Determination of the strong-coupling constant from the Z-boson transverse-momentum distribution with ATLAS

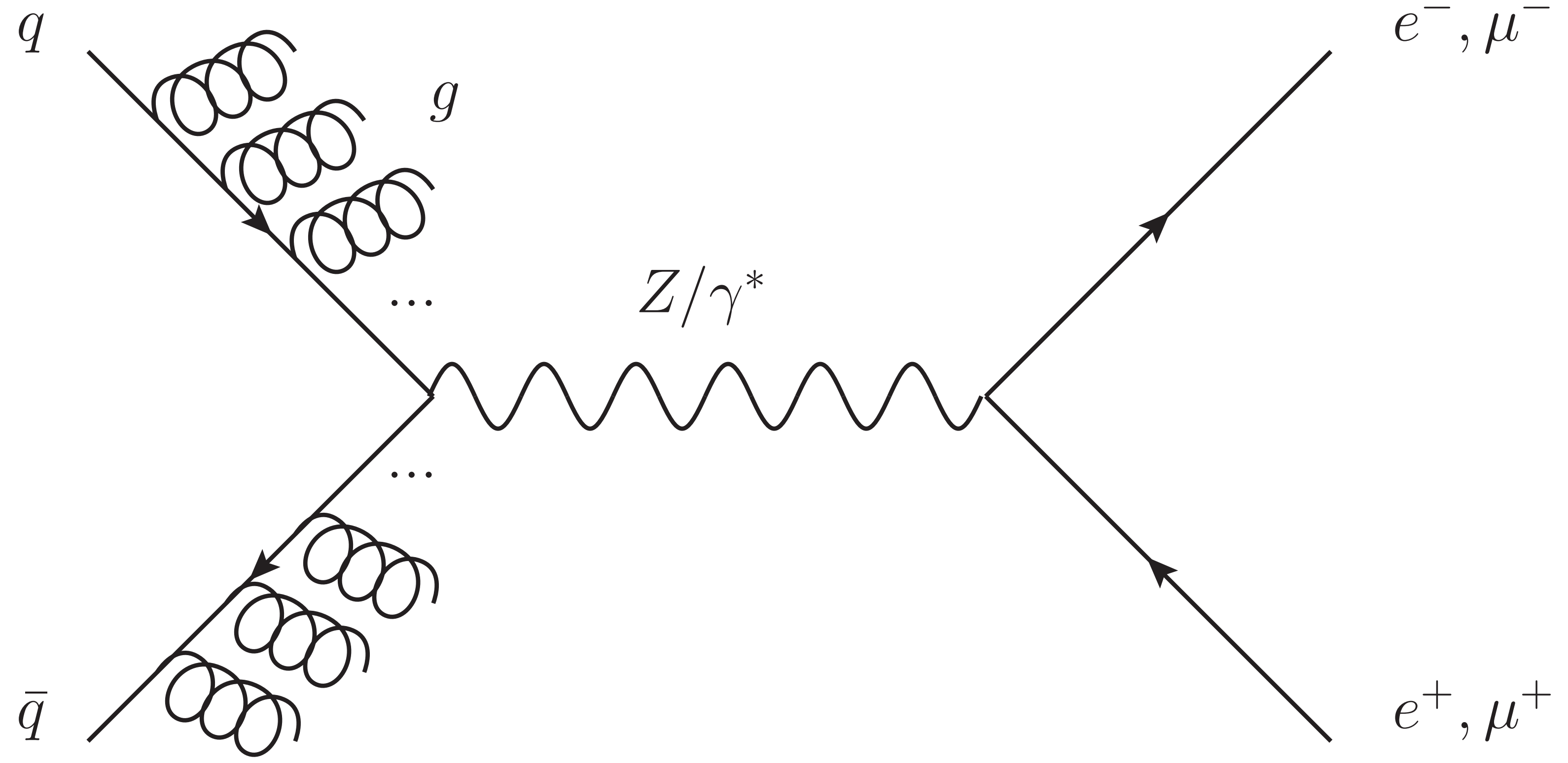
ICHEP, July 2024

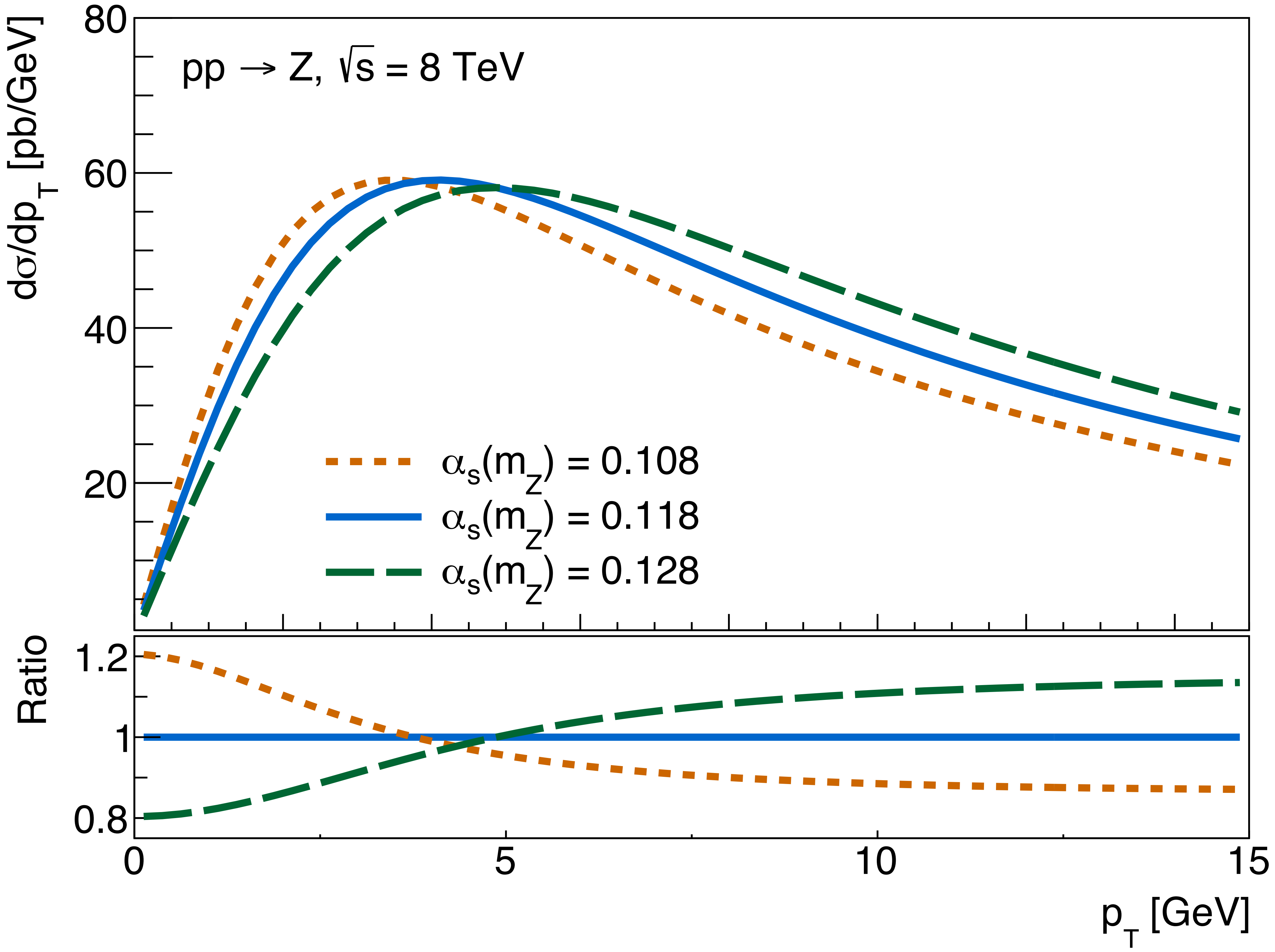
Kristof Schmieden, on behalf of the ATLAS Collaboration

Based on
https://arxiv.org/abs/2309.12986
and
Eur.Phys.J.C 84 (2024) 315

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 pT 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)



