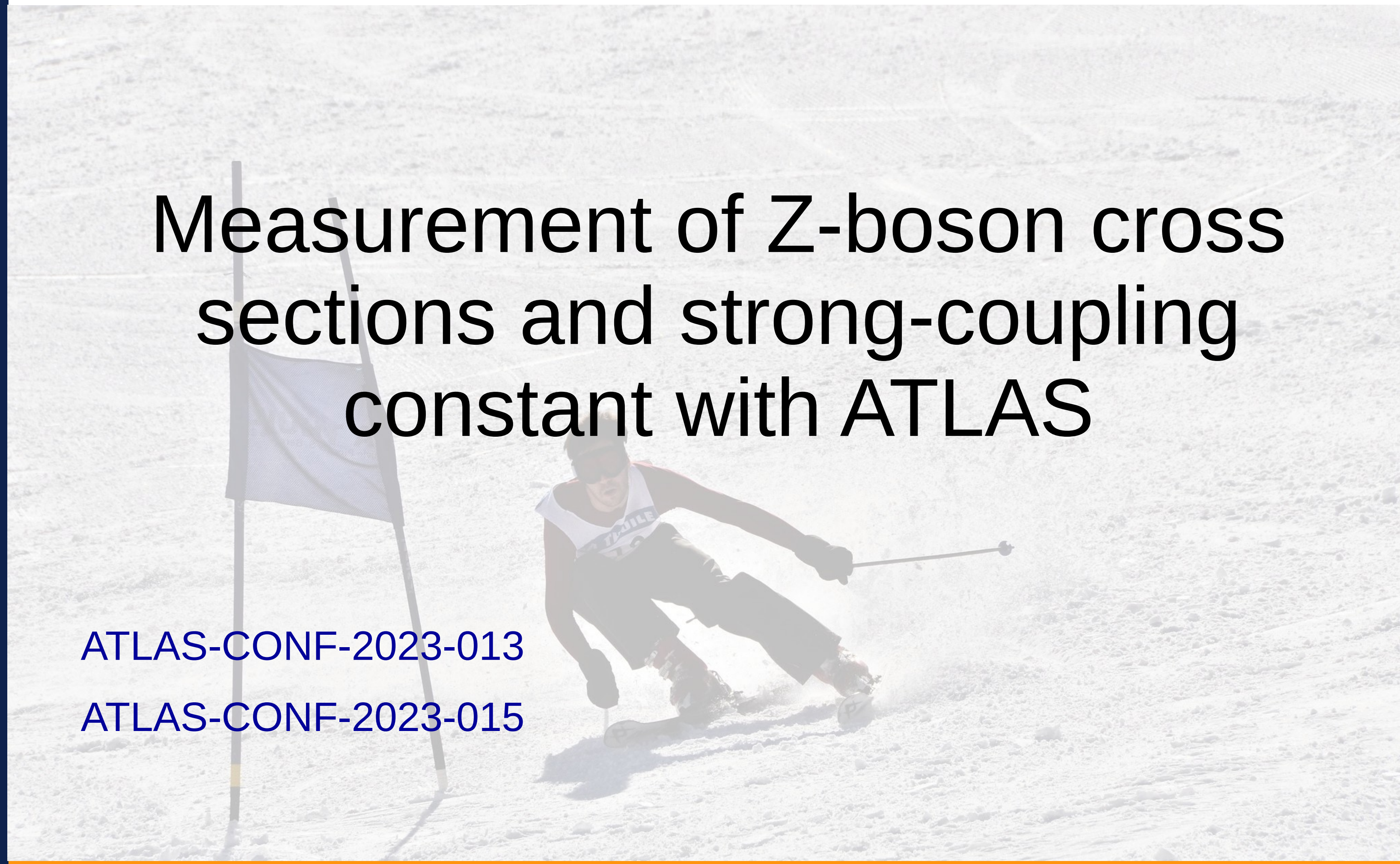


Measurement of Z-boson cross sections and strong-coupling constant with ATLAS

ATLAS-CONF-2023-013

ATLAS-CONF-2023-015

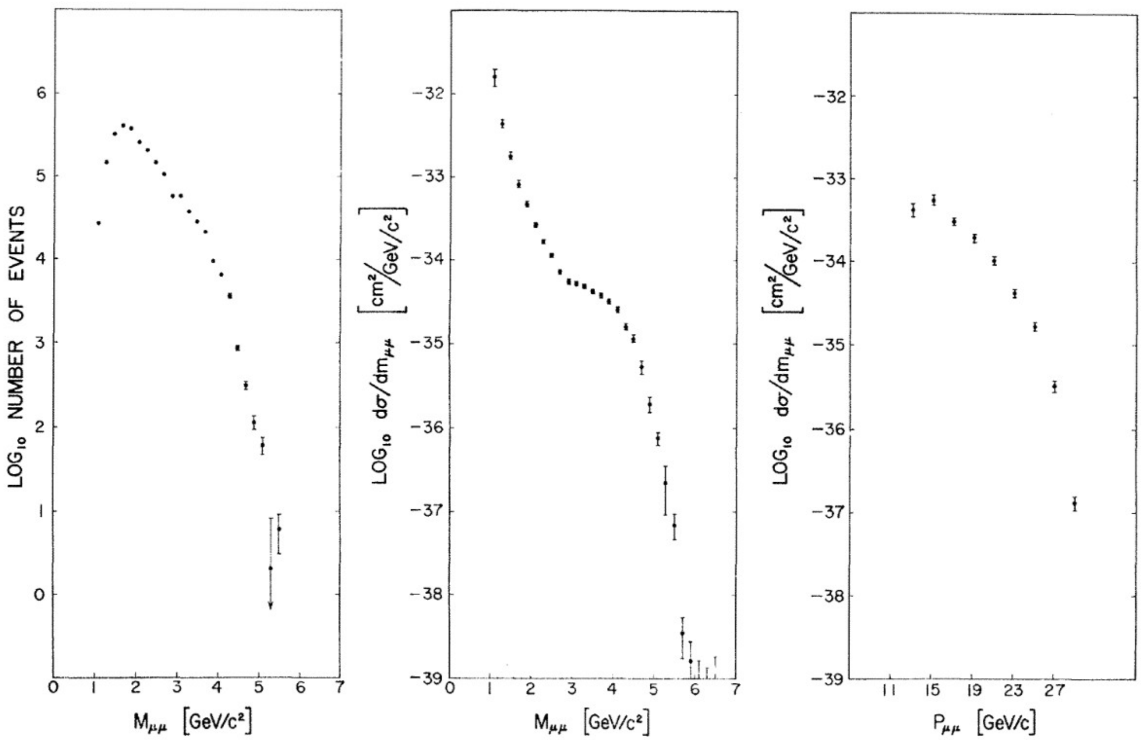
Stefano Camarda on behalf of ATLAS

Moriond EW
23rd March 2023

The Drell-Yan process

- The Drell Yan process denotes the: “Massive lepton pair production in hadron-hadron collisions at high energies” Phys. Rev.Lett.25, 316 (1970)
- 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

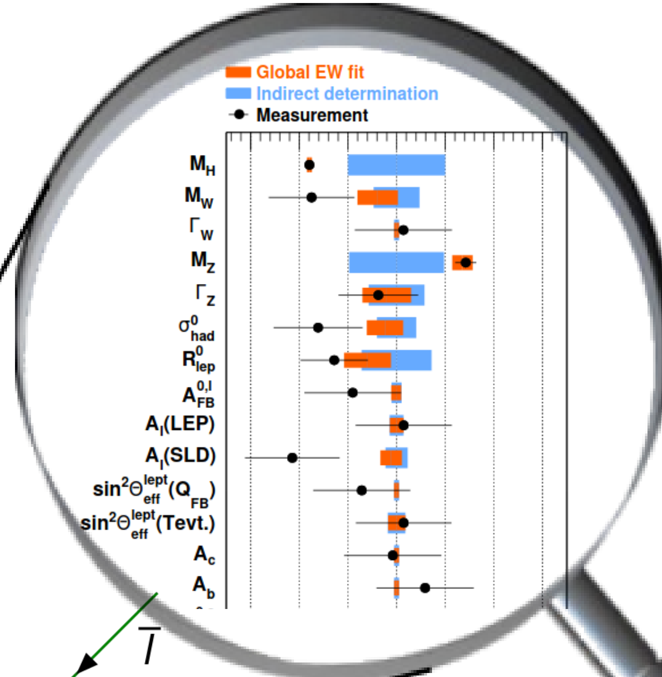


After 50 years, why is this process still of interest and what can we learn from it?

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

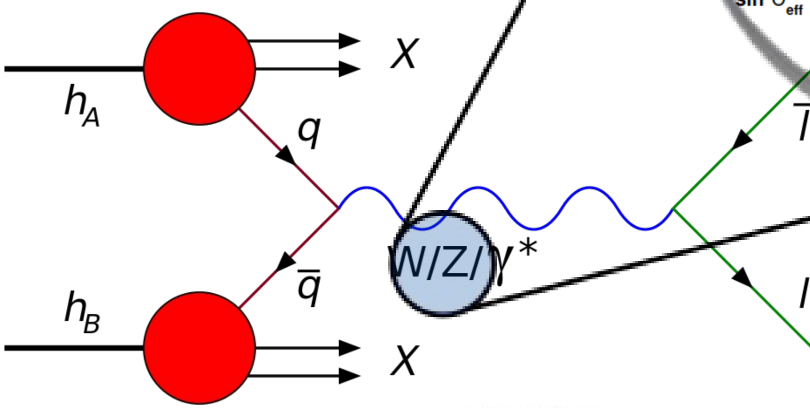
Drell-Yan and measurements of EW parameters

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

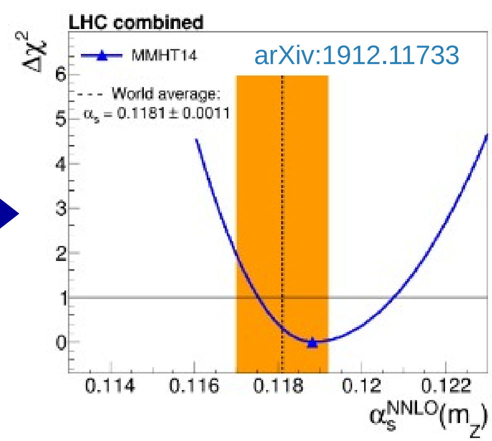


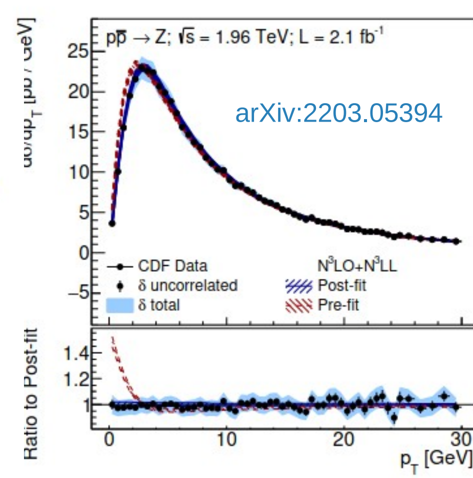
Used to measure

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



$\alpha_s(m_Z)$ recently added to the list of precision measurements performed with the DY process





Anatomy of Drell-Yan differential cross sections

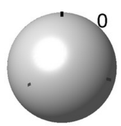
- A convenient way of expressing the radiation-inclusive DY cross section is through the factorisation of the production dynamic and the decay kinematic properties of the dilepton system

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

- $d\sigma/dp_T$: transverse dynamics
- $d\sigma/dy$: longitudinal dynamics (PDFs)
- Rich physics program of perturbative and non-perturbative QCD

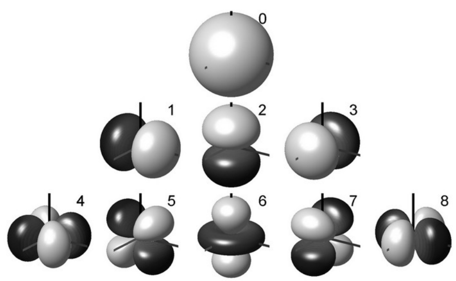
- Decomposition of $(\cos\theta,\phi)$ into 9 helicity cross sections → basis of spherical harmonics

Why 9?



