Precision measurements of the Standard Model parameters with ATLAS

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On behalf of the ATLAS Collaboration

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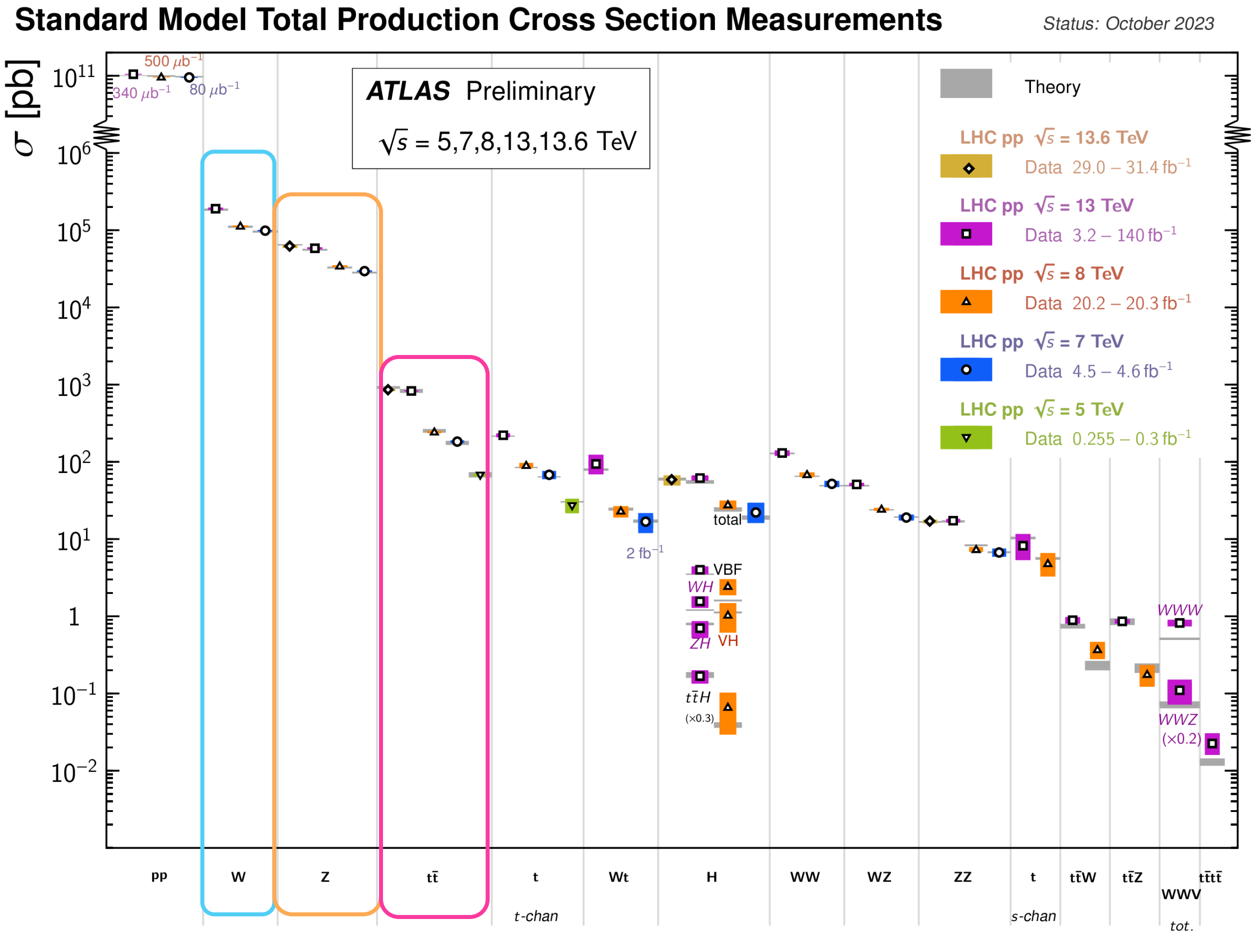
Introduction

- Standard Model being tested by ATLAS in a wide range of processes and energies
  - Cross-section spanning several orders of magnitude
- Ideal tools for QCD and EWK studies thanks the abundant production and clear signatures
  - Test of state-of-the-art predictions
  - Extraction of PDFs
  - Determination of SM parameters
  - Important backgrounds to Higgs, BSM, etc
- Today’s menu:
  - Z boson invisible width
  - α_s via Z boson recoil
  - Improved measurement of m_W
  - e/μ LFU using Ws from top quarks

ATL-PHYS-PUB-2023-039



Measurement of the Z boson invisible width

Phys. Lett. B 854 (2024) 138705

$\sqrt{s} = 13\ \mathrm{TeV},\ L = 37\ \mathrm{fb}^{-1}$

Dilepton

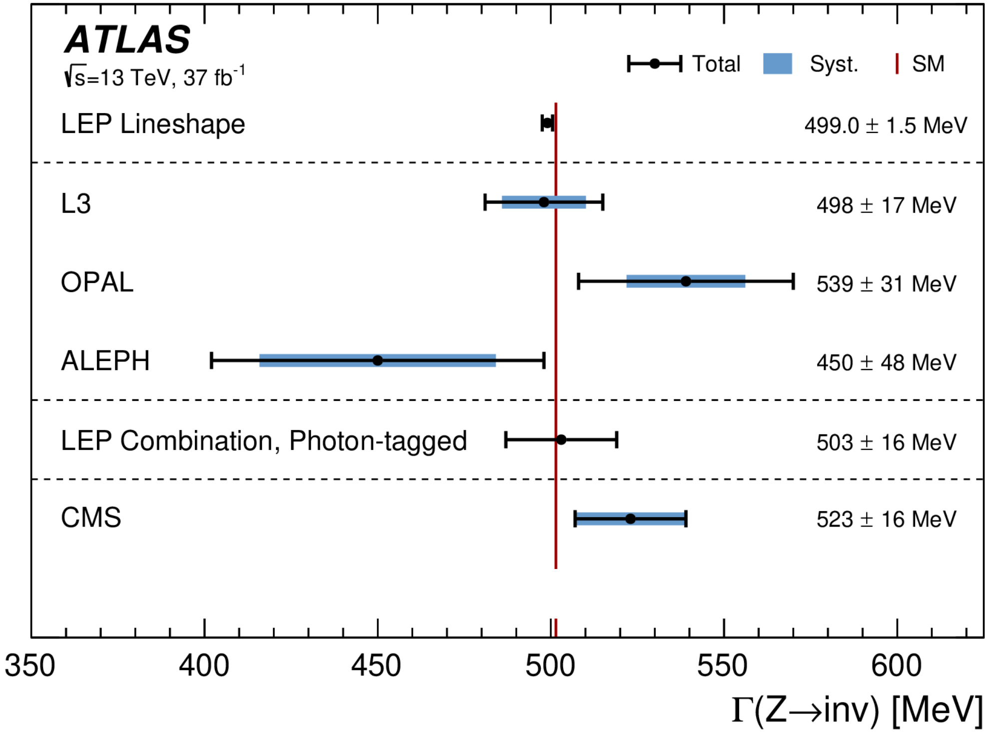
Measurement of the Z boson invisible width

Introduction

Phys. Lett. B 854 (2024) 138705

$\sqrt{s} = 13\ \text{TeV},\ L = 37\ \text{fb}^{-1}$

- Stringent test of SM
  - Assumption of 3 ν generations
  - Sensitive to new physics effects
- Proxy variable: $R^{miss}(p_T^Z) = \dfrac{\frac{d\sigma(Z(\to\text{inv})+\text{jets})}{dp_T^Z}}{\frac{d\sigma(Z(\to ll)+\text{jets})}{dp_T^Z}}$
  - Flat assuming the Standard model
  - $\hat{R}^{miss} = \dfrac{\Gamma(Z\to\text{inv})}{\Gamma(Z\to ll)} \Rightarrow$
    $\boldsymbol{\Gamma(Z\to inv)_{meas} = \hat{R}^{miss}_{meas} \times \Gamma(Z\to ll)_{LEP}}$ [1]



[1]: Phys. Rep., 427 (2006), 257

Measurement of the Z boson invisible width

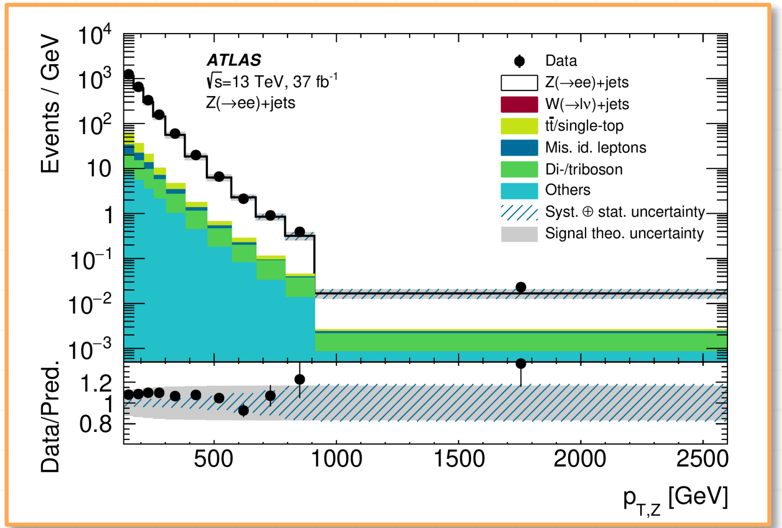
$$R^{miss}(p_T^Z) = \frac{\frac{d\sigma(Z(\to \text{inv}) + \text{jets})}{dp_T^Z}}{\frac{d\sigma(Z(\to ll) + \text{jets})}{dp_T^Z}}$$

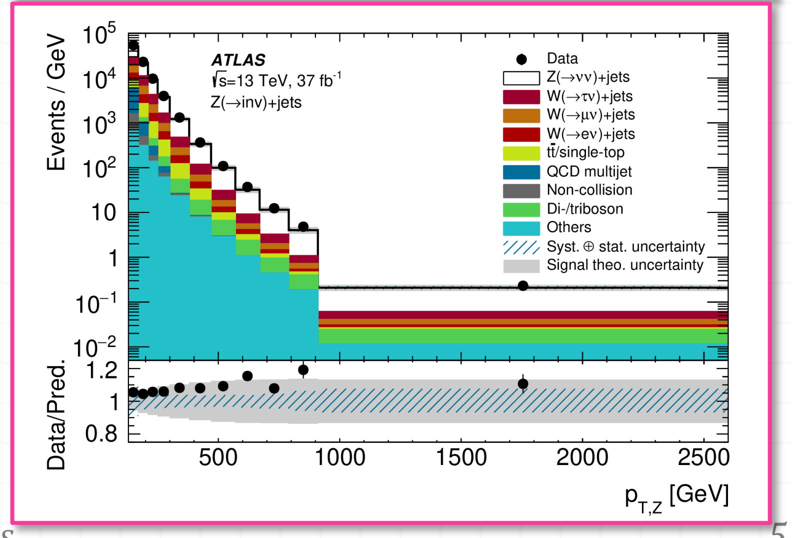
Analysis strategy

Phys. Lett. B 854 (2024) 138705

$\sqrt{s} = 13\text{ TeV},\ L = 37\text{ fb}^{-1}$

- Common phase space definition for $Z(\to \text{inv}) + \text{jets}$ and $Z(\to ee/\mu\mu) + \text{jets}$
  - One energetic jet $p_T > 110\text{ GeV}$
  - Invisible: $p_T^Z = E_T^{miss}$
  - Visible $(ee/\mu\mu)$: $p_T^Z = \left|\overrightarrow{p^{l_1}}_T + \overrightarrow{p^{l_2}}_T + \overrightarrow{E_T^{miss}}\right|$
    - Reco level: $66 < m_{ll} < 116\text{ GeV}$





Measurement of the *Z* boson invisible width

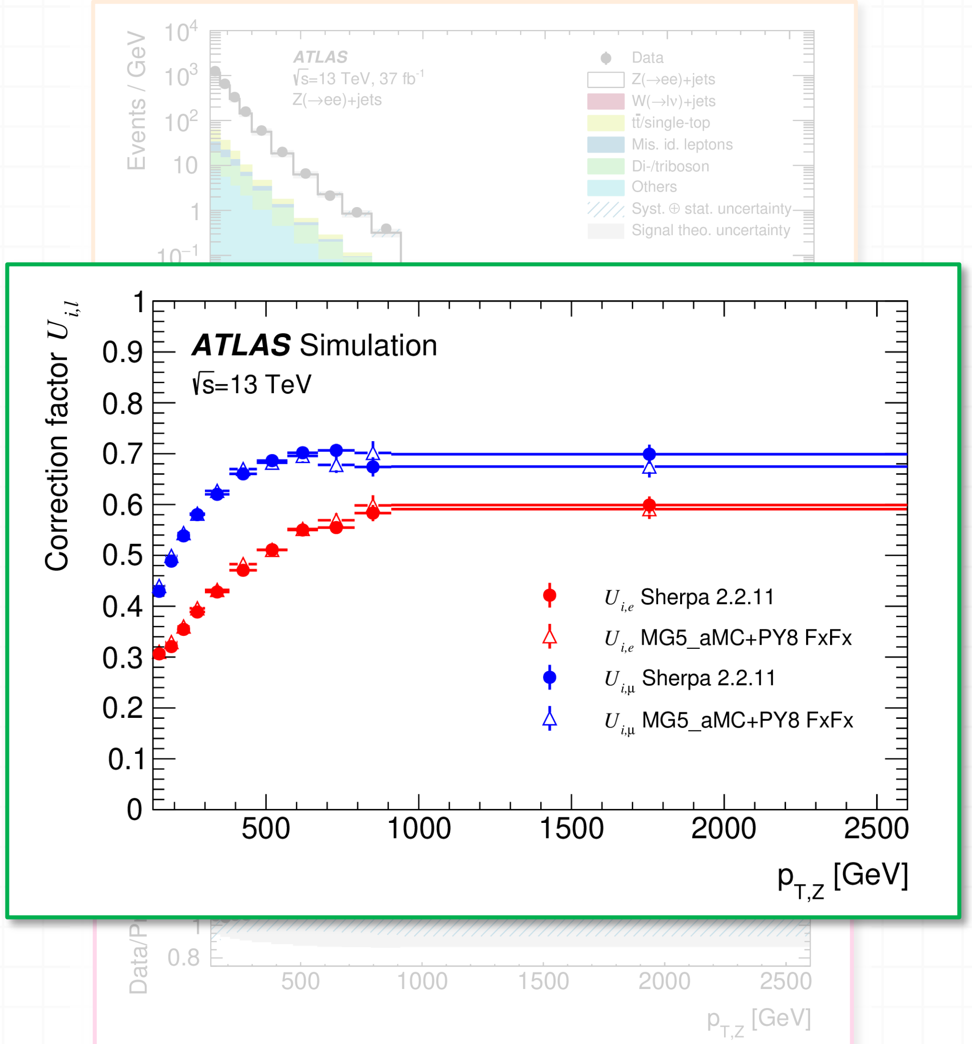
$$R^{miss}(p_T^Z) = \frac{\frac{d\sigma(Z(\to \text{inv}) + \text{jets})}{dp_T^Z}}{\frac{d\sigma(Z(\to ll) + \text{jets})}{dp_T^Z}}$$

Analysis strategy

Phys. Lett. B 854 (2024) 138705

$\sqrt{s} = 13\ \text{TeV},\ L = 37\ \text{fb}^{-1}$

- Common phase space definition for $Z(\to \text{inv}) + \text{jets}$ and $Z(\to ll) + \text{jets}$
  - One energetic jet $p_T > 110$ GeV
  - Invisible: $p_T^Z = E_T^{miss}$
  - Visible ($ee/\mu\mu$): $p_T^Z = \left|\overrightarrow{p^{l_1}}_T + \overrightarrow{p^{l_2}}_T + \overrightarrow{E_T^{miss}}\right|$
    - Reco level: $66 < m_{ll} < 116$ GeV
- $R^{miss}(p_T^Z)$ at reco level corrected to particle level
  - $R^{miss}_{data}(p_T^Z) = \frac{N_{data}(\text{inv}) - B(\text{inv})}{N_{data}(ll) - B(ll)}$
  - $U_{i,l} = \left(\frac{N_i(Z(\to\text{inv})+\text{jets})}{N_i(Z(\to ll)+\text{jets})}\right)^{\text{reco}} \Big/ \left(\frac{N_i(Z(\to\text{inv})+\text{jets})}{N_i(Z(\to ll)+\text{jets})}\right)^{\text{particle}}$
  - Additional correction applied to $Z \to ll$ to account for m_{ll} requirements and Z/γ^* interference



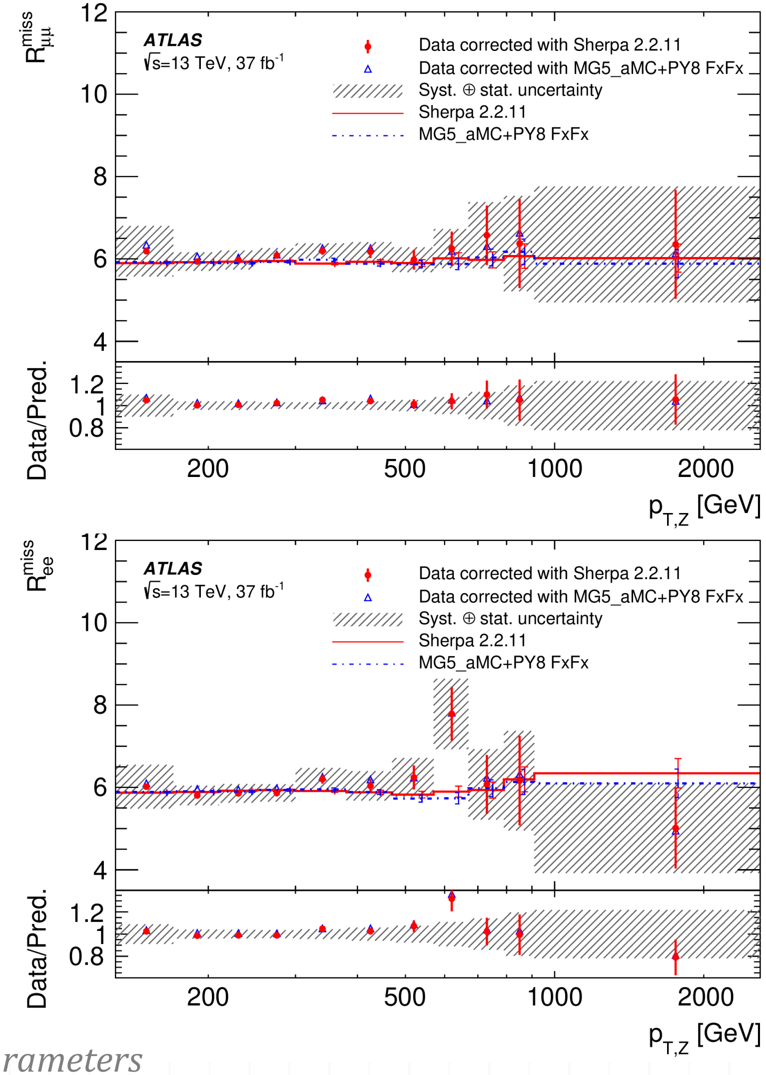
Measurement of the *Z* boson invisible width

Results

Phys. Lett. B 854 (2024) 138705

$\sqrt{s} = 13\ \text{TeV},\ L = 37\ \text{fb}^{-1}$

- $R^{miss}(p_T^Z)$ measured separately in $ee/\mu\mu$ channels
  - Flat and compatible with Standard model predictions



