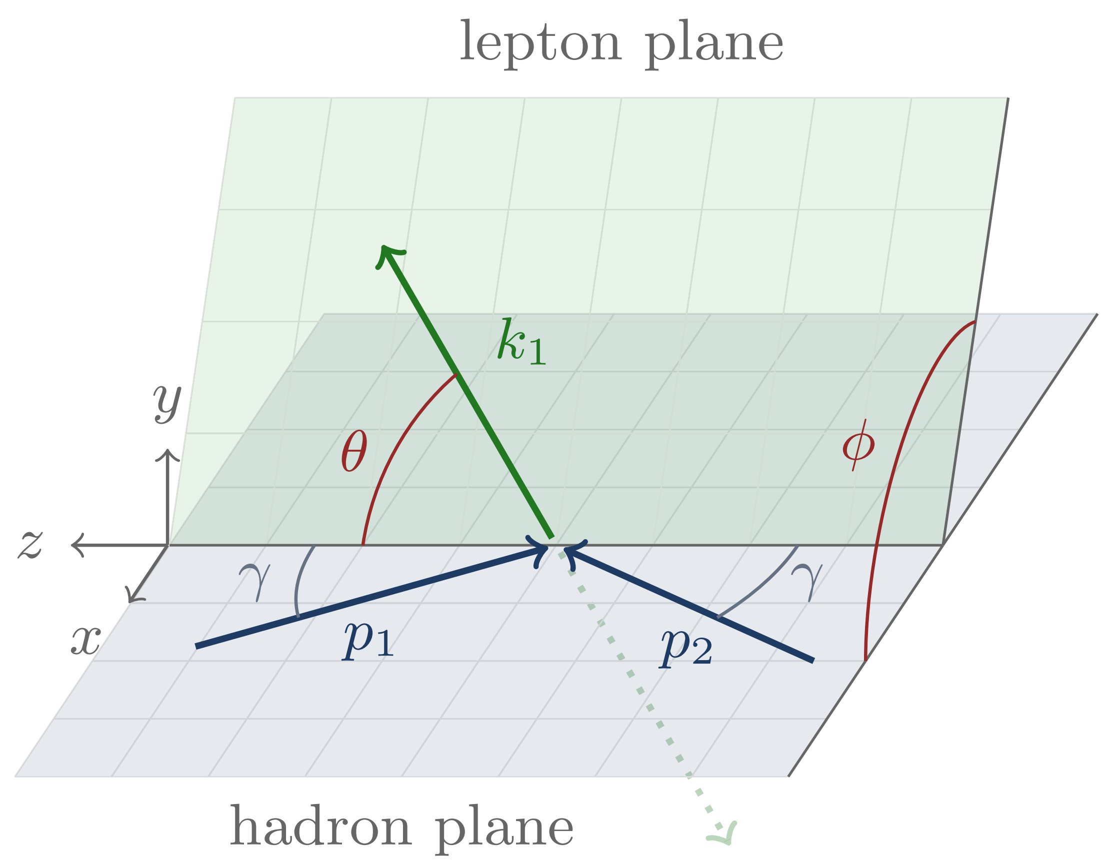
Phenomenology of Z-boson production

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

arXiv:1708.00008

Rhorry Gauld

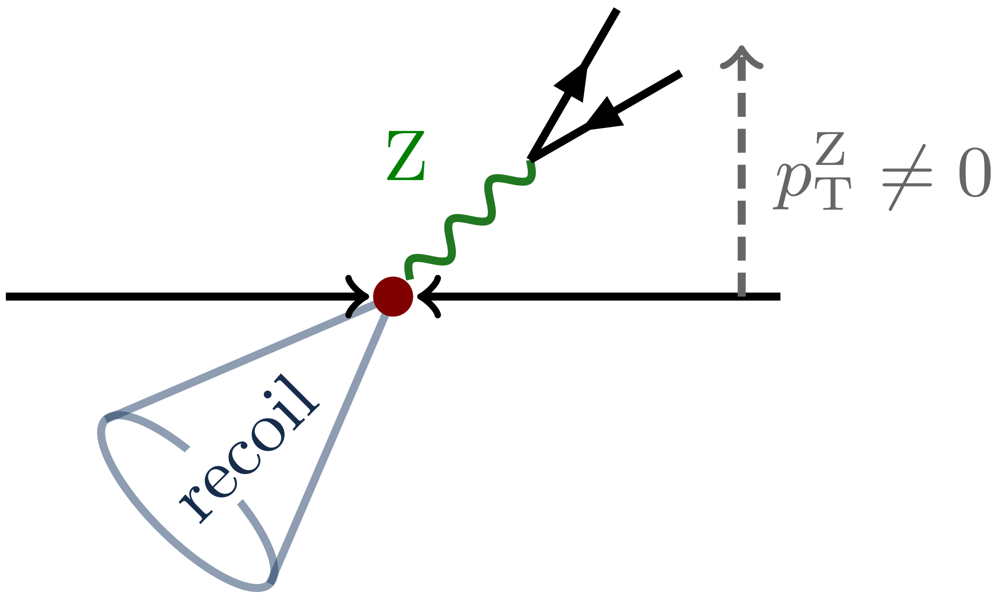
Joint Pheno. Seminar, Milano - 08.03.2018 (@Bicocca)



Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

MC@NNLO

Outline of topics:



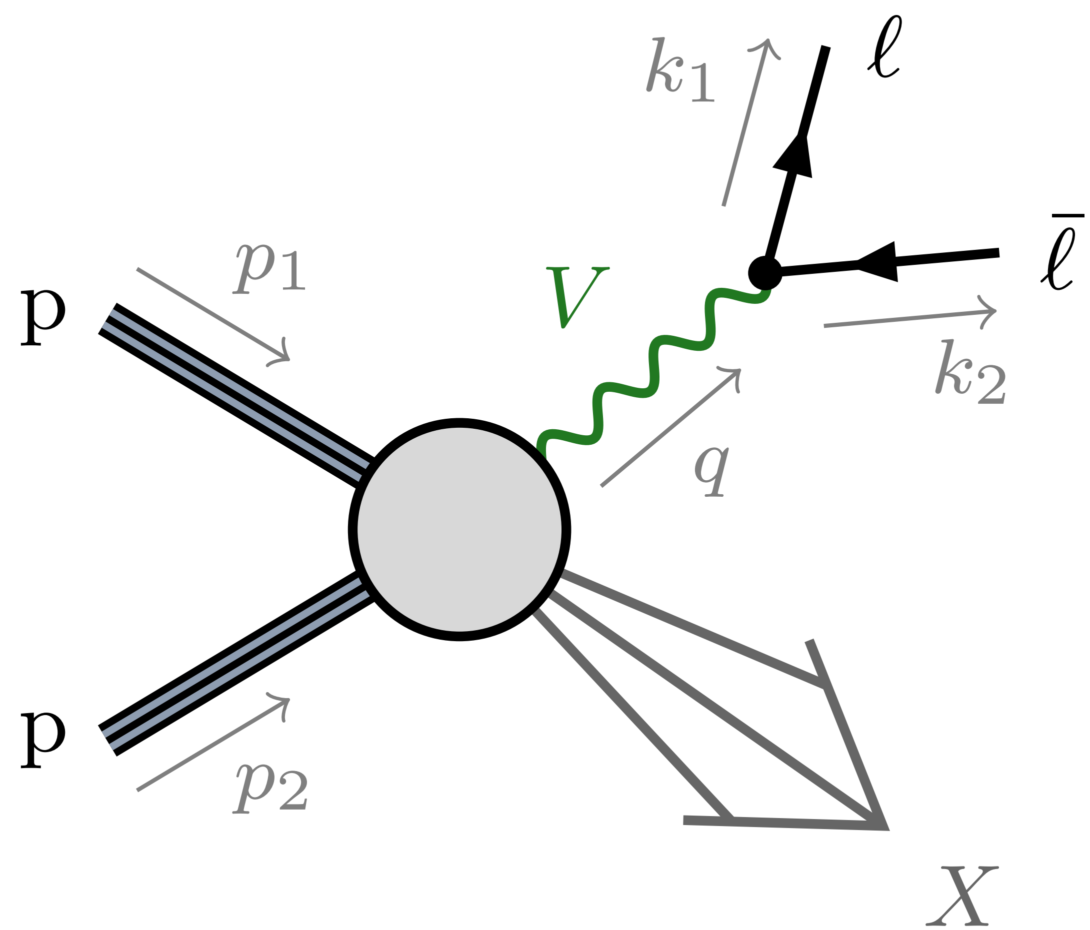
- **Introduction:**
  - physics motivation
  - framework

- **Physics results:**
  - inclusive p_T^Z spectrum
  - angular coefficients in Z-boson production

- **Conclusion:**
  - final remarks and future prospects

(time permitting)

Introduction



Assume standard factorisation theorem for $pp \to \ell\bar{\ell} + X$

Collins, Soper, Sterman - arXiv:0409313

$$\frac{d\sigma}{dQ^2 dy} \sim \sum_{a,b} \int d\xi_a d\xi_b f_{a/A}(\xi_a, \mu^2) f_{b/A}(\xi_b, \mu^2) H_{ab}\left(\frac{x_a}{\xi_a}, \frac{x_a}{\xi_b}, Q; \frac{\mu}{Q}, \alpha_s(\mu)\right)$$

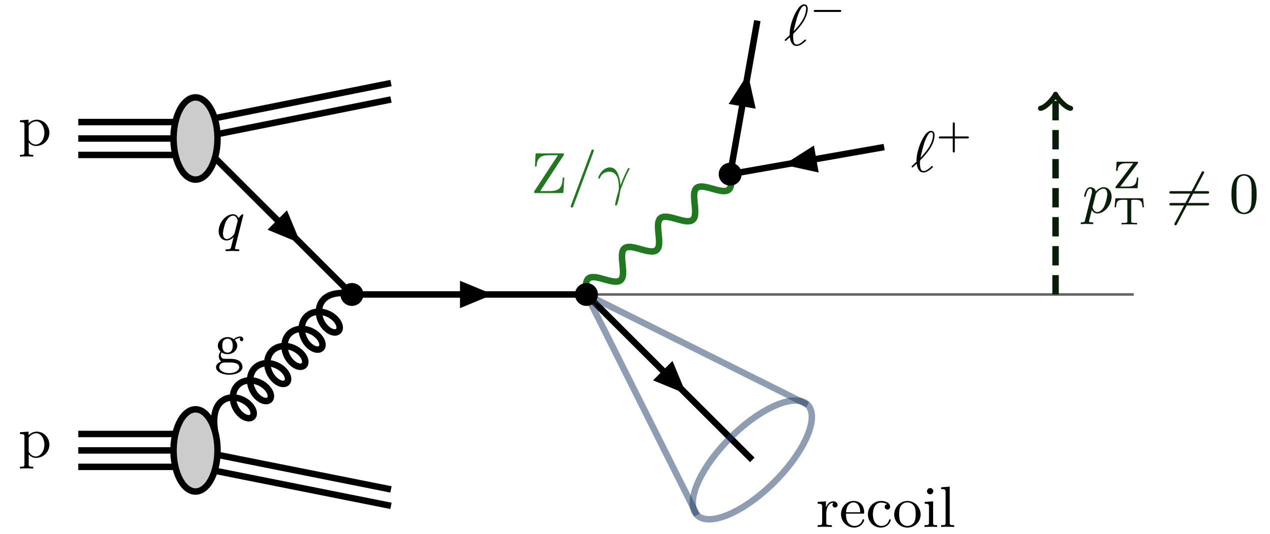
$$Q^2 = q^\mu q_\mu$$

Dilepton mass

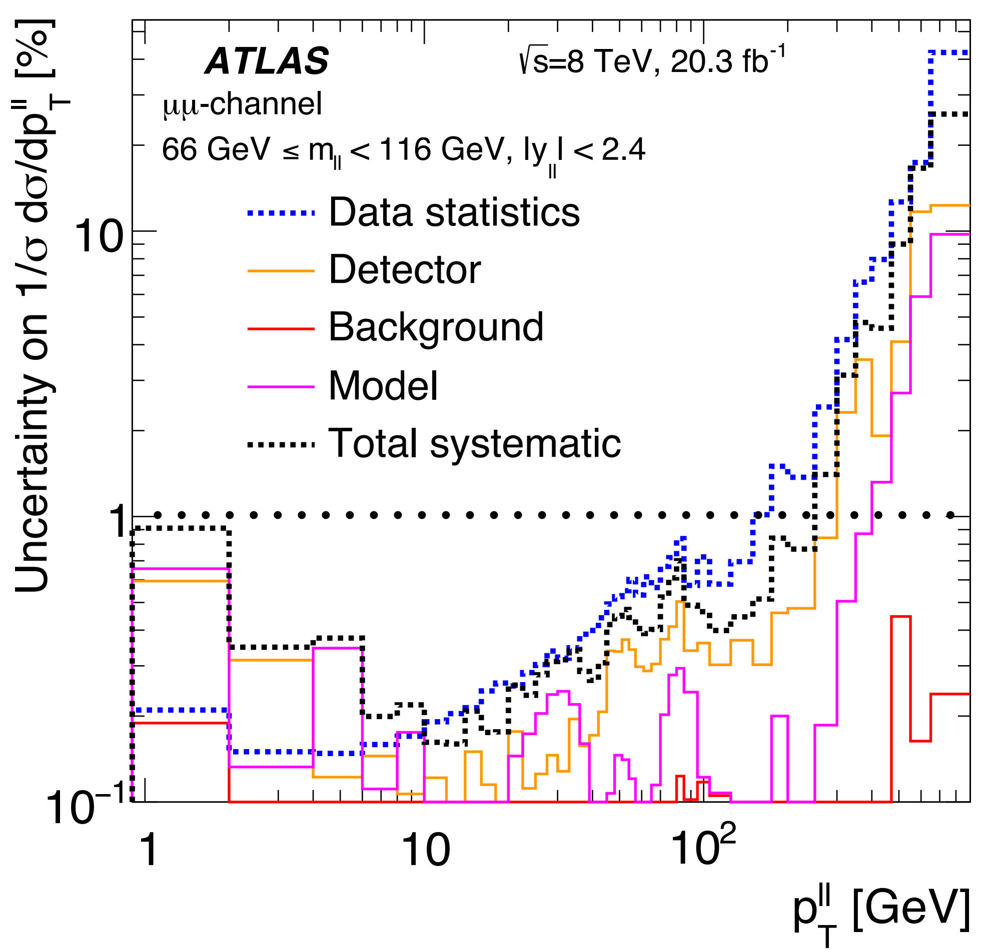
$$y = \frac{1}{2} \ln\left(\frac{q \cdot p_1}{q \cdot p_2}\right)$$

Dilepton rapidity

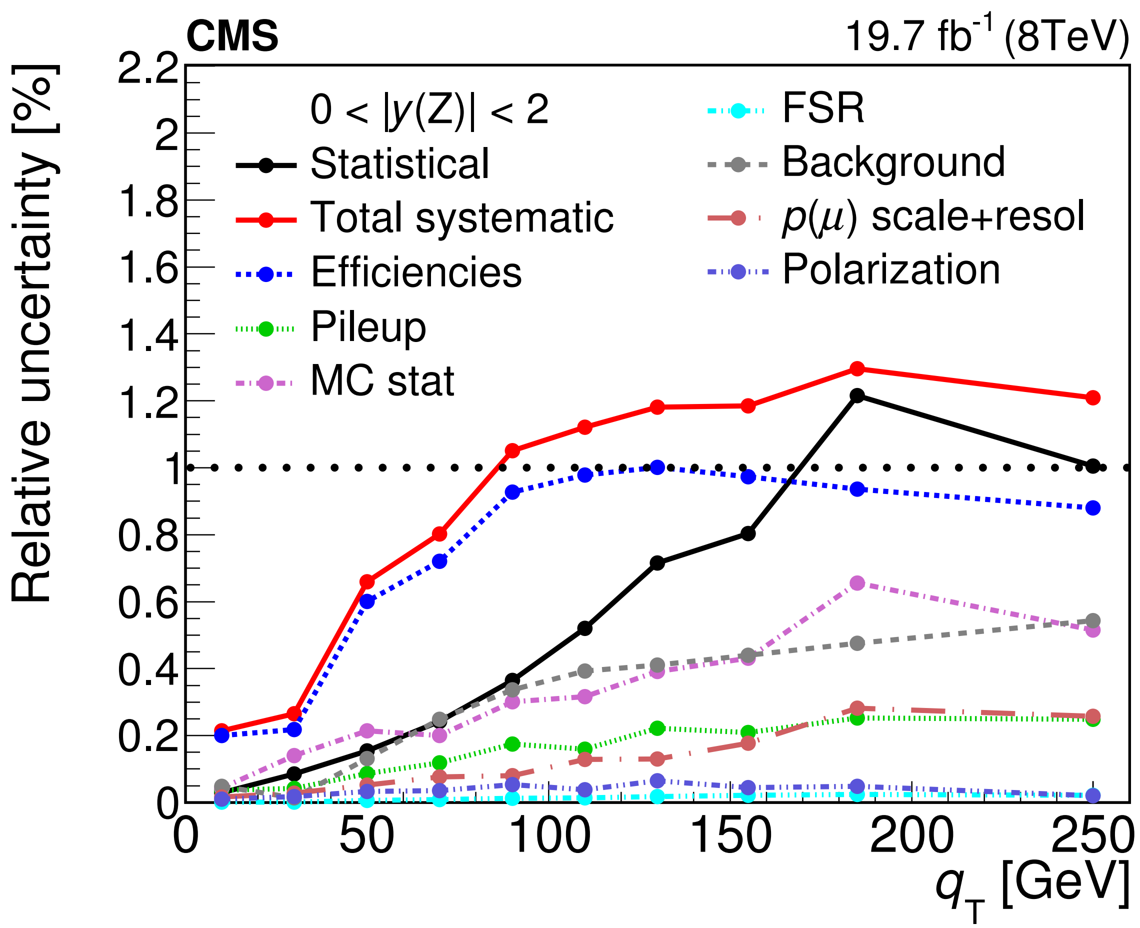
Physics motivation



Experimental status (sub %)

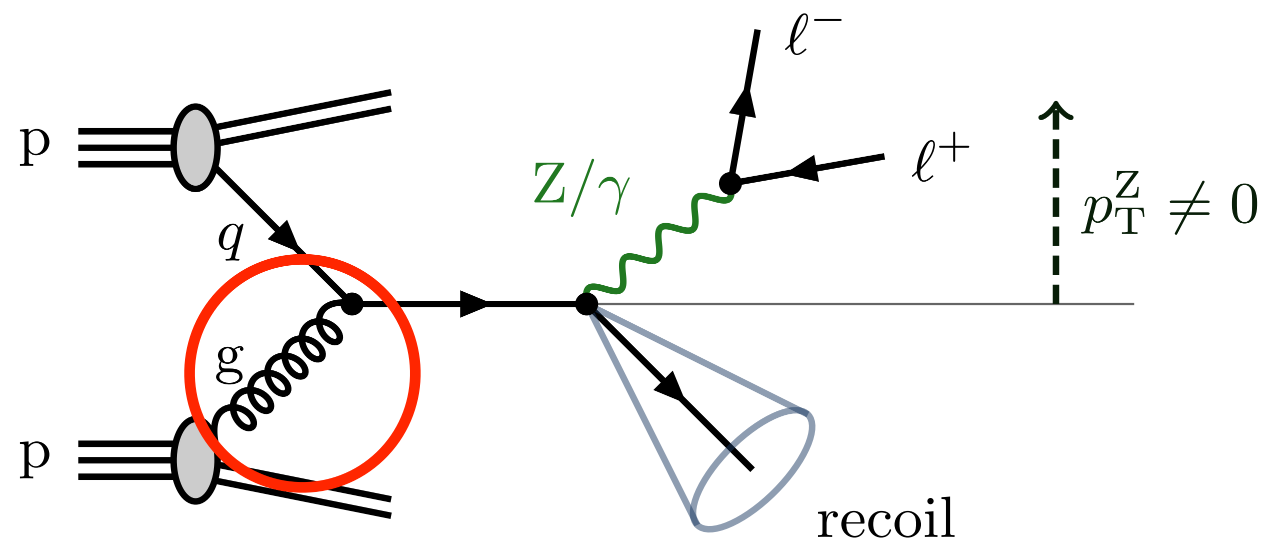


ATLAS, arXiv: 1512.02192



CMS, arXiv: 1504.03511

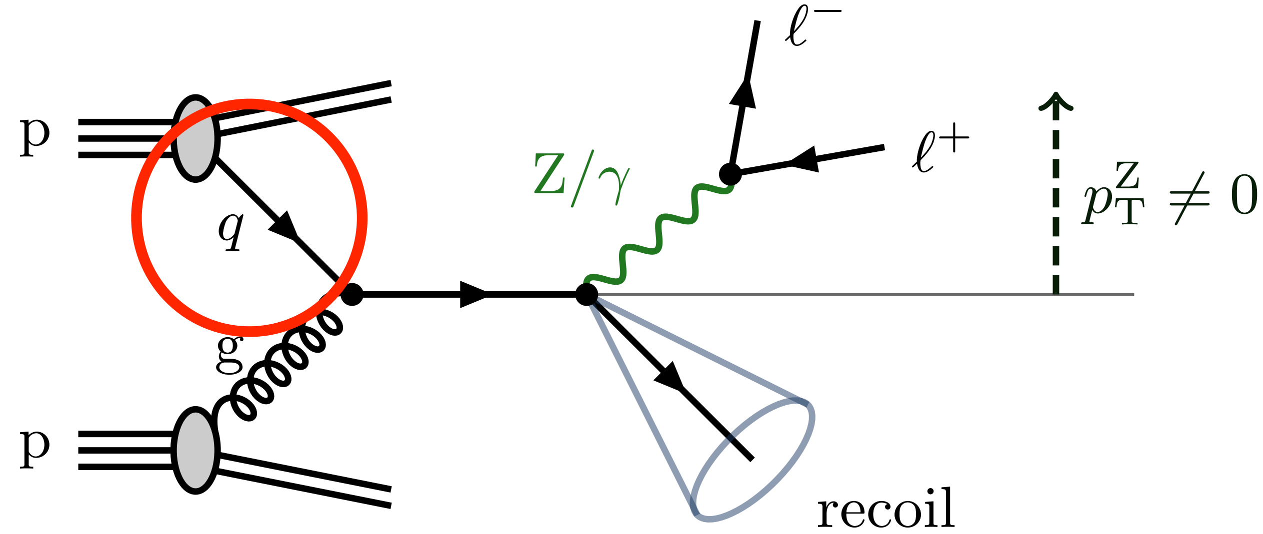
Physics motivation



Primary physics applications:

i) Direct probe of the gluon PDF: Malik, Watt - arXiv:1304.2424

Physics motivation



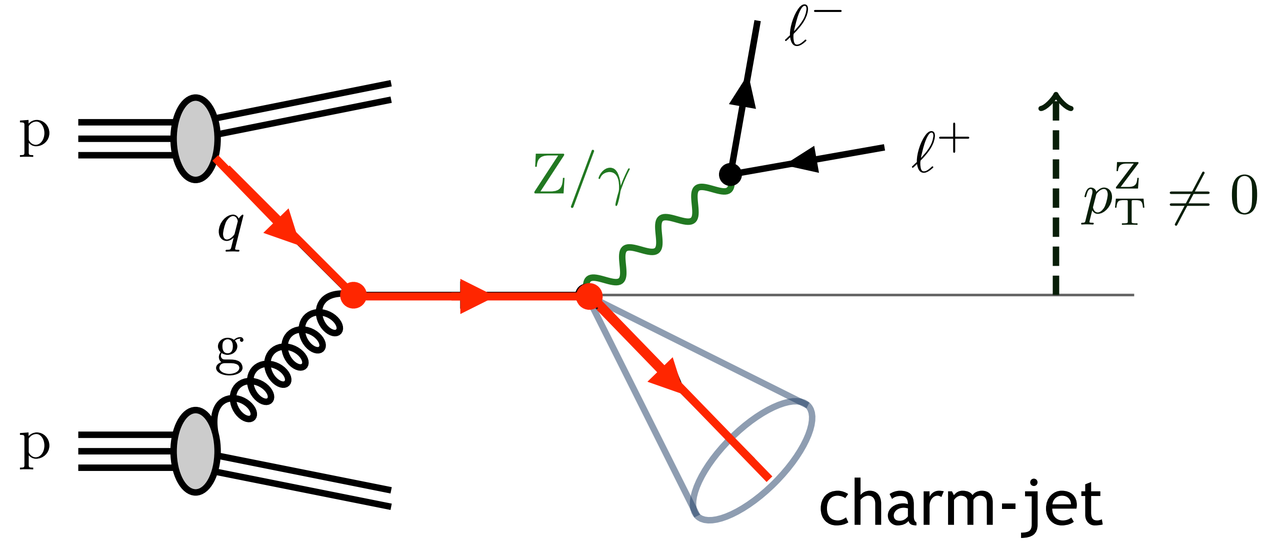
Primary physics applications:

i) Direct probe of the gluon PDF: Malik, Watt - arXiv:1304.2424

ii) Probe large-x d/u quarks in forward region: Farry, RG - arXiv:1505.01399

$$x_{1(2)} = \frac{m_T^Z e^{(-)y_Z} + p_T^j e^{(-)j}}{\sqrt{S}}$$

Physics motivation



Primary physics applications:

