Precision W and Z measurements

Standard Model at the LHC 2023

Aram Apyan
On behalf of ATLAS, CMS, and LHCb collaborations

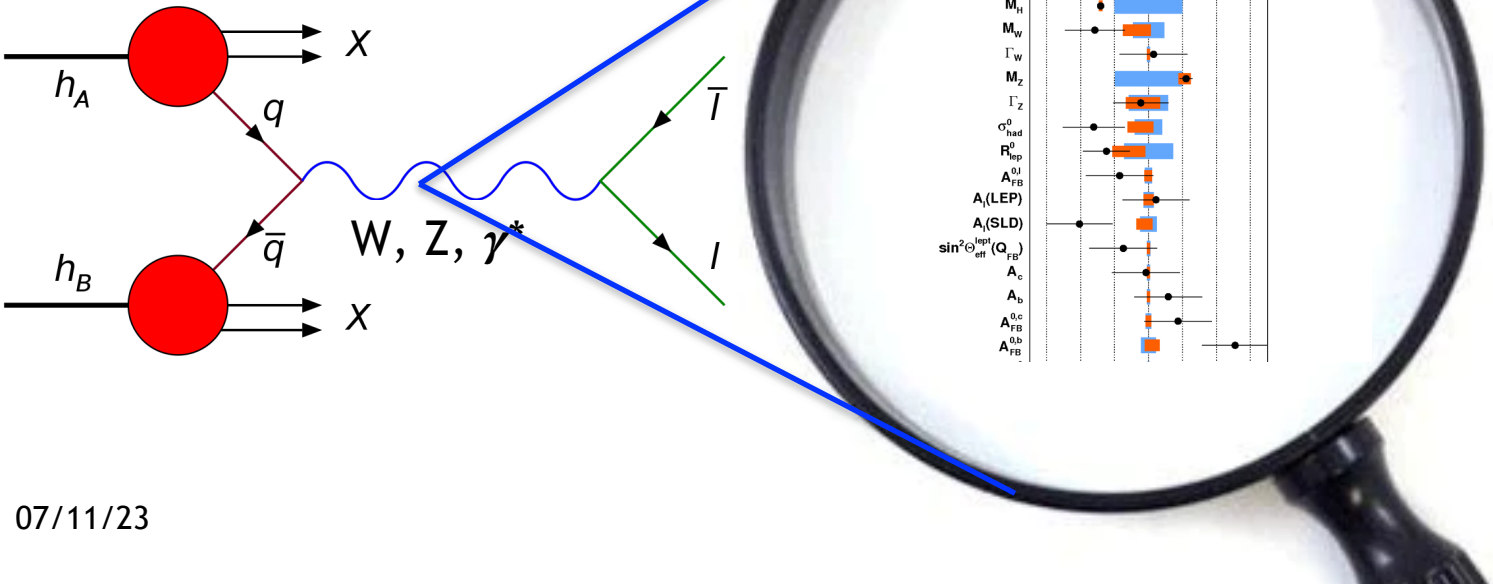
Drell-Yan Process

- The Drell-Yan (DY) process was proposed and measured in 1970
- DY process is the standard candle for precision measurements and theory at the LHC
  - What can we learn form it after 50 years?

Used to measure

- W-boson mass
- $\sin^2\theta_W$
- PDFs
- $\alpha_s(m_Z)$

Information on perturbative and non-perturbative QCD



LHC results

- The purpose of this talk is to mainly focus on the latest W and Z precision measurements by ATLAS, CMS, and LHCb
  - Selected results since the SM@LHC2022
  - See the session on Thursday for the W mass measurements
  - Z/W + heavy flavor measurements are not covered here

- Results covered in this talk:
  - ATLAS full phase space Z double differential cross section
  - ATLAS W/Z p_T with low-pileup data at 5.02 and 13 TeV
  - LHCb measurement of forward Z boson at 5 and 13 TeV
  - CMS τ lepton polarization in Z boson decays
  - CMS DY measurement: p_T and mass
  - CMS precision measurement of Z boson invisible width

ATLAS full phase space Z measurement

- First precise measurement at the LHC in the full phase space of the decay leptons ($\sqrt{s}$ = 8 TeV, L=20.2fb^{-1})
  - Statistically dominated measurement
  - Negligible theoretical uncertainties as there is no direct extrapolation to full phase space
    - Cross sections are parameters of the fit. Fit parameters are 8A_i + 1 cross section in pT-Y 176 bins

$$\frac{d\sigma}{dpdq} = \frac{d^3\sigma^{U+L}}{dp_T dydm}\left(1+\cos^2\theta+\sum_{i=0}^{7} A_i(y,p_T,m)P_i(\cos\theta,\phi)\right)$$

Expected Yield

22528 ($\cos\theta$,ϕ,p_T,y) bins

Reco (p_T^Z,y^Z,m^Z, $\cos\theta$, ϕ) bin

Cross section

Background template

$$N^n_{\text{exp}}(A,\sigma,\theta) = \left\{\sum_{j=1}^{N^{ana}_{\text{bins}}} \mathcal{L}\sigma_j \left[t^n_{8j}(\beta)+\sum_{i=0}^{7} A_{ij}t^n_{ij}(\beta)\right]\right\}\gamma^n + \sum_{B}^{\text{bkgs}} T^n_B(\beta)$$