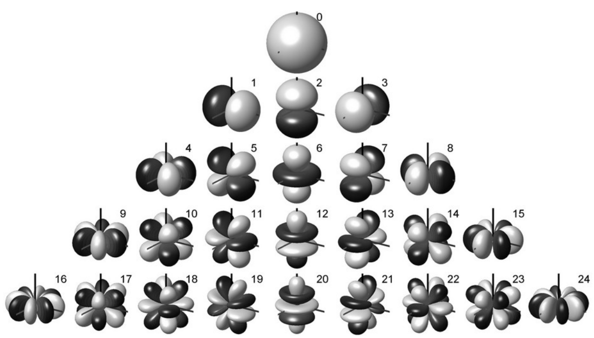
Spin 0 (Higgs)

l = 0
n = 1



Spin 1 (W,Z,γ*)

l ≤ 2
n = 1+3+5 = 9



Spin 2

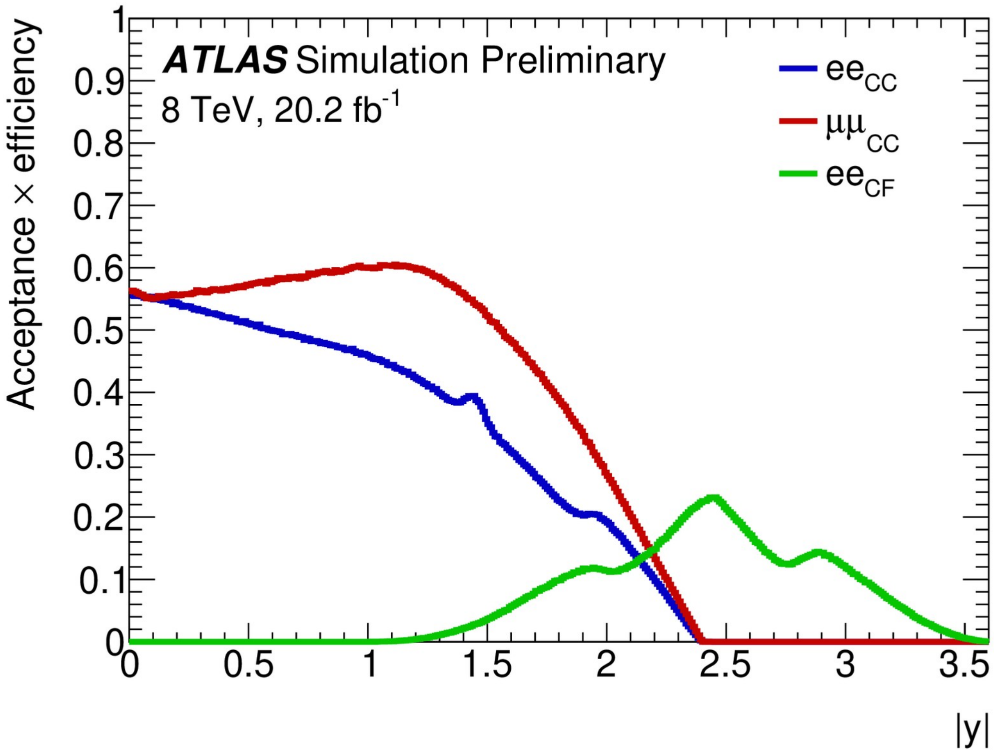
l ≤ 4
n = 1+3+5+7+9 = 25

l denotes the degree of the spherical harmonics

Event selection

- Three channels:
  - eeCC: two electrons with $p_T > 20$, $|\eta| < 2.4$
  - $\mu\mu$CC: two muons with $p_T > 20$, $|\eta| < 2.4$
  - eeCF: central electron with $p_T > 25$, $|\eta| < 2.4$, forward electron with $p_T > 20$, $2.5 < |\eta| < 4.9$
- $80 < m_{ll} < 100$ GeV
- Double differential p_T, y cross section
  - 8 y bins over $|y| < 3.6$
  - 23 p_T bins

Channel	Events
eeCC	6.2 M
$\mu\mu$CC	7.8 M
eeCF	1.3 M
Total	15.3 M



- Dedicated forward electron calibration:
  - Misalignment corrections
  - Azimuthal intercalibration
  - Improved simulation of lateral shower shapes combined with improved correlated calibration

Measurement methodology

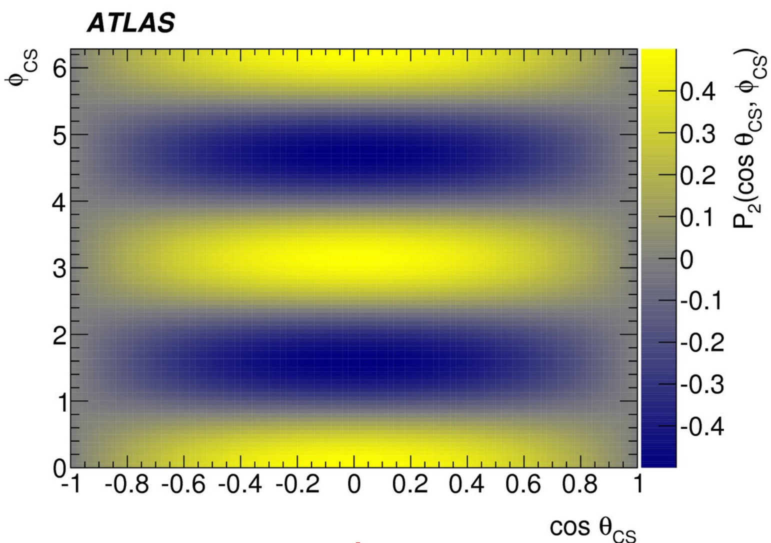
Expected Yield

Reco (p_T^Z, y^Z, m^Z, cosθ, ϕ) bin — Cross section — Background template

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

Truth (p_T^Z, y^Z, m^Z) bin — Angular coefficient — Templated polynomial

- Likelihood defined in 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



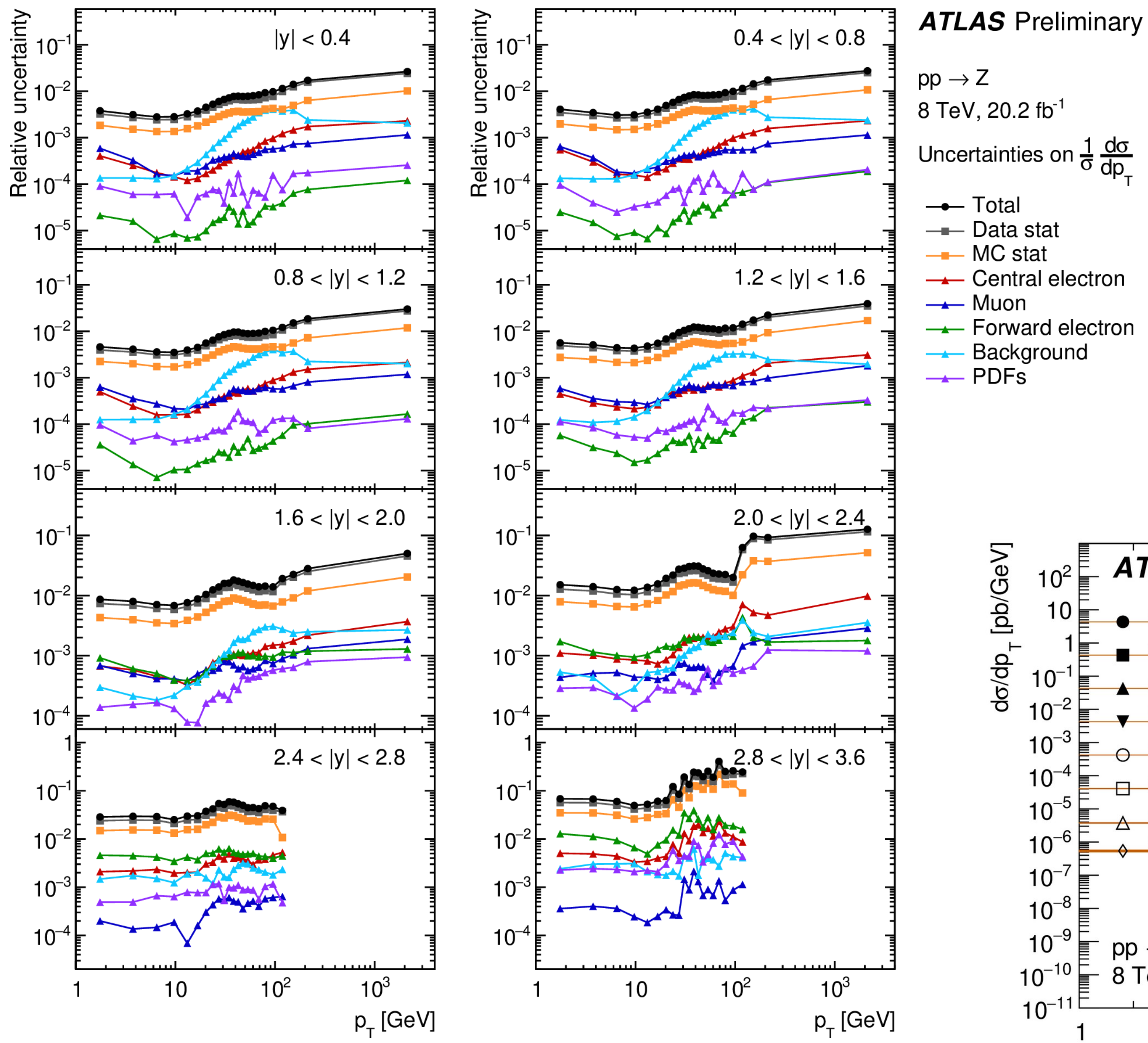
Continuous

$$\begin{pmatrix} H_0 \\ H_1 \\ H_2 \\ H_3 \\ H_4 \\ H_5 \\ H_6 \\ H_7 \\ H_8 \end{pmatrix}$$

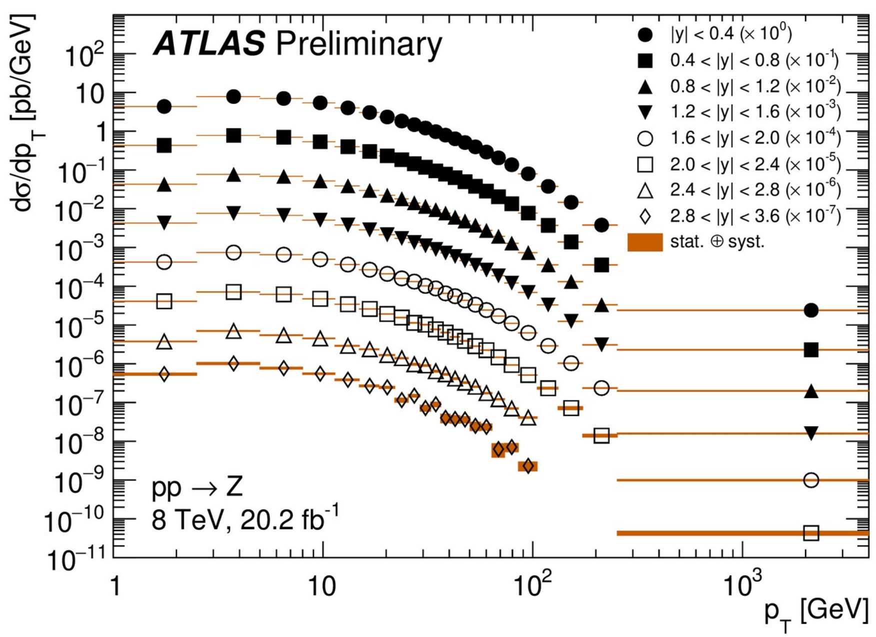
Quantized

- Measuring the angular coefficients corresponds to building a synthetic "quantized" representation of the (cosθ,ϕ) kinematic space
- Trade systematics for statistics
- Very powerful: avoids theoretical extrapolation of fiducial lepton cuts to full phase space and thereby opens the door to a rich field of precise interpretations

