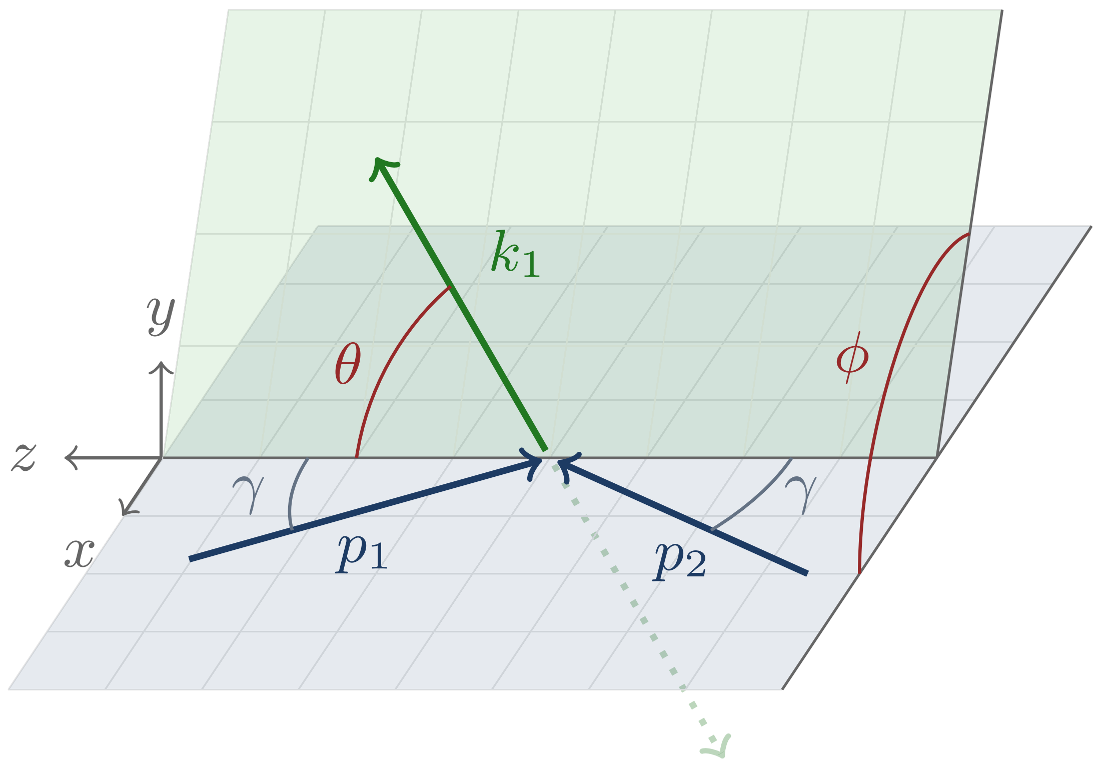
Angular coefficients in Z boson production

work with A. Gehrmann-De Ridder, T. Gehrmann, E.W.N. Glover, A. Huss

arXiv:1708.00008

Rhorry Gauld



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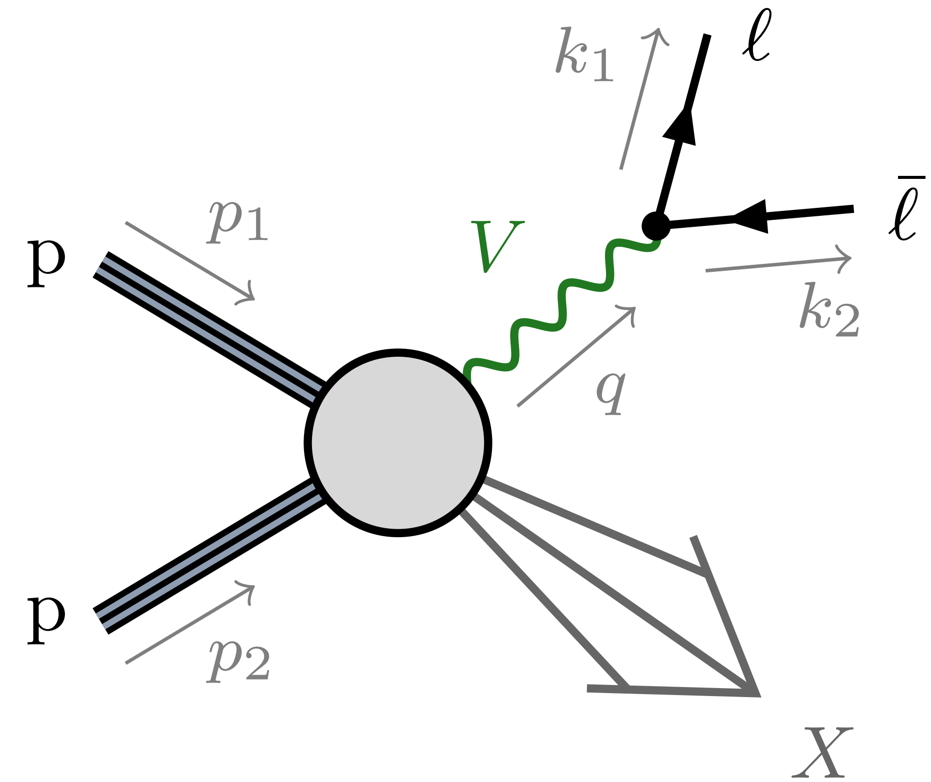
overview of talk

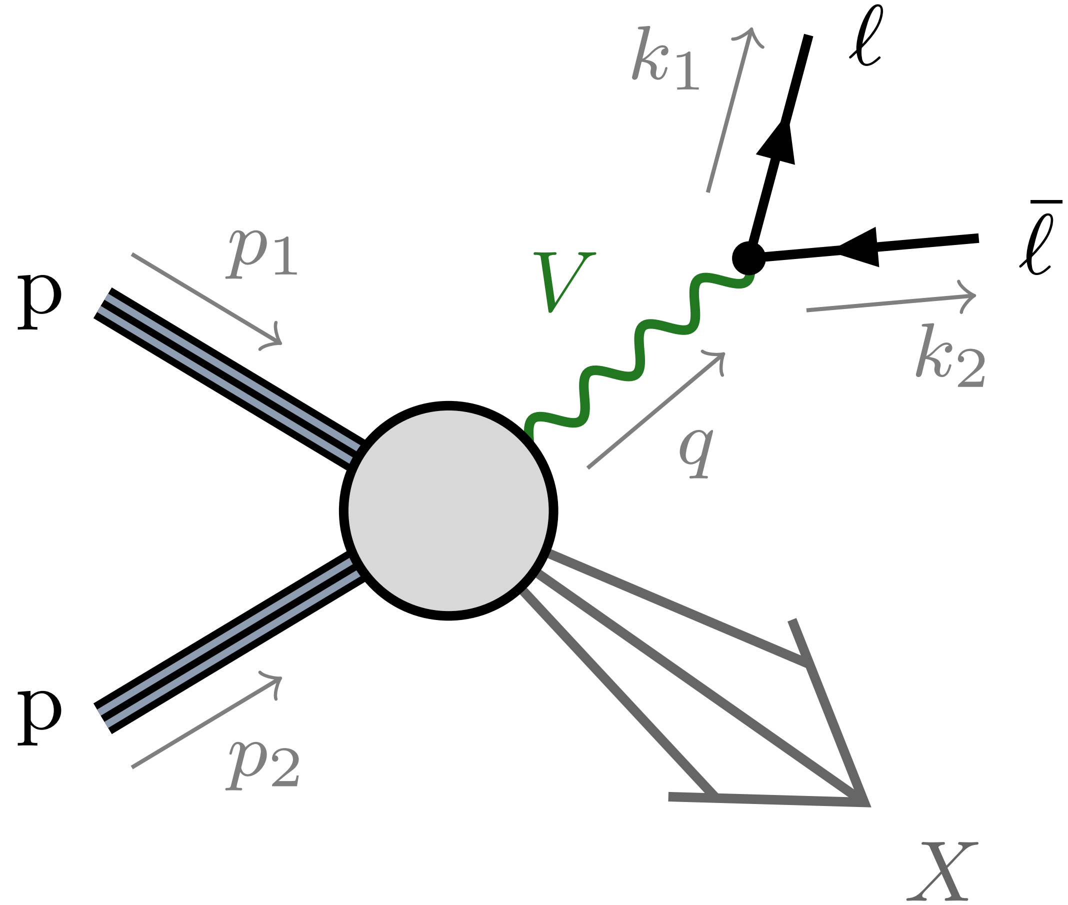


- **Introduction:**
  - experimental summary
  - theoretical framework

- **Results:**
  - Comparison to ATLAS and CMS data
  - Discussion of Lam-Tung violation
  - (Prospects for LHCb)

- **What insight do results offer for W bosons?**

general statements



i) Precise Z boson measurements: PDFs, Luminosity, $Z\bar{f}f$

ii) Case study for W bosons (both leptons reconstructed for Z)

iii) QCD production dynamics of Z bosons at non-zero $p_{T,Z}$

(as encoded by angular coefficients)

general set-up

$$p(p_1) + p(p_2) \to V(q) + X \to \boxed{\bar{\ell}(k_1) + \bar{\ell}(k_2)} + X$$

Defining lepton kinematics in V(q) rest frame

$$k^{\mu}_{1,2} = \frac{\sqrt{q^2}}{2}\,(1, \pm\sin\theta\cos\phi, \pm\sin\theta\sin\phi, \pm\cos\theta)^T$$

Decompose cross section in terms of spherical polynomials $f_i(\theta,\phi)$

$$\frac{d\sigma}{d^4q\ \cos\theta\ d\phi} = \frac{3}{16\pi}\frac{d\sigma^{\text{unpol.}}}{d^4q}\Big\{(1+\cos^2\theta) + \frac{1}{2}\,A_0\,(1-3\cos^2\theta)$$
$$+ A_1\,\sin(2\theta)\cos\phi + \frac{1}{2}\,A_2\,\sin^2\theta\,\cos(2\phi)$$
$$+ A_3\,\sin\theta\,\cos\phi + A_4\,\cos\theta + A_5\,\sin^2\theta\,\sin(2\phi)$$
$$+ A_6\,\sin(2\theta)\,\sin\phi + A_7\,\sin\theta\,\sin\phi\Big\}$$

$A_{0,..,7}(q)$

Encode QCD dynamics

$f_i(\theta,\phi)$

Lepton pair kinematics

$l=0$	$m=0$
$l=1$	$m=-1,0,1$
$l=2$	$m=-2,-1,0,1,2$

Total of 9 terms

some context

Angular coefficients A_0, A_1, A_2 first measured in low-mass Dell-Yan

* Measurements by Na10/E615 in late 80s (Pion beams on Tungsten)
* Measurements by NuSea ’06/’08 (pp and pd collisions)

(see ref. [27-30] of arXiv:1708.00008)

At LHC and TeVatron, measurements performed around Z-boson mass

(sensitive to A_3, A_4)

* CDF measurement - arXiv:1103.5699
* ATLAS/CMS measurements - arXiv:1606.00689 / arXiv:1504.03512

