# Phenomenology with $\gamma/Z + X$

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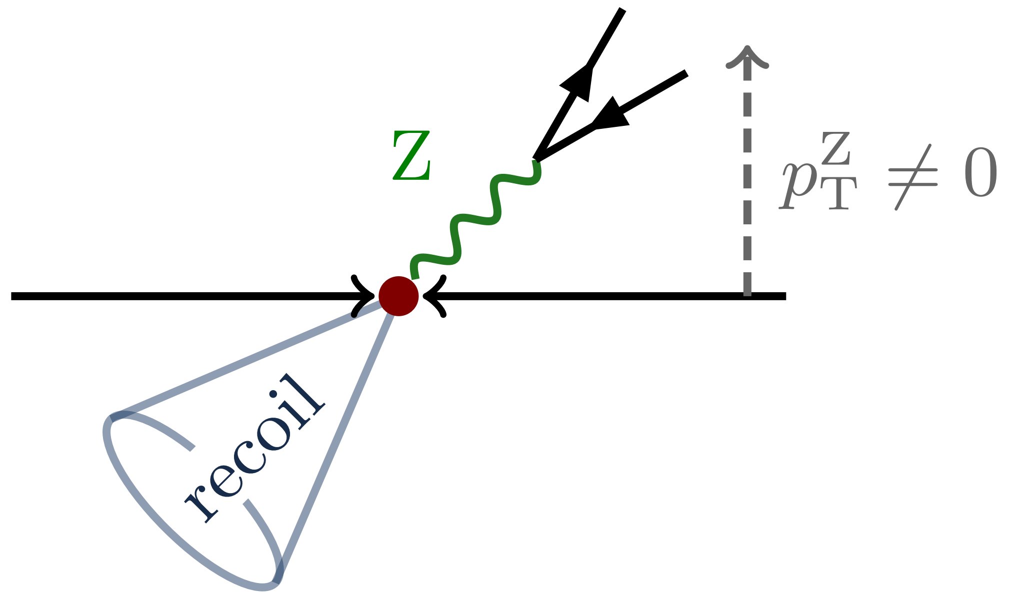
# Outline of topics:

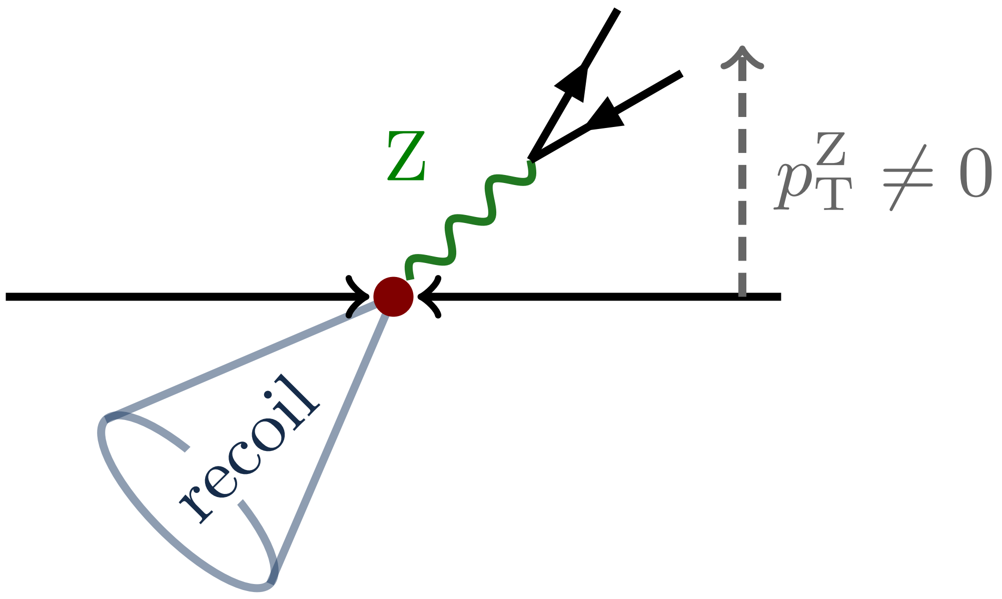
- **Introduction:**
  - physics motivation
  - framework



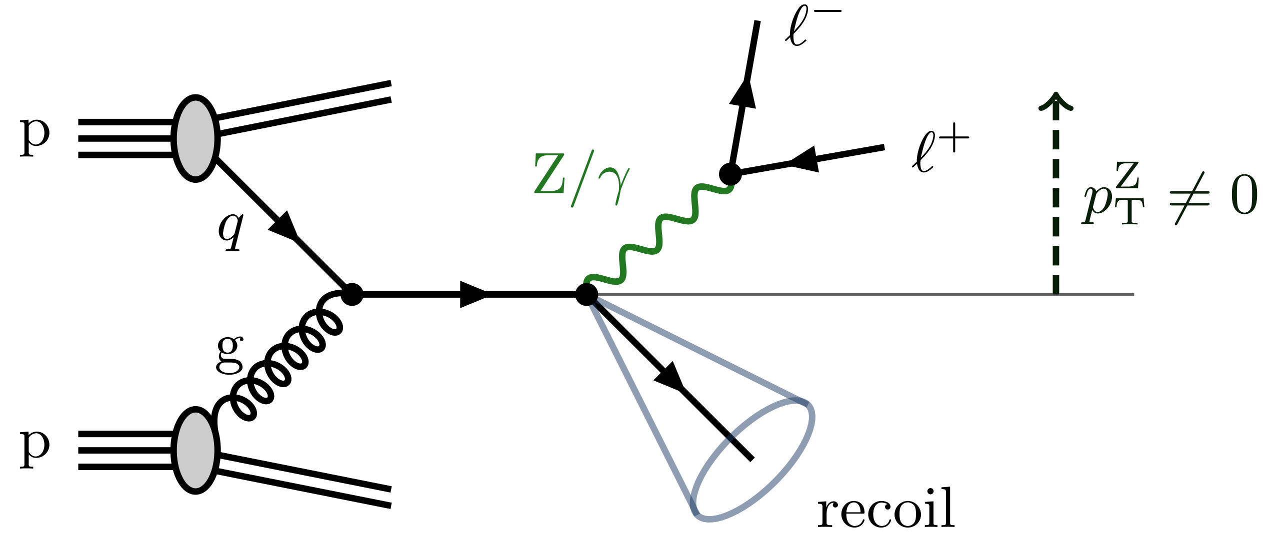

- **Summary of previous results:**
  - inclusive $p_T^Z$ spectrum
  - $\phi_\eta^*$ observable

- **New results:**
  - evaluation of angular coefficients $A_0, A_2$

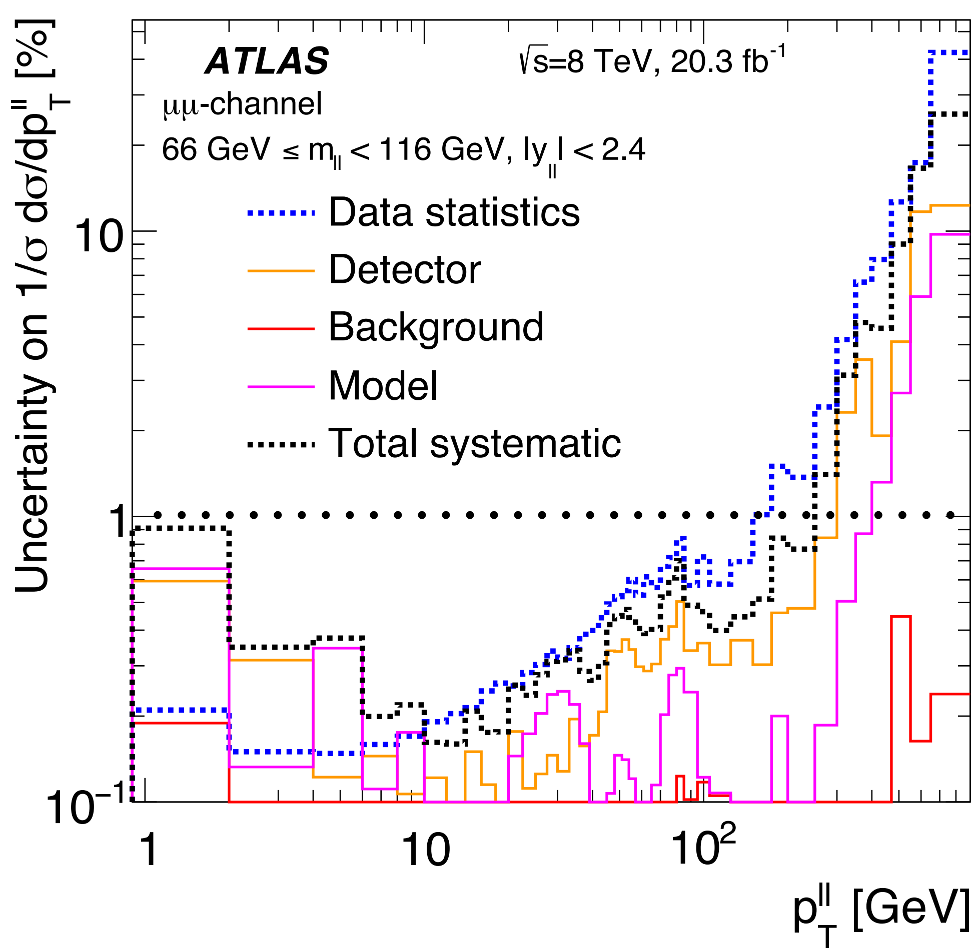
# Introduction



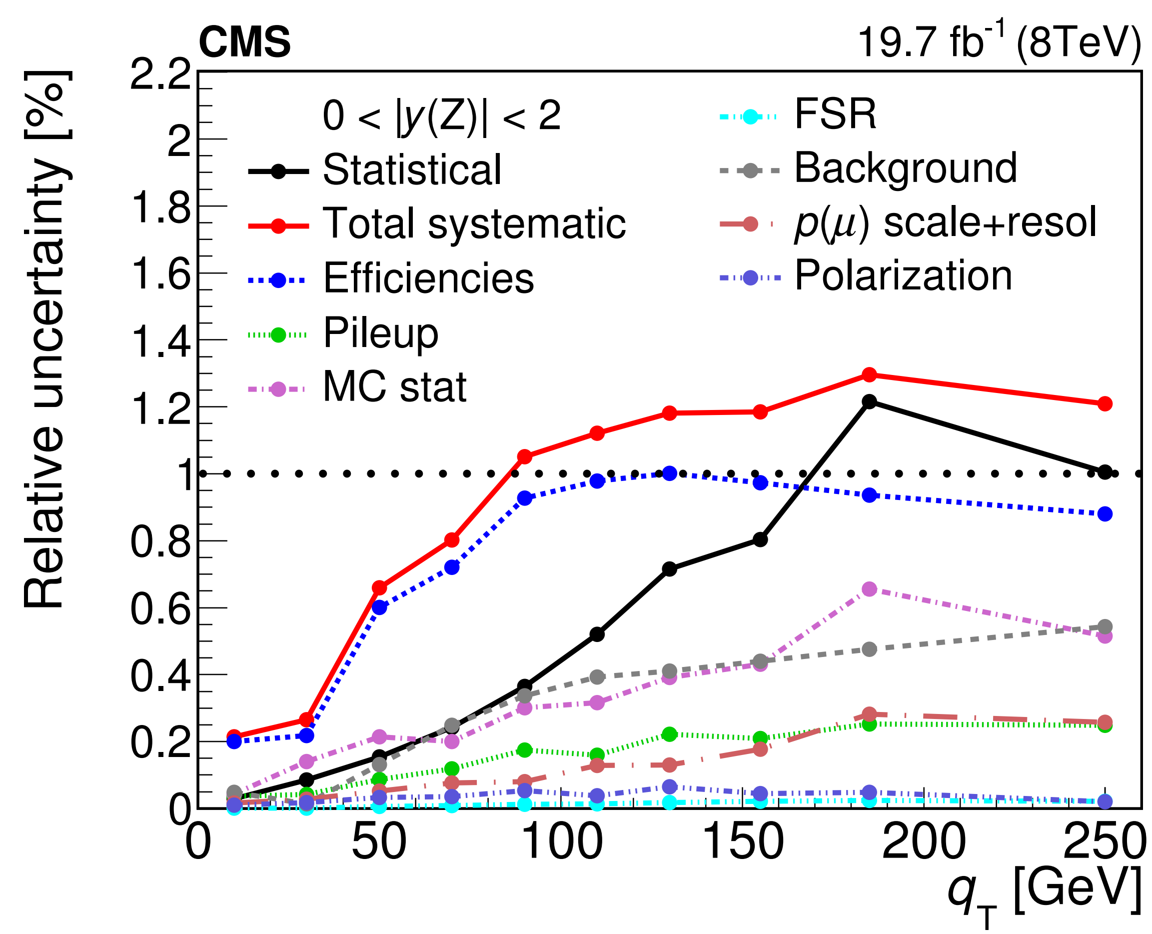
# physics motivation




## Experimental status (sub %)

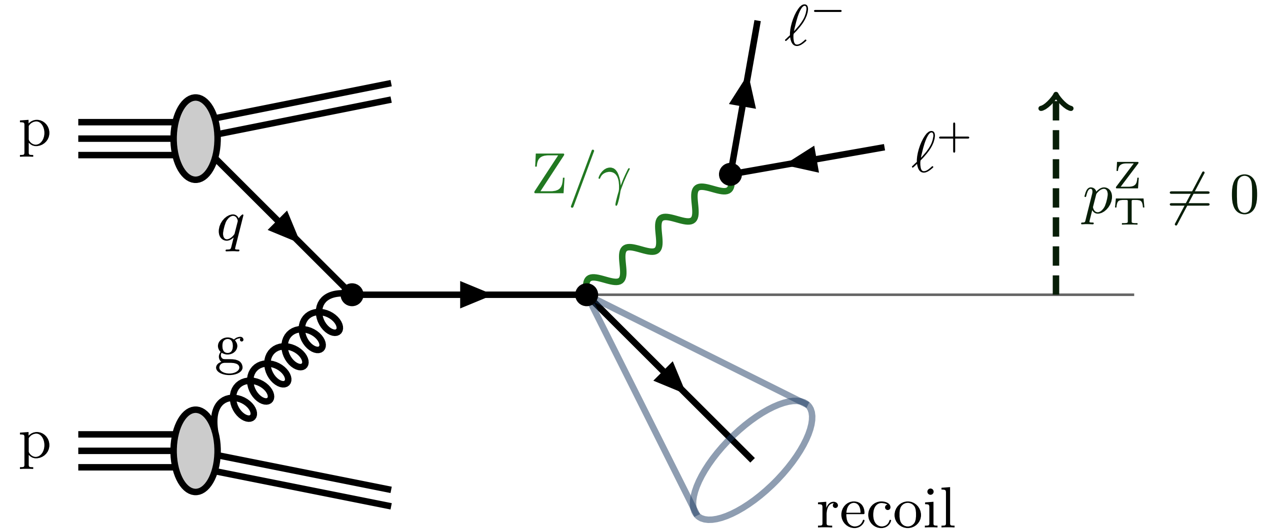



ATLAS, arXiv: 1512.02192




CMS, arXiv: 1504.03511

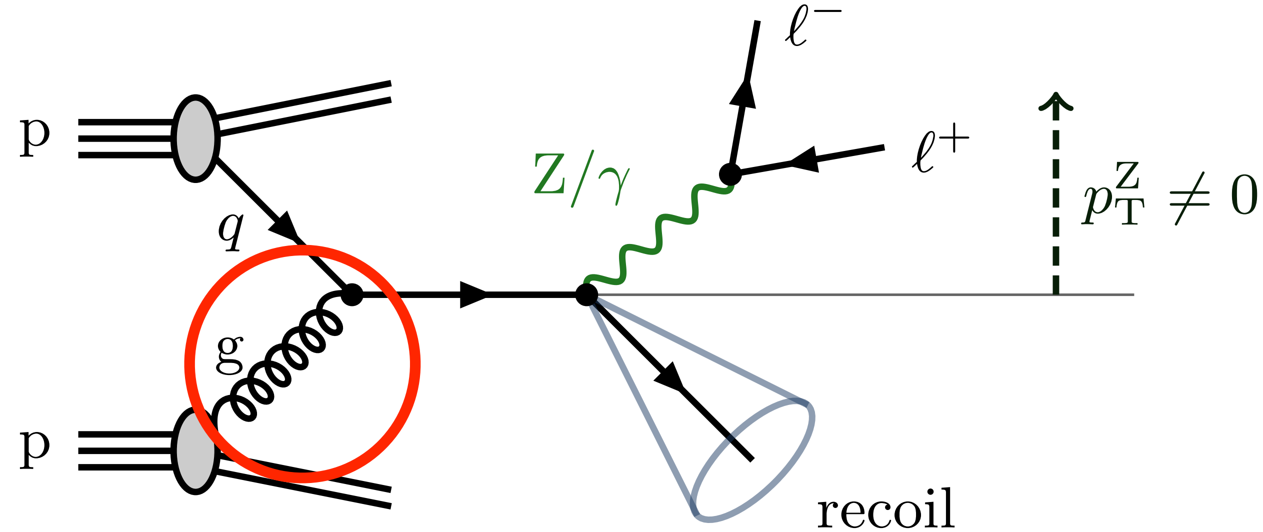
# physics motivation




First and foremost, a testing ground for precision 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 …

