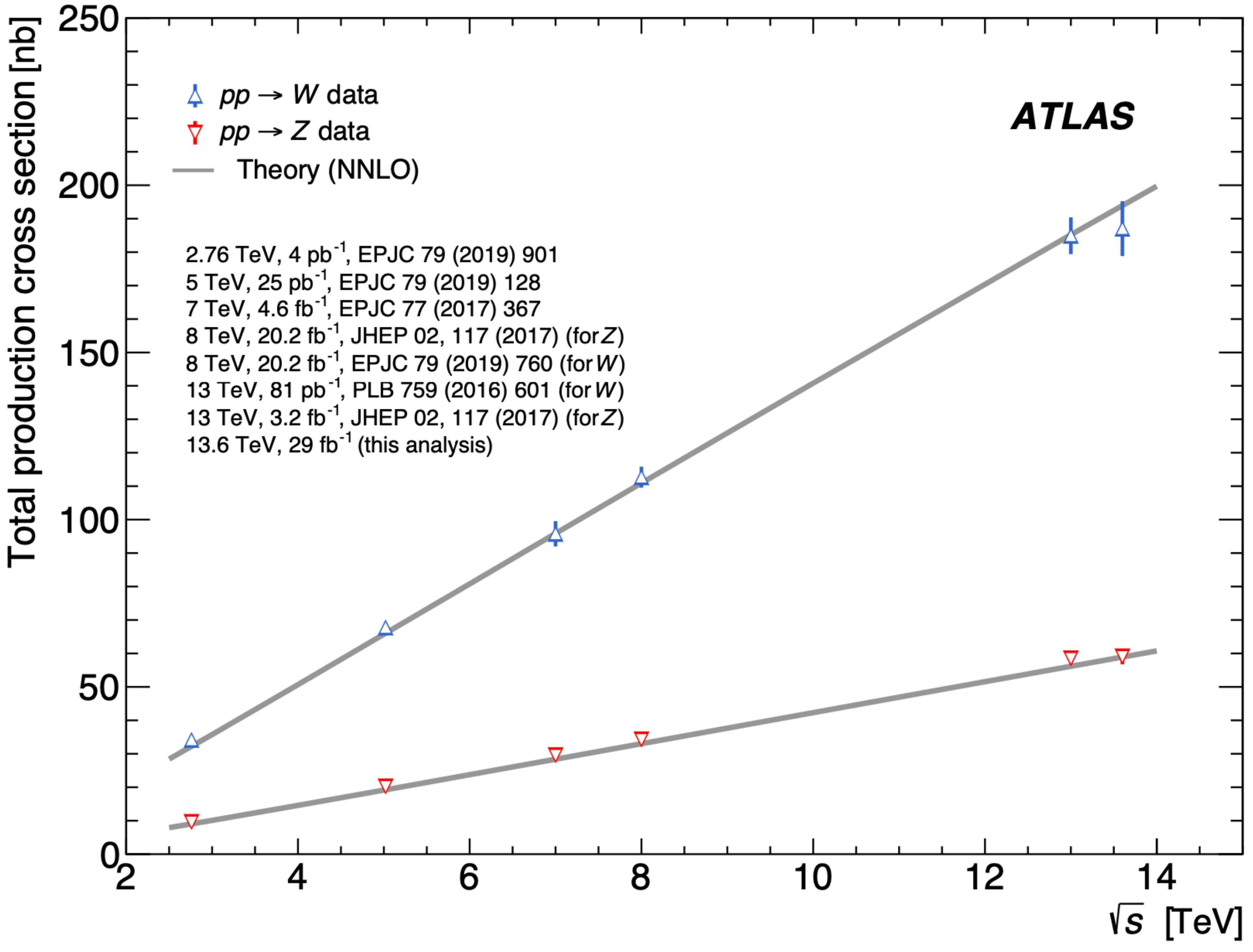
- The Run II (and Run I) data has proven rich environment for precise measurements. Run III and special runs are also providing new avenues of exploration