Measurement of the *Z* boson invisible width

Results

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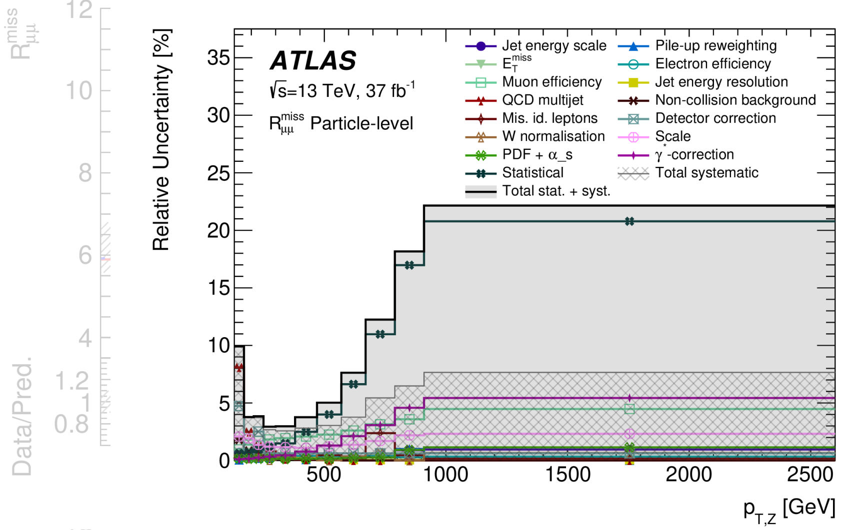
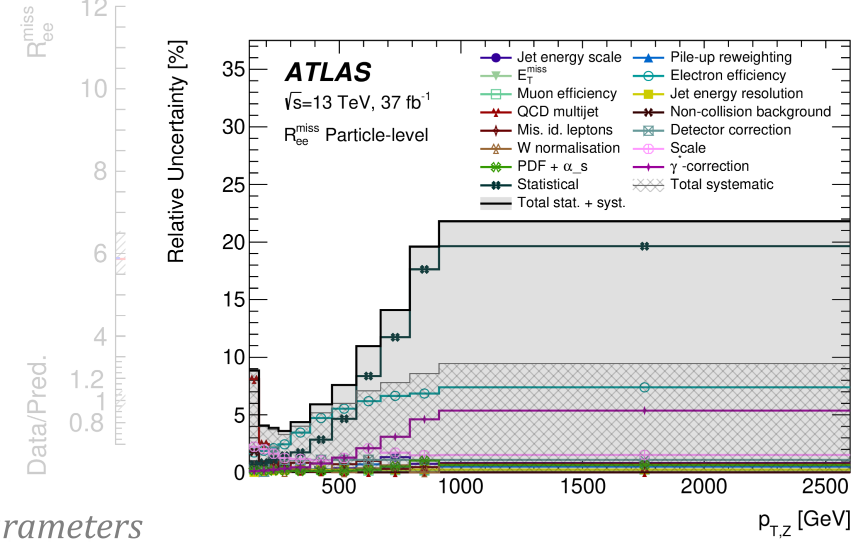
$\sqrt{s} = 13\text{ TeV},\ L = 37\text{ fb}^{-1}$

- $R^{miss}(p_T^Z)$ measured separately in $ee/\mu\mu$ channels
  - Flat and compatible with Standard model predictions
- Dominated by lepton uncertainties (low p_T) and stat. uncertainties (high p_T)





Measurement of the Z boson invisible width

Results

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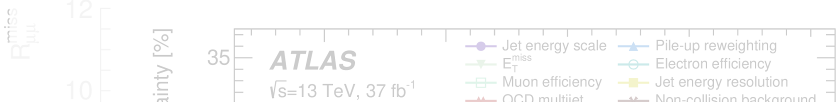
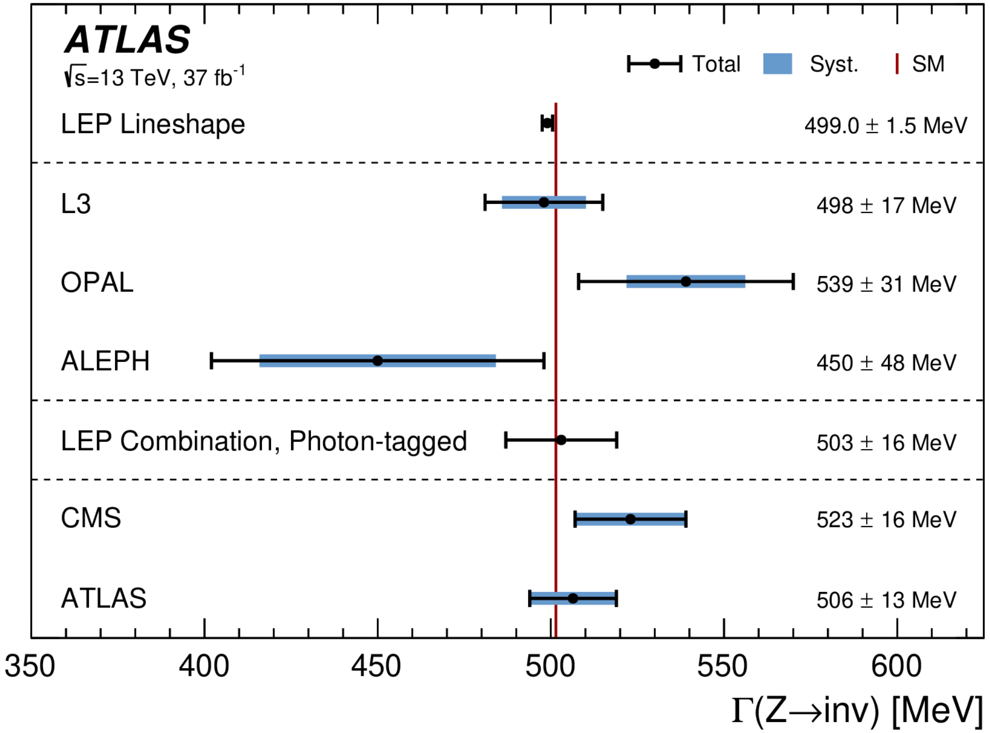
$\sqrt{s} = 13\ \text{TeV},\ L = 37\ \text{fb}^{-1}$

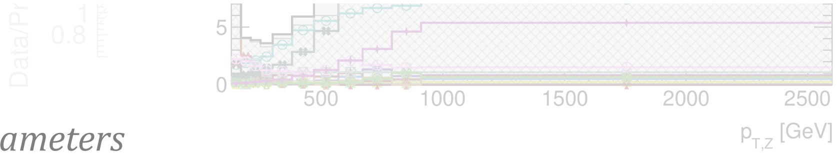
- $R^{miss}(p_T^Z)$ measured separately in $ee/\mu\mu$ channels
  - Flat and compatible with Standard model predictions
- Dominated by lepton uncertainties (low p_T) and stat. uncertainties (high p_T)
- $\hat{R}^{miss}$ obtained via χ^2 fit
  - Constant assumption (SM)

$$\chi^2 = \left(R_{data}^{miss,i} - \hat{R}^{miss}\right)^T \boldsymbol{V}^{-1}\left(R_{data}^{miss,i} - \hat{R}^{miss}\right)$$

  - Separate fit compatible with combination
  - $\boldsymbol{\Gamma(Z \to \text{inv}) = \hat{R}_{meas}^{miss} \times \Gamma(Z \to ll)_{LEP} = 506 \pm 2(\text{stat.}) \pm 12(\text{syst.})}$
  - Most precise recoil-based measurement







Measurement of α_s from recoil of Z bosons

Eur. Phys. J. C 84 (2024) 315

arXiv:2309.12986 [hep-ex], submitted to Nature Phys

$\sqrt{s} = 8\ \text{TeV},\ L = 20.2\ \text{fb}^{-1}$

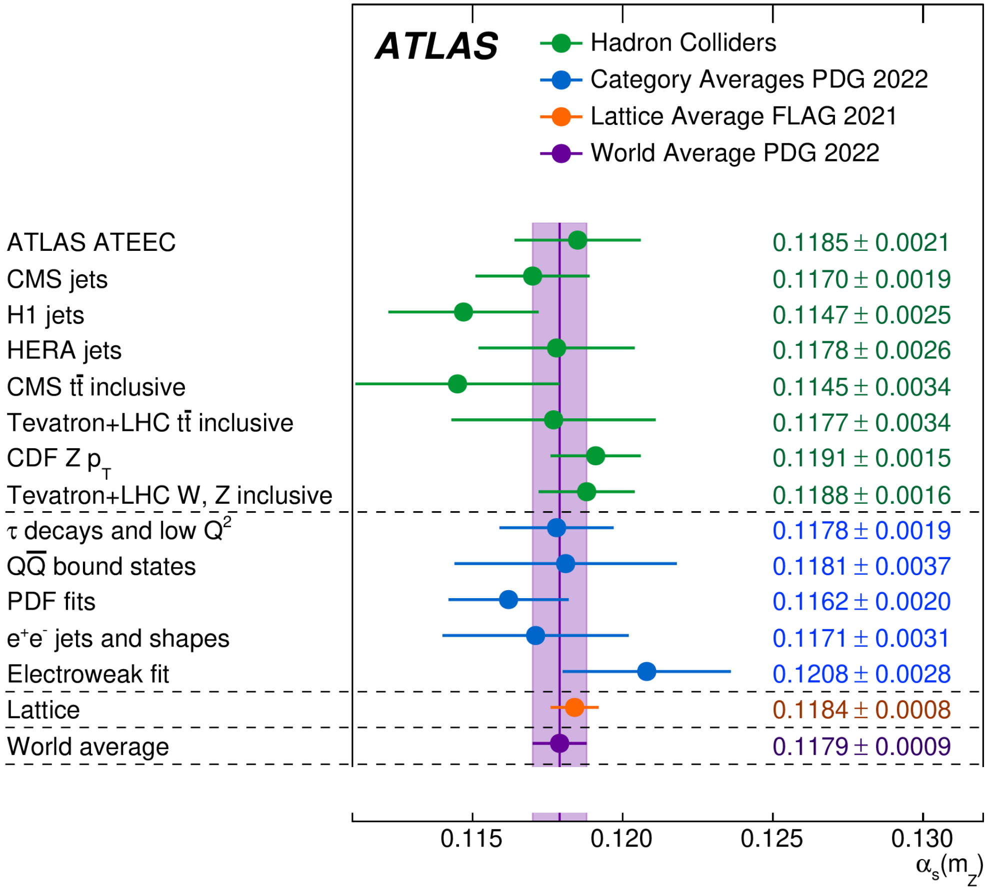
Dilepton

Measurement of α_s from recoil of Z bosons

Eur. Phys. J. C 84 (2024) 315
arXiv:2309.12986 [hep-ex]
$\sqrt{s} = 8\ \mathrm{TeV},\ L = 20.2\ \mathrm{fb}^{-1}$

Introduction

- Strong coupling constant; *the* free parameter unique to the strong interaction
  - The least precisely determined of the four fundamental couplings
  - World average $\alpha_s(m_Z) = 0.1179 \pm 0.0009\ (\pm 0.8\%)$
- Exploit a precise measurement of the Z kinematics
  - Take advantage of leptonic signatures
  - *Full phase-space* differential cross section as a function of p_T and rapidity of the Z
    - No need for predictions to model the polarization and decay of the Z boson
    - Availability of accurate pQCD predictions



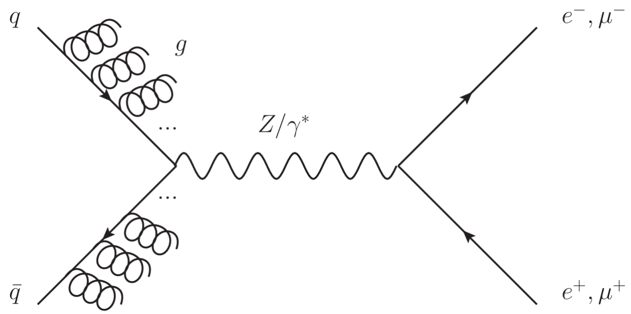
Measurement of α_s from recoil of Z bosons

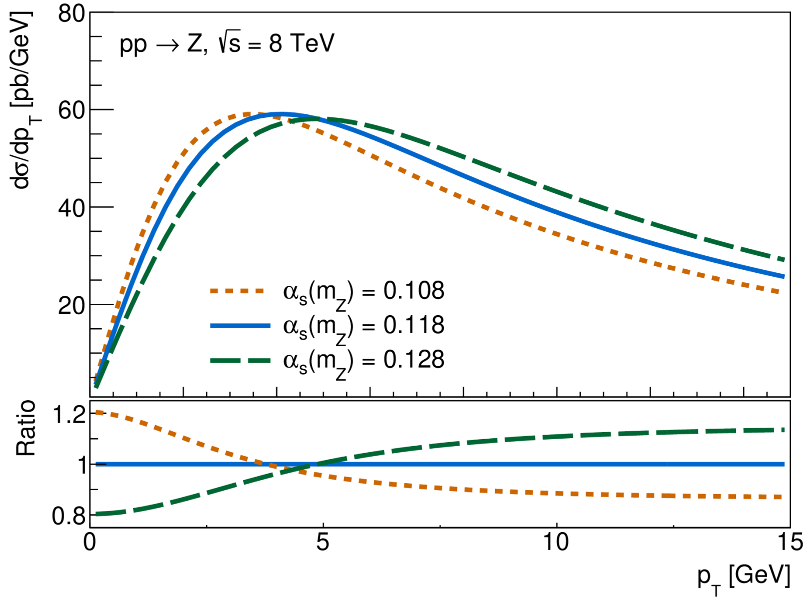
Introduction

Eur. Phys. J. C 84 (2024) 315
arXiv:2309.12986 [hep-ex]

$\sqrt{s} = 8$ TeV, $L = 20.2$ fb^{-1}

- Z bosons produced in hadron collisions recoil against QCD initial state radiation → boost in the transverse plane
- Focus in the low momentum Sudakov region
  - Gluon emission with vanishingly small momenta described by the Sudakov form factor
  - Responsible for a peak in at low p_T^Z
  - **Sensitive to $\boldsymbol{\alpha_s(m_Z)}$**





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$\sqrt{s} = 8\ \text{TeV},\ L = 20.2\ \text{fb}^{-1}$

Differential cross-section analysis strategy

- Exploit the factorization of Drell-Yan cross section by the production dynamic and the decay kinematic properties of the dilepton system

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}^{Z}\,\mathrm{d}y^{Z}\,\mathrm{d}m^{Z}\,\mathrm{d}\cos\theta\,\mathrm{d}\phi} = \frac{3}{16\pi}\boxed{\frac{\mathrm{d}\sigma^{U+L}}{\mathrm{d}p_{\mathrm{T}}^{Z}\,\mathrm{d}y^{Z}\,\mathrm{d}m^{Z}}}$$

$$\boxed{\begin{aligned}&\Big\{(1+\cos^2\theta)+\frac{1}{2}A_0(1-3\cos^2\theta)+A_1\ \sin 2\theta\ \cos\phi\\&+\frac{1}{2}A_2\ \sin^2\theta\ \cos 2\phi+A_3\ \sin\theta\ \cos\phi+A_4\ \cos\theta\\&+A_5\ \sin^2\theta\ \sin 2\phi+A_6\ \sin 2\theta\ \sin\phi+A_7\ \sin\theta\ \sin\phi\Big\}.\end{aligned}}$$

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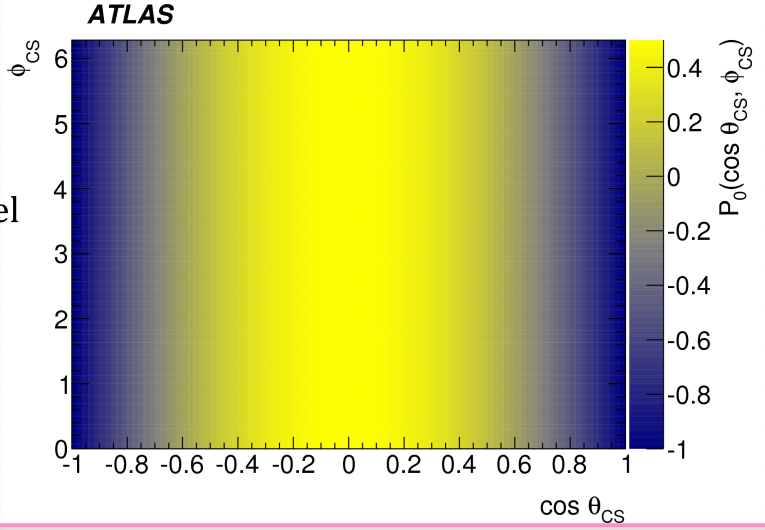
Differential cross-section analysis strategy

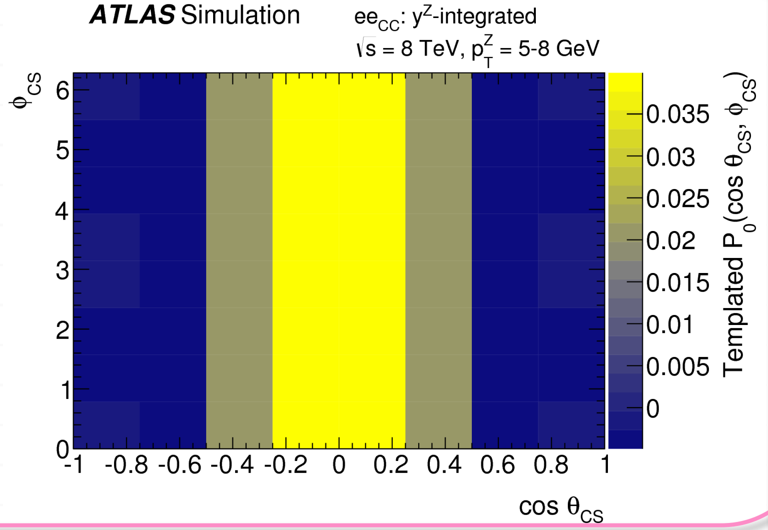
- Expected yield defined with templates of the spherical harmonics and background predictions
  - Parametrized wrt the unpolarized cross section and angular coefficients

$$\boxed{N^n_{\mathrm{exp}}}\left(\boxed{A, \sigma^{U+L}}, \beta, \gamma\right) = \left\{ \sum_j \sigma_j^{U+L} \times L \times \left[\boxed{t^n_{8j}(\beta) + \sum_{i=0}^{7} A_{ij} \times t^n_{ij}(\beta)} \right] \right\} \times \gamma^n + \boxed{\sum_B^{\mathrm{bkgs}} T^n_B(\beta)},$$

Truth-level



Reco-level



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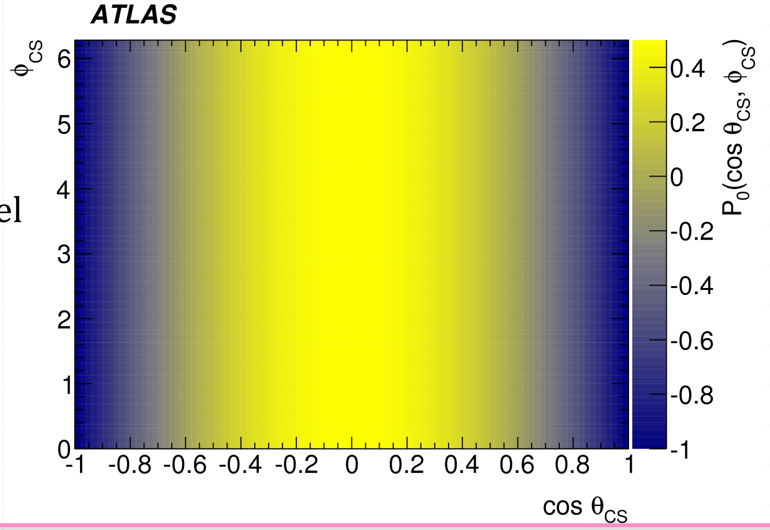
Differential cross-section analysis strategy

- Profile likelihood fit
  - simultaneously extracts 8 angular coefficients and unpolarized cross section in each bin in $p_T \times y$ space

$$\mathcal{L}(A,\sigma,\theta|N_{\text{obs}}) = \prod_{n}^{N_{\text{bins}}} \left\{ P(N_{\text{obs}}^{n}|N_{\text{exp}}^{n}(A,\sigma,\theta))P(N_{\text{eff}}^{n}|\gamma^{n}N_{\text{eff}}^{n}) \right\} \times \prod_{m}^{M} G(0|\beta^{m},1).$$

Truth-level



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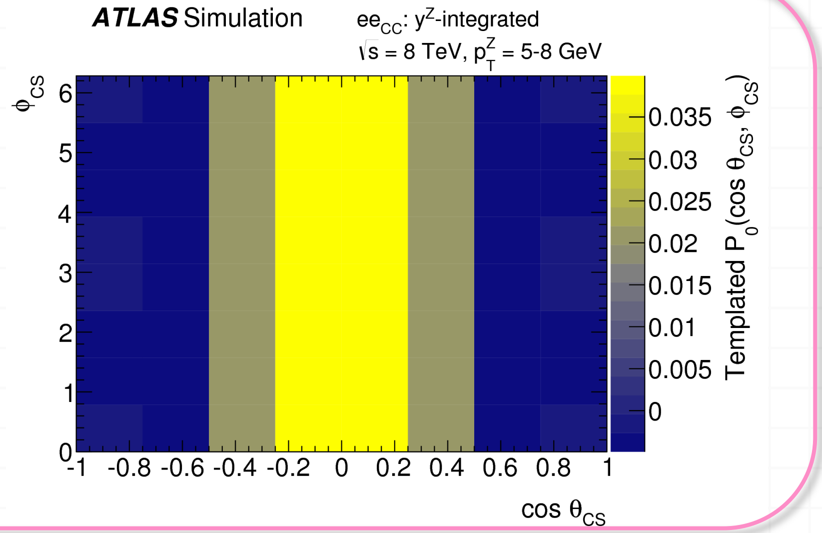

