High-precision measurements of the Z-boson transverse momentum and α_s with ATLAS

ATLAS-CONF-2023-013

ATLAS-CONF-2023-015

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on behalf of the
ATLAS Collaboration

LHC Seminar
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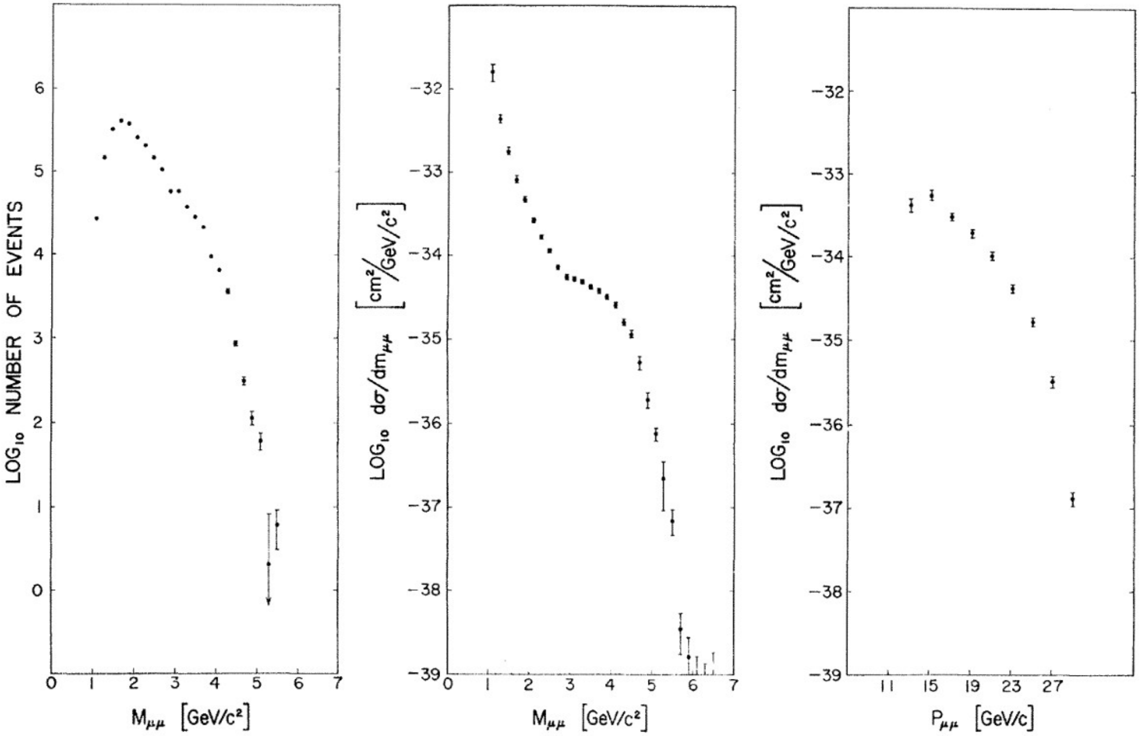
The Drell-Yan process

- The Drell-Yan process denotes the: “Massive lepton pair production in hadron-hadron collisions at high energies”, as first proposed by Sidney D. Drell and Tung-Mow Yan Phys. Rev.Lett. 25 (1970) 316
- The Drell-Yan mechanism was proposed and observed in 1970. It was a milestone in the building of QCD as the theory of the strong interaction Phys. Rev. Lett. 25 (1970) 1523

AGS at BNL

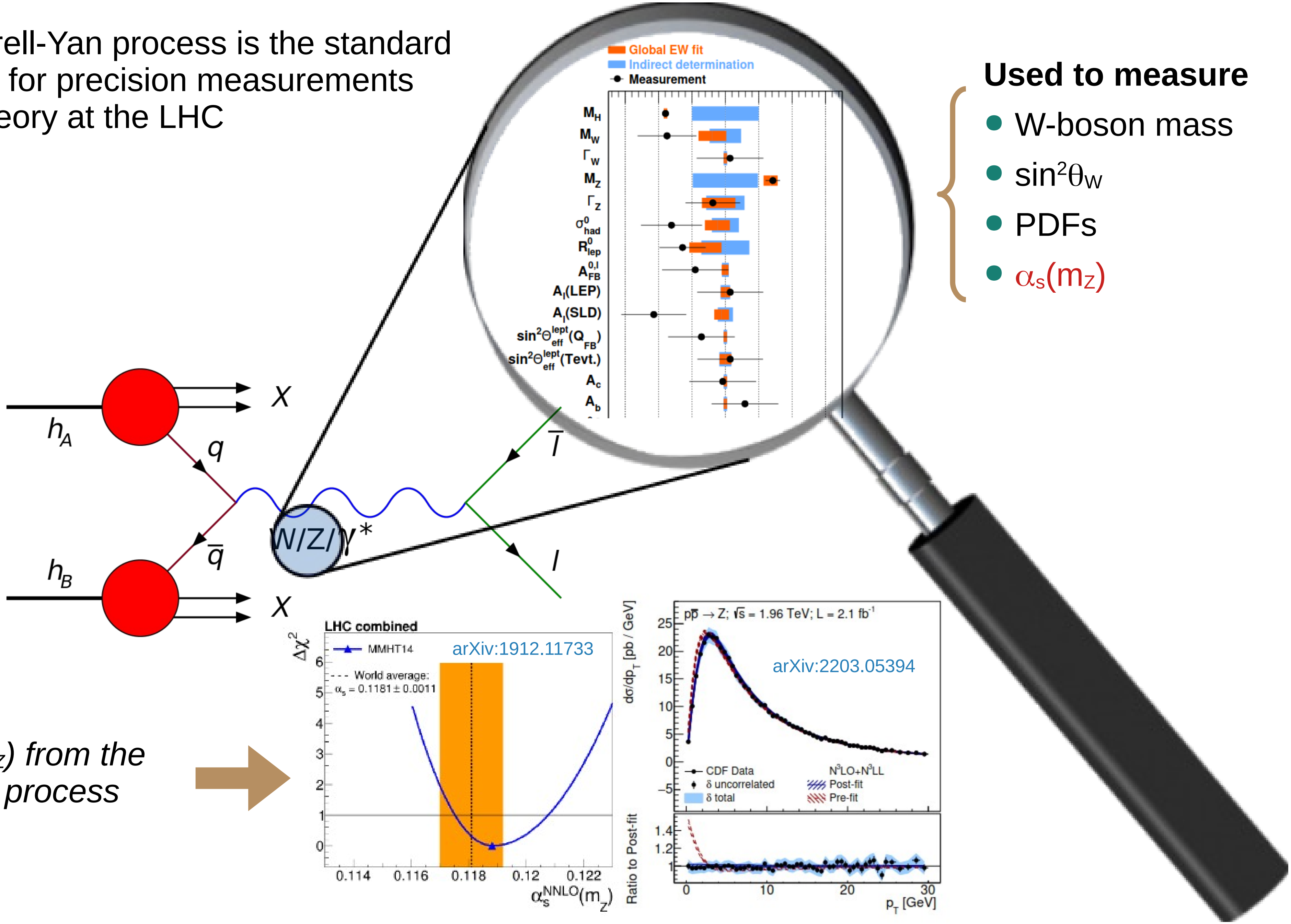


After 50 years, why is this process still of interest and what can we learn from it?

- In 1983 led to the discovery of W and Z bosons, which helped confirming the theory of the electroweak unification

Drell-Yan and EW parameters

- The Drell-Yan process is the standard candle for precision measurements and theory at the LHC



Used to measure

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

$\alpha_s(m_Z)$ from the DY process

Presenting today a high-precision determination of $\alpha_s(m_Z)$ with a novel methodology

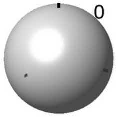
Anatomy of Drell-Yan cross sections

- A convenient way of expressing the radiation-inclusive DY cross section is through the factorisation of the production dynamic and the decay kinematic properties of the dilepton system

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

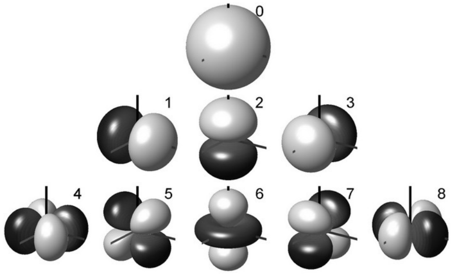
- Decomposition of $(\cos\theta,\phi)$ into 9 helicity cross sections → basis of spherical harmonics

Why 9?



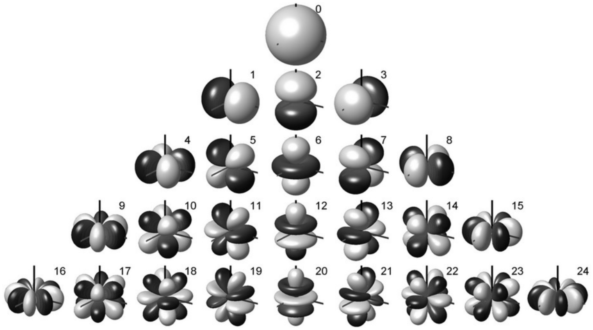
Spin 0 (Higgs)

$\ell = 0$
n = 1



Spin 1 (W,Z,γ*)

$\ell \leq 2$
n = 1+3+5 = 9



Spin 2

$\ell \leq 4$
n = 1+3+5+7+9 = 25

ℓ denotes the degree of the spherical harmonics

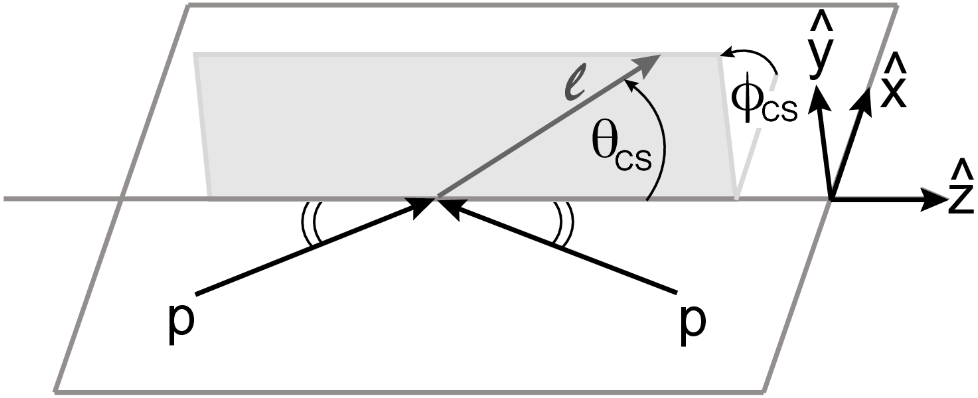
Measurement strategy

- Exploit the angular variables decomposition to perform a simultaneous 2D p_T-y measurement of
  - Unpolarised full-lepton phase space cross sections
  - Angular coefficients

$$\boxed{\frac{d^2\sigma}{dp_T dy}}\left(1+\cos^2\theta+\sum\boxed{A_i(p_T,y)}P_i(\cos\theta,\phi)\right)$$

$$\left\{\begin{aligned}
P_0(\cos\theta,\phi) &= \frac{1}{2}(1-3\cos^2\theta)\\
P_1(\cos\theta,\phi) &= \sin 2\theta\cos\phi\\
P_2(\cos\theta,\phi) &= \frac{1}{2}\sin^2\theta\cos 2\phi\\
P_3(\cos\theta,\phi) &= \sin\theta\cos\phi\\
P_4(\cos\theta,\phi) &= \cos\theta\\
P_5(\cos\theta,\phi) &= \sin^2\theta\sin 2\phi\\
P_6(\cos\theta,\phi) &= \sin 2\theta\sin\phi\\
P_7(\cos\theta,\phi) &= \sin\theta\sin\phi
\end{aligned}\right.$$

- This is in practice a 4D measurement of the DY process in p_T,y,cosθ,ϕ



- Coefficients defined in the Collins-Soper frame

Full-lepton phase space

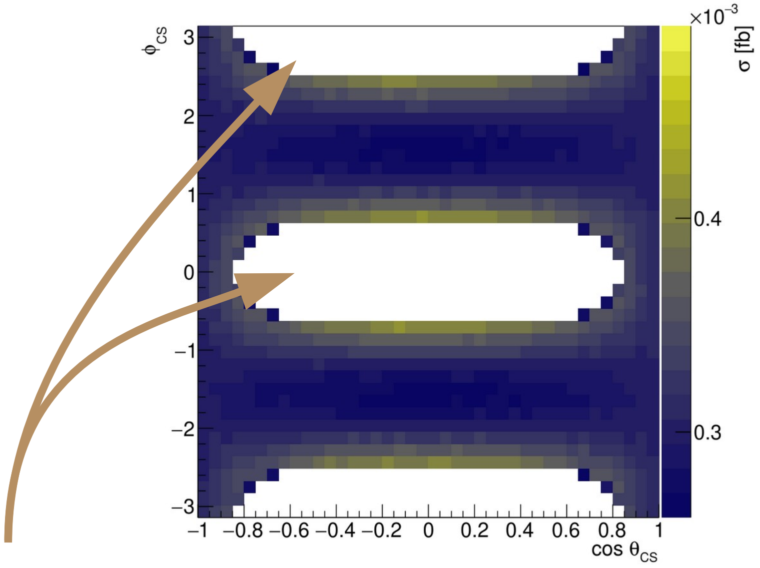
$$\frac{d^3\sigma^{U+L}}{dp_T\,dy\,dm}\left(1+\cos^2\theta+\sum_{i=0}^{7}A_i(y,p_T,m)P_i(\cos\theta,\phi)\right)$$

Boson production variables

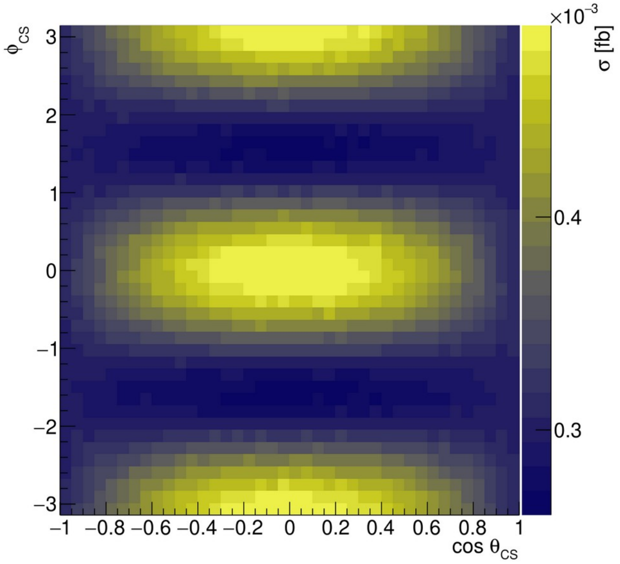
Leptonic decay variables

- The unpolarised cross sections do not depend on lepton variables, they are defined in “full-lepton phase space”, only by cuts (or bins) in p_T,y,m of the boson
- In contrast, fiducial cross sections are defined with cuts on the lepton variables $p_T(\ell)$ and $\eta(\ell)$

Fiducial



Full-lepton phase space



Effect of $p_T(\ell)$ and $\eta(\ell)$ cuts at fixed boson p_T,y,m

1) **Methodology**

2) Z-boson rapidity measurement

3) Z-boson p_T measurement

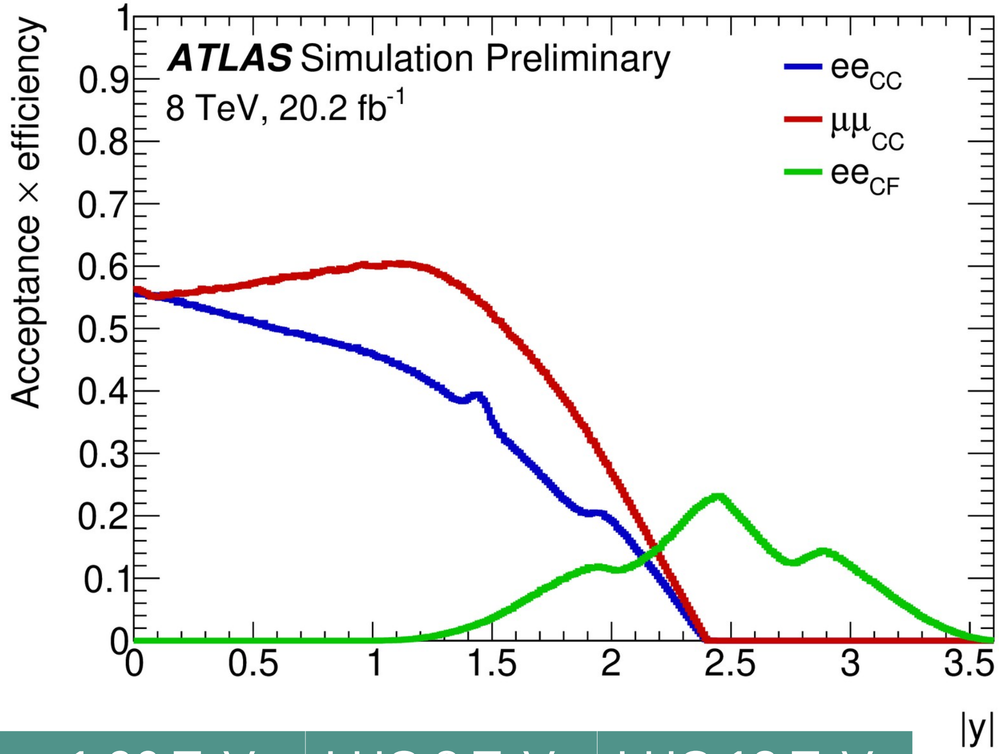
4) Connection to m_W physics modelling

5) Strong coupling constant $\alpha_s(m_Z)$

Event selection

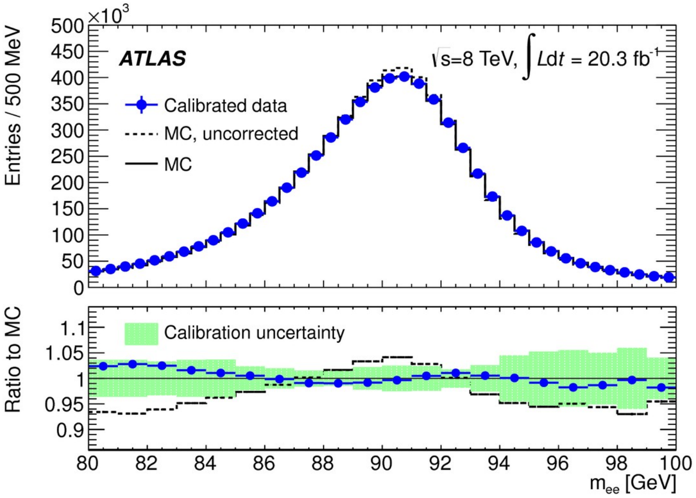
- $\sqrt{s}$ = 8 TeV, L = 20.2 fb^{-1}
- Three channels:
  - ee_{CC}: 2 electrons with p_T > 20 GeV, $|\eta| < 2.4$
  - $\mu\mu_{CC}$: 2 muons with p_T > 20 GeV, $|\eta| < 2.4$
  - ee_{CF}: central electron with p_T > 25 GeV, $|\eta| < 2.4$, forward electron with p_T > 20 GeV, $2.5 < |\eta| < 4.9$
- $80 < m_{ll} < 100$ GeV
- Double differential p_T, y cross section
  - 8 y bins over $|y| < 3.6$
  - 23 p_T bins: {0, 2.5, 5.0, 8.0, 11.4, 14.9, 18.5, 22.0, 25.5, 29.0,32.6, 36.4, 40.4, 44.9, 50.2, 56.4, 63.9, 73.4, 85.4, 105.0, 132.0, 173.0, 253.0, 4000}

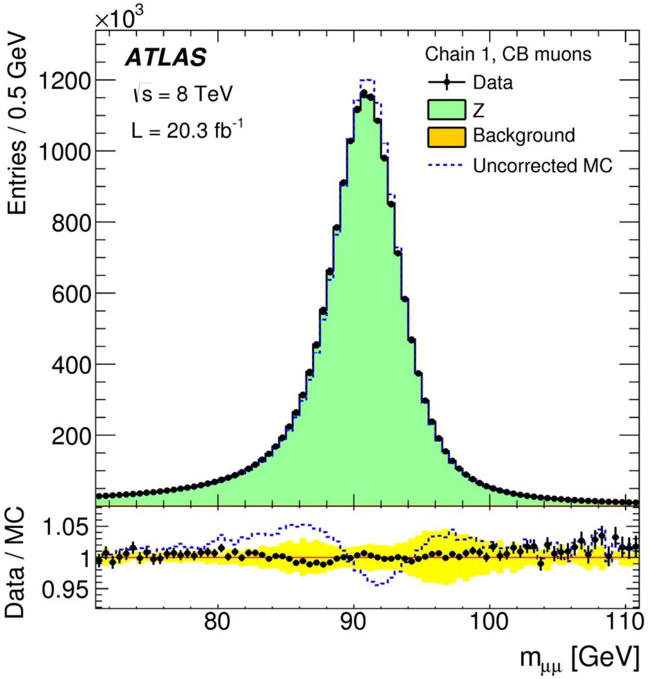
Channel	Events
ee_{CC}	6.2 M
$\mu\mu_{CC}$	7.8 M
ee_{CF}	1.3 M
Total	15.3 M