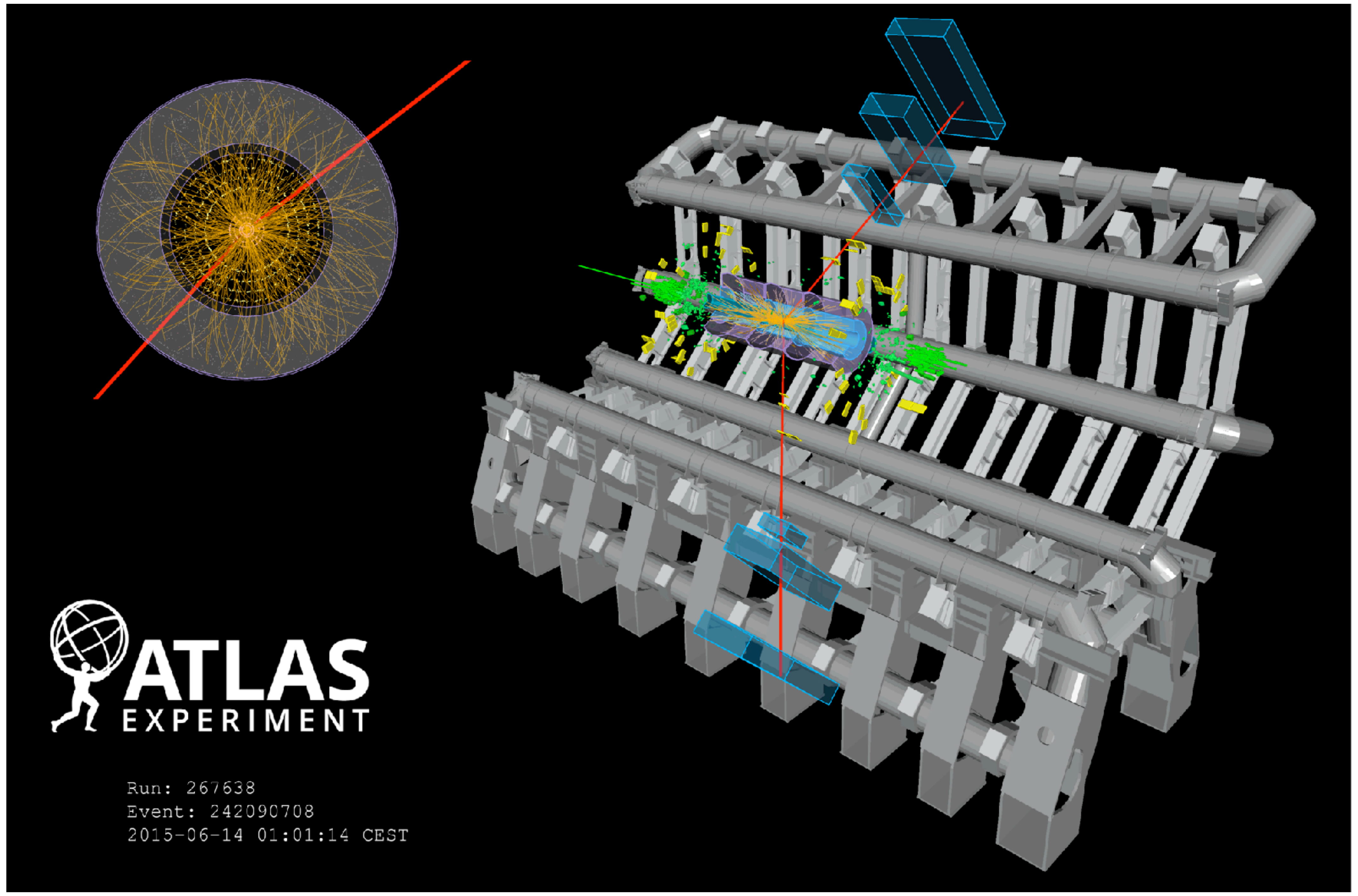


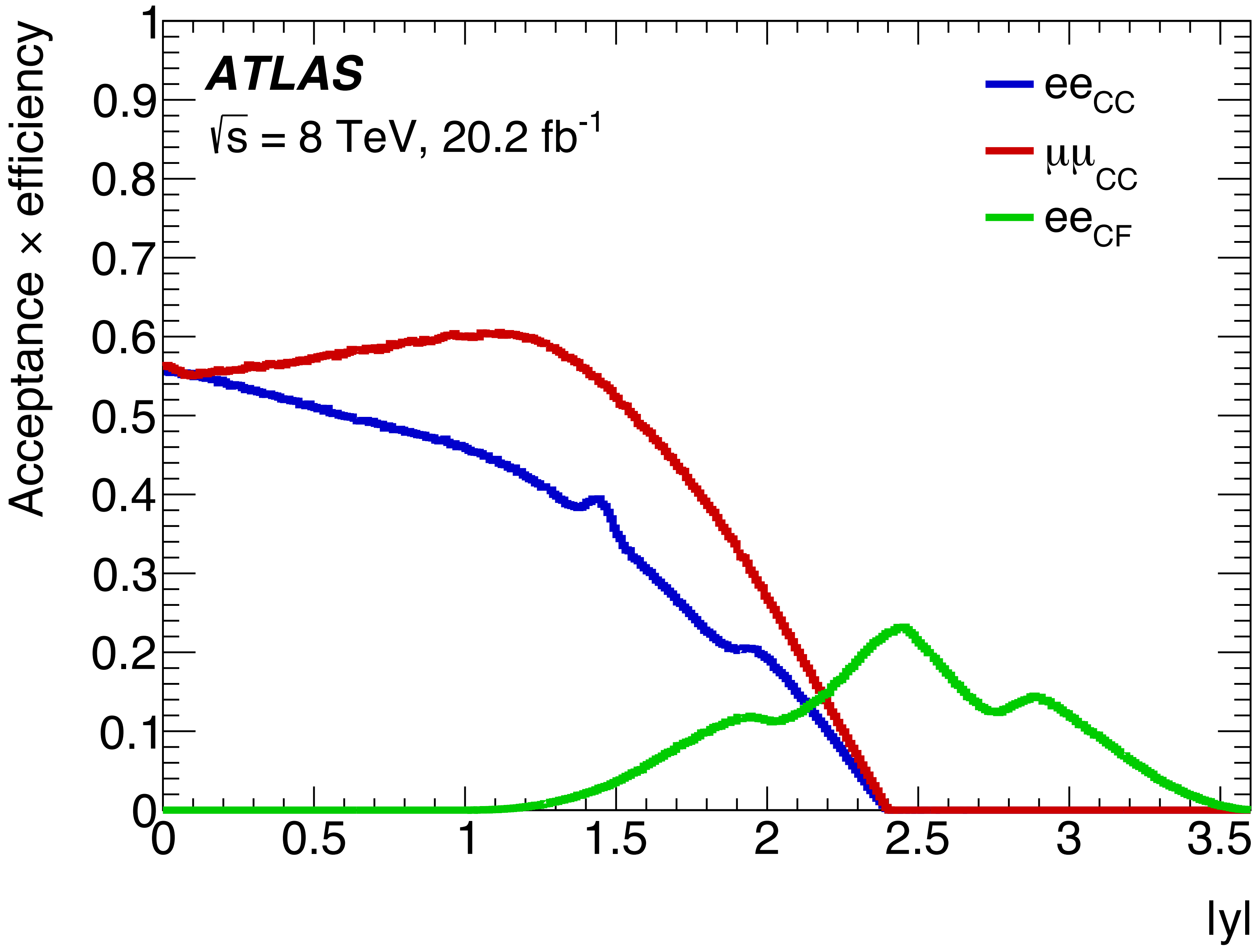
Event Selection

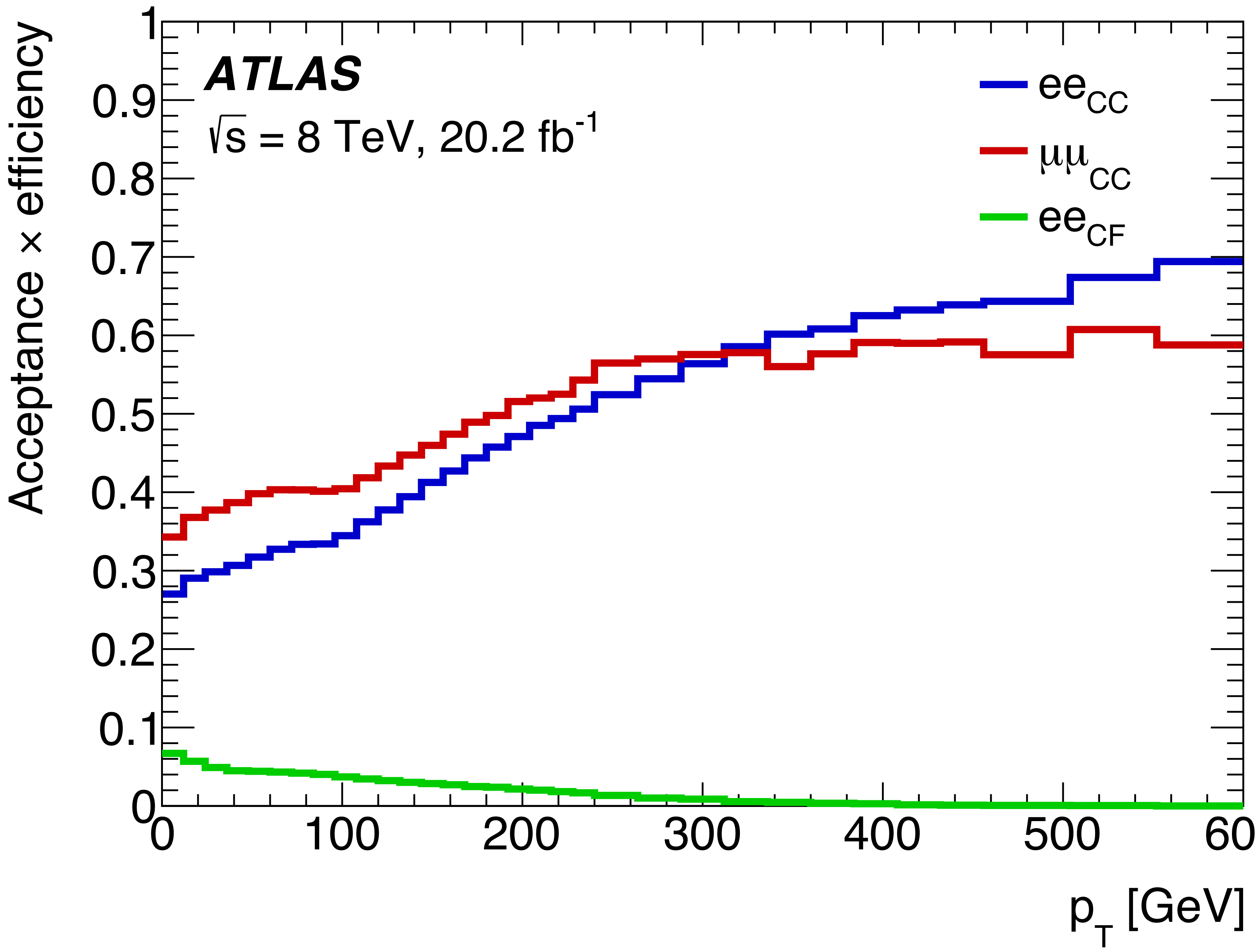
- Three channels

  - **eeCC**: two electrons (6.2M events)
    - $p_T > 20$ GeV, $|\eta| < 2.4$
  - ***μμ*CC**: two muons (7.8M events)
    - $p_T > 20$ GeV, $|\eta| < 2.4$
  - **eeCF**: central + forward electron (1.2M events)
    - Forward: $p_T > 20$ GeV, $2.5 < |\eta| < 4.9$

  - $80 \text{ GeV} < m_{ll} < 100 \text{ GeV}$







Measurement Methodology - Angular Coefficients

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

- Differential cross section decomposed into basis of spherical harmonics

Measurement Methodology - Angular Coefficients

Expected Yield

Reco (p_T^Z, y^Z, m^Z, cosθ, ϕ) bin

Cross section

Background template

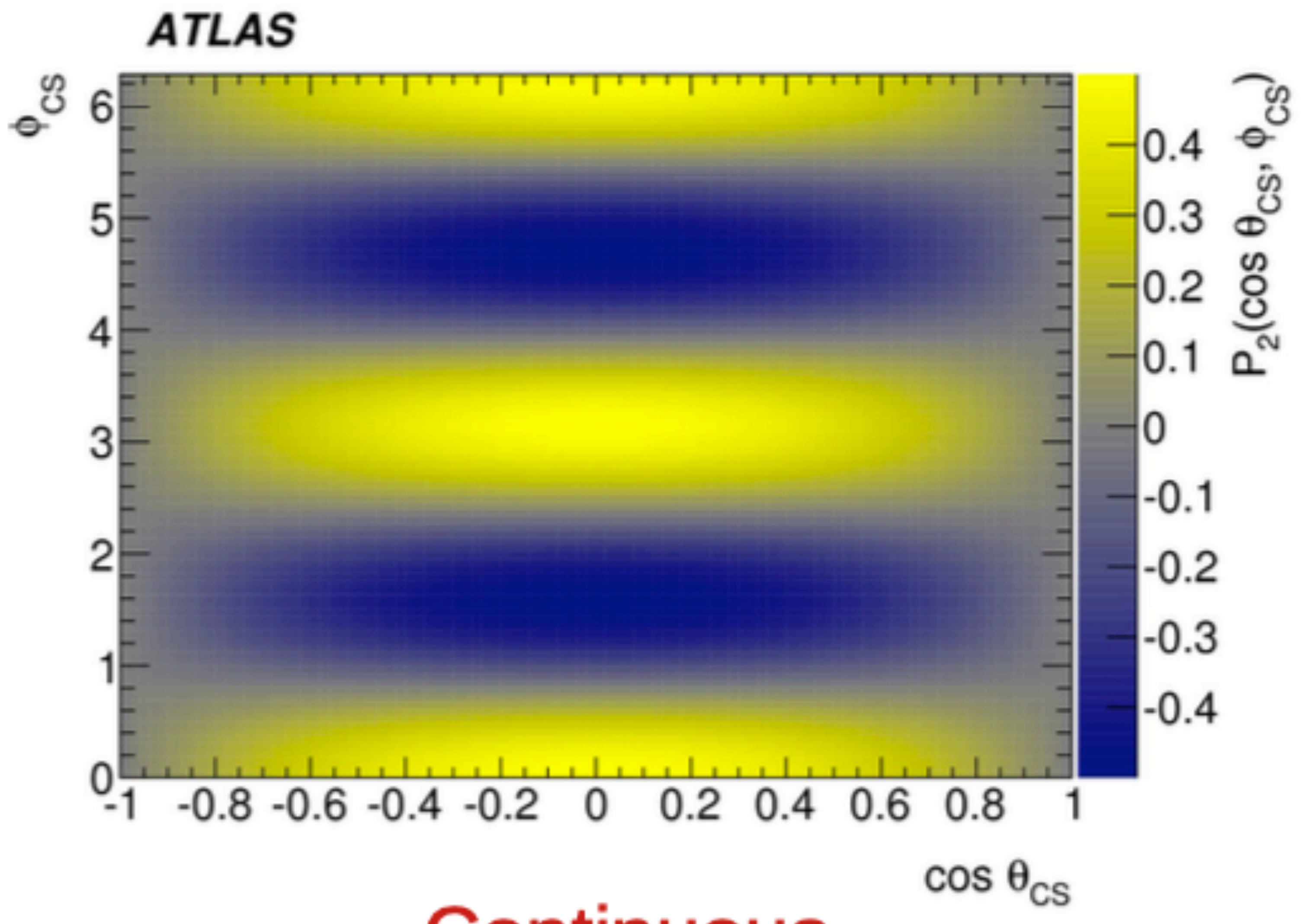
$$N^{n}_{\text{exp}}(A,\sigma,\theta) = \left\{ \sum_{j=1}^{N^{ana}_{\text{bins}}} \mathcal{L}\sigma_j \left[t^{n}_{8j}(\beta) + \sum_{i=0}^{7} A_{ij}\, t^{n}_{ij}(\beta) \right] \right\} \gamma^{n} + \sum_{B}^{\text{bkgs}} T^{n}_{B}(\beta)$$

