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Matthias Schott on behalf of the ATLAS Collaboration

Measurement of the Strong Coupling Constant with ATLAS

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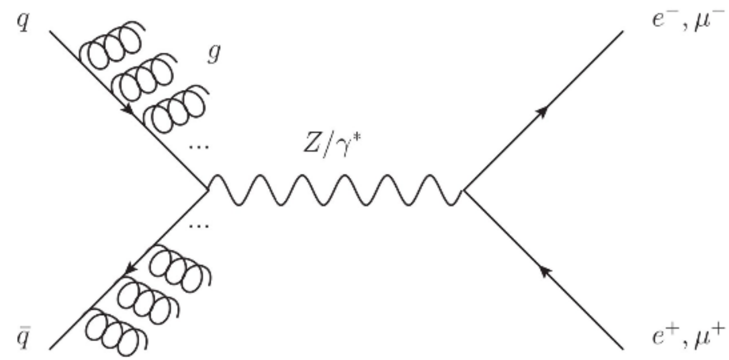
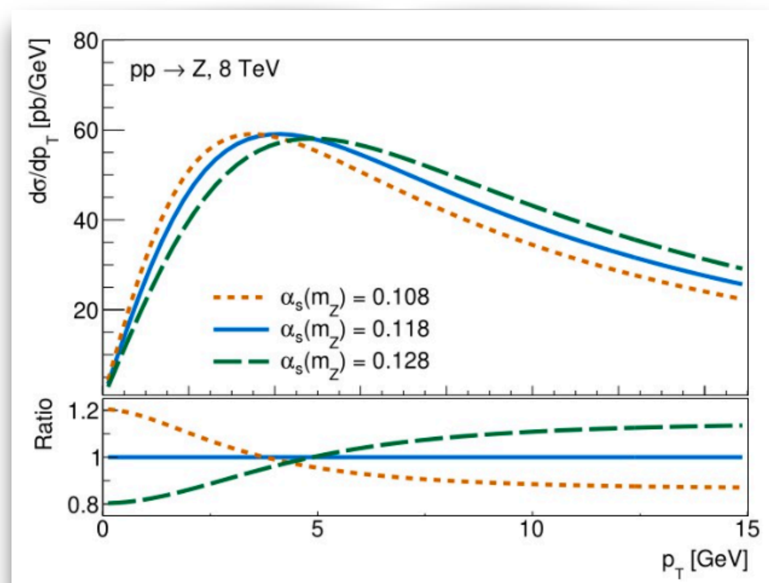
Drell-Yan Process

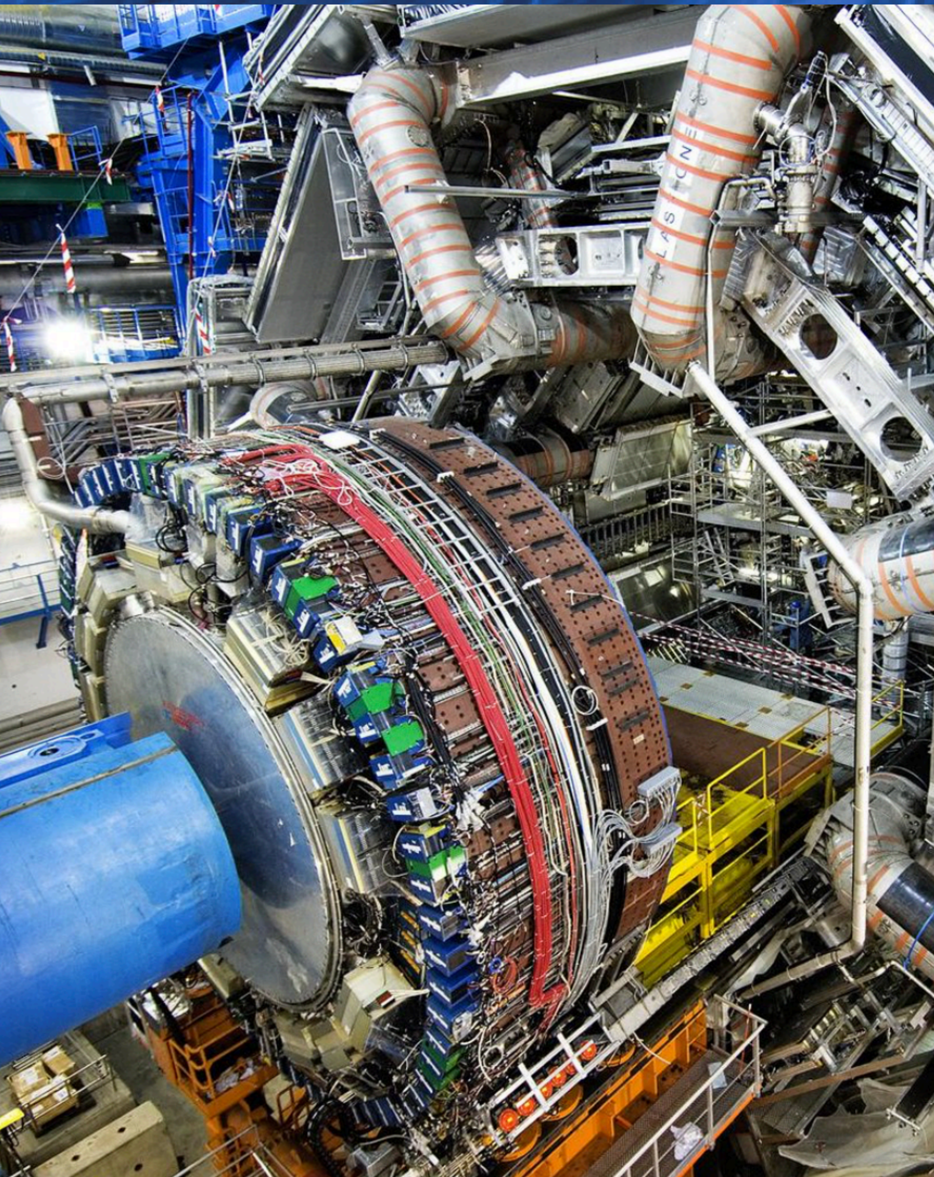
Measure $\alpha_s(m_Z)$ from the $p_T(Z)$ distribution

- 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 $\alpha_s(m_Z)$
- Semi-inclusive observable, which has advantages of
  - exclusive obs. (higher exp. sensitivity)
  - inclusive obs. (higher order theory, smaller non-pQCD effects)





Anatomy of Drell-Yan differential cross section



- DY not only interesting physics wise, but required for all aspects of detector calibration

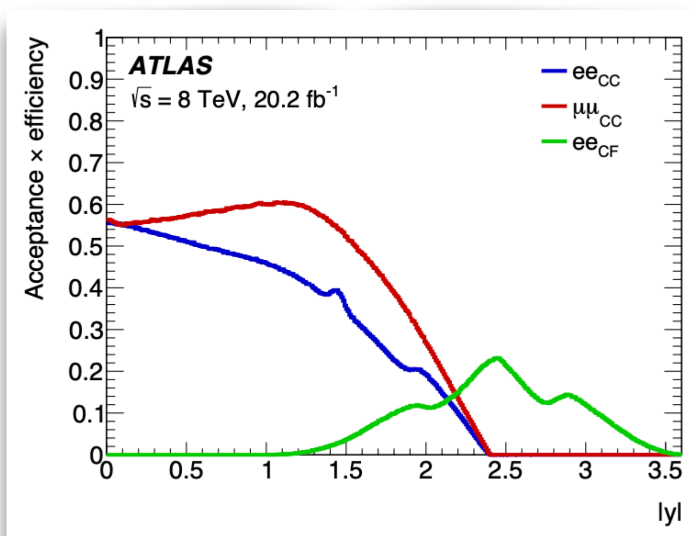
- DY cross section: factorize the production dynamic and the decay kinematic properties of the dilepton system

