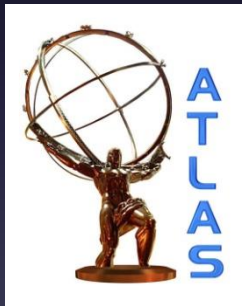


# Measurements of W and Z Production at ATLAS



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Tufts University



# V-Boson Measurements in ATLAS

- To accurately and precisely describe W and Z processes at the LHC, every aspects of QCD have to be well-understood over a large range of scales.
  - PDF, Higher-order Matrix Element calculation, parton shower, matching or merging, factorization/renormalization, hadronization.
- ATLAS performed a large set of such measurements so far (Run-1 and Run-2) providing information to the theory community that results in much improved predictions.
- Probing various phase space regions, with new observables, and different analysis techniques result in different sensitivities to the various QCD effects to be studied at the LHC.

# A Set New Measurements

- Today's presentation focuses on three measurements based on inclusive hadronic final state and improved QCD predictions.
  - Full Phase space  $Z(p_T, y)$  double differential cross section
  - Precision measurement of  $\alpha_s$  from Z recoil
  - W mass measurement update

# ATLAS measurements: Full Phase space $Z$ $p_T$ and rapidity double differential cross section

ATLAS-CONF-2023-013

\*All results can be found in:

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2023-013/>

# $Z(p_T, \gamma)$ : Motivation

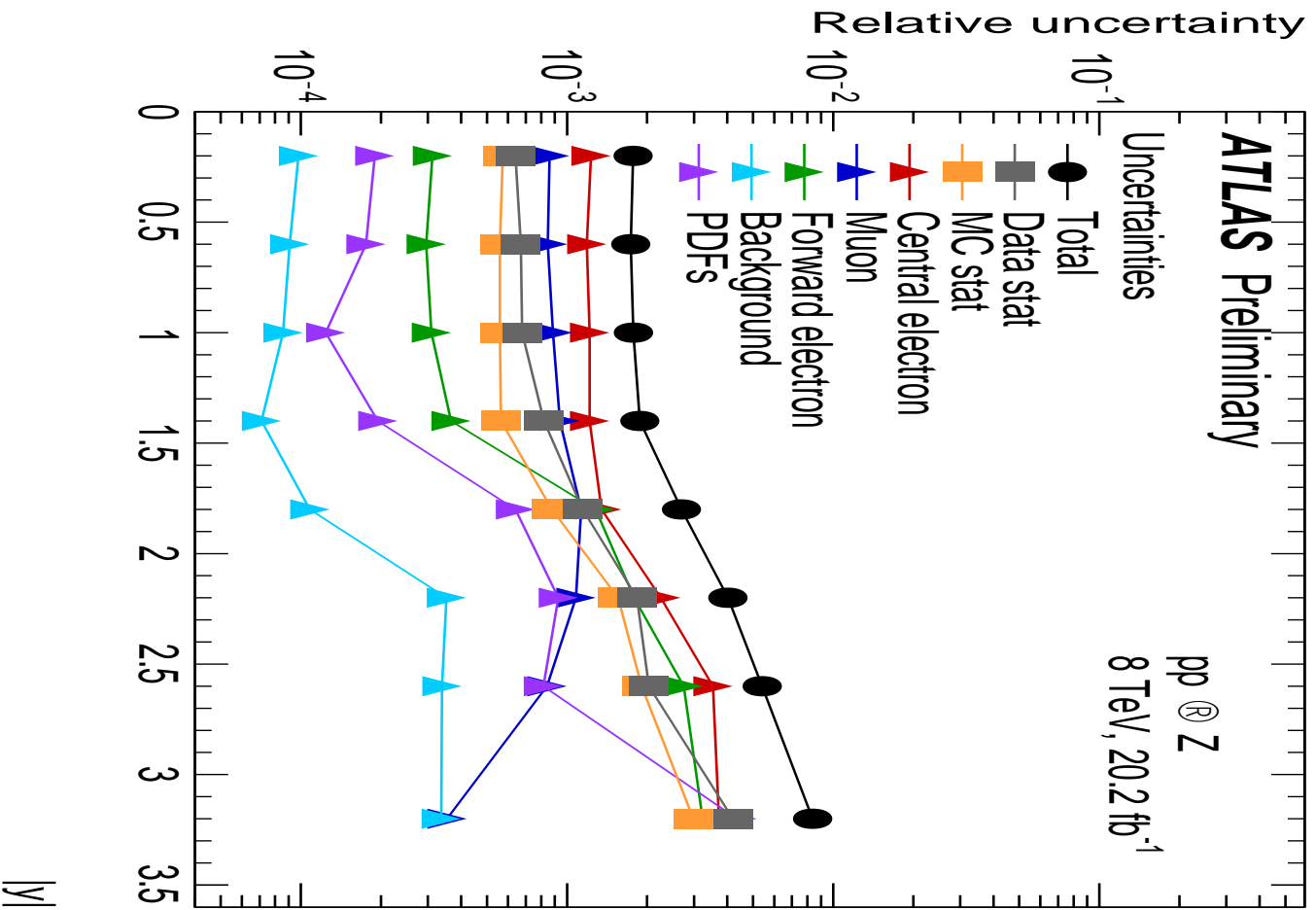
- Very high experimental precision ( $\Delta < 1\%$ ), allowed testing of approximate  $N_4LL + N_3LO$  calculations.
- Rapidity-dependence of differential cross section yields high sensitivity to Parton Distribution Functions.
- Measuring leptonic decay in the full phase space enhances the effects, while leading to higher experimental and theoretical precision

