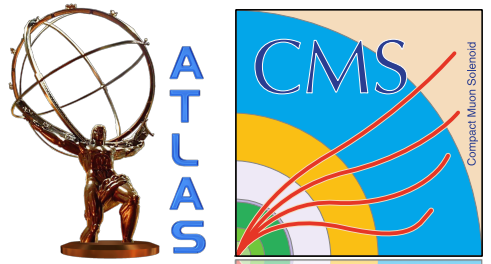


Precision measurements at LHC

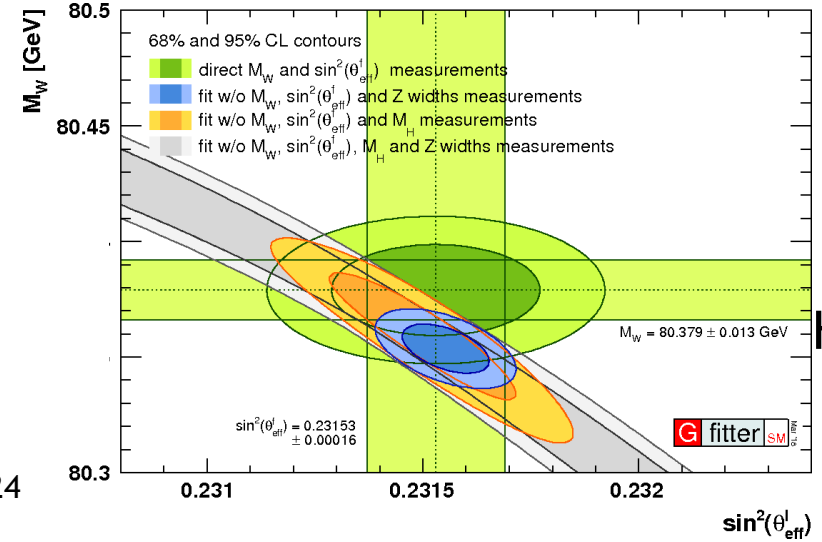
Aram Apyan

May, 2024

DPF-PHENO 2024

LHC precision results

- The purpose of this talk is to focus on the very latest Electroweak (EW) and QCD precision measurements by ATLAS and CMS Collaborations
  - Mainly showing results from the Spring 2024 conference season
- Precision EW and QCD measurements:
  - Test the consistency of the SM and probe beyond SM contributions
  - Tests of the state-of-the-art perturbative QCD calculations
  - Constraints on Parton Distribution Functions (PDFs)
  - Probe the mechanism of EW symmetry breaking



$$\sin^2\theta^{\ell}_{\text{eff}} = (1 - m^2_{\text{W}}/m^2_{\text{Z}})\kappa^{\ell}$$

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

Higher order corrections

$$M_W\left(\ln(M_H), m_t^2, M_Z, \Delta\alpha^{(5)}_{\text{had}}(M_Z^2), \alpha_S(M_Z^2)\right)$$

$$\sin^2\theta^f_{\text{eff}}\left(\ln(M_H), M_H, m_t^2, M_Z, \Delta\alpha^{(5)}_{\text{had}}(M_Z^2), \alpha_S(M_Z^2)\right)$$

Results highlighted in this talks

- W and Z cross sections at 13.6 TeV
  - Arxiv:2403.12902, CMS-PAS-SMP-22-017
- CMS Effective Leptonic Weak Mixing Angle measurement
  - CMS-PAS-SMP-22-010
- ATLAS W boson width and mass measurements
  - Arxiv:2403.15085
- ATLAS lepton universality test in W boson decays
  - Arxiv:2403.02133
- Precise measurements of Z invisible width
  - Arxiv:2312.02789, Arxiv:2206.07110
- CMS observation of γγ -> $\tau\tau$ in pp collisions
  - CMS-PAS-SMP-23-005
- ATLAS polarization in WZ production
  - Arxiv:2402.16365
- CMS Run 3 WW production
  - CMS-PAS-SMP-24-001
- Recent Vector Boson Scattering results
- ATLAS Lund subjet multiplicities
  - Arxiv:2403.02133

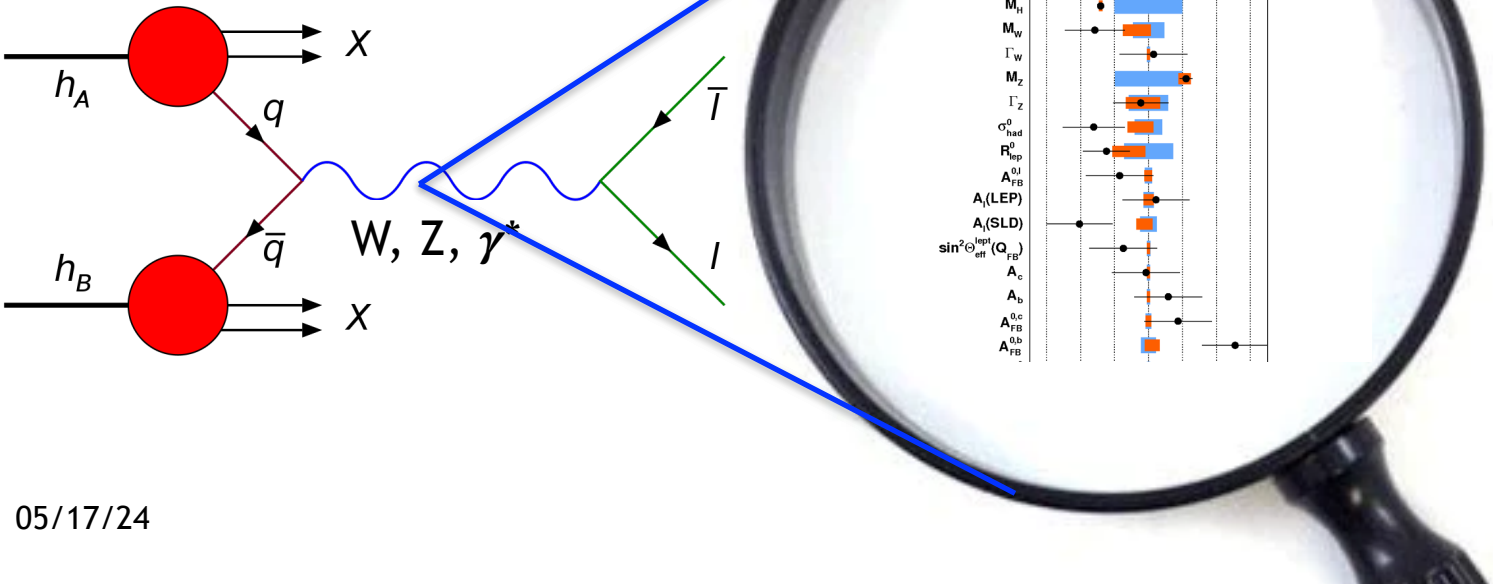
Drell-Yan Process

- 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

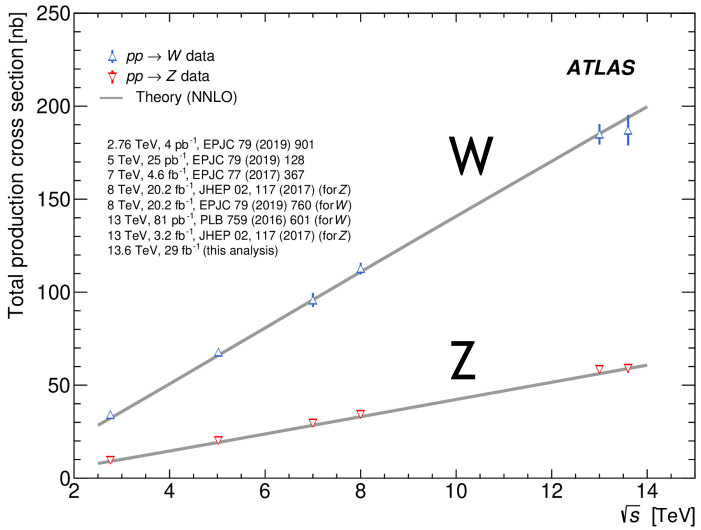
- W-boson mass
- $\sin^2\theta_W$
- PDFs
- $\alpha_s(m_Z)$

Information on perturbative and non-perturbative QCD

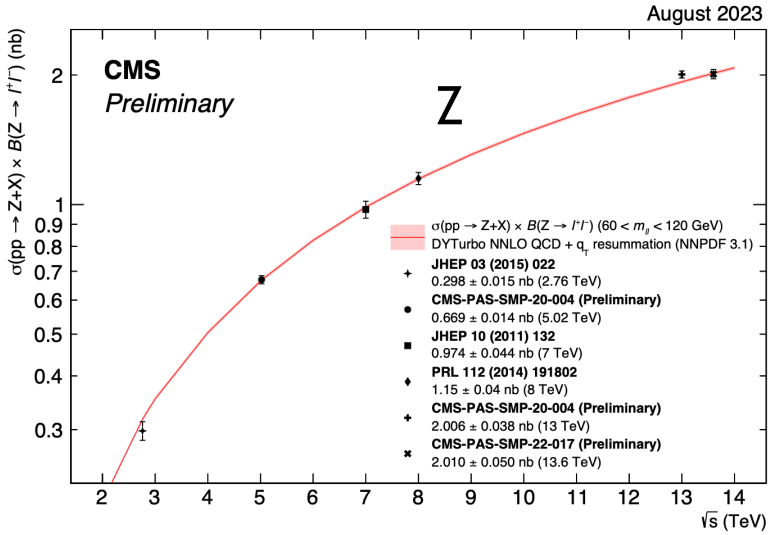


W and Z cross sections

- Inclusive W and Z boson production and ratios at 5.02, 13, and 13.6 TeV by ATLAS and CMS
  - Dedicated special low pileup LHC runs
  - Cornerstone of the experimental program
    - New opportunities at 13.6 TeV
  - Measurements are in agreement with SM calculations at NNLO in QCD and NLO in EW



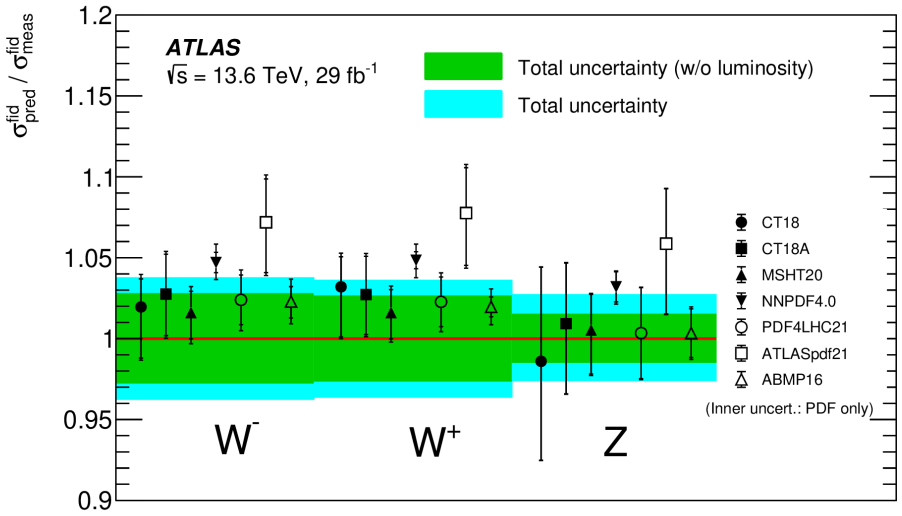
Arxiv:2403.12902

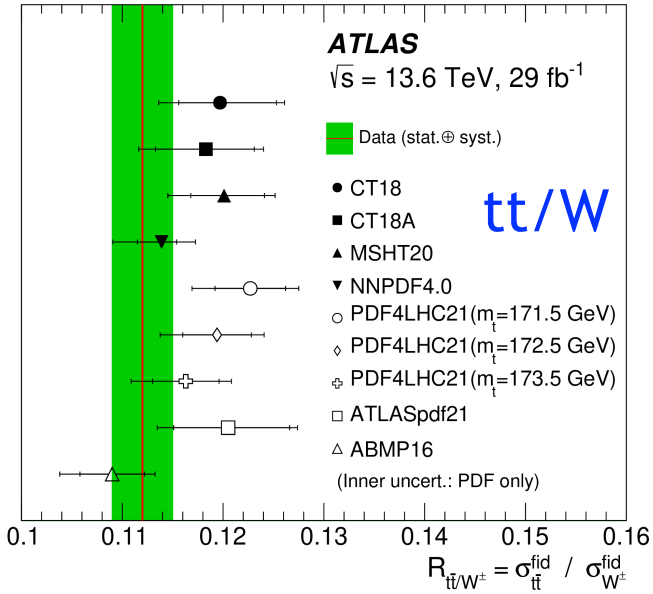


CMS-PAS-SMP-22-017

ATLAS W and Z cross sections: 13.6 TeV

- New ATLAS measurement of W and Z boson production cross section and ratios at 13.6 TeV
  - Data collected in 2022 with an integrated luminosity of 29 fb^{-1}
  - Integrated luminosity uncertainty of 2.2%
  - Ratios of tt to W boson cross sections are measured as well
  - Compared to various PDF predictions





Arxiv:2403.12902

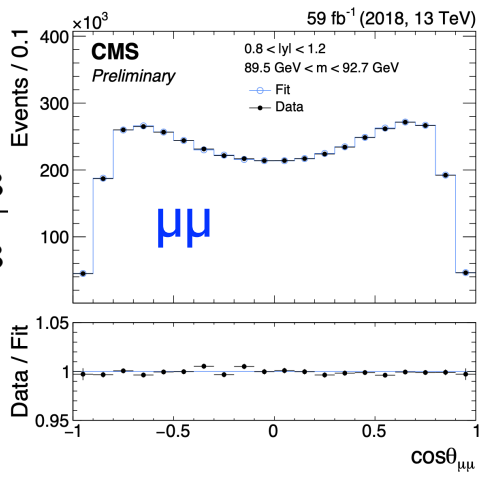
Effective Weak Mixing Angle

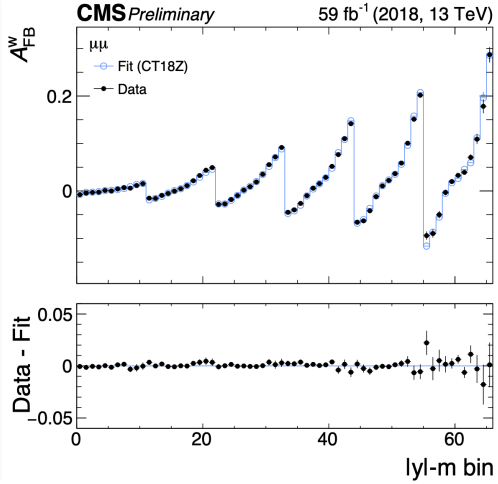
- New CMS measurement of the leptonic effective weak mixing angle
  - Using full Run 2 data at $\sqrt{s}$=13 TeV, integrated luminosity of 137fb^{-1}
  - Measurements of the forward-backward asymmetry and unfolded A_4