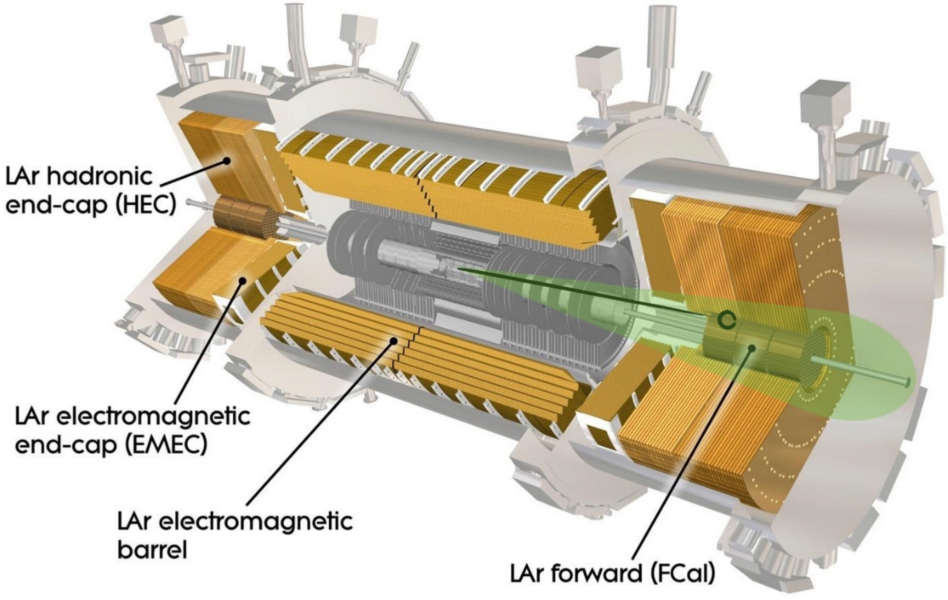
	UA1/UA2	LEP	Tevatron 1.96 TeV	LHC 8 TeV	LHC 13 TeV
$Z \rightarrow \ell\ell$ events	200	500 K	300 K	15 M	150 M

Lepton calibration



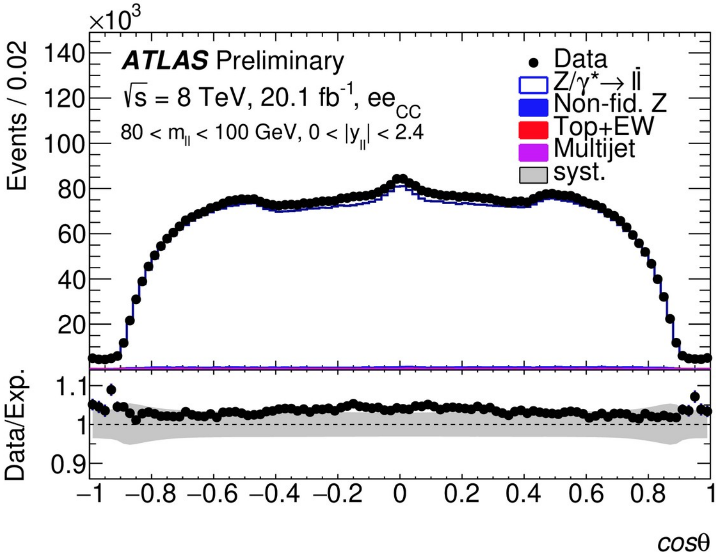


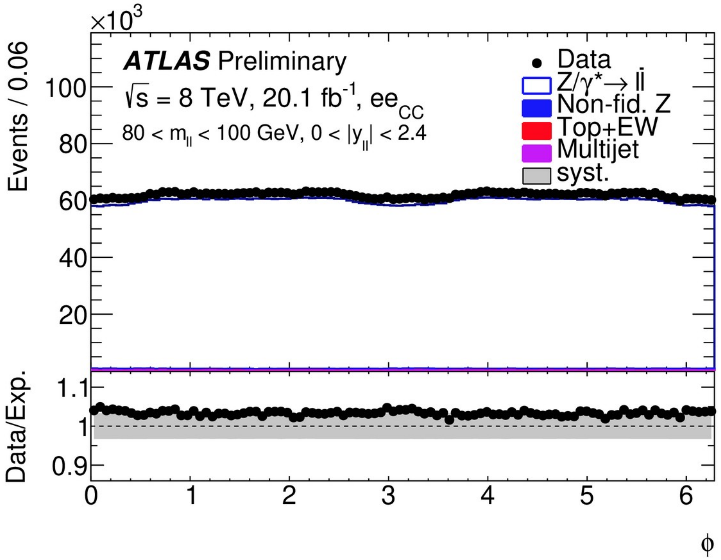
- Analysis benefits from precise Run 1 lepton calibration
- Electron and muon momentum scales typically accurate to to 0.05%
- Dedicated improved forward electron calibration including
  - Misalignment corrections
  - Azimuthal intercalibration
  - Improved simulation of lateral shower shapes combined with improved correlated calibration
  - CC/CF compatibility p-value improved from < 10^{-4} to 3%

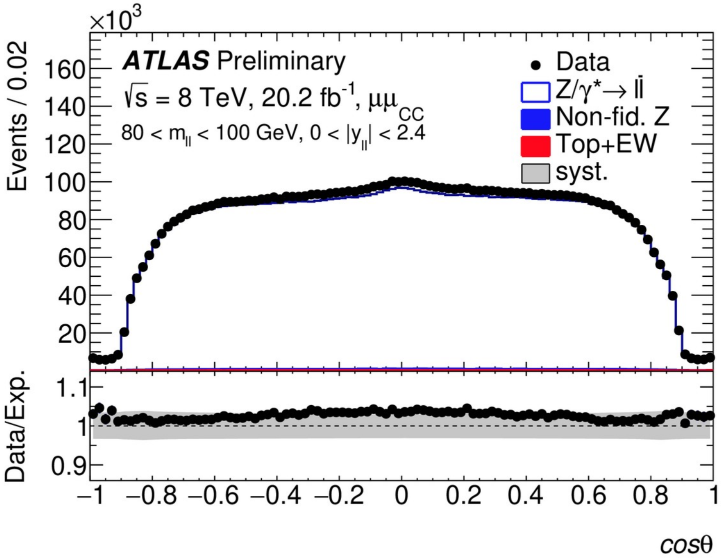


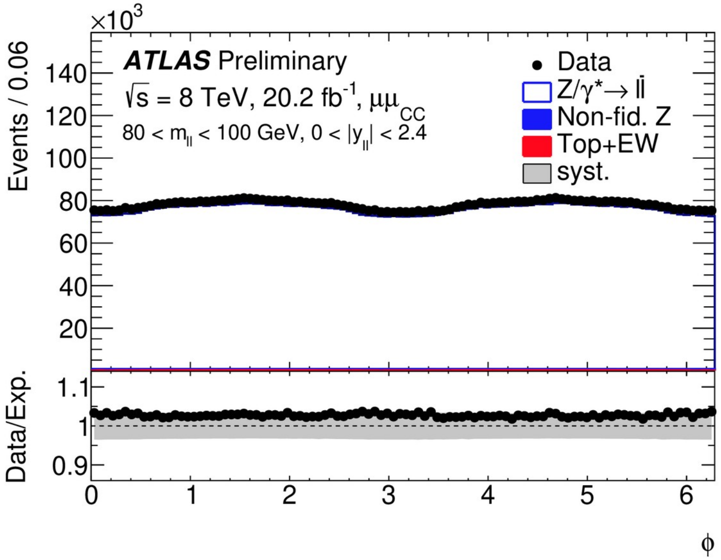
Measured angular distributions

- The foundations of the measurement are the detector-level cosθ and ϕ distributions in bins of transverse-momentum, p_T and rapidity, y





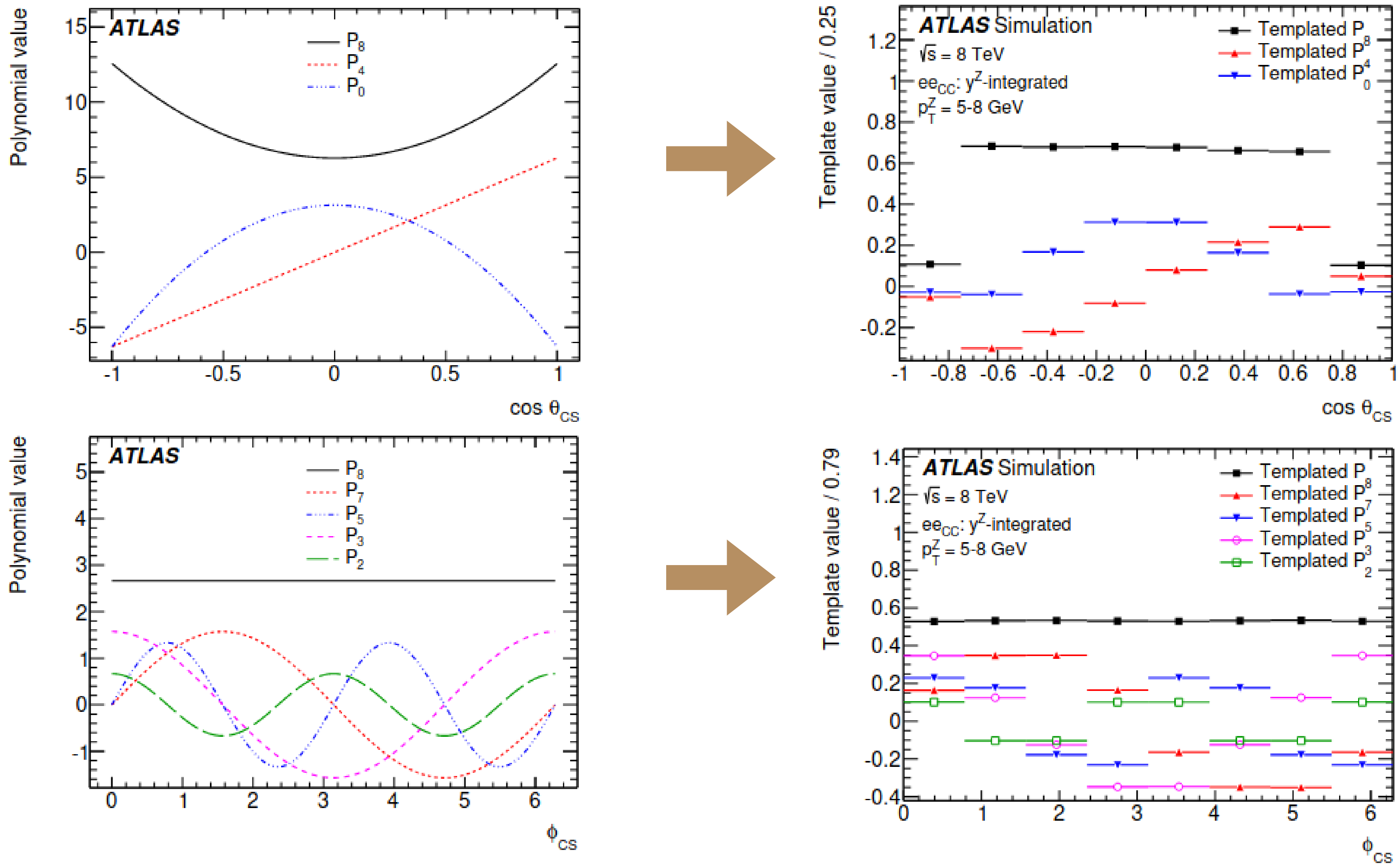




Measurement methodology

Truth level

Detector level



- Unweight the signal MC to flat cosθ-ϕ, and reweight to each spherical harmonic polynomial Pi for building detector-level templates
    - → Remove Ai dependence of the signal MC

Measurement methodology

Expected Yield

Reco (p_T^Z,y^Z,m^Z, cosθ, ϕ) bin

Cross section

Background template

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

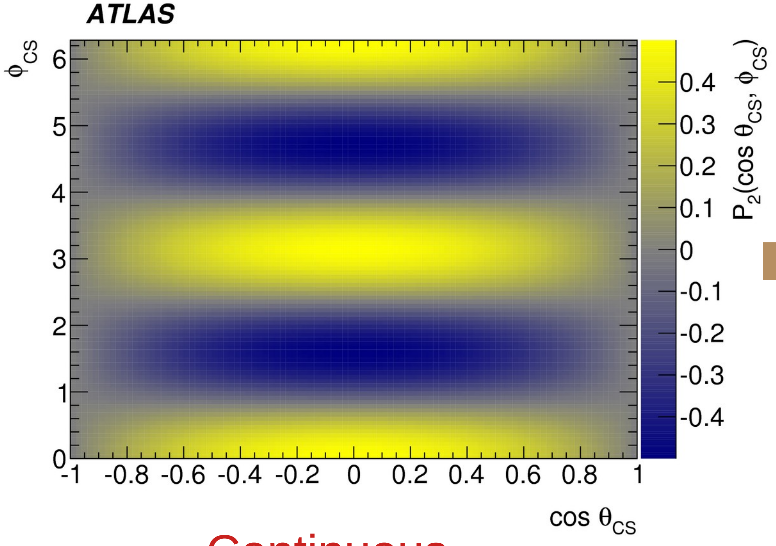
Truth (p_T^Z,y^Z,m^Z) bin

Angular coefficient

Templated polynomial

- Link detector-level observed cosθ,ϕ distributions to the MC template of spherical harmonic polynomials
- Define a likelihood with 22528 (cosθ,ϕ,p_T,y) bins
- Parameters of interests are the 8 Ai + 1 cross section in p_T-y bins: 9 parameters in 176 bins → 1584 free parameters

Measurement methodology



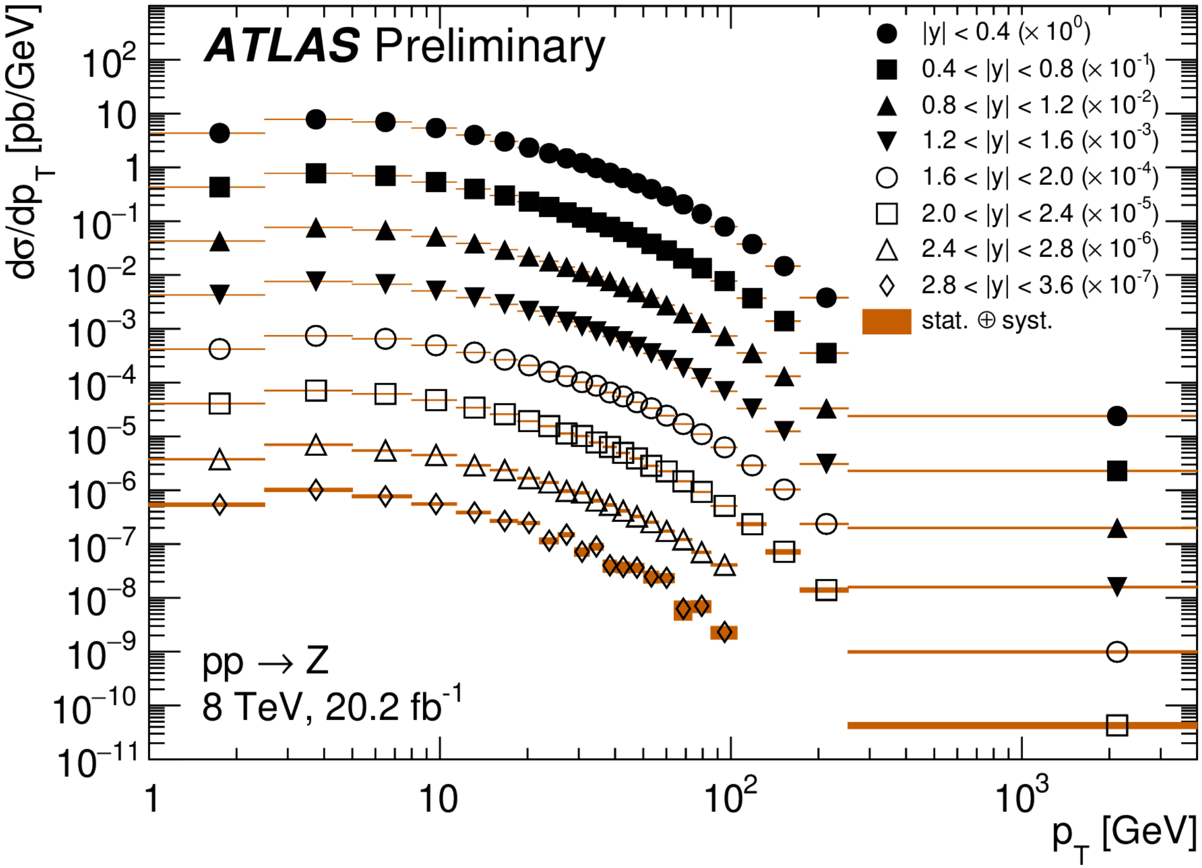
Continuous

$$\begin{pmatrix} H_0 \\ H_1 \\ H_2 \\ H_3 \\ H_4 \\ H_5 \\ H_6 \\ H_7 \\ H_8 \end{pmatrix} \times \begin{pmatrix} \frac{1}{2}(1-3\cos^2\theta) \\ \sin 2\theta\cos\phi \\ \frac{1}{2}\sin^2\theta\cos 2\phi \\ \sin\theta\cos\phi \\ \cos\theta \\ \sin^2\theta\sin 2\phi \\ \sin 2\theta\sin\phi \\ \sin\theta\sin\phi \\ 1+\cos^2\theta \end{pmatrix} \left\{ \begin{array}{l} \dfrac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta\,\mathrm{d}\phi} = \displaystyle\sum_{i=0}^{8} H_i P_i \\ A_i = \dfrac{H_i}{H_8} \\ H_8 = \sigma^{U+L} \end{array} \right.$$

Quantized

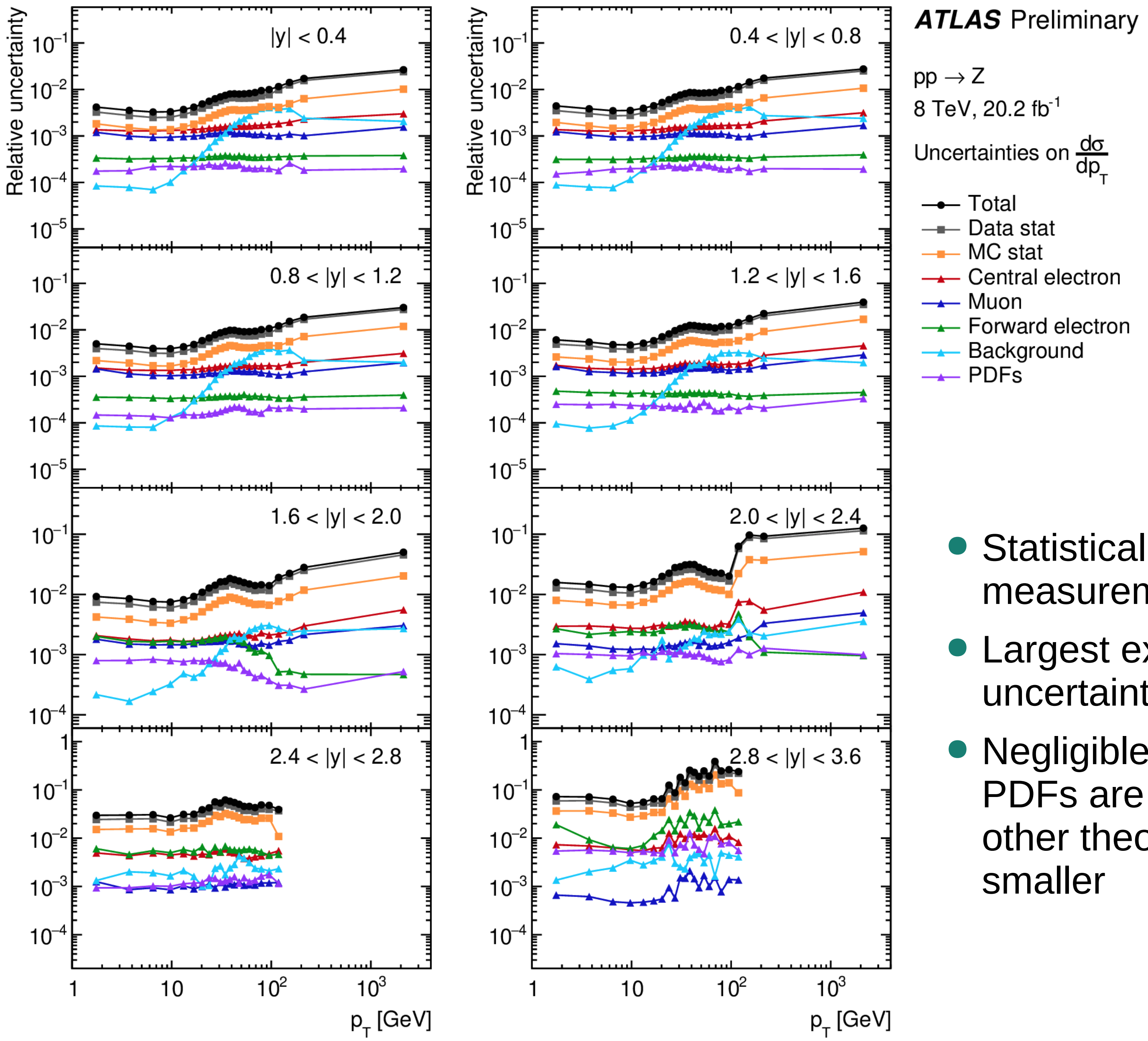
- Measuring the angular coefficients corresponds to building a synthetic “quantized” representation of the (cosθ,ϕ) kinematic space in terms of helicity cross sections $H_{0\text{-}8}$
- Trade experimental systematics for statistics
- Avoids theoretical extrapolation of fiducial lepton cuts to full phase space and thereby opens the door to a rich field of precise interpretations

