W/Z precision and differential measurements

Fabrice Balli, CEA Saclay

Large Hadron Collider Physics Conference

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Recent results (uncovered in this talk)

- See Bogdan Malaescu's talk
  - W+charm at ATLAS — arXiv:2302.00336
  - W+charm at CMS — CMS-PAS-21-005
  - ATLAS : tt̄ / Z Cross-Section Ratio at 13.6 TeV (Run 3) — ATLAS-CONF-2023-006
- See Stefanos Leontsinis' talk
  - Z+b-jets at √s=13 TeV with CMS — Phys.Rev.D 105 (2022) 9, 092014
  - Z+b-jets at √s=13 TeV with ATLAS — arXiv:2204.12355
  - Z+c-jets at √s=13 TeV with LHCb — Phys.Rev.Lett. 128 (2022) 082001
- See Armando Bermúdez Martínez talk
  - Azimuthal correlations in Z+jets with CMS — arXiv:2210.16139
- See Jianqiao Deng's talk
  - LHCb : Search for the rare decays W+→D+sγ and Z→D0γ — LHCB-PAPER-2022-033
  - Z cross section at 5 TeV — NEW
- See V. Cherepanov's talk
  - CMS : $W \to \tau\nu$ decay branching fraction — Phys. Rev. D 105, 072008

Recent results (covered)

- ***CMS : Precision measurement of the Z boson invisible width at 13 TeV*** — CMS-SMP-18-014-003
- ***CMS : τ lepton polarization in Z boson decays*** — CMS-PAS-SMP-18-010

See also V. Cherepanov's talk

- ***CMS : Measurement of the mass dependence of the transverse momentum of lepton pairs in Drell-Yan production at 13 TeV*** — CMS-SMP-20-003
- ***ATLAS : Full phase space Z double differential cross-section (p_T, y) at 8 TeV and measurement of α_S*** — ATLAS-CONF-2023-013, ATLAS-CONF-2023-015
- ***ATLAS : W mass reanalysis at 7 TeV*** — ATLAS-CONF-2023-004

See also X. Li's talk

- ***ATLAS : W/Z p_T with low-pileup data at 5.02 TeV and 13 TeV*** — ATLAS-CONF-2023-028 NEW
- ***LHCb : Precision measurement of forward Z boson production at 13 TeV*** — LHCb-PAPER-2021-037

See also J. Deng's talk

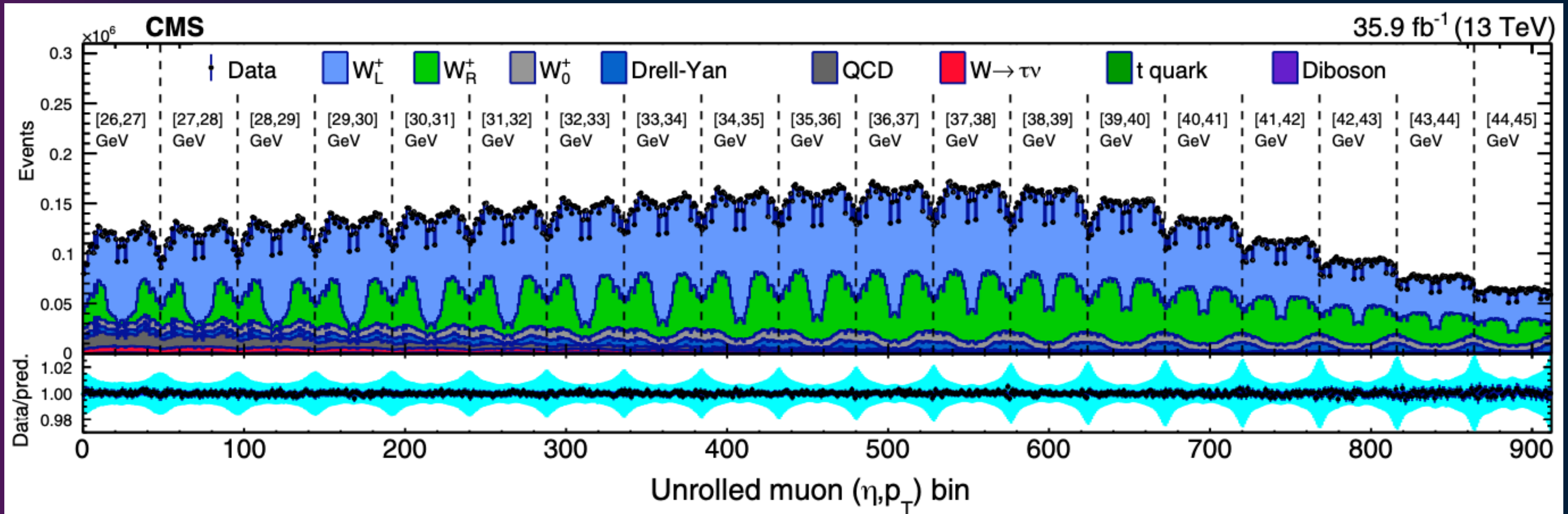
- ***LHCb : First measurement of Z→μμ angular coefficients in the forward region at 13 TeV*** — LHCb-PAPER-2021-048
- **LHCb : Z cross section at 5 TeV** — NEW

Introduction

- W/Z bosons known for decades, yet they have still a lot to tell : W mass, weak mixing angle, etc…
- Precision measurements help check the consistency of the Standard Model (SM) through the electroweak fit :
  - Example : measurements of W mass (m_W), $\alpha_{S,}$ weak mixing angle
  - Also give information on vacuum stability close to the Planck scale (m_{top}, α_S)
- Differential measurements give information on perturbative and non-perturbative QCD, in turn reducing modeling uncertainties in measurements of *e.g.* electroweak parameters
  - Examples :

    See also Tobias Neumann's talk

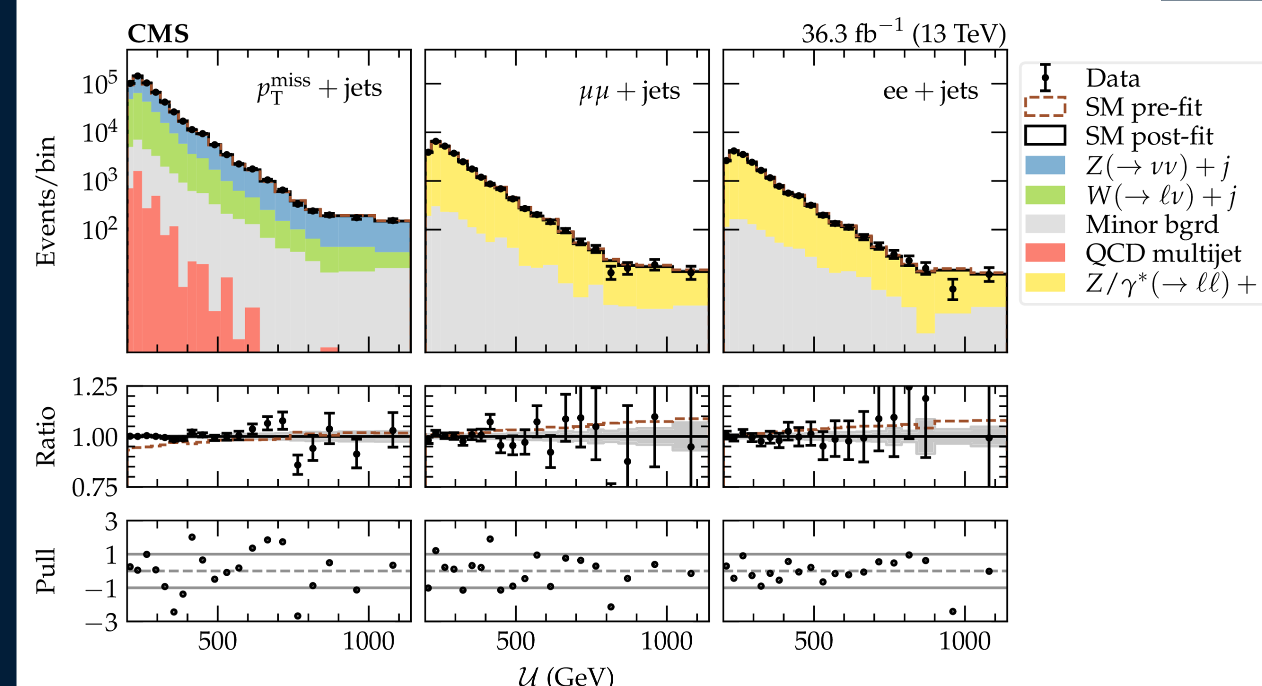
    - measuring W/Z p_T and boson angular coefficients decrease uncertainties in mW measurement
    - PDF constraints from W and Z differential cross-sections

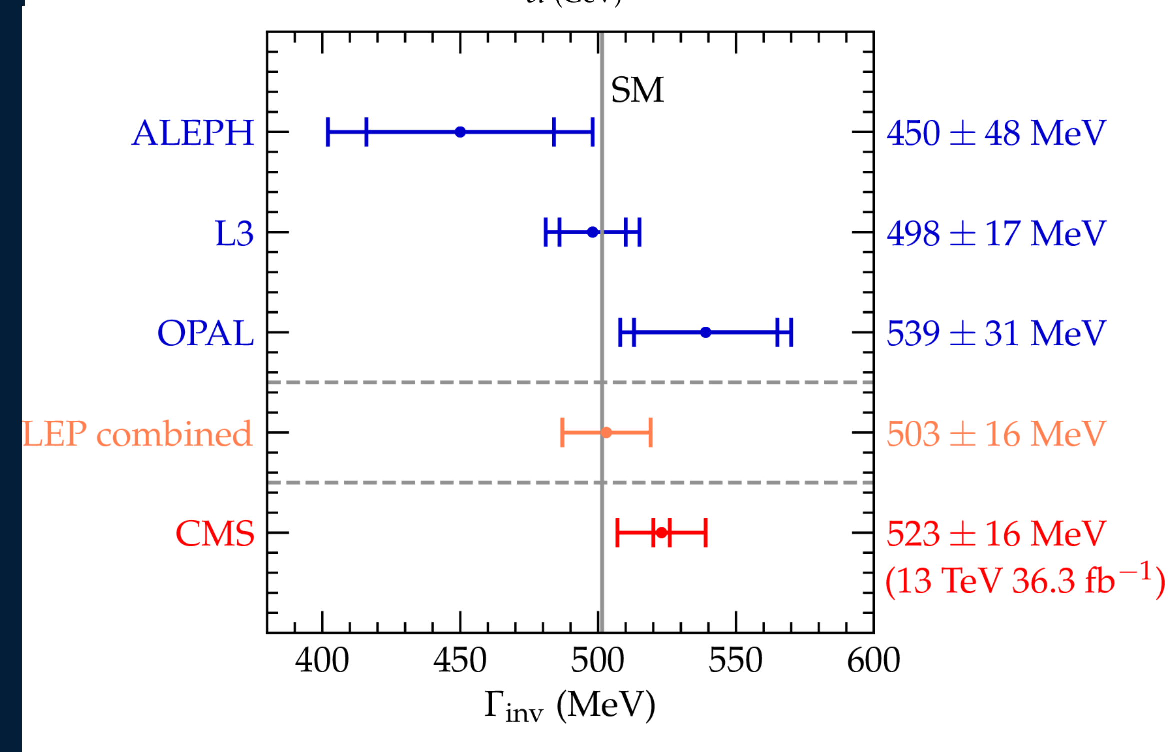


Precision measurement of the Z boson invisible width at 13 TeV

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

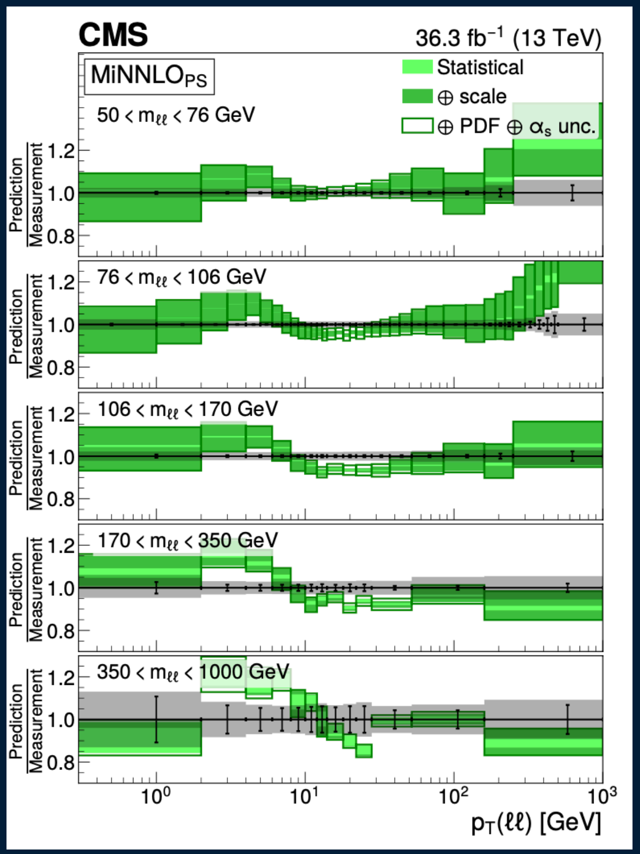
- Constraint on the number of light neutrino species
- Key ingredient : hadronic system recoiling against vector boson *(hadronic recoil),* u_T (required to be >200 GeV)
  - Enables to indirectly reconstruct the dineutrino transverse momentum in p_T^{miss} +jets:
    - $\vec{p}_T^{\,miss} = - \vec{u}_T$
- Simultaneous fit to hadronic recoil distribution in p_T^{miss} +jets, Z/γ*(μμ)+jets, Z/γ*(ee)+jets, μ+jets, and e+jets regions
  - l+jets used to determine W+jets in other regions
  - POI is r_{inv}, a scaling parameter for the Z → νν process relative to Z → ll
- **Result : Γ_{inv} = 523 ± 3 (stat) ±16 (syst) MeV**
  - **Best precision achieved, and first time in a hadron collider !**
  - Uncertainty dominated by lepton identification efficiency and jet energy scale

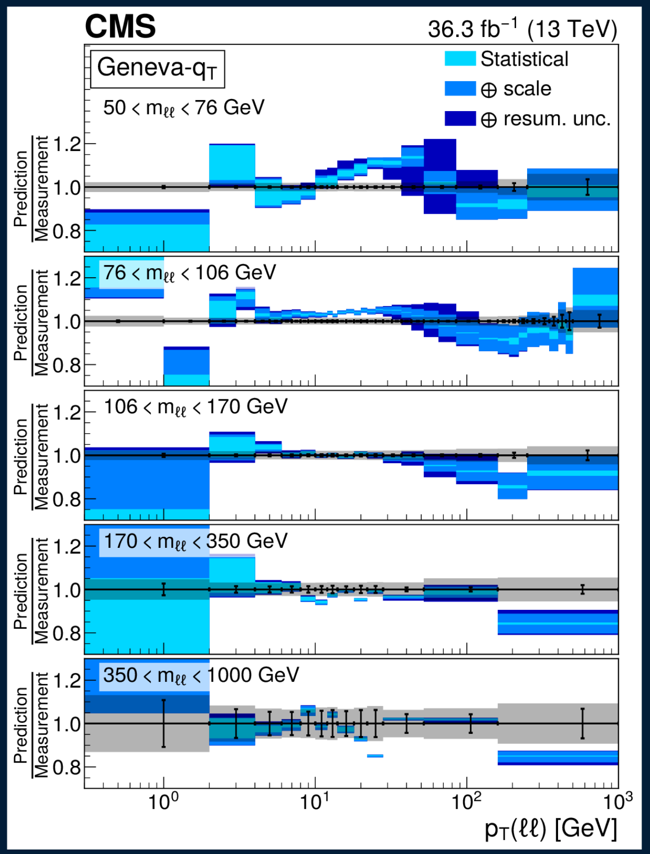


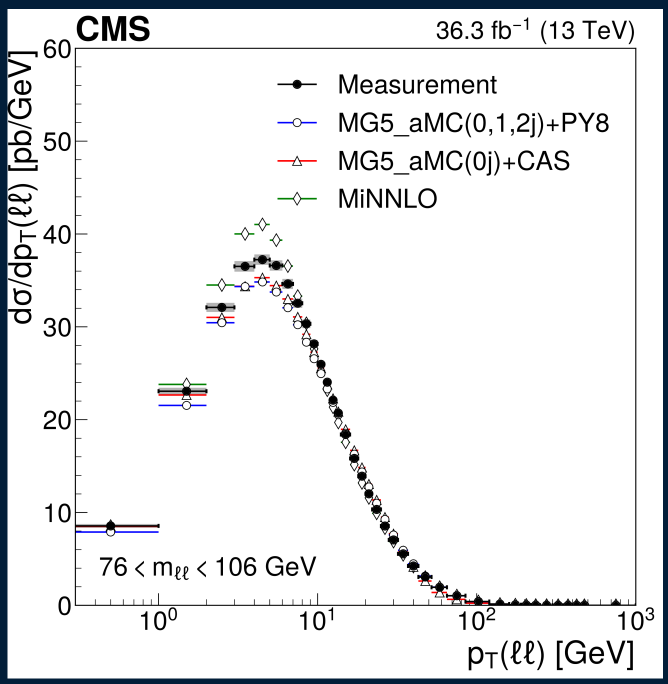


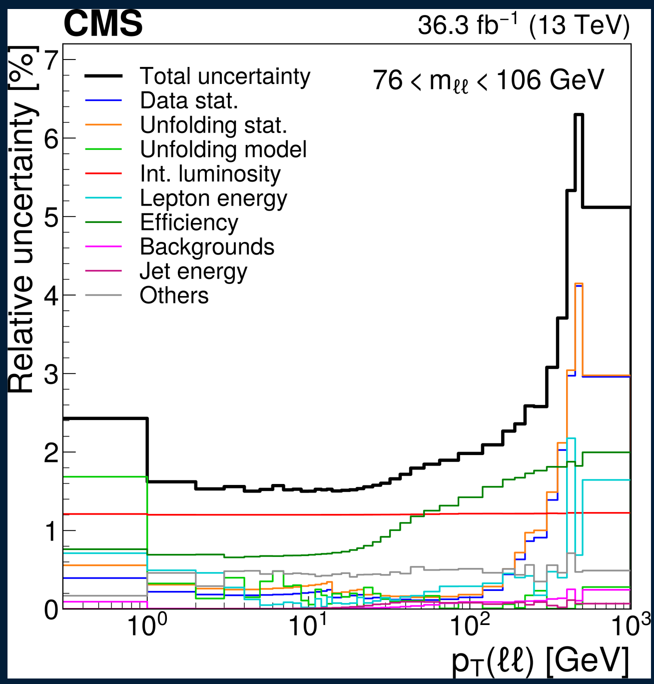
Measurement of the mass dependence of the transverse momentum of lepton pairs in Drell-Yan production at 13 TeV

- Measurement of φ^*_η, p_T in bins of m_{ll}, and ratios to the mass peak
  - Splitted in inclusive and >= 1 jet categories
- Comparison to a large variety of theory predictions
  - MadGraph5_aMC@NLO + PYTHIA 8 (tuned)
  - MiNNLO$_{PS}$: NNLO ME and Pythia8 PS and MPI
  - CASCADE 3 (parton branching TMD method)
    - TMDs from fit to HERA data
  - ArTeMiDe
    - TMD from fits to DY
  - GENEVA (2 types of resummation, NNLL and N3LL)
- Major input to modelling for precision electroweak measurements









τ polarization in Z boson decays

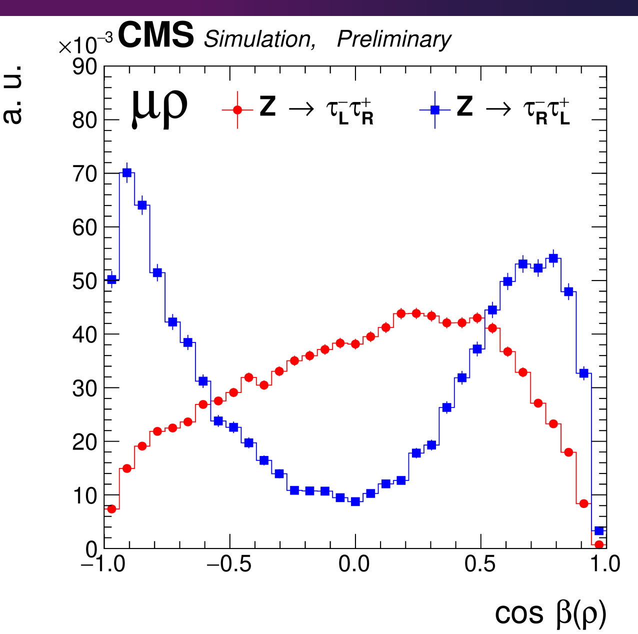
$$P_\tau = \frac{1}{\sigma}[\sigma(h_\tau = +1) - \sigma(h_\tau = -1)] \qquad P_\tau = -A_\tau = -\frac{2v_\tau a_\tau}{v_\tau^2 + a_\tau^2} \approx -2 \cdot \frac{v_\tau}{a_\tau} = -2(1 - 4\sin^2\theta_W^{\text{eff}}$$

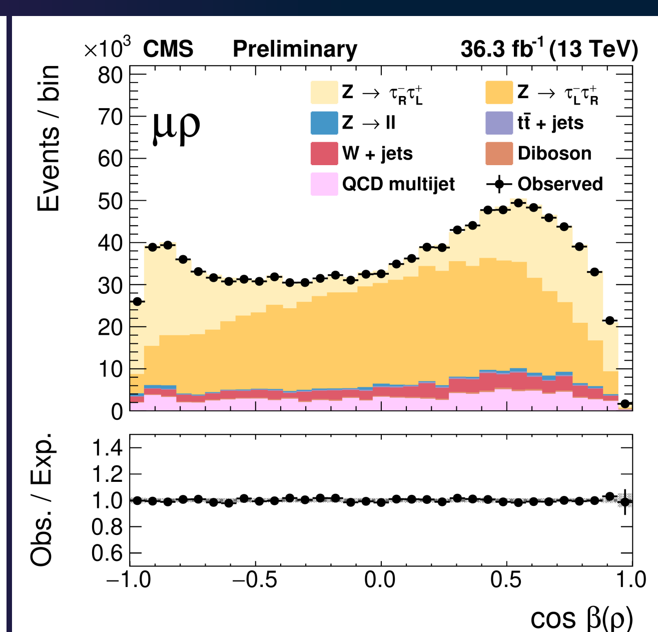
Final state	Trigger	Lepton selection	Additional selection	
$\tau_h\tau_h$	τ_h (35 GeV)τ_h (35 GeV)	$p_T^{\tau_h} > 45(40)$ GeV, $\lvert\eta^{\tau_h}\rvert < 2.1$	Med DeepTau iso	
$\tau_\mu\tau_h$	μ(22 GeV) or μ(19 GeV)τ_h (20 GeV)	$p_T^\mu > 23$ GeV, $\lvert\eta^\mu\rvert < 2.1$ $p_T^\mu > 20$ GeV, $p_T^{\tau_h} > 30$ GeV, $\lvert\eta^{\tau_h}\rvert < 2.3$	$I_{rel}(\mu) < 0.15$ Med DeepTau iso	$m_T^\mu < 50$ GeV
$\tau_e\tau_h$	e(25 GeV)	$p_T^e > 30$ GeV, $\lvert\eta^e\rvert < 2.1$ $p_T^{\tau_h} > 30$ GeV, $\lvert\eta^{\tau_h}\rvert < 2.3$	$I_{rel}(e) < 0.15$ Med DeepTau iso	$m_T^e < 50$ GeV
$\tau_e\tau_\mu$	μ(8 GeV)e(23 GeV) or μ(23 GeV)e(12 GeV)	$p_T^e > 15$ GeV, $\lvert\eta^e\rvert < 2.4$ $p_T^\mu > 15$ GeV, $\lvert\eta^\mu\rvert < 2.4$ $p_T^\ell > 24$ GeV for lead trigger leg	$I_{rel}(e) < 0.15$ $I_{rel}(\mu) < 0.20$	

2016 dataset, 36.3 fb-1

MC signal : MADGRAPH5 aMC@NLO

- Motivation :
  - foundation for **τ** polarisation measurements in Higgs—>**ττ**
  - Helps separation with signals in **ττ** final state searches
  - Can measure **τ** lepton asymmetry and infer weak mixing angle





- Use of DeepTau MVA discriminant to separate hadronic **τ** from jets, electrons, muons
- ABCD method to determine MJ and W+jets backgrounds
- Analysis relies on angular distributions of decay hadrons and leptons with respect to mother particle
  - Combined into **one** optimised observable per event category without loss of sensitivity

τ polarization in Z boson decays

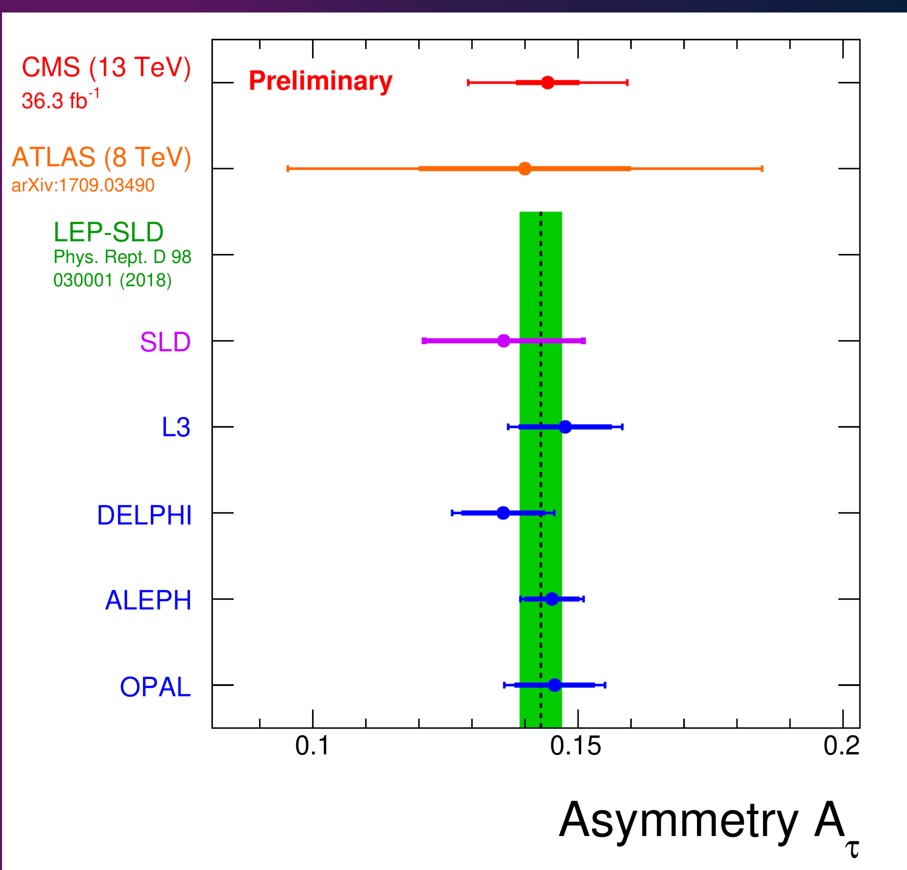
- Polarisation measured in several eta categories and nearly all **τ** decay modes
    - Strengthen confidence in modelling aspects!
- Asymmetry compatible with SLD and LEP, reaches best precision at LHC