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

Angular coefficient

Templated polynomial

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



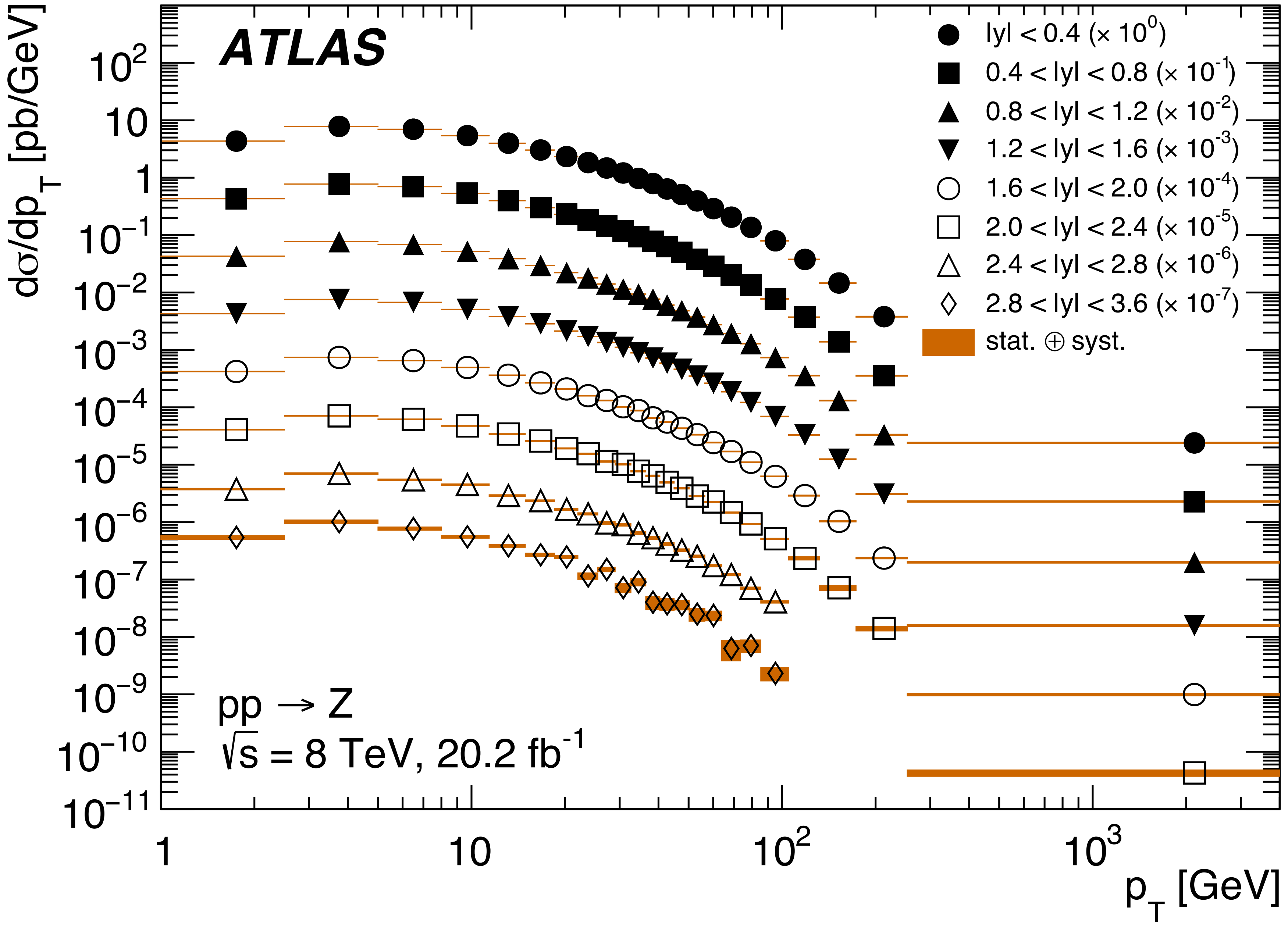
Continuous

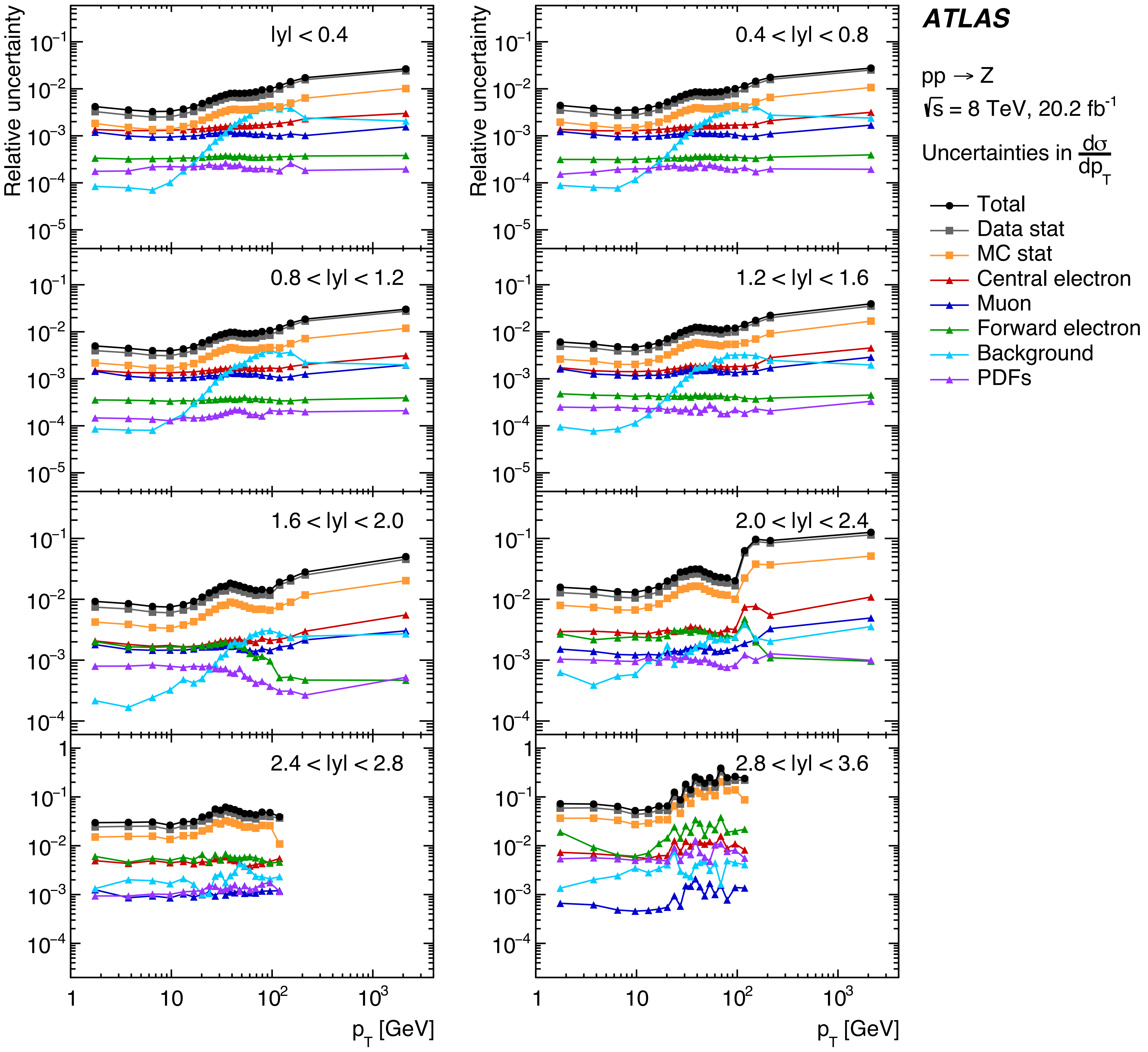
$$\begin{pmatrix} H_0 \\ H_1 \\ H_2 \\ H_3 \\ H_4 \\ H_5 \\ H_6 \\ H_7 \\ H_8 \end{pmatrix}$$

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
  - Thereby opens the door to a rich field of precise interpretations

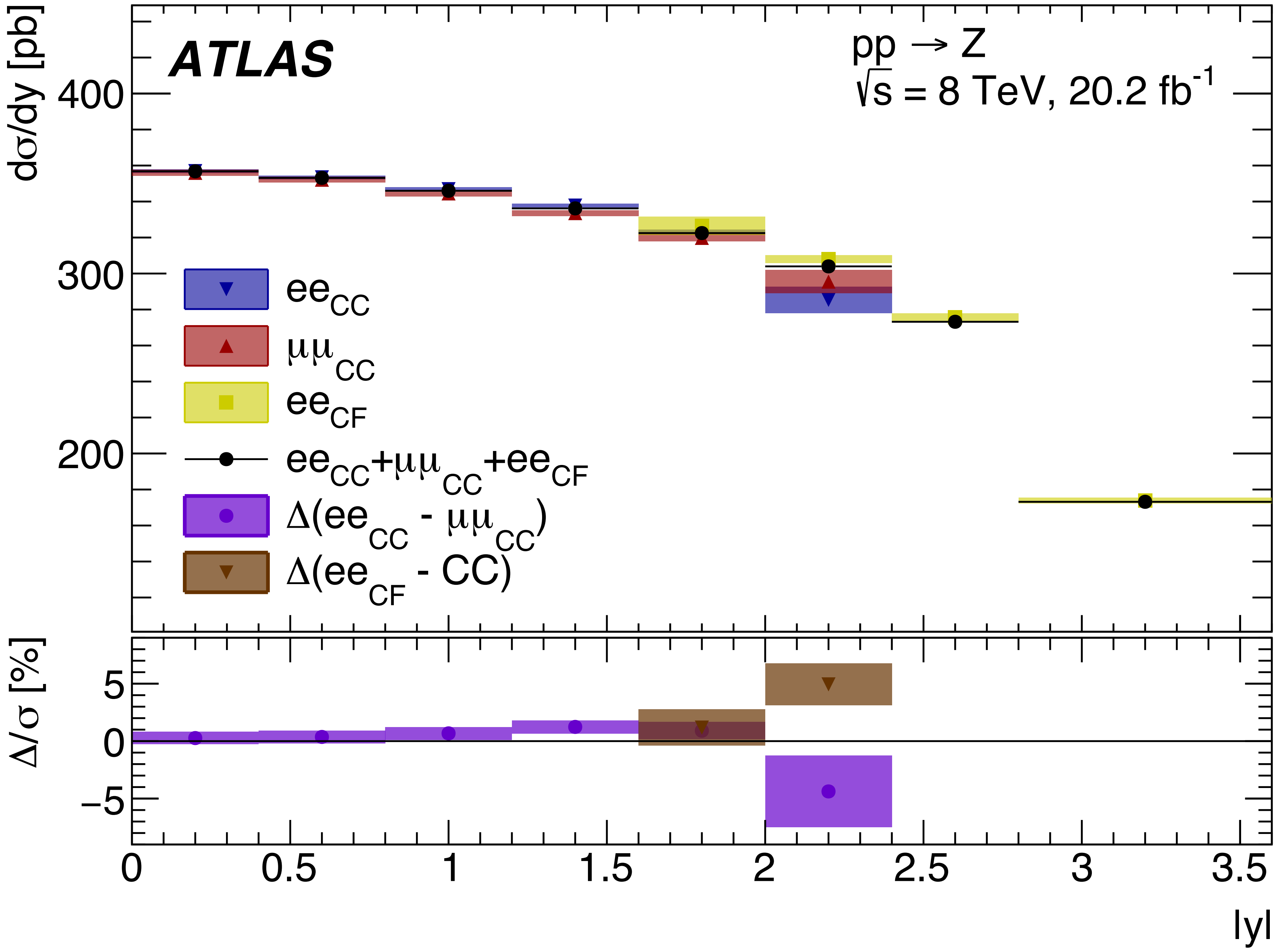
Double-Differential Drell Yan Measurement

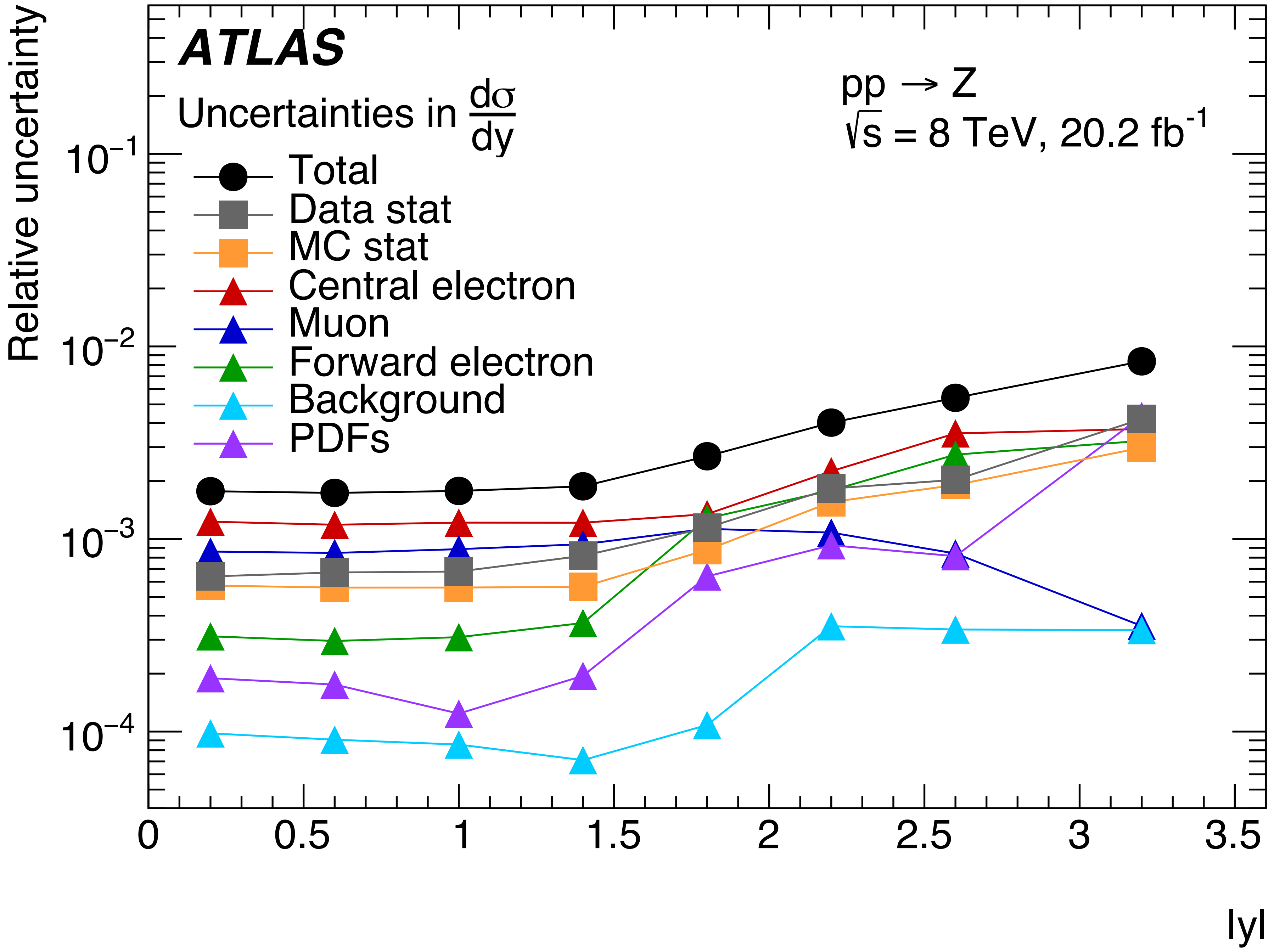




- First measurement at the LHC of full lepton phase space cross section
- Statistically dominated measurement
- Negligible theory uncertainties:
    - Cross-sections are parameters of the fit, not the result of an extrapolation

Comparison of Analysis Channels



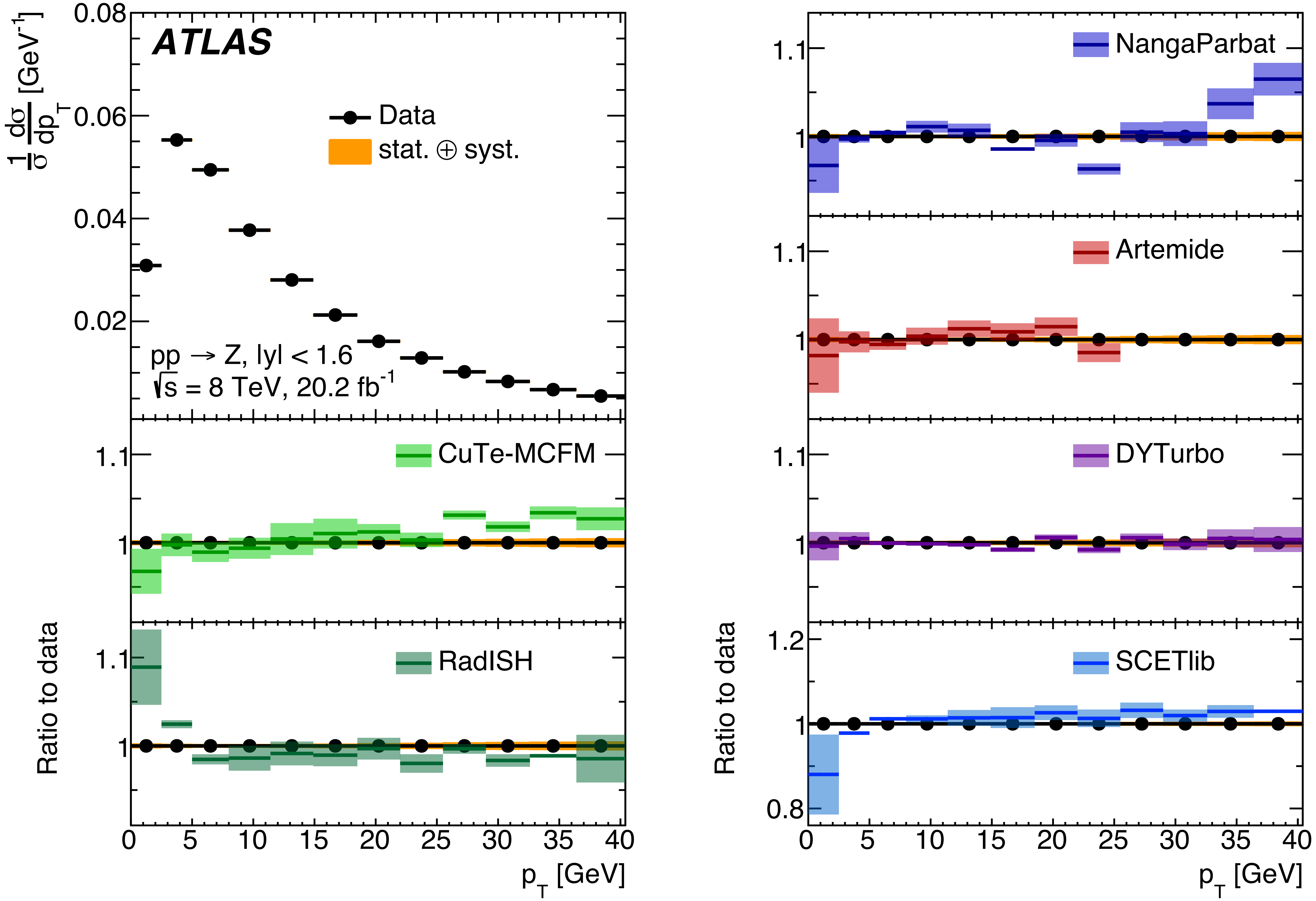


- All three channels (eeCC, μμCC, eeCF) yield compatible results
    - Important cross-check of detector calibration
    - Forward electrons allow to minimize PDF dependence