# $Z(p_T, y)$ : What is Measured?

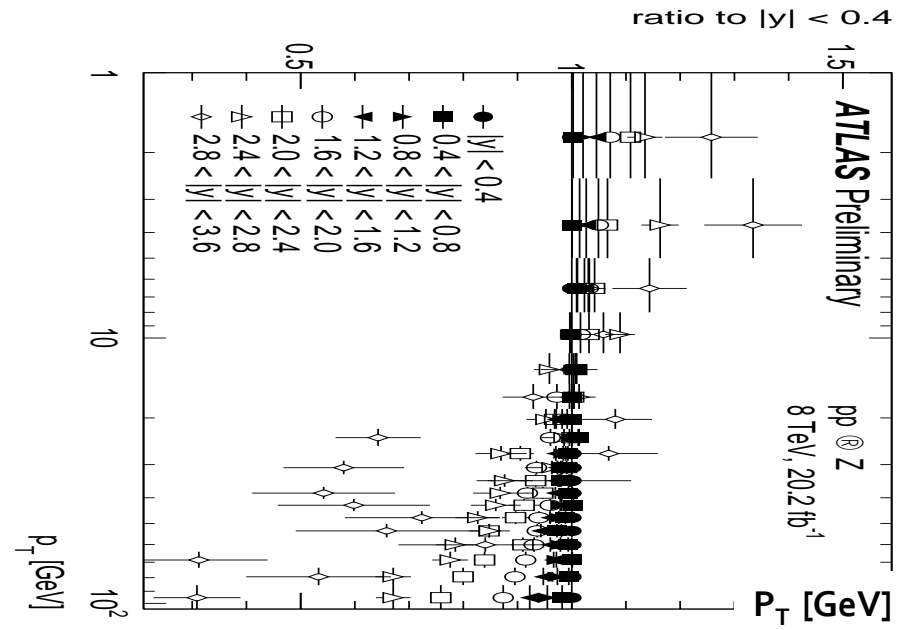
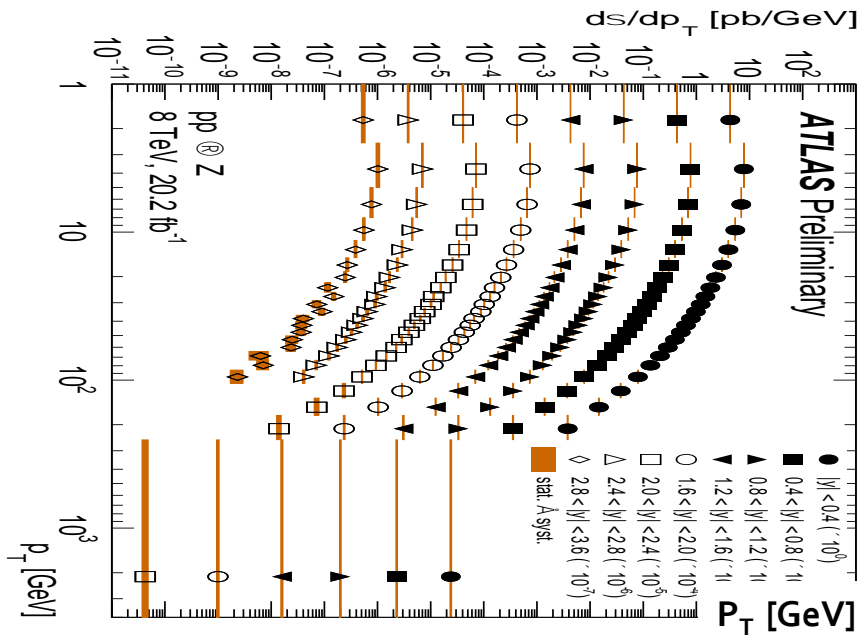
- Measure  $\theta$  and  $\phi$  distributions defined in the Collin-Soper frame and extract the  $(A_i, \sigma^{U+L})$  free parameters from a fit in  $(p_T, y)$  bins
  - Hadronic dynamics, factorized from decay kinematics in Z rest frame, fully contained in the  $(A_i, \sigma^{U+L})$  parameters
  - Analytic expression for the  $P_i(\theta, \phi)$ -dependence  $\rightarrow$  templates to fit
  - Allow to control uncertainties while accounting for correlations.

$$\frac{d\sigma}{dp_T dy dm d\cos\theta d\phi} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_T dy dm_Z} \left\{ (1 + \cos^2\theta) + \frac{1}{2} A_0 (1 - 3\cos^2\theta) + A_1 \sin 2\theta \cos\phi + \frac{1}{2} A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta \cos\phi + A_4 \cos\theta + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi \right\}$$

- Measurement performed on  $20 \text{ fb}^{-1}$  of 8 TeV ATLAS data and reach a sub-percent precision.