Measurement of angular coefficients (polarisation) in W production

* ATLAS/CMS measurements - arXiv:1203.2165 / arXiv:1104.3829

($p_{T,W} > 30/50$ GeV **)**

Enters m_W extraction through a weighting of angular variables

$$w = \frac{1+\cos^2\theta + \sum_i A_i'(p_{\mathrm{T}},y)\, P_i(\cos\theta,\phi)}{1+\cos^2\theta + \sum_i A_i(p_{\mathrm{T}},y)\, P_i(\cos\theta,\phi)},$$

(i.e. NLO+PS vs. FO)

predictions for angular coefficients

projection via spherical polynomials to obtain angular coefficients

$$\langle f(\theta,\phi)\rangle \equiv \frac{\int_{-1}^{1} \mathrm{d}\cos\theta \int_0^{2\pi} \mathrm{d}\phi \; \mathrm{d}\sigma(\theta,\phi) \; f(\theta,\phi)}{\int_{-1}^{1} \mathrm{d}\cos\theta \int_0^{2\pi} \mathrm{d}\phi \; \mathrm{d}\sigma(\theta,\phi)}.$$

practically: run pp > ll+X, perform projection in Collins-Soper frame

fill histograms (w.r.t. $m_{\ell\ell}, y_{\ell\ell}, p_T^{\ell\ell}$) weighted by $f(\theta,\phi)$

(lab-frame)

reality: integrating highly oscillating functions…

solutions: clever reweighting of P.S. + many integrand evaluations..

$$A_0 = 4 - 10\,\left\langle \cos^2\theta \right\rangle, \quad A_1 = 5\,\langle \sin(2\theta)\,\cos\phi\rangle, \quad A_2 = 10\,\left\langle \sin^2\theta\,\cos(2\phi)\right\rangle,$$

$$A_3 = 4\,\langle \sin\theta\,\cos\phi\rangle, \qquad A_4 = 4\,\langle\cos\theta\rangle$$

(relevant angular coefficients)

numerical set-up (boring stuff)

study the region: $p_{T,Z} > 10\ \mathrm{GeV}$

accuracy: NNLO (from Z+jet @ NNLO)

input scheme: G_μ-scheme

PDF set: PDF4LHC NNLO asmz0118

scale: $\mu_0 = \sqrt{m_{\ell\ell}^2 + p_{T,\ell\ell}^2}$

scale variation (arbitrary stuff)

$$1/2 < \mu_F/\mu_R < 2$$

If you correlate numerator and denominator, `artificial' cancellation

No μ_R dependence at all at LO

We independently vary in numerator/denominator, such that

31-point scale variation

$$1/2 < \mu_a^i/\mu_b^j < 2$$

i, j = num. or den.

a,b = fac. or ren.

X. Chen, J. Cruz-Martinez, J. Currie, RG, A. Gehrmann-De Ridder, T. Gehrmann, E.W.N. Glover, A. Huss, I. Maier, T. Morgan, J. Niehues, J. Pires, D. Walker
[CERN, IPPP Durham, MPI Munich, Zurich (ETH and UZH)]

Common framework for NNLO corrections

- parton level Monte Carlo generator
- basis: Antenna Subtraction formalism
  Gehrmann(-De Ridder), Glover - arXiv:0505111
- In progress: APPLfast-NNLO interface
  PDF fitting with full NNLO calculations
- Z+jet at NNLO QCD
  Gehrmann-De Ridder et al. - arXiv:1507.02850

Processes:

$pp \to V \to l\bar{l} + 0, 1 \text{ jets}$

$pp \to H + 0, 1, 2 \text{ jets}$

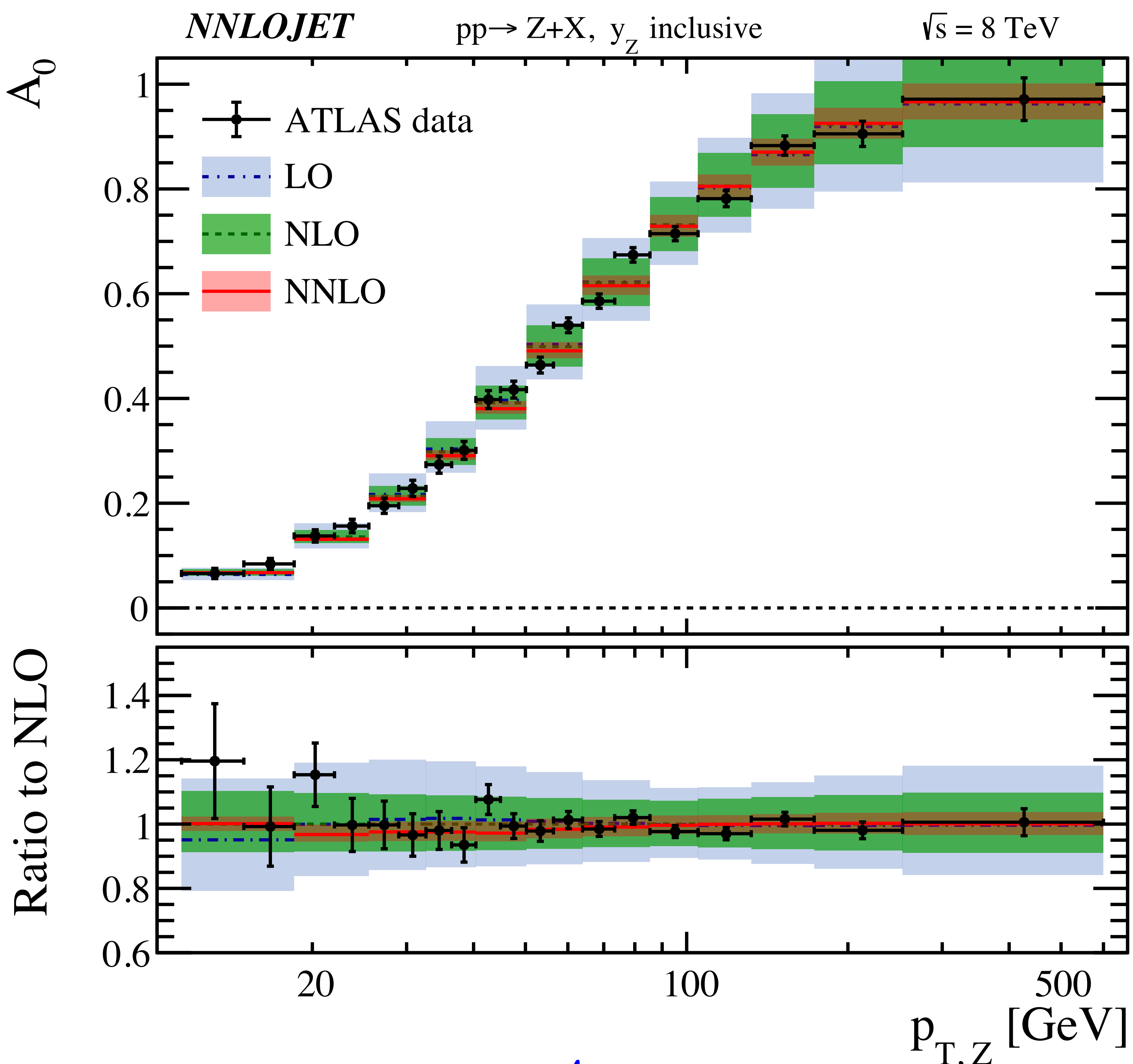
$pp \to \text{dijets}$

$ep \to 1, 2 \text{ jets}$

$e\bar{e} \to 3 \text{ jets}$

$\ldots$

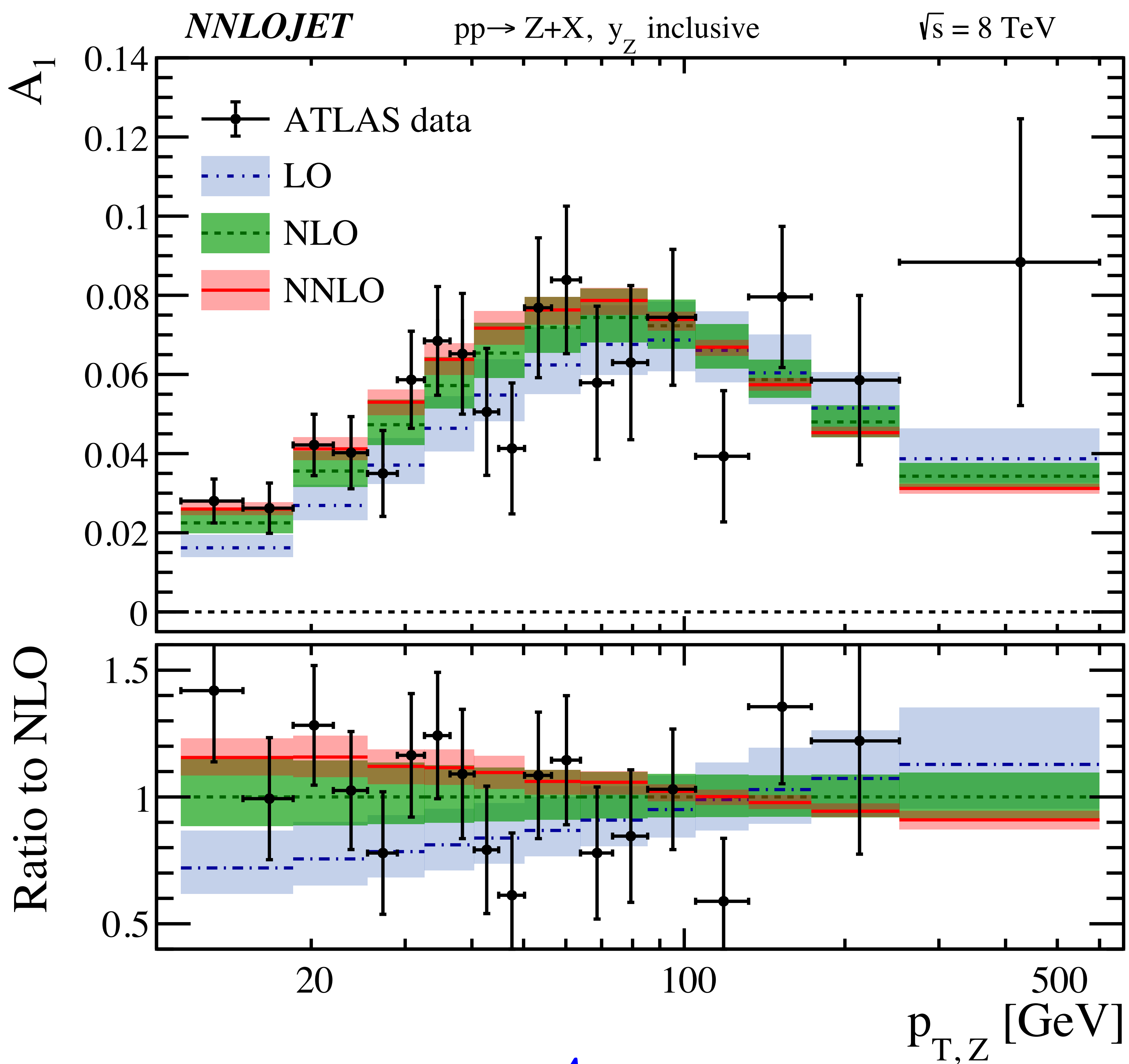
predictions vs. data



A_0

(Collins-Soper frame)