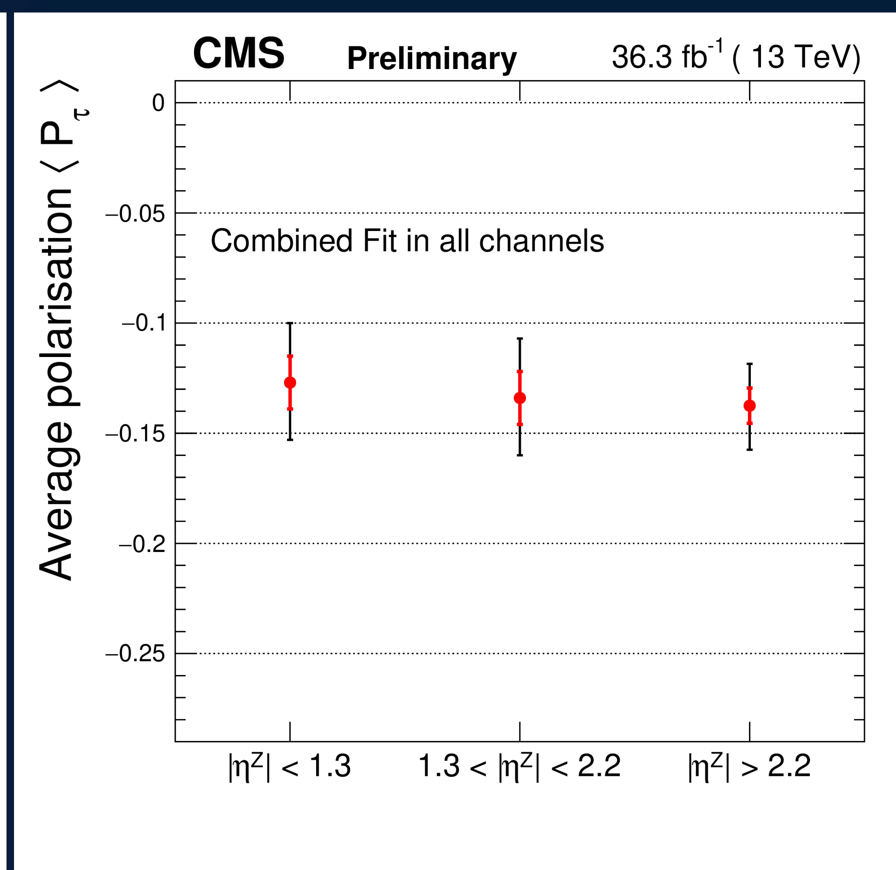
Channel	Category	Discriminat
$\tau_e\tau_\mu$	$e+\mu$	$m_{vis}(e,\mu)$
$\tau_e\tau_h$	$e+a_1$	$\omega(a_1)$
	$e+\rho$	$\omega_{vis}(\rho)$
	$e+\pi$	$\omega(\pi)$
$\tau_\mu\tau_h$	$\mu+a_1$	$\omega(a_1)$
	$\mu+\rho$	$\omega_{vis}(\rho)$
	$\mu+\pi$	$\omega(\pi)$
$\tau_h\tau_h$	a_1+a_1	$m_{vis}(a_1,a_1)$
	$a_1+\pi$	$\Omega(a_1,\pi)$
	$\rho+\tau_h$	$\omega_{vis}(\rho)$
	$\pi+\pi$	$m_{vis}(\pi,\pi)$

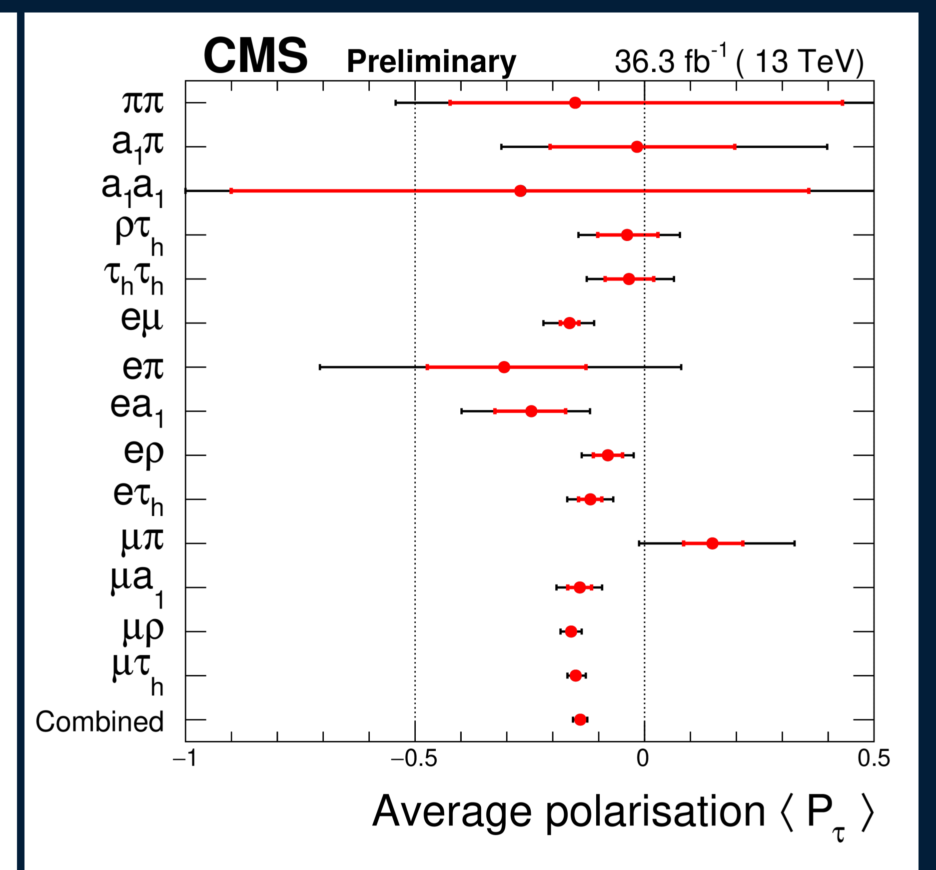
$$\mathcal{P}_\tau(Z^0) = -0.144 \pm 0.015 = -0.144 \pm 0.006\,(\text{stat}) \pm 0.014\,(\text{syst}).$$

Most precise measurement at LHC!

$$\sin^2\theta_W^{\text{eff}} = 0.2319 \pm 0.0019 = 0.2319 \pm 0.0008\,(\text{stat}) \pm 0.0018\,(\text{syst})$$



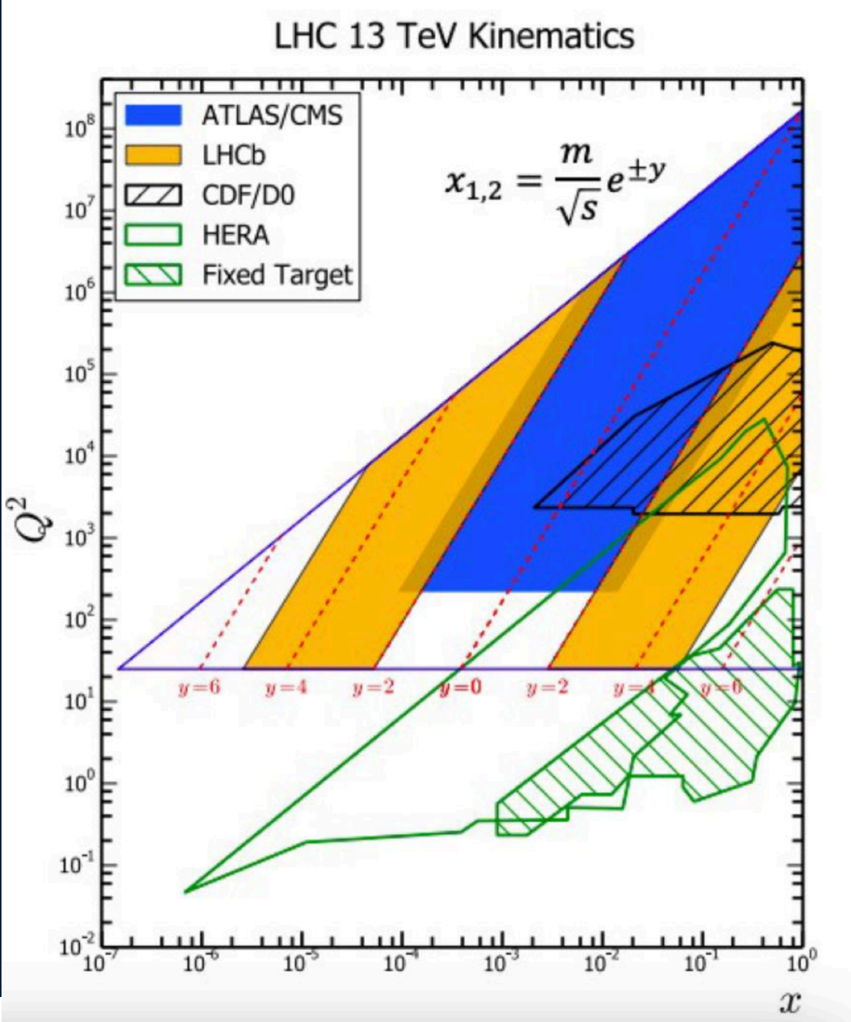




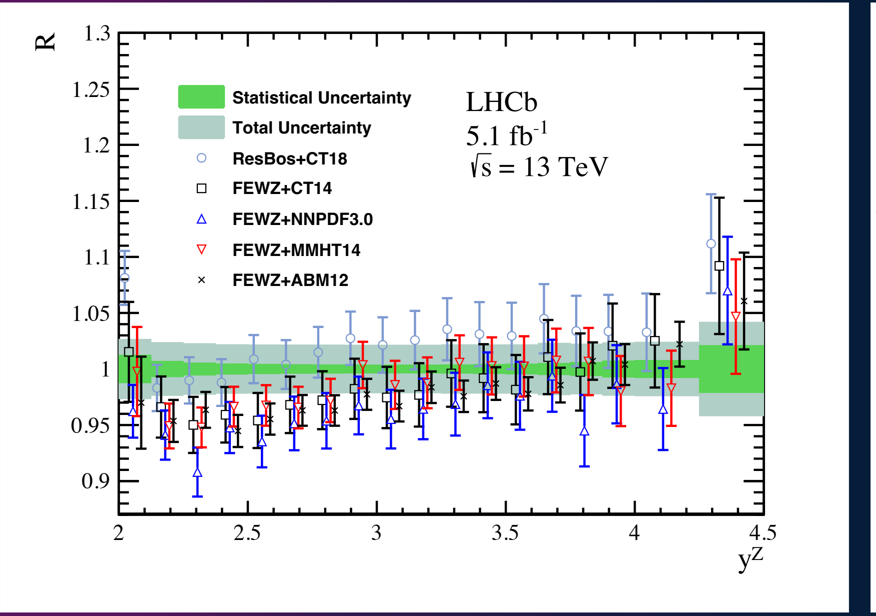
Precision measurement of forward Z boson production at 13 TeV

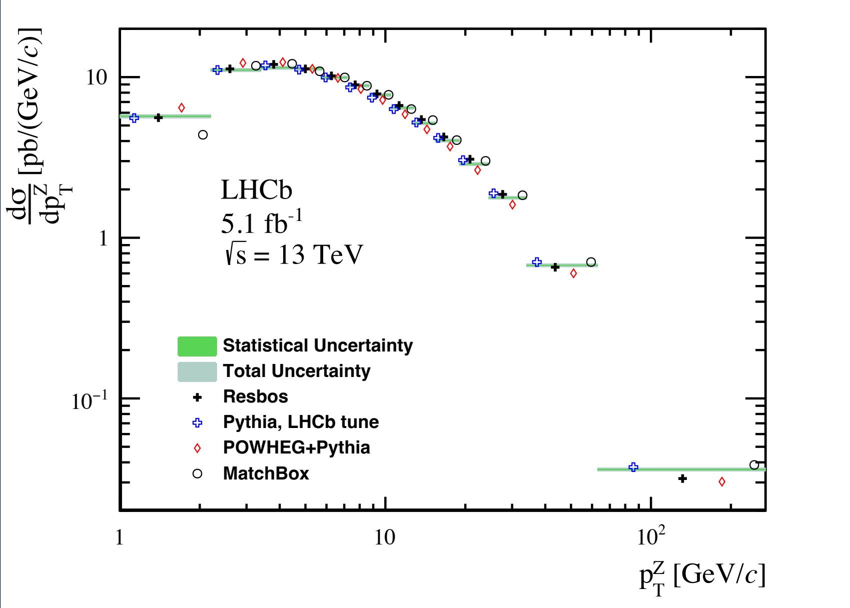
See also A.B. Martinez talk

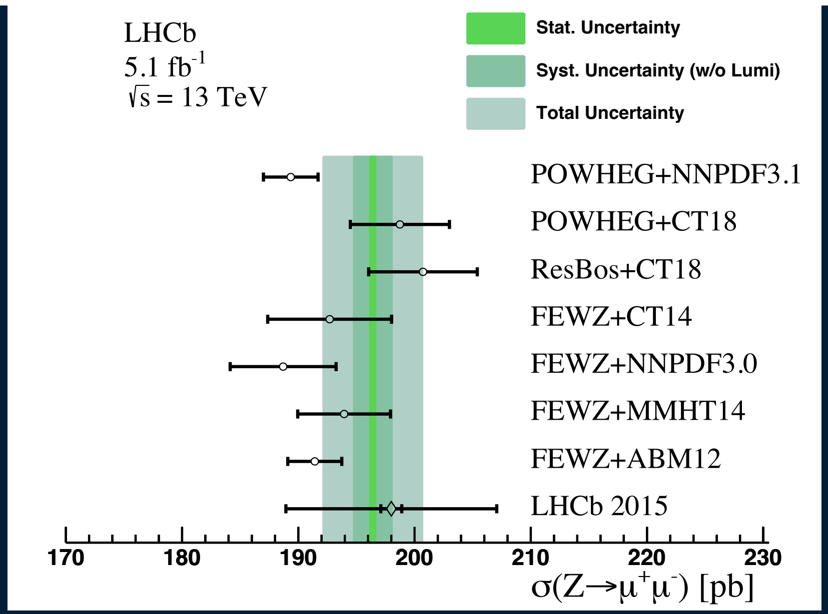
- 5.1 fb^{-1} collected in 2016, 2017, 2018
- Differential cross-section in y, φ^*_η, p_T
  - In slices of rapidity for the latter two (double differential)
- Major input to constrain PDF uncertainties at large and small x in m_W and $sin^2\theta_W$
- Most precise integrated fiducial cross-section in the forward region



$$\phi^*_\eta = \tan((\pi - \Delta\phi^{\ell\ell})/2)\sin(\theta^*_\eta)$$

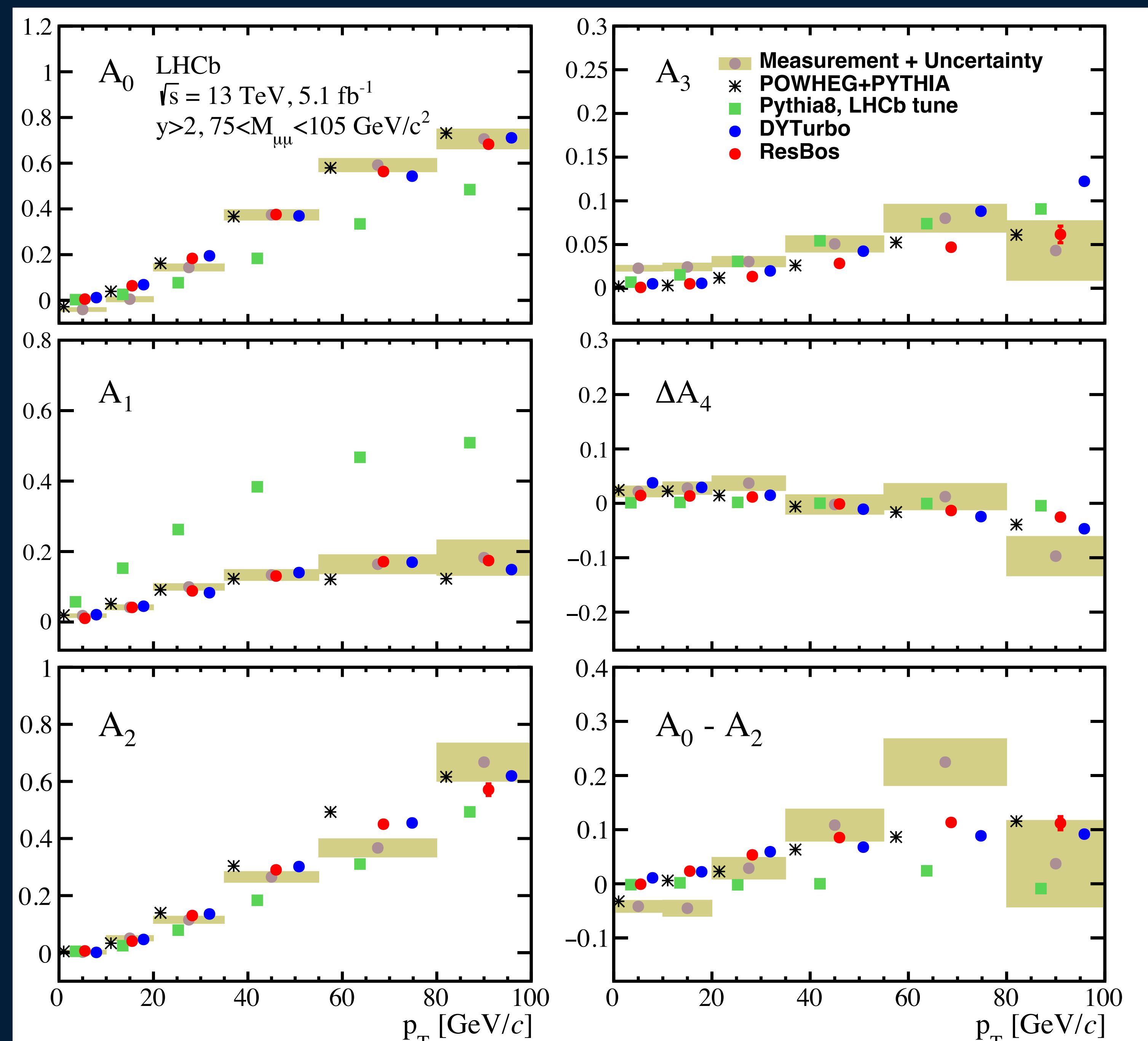






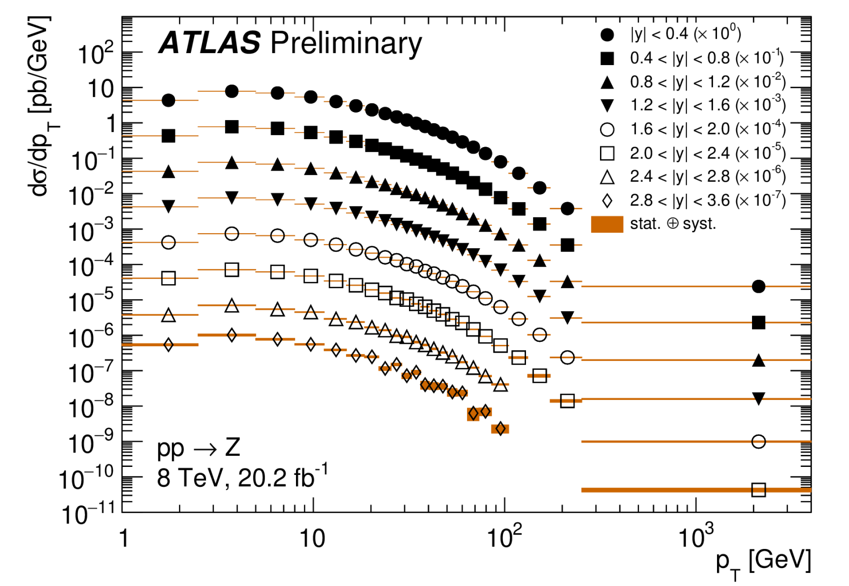
First measurement of $Z \rightarrow \mu\mu$ angular coefficients in the forward region at 13 TeV

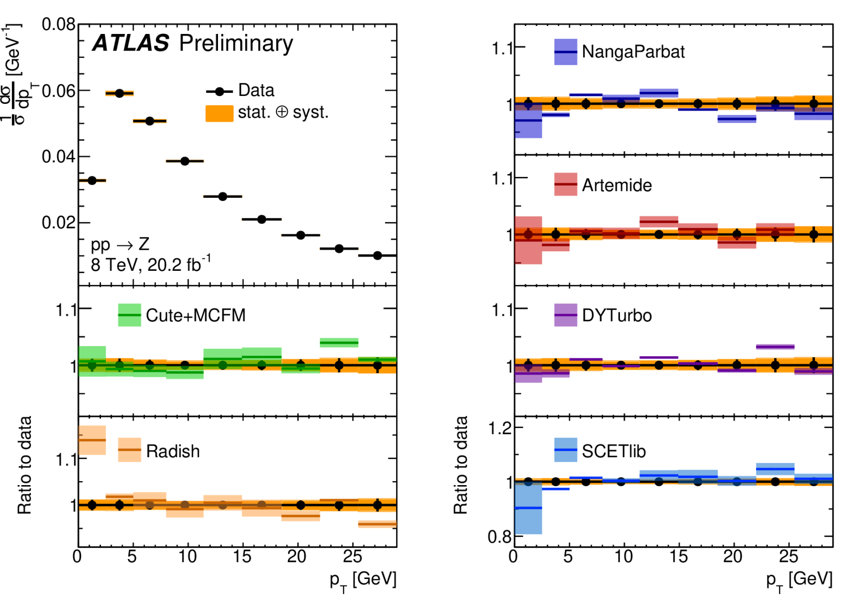
- Z A_i coefficients in 2<y<5
    - Also measured in the low-mass region
- Fit of the two decay angles cos(θ) and φ
    - A_{0-4} are the free parameters
- PDF uncertainty from CT18NNLO eigensets
- Pythia8 deviates from measurement at high p_T, others are in reasonable agreement
- Lam-Tung violation clearly observed



$$\frac{d\sigma}{d\cos\theta d\phi} \propto (1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi + \frac{1}{2}A_2 \sin^2\theta \cos 2\phi$$
$$+A_3 \sin\theta\cos\phi + A_4\cos\theta + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta\sin\phi,$$

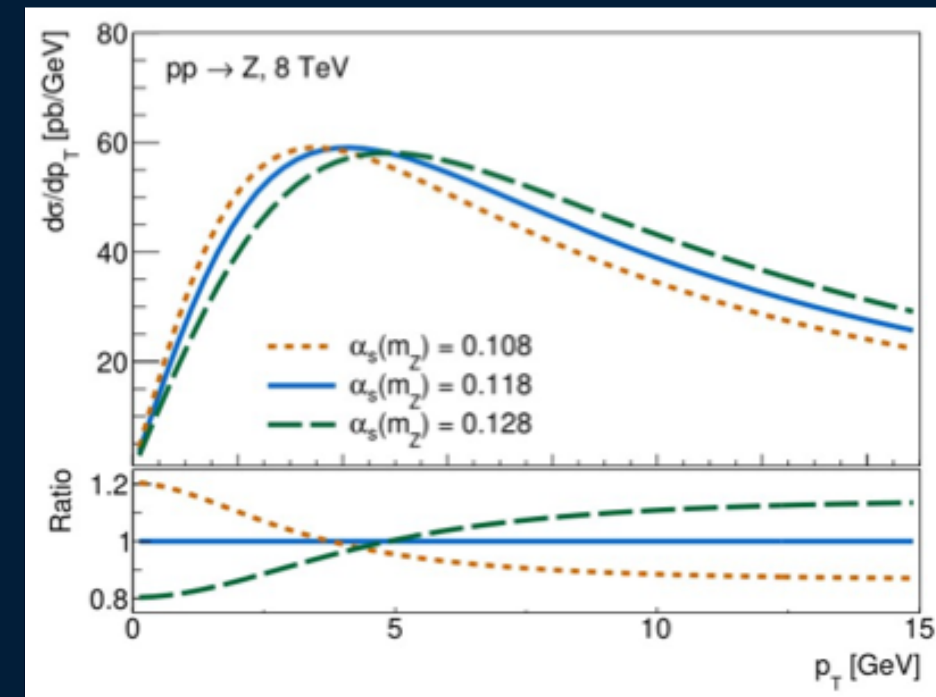
Full phase space Z double differential cross-section (p_T, y)