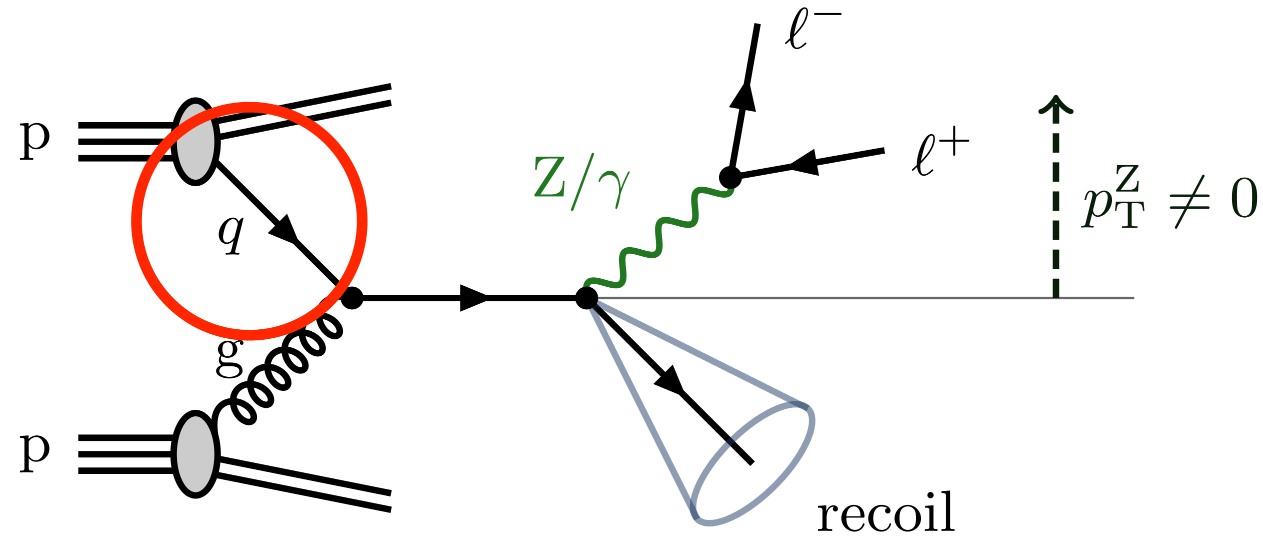
# physics motivation




Primary physics applications:

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

# physics motivation



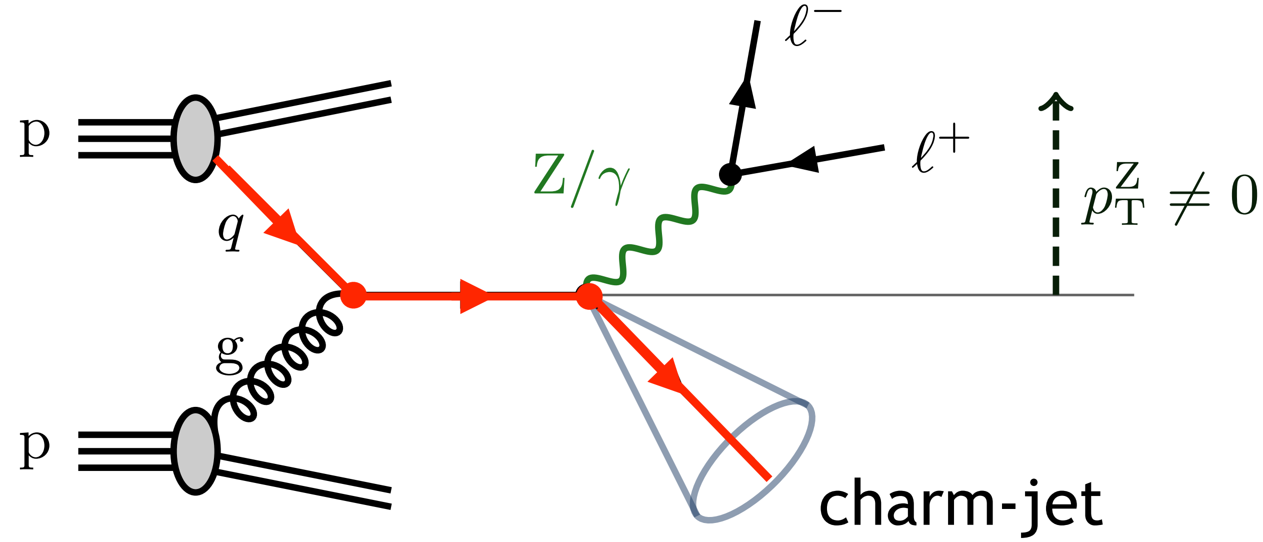

## Primary physics applications:

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

ii) Probe large-x u/d 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



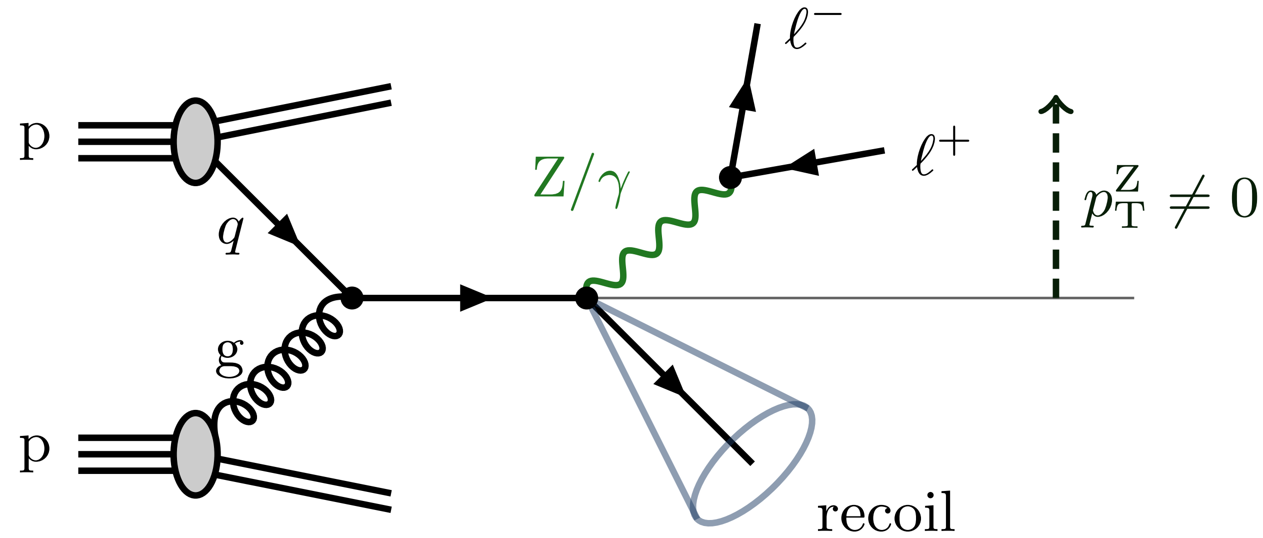

Primary physics applications:

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

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

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

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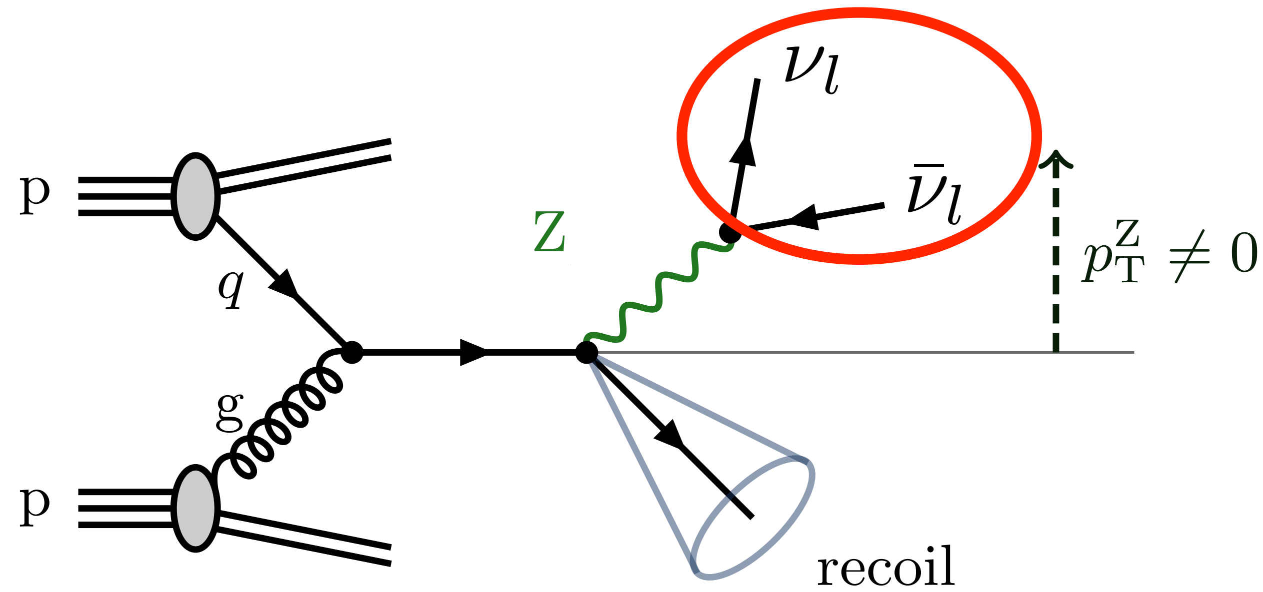
iii) Test for intrinsic charm: Boettcher, Ilten, Williams - arXiv:1512.06666

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

# physics motivation

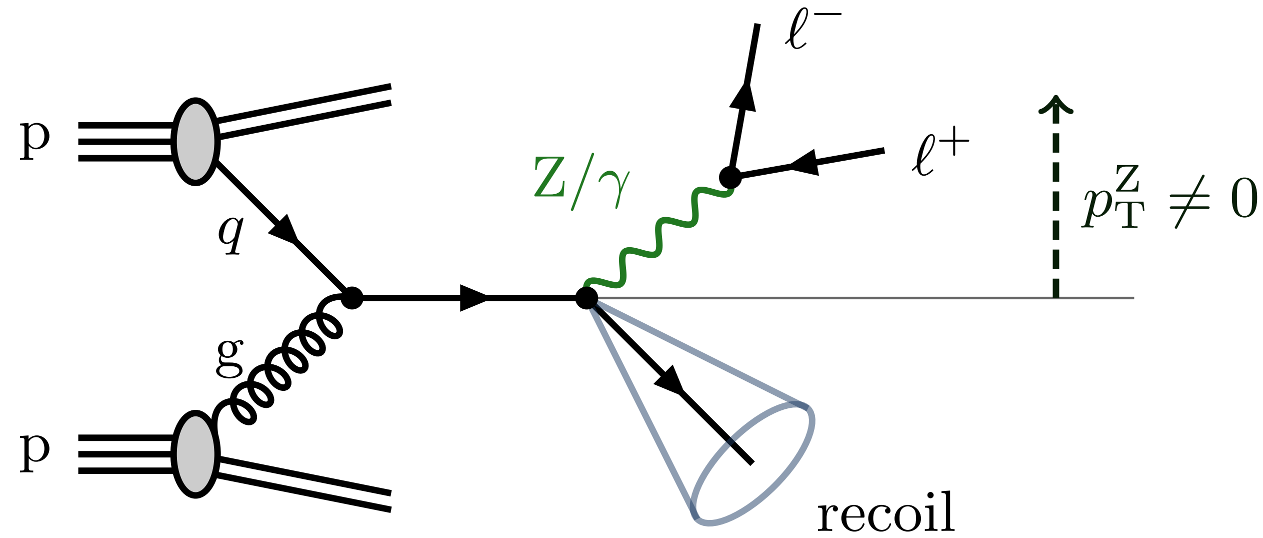



Primary physics applications:

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 (ATLAS MW extraction) -arXiv:1701.07240

Monte Carlo sample reweighting of:

- $p_T^Z/p_T^W$ - spectrum
- Angular coefficients in Z boson production

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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
[IPPP Durham, MPI Munich, Zurich (ETH and UZH), Beijing]