Likelihood

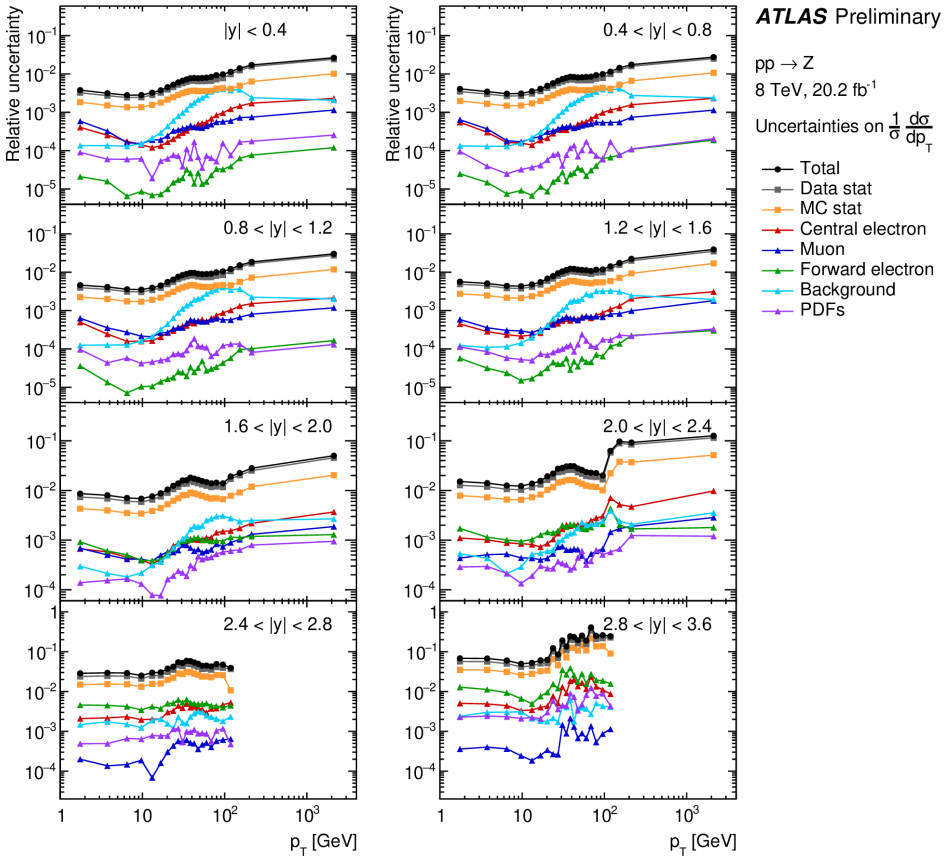
Truth (p_T^Z,y^Z,m^Z) bin

Angular coefficient

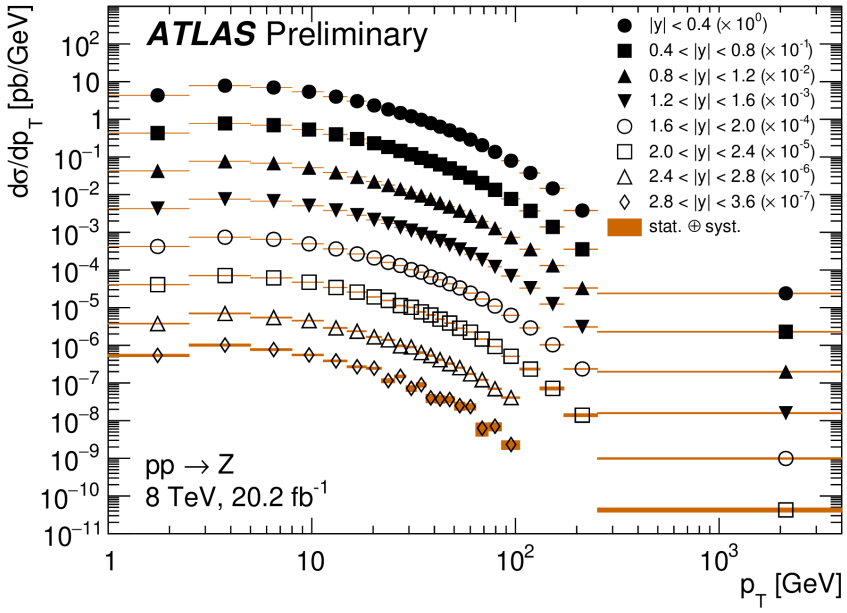
Templated polynomial

ATLAS full phase space Z measurement

- $d^2\sigma/dp_T dY$ measurement
  - Uncertainties dominated by data statistics



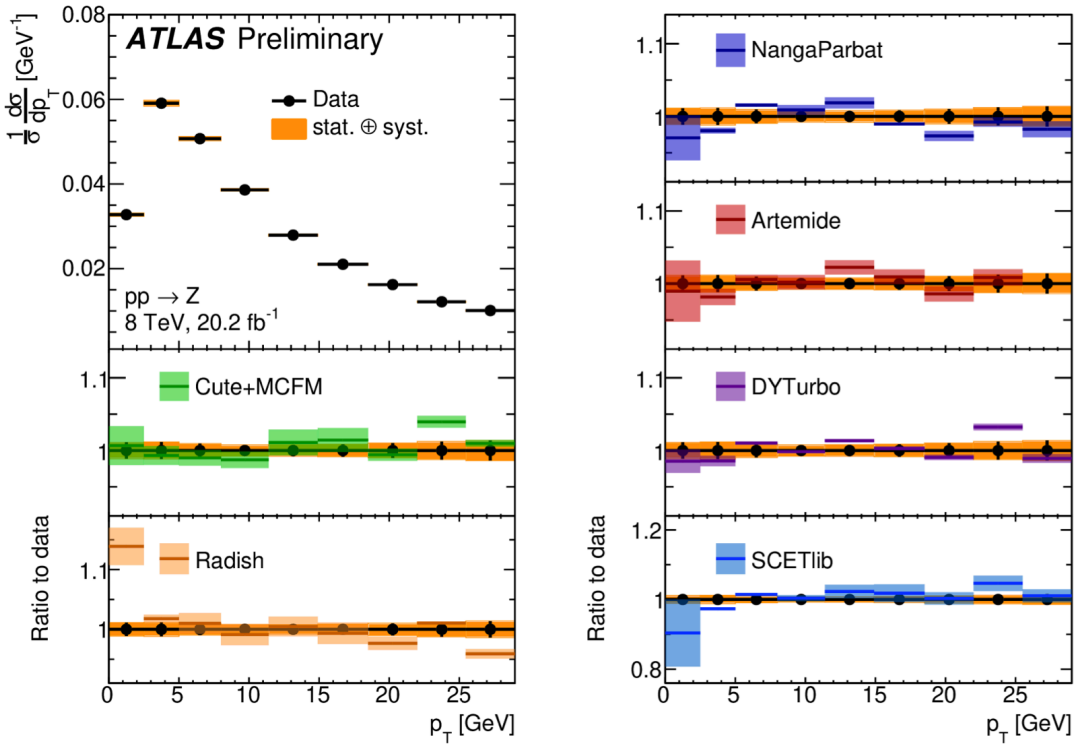
80 < m_Z < 100 GeV, |Y| < 3.6



ATLAS-CONF-2023-013

ATLAS full phase space Z measurement

- p_T cross section $d\sigma/dp_T$ $80 < m_Z < 100$ GeV, $|Y| < 3.6$
  - Measurement compared to N3LL/N4LL resummed predictions matched to $O(\alpha_s^3)$ from MCFM/NNLOJET
  - Excellent agreement with data. Crucial input for m_W measurements



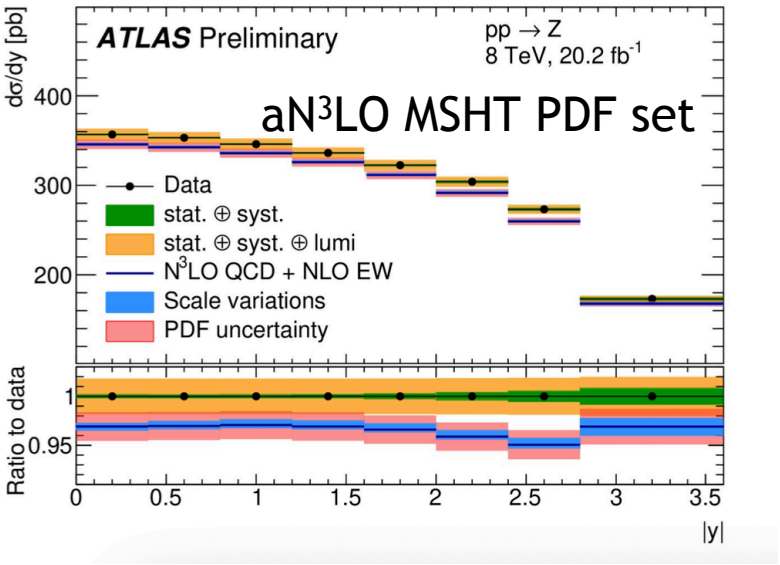
Strong effort in LPCC with benchmarking studies at N3LL/N4LL

See Francesco's talk in QCD section for the α_s extraction

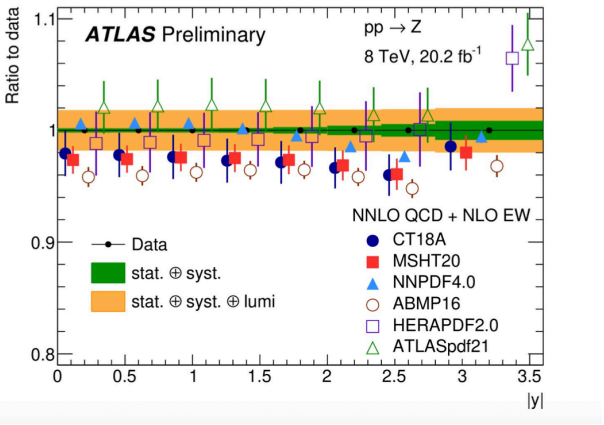
ATLAS-CONF-2023-013

ATLAS full phase space Z measurement

- Rapidity cross section $d\sigma/dY$ $80 < m_Z < 100$ GeV, $|Y| < 3.6$
  - Permille level precision in the central region. Dedicated forward electron calibration up to $|Y| < 3.6$
  - Comparison to N3LO QCD predictions (DYTurbo) and to different PDFs
    - NLO EW corrections with ReneSANCe



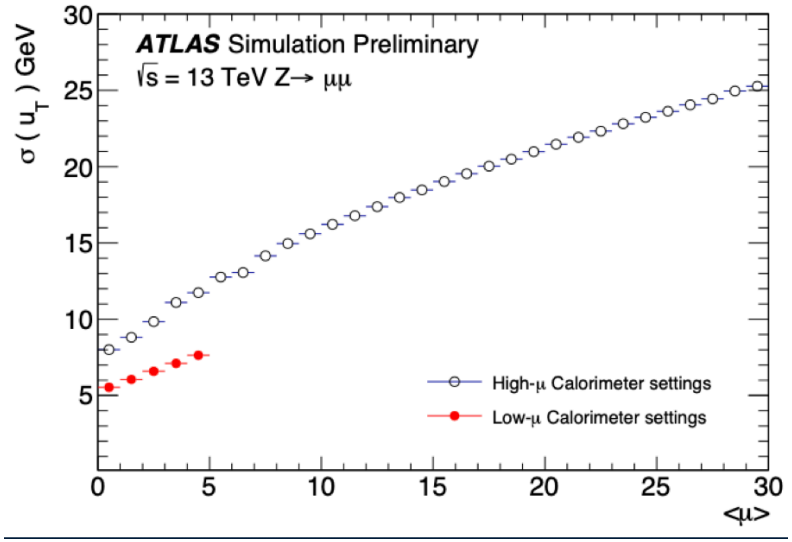
PDF set	Total χ^2 / d.o.f.	χ^2 p-value	Pull on luminosity
MSHT20aN^{3}LO [60]	13/8	0.11	1.2 ± 0.6
CT18A [61]	12/8	0.17	0.9 ± 0.7
MSHT20 [62]	10/8	0.26	0.9 ± 0.6
NNPDF4.0 [63]	30/8	0.0002	0.0 ± 0.2
ABMP16 [64]	30/8	0.0002	1.8 ± 0.4
HERAPDF2.0 [65]	22/8	0.005	-1.3 ± 0.8
ATLASpdf21 [66]	20/8	0.01	-1.1 ± 0.8