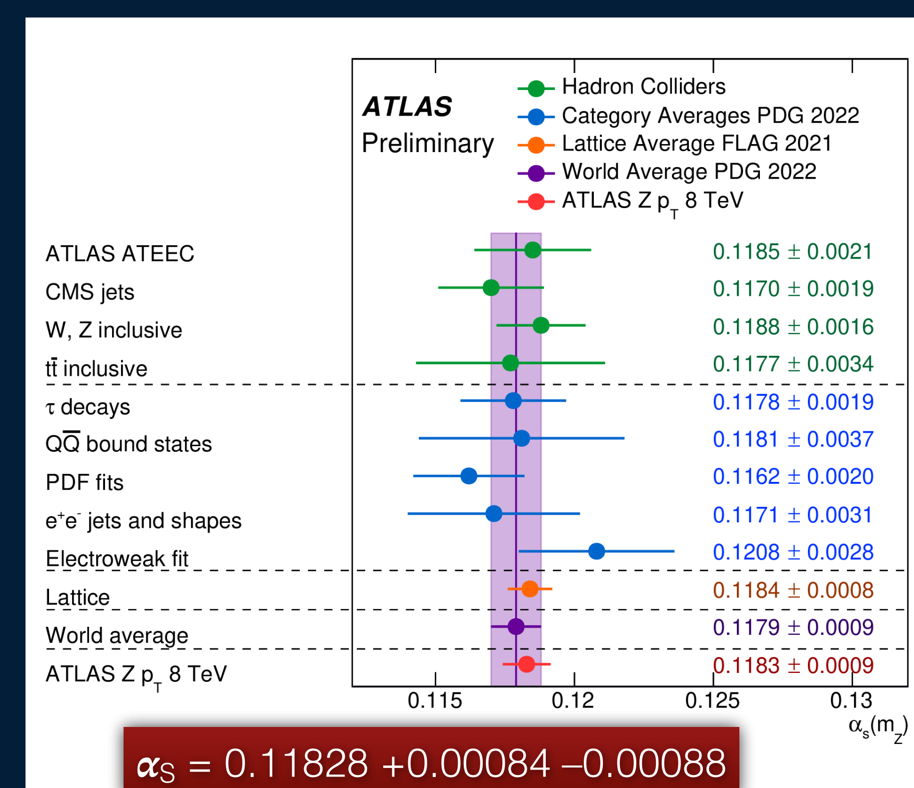




- Measurement in 22528 bins of (cos θ, ϕ, p_T, y) *extrapolated from fiducial volume to full phase space through measurement of* Ais, double differential in (p_T,y)
- **p_T(Z) comparison with N4LL** : good agreement (strong effort in LPCC)
- Subsequent measurement of α_S :

  most precise experimental measurement, and first time using N3LO+N4LL p_T(Z) predictions

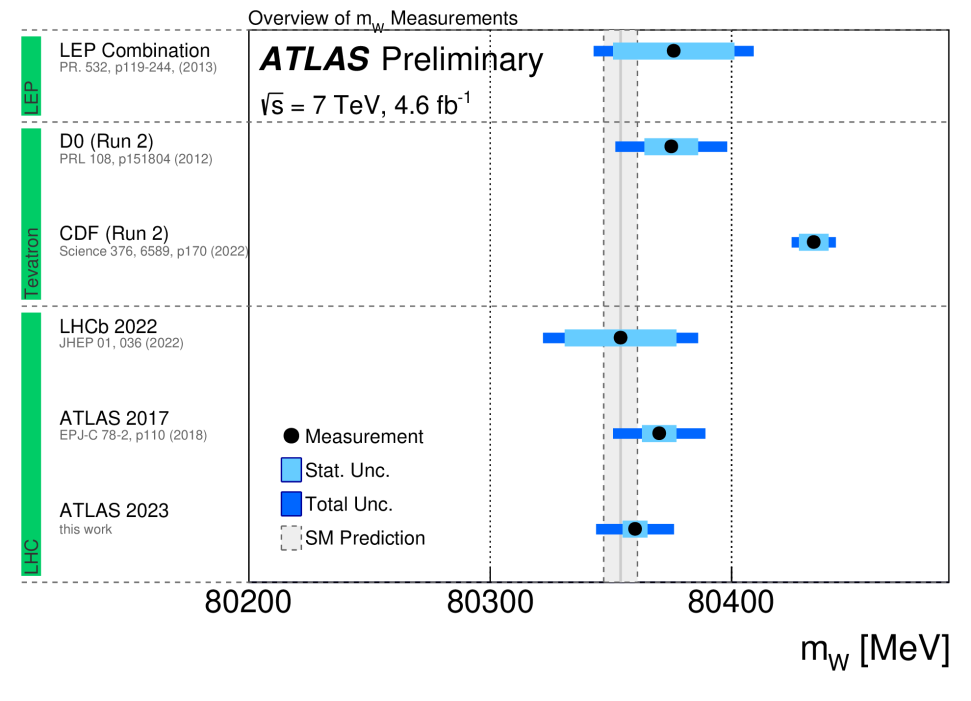


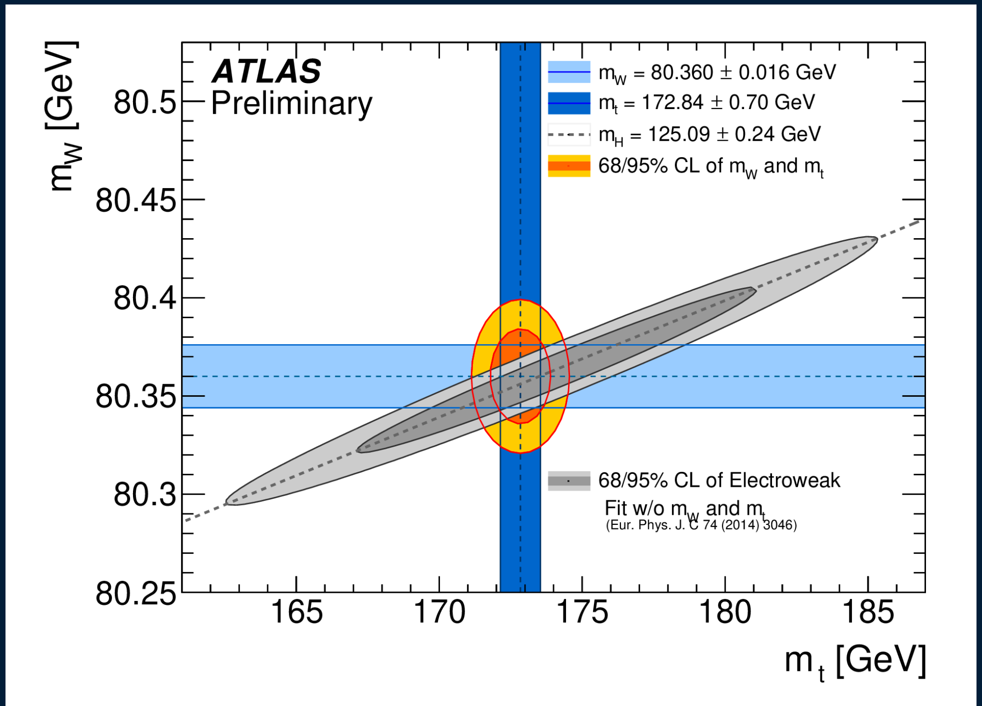


- Resummation needed at low p_T(Z) to take care of the divergences induced by soft and collinear emissions in fixed-order predictions —> Sudakov peak, sensitive to value of α_S
- Fit uses a profiled χ^2 to the Z (p_T,y) measurement for p_T(Z) < 29 GeV
- Dominant uncertainties from PDFs, experimental, and scale variations

m_W reanalysis at 7 TeV

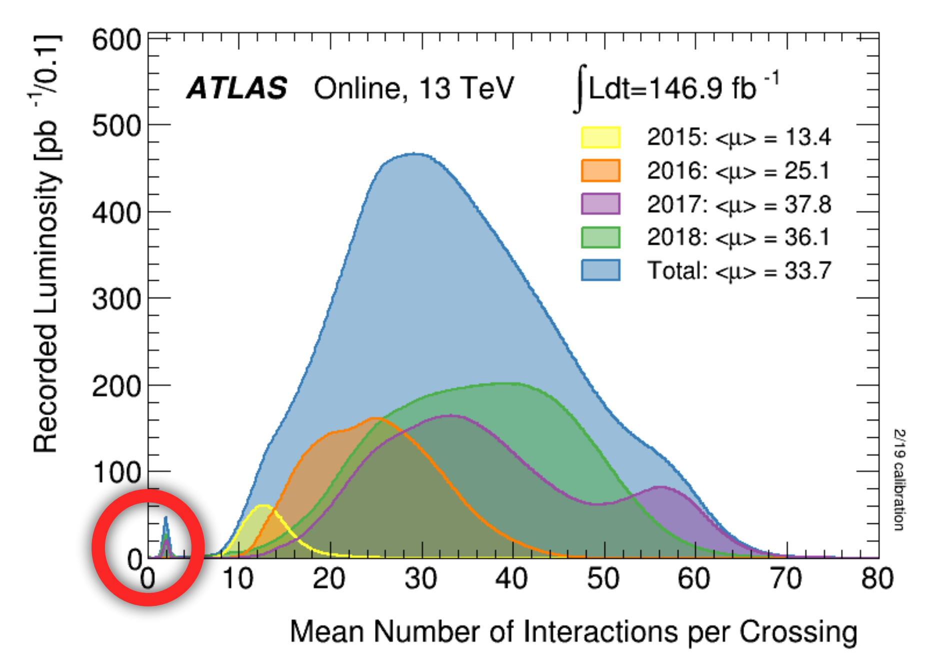
- Motivation : EW fit, indirect BSM searches, need for independent confirmation of CDF result
- Makes large use of detector calibration from initial result
- Result : **m_W = 80360 ± 5 (stat.) ± 15 (syst.) = 80360 ± 16 MeV**
    - Reduction of total uncertainty by 15 % with respect to initial measurement
- Pulls the value closer to the SM prediction from EW fit, as compared to the previous 2017 result
- Improvements in :
    - PDF set (CT10NNLO —> CT18NNLO)
    - **Statistical analysis** (χ^2 offset —> profile likelihood)
        - W width added as NP parameter
    - Multijet background
    - EW uncertainties (detector level)
- Dominant uncertainties : lepton calibration, PDFs



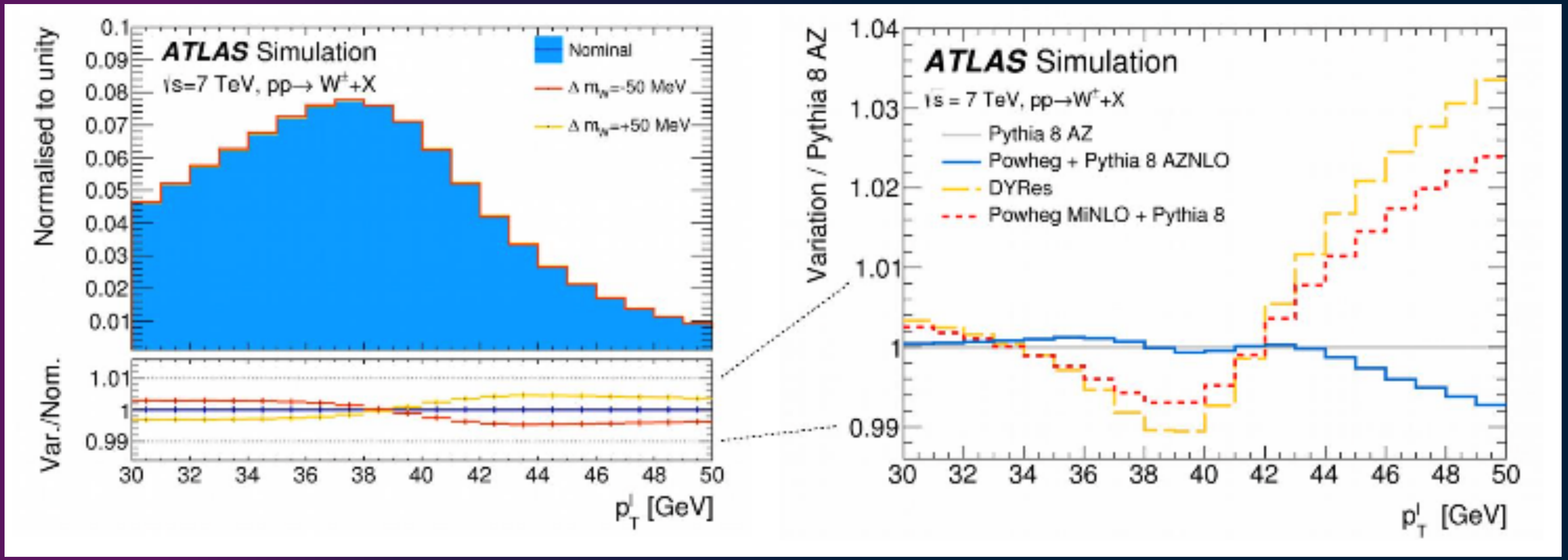


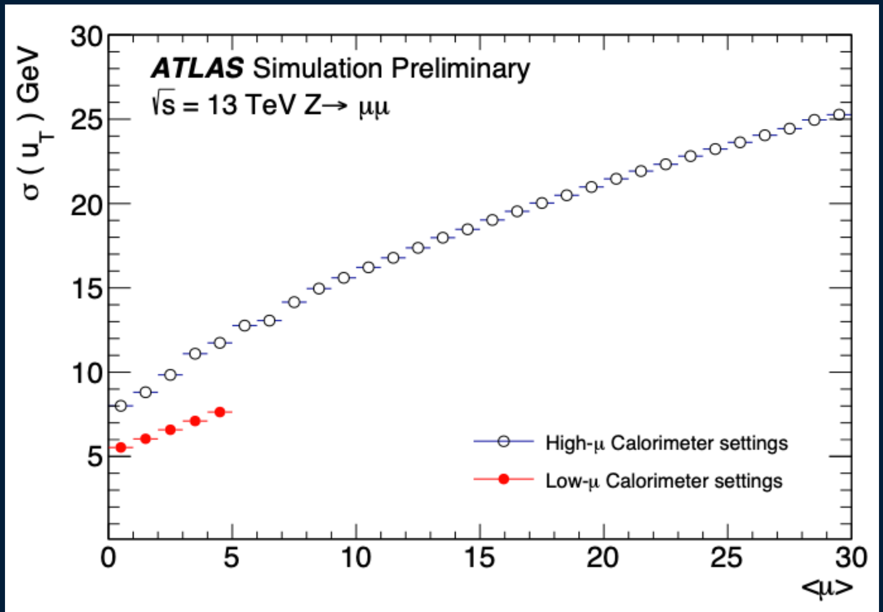
W and Z p_T with low-pileup data

- Data with $<\mu>$ ~2 taken in 2017 and 2018
  - 255 pb^{-1} at 5.02 TeV and 338 pb^{-1} at 13 TeV
- Opportunity to probe QCD (perturbative and non perturbative) in clean W events (missing p_T resolution) and in Z at 5.02 TeV



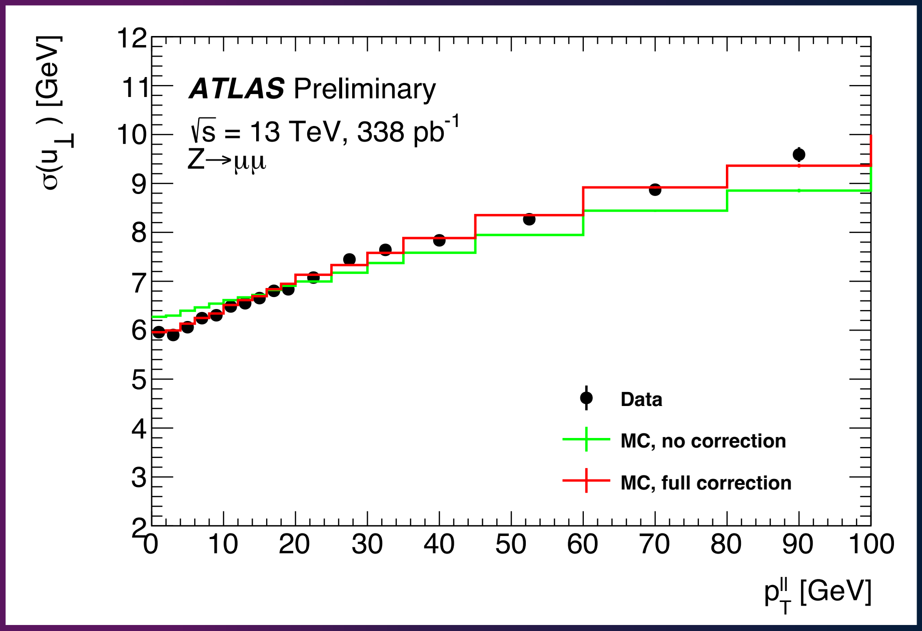
- Main motivation to $p_T(W)$ is to reduce the related modelling uncertainty in m_W measurements
  - Avoid relying on the $p_T(Z)$ measurement (needs assumptions on the extrapolation to W, $p_T(W)/p_T(Z)$ predicted by theory)
- Required dedicated effort on physics modelling and **detector calibration**

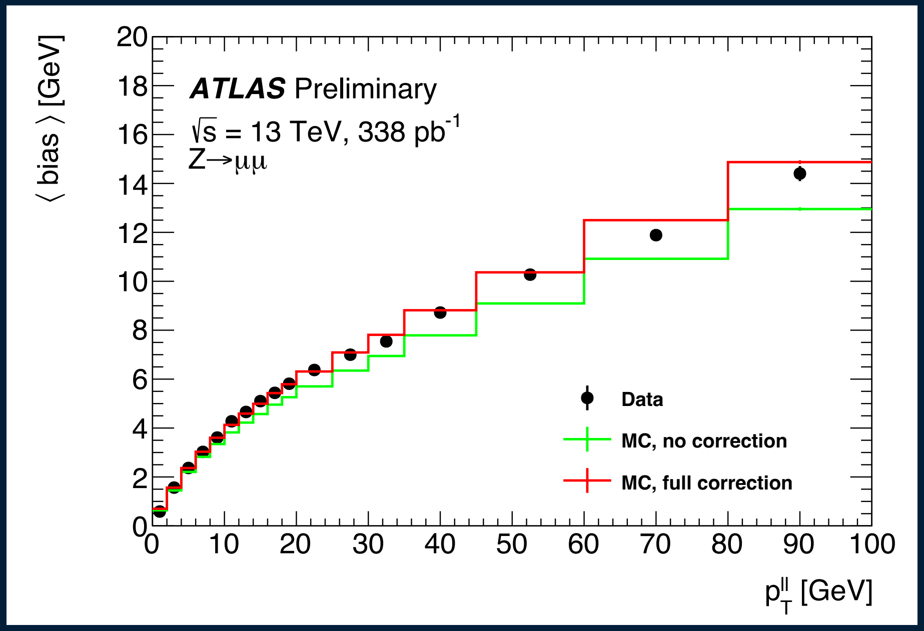




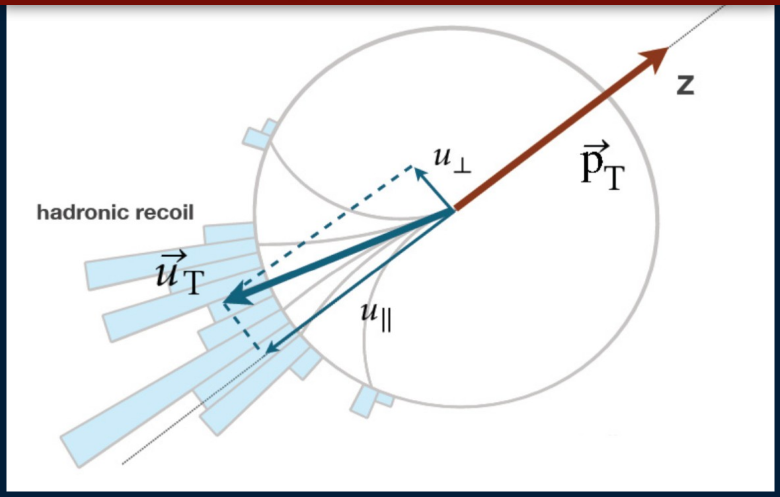
Detector calibrations

- Key ingredient (again!) : hadronic system recoiling against vector boson *(hadronic recoil)*, u_T
  - Enables to indirectly reconstruct the neutrino transverse momentum in W $\vec{p}_T^{miss} = -(\vec{u}_T + \vec{p}_T^{\ell})$
- Change in reconstruction w.r.t. m_W implementation
  - Uses particle flow objects (PFOs) —> improved resolution
- Calibration of recoil *in-situ* in Z events
  - Modeling of underlying activity
  - Response and resolution corrections, azimuthal angle
- Lepton calibration uses high pileup data extrapolated to low-pileup conditions wherever possible, otherwise in-situ calibrations, using standard ATLAS techniques





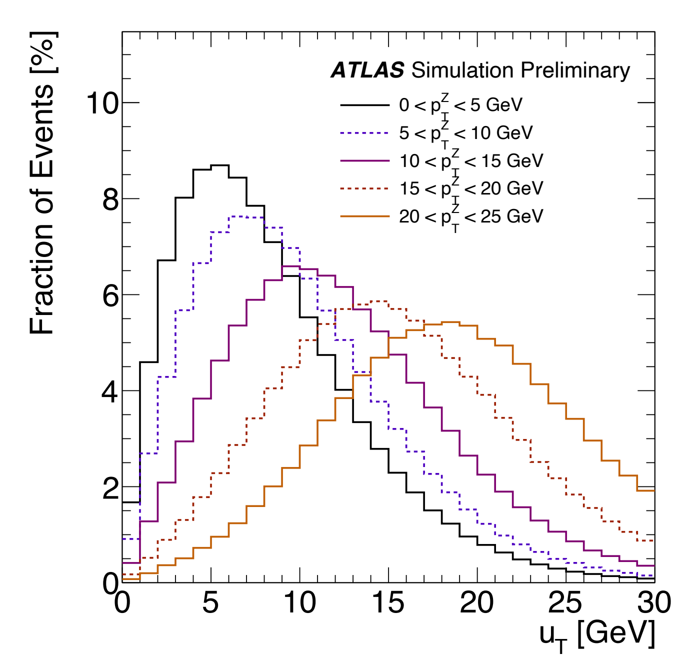
$\vec{u}_T$: vector sum of PFOs and excluding lepton deposits

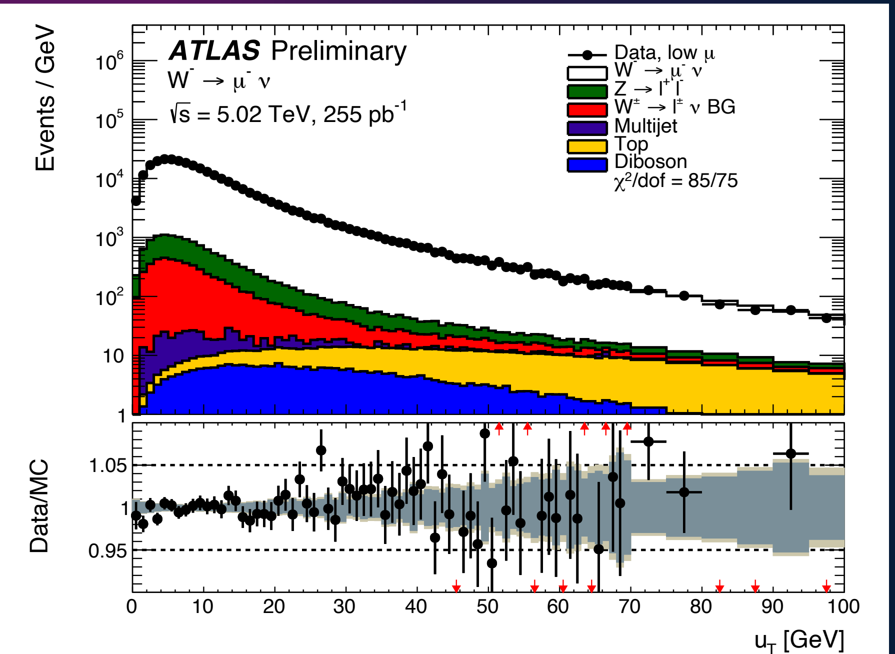


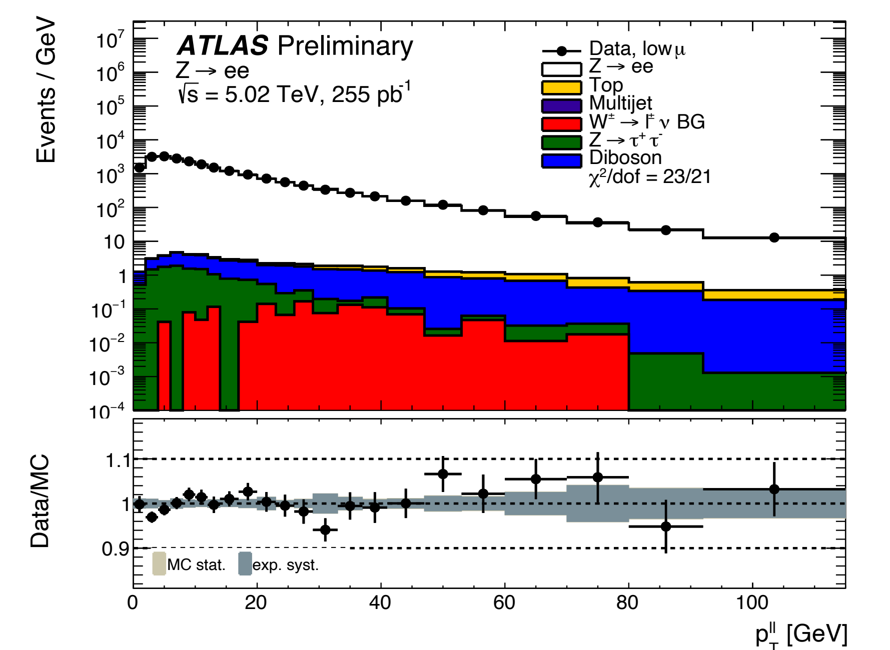
Analysis methodology

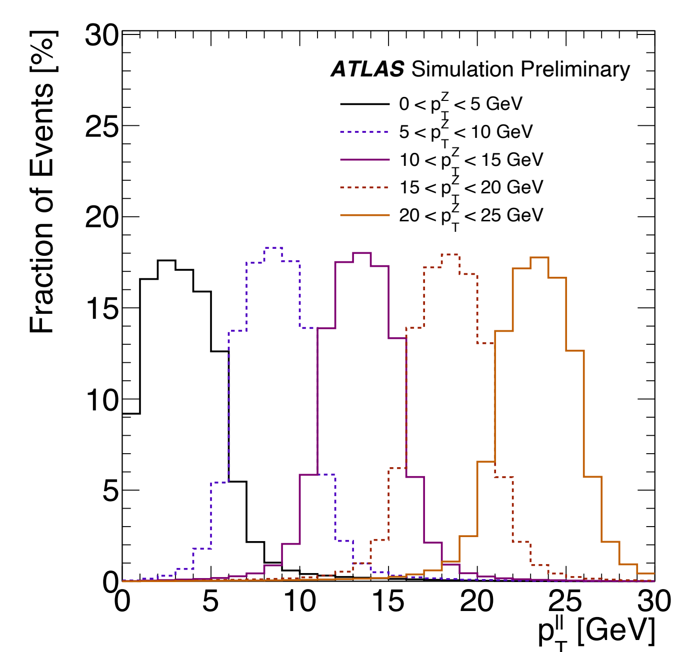
- Standard W and Z selections performed
- Multijet background estimated with data-driven ABCD method (improved and) similar as previous mW measurements
- Bayesian unfolding of u_T in the W and $p_T(\ell\ell)$ in the Z, separately in electron and muon channels
  - Binning and number of iterations optimised to minimise total uncertainty in the Sudakov region
    - 9 (25) iterations, 7 GeV bin width at low $p_T(W)$ for the W at 5.02 (13) TeV
    - 2 iterations, 2 GeV bin width at low $p_T(Z)$ for the Z
- electron and muon channels combined with BLUE, all giving good χ^2