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}^{Z}\,\mathrm{d}y^{Z}\,\mathrm{d}m^{Z}\,\mathrm{d}\cos\theta} = \frac{3}{8}\frac{d\sigma^{U+L}}{\mathrm{d}p_{\mathrm{T}}^{Z}\,\mathrm{d}y^{Z}\,\mathrm{d}m^{Z}}\left\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_4\cos\theta\right\}$$

  - The measurement includes central-central μμ and ee channels as well as central-forward ee channels (using forward calorimeters)
    - Increase sensitivity to A_{FB}

$$A_{\mathrm{FB}} = \frac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}}}$$



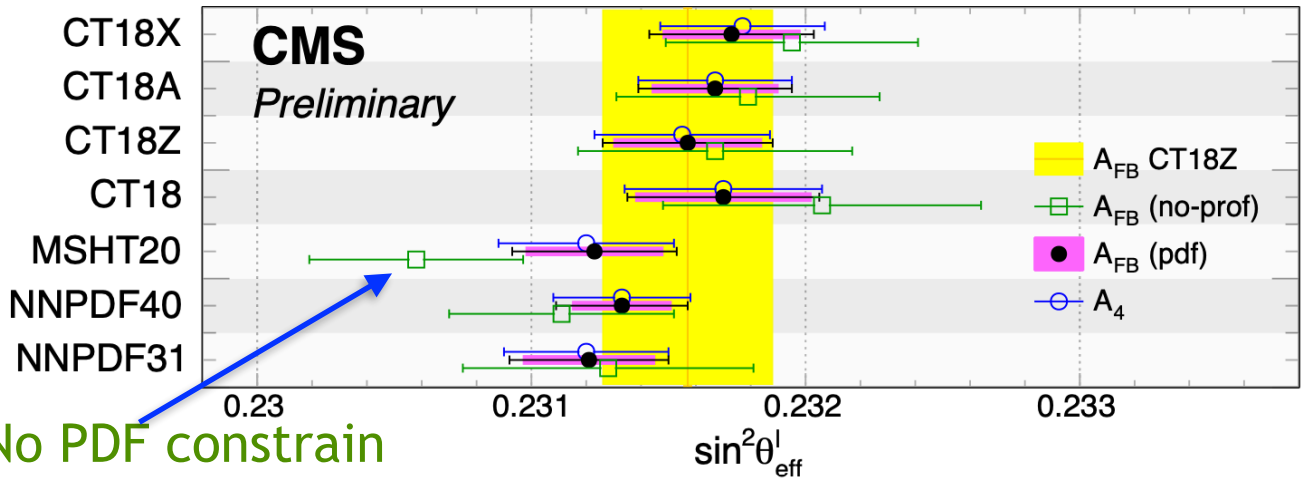


CMS-PAS-SMP-22-010

Effective Weak Mixing Angle

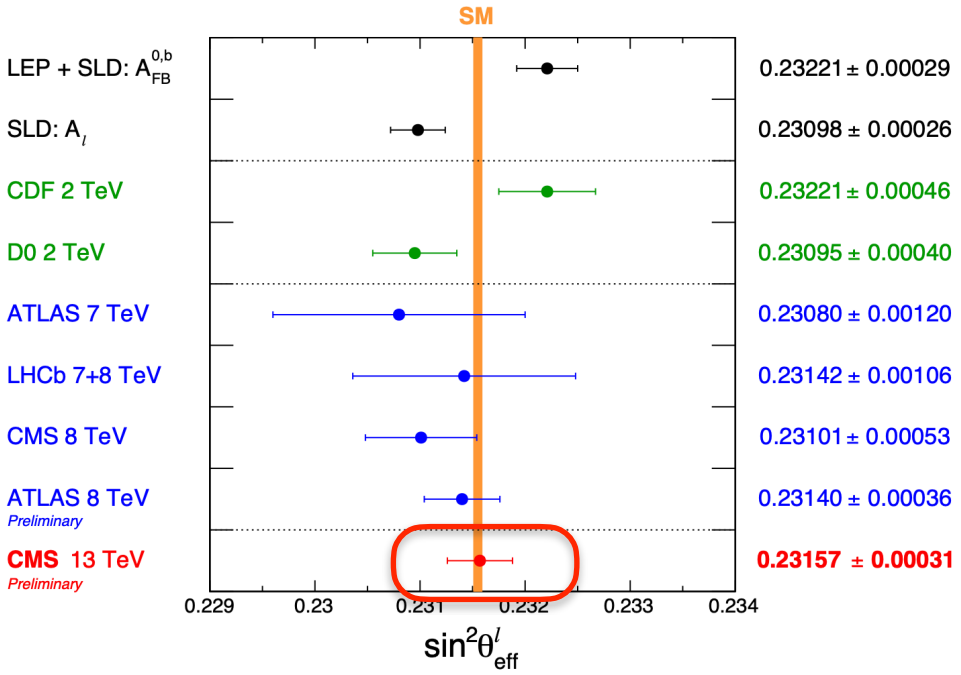
- The weak mixing angle is extracted by two methods: CMS-PAS-SMP-22-010
  - Fitting the detector level A_{FB} or unfolded A_4 measurement
- PDFs are profiled in the measurement (CT18Z is used as nominal PDF)
  - PDF uncertainties dominate the measurement

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



Effective Weak Mixing Angle

- Good agreement with previous measurements and the SM
- CMS measurement is the most precise hadron collider measurement!
  - Precision comparable to LEP and SLD results
  - PDF uncertainties dominate

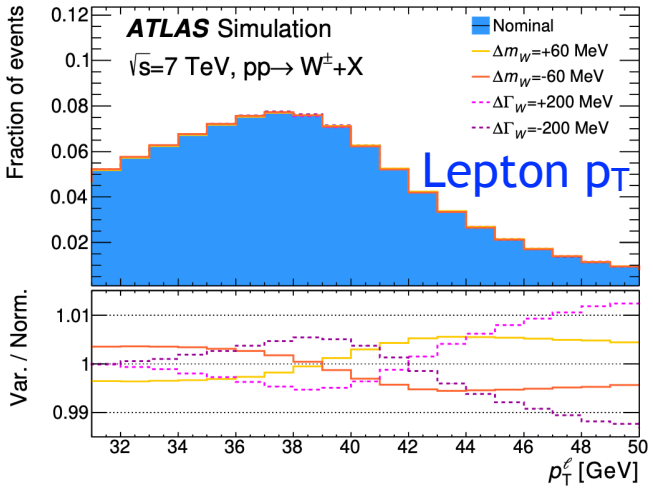


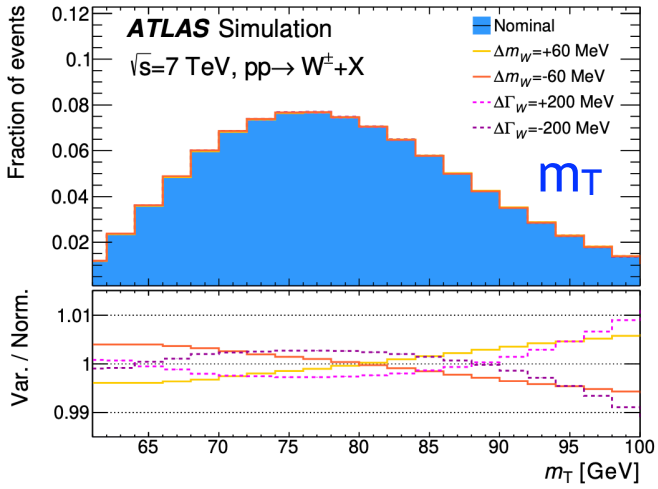
$$\sin^2\theta^{\ell}_{\text{eff}} = 0.23157 \pm 0.00010\,(\text{stat}) \pm 0.00015\,(\text{syst}) \pm 0.00009\,(\text{theo}) \pm 0.00027\,(\text{PDF}).$$

ATLAS W boson width and mass

- Measuring the W boson mass is extremely challenging at hadron colliders
  - Prone to biases due to QCD effects
- Most precise measurement from CDF is in strong tension with the EW fit and other experimental results
- ATLAS updated the previous W mass measurement using the 7 TeV data
  - Use the lepton p_T and the transverse mass m_T to extract m_W
  - First measurement of Γ_W at the LHC!
  - Simultaneous determination of m_W and Γ_W

Arxiv:2403.15085

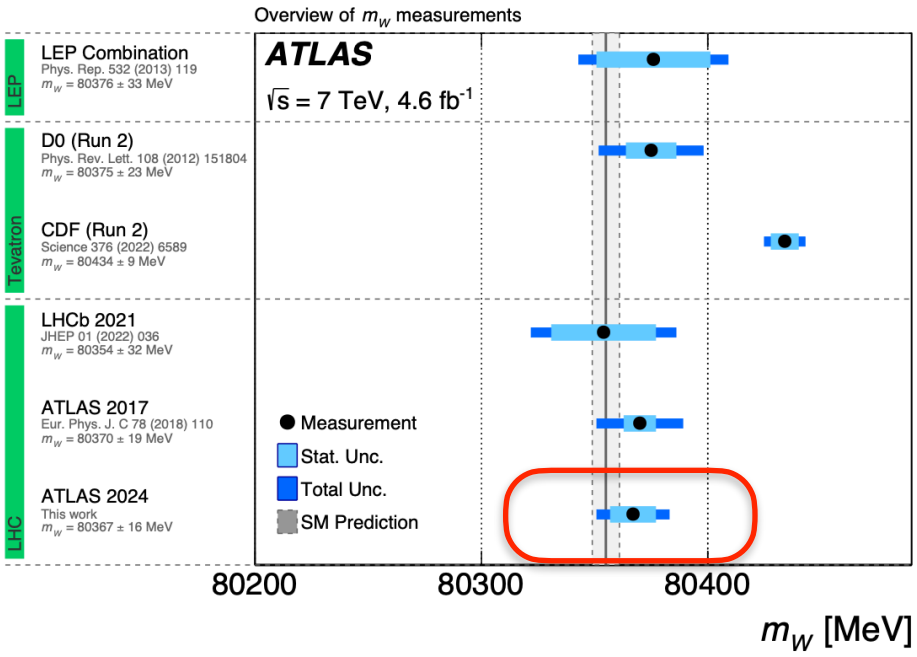




ATLAS W boson width and mass

- The m_W is compatible with the previous measurement with the same 7 TeV data sample
- Detailed studies of PDF dependence of the result are performed
  - Increased PDF priors lead to less PDF-model dependence

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



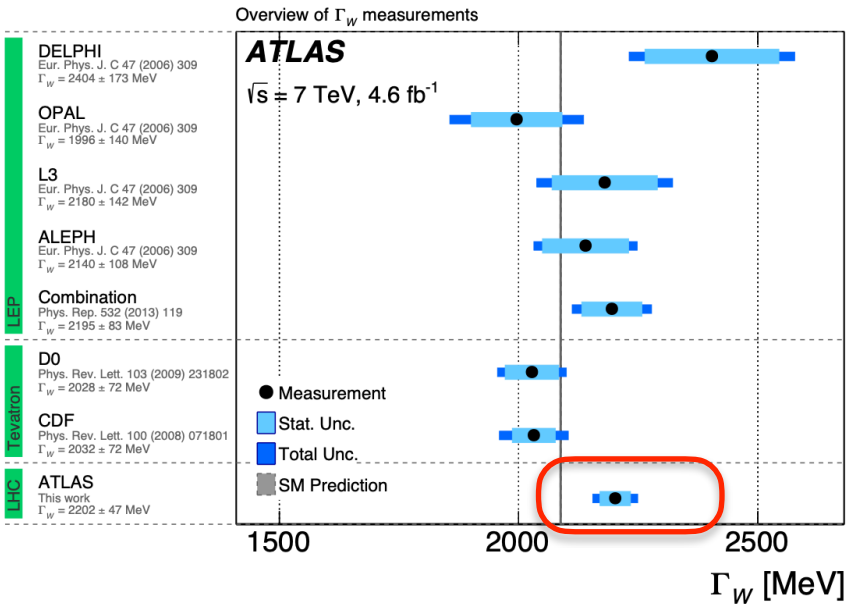
Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i
p_{T}^{ℓ}	16.2	11.1	11.8	4.9	3.5
m_{T}	24.4	11.4	21.6	11.7	4.7
Combined	15.9	9.8	12.5	5.7	3.7

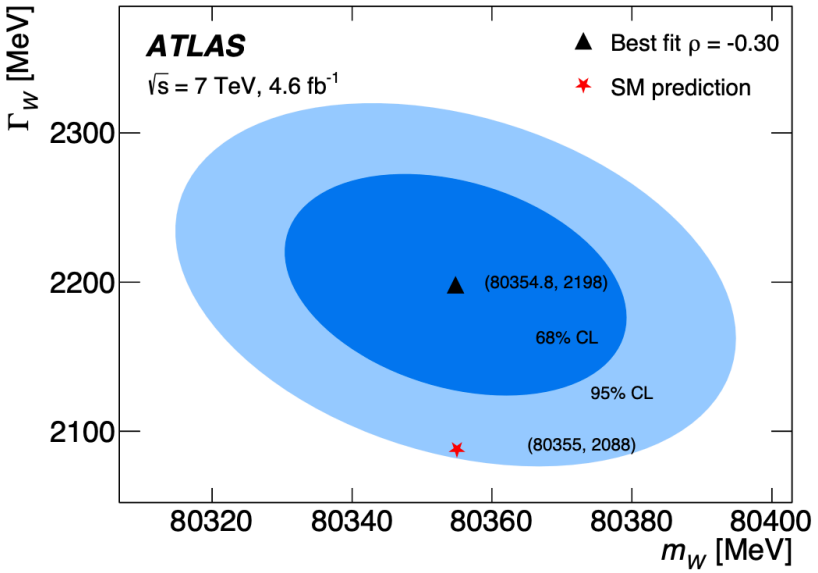
Arxiv:2403.15085

ATLAS W boson width and mass

- First measurement of Γ_W at the LHC
  - Most precise measurement from a single experiment
- Simultaneous measurement of m_W and Γ_W
  - Central value of m_W shifts down by 12 MeV
  - -30% correlation between m_W and Γ_W

Unc. [MeV]	Total	Stat.	Syst.
p_{T}^{ℓ}	71.8	27.3	66.4
m_{T}	47.5	35.5	31.6
Combined	46.8	32.0	34.1