- Exquisite per-mille level precision in the central region
- Sub-percent uncertainties up to |y| < 3.6 thanks to dedicated forward electron calibration

Differential pT corss-section Measurement

- Measurement compared to predictions currently employing N^{3}LL / N^{4}LL logarithmic accuracy calculations
  - Including O(α_s^3) matching from MCFM / NNLOJET
- Excellent agreement between data and predictions
  - Impressive progress understanding of the boson pT modelling from experimental and theoretical points of view

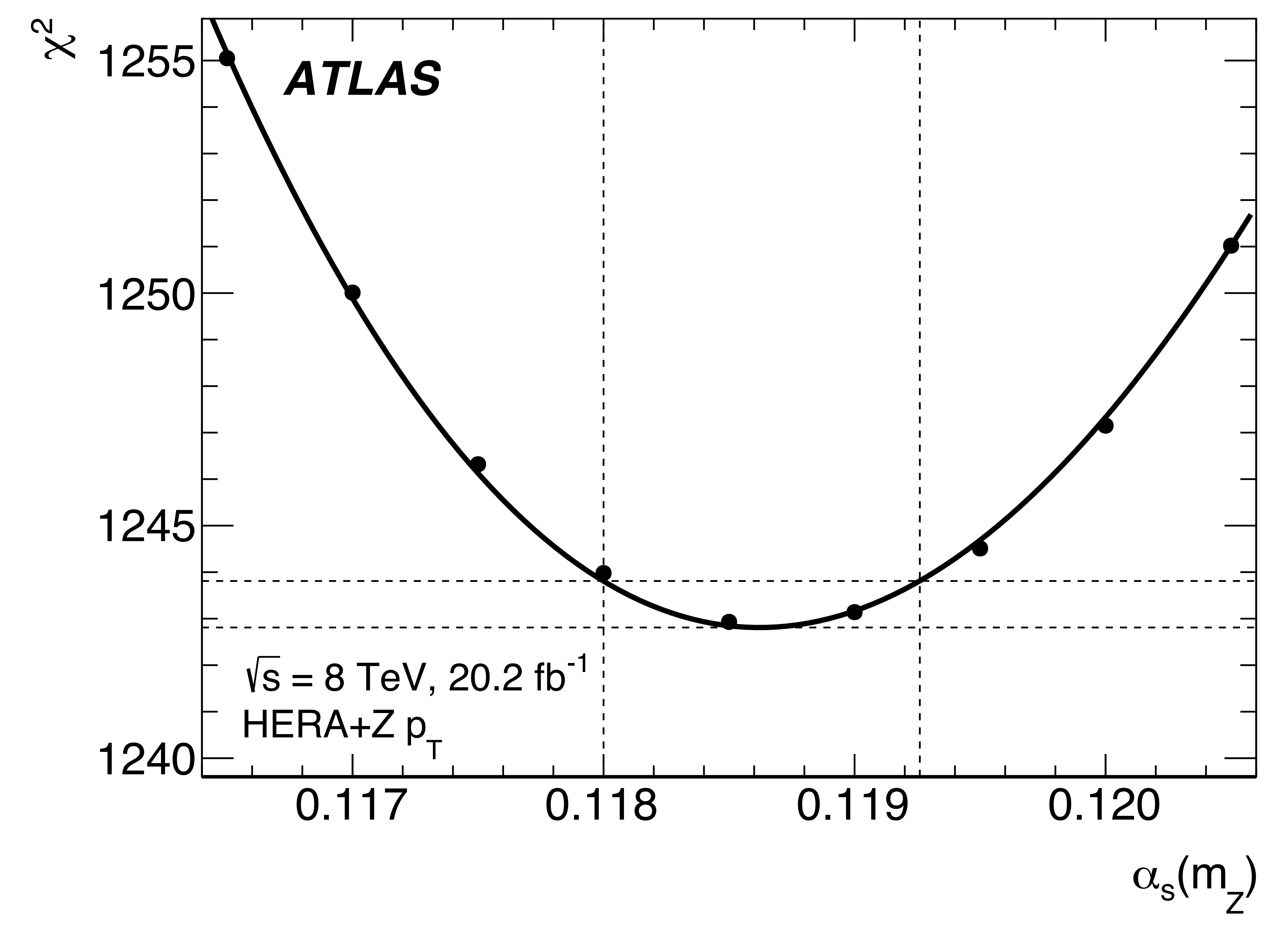


Extraction of the Strong Coupling Constant

Methodology

- Theory expectation: DYTurbo interfaced to xFitter arXiv:1410.4412
- Evaluate $\chi^2(\alpha_s)$ over variations provided in LHAPDF for each α_s point

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

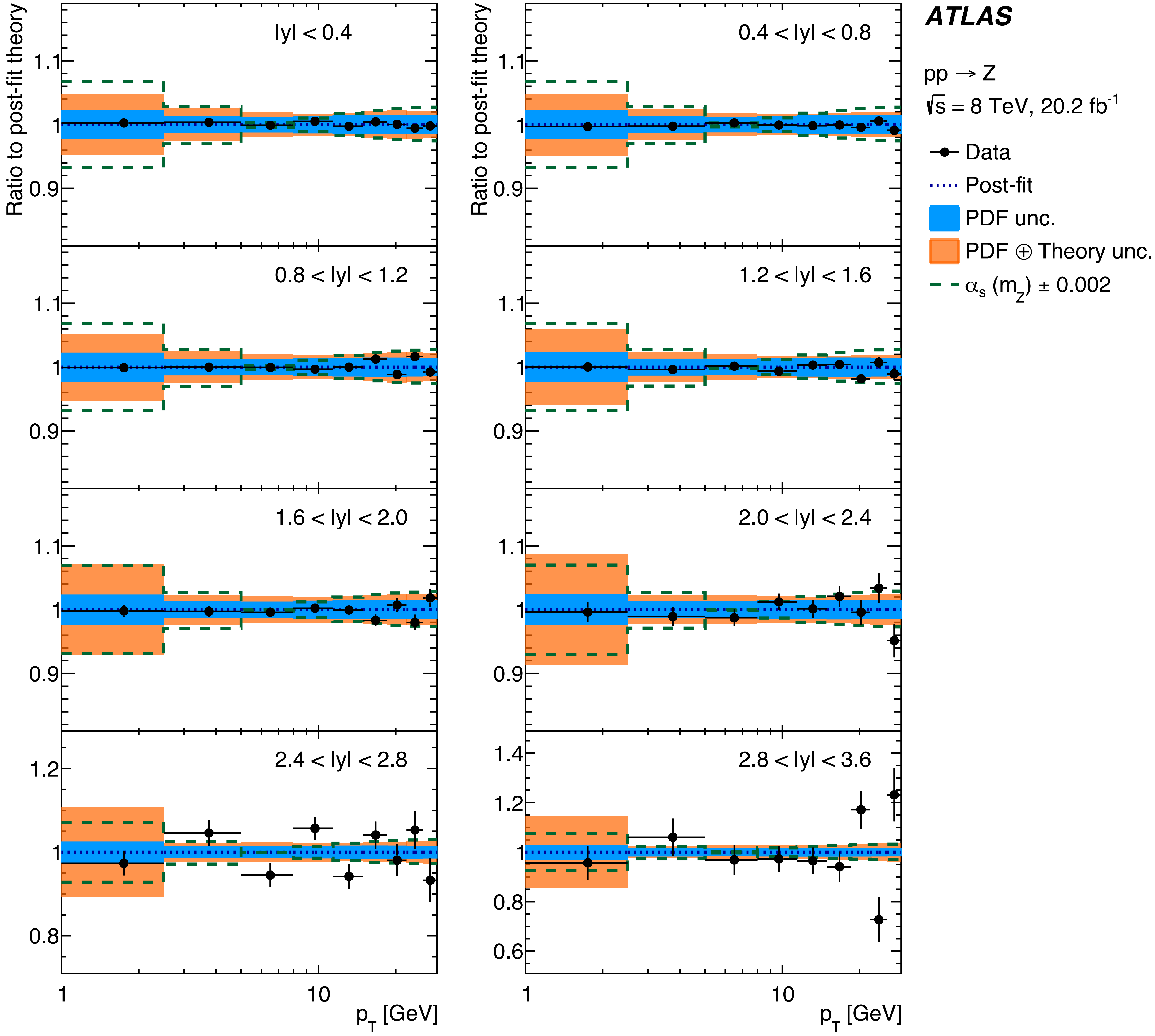


- At each value of $\alpha_s(m_Z)$ the Γ_{ik}^{th} encodes PDF Hessian
- Experimental covariance matrix $\Gamma_{ij}^{exp}\beta_{j,exp}$

- Equivalent to including the new dataset in the PDF without refitting, using profiling / reweighting Eur.Phys.J.C 75(2015) 9, 458

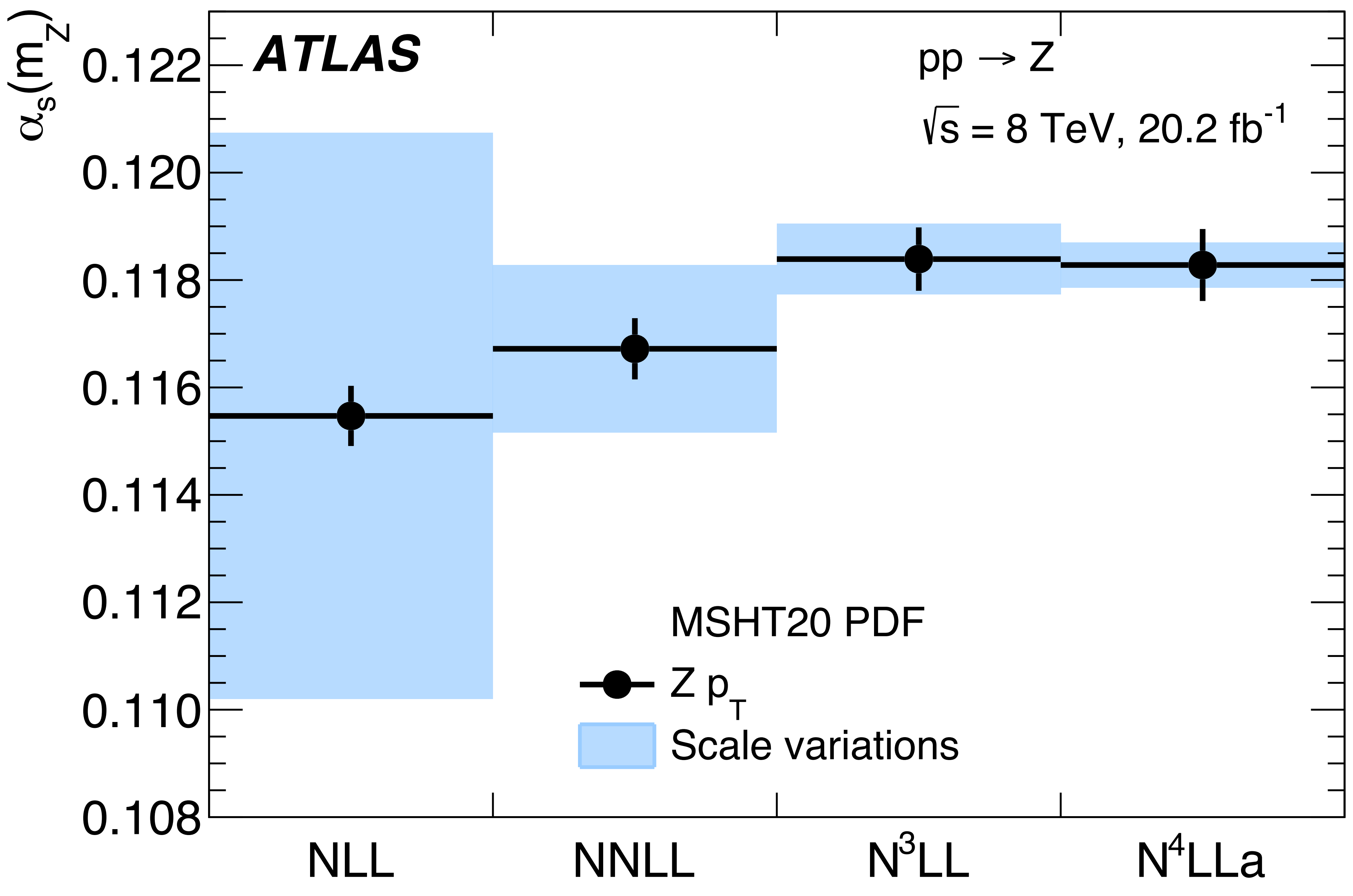
Determination of $\alpha_s(m_Z)$ from $p_T(Z)$ at 8 TeV

- $\alpha_s(m_Z)$ extracted from fit to double-differential pT-yZ cross section measured in the full lepton phase space
- Postfit χ^2/dof $= 82/72$
- Determination performed at lower orders, demonstrating good convergence of the perturbative series



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

- Use MSHT20 PDF (one of two PDFs available at N3LO)
- Repeat fit using lower orders (also with MSHT20)
    - α_s at higher orders always within uncertainties of lower orders
- Scale Variations:
    - Independent variations of renormalisation and factorisation scales and Q variations



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^{4}LL approximation	±0.04	
Total	+0.91	−0.88