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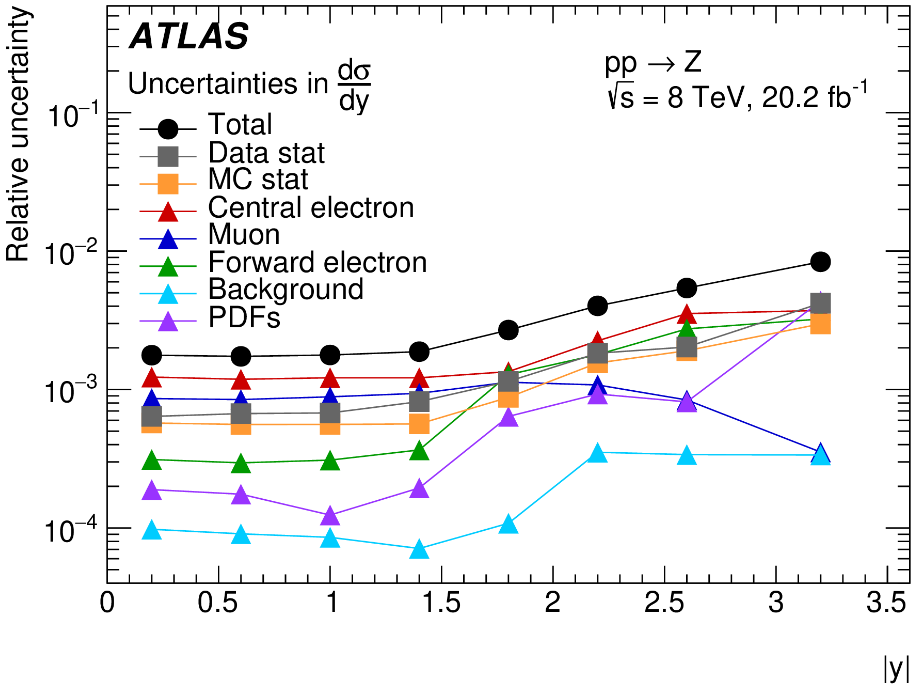
Differential cross-section analysis results

- **Per-mille** level precision in the central region
  - Sub-percent up to $|y| < 3.6$, thanks to dedicate forward electron selection and calibration



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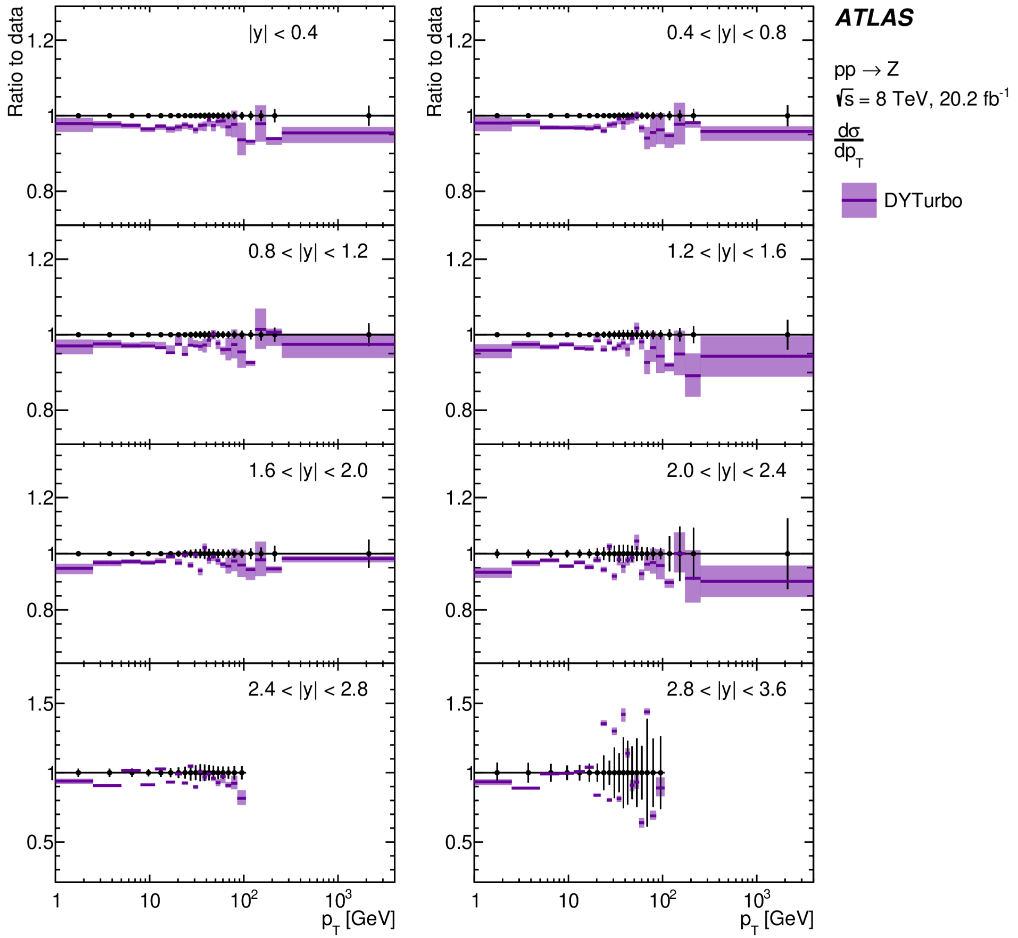
Differential cross-section analysis results

[1]: arXiv:2303.12781 [hep-ph]
[2]: Phys. Rev. Lett. 116, 152001 (2016)

- **Per-mille** level precision in the central region
  - Sub-percent up to $|y| < 3.6$, thanks to dedicate forward electron selection and calibration
- Compared to state of the art to state-of-the-art predictions
  - QCD perturbative calculations based on q_T resummation at N3LO+aN4LL accuracy
    - DYTurbo [1] matched to MCFM [2]
    - CuTe+MCFM, Nangaparbat, SCETlib, Radish+NNLOJET, Artemide



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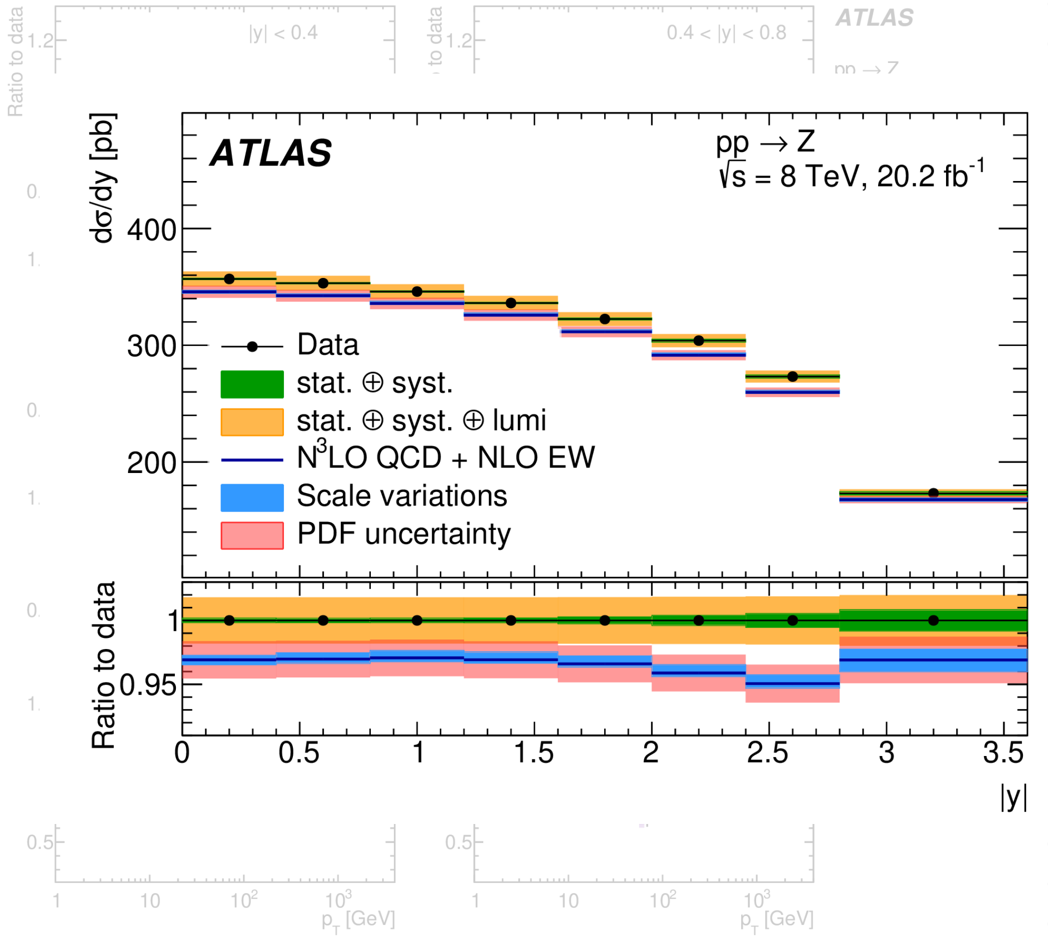
Differential cross-section analysis results

- **Per-mille** level precision in the central region
  - Sub-percent up to $|y| < 3.6$, thanks to dedicate forward electron selection and calibraiton
- Compared to state of the art to state-of-the-art predictions
  - QCD perturbative calculations based on qT resummation at aN4LL+N3LO accuracy
  - Fixed order N3LO (p_T-integrated spectra)
    - Not affected by q_{T} resummation
    - First comparison of this kind



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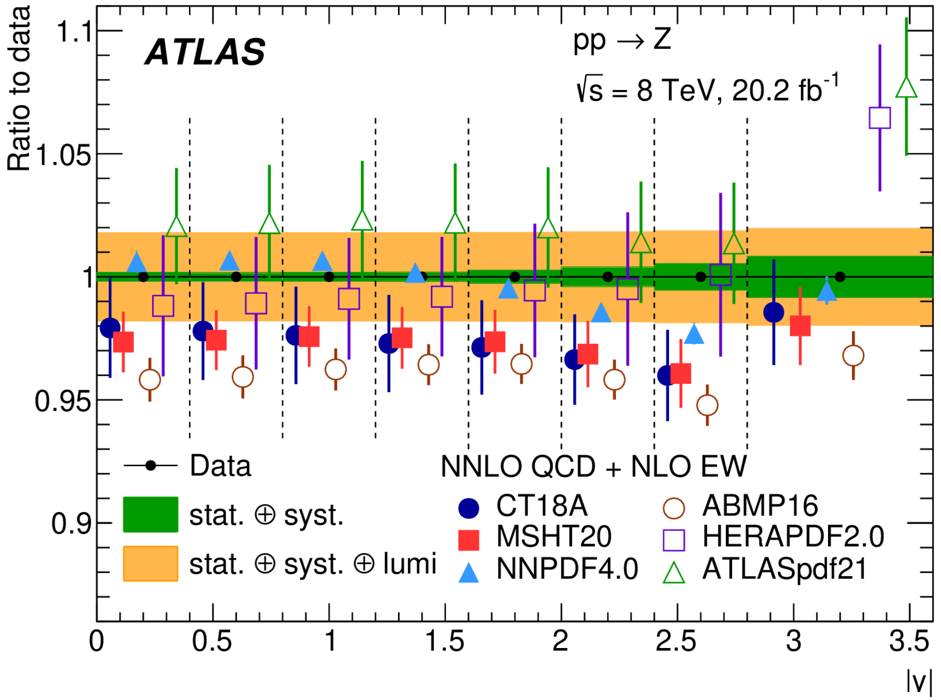
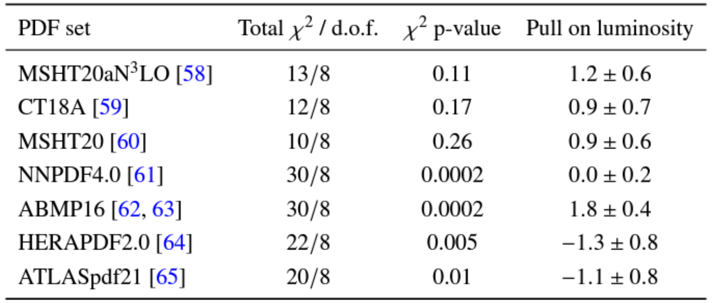
Differential cross-section analysis results

- **Per-mille** level precision in the central region
  - Sub-percent up to $|y| < 3.6$, thanks to dedicate forward electron selection and calibraiton
- Compared to state of the art to state-of-the-art predictions
  - QCD perturbative calculations based on qT resummation at approximate N4LL accuracy
  - Fixed order N3LO (p_T-integrated spectra)
  - Enhanced sensitivity to PDF with reduction of scale uncertainties at high pQCD order





PDF set	Total χ^2 / d.o.f.	χ^2 p-value	Pull on luminosity
MSHT20aN^{3}LO [58]	13/8	0.11	1.2 ± 0.6
CT18A [59]	12/8	0.17	0.9 ± 0.7
MSHT20 [60]	10/8	0.26	0.9 ± 0.6
NNPDF4.0 [61]	30/8	0.0002	0.0 ± 0.2
ABMP16 [62, 63]	30/8	0.0002	1.8 ± 0.4
HERAPDF2.0 [64]	22/8	0.005	−1.3 ± 0.8
ATLASpdf21 [65]	20/8	0.01	−1.1 ± 0.8

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arXiv:2309.12986 [hep-ex]

$\sqrt{s} = 8$ TeV, $L = 20.2$ fb^{-1}

α_s measurement strategy

- $\chi^2(\alpha_s)$ minimization with xFitter
- Inputs
  - Measured differential cross sections
    - Experimental uncertainties parametrized with Gaussian NPs $\beta_{j,exp}$
  - DYTurbo predictions (N3LO+aN4LL)
    - MSHT20 PDF (only PDF Set which was* available at aN3LO order)
      - Uncertainties parametrized in $\beta_{j,exp}$
    - α_s variations as provided in LHAPDF
    - Scale uncertainties: independent $\mu_{R/F}/Q$ variations
      - Uncertainty from the envelope of the 14 variations

$$\chi^2(\beta_{\mathrm{exp}}, \beta_{\mathrm{th}}) = \sum_{i=1}^{N_{\mathrm{data}}} \frac{\left(\boxed{\sigma_i^{\mathrm{exp}}} + \sum_j \Gamma_{ij}^{\mathrm{exp}} \beta_{j,\mathrm{exp}} \boxed{- \sigma_i^{\mathrm{th}}} - \sum_k \Gamma_{ik}^{\mathrm{th}} \beta_{k,\mathrm{th}}\right)^2}{\Delta_i^2} + \sum_j \boxed{\beta_{j,\mathrm{exp}}^2} + \sum_k \boxed{\beta_{k,\mathrm{th}}^2} .$$

*: aN3LO now implemented also in NNPDF40

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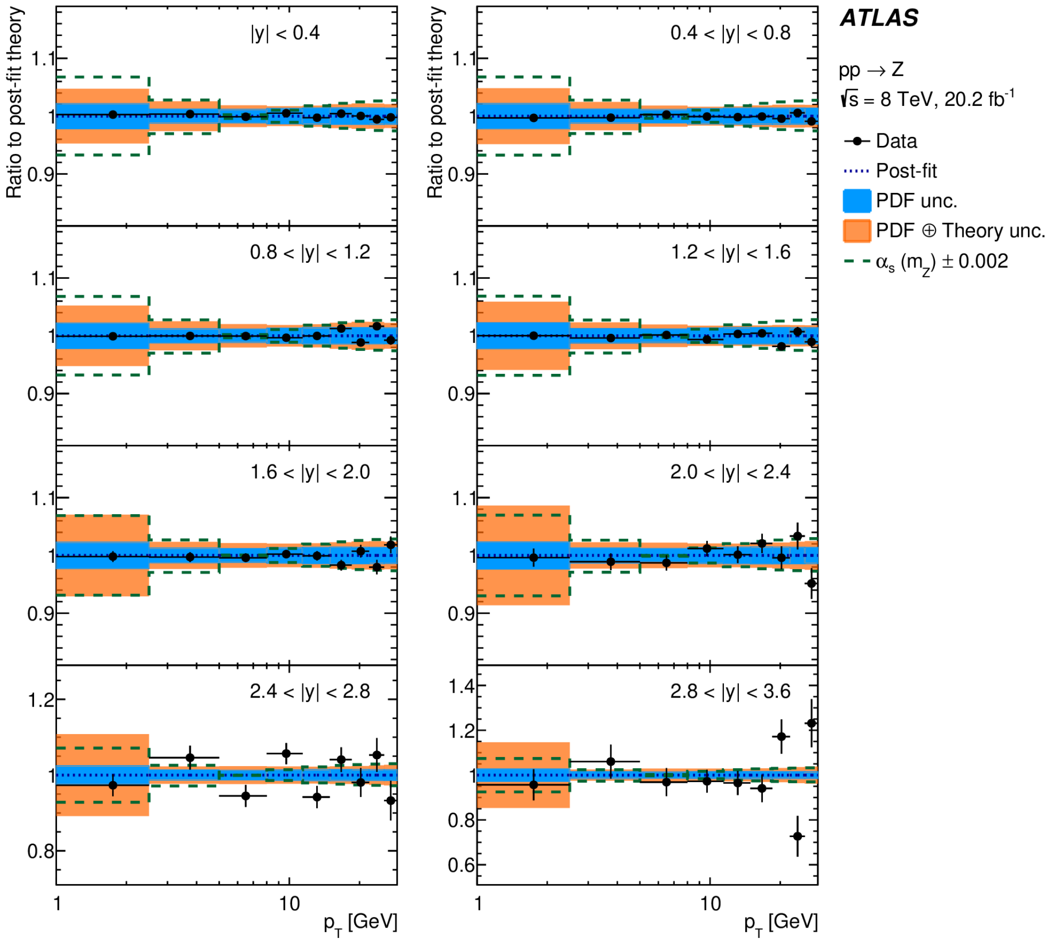
arXiv:2309.12986 [hep-ex]

$\sqrt{s} = 8\ \text{TeV},\ L = 20.2\ \text{fb}^{-1}$

Results

- Most sensitivity to α_s in the very low p_T regions



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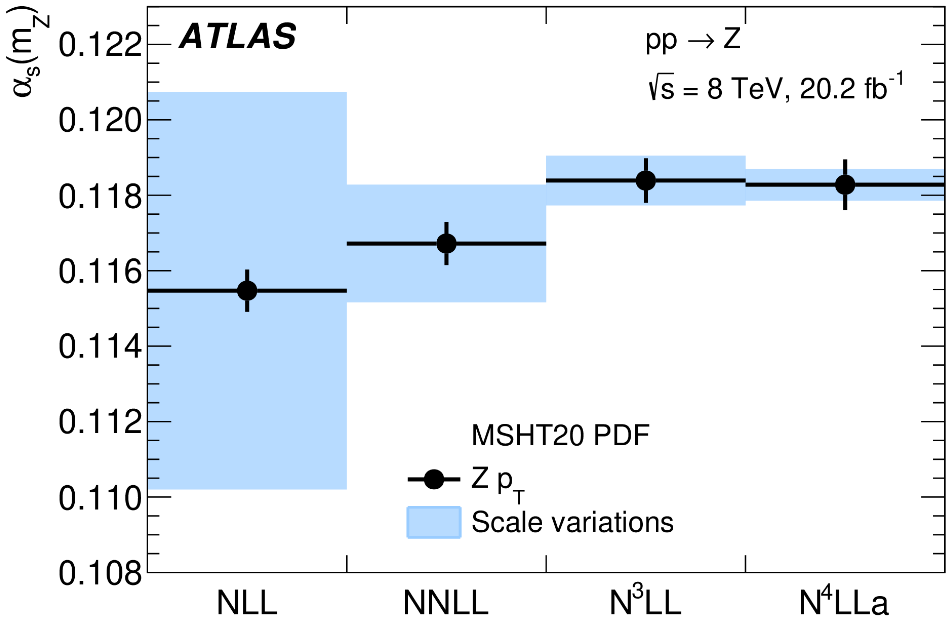
arXiv:2309.12986 [hep-ex]

$\sqrt{s} = 8$ TeV, $L = 20.2$ fb^{-1}

Results

- Most sensitivity to α_s in the very low p_T regions
- Scale uncertainties cross checked with fits at different pQCD orders
  - gradual convergence gives confidence on the robustness of the fit