dσ/dp$_T$dy measurement uncertainties

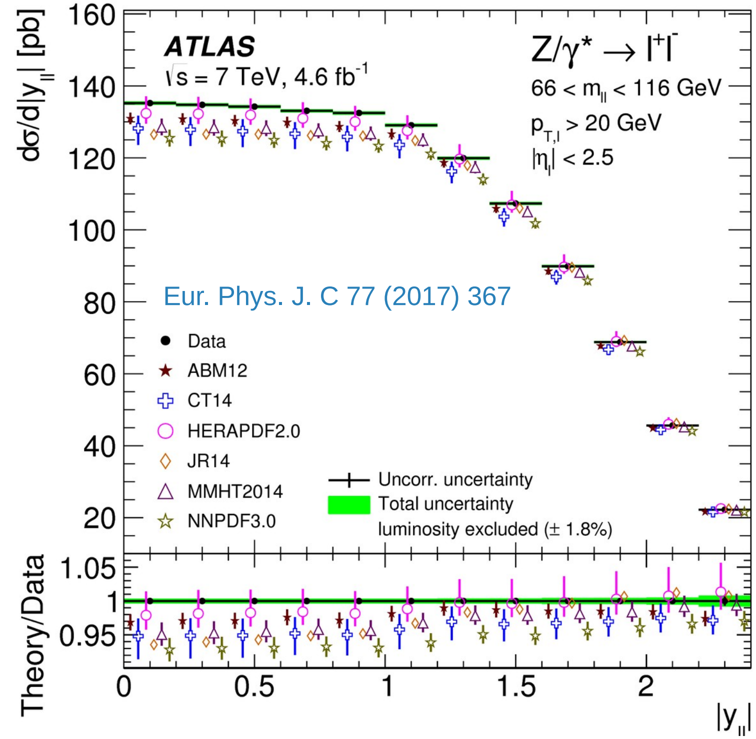


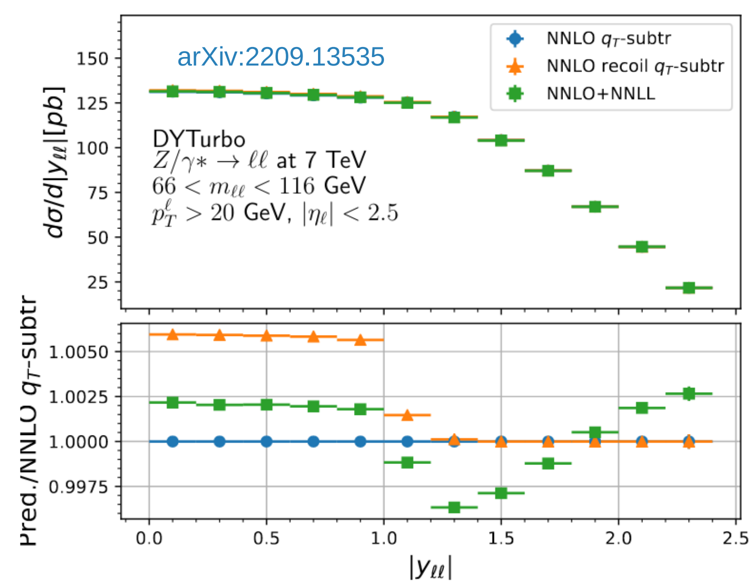
- First measurement at the LHC of full-lepton phase space cross sections
- Statistically dominated measurement
- Negligible theory uncertainties: cross sections are parameters of the fit, and not the result of an extrapolation



Full-lepton phase space rapidity cross section

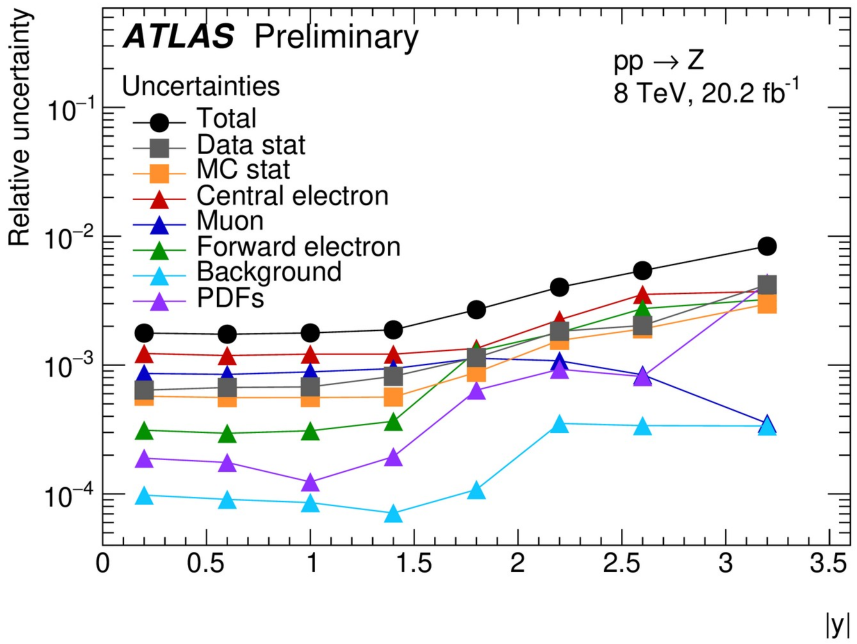
- Interpretation of fiducial cross sections hampered by breakdown of fixed order perturbation theory
  - Fiducial linear power corrections, unphysical predictions, alternating non-convergent perturbative QCD series
- Proposed solutions:
  - Change the definition of fiducial cuts
    arXiv:2106.08329 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.
- 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

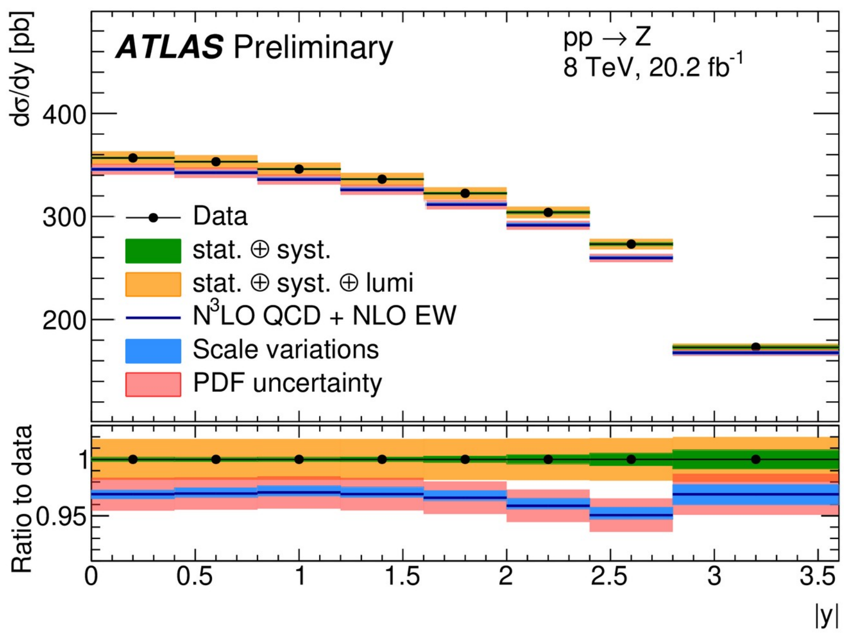


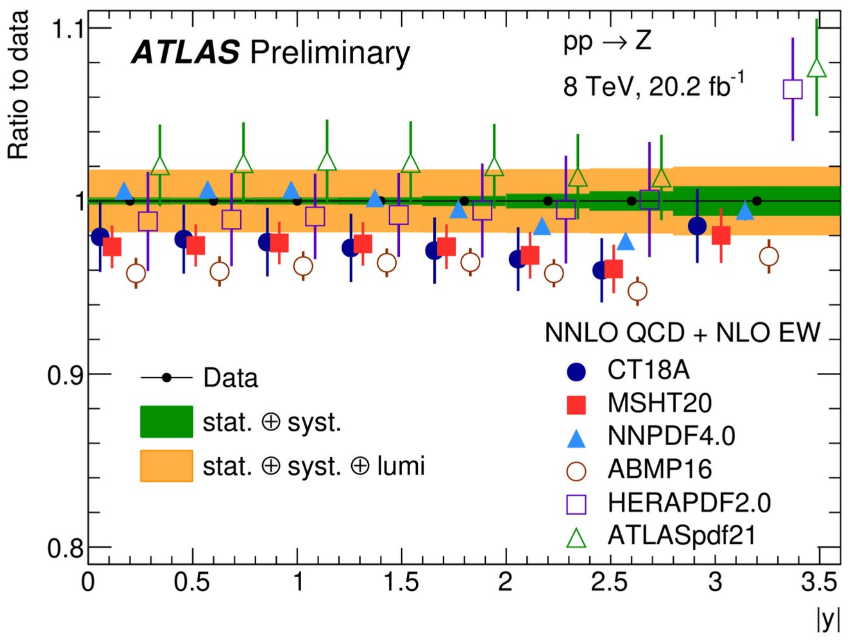


Full-lepton phase space rapidity cross section

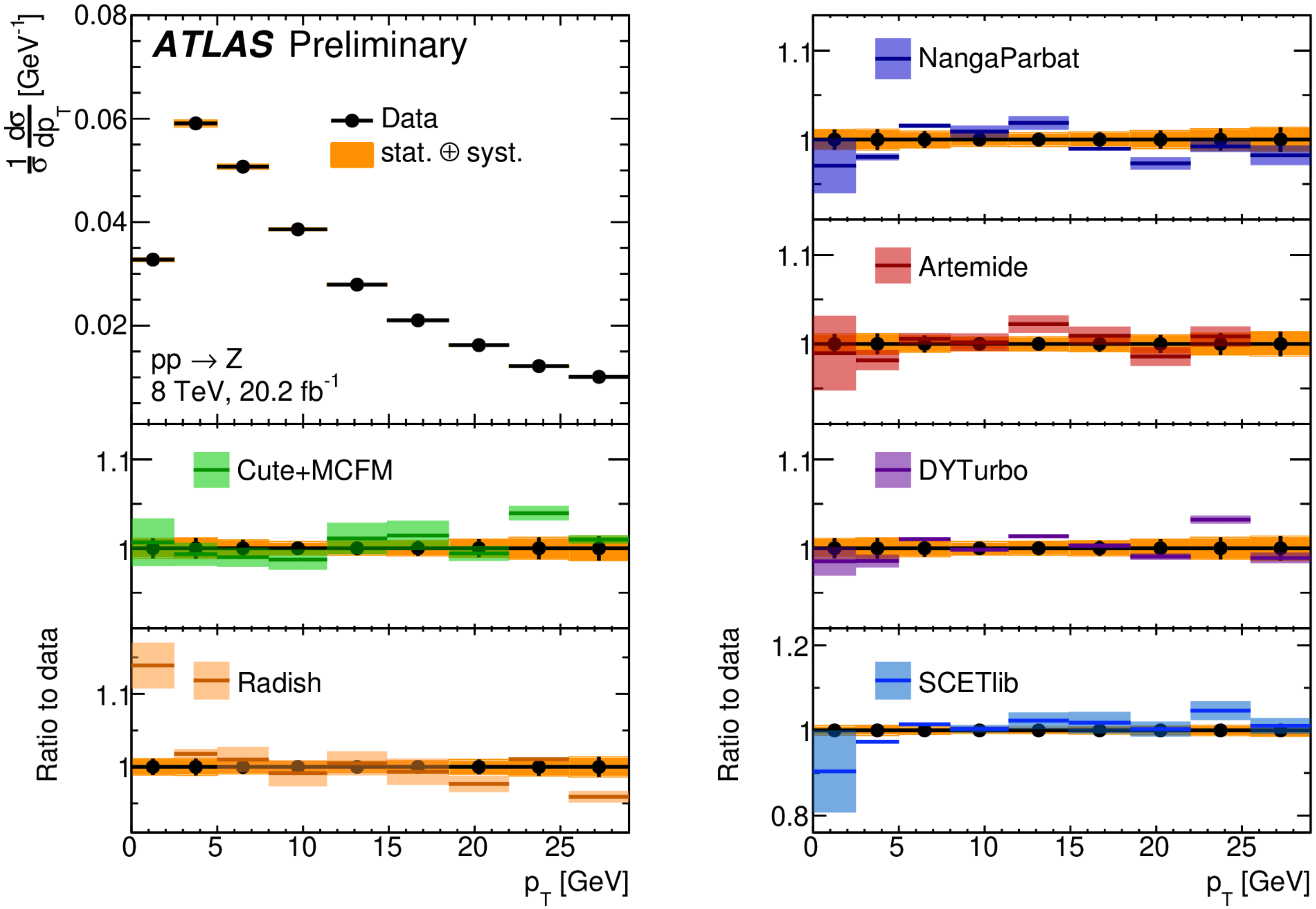
- Exquisite permille level precision in the central region
- Subpercent uncertainties up to |y| < 3.6 thanks to dedicated forward electron calibration
- First comparison to N3LO QCD predictions
- Enables precise and unambiguous PDF interpretation with QCD scale variations now smaller than PDF uncertainties