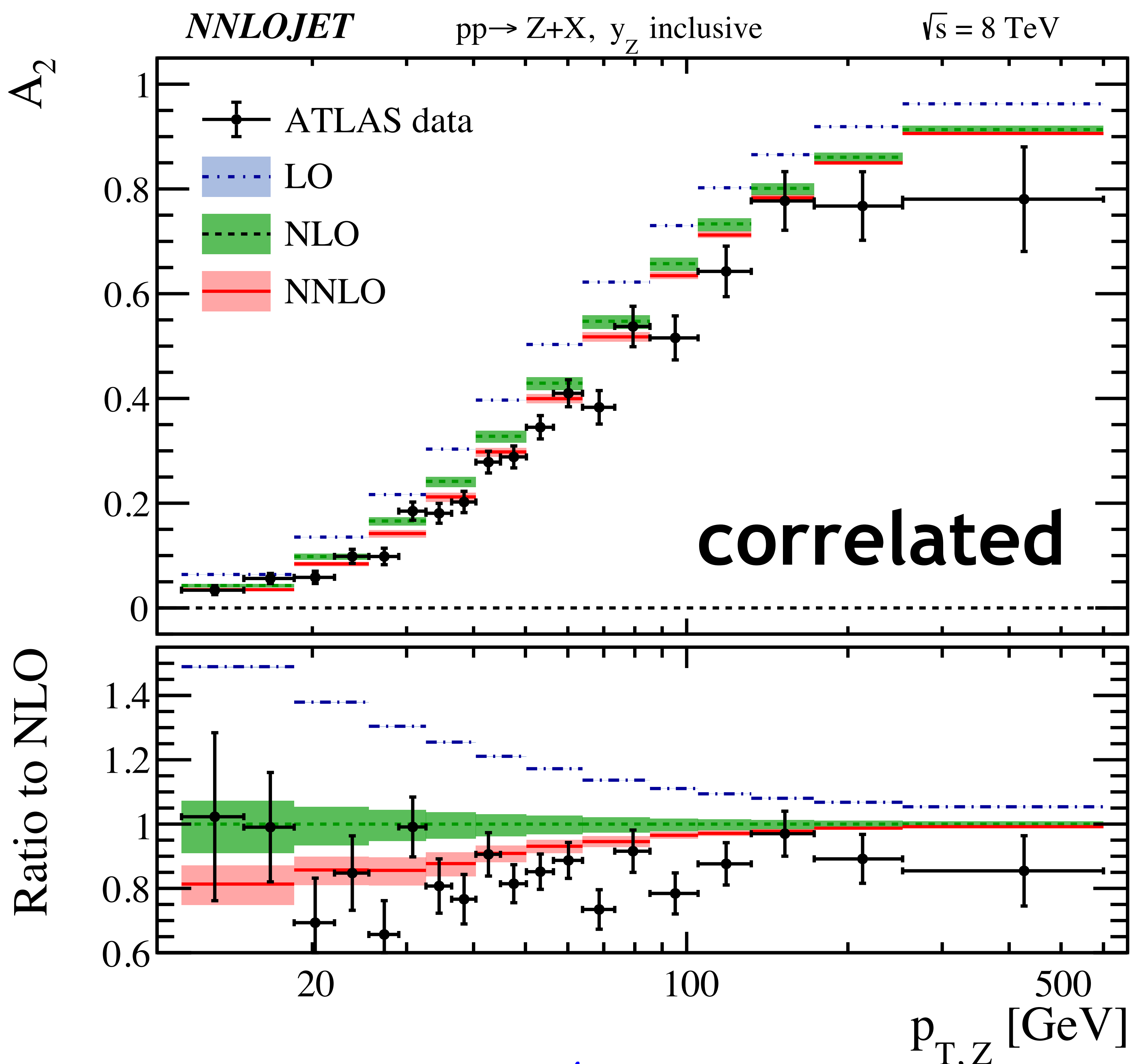
predictions vs. data



A_1

(Collins-Soper frame)

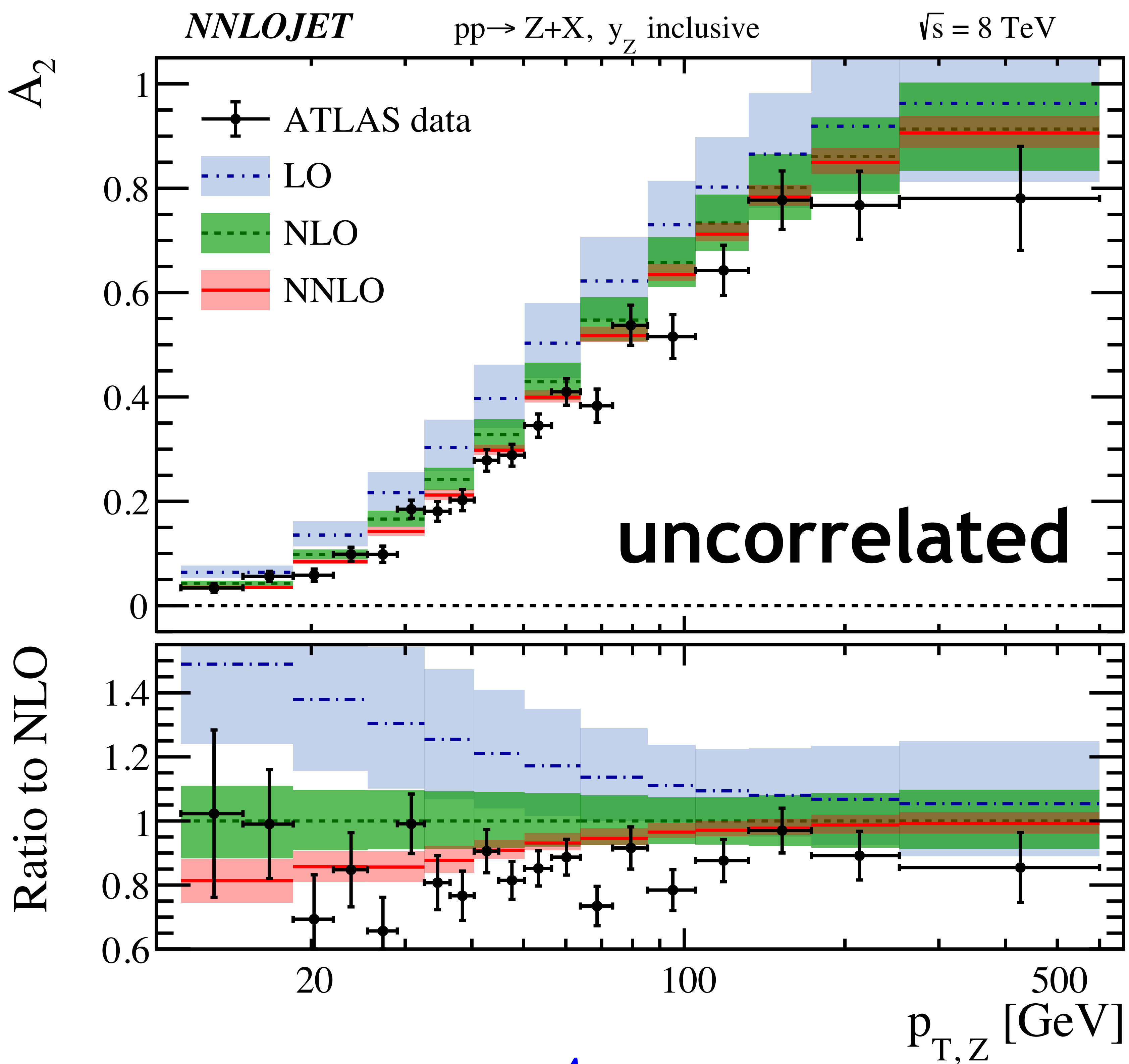
predictions vs. data



A_2

(Collins-Soper frame)

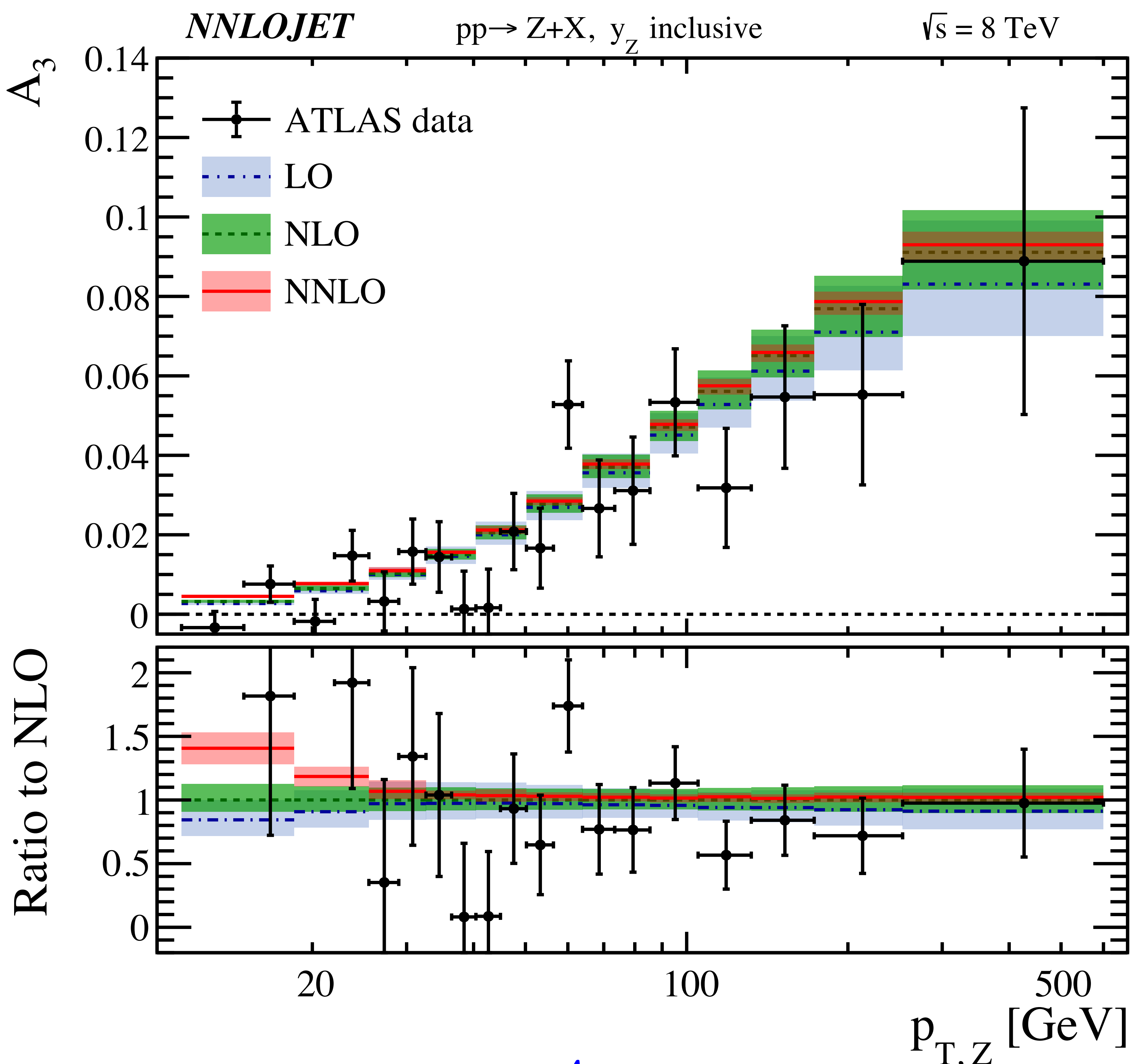
predictions vs. data



A_2

(Collins-Soper frame)