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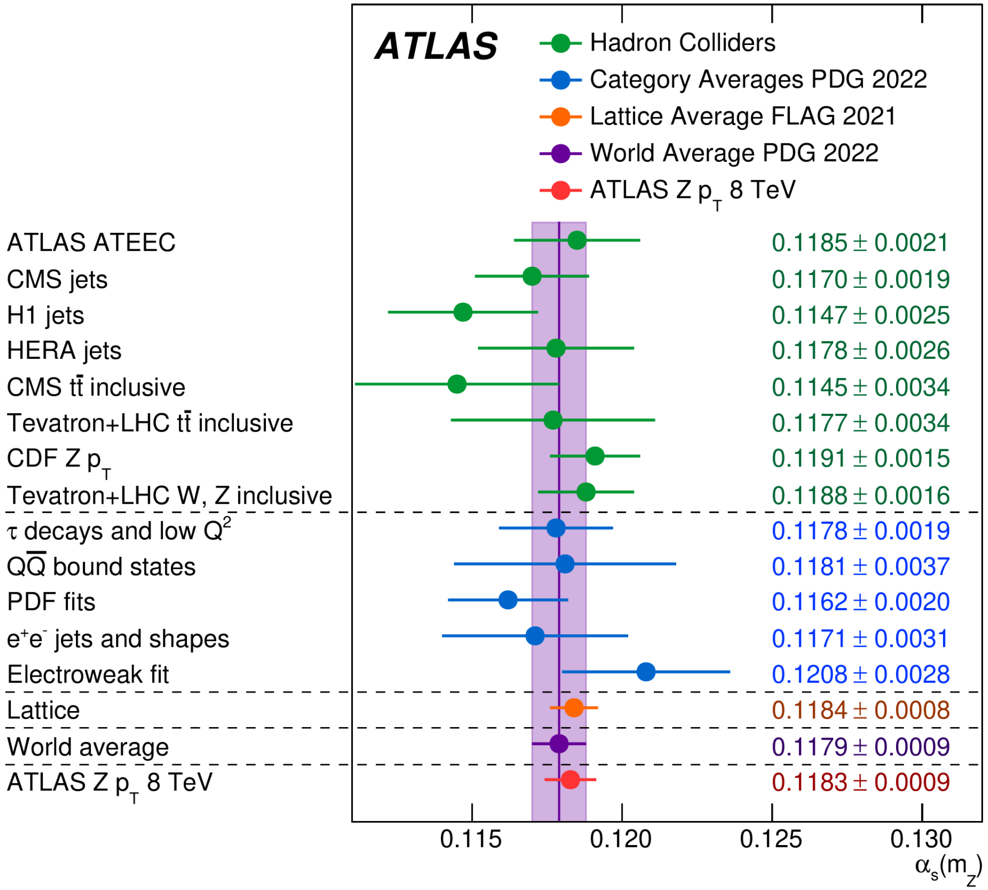
Results

- Most sensitivity to α_s in the very low p_T regions
- Scale uncertainties cross checked with fits at different pQCD orders
- $\boldsymbol{\alpha_s(m_Z) = 0.11828^{+0.00084}_{-0.00088}}$
  - Most precise measurement, comparable with the PDG and Lattice world averages
  - Leptonic signature (highest experimental sensitivity)
  - First determination using N3LO+aN4LL predictions



Measurement of m_W and Γ_W

arXiv:2403.15085 [hep-ex], submitted to EPJC

$\sqrt{s} = 7\ \text{TeV},\ L = 4.6/4.1\ \text{fb}^{-1}$

Lepton+jets

Measurement of m_W and Γ_W

Introduction

arXiv:2403.15085 [hep-ex]

$\sqrt{s} = 7$ TeV, $L = 4.6/4.1$ fb^{-1}

- Important EWK parameter in the SM
  - Constrained by theory by measuring other parameters

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

Tree-level

Measurement of m_W and Γ_W

Introduction

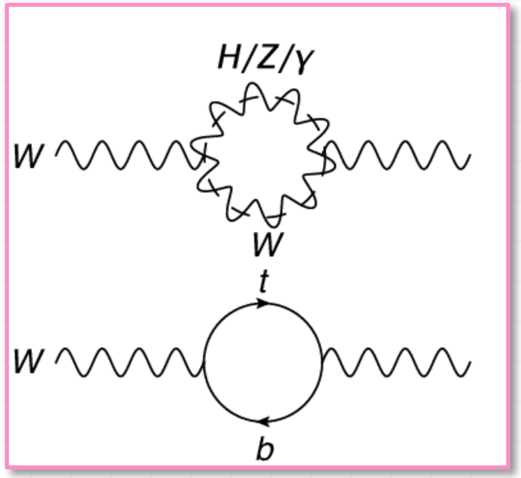
arXiv:2403.15085 [hep-ex]

$\sqrt{s} = 7\ \text{TeV},\ L = 4.6/4.1\ \text{fb}^{-1}$

- Important EWK parameter in the SM
  - Constrained by theory by measuring other parameters

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

Tree-level + loops



+…+BSM?

Measurement of m_W and Γ_W

[1]: Eur. Phys. J. C 78 (2018) 110

Introduction

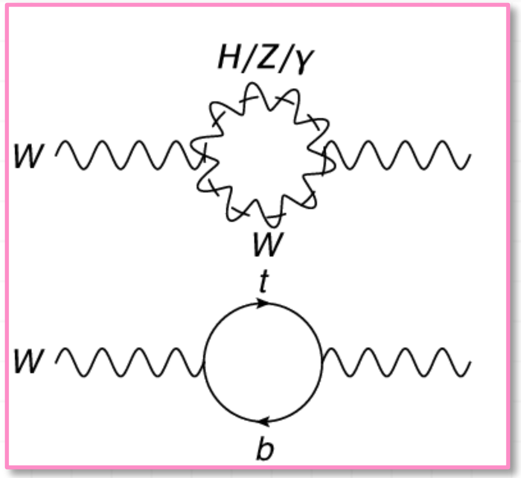
arXiv:2403.15085 [hep-ex]

$\sqrt{s} = 7$ TeV, $L = 4.6/4.1$ fb^{-1}

- Important EWK parameter in the SM
  - Constrained by theory by measuring other parameters

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

Tree-level + loops



+…+BSM?

- Already measured by ATLAS in 2018 with 7 TeV data [1]
- This result: re-analysis of same data
  - Better understanding of PDF dependence
  - New statistics model
  - Provides new measurement of Γ_W (first at LHC)
  - Focus on updates wrt the legacy measurement

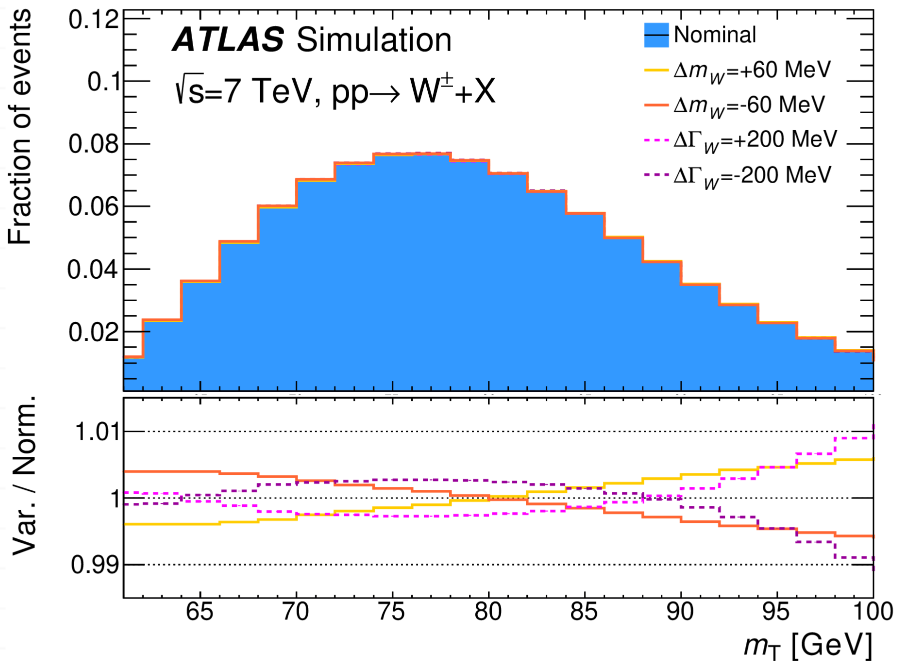
Measurement of m_W and Γ_W

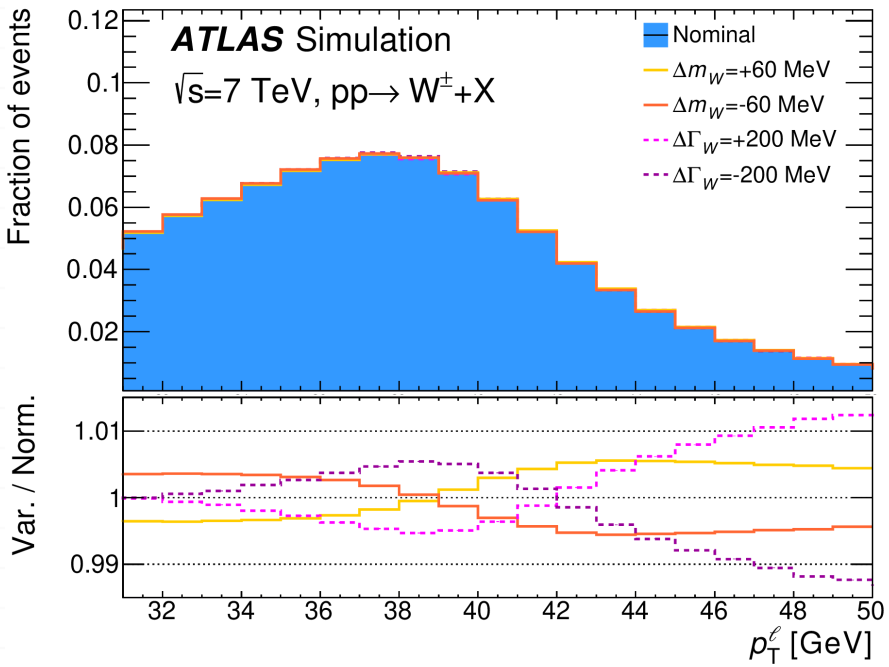
Analysis strategy

arXiv:2403.15085 [hep-ex]

$\sqrt{s} = 7\ \text{TeV},\ L = 4.6/4.1\ \text{fb}^{-1}$

- Exploit the dependence of the leptonic transverse momentum (p_T) and the transverse mass (m_T) to determine m_W





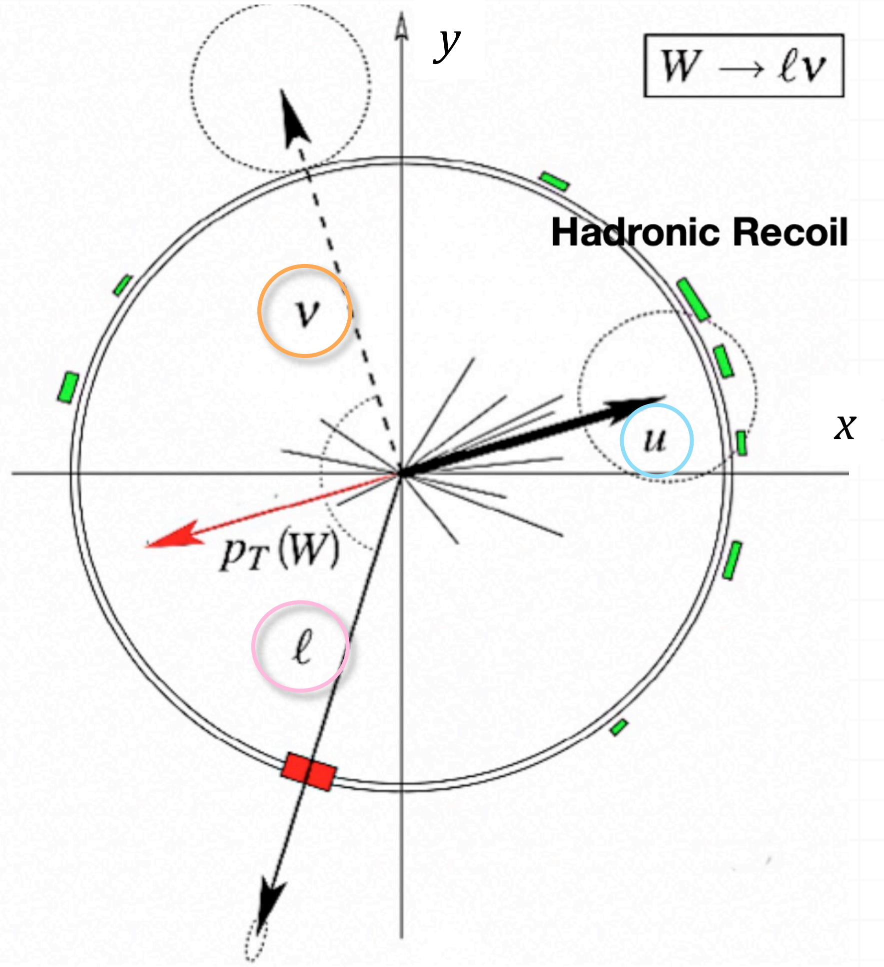
Measurement of m_W and Γ_W

Analysis strategy

arXiv:2403.15085 [hep-ex]

$\sqrt{s} = 7$ TeV, $L = 4.6/4.1$ fb^{-1}

- Event selection in the e/μ+jets channel
  - Isolated leptons, $p_T > 30$ GeV
  - $u_T < 30$ GeV
  - $\left|\vec{u}_T + \overrightarrow{p^l}_T\right| = p_T^{miss} > 30$ GeV
  - $m_T = \sqrt{2p_T^l p_T^{miss}(1 - cos\Delta\varphi)} > 30$ GeV
- p_T^l and m_T fits in several categories
  - Lepton flavor
  - Lepton η (3/4 regions for e/μ channels)
  - W charge
  - Extended p_T^l and m_T fit ranges



[1]: arXiv:2404.06204

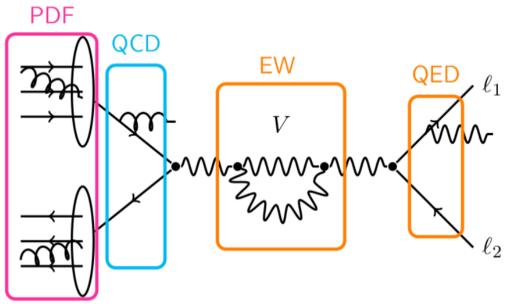
Measurement of m_W and Γ_W

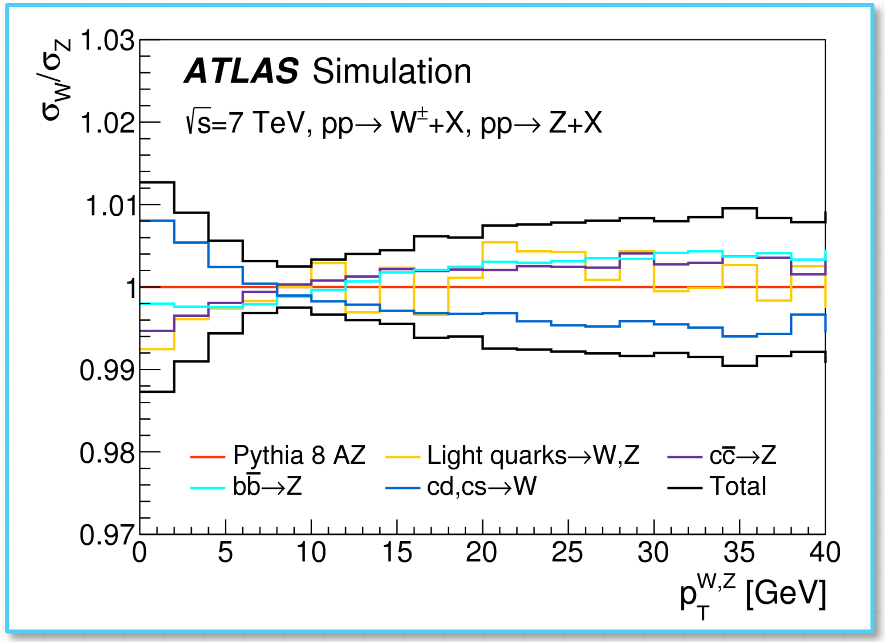
Signal modelling

arXiv:2403.15085 [hep-ex]

$\sqrt{s} = 7$ TeV, $L = 4.6/4.1$ fb^{-1}

- QCD baseline model: Powheg+Pythia8+PHOTOS
  - p_T^W corrected to Pythia 8 (AZ tune, based on Z boson data)
  - Propagated to W-boson and validated against 5.02 and 13 TeV measurements [1]
- EW corrections: mostly unchanged and subdominant





[1]: arXiv:2404.06204

Measurement of m_W and Γ_W

Signal modelling

arXiv:2403.15085 [hep-ex]

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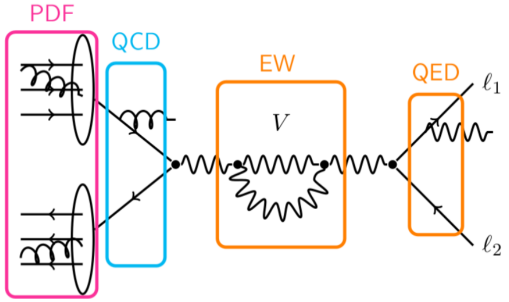
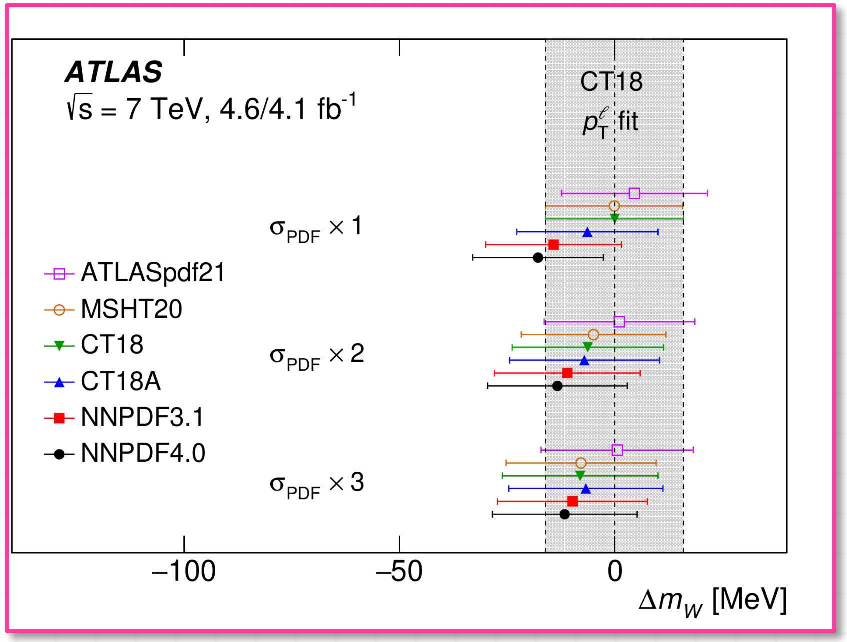


- QCD baseline model: Powheg+Pythia8+PHOTOS
  - p_T^W corrected to Pythia 8 (AZ tune, based on Z boson data)
  - Propagated to W-boson and validated against 5.02 and 13 TeV measurements [1]
- EW corrections: mostly unchanged and subdominant
- Parton distribution functions
  - One of the largest source of uncertainties for m_W
    - $x_1 \sim \frac{M_W}{\sqrt{s}} e^{+y_W}$, $x_2 \sim \frac{M_W}{\sqrt{s}} e^{-y_W}$
    - ~anti-correlated between W+ and W-
  - Studied extended set of available PDF Sets at NNLO: CT10, CT14, CT18, MMHT2014, MSHT20, NNPDF3.1, NNPDF4.0, ATLASpdf21
  - CT18 used as new baseline



[1]: arXiv:2112.07274

Measurement of m_W and Γ_W

Statistics model

arXiv:2403.15085 [hep-ex]
$\sqrt{s} = 7\ \mathrm{TeV},\ L = 4.6/4.1\ \mathrm{fb}^{-1}$

- p_T^l and m_T templates via m_W and Γ_W polynominal morphing
  - Morphing tested to 0.1 MeV precision
  - Templates for two-side uncertainties obtained with $\pm 1\sigma$ and $\pm 2\sigma$ variations of the corresponding parameters (NPs)
    - Uncertainties estimated independently in many kinematic bins reduced to two-side uncertainties via Principal Component Analysis (PCA)
    - $\Gamma_W(m_W)$ added as NPs for the $m_W(\Gamma_W)$ fits (values and uncertainties from the Global EW fit [1])