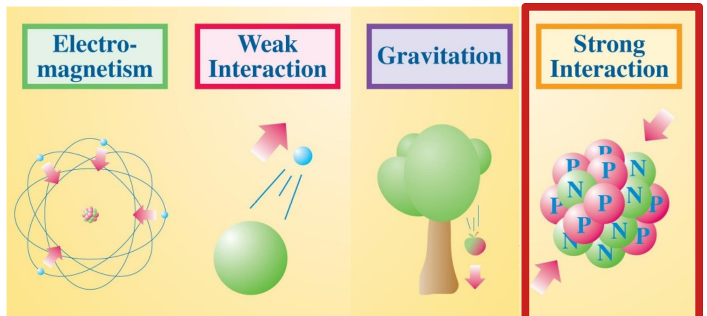
p_T cross section measurement



- Measurement compared to six predictions currently involved in the LPCC p_T W,Z benchmark study at N3LL/N4LL logarithmic accuracy, including $O(\alpha_s^3)$ matching from MCFM/NNLOJET
- Excellent agreement between data and 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

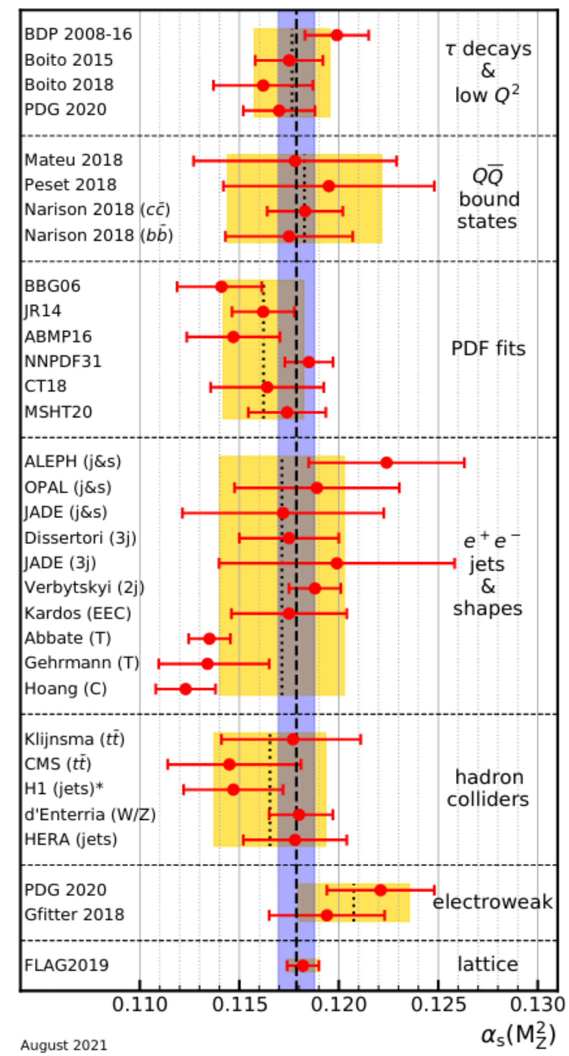
The strong-coupling strength $\alpha_s(m_Z)$

The strong force is the least well known interaction of nature



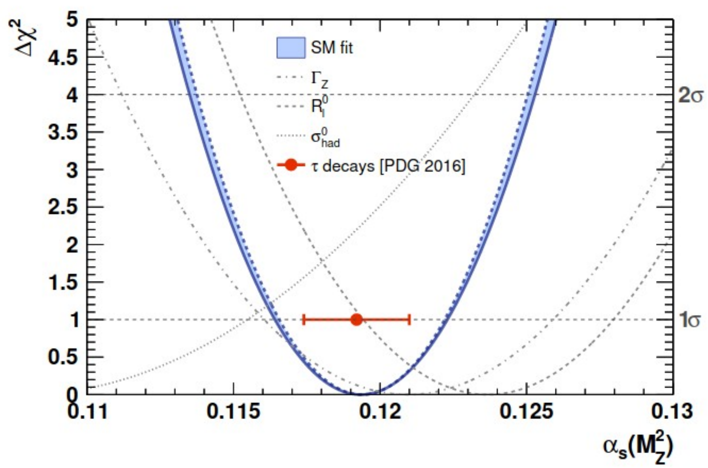
	Electro-magnetism	Weak Interaction	Gravitation	Strong Interaction
Relative uncertainty	10^{-10}	10^{-7}	10^{-5}	10^{-2}

World average:
$\alpha_s(m_Z) = 0.1179 \pm 0.0009$
[PDG 22]



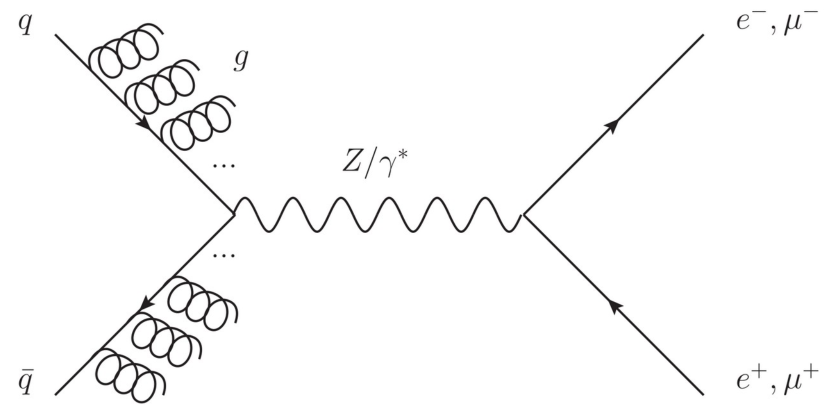
- Single free parameter of QCD in the $m_q \to 0$ limit
- Conventionally determined at the reference scale $Q = m_Z$
- Decreases ("runs") as $\alpha_s \sim \ln(Q^2/\Lambda^2)^{-1}$

- 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



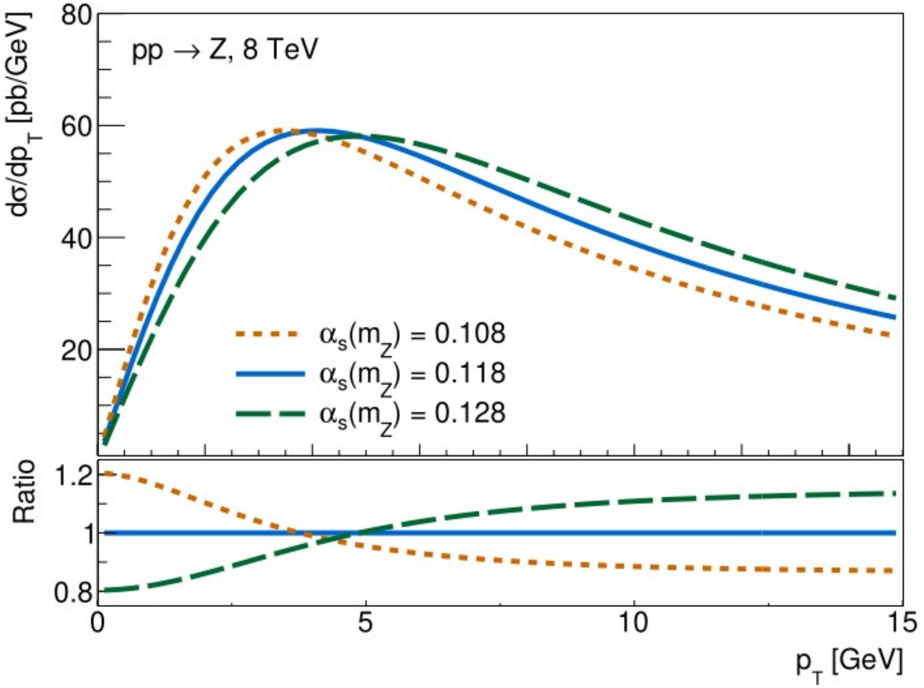
Measure $\alpha_s(m_Z)$ from the Z p_T distribution

- 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 position of the peak is sensitive 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

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

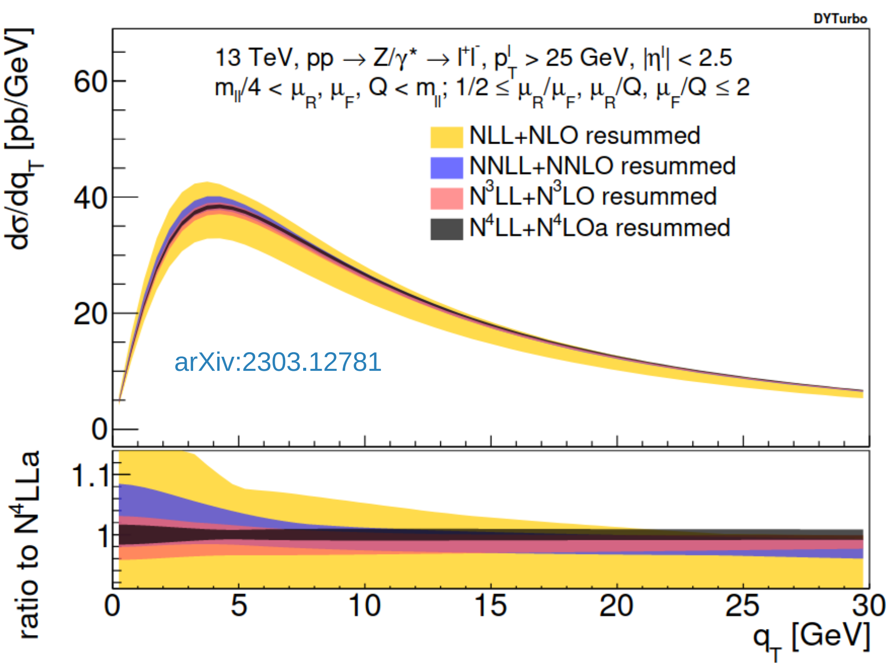
Born cross section

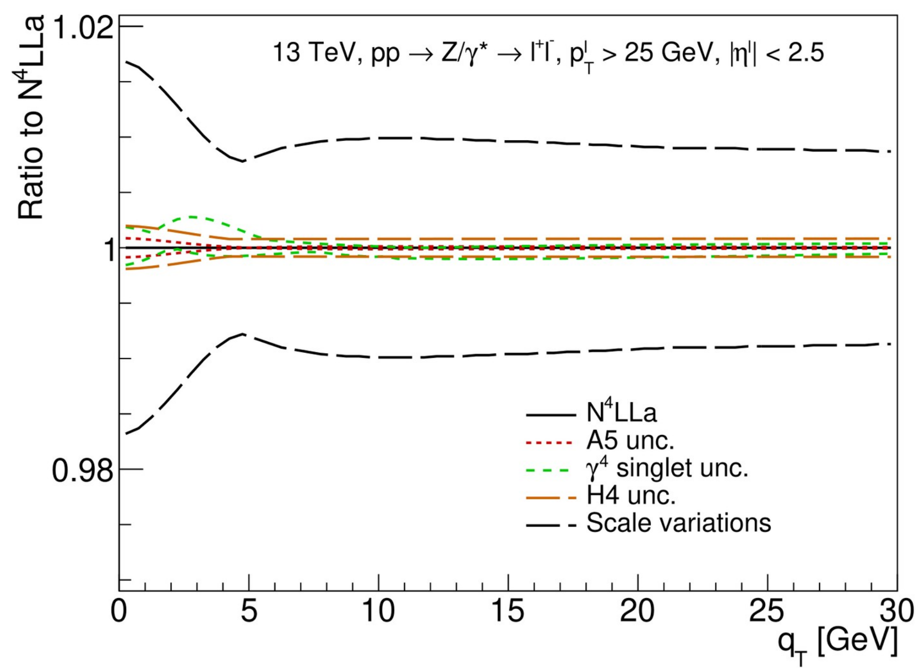
perturbative Sudakov form factor

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

Hard virtual

Sensitivity to α_s





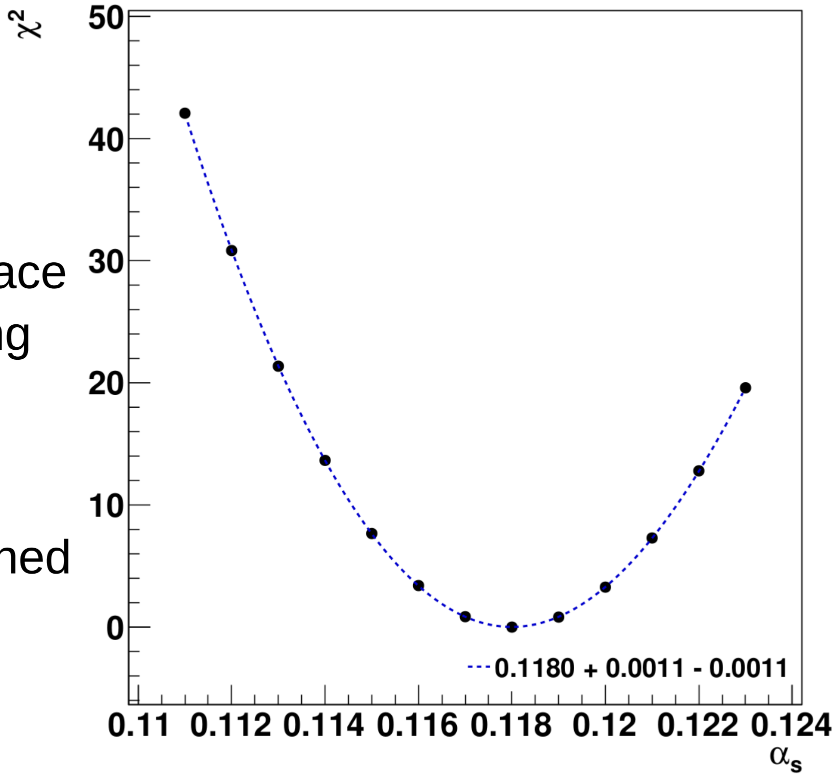
- N4LL approximations are much smaller than missing higher order uncertainties