dσ/d$p_T$dy measurement



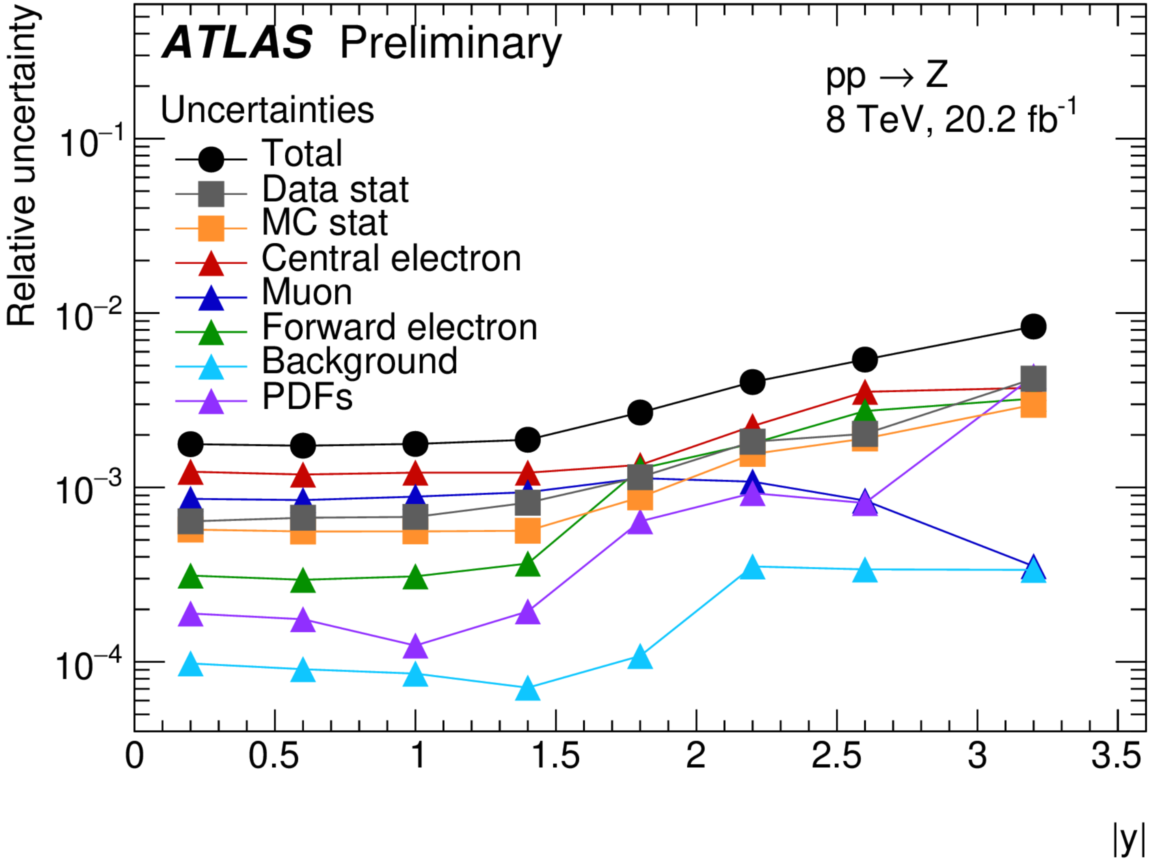
- First measurement at the LHC of full-lepton phase space cross sections
- Double differential in p_T and rapidity
- Angular coefficients are simultaneously measured, updating and extending previous ATLAS measurement

dσ/dp$_T$dy measurement uncertainties



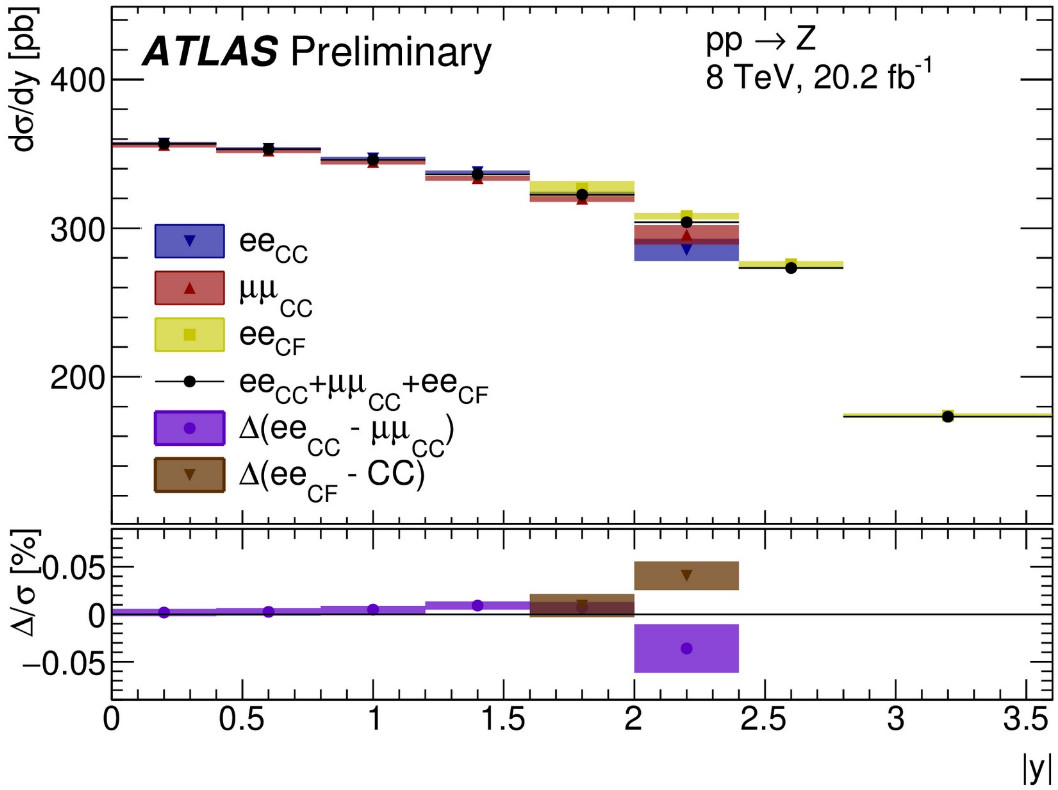
- Statistically dominated measurement
- Largest experimental systematic uncertainties from lepton calibration
- Negligible theory uncertainties: PDFs are at the level of 10^{-4} / 10^{-3}, other theory uncertainties even smaller

dσ/dy measurement uncertainties



- Permille level precision in the central region, subpercent uncertainties up to |y| < 3.6, with a factor of 2 improvement in the forward region with respect to previous measurement
- Dominant uncertainties from lepton calibration
- Also in this case small/negligible theory uncertainties (PDFs)

Channels compatibility



- Compatibility between channels was checked double differentially in p_T and rapidity
- Most stringent test of compatibility in the dσ/dy cross section, which is dominated by lepton systematic uncertainties

1) Methodology

2) Z-boson rapidity measurement

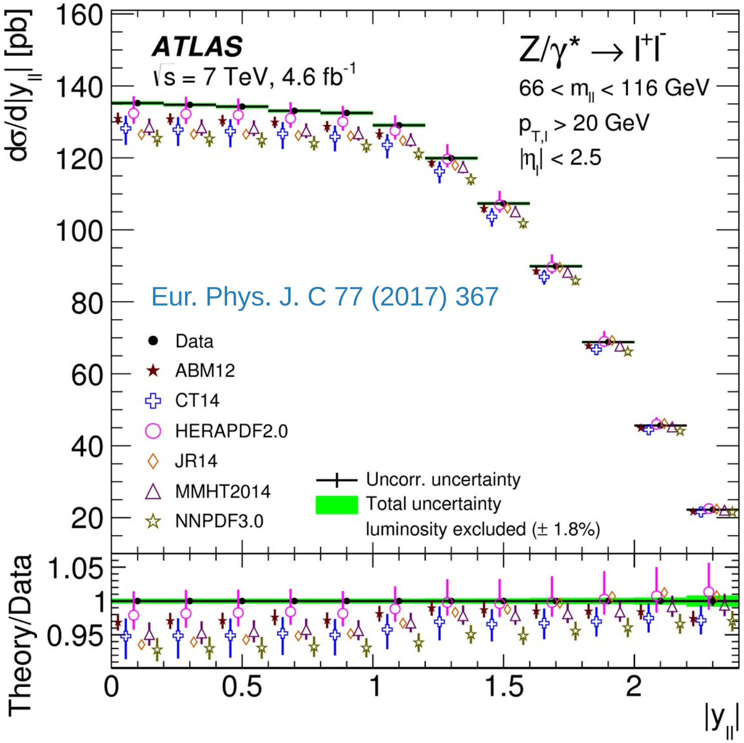
3) Z-boson p_T measurement

4) Connection to m_W physics modelling

5) Strong coupling constant $\alpha_s(m_Z)$

Full-lepton phase space rapidity

- Interpretation of fiducial cross sections hampered by breakdown of fixed order perturbation theory
  - Fiducial cuts lead to unphysical fixed order predictions
  - When approaching the limit $p_{T,2} \rightarrow p_{T,1}$ fixed order becomes unreliable
  - The issue is more critical when $p_T(\ell)$ is closer to $m_{\ell\ell}$, and at forward rapidities



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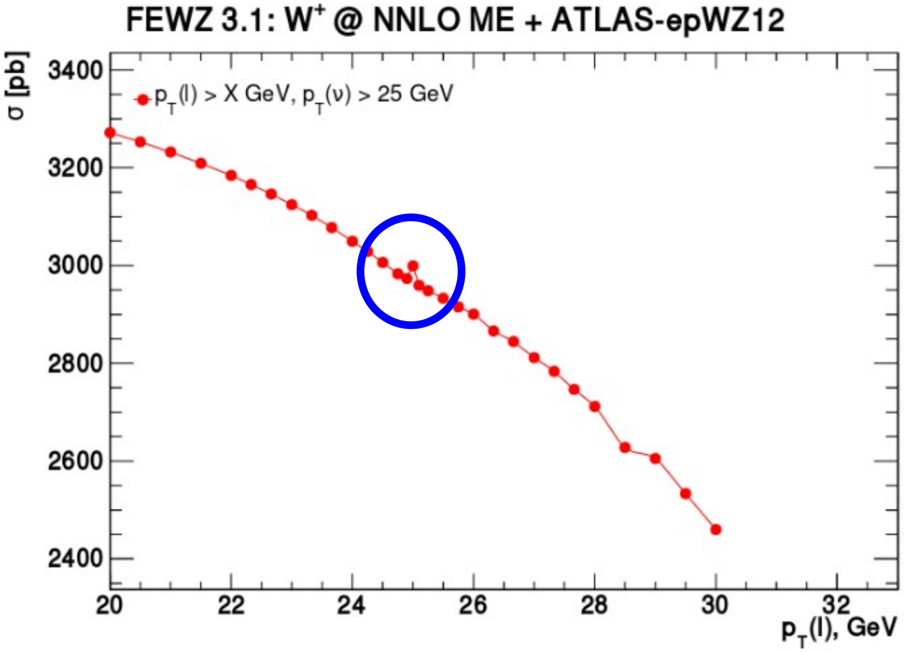
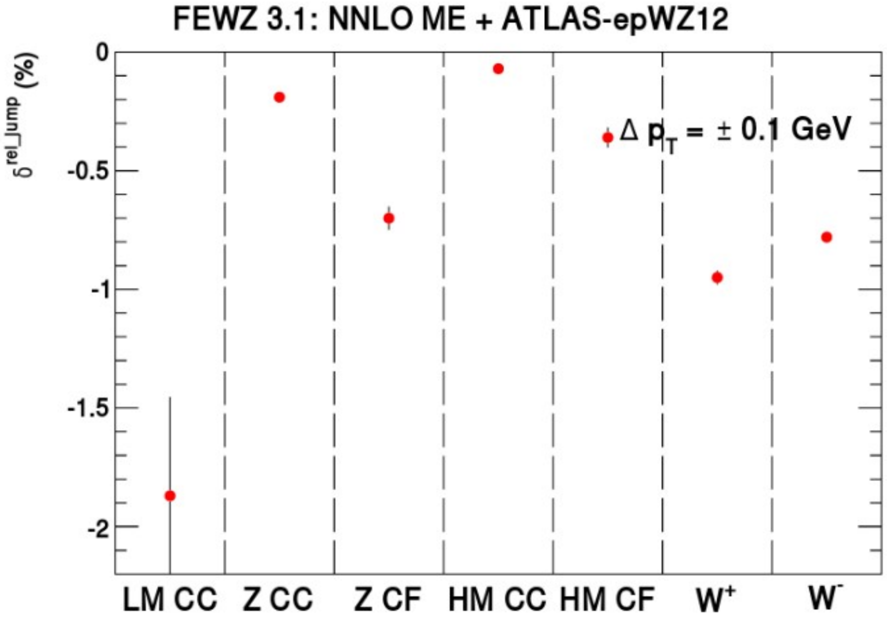
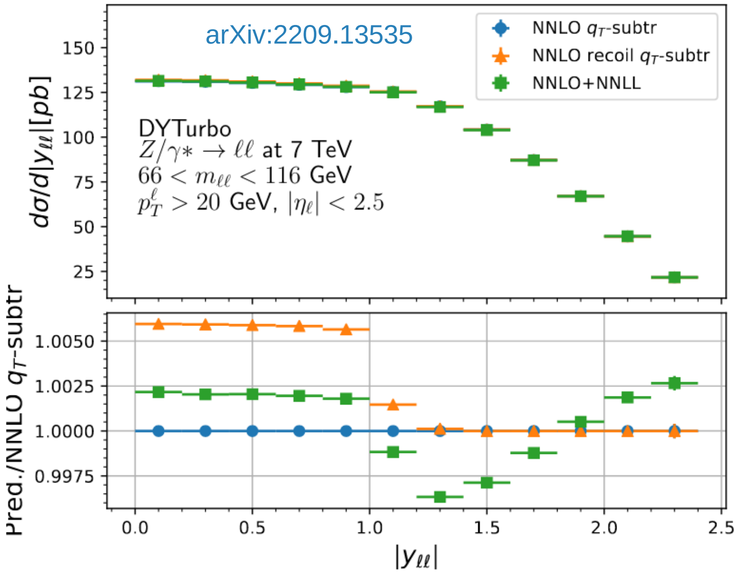


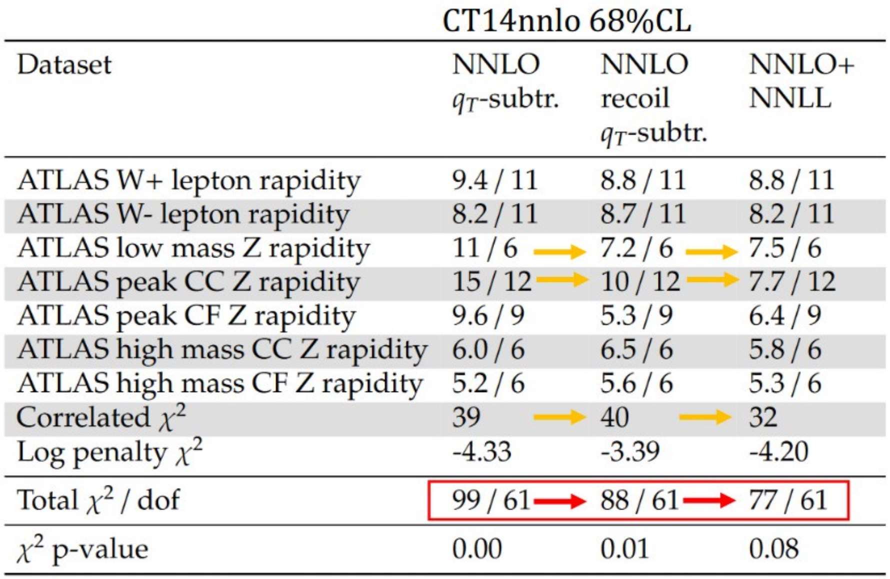


Full-lepton phase space rapidity

- The problem has received large attention with several proposed solutions:
  - Use local-subtraction scheme for fixed order predictions
    arXiv:2104.02400 Alekhin et al.
  - Change the definition of fiducial cuts
    arXiv:2106.08329 Salam, Slade
  - Use A_i theory predictions to extrapolate the measured cross sections
    arXiv:2001.02933 Glazov
  - Include resummation corrections into predictions
    arXiv:2209.13535 Amoroso et al. arXiv:2006.11382 Ebert et al.



- All above solutions introduce either experimental or theoretical uncertainties/problems
- Ai-based elegant solution:
  - Fiducial cuts removed by analytic integration of (cosθ,ϕ) in the full phase space of the decay leptons through the measured A_i coefficients
  - With only Run-1 8 TeV data, few permille total uncertainties for dσ/dy and negligible theoretical uncertainties for all measurements

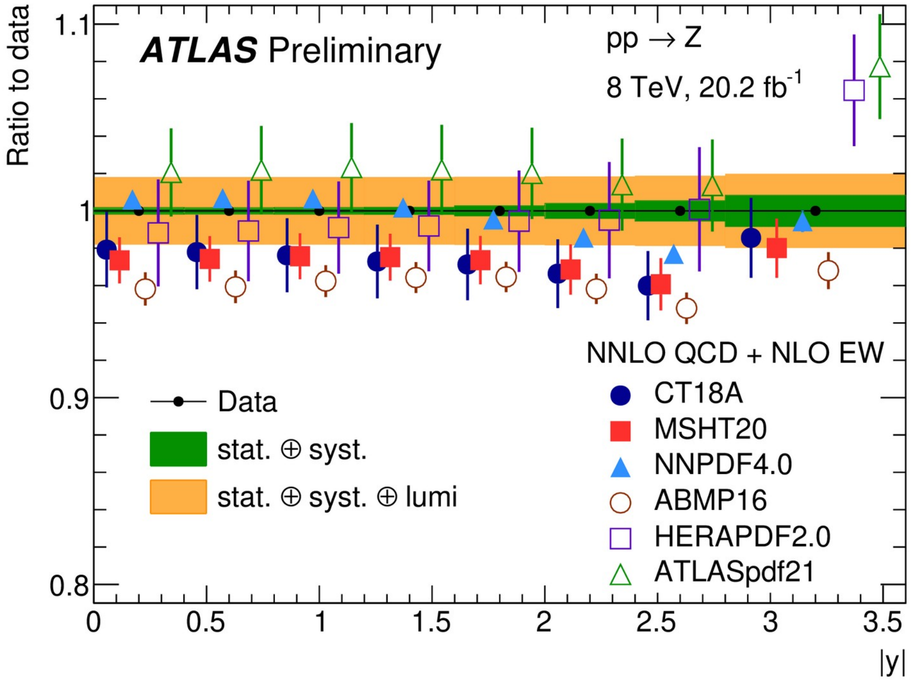


CT14nnlo 68%CL

Dataset	NNLO q_T-subtr.	NNLO recoil q_T-subtr.	NNLO+ NNLL
ATLAS W+ lepton rapidity	9.4 / 11	8.8 / 11	8.8 / 11
ATLAS W- lepton rapidity	8.2 / 11	8.7 / 11	8.2 / 11
ATLAS low mass Z rapidity	11 / 6 →	7.2 / 6 →	7.5 / 6
ATLAS peak CC Z rapidity	15 / 12 →	10 / 12 →	7.7 / 12
ATLAS peak CF Z rapidity	9.6 / 9	5.3 / 9	6.4 / 9
ATLAS high mass CC Z rapidity	6.0 / 6	6.5 / 6	5.8 / 6
ATLAS high mass CF Z rapidity	5.2 / 6	5.6 / 6	5.3 / 6
Correlated χ^2	39 →	40 →	32
Log penalty χ^2	-4.33	-3.39	-4.20
Total χ^2 / dof	99 / 61 →	88 / 61 →	77 / 61
χ^2 p-value	0.00	0.01	0.08

Full-lepton phase space rapidity

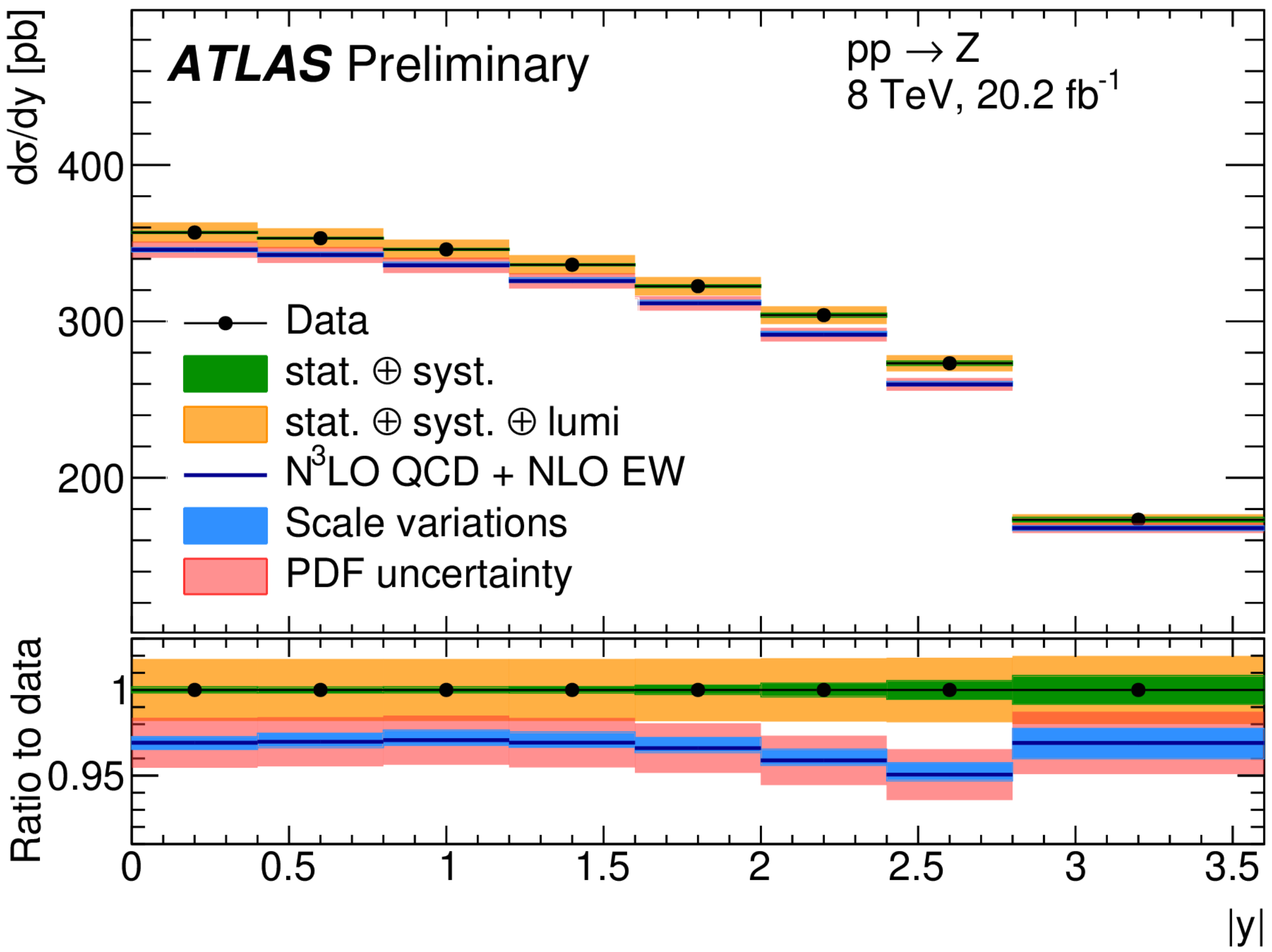
- Full-lepton phase space rapidity cross section enables precise and unambiguous PDF interpretation
- Measured total cross section in agreement with fixed order predictions within PDFs and 1.8% luminosity uncertainty
- Measurement precision provides strong PDF sensitivity from the y-differential shape
- NLO EW corrections included in the comparison (-0.4%)