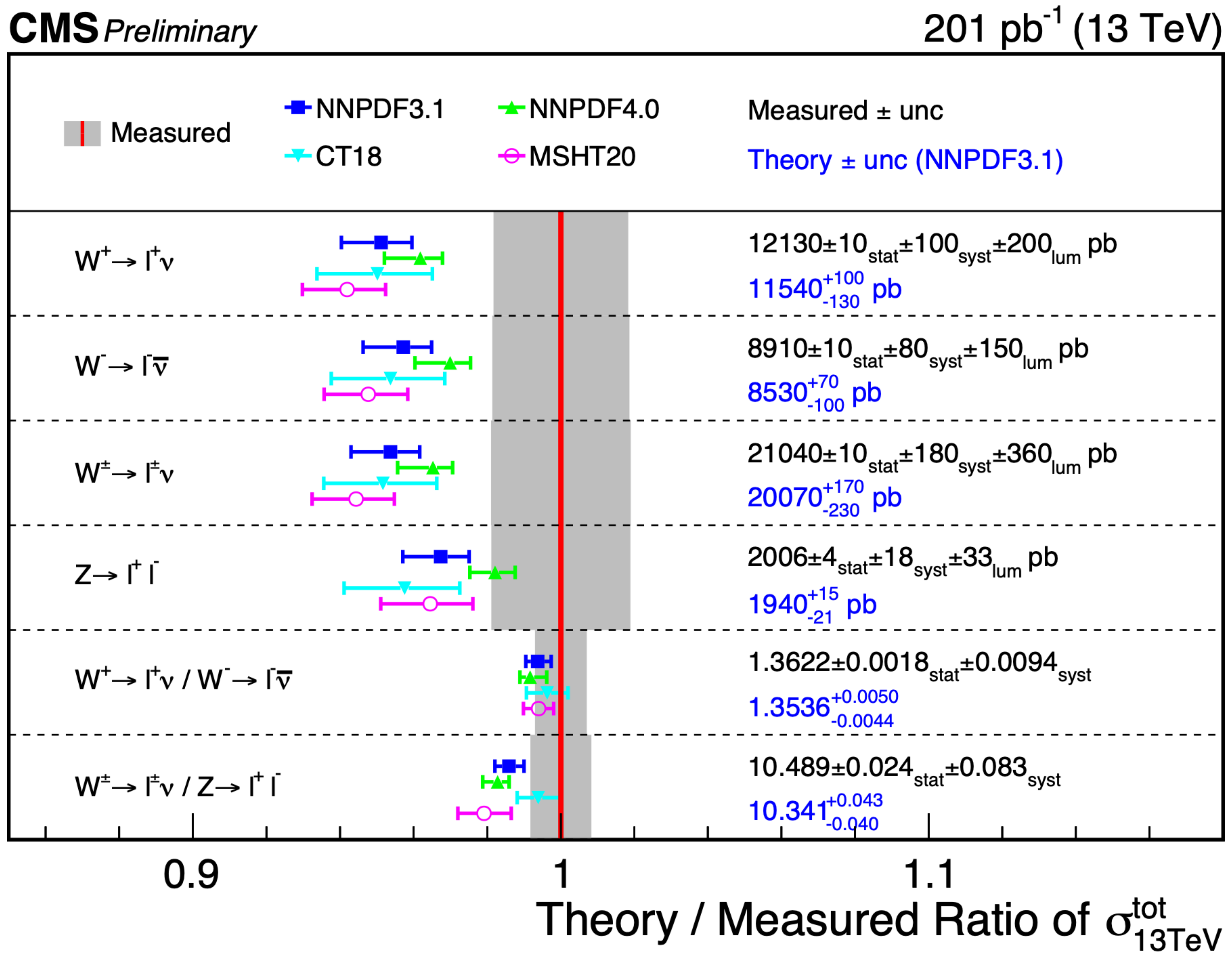
- Techniques built for precision physics become **increasingly relevant with huge data sets**, especially towards HL-LHC

Backup

W/Z cross sections







Electroweak precision: m_W and Γ_W at ATLAS

Width unc.

Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	m_W	PS
p_T^ℓ	71.8	27.3	66.4	21.2	13.9	10.4	4.9	13.2	11.5	12.0	9.6	6.3	55.2
m_T	47.5	35.5	31.6	4.9	6.6	9.6	3.3	13.2	9.2	17.6	9.1	5.5	12.1
Combined	46.8	32.0	34.1	6.7	7.5	9.4	3.3	13.1	9.4	16.7	9.1	5.6	17.7

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

Result with various PDFs

	p_T^ℓ fit				m_T fit			
PDF set	m_W	σ_{tot}	σ_{PDF}	χ^2/n.d.f.	m_W	σ_{tot}	σ_{PDF}	χ^2/n.d.f.
CT14	80358.3	$^{+16.1}_{-16.2}$	4.6	543.3/558	80401.3	$^{+24.3}_{-24.5}$	11.6	557.4/558
CT18	80362.0	$^{+16.2}_{-16.2}$	4.9	529.7/558	80394.9	$^{+24.3}_{-24.5}$	11.7	549.2/558
CT18A	80353.2	$^{+15.9}_{-15.8}$	4.8	525.3/558	80384.8	$^{+23.5}_{-23.8}$	10.9	548.4/558
MMHT2014	80361.6	$^{+16.0}_{-16.0}$	4.5	539.8/558	80399.1	$^{+23.2}_{-23.5}$	10.0	561.5/558
MSHT20	80359.0	$^{+13.8}_{-15.4}$	4.3	550.2/558	80391.4	$^{+23.6}_{-24.1}$	10.0	557.3/558
ATLASpdf21	80362.1	$^{+16.9}_{-16.9}$	4.2	526.9/558	80405.5	$^{+28.2}_{-27.7}$	13.2	544.9/558
NNPDF3.1	80347.5	$^{+15.2}_{-15.7}$	4.8	523.1/558	80368.9	$^{+22.7}_{-22.9}$	9.7	556.6/558
NNPDF4.0	80343.7	$^{+15.0}_{-15.0}$	4.2	539.2/558	80363.1	$^{+21.4}_{-22.1}$	7.7	558.8/558

Electroweak precision: m_W and Γ_W at ATLAS

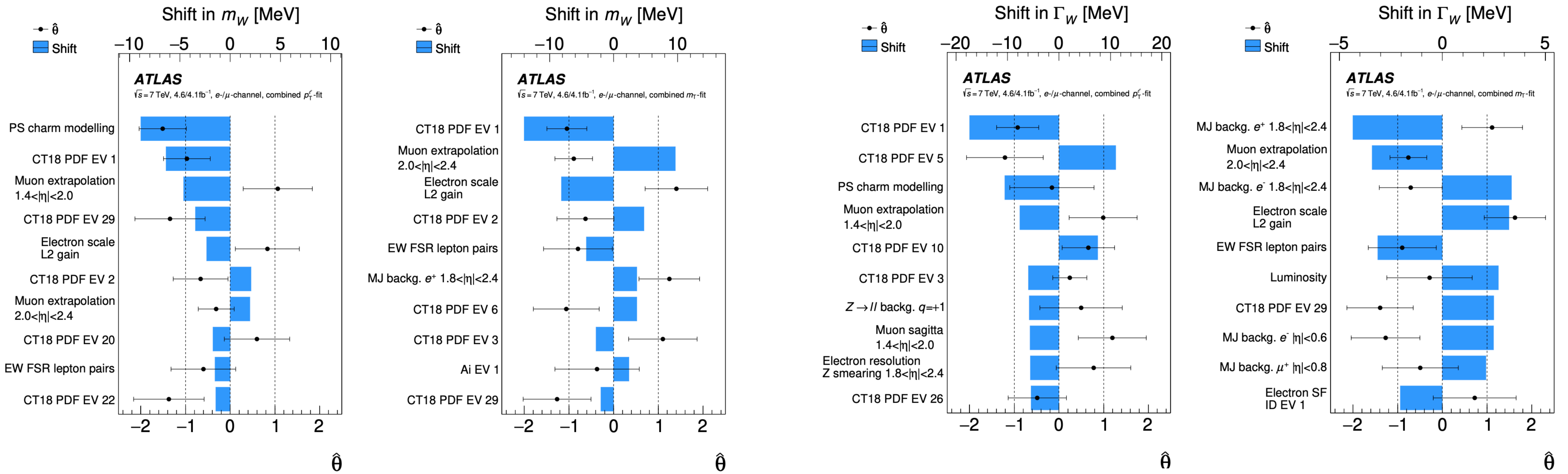


Table 5: Best-fit value of Γ_W, total and PDF uncertainties, in MeV, and goodness-of-fit for the p_T^ℓ and m_T distributions and the PDF sets described in the text. Each fit uses 14 event categories with 40 bins, for 558 degrees of freedom.