Methodology for the $\alpha_s(m_Z)$ determination

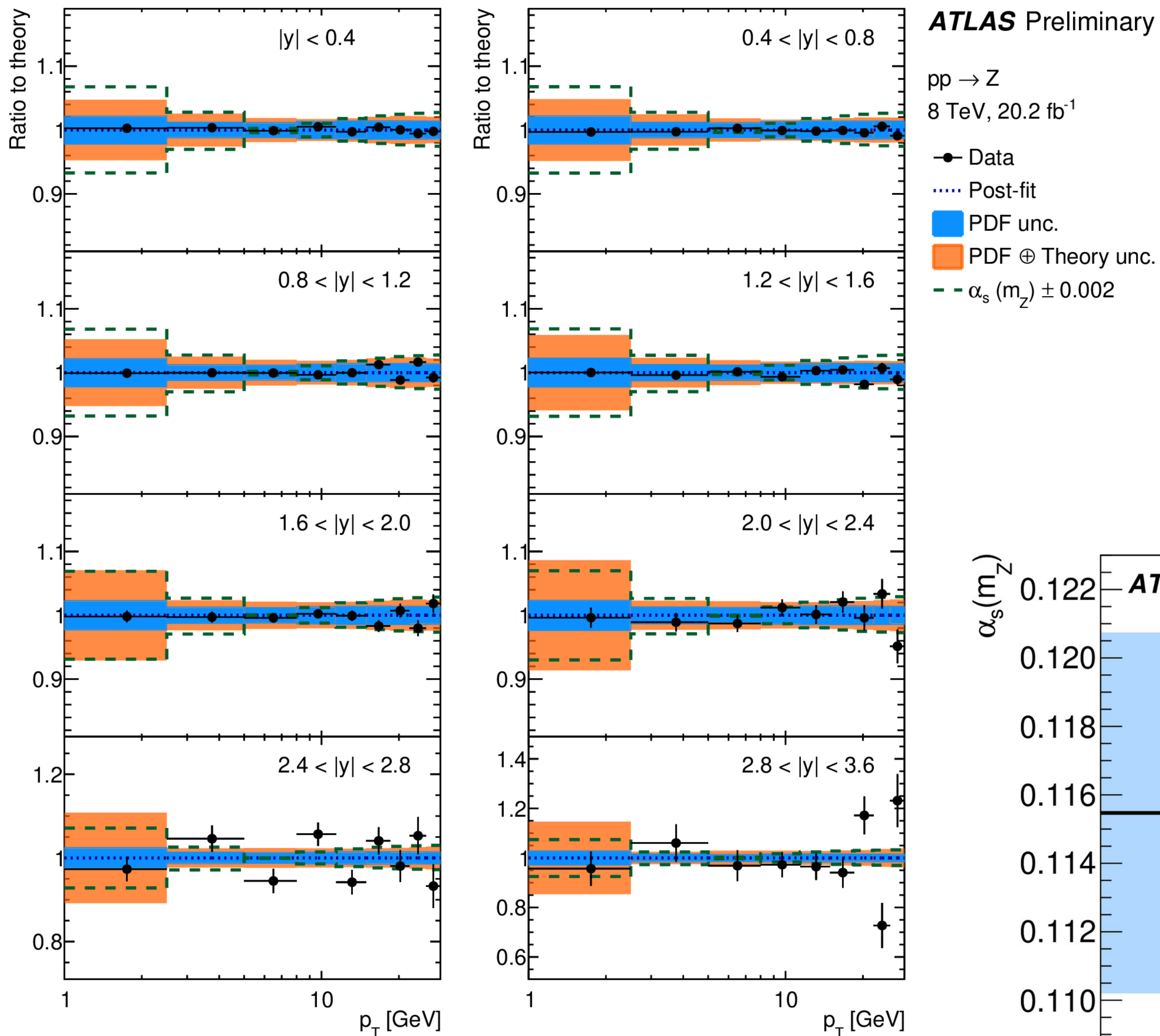
- DYTurbo interfaced to xFitter arXiv:1410.4412
- Evaluate $\chi^2(\alpha_s)$ with α_s variations as provided in LHAPDF
- Include experimental ($\beta_{j,exp}$) and PDF ($\beta_{k,th}$) uncertainties in the χ^2

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

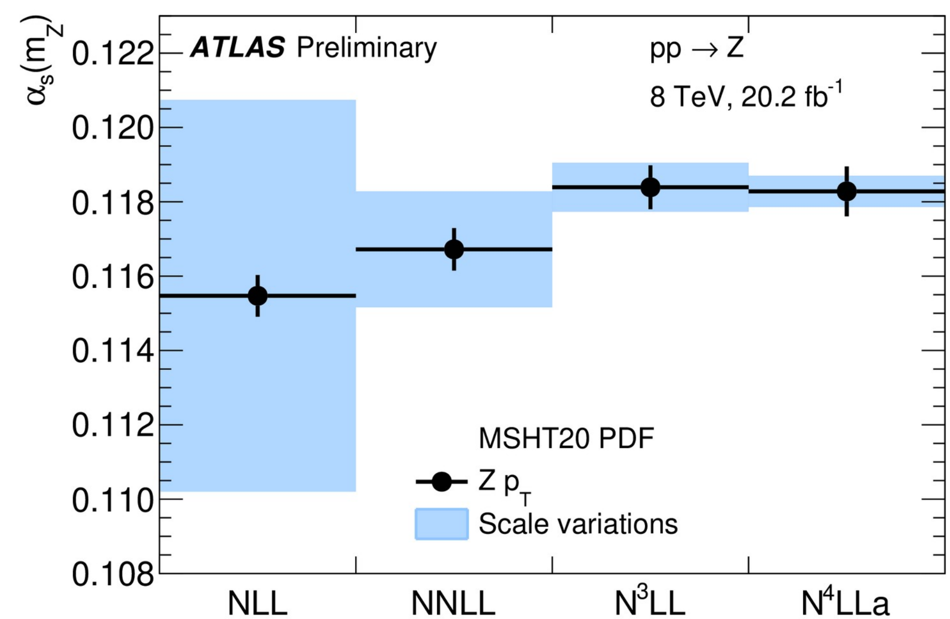
- At each value of $\alpha_s(m_Z)$ the $\beta_{k,th}$ terms explore the PDF space to find the best fit to the Z p_T data → equivalent to including the new dataset in the PDF without refitting, using profiling/reweighting Eur.Phys.J.C 75 (2015) 9, 458
- The non-perturbative form factor is added with unconstrained 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
- Postfit χ^2/dof = 82/72
- Determination performed at lower orders, demonstrating good convergence of the perturbative series

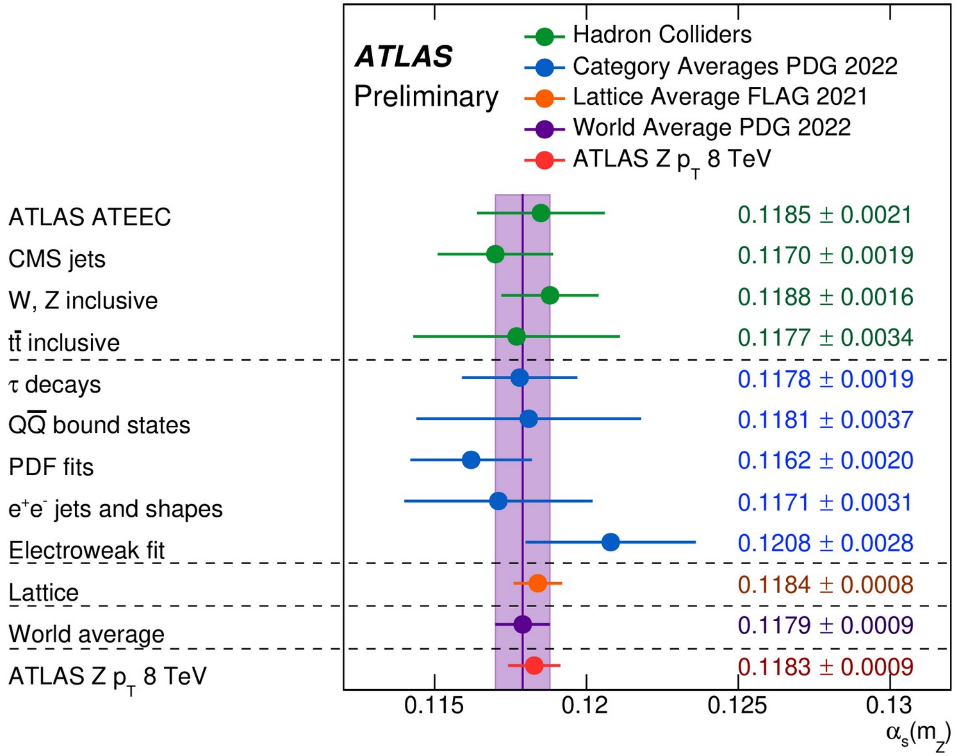


Outlook

- 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+N4LL
- 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)
- Determination focusing on the Sudakov region (usually avoided to determine α_s)
- Quadratic Λ_{QCD}/Q power corrections, compared to linear in LEP event shapes
- Observable not suitable for inclusion in PDF fits $\rightarrow$ no correlation with $\alpha_s(m_Z)$ determinations from PDF fits