[1]: arXiv:2112.07274

Measurement of m_W and Γ_W

Statistics model

arXiv:2403.15085 [hep-ex]

$\sqrt{s} = 7$ TeV, $L = 4.6/4.1\ \mathrm{fb}^{-1}$

$$\mathcal{L}\left(\vec{n}\,|\,\mu,\vec{\theta}\right) = \prod_j \prod_i \mathrm{Poisson}\left(n_{ji}\,\middle|\,\boxed{\nu_{ji}(\mu,\vec{\theta})}\right)\cdot \mathrm{Gauss}\left(\vec{\theta}\right),$$

- p_T^l and m
  - Morphing tested to 0.1 MeV precision
  - Template ... ons of the correspon...
    - Uncerta... -side uncertainties via Principa...
    - $\Gamma_W(m_W)$ added as NPs for the m_W and Γ_W fits (using the Global EW fit [1])

$$\nu_{ji}(\mu,\vec{\theta}) = \Phi \times \left[S_{ji}^{\mathrm{nom}} + \mu \times \left(S_{ji}^{\mu} - S_{ji}^{\mathrm{nom}}\right)\right] + \sum_s \theta_s \times \left(S_{ji}^{s} - S_{ji}^{\mathrm{nom}}\right)$$
$$+ B_{ji}^{\mathrm{nom}} + \sum_b \theta_b \times \left(B_{ji}^{b} - B_{ji}^{\mathrm{nom}}\right),$$

- *Profile likelihood fit* incorporating all NPs
  - Instead of repeating the stat-only fit separately for each uncertainty template (offset method)
  - Φ and μ allowed to free-float
  - Separately for p_T^l and m_T and then combined

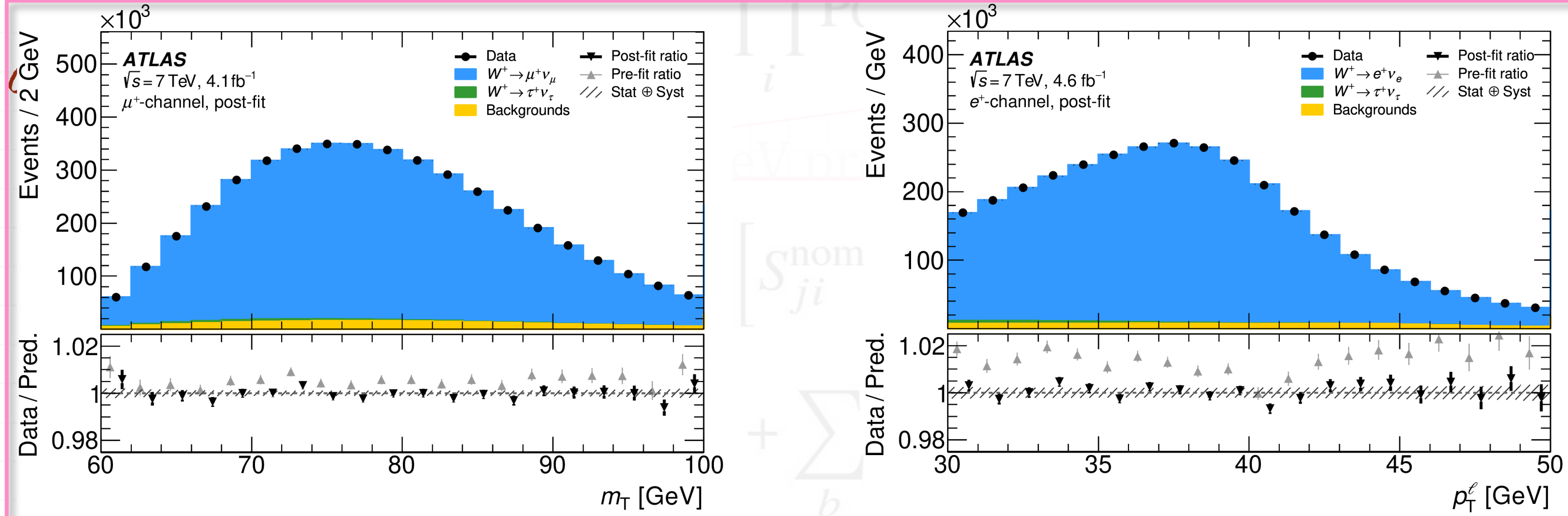
[1]: arXiv:2112.07274

Measurement of m_W and Γ_W

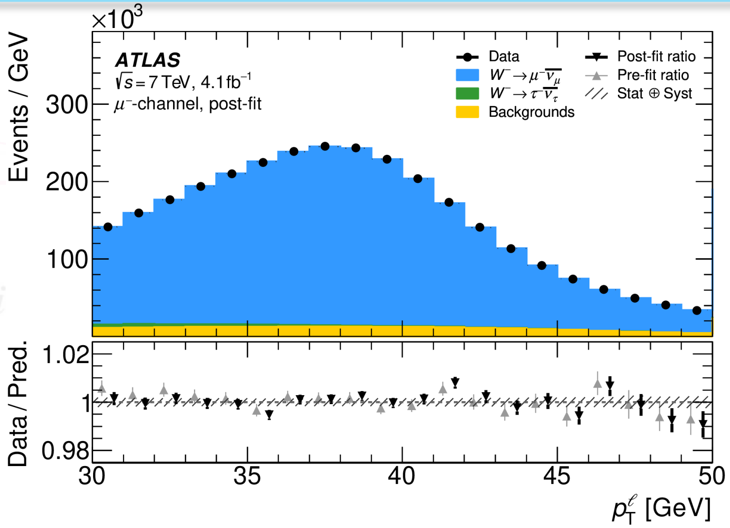
Statistics model

arXiv:2403.15085 [hep-ex]

$\sqrt{s} = 7\ \text{TeV},\ L = 4.6/4.1\ \text{fb}^{-1}$



From m_W fit



From Γ_W fit

- *Profile likelihood fit* incorporating all NPs
  - Instead of repeating the stat-only fit separately for each uncertainty template (offset method)
  - Φ and μ allowed to free-float
  - Separately for p_T^l and m_T and then combined
  - Very good post-fit agreement with data

Measurement of m_W and Γ_W

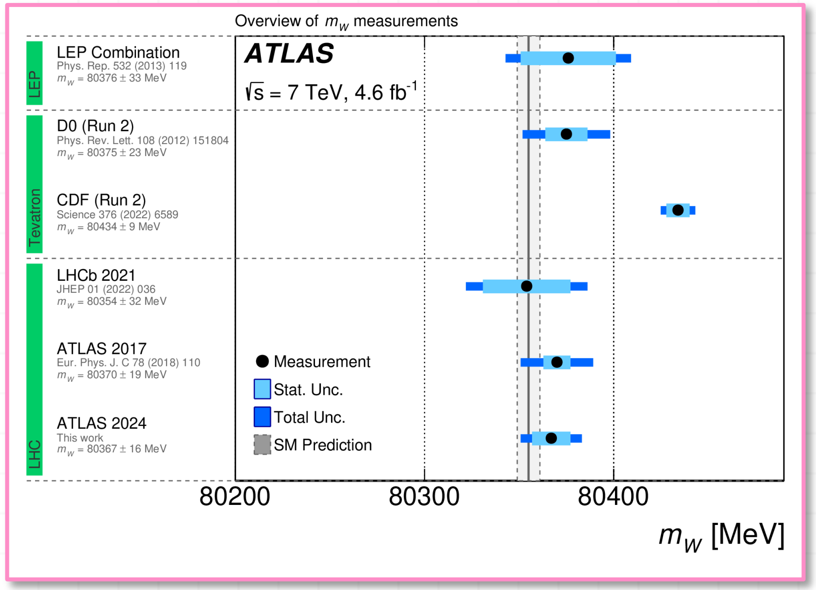
Results

arXiv:2403.15085 [hep-ex]

$\sqrt{s} = 7\ \text{TeV},\ L = 4.6/4.1\ \text{fb}^{-1}$

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

- One of the most precise SM parameter measurement at LHC ($\delta = 0.02\%$)



Measurement of m_W and Γ_W

Results

arXiv:2403.15085 [hep-ex]

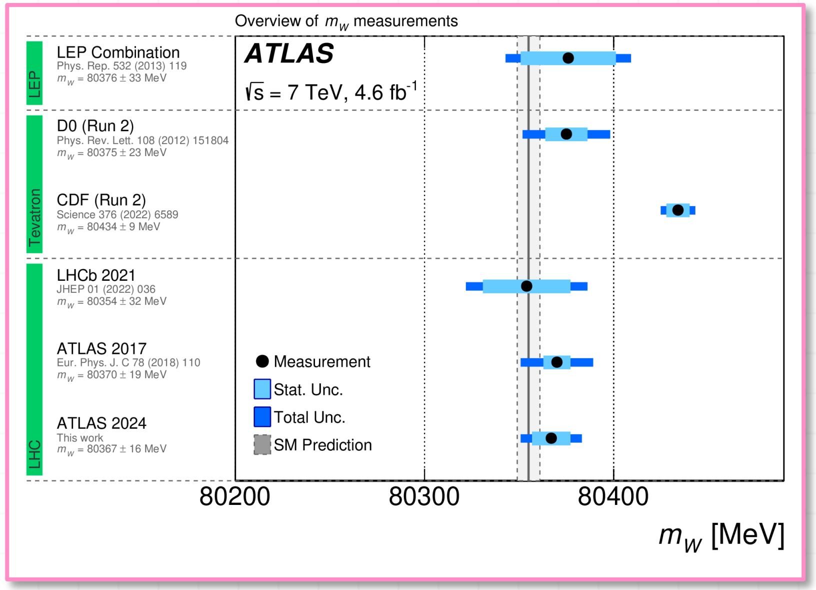
$\sqrt{s} = 7\ \mathrm{TeV},\ L = 4.6/4.1\ \mathrm{fb}^{-1}$

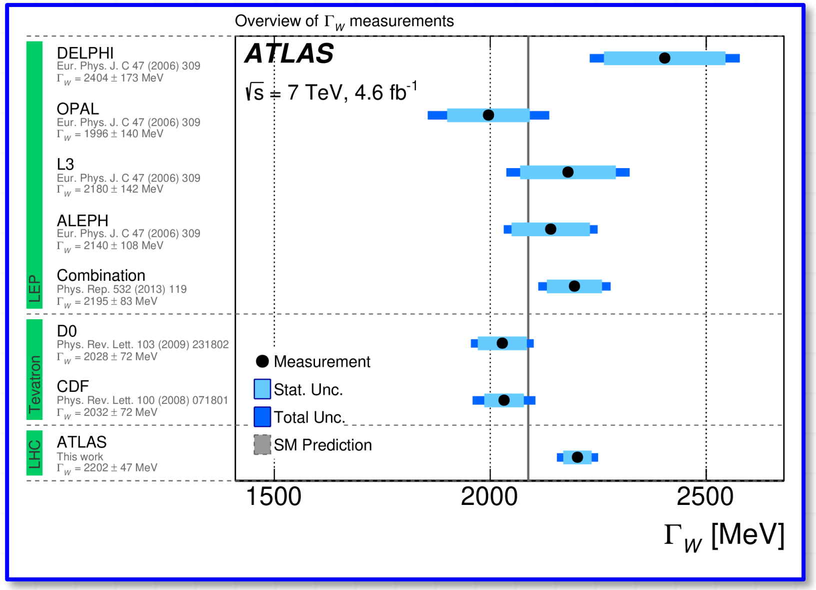
$$\boldsymbol{m_W = 80366.5 \pm 9.8(\mathrm{stat.}) \pm 12.5(\mathrm{syst.})\ \mathrm{MeV}}$$

- One of the most precise SM parameter measurement at LHC ($\delta = 0.02\%$)

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

- Most precise measurement ($\delta = 2\%$), within 2 sigma from the SM





Measurement of m_W and Γ_W

Results

arXiv:2403.15085 [hep-ex]

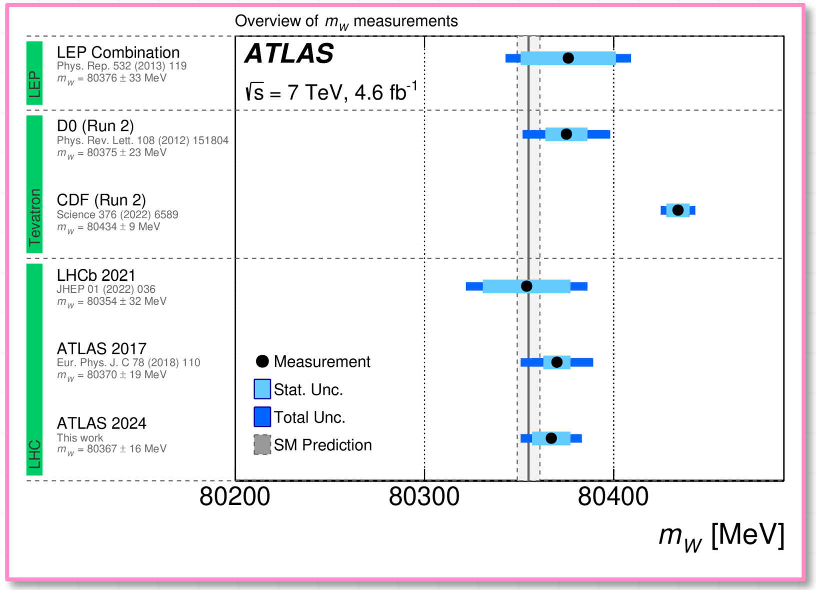
$\sqrt{s} = 7\ \text{TeV},\ L = 4.6/4.1\ \text{fb}^{-1}$

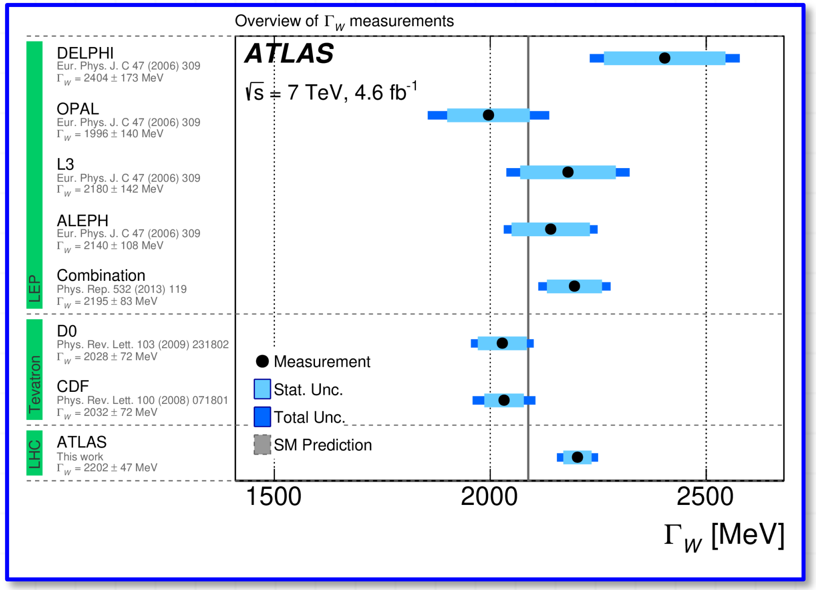
$$m_W = \mathbf{80366.5 \pm 9.8(stat.) \pm 12.5(syst.)\ MeV}$$

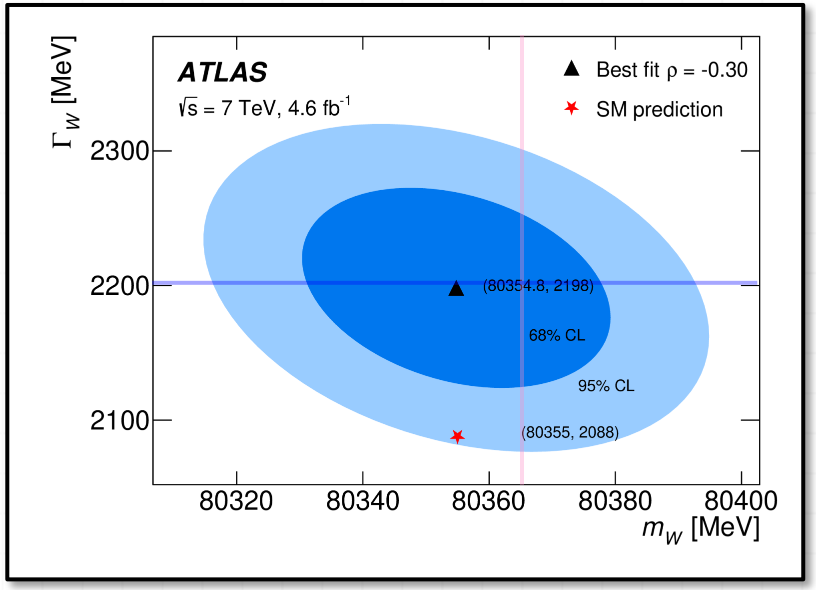
- One of the most precise SM parameter measurement at LHC ($\delta = 0.02\%$)

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

- Most precise measurement ($\delta = 2\%$), within 2 sigma from the SM
- Simultaneous fit performed by allowing m_W and Γ_W
  - Removal of constraints → increased uncertainties







Measurement of m_W and Γ_W

Results

arXiv:2403.15085 [hep-ex]

$\sqrt{s} = 7$ TeV, $L = 4.6/4.1$ fb^{-1}

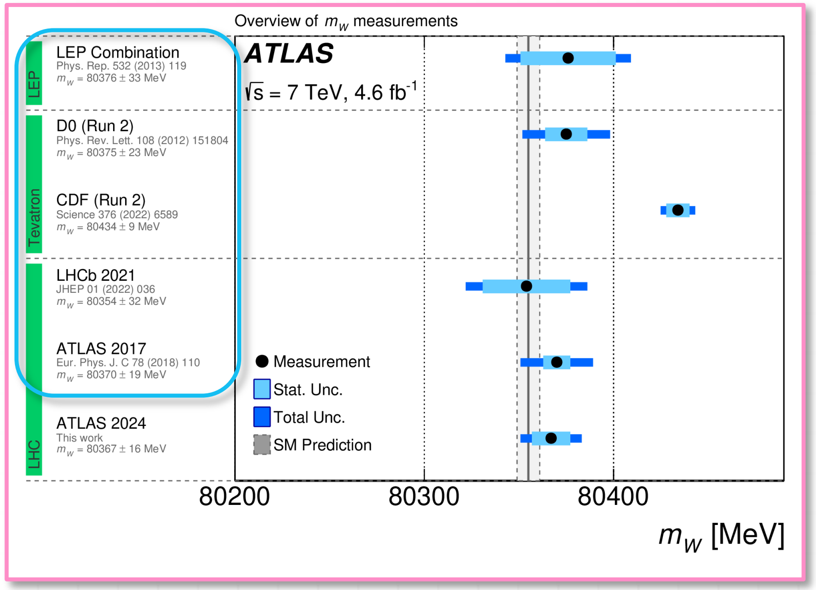
$$m_W = 80366.5 \pm 15.9(\text{stat.}+\text{syst}) \text{ MeV}$$

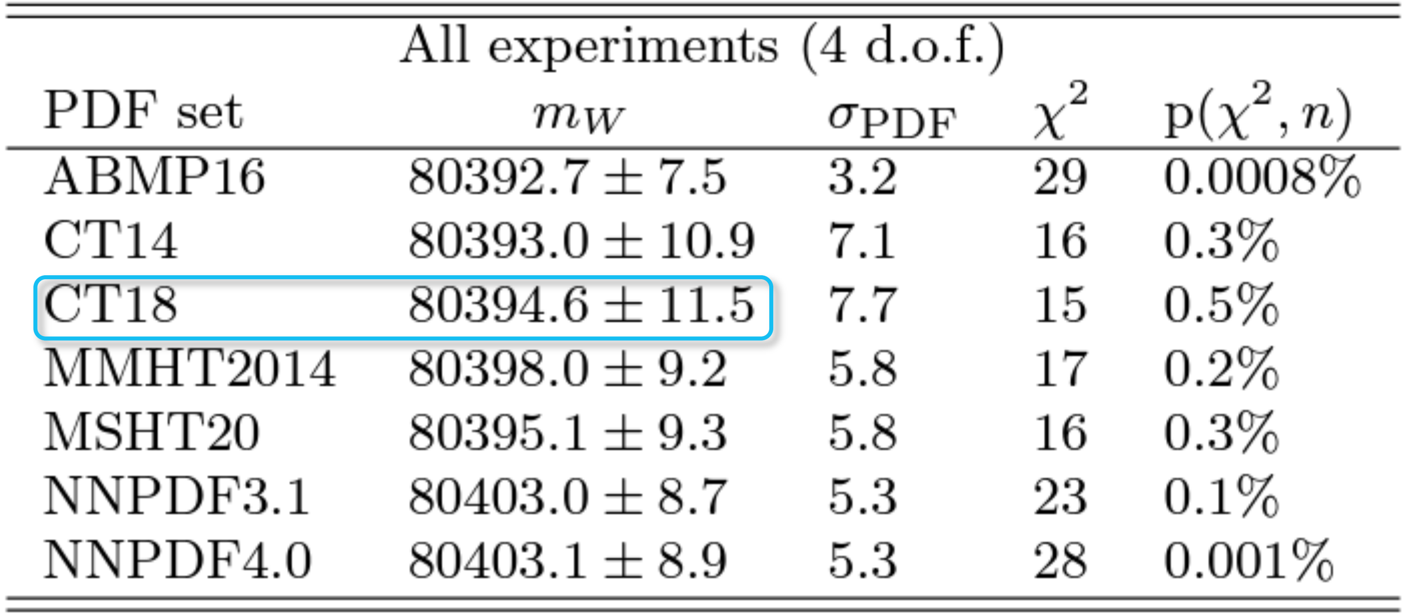
- One of the most precise SM parameter measurement at LHC ($\delta = 0.02\%$)

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

Latest world (LEP+Tevatron+LHC) combination (2308.09417 [hep-ex])

- Most precise measurement ($\delta = 2\%$), within 2 sigma from the SM
- Simultaneous fit performed by allowing m_W and Γ_W
  - Removal of constraintes → increasec





All experiments (4 d.o.f.)