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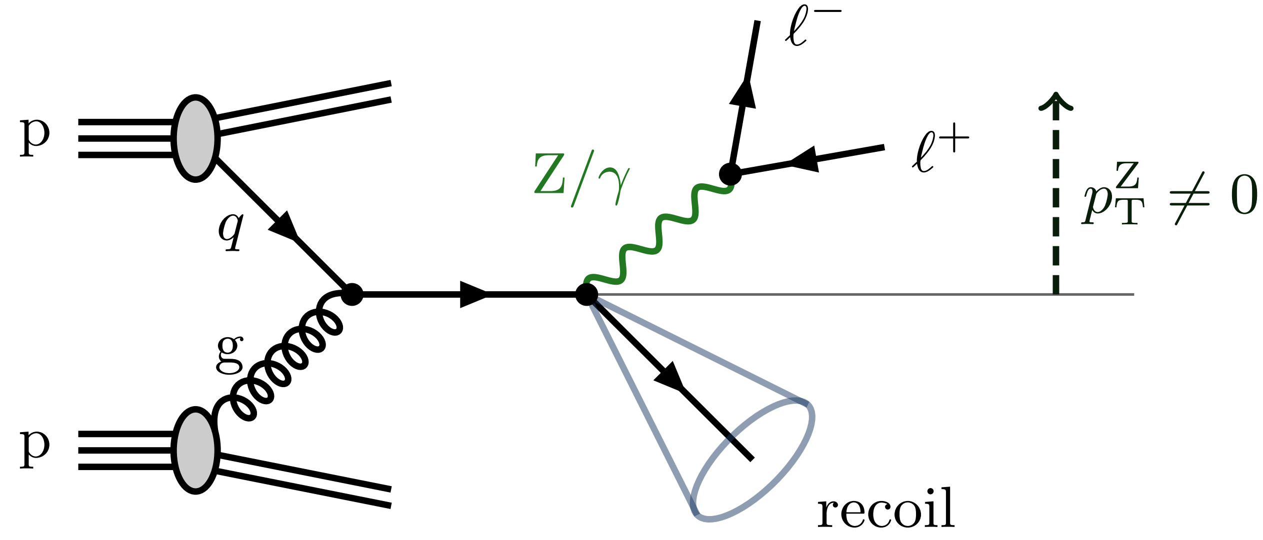
iii) Test for intrinsic charm: Boettcher, Ilten, Williams - arXiv:1512.06666

Physics motivation



Primary physics applications:

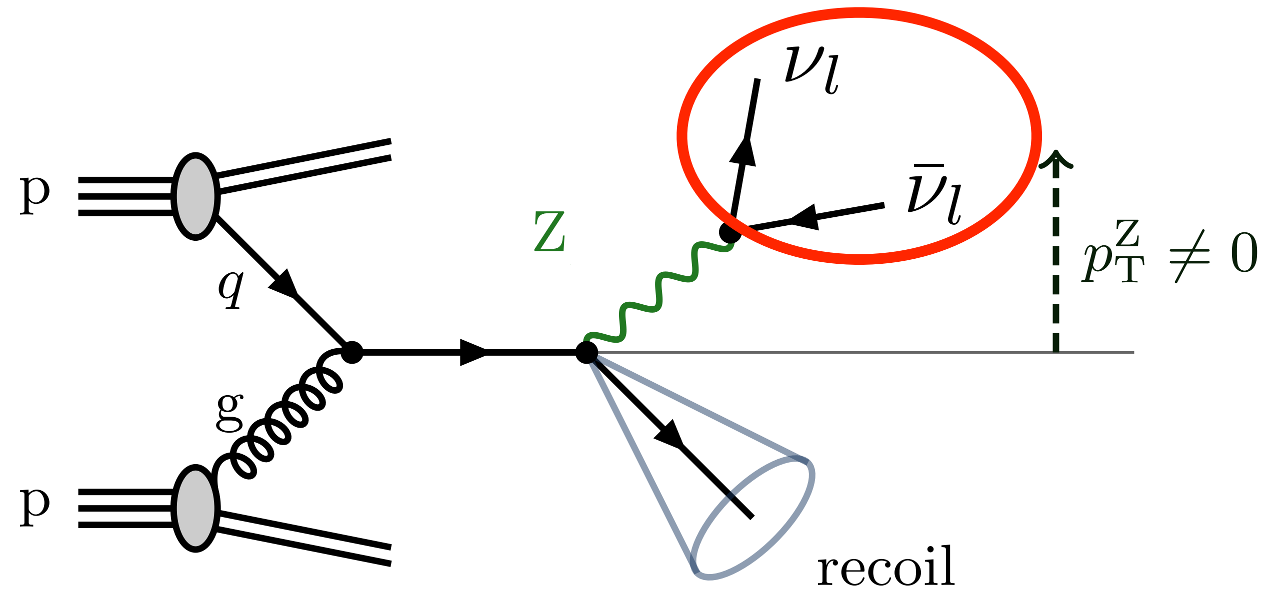
i) Direct probe of the gluon PDF: Malik, Watt - arXiv:1304.2424

ii) Probe large-x d/u quarks in forward region: Farry, RG - arXiv:1505.01399

iii) Test for intrinsic charm: Boettcher, Ilten, Williams - arXiv:1512.06666

iv) see also: Boughezal, Guffanti, Petriello, Ubiali - arXiv:1705.00343
NNPDF Collaboration - arXiv:1706.00428

Physics motivation

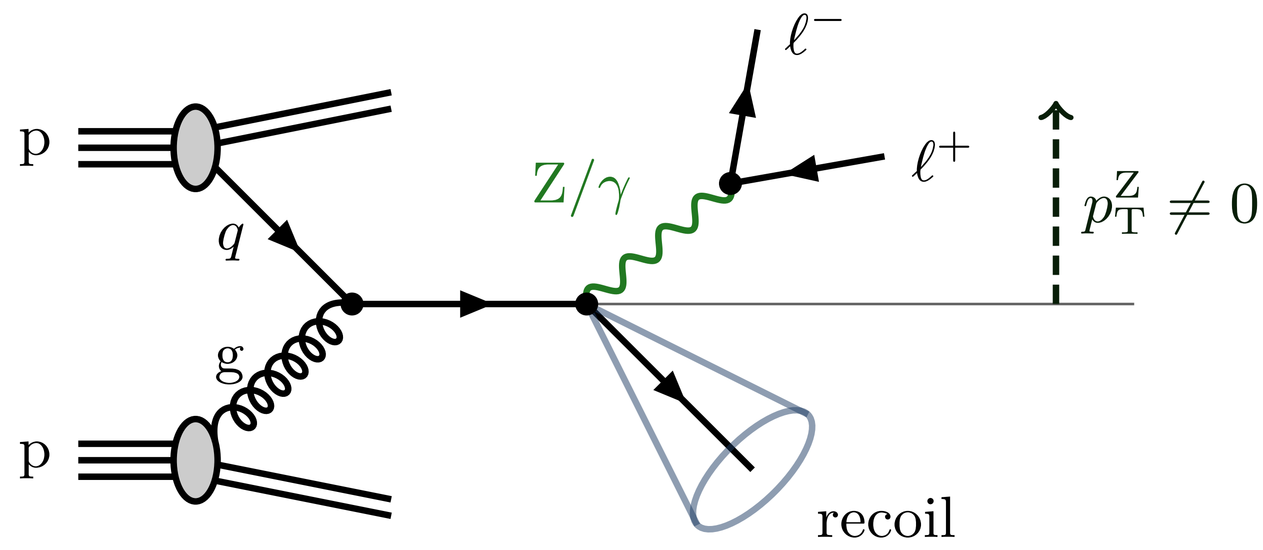


Primary physics applications:

Beyond PDFs, also many other applications

i) Searches for dark matter (jet+MET): Lindert et al. -arXiv:1706.04664

Physics motivation



Primary physics applications:

Beyond PDFs, also many other applications

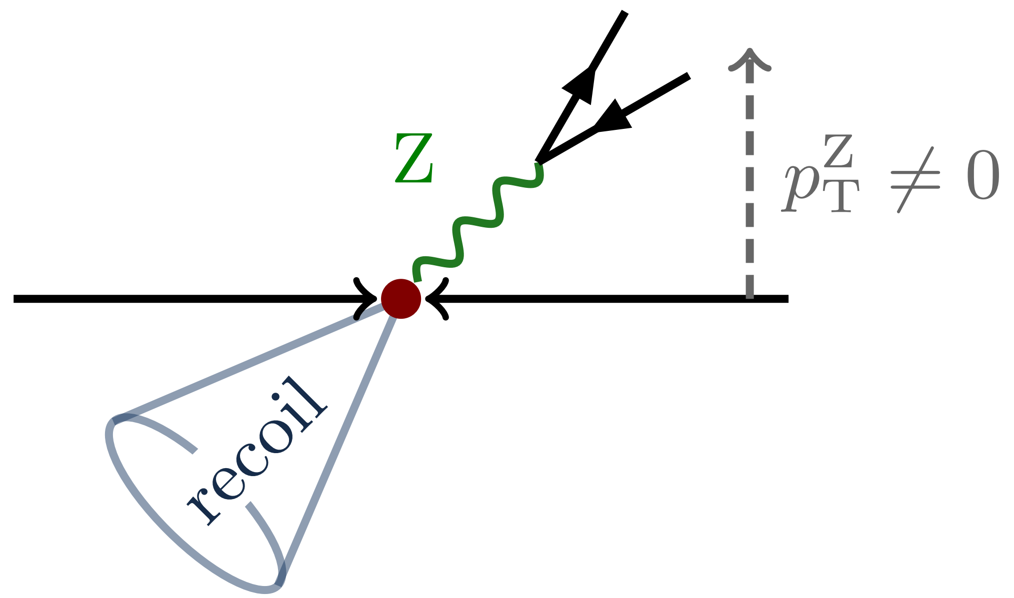
i) Searches for dark matter (jet+MET): Lindert et al. -arXiv:1706.04664

ii) Precision SM measurements (MW extraction): ATLAS -arXiv:1701.07240

Monte Carlo sample reweighting of:

- p_T^Z/p_T^W - spectrum
- Angular coefficients in Z boson production (validation for W boson)

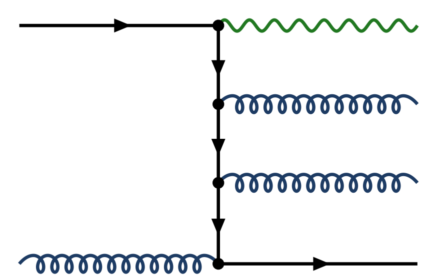
Framework - status of calculations



NLO QCD: Giele, Glover, Kosower - arXiv:hep-ph/9302225
NLO EW: Kuhn, Kulesza, Pozzorini, Schulze - arXiv:hep-ph/0507178
Denner, Dittmaier, Kasprzik, Muck - arXiv:1103.0914
NLO QCD+EW: (+merging) Kallweit, .. et al. - arXiv:1511.08692
NNLO QCD: (antenna) Gehrmann-De Ridder,.. et al. - arXiv:1507.02850
(N-jettiness) Boughezal, .. et al. - arXiv:1512.01291
+Resummation calculations …
+Further phenomenological studies …

Framework - NNLO corrections

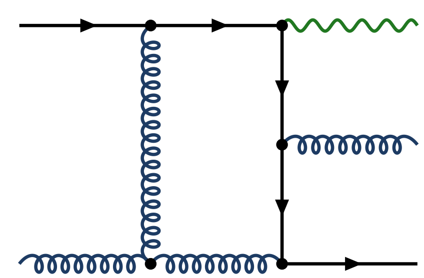
$$\sigma_{\rm NNLO} = \int_{\phi_{n+2}} {\rm d}\sigma^{RR}_{\rm NNLO}$$



Single unresolved

Double unresolved

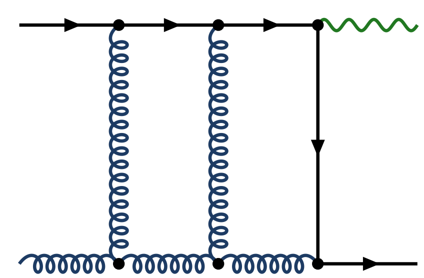
$$+ \int_{\phi_{n+1}} {\rm d}\sigma^{RV}_{\rm NNLO}$$



Single unresolved

$1/\epsilon,\ 1/\epsilon^2$

$$+ \int_{\phi_{n+0}} {\rm d}\sigma^{VV}_{\rm NNLO}$$



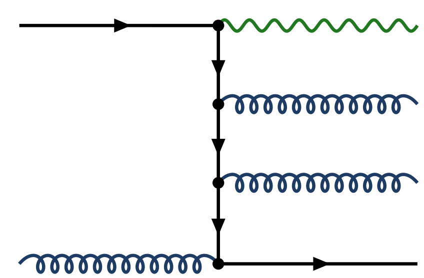
$1/\epsilon,\ 1/\epsilon^2,\ 1/\epsilon^3,\ 1/\epsilon^4$

$$\sum = \text{Finite}$$

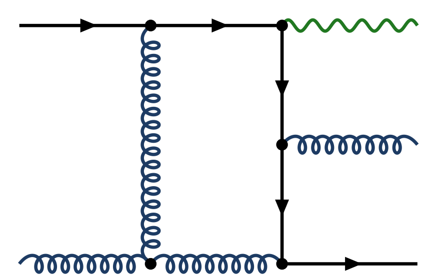
Non-trivial cancellation of IR divergences

Framework - NNLO corrections

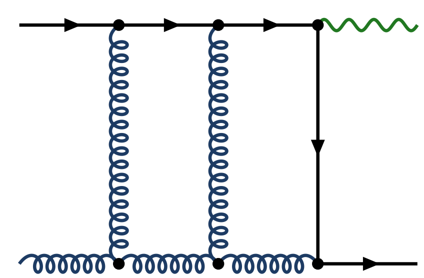
$$\sigma_{\mathrm{NNLO}} = \int_{\phi_{n+2}} \mathrm{d}\sigma^{RR}_{\mathrm{NNLO}}$$



$$+ \int_{\phi_{n+1}} \mathrm{d}\sigma^{RV}_{\mathrm{NNLO}}$$



$$+ \int_{\phi_{n+0}} \mathrm{d}\sigma^{VV}_{\mathrm{NNLO}}$$



Hagiwara, Zeppenfeld `89
Berends, Giele, Kuijf `89
Falck, Graudenz, Kramer `89

Glover, Miller `97
Bern, et al. `97
Campbell, Glover, Miller `97
Ben, Dixon, Kosower `98

Moch, Uwer, Weinzierl `02
Garland et al. `02
Gehrmann, Tancredi `12

$$\sum = \mathrm{Finite}$$

Non-trivial cancellation of IR divergences

Framework - NNLO corrections

$$\sigma_{\mathrm{NNLO}} = \int_{\phi_{n+2}} \mathrm{d}\sigma^{RR}_{\mathrm{NNLO}} + \int_{\phi_{n+1}} \mathrm{d}\sigma^{RV}_{\mathrm{NNLO}} + \int_{\phi_{n+0}} \mathrm{d}\sigma^{VV}_{\mathrm{NNLO}}$$

Antenna subtraction
Gehrmann(-De Ridder), Glover `05

CoLorFul subtraction
Del Duca, Somogyi, Trocsanyi `05

qT subtraction
Catani, Grazzini `05

Sector-Improved residue subtraction
Czakon `10
Boughezal, Melnikov, Petriello `11

N-jettiness subtraction
Gaunt, Stahlhofen, Tackmann, Walsh `15
Boughezal, Melnikov, Petriello `15

Projection-to-Born
Cacciari et al. `15

$$\sum = \mathrm{Finite}$$

Organisation of calculation to allow numerical integration

Framework - subtraction

$$\sigma_{\mathrm{NNLO}} = \int_{\phi_{n+2}} \left(\mathrm{d}\sigma^{RR}_{\mathrm{NNLO}} - \mathrm{d}\sigma^{S}_{\mathrm{NNLO}}\right)$$

$$+ \int_{\phi_{n+1}} \left(\mathrm{d}\sigma^{RV}_{\mathrm{NNLO}} - \mathrm{d}\sigma^{T}_{\mathrm{NNLO}}\right)$$

$$+ \int_{\phi_{n+0}} \left(\mathrm{d}\sigma^{VV}_{\mathrm{NNLO}} - \mathrm{d}\sigma^{U}_{\mathrm{NNLO}}\right)$$

mimic unresolved

explicit pole cancellation

$$\sum = \mathrm{Finite} - 0$$

Each line individually finite, can be integrated in 4-d

Framework - antenna subtraction

- Exploits factorisation properties in IR limits
- Formalism operates on colour-ordered amplitudes

$$|\mathcal{M}^0_{m+1}(..,i,j,k,..)|^2 \xrightarrow{\text{j unresolved}} X^0_3(i,j,k)\,|\mathcal{M}^0_m(..,I,K,..)|^2$$

Partial amplitude

Antenna function

Reduced amplitude $\{p_i, p_j, p_k\} \to \{p_I, p_K\}$

The antenna function captures multiple IR limits, e.g.

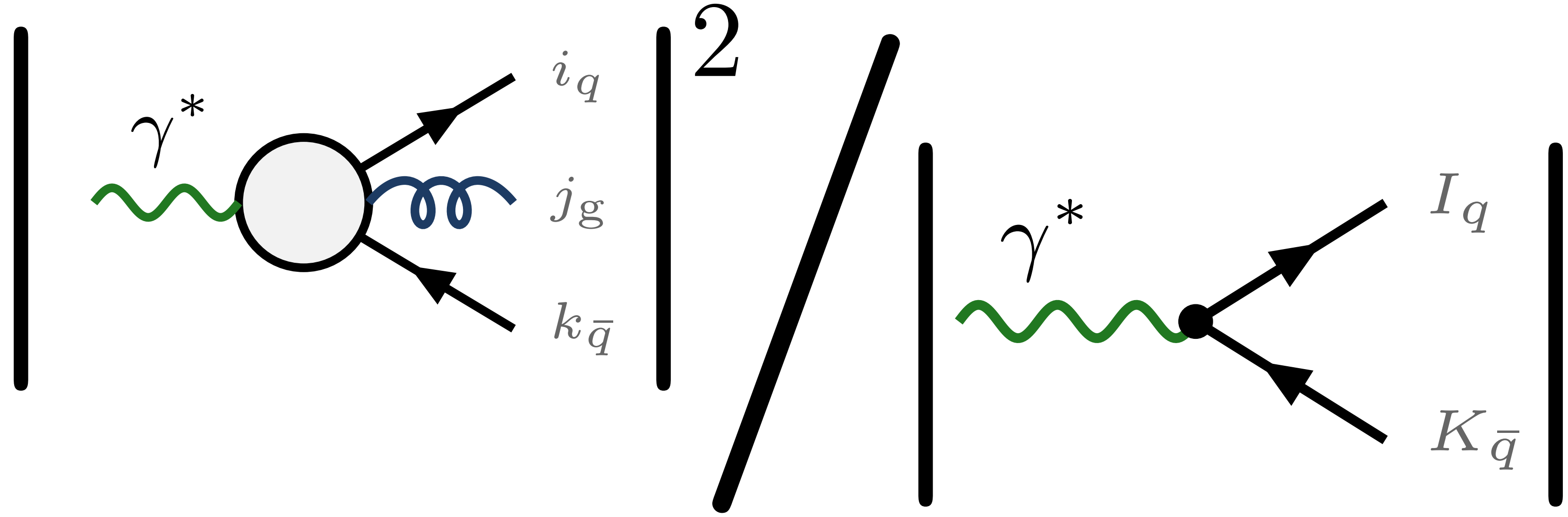
limit	$X^0_3(i,j,k)$	mapping
$p_j \to 0$	$\frac{2s_{ik}}{s_{ij}s_{kj}}$	$p_i \to p_I,\, p_k \to p_K$
$p_j \parallel p_k$	$\frac{1}{s_{kj}}P_{kj}(z)$	$p_i \to p_I,\, (p_k + p_j) \to p_K$
$p_j \parallel p_i$	$\frac{1}{s_{ij}}P_{ij}(z)$	$(p_i + p_j) \to p_I,\, p_k \to p_K$

Framework - antenna subtraction

- Exploits factorisation properties in IR limits
- Formalism operates on colour-ordered amplitudes

Example: tree-level quark, anti-quark antenna

$$X_3^0(i_q, j_g, k_{\bar{q}}) \sim$$



$$p_j \parallel p_i \qquad \frac{1}{s_{ij}} P_{ij}(z) \qquad (p_i + p_j) \to p_I\,,\; p_k \to p_K$$