Fiducial volume :
- lepton p_T > 25 GeV, lepton $|\eta|$ < 2.5
- W :
  - p_T^{ν} >25 GeV
  - m_T > 50 GeV
- Z : 66 < m_ll < 116 GeV

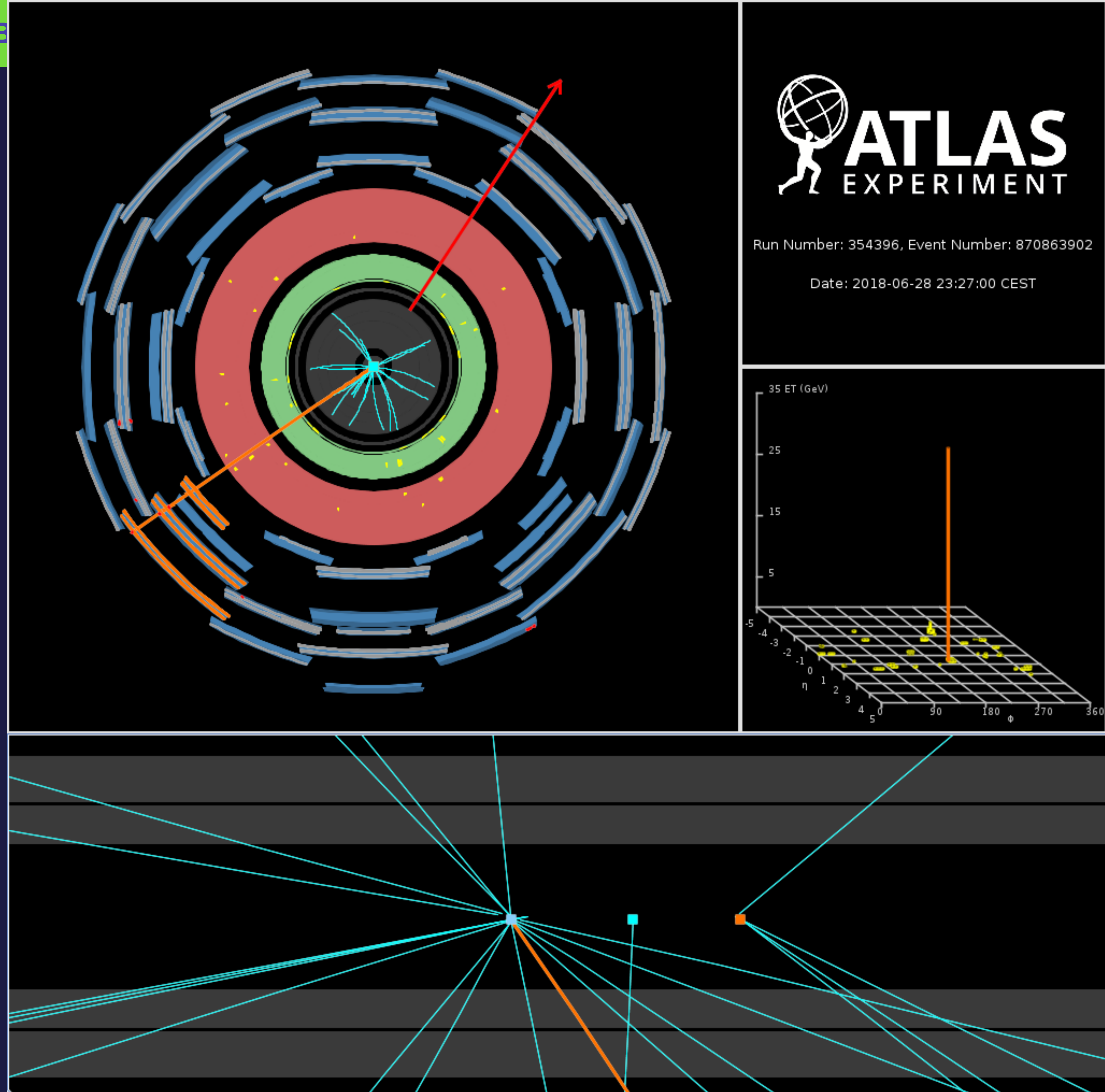






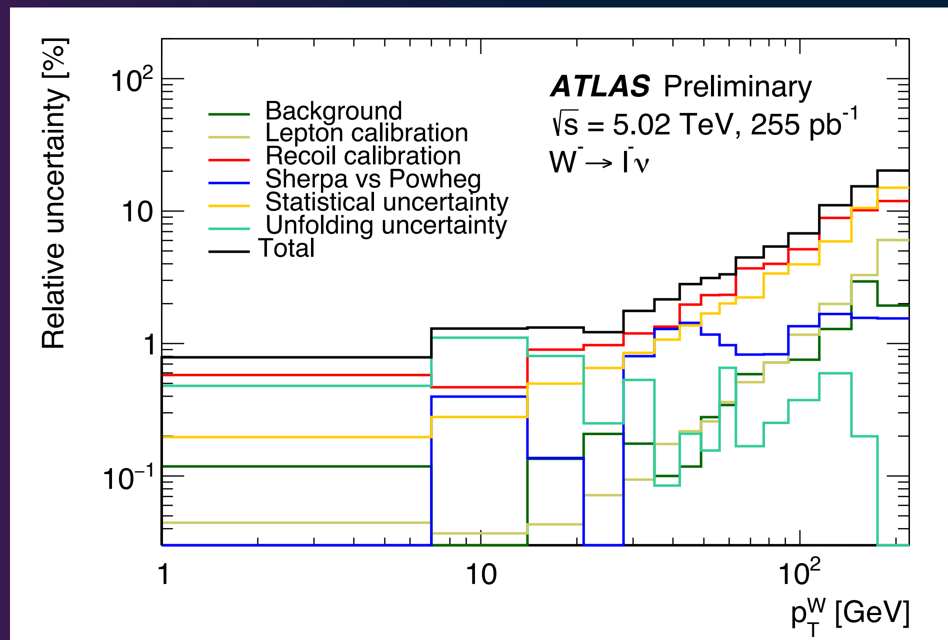


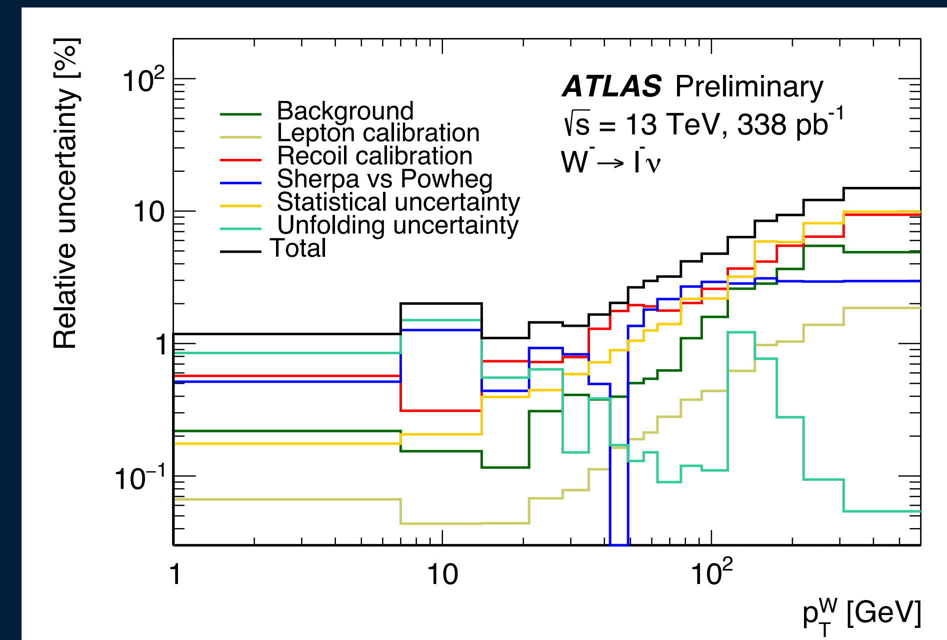
F.B

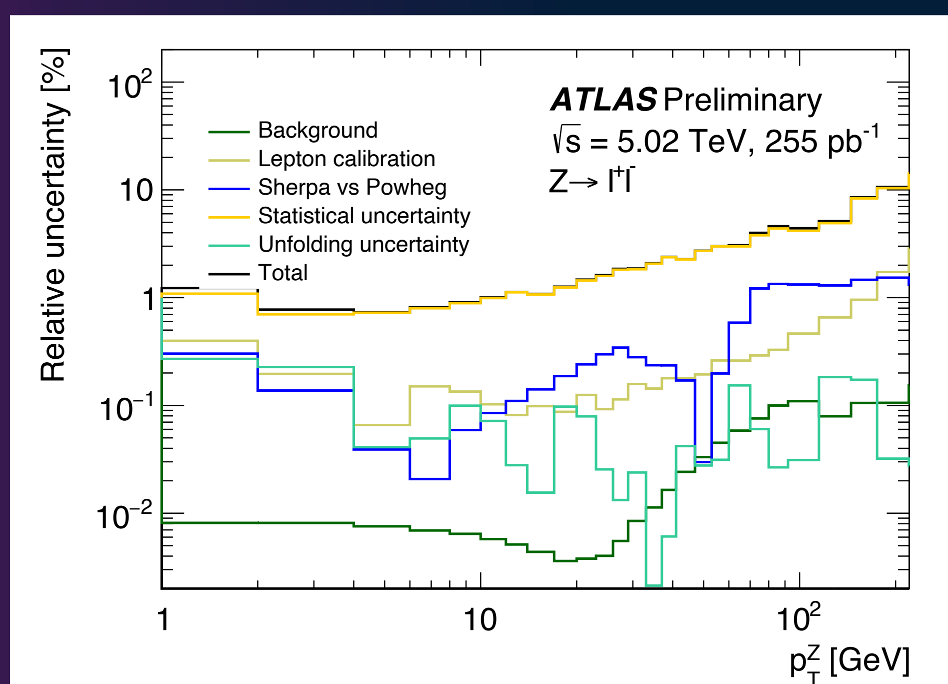


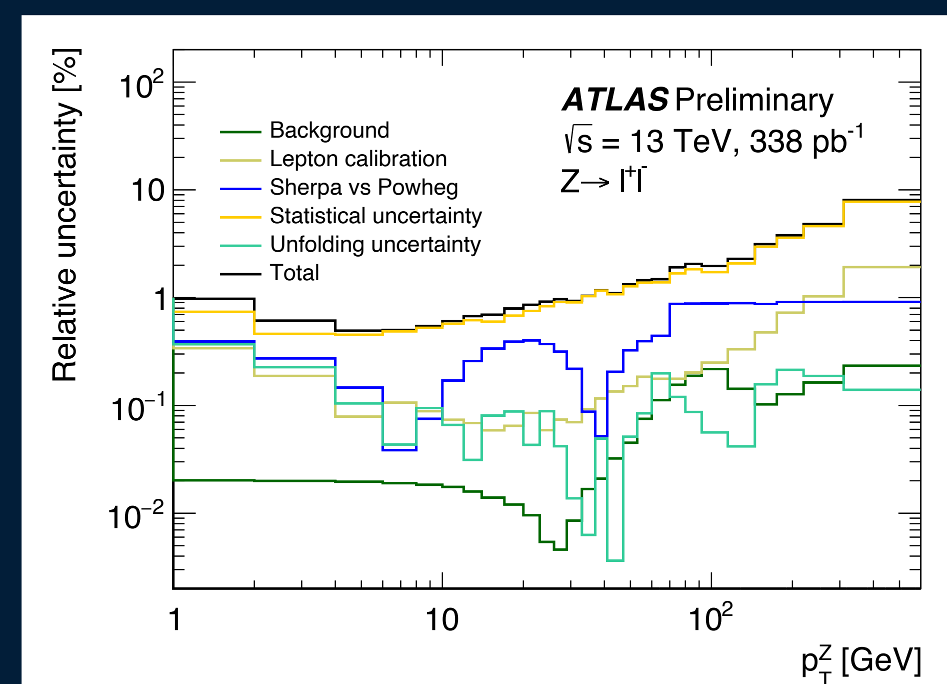
- W^- —> $\mu\nu$ @13 TeV candidate
  - m_T = 77 GeV
  - u_T = 16 GeV
  - p_T^{miss} = 49 GeV
  - $p_T(\mu)$ = 35 GeV

Uncertainties



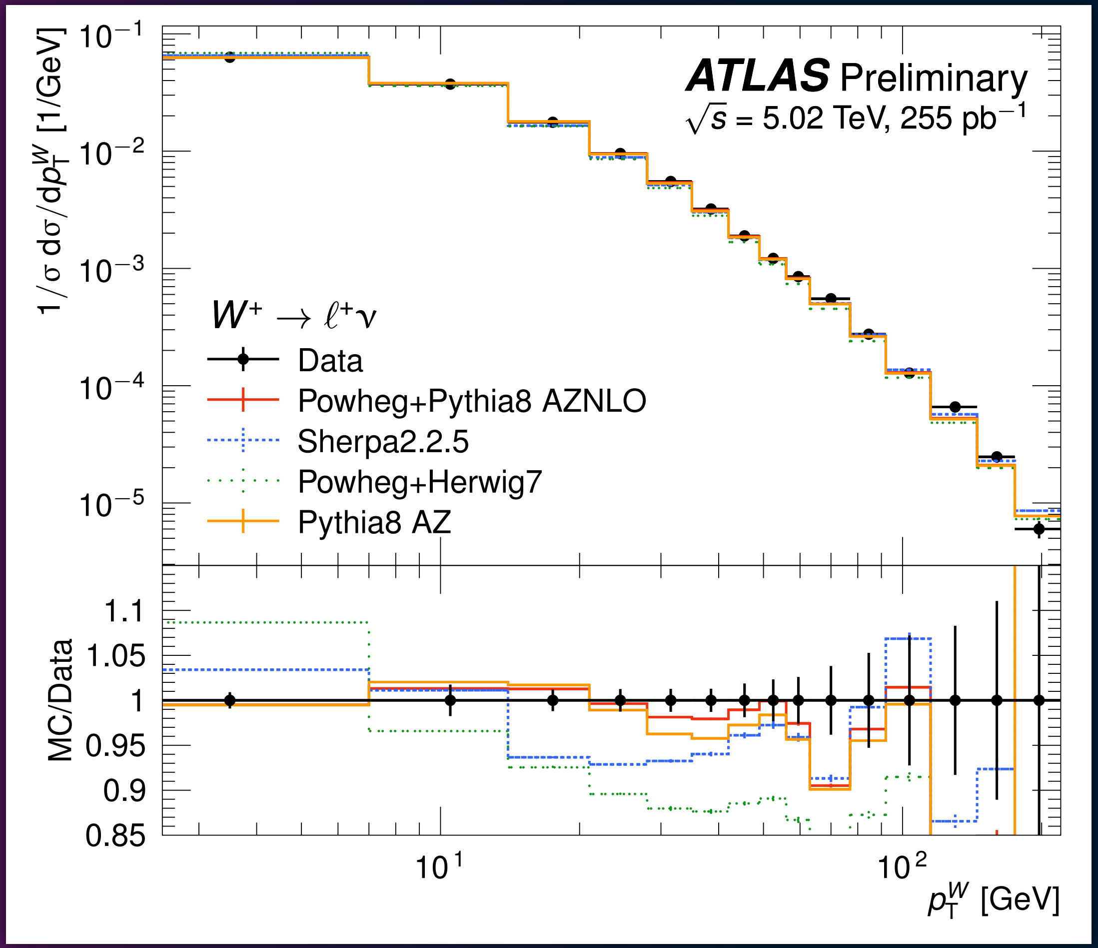


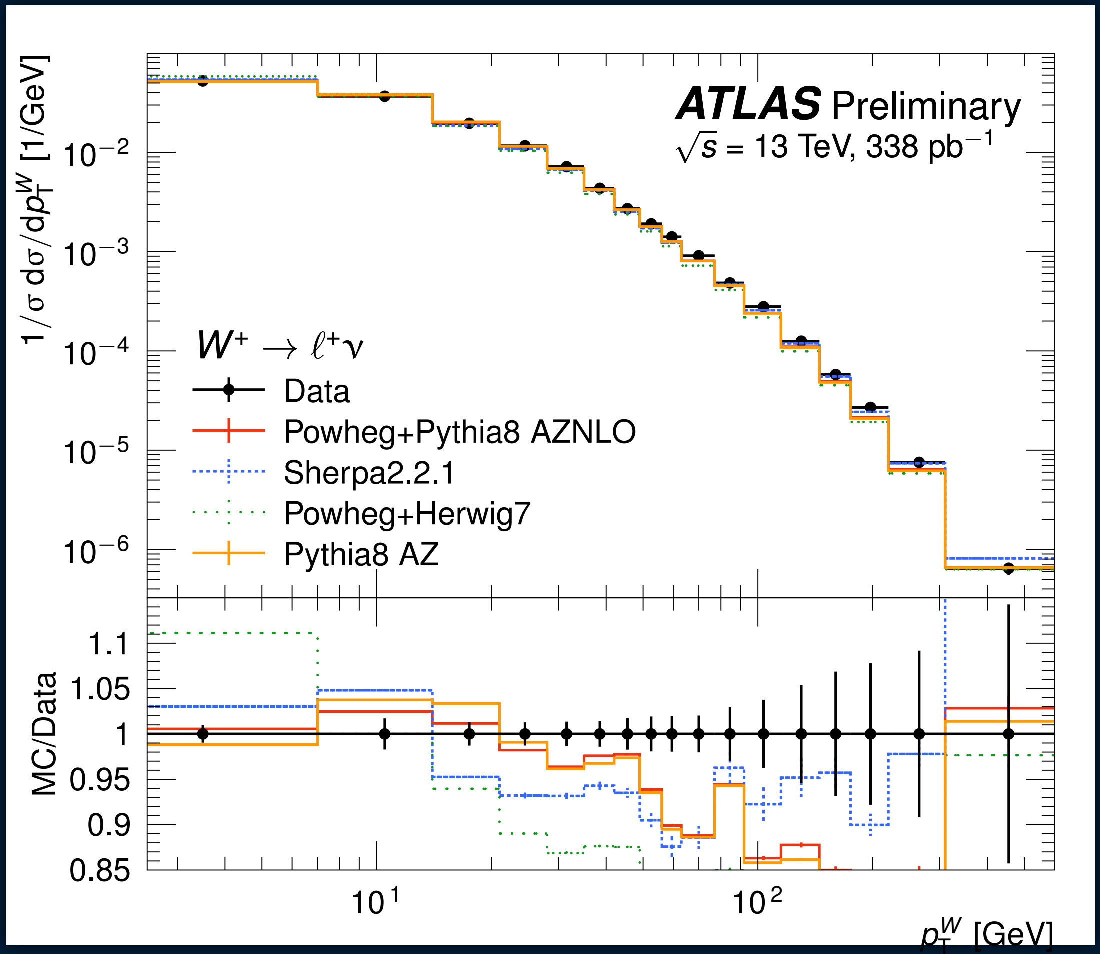




- W : dominant uncertainties from hadronic recoil calibration, unfolding bias, Sherpa vs Powheg and data statistics
- Z : dominated by data statistics

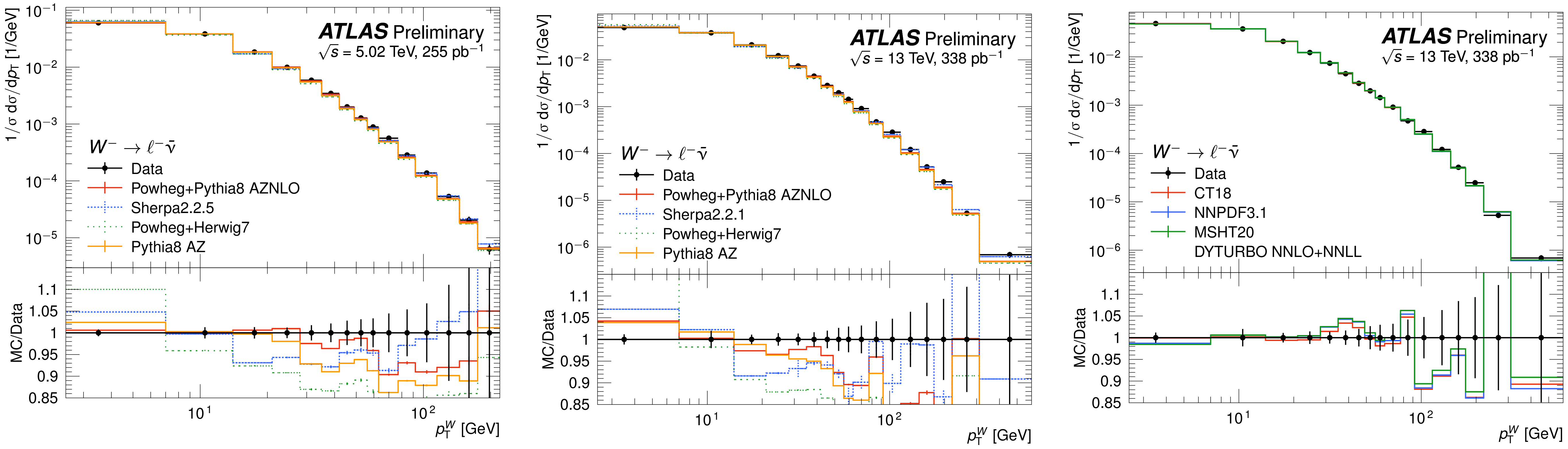
Results : W+





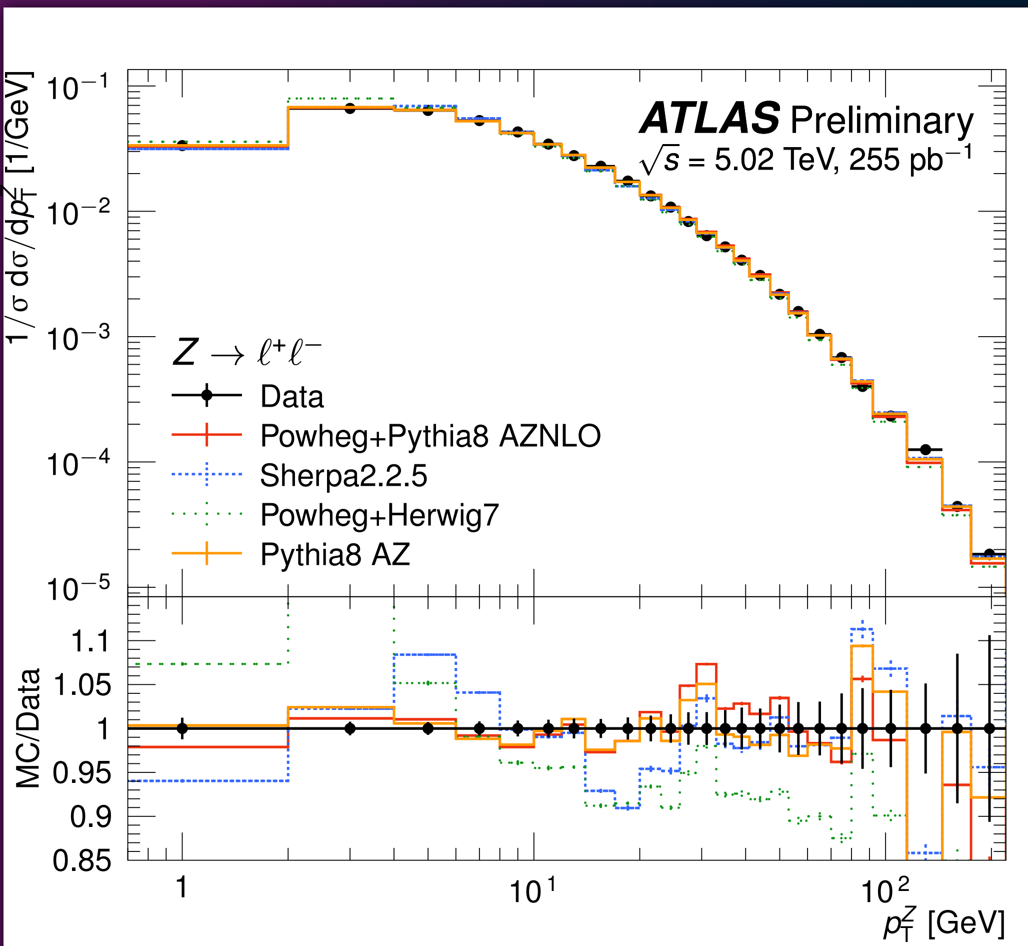
- 5 TeV : Good description of W p_T from ATLAS tunes on 7 TeV Z data at low p_T
- 13 TeV : none of the generators agrees well
- Better performance of Sherpa 2.2.5 and 2.2.1 at high p_T