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

$\alpha_s = 0.11828 \; {+0.00084} \; {-0.00088}$



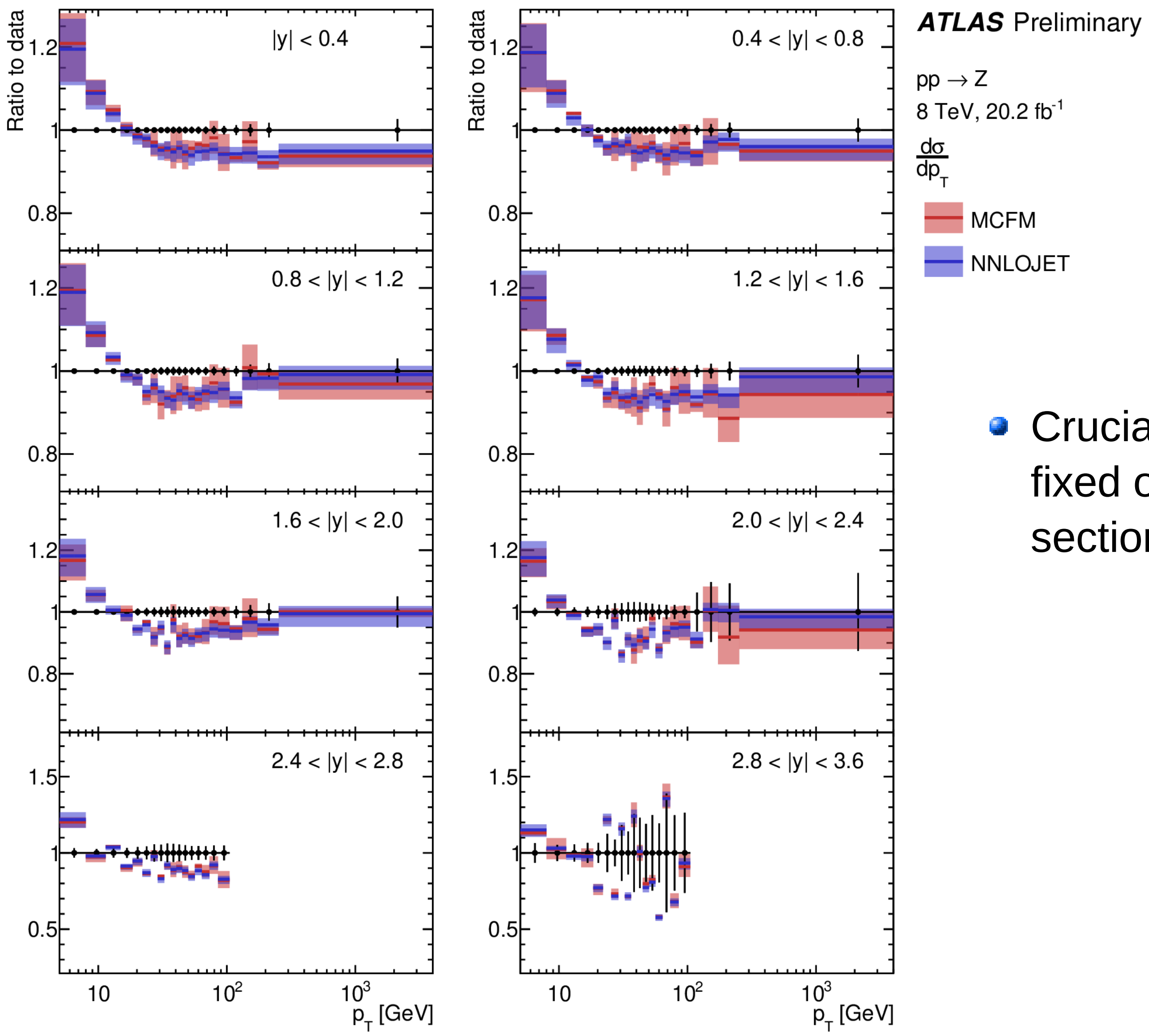
BACKUP

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

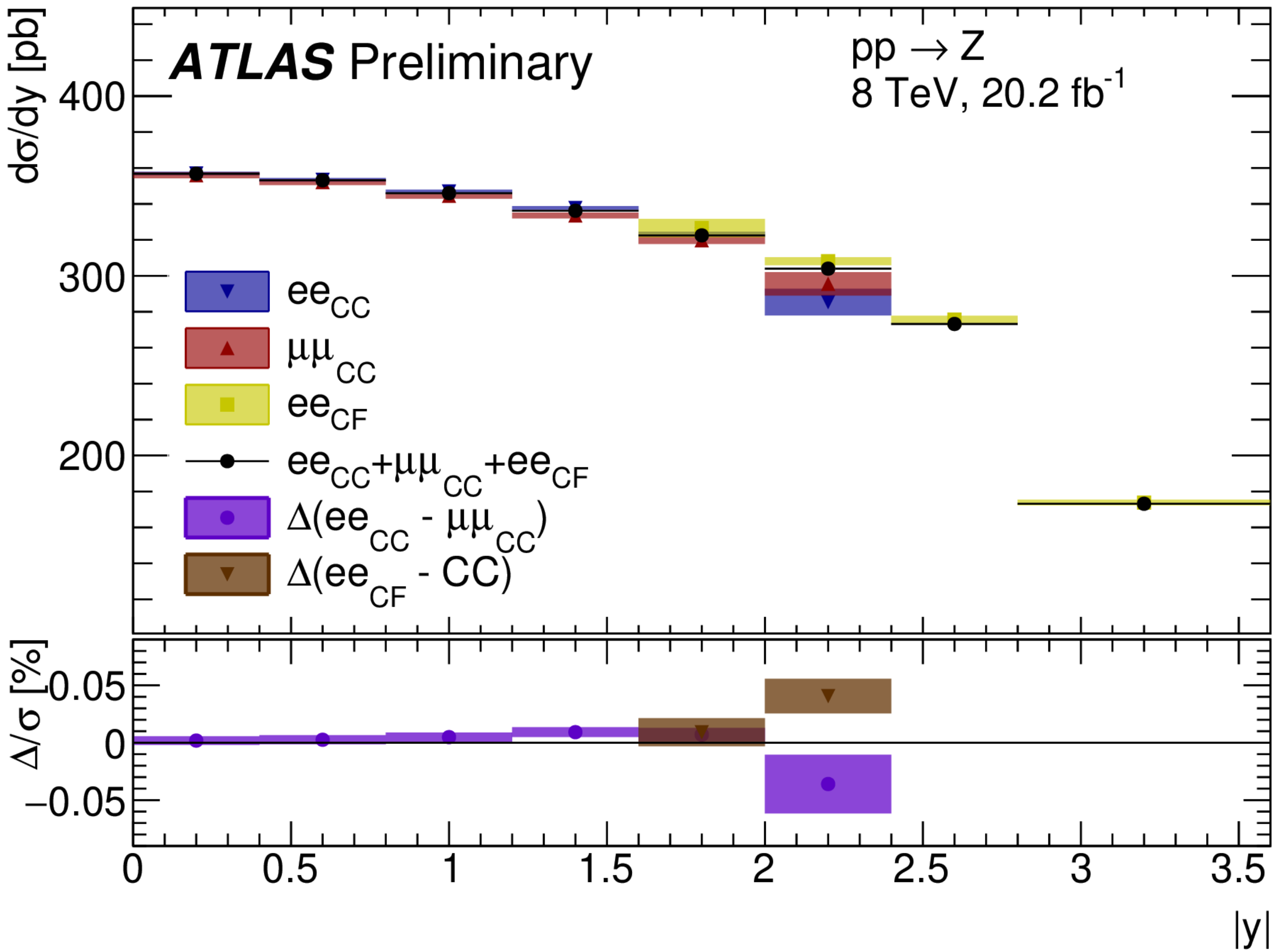
Known analytically
Approximated numerically
Unknown, estimated with series acceleration
Not included

Fixed order Z+jet at NNLO

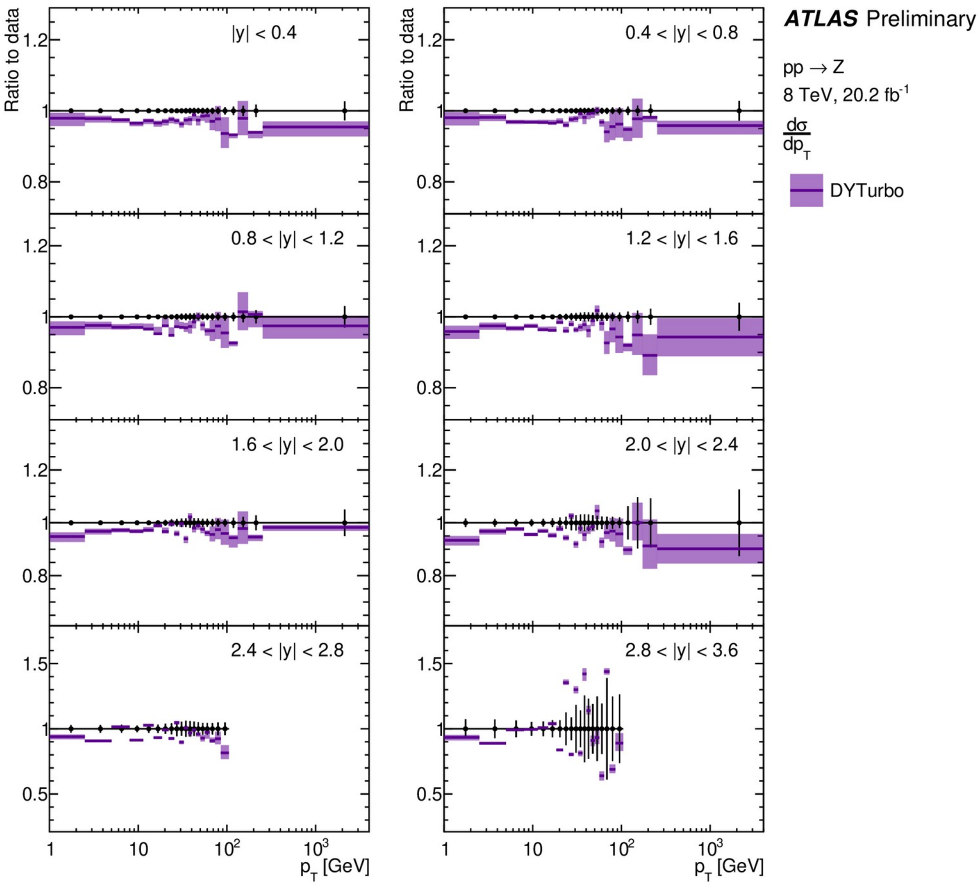


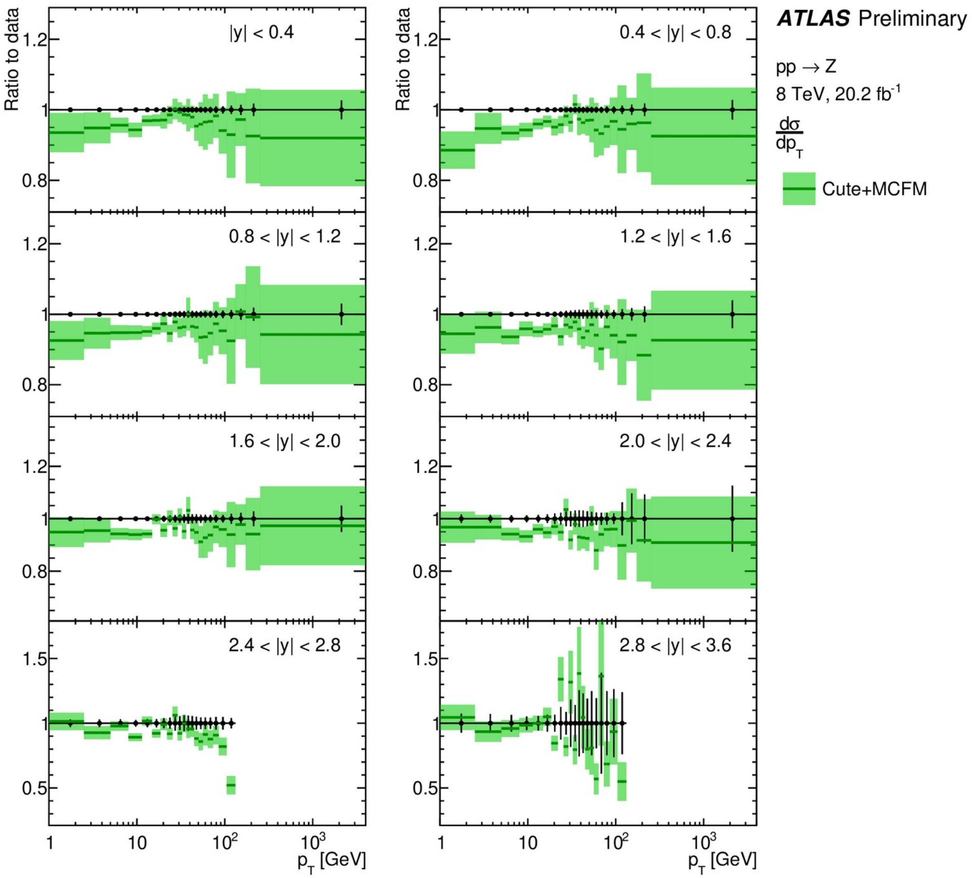
- Crucial ingredient for the matching to fixed order of q_T-resummed cross sections, and of the N3LO predictions