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

Lepton Universality in W boson decays

- ATLAS measurement of the W boson decay rates to muons and electrons
  - Using 140 fb^{-1} at $\sqrt{s}$=13 TeV
  - Using tt production offers a high purity sample of W boson pairs

  - Fully leptonic final state is used
  - Use the precise value of Z branching ratios to muons and electrons to reduce the lepton identification systematic uncertainties

$$R_W^{\mu/e} = \frac{\mathcal{B}(W \to \mu\nu_\mu)}{\mathcal{B}(W \to e\nu_e)}$$

$$R_{WZ}^{\mu/e} = \frac{R_W^{\mu/e}}{\sqrt{R_Z^{\mu\mu/ee}}}$$

$$R_W^{\mu/e}(\mathrm{ATLAS}) = R_{WZ}^{\mu/e}(\mathrm{ATLAS}) \cdot \sqrt{R_Z^{\mu\mu/ee}}(\mathrm{LEP{+}SLD})$$

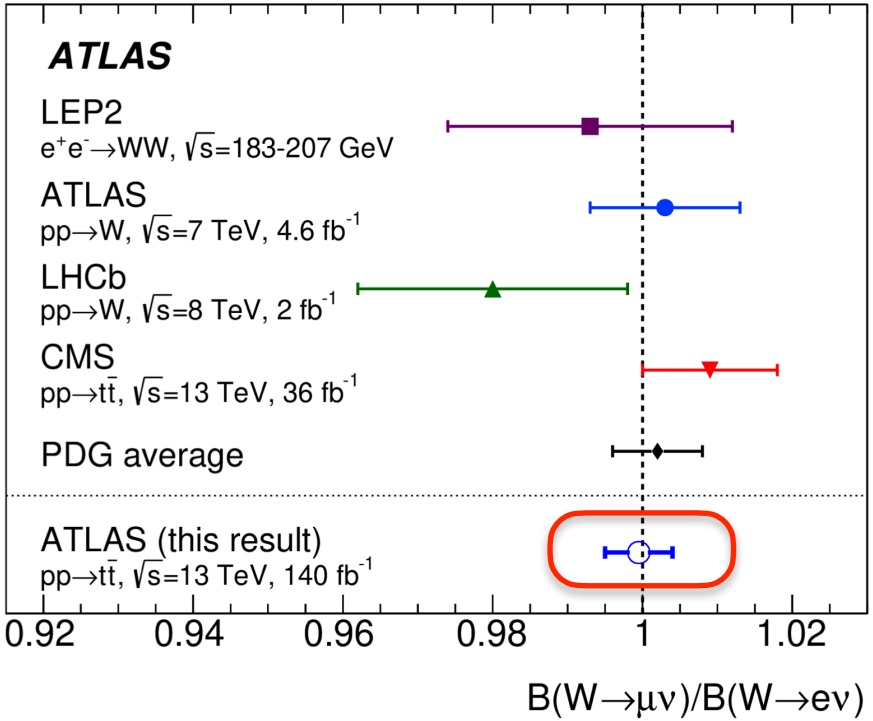
Arxiv:2403.02133

Lepton Universality in W boson decays

- ATLAS measurement of the W boson decay rates to muons and electrons
  - Most precise measurement to date
  - Relative uncertainty of 0.45%
  - Consistent with lepton universality

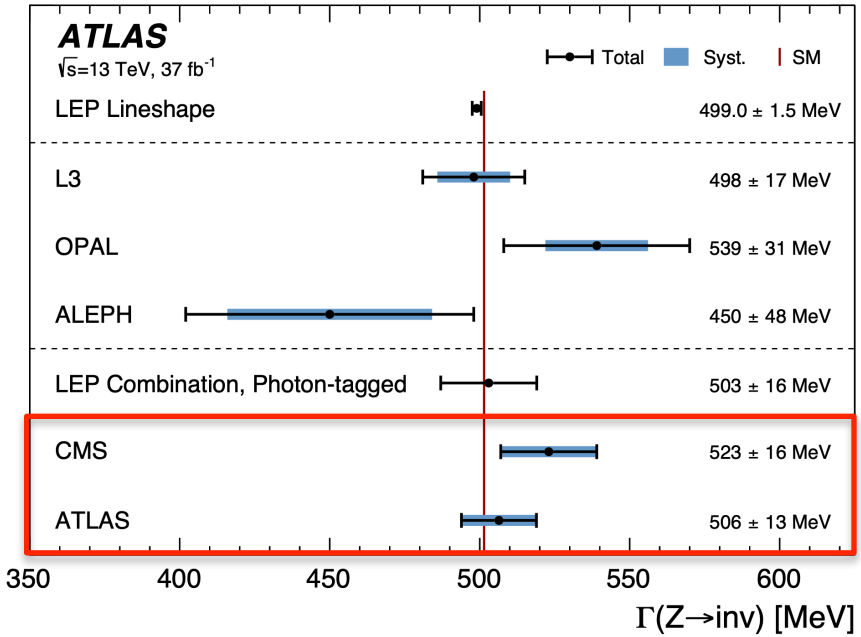
$$R_W^{\mu/e} = 0.9995 \pm 0.0022\,(\text{stat}) \pm 0.0036\,(\text{syst}) \pm 0.0014\,(\text{ext})\,.$$

Arxiv:2403.02133



Precise measurement of Z invisible width

- Precise measurement of Z invisible width at a hadron collider
- Constraint on number of light neutrino species coupling to the Z boson
- New ATLAS result is the most precise measurement
  - Uncertainty dominated by lepton efficiency



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

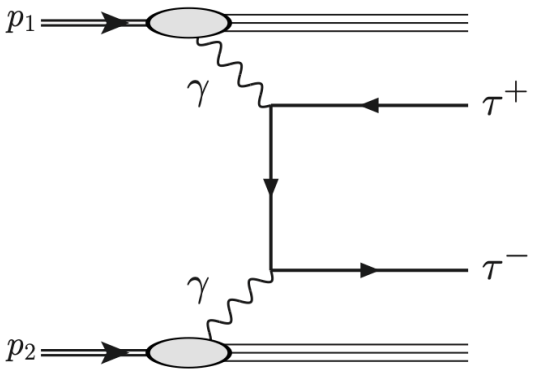
$$\Gamma_{Z\to\nu\nu} = 506 \pm 2\,(\text{stat.}) \pm 12\,(\text{syst.})\ \text{MeV}$$

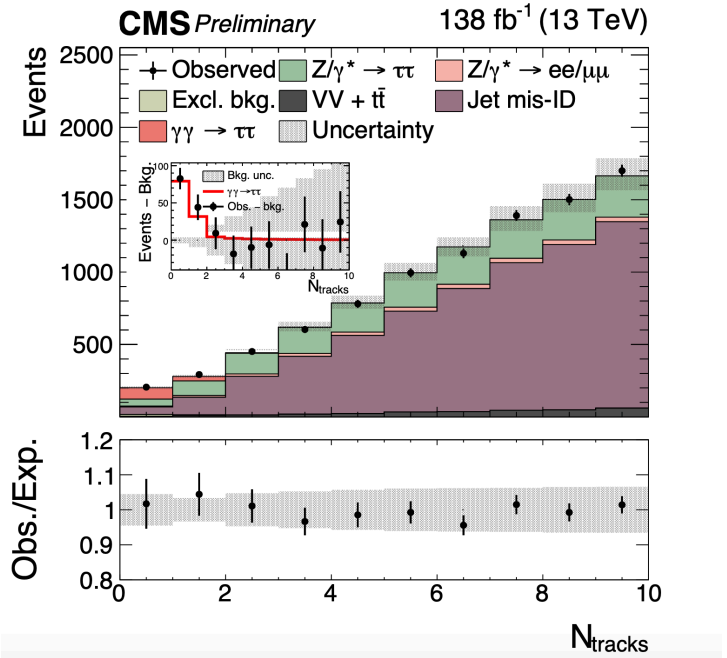
ATLAS: Arxiv:2312.02789

CMS: Arxiv:2206.07110

Observation of γγ -> $\tau\tau$

- CMS observation of photon induced production of pair of τ leptons in pp collisions
  - Previously observed by ATLAS and CMS in PbPb collisions
  - Run 2 data sample at 13 TeV and integrated luminosity of 138 fb^{-1}
  - Events with small number of tracks are close to the di-tau vertex are selected to isolate photon induced processes
    - Correct the number of tracks in simulation



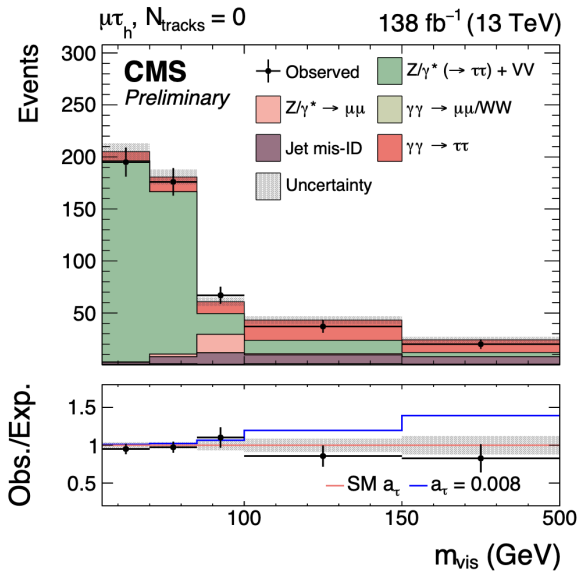


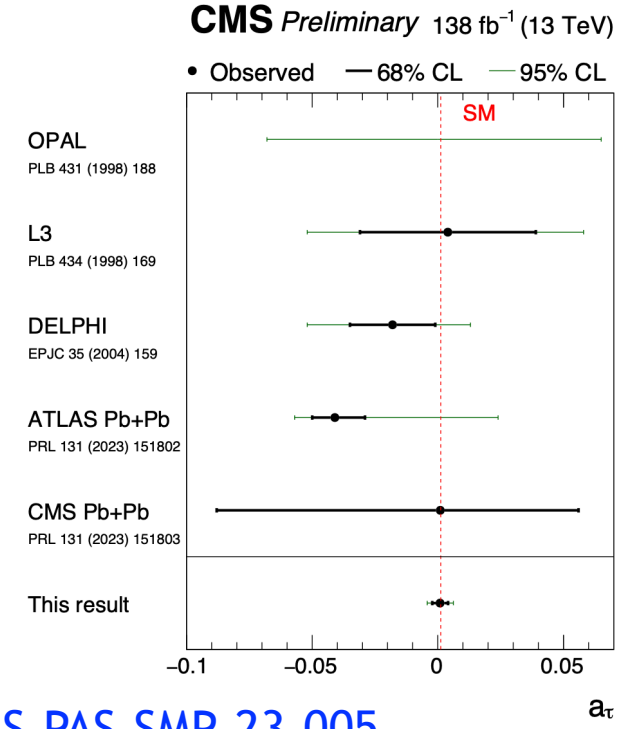
CMS-PAS-SMP-23-005

Observation of γγ -> $\tau\tau$

- CMS observation of photon induced production of pair of τ leptons in pp collisions
  - γγ -> $\tau\tau$ in pp: 5.3 (6.5) observed (expected) standard deviations
  - Systematic and statistical uncertainties comparable in size
  - Constrain the anomalous electromagnetic moments of τ lepton using the visible mass distribution

$$a_\tau = 0.0009^{+0.0016}_{-0.0015}\,(\text{syst})^{+0.0028}_{-0.0027}\,(\text{stat}).$$

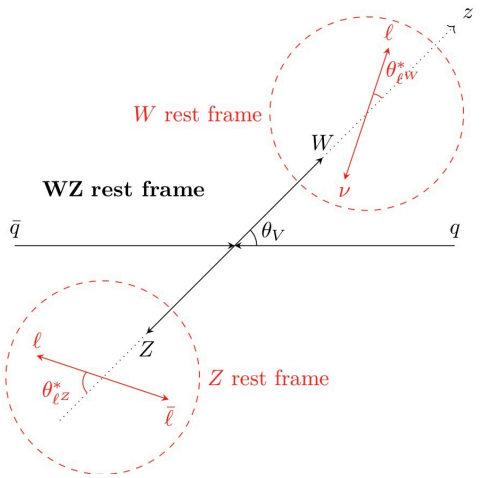


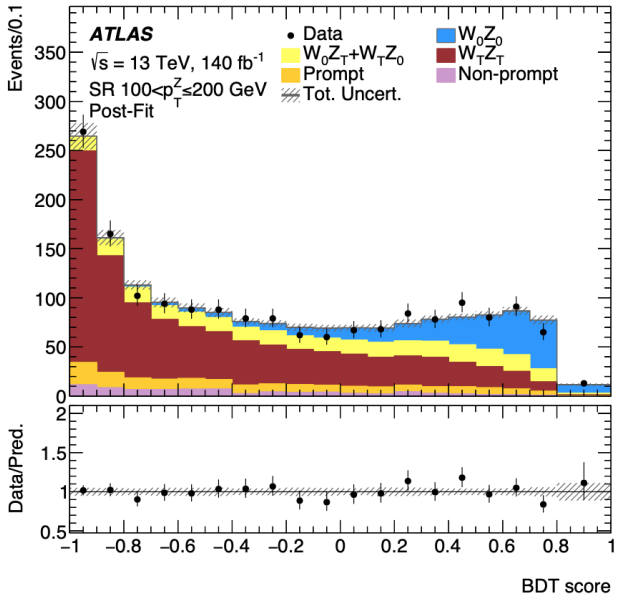


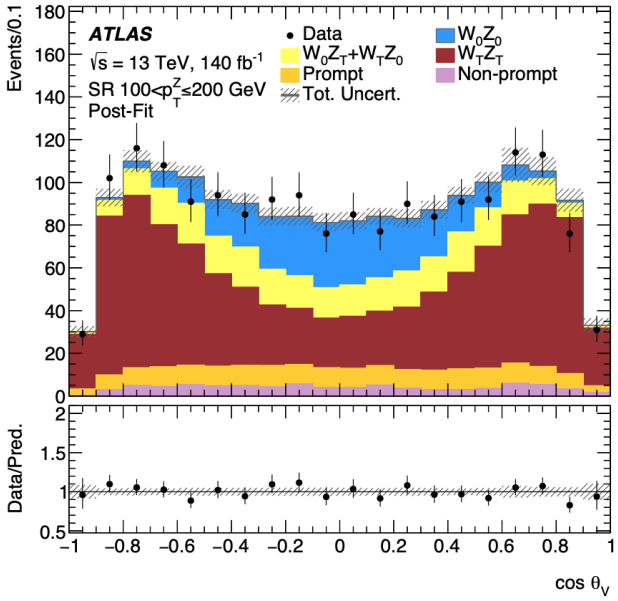
CMS-PAS-SMP-23-005

Polarization in WZ production

- ATLAS WZ polarization measurement using Run 2 data
  - Fully leptonic final state
  - Explore the energy dependence of the polarization fractions
  - Target events with high pT Z boson and measure the fraction of events with two longitudinally polarized bosons
    - W_LZ_L production observed significance: 5.3 standard deviations