Results : W-



- Description of W- p_T from ATLAS tunes on 7 TeV Z data at low p_T
  - Good at 5 TeV
  - Bad at 13 TeV
- Reasonable description of the peak at 13 TeV by NNLO+NNLL DYTURBO
- Higher p_T region a bit better in Sherpa 2.2.5 at 5 TeV and better in Sherpa 2.2.1 at 13 TeV
- Powheg+Herwig7 has poor agreement over the full spectrum

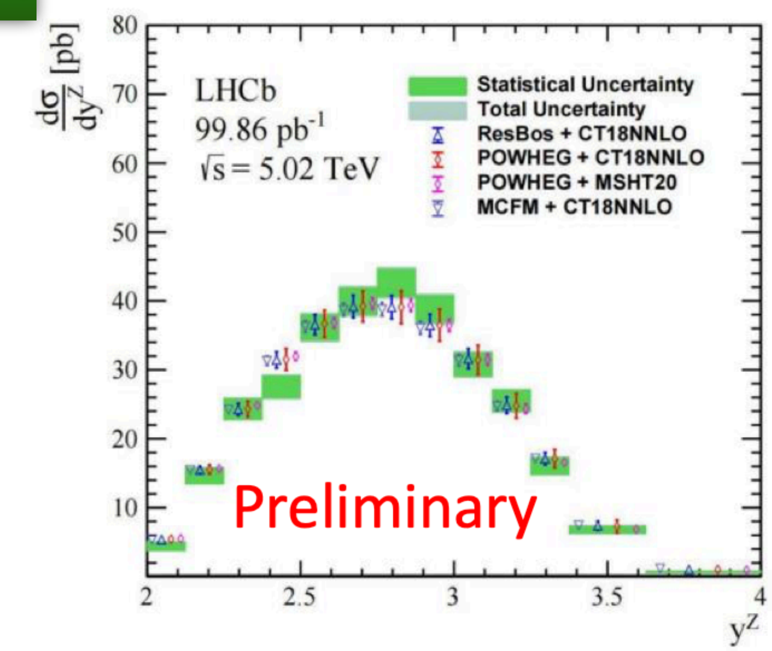
Results : 5.02 TeV Z

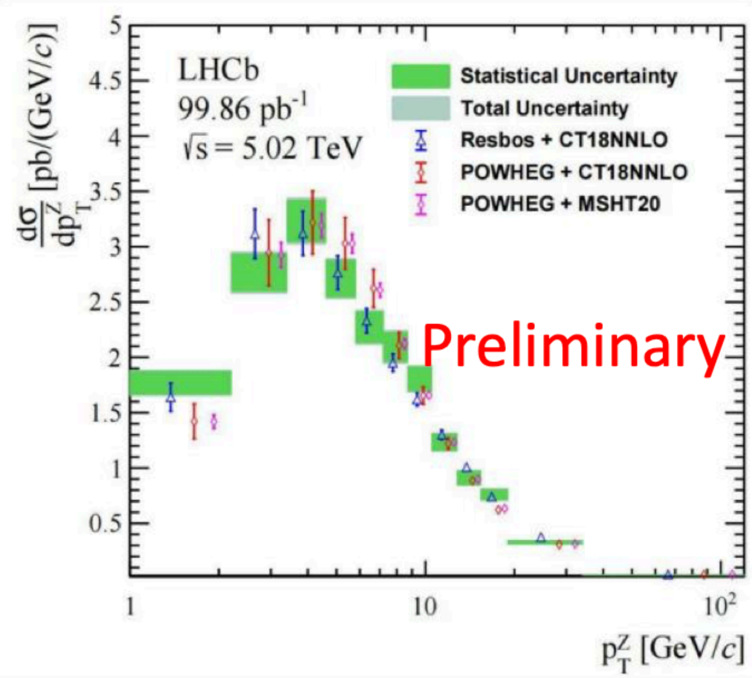


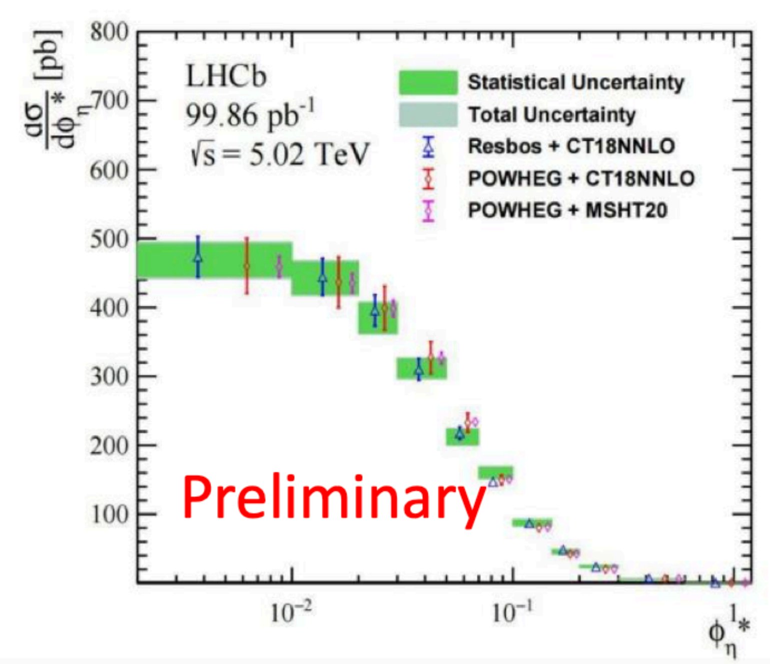
New LHCb preliminary result

Source	$\Delta\sigma/\sigma$ [%]
Statistical	1.77
Background	0.48
Momentum scale/smear	0.01
Tracking	1.01
Identification	0.25
Trigger	0.54
Efficiency Closure	0.61
FSR	0.18
Total Systematic (excl. lumi.)	1.42
Luminosity	2.00
Total	3.02

Preliminary

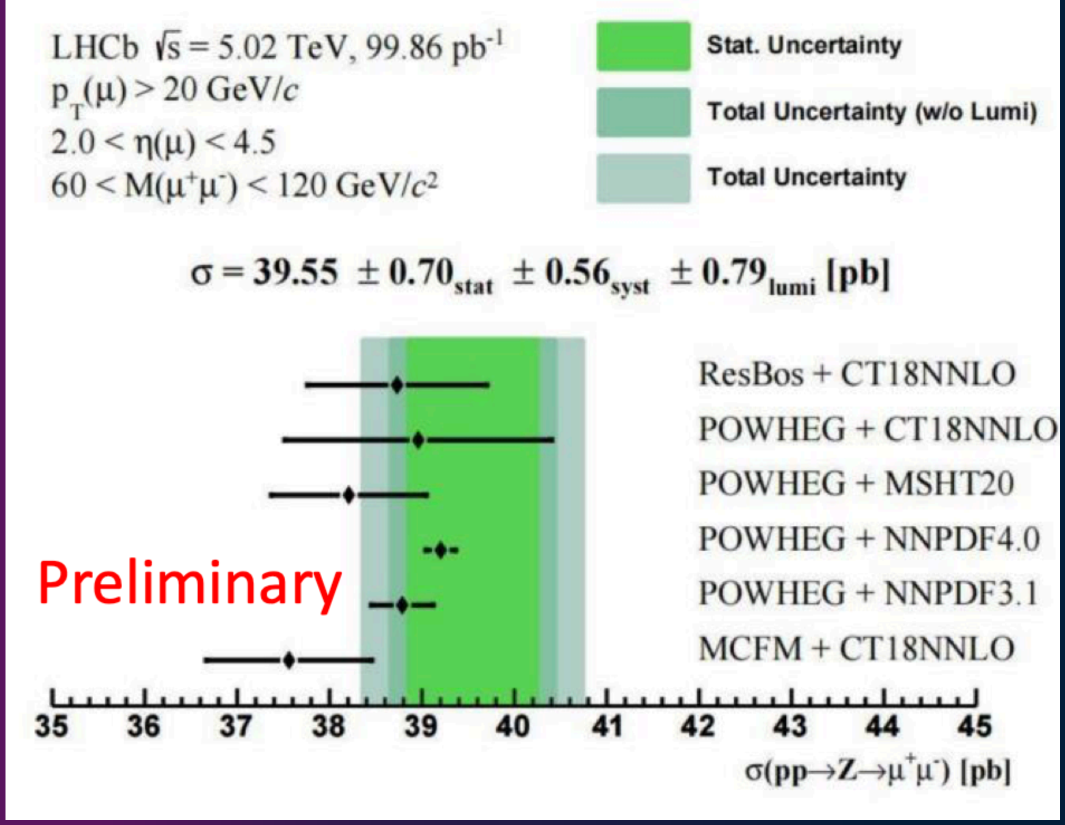






- Decent description from ATLAS tunes on 7 TeV Z data at low p_T
- Powheg+Herwig7 has poor agreement over the full spectrum
- New LHCb preliminary result
    - Dominated by statistics

Results : Integrated cross-sections and cross-section ratios



PDF set	$W^- \to \ell\nu$	$W^+ \to \ell\nu$	$Z \to \ell\ell$
Cross-section at 5.02 TeV [pb]			
CT18	1364	2199	320.9
MSHT20	1351	2185	324.3
NNPDF3.1	1381	2232	329.8
Data	1385 ± 16	2228 ± 25	333.0 ± 4.1
Cross-section at 13 TeV [pb]			
CT18	3410	4462	749.8
MSHT20	3397	4457	766.1
NNPDF3.1	3452	4513	771.4
Data	3486 ± 38	4571 ± 49	780.3 ± 10.4

- *Results agree with previous 13 TeV* measurements in ATLAS (early Run2)
- **Best precision on fiducial cross-sections** for these processes, thanks to clean pileup conditions and **best luminosity determination (<1%)** achieved at LHC !

https://arxiv.org/abs/2212.09379

- Several centre of mass energies : may further help constrain parameters in parton shower tunes
- **Opens the window towards a low-pileup W mass measurement**, complementary to high-pileup existing one
  - more weight to transverse mass in these measurements

PDF set	$W^- \to \ell\nu$	$W^+ \to \ell\nu$	$Z \to \ell\ell$
Ratio $\sigma_{fid}(13\,\text{TeV})/\sigma_{fid}(5.02\,\text{TeV})$			
CT18	2.499	2.029	2.337
MSHT20	2.515	2.040	2.362
NNPDF3.1	2.500	2.022	2.339
Data	2.517 ± 0.038	2.051 ± 0.031	2.343 ± 0.036

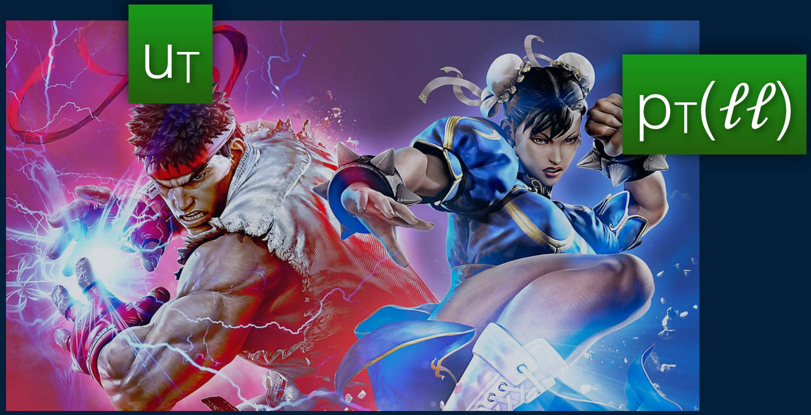
Summary and outlooks

- Z invisible width in CMS : **best precision achieved**, and **first time in a hadron collider**
- p_T(ll) **and φ^*_η in bins of** m(ll) **in CMS : large set of measurement, major input to constrain QCD models!**
- **τ polarization** in Z decays (CMS) : **most precise measurement** at LHC, lepton flavour universality test
- LHCb measurements probe **complementary phase space : NEW result at 5 TeV**
- New **preliminary m_W measurement by ATLAS**, reduces total uncertainty by 15% mostly thanks to better fitting techniques
    - Hot topic : more measurements foreseen in the future at LHC
- **Most precise experimental determination of α_S by ATLAS**
- **NEW** preliminary p_T(W) and p_T(Z) measurements thanks to low-pileup data, **sensitivity to the Sudakov region** will bring improvements in future m_W measurements !
    - 7 GeV bin width, in 8 channels, together with ratios, with uncertainty about 1.5-2% in the peak
    - Comes with **most precise integrated W/Z cross-sections**
    - Statistics is a dominant effect, in measurement and calibrations : **strong case for more low-pileup data taking at LHC**

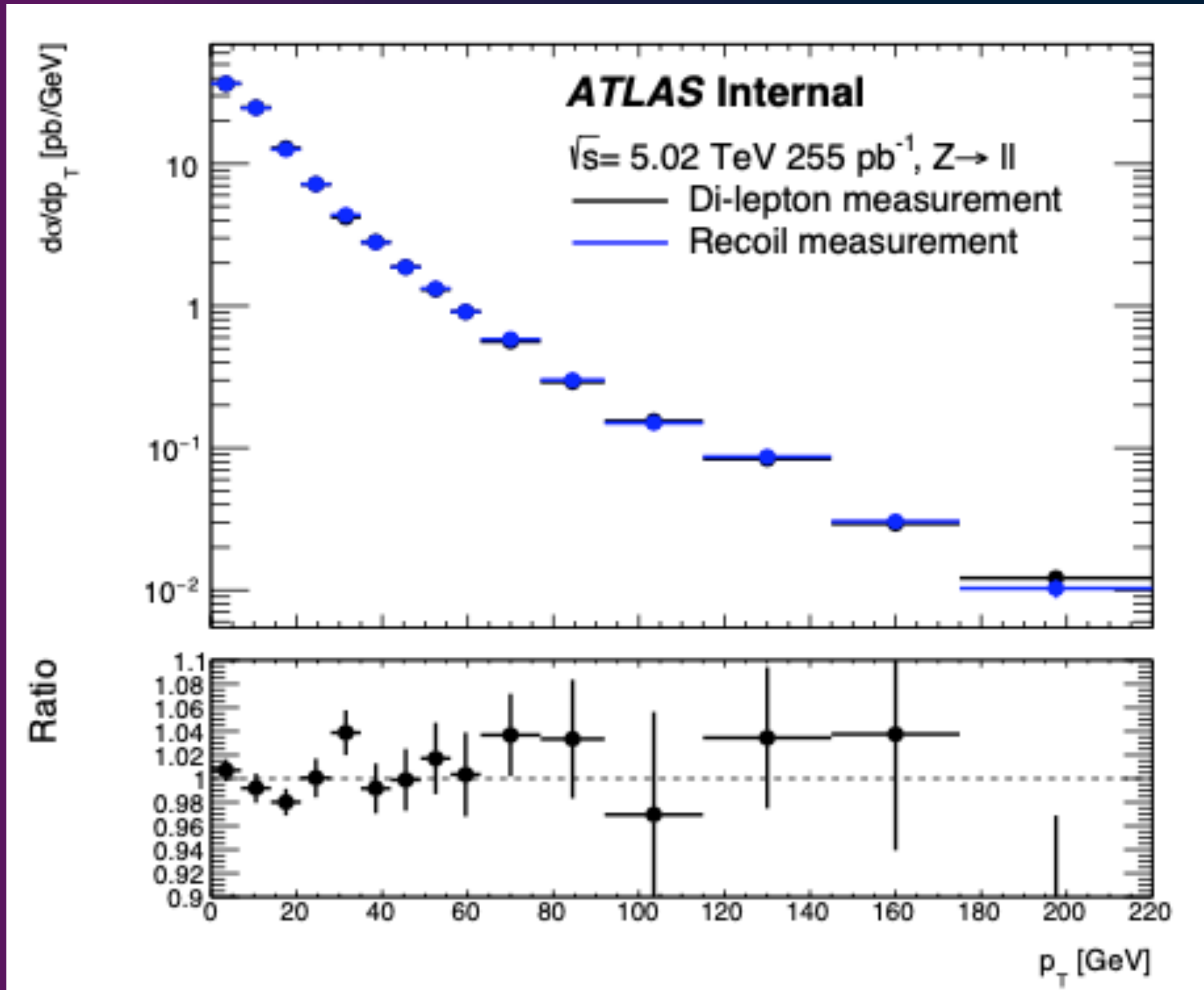
BACKUP

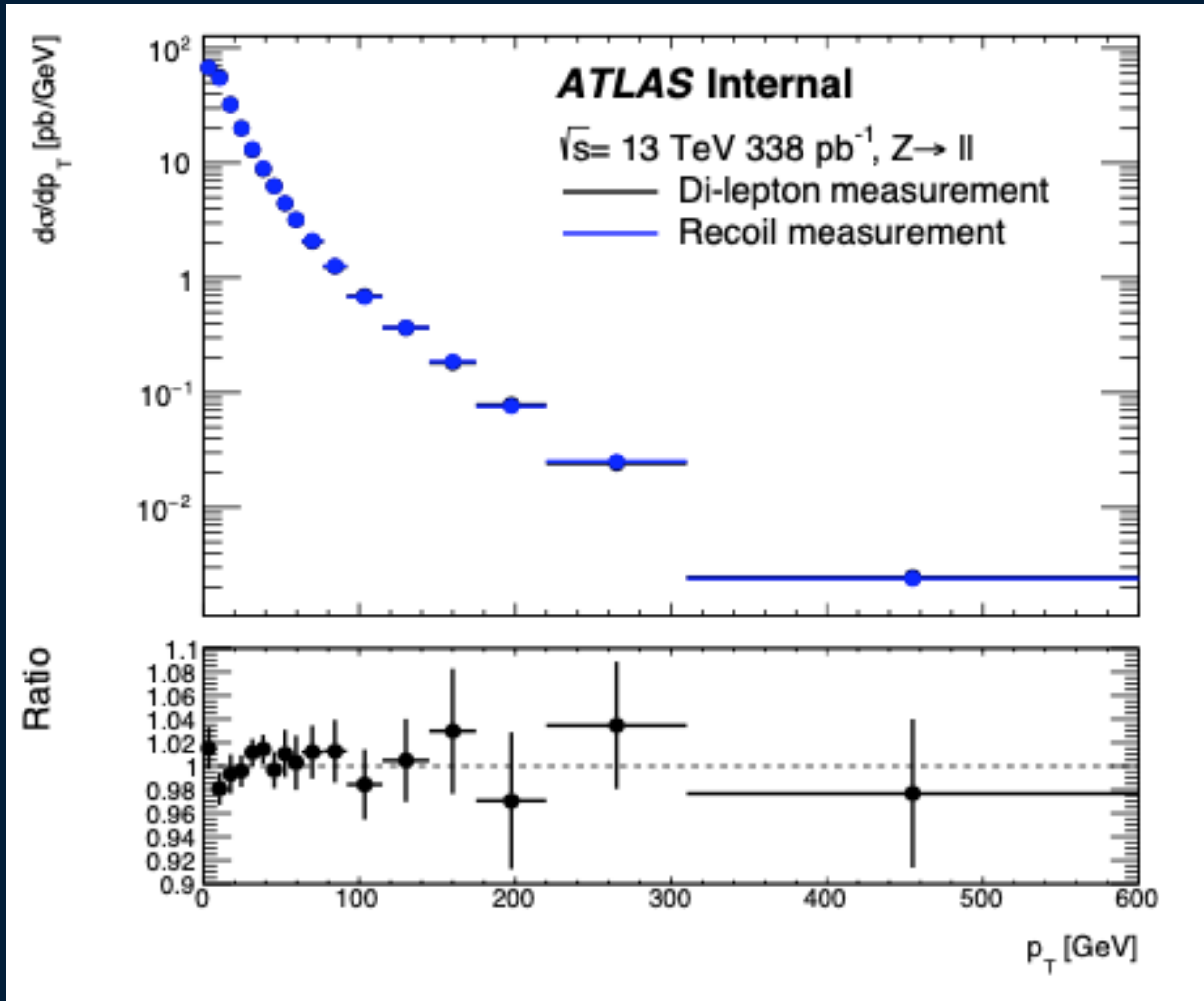
pTW at low mu : Analysis check with the Z : u_T vs $p_T(\ell\ell)$

- Calculate compatibility χ^2 between $p_T(\ell\ell)$ and u_T measurements
  - Taking all correlations into account
  - Powerful check of recoil calibration (absent in $p_T(\ell\ell)$) and of unfolding bias strategy (almost absent in $p_T(\ell\ell)$)
    - In addition, events are the same —> statistical uncertainties partially cancel
  - Good compatibility is found



	χ^2/DOF
5.02 TeV	14.9/14
13 TeV	8.7/16





pT(W) : MJ background

Channel	$W^- \to e^-\nu$	$W^+ \to e^+\nu$	$W^- \to \mu^-\nu$	$W^+ \to \mu^+\nu$
		5.02 TeV $W \to \ell\nu$		
MJ background yield	2200	2300	300	500
Statistics	300 (14%)	340 (14%)	120 (40%)	140 (25%)
Extrapolation	290 (13%)	340 (15%)	210 (70%)	230 (40%)
u_T-dependence	600 (29%)	800 (40%)	270 (90%)	300 (50%)
Total uncertainty	700 (32%)	900 (40%)	340 (110%)	400 (70%)
		13 TeV $W \to \ell\nu$		
MJ background yield	27000	29000	6000	6000
Statistics	800 (3.0%)	900 (3.0%)	310 (5%)	330 (5%)
Extrapolation	2400 (9%)	2400 (8%)	1400 (25%)	1500 (23%)
u_T-dependence	4200 (15%)	4300 (15%)	1400 (24%)	1400 (21%)
Total uncertainty	5000 (18%)	5000 (17%)	2000 (34%)	2000 (31%)

MJ Background fractions

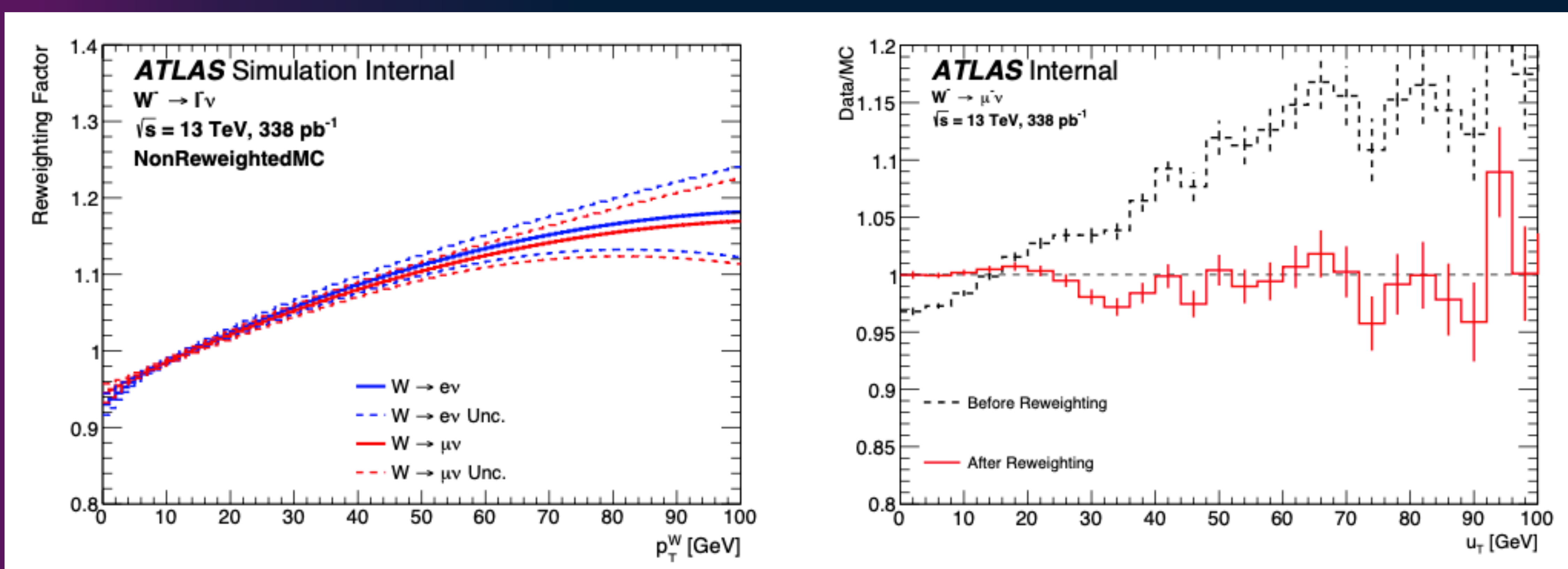
- 13 TeV electron : 2.4-2.9%
- 13 TeV muon : 0.5-0.6 %
- 5 TeV electron : 0.5-0.8%
- 5 TeV muon : 0.1%