Channels compatibility

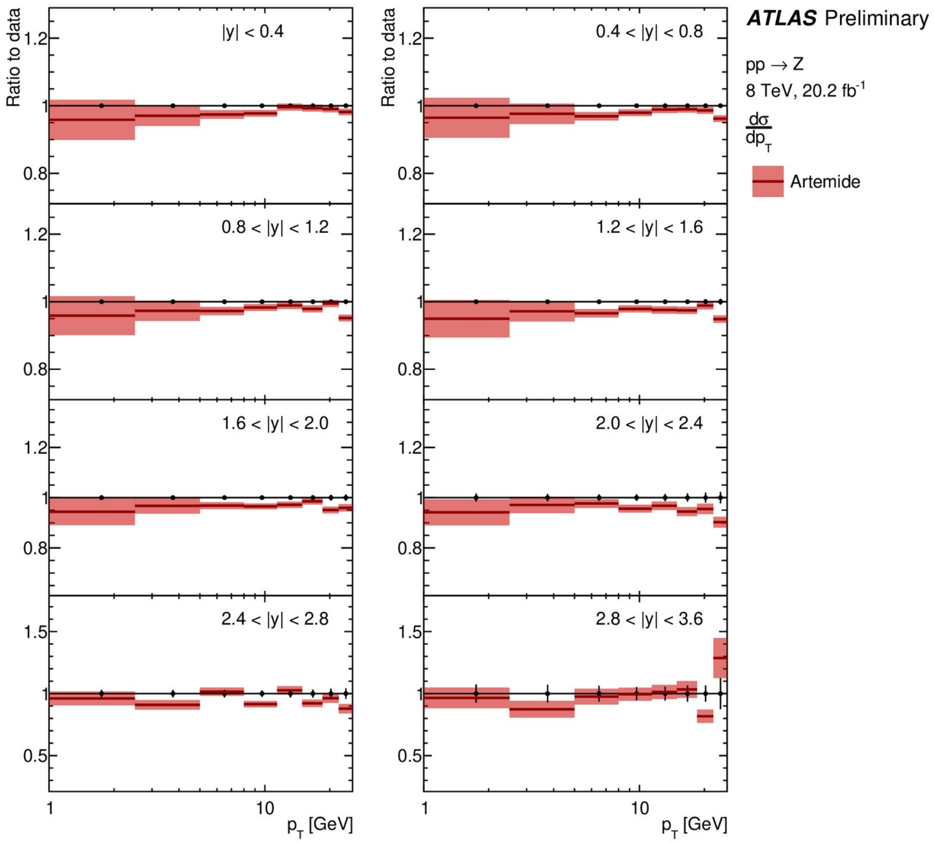


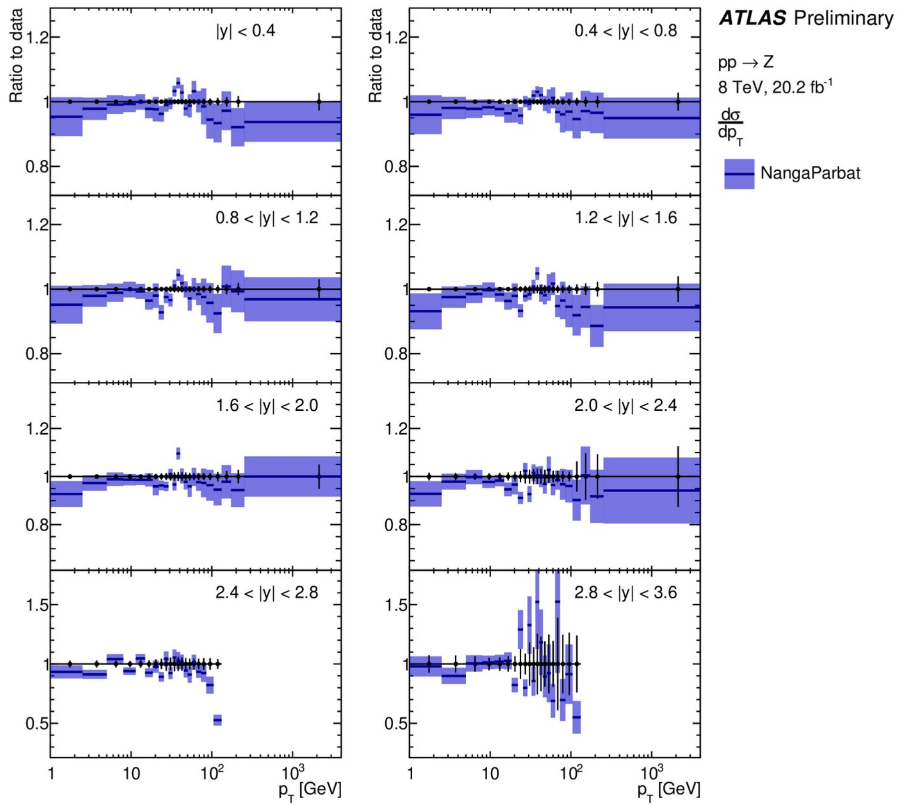
Comparison to q_T-resummation



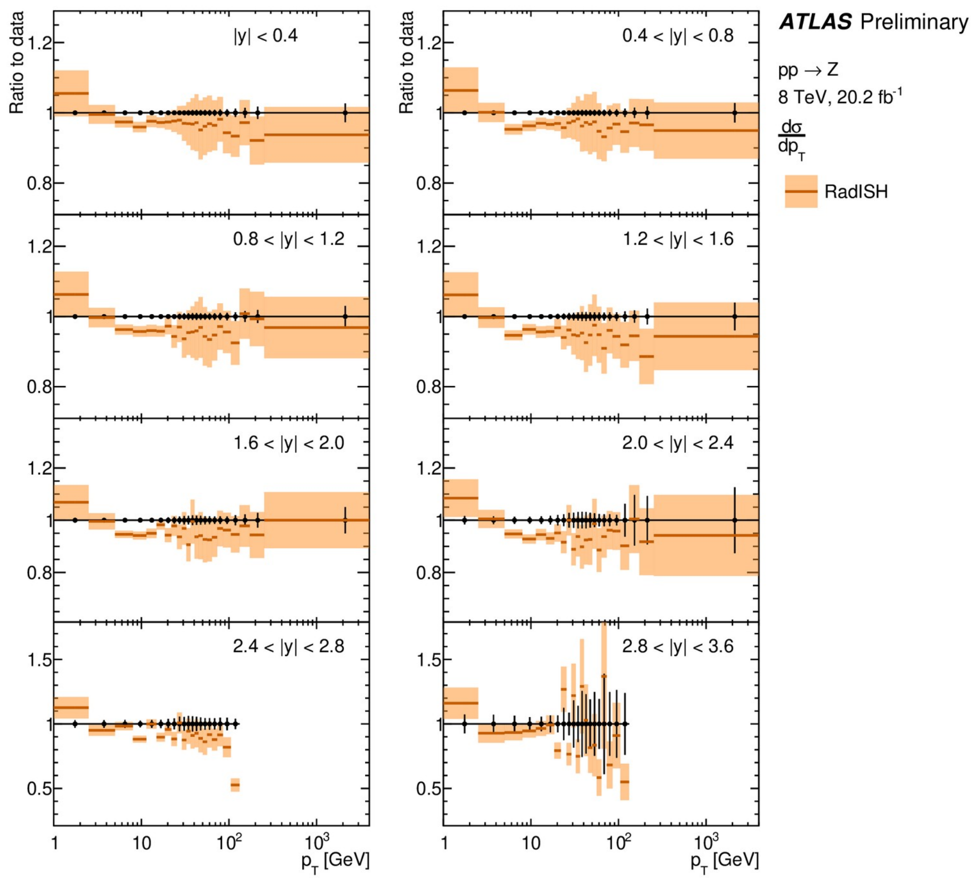


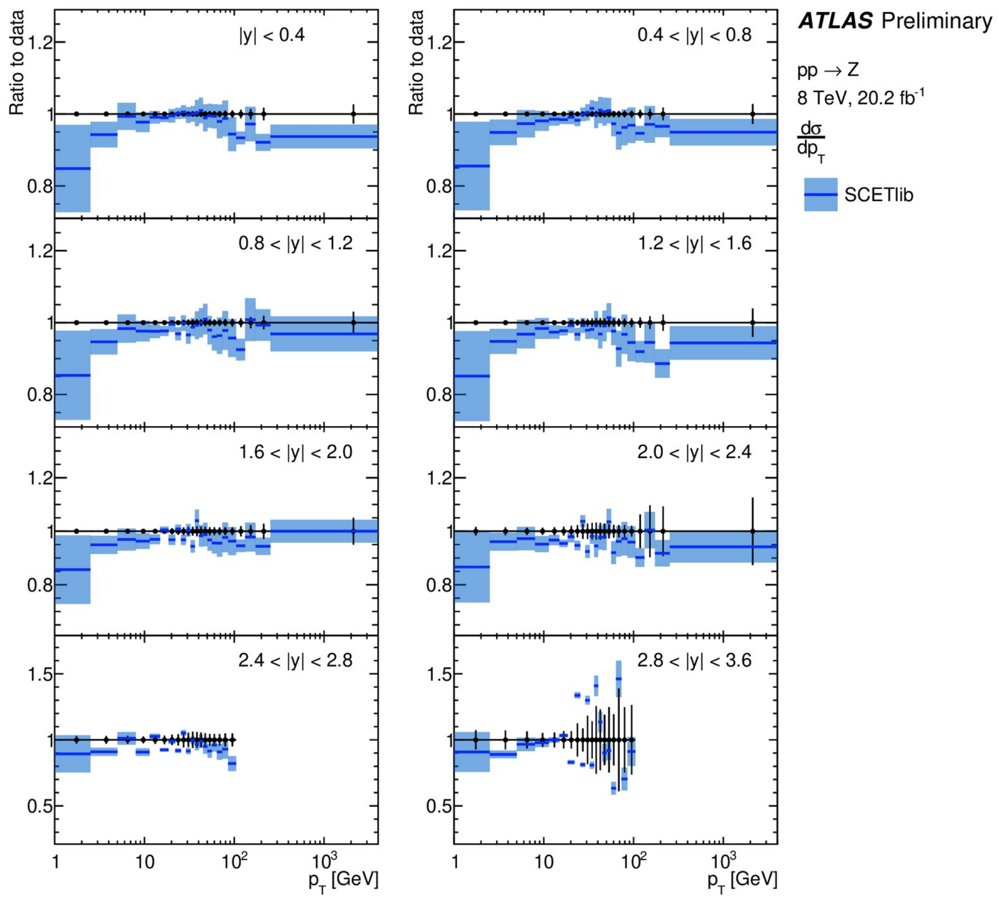
Comparison to q_T-resummation





Comparison to q_T-resummation





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

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

$$S_{\rm NP}(b) = \exp\left[-g_j(b) - g_K(b)\log\frac{m_{\ell\ell}{}^2}{Q_0}\right]$$

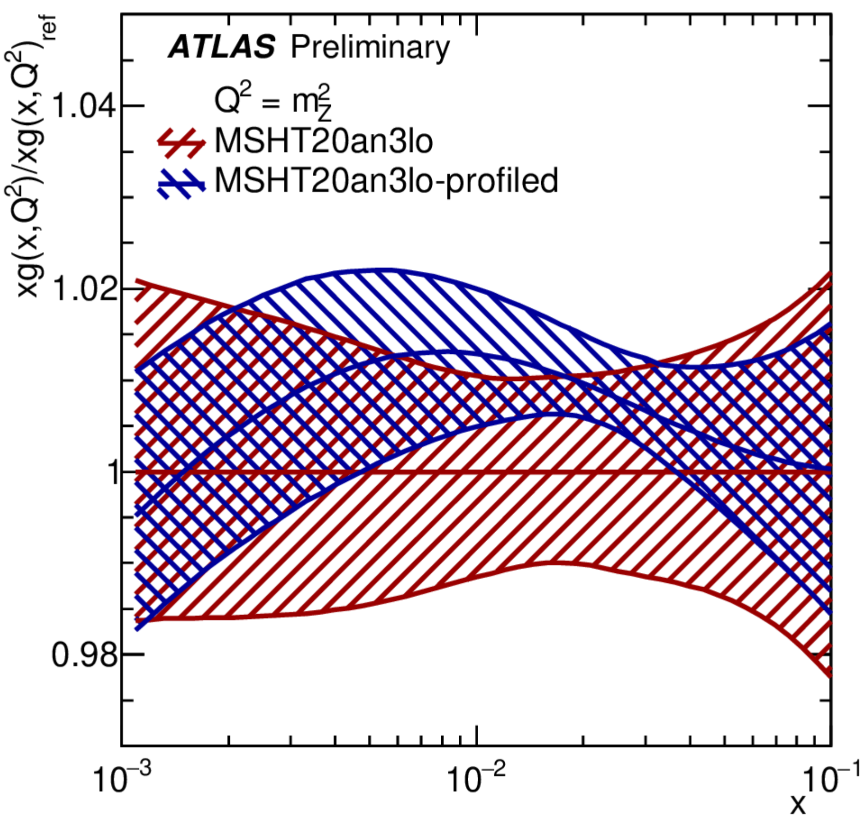
$$g_j(b) = \frac{g\, b^2}{\sqrt{1+\lambda\, b^2}} + \mathrm{sign}(q)\left(1 - \exp\left[-|q|\, b^4\right]\right)$$