Framework - antenna subtraction

Real subtraction then numerically integrated

$$d\sigma^S = \frac{1}{S_{m+1}}\, d\phi_{m+1}(..., p_i, p_j, p_k, ...)\, X^0_{ijk}(i,j,k)\, |\mathcal{M}^0_m(.., I, K, ..)|^2 J^{(m)}_m(.., p_I, p_K, ..)$$

m+1 parton phase-space	Antenna function	Reduced amplitude	Jet function

Framework - antenna subtraction

Real subtraction then numerically integrated

$$d\sigma^S = \frac{1}{S_{m+1}}\, d\phi_{m+1}(\ldots, p_i, p_j, p_k, \ldots)\, X^0_{ijk}(i,j,k)\, |\mathcal{M}^0_m(.., I, K, ..)|^2 J^{(m)}_m(.., p_I, p_K, ..)$$

m+1 parton phase-space | Antenna function | Reduced amplitude | Jet function

Note that (phase-space factorisation):

$$d\phi_{m+1}(\ldots, p_i, p_j, p_k, \ldots) = d\phi_m(\ldots, p_I, p_K, \ldots) \cdot d\phi_{X_{ijk}}(p_i, p_j, p_k; p_I + p_K)$$

can be used to re-write subtraction term according to:

$$d\phi_m(\ldots, p_I, p_K, \ldots)\, |\mathcal{M}^0_m(.., I, K, ..)|^2 J^{(m)}_m(.., p_I, p_K, ..) \int d\phi_{X_{ijk}} X^0_{ijk}(i,j,k)$$

analytically integrated in d-dimensions

which allows to construct integrated subtraction term $d\sigma^T$.

```
    _   ___   ____    ____      ____________
   / | / / | / / /   / __ \__  / / ____/_  __/
  /  |/ /  |/ / /   / / / / / / / __/   / /
 / /|  / /|  / /___/ /_/ / /_/ / /___  / /
/_/ |_/_/ |_/_____/\____/\____/_____/ /_/
```

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, Zurich (ETH and UZH), Lisbon (CFTP)]

Common framework for NNLO corrections

- parton-level Monte Carlo generator
- basis: Antenna subtraction formalism
  Gehrmann(-De Ridder), Glover - arXiv:0505111
- implementation strongly follows:
  Currie, Glover, Wells - arXiv:1301.4693
- In progress: APPLfast-NNLO interface
  PDF fitting with full NNLO calculations

Processes:

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

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

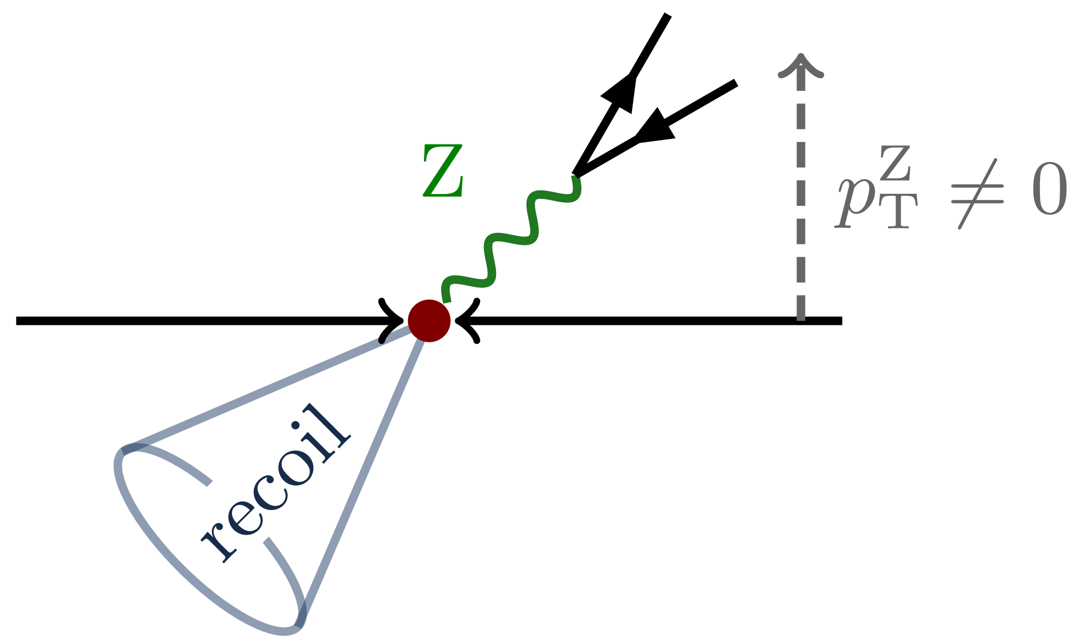
$pp \to \text{dijets}$

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

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

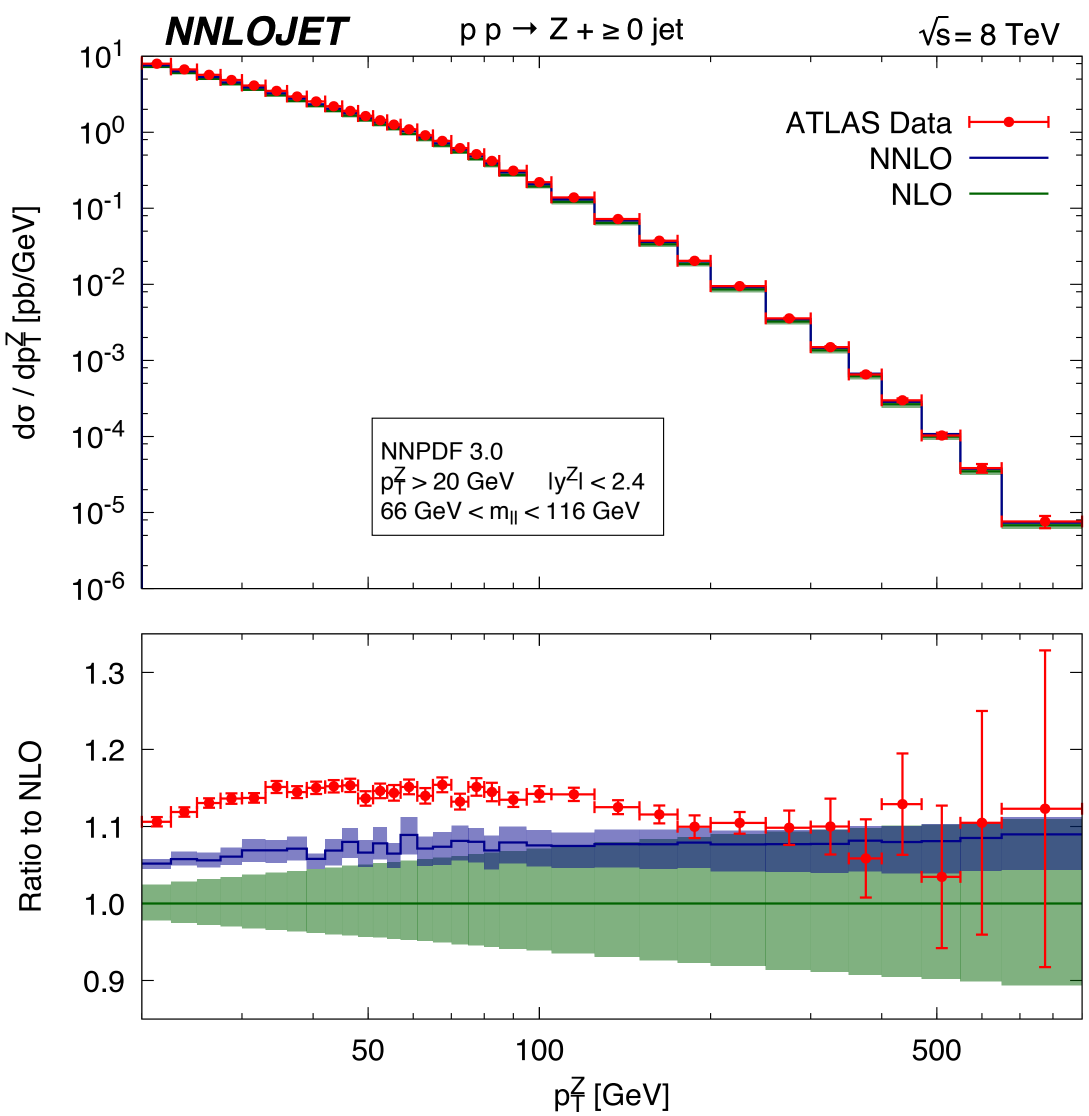
$\ldots$

Previous results: inclusive p_T^Z spectrum

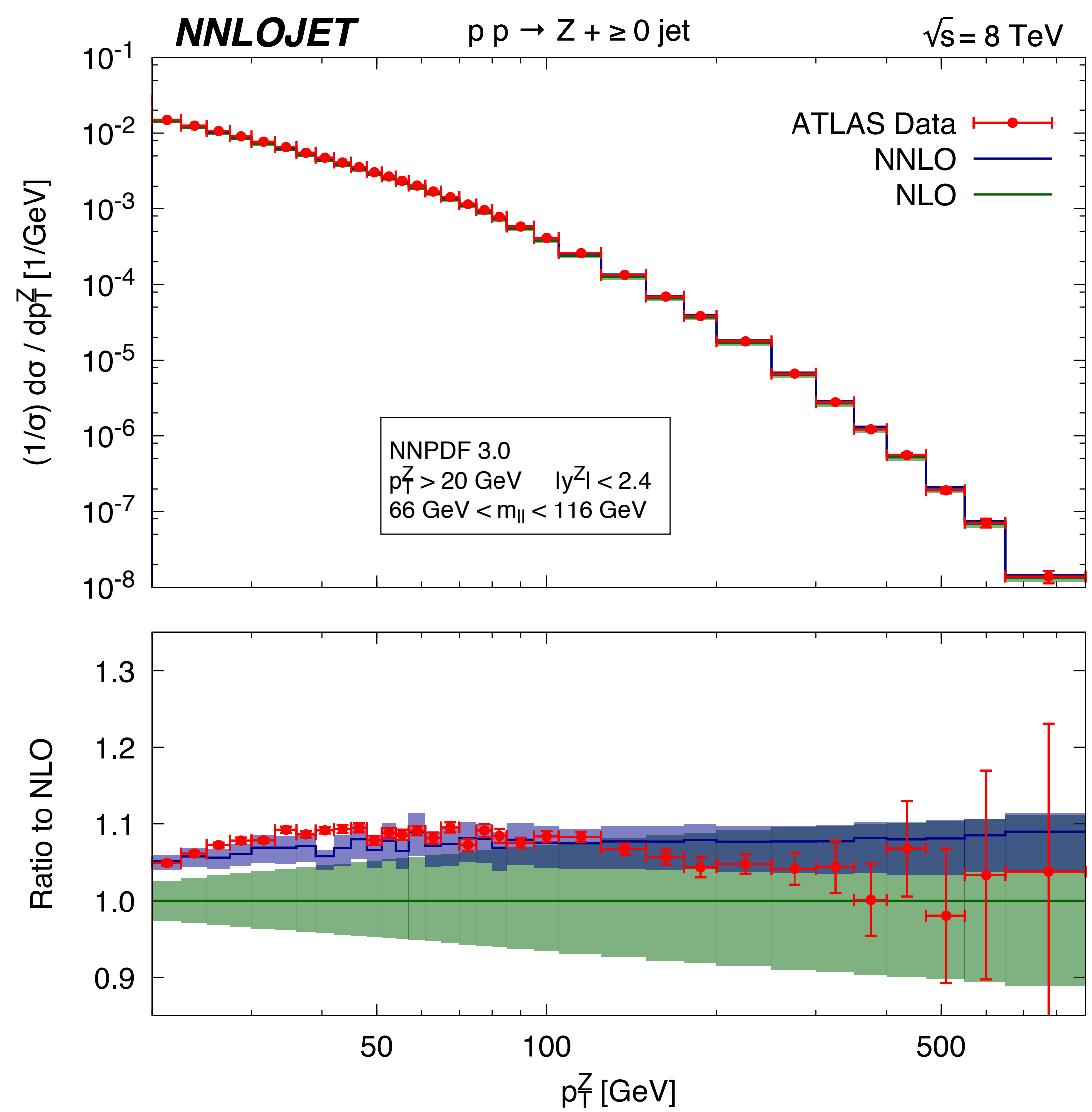


Gehrmann-De Ridder, Gehrmann, Glover, Huss, Morgan - arXiv:1605.04295
JHEP 07(2016)133

Inclusive p_T^Z spectrum



Absolute cross-section



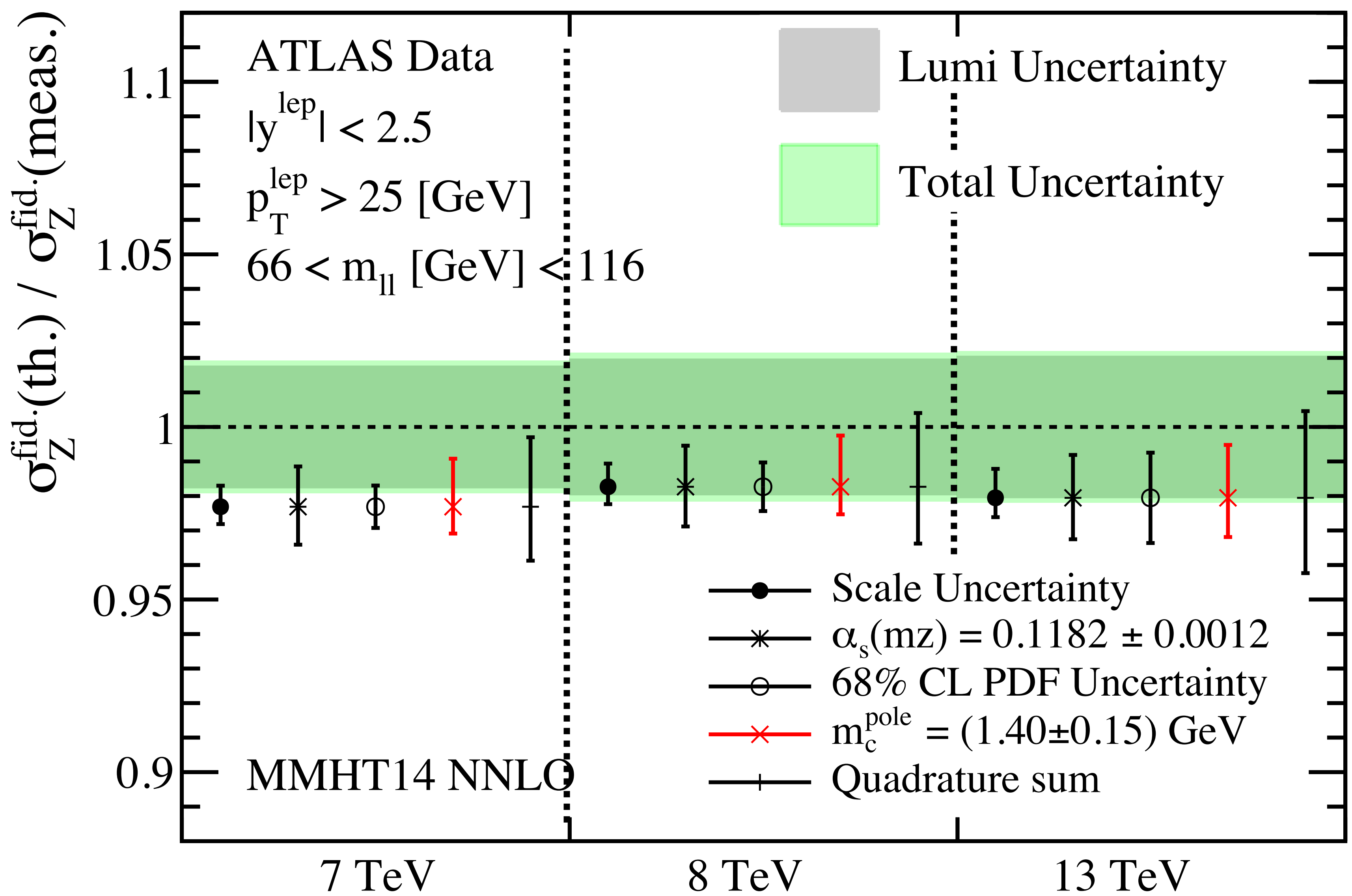
Normalised cross-section

Scale variation: $\mu_0 = E_T^Z\,, \quad 1/2 < \mu_F/\mu_R < 2$

Input PDFs: $\mathrm{NNPDF3.0\ NNLO}\ \alpha_s(m_Z) = 0.118,\ \mathrm{mem.}\ 0$

EW scheme: $\alpha - G_F$ scheme

Fiducial Z cross-section uncertainties



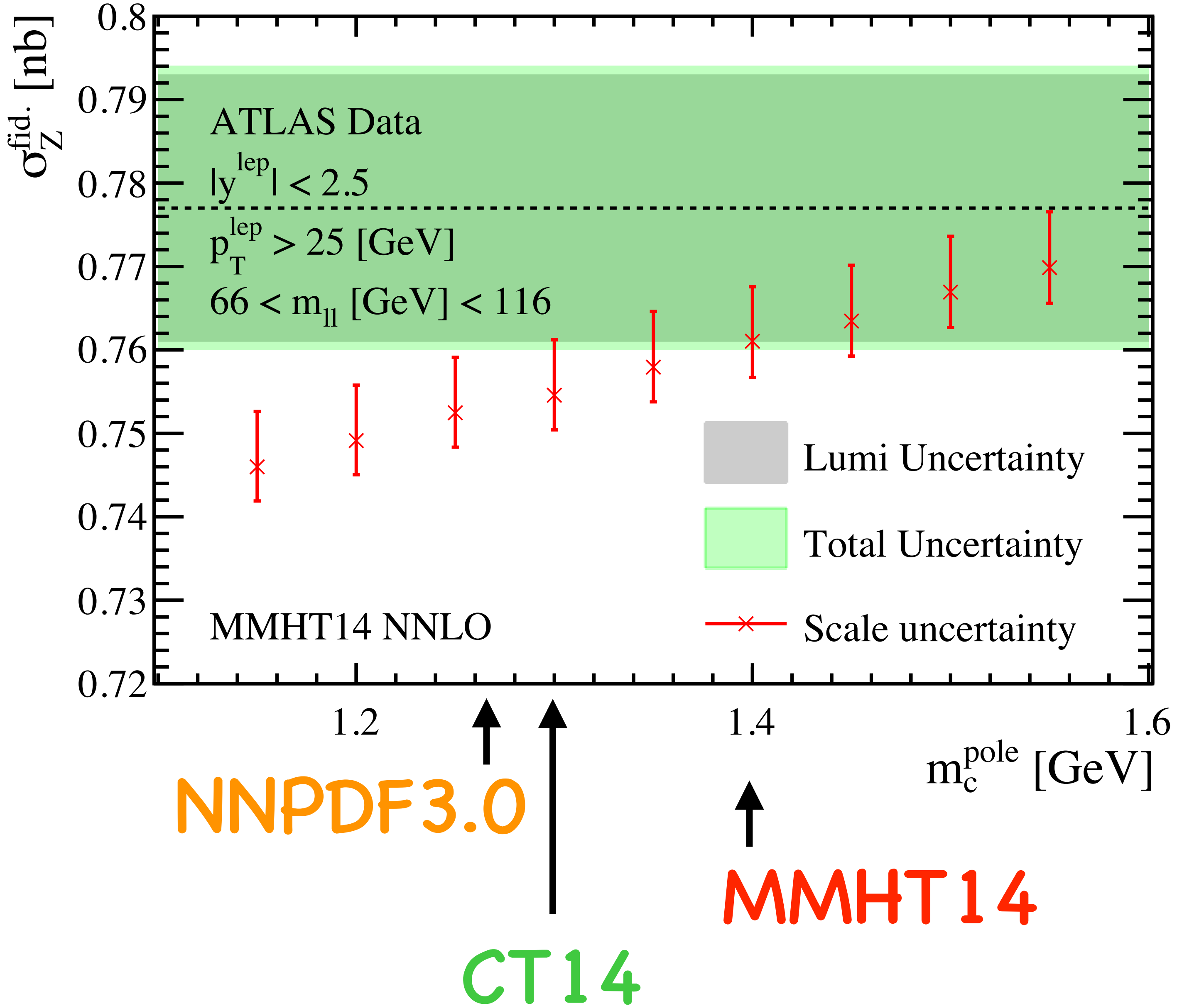
$M_Z^T\,, \quad 1/2 < \mu_F/\mu_R < 2$

$\alpha_s(m_Z) = 0.1182 \pm 0.0012$

$\delta\mathrm{PDF} = 1\sigma\,\mathrm{CL}$

$m_c^{\mathrm{pole}} = 1.4 \pm 0.15\mathrm{GeV}$

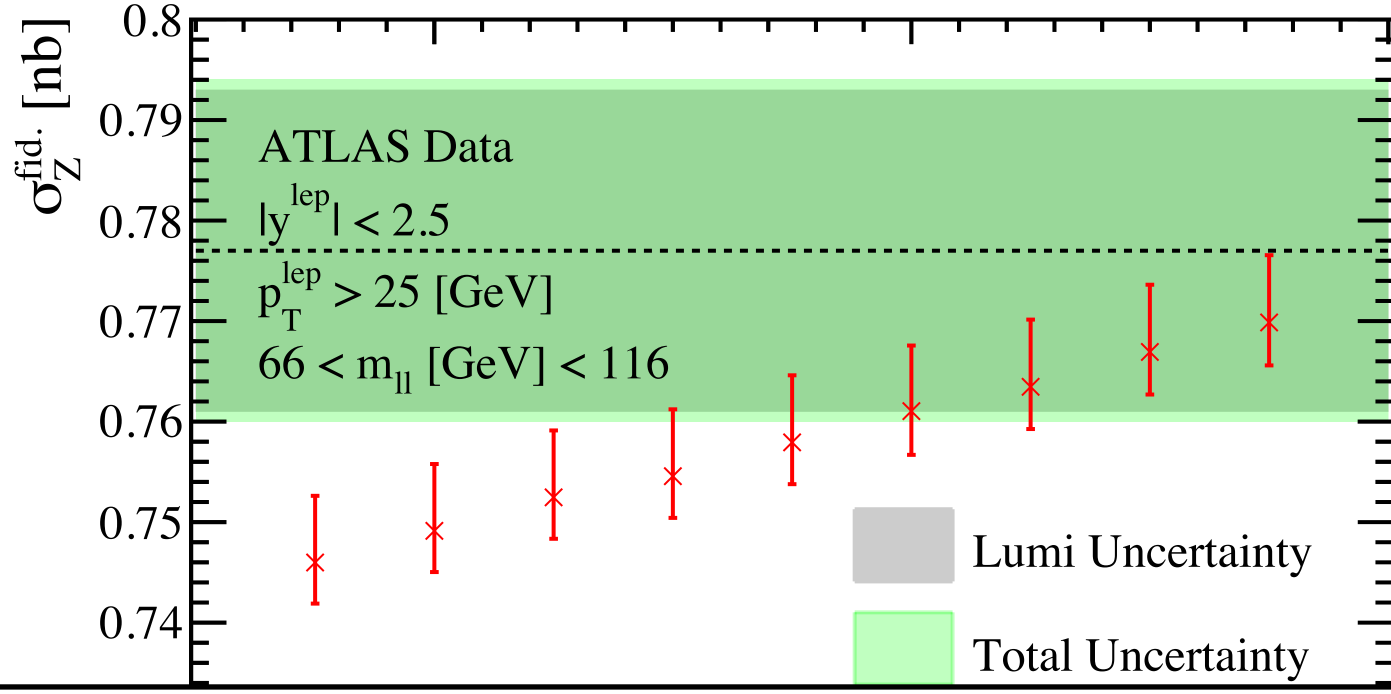
Impact of input value of m_c^{pole} in global fit