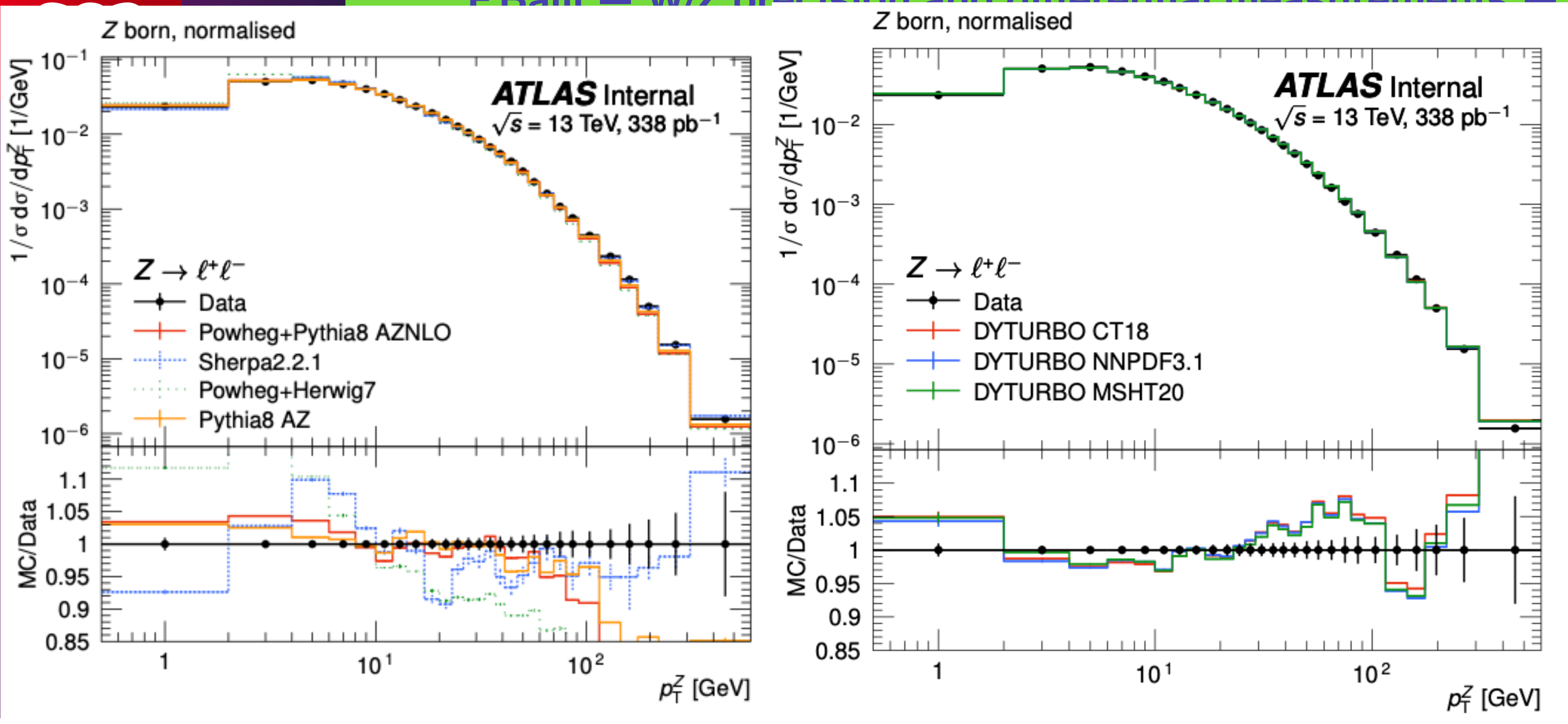
- Data-driven method is applied using 4 regions and 3 observables (MET, mT, pTlep) :
  - Determination of yield with a fraction fit in FR using templates from CR1, then extrapolated to SR with CR2/CR1 ratio
  - Determination of shape in SR using CR2
    - Smoothing procedure at high uT for electron channel at 13 TeV
- Need for dedicated hadronic recoil correction because of the recoil algorithm removing hard activity in non-isolated regions

pT(W) : physics modelling corrections

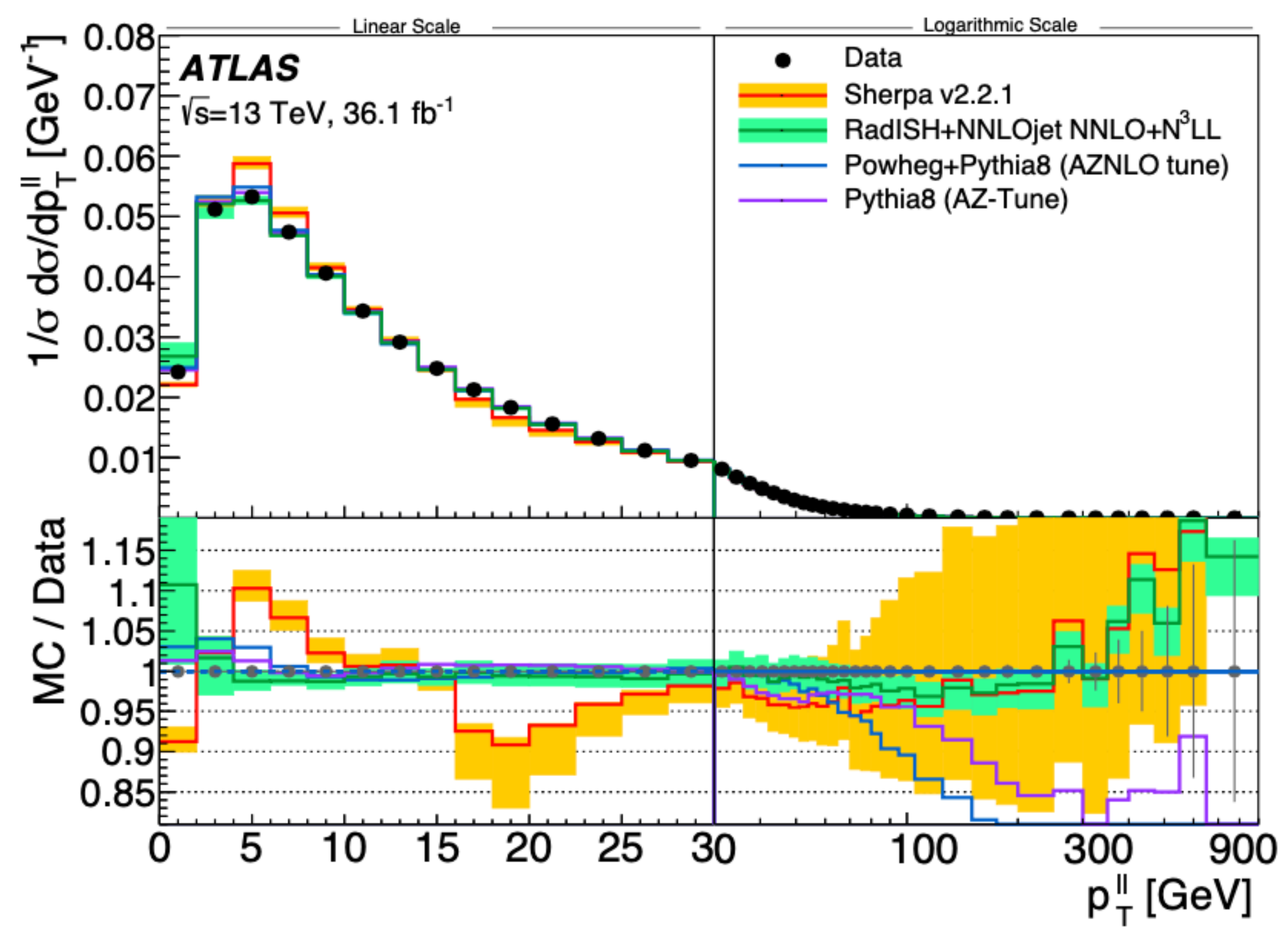
- Samples matching low-pileup conditions
  - W,Z : Powheg+Pythia8 AZNLO CT10 PDF set
    - Alternative : Sherpa 2.2.2 @13TeV, Sherpa 2.2.5@5TeV
  - Diboson : Sherpa 2.2.1 and 2.2.2 (depending on the process)
  - Top : Powheg+Pythia8
    - Alternatives : rad-low, rad-up, Powheg+Herwig7

- Vertex efficiency correction: Correct the efficiency of primary vertex association for W→lν events in the simulations
- Z_{vertex} reweighting
- QED FSR: Powheg+Pythia8 interfaced to PHOTOS++
- W, Z polarization: Ai's are calculated by DYTURBO at fixed-order NNLO using CT10NNLO PDF
- pTW modelling correction : The truth pTW spectra predicted by Powheg+Pythia8 are reweighted by functions that optimize the reco-level data/MC agreement.



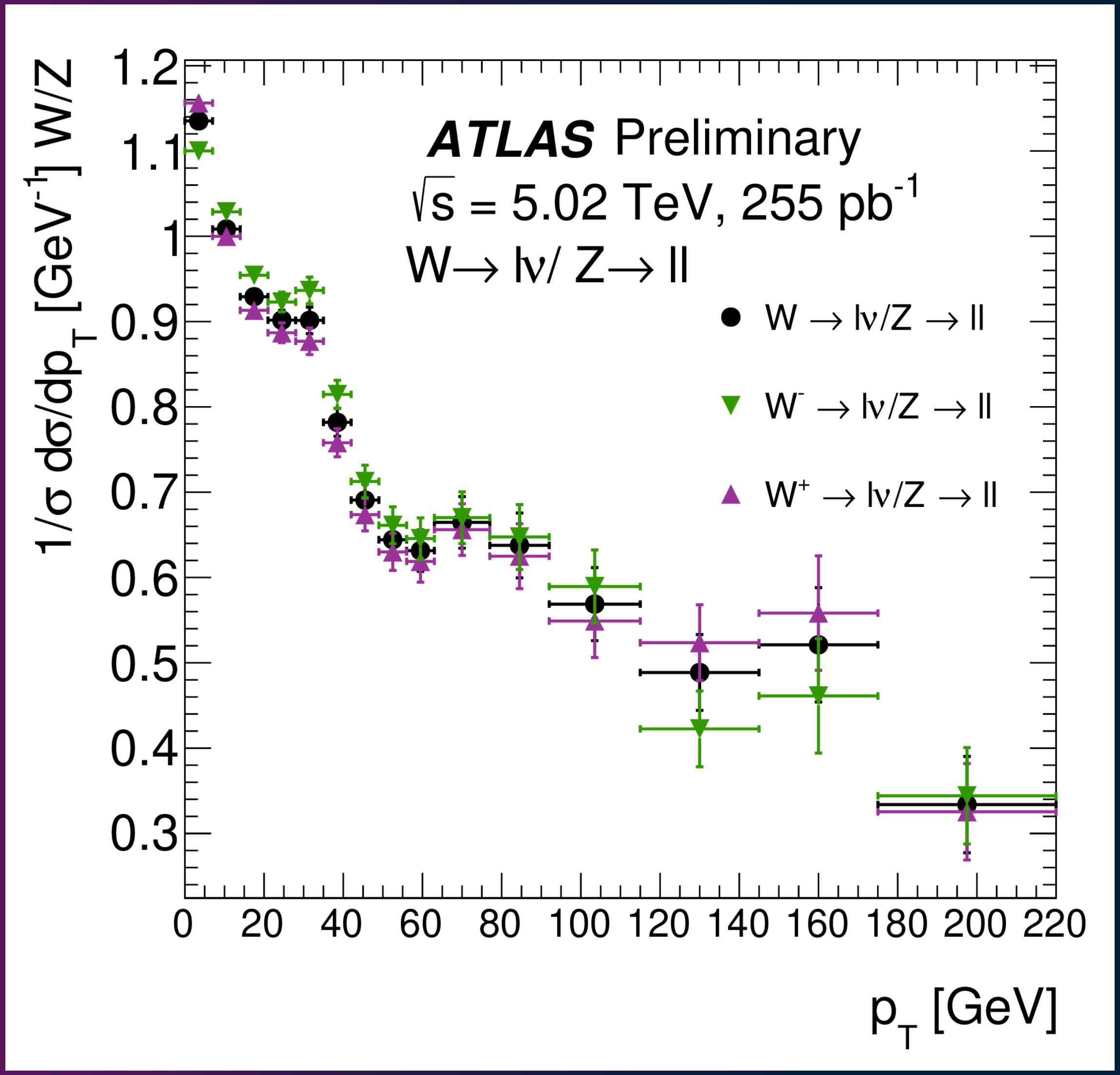


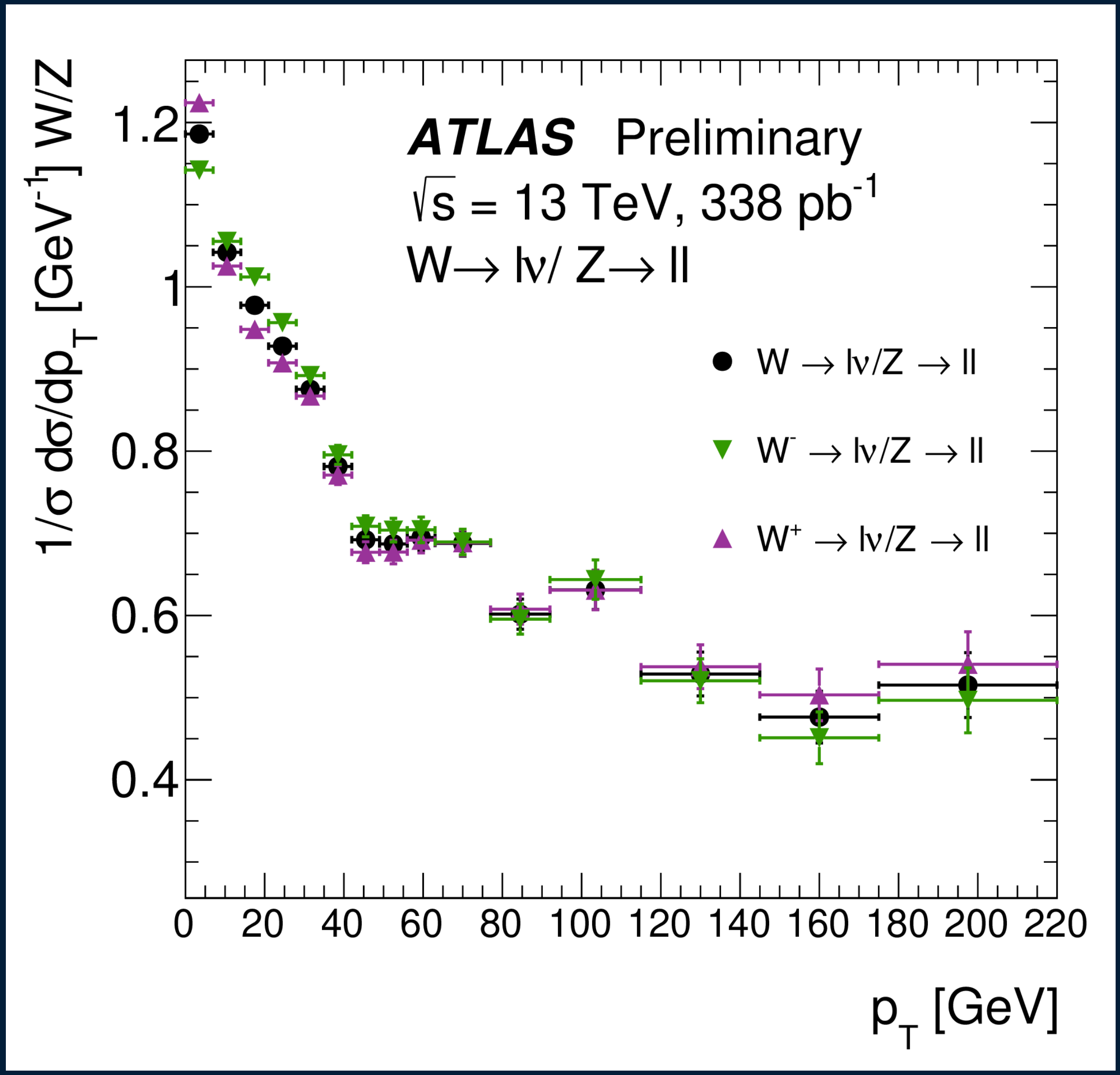
- None of the generators agrees well - also seen in high mu measurement



