Measurements of W and Z Production at ATLAS

Hugo Beauchemin

Tufts University

DIS 2023, Michigan State University (USA), March 27-31, 2023

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 α_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/

$Z(p_T,y)$: Motivation

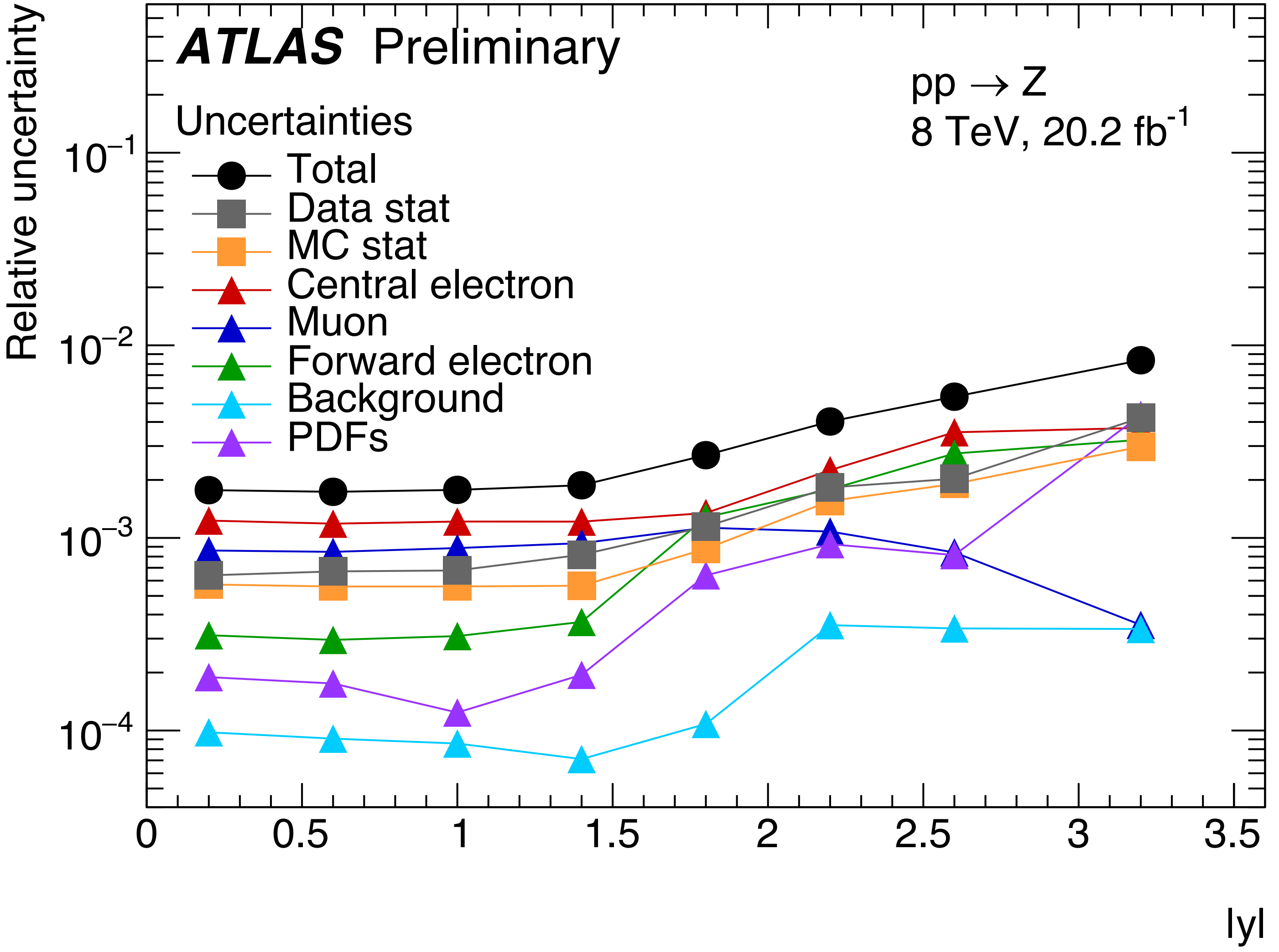
- Very high experimental precision (Δ<1%), allowed testing of approximate N4LL+ N3LO+ calculations.
- Rapidity-dependence of differential cross section yields high sensitivity to Parton Distribution Functions.
- Measuring leptonic decay in the full phase space enhances the effects, while leading to higher experimental and theoretical precision

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

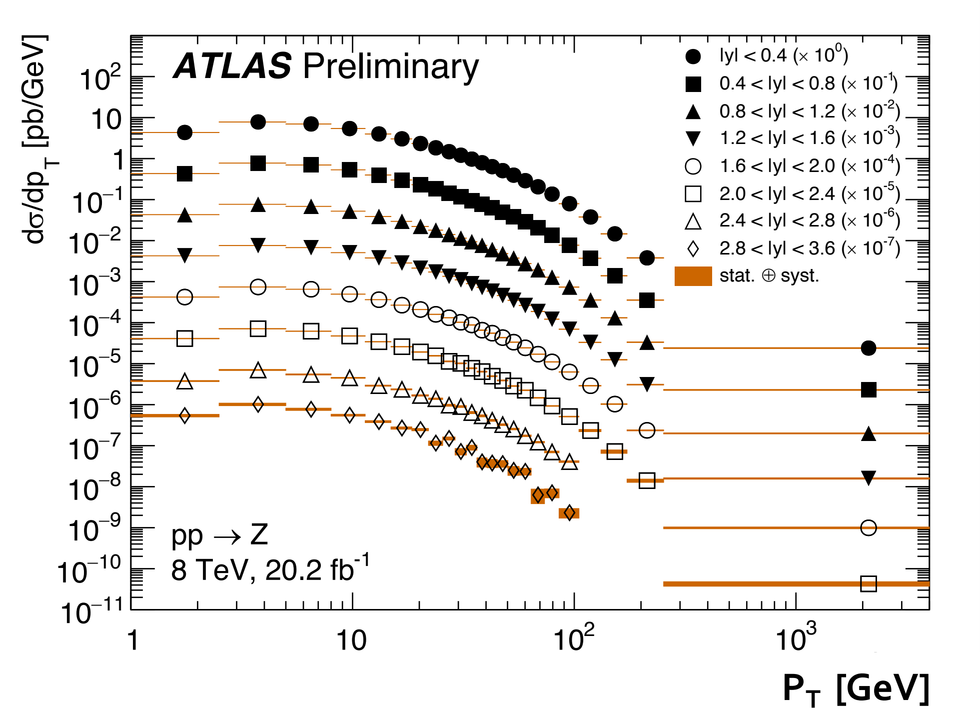
- Measure θ and ϕ distributions defined in the Collin-Soper frame and extract the (A_i, σ^{U+L}) free parameters from a fit in (p_T,y) bins
  - Hadronic dynamics, factorized from decay kinematics in Z rest frame, fully contained in the (A_i, σ^{U+L}) parameters
  - Analytic expression for the $P_i(\theta,\phi)$-dependence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