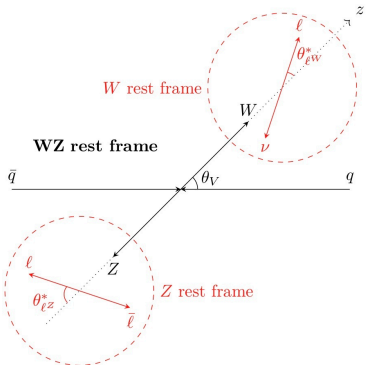


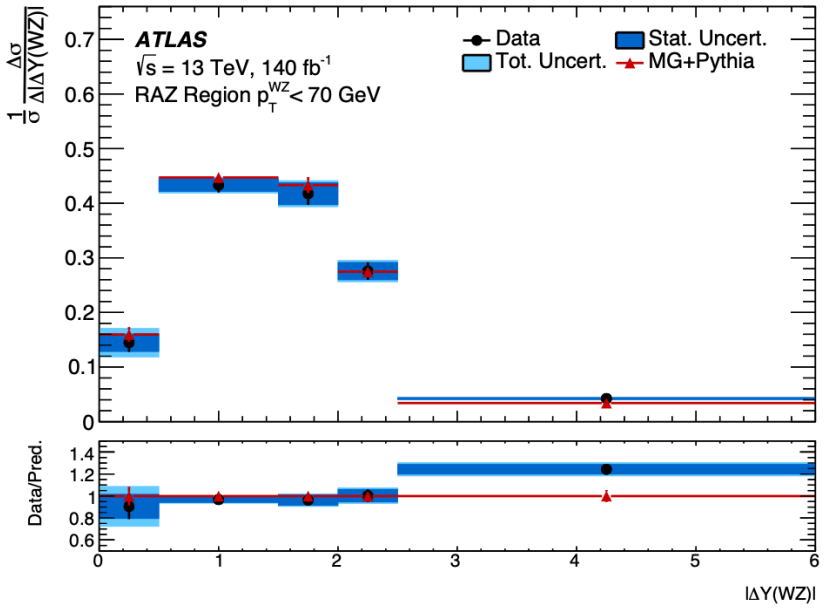
Arxiv:2402.16365

Polarization in WZ production

- ATLAS WZ polarization measurement using Run 2 data
  - Also report the first study of Radiation Amplitude Zero effect in WZ production (previously observed in Wγ)
    - TT exact zero amplitude at LO in the region where $\cos\theta_W \sim 0$
  - Requirement on pT(WZ)<70 GeV to reduce jet activity and to enhance the significance of the dip

- Observed using rapidity differences
  - Dip at zero
- LT+TL+LL contributions are subtracted in the plot

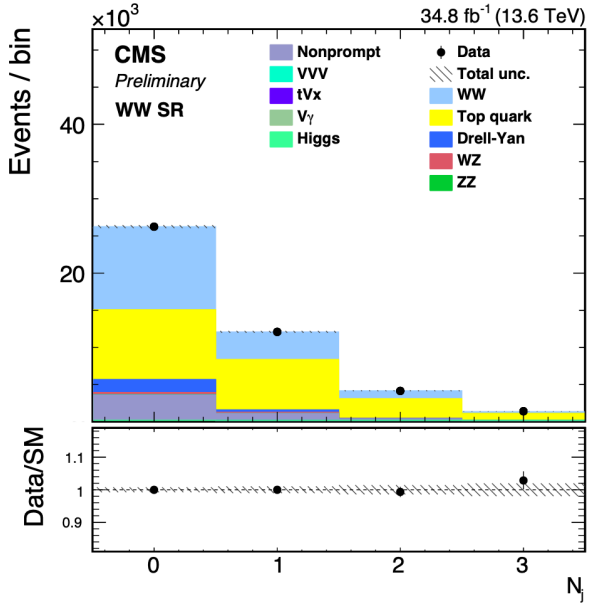


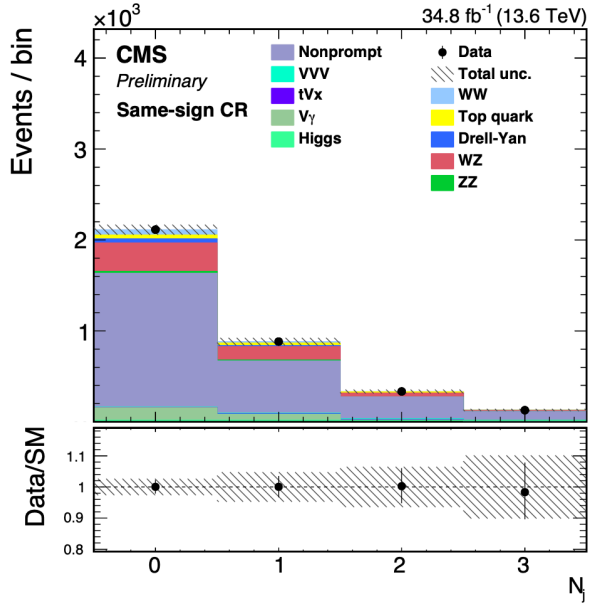


Arxiv:2402.16365

Run 3 Di-boson measurements

- CMS first measurement of WW production at 13.6 TeV
  - Using 2022 data with an integrated luminosity of 34.8 fb^{-1}
  - Important tests of perturbative QCD and EW and sensitive to self interactions
  - Opposite charge electron and muon final state
    - Dedicated top, Drell-Yan and nonprompt control regions

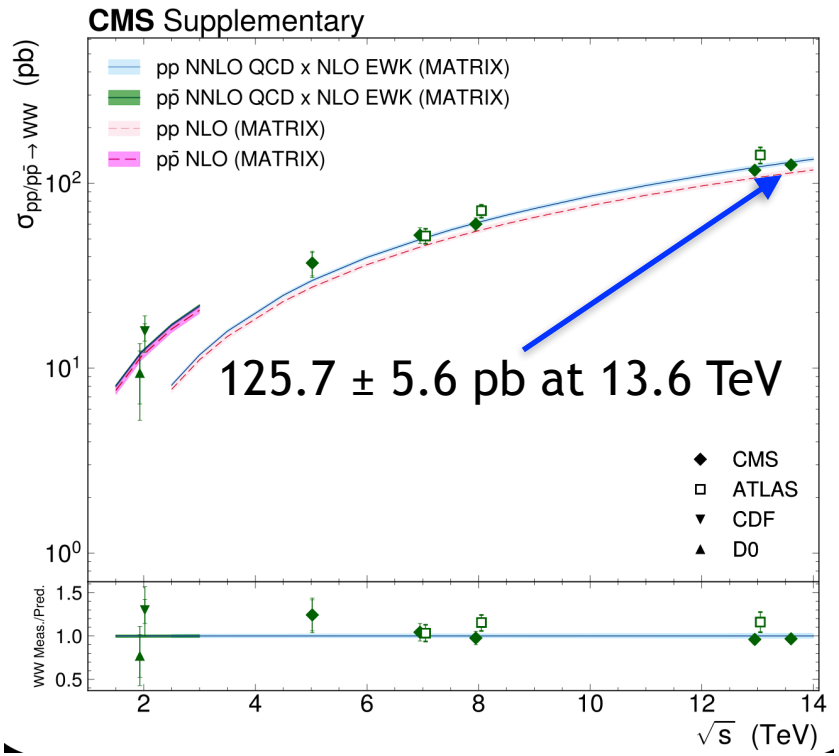


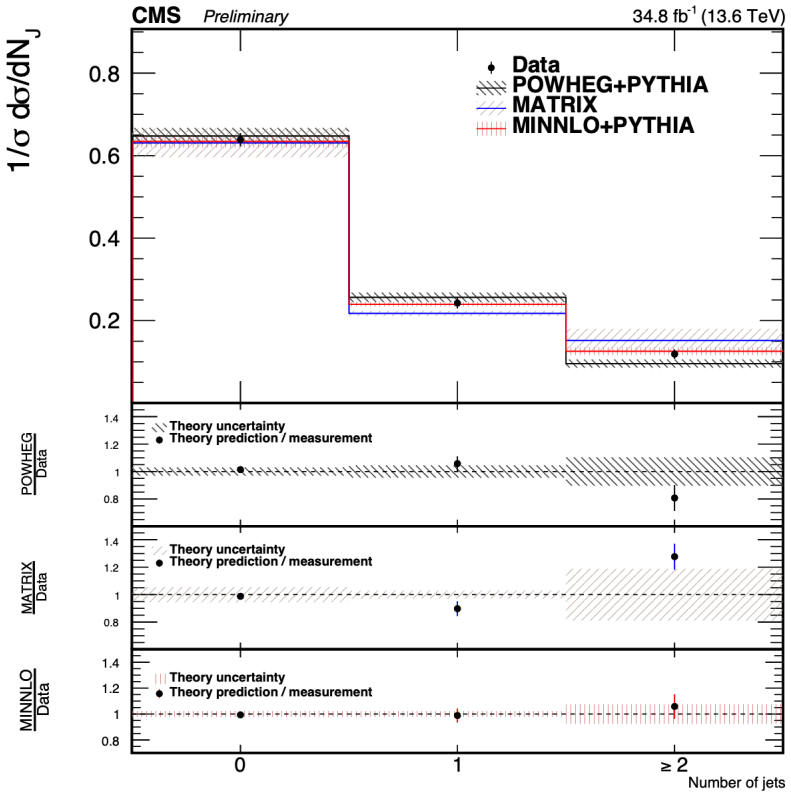


CMS-PAS-SMP-24-001

Run 3 Di-boson measurements

- CMS first measurement of WW production at 13.6 TeV
  - Integrated and differential cross sections are reported
    - Good agreement with the SM predictions

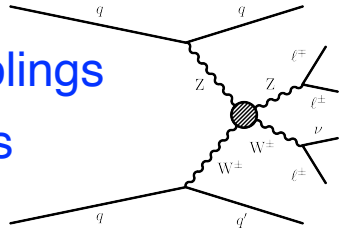


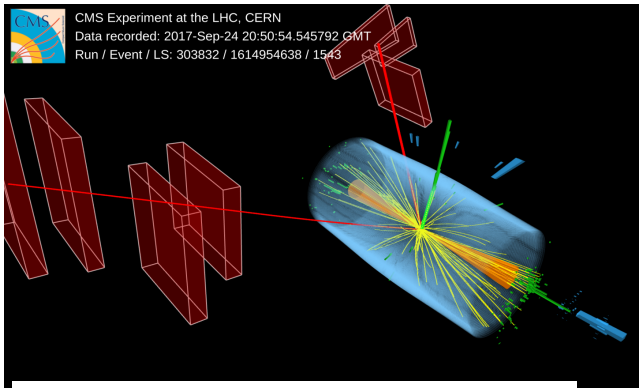


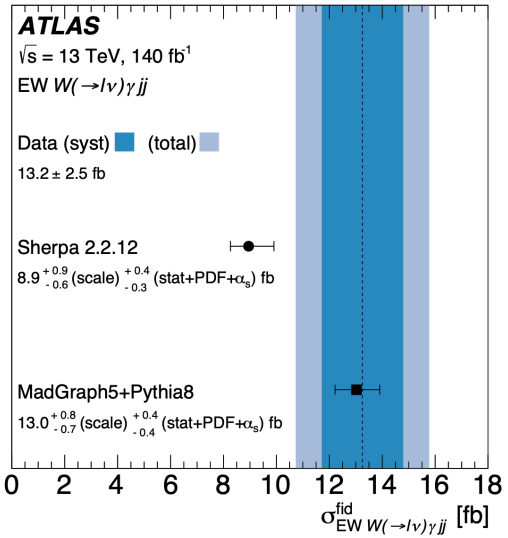
CMS-PAS-SMP-24-001

EW VVjj production

- From first observations->precision measurements
  - ATLAS and CMS completing Run 2 measurements
- Probe EW symmetry breaking
- Probe triple and quartic gauge couplings
- Theory predictions: NLO corrections
- Recent results to highlights:

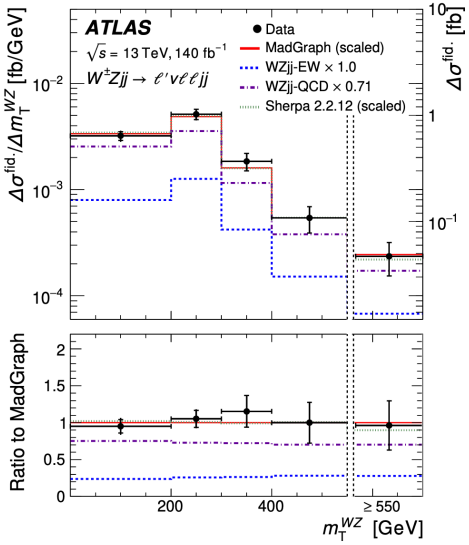






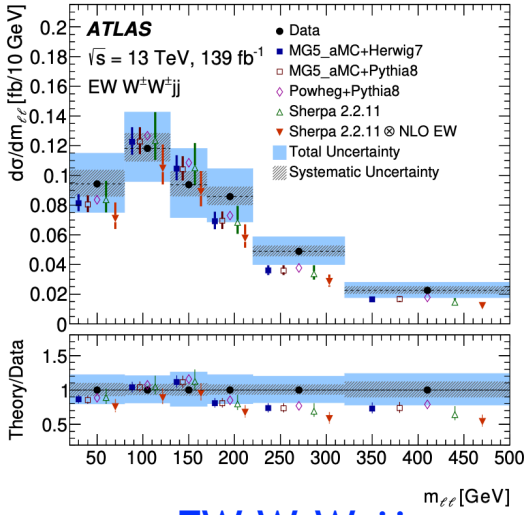
EW Wγjj

Arxiv:2403.02809



EW WZjj

Arxiv:2403.15296



EW W±W±jj

Arxiv:2312.00420

CMS-PAS-SMP-22-008

Many more results…

- Several selected recent measurements discussed today
  - Many other interesting results not covered today!
  - Can be found in ATLAS and CMS public pages