	σ_Z (pb)
Data	1055 ± 19
MSHT20aN^{3}LO [60]	1023^{+6}_{-4} (scale) ± 15 (PDF)
CT18A [61]	1028 ± 19
MSHT20 [62]	1027 ± 13
NNPDF4.0 [63]	1054 ± 4
ABMP16 [64]	1014 ± 9
HERAPDF2.0 [65]	1058 ± 25
ATLASpdf21 [66]	1084 ± 25

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

Full-lepton phase space rapidity



- First comparison to N3LO QCD predictions
- Enables precise and unambiguous PDF interpretation with QCD scale variations now smaller than PDF uncertainties
- Ideal measurement to be included in the current and upcoming N3LO PDF fits

1) Methodology

2) Z-boson rapidity measurement

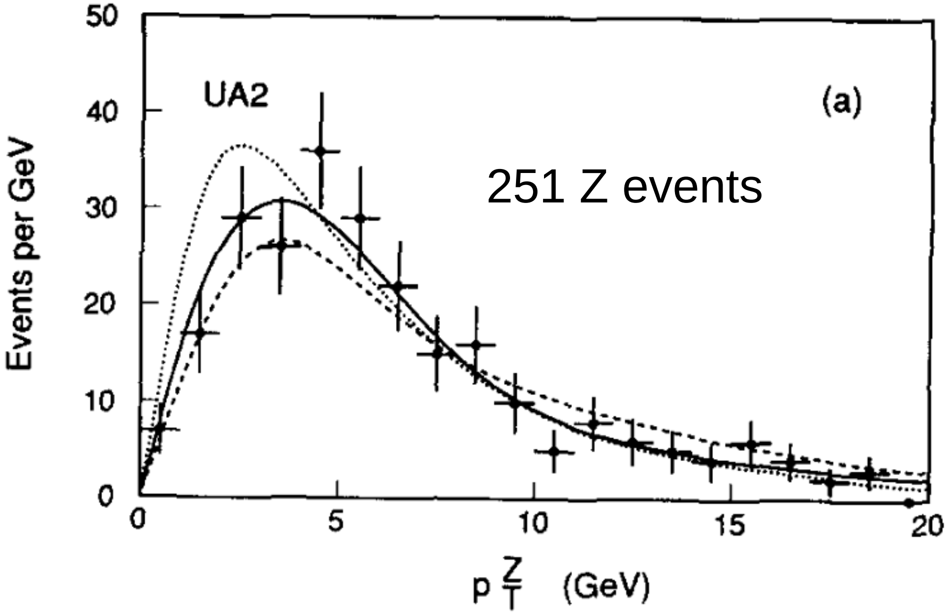
3) Z-boson p_T measurement

4) Connection to m_W physics modelling

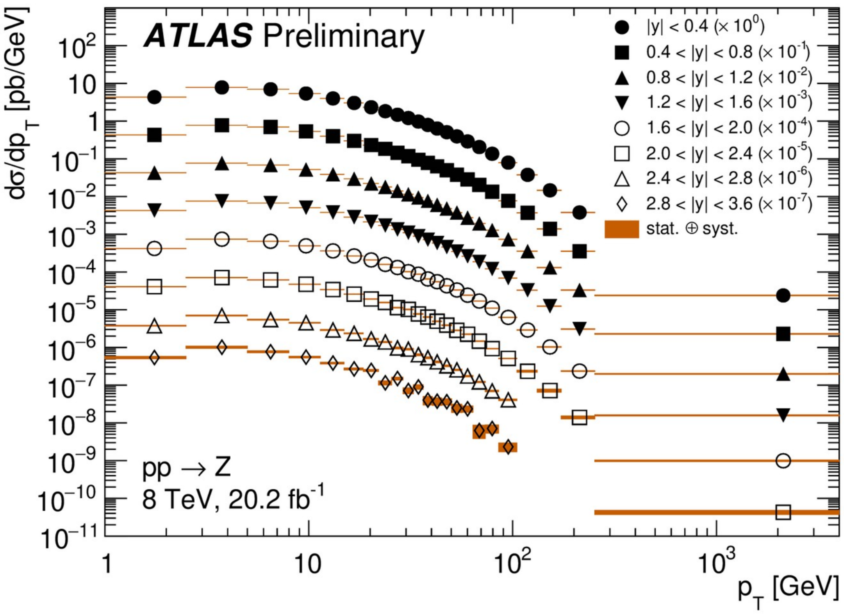
5) Strong coupling constant $\alpha_s(m_Z)$

Z-boson p_T measurement

Phys.Lett.B 276 (1992) 354-364



251 Z events



Theory predictions for p_T cross sections

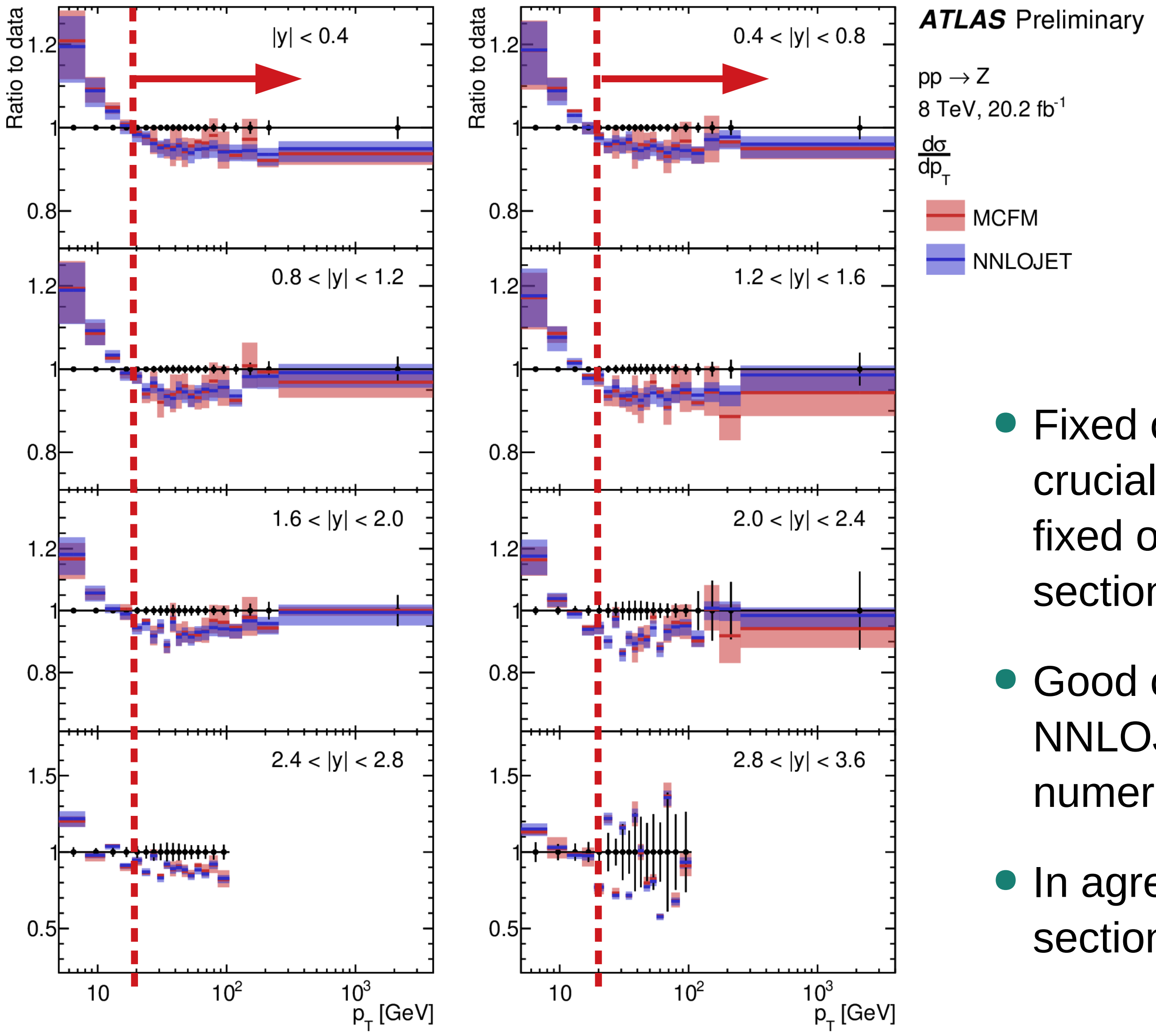
- p_T resummation can be implemented according to various different formalisms: CSS, CdFG, SCET, TMD, PS-like
- Measurement compared to all six predictions currently involved in the LPCC p_T W,Z benchmark study

Program	Formalism	Type	Reference
DYTurbo	CdFG	b-space	arXiv:1910.07049
CuTe+MCFM	SCET	p_T-space	arXiv:2207.07056
NangaParbat	TMD	b-space	arXiv:1912.07550
Artemide	TMD	b-space	arXiv:1706.01473
Radish	PS-like	p_T-space	arXiv:2104.07509
SCETlib	SCET	b-space	arXiv:2102.08039

- Not an exhaustive list, other predictions not shown:
  - RESBOS
  - ReSolve
  - CASCADE
  - Geneva
  - PBTMD
  - MiNNLO
  - ...

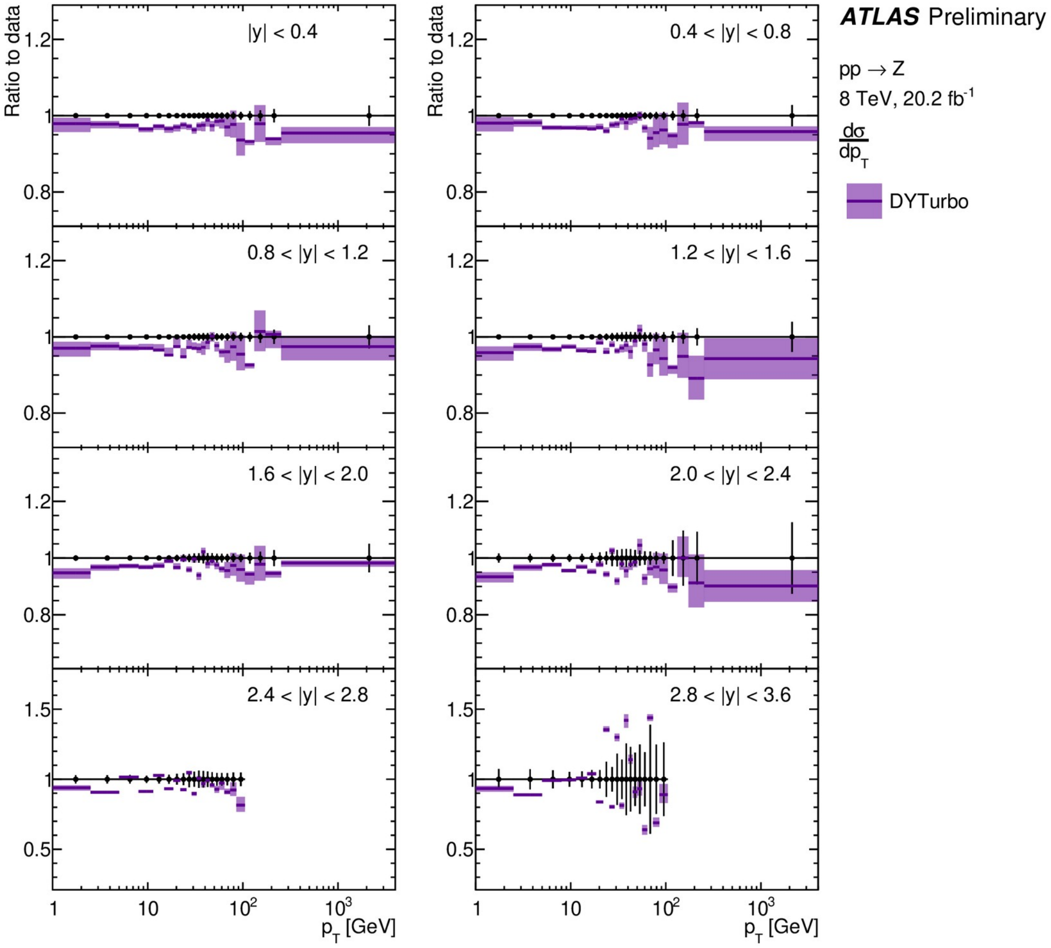
- All programs implement state-of-the-art N3LL/N4LL logarithmic accuracy
- Matching to fixed order at $O(\alpha_s^3)$ using predictions from MCFM/NNLOJET
- Many differences in methods: b-space or direct p_T space, Landau pole, matching to fixed order, scales
- All predictions provided by the authors with best settings

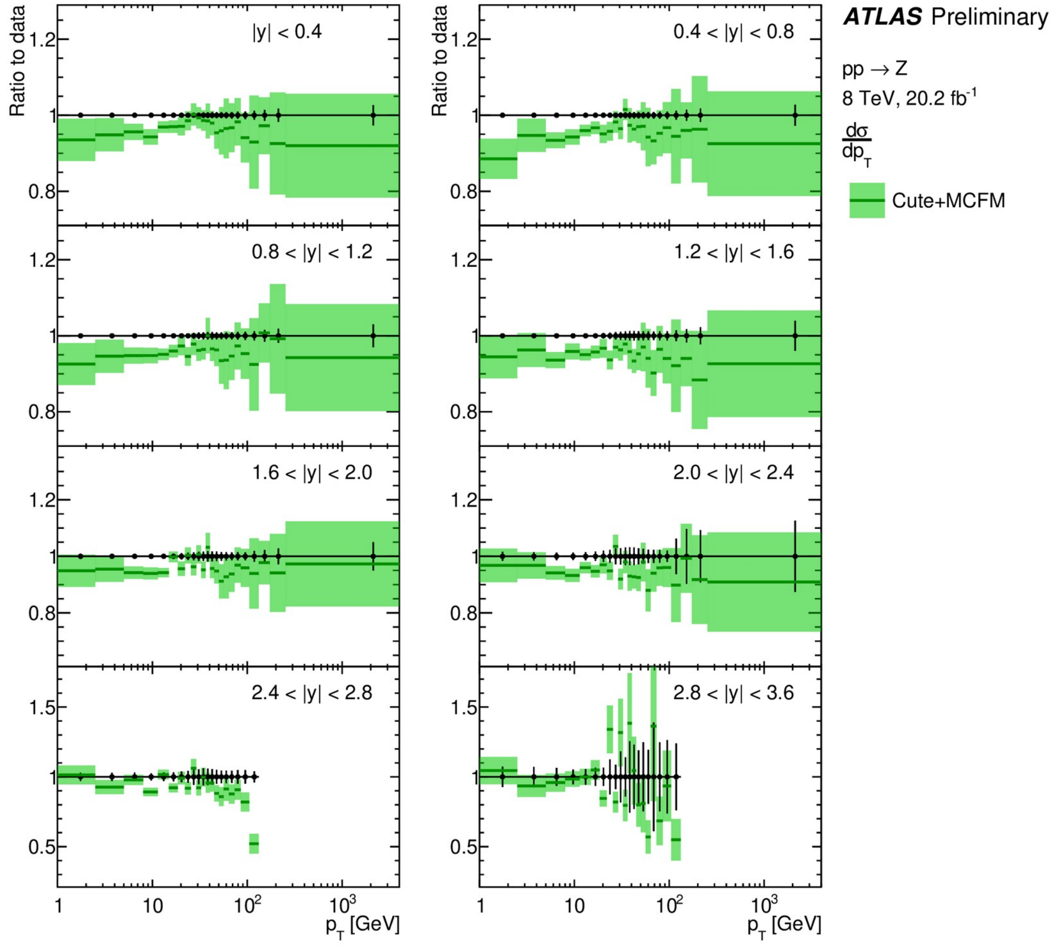
Fixed order Z+jet at NNLO



- Fixed order Z+jet at NNLO is a crucial ingredient for the matching to fixed order of q_T-resummed cross sections, and of the N3LO predictions
- Good compatibility of MCFM and NNLOJET predictions within numerical uncertainties
- In agreement with measured cross sections for p_T above 20-30 GeV