## Common framework for NNLO corrections

- parton level Monte Carlo generator
- basis: Antenna Subtraction formalism

*Gehrmann-De Ridder, Gehrmann, Glover - arXiv:0505111*

- In progress: APPLfast-NNLO interface

*PDF fitting with full NNLO calculations*

**Processes:**

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

$pp \to H + 0, 1, 2$ jets

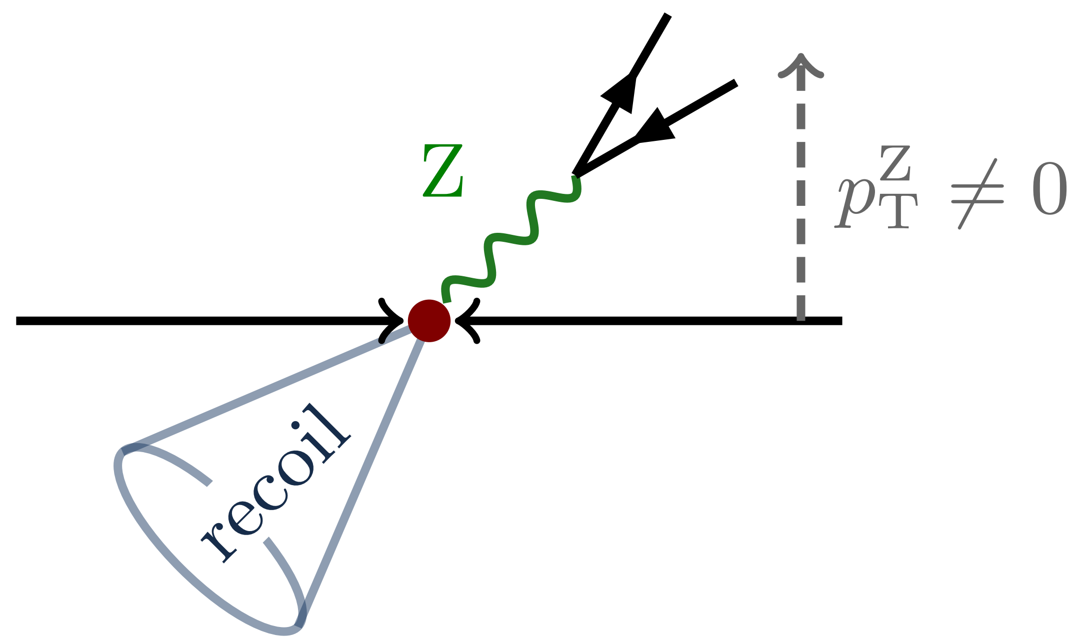
$pp \to$ dijets

$ep \to 1, 2$ jets

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

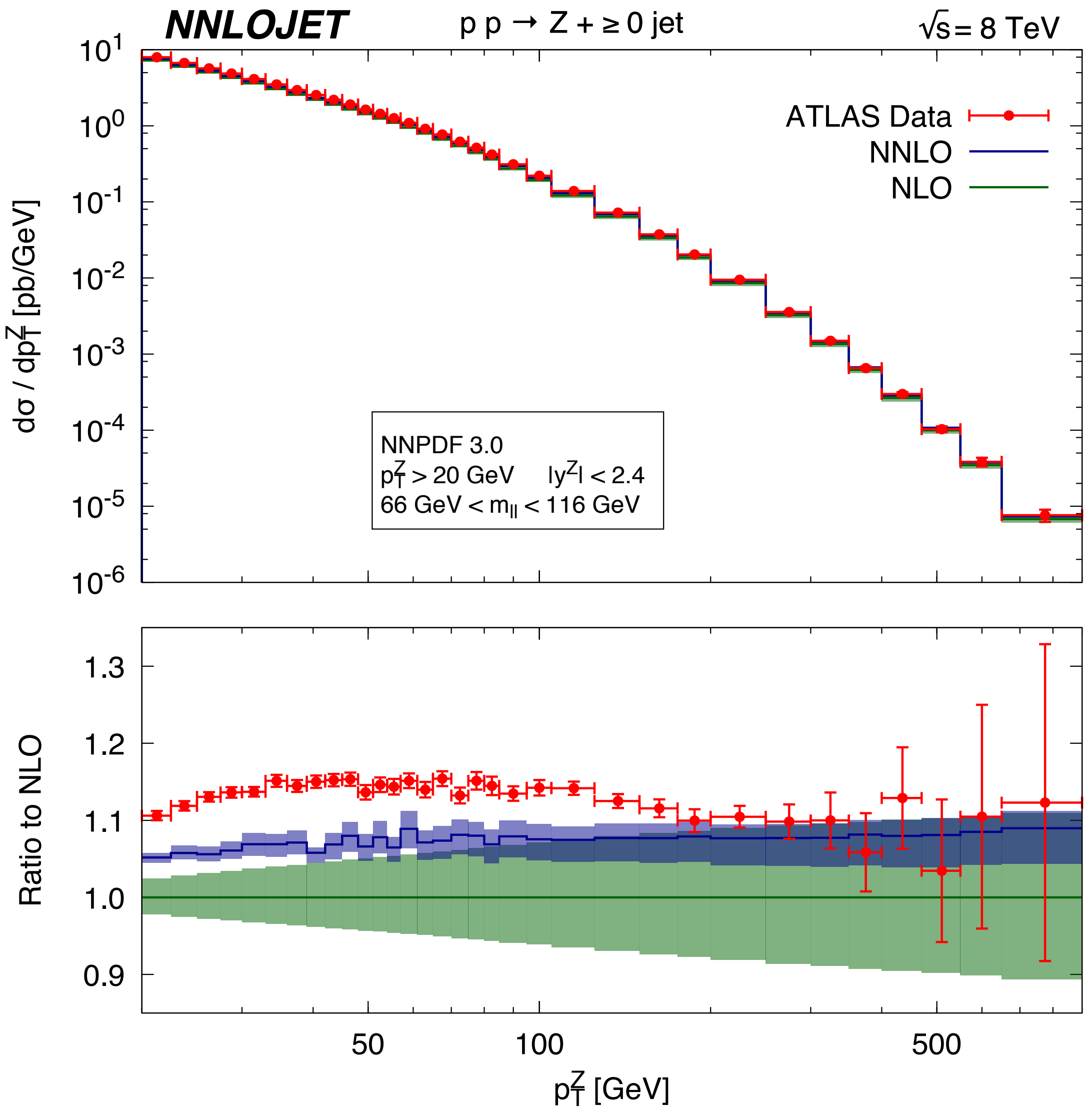
...

# Previous results: inclusive $p_T^Z$ spectrum

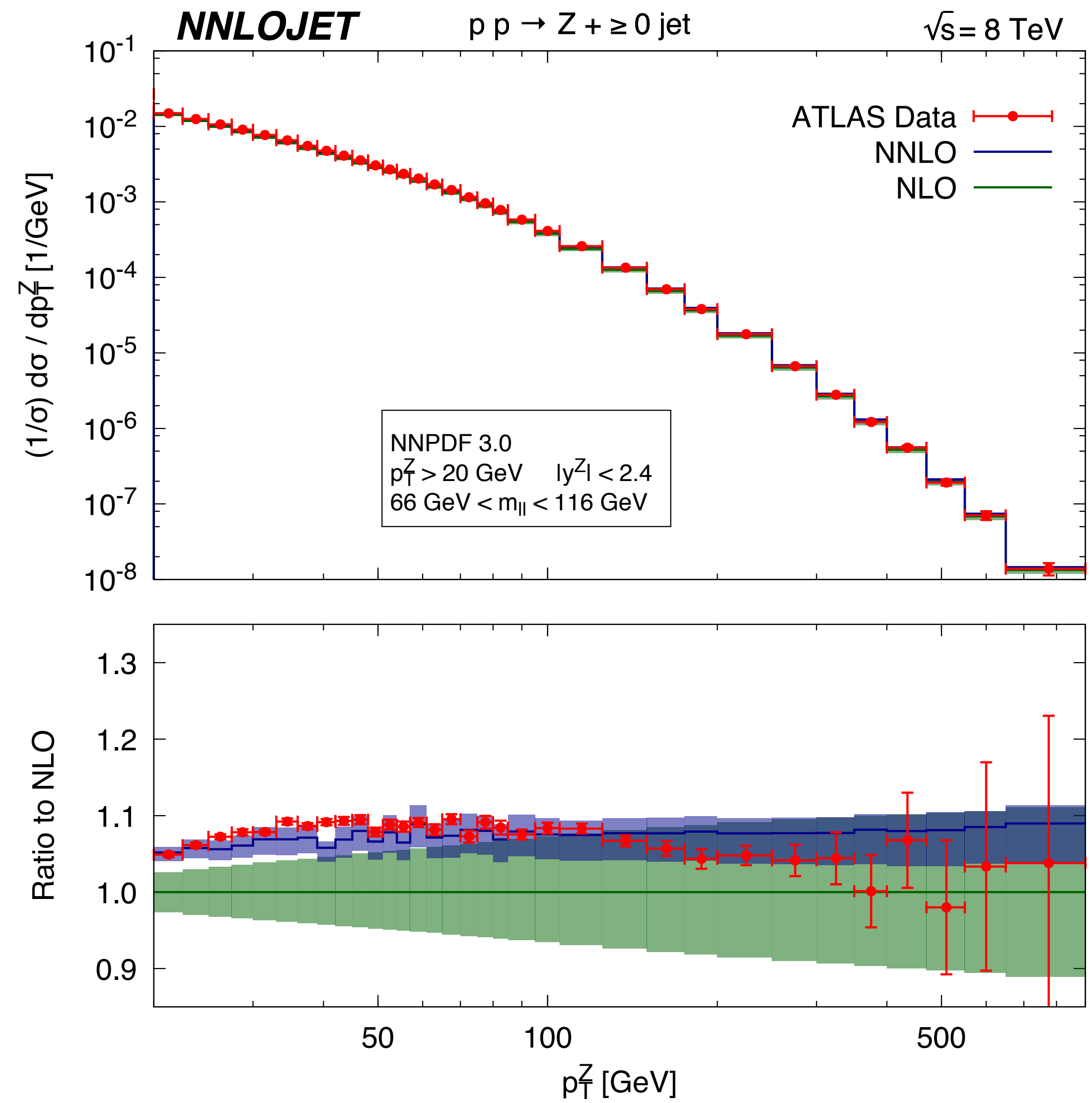



Gehrmann-De Ridder, Gehrmann, Glover, Huss, Morgan - arXiv:1605.04295
JHEP 07(2016)133