	p_T^ℓ fit				m_T fit			
PDF set	Γ_W	σ_{tot}	σ_{PDF}	χ^2/n.d.f.	Γ_W	σ_{tot}	σ_{PDF}	χ^2/n.d.f.
CT14	2228	$^{+67}_{-83}$	24	550.0/558	2202	$^{+48}_{-48}$	5	556.8/558
CT18	2221	$^{+68}_{-76}$	21	534.5/558	2200	$^{+47}_{-48}$	5	548.8/558
CT18A	2207	$^{+68}_{-75}$	18	533.0/558	2181	$^{+47}_{-48}$	5	550.6/558
MMHT2014	2155	$^{+71}_{-78}$	19	546.0/558	2186	$^{+48}_{-48}$	5	562.2/558
MSHT20	2206	$^{+66}_{-79}$	15	556.5/558	2179	$^{+47}_{-48}$	4	559.4/558
ATLASpdf21	2213	$^{+67}_{-73}$	18	531.3/558	2190	$^{+47}_{-48}$	6	545.6/558
NNPDF31	2203	$^{+65}_{-78}$	20	531.7/558	2180	$^{+47}_{-47}$	6	560.4/558
NNPDF40	2182	$^{+69}_{-68}$	12	550.5/558	2184	$^{+47}_{-47}$	4	564.0/558

Electroweak precision: ATLAS and CMS $\Gamma_{Z\rightarrow\nu\nu}$

CMS

Source of systematic uncertainty	Uncertainty (%)
Muon identification efficiency (syst.)	2.1
Jet energy scale	1.8–1.9
Electron identification efficiency (syst.)	1.6
Electron identification efficiency (stat.)	1.0
Pileup	0.9–1.0
Electron trigger efficiency	0.7
τ_h veto efficiency	0.6–0.7
p_T^{miss} trigger efficiency (jets plus p_T^{miss} region)	0.7
p_T^{miss} trigger efficiency ($Z/\gamma^* \rightarrow \mu\mu$ region)	0.6
Boson p_T dependence of QCD corrections	0.5
Jet energy resolution	0.3–0.5
p_T^{miss} trigger efficiency (μ+jets region)	0.4
Muon identification efficiency (stat.)	0.3
Electron reconstruction efficiency (syst.)	0.3
Boson p_T dependence of EW corrections	0.3
PDFs	0.2
Renormalization/factorization scale	0.2
Electron reconstruction efficiency (stat.)	0.2
Overall	3.2

ATLAS

Systematic Uncertainty	Impact on $\Gamma(Z \rightarrow \text{inv})$ in [MeV]	in [%]
Muon efficiency	7.4	1.5
Renormalisation & factorisation scales	5.9	1.2
Electron efficiency	4.9	1.0
Detector correction	4.4	0.9
QCD multijet	3.2	0.6
E_T^{miss}	2.4	0.5
$Z(\rightarrow \mu\mu)$+jets misid. lepton estimate	1.9	0.4
Jet energy resolution	1.6	0.3
$W(\rightarrow \ell\nu)$+jets normalisation	1.5	0.3
Pile-up reweighting	1.5	0.3
Non-collision background estimate	1.3	0.3
Jet energy scale	1.3	0.3
γ^*-correction	1.0	0.2
$Z(\rightarrow ee)$+jets misid. lepton estimate	1.0	0.2
Luminosity	1.0	0.2
Parton distribution functions + α_s	0.7	0.1
$\Gamma(Z \rightarrow \ell\ell)$ [5, 9]	0.5	0.1
Tau energy scale	0.4	0.1
Muon momentum scale	0.3	0.1
$W(\rightarrow \ell\nu)$+jets misid. lepton estimate	0.3	0.1
(Forward) jet vertex tagging	0.2	< 0.1
Top subtraction scheme	0.2	< 0.1
Electron energy scale	0.1	< 0.1
Systematic	12	2.4
Statistical	2	0.4
Total	13	2.5