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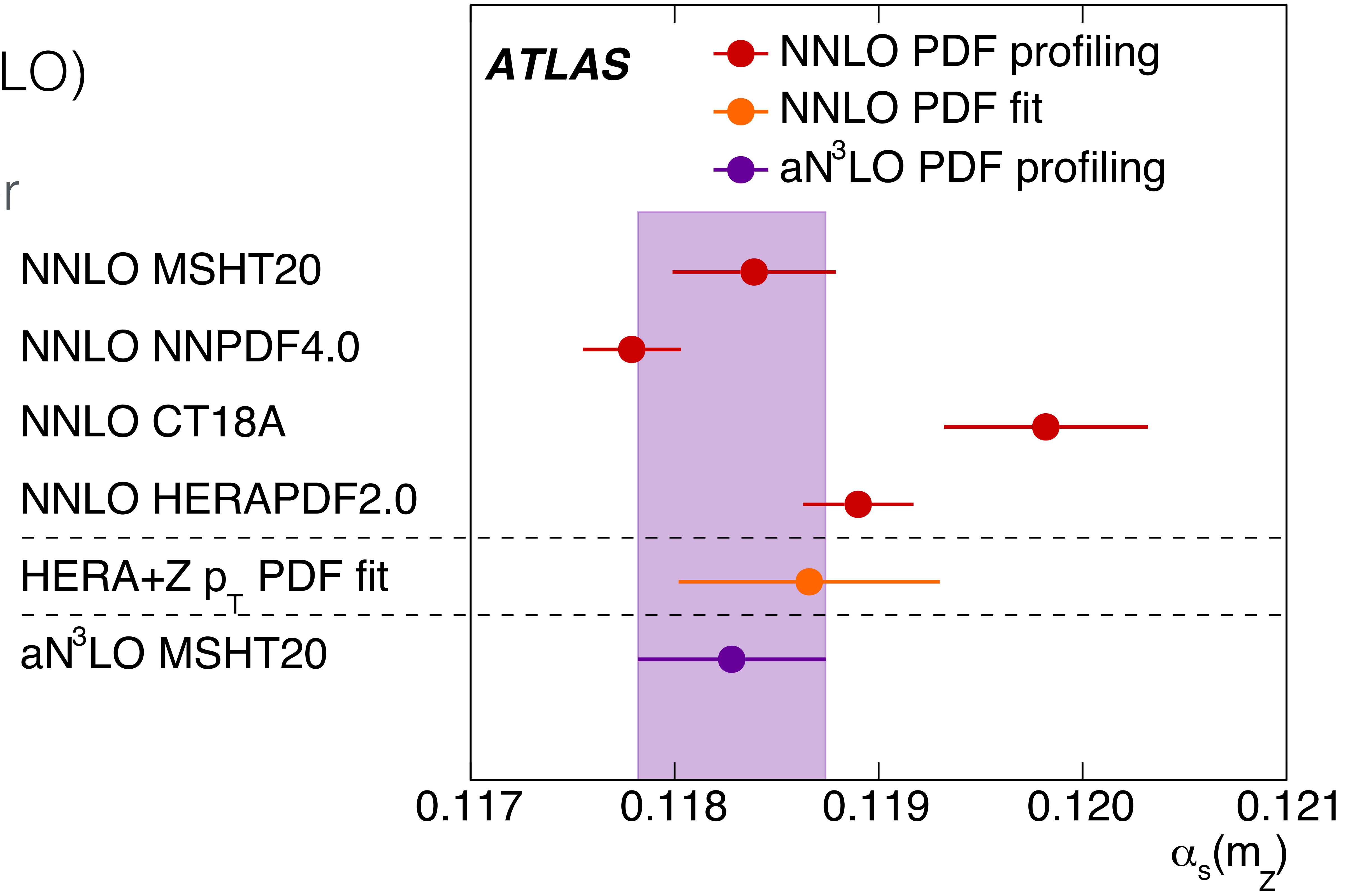
  - Study impact of PDF choice by fitting PDFs of one order lower, i.e. N3LLa+N3LO using NNLO PDFs
- Spread observed: ± 0.00102
  - Origin of this difference?



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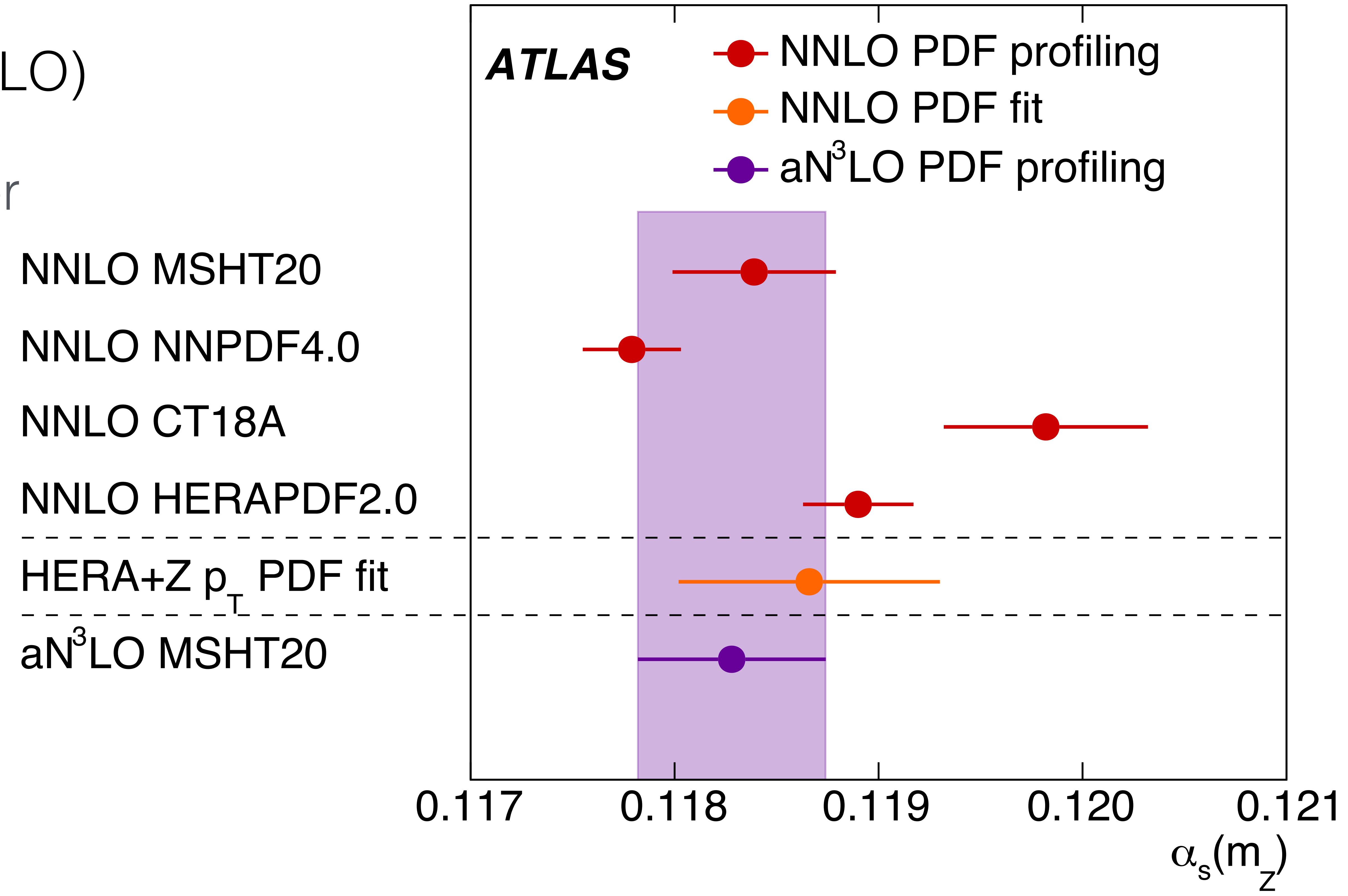

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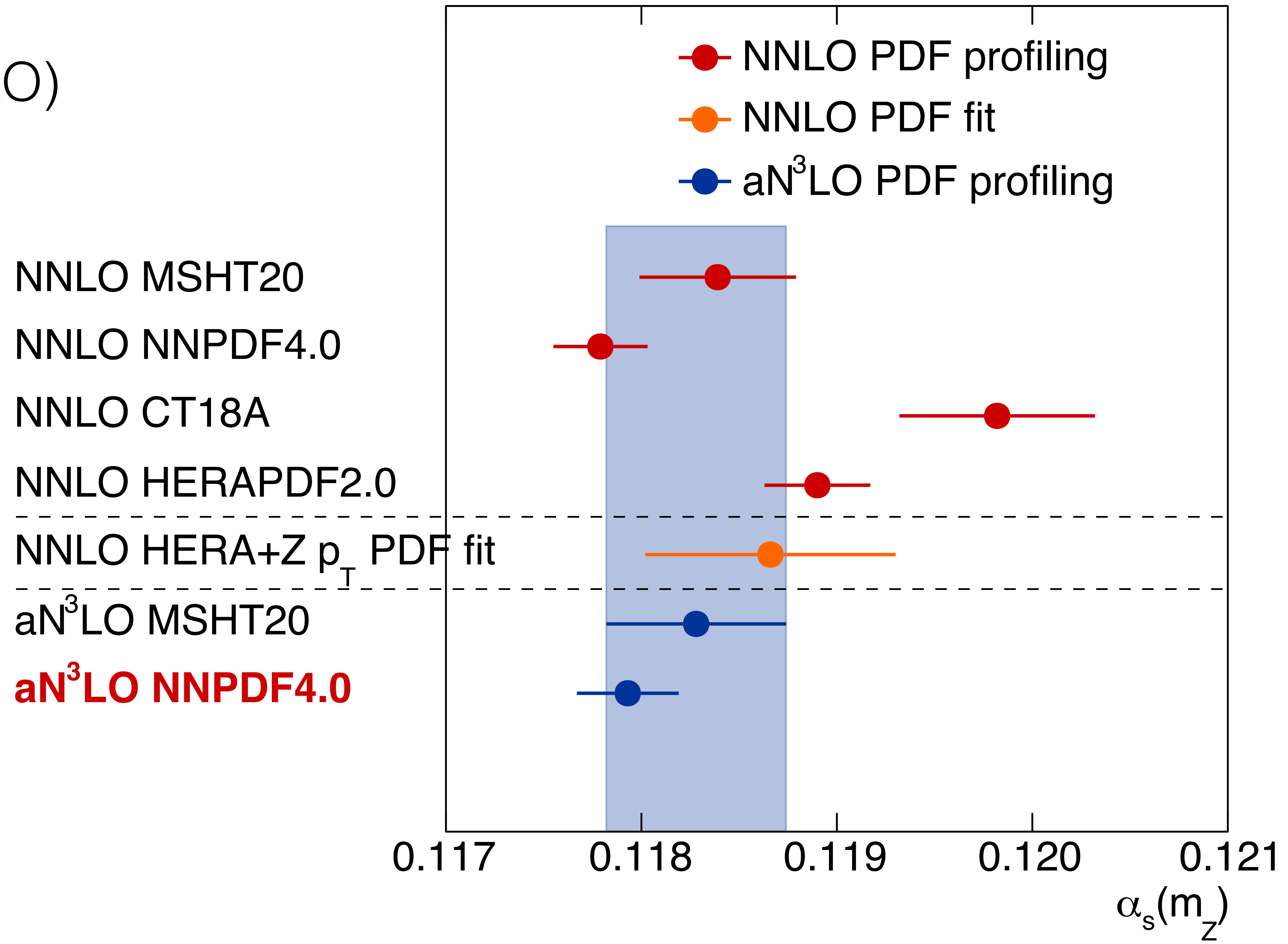

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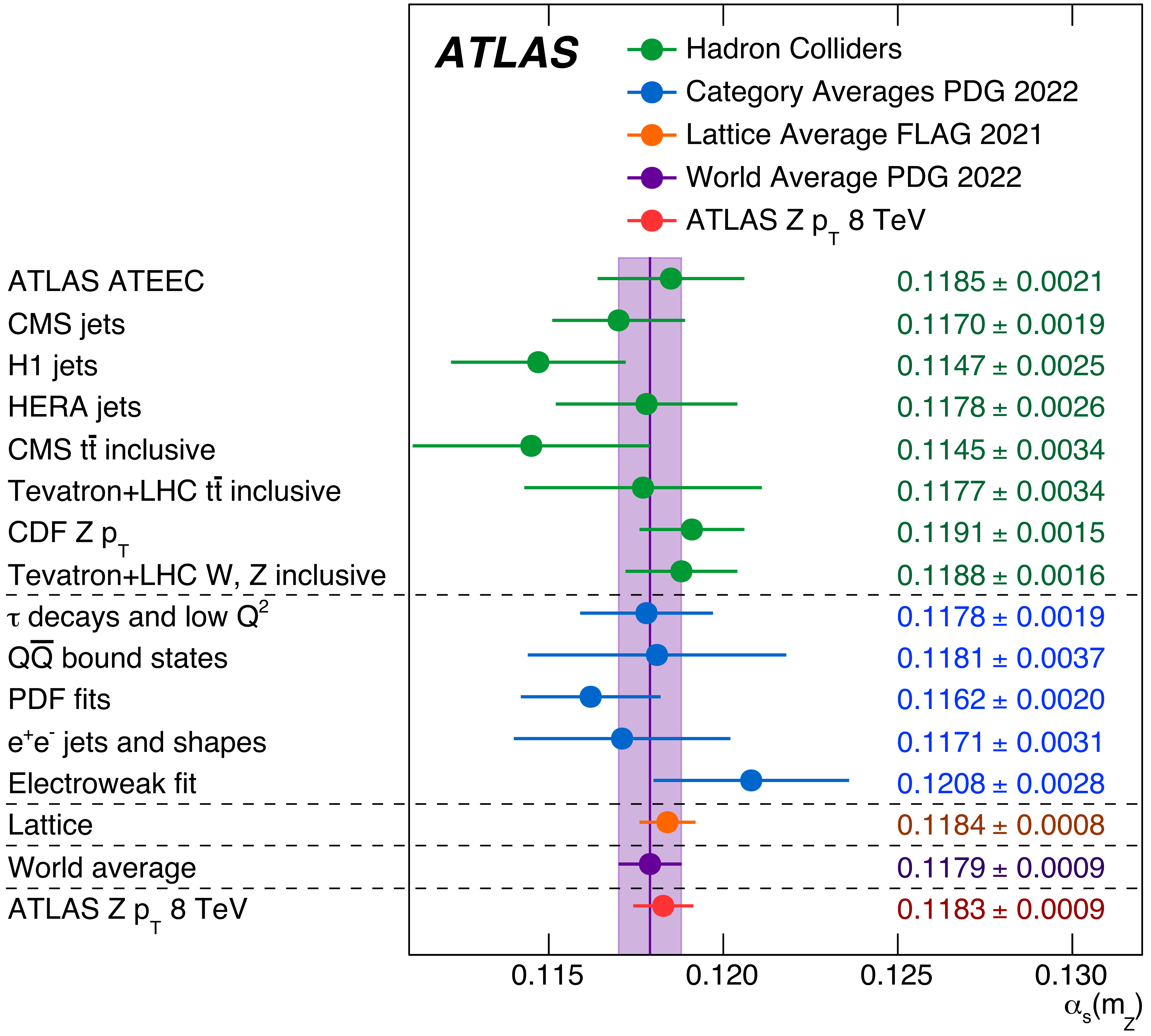
Final Result

$$\alpha_s(m_Z) = 0.11828^{+0.00084}_{-0.00088}$$

- Most precise experimental determination of $\alpha_s(m_Z)$
  - As precise as PDG and Lattice world averages!
- First $\alpha_s(m_Z)$ determination at N^{3}LO + N^{4}LL
- Determination focusing on Sudakov region (usually avoided to determine α_s)
- Observable not suitable for inclusion in PDF fits
  - No correlation with $\alpha_s(m_Z)$ determination from PDF fits