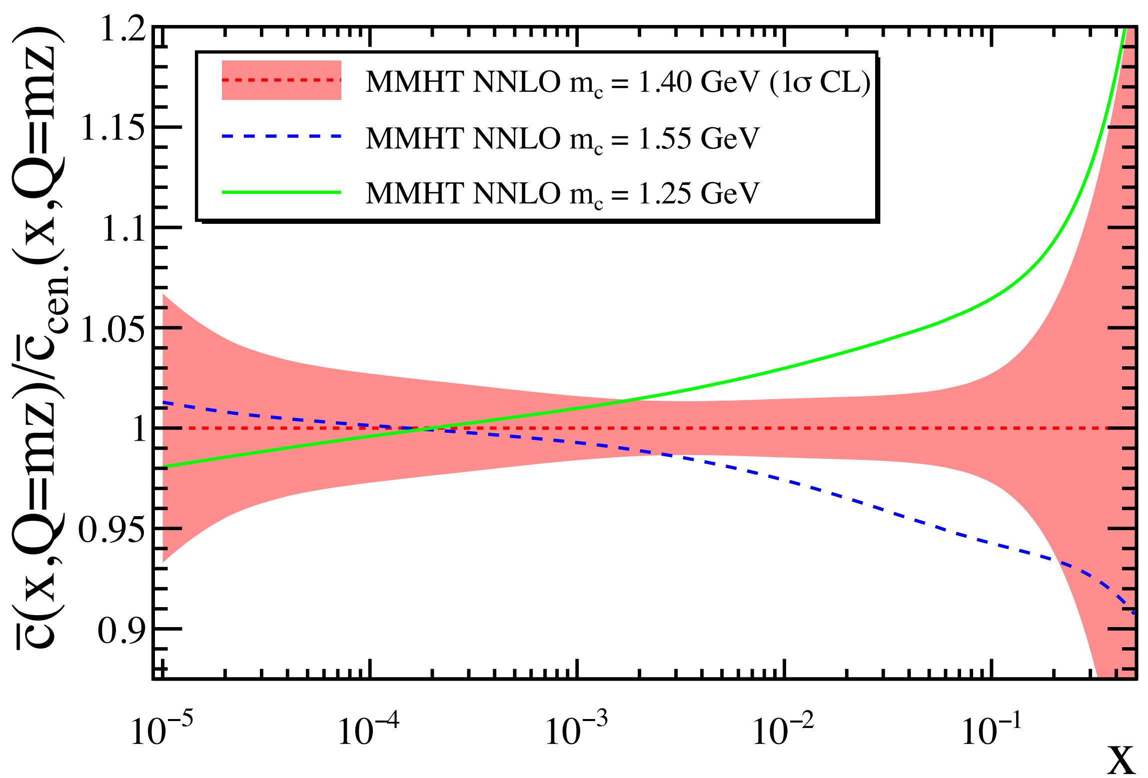


Input PDFs: MMHT'14, heavy quark variation

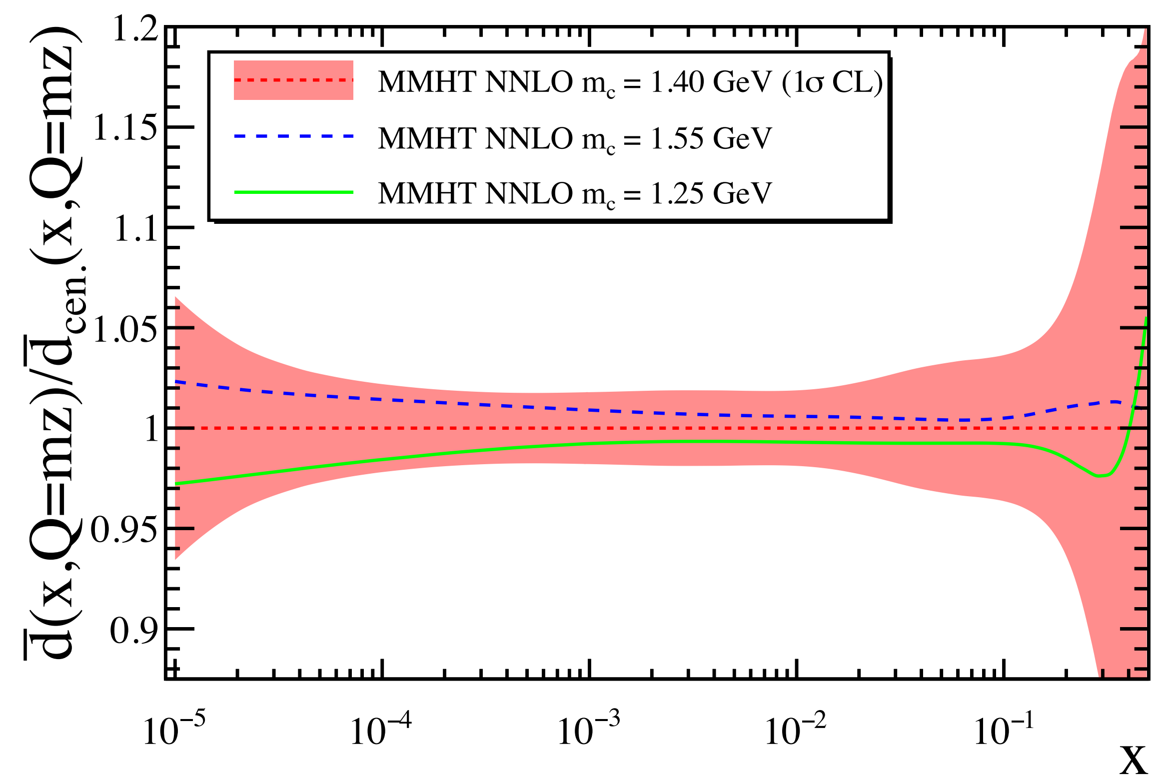
arXiv:1510.02332

Impact of input value of $m_c^{\rm pole}$ in global fit



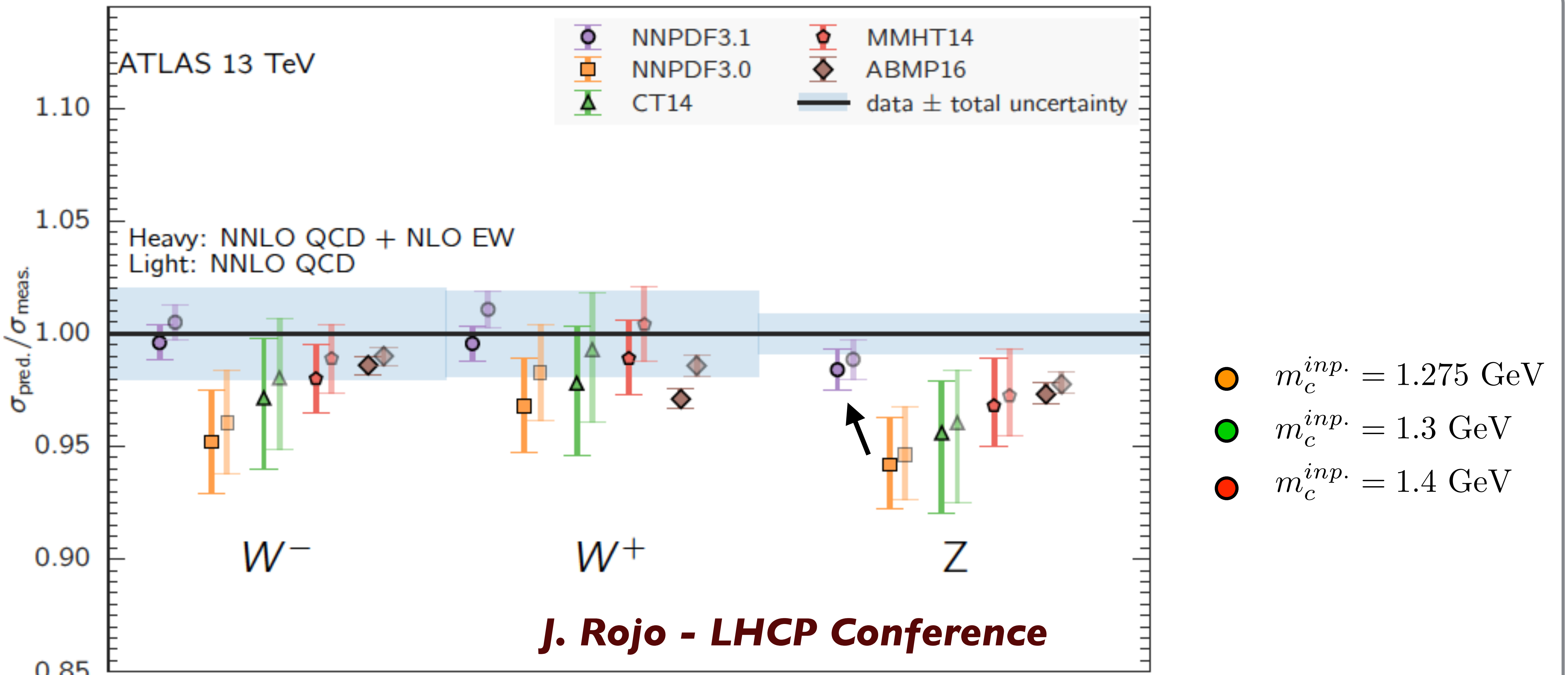


charm PDF



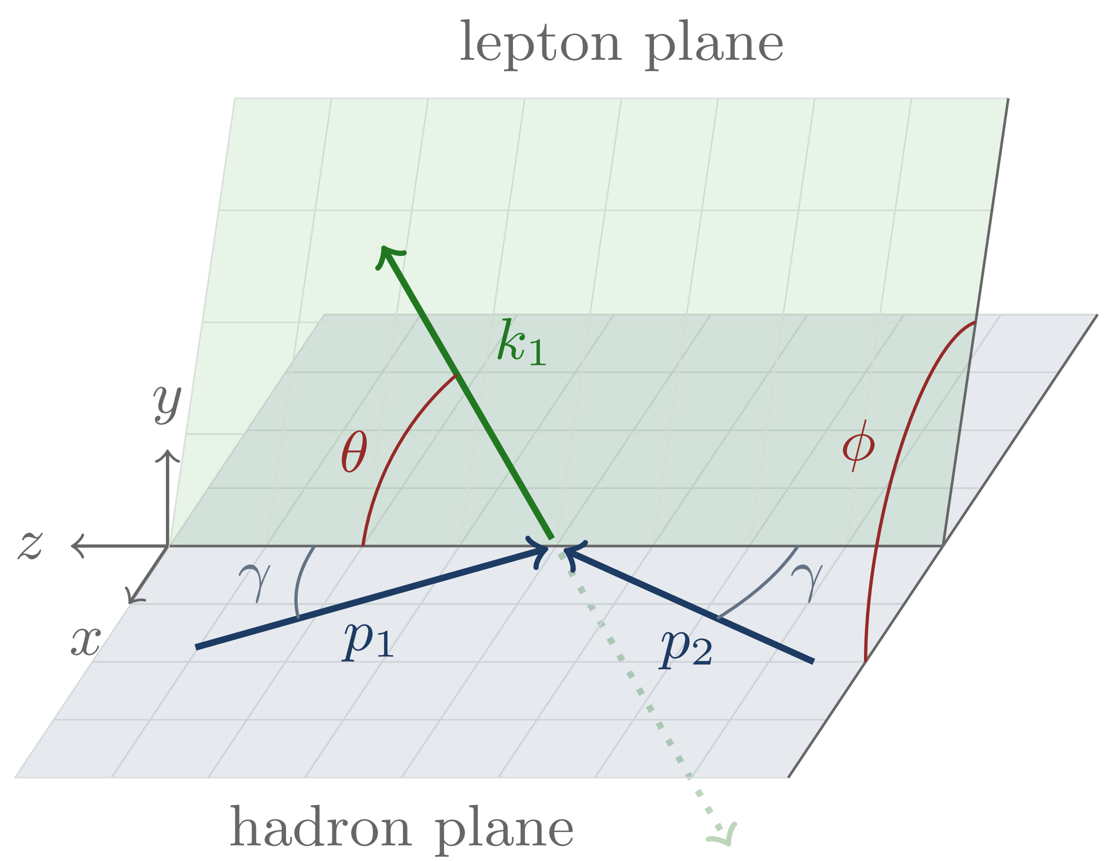
down PDF

Precision calculations → Precision PDF extractions



- NNPDF3.0 → NNPDF3.1, fit non-perturbative charm
- NNPDF3.0 → NNPDF3.1, $m_c^{inp.}$ = 1.275 → 1.51 GeV
- NNPDF3.0 → NNPDF3.1, p_T^Z data included

Angular coefficients in Z-boson production



RG, Gehrmann-De Ridder, Gehrmann, Glover, Huss - arXiv:1708.00008
JHEP 01(2017)003

General set-up

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

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 via 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. ATLAS P8 Tune vs. FO)

Predictions of 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..

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

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

(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

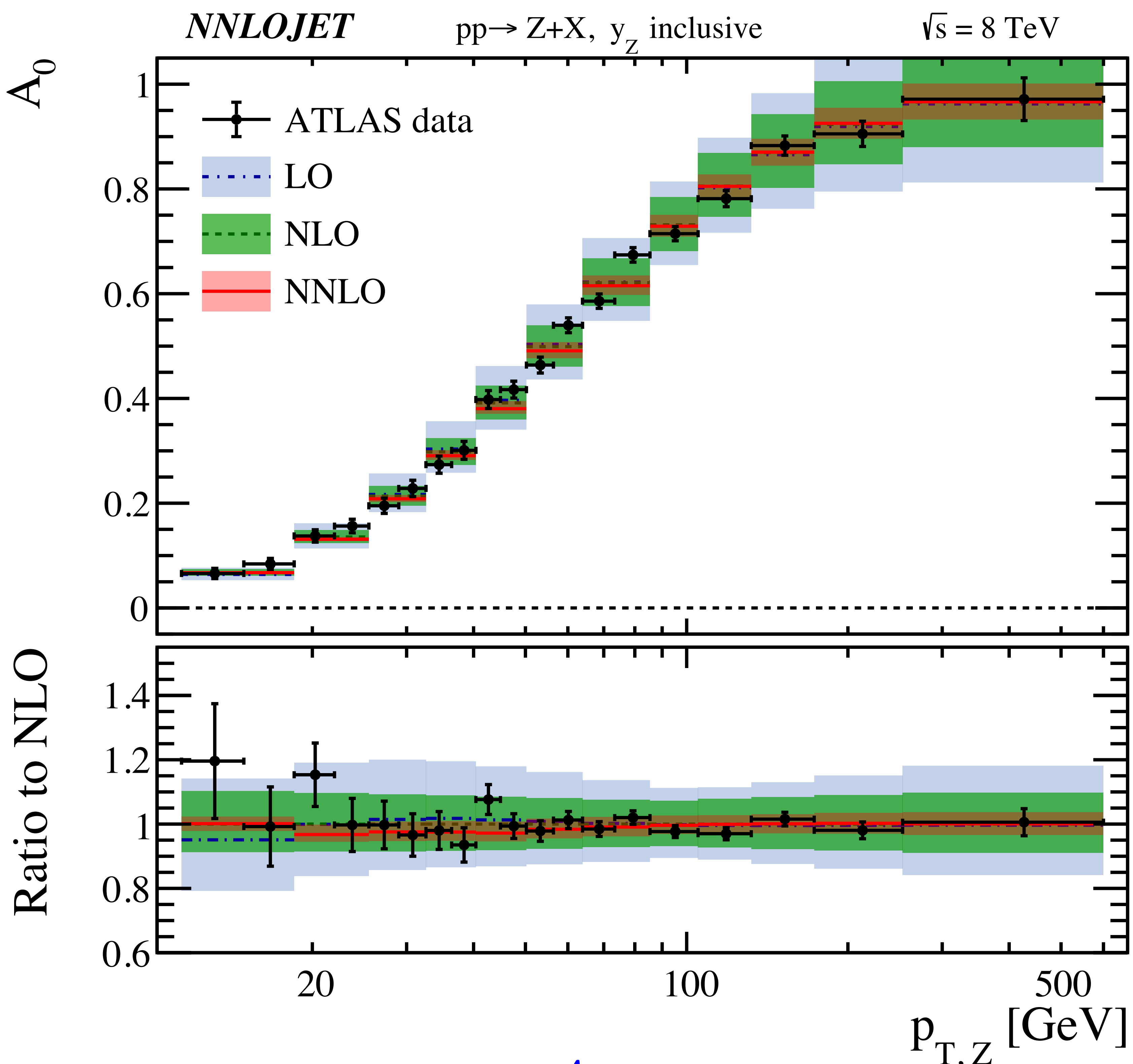
31-point scale variation

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

i, j = num. or den.

a,b = fac. or ren.

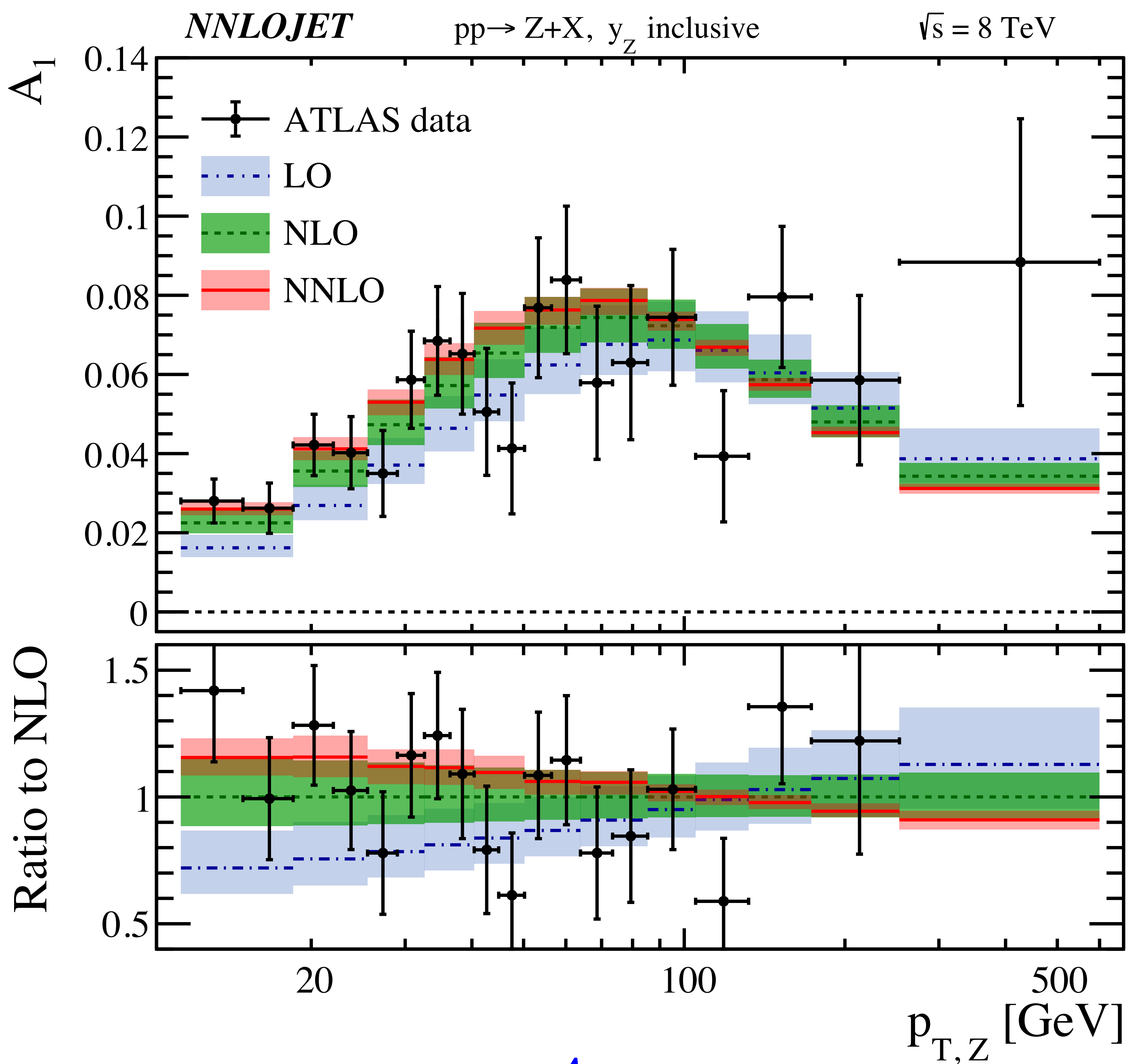
Predictions vs. data



A_0

(Collins-Soper frame)

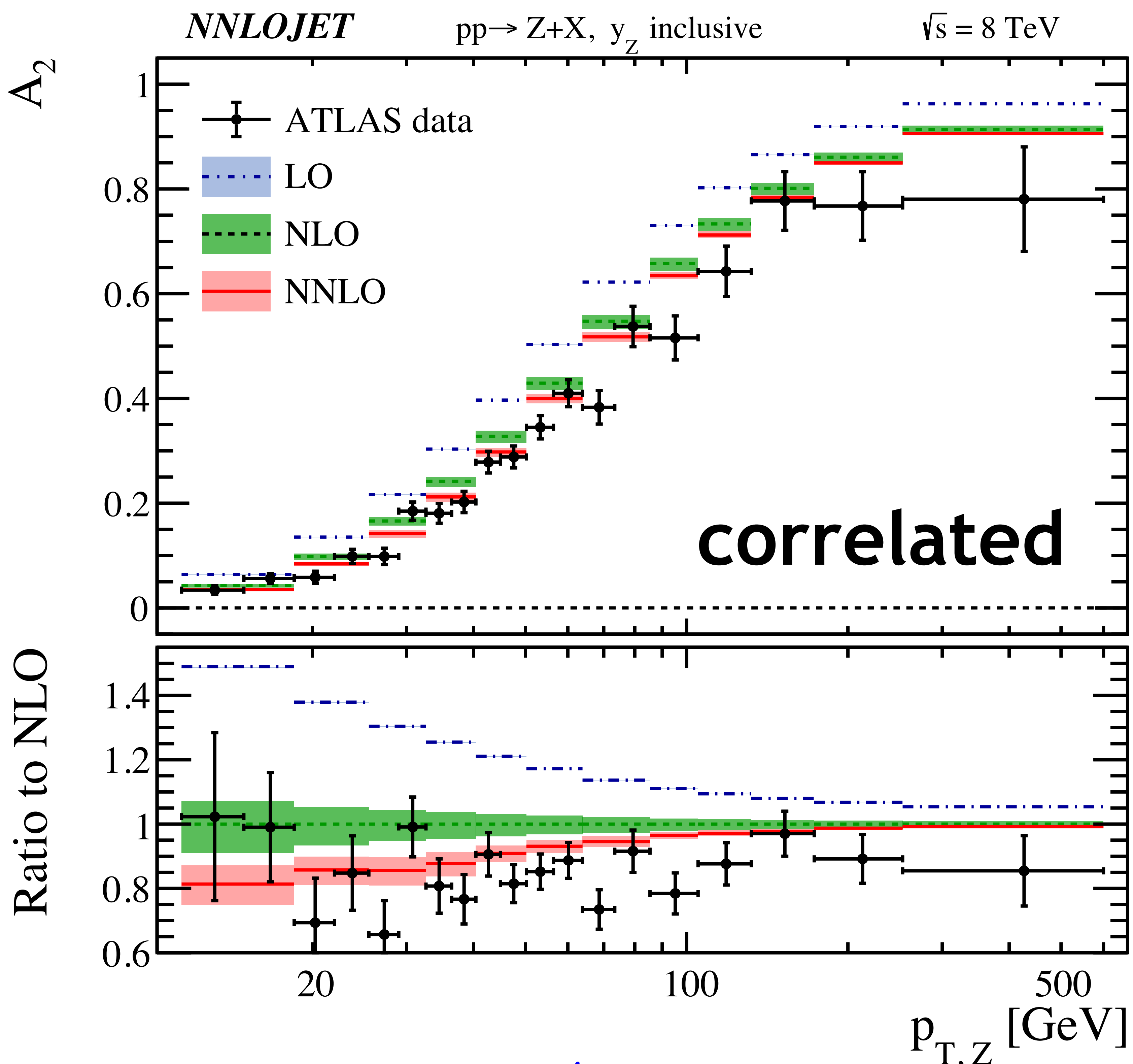
Predictions vs. data



A_1

(Collins-Soper frame)