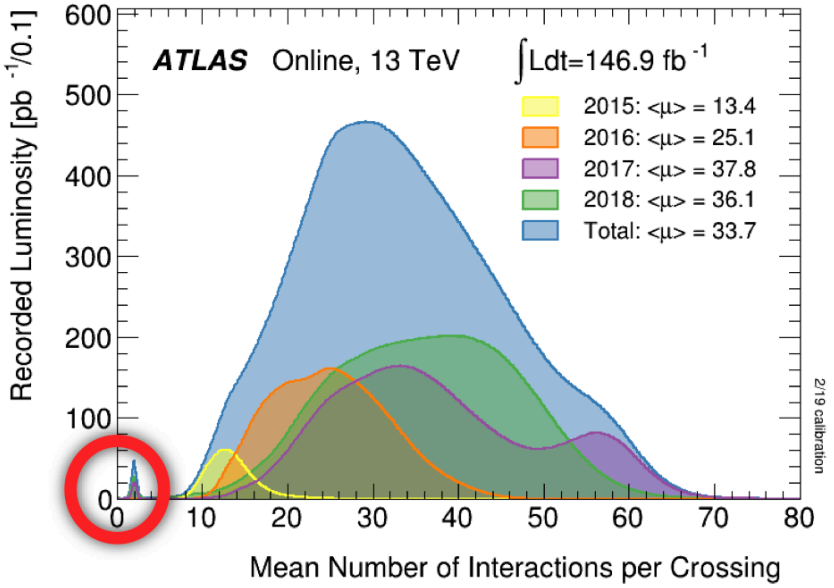


ATLAS-CONF-2023-013

ATLAS W and Z pT with low-pileup data

- Precise measurement of the W p_T is important in reducing the modeling uncertainty in the W mass measurements
- Hadronic recoil is the main limitation of the p_T W measurements
  - Recoil resolution degrades with pileup
- Dedicated low-pileup runs with <μ> of about 2 taken in 2017 and 2018
  - 255 pb^{-1} at 5.02 TeV and 338 pb^{-1} at 13 TeV



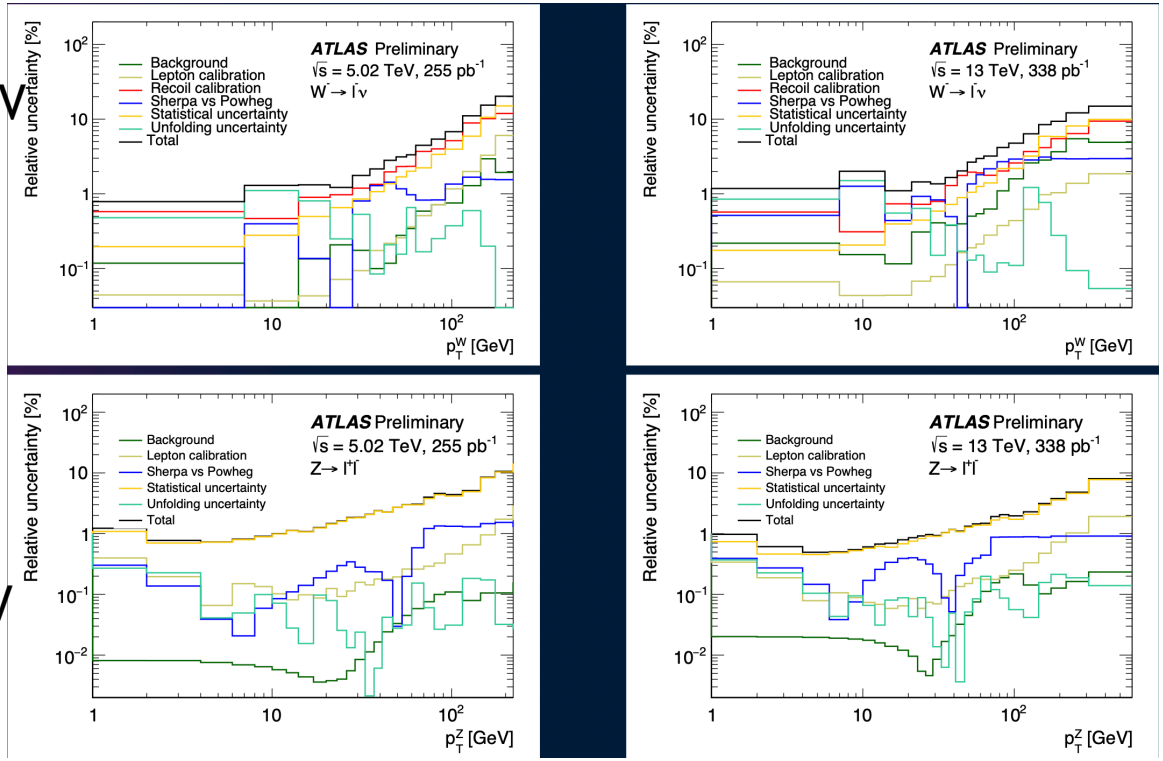


ATLAS-CONF-2023-028

ATLAS W and Z p_T with low-pileup data

- Measurements of W^+, W^-, and Z p_T and ratios at 13 and 5.02 TeV
- Z measurement uncertainties dominated by data statistics
- W measurement uncertainties dominated by recoil calibration, unfolding, and data statistics (strong case for future low pileup runs)