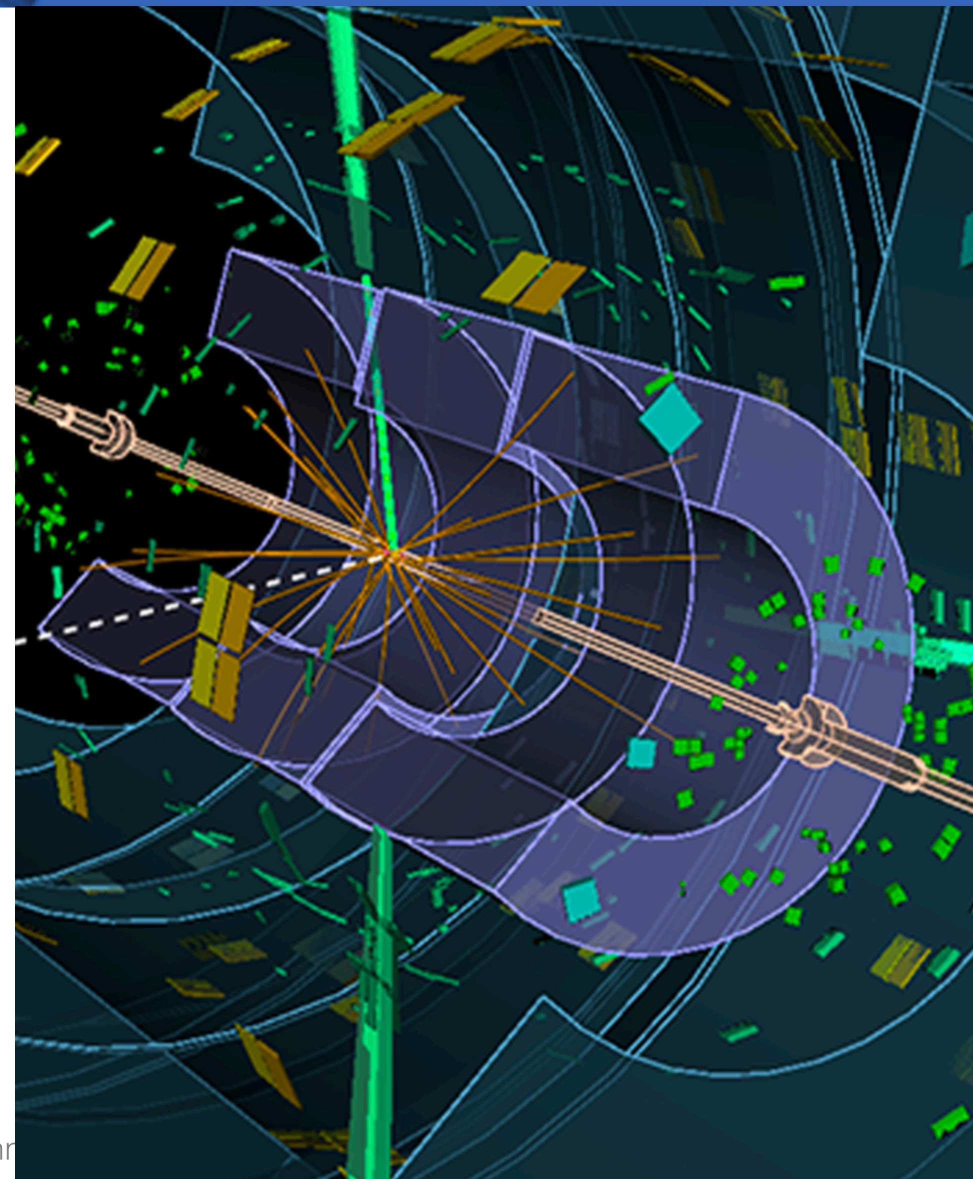
$$\frac{d\sigma}{dpdq} = \frac{d^3\sigma^{U+L}}{dp_T dy dm}\left(1 + \cos^2\theta + \sum_{i=0}^{7} A_i(y, p_T, m) P_i(\cos\theta, \phi)\right)$$

- ds/dp_T: transverse dynamics
- ds/dy: longitudinal dynamics (PDFs)
- decomposition of (cosθ,Φ) into 9 helicity cross sections
- basis of spherical harmonics

Event selection

- Three Channels
  - eeCC: two electrons (6.2M events) p_T>20 GeV, $|\eta|$ < 2.4
  - μμCC: two muons (7.8M events) p_T>20 GeV, $|\eta|$ < 2.4
  - eeCF: central electron with p_T > 25 GeV, $|\eta|$ < 2.4, forward electron with p_T > 20 GeV, 2.5 < $|\eta|$ < 4.9 (1.2M events)
  - 80<mll <100GeV



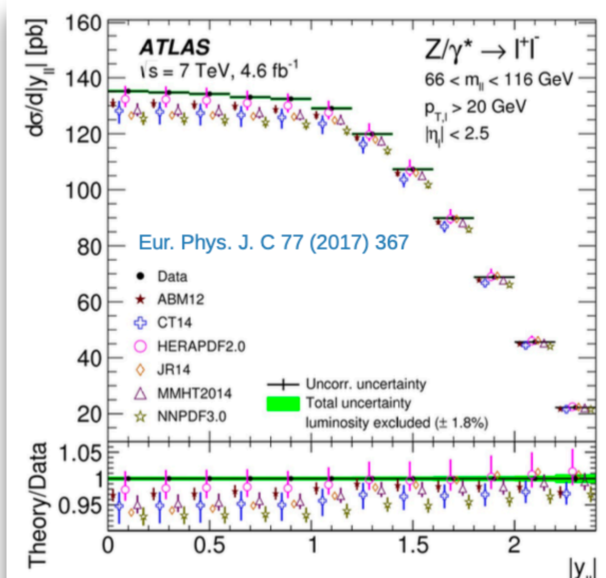


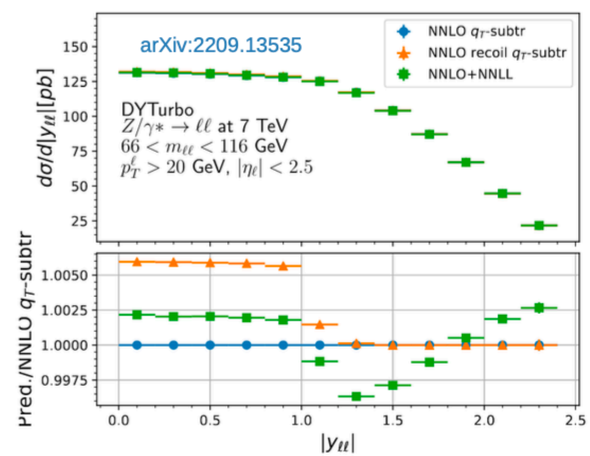
Full-lepton phase space rapidity cross section

- Interpretation of fiducial cross sections hampered by breakdown of fixed order perturbation theory
  - Problem: low pT(Z) spectrum impacts pT lepton spectrum

- Proposed solutions:
  - Change the definition of fiducial cuts arXiv:2106.08329
  - Use Ai theory predictions to extrapolate the measured cross sections arXiv:2001.02933
  - Include resummation corrections into predictions arXiv:2209.13535 Amoroso et al.
  - All above solutions introduce either experimental or theoretical uncertainties/problems