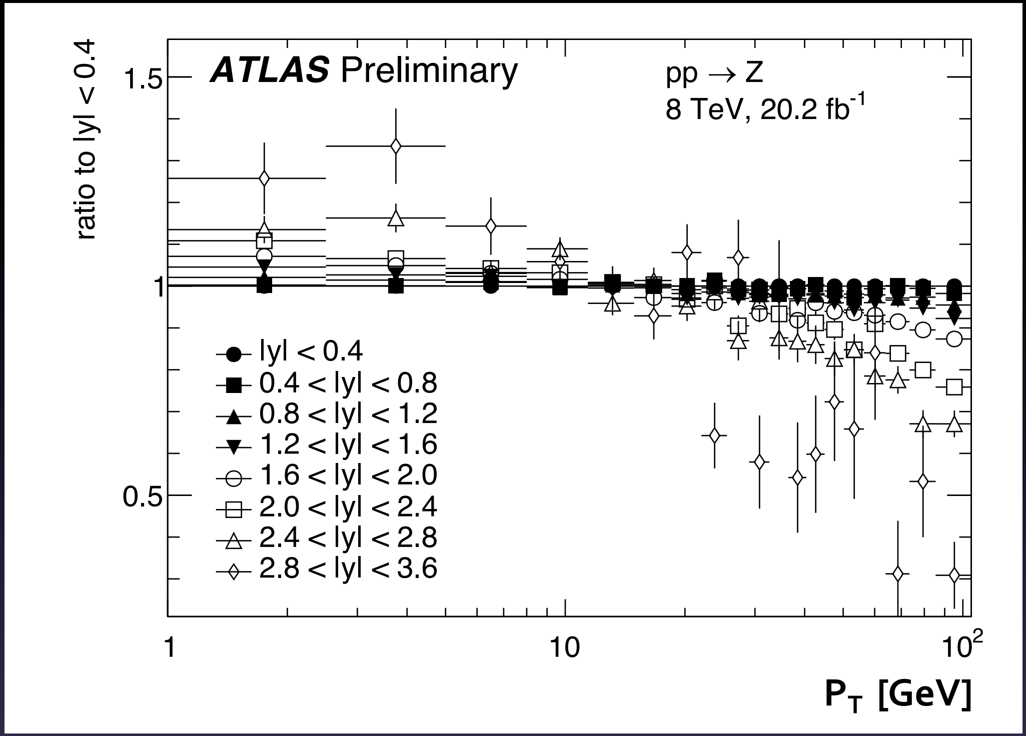
$$
\begin{aligned}
\frac{d\sigma}{dp_T\,dy\,dm\,d\cos\theta\,d\phi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T\,dy\,dm_Z}
&\Big\{(1+\cos^2\theta) + \frac{1}{2}\boxed{A_0}(1-3\cos^2\theta) + \boxed{A_1}\ \sin 2\theta\ \cos\phi \\
&+\frac{1}{2}\boxed{A_2}\sin^2\theta\ \cos 2\phi + \boxed{A_3}\ \sin\theta\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

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


ATLAS Preliminary
pp → Z
8 TeV, 20.2 fb^{-1}
Uncertainties
Total
Data stat
MC stat
Central electron
Muon
Forward electron
Background
PDFs
Relative uncertainty
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.5
1
1.5
2
2.5
3
3.5
|y|