W^-, 5.02 TeV



W^-, 13 TeV

Z, 5.02 TeV

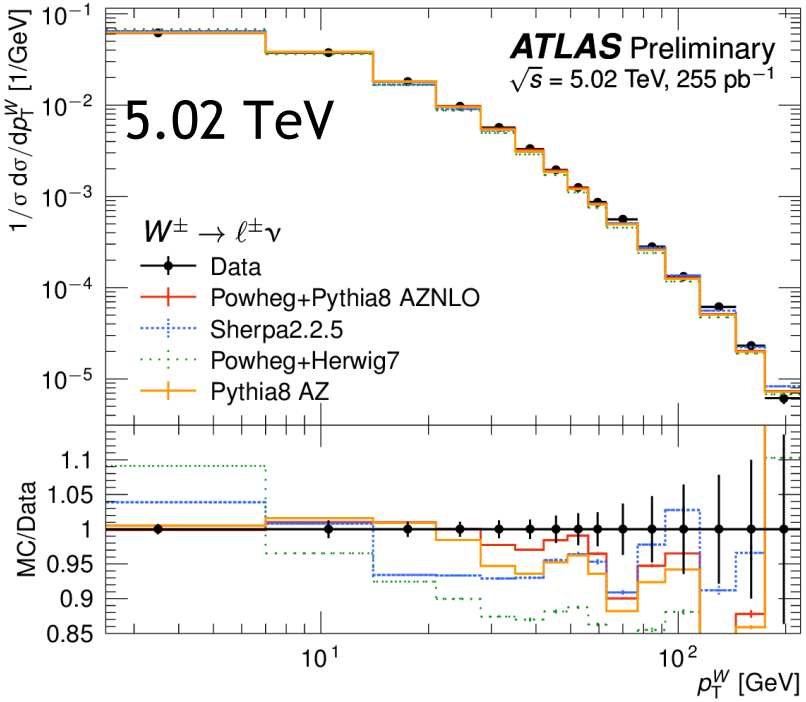
Z, 13 TeV

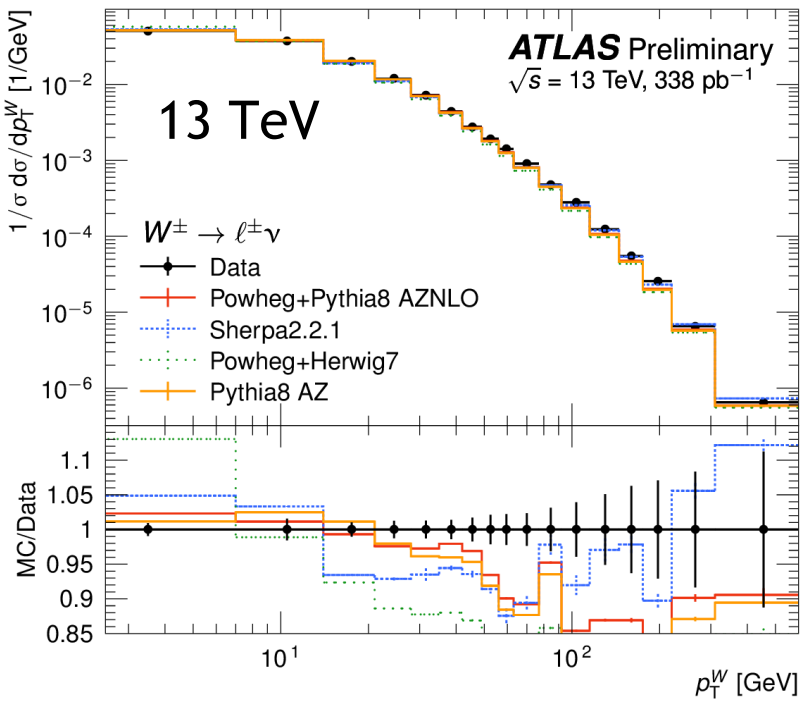
Fiducial volume :
- lepton p_T > 25 GeV, lepton |η| < 2.5
- W :
  - $p_T{}^{\nu}$ >25 GeV
  - m_T > 50 GeV
- Z : 66 < m_ll < 116 GeV

ATLAS-CONF-2023-028

ATLAS W and Z p_T with low-pileup data

- W cross sections compared to various Monte-Carlo predictions
  - Predictions using the ATLAS tune (used for the W mass measurement on 7 TeV data) describe data reasonably at low pT especially at √s=5.02 TeV





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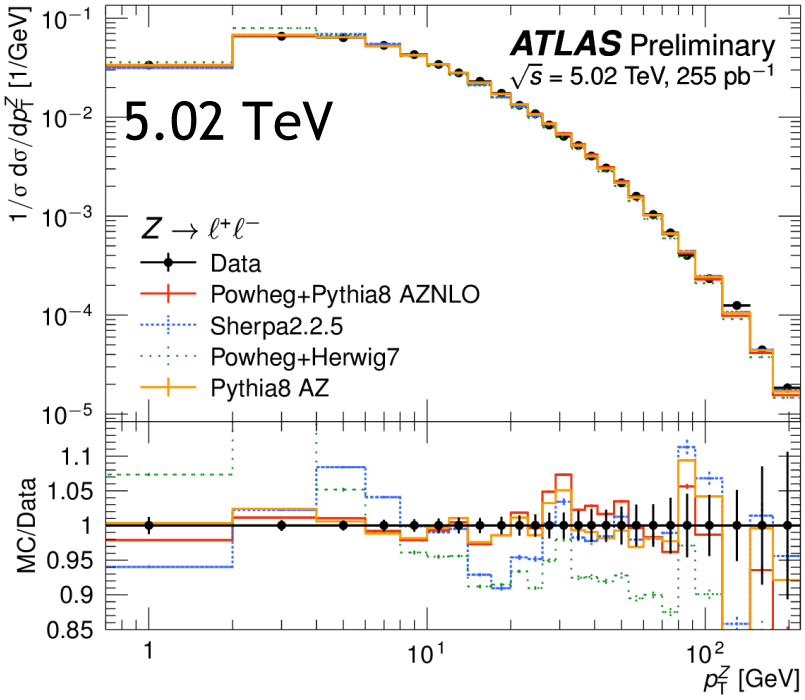
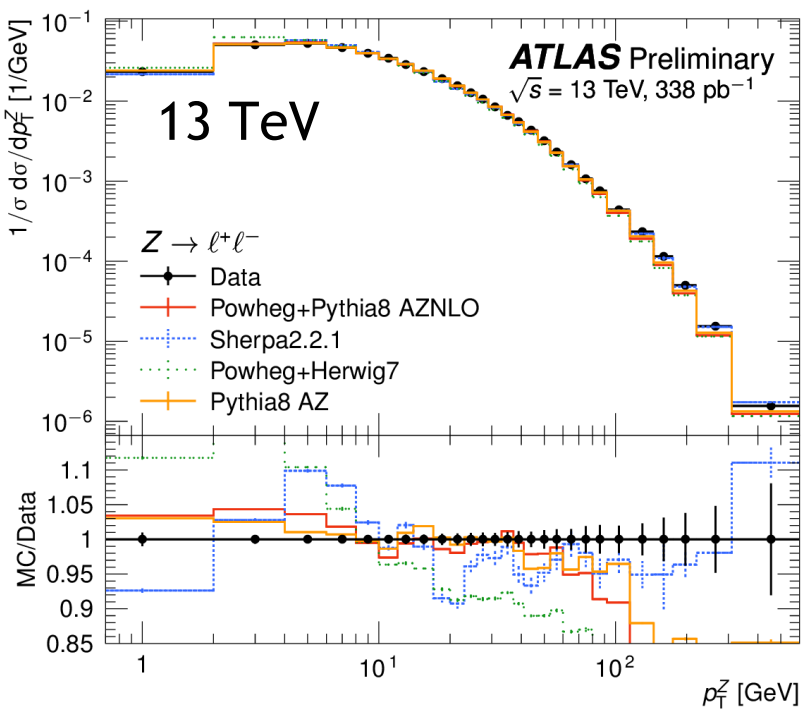




ATLAS-CONF-2023-028

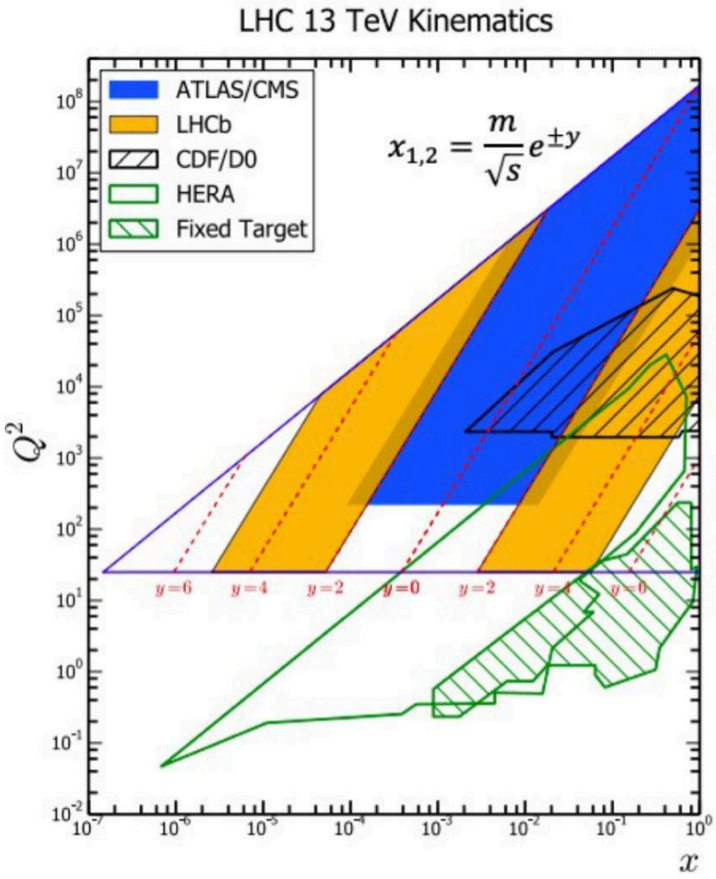
LHCb forward Z measurements

- Differential cross sections in Y, p_T, and ϕ_η^*
- Access to PDFs at large and small x
- 5.1fb^{-1} collected in 2016-18

- Fiducial region:
  - Muon p_T > 20 GeV, 2 < η < 4.5
  - 60 < $m_{\mu\mu}$ < 120 GeV