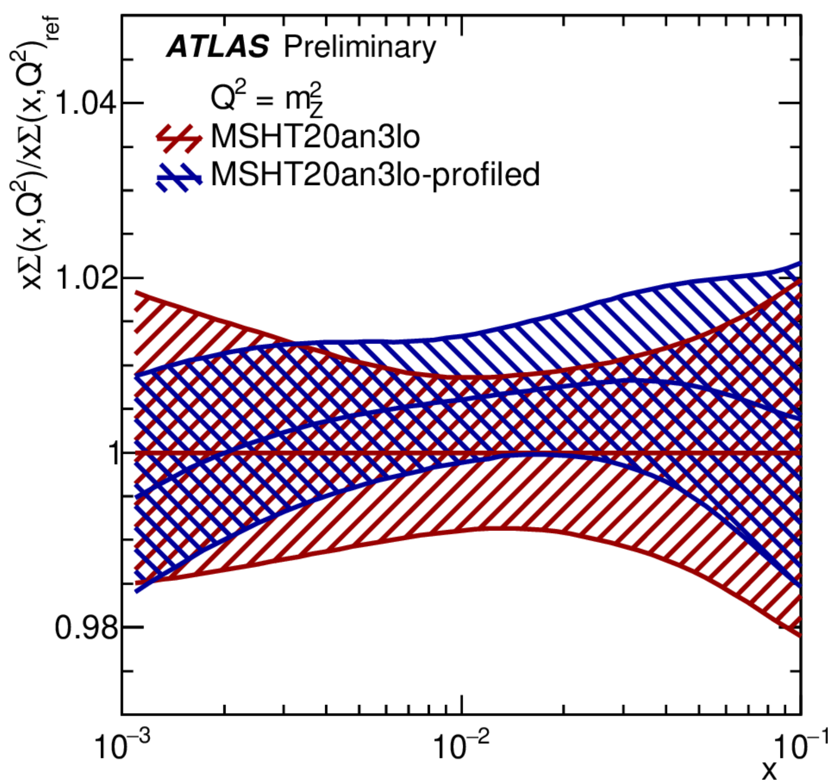
$$g_K(b) = g_0\left(1 - \exp\left[-\frac{C_F \alpha_s(b_0/b_*) b^2}{\pi g_0\, b_{\rm lim}^2}\right]\right),$$

- 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 blim (freezing scale) and Q0 (starting scale), provided SNP is flexible enough. Q0 and blim are varied to assess a parameterisation uncertainty
- g0 controls the very high b (very small pT) behaviour, should be fitted to data, but we have no sensitivity to it, so it is varied
- New parameter lambda controls the transition from Gaussian to exponential, set to 1 and varied by factor of 2 up and down

PDF profiling

- PDF profiling at the best $\alpha_s(m_Z)$ shows reduction of gluon and sea quark PDF uncertainties





NNLO PDF sets

- Spread of PDFs at NNLO is +- 0.00102
- Driven by NNPDF4.0-CT18A difference

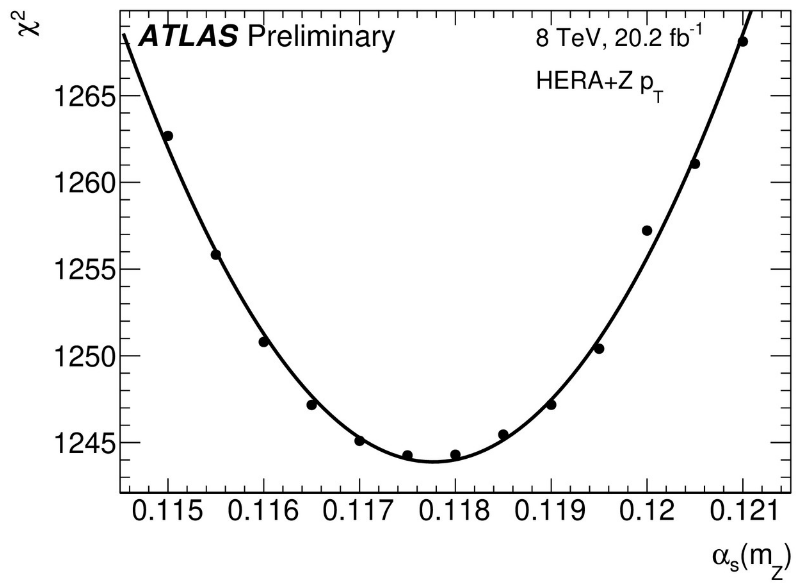
PDF set	$\alpha_s(m_Z)$	PDF uncertainty	g [GeV^2]	q [GeV^4]	χ^2/dof
MSHT20 [32]	0.11839	0.00040	0.44	-0.07	96.0 /69
NNPDF40 [78]	0.11779	0.00024	0.50	-0.08	116.0/69
CT18A [79]	0.11982	0.00050	0.36	-0.03	97.7 /69
HERAPDF20 [63]	0.11890	0.00027	0.40	-0.04	132.3/69

- Adding HERA data to the fit (counted twice), the spread is reduced to +- 0.00016

- Indication that the large spread is due to the tension in the gluon PDF between different dataset, and how this is solved by each PDF group
- MSHT20an3lo analysis shows that the gluon PDF tension is much reduced at N3LO

Full PDF+NP+as fit at N3LL

- Performed a full fit at N3LL, using NNLO DGLAP evolution (and NNLO DIS predictions)
- Recently it was claimed that this is the only correct way of determining $\alpha_s(m_Z)$, but not everybody subscribes to this opinion
- Anyway, it provides a cross check of the Hessian profiling methodology
- Also, the PDG likes to provide a version of the world average with only “full PDF fits” included
- $\alpha_s(m_Z) = 0.11777 \pm 0.00065$
- When adding +- 0.00066 of scale variations and all uncertainties: 0.11777 +0.00097 -0.00100



Experimental sensitivity

- Scanning the $\alpha_s(m_Z)$ dependence of the χ^2 with α_s-series of PDFs
- Experimental sensitivity evaluated with pseudodata:

$\alpha_s(m_Z)$ = 0.11801 +- 0.00006

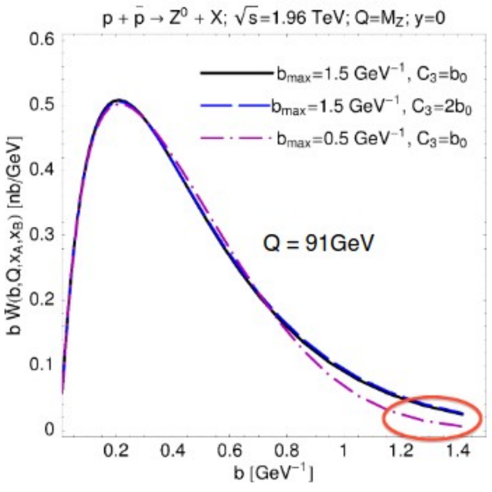
$\Delta\alpha_s/\alpha_s$ = 0.05%

Remarks on the generality of the NP model

- Tafat, renormalon analysis (hep-ph/0102237):
  - Small b behavior should be Gaussian $$W_0 = \exp\left(-\ln\frac{Q^2}{Q_0^2}\left[c_1 b^2 + c_2 b^4 + c_3 b^6 + \mathcal{O}(b^8)\right]\right),$$
  - Large b behavior should be exponential

- 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”

- Fits excluding the region 0-5 GeV yields $\alpha_s(m_Z)$ with a spread of + 0.00017 – 0.00010
- Fit uncertainty increased from 0.00067 to 0.00071
- Correlation between $\alpha_s(m_Z)$ and g largely reduced
- Demonstrates good modelling of NP effects

HF model

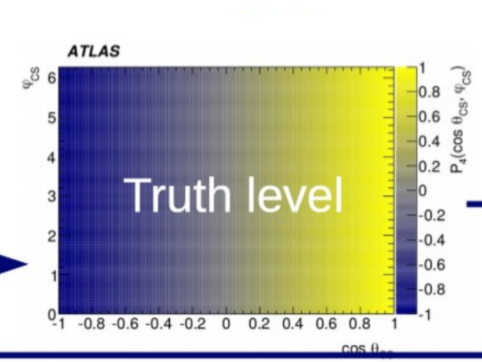
- VFN PDF: -0.00029
- VFN as: +0.00021
- μ_c: +0.00007
- μ_b: -0.00029

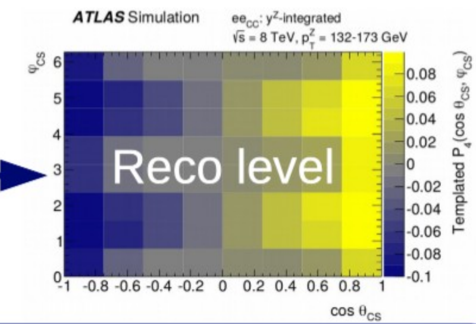
HF model:

$\delta\alpha_s$ = +0.00021 – 0.00029

Ai measurement methodology

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





Expected Yield

Reco (p_T^Z, y^Z, m^Z, cosθ, ϕ) bin

Cross section

Background template

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

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

Angular coefficient

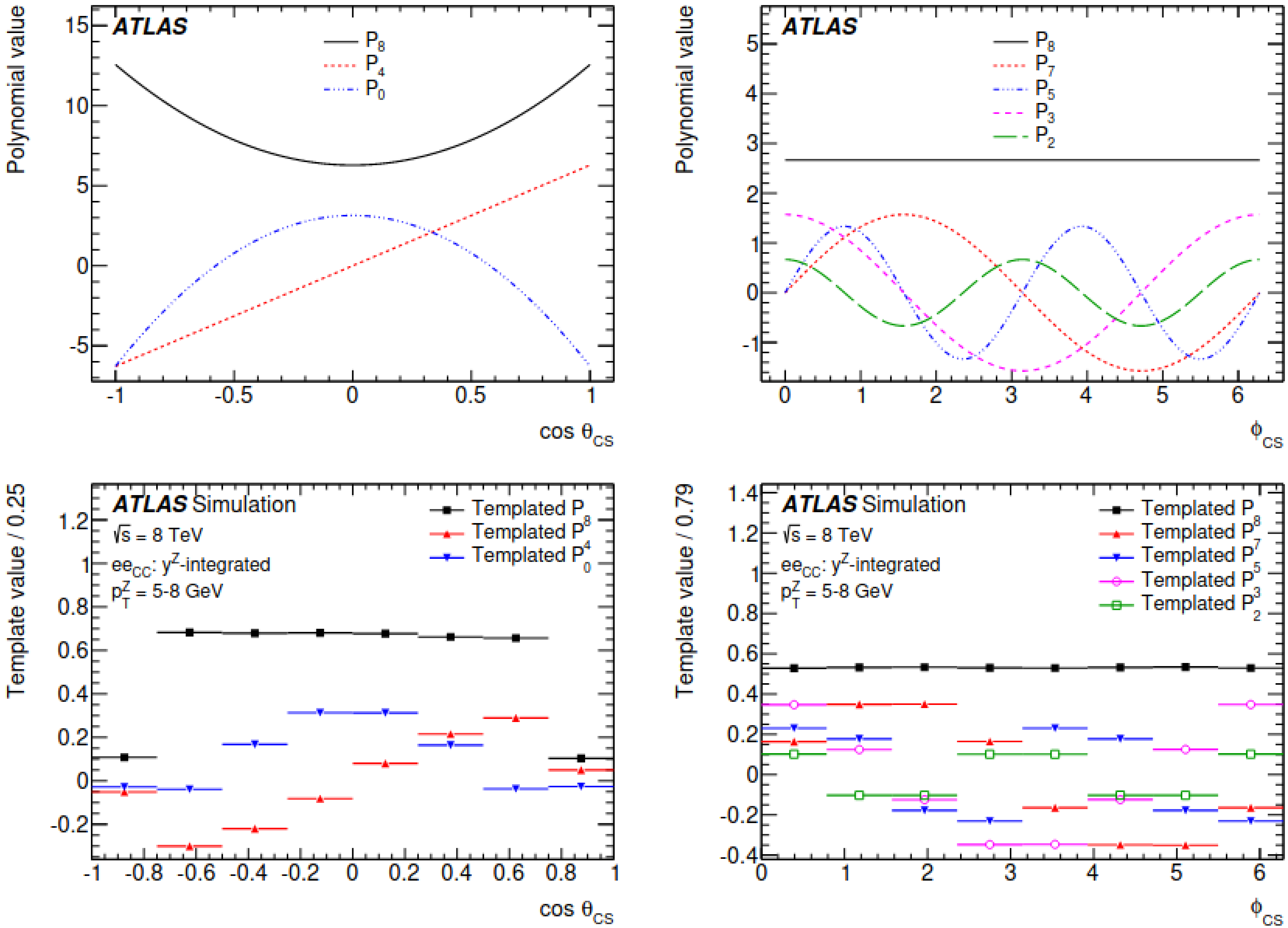
Templated polynomial

Likelihood

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

2

Ai measurement methodology



Result at the Tevatron

α_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

- Measurement in agreement with the world average
- Uncertainty comparable to other determinations

arXiv:2203.05394