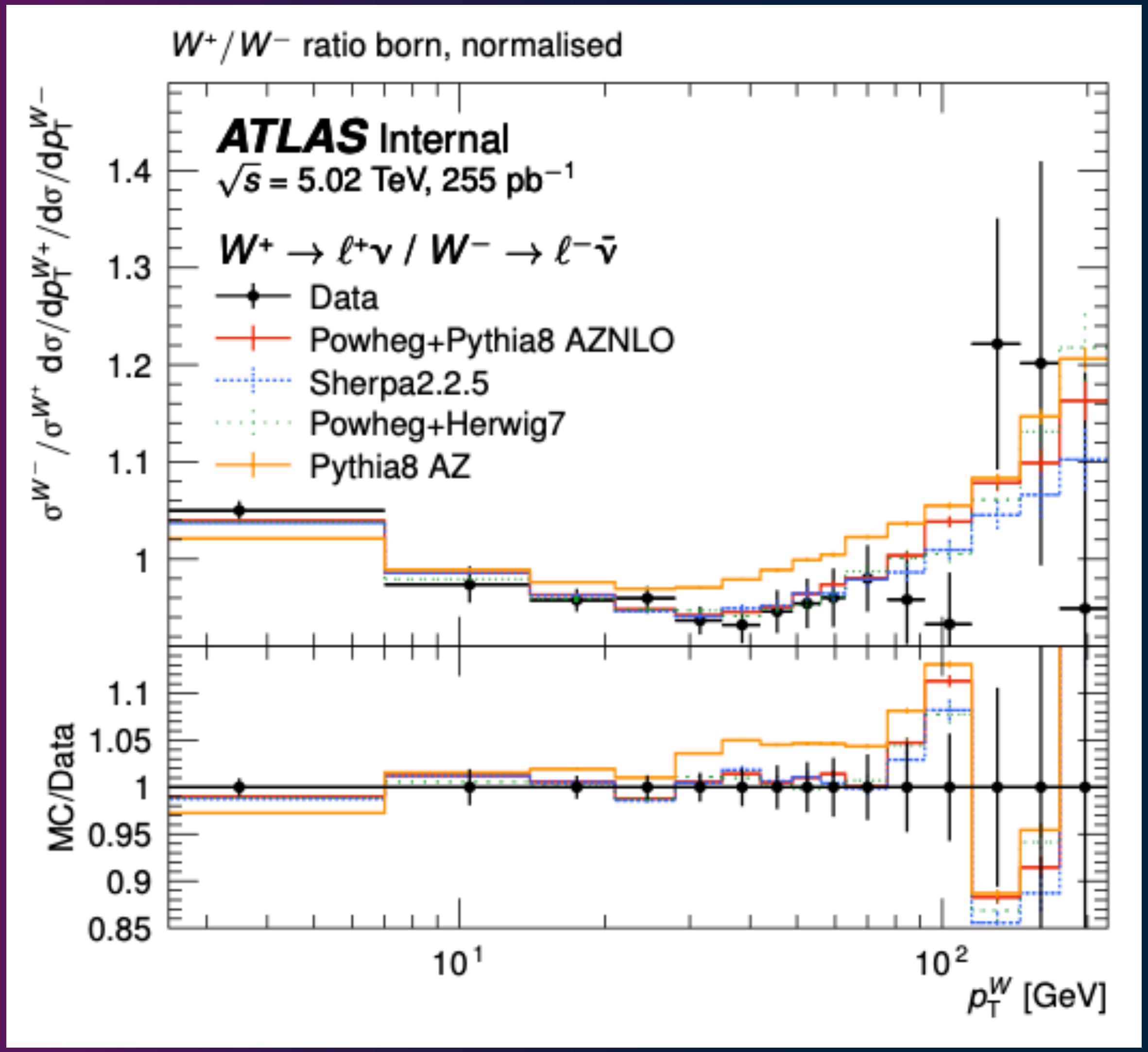
pTW and pTZ Results : 13 TeV Z

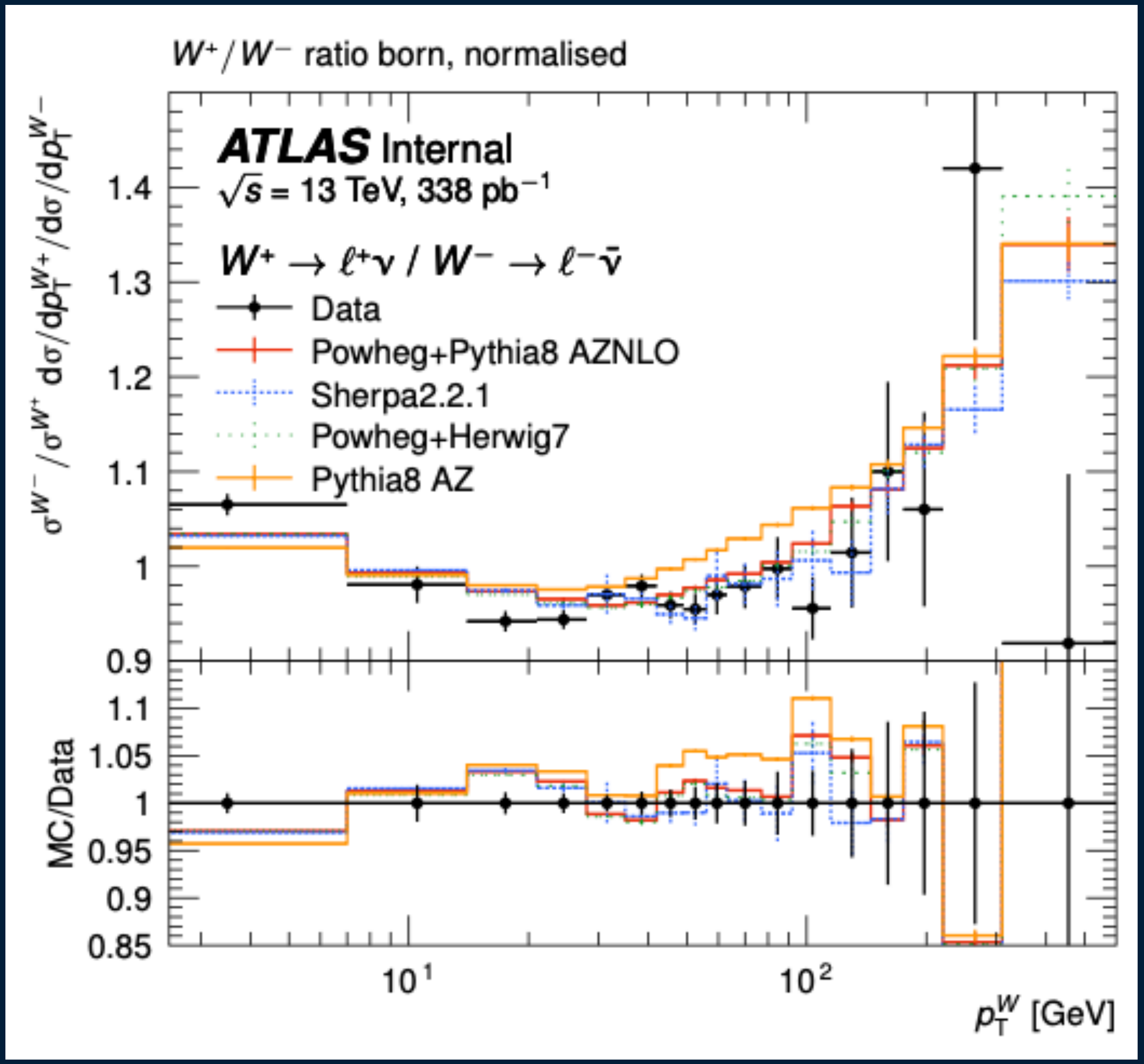
Results : W/Z ratios





Results : W+/W- ratios

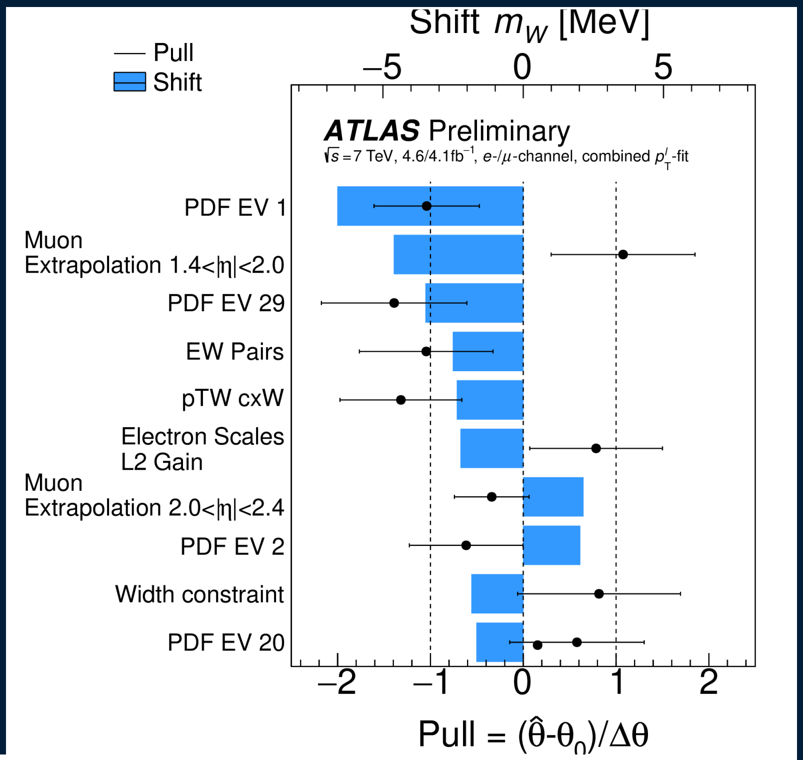


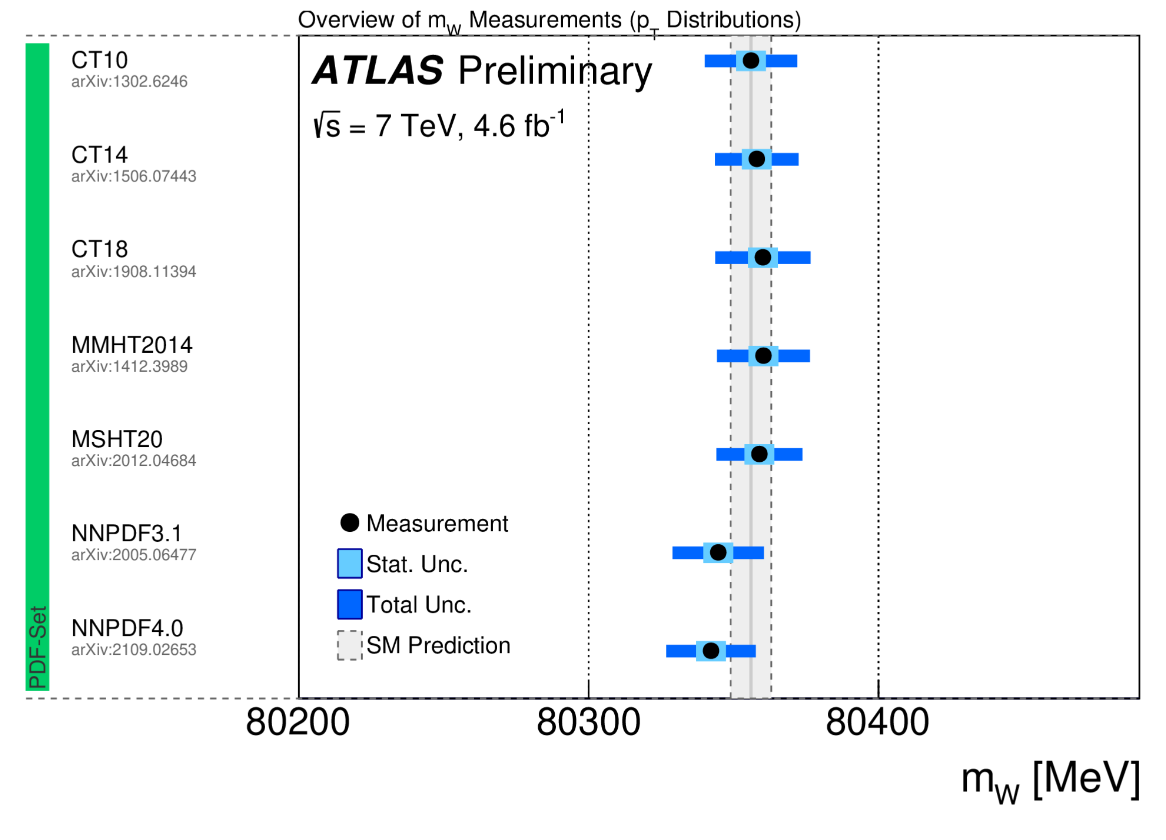


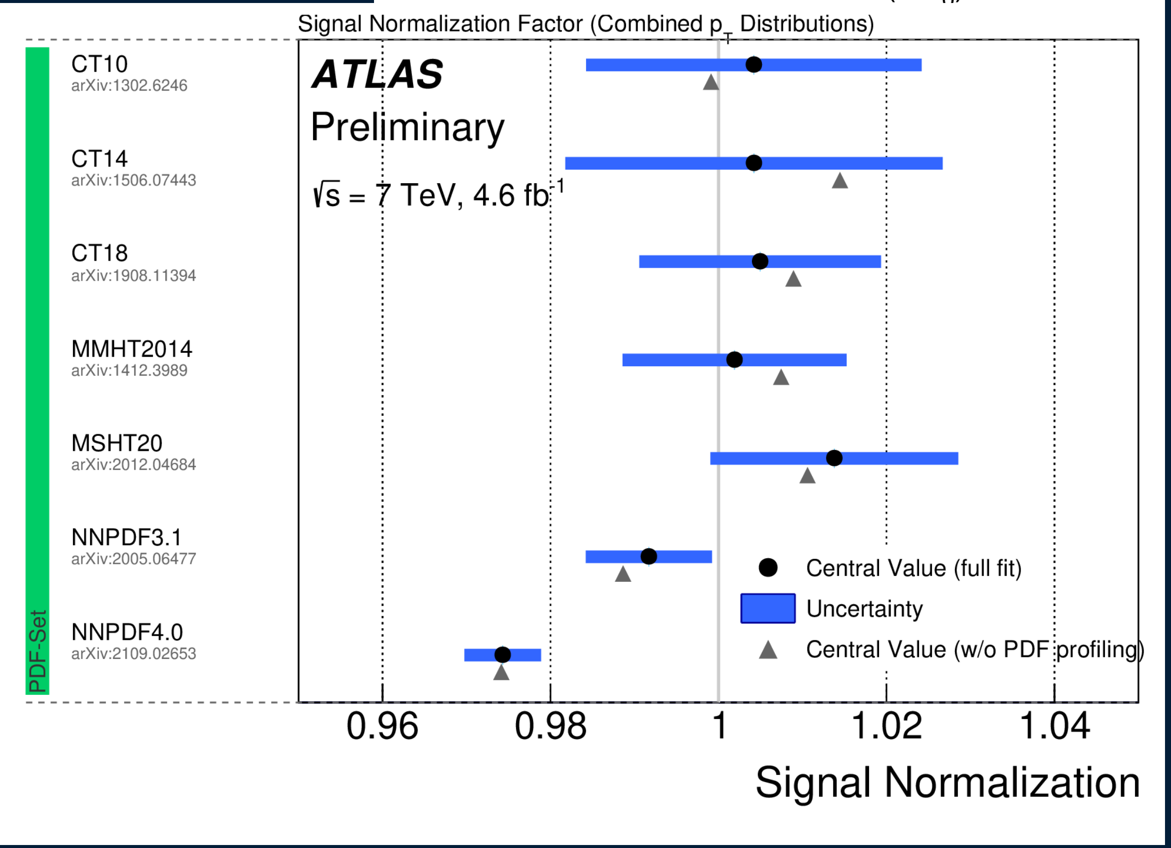
- Good description from ~all MCs of the W+/W- ratio at 5.02 TeV
- Bad description at 13 TeV

m_W : PDFs

- Dominant uncertainties from
  - PDF Eigenvectors 1 and 29 of CT18
  - Muon momentum scale extrapolation to forward region
- Fit repeated with other PDF sets, profiling helps aligning the stars
- CT18 yields conservative uncertainties when compared to other recent sets and covers differences with them

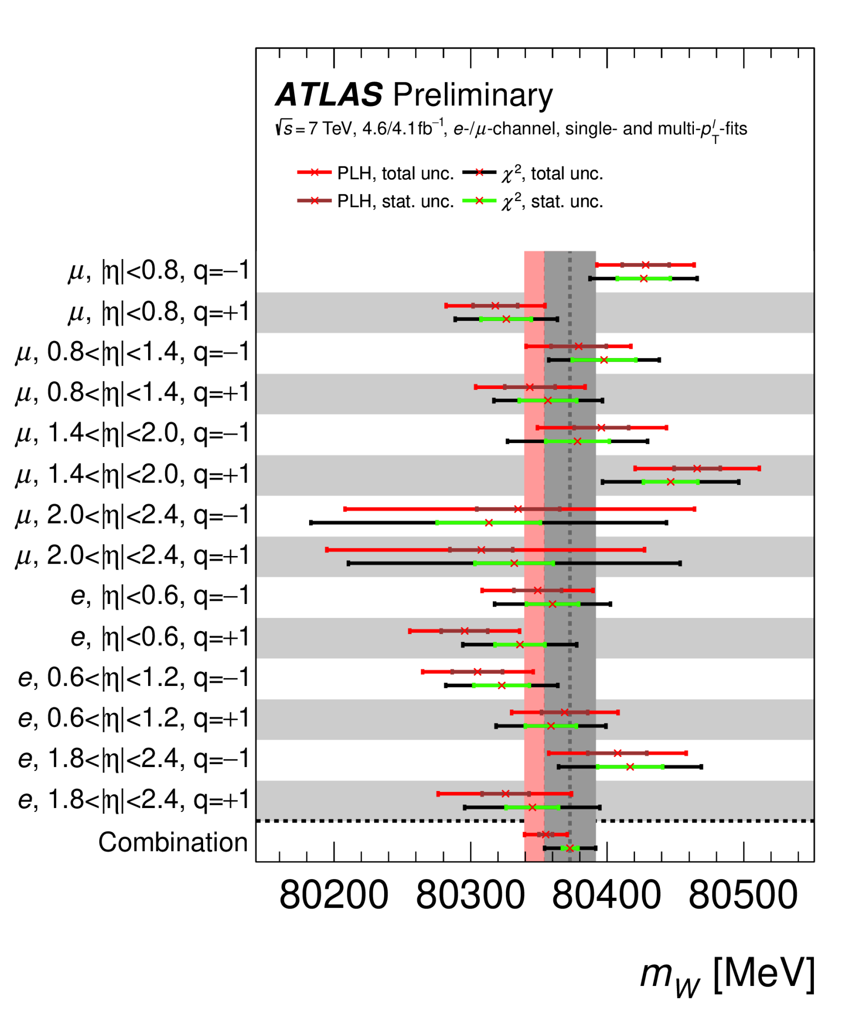


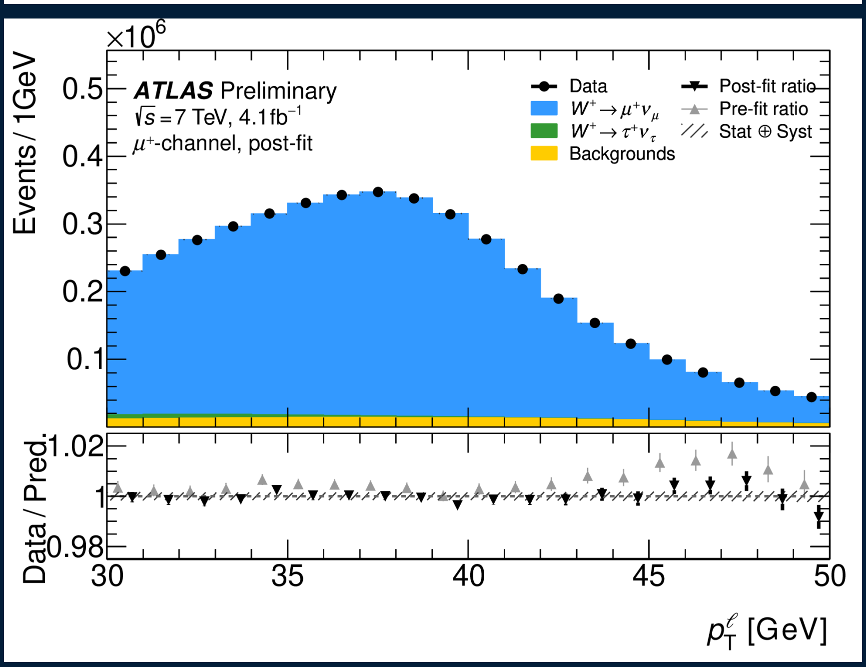




m_W : likelihood fit

- W width added as NP parameter
- Two observables pTl and mT combined afterwards with BLUE using a correlation factor obtained with bootstrap toys (63 ± 3%)
  - pTl has the largest weight (~95%) mainly because of better resolution on the Jacobian peak in such pileup conditions
- Thorough cross-checks of consistency between the χ^2 offset and profile likelihood analyses, using the same PDF set (CT10NNLO)
  - Comparison of results in each category with statistical uncertainties only
    - Slight shift in central value, mainly due to multijet background update





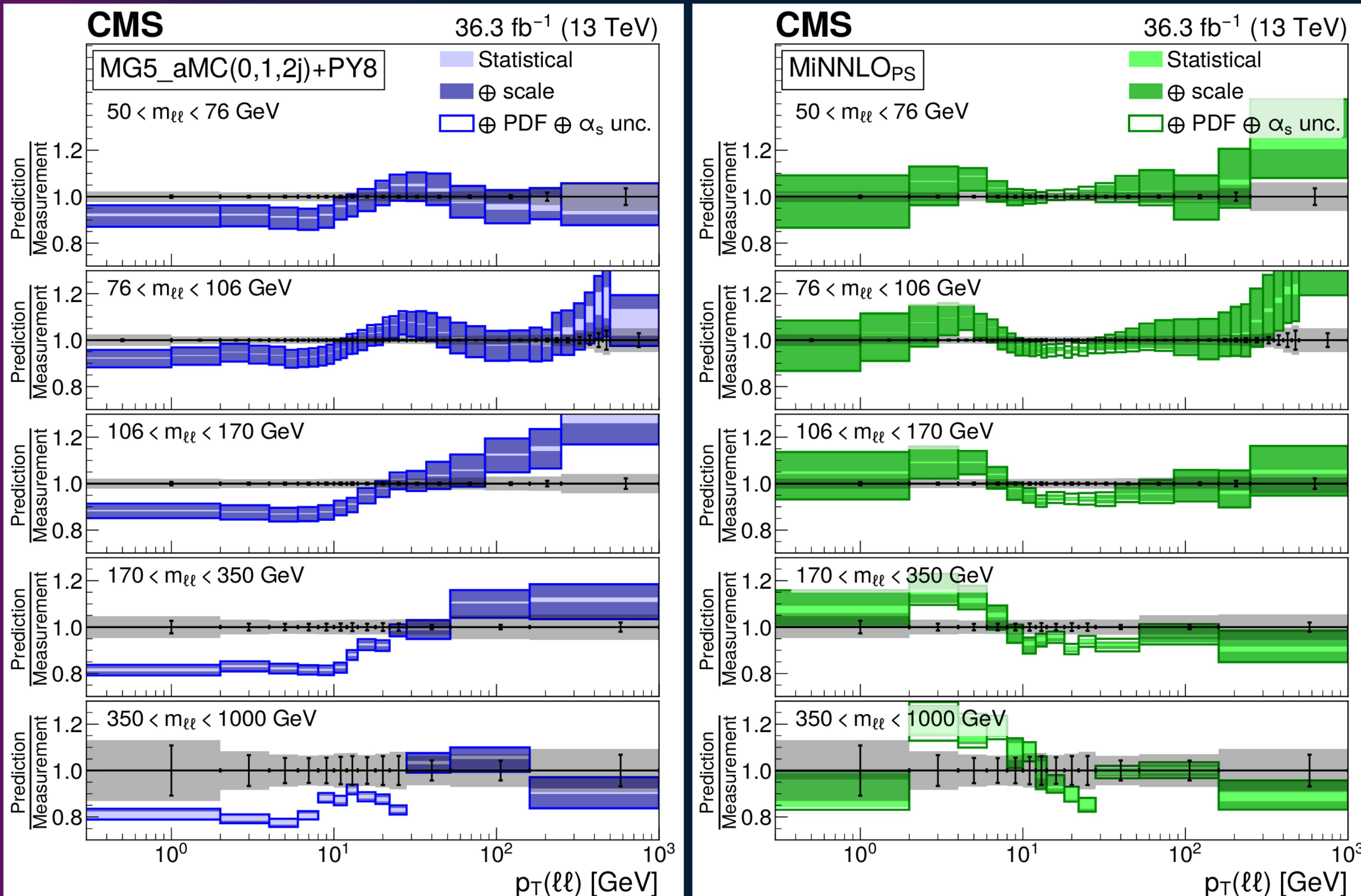
Tau polarisation : distributions uncertainties

Source of uncertainty	Prefit uncertainty per channel			
	$\tau_h\tau_h$	$\tau_\mu\tau_h$	$\tau_e\tau_h$	$\tau_e\tau_\mu$
$e \to \tau_h$ fake rate	10%	$< 40\%$	10%	-
$\mu \to \tau_h$ fake rate		$< 40\%$		-
jet $\to \tau_h$ fake rate	p_T-dependent $\approx 20\% \times p_T^{jet}/100\text{GeV}$			
Tau identification efficiency		p_T MVA-DM		-
Tau trigger efficiency	p_T MVA-DM		-	-
Electron trigger efficiency	-	-	p_T MVA-DM	
Muon trigger efficiency	-	p_T η	-	p_T MVA-DM
Hadronic tau energy scale		p_T MVA-DM $< 2\%$		-
Neutral, charged hadrons energy	2%	2%	2%	-
Muon energy scale	-	0.4–2.7%	-	0.4–2.7 %
Muon to tau fake energy scale	-	1%	-	-
Electron energy scale	-	-	Event-dependent	
Electron to tau fake energy scale	-	-	0.8–6.6%	-
Misidentified $\tau_h \to h^\pm$	2.8%	2.8%	2.8%	-
Misidentified $\tau_h \to h^\pm\pi^0$	3.2%	3.2%	3.2%	-
Misidentified $\tau_h \to h^\pm h^\pm h^\pm$	3.7%	3.7%	3.7%	-
Parton re-weighting	100% for all channels			
Drell-Yan MC re-weighting	100% for all channels			
Top p_T re-weighting	100% for all channels			
MC comparison for signal	100% for all channels			
p_T^{miss} unclustered scale	Event-dependent, but negligible			
p_T^{miss} recoil correction	Event-dependent, but negligible			
Limited MC statistics	Bin by bin fluctuations			

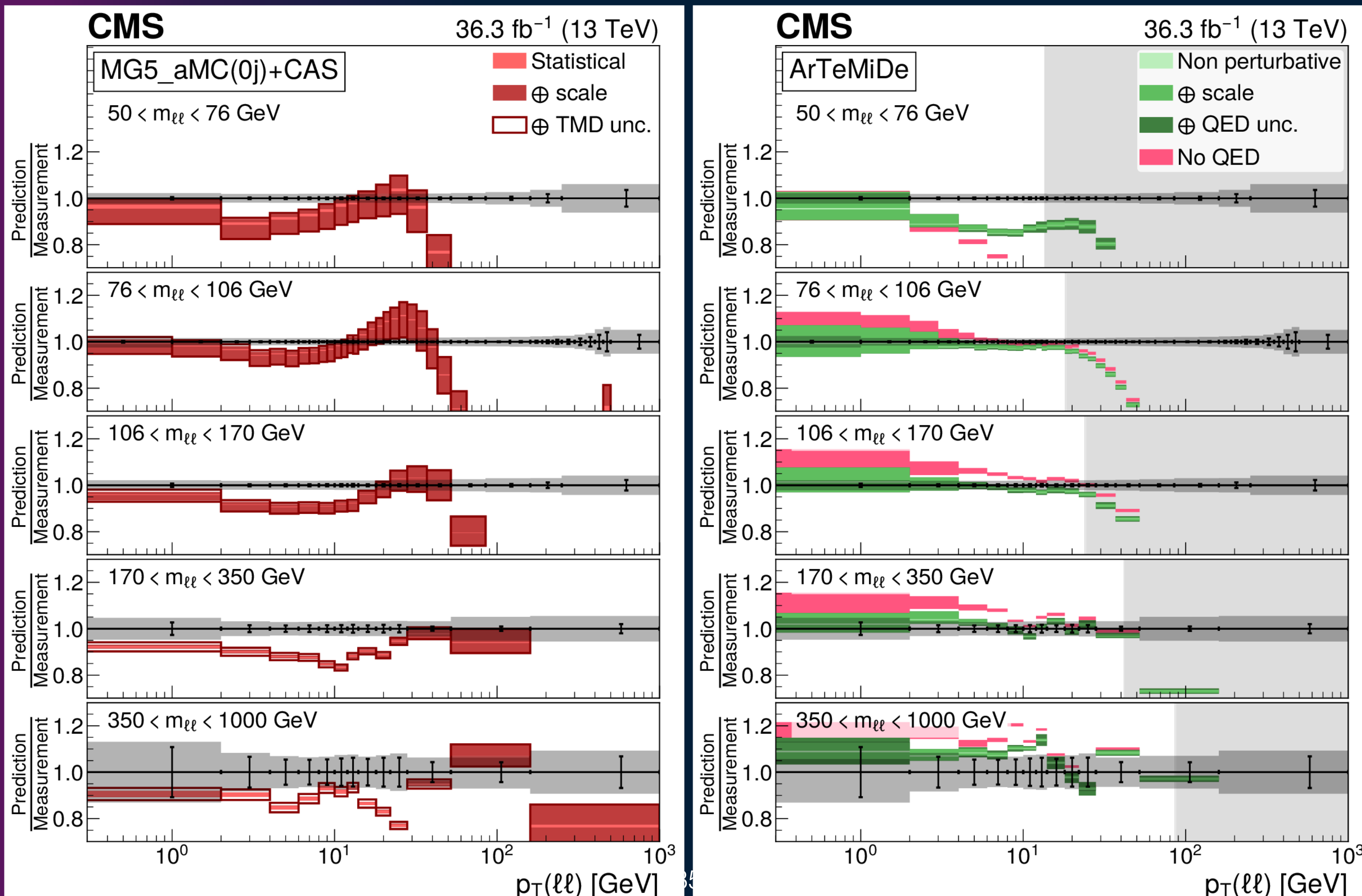
Tau polarisation : normalisation uncertainties

Source of uncertainty	Prefit uncertainty per channel			
	$\tau_h\tau_h$	$\tau_\mu\tau_h$	$\tau_e\tau_h$	$\tau_e\tau_\mu$
Integrated luminosity	1.2%	1.2%	1.2%	1.2%
μ identification efficiency (correlated)	–	2%	–	2%
e identification efficiency (correlated)	–	–	2%	2%
e tracking efficiency (correlated)	–	–	1%	1%
DY cross section	5.6%	5.6%	5.6%	5.6%
$t\bar{t}$ cross section	4.2%	4.2%	4.2%	4.2%
Diboson cross section	5%	5%	5%	5%
Electro-weak cross sections	4%	4%	4%	4%
W+jets cross section & normalization	4%	10%	10%	20%
QCD normalization	3%	20%	20%	10%
B-tag efficiency	$\leq$0.1% except for $t\bar{t}$ and VV (1%-9%)			