- Most precise integrated cross sections in the forward region

- New result at √s=5.02 TeV, 99.86 pb^{-1}

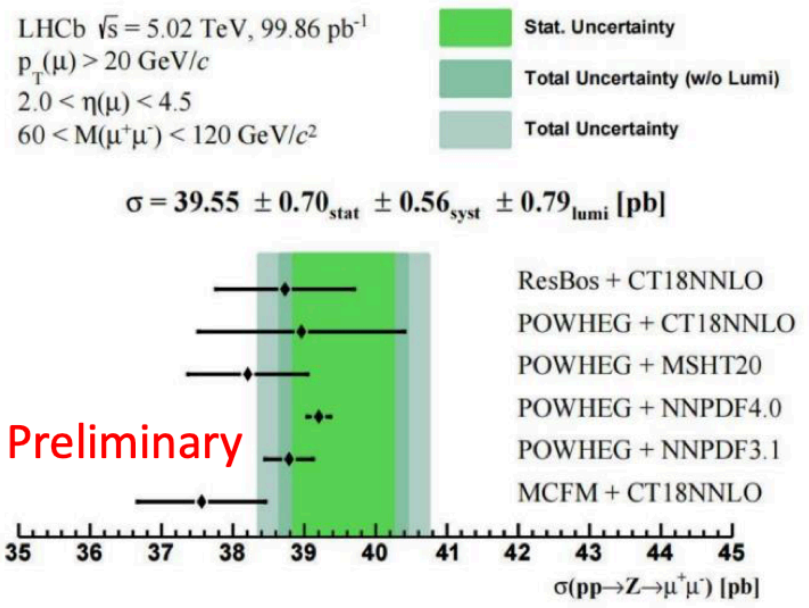


$$\phi_\eta^* = \tan\left(\frac{\pi - \Delta\phi}{2}\right) \times \sin(\theta_\eta^*), \qquad \cos(\theta_\eta^*) = \tanh[(\eta^- - \eta^+)/2]$$

LHCb forward Z measurements

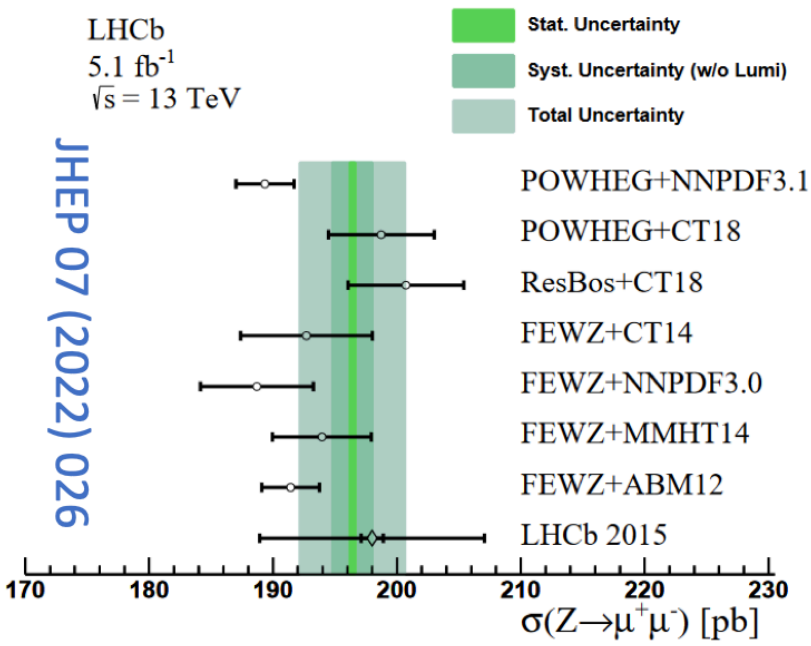
- Z cross sections at 5.02 TeV and 13 TeV
  - The most precise measurements in the forward region
  - The measurement at 5.02 TeV dominated by statistical uncertainty

5.02 TeV



LHCb paper in preparation

13 TeV



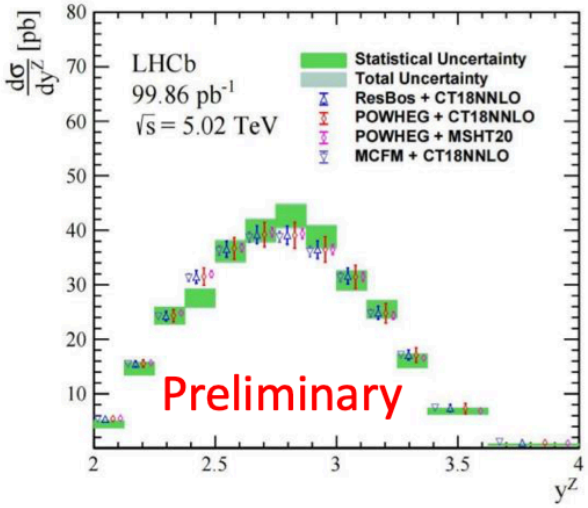
Arxiv:2112.07458

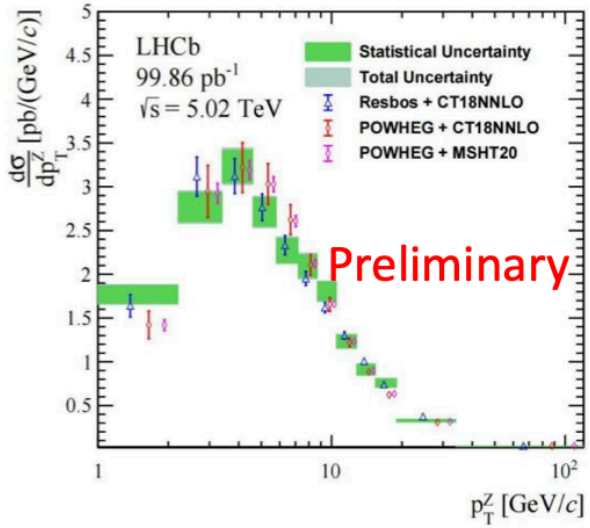
LHCb forward Z measurements

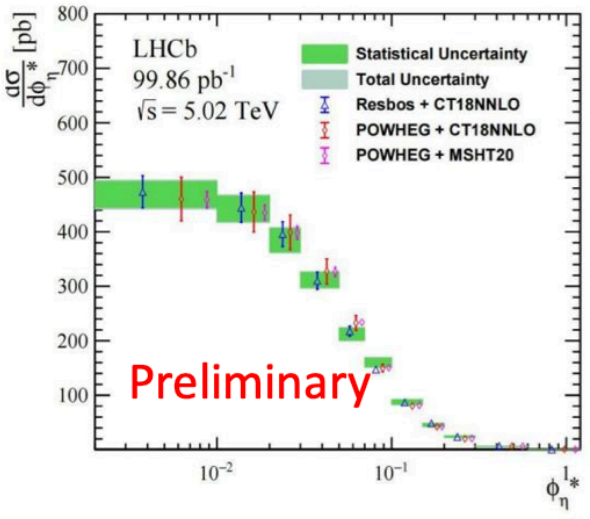
- New differential cross section measurements at 5.02 TeV