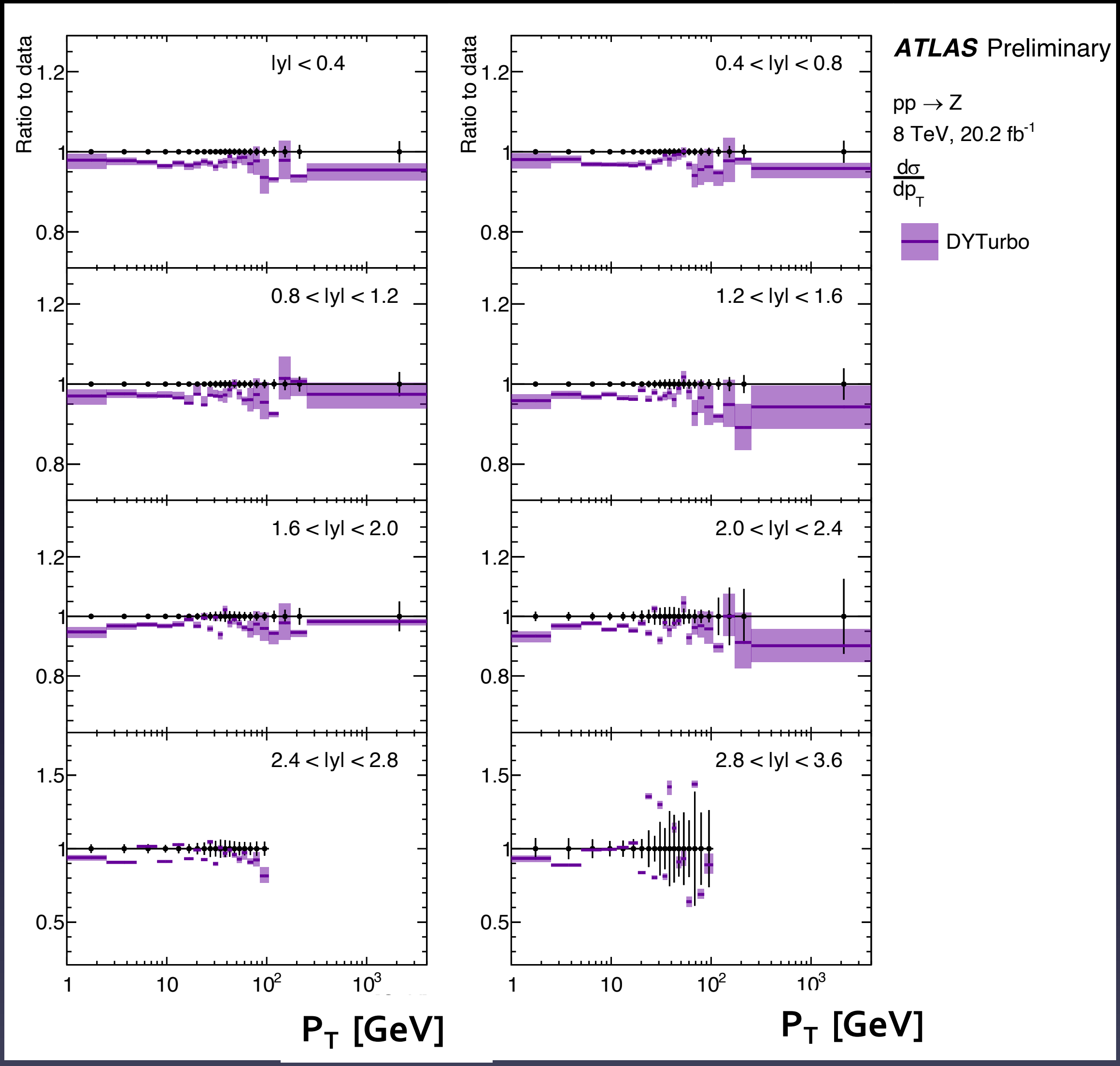
Z(p_T,y): Differential Cross Section





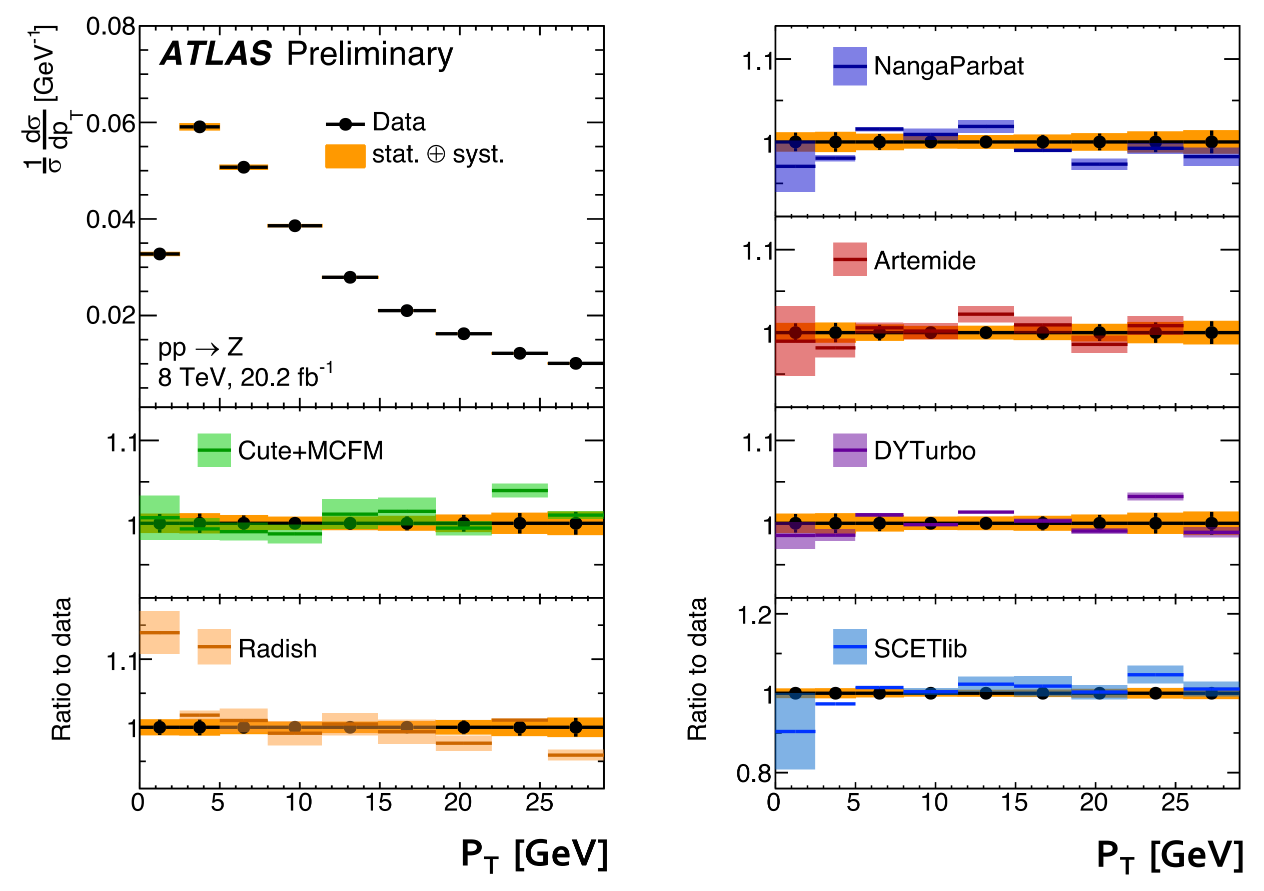
- Softening of the p_T spectrum as a function of rapidity (y) measured for the first time because typical fiducial cuts suppress this effect.