# inclusive $p_T^Z$ spectrum




Absolute cross section



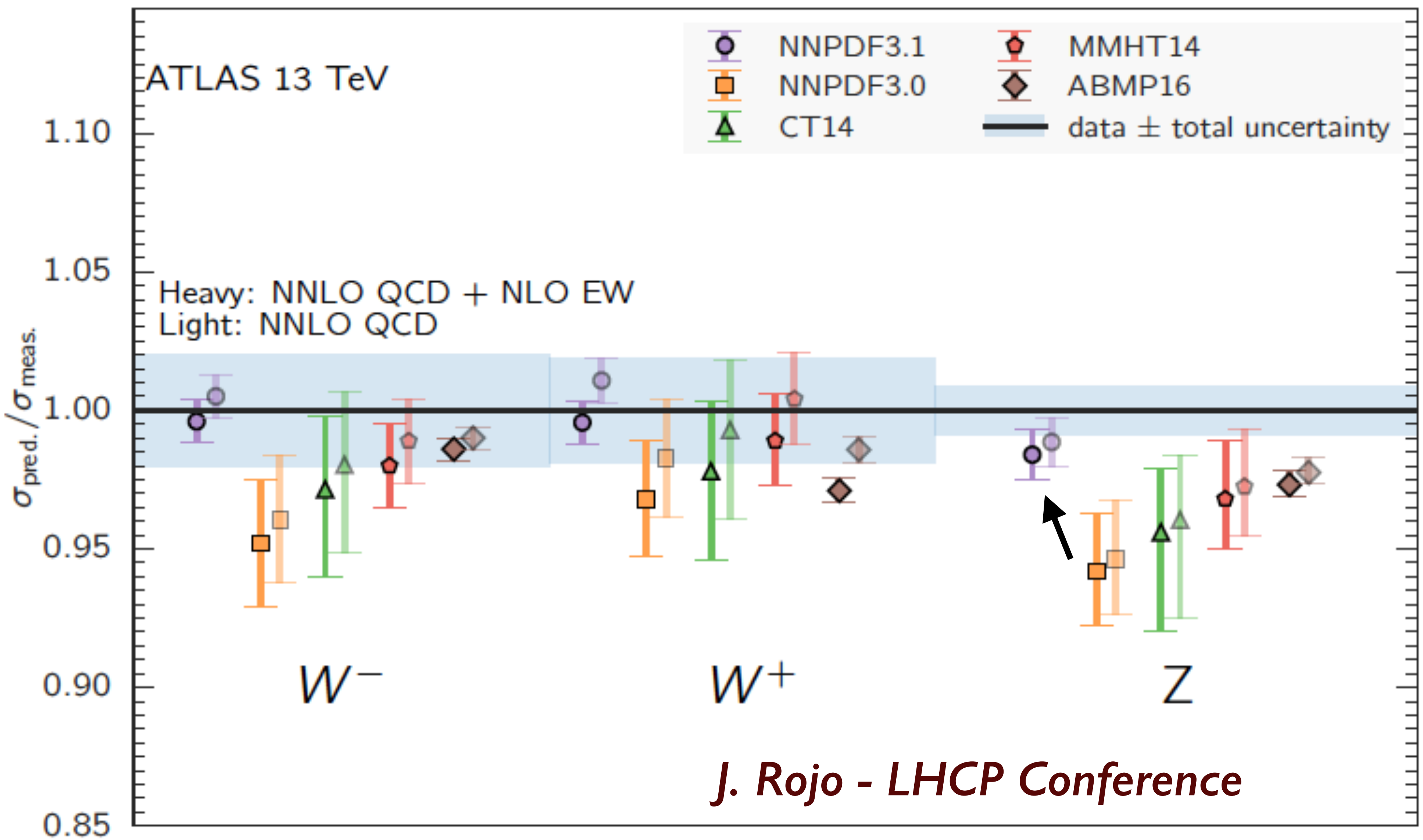

Normalised cross section

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

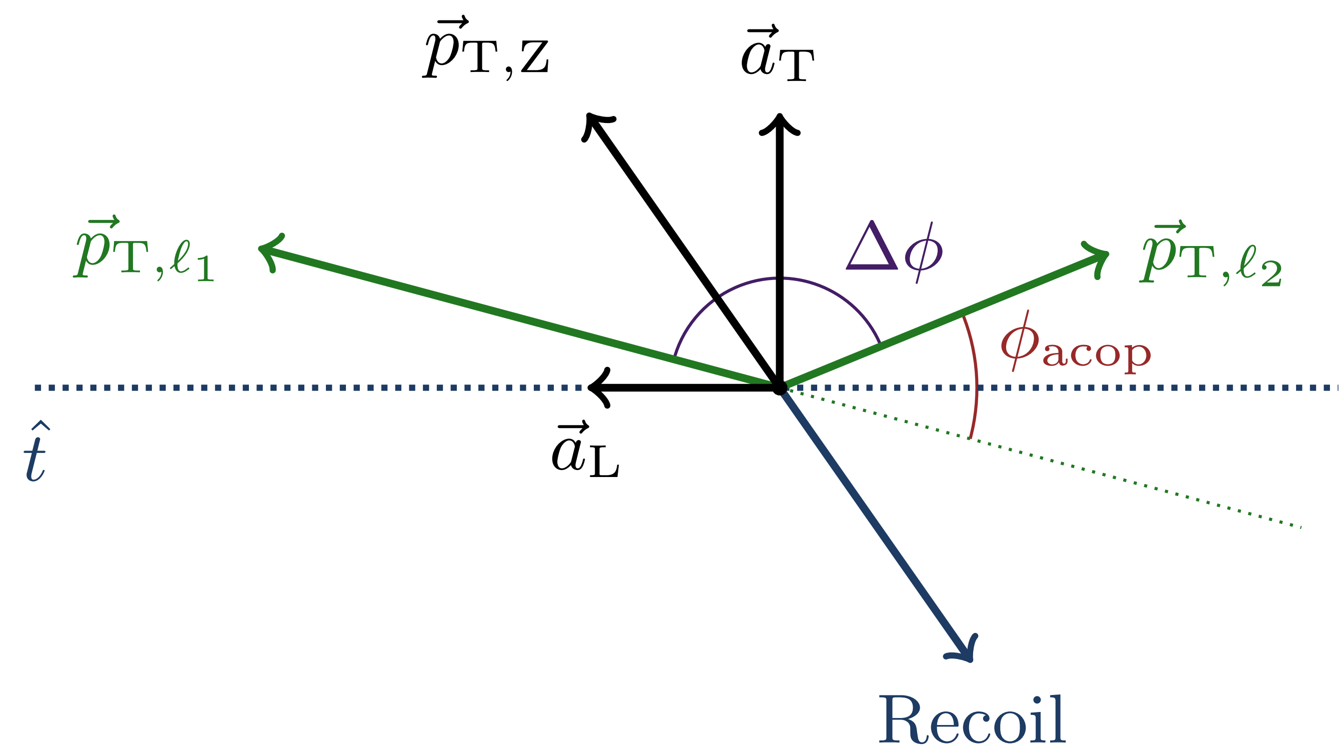
# inclusive $p_T^Z$ spectrum




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

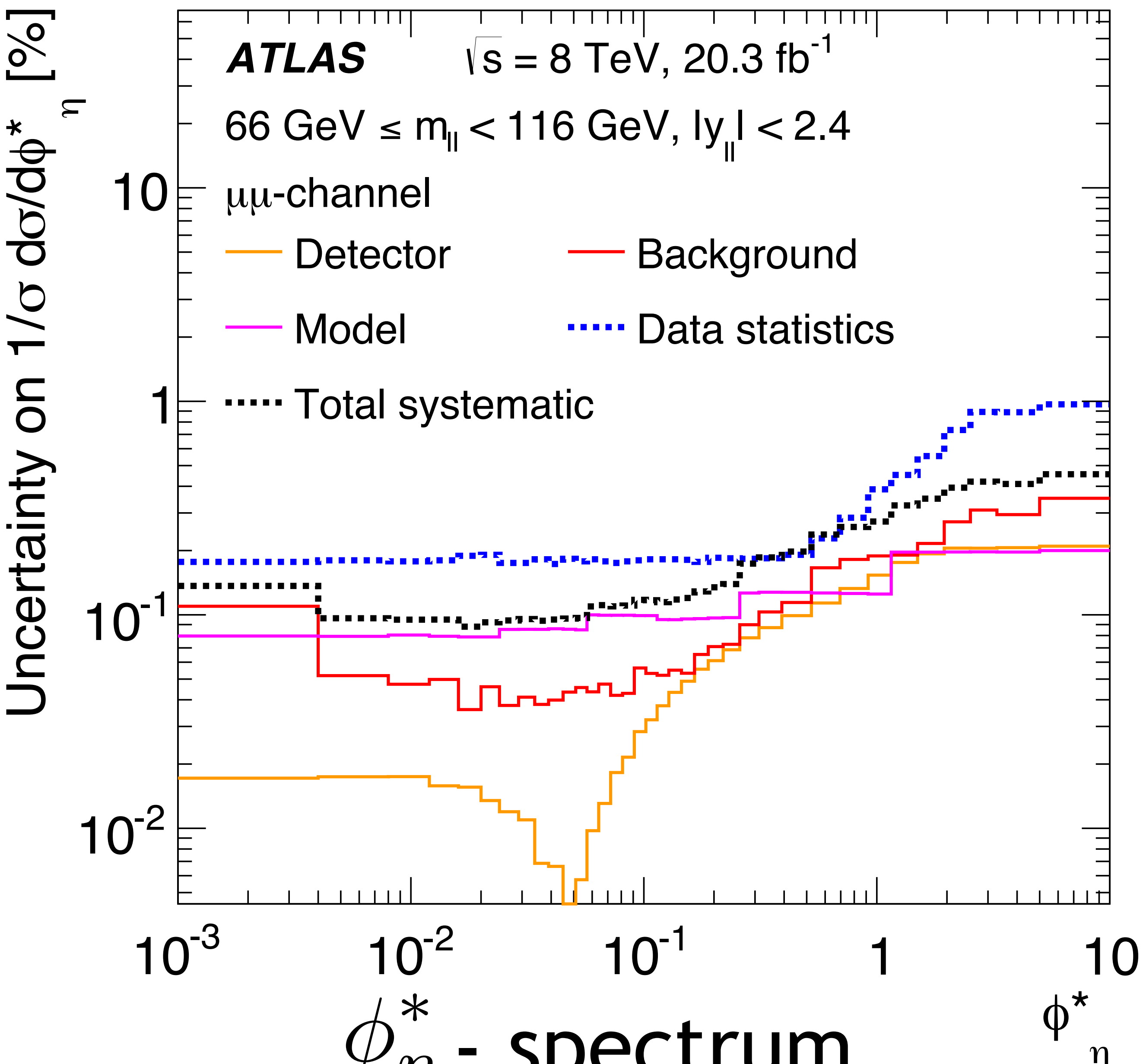
- NNPDF3.0 $\rightarrow$ NNPDF3.1, fit non-perturbative charm
- NNPDF3.0 $\rightarrow$ NNPDF3.1, $m_c^{inp.}$ = 1.275 $\rightarrow$ 1.51 GeV

# Previous results: $\phi^*_\eta$ observable

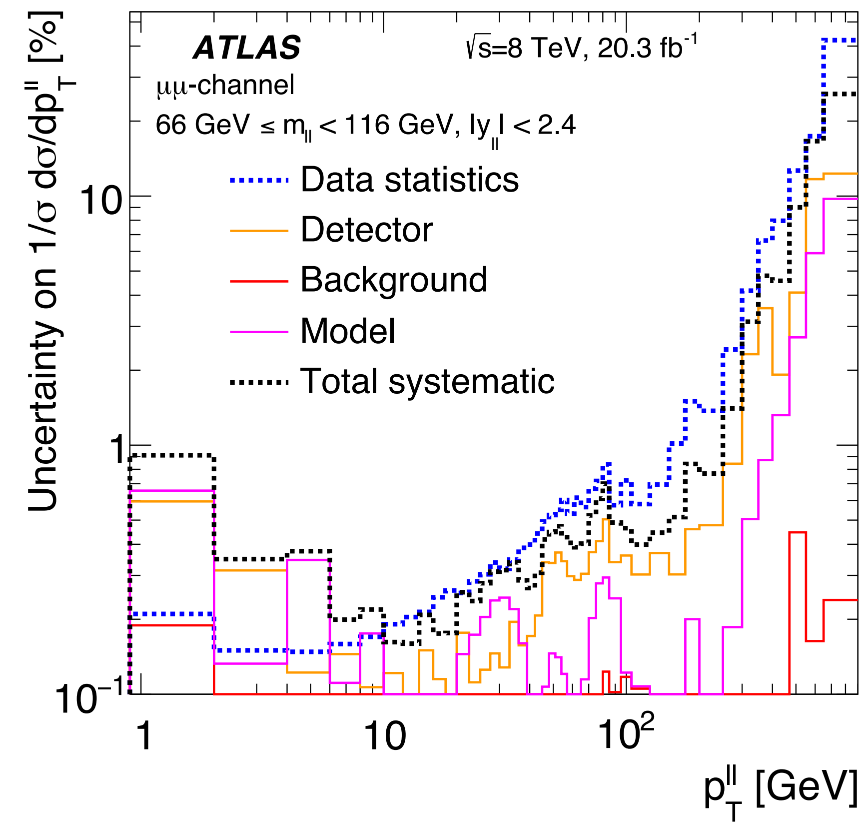



Gehrmann-De Ridder, Gehrmann, Glover, Huss, Morgan - arXiv:1610.01843
JHEP 11(2016)094

# $\phi^*_\eta$ observable




$\phi^*_\eta$ - spectrum




$p_T^Z$ - spectrum

$\phi^*_\eta$ depends on $l^\pm$ directions

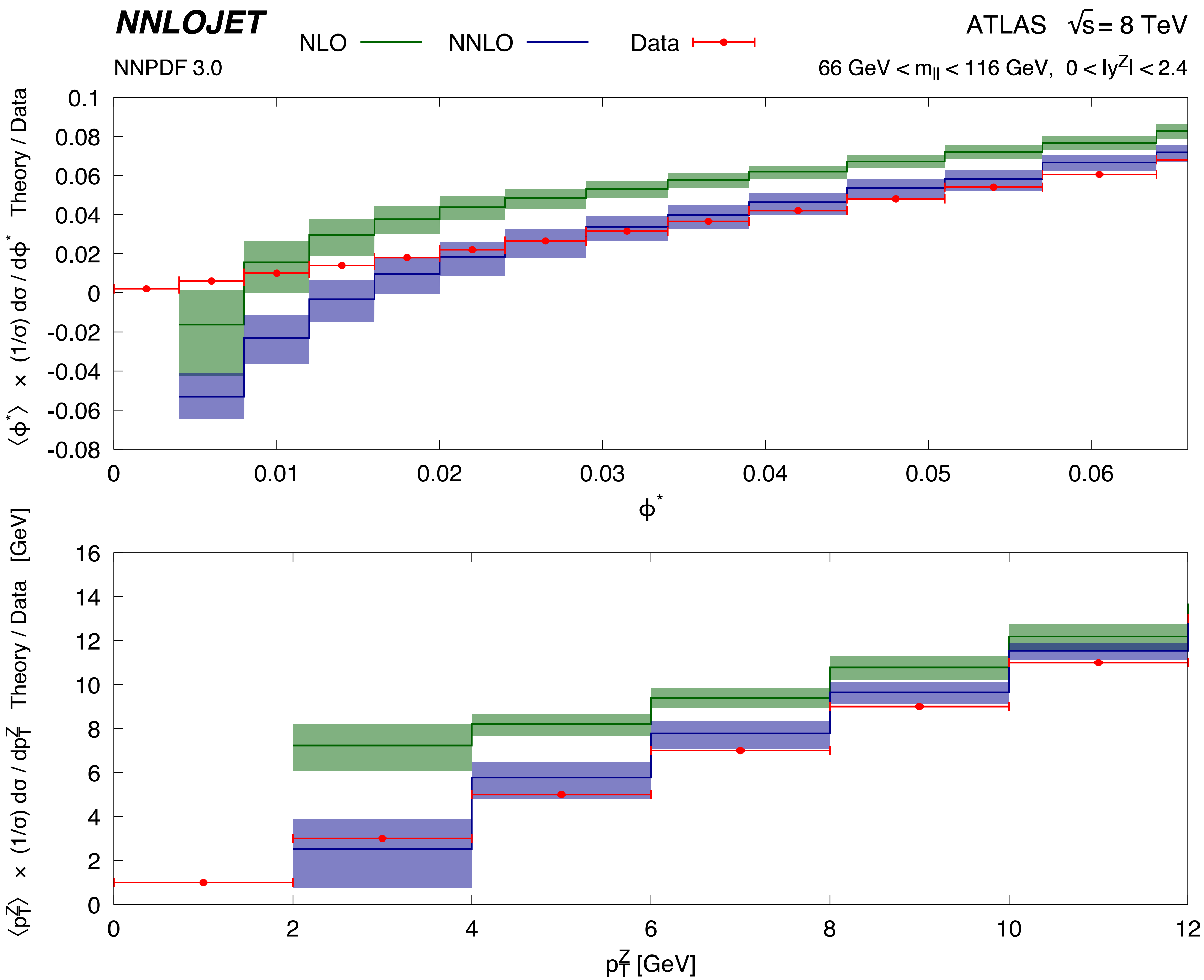
***Not on lepton energies - Banfi et al.***

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

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

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

# $\phi^*_\eta$ observable

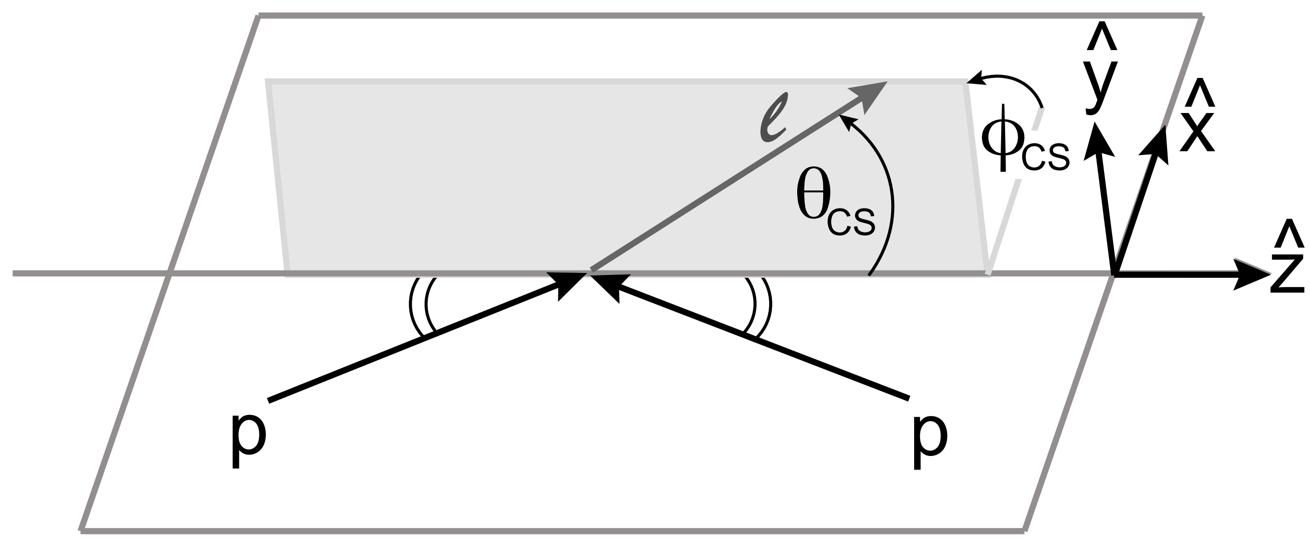



Approx. relation $\phi^*_\eta \approx \frac{p_T^Z}{2m_{ll}}$

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

NLO - not reliable

# New results: angular coefficients




**RG**, Gehrmann-De Ridder, Gehrmann, Glover, Huss - Ongoing

# New results: angular coefficients

Consider the process: $pp \to (Z \to l^+ l^-) + X$

Expand multi-diff. cross section in harmonic polynomials $p_i(\theta,\ \phi)$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^Z\ \mathrm{d}y_Z\ \mathrm{d}m_Z\ \mathrm{d}\cos\theta\ \mathrm{d}\phi} = \frac{3}{16\pi}\frac{\mathrm{d}\sigma^{U+L}}{\mathrm{d}\mathbf{p_T^Z}\ \mathrm{d}\mathbf{y_Z}\ \mathrm{d}\mathbf{m_Z}}$$

$$\Big\{(1+\cos^2\theta) + \frac{1}{2}\ \mathbf{A_0}(1-3\cos^2\theta) + \mathbf{A_1}\ \sin 2\theta\ \cos\phi$$

$$+\frac{1}{2}\ \mathbf{A_2}\ \sin^2\theta\ \cos 2\phi + \mathbf{A_3}\ \sin\theta\ \cos\phi + \mathbf{A_4}\ \cos\theta$$

$$+\mathbf{A_5}\ \sin^2\theta\ \sin 2\phi + \mathbf{A_6}\ \sin 2\theta\ \sin\phi + \mathbf{A_7}\ \sin\theta\ \sin\phi\Big\}$$