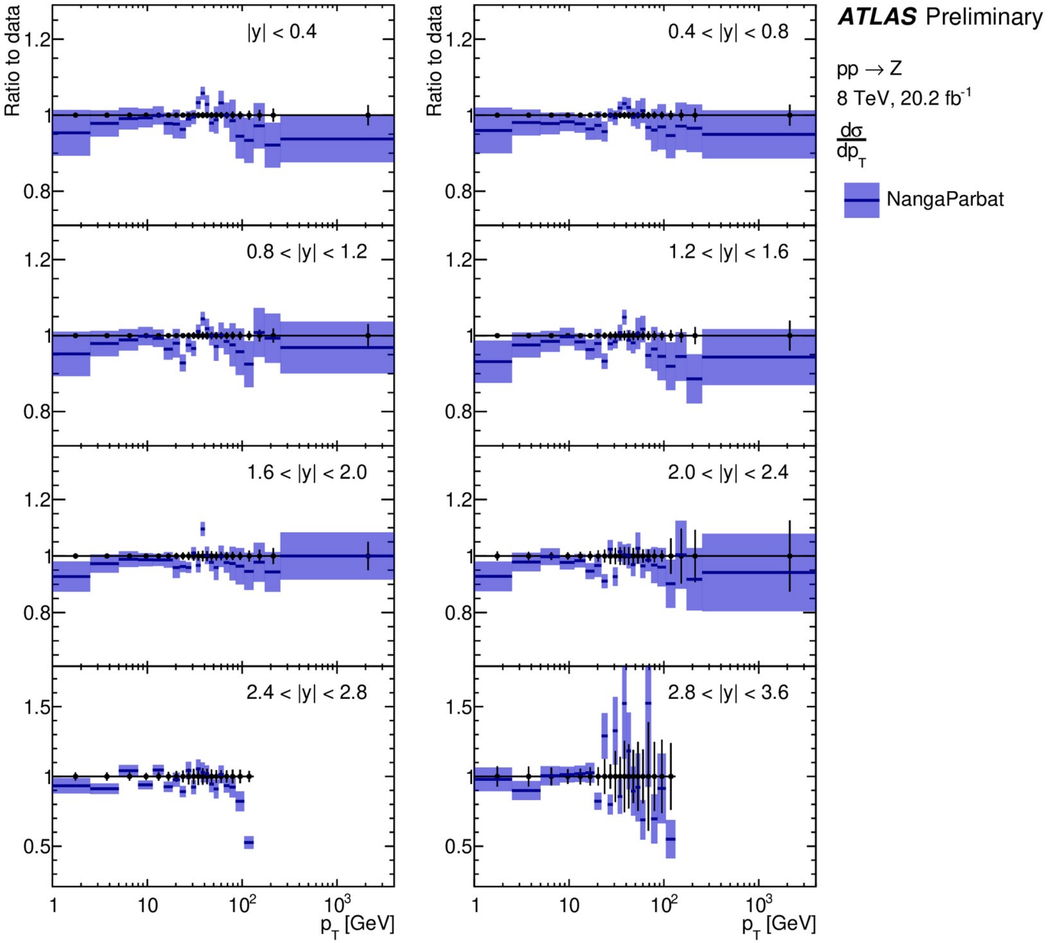
Comparison to p_T-resummation

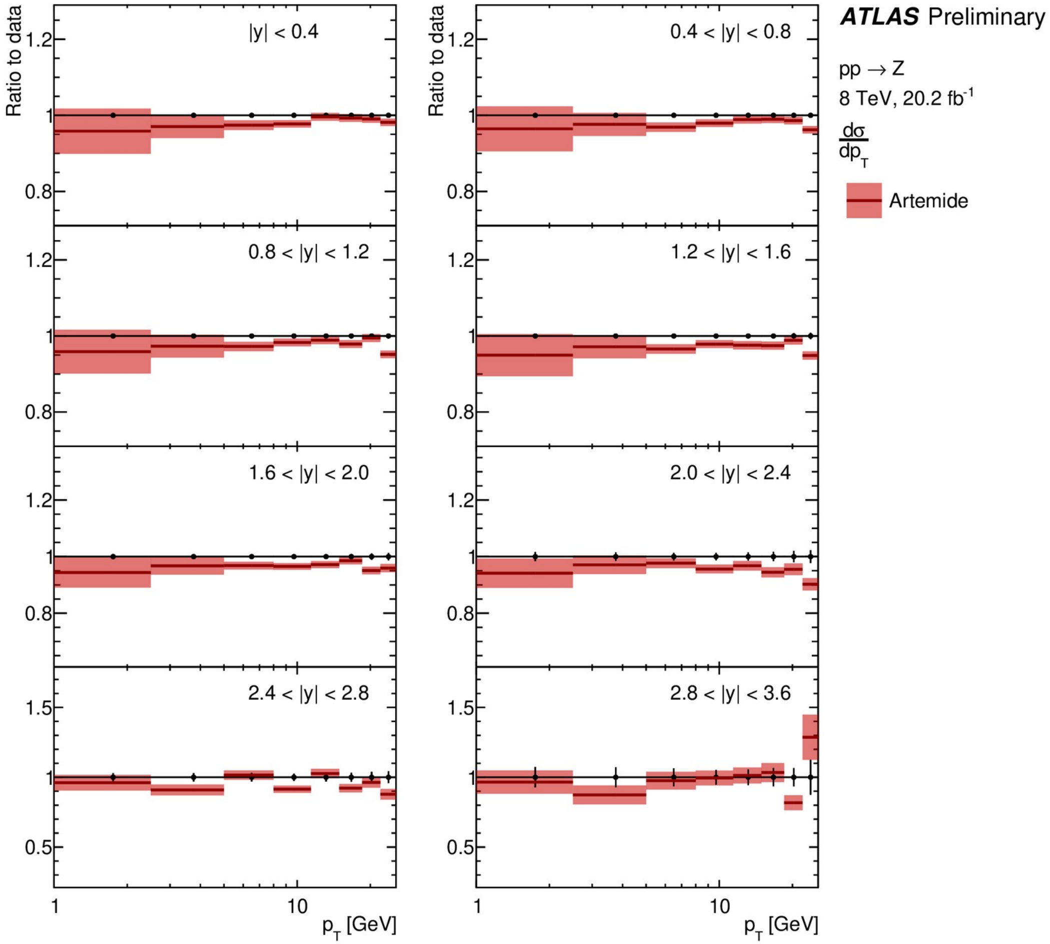




- DYTurbo, CuTe+MCFM
  - Approximate N4LL accuracy

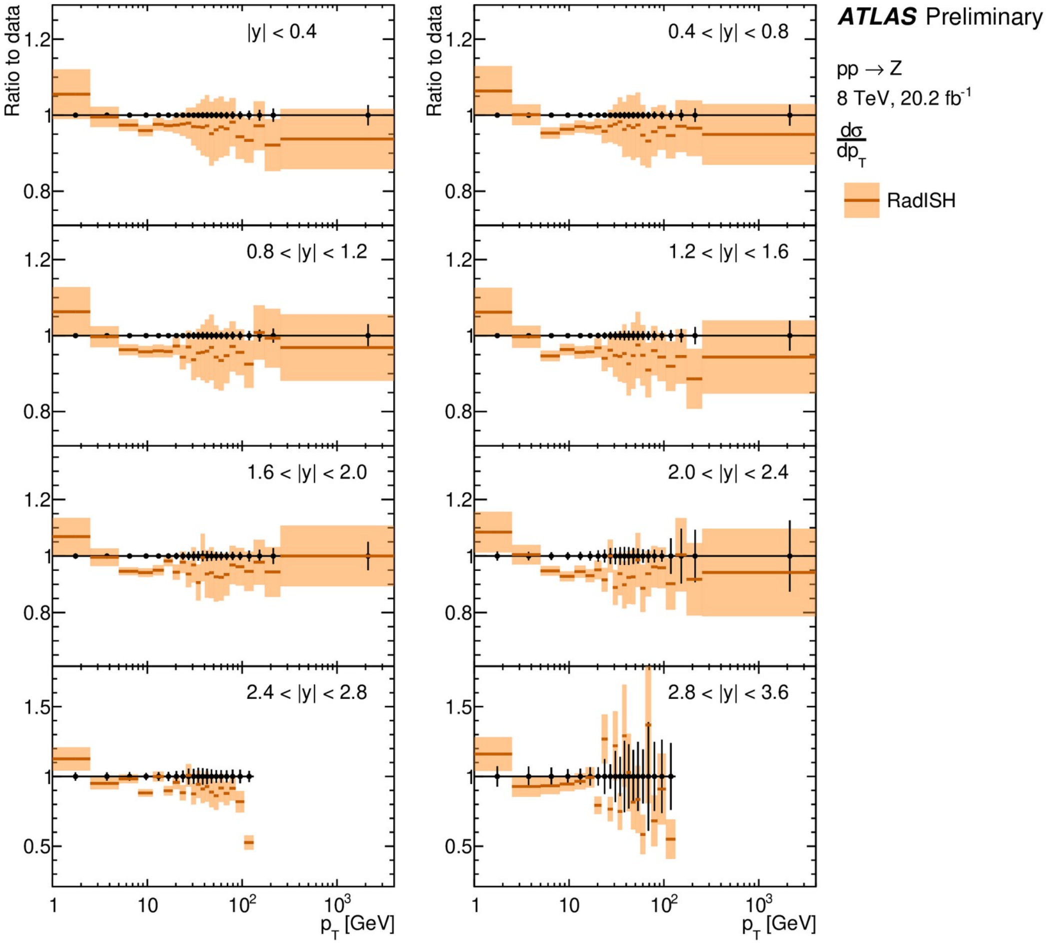
Comparison to p_T-resummation

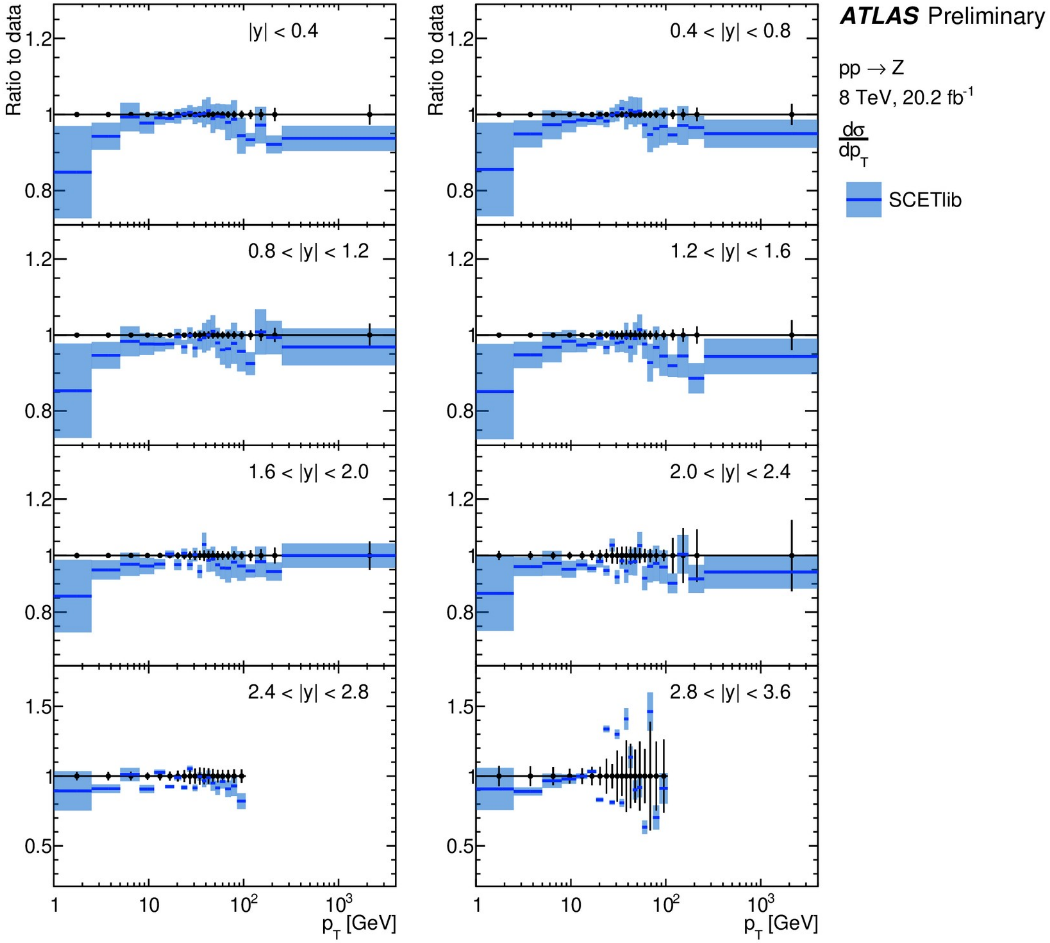




- NangaParbat and Artemide
  - Excellent agreement at low p_T
  - Non perturbative effects modelled with TMD fitted to DY and SIDIS data

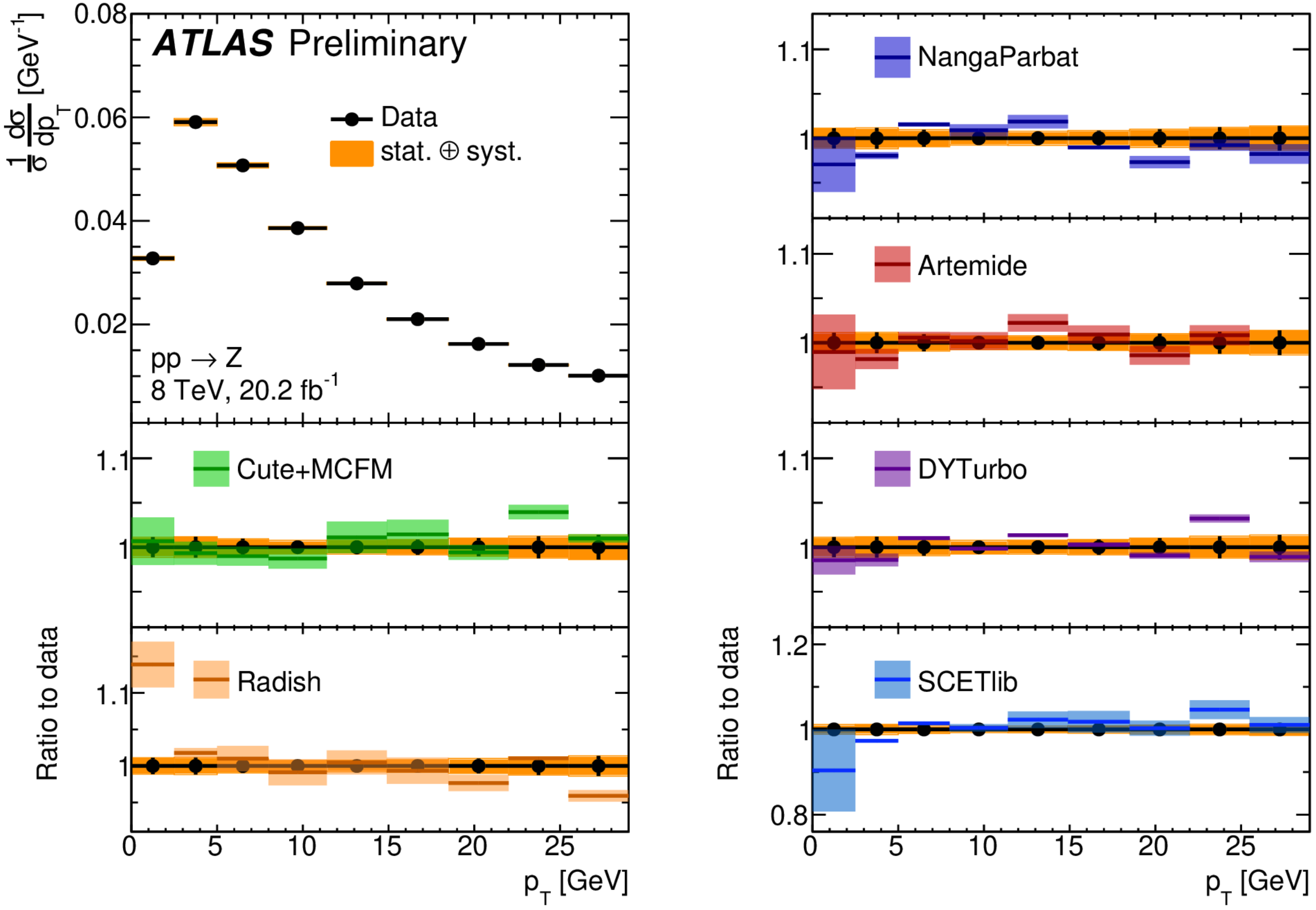
Comparison to p_T-resummation





- Radish: multiplicative matching
- SCETlib: non perturbative effects from first principles

Comparison to p_T-resummation



- Rapidity-integrated cross sections in the low p_T region
- Excellent agreement between data and all predictions
  - The result of an impressive progress in the understanding of the boson p_T modelling from the experimental and theoretical points of view
- Crucial input for m_W

1) Methodology

2) Z-boson rapidity measurement

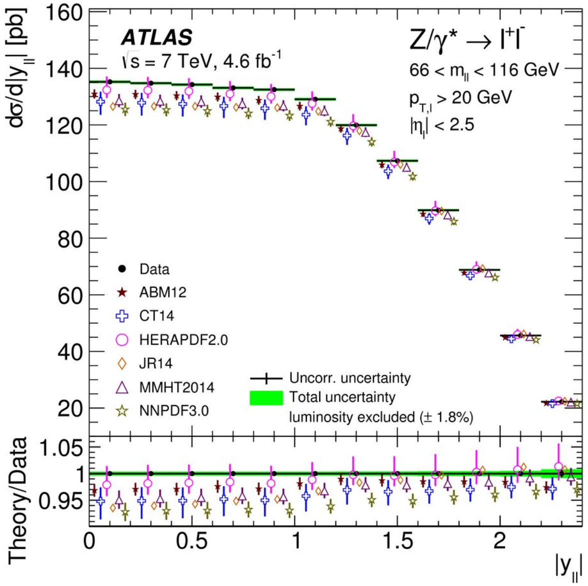
3) Z-boson p_T measurement

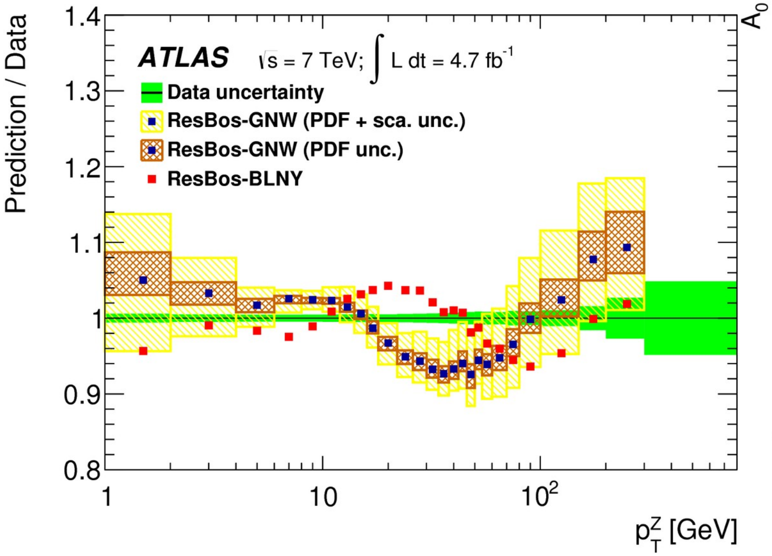
4) Connection to m_W physics modelling

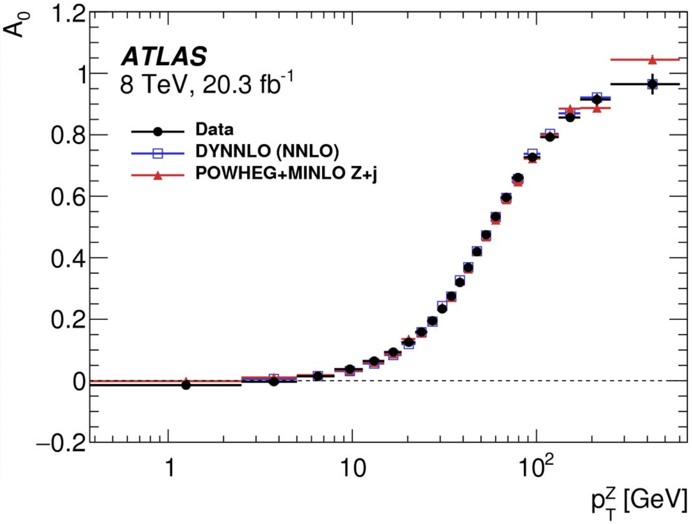
5) Strong coupling constant $\alpha_s(m_Z)$

m_W Physics modelling

$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T,y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta)+\sum_{i=0}^{7}A_i(p_T,y)P_i(\cos\theta,\phi)\right]$$

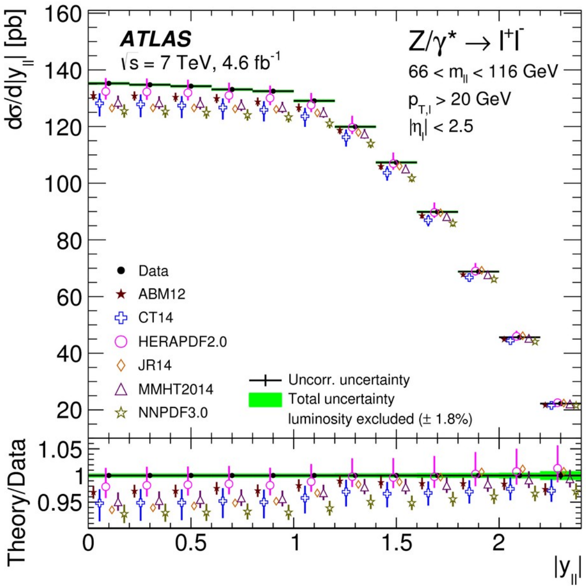


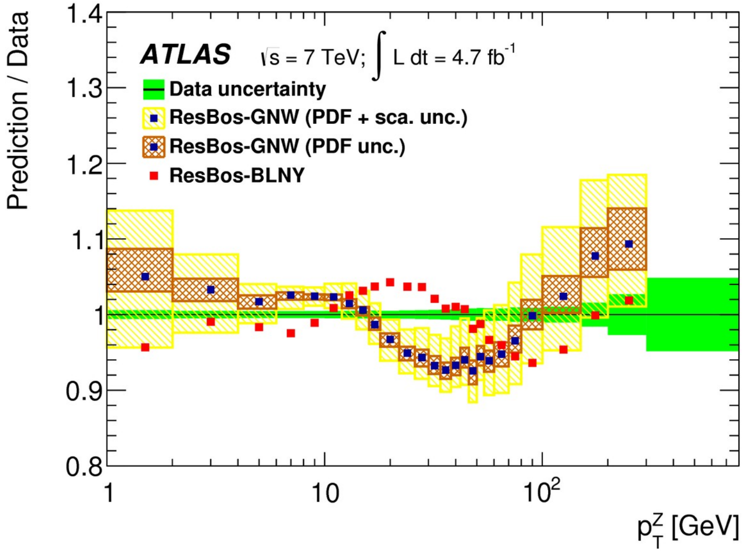


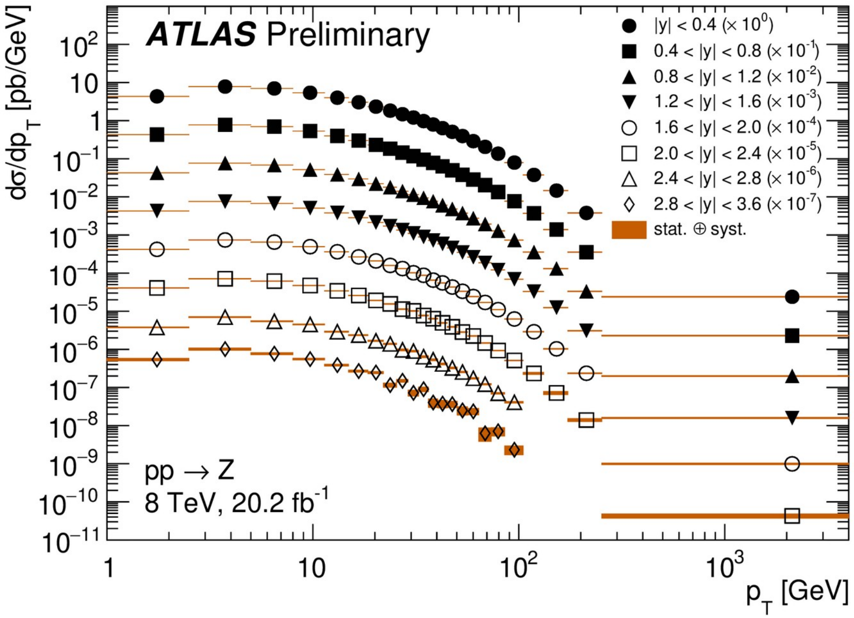


- m_W physics modelling at the LHC (ATLAS, LHCb) based on the very same spherical harmonics decomposition of helicity cross sections used in this measurement
- This new analysis has directly measured the elements of the factorisation formula used in the m_W physics modelling

m_W Physics modelling







- Interpretation of fiducial p_T and y measurement suffers from Ai modelling uncertainties
- Full-lepton phase space measurements provide a cleaner framework for the m_W physics modelling, insofar their interpretation is not affected by correlation with Ai predictions
- Much cleaner separation between Ai and cross sections