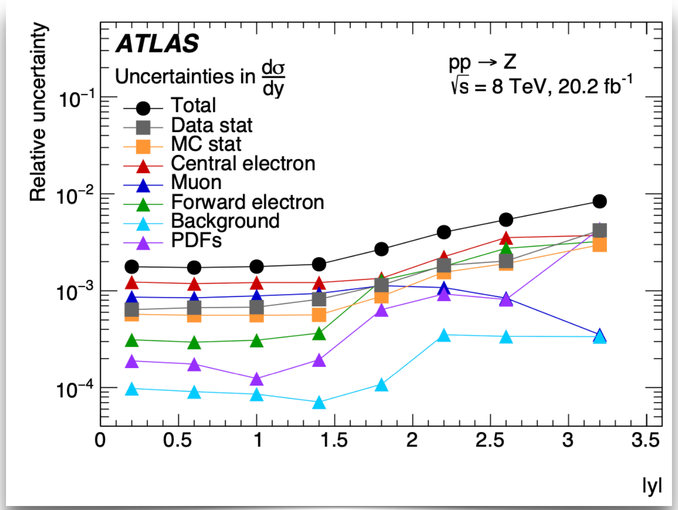
- Ai-based elegant solution:
  - Fiducial cuts removed by analytic integration of (cosθ,Φ) in the full phase space of the decay leptons through the measured Ai coefficients
  - few permille total uncertainties for ds/dy and negligible theoretical uncertainties

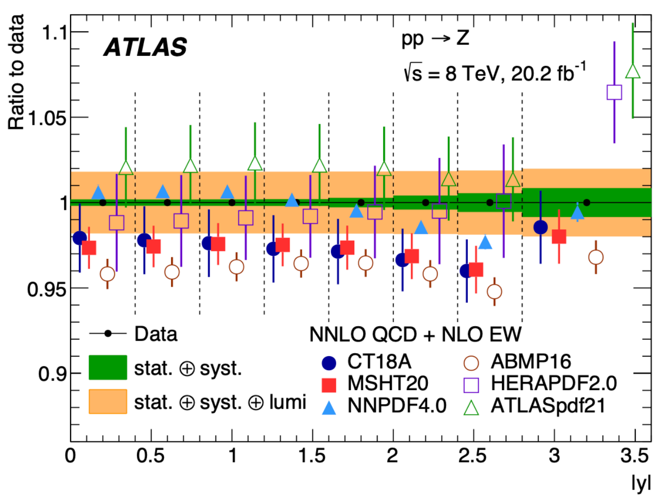




Full-lepton phase space rapidity cross section

- 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





Measurement methodology

Expected Yield

Reco (p_T^Z, y^Z, m^Z, cosθ, ϕ) bin

Cross section

Background template

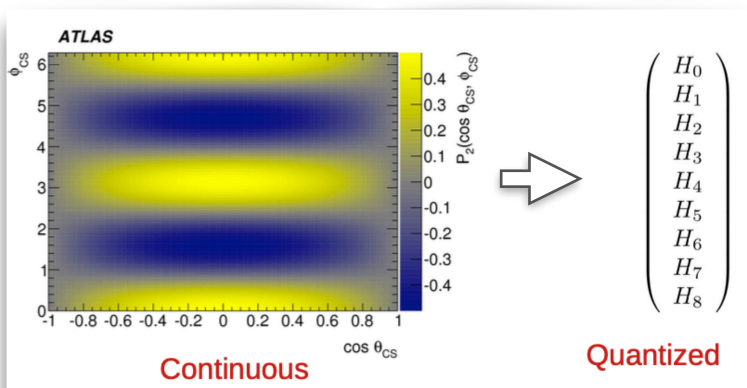
$$N^{n}_{\mathrm{exp}}(A,\sigma,\theta) = \left\{ \sum_{j=1}^{N^{ana}_{\mathrm{bins}}} \mathcal{L}\sigma_j \left[t^n_{8j}(\beta) + \sum_{i=0}^{7} A_{ij}\, t^n_{ij}(\beta) \right] \right\} \gamma^n + \sum_{B}^{\mathrm{bkgs}} T^n_B(\beta)$$

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

Angular coefficient

Templated polynomial

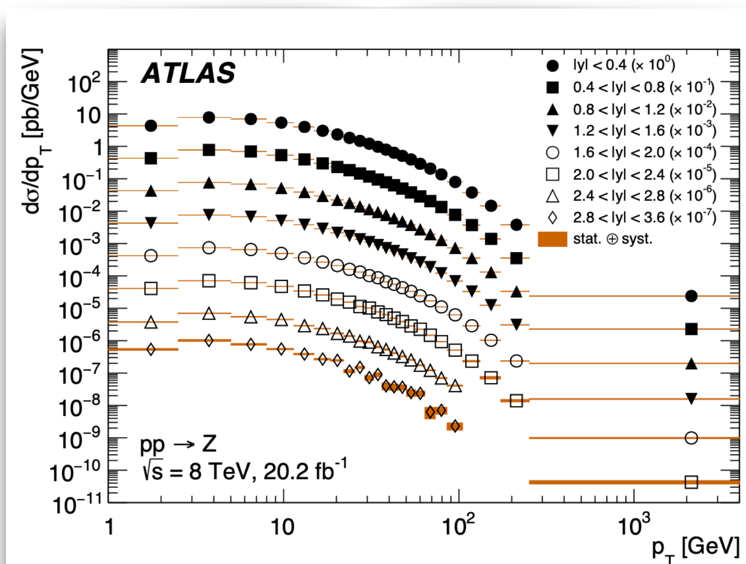
- Likelihood defined in 22528 (cosθ,Φ,pT,y) bins
- Parameters of interests are the 8 Ai + 1 cross section in pT-y bins: 9 parameters in 176 bins

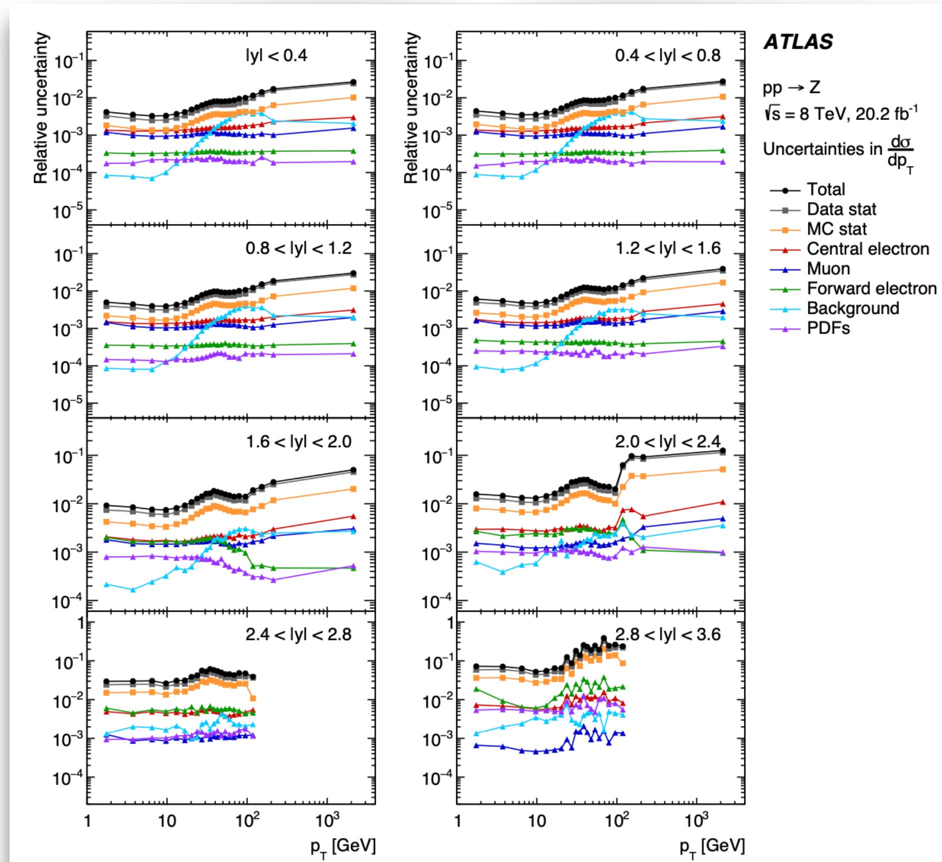


- Measuring the angular coefficients corresponds to building a synthetic "quantized" representation of the (cosθ,Φ) kinematic space
- Trade systematics for statistics
- Very powerful: avoids theoretical extrapolation of fiducial lepton cuts to full phase space and thereby opens the door to a rich field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