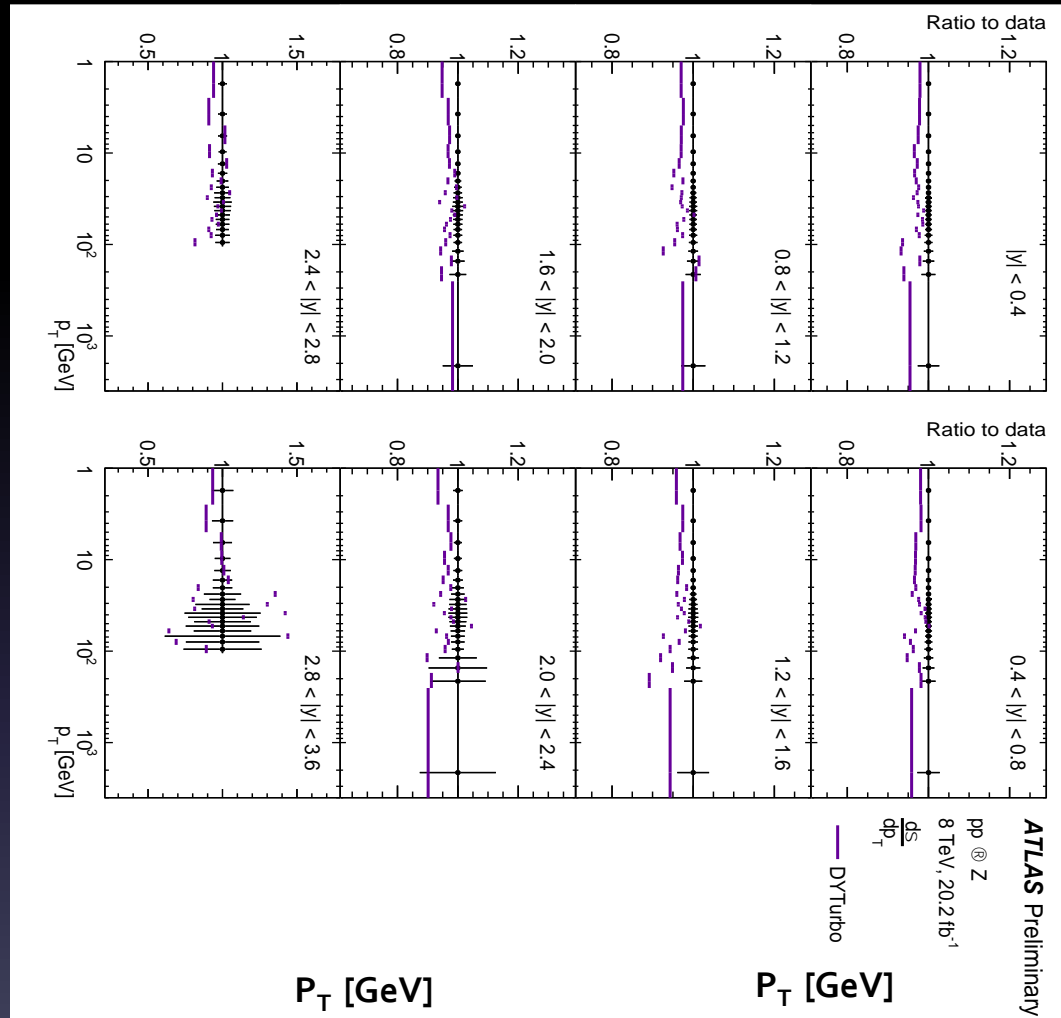
# Z( $p_T, y$ ): Differential Cross Section



- Softening of the  $p_T$  spectrum as a function of rapidity ( $y$ ) measured for the first time because typical fiducial cuts suppress this effect.