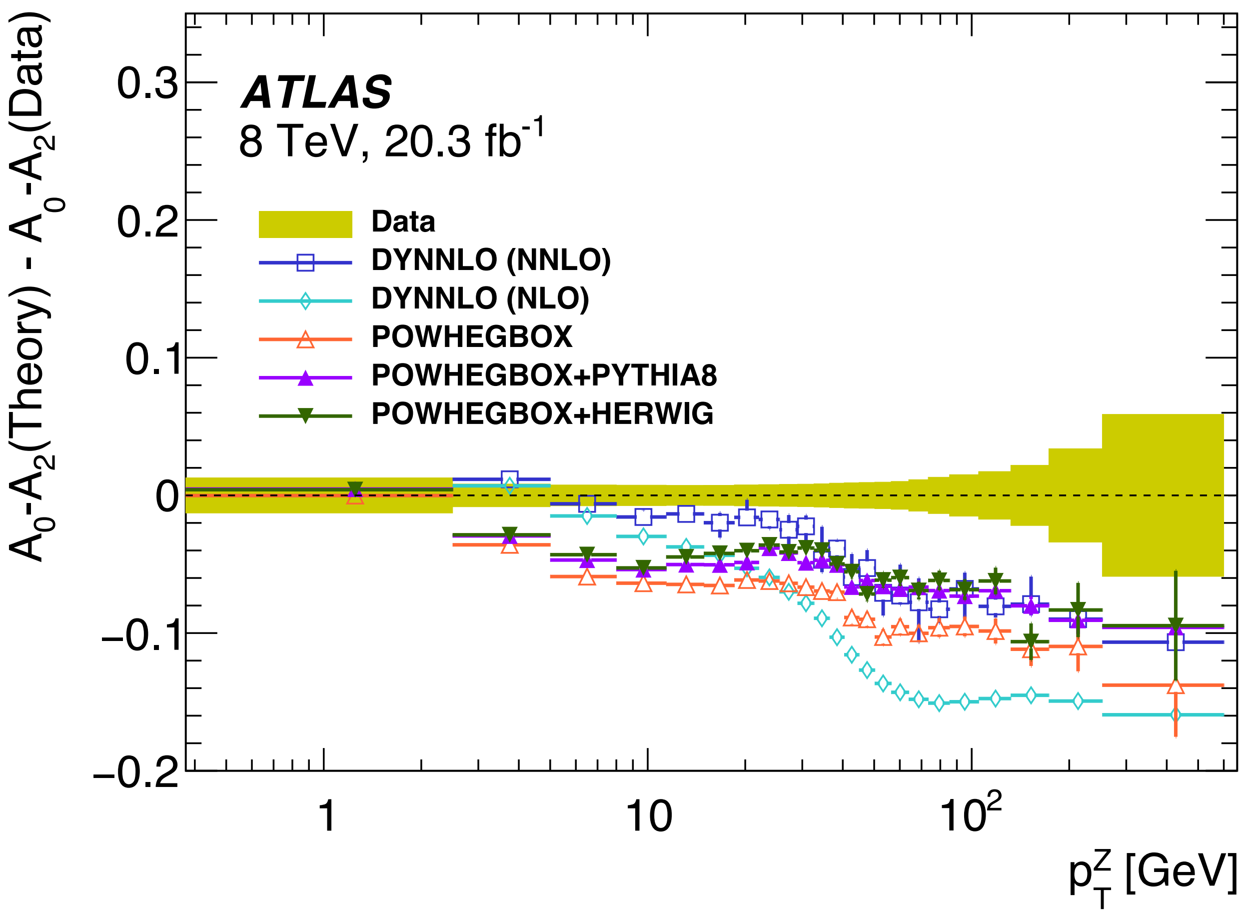
$$\mathbf{A_{0,..,7}}\left[\mathbf{m^Z},\ \mathbf{p_T^Z},\ \mathbf{y^Z}\right] \qquad\qquad p_i(\theta,\phi)$$

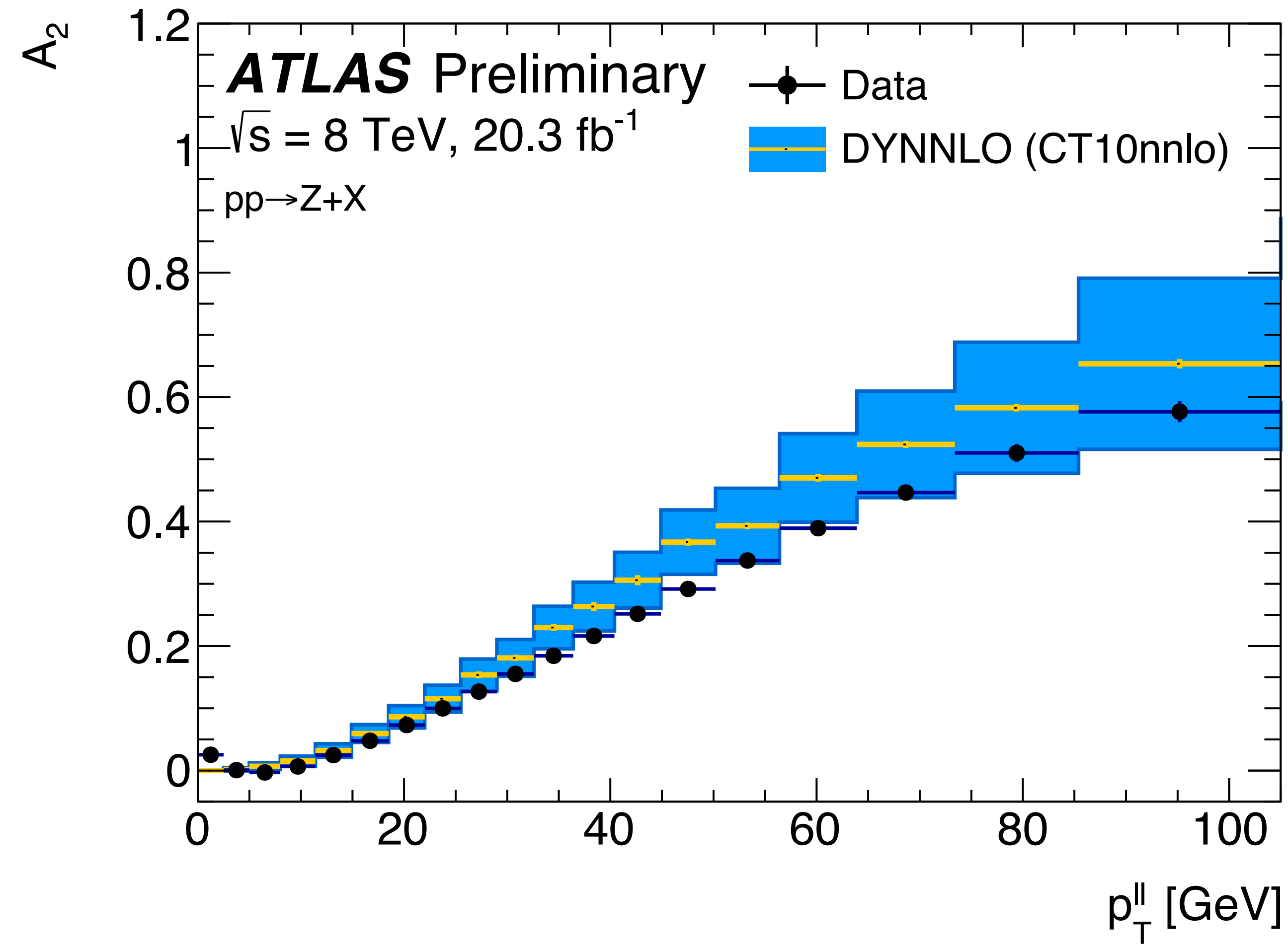
Encode QCD dynamics — Lepton pair kinematics

$$\langle p_i(\theta,\phi)\rangle = \int_{-1}^{1}\mathrm{d}(\cos\theta)\int_0^{2\pi}\mathrm{d}\phi\,\frac{d\sigma}{\mathrm{d}(\cos\theta)\mathrm{d}\phi}p_i(\theta,\phi)$$

*(reference frame dependent)*

# New results: angular coefficients




Large discrepancy for $\mathbf{A_0 - A_2}$

Observed solely for $\mathbf{A_2}$

*(uncertainty `enlarged' to match data)*

For the Z+j process:

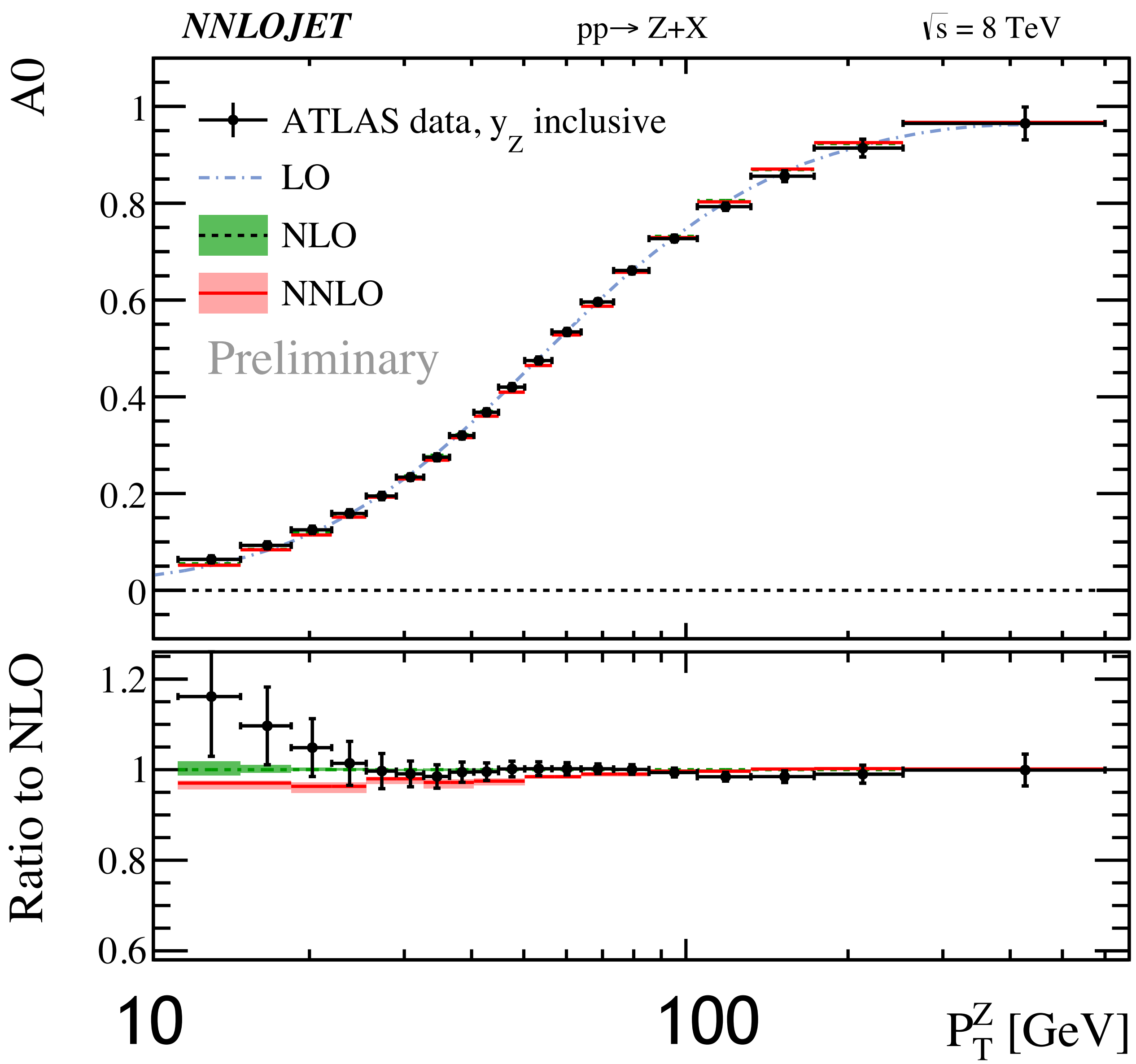
$$\mathbf{A_0[p_T^Z] - A_2[p_T^Z]} = 0\,, \quad \mathcal{O}(\alpha_s^0) \quad \text{Lam-Tung relation}$$

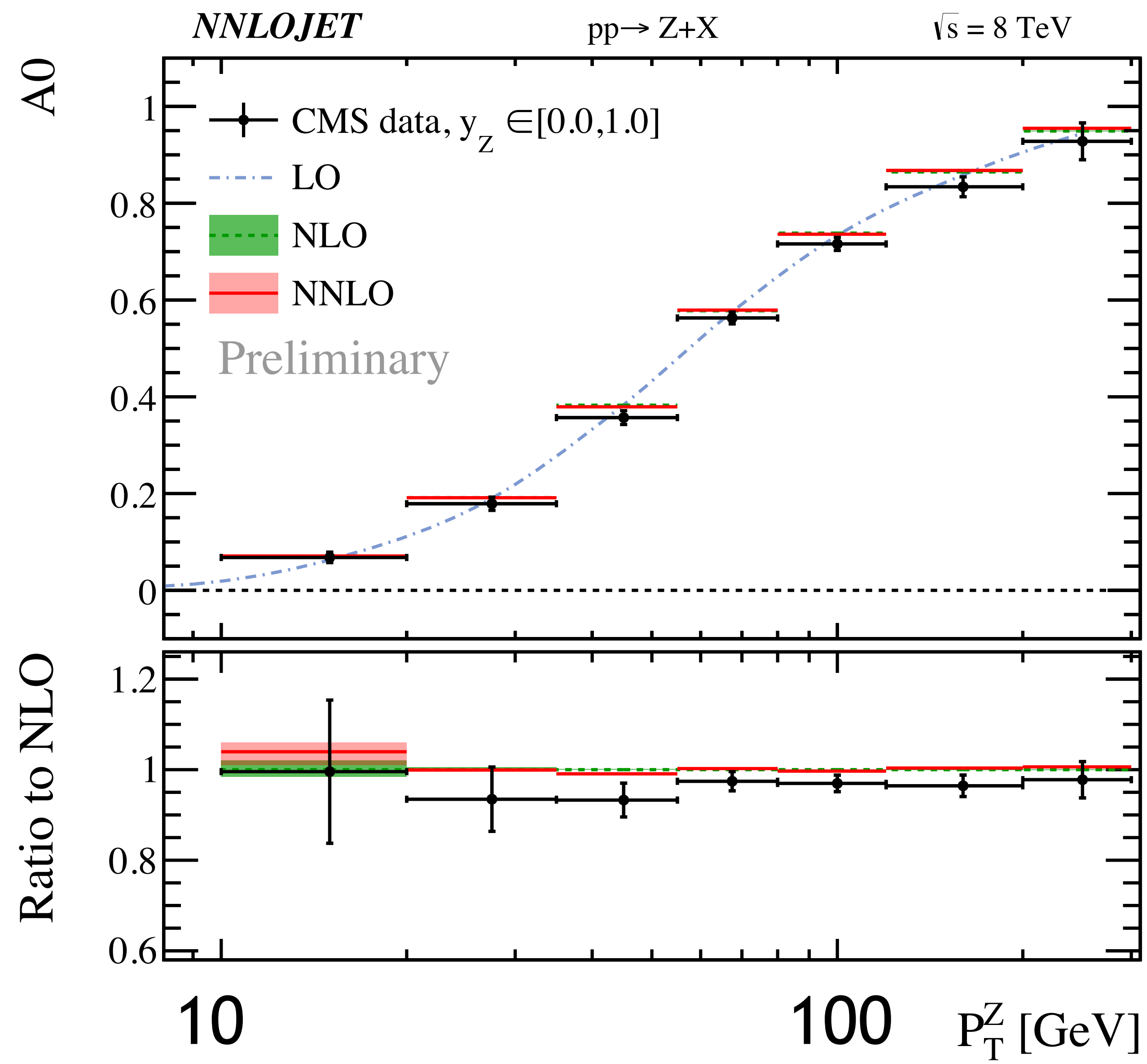
$$\mathbf{A_0[p_T^Z] - A_2[p_T^Z]} \neq 0\,, \quad \mathcal{O}(\alpha_s^1) \quad \text{Effectively 'LO'}$$

$$\mathbf{A_0[p_T^Z] - A_2[p_T^Z]} \neq 0\,, \quad \mathcal{O}(\alpha_s^2) \quad \text{Effectively 'NLO'}$$