dσ/dp$_T$dy measurement uncertainties

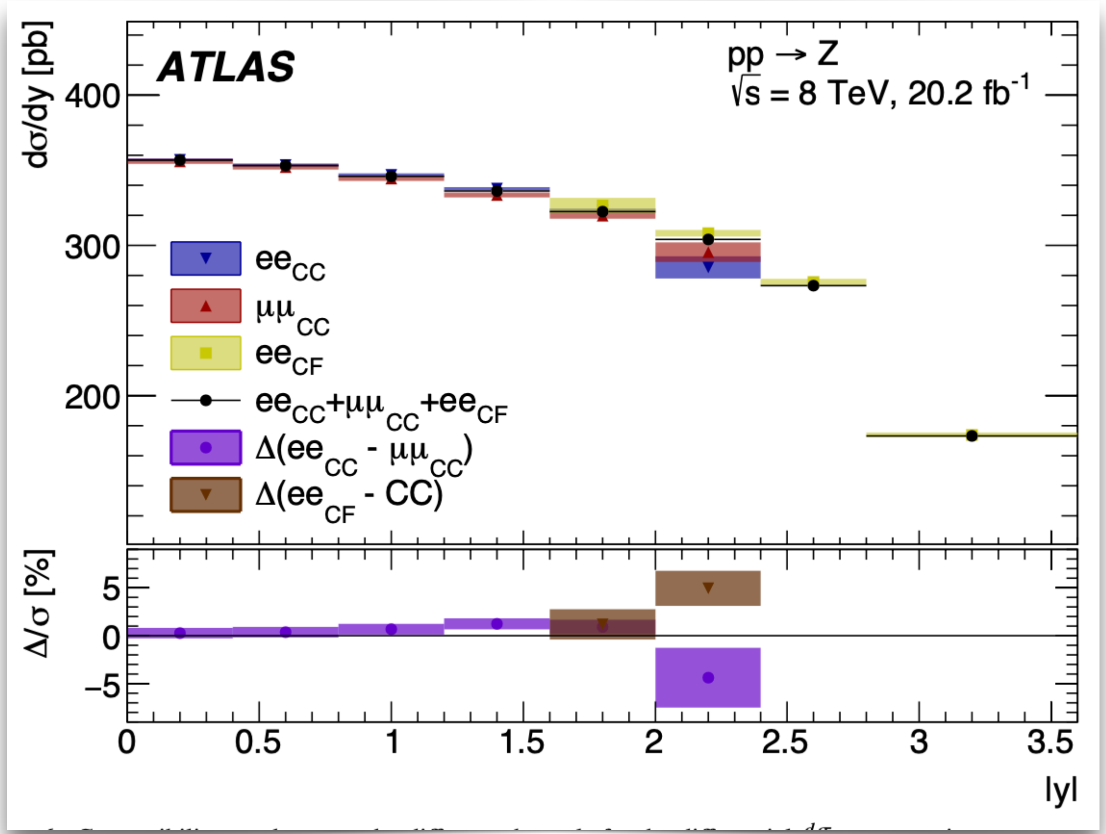
- First measurement at the LHC of full-lepton phase space cross sections
- Statistically dominated measurement
- Negligible theory uncertainties: cross sections are parameters of the fit, and not the result of an extrapolation





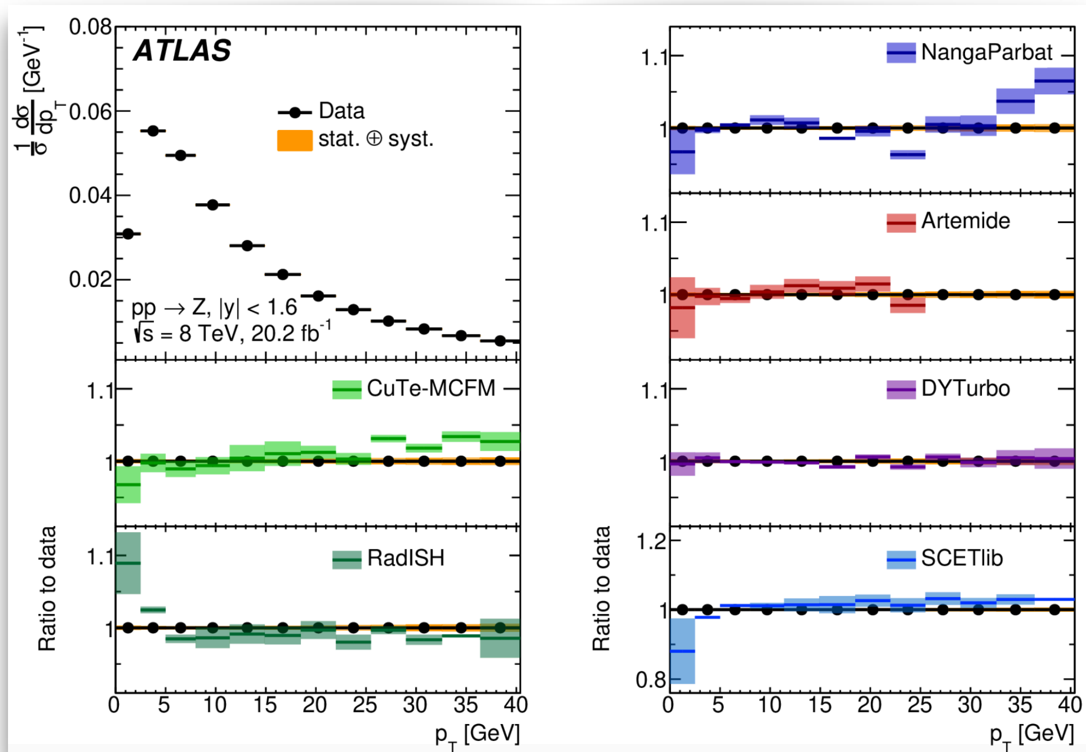
Channels compatibility

- All three channels (eeCC, μμCC, eeCF) yield compatible results
  - Important cross-check of detector calibration
  - Forward electrons allow to minimize PDF dependence



p_T cross section measurement

- Measurement compared to six predictions currently involved in the at N^{3}LL/ N^{4}LL logarithmic accuracy
  - including $O(a_s^3)$ matching from MCFM/NNLOJET
- Excellent agreement between data and predictions
  - impressive progress in the understanding of the boson p_T modelling from the experimental and theoretical points of view



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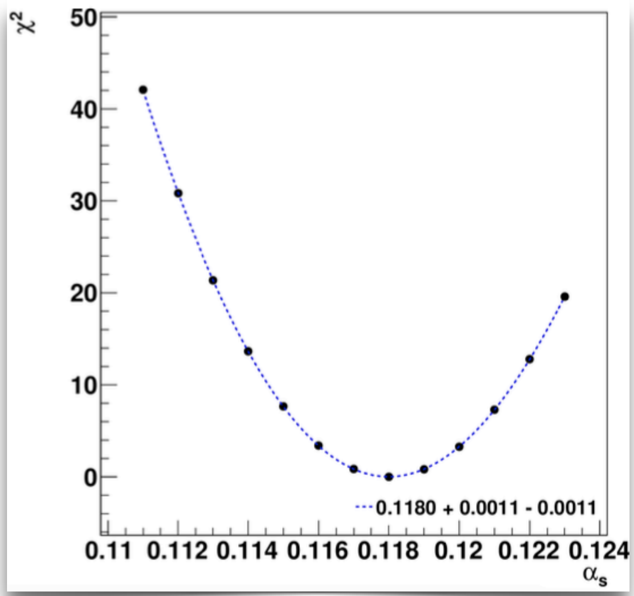
Extraction of the strong coupling constant