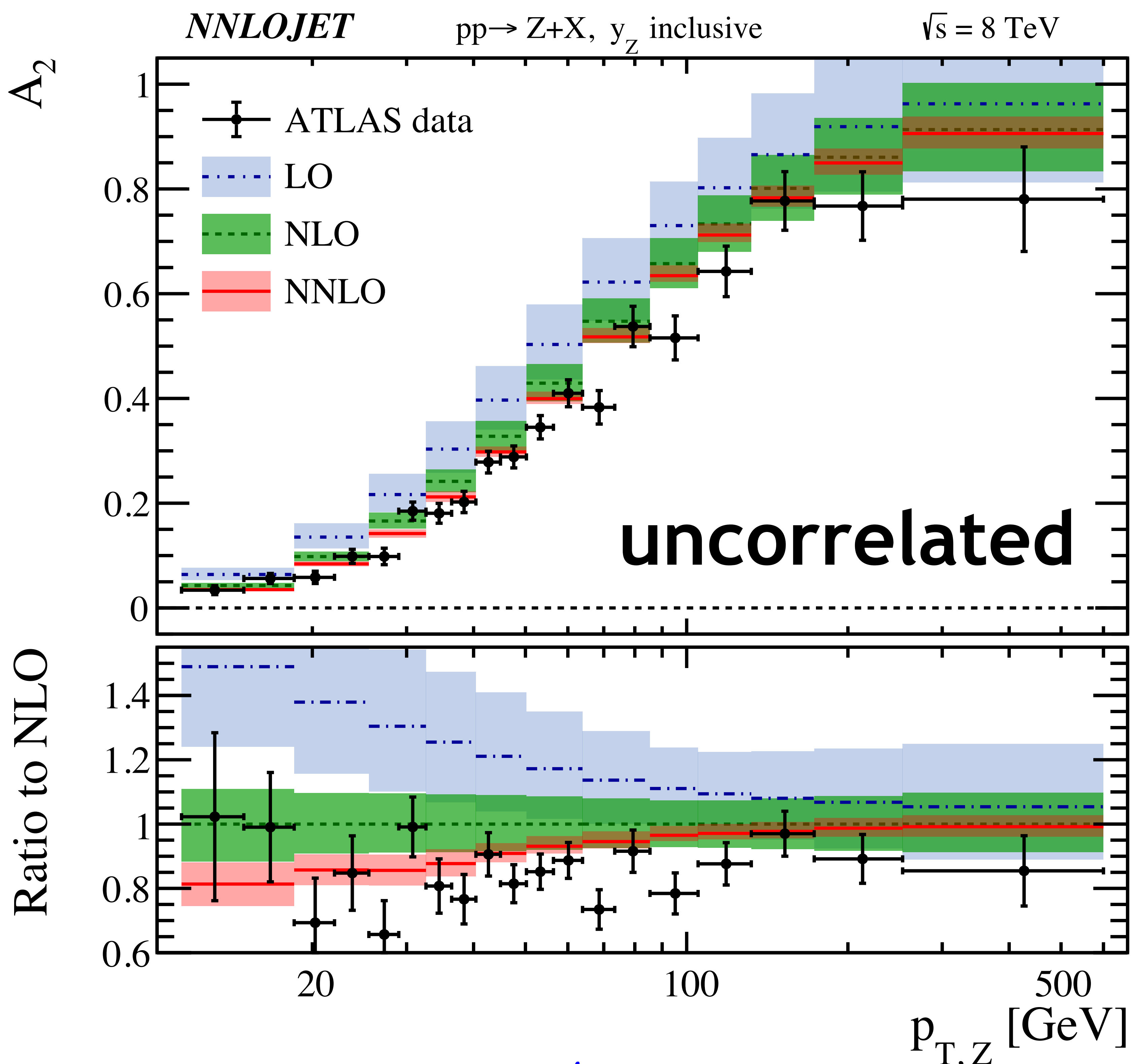
Predictions vs. data



A_2

(Collins-Soper frame)

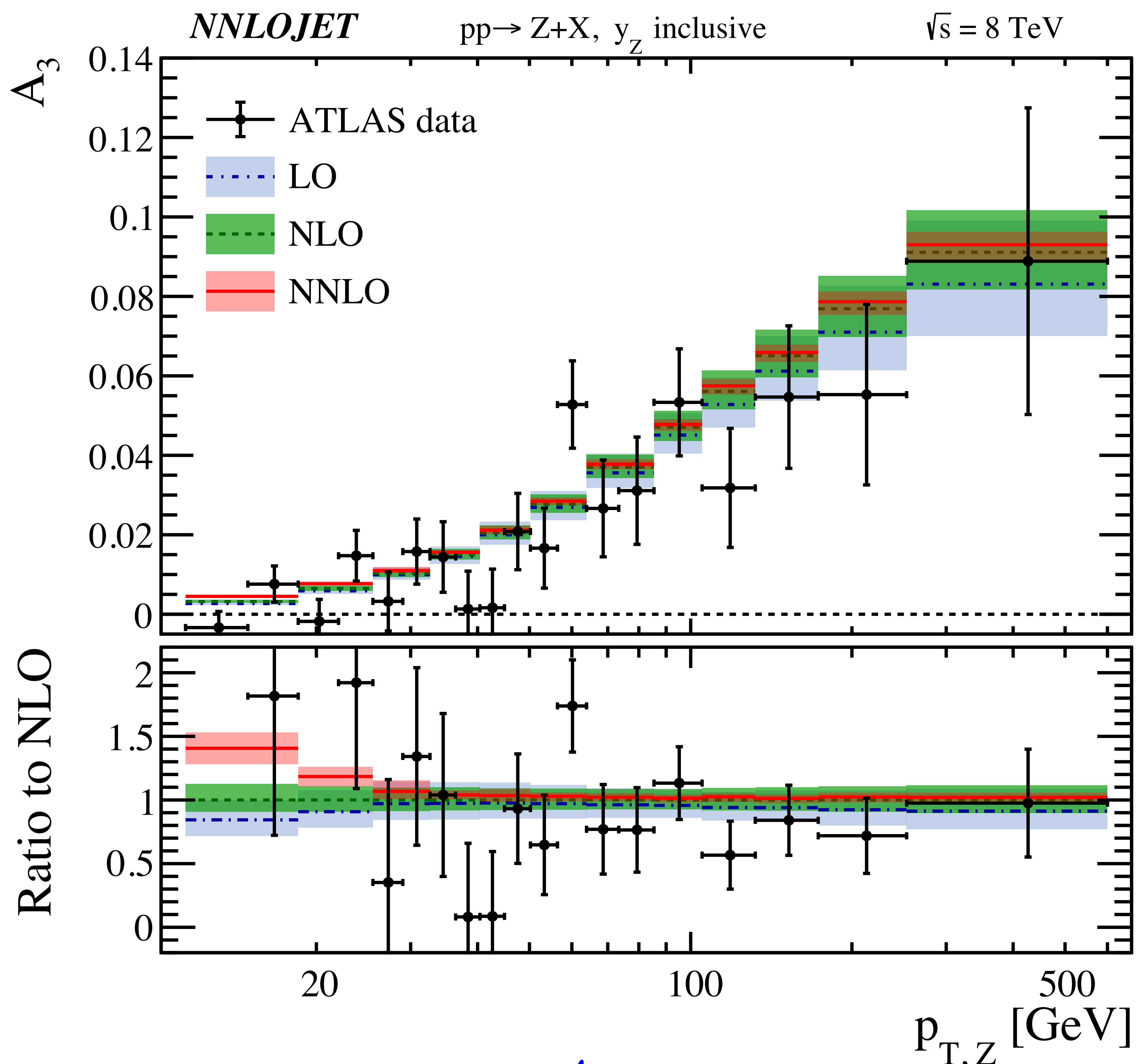
Predictions vs. data



A_2

(Collins-Soper frame)

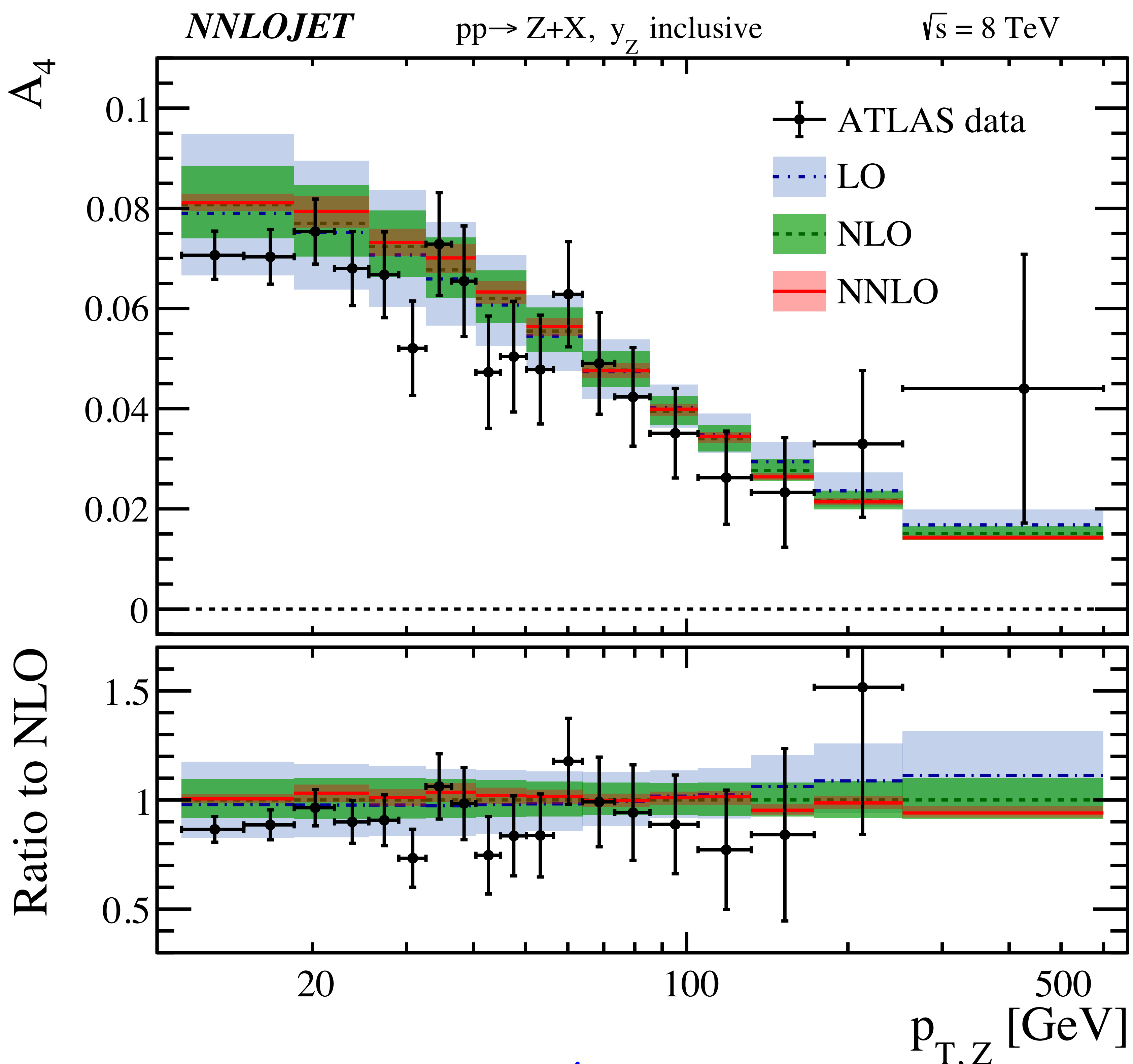
Predictions vs. data



A_3

(Collins-Soper frame)

Predictions vs. data



A_4

(Collins-Soper frame)

Aside:Input parameters for angular coefficients

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:

$$s_w^{os,2} = 1 - \frac{M_W^{os,2}}{M_Z^{os,2}} \approx 0.223 \qquad s^2_{\mathrm{eff.}} = 1 - \frac{m_W^2}{\rho\, m_Z^2}\,, \qquad \delta\rho = 0.0082$$

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

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

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

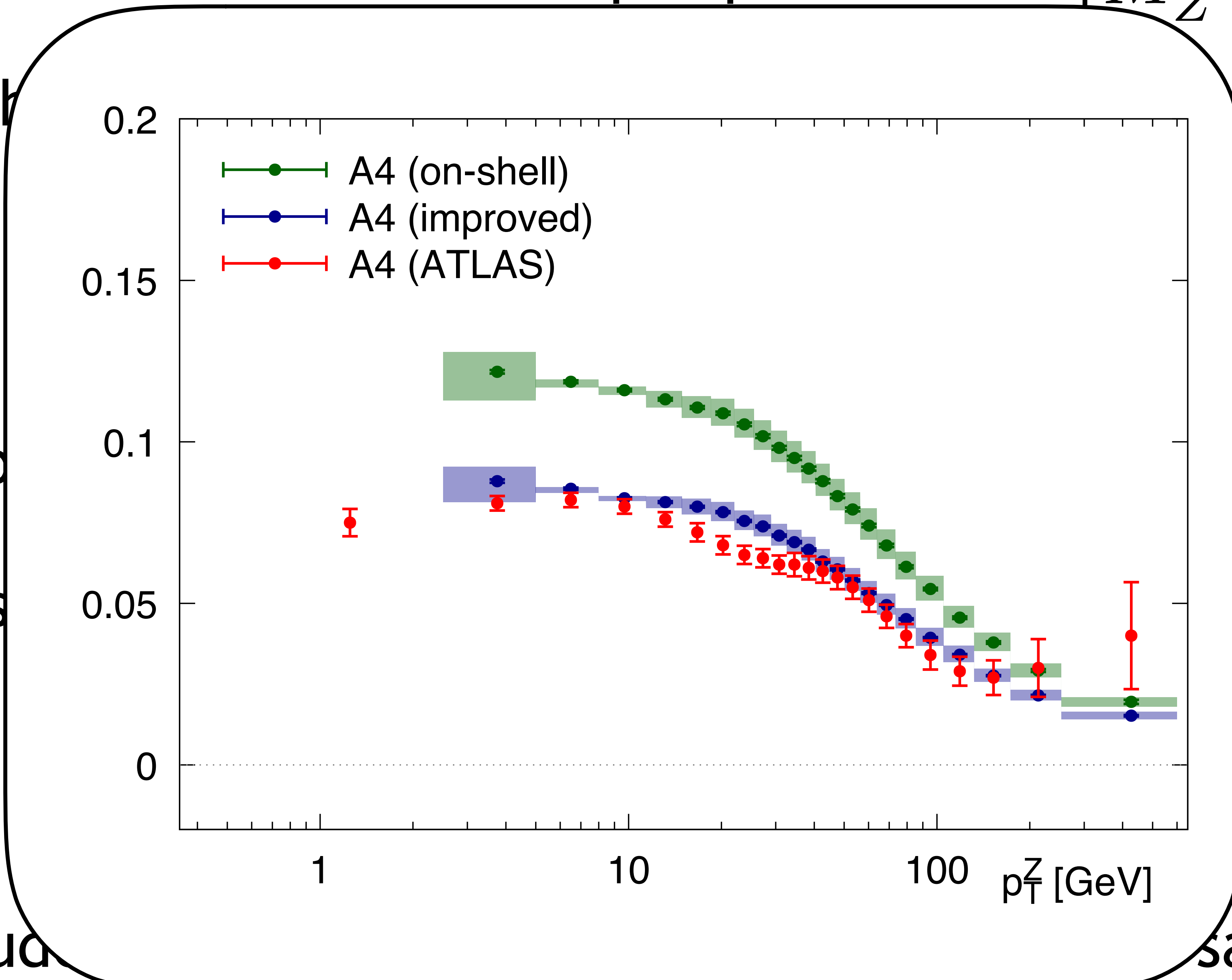
$$\approx 0.043C\left[s_w^2 = 0.223\right]$$

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

Aside:Input parameters for angular coefficients

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

In th



, $\delta\rho = 0.0082$

Prob ... coupling (A3,A4)

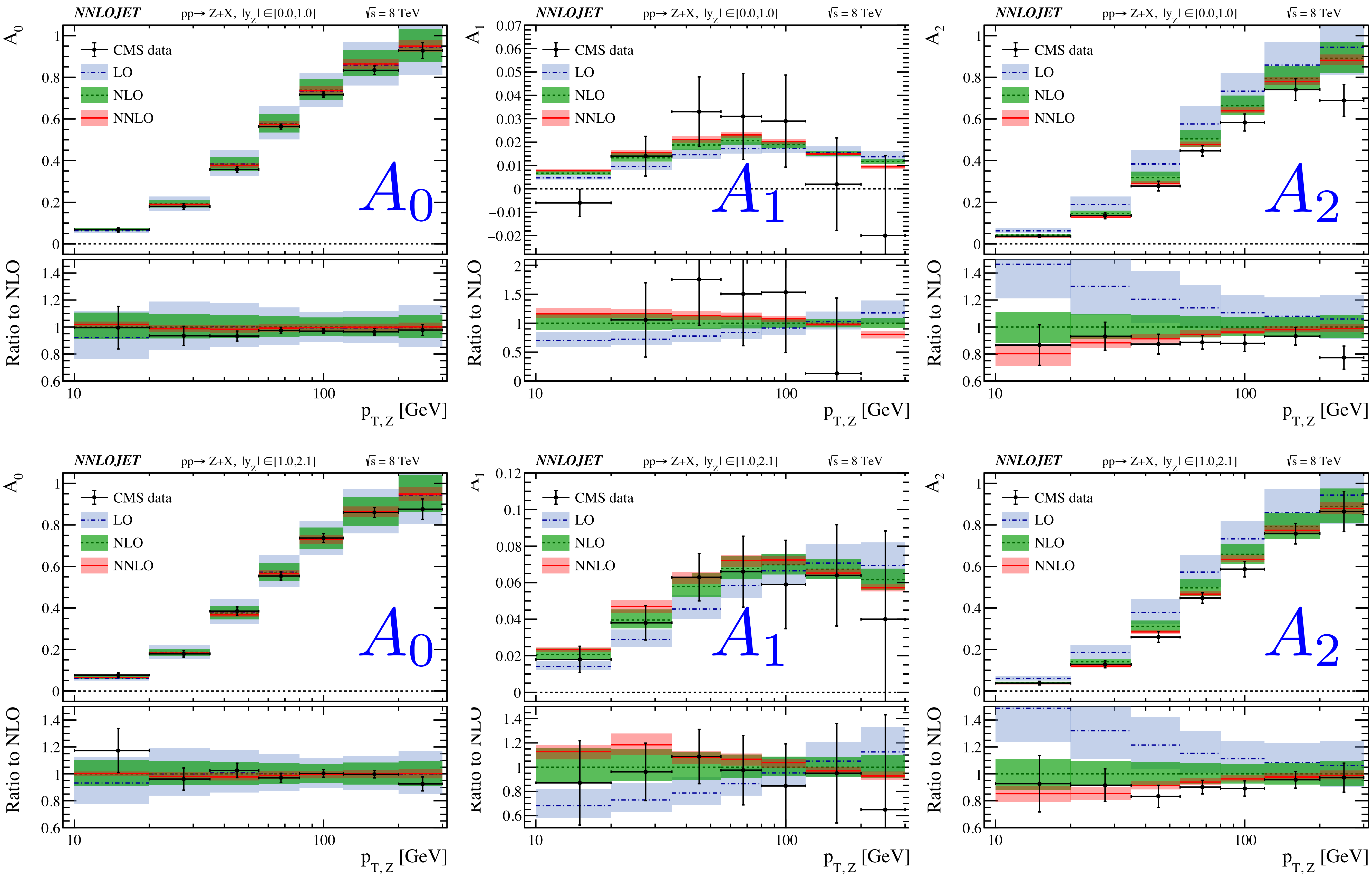
Cros ... $^{up}_{V} + \frac{1}{3} g_V^{do}$