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





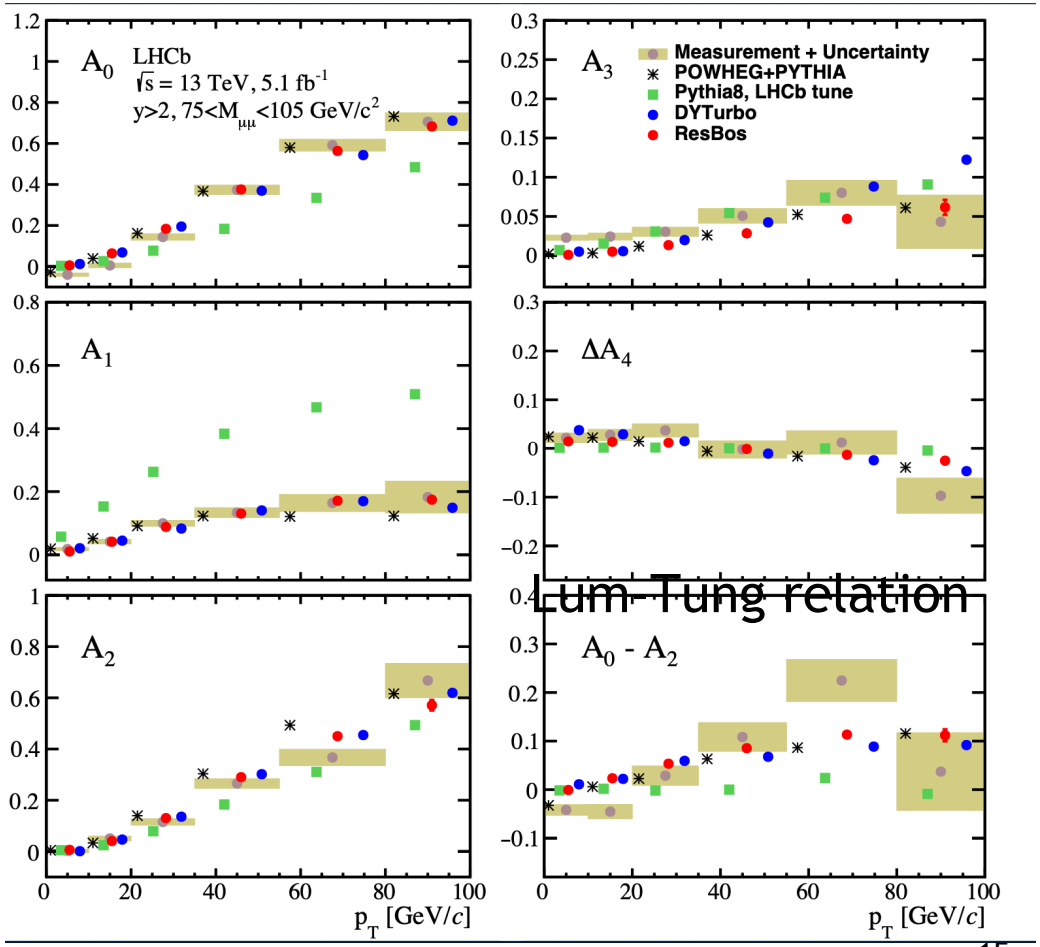


LHCB-PAPER-2023-010 in preparation

LHCb forward Z measurements

- First measurement of angular coefficients in forward region at 13 TeV

- Measurements performed as functions of p_T and Y
- Also measured in the low and high $m_{\mu\mu}$ regions
- Measurements dominated by data statistics
- Results are compared to Pythia8, Powheg, DYTurbo, and ResBos predictions
- The measured violation of Lam-Tung relations consistent with previous ATLAS and CMS measurements



Lum-Tung relation

Phys. Rev. Lett. 129 (2022) 091801

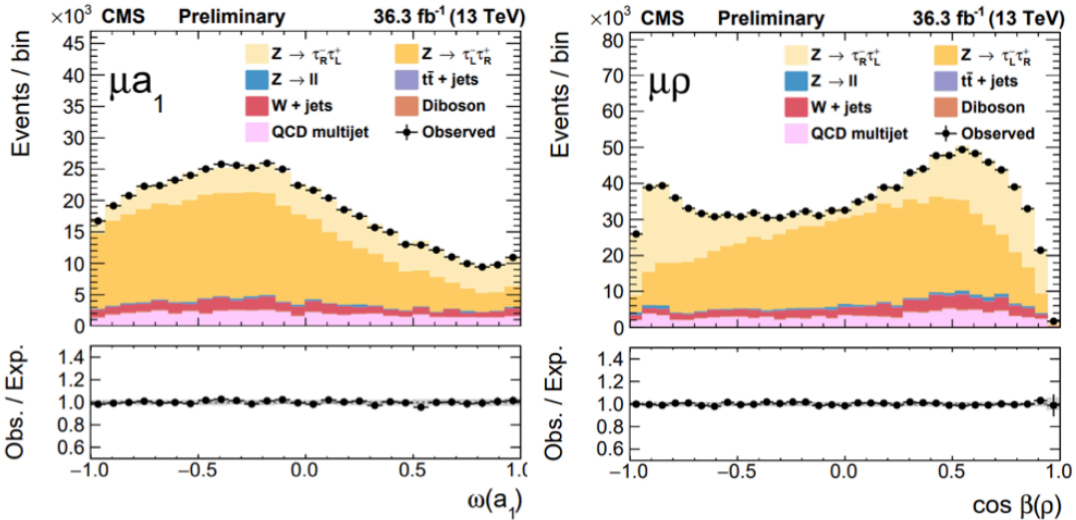
CMS τ lepton polarization in Z boson decays

- Leptonic and hadronic τ decays used for the measurement
- Optimal observables exploited at LEP utilized
  - Polarimetric vector, helicity correlations, etc.
- CMS data at 13 TeV with 36.3 fb^{-1}

$$\omega_h = \cos\zeta_h,$$

$$\Omega = \frac{\omega_1 + \omega_2}{1 + \omega_1\omega_2}.$$

Channel	Category	Discriminator	
$\tau_e\tau_\mu$	$e+\mu$	$m_{\text{vis}}(e,\mu)$	visible mass
$\tau_e\tau_h$	$e+a_1$	$\omega(a_1)$	optimal observable with SVfit
	$e+\rho$	$\omega_{\text{vis}}(\rho)$	visible optimal observable
	$e+\pi$	$\omega(\pi)$	optimal observable with SVfit
$\tau_\mu\tau_h$	$\mu+a_1$	$\omega(a_1)$	optimal observable with SVfit
	$\mu+\rho$	$\omega_{\text{vis}}(\rho)$	visible optimal observable
	$\mu+\pi$	$\omega(\pi)$	optimal observable with SVfit
$\tau_h\tau_h$	a_1+a_1	$m_{\text{vis}}(a_1,a_1)$	visible mass
	$a_1+\pi$	$\Omega(a_1,\pi)$	combined optimal observable with SVfit
	$\rho+\tau_h$	$\omega_{\text{vis}}(\rho)$	visible optimal observable (for leading ρ)
	$\pi+\pi$	$m_{\text{vis}}(\pi,\pi)$	visible mass



SMP-18-010

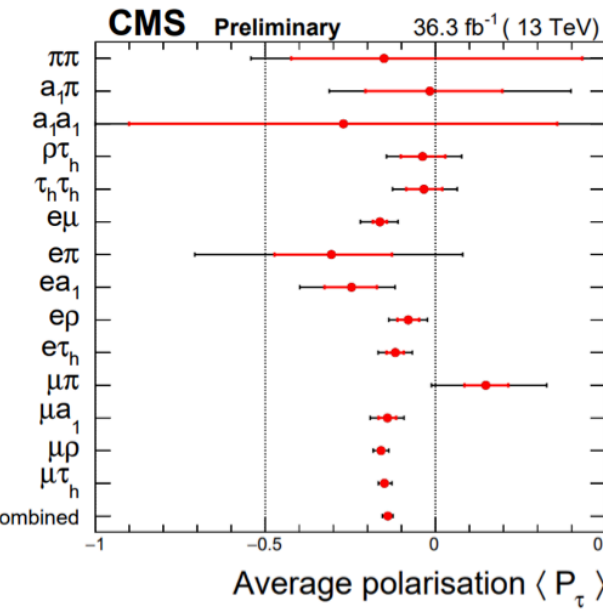
CMS τ lepton polarization in Z boson decays

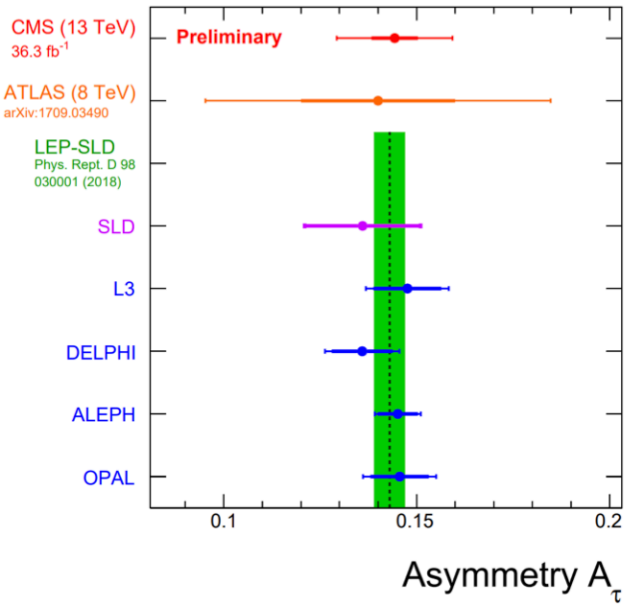
- Measured polarization is in good agreement with the SLD/LEP

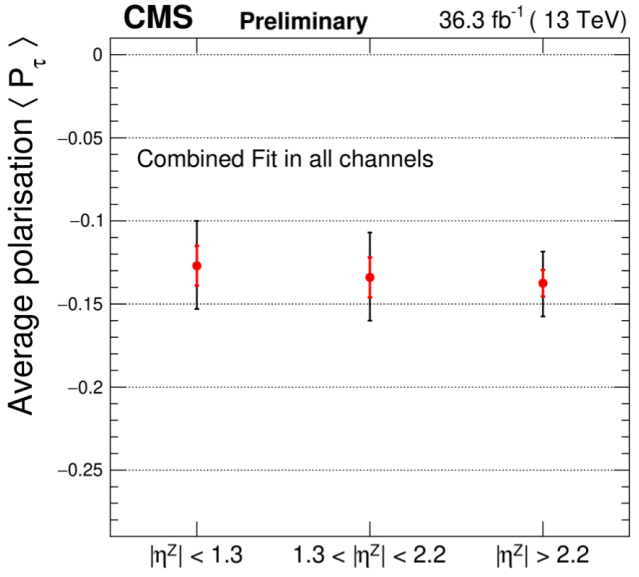
$$P_\tau = \frac{1}{\sigma}[\sigma(h_\tau = +1) - \sigma(h_\tau = -1)] \qquad P_\tau = -A_\tau = -\frac{2v_\tau a_\tau}{v_\tau^2 + a_\tau^2} \approx -2 \cdot \frac{v_\tau}{a_\tau} = -2(1 - 4\sin^2\theta_W^{\text{eff}})$$