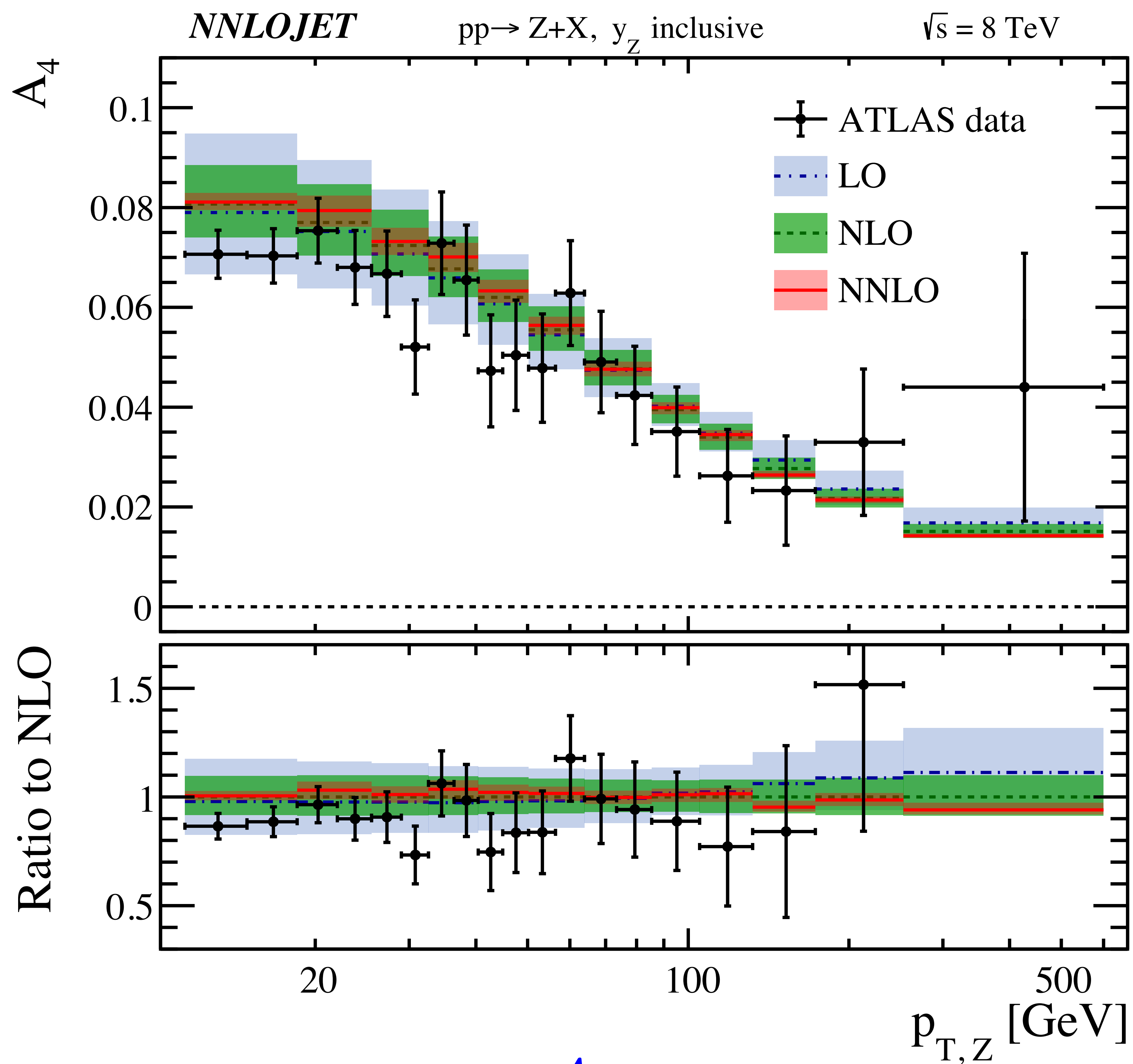
predictions vs. data



A_3

(Collins-Soper frame)

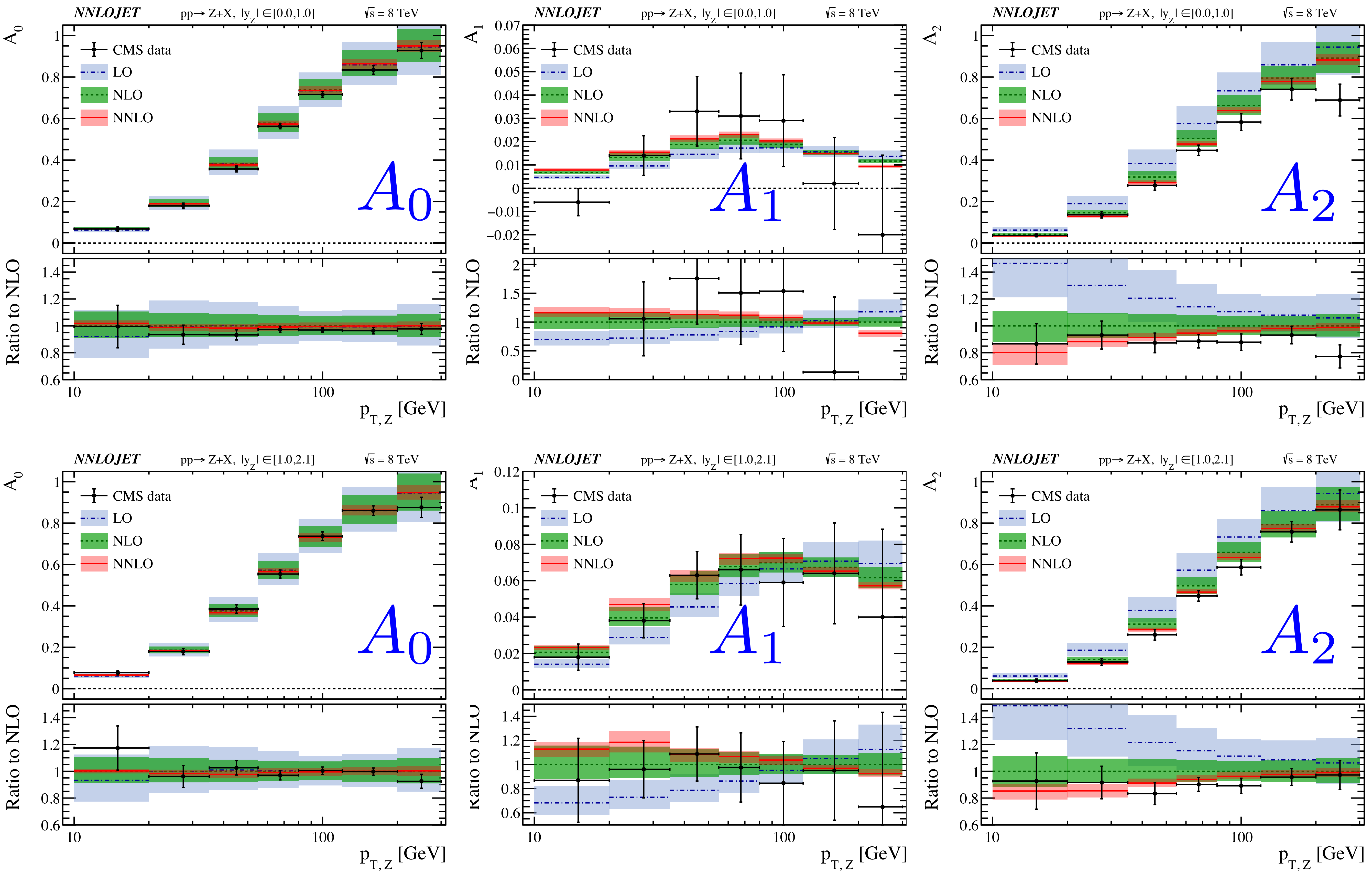
predictions vs. data



A_4

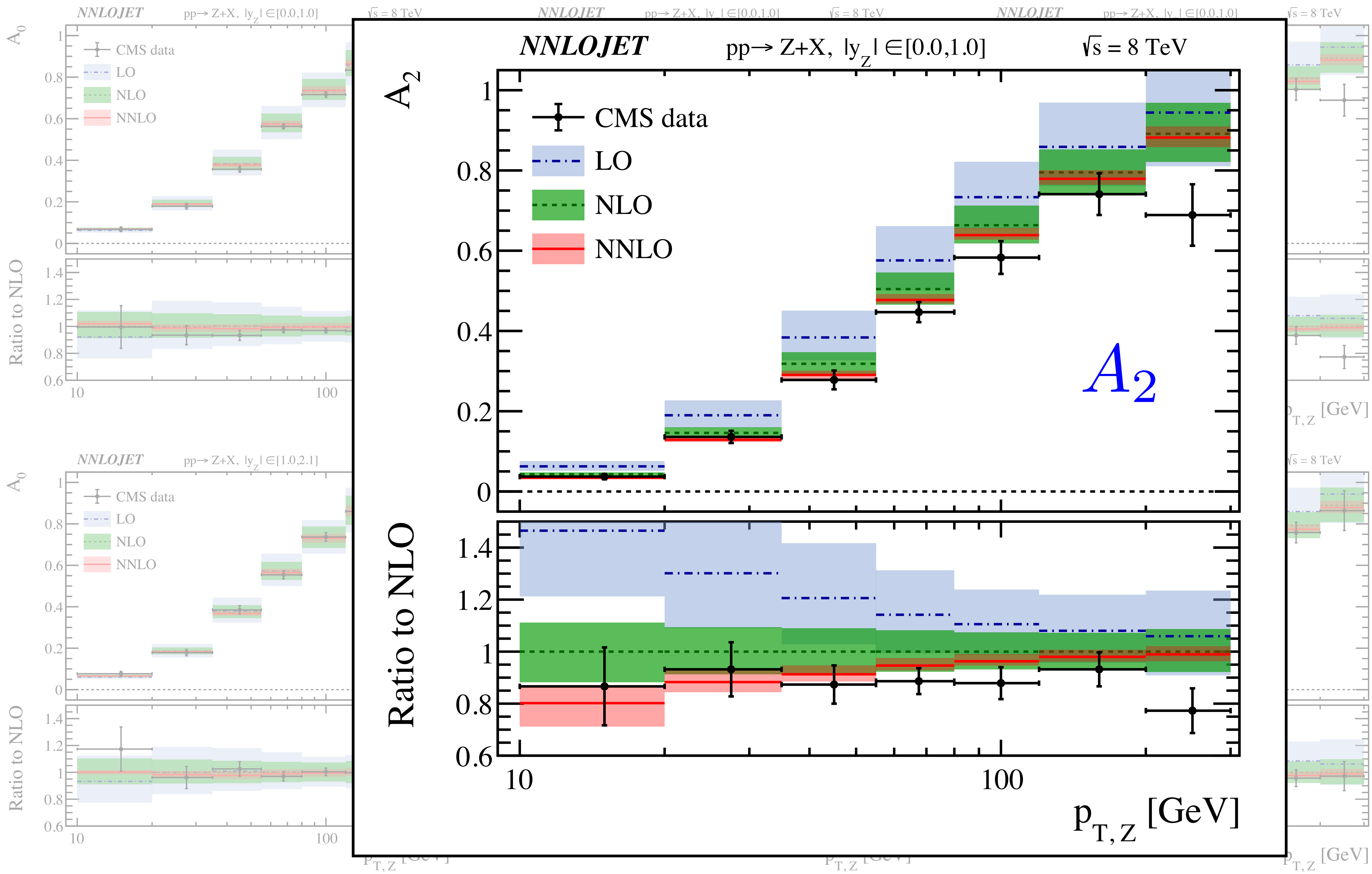
(Collins-Soper frame)

predictions vs. data (CMS)