ATLAS

Precise measurements of W and Z transverse momentum spectra	STDM	Submitted to EPJC	2024-04-16	13, 5.02
Electroweak, QCD and flavour physics studies	STDM	Submitted to Physics Reports	2024-04-10	13
Measurement of the W-boson mass and width	STDM	Submitted to EPJC	2024-03-22	7
Electroweak WZ boson pair production in association with two jets	STDM	Submitted to JHEP	2024-03-22	13
Production cross-section for a Z boson in association with b- or c-jets	STDM	Submitted to EPJC	2024-03-22	13
Measurement of vector boson production cross sections and their ratios	STDM	Submitted to PLB	2024-03-19	13.6
Observation of electroweak production of W+W- in association with jets	STDM	Submitted to JHEP	2024-03-07	13
Differential cross sections for the production of missing transverse momentum and jets	STDM	Submitted to JHEP	2024-03-05	13
Observation and differential cross-section measurements of electroweak Wyjj production	STDM	Submitted to EPJC	2024-03-05	13
Diboson polarization fractions and Radiation Amplitude Zero effect in WZ production	STDM	Submitted to PRL	2024-02-23	13
Measurements of Lund subjet multiplicities	STDM	Submitted to PLB	2024-02-20	13
Jet substructure in boosted tt events	TOPQ	Submitted to PRD	2023-12-06	13
Measurement of the Z boson invisible width	STDM	Submitted to PLB	2023-12-05	13
Measurement of same-sign W boson pair production in association with two jets	STDM	JHEP 04 (2024) 026	2023-12-01	13
Measurement of ZZ production cross-sections in the four-lepton final state	STDM	Submitted to PLB	2023-11-16	13.6
Study of Z(→lly) decays	STDM	Eur. Phys. J. C 84 (2024) 195	2023-10-18	8

CMS

Measurement of the $Z(\nu\bar{\nu})+\gamma$ production cross section and search for anomalous neutral triple gauge couplings in pp collisions at 13 TeV			12 April 2024
Measurement of the Drell-Yan forward-backward asymmetry and of the effective leptonic weak mixing angle using proton-proton collisions at $\sqrt{s}=$ 13 TeV			27 March 2024
Measurement of W^+W^- inclusive and differential cross sections in pp collisions at $\sqrt{s}=$ 13.6 TeV with the CMS detector			24 March 2024
Observation of $\gamma\gamma\to\tau\tau$ in proton-proton collisions and limits on the anomalous electromagnetic moments of the τ lepton			12 March 2024
SMP-22-016	**Search for the Z boson decay to $\tau\tau\mu\mu$ in proton-proton collisions at $\sqrt{s}=$ 13 TeV**	Submitted to PRL	29 April 2024
SMP-22-005	**Measurement of multijet azimuthal correlations and determination of the strong coupling in proton-proton collisions at $\sqrt{s}=$ 13 TeV**	Submitted to EPJC	24 April 2024
SMP-22-001	**Measurement of differential ZZ+jets production cross sections in pp collisions at $\sqrt{s}=$ 13 TeV**	Submitted to JHEP	3 April 2024
SMP-22-015	**Measurement of energy correlators inside jets and determination of the strong coupling $\alpha_S(m_Z)$**	Submitted to PRL	21 February 2024
SMP-21-004	**Nonresonant central exclusive production of charged-hadron pairs in proton-proton collisions at $\sqrt{s}=$ 13 TeV**	Accepted by PRD	25 January 2024
SMP-21-009	**Measurement of the double-differential inclusive jet cross section in proton-proton collisions at $\sqrt{s}=$ 5.02 TeV**	Submitted to JHEP	21 January 2024
SMP-21-008	**Measurement of multidifferential cross sections for dijet production in proton-proton collisions at $\sqrt{s}=$ 13 TeV**	Submitted to EPJC	28 December 2023
SMP-22-007	**Measurement of the primary Lund jet plane density in proton-proton collisions at $\sqrt{s}=$ 13 TeV**	Accepted by JHEP	27 December 2023
SMP-22-006	**Observation of WWγ production and search for Hγ production in proton-proton collisions at $\sqrt{s}=$ 13 TeV**	PRL 132 (2024) 121901	2024-03-19
SMP-18-010	**Measurement of the τ lepton polarization in Z boson decays in proton-proton collisions at $\sqrt{s}=$ 13 TeV**	JHEP 01 (2024) 101	2024-01-19
SMP-21-005	**Measurement of the production cross section for a W boson in association with a charm quark in proton-proton collisions at $\sqrt{s}=$ 13 TeV**	EPJC 84 (2024) 27	2024-01-10

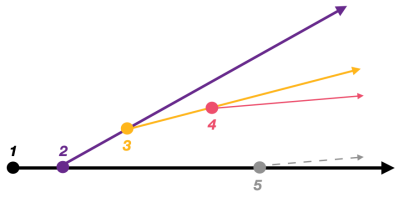
Summary

- Wealth of EW and QCD precision measurements
  - LHC is a precision tool!
  - Measurements of some precision observables competitive with lepton colliders
  - Mostly agreement with the SM predictions
- Many more results still to come -> Run 3 is here!
  - Run 2 (and Run 1) continue to provide new and creative precision measurements
  - Special low pileup LHC runs also provide new avenues of exploration

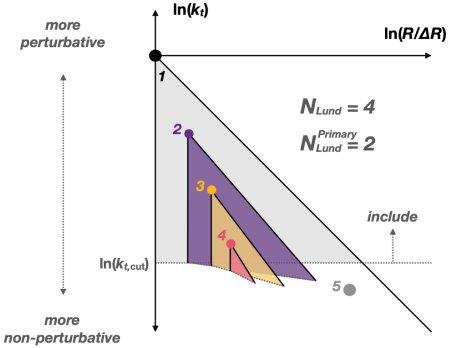
ADDITIONAL MATERIAL

Lund subjet multiplicities

- Parton shower modeling is crucial at hadron colliders
  - Most precise measurement to date
  - Higher order QCD effects like “double soft” splittings needs to be understood and incorporated
  - Measurements of Lund subjet multiplicities is sensitive to higher order effects
- The measurement is performed in dijet events
  - At 13 TeV, 140 fb^{-1}



$$k_t = p_{\mathrm{T}}^{\mathrm{emission}} \cdot \Delta R(p^{\mathrm{emission}}, p^{\mathrm{core}}).$$



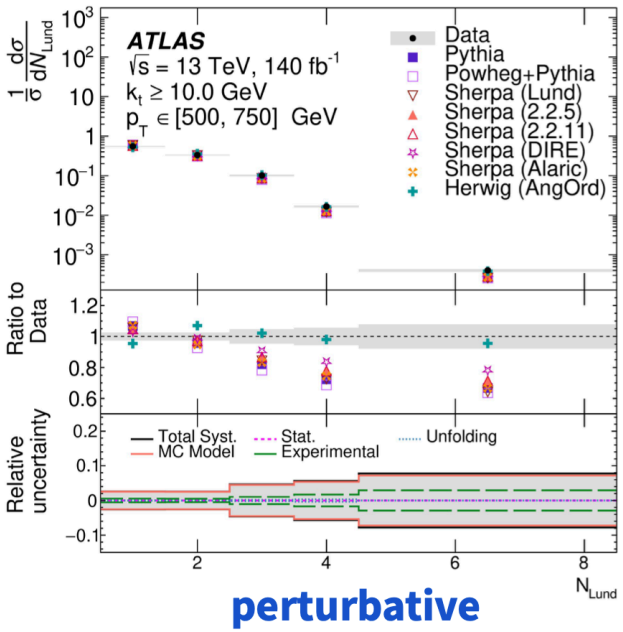
- Recluster the jet constituents with CA algorithm
- Count emissions above a specified k_t requirement

Arxiv:2402.13052

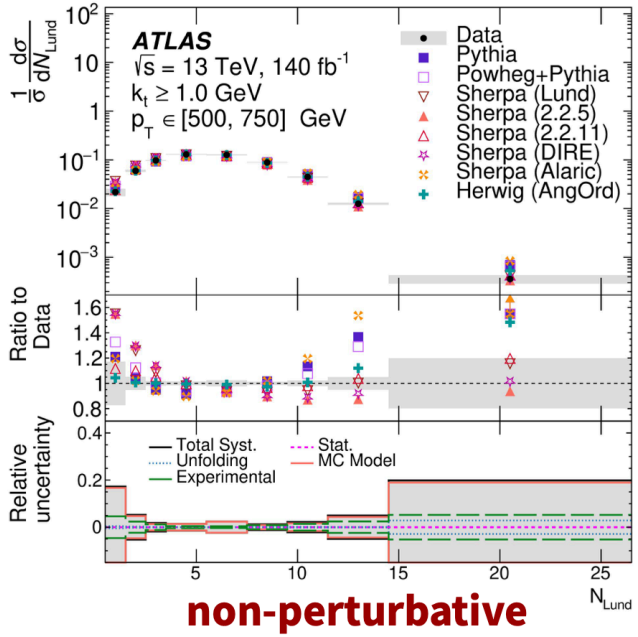
Lund subjet multiplicities

Arxiv:2402.13052

- Unfolded differential cross sections of N_{Lund} are measured for different k_t requirements in jet p_T bins and relative rapidity
  - Results are compared to different Parton shower models as well as recent resummed calculations
  - Herwig gives overall best description of data
  - Sherpa performs well when non-perturbative emissions are allowed