Z(p_T,y): Comparison to Theory



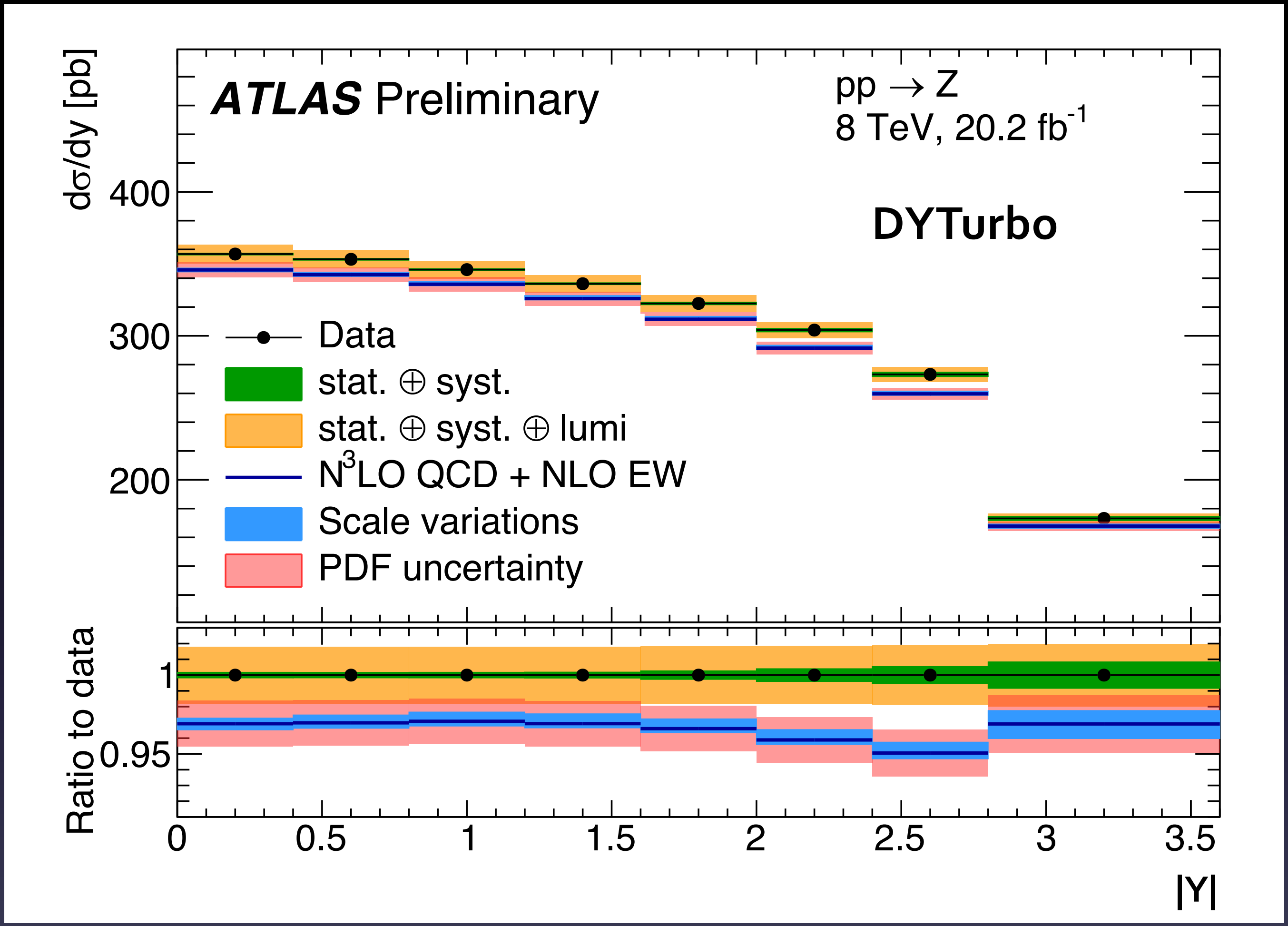
Comparison with DYTurbo, an approximate N4LL resummation calculations, matched at higher p_T to MCFM, an N3LO fixed order calculations. The normalization is generally slightly under predicted by the calculation in each (p_T,y) bin.

Z(p_T,y): Z Transverse Momentum



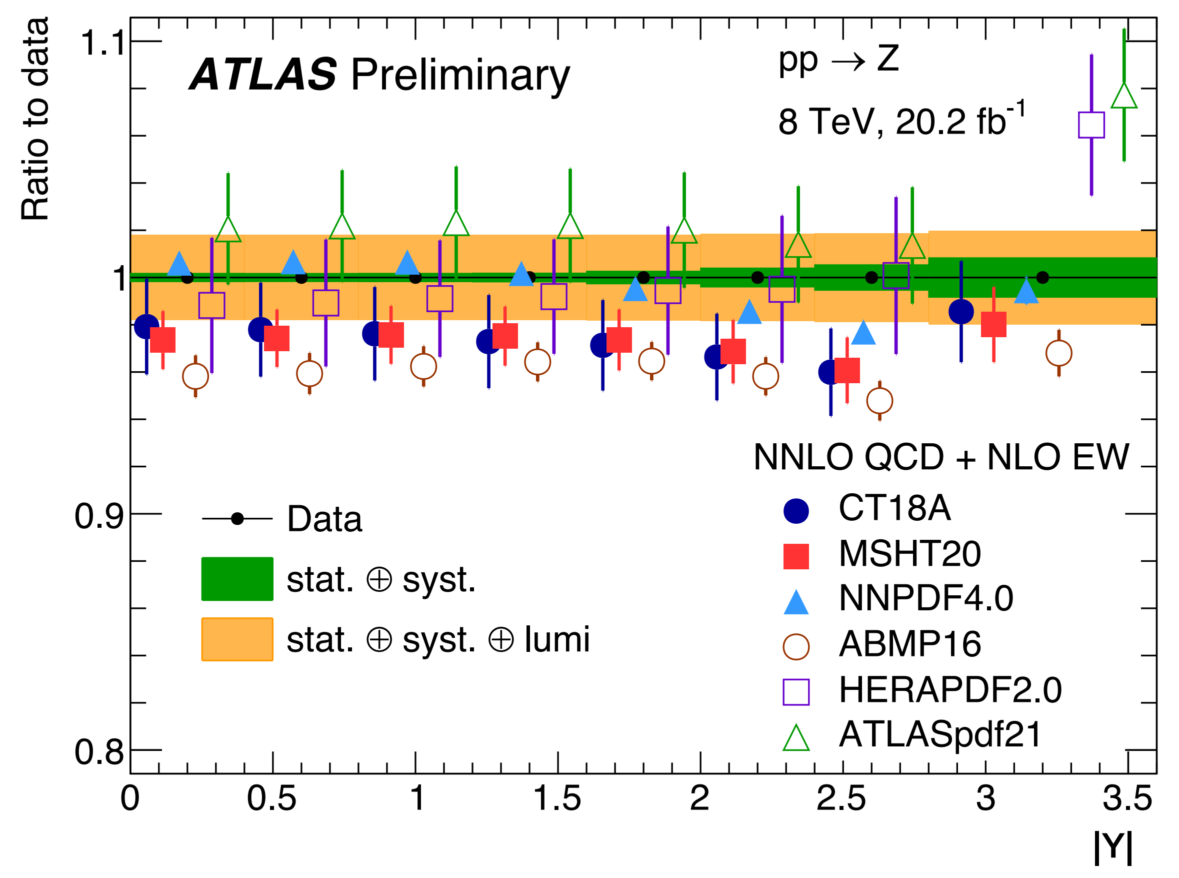
Shape comparison between data, integrated over y, and various N4LL+N3LO calculations (except Artemide). These calculations describe the p_T shape very well.