(Collins-Soper frame)

predictions vs. data (CMS)



(Collins-Soper frame)

intermediate conclusions

1) Uncorrelated scale uncertainties more conservative

   * Leads to similar uncertainties @ NNLO as correlated

2) Shapes of A_0, A_1, A_2 distributions altered @ NNLO

   * Leads to better description of ATLAS/CMS data

3) Shapes of A_3, A_4 distributions **<u>not</u>** altered @ NNLO

   * To accuracy of data, central NLO prediction adequate
   **PDF and EW effects to be considered if data improves

encore: assessing Lam-Tung violation

In Collins-Soper reference frame, a relation (in FO) between A_0, A_2:

$$A_0 = A_2, \text{ valid to } \mathcal{O}(\alpha_s)$$

Shown by Lam, Tung for DY('78,'79,'80), known as Lam-Tung relation

However, in FO this relation is broken at $\mathcal{O}(\alpha_s^2)$, by real and virtual

$$A_0 - A_2 \neq 0$$

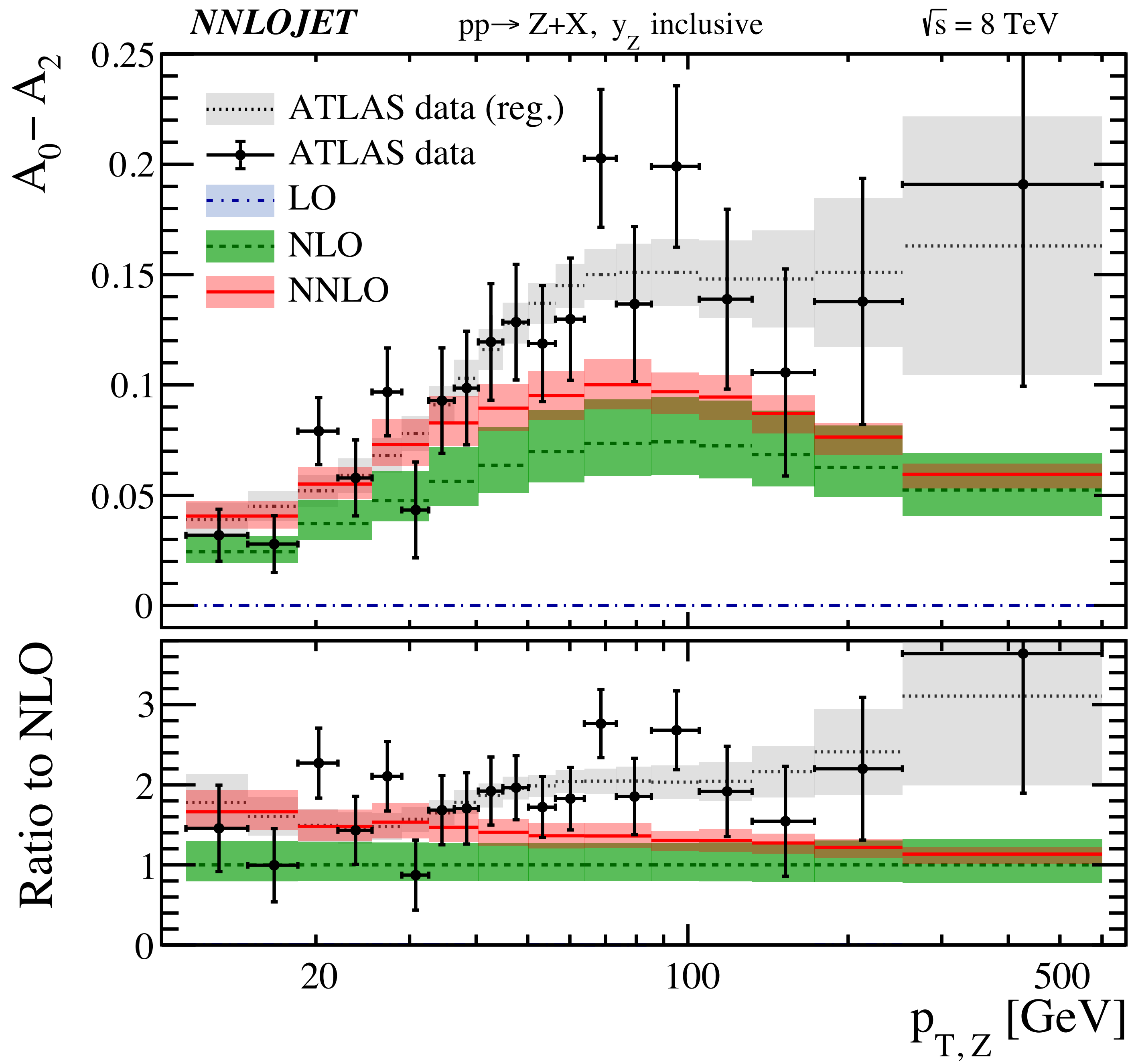
$$\Delta^{\mathrm{LT}} = 1 - \frac{A_2}{A_0}$$

(dependence on unpol. sigma cancels)

Can quantify agreement with data with chi-squared test to $A_0 - A_2$

$$\chi^2 = \sum_{i,j}^{\mathrm{N_{data}}} (O^i_{\mathrm{exp}} - O^i_{\mathrm{th.}}) \sigma^{-1}_{ij} (O^j_{\mathrm{exp}} - O^j_{\mathrm{th.}}),$$