1) Methodology

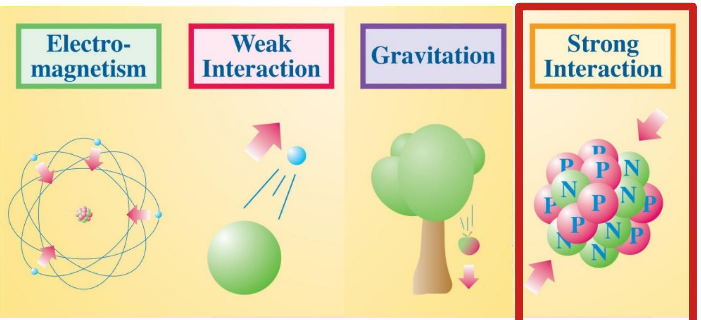
2) Z-boson rapidity measurement

3) Z-boson p_T measurement

4) Connection to m_W physics modelling

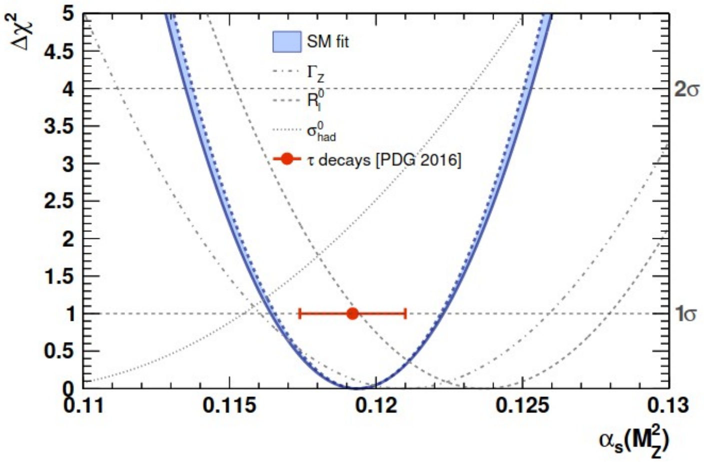
5) Strong coupling constant $\alpha_s(m_Z)$

The strong-coupling strength $\alpha_s(m_Z)$



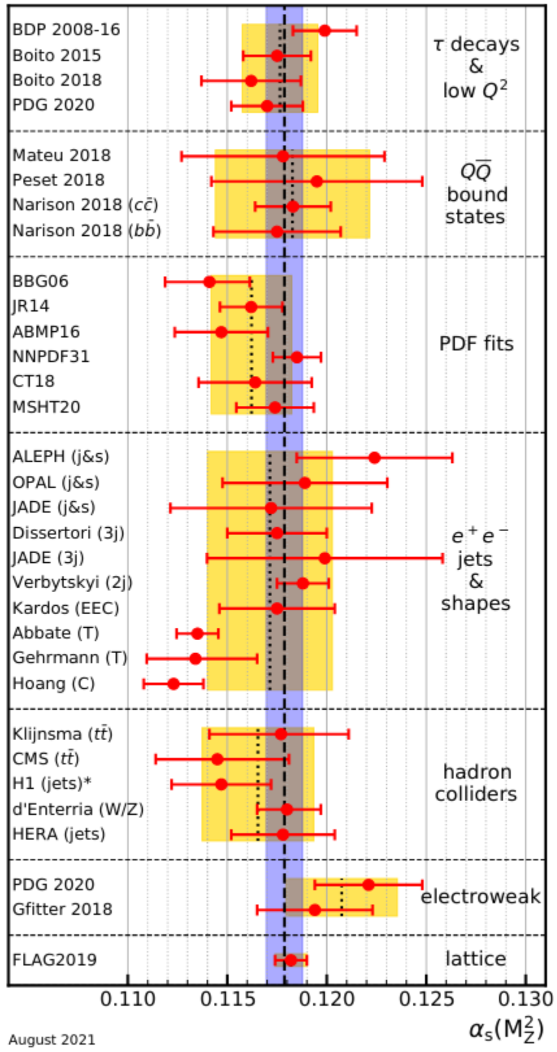
The strong force is the least well known interaction of nature	Electro-magnetism	Weak Interaction	Gravitation	Strong Interaction
Relative uncertainty	10^{-10}	10^{-7}	10^{-5}	10^{-2}

- Impacts physics at the Planck scale: EW vacuum stability, GUT
- Is among the dominant uncertainties of several precision measurements at colliders
    - Higgs couplings at the LHC
    - EW precision observables at e+e- colliders



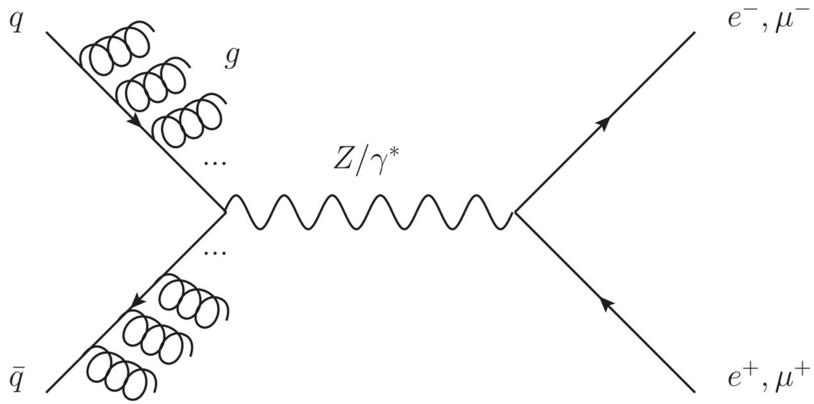
World average:
$\alpha_s(m_Z) = 0.1179 \pm 0.0009$

[PDG 22]

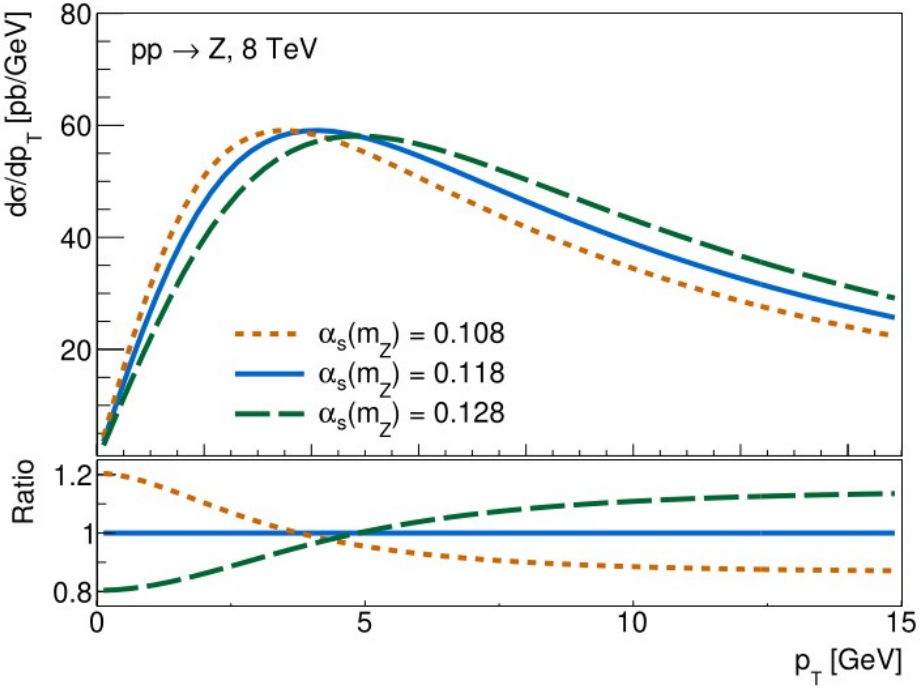


Measure $\alpha_s(m_Z)$ from the Z p_T distribution

- Z bosons produced in hadron collisions recoil against QCD initial-state radiation: by momentum conservation, ISR gluons will boost the Z in the transverse plane



- The Sudakov factor is responsible for the existence of a peak in the Z-boson p_T distribution, at values of approximately 4 GeV
- The Sudakov region of the p_T distribution has a linear sensitivity to $\alpha_s(m_Z)$



Desirable features for a measurement of $\alpha_s(m_Z)$

- Large observable's sensitivity to $\alpha_s(m_Z)$ compared to the experimental precision

} Exclusive observables

- High accuracy of the theory prediction
- Small size of non-perturbative QCD effects

} Inclusive observables

The Z p_T is a semi-inclusive observable which takes benefits from both categories

Theory predictions at approximate N4LL

- Theory predictions evaluted with DYTurbo, implementing CdFG q_T-resummation in b-space arXiv:1910.07049

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

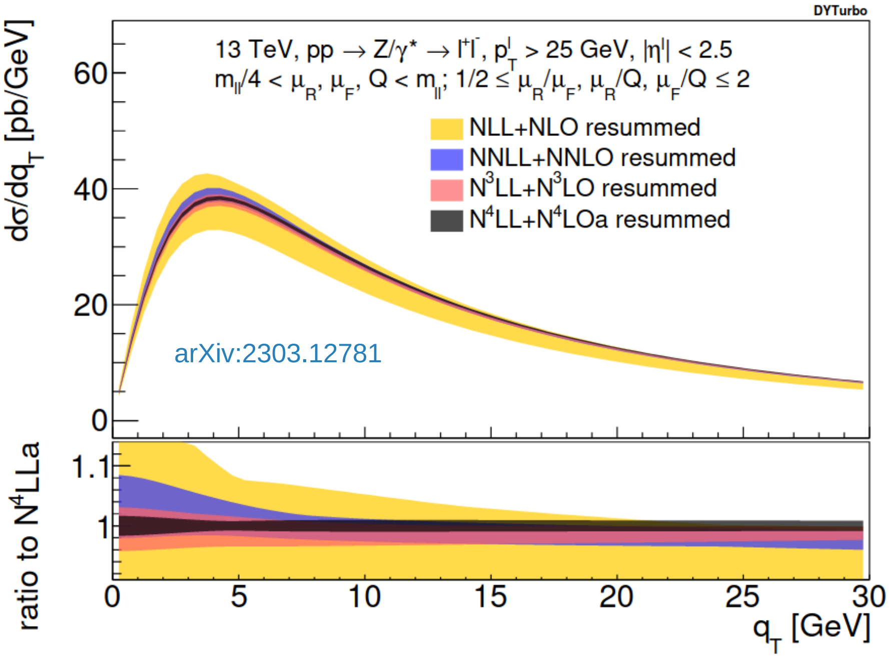
Born cross section

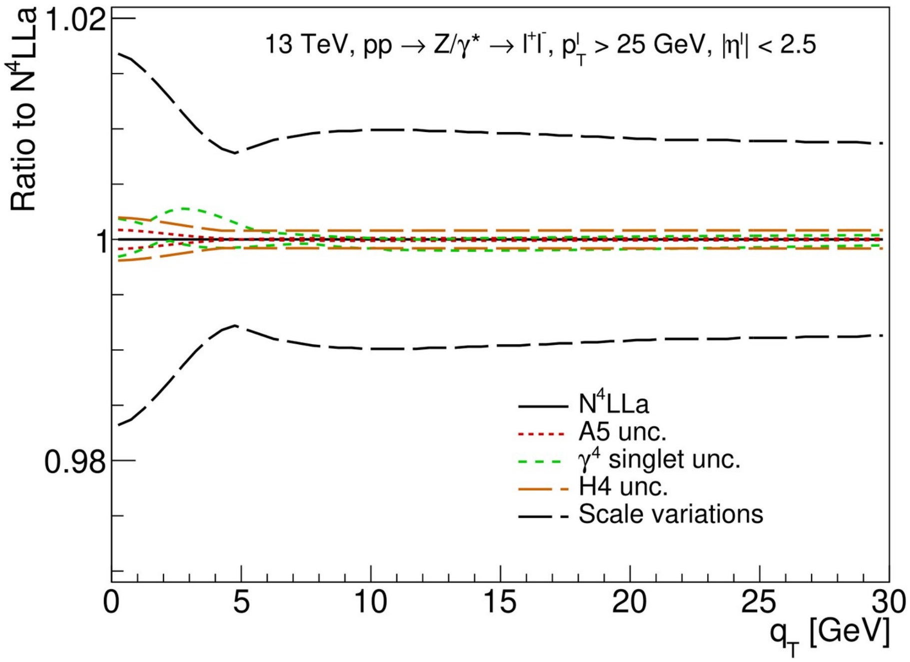
perturbative Sudakov form factor

$$d\sigma^{\text{res}} = d\hat{\sigma}^{V}_{\text{LO}}(q_{\text{T}}) \times \mathcal{H}^{V} \times \exp\{\mathcal{G}(\boxed{\alpha_s}, L)\}$$

Hard virtual

Sensitivity to α_s



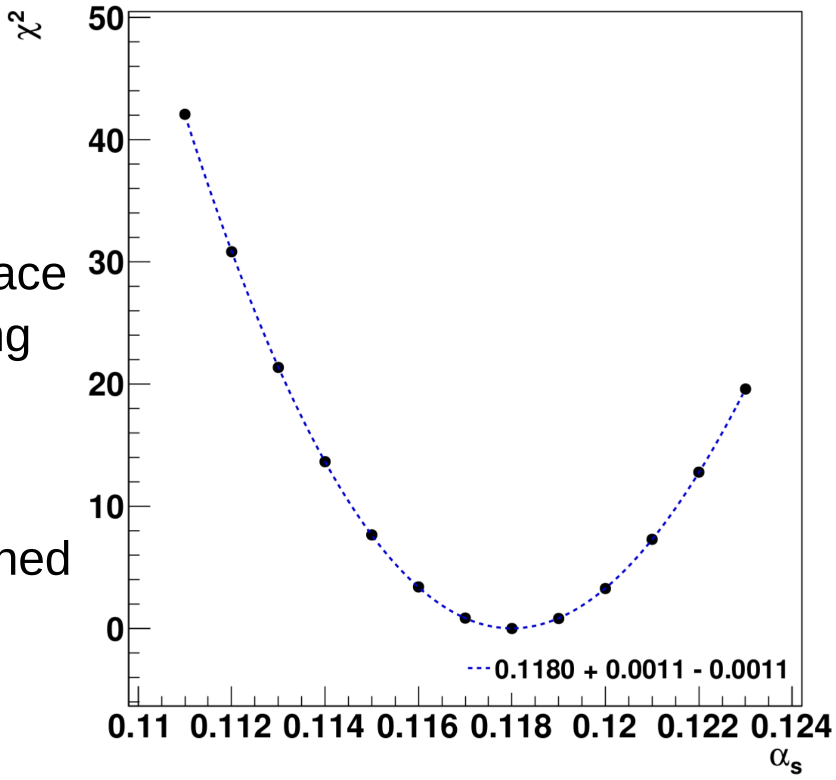


- N4LL approximations are much smaller than missing higher order uncertainties

Methodology for the $\alpha_s(m_Z)$ determination

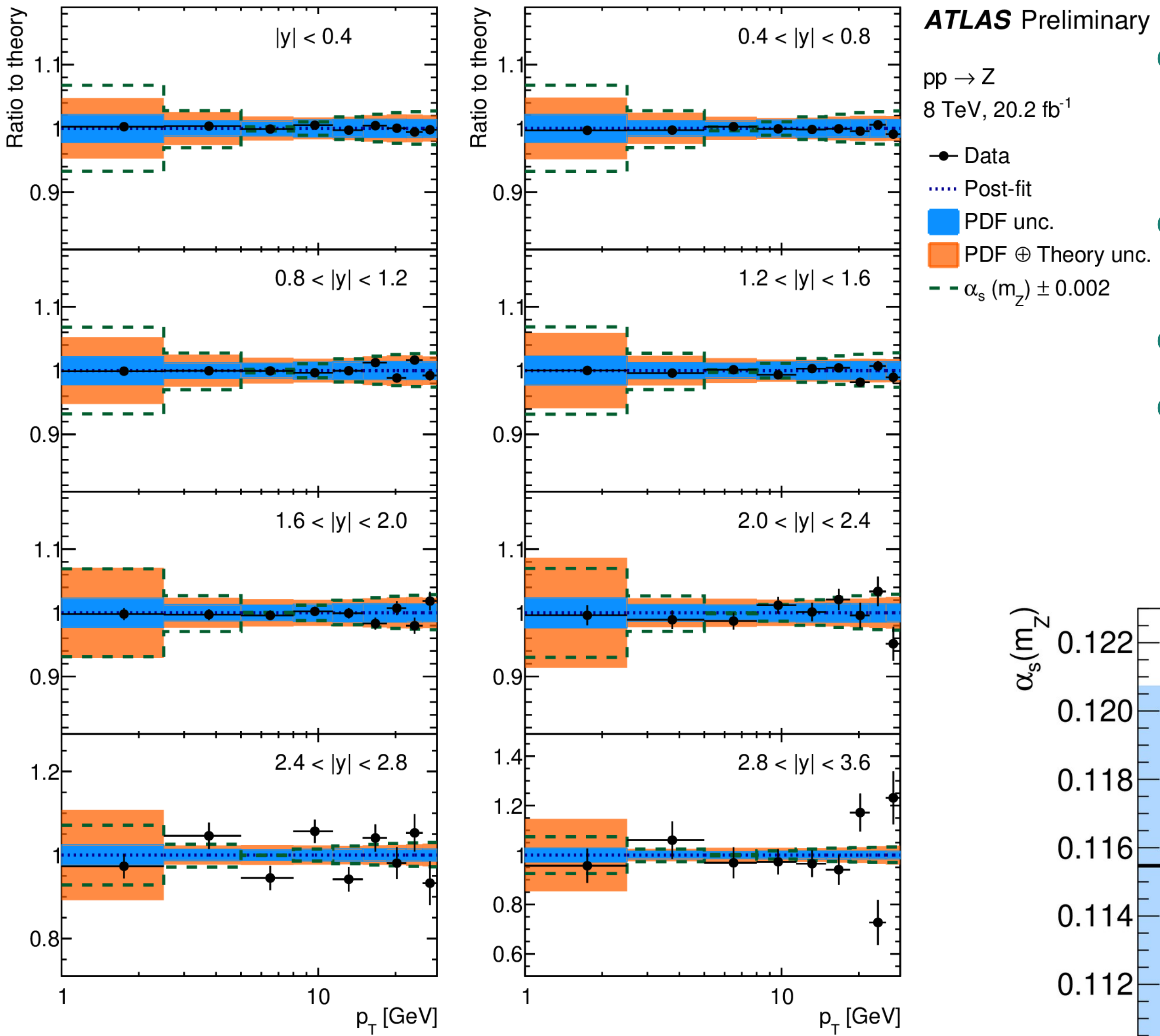
- DYTurbo interfaced to xFitter arXiv:1410.4412
- Evaluate $\chi^2(\alpha_s)$ with α_s variations as provided in LHAPDF
- Include experimental ($\beta_{j,\text{exp}}$) and PDF ($\beta_{k,\text{th}}$) uncertainties in the χ^2

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

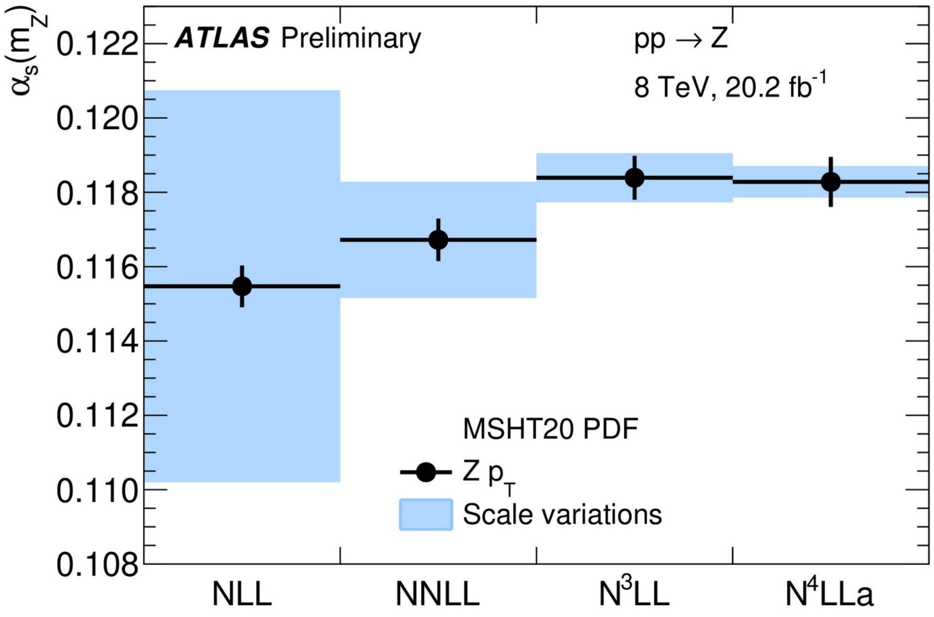


- At each value of $\alpha_s(m_Z)$ the $\beta_{k,\text{th}}$ terms explore the PDF space to find the best fit to the Z p_T data → equivalent to including the new dataset in the PDF without refitting, using profiling/reweighting Eur.Phys.J.C 75 (2015) 9, 458
- The non-perturbative form factor is added with unconstrained nuisance parameters ($\beta = 0$) i.e. left free in the fit
- Fit the region of Z p_T < 29 GeV

Determination of $\alpha_s(m_Z)$ from p_T Z at 8 TeV

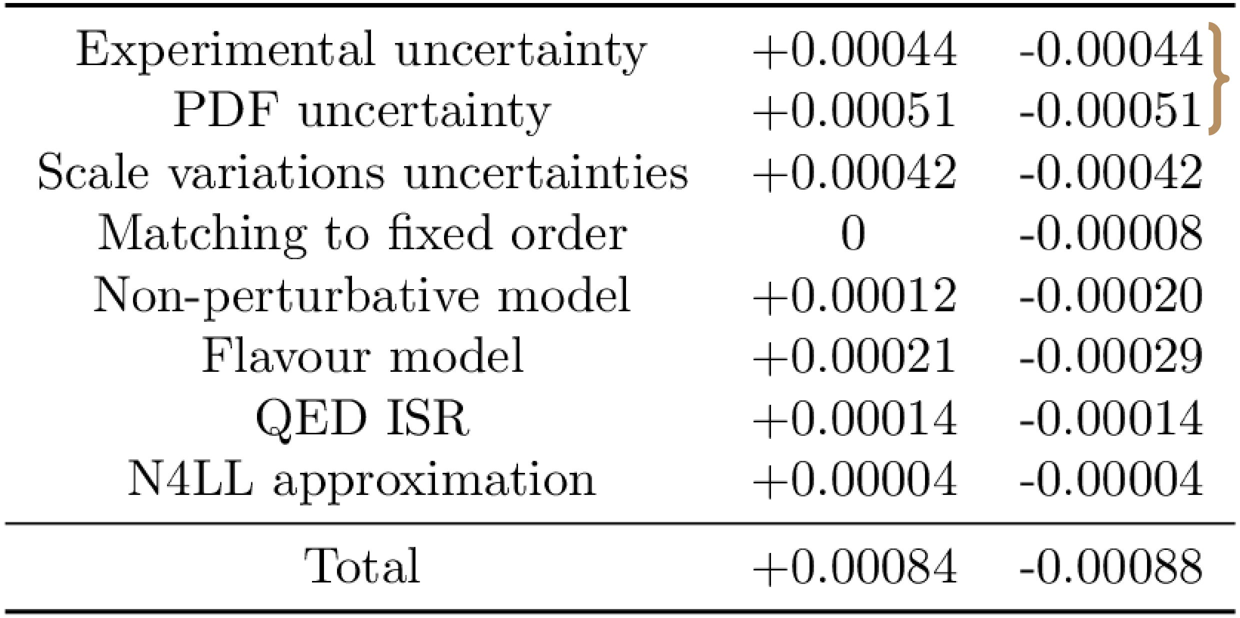


- $\alpha_s(m_Z)$ from a fit to the double-differential p_T-y Z cross section measured in full-lepton phase space
- Experimental sensitivity evaluated with pseudodata: $\Delta\alpha_s/\alpha_s = 0.05\%$
- Postfit χ^2/dof = 82/72
- Determination performed at lower orders demonstrating convergence of the perturbative series



$$\alpha_s = 0.11828 \pm 0.00067(\text{fit}) \pm 0.00042\ (\text{scales})$$

Theory uncertainties



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

Fit unc.