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

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





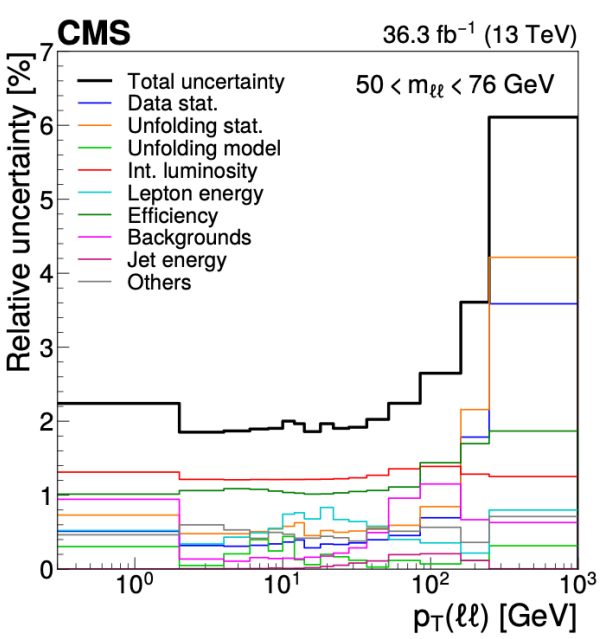


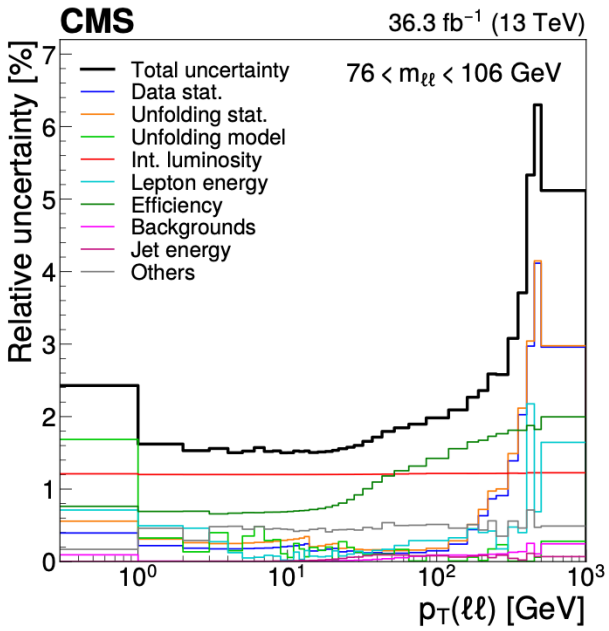
SMP-18-010

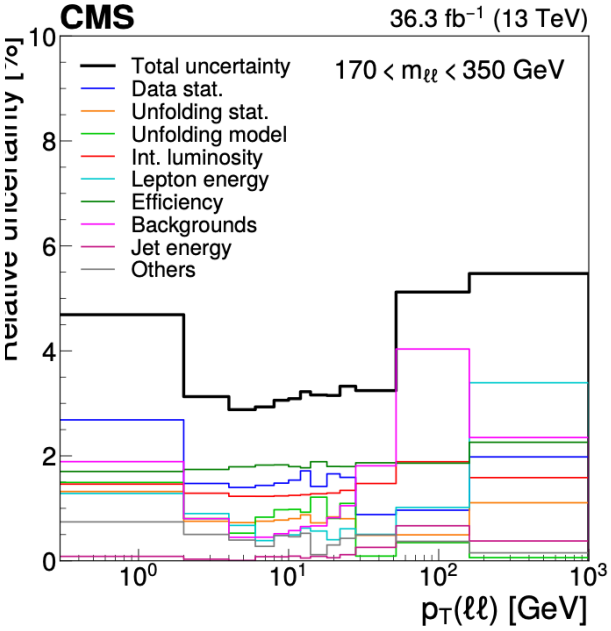
CMS DY measurement

Arxiv:2205.0489

- Double differential cross sections in m_{ll}, p_T, and ϕ_η^*
  - Inclusive and >= 1 jet categories
  - 5 m_{ll} bins. Fiducial region: p_T > 25 (20) GeV for leading (subleading) lepton, $|\eta|$ < 2.4
- $\sqrt{s}$ = 13 TeV, L=36.3 fb^{-1}
- Measurement compared to large variety of theory predictions