$Z(p_T, y)$: Z Rapidity



- Measurement results are significantly more precise than predictions (except for ΔLumi) → excellent test of PDFs.

Z(pT,y): PDF Measurements



Calculations obtained with DYTurbo+MCFM

- First comparison to aN3LO PDF sets (MSHT20). Comparison to other NNLO PDFs are also provided.
- Rather good description of Z p_T data by various PDF sets that includes 7 TeV ATLAS W/Z data, even if χ^2 differ largely due (small uncertainties in both data and PDFs).

ATLAS measurements: Strong coupling

ATLAS-CONF-2023-015

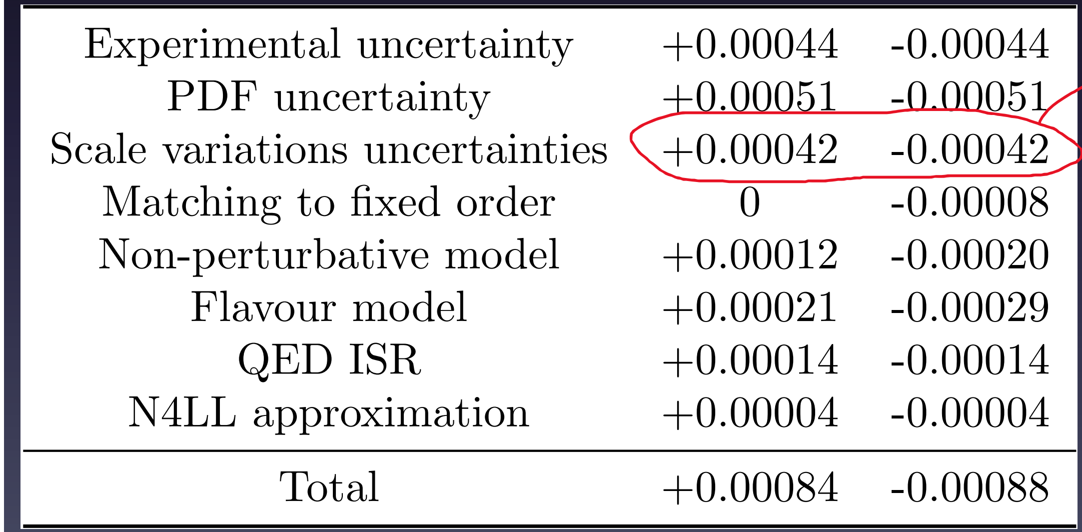
*All results can be found in:
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2023-015/

$\alpha_s(M_Z)$: Motivation

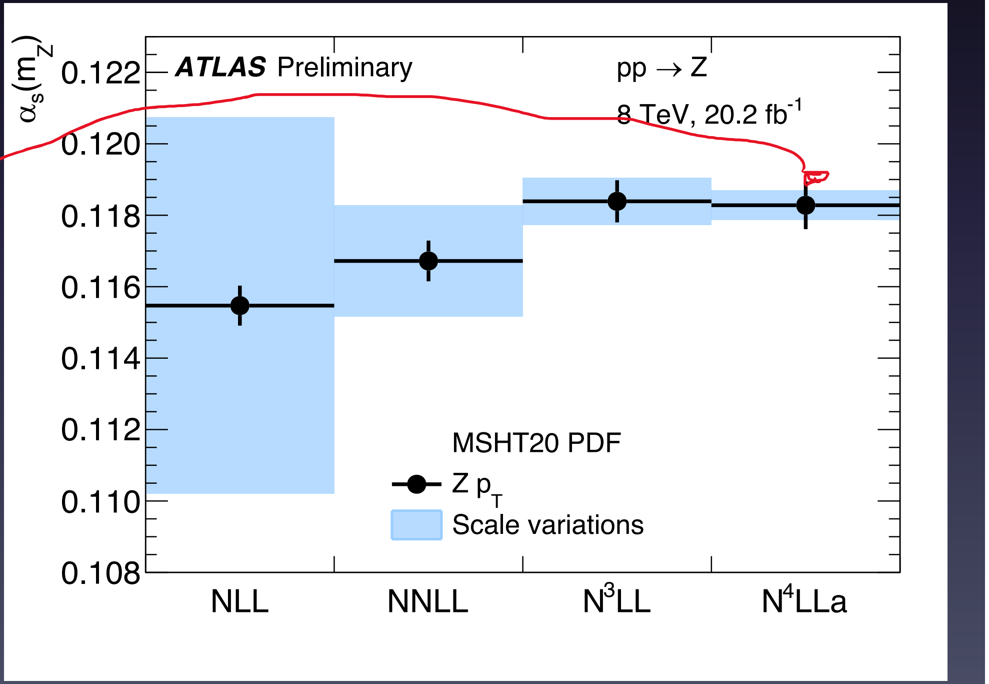
- Provide a more precise measurement of $\alpha_s(M_Z)$ than what can be obtained from LHC events with high-p_T jets.
  - Suffer from large uncertainties on perturbative predictions
  - Impact many different measurements from PDF, to various cross section, and new physics models.