- PDFs is the single largest source of uncertainties
- QED ISR uncertainty from half the LL corrections, validated at NLL
- Matching uncertainty estimated by removing the unitarity constraint (canonical logarithms)
- Uncertainty of the N4LL approximation one order of magnitude smaller than missing higher order uncertainties from scale variations
- Heavy flavour model uncertainties dominated by VFN PDF evolution and VFN α_s running

Non perturbative QCD model

- The NP model is characterized by a non-perturbative Sudakov form factor and a prescription for regularizing the Landau pole of the α_s running

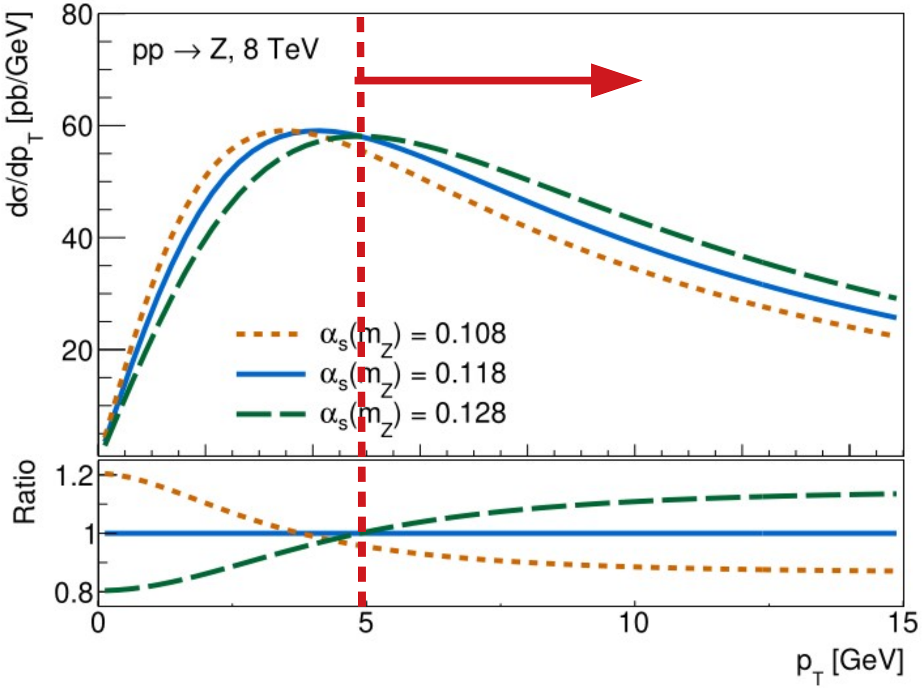
$$S_{\mathrm{NP}}(b) = \exp\left[-g_j(b) - g_K(b)\log\frac{m_{\ell\ell}^2}{Q_0^2}\right] \qquad b_\star^2 = \frac{b^2}{1 + b^2/b_{\mathrm{lim}}^2}$$

- The non perturbative model includes a total of 6 parameters which are either fitted to the data or varied to assess an uncertainty

- Fits excluding the region 0-5 GeV yields $\alpha_s(m_Z)$ with a spread of ±0.0002, and fit uncertainty increased from 0.00067 to 0.00071

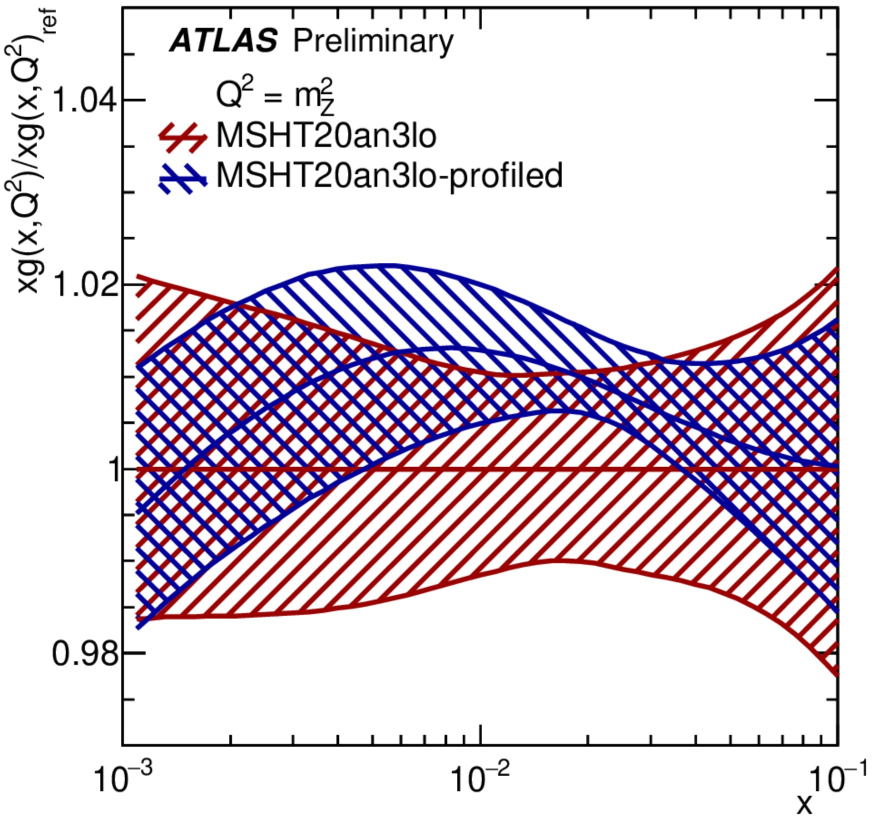
- Correlation between $\alpha_s(m_Z)$ and g largely reduced

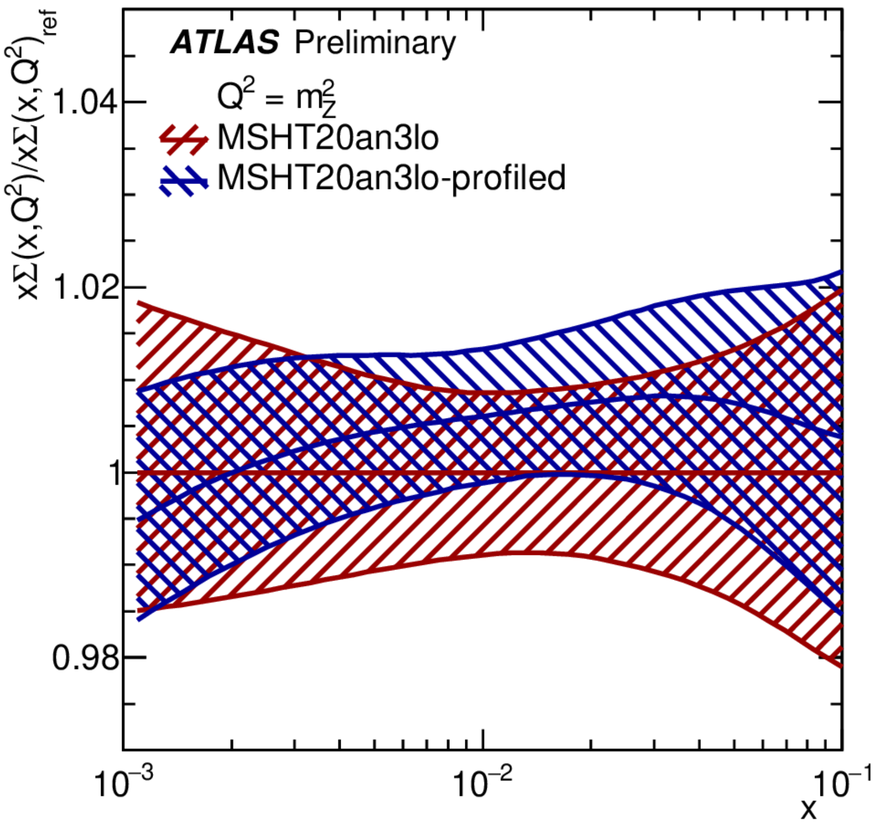
- Demonstrates independence of the result from NP effects and good modelling of NP effects



PDF profiling

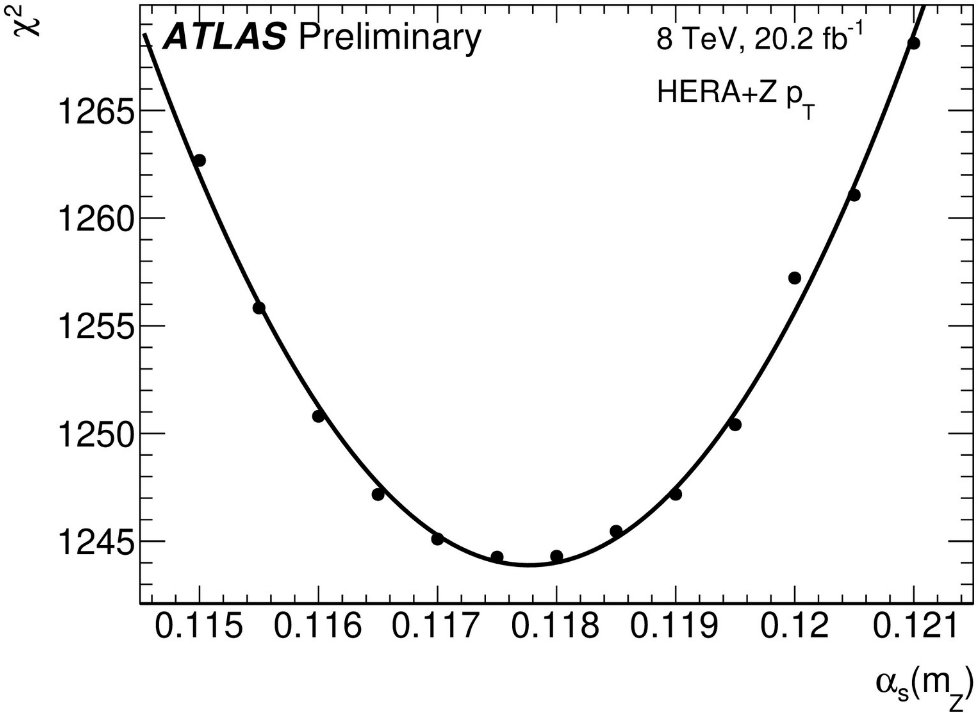
- PDF profiling at the best $\alpha_s(m_Z)$ shows reduction of gluon and sea quark PDF uncertainties
- The measurement is most sensitive to the gluon PDF





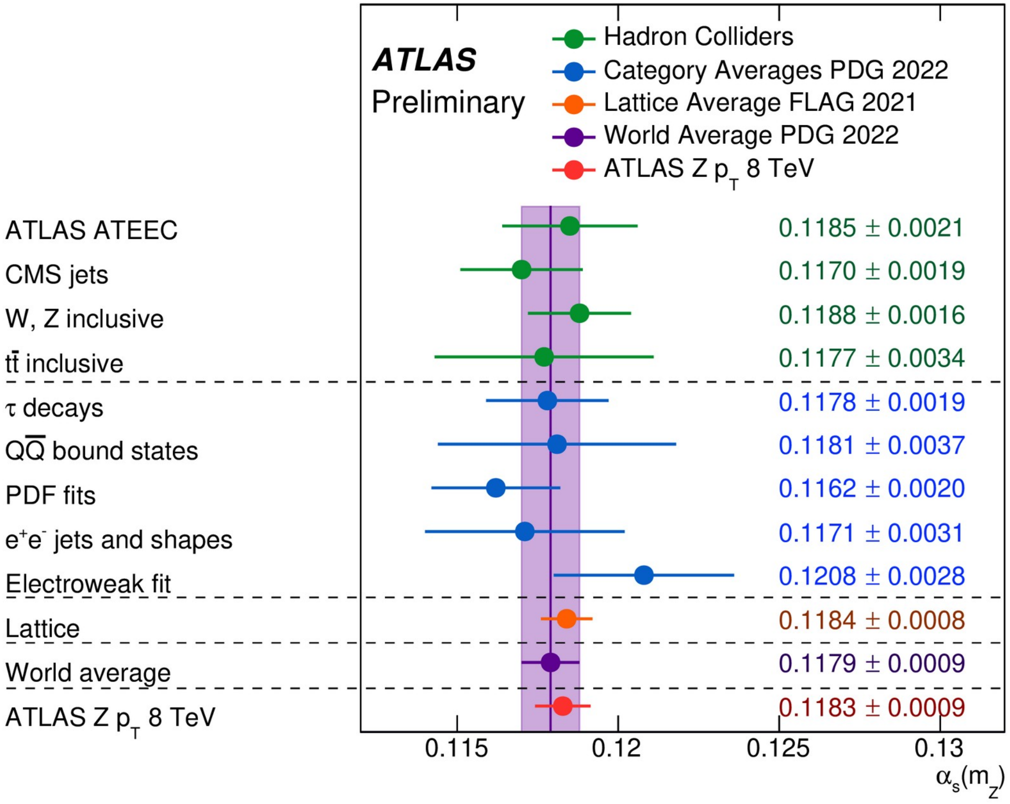
Full PDF+NP+α_s fit at N3LL

- Performed a simultaneous PDF+NP+α_s fit at N3LL+N3LO, using NNLO DGLAP evolution (and NNLO DIS predictions), including HERA data with $Q^2_{min} > 10$ GeV^2
- Recently argued this is the only correct way of determining $\alpha_s(m_Z)$, but PDFs profiling/reweighting are approximations to a simultaneous fit. The simultaneous fit provides a cross check of the Hessian profiling methodology arXiv:2001.04986
- Result: $\alpha_s(m_Z) = 0.11777 \pm 0.00065$, when adding +- 0.00066 of scale variations and all theory uncertainties: $\alpha_s(m_Z) = 0.11777 +0.00097 -0.00100$
- This is the result that should be considered in the PDG version of the world average with only "simultaneous fit of PDFs"



Outlook

- Most precise experimental determination of $\alpha_s(m_Z)$, as precise as the PDG and Lattice world averages
- First $\alpha_s(m_Z)$ determination at N3LO+N4LLa
- Clean experimental signature (leptons) with highest exp sensitivity
- α_s measured directly at m_Z scale (as in LEP event shapes)
- Semi-inclusive observable, which has advantages of exclusive (higher exp. sensitivity) and inclusive (higher order theory, smaller non-pQCD effects)
- Quadratic Λ_{QCD}/Q power corrections, compared to linear in LEP event shapes
- No correlation with $\alpha_s(m_Z)$ determinations from PDF fits, as Z p_T in the Sudakov region is not suitable for inclusion in PDF fits
- First determination using QCD resummed theory predictions based on a semi-inclusive observable at hadron-hadron colliders



$$\boxed{\alpha_s = 0.11828 \, {+0.00084} \, {-0.00088}}$$

Summary

ATLAS-CONF-2023-013

ATLAS-CONF-2023-015

- First high-precision measurements of p_T-y Z-boson cross sections in full-lepton phase space with a new methodology based on the angular coefficients decomposition
- First comparison of Z rapidity cross section at N3LO, and unambiguous PDF interpretation free of fiducial power corrections
- Thorough percent-level comparison of transverse-momentum distributions to state-of-the-art p_T-resummed predictions opens the door to an improved physics modelling for m_W
- Enables most precise experimental determination of $\alpha_s(m_Z)$

BACKUP

Orders

	Virtual		Sudakov			Real
	H[δ(1-z)]	H[z]	Cusp AD	Collinear, RAD	PDF	CT,V+jet
LL+LO	1	1	1-loop	0	const.	1
NLL+NLO	α_s	C1	2-loop	1-loop	LO	α_s
NLL*+NLO	α_s	C1	2-loop	1-loop	NLO	α_s
NNLL+NNLO	α_s^2	C2	3-loop	2-loop	NLO	α_s^2
N3LL+N3LO	α_s^3	C3	4-loop	3-loop	NNLO	α_s^3
N4LLa+N3LO	α_s^4	C4	5-loop	4-loop	N3LO	α_s^4

Known analytically
Approximated numerically
Unknown, estimated with series acceleration
Not included

Non perturbative QCD model

- NP model is generally determined from the data, parameters values depend on the chosen prescription to avoid the Landau pole in b-space

$$b_\star = \frac{b}{1+b^2/b_{\text{lim}}^2}$$

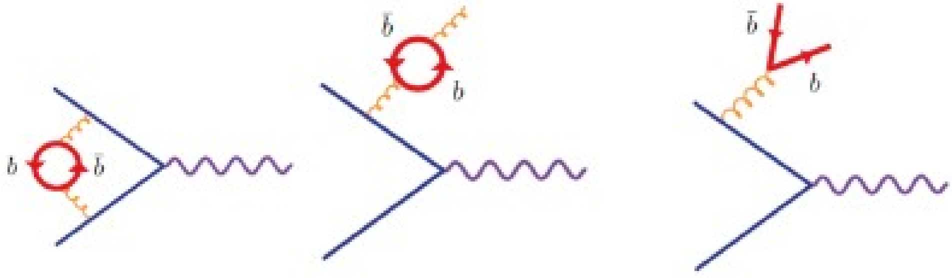
$$S_{\text{NP}}(b) = \exp\left[-g_j(b) - g_K(b)\log\frac{m_{\ell\ell}^2}{Q_0^2}\right] \quad \left\{ \begin{aligned} g_j(b) &= \frac{g\,b^2}{\sqrt{1+\lambda\,b^2}} + \text{sign}(q)\left(1-\exp\left[-|q|\,b^4\right]\right) \\ g_K(b) &= g_0\left(1-\exp\left[-\frac{C_F\alpha_s(b_0/b_*)b^2}{\pi g_0\,b_{\text{lim}}^2}\right]\right) \end{aligned} \right.$$

- g_j functions include a quadratic and a quartic term, with g and q free parameters of the fit
- The theory should not depend on b_{lim} (freezing scale) and Q_0 (starting scale of the TMD evolution), provided S_{NP} is flexible enough. Q_0 and b_{lim} are varied to assess a parameterisation uncertainty
- g_0 controls the very high b (very small p_T) behaviour, should be fitted to data, but there is no sensitivity to it, so it is varied
- λ controls the transition from Gaussian (quadratic) to exponential (linear), set to 1 GeV^{-2} and varied by factor of 2 up and down
- Total of 6 NPQCD parameters which are either fitted to the data or varied to assess an uncertainty

Heavy flavour thresholds

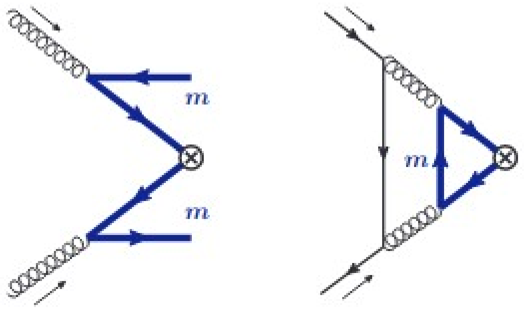
- Nominal results with fixed flavour number scheme and nf=5 active flavours
- Backward PDF evolution with FFN nf = 5, charm and bottom PDF switched off at their threshold with a b* prescription
- Estimate uncertainties related to heavy flavour thresholds with envelope of variations:
  - VFN forward PDF evolution
  - VFN running of α_s in the Sudakov form factor
  - Variations of charm threshold, μ_c
  - Variations of bottom threshold, μ_b
- Uncertainty of +0.00029 -0.00021 dominated by VFN PDF and VFN α_s variations