Methodology

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

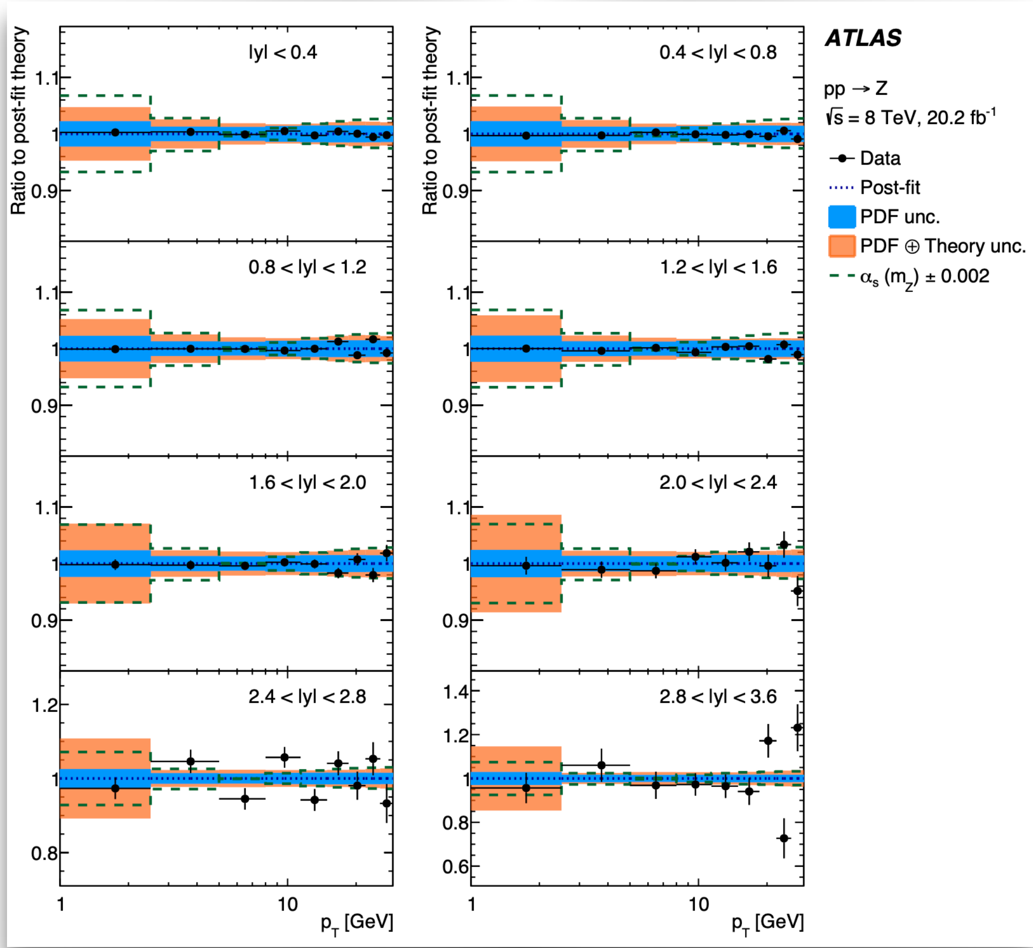
$$\chi^2(\boldsymbol{\beta}_{\mathbf{exp}}, \boldsymbol{\beta}_{\mathbf{th}}) = \sum_{i=1}^{N_{\mathrm{data}}} \frac{\left(\sigma_i^{\mathrm{exp}} + \sum_j \Gamma_{ij}^{\mathrm{exp}} \beta_{j,\mathrm{exp}} - \sigma_i^{\mathrm{th}} - \sum_k \Gamma_{ik}^{\mathrm{th}} \beta_{k,\mathrm{th}}\right)^2}{\Delta_i^2}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

- At each value of $\alpha_s(m_Z)$ the $\beta_{k,\mathrm{th}}$ terms explore the PDF space to find the best fit to the $p_T(Z)$ 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 (b = 0) i.e. left free in the fit
- Fit the region of $p_T(Z)$ <29GeV



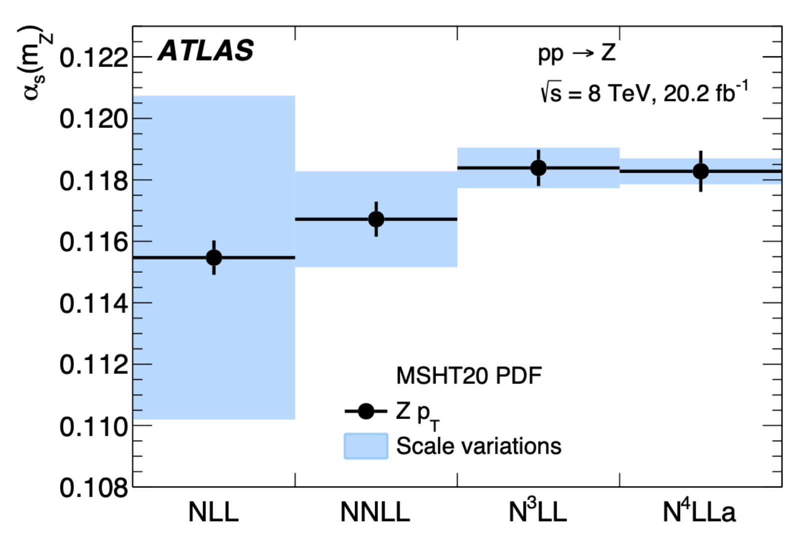
Determination of $\alpha_s(m_Z)$ from $p_T(Z)$ at 8 TeV

- $\alpha_s(m_Z)$ 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



Uncertainties

- Use MSHT20 PDF (only PDF Set which is available at N3LO order)
- Repeat Fit using lower orders (also with MSHT20)
  - aS at higher orders is always within uncertainties of lower orders
- Scale Variations: independent uR, uF and Q variations
- Variations of the lower fit range (0 GeV → 5GeV) and the upper fit range (29 GeV → 22 GeV) of the fit range, are performed to test the stability
  - test for non-perturbative and quark flavor effects



Experimental uncertainty	± 0.44	
PDF uncertainty	± 0.51	
Scale variation uncertainties	± 0.42	
Matching to fixed order	0	-0.08
Non-perturbative model	$+0.12$	-0.20
Flavour model	$+0.40$	-0.29
QED ISR	± 0.14	
N^4LL approximation	± 0.04	
Total	$+0.91$	-0.88

NNLO PDF Sets (1/2)