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

- Exploit N4LLa+N3LO 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 $\alpha_s(M_Z)$.

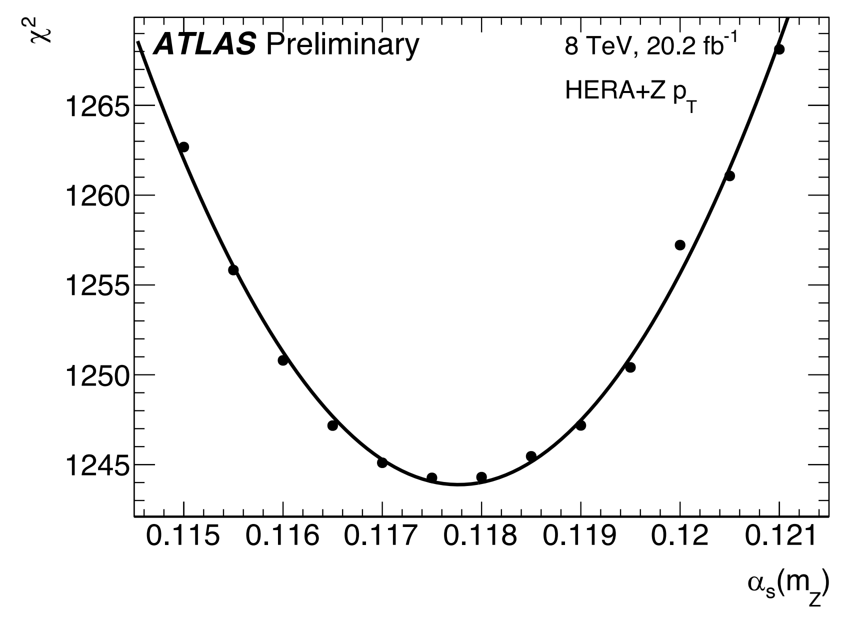


Experimental uncertainty	+0.00044	-0.00044
PDF uncertainty	+0.00051	-0.00051
Scale variations uncertainties	+0.00042	-0.00042
Matching to fixed order	0	-0.00008
Non-perturbative model	+0.00012	-0.00020
Flavour model	+0.00021	-0.00029
QED ISR	+0.00014	-0.00014
N4LL approximation	+0.00004	-0.00004
Total	+0.00084	-0.00088

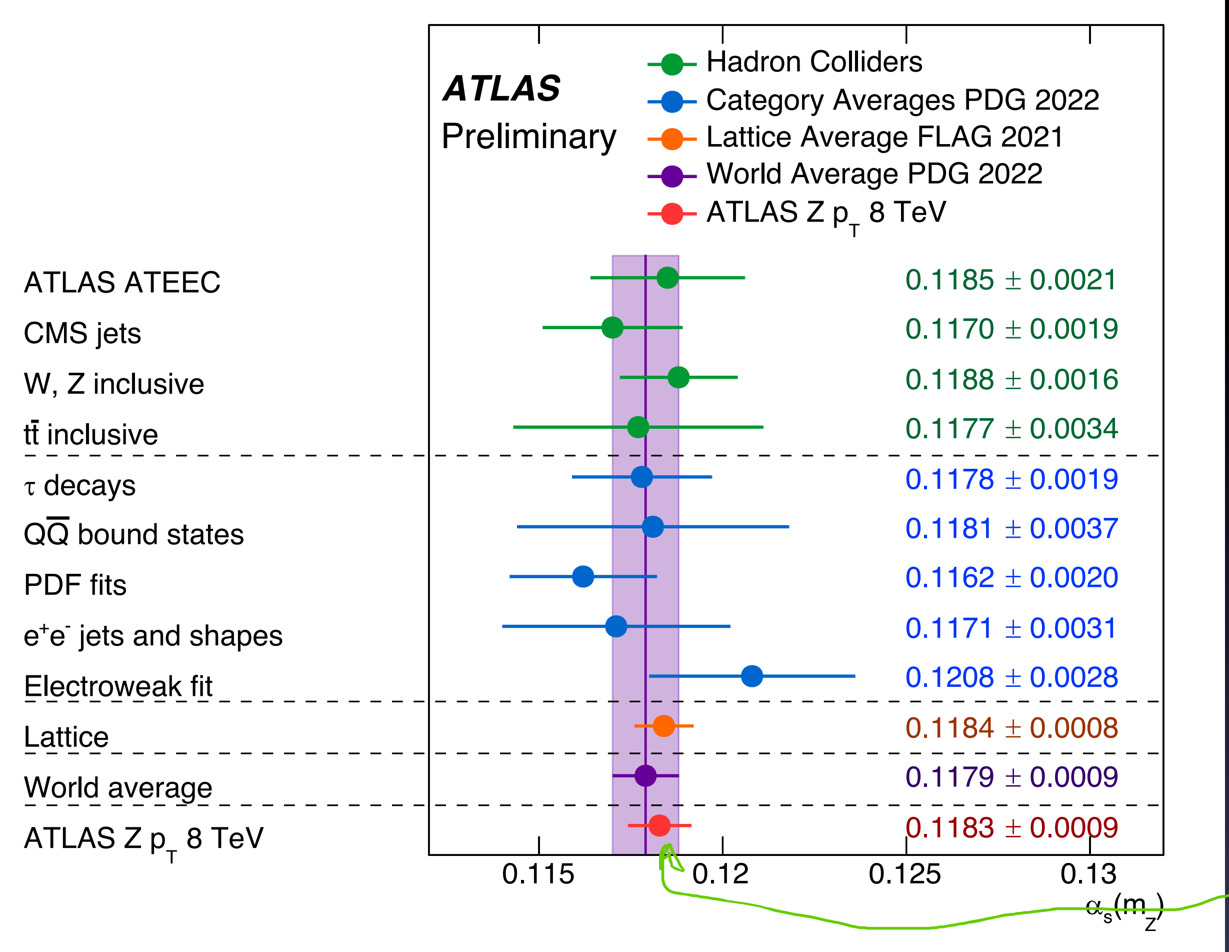


- Extract the measured $\alpha_s(M_Z)$ value from a χ^2 fit of the p_T^Z peak

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



$\alpha_s(M_Z)$: Measurement Results



$\alpha_s(M_Z)$=
0.11828 ±
0.0009

- Most precise **experimental** determination of $\alpha_s(M_Z)$ to date and first based on N4LLa+N3LO 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, α, 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.