perturbative



non-perturbative

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 (cosθ,ϕ,p_T,y) bins

Reco (p_T^Z,y^Z,m^Z, cosθ, 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

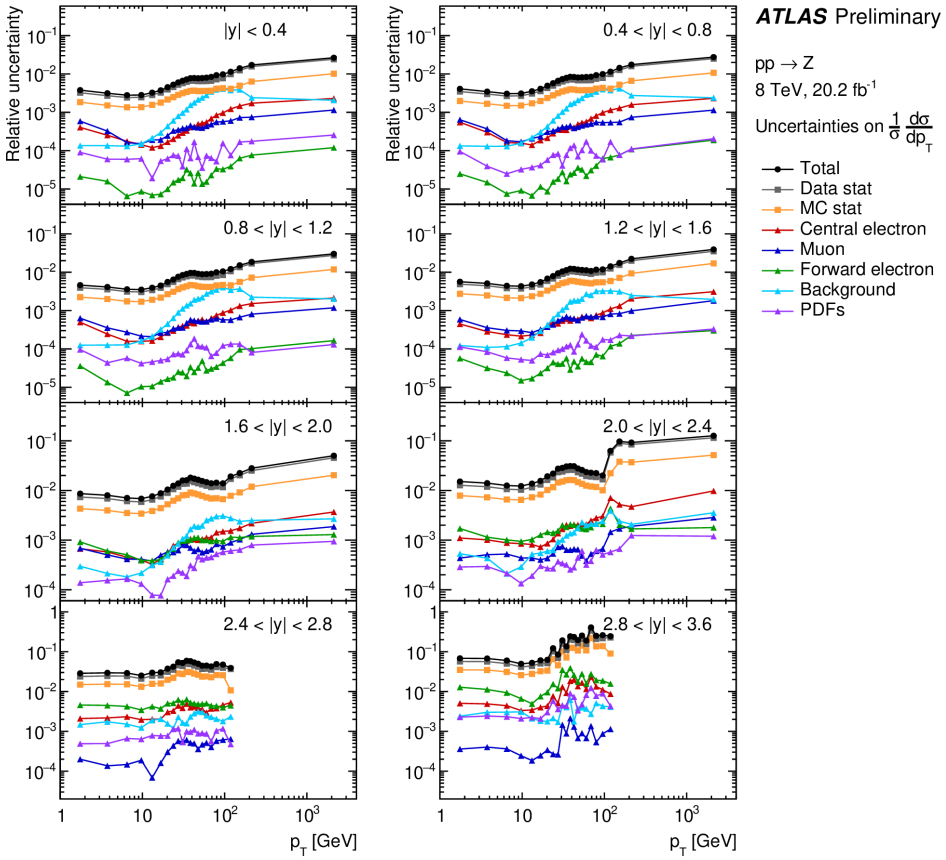
Angular coefficient

Templated polynomial

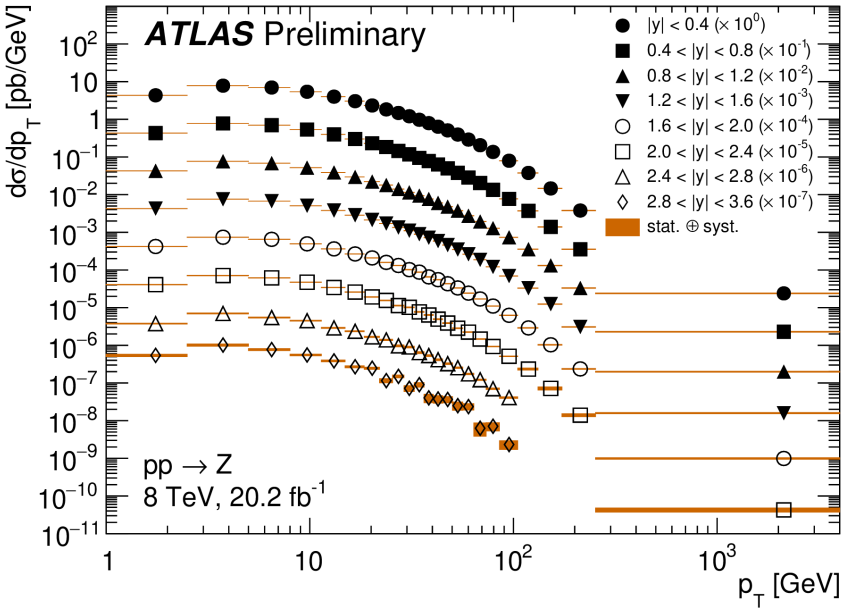
ATLAS-CONF-2023-013

ATLAS full phase space Z measurement

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



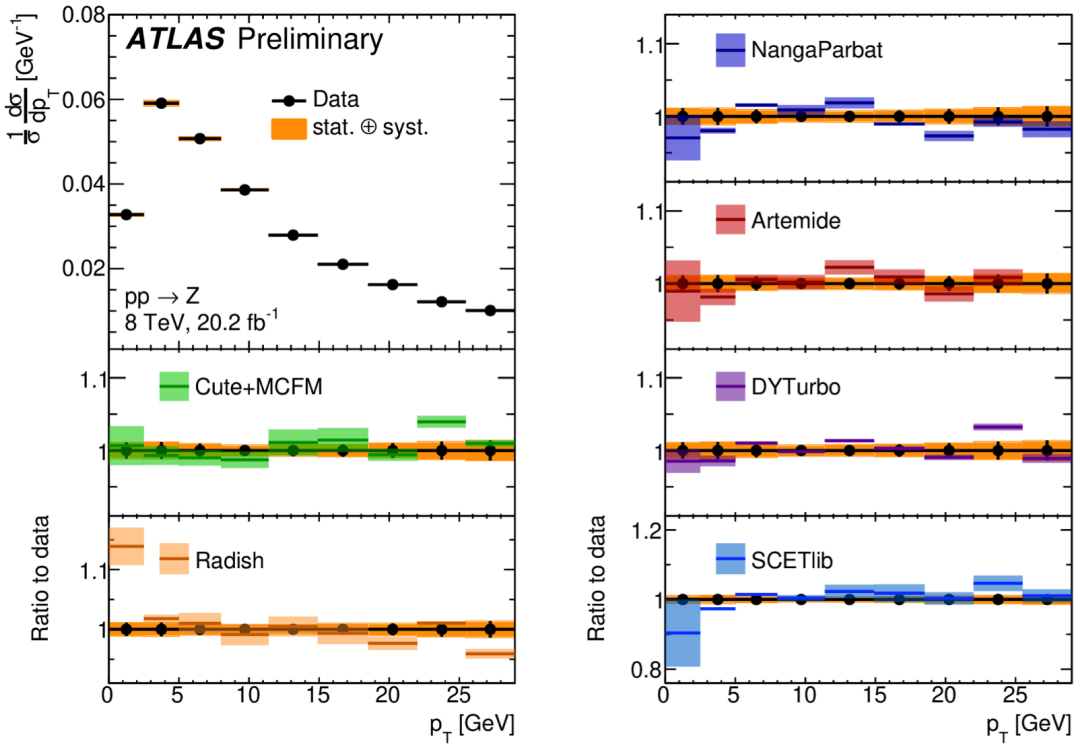
80 < m_Z < 100 GeV, |Y| < 3.6



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



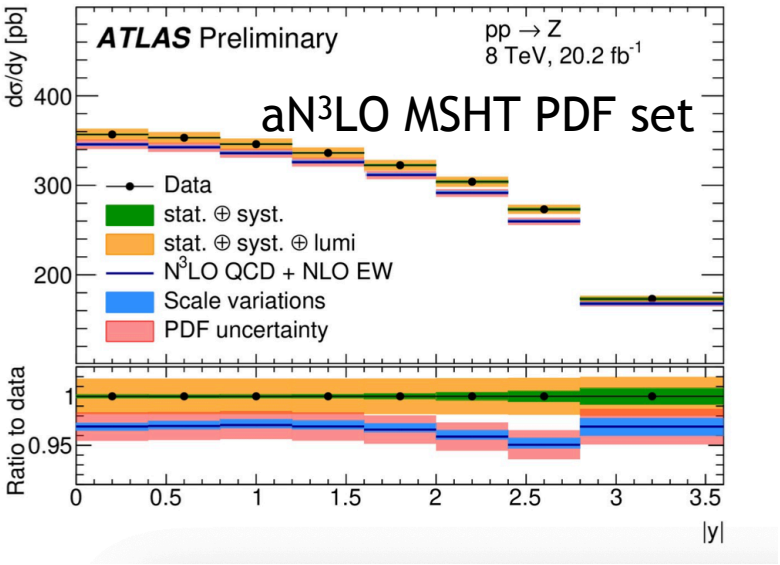
Strong effort in LPCC with benchmarking studies at N3LL/N4LL

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

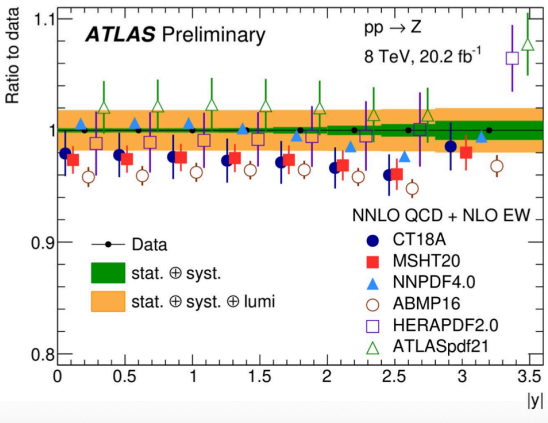
ATLAS-CONF-2023-013

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



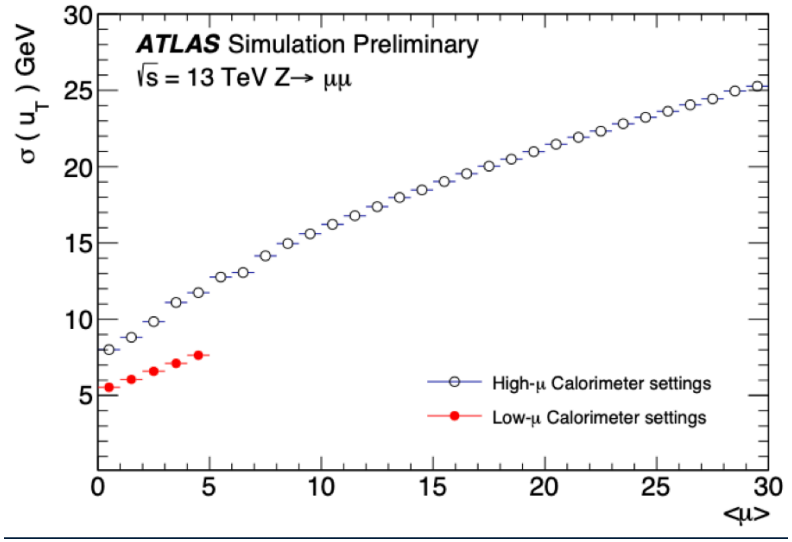
PDF set	Total χ^2 / d.o.f.	χ^2 p-value	Pull on luminosity
MSHT20aN^{3}LO [60]	13/8	0.11	1.2 ± 0.6
CT18A [61]	12/8	0.17	0.9 ± 0.7
MSHT20 [62]	10/8	0.26	0.9 ± 0.6
NNPDF4.0 [63]	30/8	0.0002	0.0 ± 0.2
ABMP16 [64]	30/8	0.0002	1.8 ± 0.4
HERAPDF2.0 [65]	22/8	0.005	-1.3 ± 0.8
ATLASpdf21 [66]	20/8	0.01	-1.1 ±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

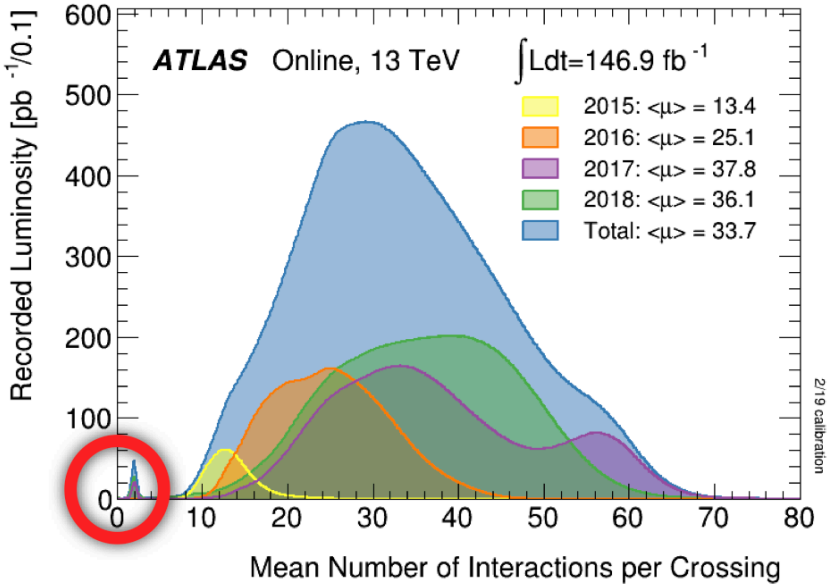


ATLAS-CONF-2023-013

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



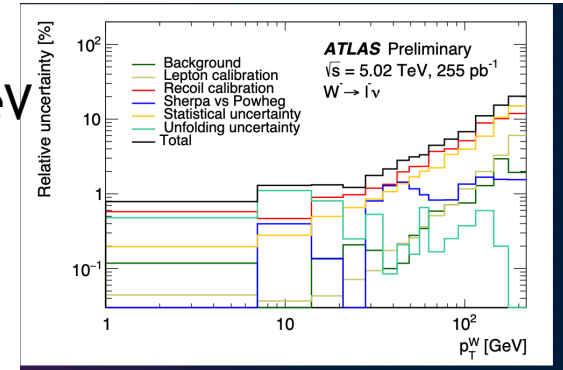


ATLAS-CONF-2023-028

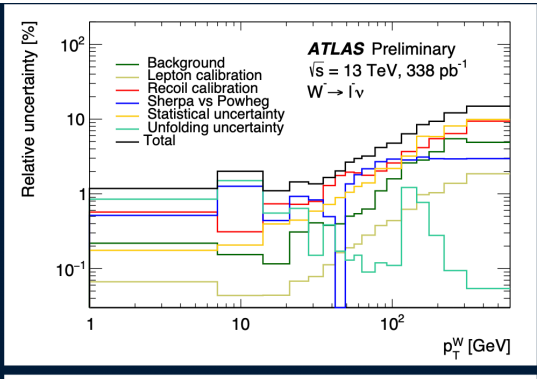
ATLAS W and Z p_T with low-pileup data

- 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)

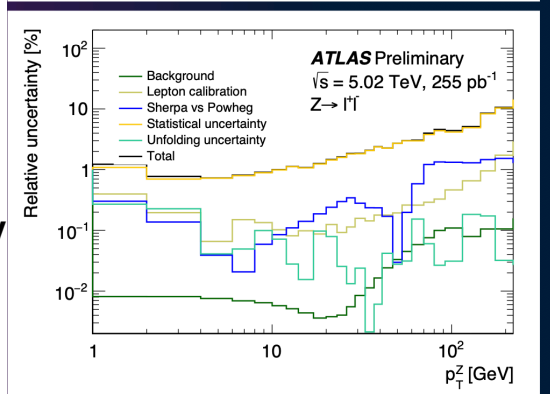
W^-, 5.02 TeV



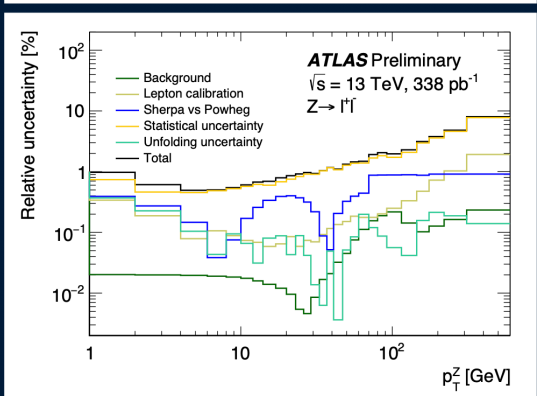
W^-, 13 TeV



Z, 5.02 TeV



Z, 13 TeV

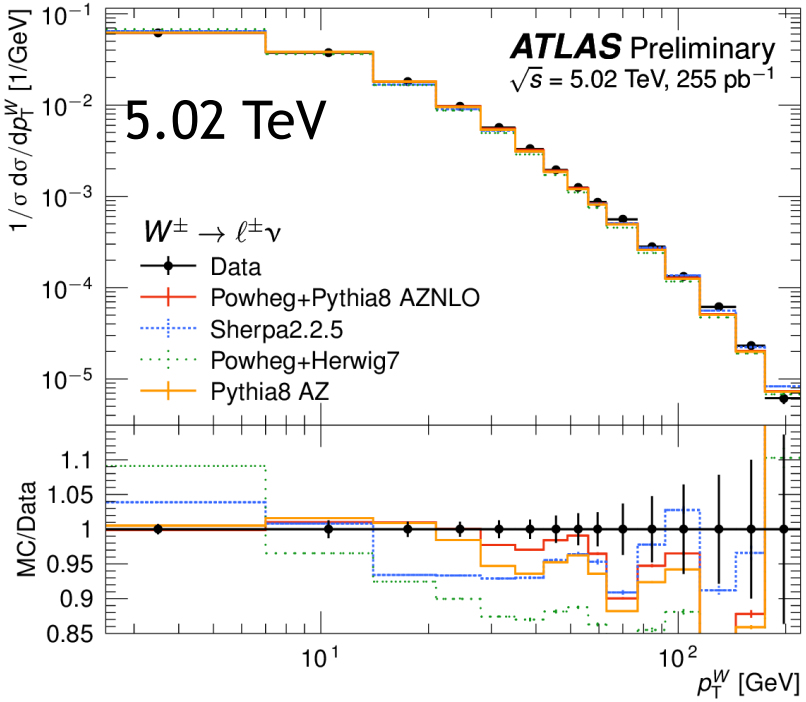


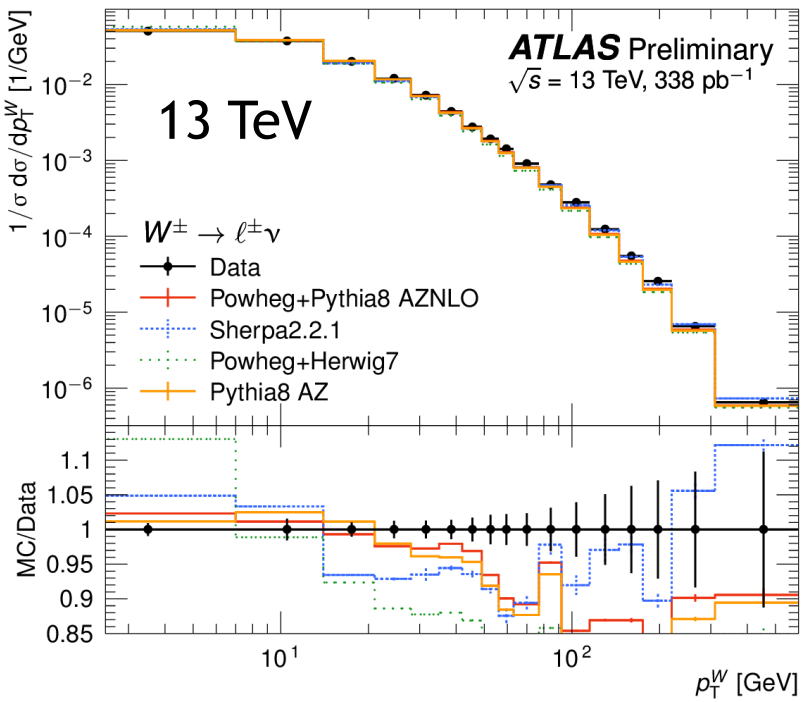
Fiducial volume :
- lepton p_T > 25 GeV, lepton |η| < 2.5
- W :
  - $p_T{}^{\nu}$ >25 GeV
  - m_T > 50 GeV
- Z : 66 < m_ll < 116 GeV