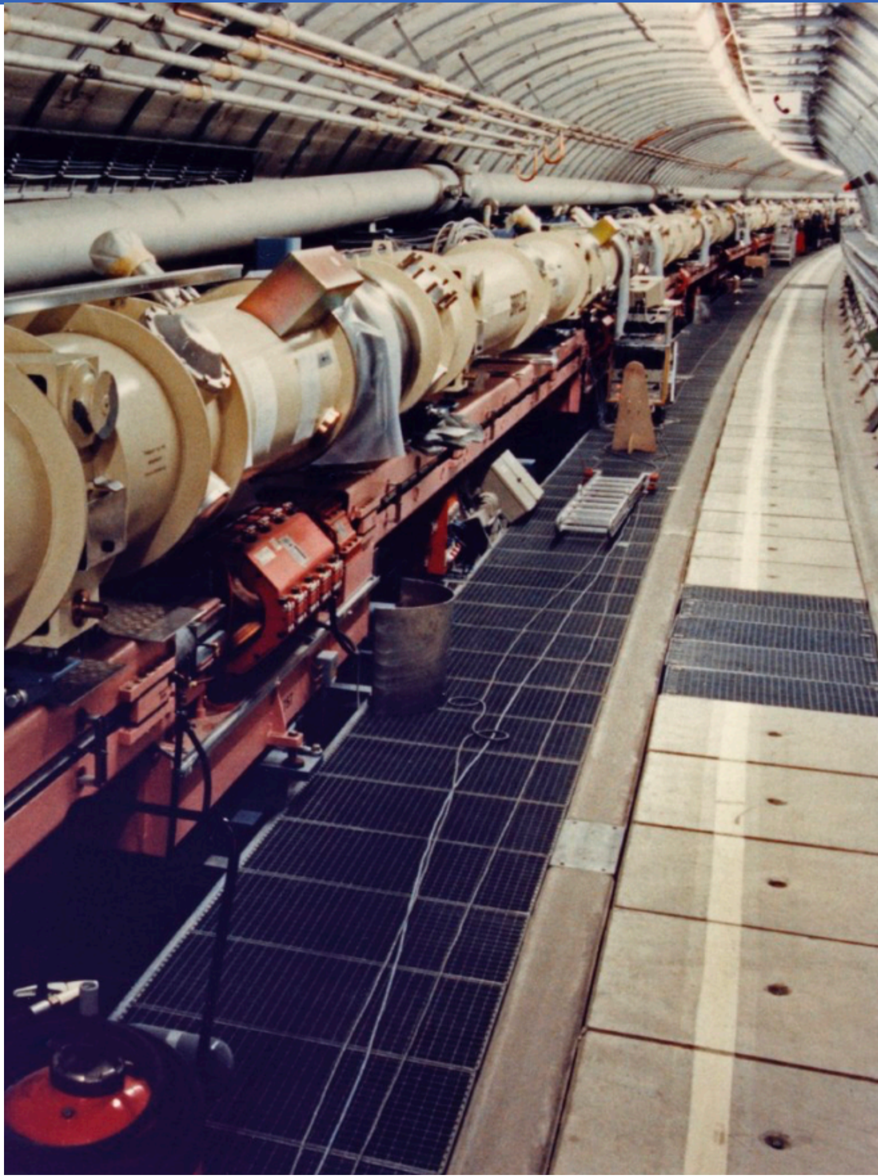
- At order N4LLa+N3LO, only one N3LO PDF set available: MSHT20aN3LO
  - Study the dependence of the results on the choice of PDF set by fitting one order lower, i.e. N3LLa+N3LO using NNLO PDFs.

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

- At this order, the spread observed is ±0.00102
  - driven by the difference between the NNPDF4.0 and CT18A PDF sets
- What causes this difference?

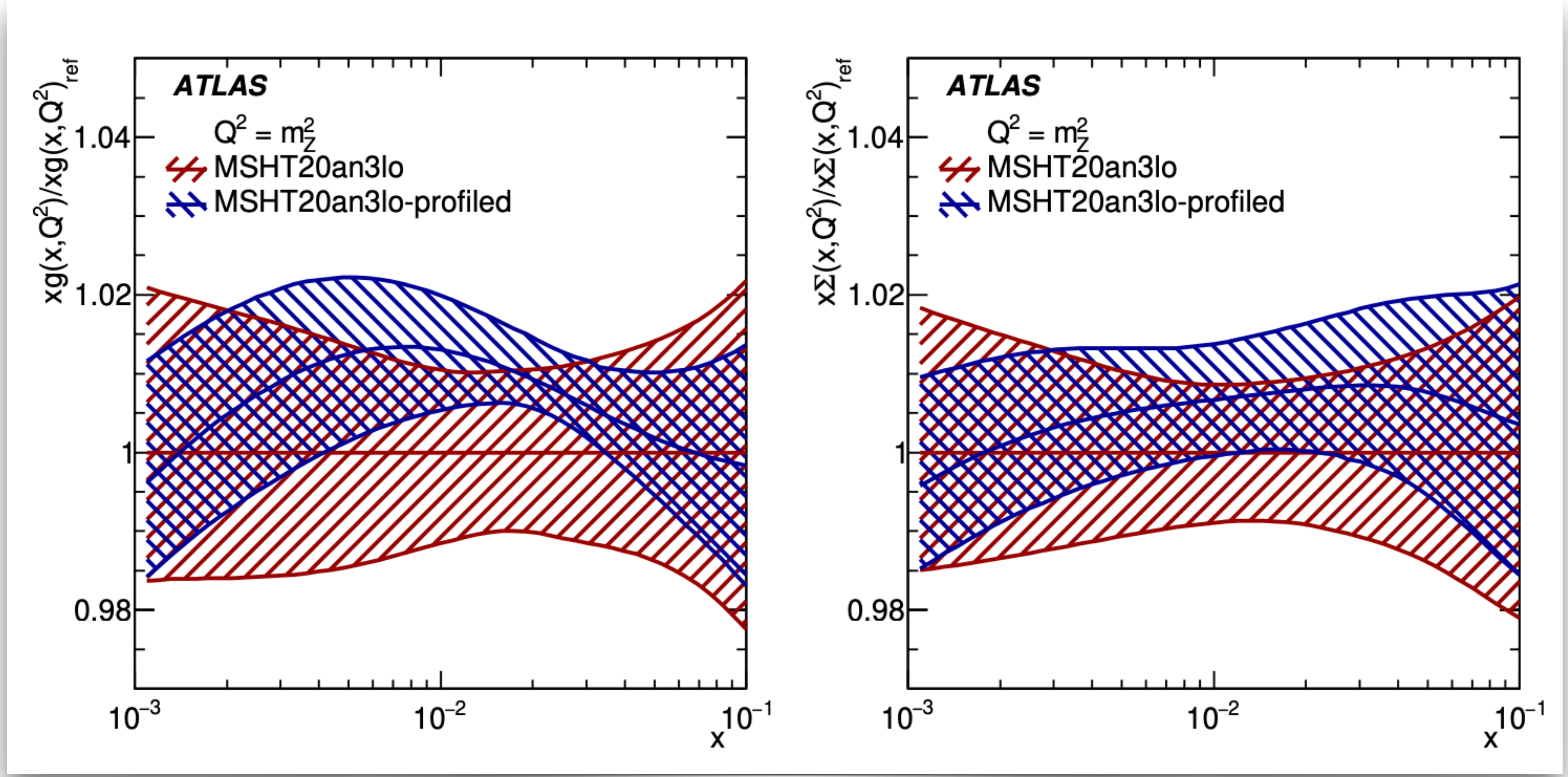
NNLO PDF Sets (2/2)

- $p_T(Z)$ very sensitive to gluon PDF
  - PDF determinations at NNLO are affected by significant tension between low-x (from HERA) and high-x gluon PDFs (Hadron Collider Jets)
- Effect of this tension has been studied at N^3LL
  - Refit when including DIS cross-section data from HERA with Q^2>10 GeV2 plus $p_T(Z)$
    - → Double Count HERA to reduce impact of other data-sets. CT18A is shifted downwards and the spread is reduced to ± 0.00016.
- Using MSHT20an^{3}lo largely removes the tension in the gluon PDF
  - indicated by the significant improvement in the χ^2 of the $p_T(Z)$ and DIS Data.
    - →indication that the spread of PDFs at NNLO is not representative of the true PDF uncertainty on N3LO.