PDF set	m_W	σ_{PDF}	χ^2	$p(\chi^2, n)$
ABMP16	80392.7 ± 7.5	3.2	29	0.0008%
CT14	80393.0 ± 10.9	7.1	16	0.3%
CT18	80394.6 ± 11.5	7.7	15	0.5%
MMHT2014	80398.0 ± 9.2	5.8	17	0.2%
MSHT20	80395.1 ± 9.3	5.8	16	0.3%
NNPDF3.1	80403.0 ± 8.7	5.3	23	0.1%
NNPDF4.0	80403.1 ± 8.9	5.3	28	0.001%

$\boldsymbol{e/\mu}$ lepton flavour universality in W decays

arXiv:2403.02133 [hep-ex], submitted to EPJC

$\sqrt{s} = 13\ \text{TeV},\ L = 140\ \text{fb}^{-1}$

Dilepton

e/μ lepton flavour universality in W decays

Introduction

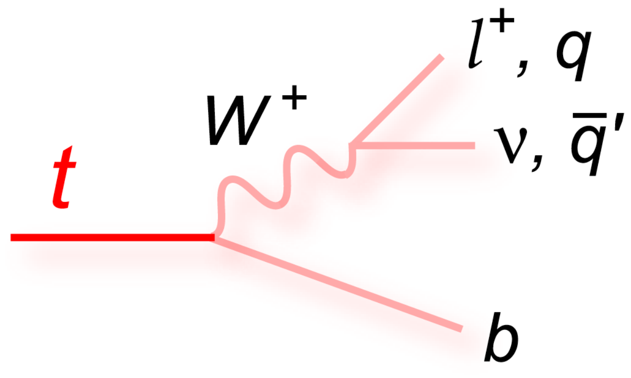
arXiv:2403.02133 [hep-ex]

$\sqrt{s} = 13$ TeV, $L = 140$ fb^{-1}

- LHC is a $t\bar{t}$ factory: $\sigma(t\bar{t})$ ~830pb at $\sqrt{s} = 13$TeV

Decays

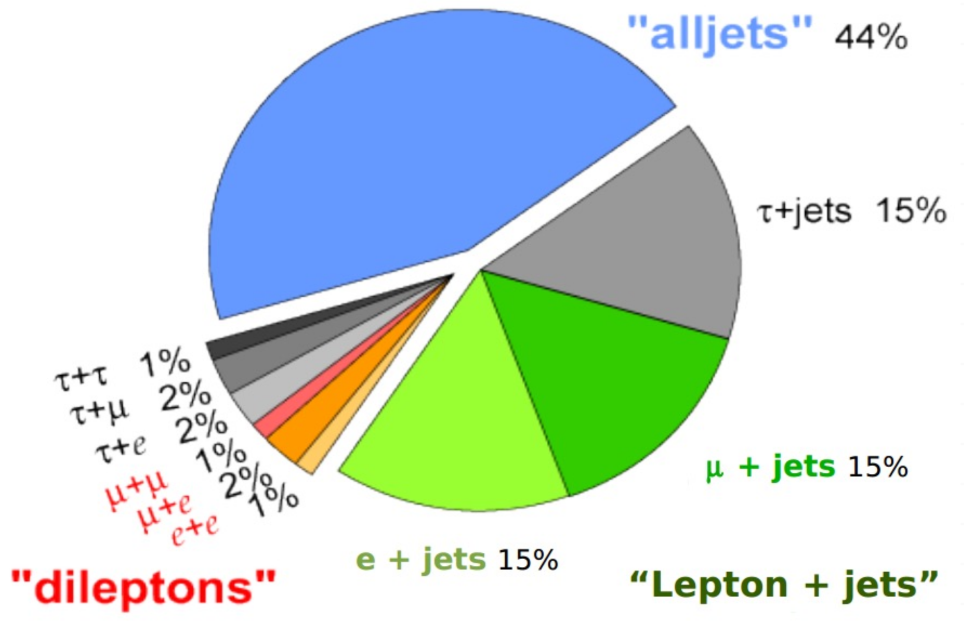
- $t \rightarrow Wb(\sim 100\%)$



$W \rightarrow l\nu_l \sim 33\%$

$W \rightarrow q\bar{q}' \sim 66\%$

Top pair final states



e/μ lepton flavour universality in W decays

Introduction

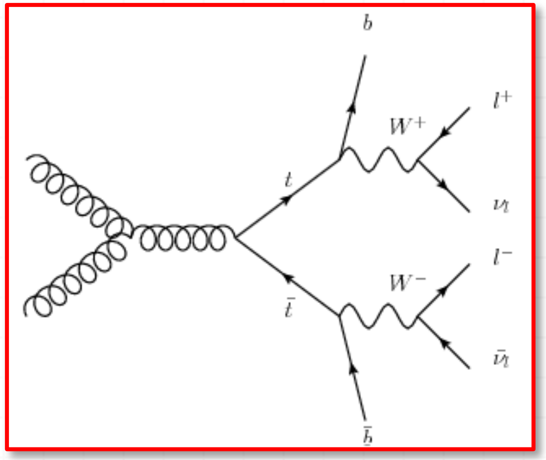
arXiv:2403.02133 [hep-ex]

$\sqrt{s} = 13$ TeV, $L = 140$ fb^{-1}

- LHC is a $t\bar{t}$ factory: $\sigma(t\bar{t})$ ~830pb at $\sqrt{s} = 13$TeV
- Can use the Ws from tops for the measurement of

$$R_W^{\mu/e} = \frac{BR(W \to \mu\nu)}{BR(W \to e\nu)}$$

  - SM predicts $R_W^{\mu/e}$~1
- Dilepton channel
  - small background and small systematic uncertainties



e/μ lepton flavour universality in W decays

[1]: Phys.Rept.427:257-454,2006

Introduction

arXiv:2403.02133 [hep-ex]

$\sqrt{s} = 13$ TeV, $L = 140$ fb^{-1}

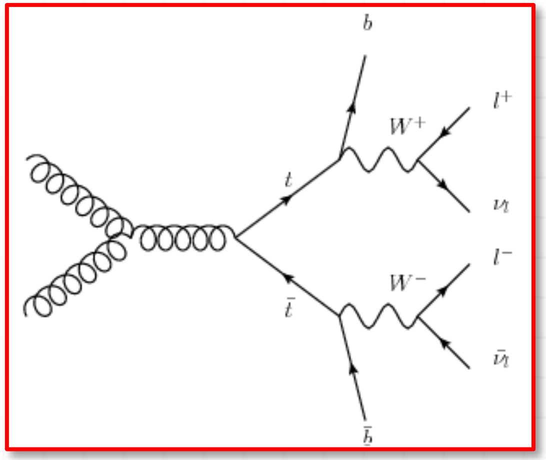
- LHC is a $t\bar{t}$ factory: $\sigma(t\bar{t})$ ~830pb at $\sqrt{s} = 13$TeV
- Can use the Ws from tops for the measurement of

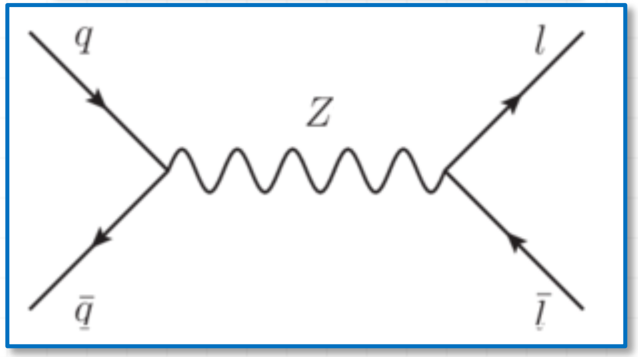
$$R_W^{\mu/e} = \frac{BR(W \to \mu\nu)}{BR(W \to e\nu)}$$

  - SM predicts $R_W^{\mu/e} \sim 1$
- Dilepton channel
  - small background and small systematic uncertainties
- Use $R_{WZ}^{\mu/e} = \frac{R_W^{\mu/e}}{\sqrt{R_Z^{\mu\mu/ee}}}$ as POI in the fits
  - $R_W^{\mu/e} = \frac{\boxed{\bar{W}}(1+\Delta_W)}{\bar{W}(1-\boxed{\Delta_W})}$

    Average SM-predicted BR

    Measured deviation from SM
  - $R_Z^{\mu\mu/ee} = \frac{BR(Z\to\mu\mu)}{BR(Z\to ee)} = \frac{\bar{Z}(1+\Delta_Z)}{\bar{Z}(1-\Delta_Z)}$
  - Simulatenous measurement of $R_W^{\mu/e}$ and $R_Z^{\mu\mu/ee}$
    - Reduced dependency on lepton-related uncertainties
- Employ the precise LEP+SLD $R_Z^{\mu\mu/ee}$ = 1.0009 ±0.0028 measurement [1] ⇒ $\boldsymbol{R_W^{\mu/e} = R_{WZ(ATLAS)}^{\mu/e}\sqrt{R_{Z(LEP+SLD)}^{\mu\mu/ee}}}$





$\boldsymbol{e/\mu}$ lepton flavour universality in W decays

Analysis strategy

arXiv:2403.02133 [hep-ex]

$\sqrt{s} = 13\ \text{TeV},\ L = 140\ \text{fb}^{-1}$

- Event selection
  - $ee/\mu\mu/e\mu$ + $1b/2b$ ($t\bar{t}$-focused)
  - $ee/\mu\mu$ (Z-focused)
- Corrections to reduce sensitivity to lepton reconstruction bias and mismodelling

e/μ lepton flavour universality in W decays

Analysis strategy

arXiv:2403.02133 [hep-ex]

$\sqrt{s} = 13$ TeV, $L = 140$ fb^{-1}

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  - $ee/\mu\mu/e\mu$ + $1b/2b$ ($t\bar{t}$-focused)
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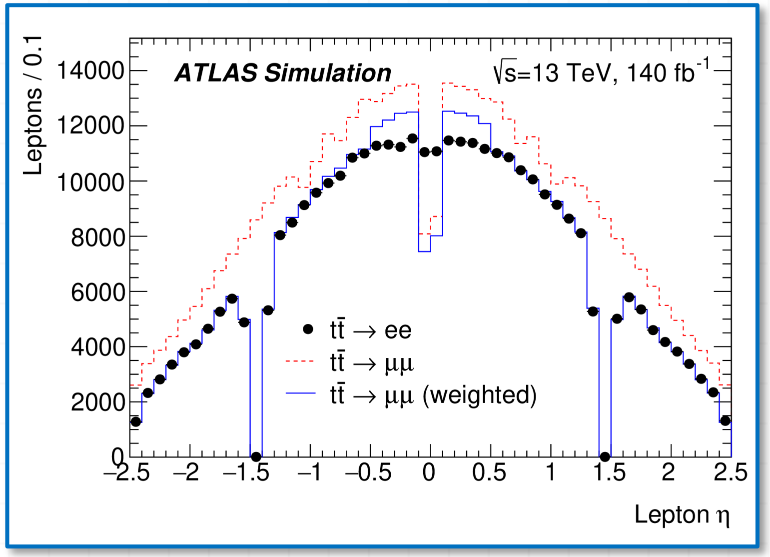
- Muon reweighting to reduce electron vs muon kinematic differences
  - Reduces impact of modelling uncertainties
  - Parametrized in p_T and η
  - Applied to both MC and data



e/μ lepton flavour universality in W decays

Analysis strategy

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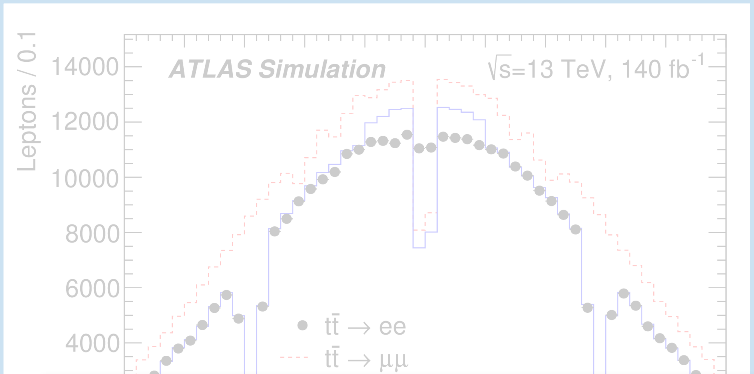
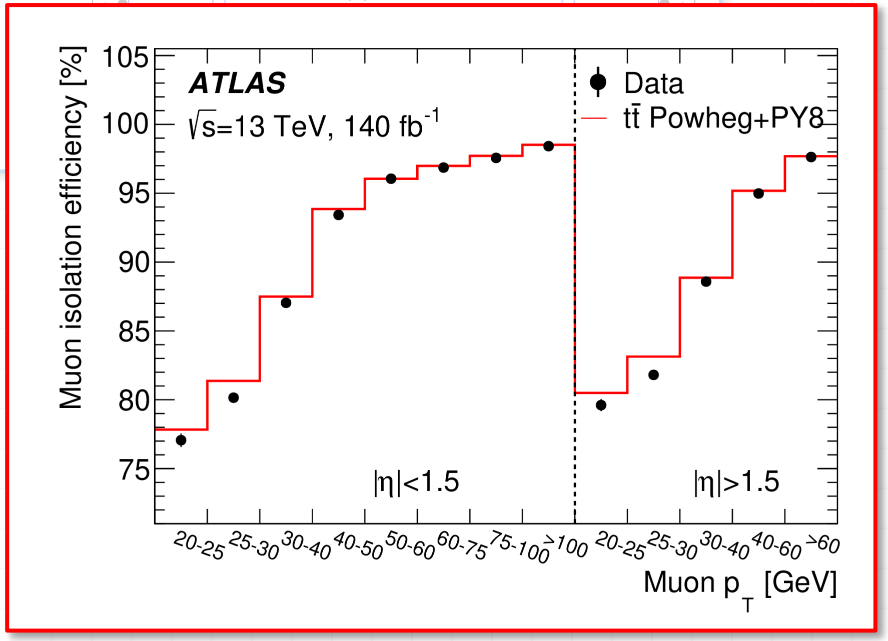
- Event selection
  - $ee/\mu\mu/e\mu$ + $1b/2b$ ($t\bar{t}$-focused)
  - $ee/\mu\mu$ (Z-focused)
- Muon reweighting to reduce electron vs muon kinematic differences
  - Reduces impact of modelling uncertainties
  - Parametrized in p_T and η
  - Applied to both MC and data
- *In-situ* precise measurement of lepton efficiencies
  - Isolation not well modelled, expecially in tt events
  - **Separate** tag-and-probe measurement in tt and Z events
    - As a function of lepton pT and η of the leptons





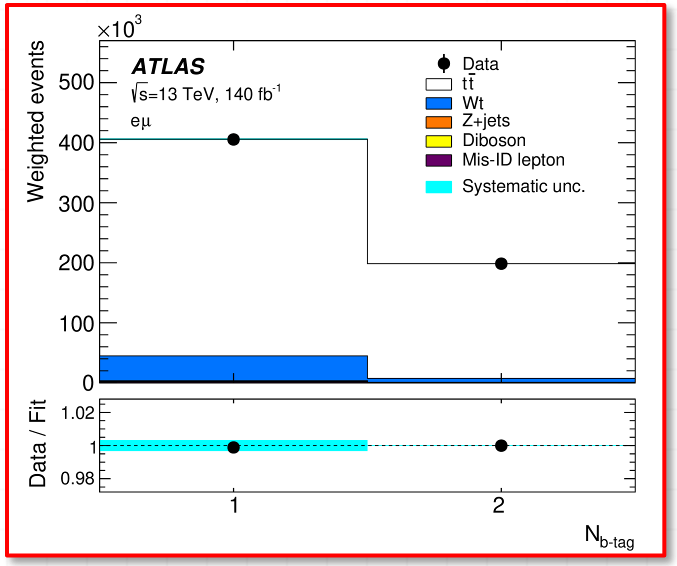
e/μ lepton flavour universality in W decays

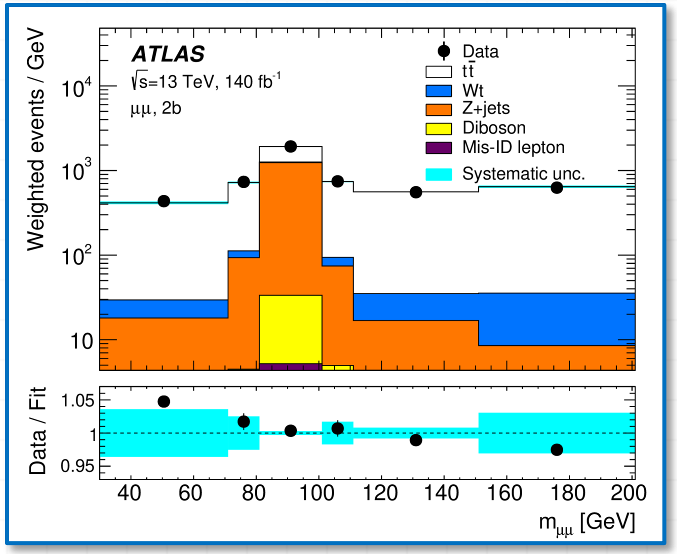
Fit strategy

arXiv:2403.02133 [hep-ex]

$\sqrt{s} = 13\ \text{TeV},\ L = 140\ \text{fb}^{-1}$

- Simultaneous maximum likelihood fit in all tt and Z regions
  - yields in $1b/2b$ $e\mu$ regions and in the inclusive ll regions
  - m_{ll} spectrum in ll + $1b/2b$ regions
  - BR deviations correlated for signal and prompt-lepton backgrounds
    - tW and diboson effectively treated as signal in the tt regions
    - Δ_Z in $1b/2b$ regions corrected by an $R^{\mu\mu/ee}_{Z+b}$ fit parameter





$\boldsymbol{e}/\boldsymbol{\mu}$ lepton flavour universality in W decays

Fit strategy

arXiv:2403.02133 [hep-ex]