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

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

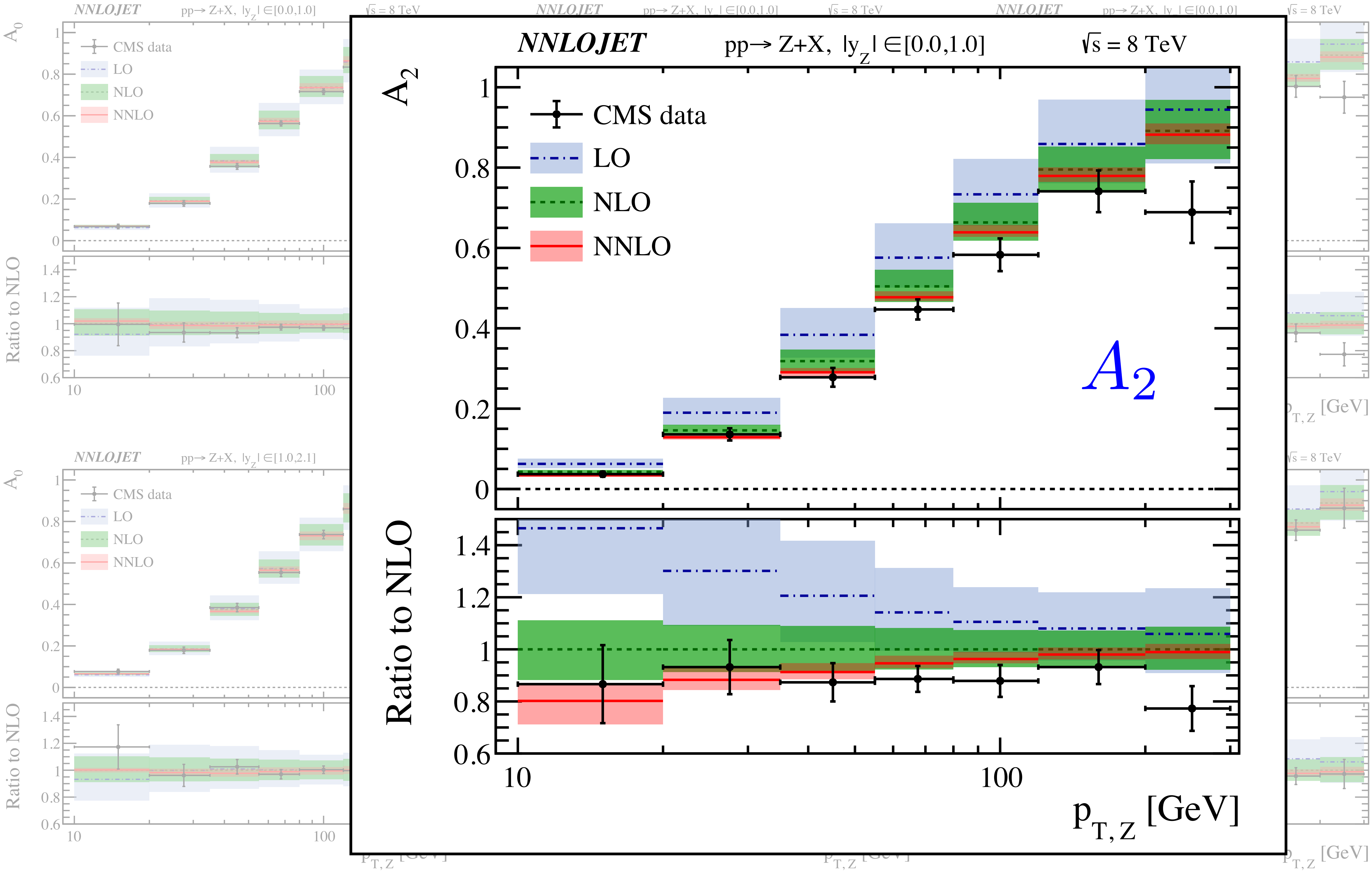
Includ ... sal corrections
relating MW-MZ, allows for matching to EW corrections

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

   (Normalisation better determined)

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 **not** altered @ NNLO

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

Assessing Lam-Tung violation

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

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

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

$$\boxed{A_0 - A_2 \neq 0}$$

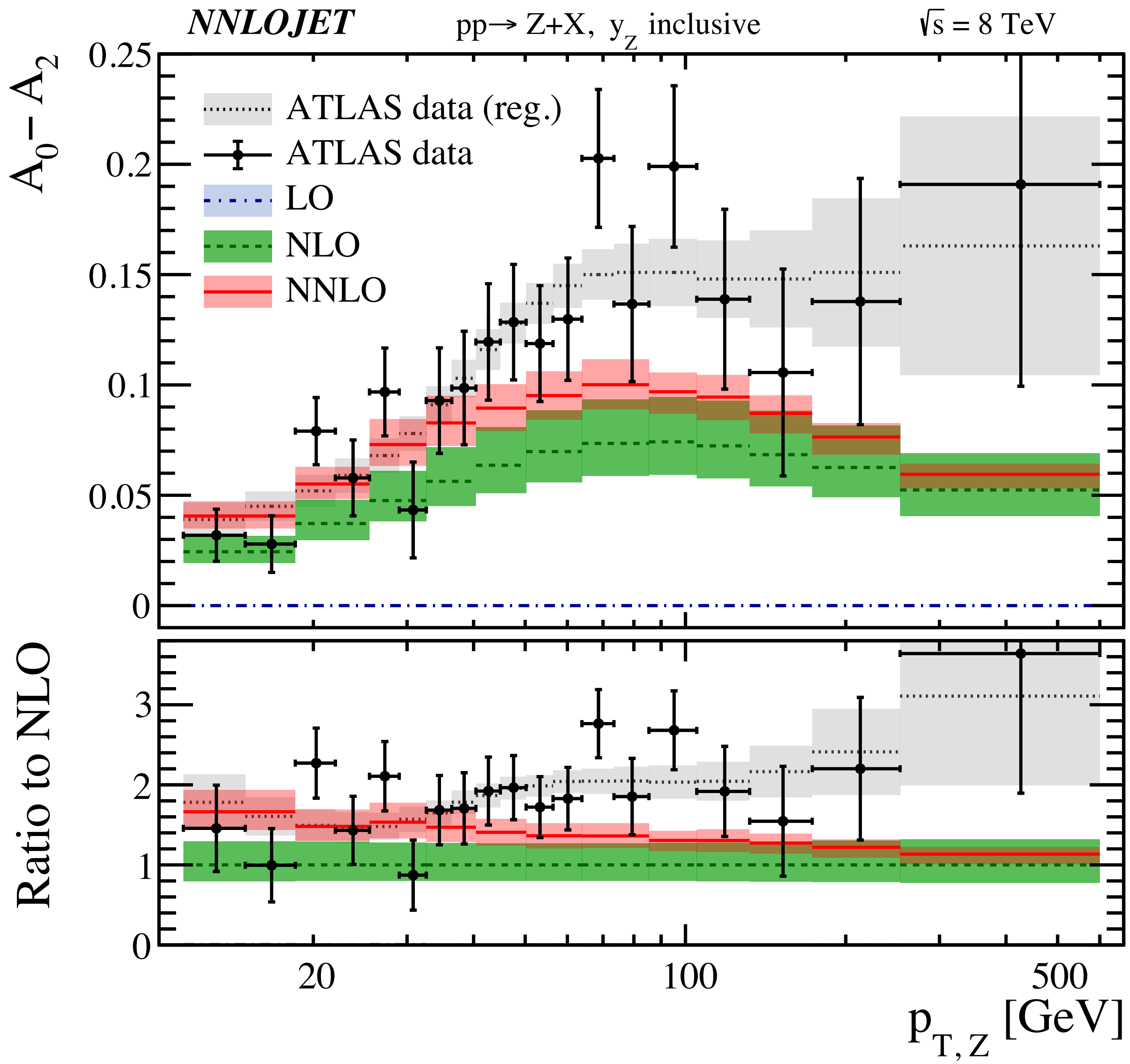
$$\boxed{\Delta^{\mathrm{LT}} = 1 - \frac{A_2}{A_0}}$$

(dependence on unpol. sigma cancels)

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

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

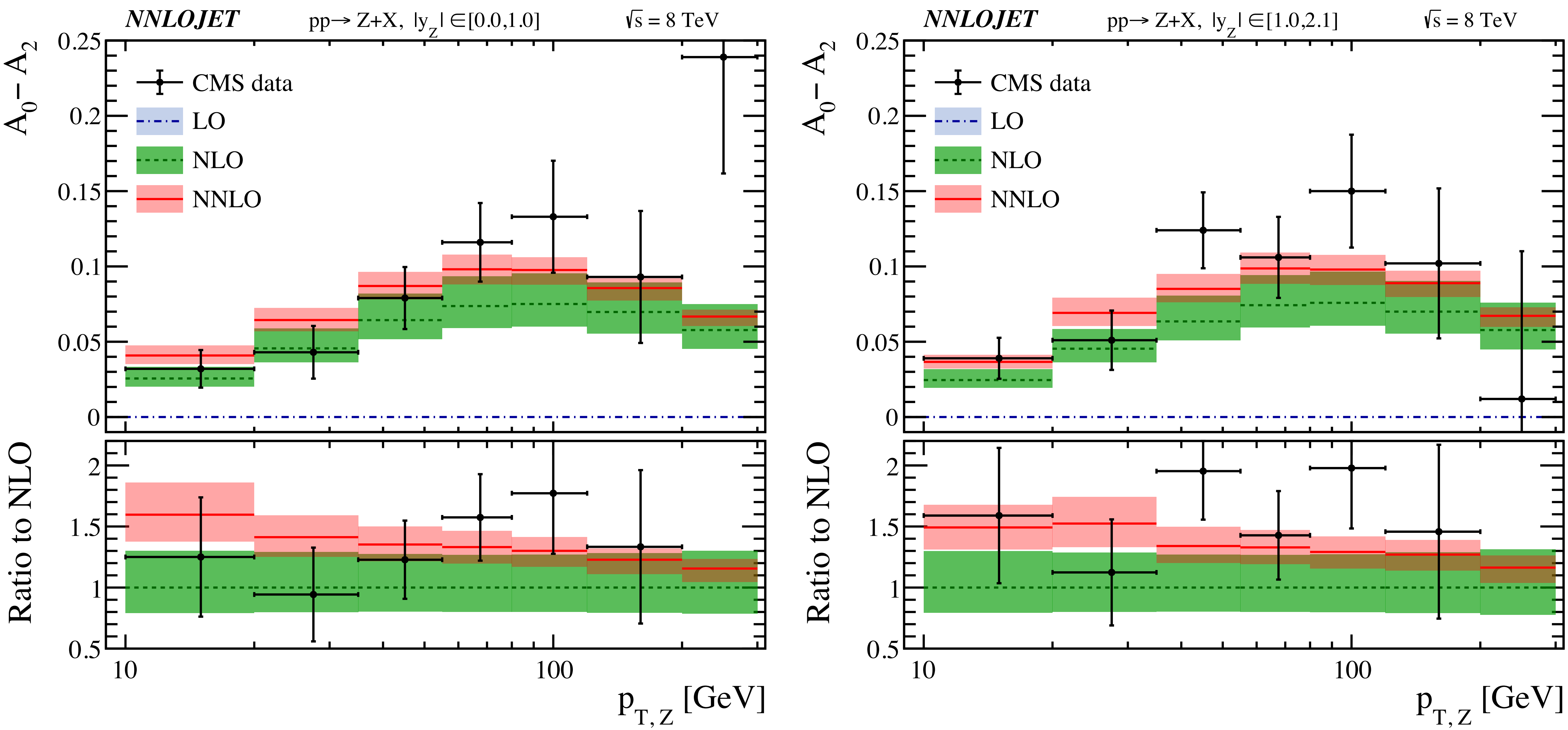
Assessing Lam-Tung violation



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

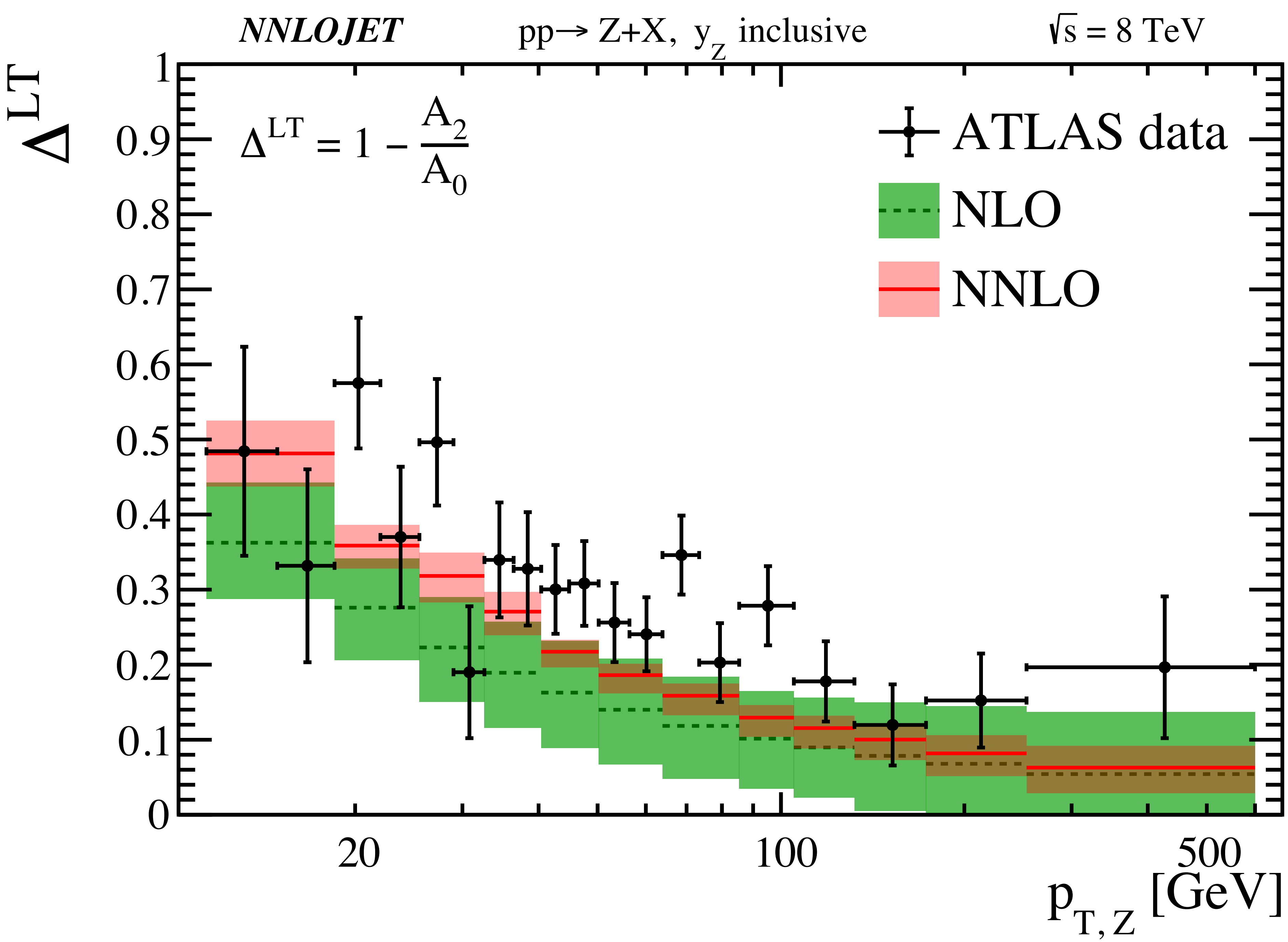
$$\text{NNLO (ATLAS)}: \quad \chi^2/N_{\text{data}} = 68.3/38 = 1.80\,.$$

Assessing Lam-Tung violation



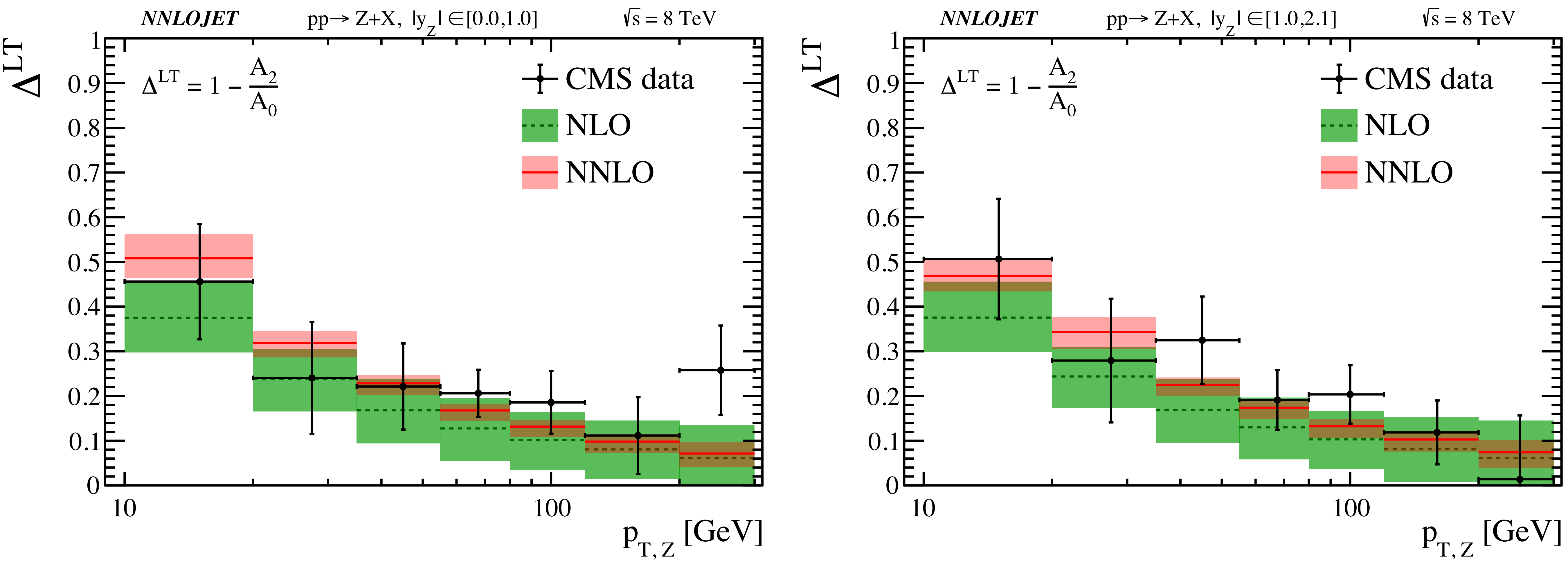
$$\text{NLO (CMS):} \qquad \chi^2/\text{N}_{\text{data}} = 24.5/14 = 1.75\,,$$
$$\text{NNLO (CMS):} \qquad \chi^2/\text{N}_{\text{data}} = 14.2/14 = 1.01\,.$$

Assessing Lam-Tung violation



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

Assessing Lam-Tung violation



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

Angular coefficients

- NNLO QCD necessary to describe data (NLO QCD inadequate)
- Impacts other measurements (e.g. MW, ATLAS arXiv:1701.07240)

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

- We can provide NNLO predictions for W/Z distributions

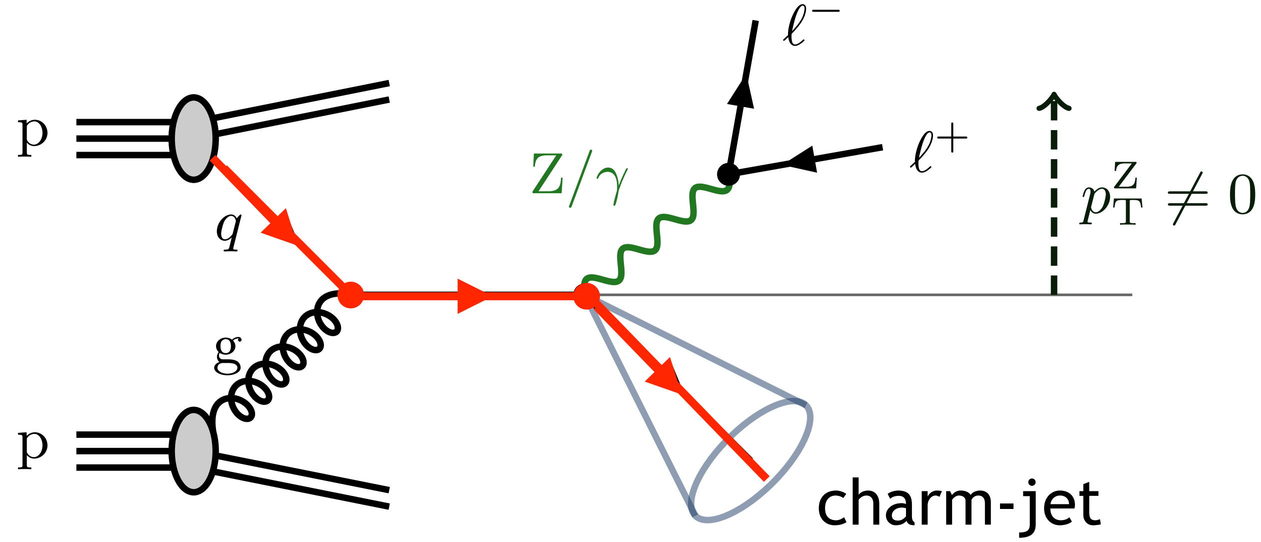
(for future MW extractions)

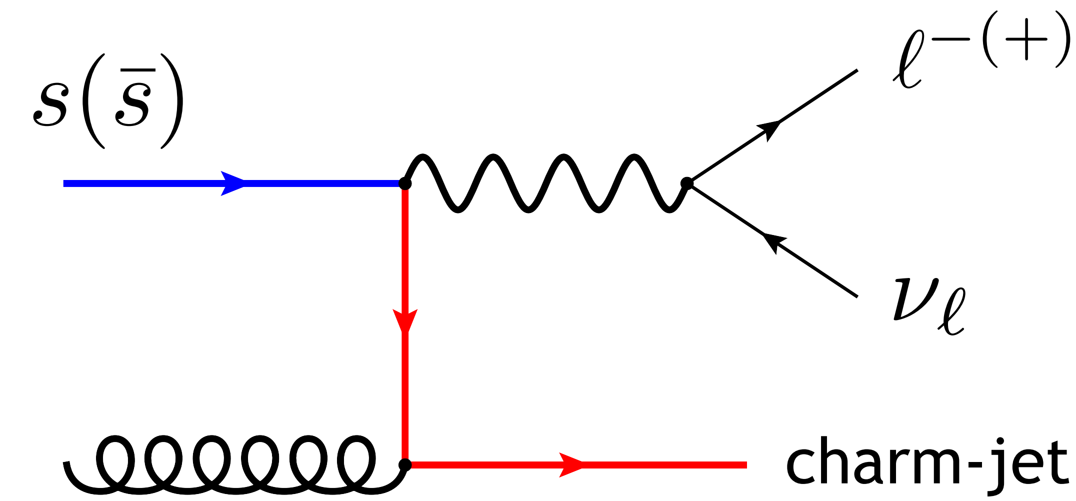
NNLO QCD accurate observables

- Scale uncertainties (in some cases) become sub-dominant
- Become sensitive to a number interesting physics effects
  - Heavy quark mass effects
  - PDFs
  - Strong coupling
  - Non-perturbative effects
  - $\mathrm{EW} \otimes \mathrm{QCD}$ corrections
  - ...