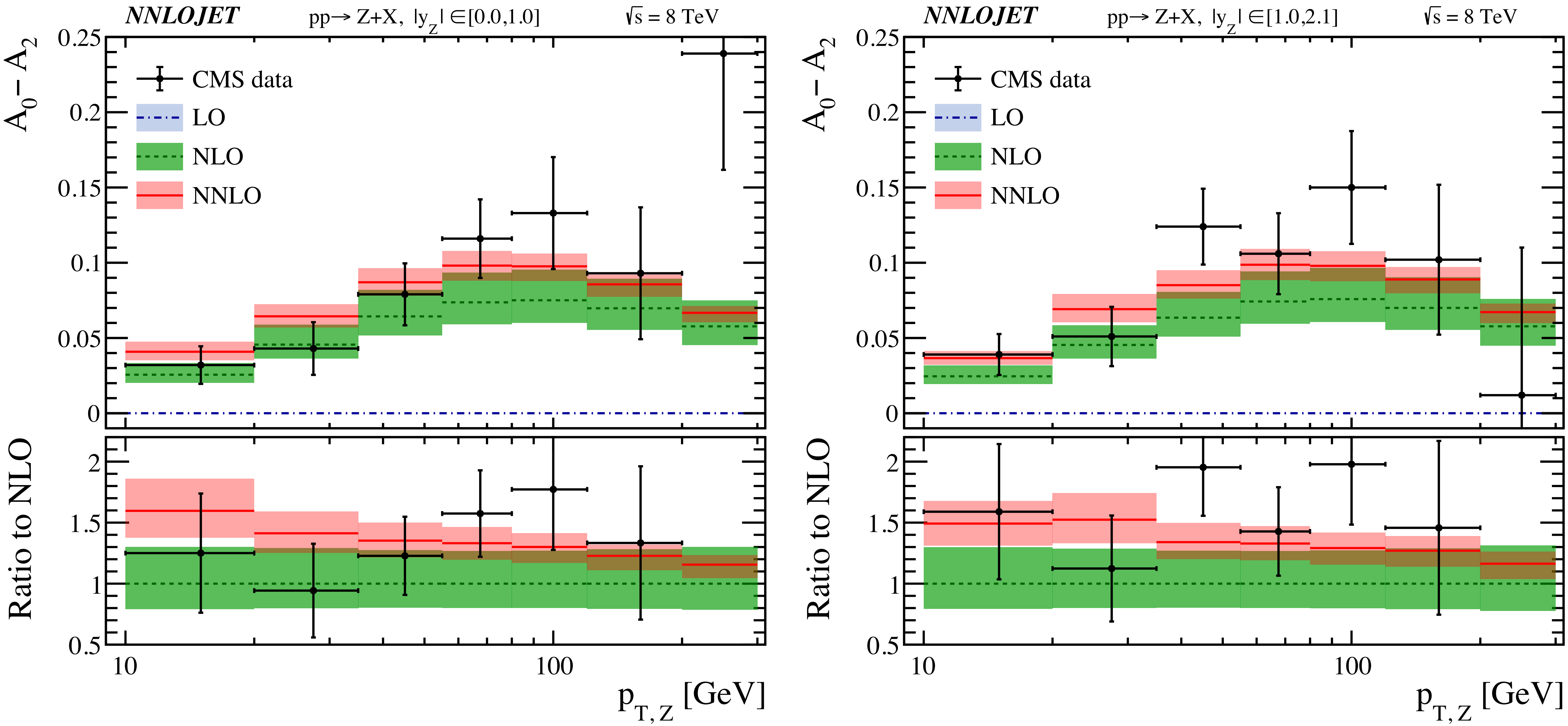
encore: assessing Lam-Tung violation



$$\text{NLO (ATLAS):} \qquad \chi^2/N_{\text{data}} = 185.8/38 = 4.89\,,$$

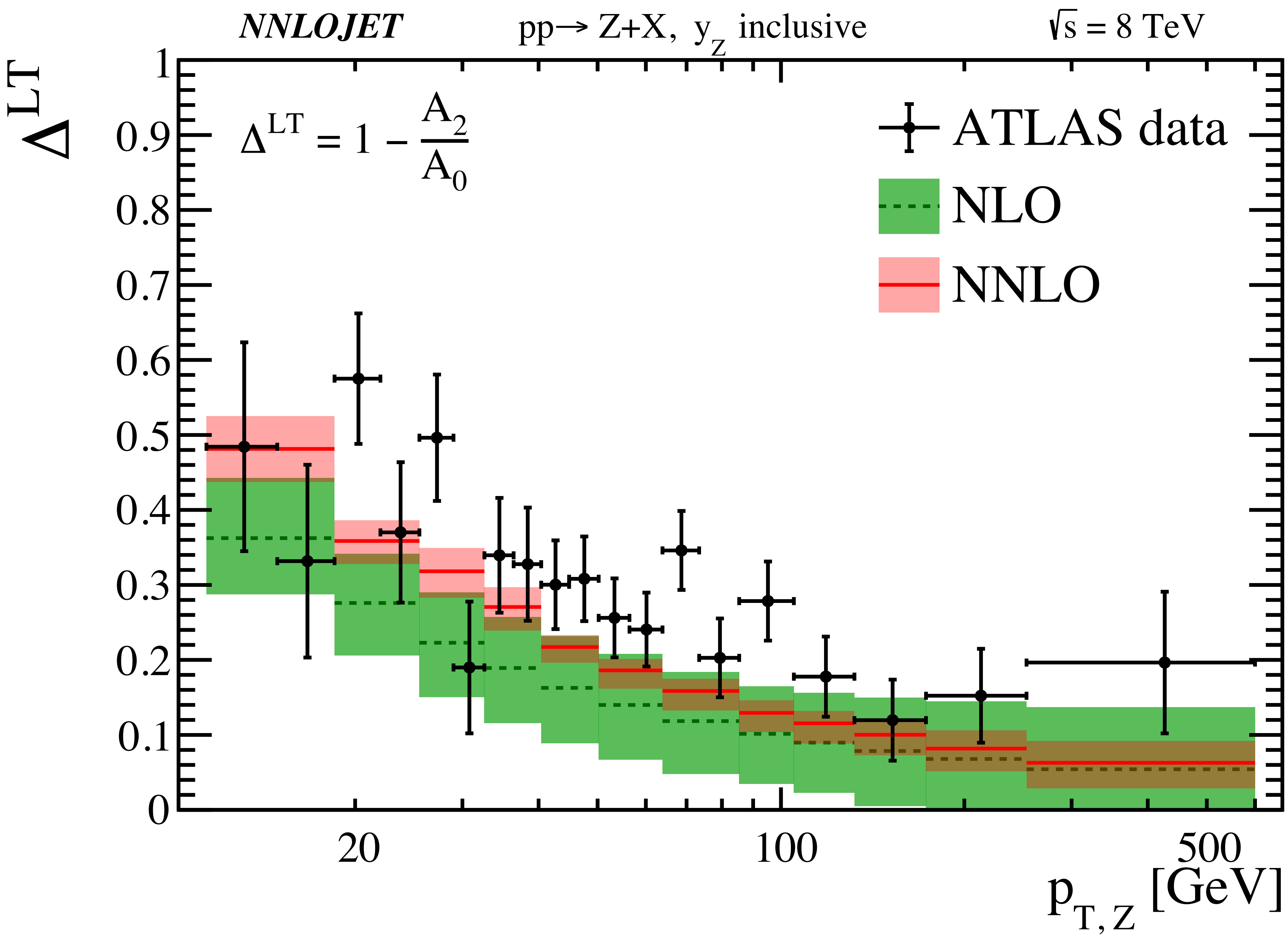
$$\text{NNLO (ATLAS):} \qquad \chi^2/N_{\text{data}} = 68.3/38 = 1.80\,.$$

encore: assessing Lam-Tung violation



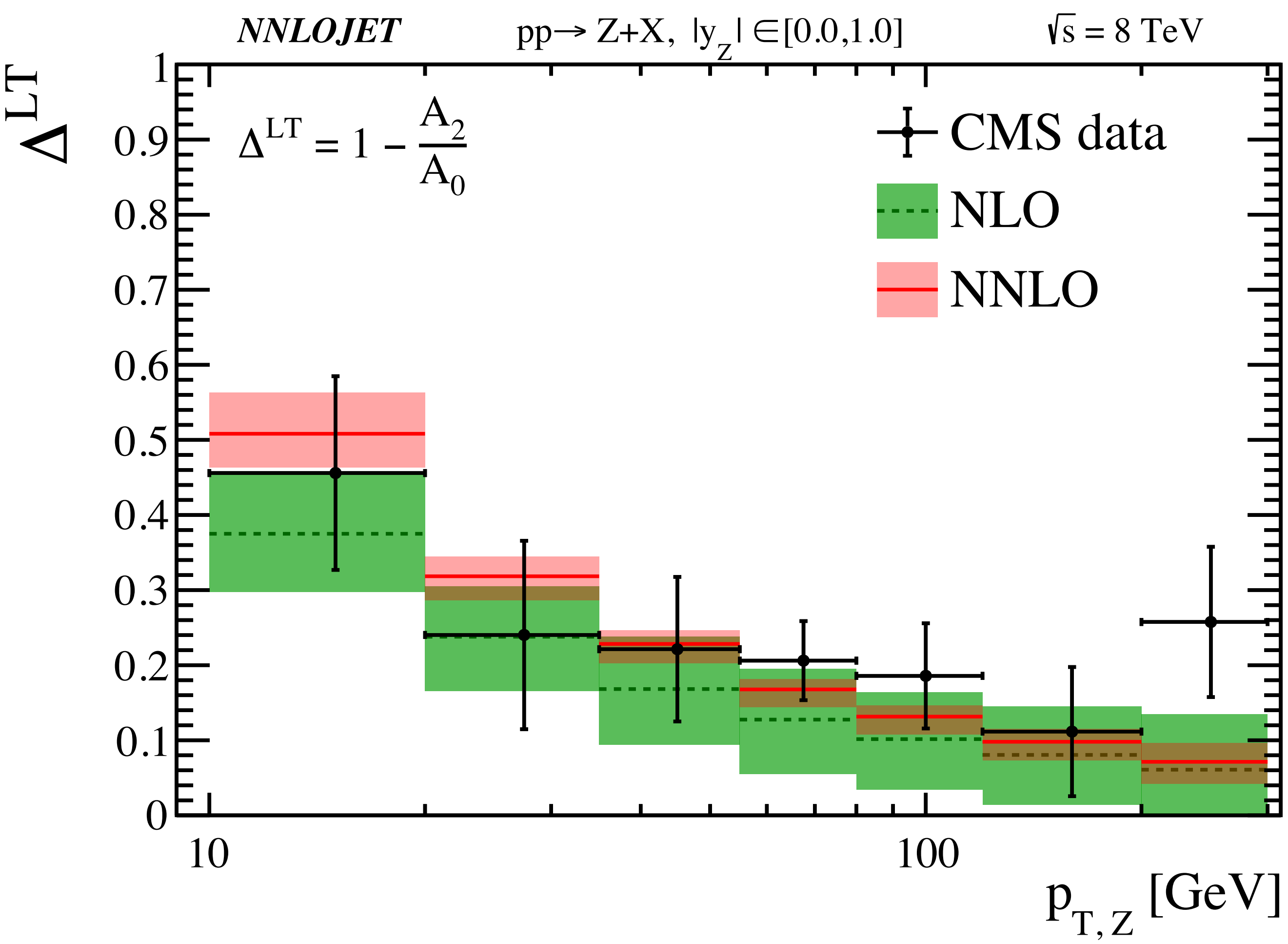
$$\text{NLO (CMS):} \qquad \chi^2/\mathrm{N_{data}} = 24.5/14 = 1.75\,,$$
$$\text{NNLO (CMS):} \qquad \chi^2/\mathrm{N_{data}} = 14.2/14 = 1.01\,.$$

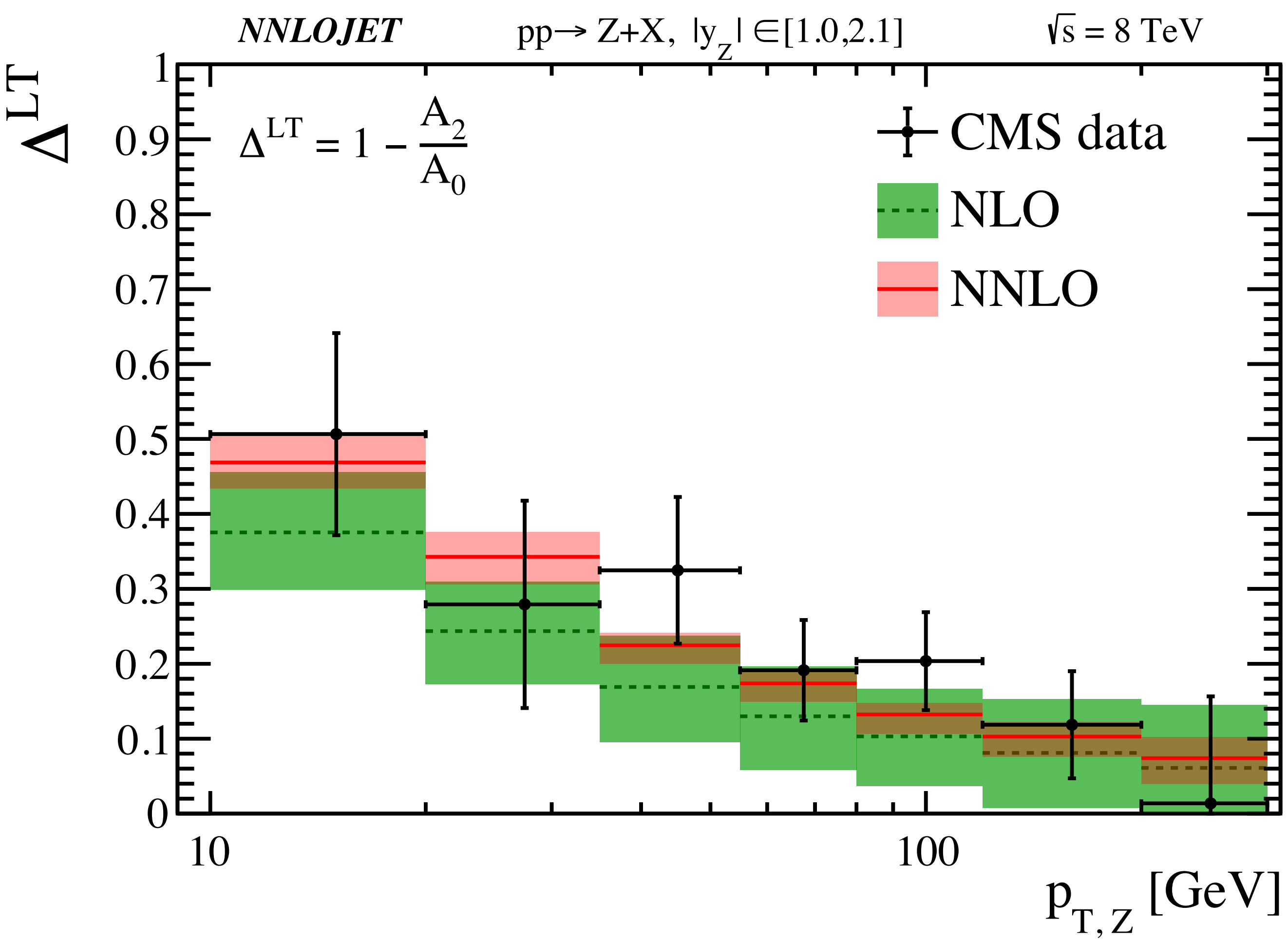
encore: assessing Lam-Tung violation



$$\Delta^{\mathrm{LT}} = 1 - \frac{A_2}{A_0}$$

encore: assessing Lam-Tung violation





$$\Delta^{\mathrm{LT}} = 1 - \frac{A_2}{A_0}$$

conclusions/discussion points

- Have provided NNLO corrections to ang. distr. for $p_{T,Z} > 10\ \mathrm{GeV}$
  * Important impact for A_0, A_1, A_2 distributions
  * Central NLO prediction for A_3, A_4 accurate

- NNLO more accurate (and consistent with available data)

- NNLO corrections largest to A_1, A_2 - not probed in W measurement

- Uncorrelating scales in extraction of Angular coefficients
  -> Introduces sensitivity to normalisation of unpolarised cross-section
  -> Also accounting for this in reweighting of dsigma/dpt/dy?