PDF profiling

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



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

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

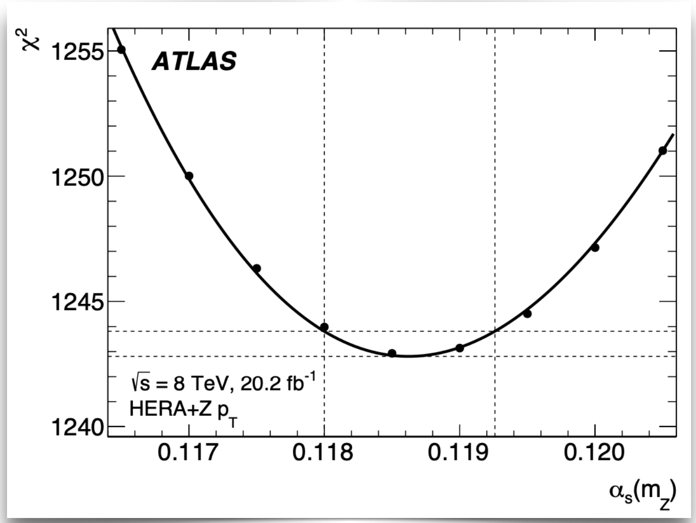
$$b_\star = \frac{b}{1+b^2/b_{\mathrm{lim}}^2}$$

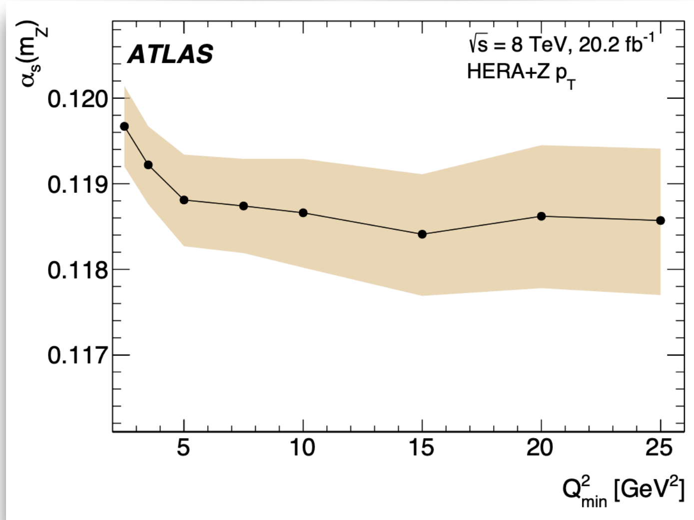
$$g_j(b) = \frac{g\, b^2}{\sqrt{1+\lambda\, b^2}} + \mathrm{sign}(q)\left(1 - \exp\left[-|q|\, b^4\right]\right) \qquad g_K(b) = g_0\left(1 - \exp\left[-\frac{C_F\alpha_s(b_0/b_*)b^2}{\pi g_0\, b_{\mathrm{lim}}^2}\right]\right)$$

- g_j functions include a quadratic/quartic term: g and q free parameters of the fit
  - The theory should not depend on b_{lim} (freezing scale) and Q_0 (starting scale), provided SNP is flexible enough. Q_0 and b_{lim} estimated as parameterisation unc.
- g_0 controls the very high b (very small p_T) behaviour, should be fitted to data, but we have no sensitivity to it, so it is varied
- Lambda controls transition from Gaussian to exponential: varied between 0.5-2
  - Fits excluding 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

More checks

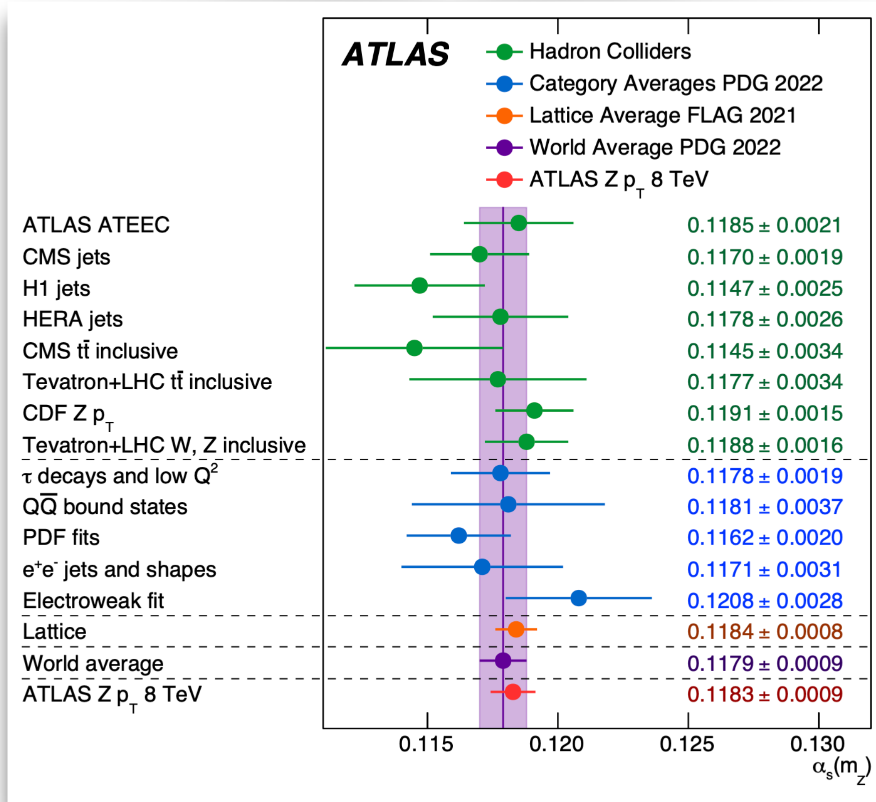
- Simultaneous determination of α_S, the PDFs, and the non-perturbative parameters
  - N3LL+N3LO, with PDFs evolved at NNLO.
- The light-quark coefficient functions of the DIS cross sections are calculated in the MS scheme.
- The heavy quarks (c, b) generated dynamically
  - using general-mass variable-flavour-number scheme, with up to five active quark flavours.
- Fits performed at fixed values of α_S via a quadratic interpolation of the χ^2 function
  - 0.11866±0.00064
- The dependence of α_S on the minimum squared four-momentum transfer Q^2 of the HERA data is studied in the range from 2.5 GeV to 25 GeV
  - No sign. dependence is observed for >5 GeV .





Final Result

- $\alpha_s(m_Z)$ = 0.11828 +0.00084 –0.00088
- 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
- Determination focusing on the Sudakov region (usually avoided to determine as)
- Observable not suitable for inclusion in PDF fits → no correlation with $\alpha_s(m_Z)$ determinations from PDF fits



Summary

- New window for the determination of the strong coupling using the transverse momentum of Z bosons
- New measurements might reduce further PDF uncertainties
- New measurements required to constrain further non-perturbative effects

Orders

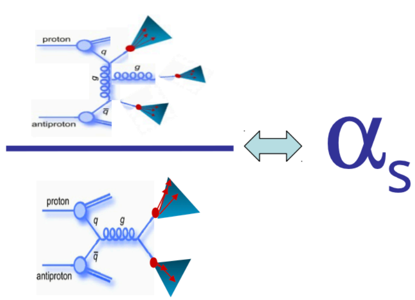
	Virtual		Sudakov			Real
	H[δ(1-z)]	H[z]	Cusp AD	Collinear, RAD	PDF	CT,V+jet
LL+LO	1	1	1-loop	0	const.	1
NLL+NLO	α_s	C1	2-loop	1-loop	LO	α_s
NLL*+NLO	α_s	C1	2-loop	1-loop	NLO	α_s
NNLL+NNLO	α_s^2	C2	3-loop	2-loop	NLO	α_s^2
N3LL+N3LO	α_s^3	C3	4-loop	3-loop	NNLO	α_s^3
N4LLa+N3LO	α_s^4	C4	5-loop	4-loop	N3LO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