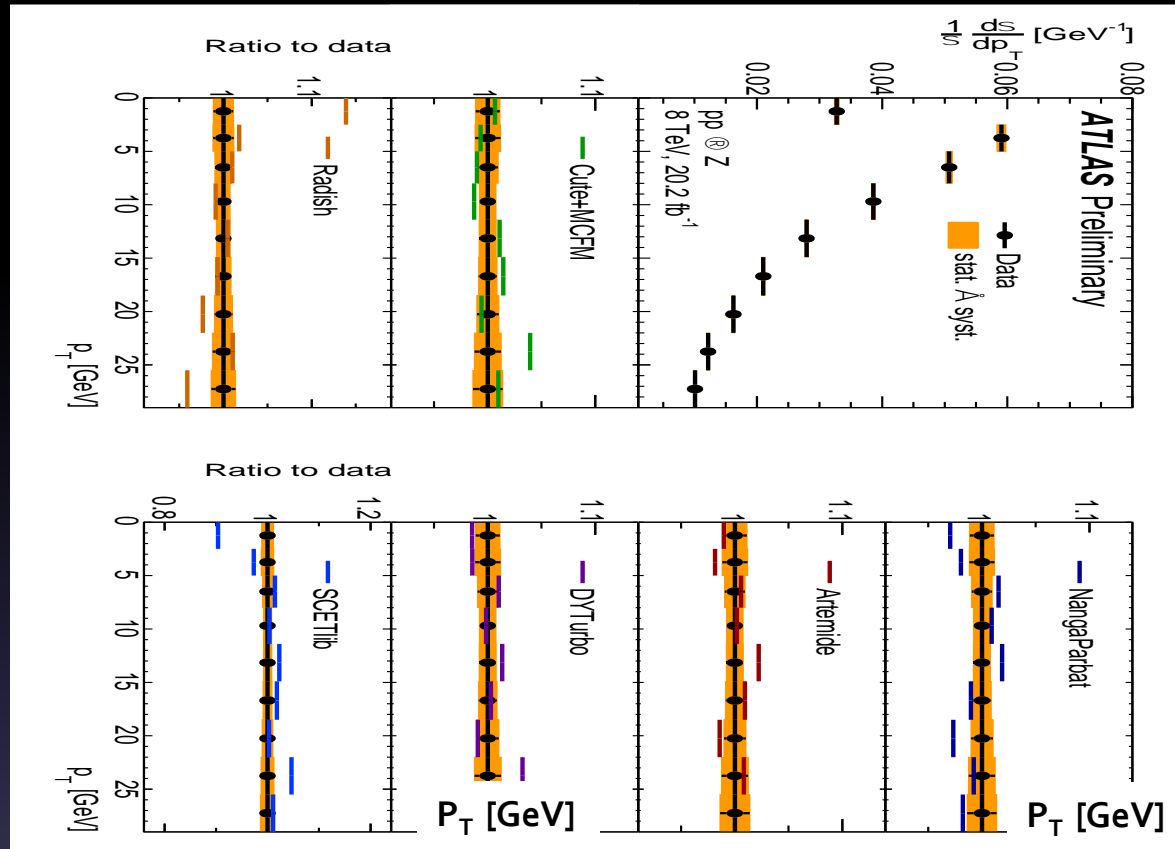


# $Z(p_T, \gamma)$ : Comparison to Theory



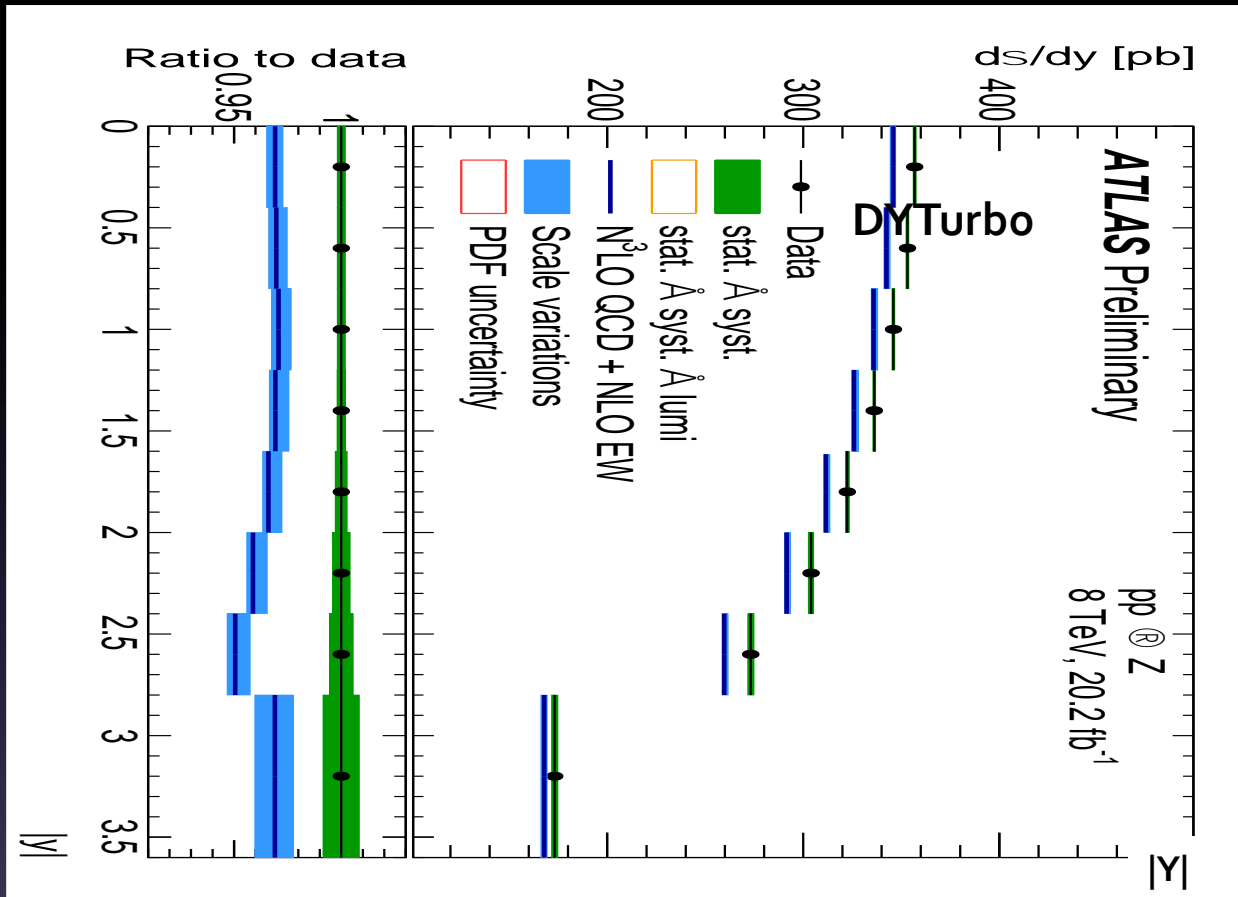
Comparison with DYTurbo, an approximate  $N_4$ LL resummation calculations, matched at higher  $p_T$  to MCFM, an  $N_3$ LO fixed order calculations. The normalization is generally slightly under predicted by the calculation in each  $(p_T, \gamma)$  bin.