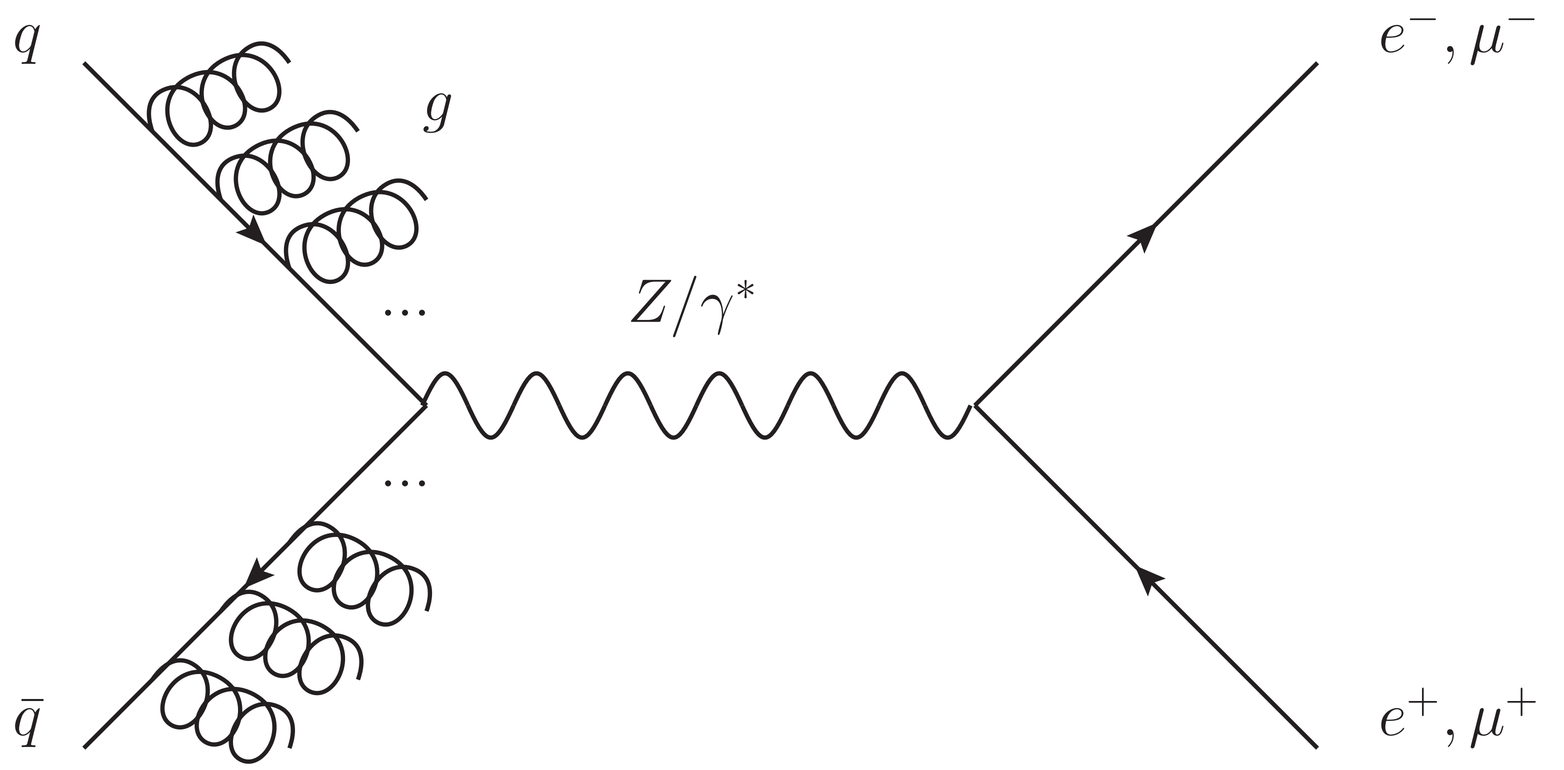
Summary

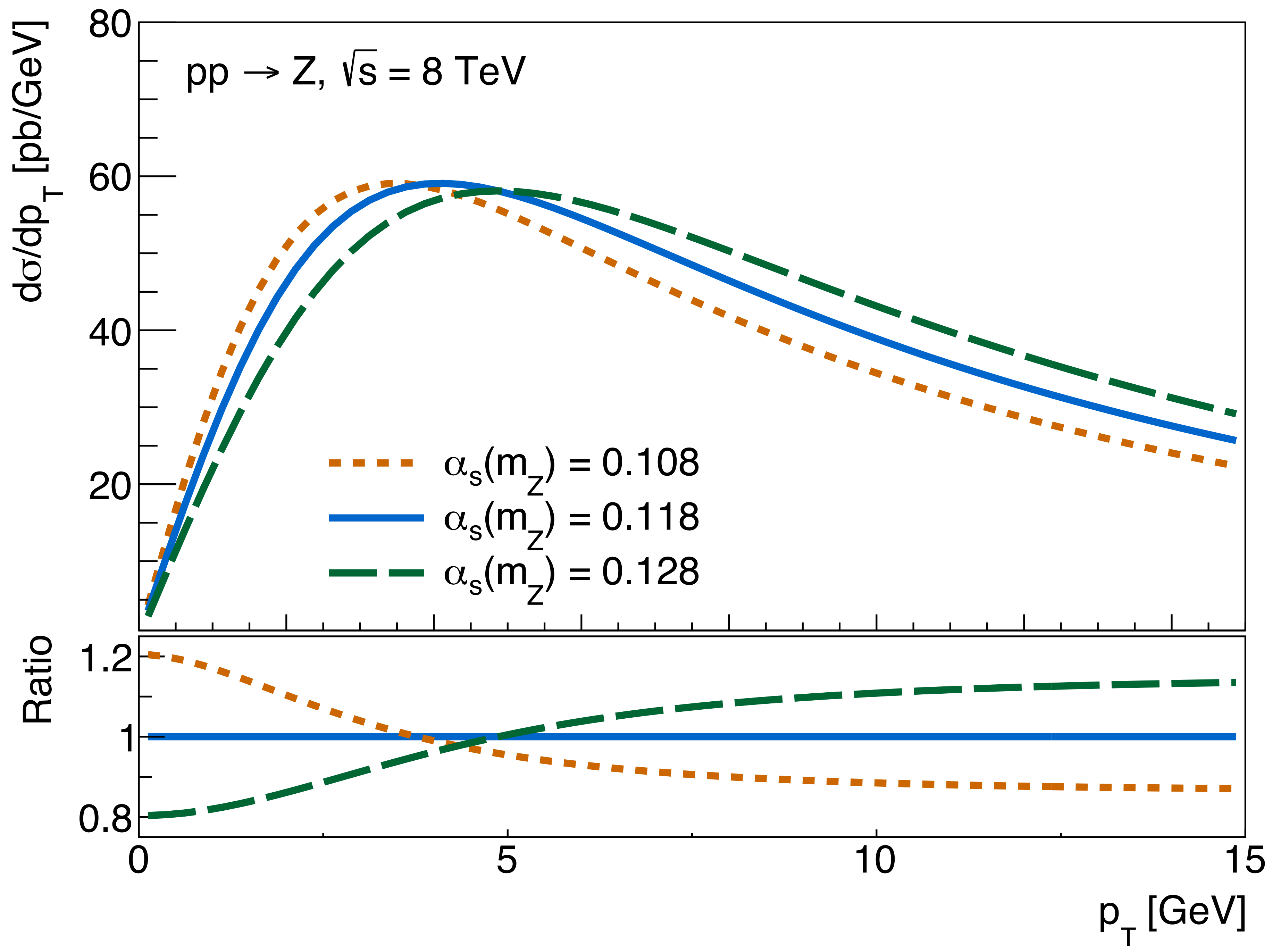
$$\alpha_s(m_Z) = 0.11828^{+0.00084}_{-0.00088}$$

- New window for the determination of $\alpha_s(m_Z)$, the strong coupling constant
  - Using the transverse momentum of Z bosons