*(Collins-Soper frame)*

# New results: angular coefficients




LHS: Comparison to ATLAS

$y_Z$ inclusive

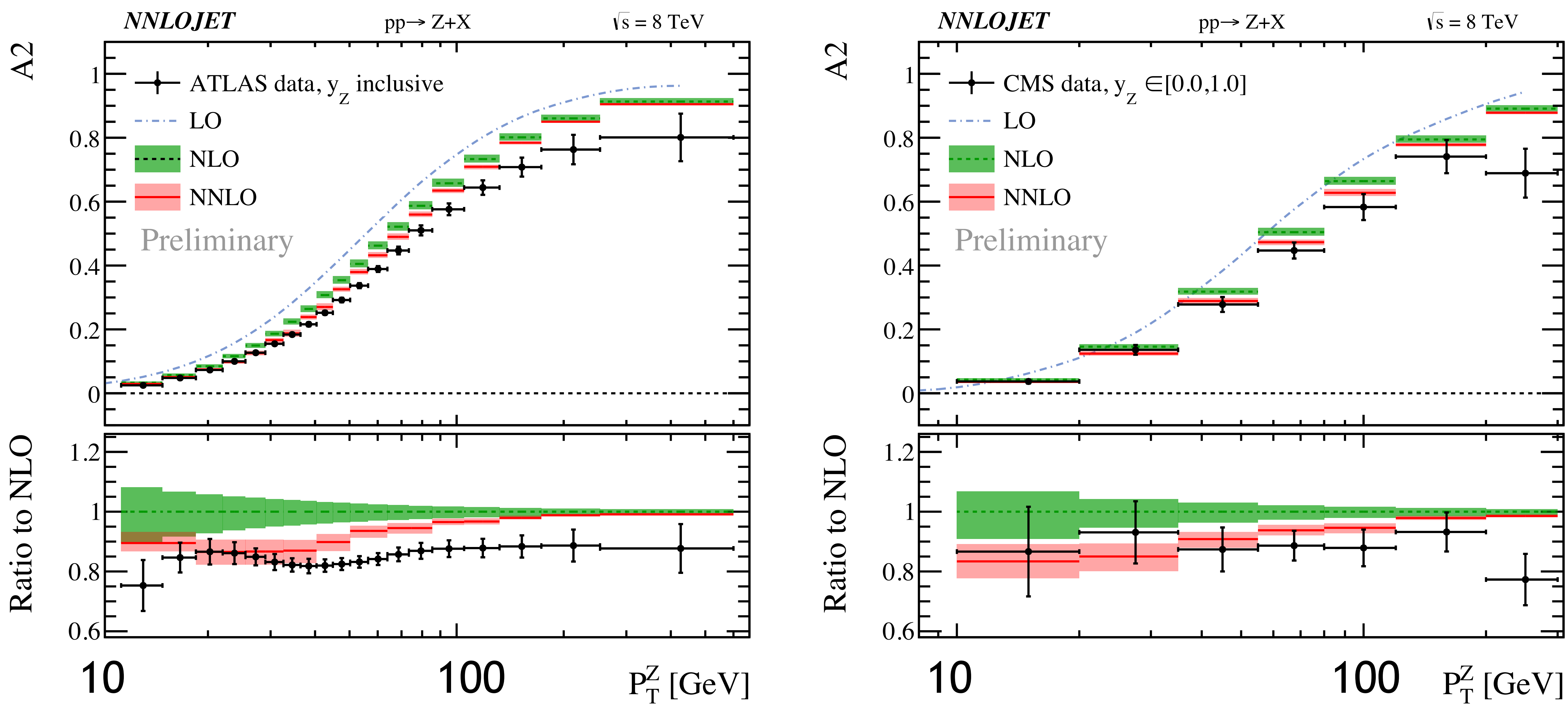
RHS: Comparison to CMS

$y_Z \in [0.0, 1.0]$

# $A_0$

*(Collins-Soper frame)*

# New results: angular coefficients




LHS: Comparison to ATLAS

$y_Z$ inclusive

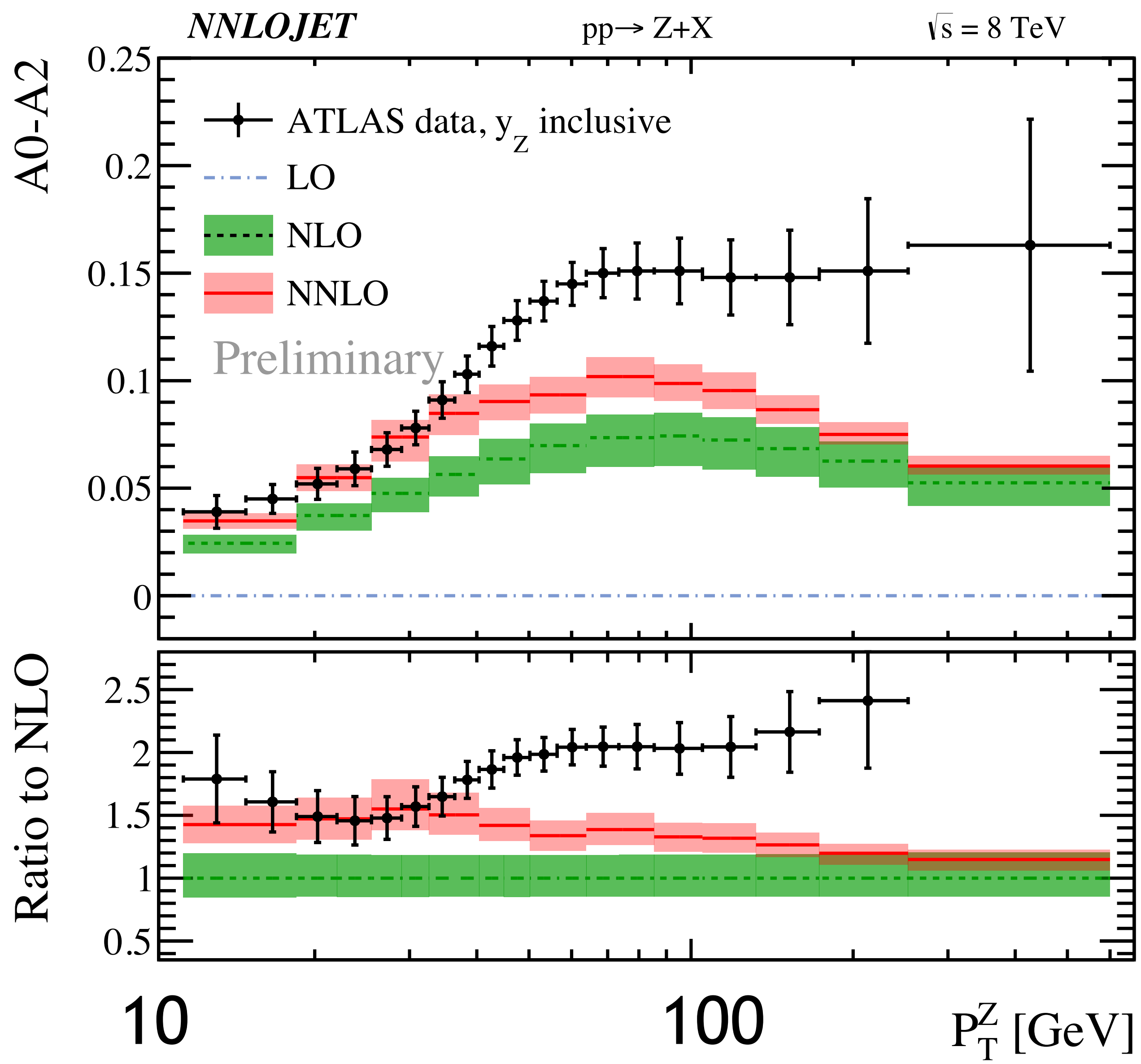
RHS: Comparison to CMS

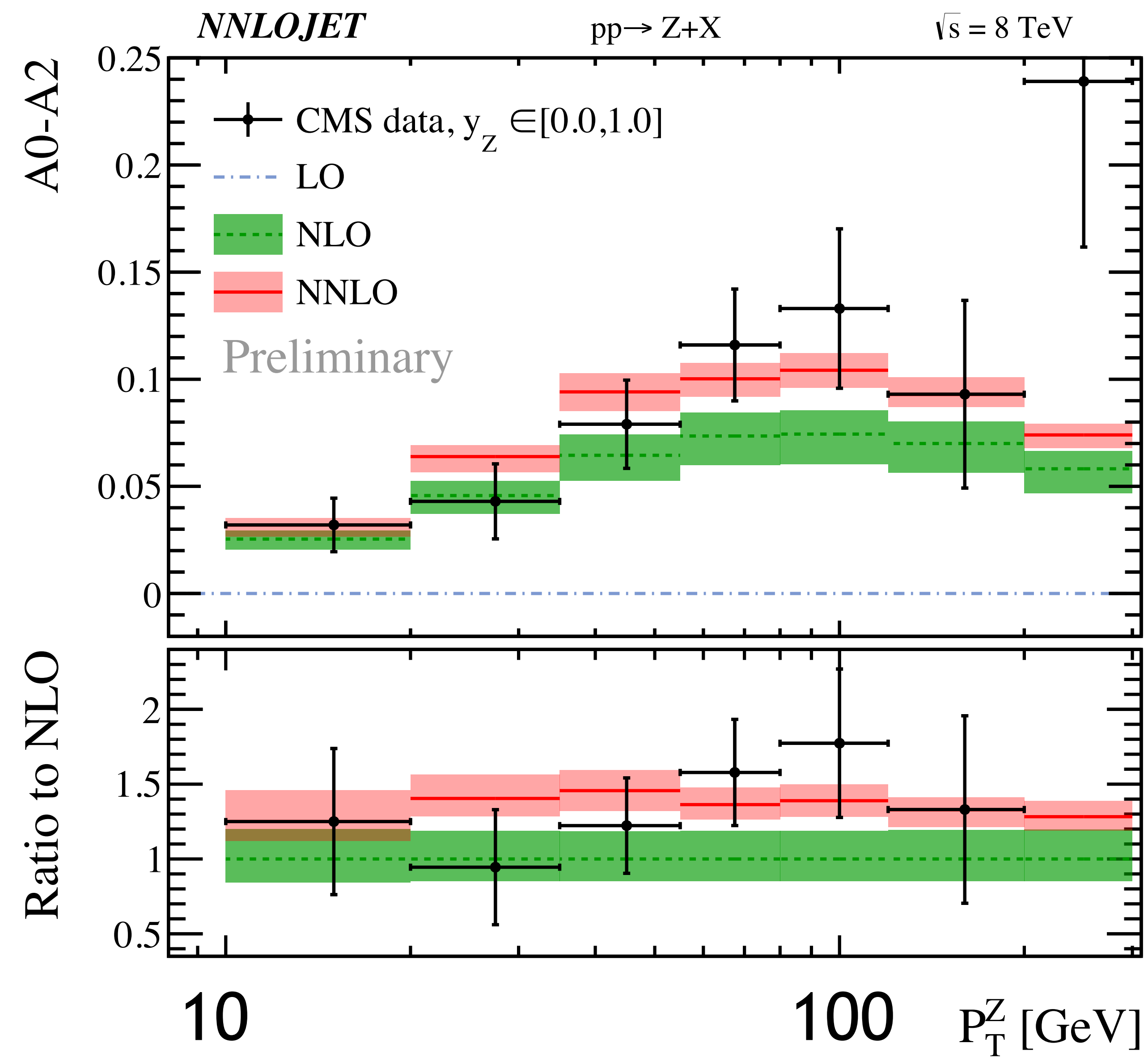
$y_Z \in [0.0, 1.0]$

$\mathbf{A_2}$

*(Collins-Soper frame)*

# New results: angular coefficients




LHS: Comparison to ATLAS

$y_Z$ inclusive

RHS: Comparison to CMS

$y_Z \in [0.0, 1.0]$

$$\mathbf{A_0 - A_2}$$

*(Collins-Soper frame)*

# Summary and conclusions

In general:

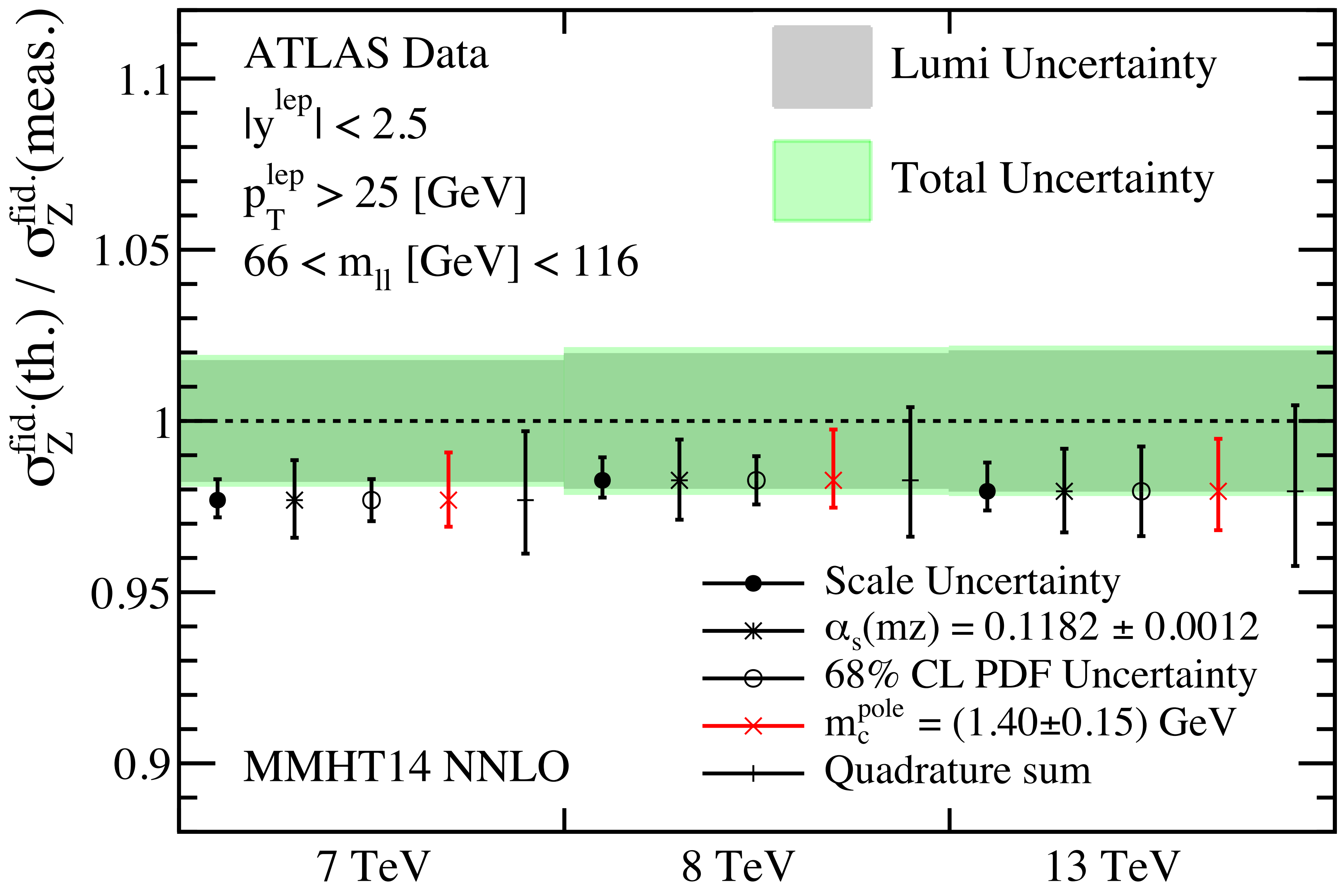
- Experimentally: $p_T^Z$ in realm of %-level precision
- Combined with NNLO predictions (precision pheno.): PDF fits, input for precision measurements ( $m_W$ ), …
- Can also assess region where fixed-order breaks down:
  $p_T^Z \sim 4\ \mathrm{GeV}$
  $\phi^* \sim 0.02$

Angular coefficients:

- **Large negative** corrections to $\mathbf{A_2}$ (20%)
- Improves comparison with data (in contact with exp's)

# Back-up slides

# Inclusive Z cross-section uncertainties



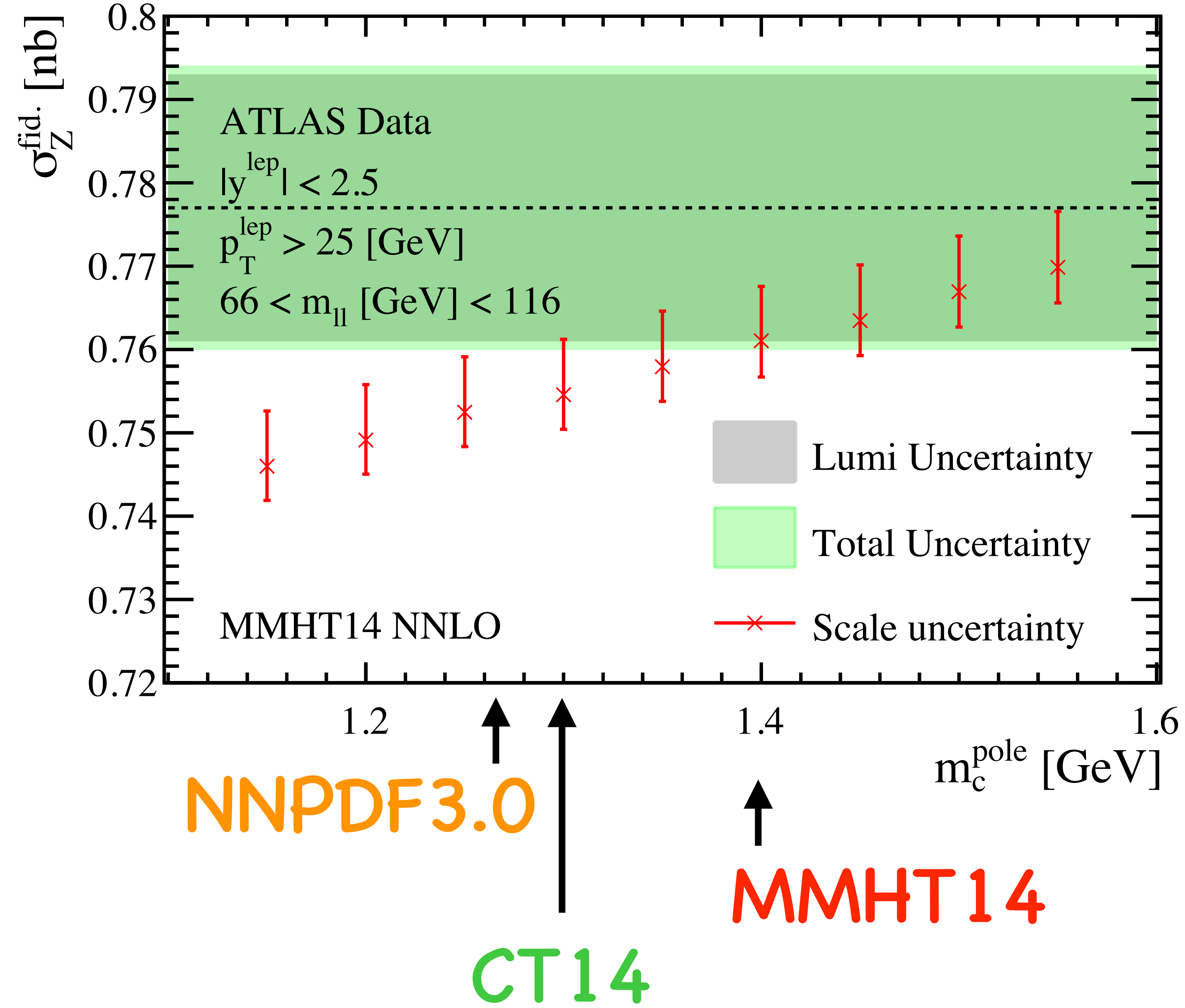

$$\alpha_s(m_Z) = 0.1182 \pm 0.0012$$

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

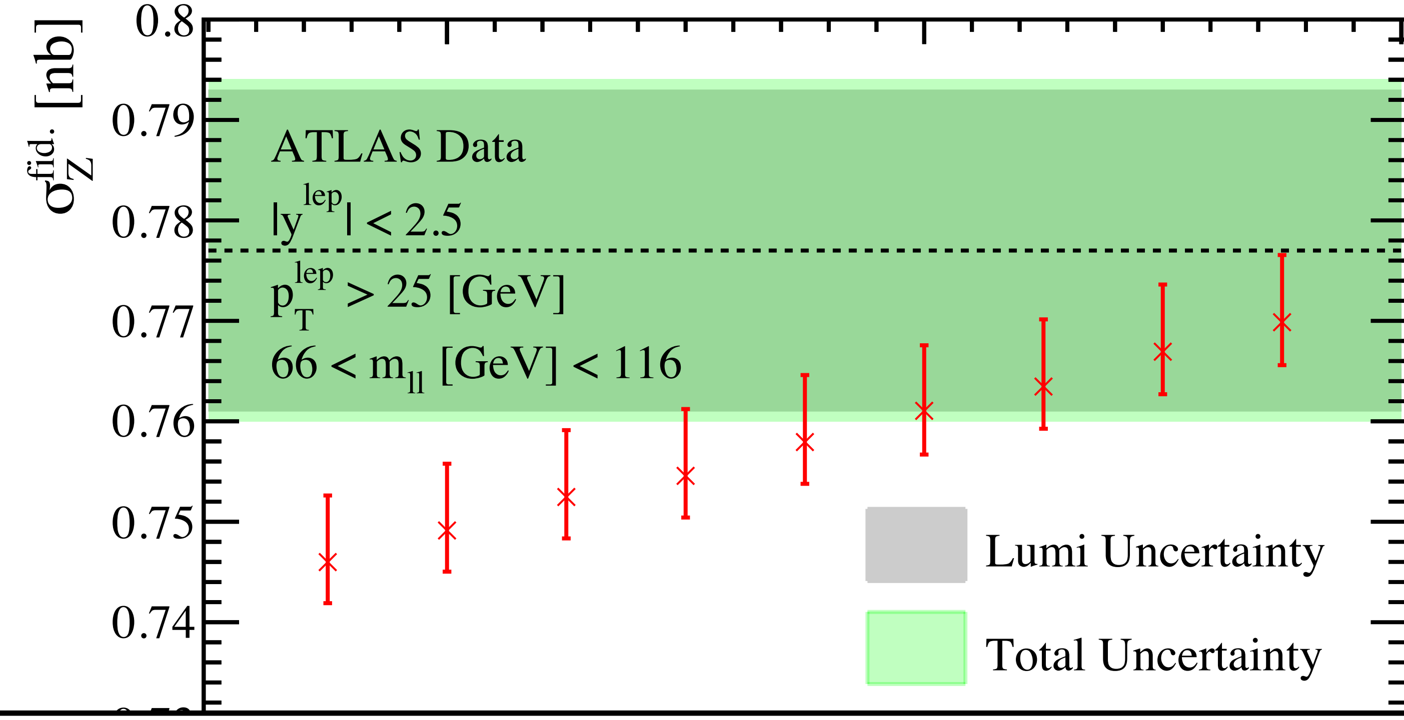
$$M_Z^T\,, \quad 1/2 < \mu_F/\mu_R < 2$$

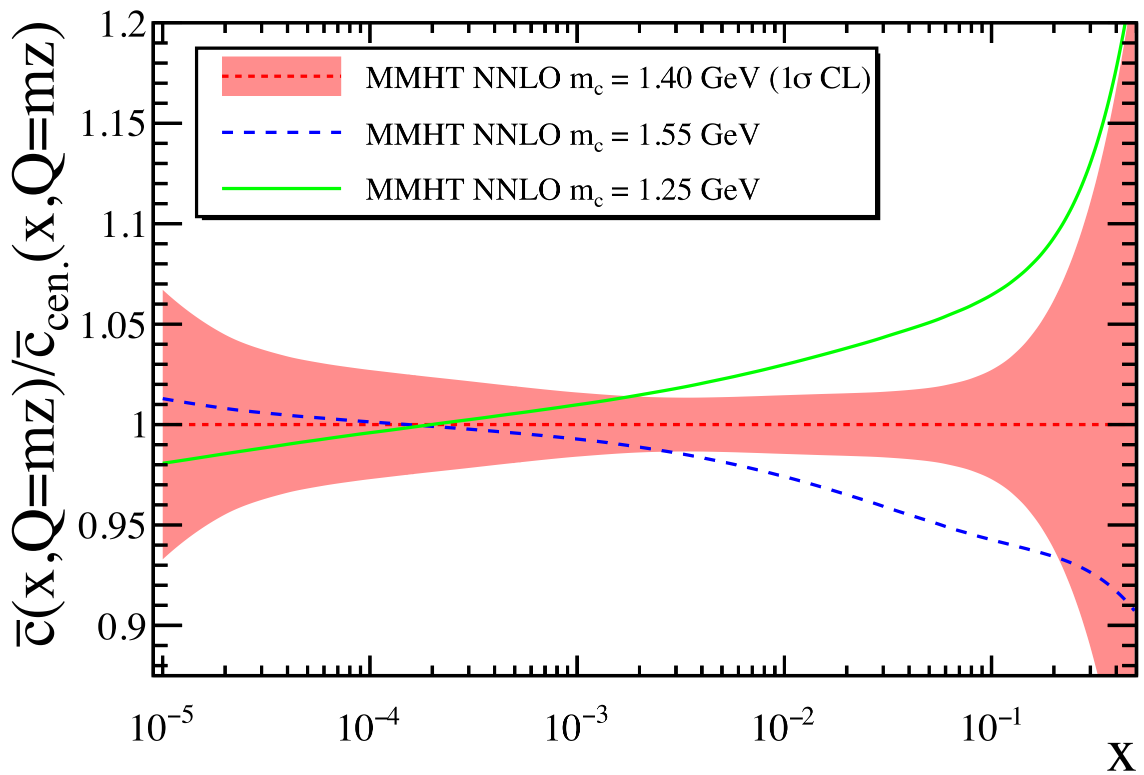
$$m_c^{\mathrm{pole}} = 1.4 \pm 0.15\mathrm{GeV}$$

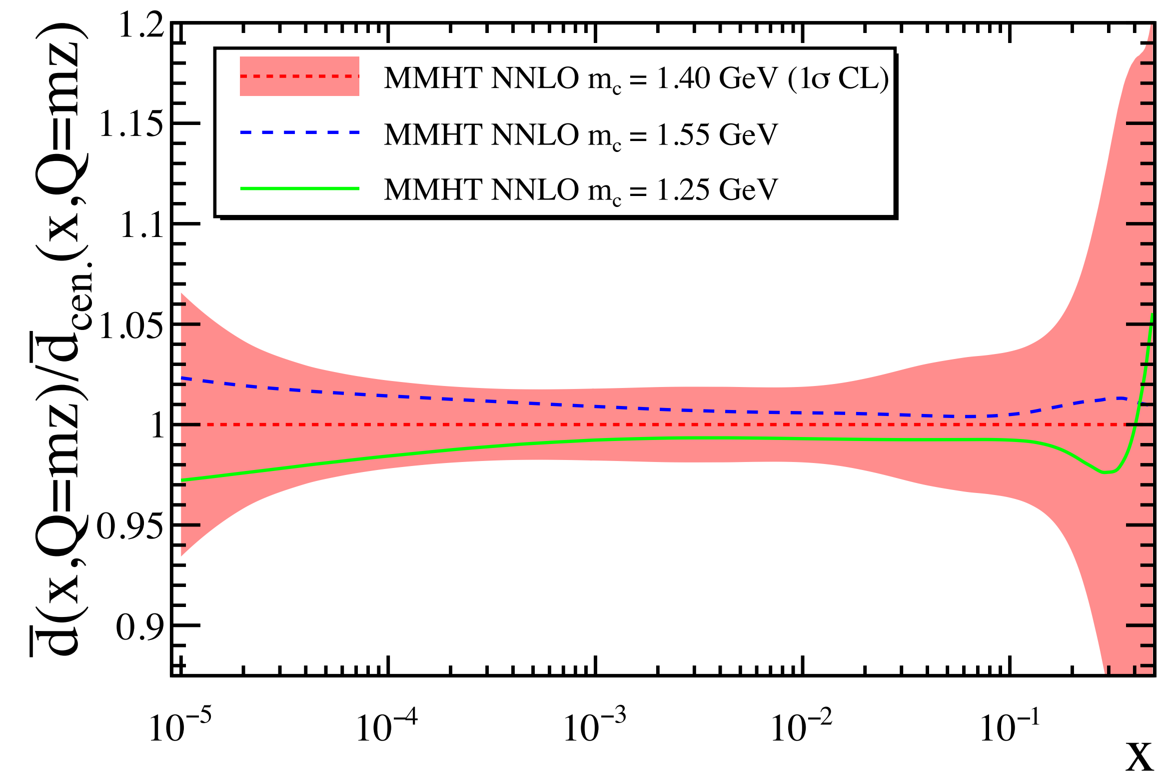
# Impact of input value of $m_c^{\text{pole}}$ in global fit