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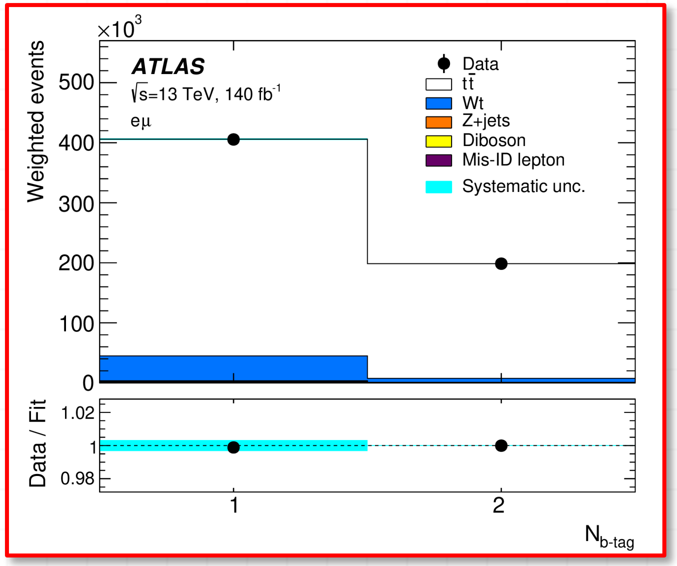
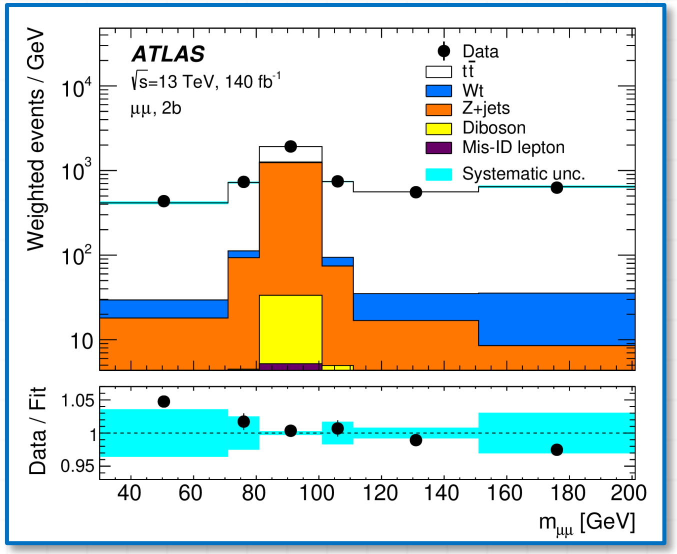
  - BR deviations correlated for signal and prompt-lepton backgrounds
    - tW and diboson effectively treated as signal in the tt regions
    - Δ_Z in $1b/2b$ regions corrected by an $R^{\mu\mu/ee}_{Z+b}$ fit parameter
- Extract 10 parameters in total
  - **Cross-sections $\boldsymbol{\sigma_{tt}, \sigma_Z}$**
  - **Ratios $\boldsymbol{R^{\mu/e}_{WZ}}$ and $\boldsymbol{R^{\mu\mu/ee}_{Z}}$**
  - b-jet efficiencies ε^{ll}_b
  - Z+HF normalisations in the 1 and 2 bjets regions
  - Z+b isolation efficiency parameter $R^{\mu\mu/ee}_{Z+b}$





e/μ lepton flavour universality in W decays

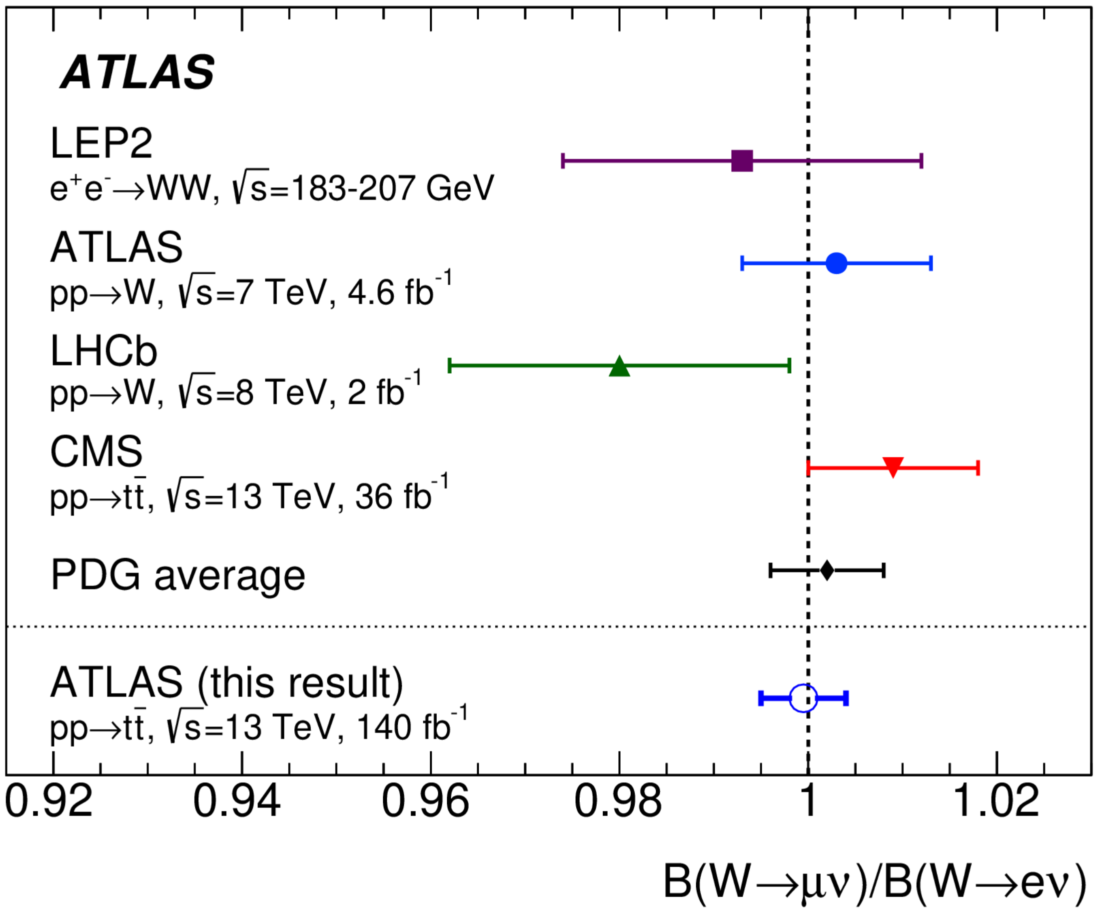
$$R^{\mu/e}_{W(ATLAS)} = R^{\mu/e}_{WZ(ATLAS)}\sqrt{R^{\mu\mu/ee}_{Z(LEP+SLD)}}$$

Results

arXiv:2403.02133 [hep-ex]

$\sqrt{s} = 13\ \text{TeV},\ L = 140\ \text{fb}^{-1}$

- $\boldsymbol{R^{\mu/e}_{W}} = 0.9995 \pm 0.0022(\text{stat.}) \pm 0.0036(\text{syst.}) \pm 0.0014(\text{LEP} + \text{SLD}) = \mathbf{0.9995 \pm 0.0046}$
- **Compatible with lepton flavour universality**
- **Better precision than the current world average**
- Results for cross-sections:
  - $\sigma_{t\bar{t}} = 809.5 \pm 21.6$ pb
  - $\sigma_{Z_{fid}} = 774.7 \pm 6.7$ pb
  - In agreement with previous results
- Measurement dominated by systematic uncertainties:
  - PDFs, $t\bar{t}$ and Z modelling, uncertainties related to lepton identification and scale/resolution



Summary and outlook

- **A lot of interesting results produced by ATLAS** thanks to the combined performance of LHC & detectors
  - Both Run 1 and Run 2
  - Presented today only a small selection of recent results
    - Many more can be found in the ATLAS Public results page*
- **Very high precision reached in the measurement of many SM parameters**
  - Precision on α_S, m_W and Γ_W comparable or better than world averages
  - Γ_W measured for the first time at LHC
  - Important SM assumptions on number of generations and LFU tested and confirmed

*: https://twiki.cern.ch/twiki/bin/view/AtlasPublic

Backup

Measurement of α_s from recoil of Z bosons

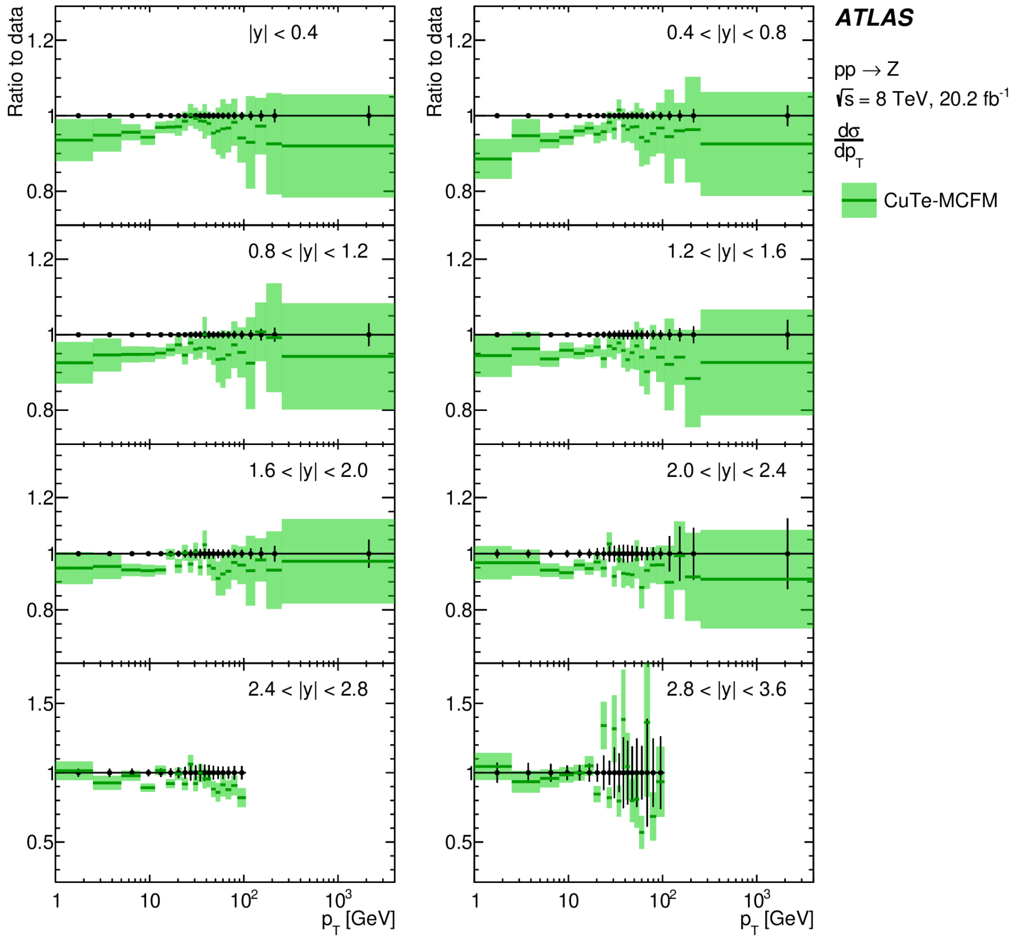
Eur. Phys. J. C 84 (2024) 315

arXiv:2309.12986 [hep-ex]

$\sqrt{s} = 8$ TeV, $L = 20.2$ fb^{-1}

Differential cross-section analysis results

- **Per-mille** level precision in the central region
  - Sub-percent up to $|y| < 3.6$, thanks to dedicate forward electron selection and calibration
- Compared to state of the art to state-of-the-art predictions
  - QCD perturbative calculations based on q_T resummation at aN4LL+N3LO accuracy



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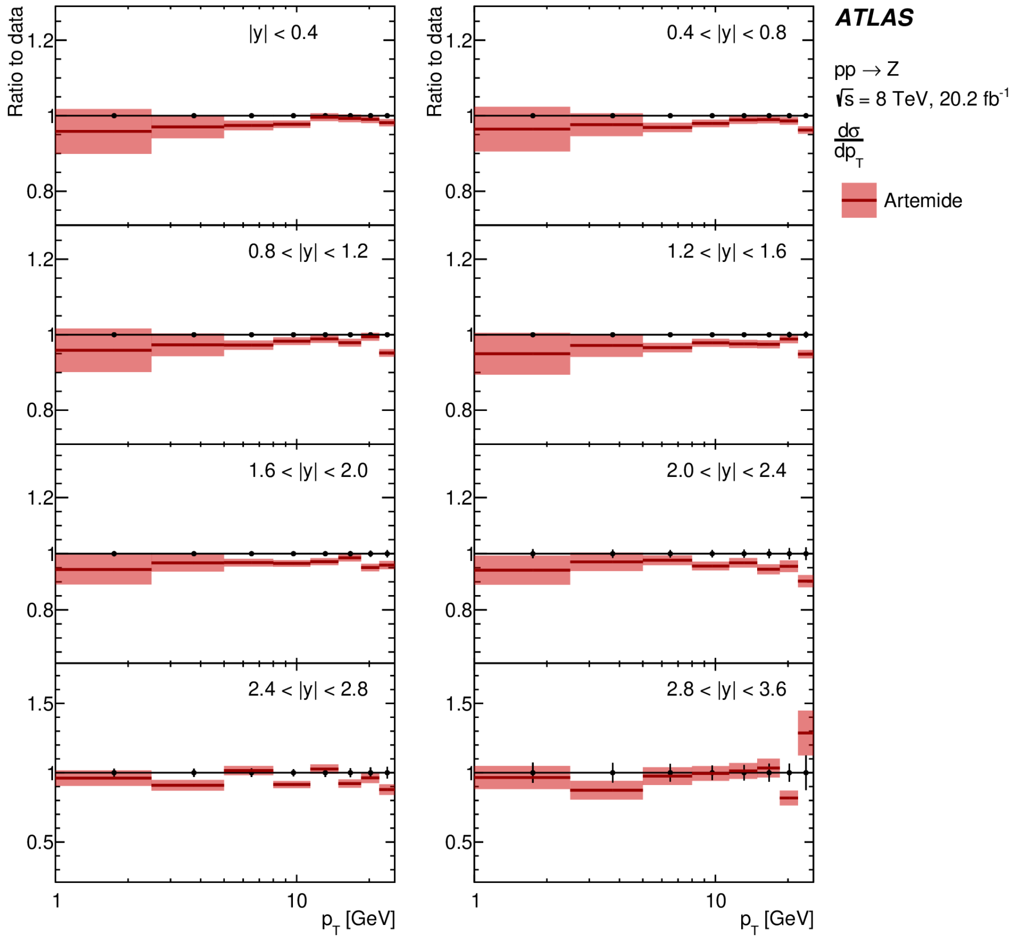

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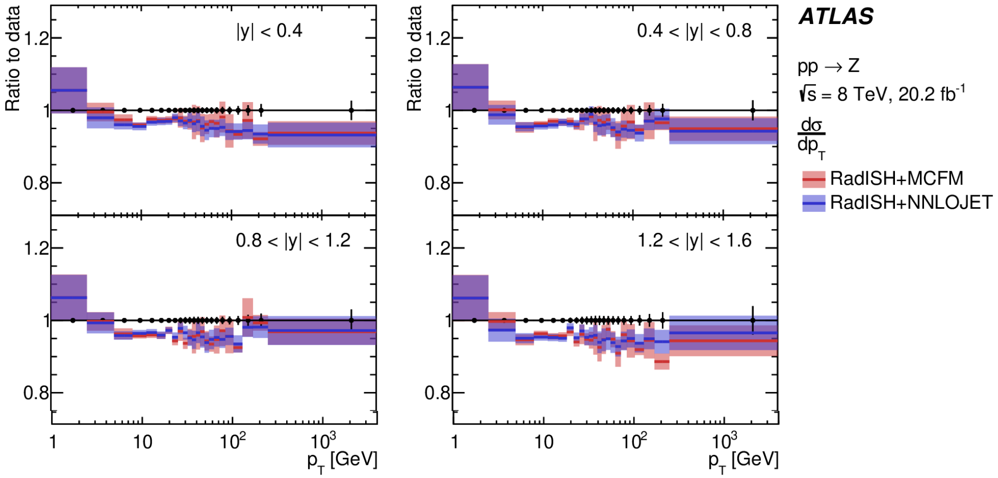
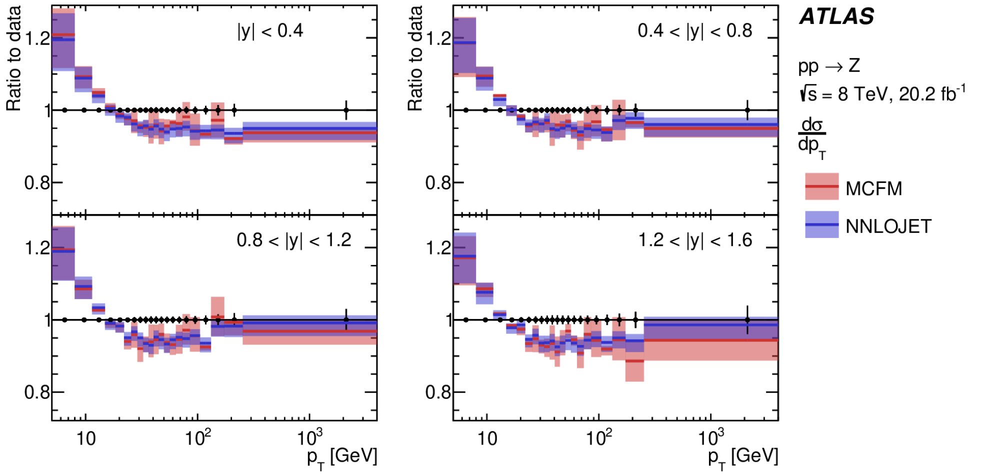
  - Effects of resummation





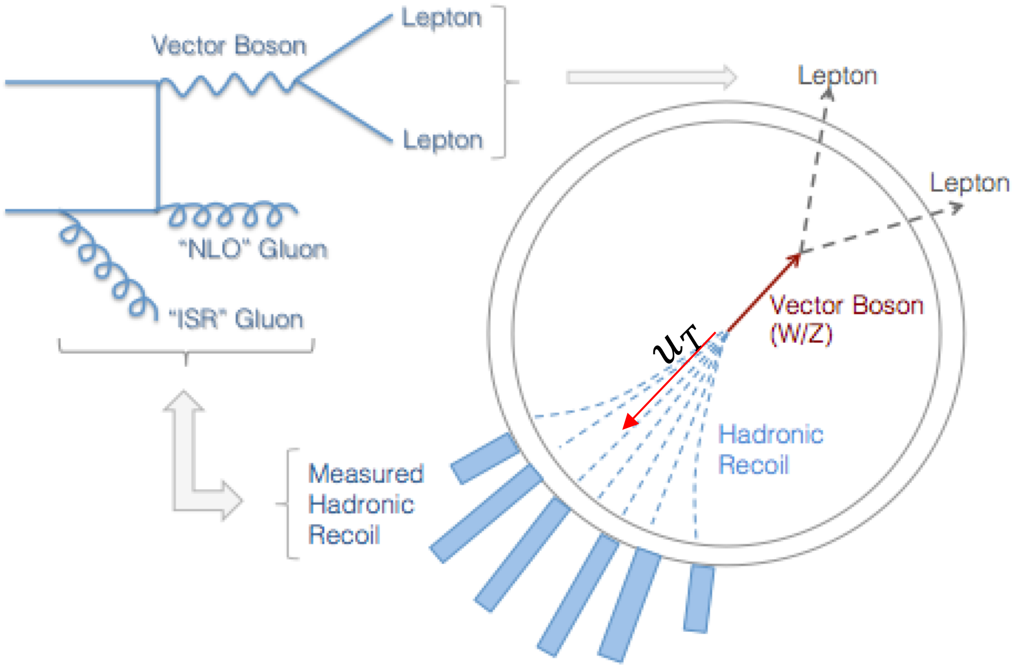
Measurement of m_W and Γ_W

Analysis strategy

arXiv:2403.15085 [hep-ex]

$\sqrt{s} = 7\ \text{TeV},\ L = 4.6/4.1\ \text{fb}^{-1}$

- Event selection in the e/μ+jets channel
  - Isolated leptons, $p_T > 30$ GeV
  - $u_T < 30$ GeV: vector sum of the transverse energy of all clusters reconstructed in the calorimeters, not associated with the decay leptons $\vec{u}_\mathrm{T} = \sum_i \overrightarrow{E^i}_\mathrm{T}$
    - does not involve the explicit reconstruction of jets



Measurement of m_W and Γ_W

More on signal modelling

arXiv:2403.15085 [hep-ex]

$\sqrt{s} = 7\ \text{TeV},\ L = 4.6/4.1\ \text{fb}^{-1}$

Main MC Powheg r (v1/r1556) + Py8 (AZNLO tune) + PHOTOS for FSR

EWK Uncertainties:

- Dominant EW correction from QED FSR simulated with PHOTOS
- Same missing higher order EWK uncertainties as the previous analysis

QCD Uncertainties:

- Reweighted to highest possible prediction
- Transverse momentum spectrum is modelled with retuned Pythia8 to fit measured p_T of the Z at 7 TeV, validate for W at 5.02 and 13 TeV
- NNLO predictions for A0-A7 validated

PDF uncertainties

- using hessian method
  - Constrained based on the Z measurement such that they leave the pTZ distribution unchanged, propagating only uncorrelated ones to W

PS uncertainties

- taken from Z measurement, propagated through the AZ tune
- IS charm and bottom quark masses varied and propagated (+-0.5-0.8 GeV)
- Factorisation scale variation 0.5,2.
- Differences between generators (pythia herwig negligible)