# $Z(p_T, y)$ : Z Transverse Momentum



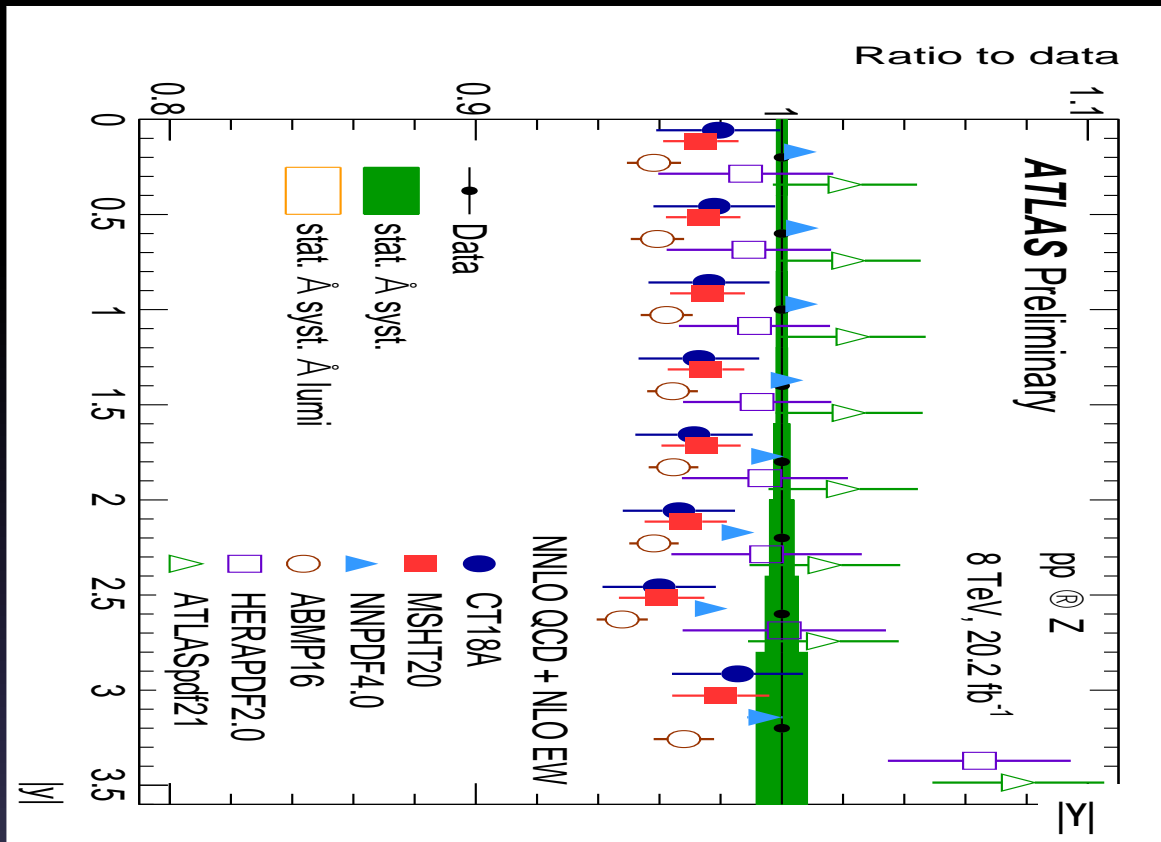
Shape comparison between data, integrated over  $y$ , and various  $N_4LL+N_3LO$  calculations (except Artemide). These calculations describe the  $p_T$  shape very well.

# $Z(p_T, \gamma)$ : Z Rapidity



- Measurement results are significantly more precise than predictions (except for  $\Delta$ Lumi) → excellent test of PDFs.

# Z(pT,y): PDF Measurements



Calculations  
obtained with  
DYTurbo+MCFM

- First comparison to aN<sub>3</sub>LO PDF sets (MSHT20). Comparison to other NNLO PDFs are also provided.
- Rather good description of Z p<sub>T</sub> data by various PDF sets that includes 7 TeV ATLAS W/Z data, even if  $\chi^2$  differ largely due (small uncertainties in both data and PDFs).

# ATLAS measurements: Strong coupling

ATLAS-CONF-2023-015

\*All results can be found in:

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2023-015/>

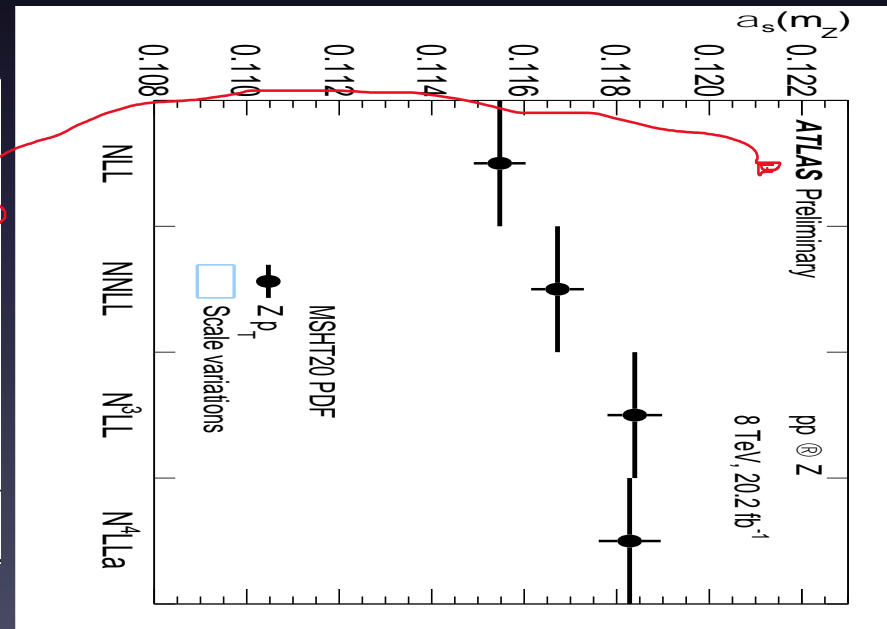
# $\alpha_s(M_Z)$ : Motivation

- Provide a more precise measurement of  $\alpha_s(M_Z)$  than what can be obtained from LHC events with high- $p_T$  jets.
  - Suffer from large uncertainties on perturbative predictions
  - Impact many different measurements from PDF, to various cross section, and new physics models.