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

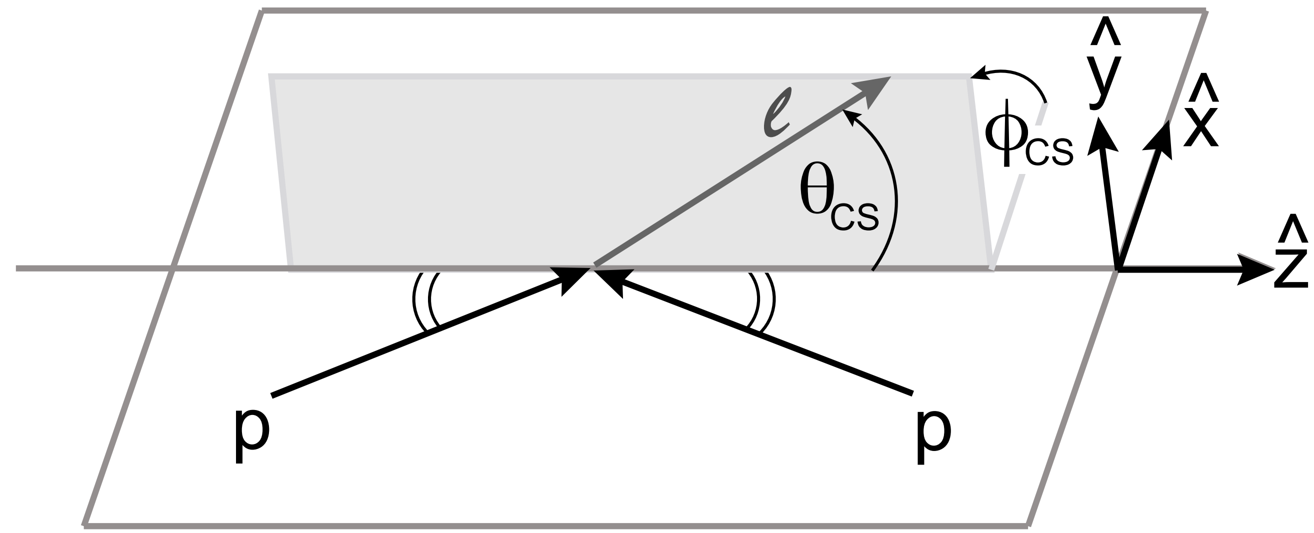


# Project out A.C.

Analysis performed in:
Collins-Soper frame




Predictions for $\mathbf{A_{0,..,7}}\ [\mathbf{m^Z},\ \mathbf{p_T^Z},\ \mathbf{y^Z}]$ obtained from:

$$\langle p_i(\theta_{CS},\phi_{CS})\rangle = \int_{-1}^{1} d(\cos\theta_{CS}) \int_0^{2\pi} d\phi_{CS} \frac{1}{\sigma} \frac{d\sigma}{d(\cos\theta_{CS})d\phi_{CS}} p_i(\theta_{CS},\phi_{CS})$$

weighted with harmonic polynomial

$$A_0 = 4 - \langle 10\cos^2\theta\rangle \qquad A_2 = \langle 10\sin^2\theta\cos 2\phi\rangle$$

# Input parameters for A.C.

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 $\propto \frac{2}{3} g_V^{up} + \frac{1}{3} g_V^{do}$

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

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

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

# Input parameters for A.C.

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

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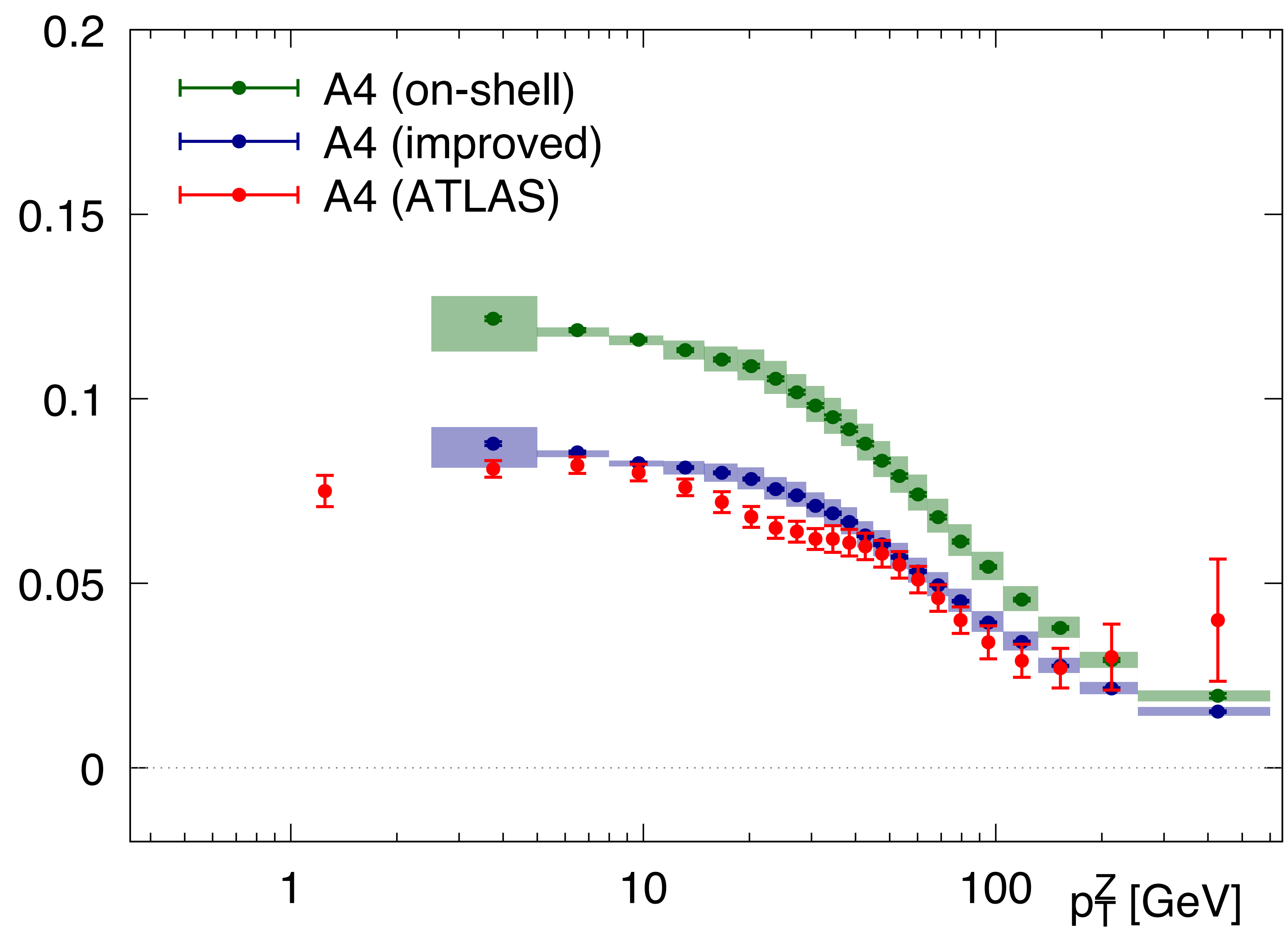



Prob coupling (A3,A4)

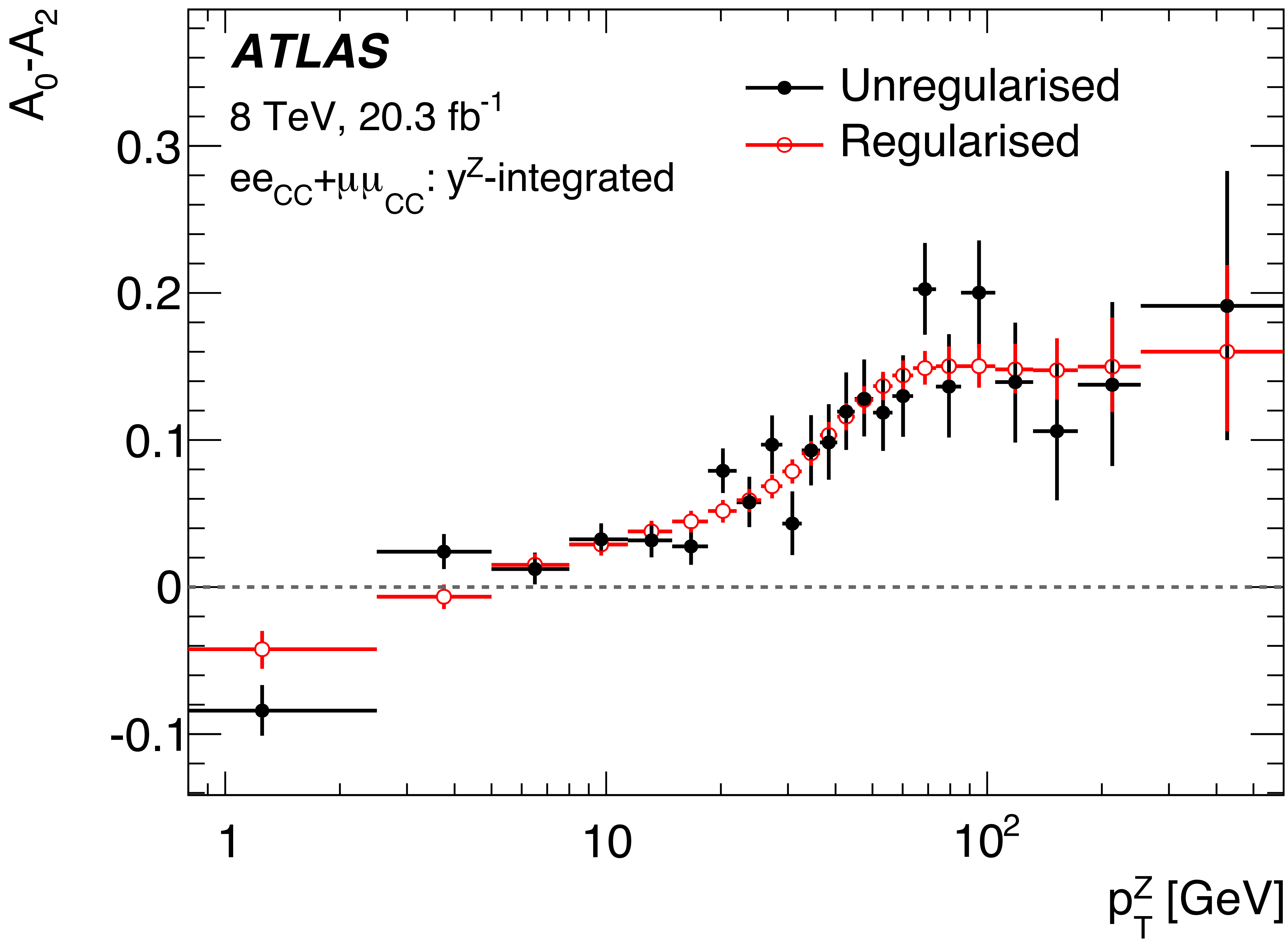
Cros $^{up}_{V} + \frac{1}{3} g_V^{do}$

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

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

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

# ATLAS, ‘unregularised’ A.C.



# CMS, absolute uncertainties

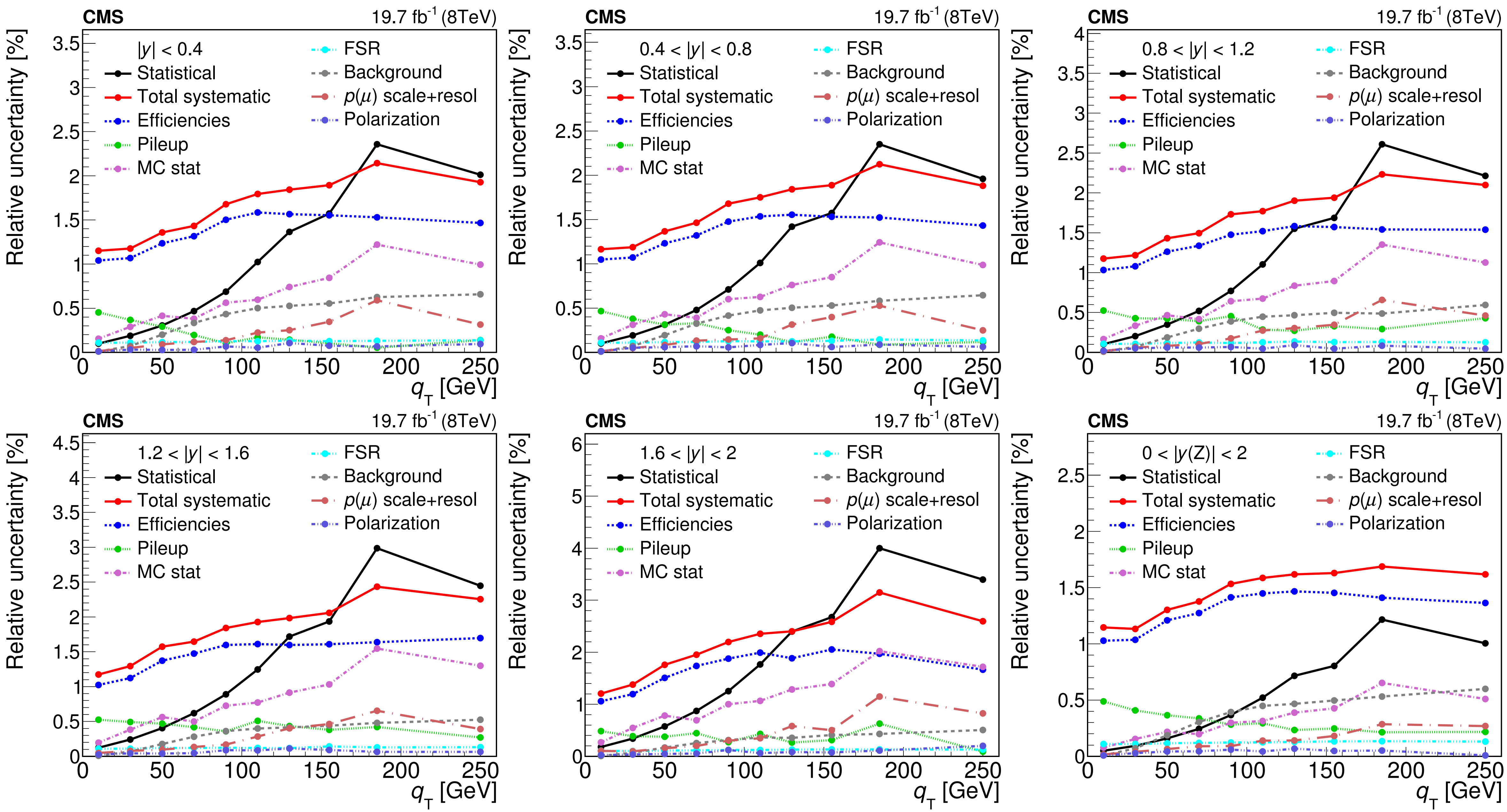



Figure 2: Relative uncertainties in percent of the absolute fiducial cross section measurement. The 2.6% uncertainty in the luminosity is not included. Each plot shows the $q_T$ dependence in the indicated ranges of $|y|$.

# Low $p_T^Z$ backups