Lots of work still left to do…

Flavour tagging





$$c(x, Q_0) \neq 0?$$

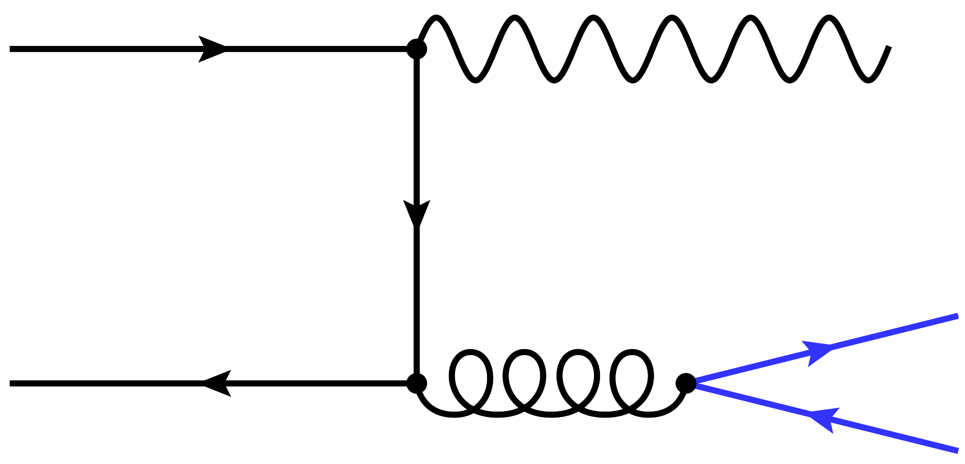
$$A_s = s(x, Q^2) - \bar{s}(x, Q^2)$$

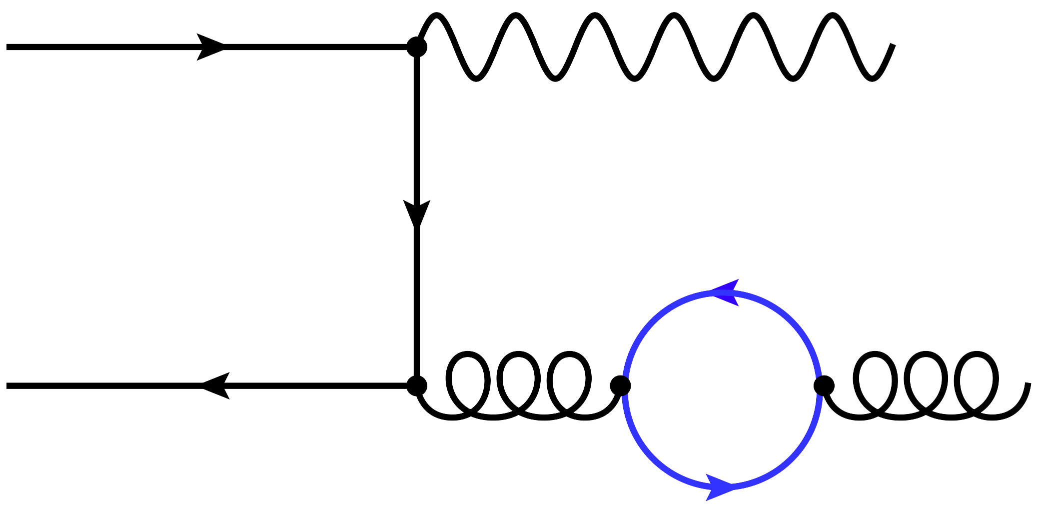
$$R_s = \frac{s(x, Q^2) + \bar{s}(x, Q^2)}{\bar{u}(x, Q^2) + \bar{d}(x, Q^2)}$$

- Probe assumption of intrinsic charm at NNLO
- Probe the strange PDF asymmetry and suppression

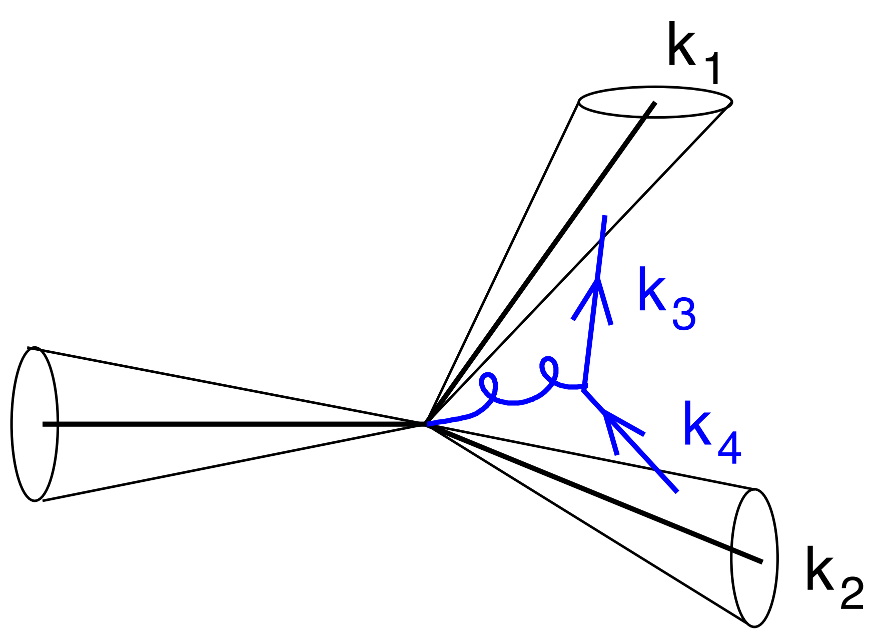
Flavour tagging

Collinear $g \to q\bar{q}$ splittings (NLO)





The soft-quarks problem (NNLO)



$$d_{ij} = \frac{2\ \min(E_i^{2p}, E_j^{2p})}{Q^2} (1 - \cos\theta_{ij})$$

E_3 soft, combines with closest parton

Can result in k1+k3 combining b-jet

What is APPLfast?

- Started as common project of NNLOJET, APPLgrid, and fastNLO authors at QCD@LHC in London
- Interface between NNLOJET and fast grid technology - APPLgrid and fastNLO
- Aimed to be the least obtrusive as possible for both ends of the interface
- Intended to be reusable by other theory programs

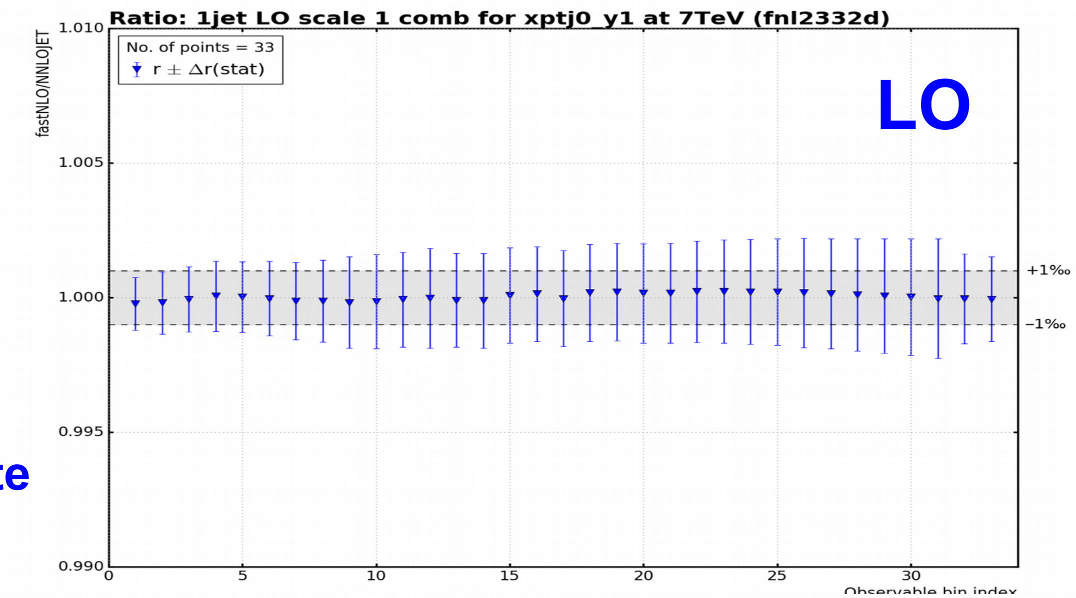
D. Britzger (Heidelberg), C. Gwenlan (Oxford), A. Huss (CERN), **K. Rabbertz (KIT)**, M. Sutton (Sussex)

PDF grids

Inclusive jet pT – combined grid

Ratio FastNLO / NNLOJET

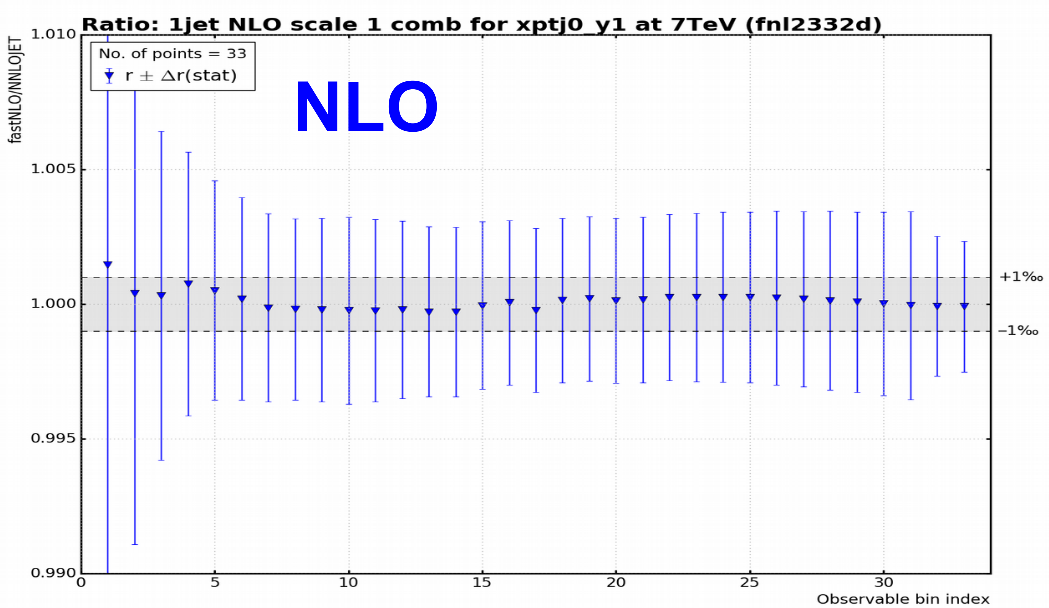
Error bars:
stat. uncertainty estimate from NNLOJET

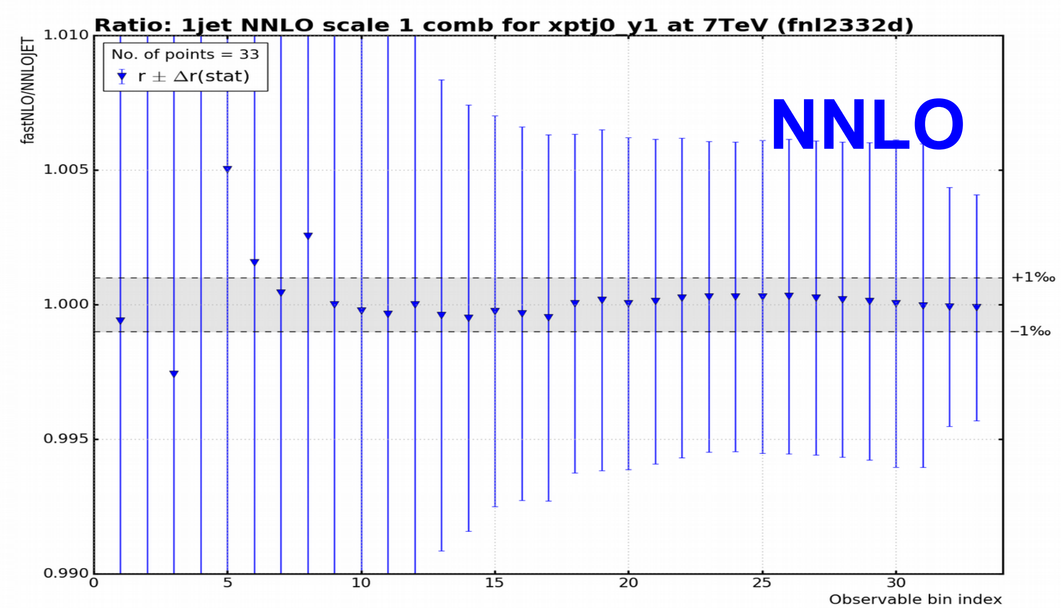


+1%

±1‰

-1%





Angular coefficients for W

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

Defining lepton kinematics in V(q) rest frame

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

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

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

$\vec{p}_{T,\nu}$ $\quad p_\ell^\mu$ $\quad (p_\nu + p_\ell)^2 = m_W^2 \to |p_{z,\nu}|$

$$\theta \equiv \pi - \theta$$

Angular coefficients for W

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

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$$+ A_1\,\sin(2\theta)\cos\phi + \frac{1}{2}\,A_2\,\sin^2\theta\,\cos(2\phi)$$
$$+ A_3\,\sin\theta\,\cos\phi + A_4\,\cos\theta + A_5\,\sin^2\theta\,\sin(2\phi)$$
$$+ A_6\,\sin(2\theta)\,\sin\phi + A_7\,\sin\theta\,\sin\phi\Big\}$$

$\vec{p}_{T,\nu}$ $\quad p^{\mu}_{\ell}$ $\quad (p_\nu + p_\ell)^2 = m_W^2 \to |p_{z,\nu}|$

$$\theta \equiv \pi - \theta$$

ATLAS sample reweighting

The correction procedure is based on the factorisation of the fully differential leptonic Drell–Yan cross section [31] into four terms:

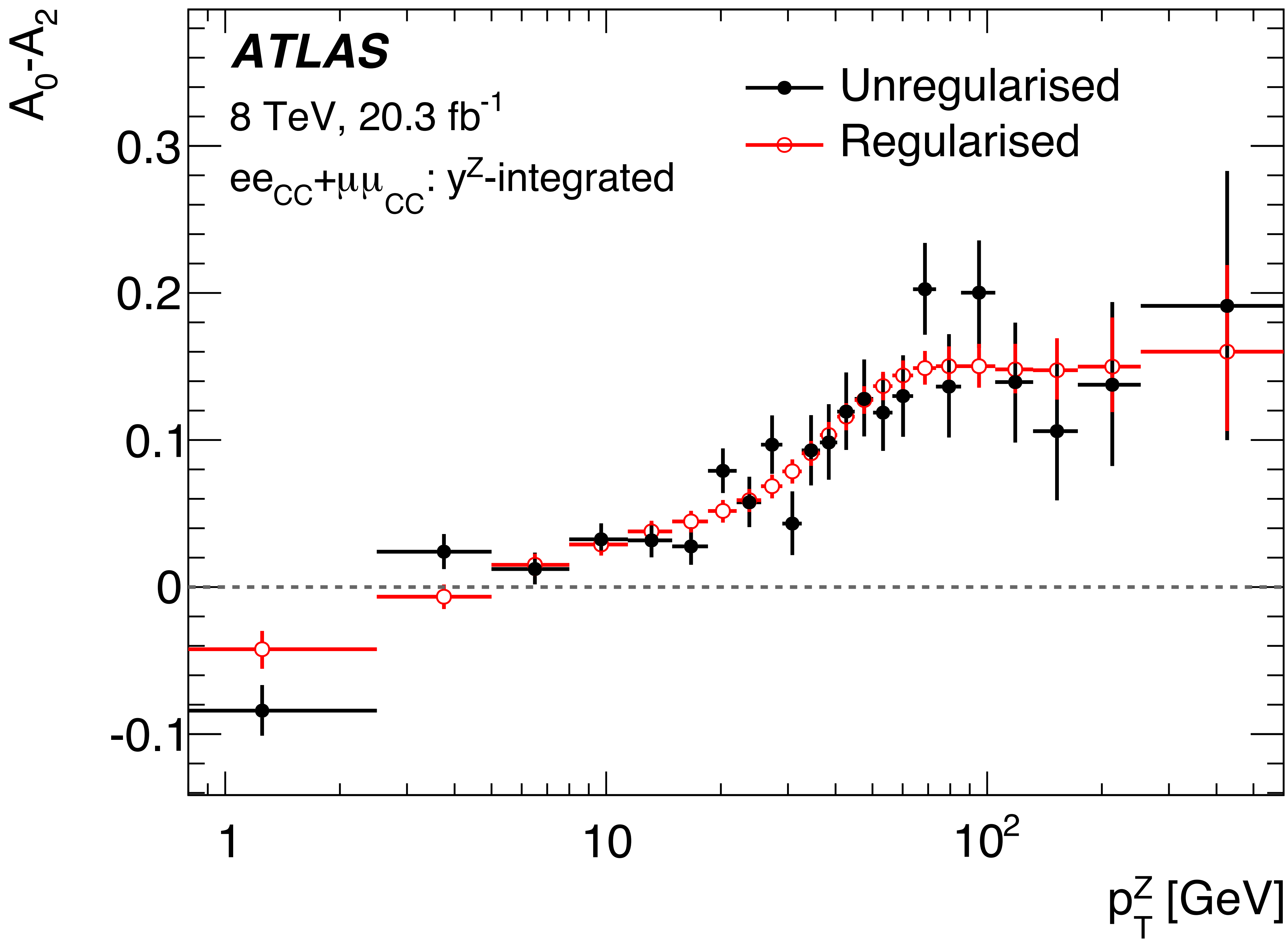
$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_1\,\mathrm{d}p_2} = \left[\frac{\mathrm{d}\sigma(m)}{\mathrm{d}m}\right]\left[\frac{\mathrm{d}\sigma(y)}{\mathrm{d}y}\right]\left[\frac{\mathrm{d}\sigma(p_\mathrm{T},y)}{\mathrm{d}p_\mathrm{T}\,\mathrm{d}y}\left(\frac{\mathrm{d}\sigma(y)}{\mathrm{d}y}\right)^{-1}\right]\left[(1+\cos^2\theta)+\sum_{i=0}^{7}A_i(p_\mathrm{T},y)P_i(\cos\theta,\phi)\right], \qquad (2)$$

The reweighting is performed in several steps. First, the inclusive rapidity distribution is reweighted according to the NNLO QCD predictions evaluated with DYNNLO. Then, at a given rapidity, the vector-boson transverse-momentum shape is reweighted to the Pythia 8 prediction with the AZ tune. This procedure provides the transverse-momentum distribution of vector bosons predicted by Pythia 8, preserving the rapidity distribution at NNLO. Finally, at given rapidity and transverse momentum, the angular variables are reweighted according to:

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

where A_i' are the angular coefficients evaluated at $O(\alpha_\mathrm{s}^2)$, and A_i are the angular coefficients of the Powheg+Pythia 8 samples. This reweighting procedure neglects the small dependence of the two-dimensional (p_T,y) distribution and of the angular coefficients on the final state invariant mass. The procedure is used to include the corrections described in Sections 6.2 and 6.3, as well as to estimate the impact of the QCD modelling uncertainties described in Section 6.5.

ATLAS, 'unregularised' A.C.



CMS, absolute uncertainties

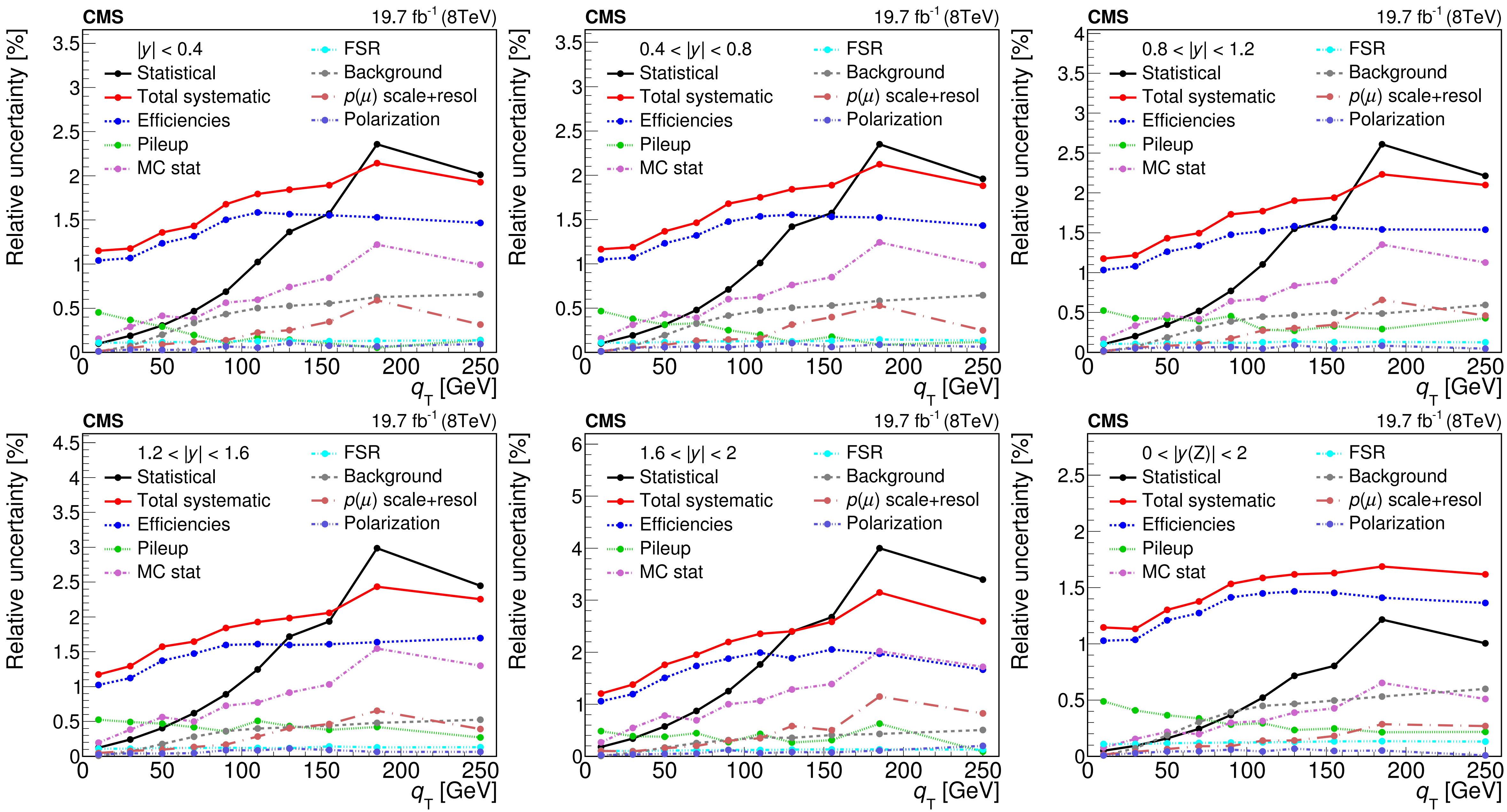
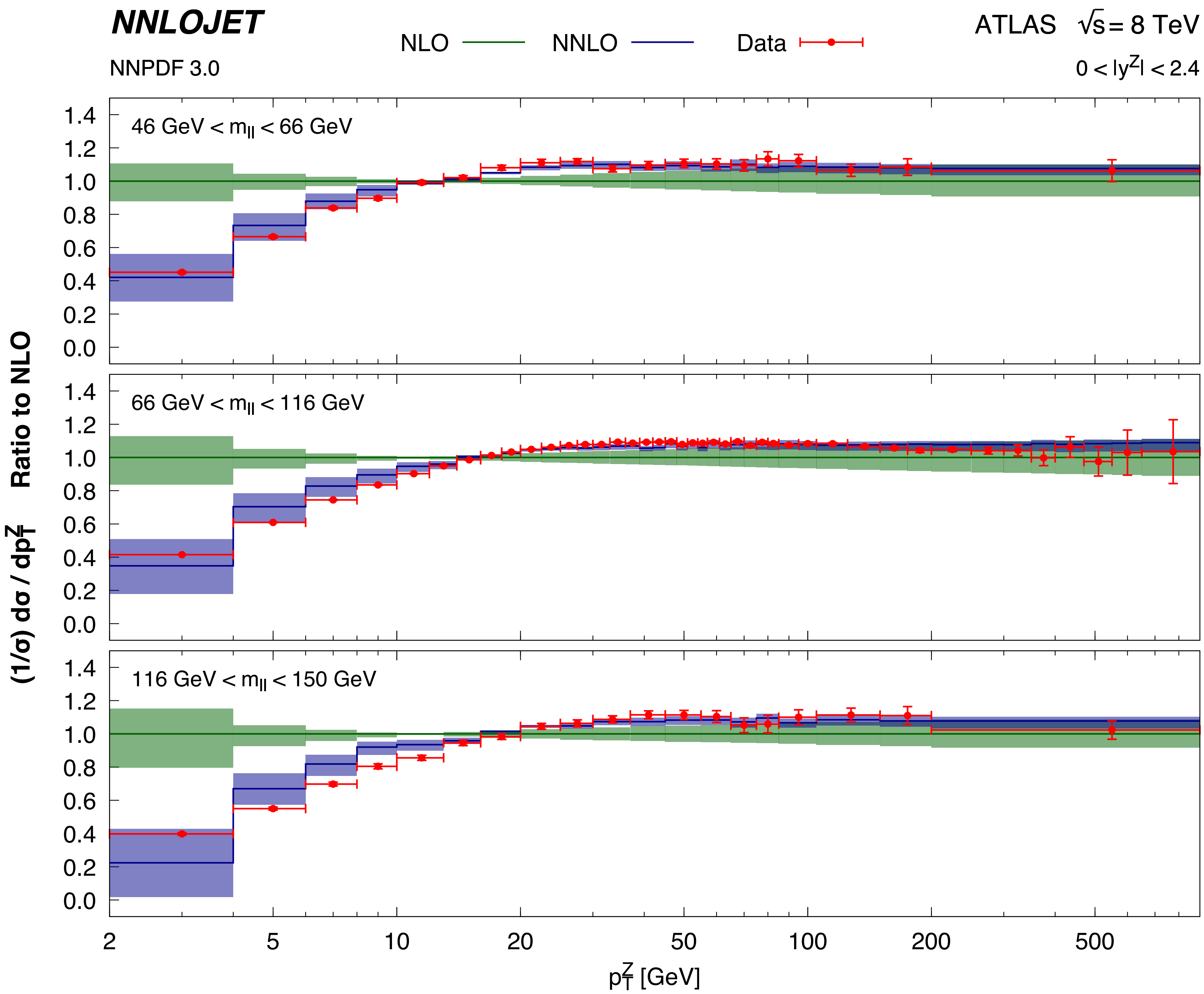
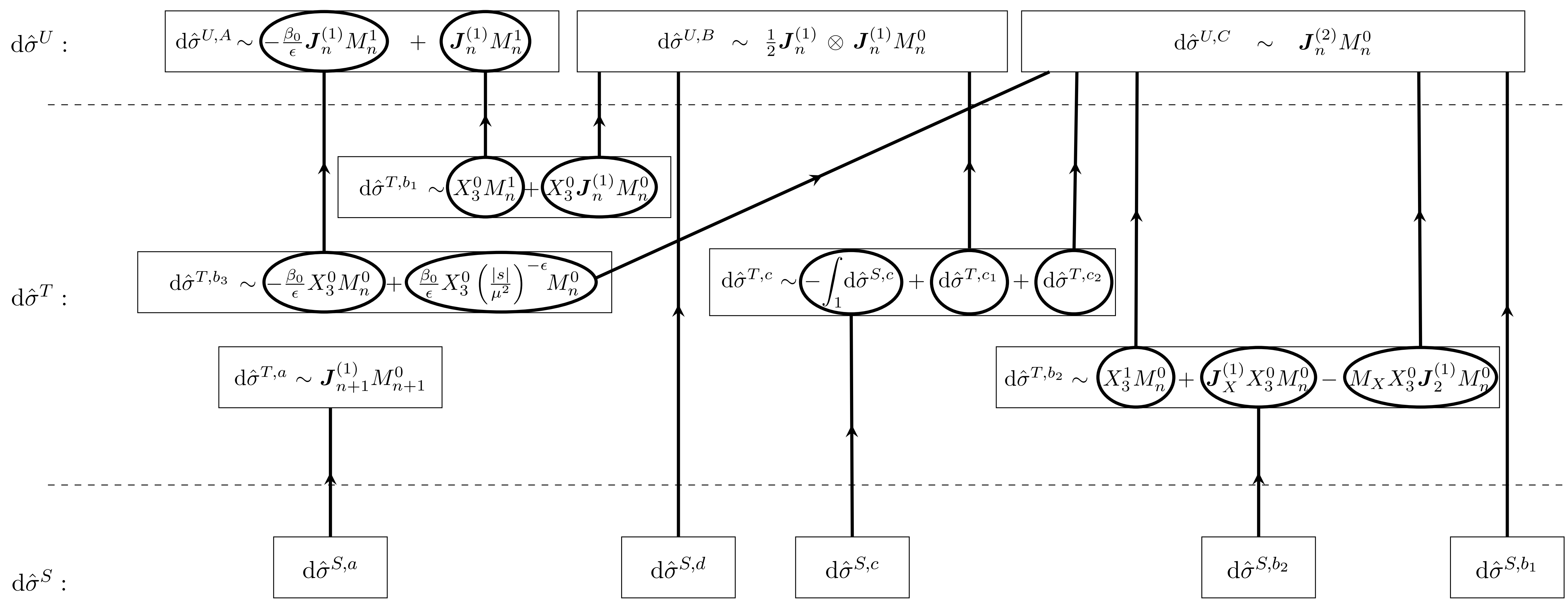