Measurement of m_W and Γ_W

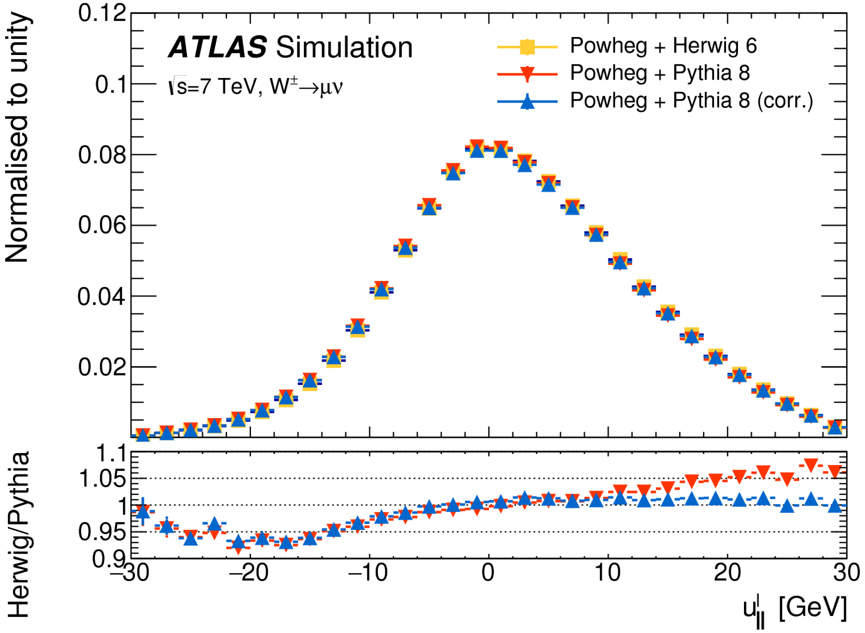
Calibration

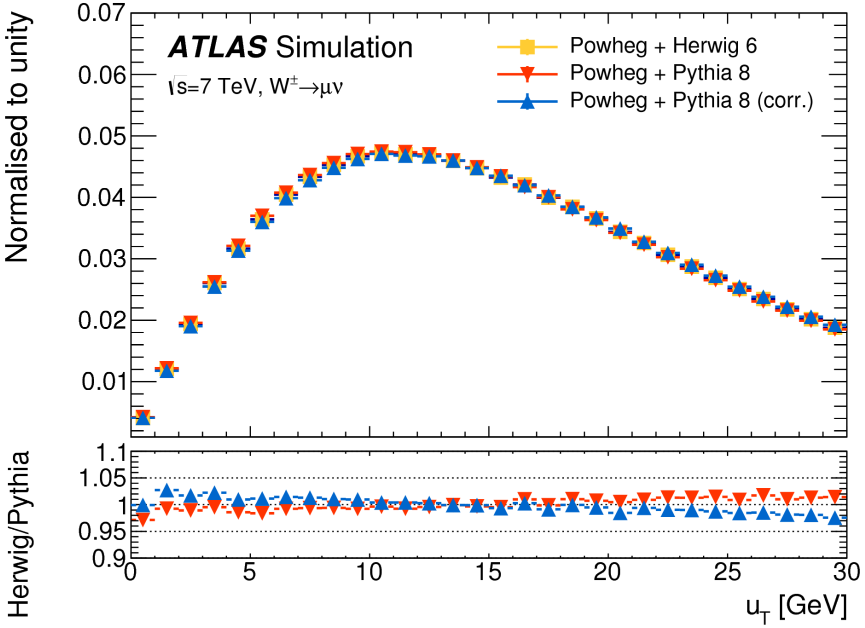
[1]: Eur. Phys. J. C 78 (2018) 110

arXiv:2403.15085 [hep-ex]

$\sqrt{s} = 7\ \text{TeV},\ L = 4.6/4.1\ \text{fb}^{-1}$

- Unchanged wrt legacy measurement [1]
- Recoil response calibrated with the hadronic recoil in Z+jets events
  - Scale and resolution using $u_{\parallel}$ and $u_{\perp}$
  - Closure tests performed by using a PWG+Herwig6 sample as pseudo data





Measurement of m_W and Γ_W

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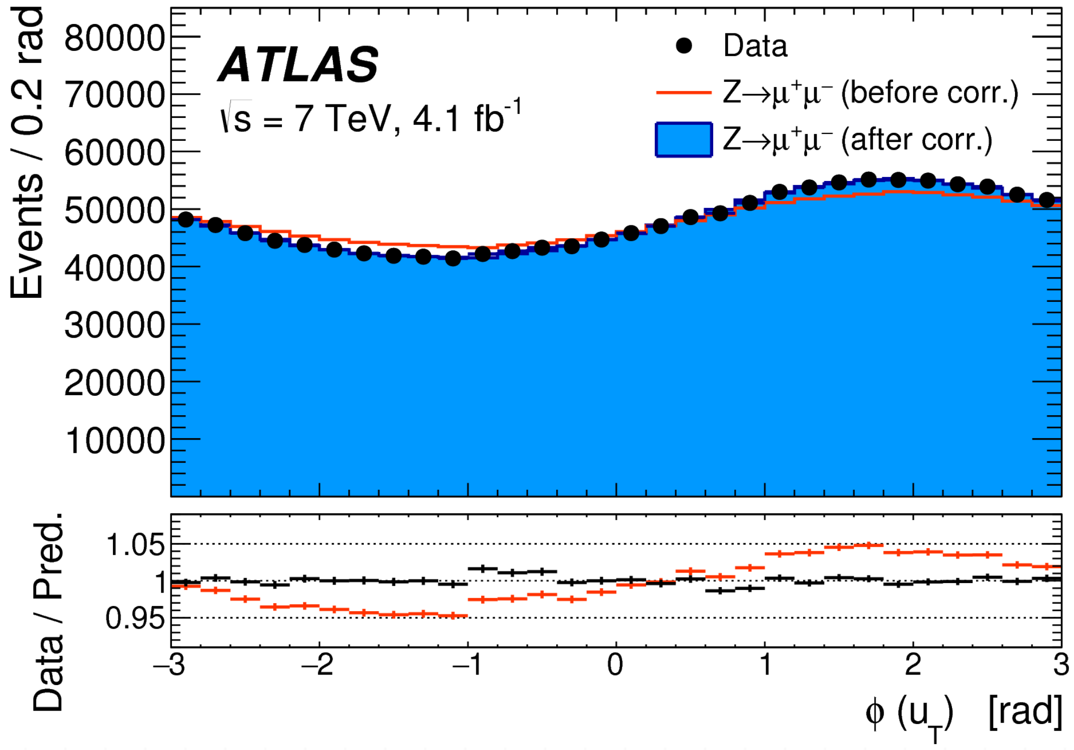
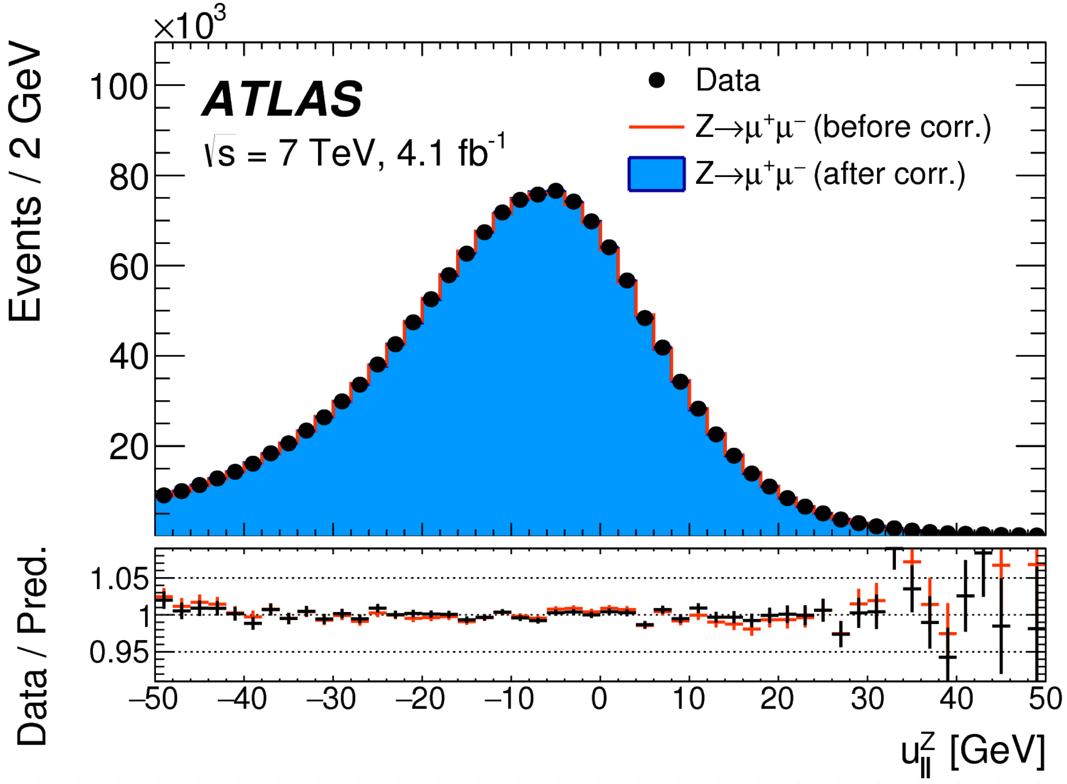




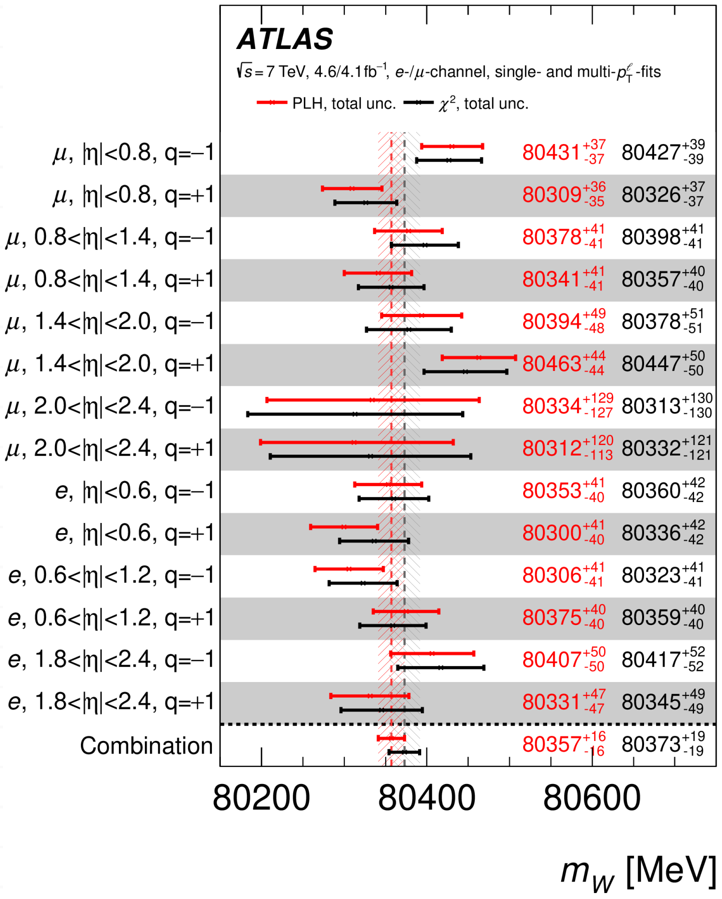
Measurement of m_W and Γ_W

Constency of the results

arXiv:2403.15085 [hep-ex]

$\sqrt{s} = 7$ TeV, $L = 4.6/4.1$ fb^{-1}

- Test 1: reproduce the legacy results
  - Stat-only fit + offset method
  - Good closure (shifts ~12.5 MeV)



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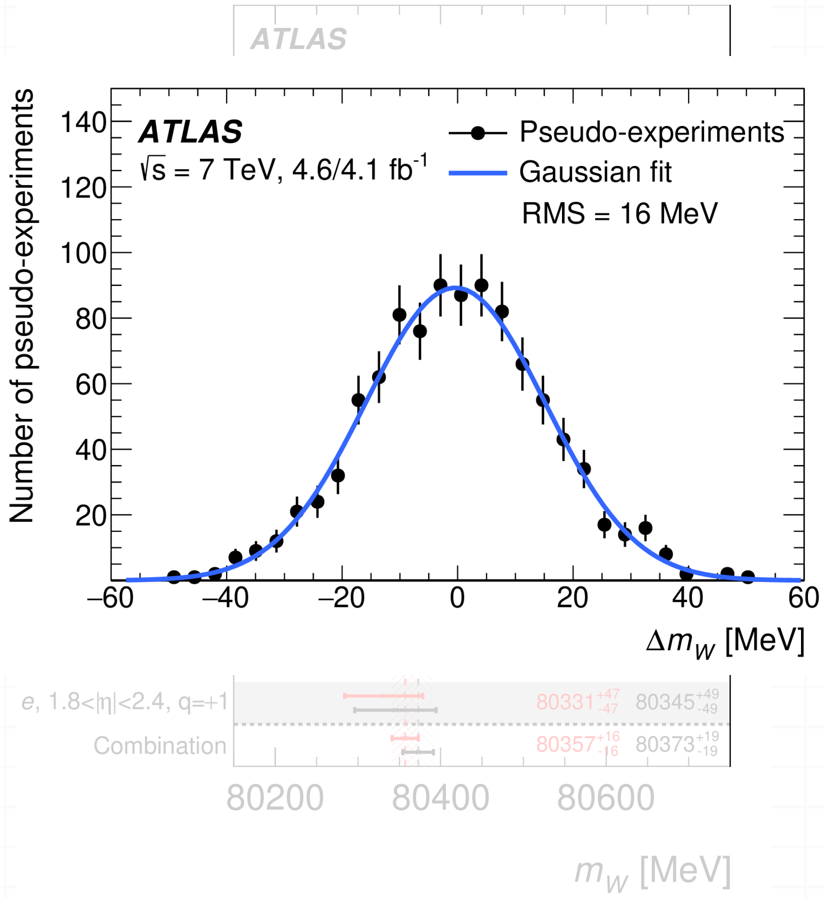

Measurement of m_W and Γ_W

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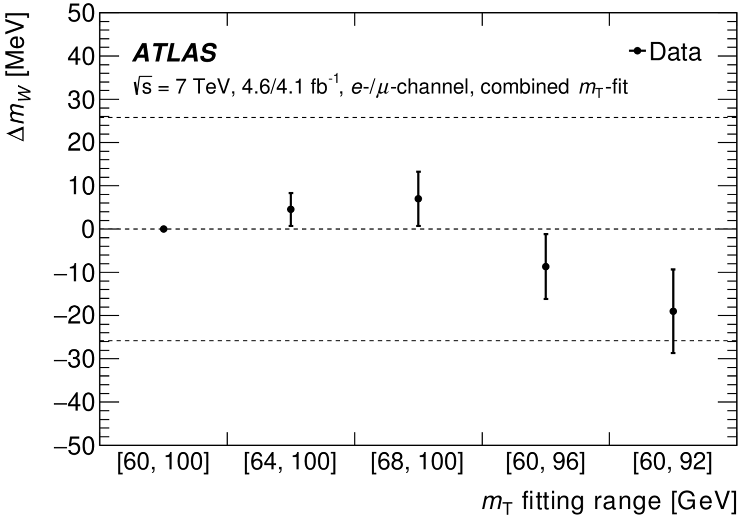
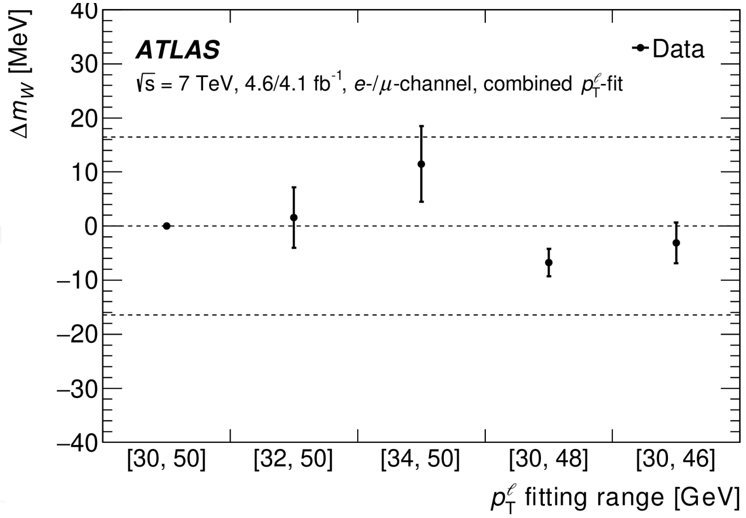
- Test 3: partial fits and different fit ranges





$\boldsymbol{e/\mu}$ lepton flavour universality in W decays

Fit equations

arXiv:2403.02133 [hep-ex]

$\sqrt{s} = 13$ TeV, $L = 140$ fb^{-1}

- $t\bar{t}$ selection, different flavors

$$
\begin{aligned}
N_1^{e\mu} &= L\sigma_{t\bar{t}}\,\epsilon_{e\mu}\boxed{g_{e\mu}^{t\bar{t}}}\,2\epsilon_b^{e\mu}(1 - C_b^{e\mu}\epsilon_b^{e\mu}) + \sum_{k=\mathrm{bkg}} s_1^k \boxed{g_{e\mu}^k} N_1^{e\mu,k} \text{ and} \\
N_2^{e\mu} &= L\sigma_{t\bar{t}}\,\epsilon_{e\mu}\boxed{g_{e\mu}^{t\bar{t}}}\,C_b^{e\mu}(\epsilon_b^{e\mu})^2 + \sum_{k=\mathrm{bkg}} s_2^k \boxed{g_{e\mu}^k} N_2^{e\mu,k},
\end{aligned}
$$

- $t\bar{t}$ selection, same flavors

$$
\begin{aligned}
N_{1,m}^{\ell\ell} &= L\sigma_{t\bar{t}}\,\epsilon_{\ell\ell}\boxed{g_{\ell\ell}^{t\bar{t}}}\,2\epsilon_b^{\ell\ell}(1 - C_b^{\ell\ell}\epsilon_b^{\ell\ell})\, f_{1,m}^{\ell\ell,t\bar{t}} + \sum_{k=\mathrm{bkg}} s_1^k \boxed{g_{\ell\ell}^k} f_{1,m}^{\ell\ell,k} N_1^{\ell\ell,k} \text{ and} \\
N_{2,m}^{\ell\ell} &= L\sigma_{t\bar{t}}\,\epsilon_{\ell\ell}\boxed{g_{\ell\ell}^{t\bar{t}}}\,C_b^{\ell\ell}(\epsilon_b^{\ell\ell})^2\, f_{2,m}^{\ell\ell,t\bar{t}} + \sum_{k=\mathrm{bkg}} s_2^k \boxed{g_{\ell\ell}^k} f_{2,m}^{\ell\ell,k} N_2^{\ell\ell,k},
\end{aligned}
$$

- Z selection

$$
\begin{aligned}
N_Z^{ee} &= L\,\sigma_{Z\to\ell\ell}\,\epsilon_{Z\to ee}(1 - \Delta_Z) + \sum_{k=\mathrm{bkg}} s_Z^k N_Z^{ee,k} \text{ and} \\
N_Z^{\mu\mu} &= L\,\sigma_{Z\to\ell\ell}\,\epsilon_{Z\to\mu\mu}(1 + \Delta_Z) + \sum_{k=\mathrm{bkg}} s_Z^k N_Z^{\mu\mu,k},
\end{aligned}
$$

Factors accouting for deviations in R_W

$$
\begin{aligned}
g_{ee}^{t\bar{t}} &= f_{0\tau}^{ee}(1 - \Delta_W)^2 && + f_{1\tau}^{ee}(1 - \Delta_W) && + f_{2\tau}^{ee} \\
g_{e\mu}^{t\bar{t}} &= f_{0\tau}^{e\mu}(1 - \Delta_W)(1 + \Delta_W) && + f_{1\tau}^{e\mu} && + f_{2\tau}^{e\mu} \\
g_{\mu\mu}^{t\bar{t}} &= f_{0\tau}^{\mu\mu}(1 + \Delta_W)^2 && + f_{1\tau}^{\mu\mu}(1 + \Delta_W) && + f_{2\tau}^{\mu\mu}
\end{aligned}
$$

For tW and diboson backgrounds

$$g_{ll'}^{k} = g_{ll'}^{t\bar{t}}$$

For Z+jets background

$$
\begin{aligned}
g_{ee}^{Z\text{+jets}} &= (1 - \Delta_Z)(1 - \Delta_{Z+b}) \\
g_{e\mu}^{Z\text{+jets}} &= 1 \\
g_{\mu\mu}^{Z\text{+jets}} &= (1 + \Delta_Z)(1 + \Delta_{Z+b})
\end{aligned}
\quad .
$$

With Δ_{Z+b} being related to R_{Z+b} to account for isolation differences in Z+jets wrt Z inclusive