- New measurements might **reduce PDF uncertainties** further

- New measurements required to **constrain further non-perturbative effects**

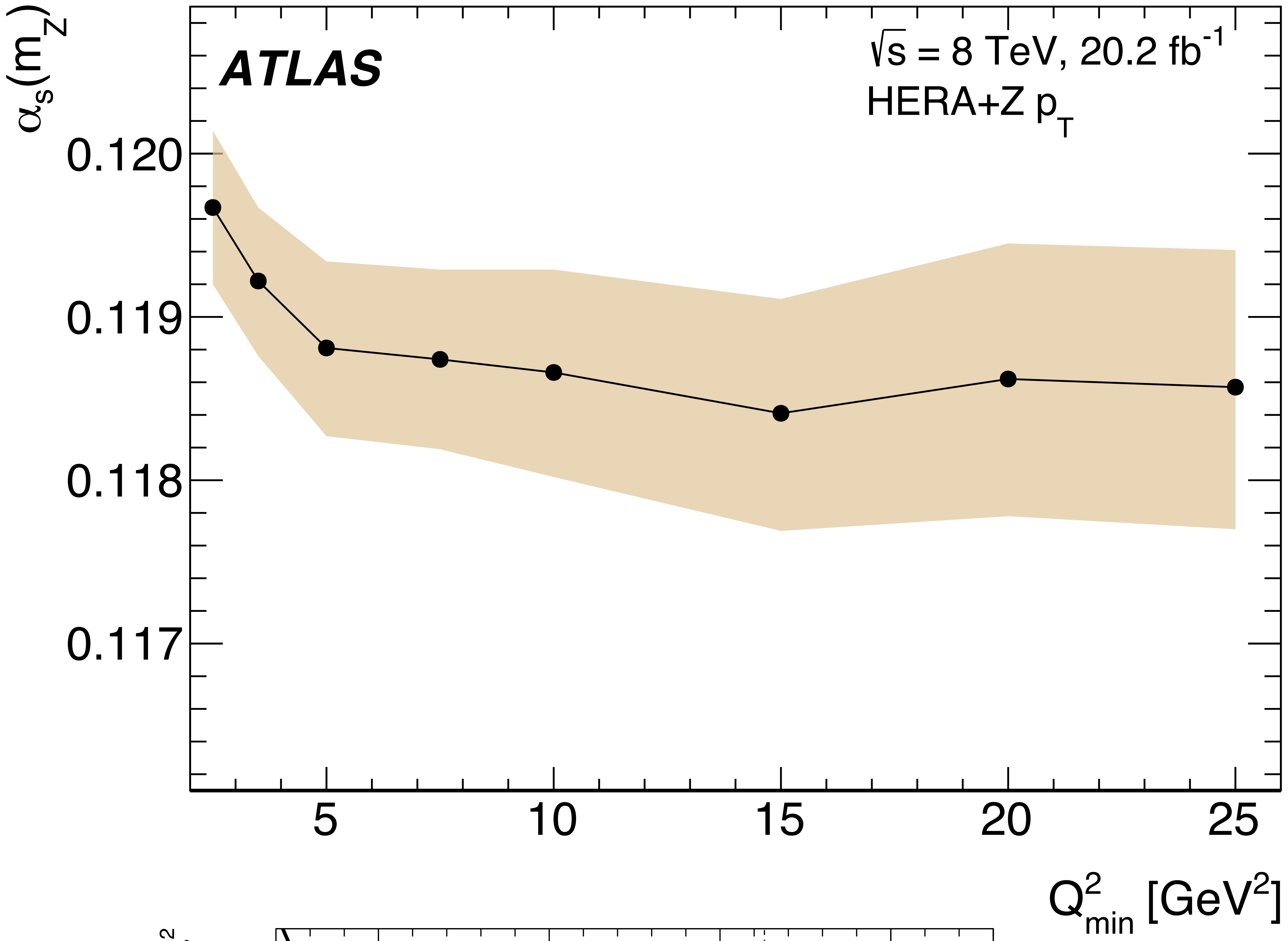


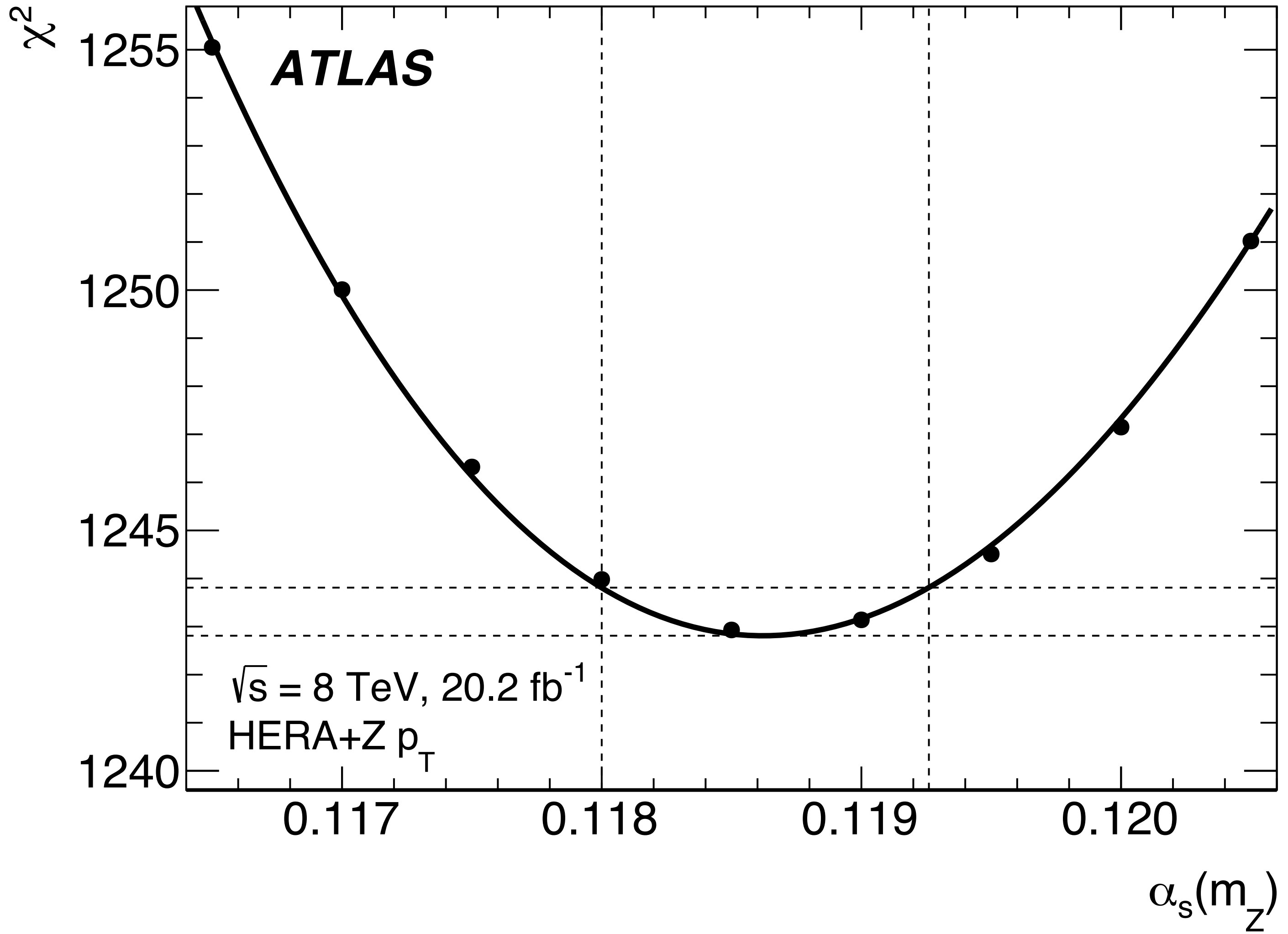


BACKUP

Cross Checks

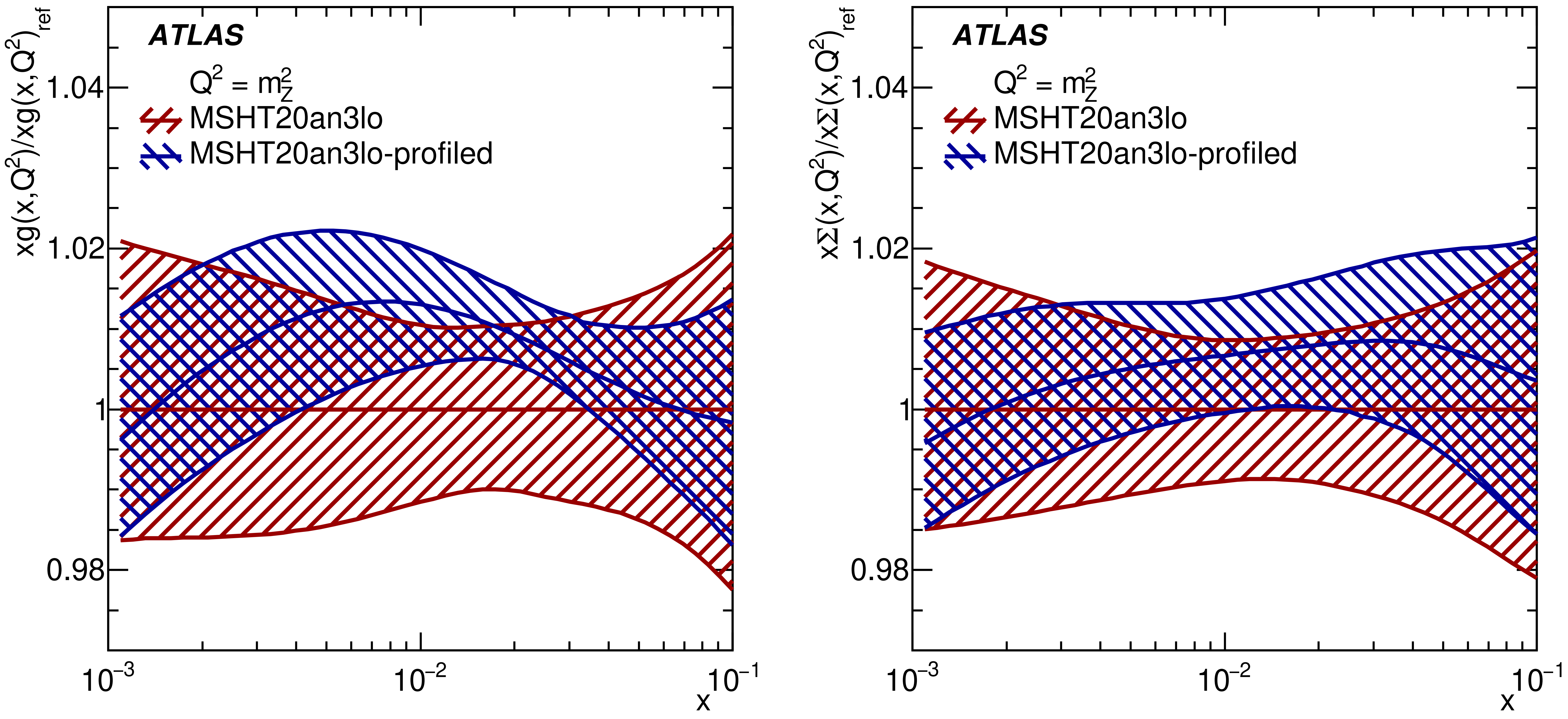
- Simultaneous determination of α_s, the PDFs, and the non-perturbative parameters
    - N3LL+N3LO, with PDFs evolved at NNLO.
- The light-quark coefficient functions of the DIS cross sections are calculated in the MS scheme.
- The heavy quarks (c, b) generated dynamically
    - using general-mass variable-flavour-number 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 .





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

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

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

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

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

- 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

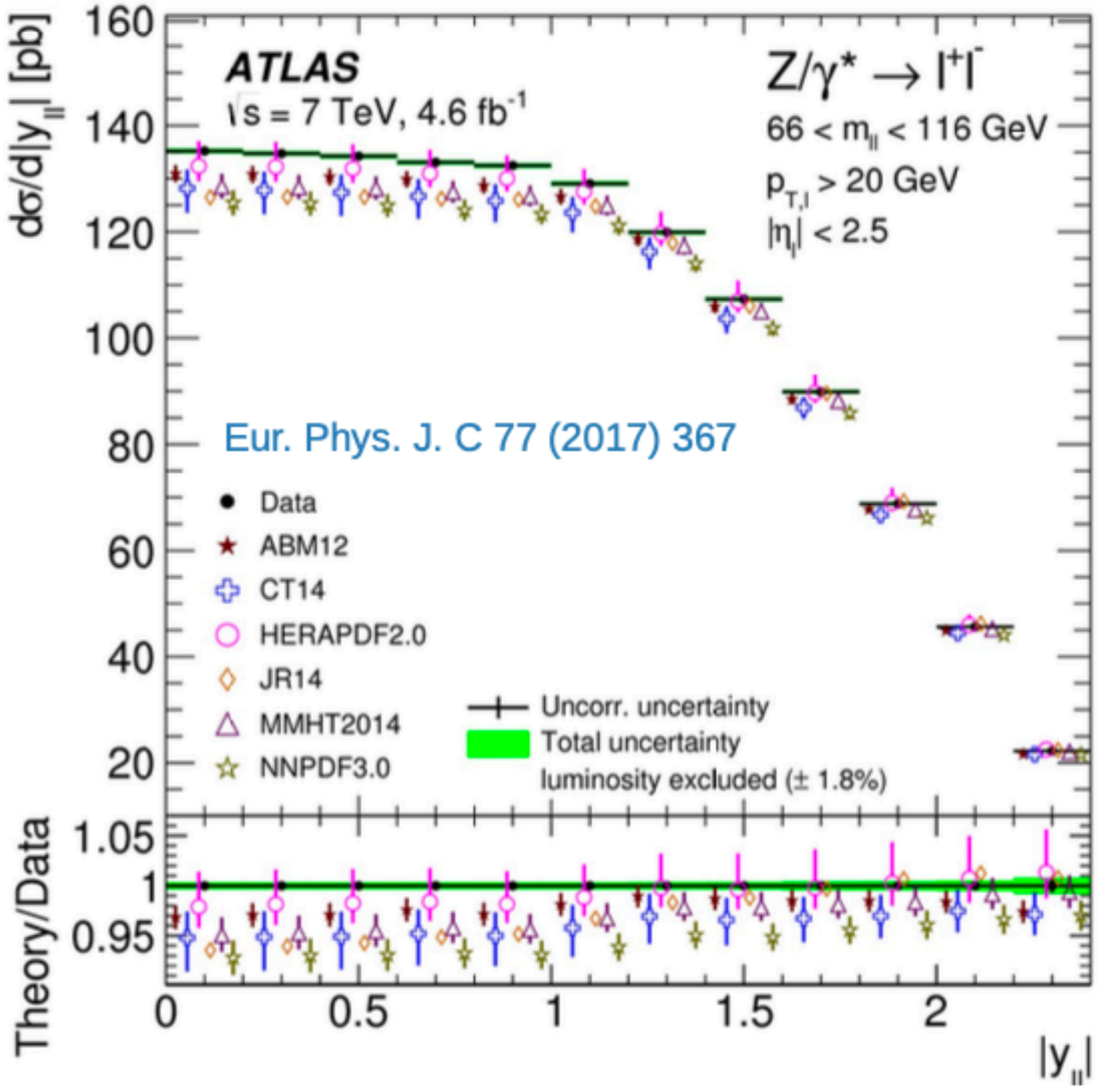
- Lambda controls transition from Gaussian to exponential: varied between 0.5-2
  - Fits excluding 0-5 GeV yields $\alpha_s(m_Z)$ with a spread of + 0.00017 – 0.00010
  - Fit uncertainty increased from 0.00067 to 0.00071
  - Correlation between $\alpha_s(m_Z)$ and g largely reduced

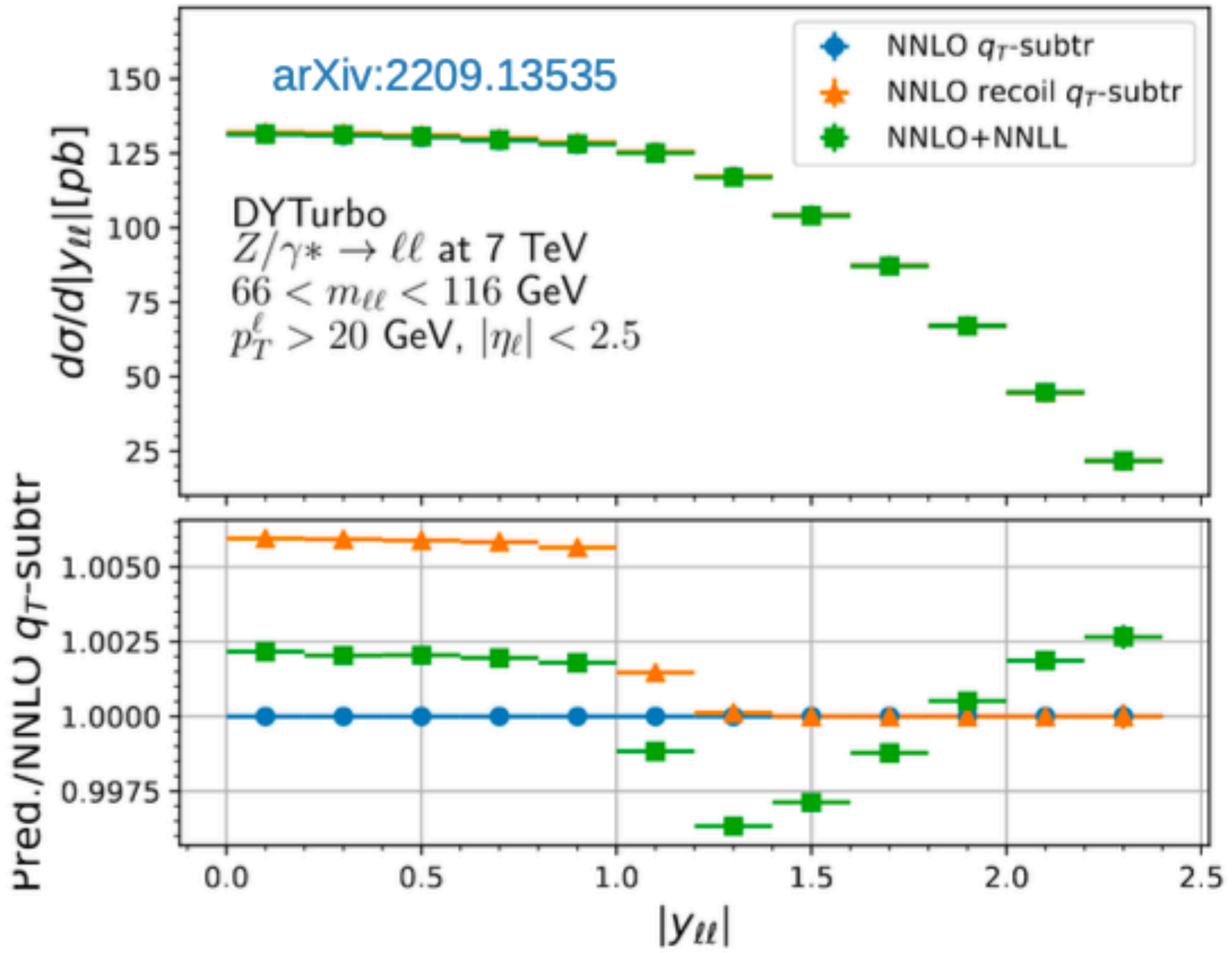
Full Lepton Phase-Space Rapidity Cross-Section