- Propagation of uncertainties from ‘regularised’ Z boson data?

Back-up slides

Input parameters for Ang.Coeff.

PDFs: PDF4LHC NNLO Hessian 30 member set
Choice of electroweak input parameters: $\{M_Z^{os},\, M_W^{os},\, G_F^{\mu}\}$

In this scheme $s_w^{os,2}$ is a derived parameter:

$$s_w^{os,2} = 1 - \frac{M_W^{os,2}}{M_Z^{os,2}} \approx 0.223$$

Problem for observables proportional to vector coupling (A3,A4)

Cross section for these contributions is $\propto \frac{2}{3} g_V^{up} + \frac{1}{3} g_V^{do}$

$$\approx 0.031C \left[s_w^2 = 0.230\right]$$

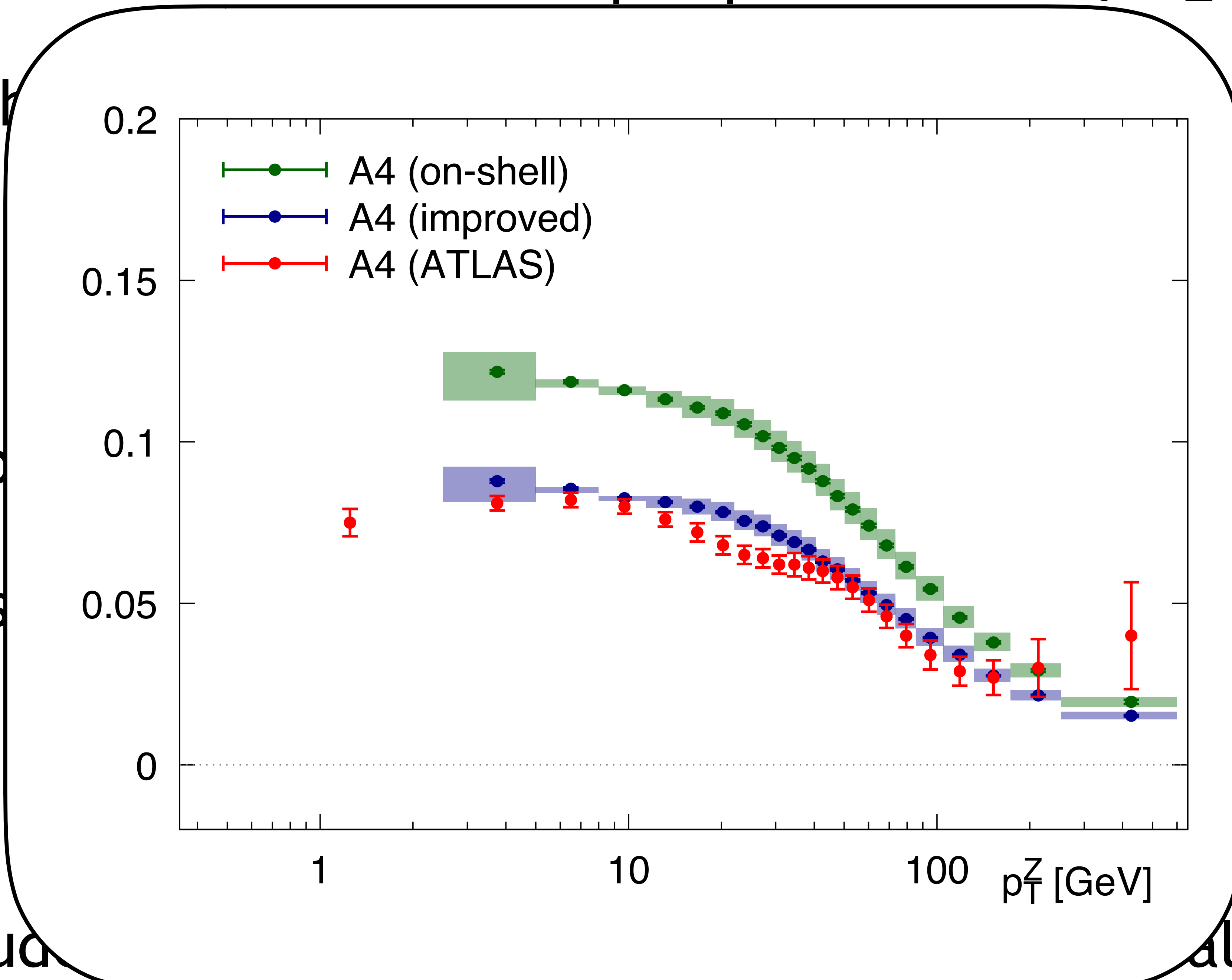
$$\approx 0.043C \left[s_w^2 = 0.223\right]$$

Include the leading one- and two-loop universal corrections relating MW-MZ, allows for matching to EW corrections

Input parameters for Ang.Coeff.

PDFs: PDF4LHC NNLO Hessian 30 member set
Choice of electroweak input parameters: $\{M_Z^{os},\ M_W^{os},\ G_F^{\mu}\}$

In th



Prob ... coupling (A3,A4)

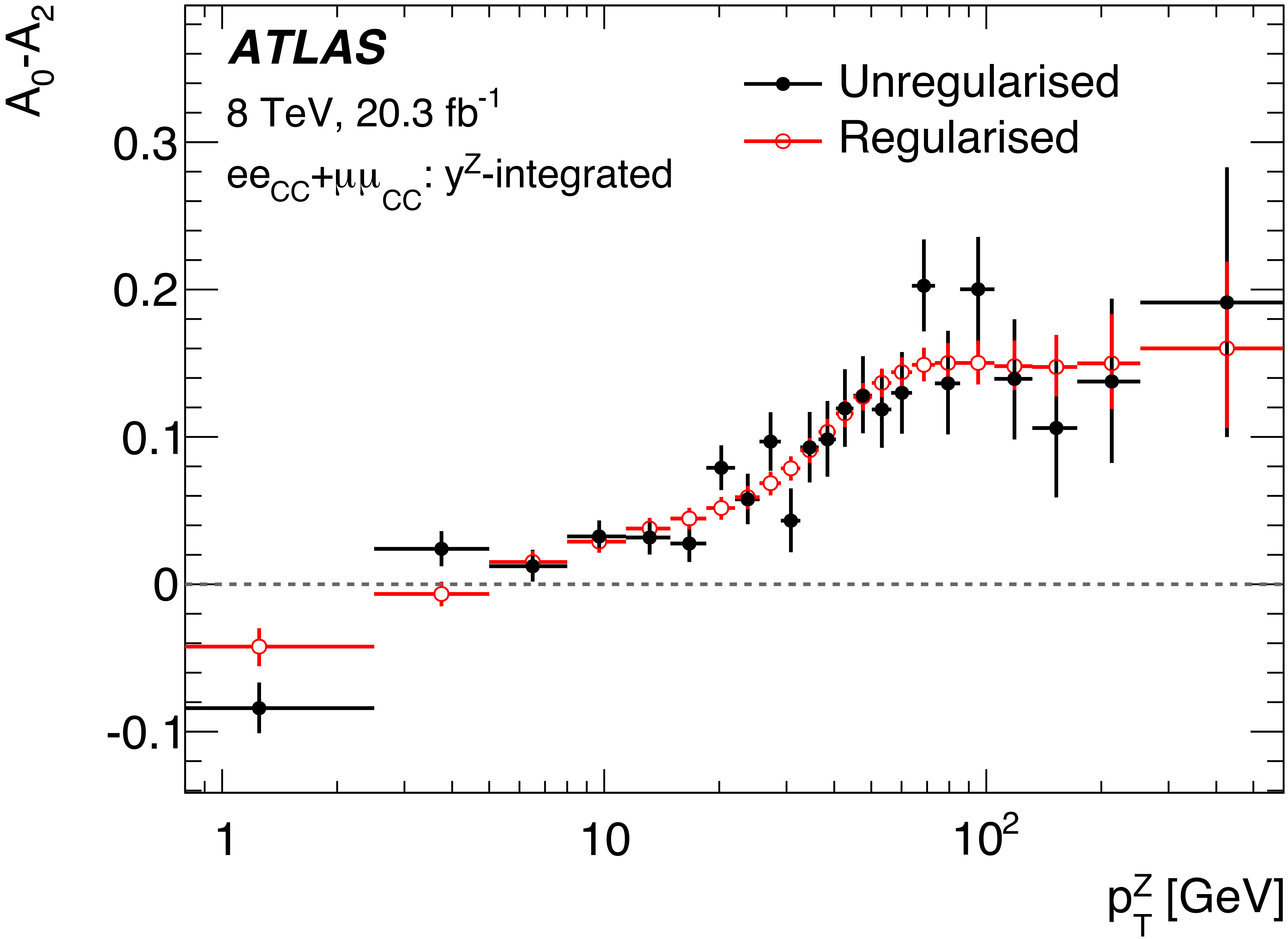
Cros ... $^{up}_{V} + \frac{1}{3} g_V^{do}$