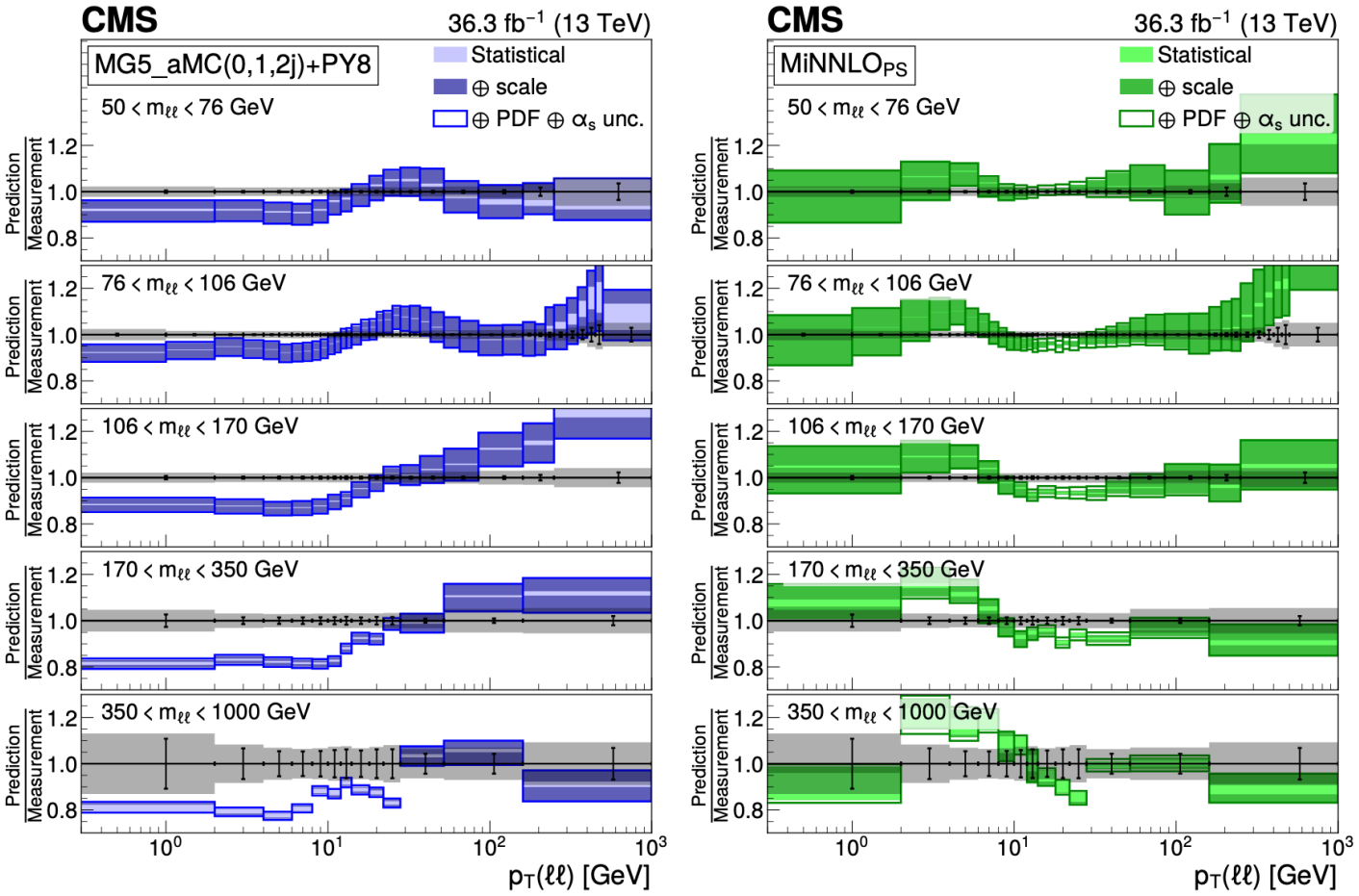




CMS DY measurement

Arxiv:2205.0489

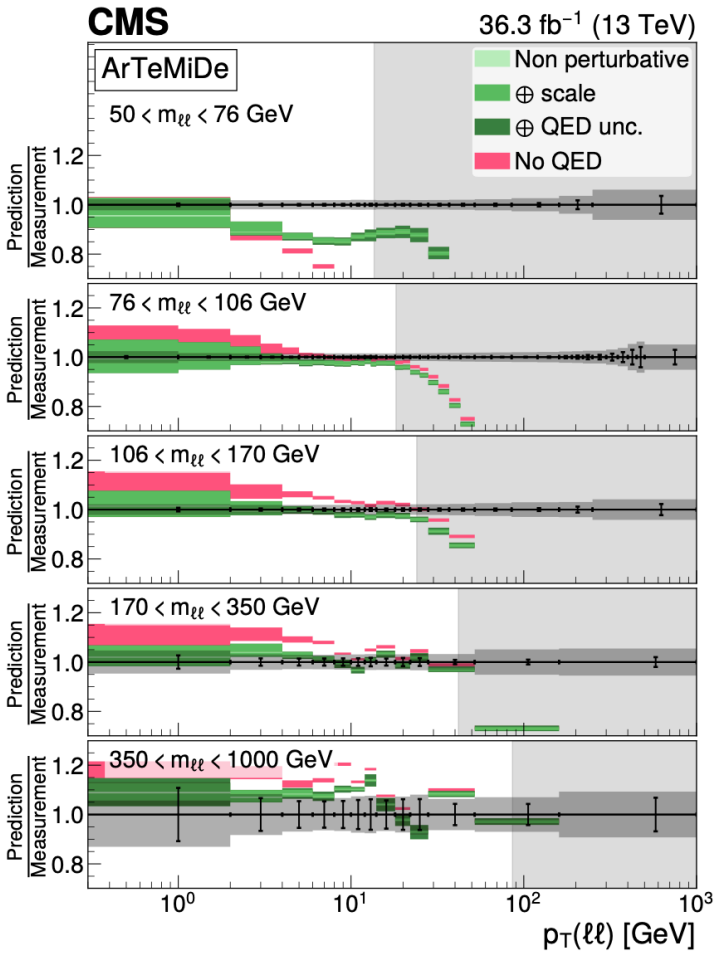
- Measurement compared with MadGraph5_aMC@NLO + PYTHIA 8 and MiNNLOPS : NNLO ME and Pythia8 PS and MPI

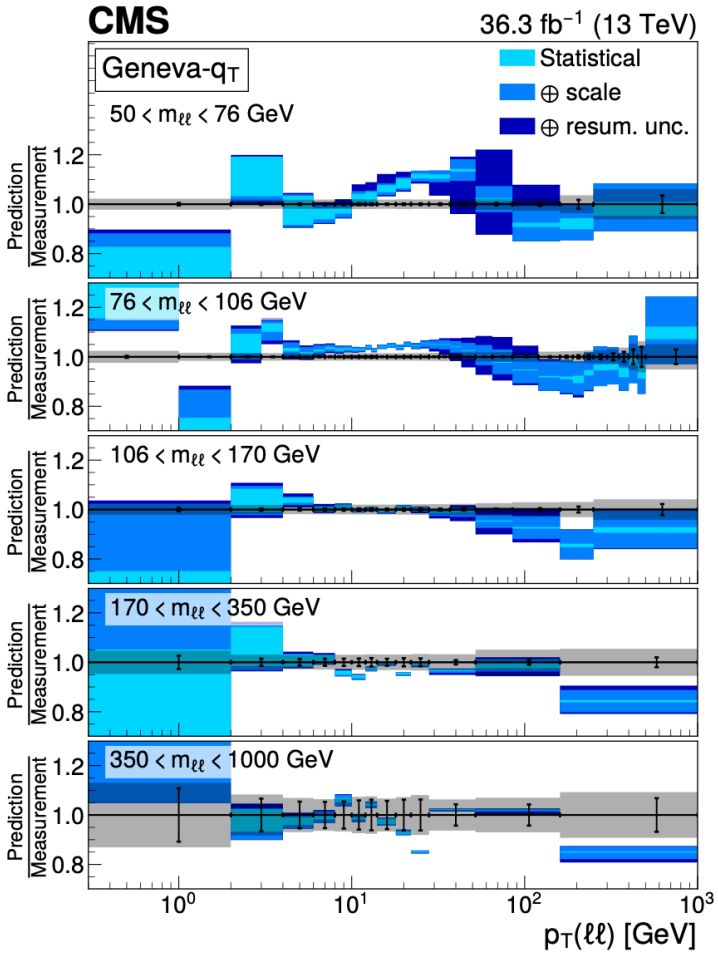


CMS DY measurement

Arxiv:2205.0489

- Measurement compared with TMD based predictions (Parton-Branching with CASCADE3, ArTeMiDe) and resummed predictions with Geneva



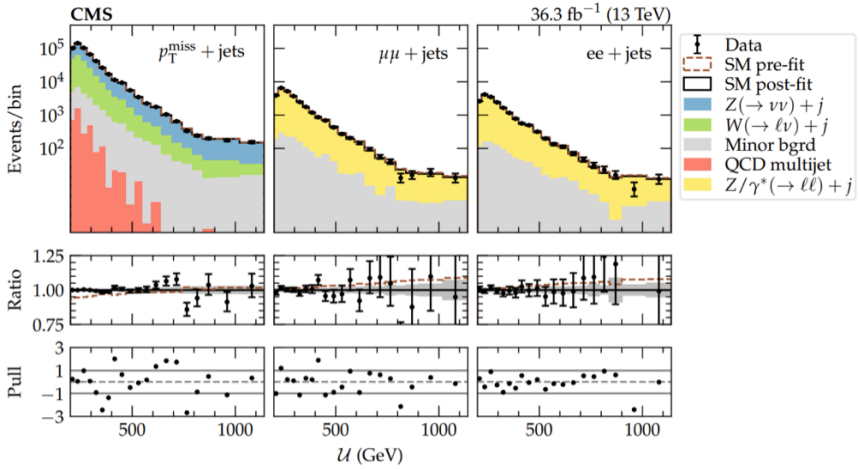


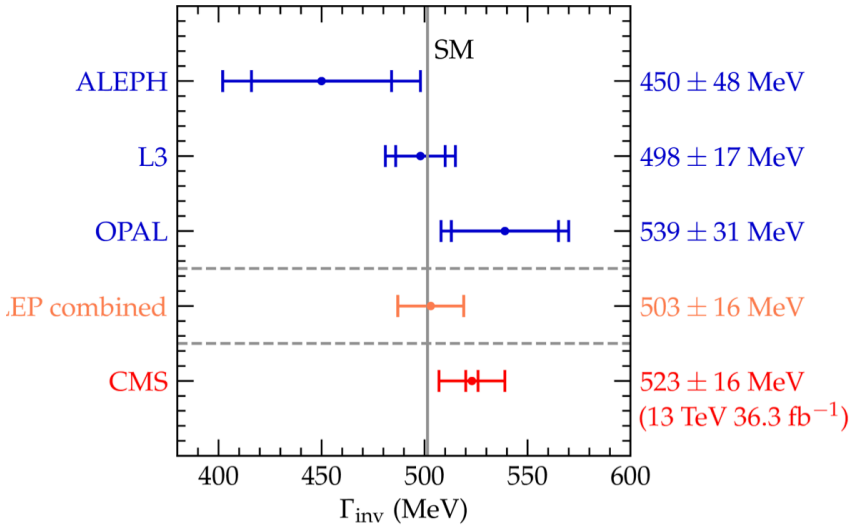
CMS precise measurement of Z invisible width

- First direct precise measurement of Z invisible width at a hadron collider
- Constraint on number of light neutrino species coupling to the Z boson
- Simultaneous fit of the hadronic recoil distribution in Z->ll + jets and MET+jets regions
  - Fit parameter scales Z->vv process relative to Z-> ll

Arxiv:2206.07110

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





Uncertainty dominated by lepton efficiency and jet energy scale

Summary

- Wealth of precise measurements with W and Z bosons at the LHC
  - Selected recent results were covered in this talk
- New results from the ATLAS collaboration
  - First precise measurements of Z boson production in the full phase space of the decay leptons
  - Precise measurements of W and Z boson p_T in dedicated low pileup datasets
- LHCb measurements probe the forward region
  - Precise measurements of the Z boson production at 5.02 and 13 TeV
- CMS τ lepton polarization in Z boson decays
- Detailed measurements of DY process by CMS at 13 TeV
- First hadron collider measurement of Z invisible width by CMS

- Many more results still to come!