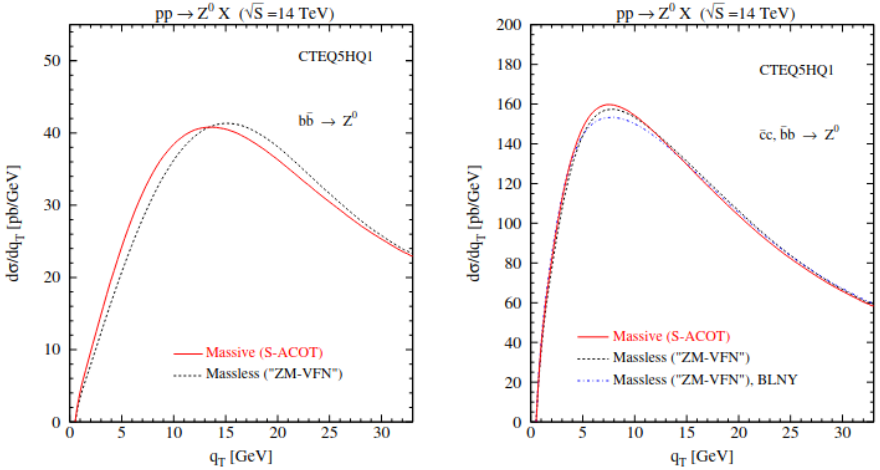
Heavy flavour mass effects



(a) *Double virtual contribution* (b) *Real-virtual Contribution* (c) *Double real Contribution*

- Secondary or final state HF mass effects: softer pT spectrum, estimated $\delta\alpha_s$ of the same order of the VFN evolution, with opposite sign
- Effect covered by flavour model uncertainties
- If both VFN PDFs and HFFS included, their effect would largely cancel





- 2% bb
- 6% cc

- Primary or initial state HF mass effects: softer p_T spectrum in the bb → Z, cc → Z channels
- Expected to be negligible for α_s (but important for the W/Z p_T ratio, and for m_W)

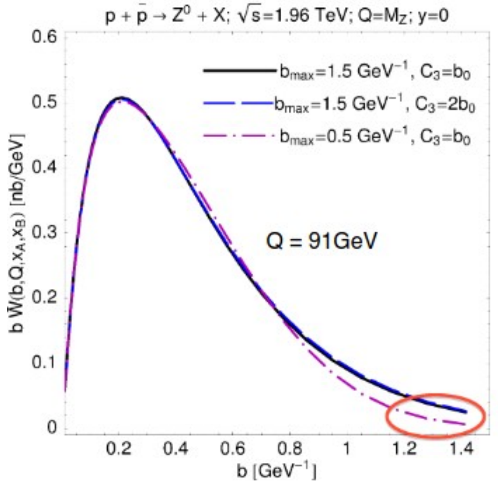
Remarks on the generality of the NP model

- Tafat, renormalon analysis (hep-ph/0102237):
  - Small b behavior should be Gaussian
  - Large b behavior should be exponential

$$W_0 = \exp\left(-\ln\frac{Q^2}{Q_0^2}\left[c_1 b^2 + c_2 b^4 + c_3 b^6 + \mathcal{O}(b^8)\right]\right),$$

- Collins and Rogers (arxiv:1507.05542)
  - At large Q=mll the cross section is eventually dominated by perturbative effects, even at qT = 0
  - Z production is dominated by small b (peak at b = 0.2, negligible contribution for b > 1.5)

- Schweitzer, Strikman and Weiss (arXiv:1210.1267)
  - Exponential behavior driven by a chiral scale of 0.3 fm = 1.5 GeV^{-1} and a confinement scale of 1 fm = 5 GeV^{-1}



$Q = m_Z,\ \sqrt{s} = 1800\,\mathrm{GeV}$

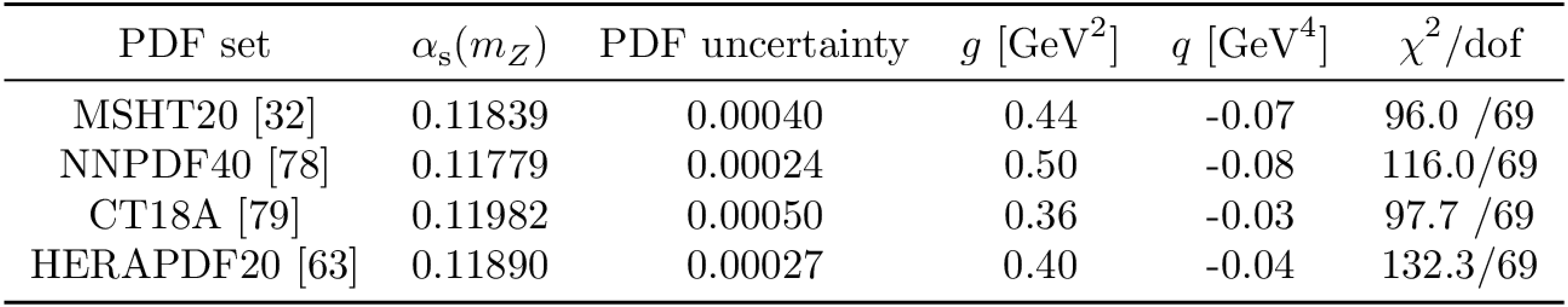
Gaussian behavior of primordial kT

- Ferrario-Ravasio, Limatola, Nason (arxiv:2011.14114):

“The absence of linear corrections in this context has also a rather simple intuitive explanation. The primordial transverse momentum smearing gives a transverse kick, of the order of typical hadronic scales, to the perturbative distribution. However, it is azimuthally symmetric. Thus, its first-order effects cancel out, leaving only quadratic corrections”

NNLO PDF sets

- At N4LL+N3LO only one N3LO PDF set is available: MSHT20an3lo
- Different PDF sets can be studied at N3LL+N3LO, where the spread of NNLO PDFs is ±0.00102, driven by NNPDF4.0-CT18A difference (with CT14 the spread would be a factor of 2 smaller)



PDF set	$\alpha_s(m_Z)$	PDF uncertainty	g [GeV^2]	q [GeV^4]	χ^2/dof
MSHT20 [32]	0.11839	0.00040	0.44	-0.07	96.0 /69
NNPDF40 [78]	0.11779	0.00024	0.50	-0.08	116.0/69
CT18A [79]	0.11982	0.00050	0.36	-0.03	97.7 /69
HERAPDF20 [63]	0.11890	0.00027	0.40	-0.04	132.3/69

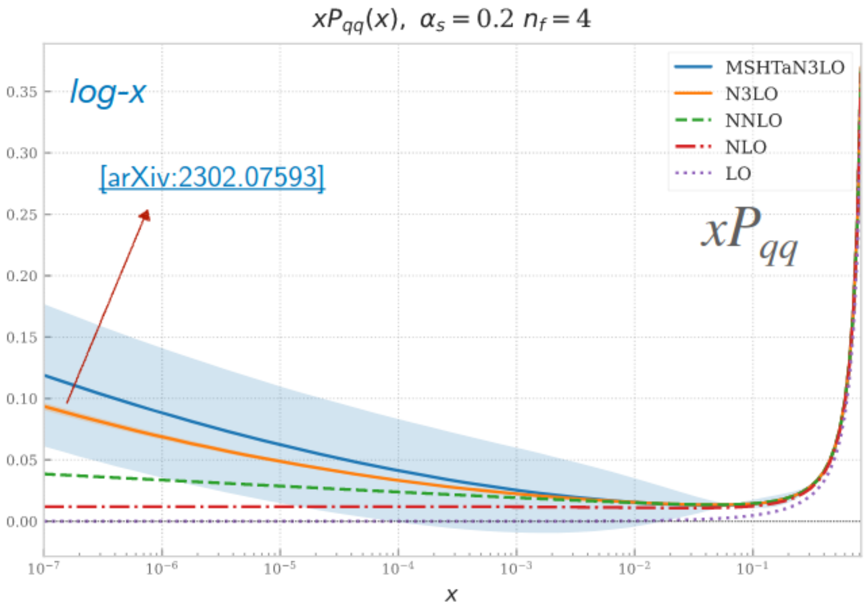
- Adding HERA data to the fit (counted twice), the spread is reduced to ±0.00016, around a central value of 0.11804
- Indication that the large spread is due to the tension in the gluon PDF between different datasets, and how this is solved by each PDF group
- MSHT20an3lo analysis shows that the gluon PDF tension is much reduced at N3LO

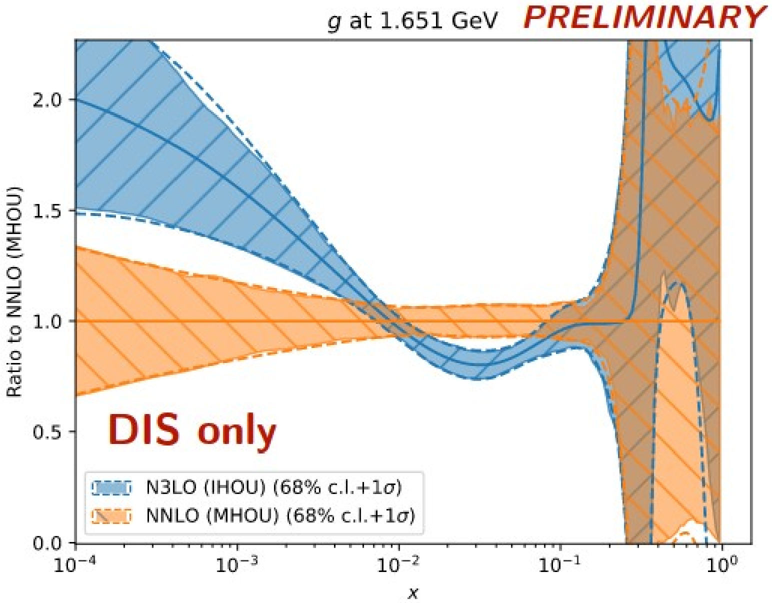
MSHT aN3LO PDFs

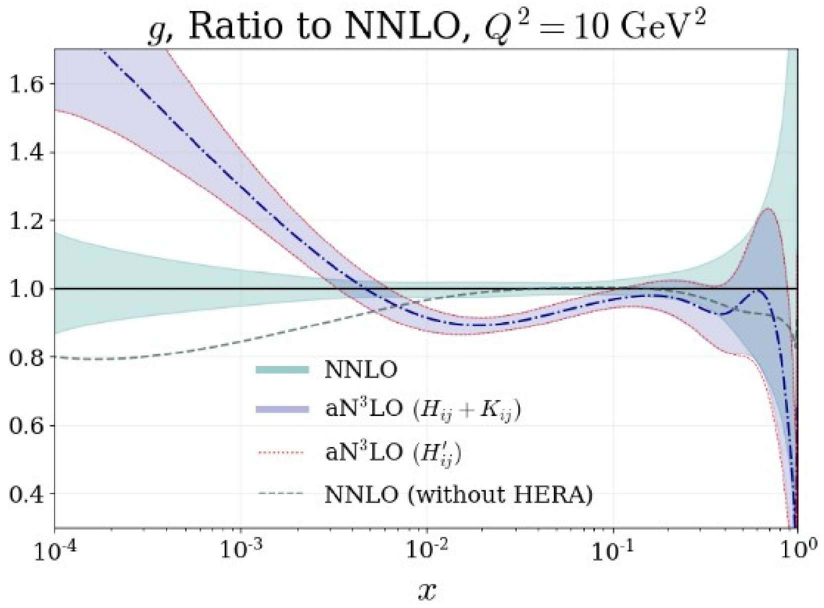
- aN3LO PDFs represent a genuine description of N3LO PDFs, but with some associated uncertainty which represent the missing parts of information at N3LO
- They include significant pieces of information at N3LO on all splitting functions, transition matrix elements, and most necessary information on cross sections for DIS data, which is still the primary constraint on PDFs
- The additional empirical observation is that assumptions on the least known parts, i.e. cross sections for hadronic processes, have very little effect on the PDFs
- The situation is reminiscent of what happened in about 2001 when preliminary aNNLO PDF sets were produced which ultimately were very similar to the correct NNLO sets which appeared a few years later. At aN3LO we have now also uncertainties associated with our missing pieces of information.
- There is also good additional supporting evidence, i.e. the improvement in fit quality and the significant reduction in tensions

MSHT aN3LO PDFs

- Recent precise numerical calculation of 4-loop pure-singlet Pqq in agreement with MSHTaN3LO estimate
- Pqq was the dominant uncertainty in the N4LLa approximation for the Z p_T spectrum (4-loop Pqg Pgq Pgg are formally of higher order for the Z p_T)
- Preliminary NNPDF aN3LO PDF determination shows similar trend on the gluon PDF

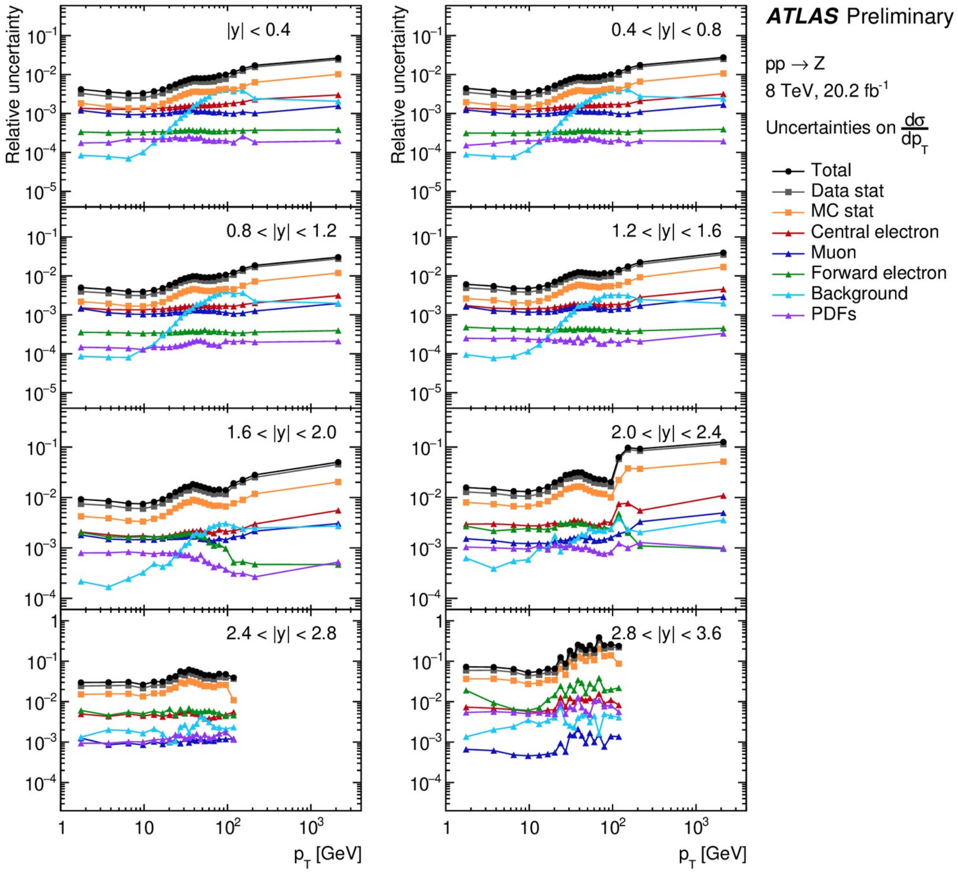




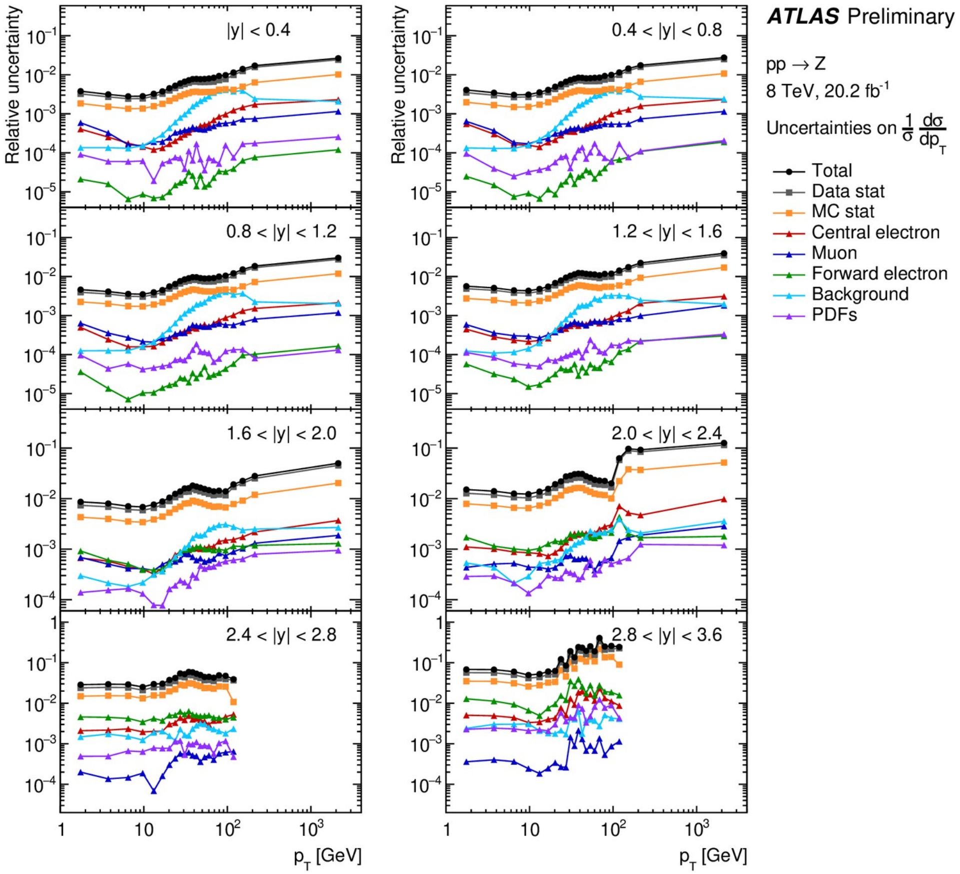


dσ/d$p_T$dy measurement uncertainties

Absolute



Normalised



- Statistically dominated measurement
- Negligible theory uncertainties: cross sections are parameters of the fit, and not the result of an extrapolation
  - PDFs are at the level of 10^{-4} / 10^{-3}, other theory uncertainties even smaller
- Smaller lepton uncertainties in the normalised cross sections, as efficiency uncertainties are largely bin-to-bin correlated

Result at the Tevatron

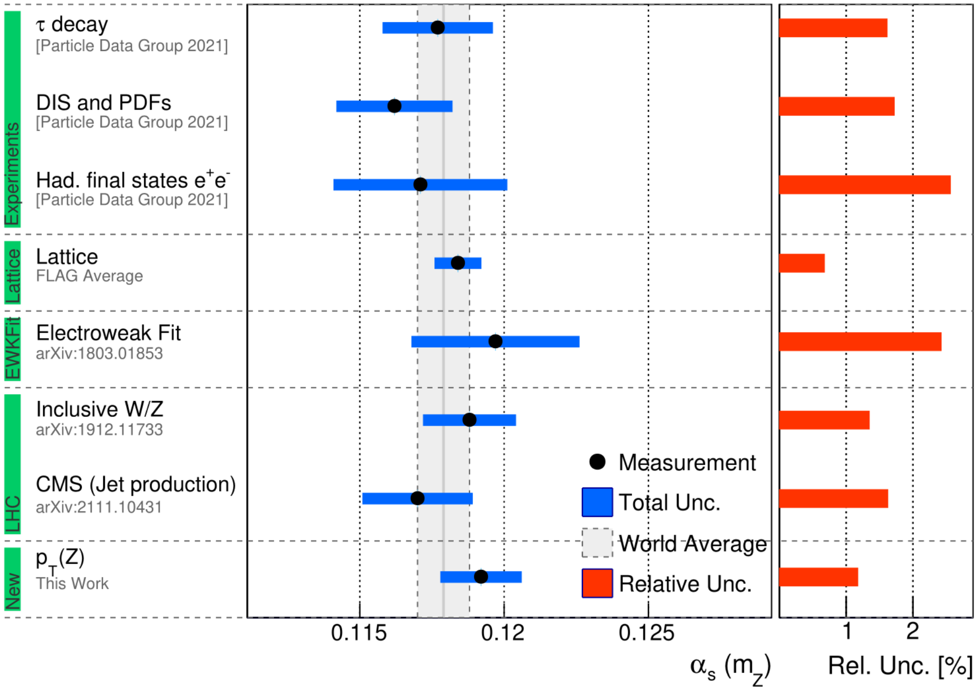
- Result at N3LO+N3LL

$$\boxed{\alpha_s = 0.1191 \; {+0.0013} \; {-0.0016}}$$

Breakdown of uncertainties

	$\delta\alpha_s(m_Z,+)$	$\delta\alpha_s(m_Z,-)$
Exp. unc.	+0.00073	–0.00073
PDF unc.	+0.00074	–0.00074
Scale var.	+0.00040	–0.00096
Theory unc.	+0.00066	–0.00073

arXiv:2203.05394



- Updated result at N3LO+N4LLa

$$\alpha_s = 0.1181 \pm 0.0012(\text{exp}) \pm 0.0005\,(\text{PDFs}) \pm 0.0009\,(\text{scales})$$

- Compatibility verified also with a simultaneous fit of ATLAS and CDF data