$31C\ [s_w^2 = 0.230]$

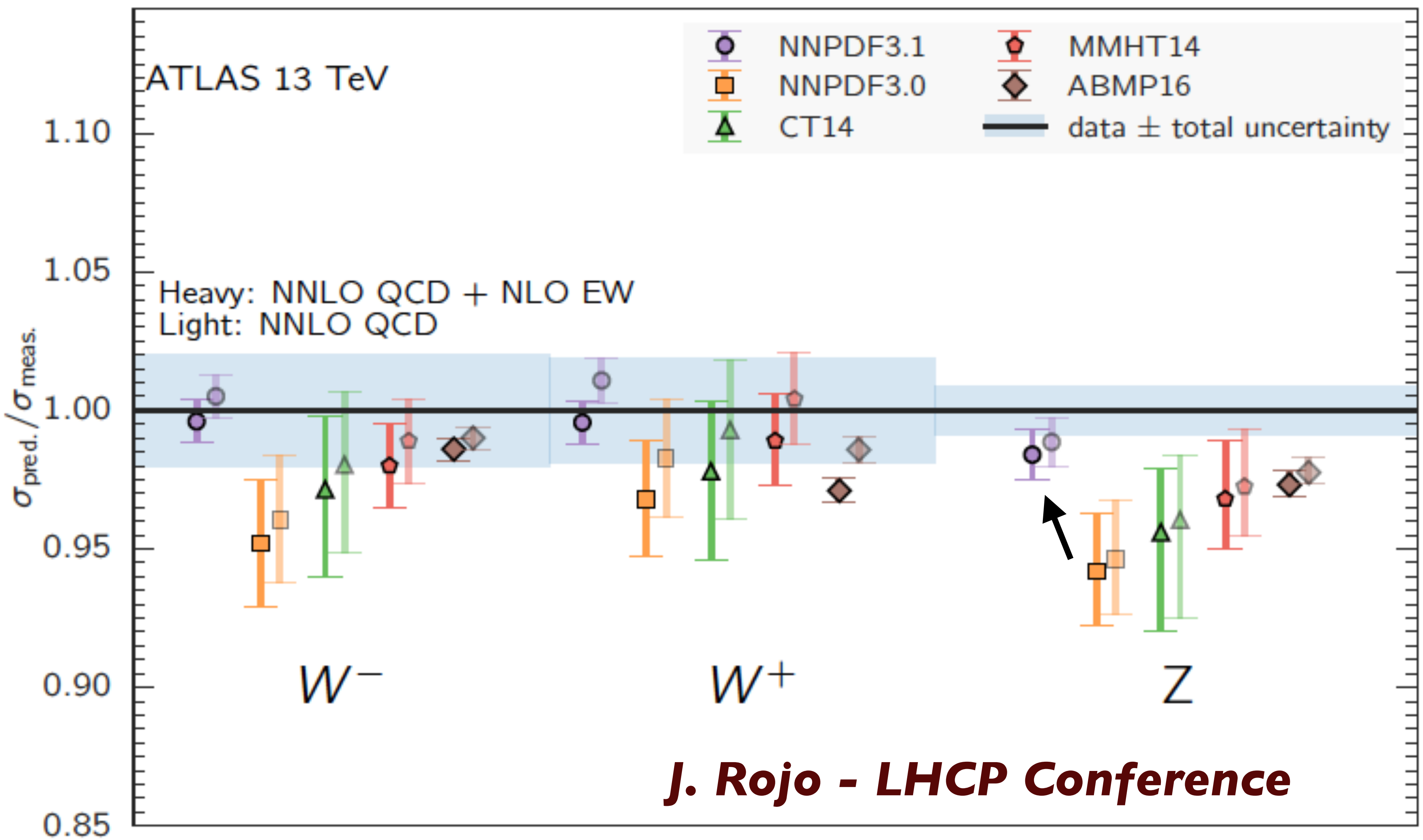
$43C\ [s_w^2 = 0.223]$

Includ ... al corrections
relating MW-MZ, allows for matching to EW corrections

ATLAS, ‘unregularised’ A.C.



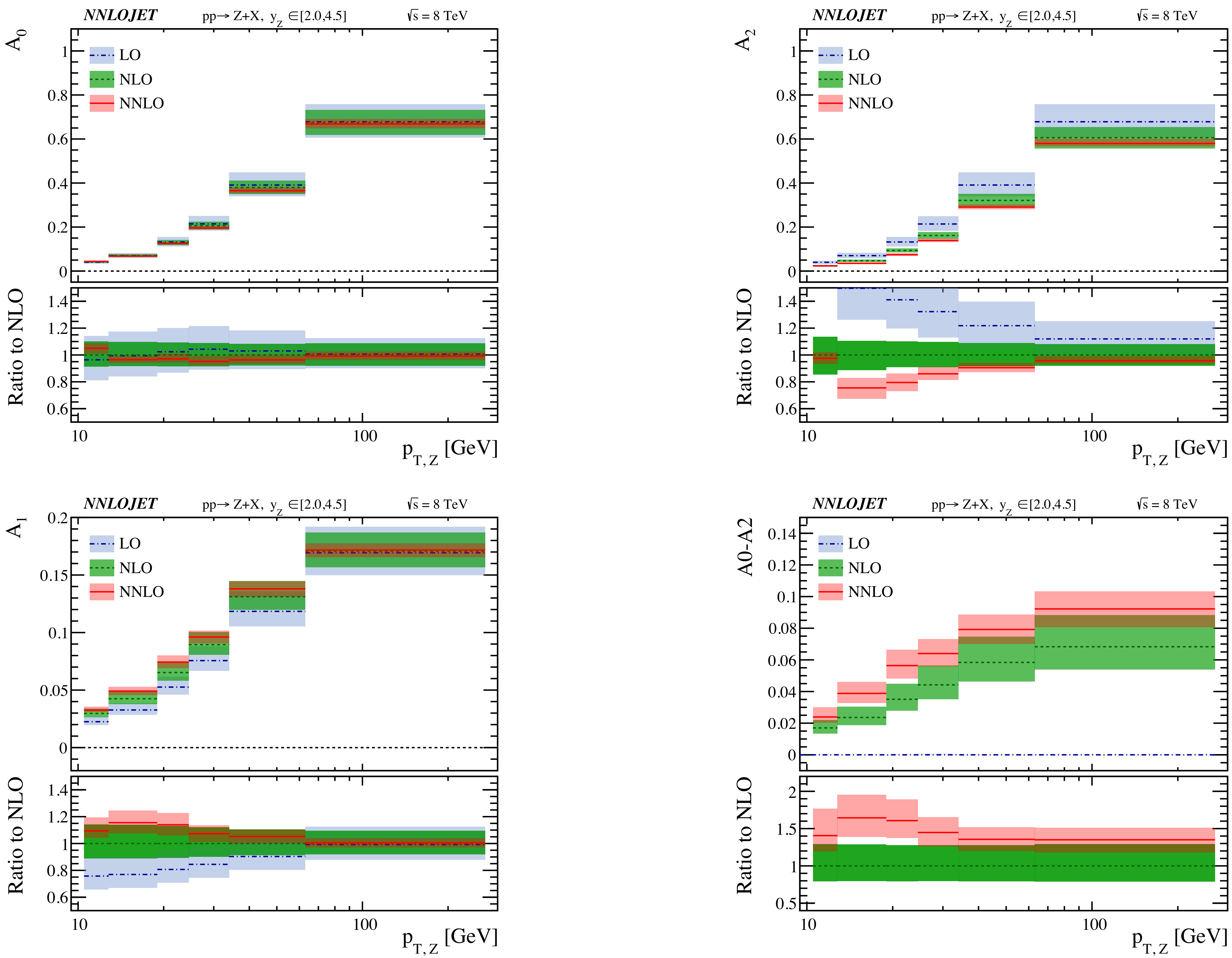
inclusive p_T^Z spectrum



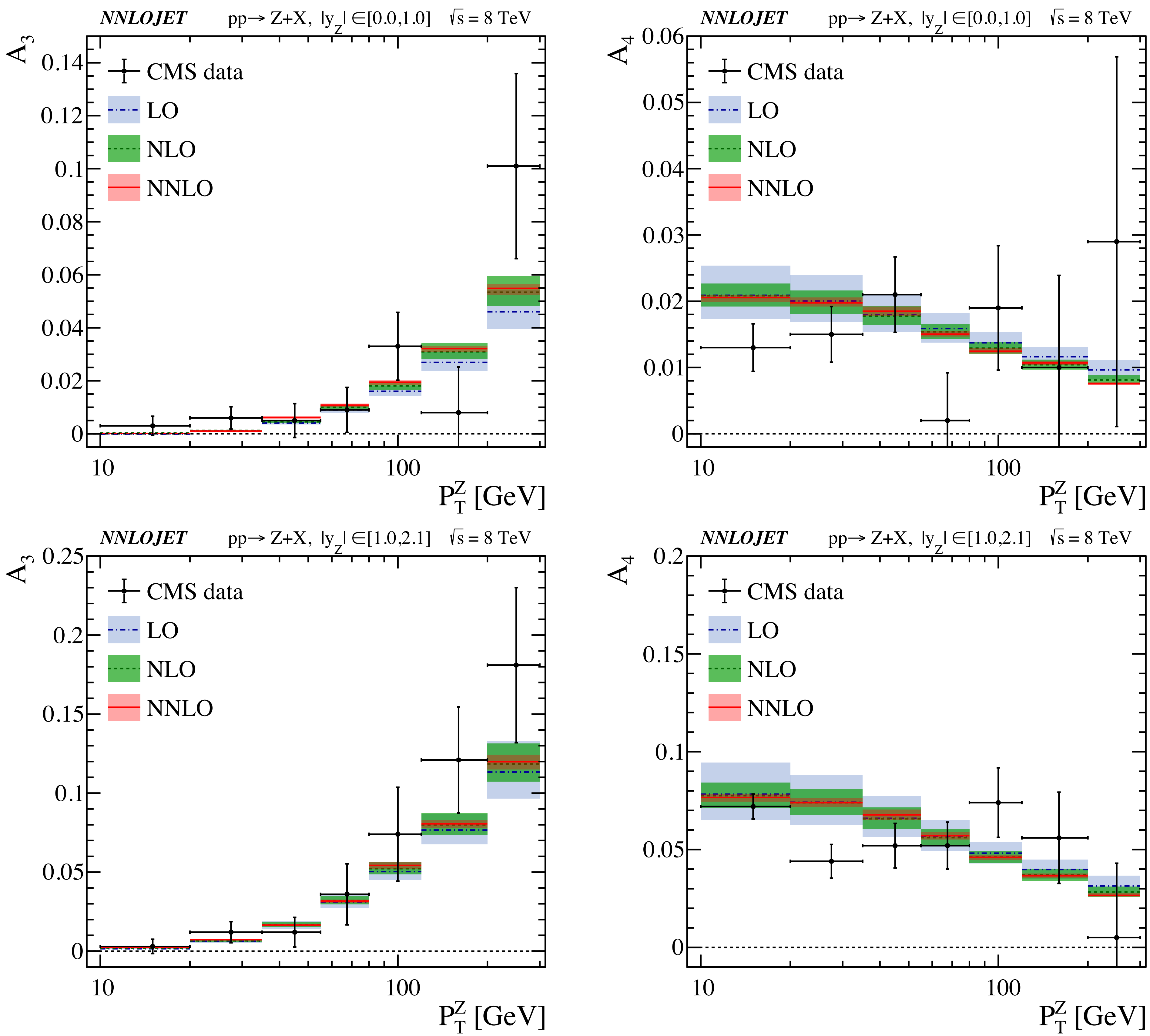
- $m_c^{inp.} = 1.275$ GeV
- $m_c^{inp.} = 1.3$ GeV
- $m_c^{inp.} = 1.4$ GeV

- NNPDF3.0 $\rightarrow$ NNPDF3.1, fit non-perturbative charm
- NNPDF3.0 $\rightarrow$ NNPDF3.1, $m_c^{inp.}$ = 1.275 $\rightarrow$ 1.51 GeV

LHCb prospects



CMS A3, A4



NNLOJET
pp→ Z+X, |y_Z| ∈[0.0,1.0]
√s = 8 TeV
A3
CMS data
LO
NLO
NNLO
P_T^Z [GeV]
A4
pp→ Z+X, |y_Z| ∈[1.0,2.1]