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 $\sqrt{s}$=5.02 TeV





ATLAS-CONF-2023-028

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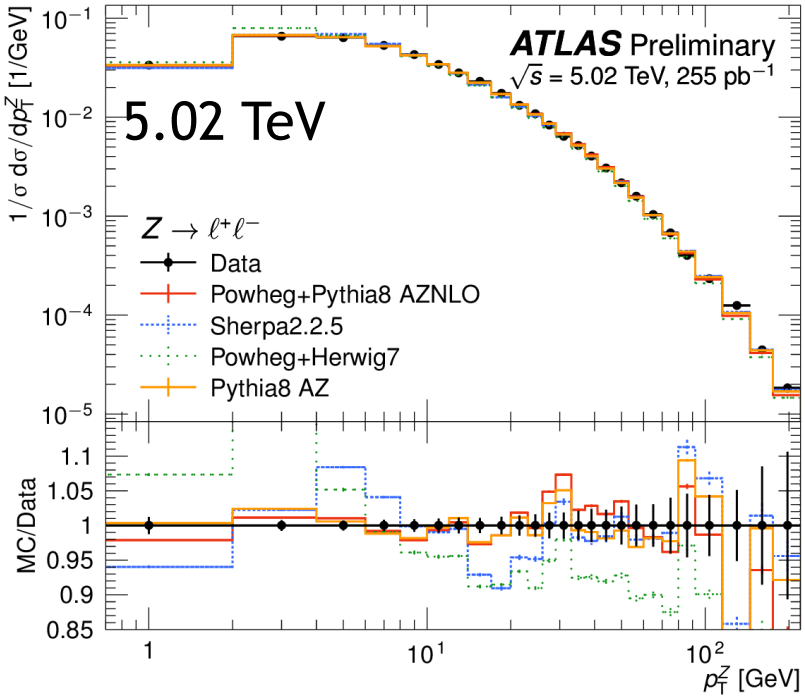
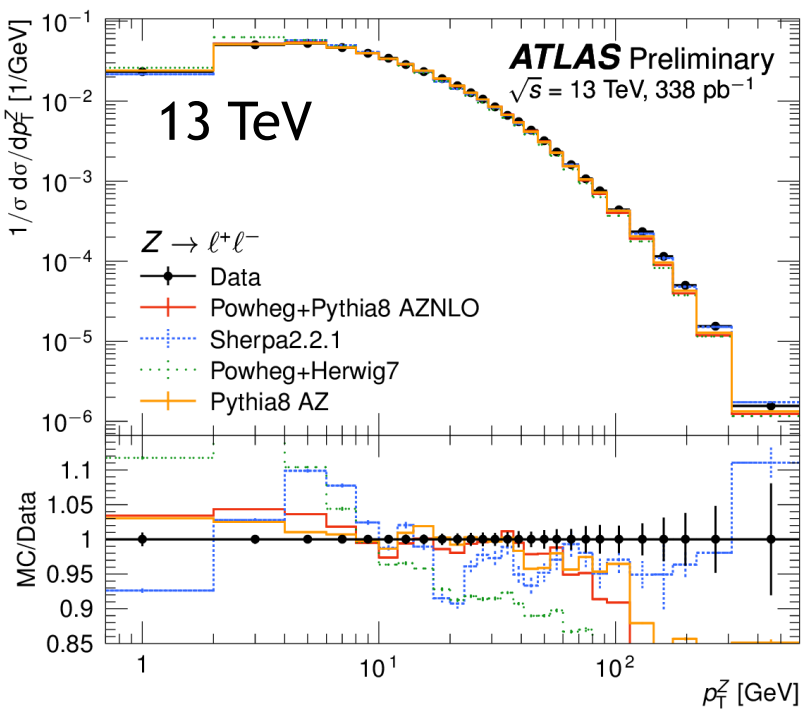




ATLAS-CONF-2023-028

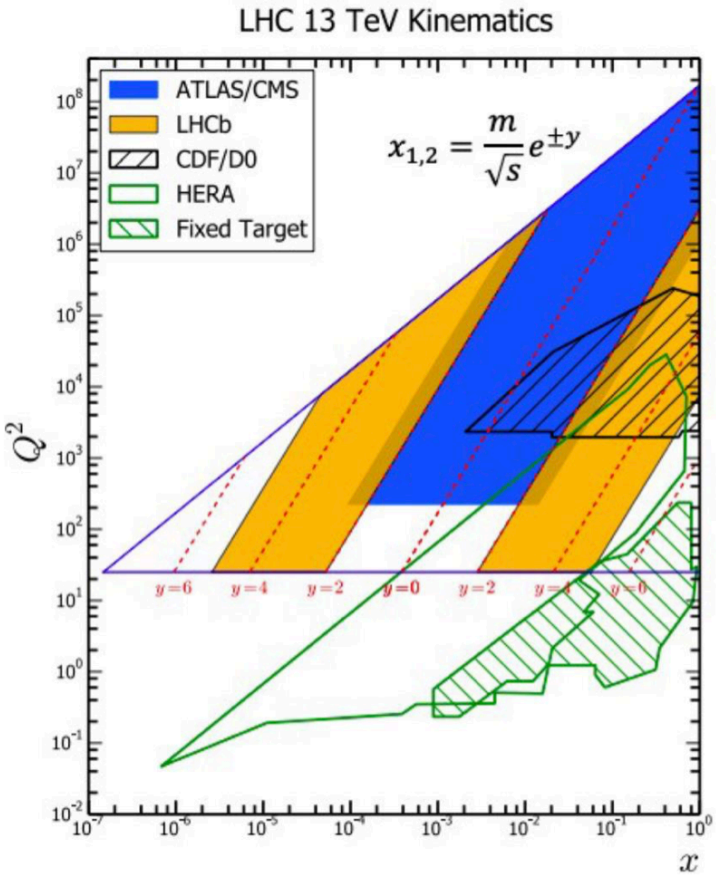
LHCb forward Z measurements

- 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}

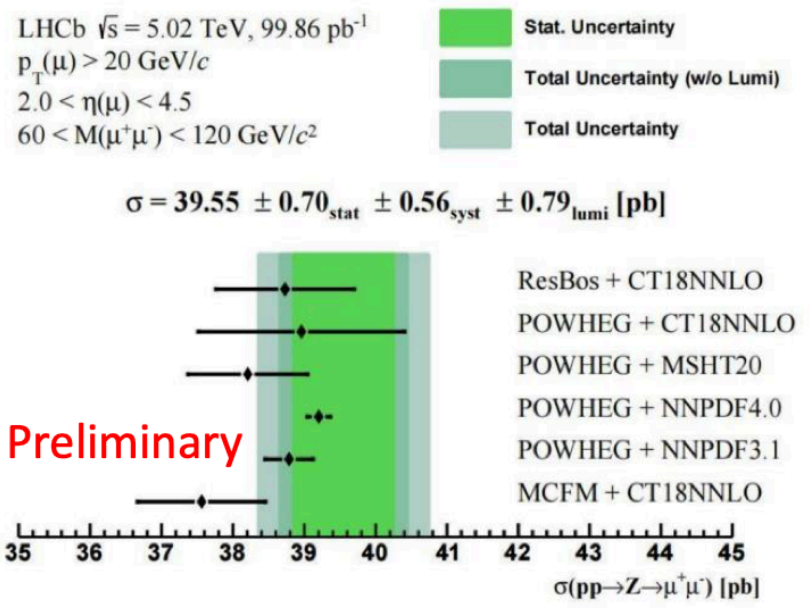


$$\phi_\eta^* = \tan\left(\frac{\pi - \Delta\phi}{2}\right) \times \sin(\theta_\eta^*), \qquad \cos(\theta_\eta^*) = \tanh[(\eta^- - \eta^+)/2]$$

LHCb forward Z measurements

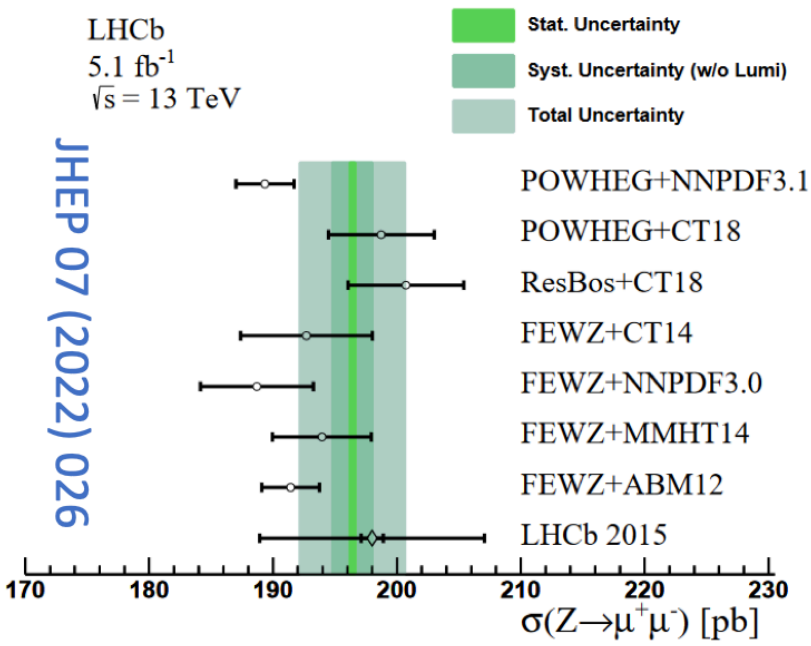
- Z cross sections at 5.02 TeV and 13 TeV
  - The most precise measurements in the forward region
  - The measurement at 5.02 TeV dominated by statistical uncertainty

5.02 TeV



LHCb paper in preparation

13 TeV



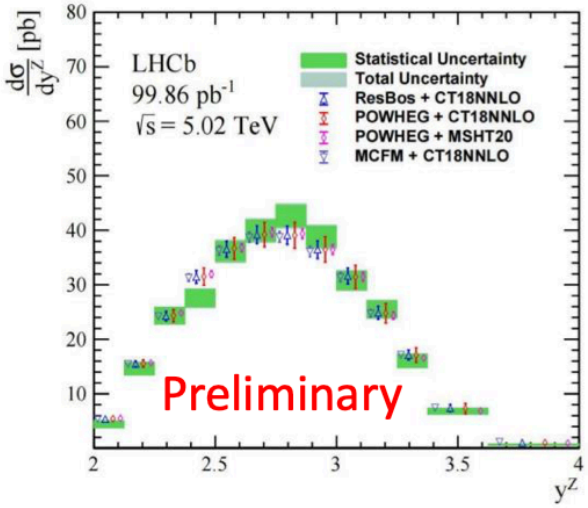
Arxiv:2112.07458

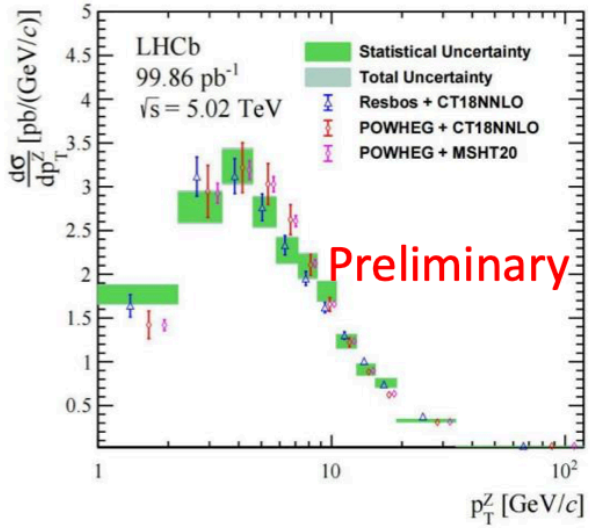
LHCb forward Z measurements

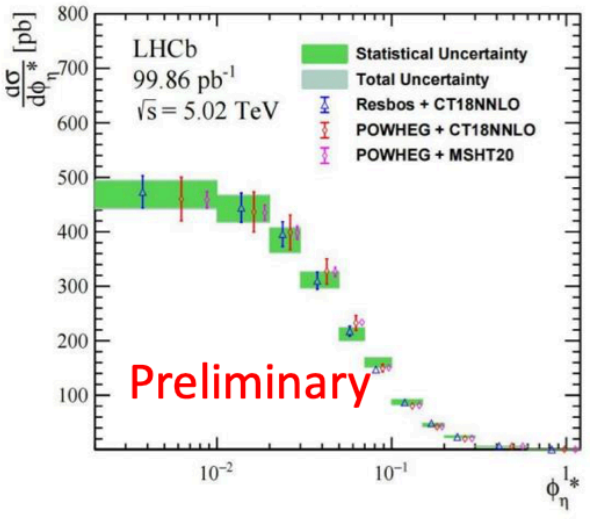
- New differential cross section measurements at 5.02 TeV