# $\alpha_s(M_Z)$ : What is Measured?

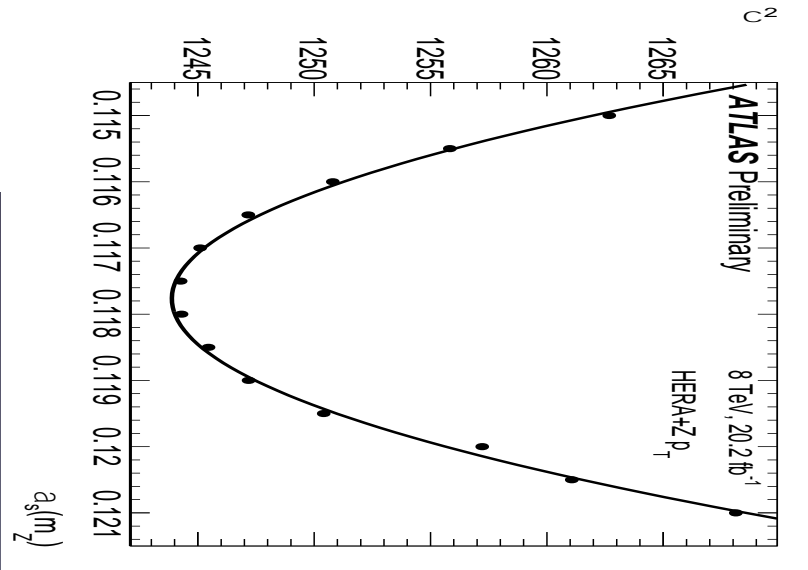
- Exploit N<sub>4</sub>LLa+N<sub>3</sub>LO calculations available for the low-momentum Sudakov region of  $p_T^Z$  to obtain a precise determination of  $\alpha_s(M_Z)$ .
  - Position of  $p_T^Z$  peak is low (radiation inhibited observable), and largely sensitive to  $\alpha_s(M_Z)$ .

Experimental uncertainty	+0.00044	-0.00044
PDF uncertainty	+0.00051	-0.00051
Scale variations uncertainties	+0.00042	-0.00042
Matching to fixed order	0	-0.00008
Non-perturbative model	+0.00012	-0.00020
Flavour model	+0.00021	-0.00029
QED ISR	+0.00014	-0.00014
N <sub>4</sub> LL approximation	+0.00004	-0.00004
<b>Total</b>	<b>+0.00084</b>	<b>-0.00088</b>



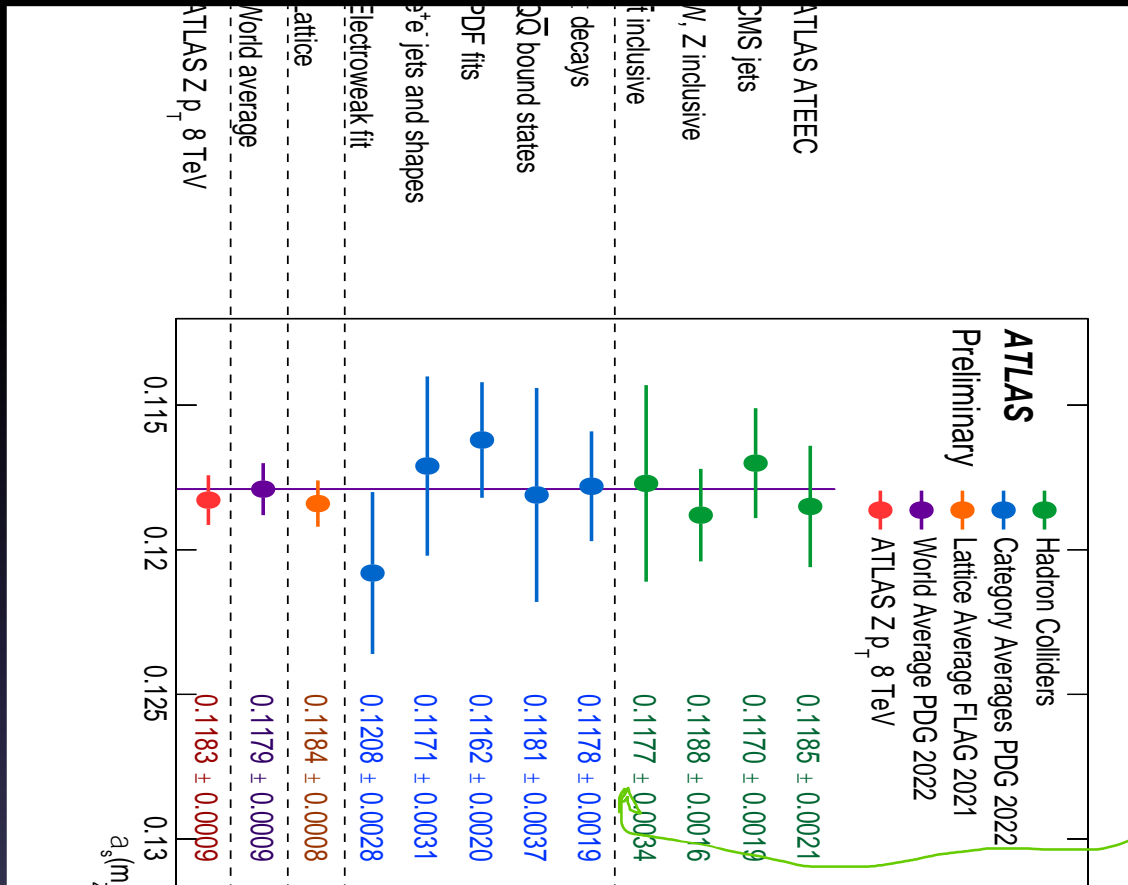
- Extract the measured  $\alpha_s(M_Z)$  value from a  $\chi^2$  fit of the  $p_T^Z$  peak