- 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

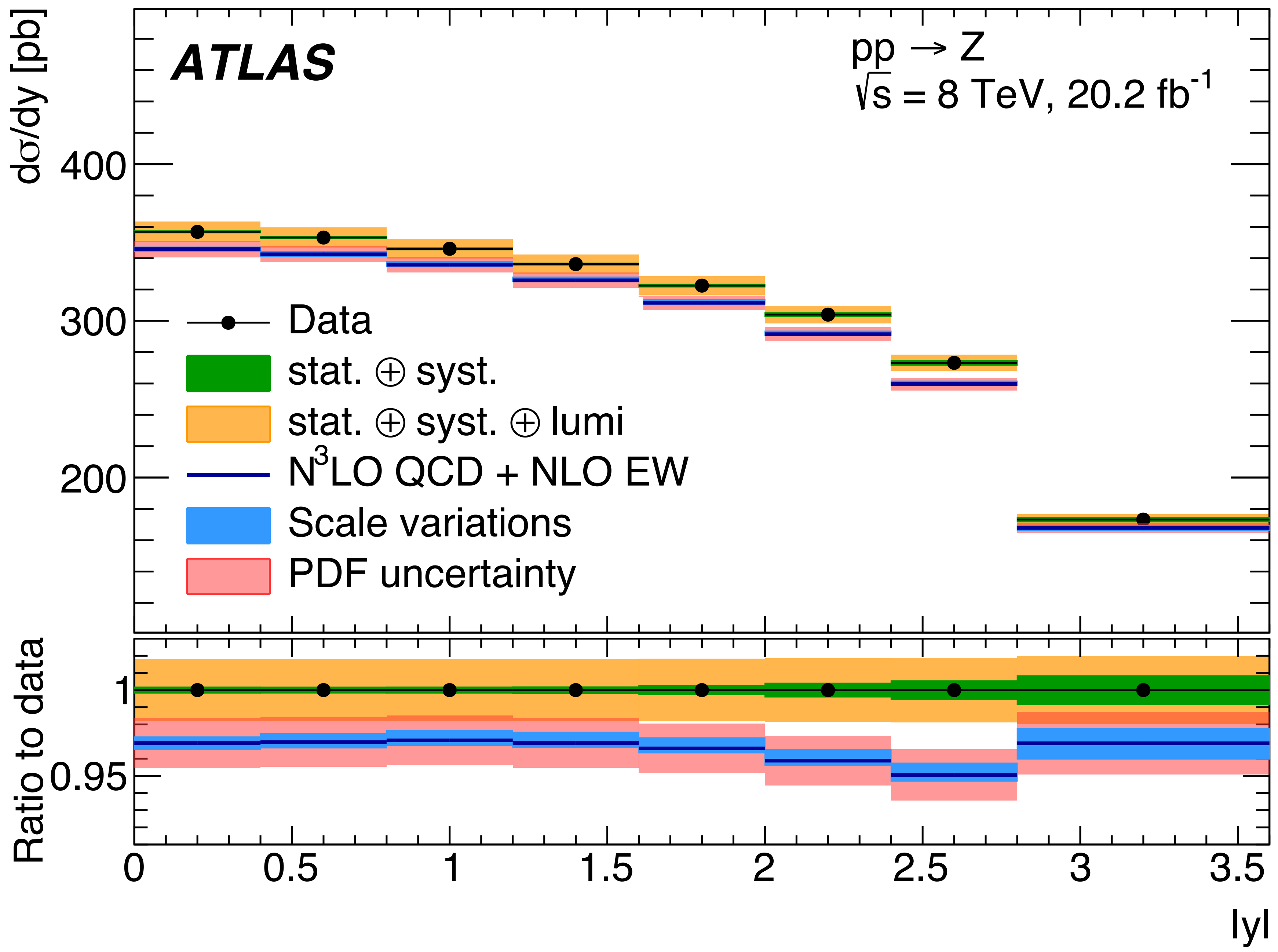
- Ai-based elegant solution:
  - Fiducial cuts removed by analytic integration of (cosθ,Φ) in the full phase space of the decay leptons through the measured Ai coefficients
  - few permille total uncertainties for ds/dy and negligible theoretical uncertainties

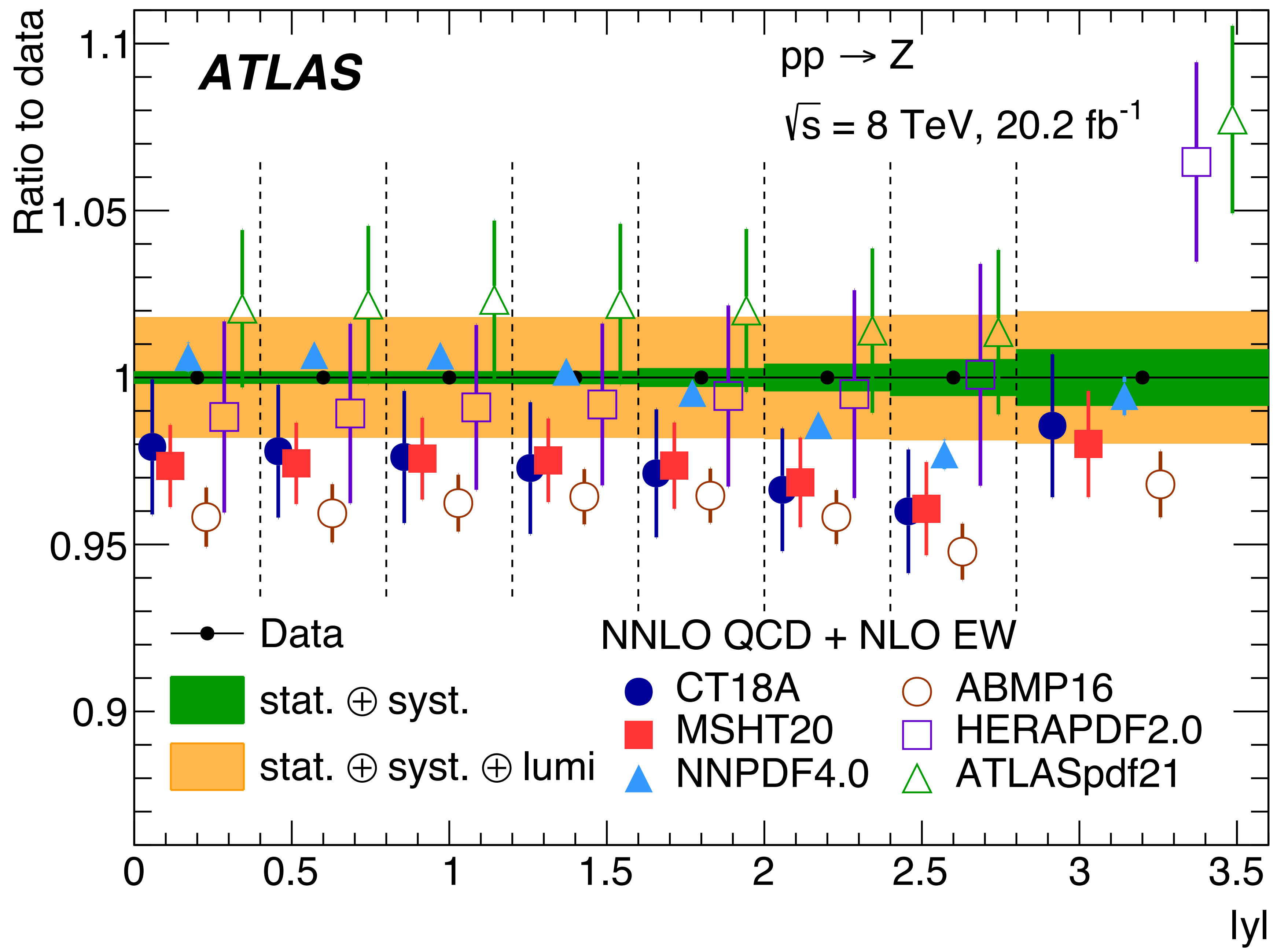




Full Lepton Phase-Space Rapidity Cross-Section

- First comparison to N3LO QCD predictions
- Enables precise and unambiguous PDF interpretation with QCD scale variations now smaller than PDF uncertainties





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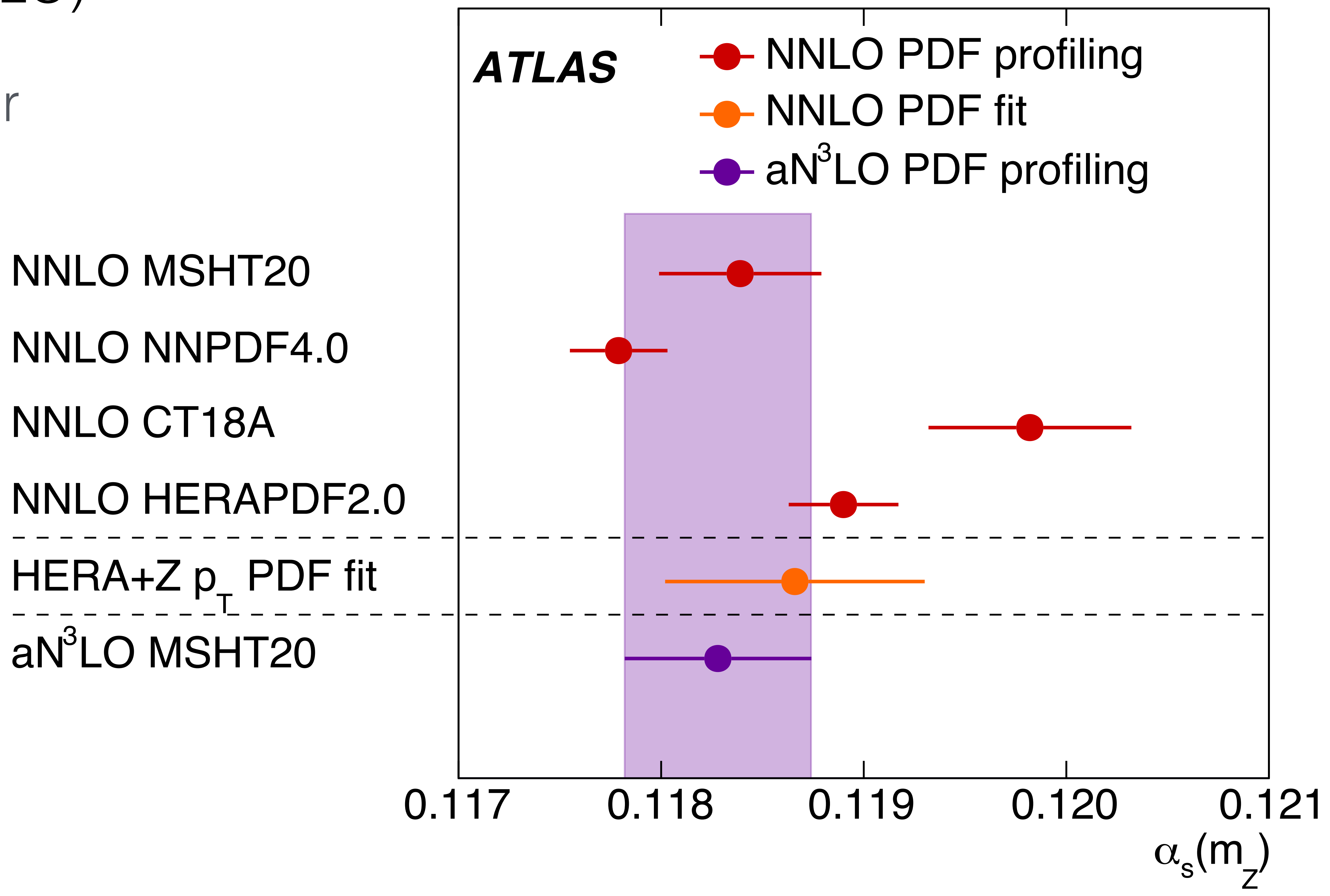

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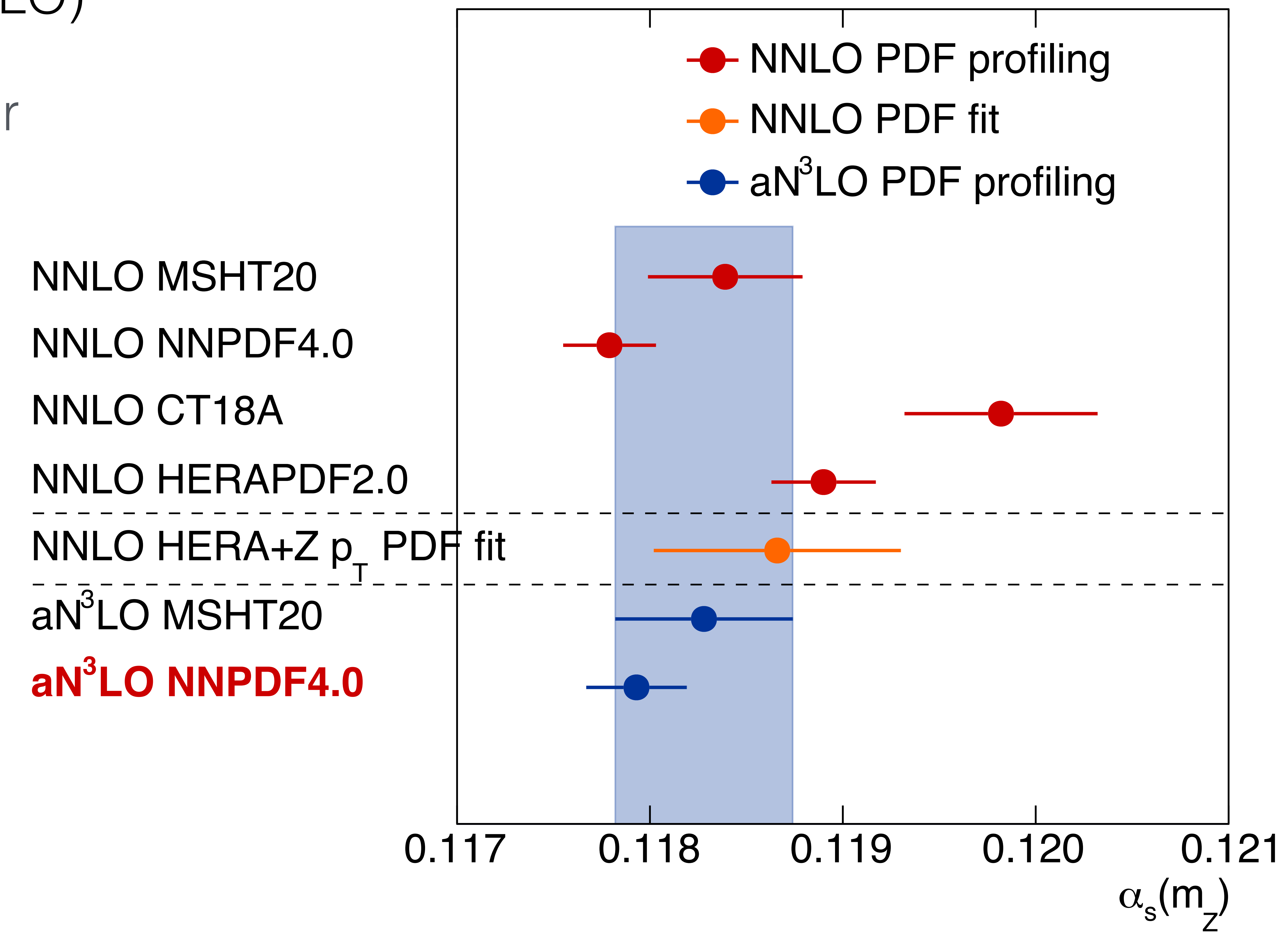

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