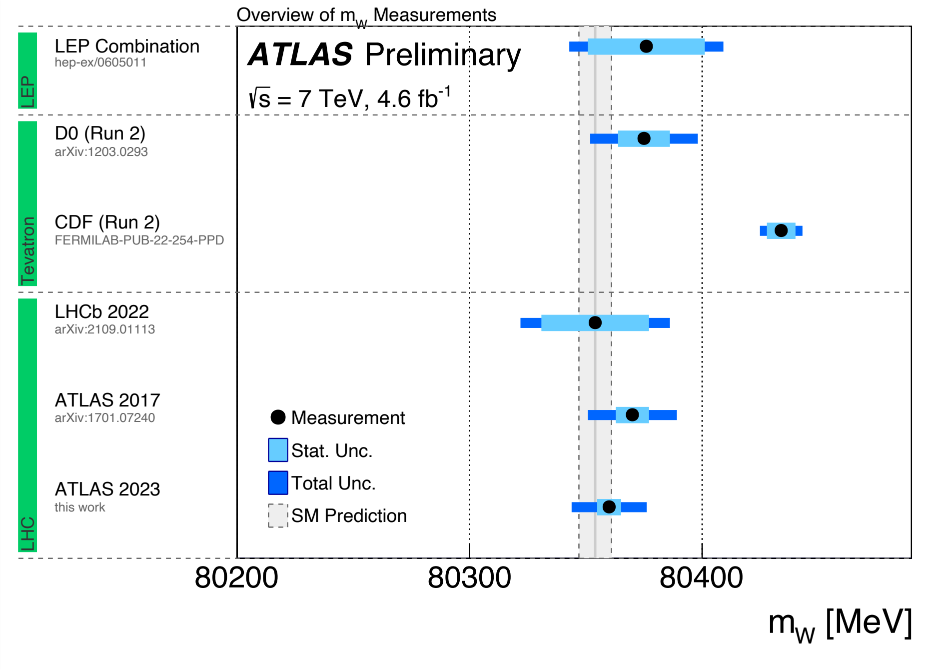
- Improve precision tests tension with recent CDF results
  - Update the latest ATLAS measurement by taking advantage of new theory calculations, and new statistical method to improve the published result.

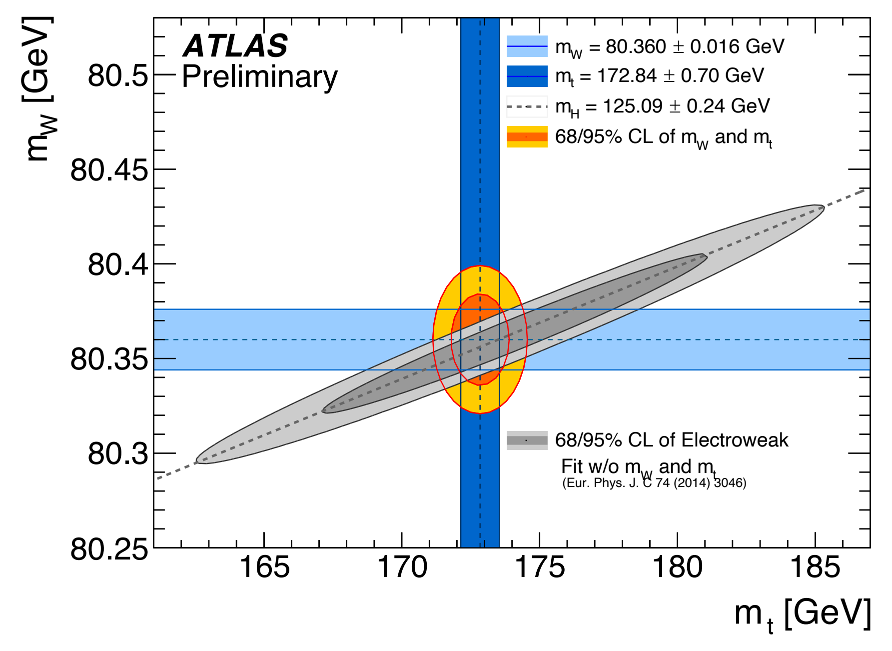
W Mass: What is Measured?

- Use the Run-1 result with 4.6fb^{-1} of 7 TeV ATLAS data
- Perform a fit of the p_T^l and m_T distributions on MC templates with different M_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 ± 5 (stat) ± 15 (syst) 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 (1σ); 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