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





# $\alpha_s(M_Z)$ : Measurement Results



$\alpha_s(M_Z) =$   
 $0.11828 \pm$   
 $0.0009$

- Most precise **experimental** determination of  $\alpha_s(M_Z)$  to date and first based on N<sub>4</sub>LLa+N<sub>3</sub>LO calculation.
- Largely uncorrelated to other determination of PDF because PDF fits do not include  $p_T^Z$  in Sudakov region.

# ATLAS measurements: W Mass Update

ATLAS-CONF-2023-004

\*All results can be found in:

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2023-004/>

# W Mass: Motivation

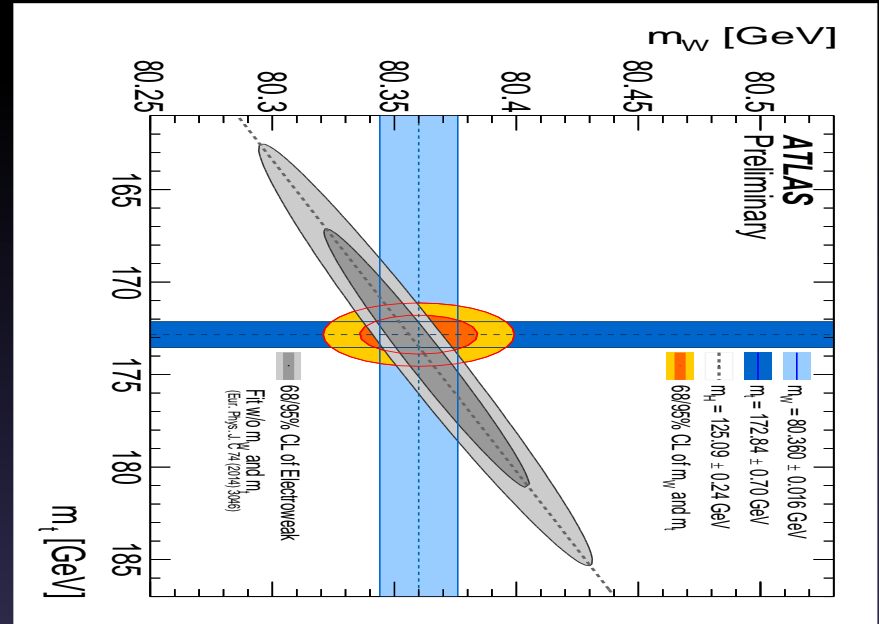
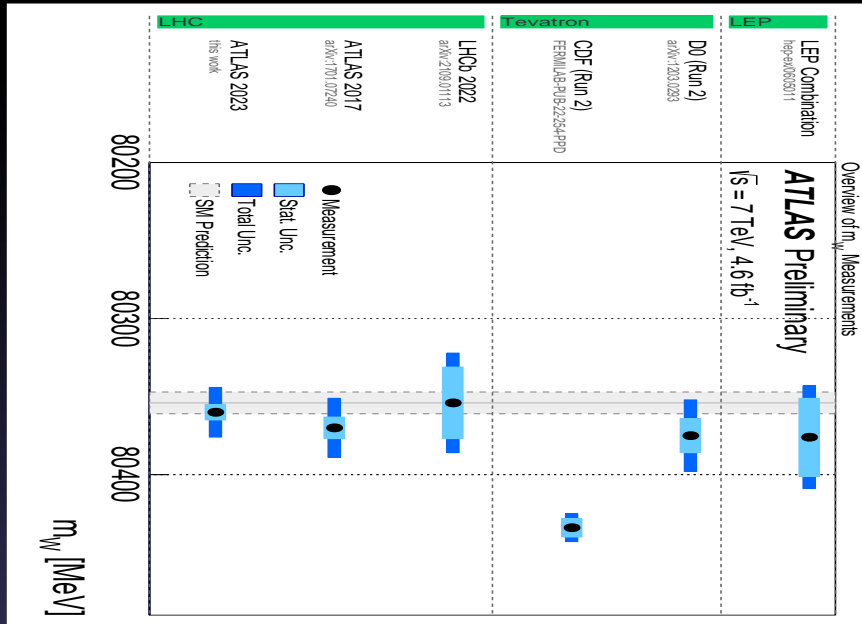
- Higher order calculations relate  $M_W$  to a large number of free parameters of the SM through specific relationships
  - $M_Z, \alpha, G_F, m_t, M_H,$  gauge couplings
  - Important for consistency test of the SM (EWK fits)
  - Powerful test of higher order predictions
- Probe new physics through the contribution of higher mass states to loop corrections to  $M_W$ .
- Improve precision tests tension with recent CDF results
  - Update the latest ATLAS measurement by taking advantage of new theory calculations, and new statistical method to improve the published result.