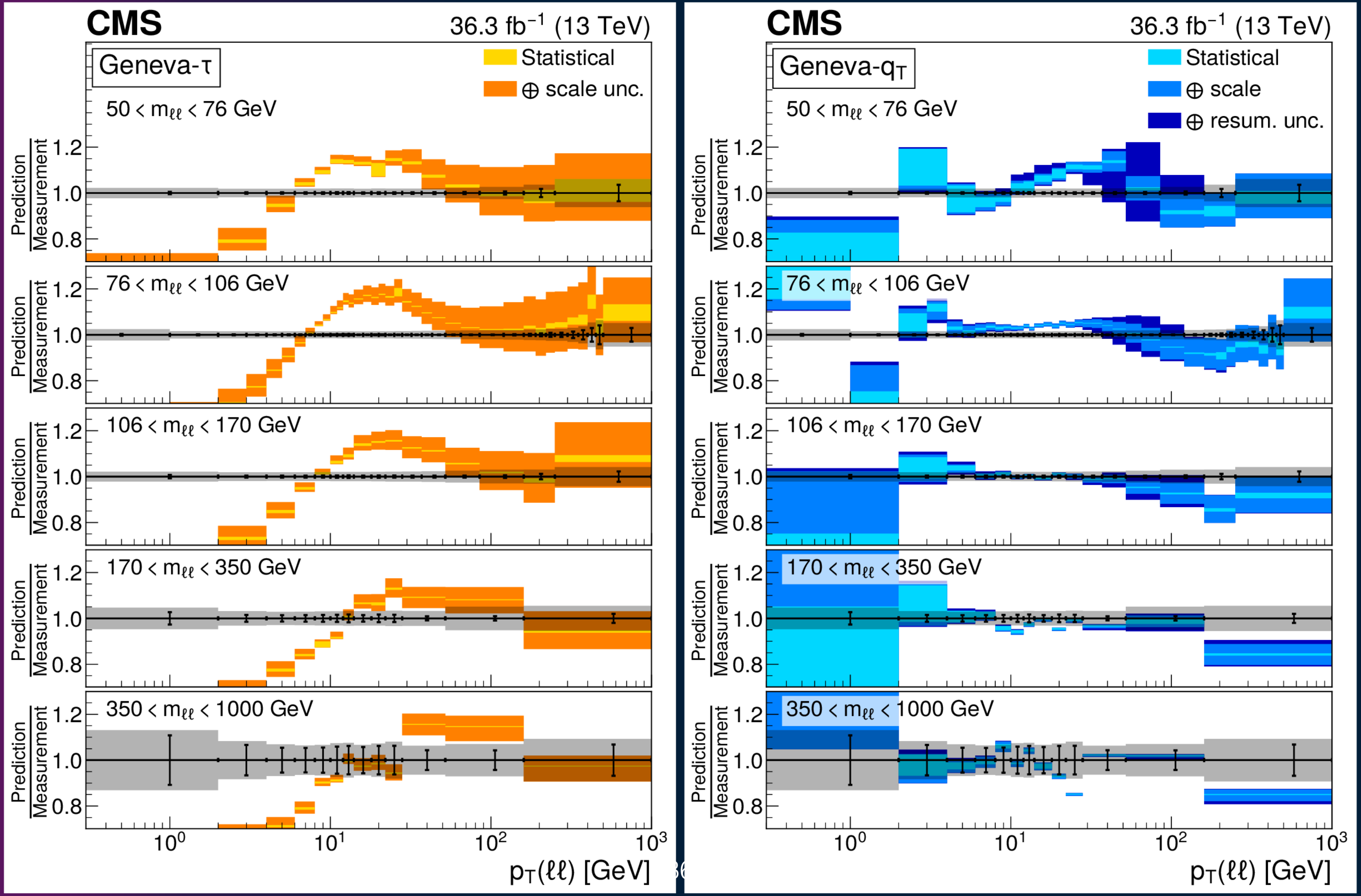
Z cross-sections at CMS : more results

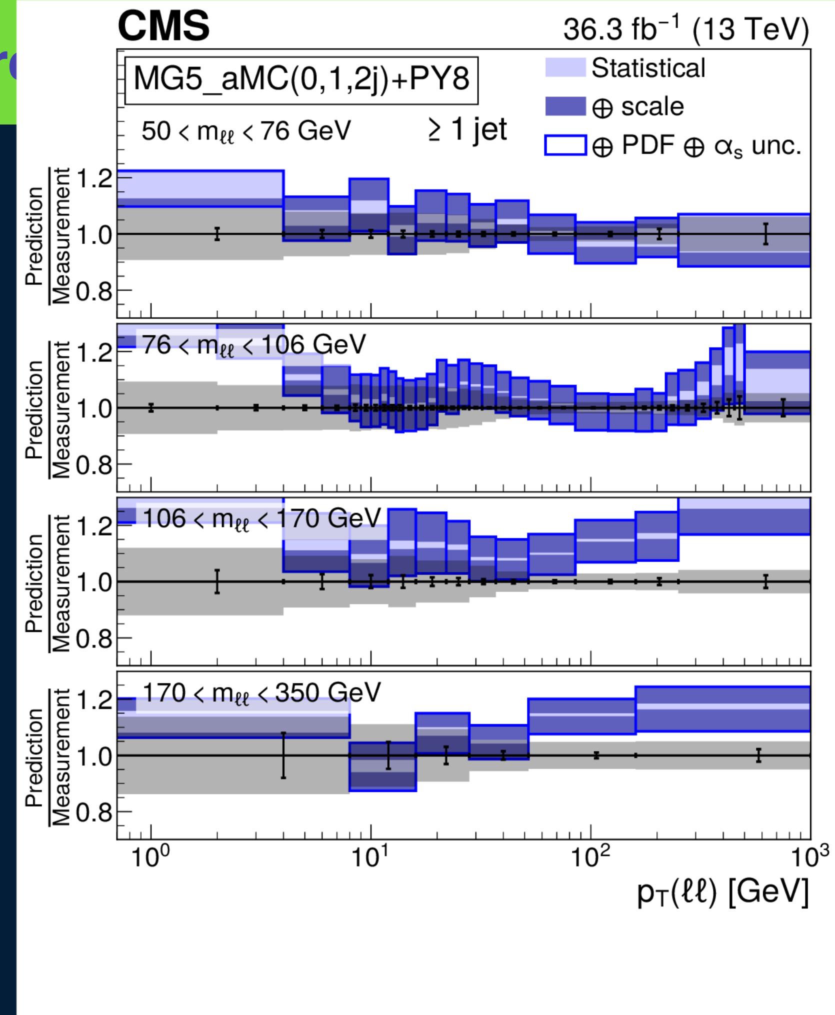


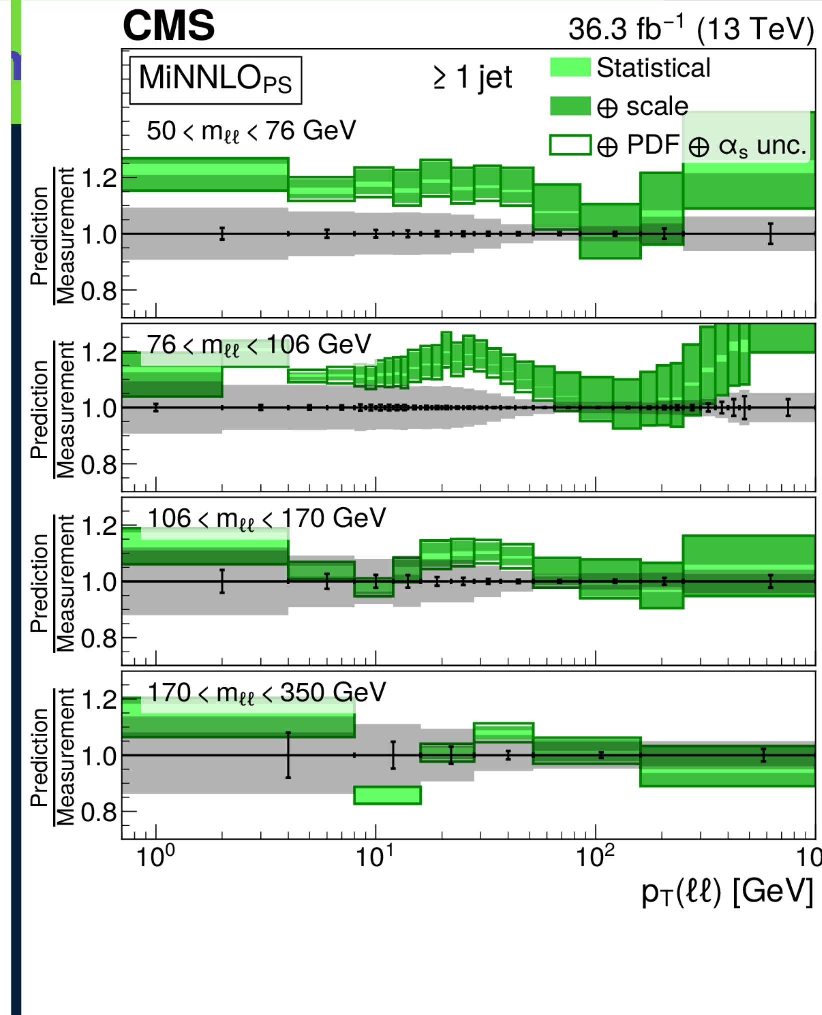
Z cross-sections at CMS : more results



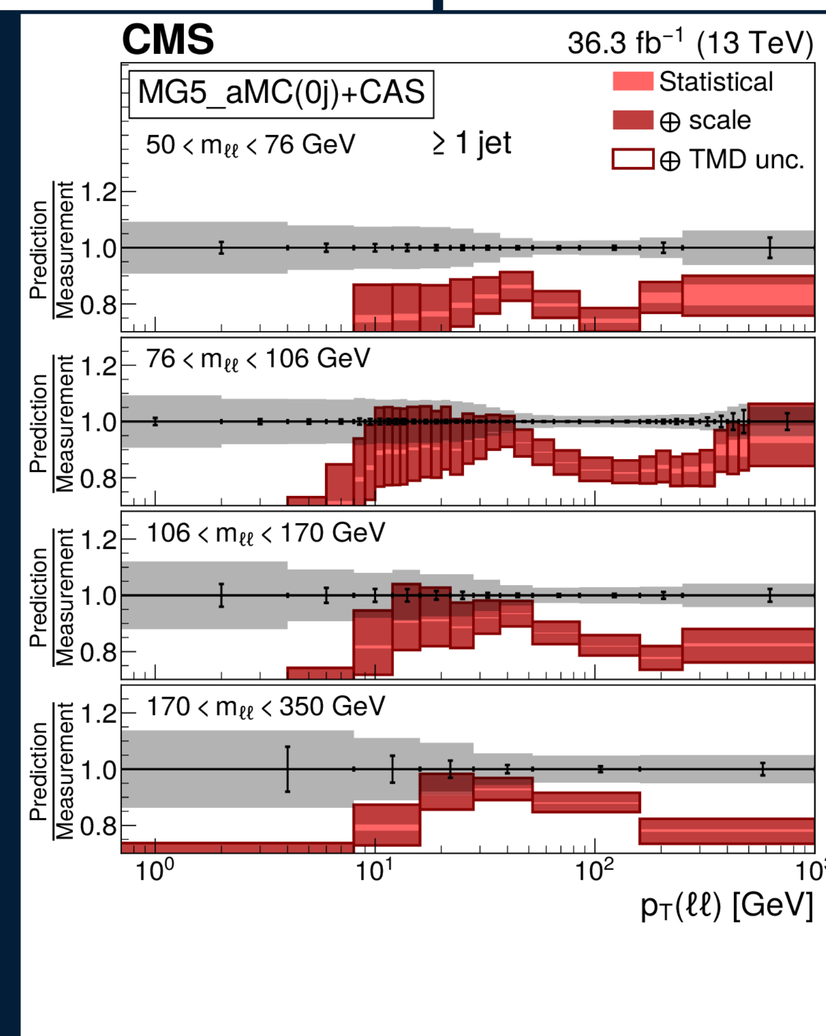
Z cross-sections at CMS : more results



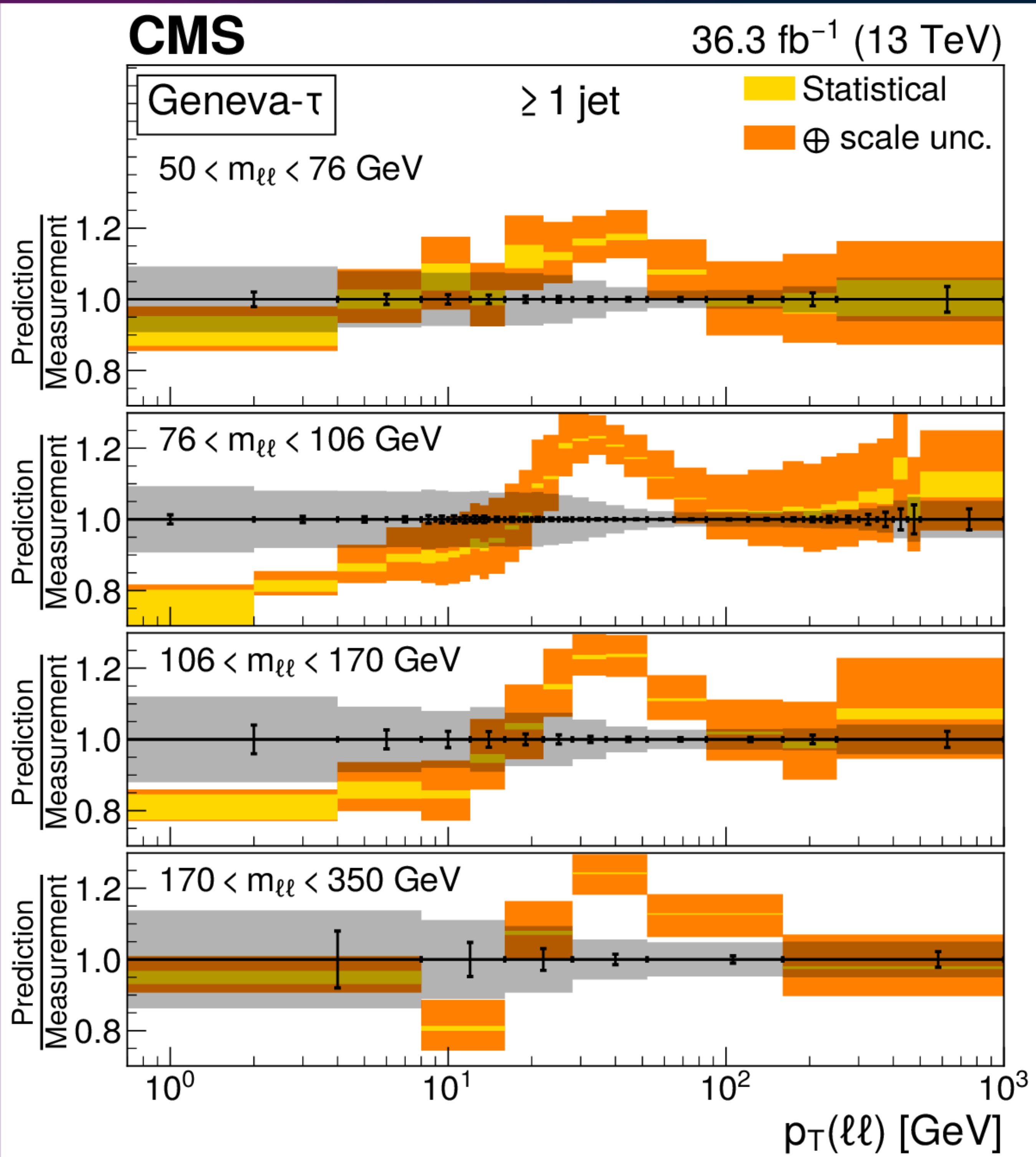


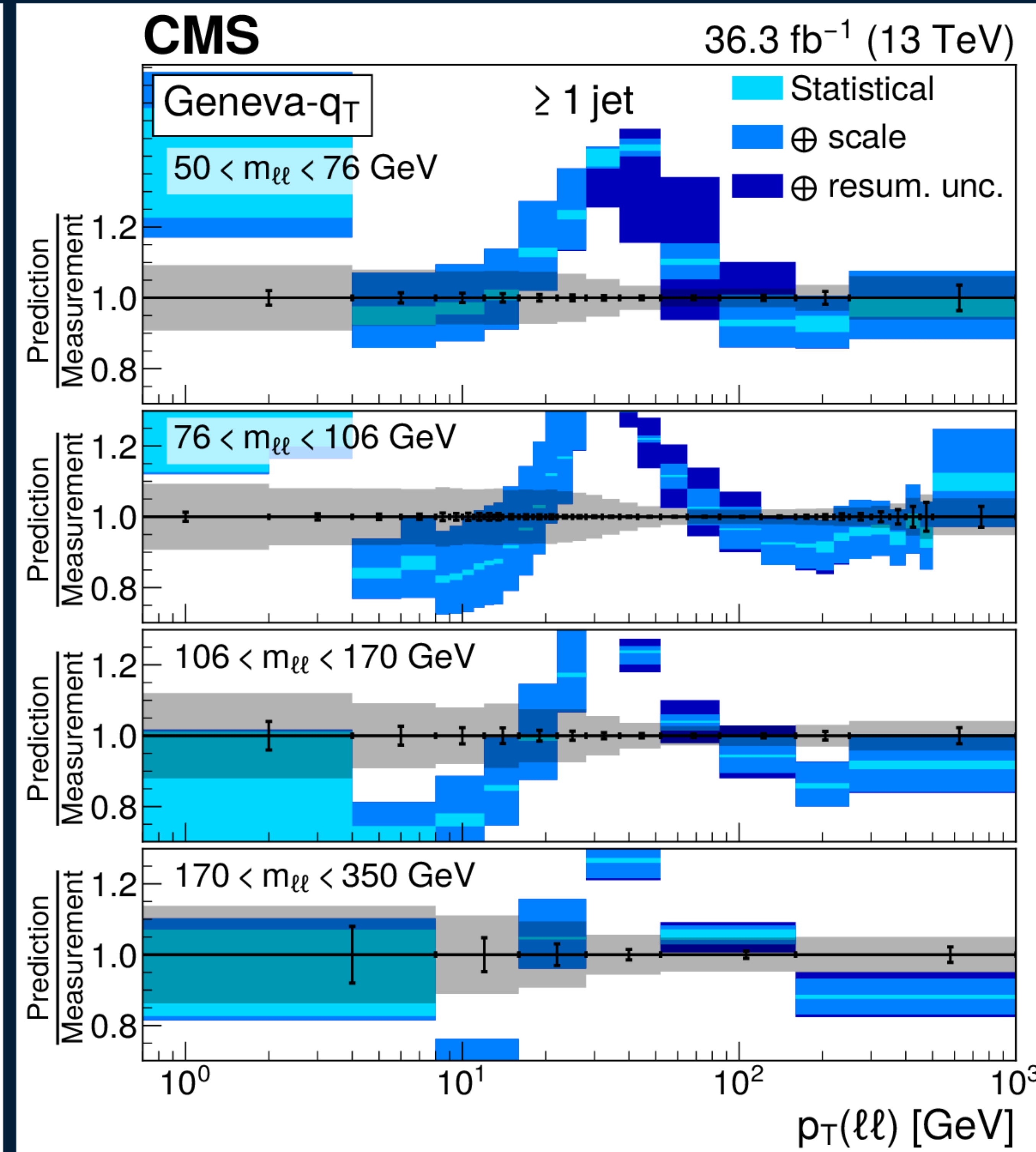


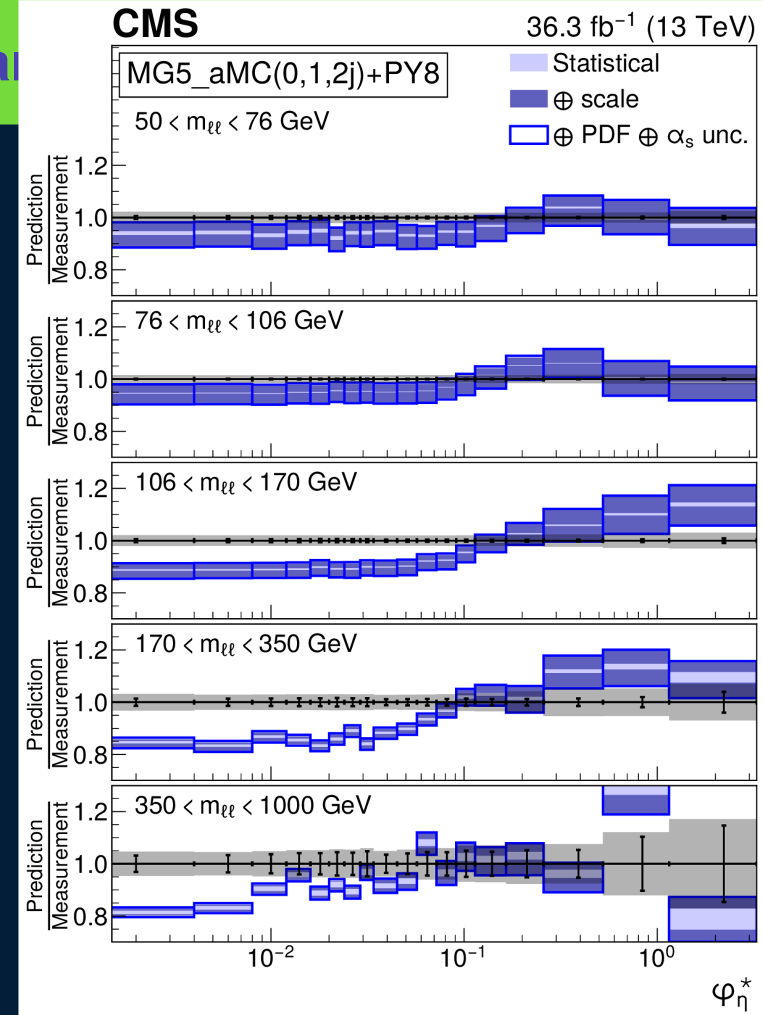
Z cross-sections at CMS : >= 1 jet

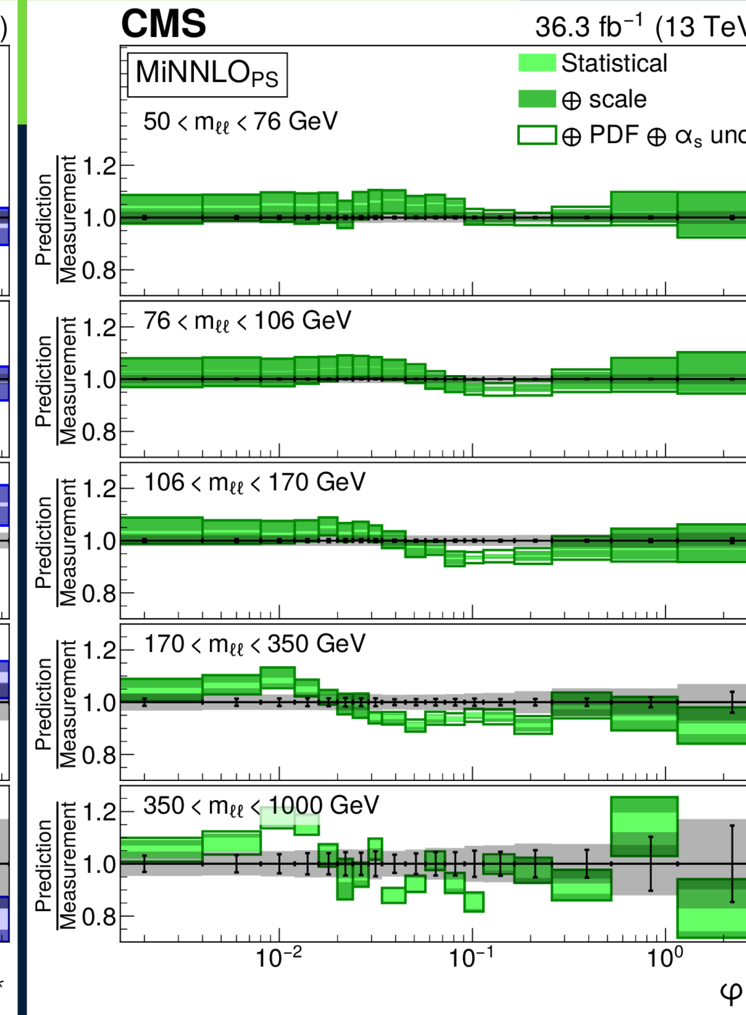


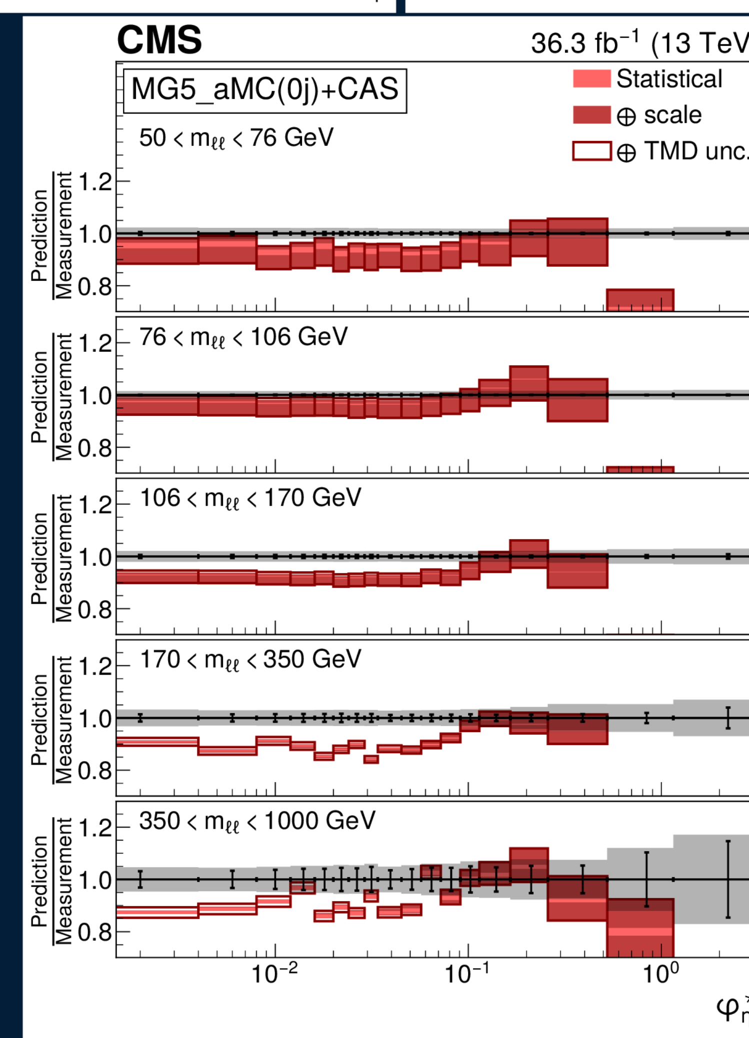
Z cross-sections at CMS : >= 1 jet





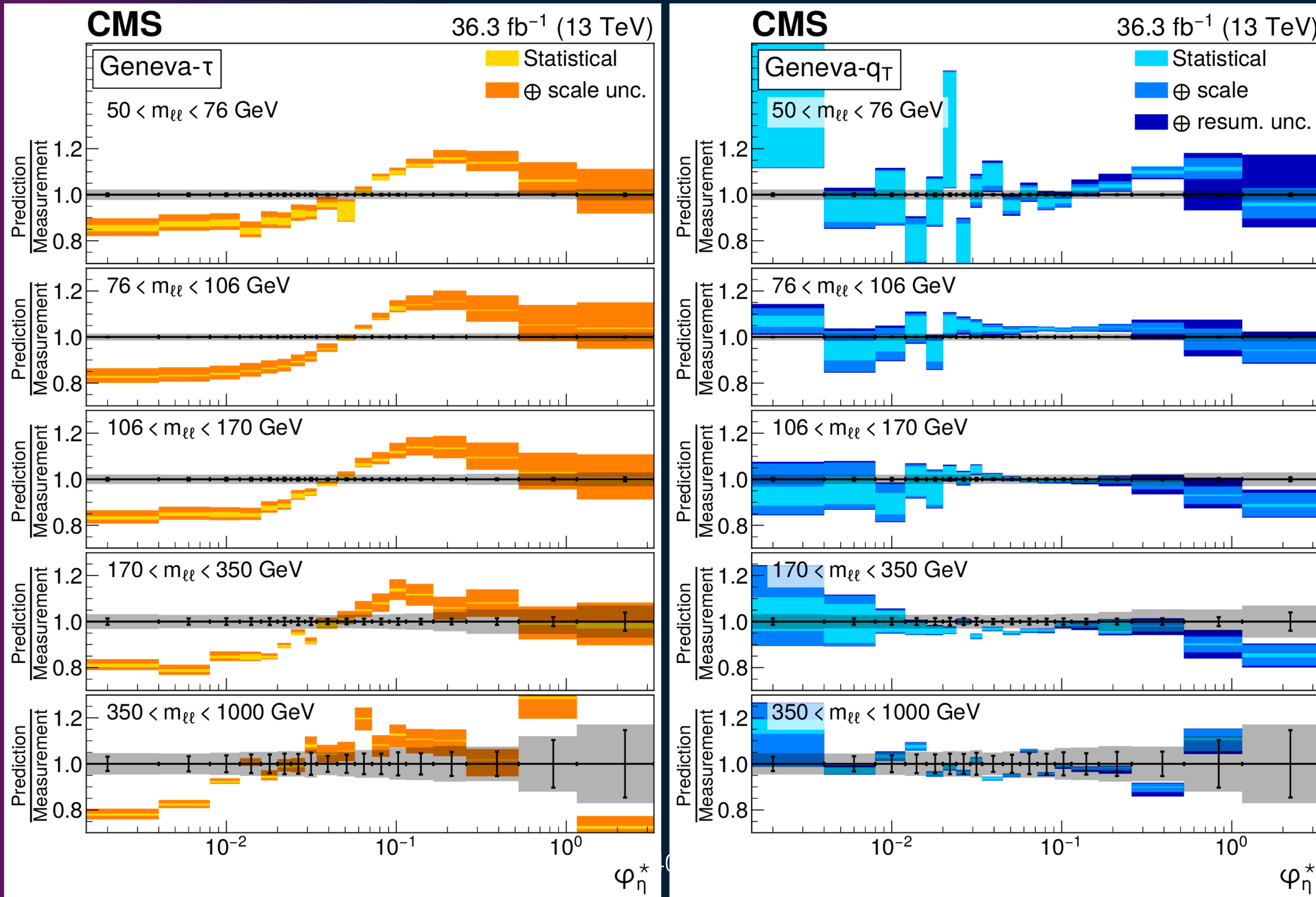






Z cross-sections at CMS : phi*eta

Z cross-sections at CMS : phi*eta



Z Invisible width : uncertainties

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 ($Z/\gamma^* \to \mu\mu$ 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