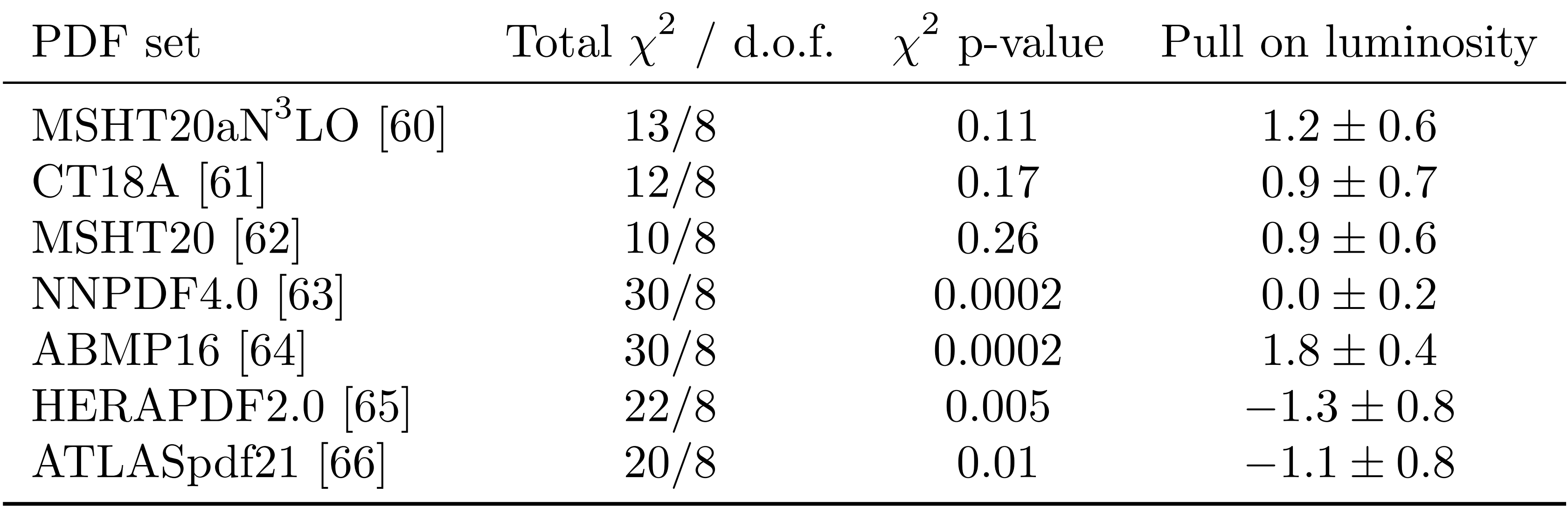
- Two very new Run-2 data Z measurements at low p_T are presented
  - A Full phase space Z $d\sigma/dp_T dy$ cross section from angular coefficients;
  - The strong coupling constant at the scale M_Z.

- Also improved on the W mass measurement

- From these measurements, we learned :
  - Extraordinary precision showed the accuracy of N4LLa+ N3LO shape predictions (light tension with normalization), as well as N3LO 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 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

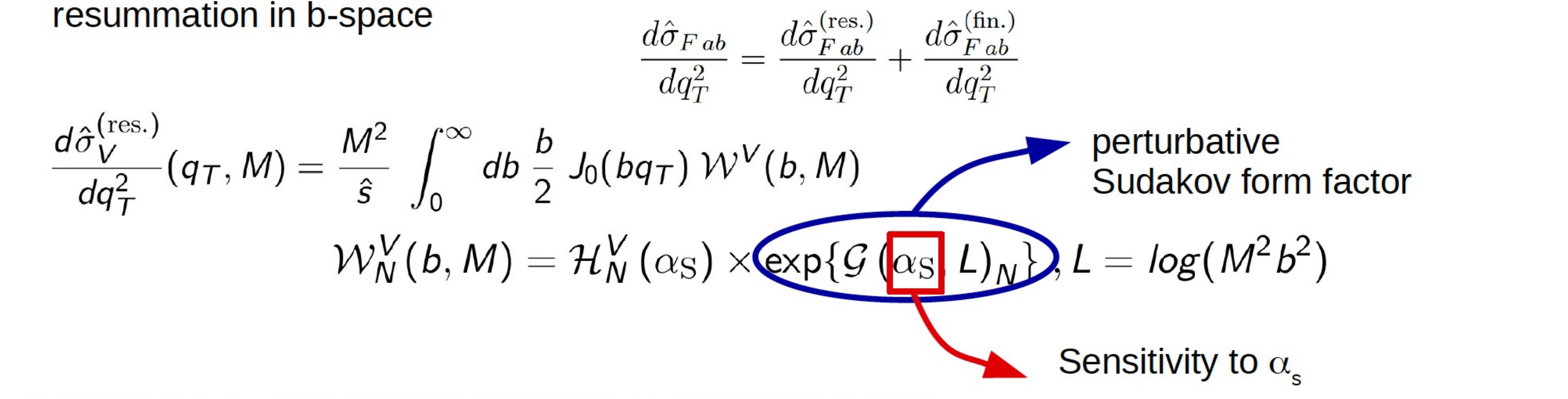
NNPDF4.0 PDF set with its much smaller uncertainties displays poor agreement with the data. This is due to the shape of the predicted distribution since the pull on the integrated luminosity is small

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(pT,y): Theory Predictions

- DYTurbo resums log-enhanced low p_T^{ll} contribution at approximate N⁴LL accuracy, combined to hard-collinear contribution at N³LO, and matched to fixed order predictions at N³LO to account for Z+jets contributions at larger p_T.
  - Performed in the impact-parameter space b (Fourier conjugate of p_T).
  - A universal (process independent) Sudakov form factor accounts for all log-divergent term in the $p_T \to 0$ limit.
  - Matching cutoff was chosen to be 5 GeV, but matching correctioons were extrapolated down to pt=0.
  - Sudakov form factors are singular for $p_T < \Lambda_{QVD}$: non-perturbative effects dominate, and are included in a form factor.



$$\frac{d\hat{\sigma}_{F\,ab}}{dq_T^2} = \frac{d\hat{\sigma}^{(\mathrm{res.})}_{F\,ab}}{dq_T^2} + \frac{d\hat{\sigma}^{(\mathrm{fin.})}_{F\,ab}}{dq_T^2}$$

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

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

W Mass: Fitting Strategy

$$L\left(\mu,\vec{\theta}|N^{obs}\right)=\prod_{j}\prod_{i}\text{Poisson}\left(n_{ji}|\nu_{ji}(\mu,\vec{\theta})\right)\cdot\text{Gauss}\left(\vec{\theta}\right),$$

$$\begin{aligned}\nu_{\text{ji}}(\mu,\vec{\theta})=\Phi\times\left[S_{\text{ji}}^{\text{nom}}+\mu\times\left(S_{\text{ji}}^{\mu}-S_{\text{ji}}^{\text{nom}}\right)\right]+\sum_{s}\theta_{s}\times\left(S_{\text{ji}}^{p}-S_{\text{ji}}^{\text{nom}}\right)\\+B_{\text{ji}}^{\text{nom}}+\sum_{b}\theta_{b}\times\left(B_{\text{ji}}^{p'}-B_{\text{ji}}^{\text{nom}}\right),\end{aligned}$$

N^{obs} : Number of observed data events

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

μ : Parameter of interest, variations of MW with respect to reference

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

v_{ji} : Expectations value given in tersm of signal (Sij) and background (Bij)

Φ : Overall unconstrained normalization to ensure signal rate matches data