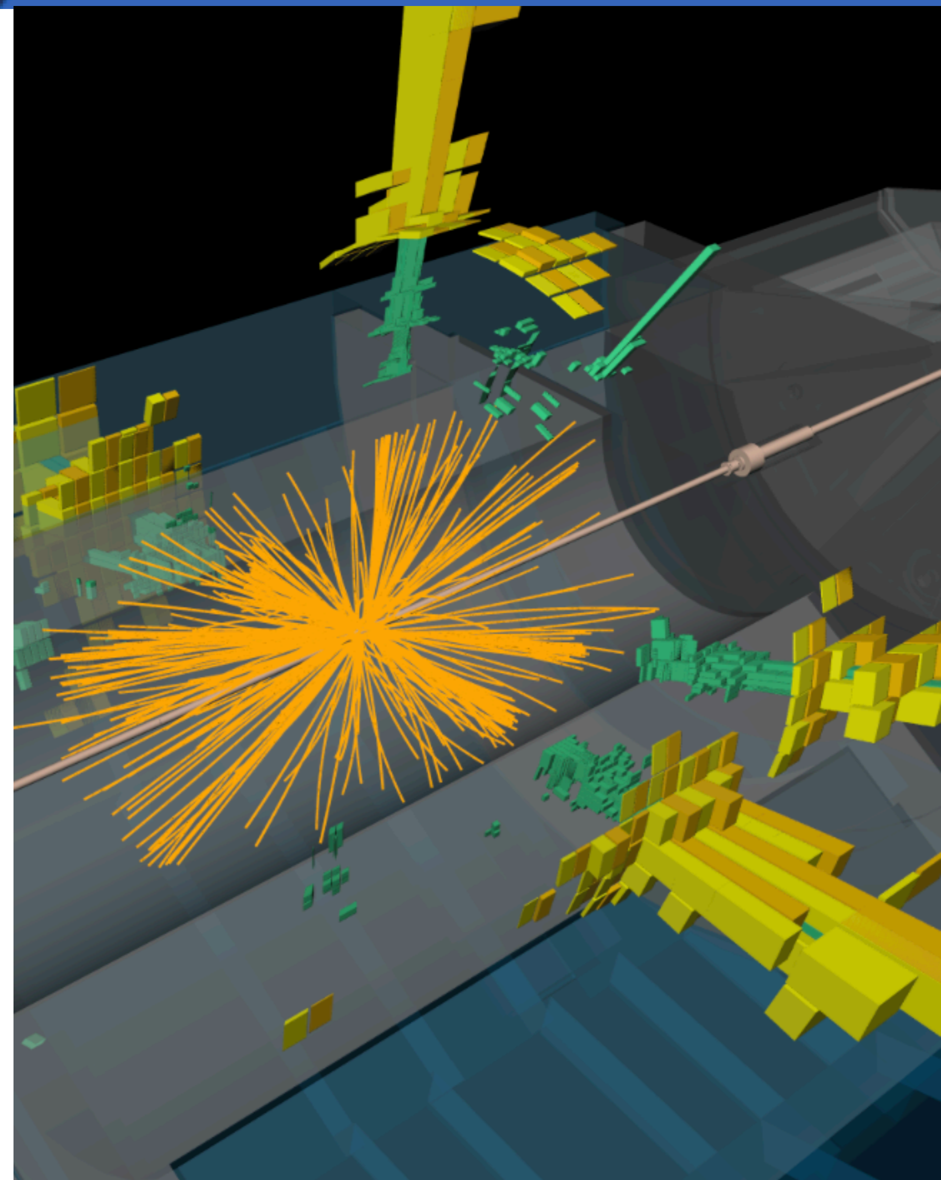
Known analytically
Approximated numerically
Unknown, estimated with series acceleration
Not included

Strong Coupling in Jet Correlations

Jet Measurements

- Use Transverse enery-energy correlations (TEEC) and Associated asymmetry (ATEEC)
- TEEC: defined as the transverse-energy-weighted distribution of the azimuthal differences between jet pairs in the final state
- ATEEC: defined as the difference between the forward ($\cos\phi>0$) and the backward ($\cos\phi<0$) part of TEEC
- TEEC and ATEEC functions are sensitive to gluon radiation and show a clear dependence on the strong coupling





Event Selection and Results

ATLAS Collab. Eur.Phys.J. C77 (2017) 12, 872

- Selection: Multijet events
  - Leading Jet p_T>460 GeV
  - Leading Two Jets with $p_{T1}+p_{T2}$>1 TeV
  - All Jet p_T's>60 GeV
  - 57.6M events at 8 TeV

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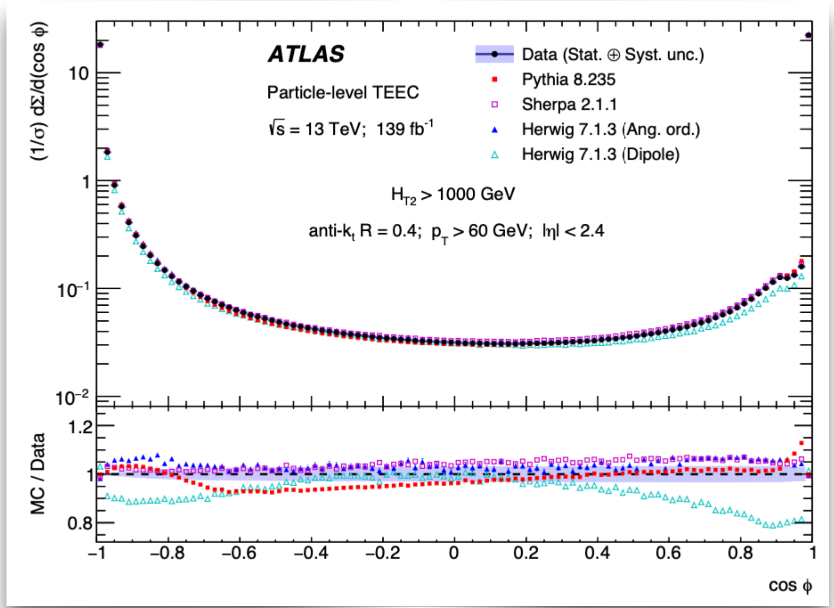

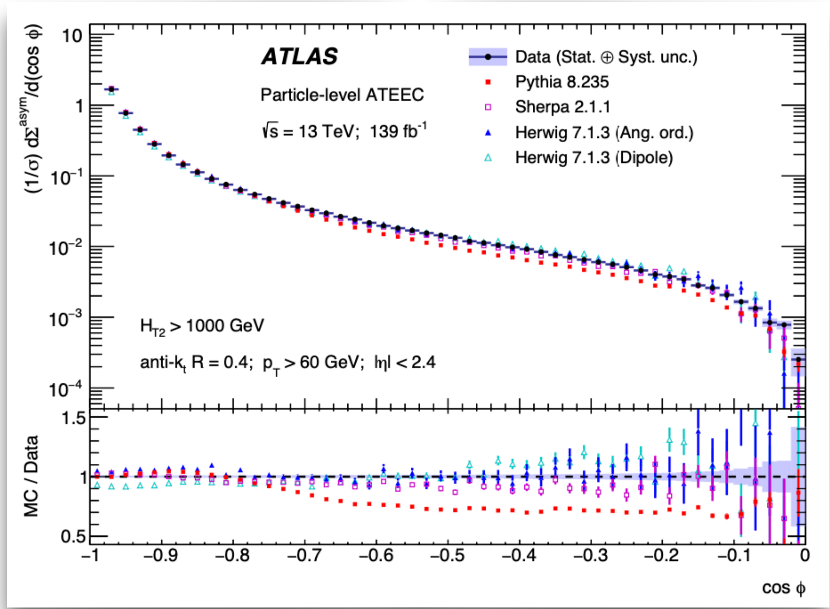

Extraction of $\alpha_s(m_Z)$

- Determination of α_s with a χ^2 fit
  - Predictions based in NNLO
  - Dominant uncertainties from PDFs

$$\alpha_s(m_Z) = 0.1175 \pm 0.0006\ (\text{exp.})^{+0.0034}_{-0.0017}\ (\text{theo.})$$

$$\alpha_s(m_Z) = 0.1185 \pm 0.0009\ (\text{exp.})^{+0.0025}_{-0.0012}\ (\text{theo.})$$