# W Mass: What is Measured?

- Use the Run-1 result with  $4.6\text{fb}^{-1}$  of 7 TeV ATLAS data
- Perform a fit of the  $p_{\text{T}}^l$  and  $m_{\text{T}}$  distributions on MC templates with different  $M_{\text{W}}$  values
  - Measurement independently performed in different muon and electron charge and rapidity bins, the combination of which helps constraining uncertainties
- Improvements from:
  - Recent improvements on PDFs
  - Improved fitting techniques based on profile likelihood approach including experimental and model uncertainties
  - Updated multijet background estimate

# W Mass: Measurement Results

$$M_W = 80360 \pm 5 \text{ (stat)} \pm 15 \text{ (syst)} \text{ MeV}$$



- Measured value with improved precision consistent with SM and other measurements except CDF
  - New multijet estimate increases  $M_W$  by 1.9 MeV, but profiling with systematics reduces  $M_W$  by 16 MeV ( $1\sigma$ ); total uncertainty 3 MeV better
  - CT18 is used for central results (more conservative and compatible), improving the PDF uncertainty by 2MeV

# Conclusion

- ATLAS performed comprehensive studies of various pQCD effects in various W/Z inclusive jet production final states
- Two very new Run-2 data Z measurements at low  $p_T$  are presented
  - A Full phase space Z  $d\sigma/dp_T dy$  cross section from angular coefficients;
  - The strong coupling constant at the scale  $M_Z$ .
- Also improved on the W mass measurement
- From these measurements, we learned :
  - Extraordinary precision showed the accuracy of N<sub>4</sub>LLa+ N<sub>3</sub>LO shape predictions (light tension with normalization), as well as N<sub>3</sub>LO PDF
  - The Z  $p_T$  spectrum gets softer at larger rapidity
  - The most precise experimental determination of  $\alpha_s(M_Z)$  agrees with best lattice calculation
  - The W Mass results are more precise by 3 MeV and consistent with SM

# Back-up slides



# Z(pT,y): PDF Measurements

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

**NNPDF4.0** PDF set with its much smaller uncertainties displays poor agreement with the data. This is due to the shape of the predicted distribution since the pull on the integrated luminosity is small

**ABMP16** PDF set is the one which most strongly pulls the integrated luminosity but its poor agreement with the data is also due to its significant difference in shape with respect to the data.

**HERAPDF2.0** and **ATLASPDF21** sets also display ok agreement: a large discrepancy with the data in the highest  $y$  bin, pull results a little.

# Z(p<sub>T</sub>,y): Theory Predictions

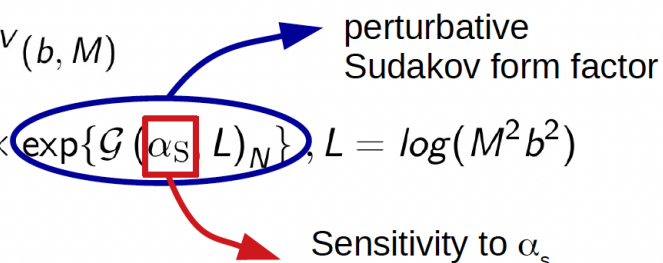
- DYTurbo resums log-enhanced low p<sub>T</sub><sup>||</sup> contribution at approximate N<sup>4</sup>LL accuracy, combined to hard-collinear contribution at N<sup>3</sup>LO, and matched to fixed order predictions at N<sup>3</sup>LO to account for Z+jets contributions at larger p<sub>T</sub>.
  - Performed in the impact-parameter space b (Fourier conjugate of p<sub>T</sub>).
  - A universal (process independent) Sudakov form factor accounts for all log-divergent term in the p<sub>T</sub>→0 limit.
  - Matching cutoff was chosen to be 5 GeV, but matching corrections were extrapolated down to pt=0.
  - Sudakov form factors are singular for p<sub>T</sub><Λ<sub>QVD</sub>: non-perturbative effects dominate, and are included in a form factor.

resummation in b-space

$$\frac{d\hat{\sigma}_{Fab}}{dq_T^2} = \frac{d\hat{\sigma}_{Fab}^{(res.)}}{dq_T^2} + \frac{d\hat{\sigma}_{Fab}^{(fin.)}}{dq_T^2}$$

$$\frac{d\hat{\sigma}_V^{(res.)}}{dq_T^2}(q_T, M) = \frac{M^2}{\hat{s}} \int_0^\infty db \frac{b}{2} J_0(bq_T) \mathcal{W}^V(b, M)$$

$$\mathcal{W}_N^V(b, M) = \mathcal{H}_N^V(\alpha_s) \times \exp\{\mathcal{G}(\alpha_s, L)_N\}, L = \log(M^2 b^2)$$



# W Mass: Fitting Strategy

$$L(\mu, \vec{\theta} | N^{obs}) = \prod_j \prod_i \text{Poisson}(n_{ji} | \nu_{ji}(\mu, \vec{\theta})) \cdot \text{Gauss}(\vec{\theta}),$$

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

$N^{obs}$ : Number of observed data events

$n_{ji}$ : Number of observed data events in  $i$  of the distribution in category  $j$

$\mu$ : Parameter of interest, variations of MW with respect to reference

$\vec{\theta}$ : Nuisance parameters i.e. various systematic uncertainties assuming a normal distribution.

$\nu_{ji}$ : Expectations value given in terms of signal ( $S_{ij}$ ) and background ( $B_{ij}$ )

$\Phi$ : Overall unconstrained normalization to ensure signal rate matches data <sup>27</sup>