Figure 2: Relative uncertainties in percent of the absolute fiducial cross section measurement. The 2.6% uncertainty in the luminosity is not included. Each plot shows the q_T dependence in the indicated ranges of $|y|$.

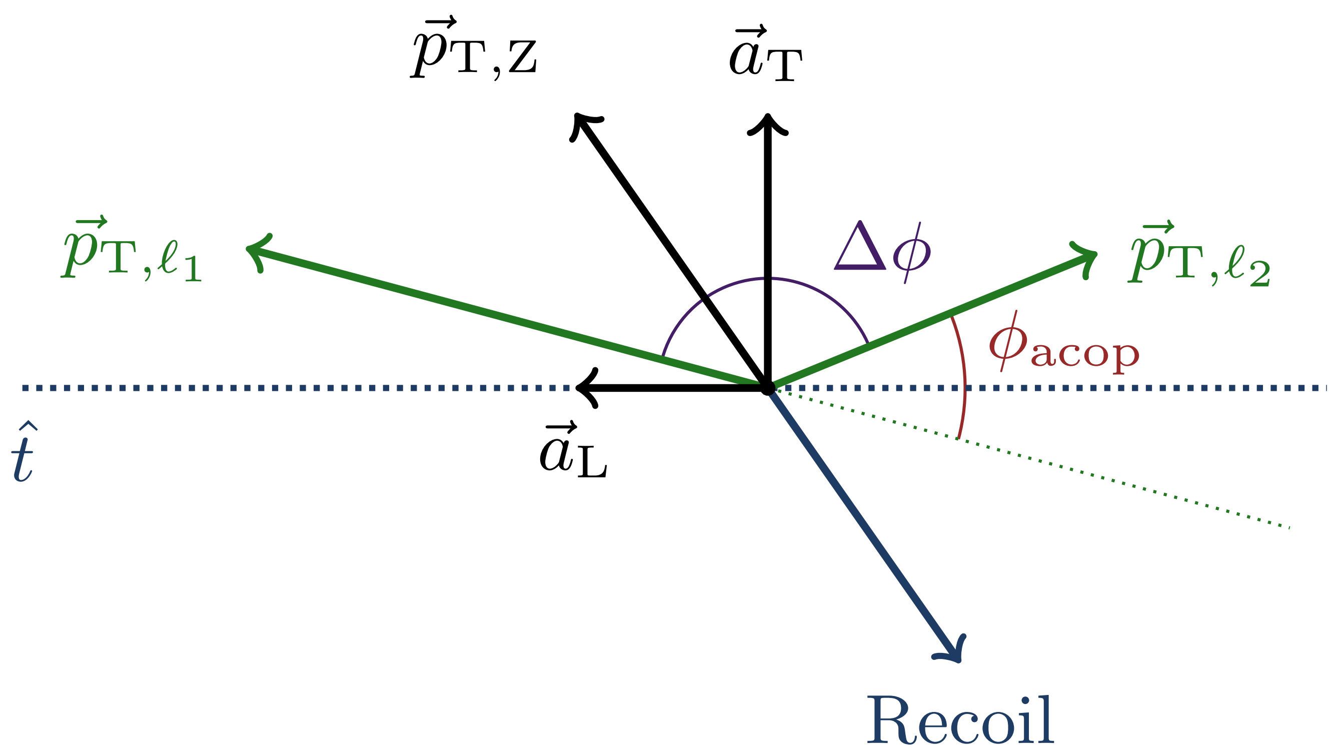
Low p_T^Z backups



Antenna subtraction - NNLO workflow

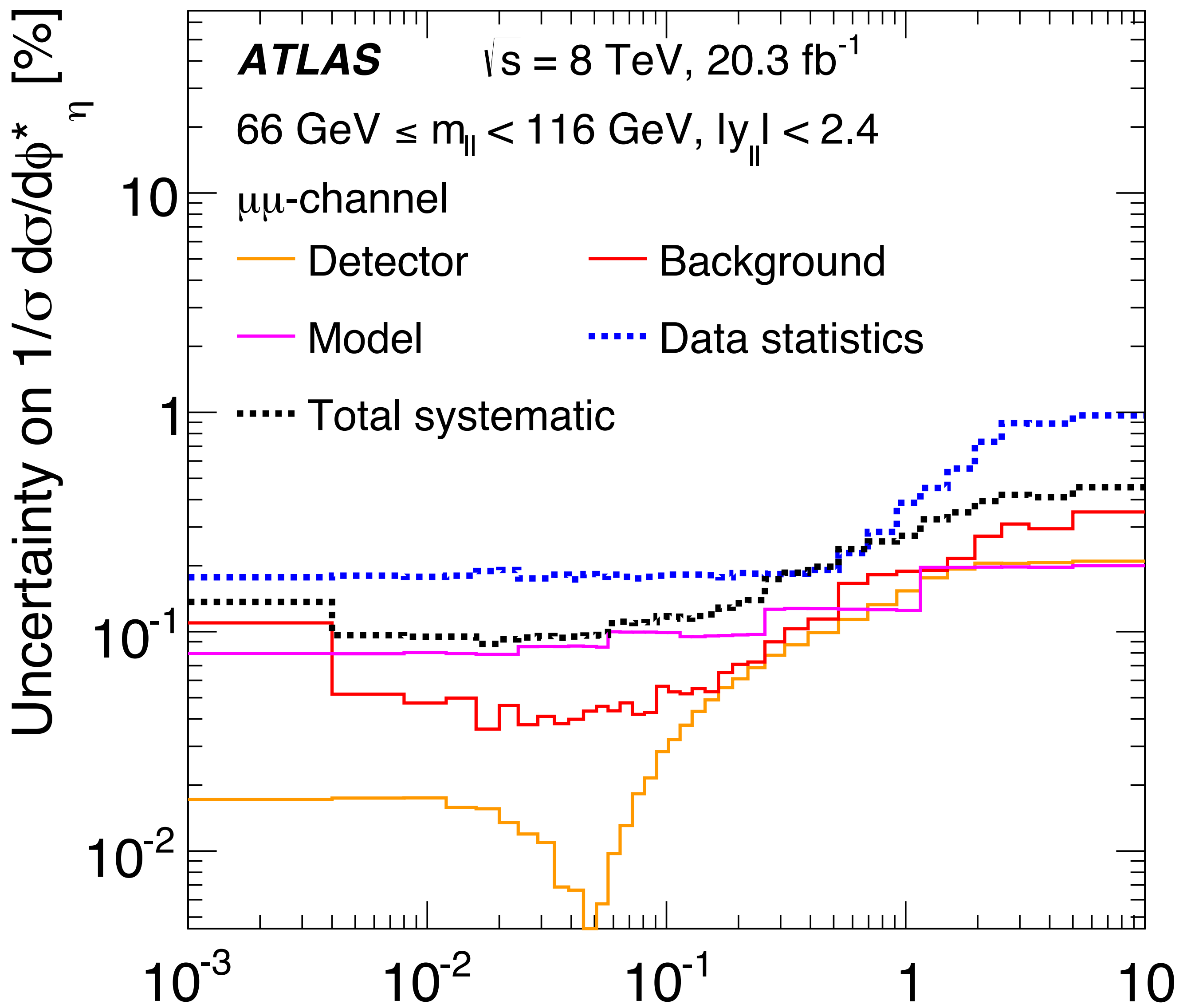


Previous results: ϕ^*_η observable

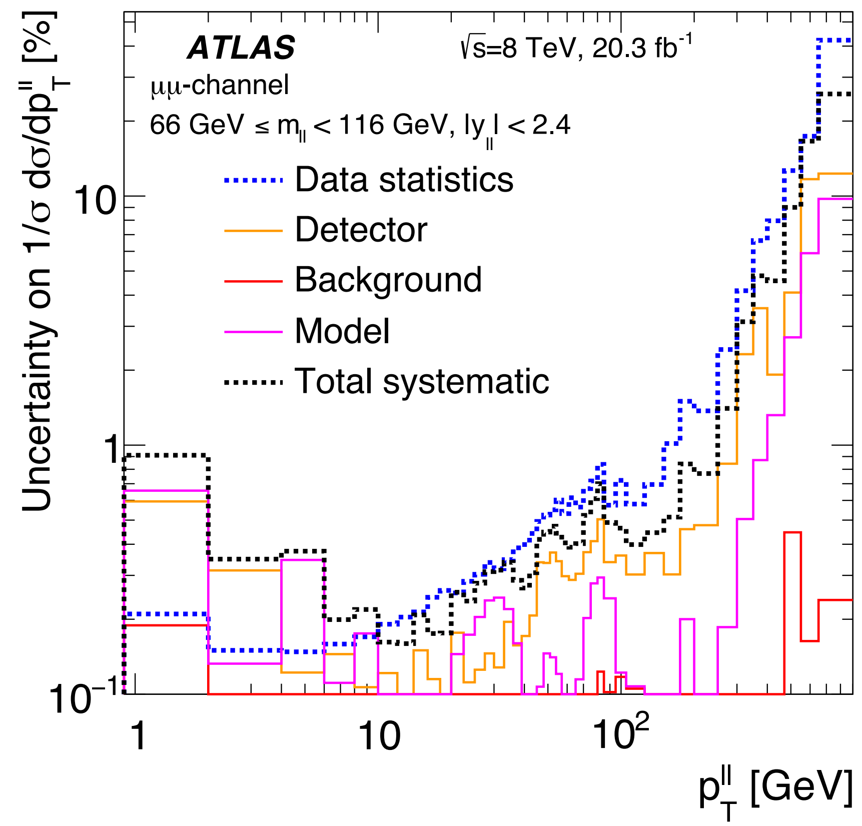


Gehrmann-De Ridder, Gehrmann, Glover, Huss, Morgan - arXiv:1610.01843
JHEP 11(2016)094

ϕ^*_η observable



ϕ^*_η - spectrum



p_T^Z - spectrum

$$\phi^*_\eta = \tan\left(\frac{\phi_{\rm acop}}{2}\right) \cdot \sin(\theta^*_\eta)$$

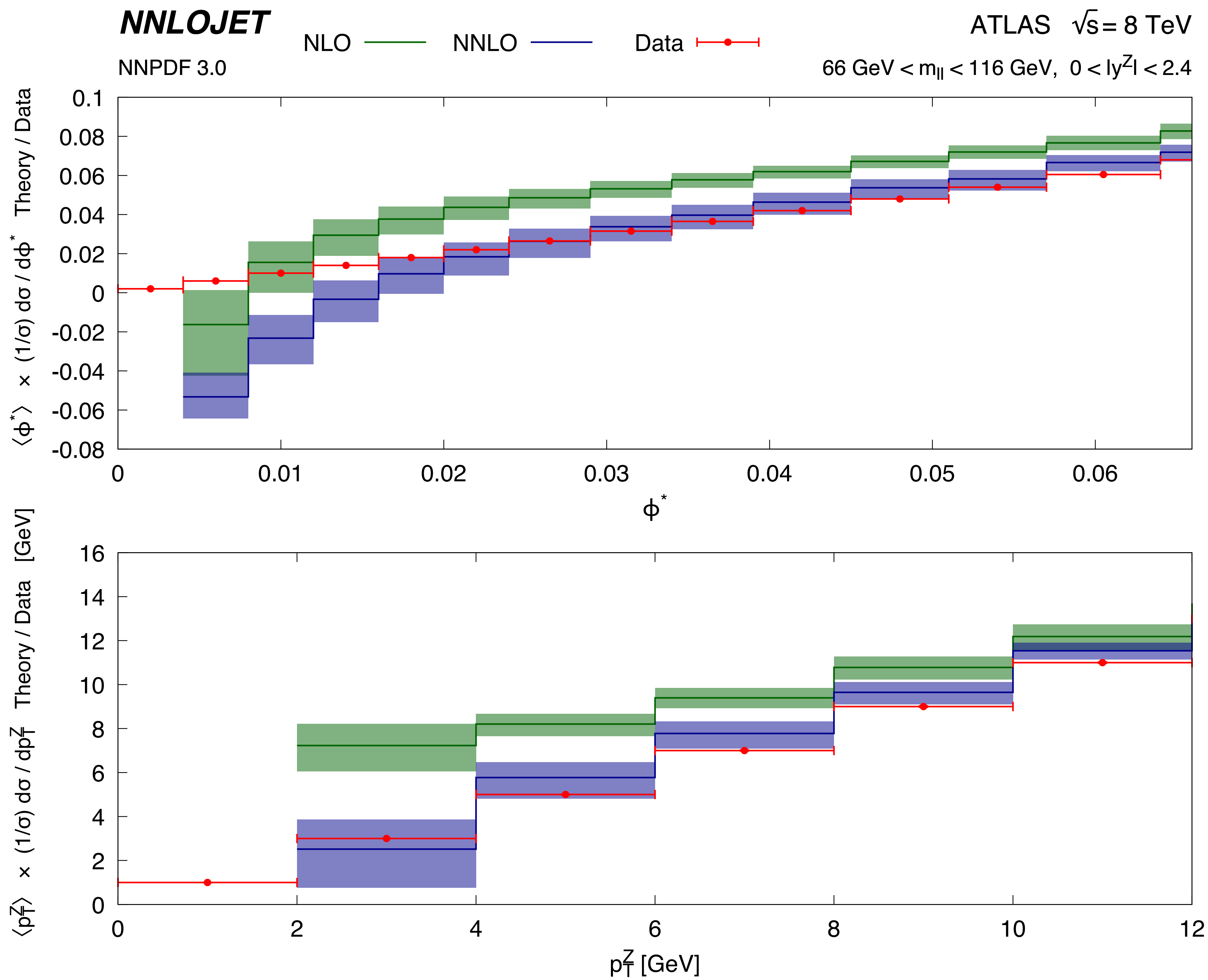
ϕ^*_η depends on $l^\pm$ directions

Not on lepton energies - Banfi et al.

$$\phi_{\rm acop} = \pi - \Delta\phi$$

$$\cos(\theta^*_\eta) = \tanh[(\eta^l - \eta^{\bar{l}})/2]$$

ϕ^*_η observable



Approx. relation $\phi^*_\eta \approx \frac{p_T^Z}{2m_{ll}}$

NNLO - 'reliable' to: $p_T^Z \sim 4$ GeV, $\phi^* \sim 0.02$

NLO - not reliable

$$(T^{a_1}T^{a_2}\cdots T^{a_{n-1}}T^{a_n})_{ij} \equiv (a_1 a_2 \cdots a_{n-1} a_n)_{ij},$$

$$\mathrm{Tr}(T^{a_1}T^{a_2}\cdots T^{a_{n-1}}T^{a_n}) \equiv (a_1 a_2 \cdots a_{n-1} a_n).$$

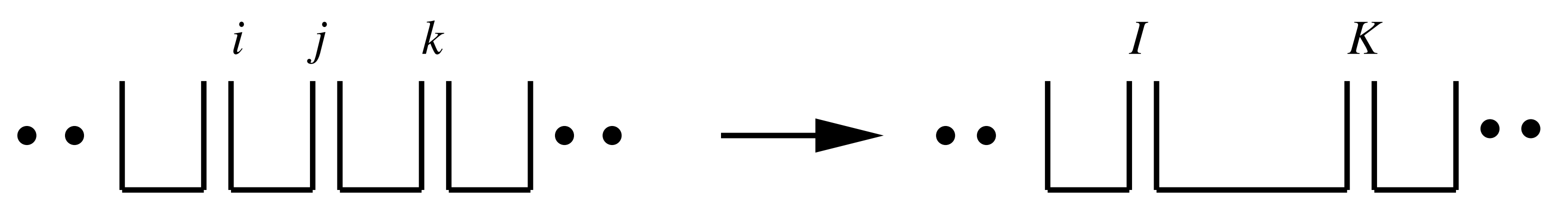


Figure 2: Colour connection of the partons showing the parent and daughter partons for the single unresolved antenna.

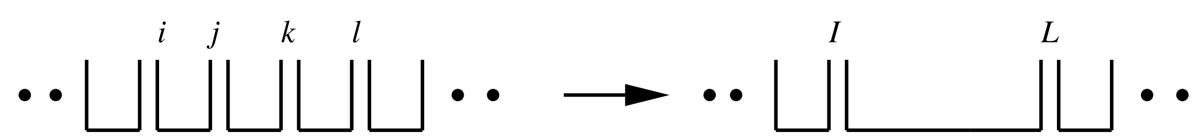


Figure 4: Colour connection of the partons showing the parent and daughter partons for the double unresolved antenna.

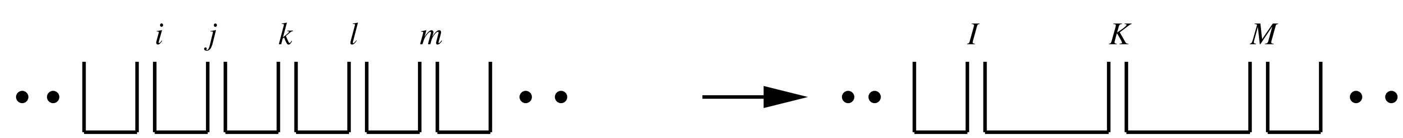


Figure 5: Colour connection of the partons showing the parent and daughter partons for two adjacent single unresolved antennae.

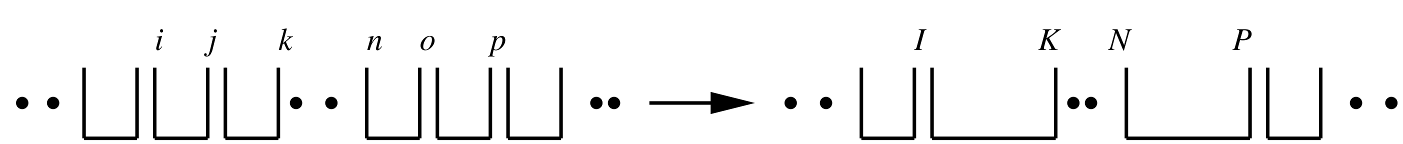


Figure 6: Colour connection of the partons showing the parent and daughter partons for two disconnected single unresolved antennae.