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





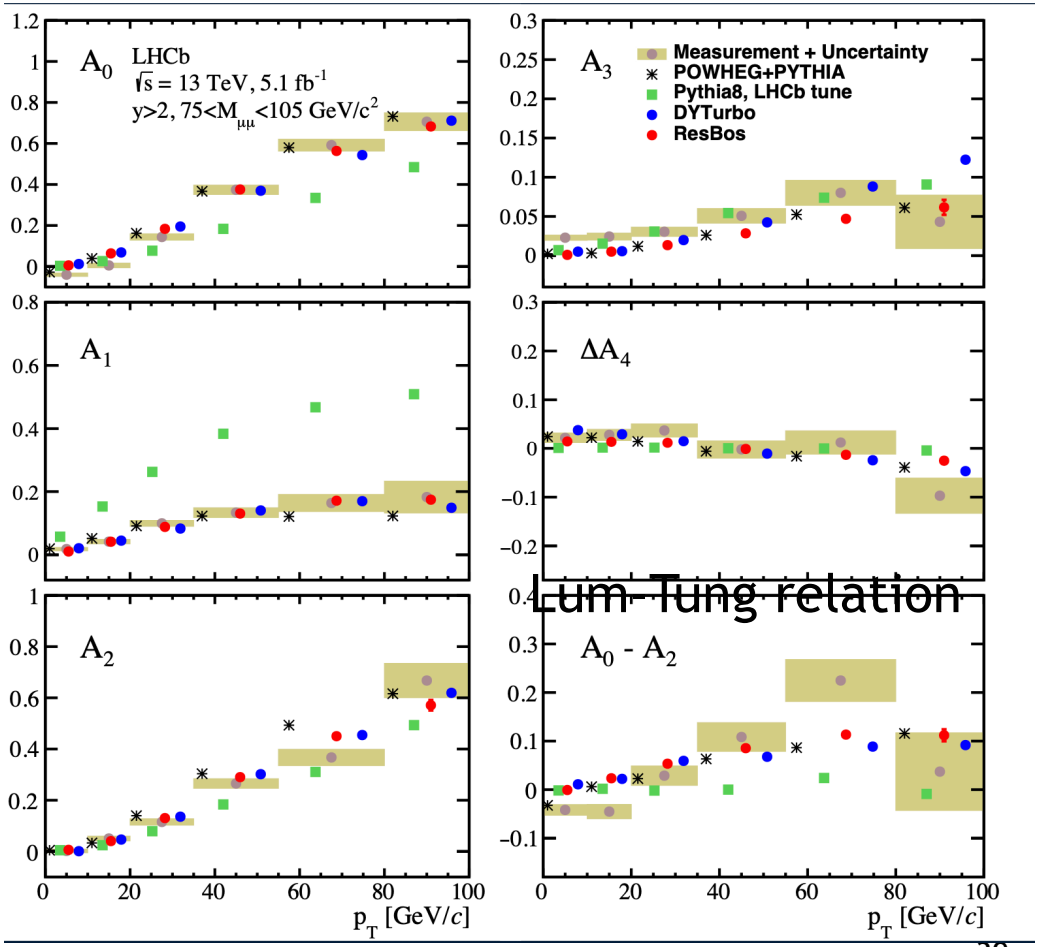


LHCB-PAPER-2023-010 in preparation

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

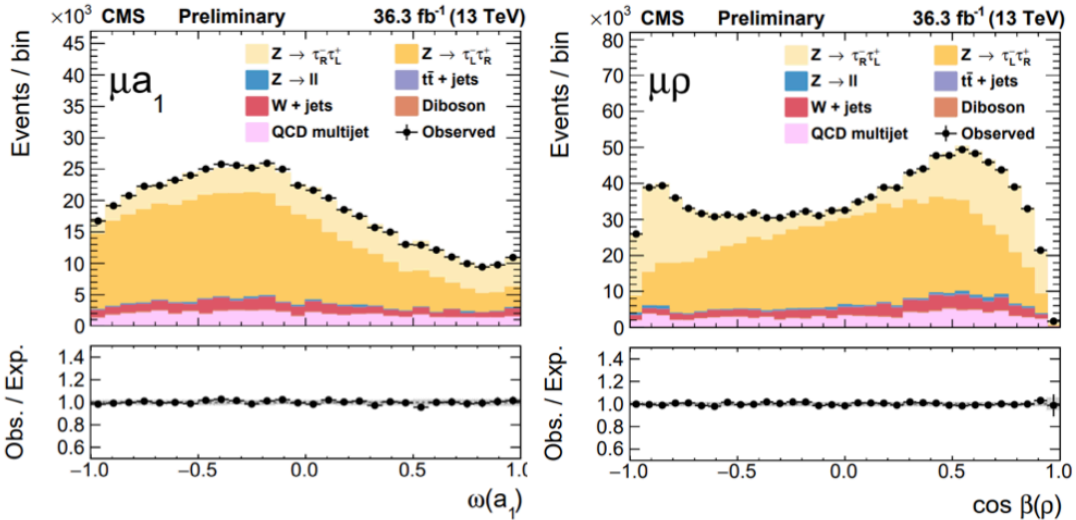
CMS τ lepton polarization in Z boson decays

- 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

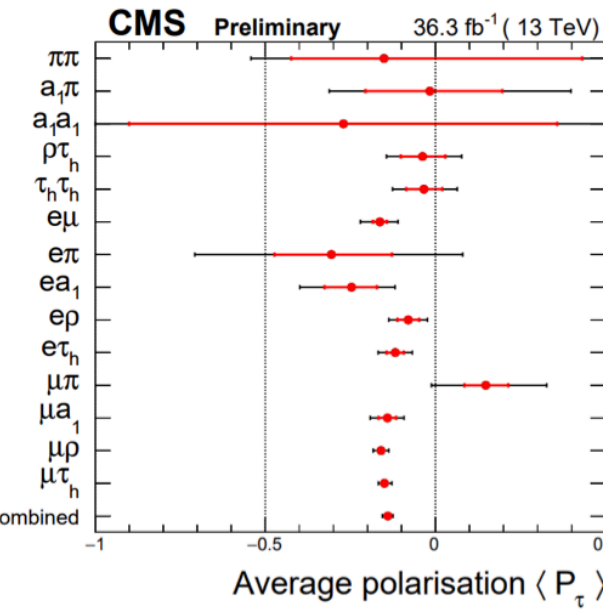
CMS τ lepton polarization in Z boson decays

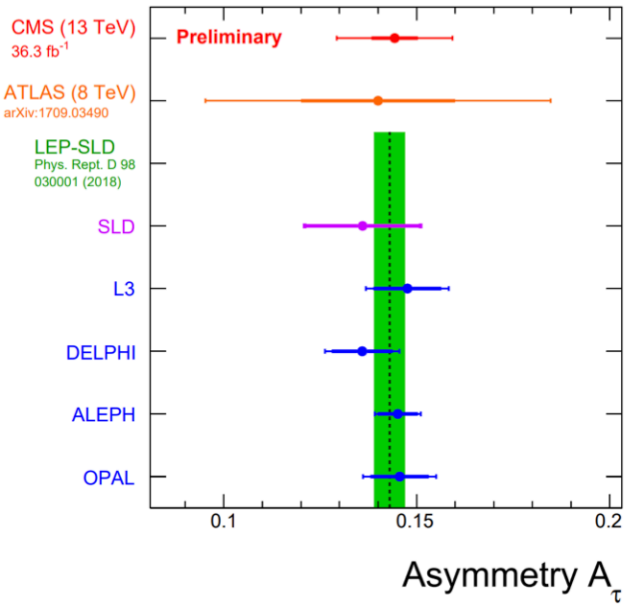
- Measured polarization is in good agreement with the SLD/LEP

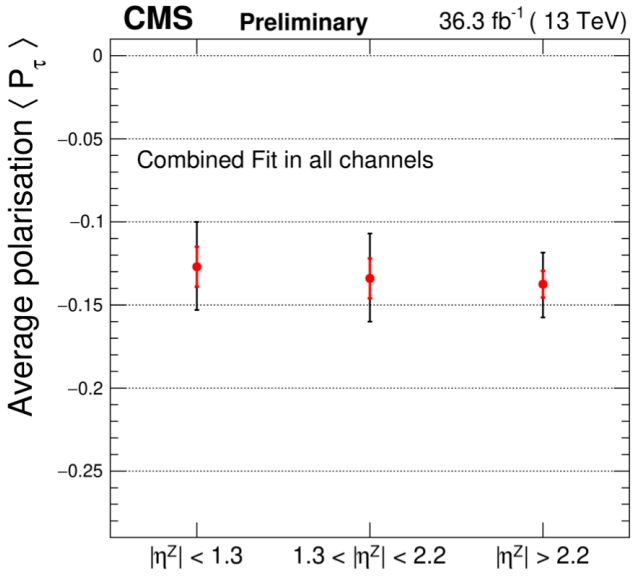
$$P_\tau = \frac{1}{\sigma}[\sigma(h_\tau = +1) - \sigma(h_\tau = -1)] \qquad P_\tau = -A_\tau = -\frac{2v_\tau a_\tau}{v_\tau^2 + a_\tau^2} \approx -2 \cdot \frac{v_\tau}{a_\tau} = -2(1 - 4\sin^2\theta_W^{\text{eff}})$$

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

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





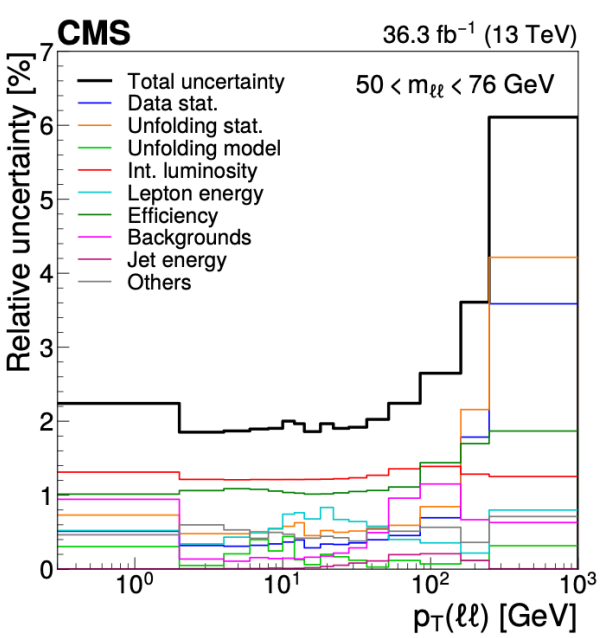


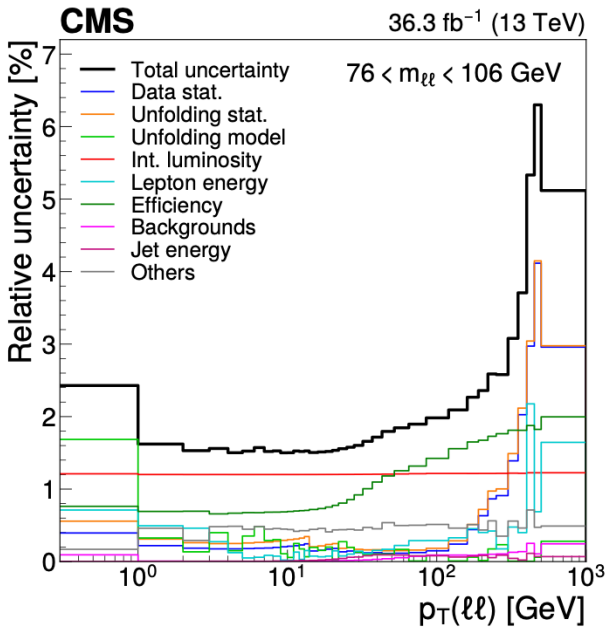
SMP-18-010

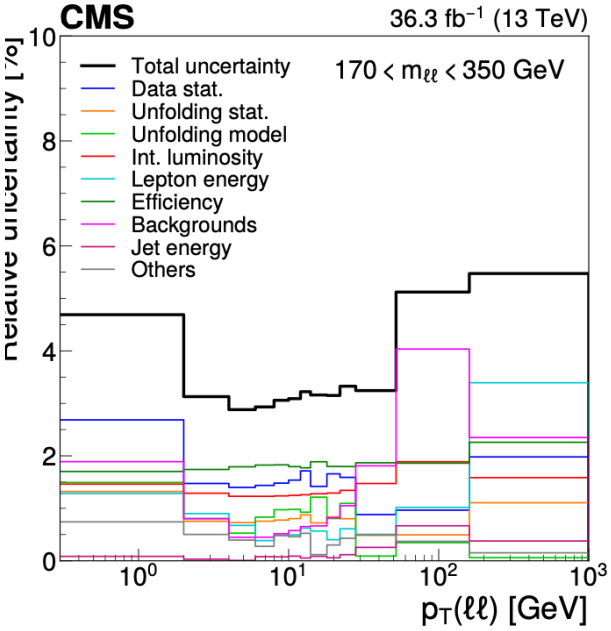
CMS DY measurement

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

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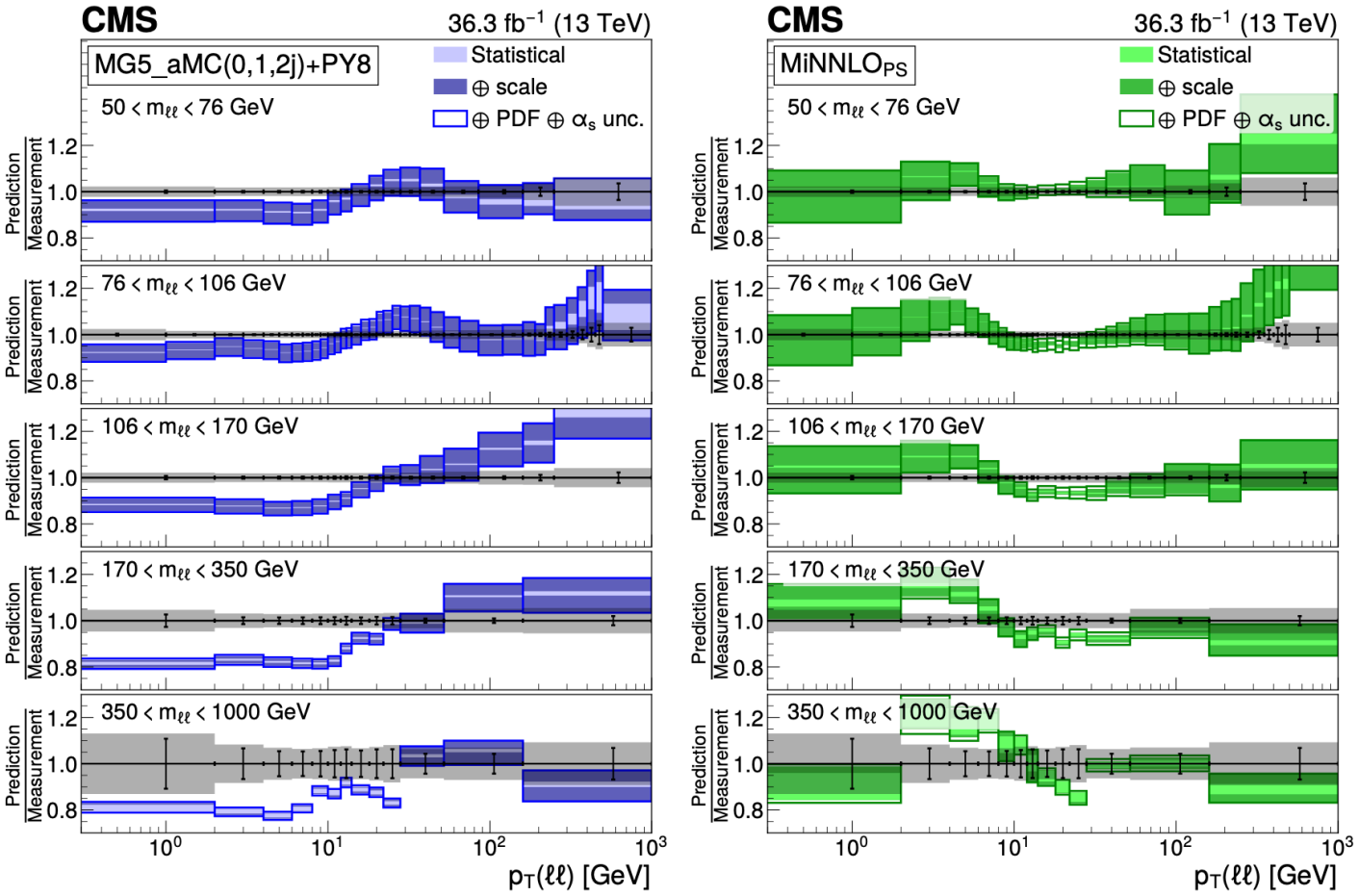
- Measurement compared with MadGraph5_aMC@NLO + PYTHIA 8 and MiNNLOPS : NNLO ME and Pythia8 PS and MPI



CMS DY measurement

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