Angular Coefficients in Z-boson production

work with R. Gauld, A. Gehrmann–De Ridder,
T. Gehrmann, and E.W.N. Glover

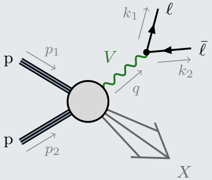
Alexander Huss

7^{th} LHCb Implications Workshop

CERN — November 8^{th} 2017

based on arXiv:1708.00008 [hep-ph]

The Drell–Yan process — a “standard candle” at the LHC



$$\mathrm{p\,p} \to Z/\gamma^* + X \to \ell^-\ell^+ + X$$

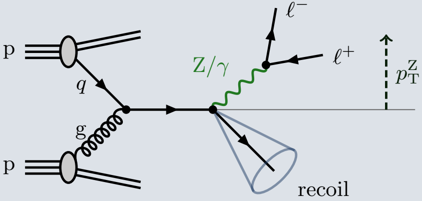
- large cross section
- clean leptonic signature

- precise Z-boson measurements: $p_{\mathrm{T,Z}}$, ϕ^*_η, y_{Z}, A_{FB}, …
  - ↪ test pQCD, constrain PDFs, $\sin^2\theta_{\mathrm{w}}$, ($M_{\mathrm{W}}$), …
  - ↪ detector calibration, luminosity monitor, …
  - ↪ searches for BSM physics
- retain full differential information on the leptons?
  - ↪ can be encoded in eight angular coefficients: $A_{i=0,\dots,7}$
  - ↪ directly probe production dynamics! tension @ $\mathcal{O}(\alpha_s^2)$
  - ↪ genuine NNLO corrections at $\mathcal{O}(\alpha_s^3)$ ⟵ this talk

This talk

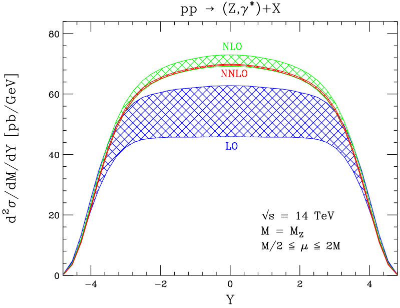
1. NNLO QCD predictions
2. Angular coefficients — overview
3. $\mathcal{O}(\alpha_\mathrm{s}^3)$ predictions for A_i
4. The Lam–Tung relation

NNLO QCD predictions



What NNLO might give you

- high-precision mandatory
  - ↪ processes with large K-factors (H)
  - ↪ "standard candles" (jets, V, t, ...)
- reduction of scale uncertainties
  - ↪ variation of μ_R & μ_F

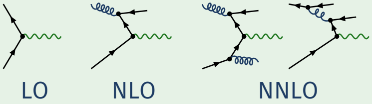


[Anastasiou, Dixon, Melnikov, Petriello '04]

Jet clustering

- better modelling of jet algorithm between theory & experiment

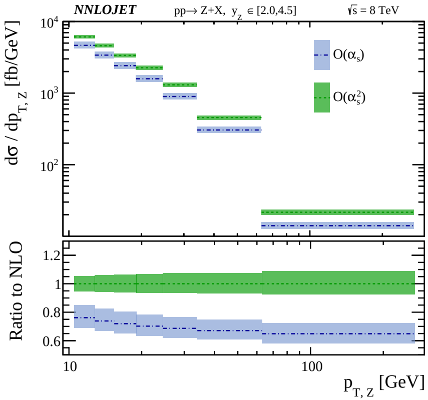
Initial-state radiation



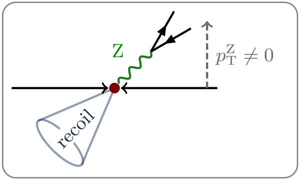
LO	NLO	NNLO
$q\bar{q}$	$\oplus\ qg,\ \bar{q}g$	$\oplus\ gg,\ qq',\ q\bar{q}',\ \bar{q}\bar{q}'$

- opening up of all channels
- more complicated p_T recoil

Inclusive $p_{T,Z}$ spectrum at fixed order

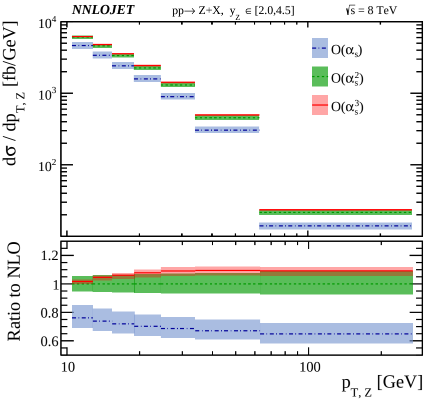


FEWZ
DYNNLO } $\mathrm{Z} + 0\,\mathrm{jet}$ @ NNLO

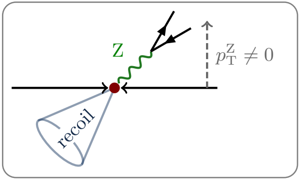


$\hookrightarrow$ Only NLO accurate in this distribution!

Inclusive $p_{\mathrm{T,Z}}$ spectrum at fixed order



FEWZ
DYNNLO
} $\mathrm{Z} + 0\,\mathrm{jet}$ @ NNLO



↪ Only NLO accurate in this distribution!

NNLO

$p_{\mathrm{T}}^{\mathrm{Z}} > p_{\mathrm{T,cut}}^{\mathrm{Z}} = 10\ \mathrm{GeV}$

- requires hadronic recoil

⇝ $\mathrm{Z} + \geq 1\mathrm{jet}$ @ NNLO

```
   _  ___  ____    ____      ___________
  / |/ / |/ / /   / __ \__ / / __/_  __/
 /    /    / /__/ /_/ / // / _/  / /
/_/|_/_/|_/____/\____/\___/___/ /_/
```

X. Chen, J. Cruz-Martinez, J. Currie, R. Gauld, A. Gehrmann-De Ridder, T. Gehrmann, E.W.N. Glover, AH, I. Majer, T. Morgan, J. Niehues, J. Pires, D. Walker

Common framework for NNLO corrections using Antenna Subtraction

- parton-level event generator
- based on antenna subtraction
- test & validation framework
- `APPLfast-NNLO` interface

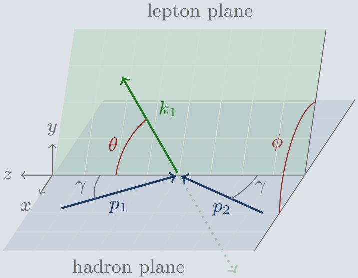
  (Work in progress)

  [Britzger, Gwenlan, AH, Morgan, Sutton, Rabbertz]
- ...

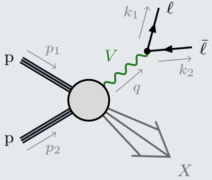
Processes:

- $\mathrm{pp} \to V \to \bar{\ell}\ell \; + 0, 1$ jets
- $\mathrm{pp} \to \mathrm{H} \; + 0, 1, 2$ jets
- $\mathrm{pp} \to$ dijets
- $\mathrm{ep} \to 1, \; 2$ jets
- $\mathrm{e}^+\mathrm{e}^- \; \to 3$ jets
- ...

Angular coefficients — overview



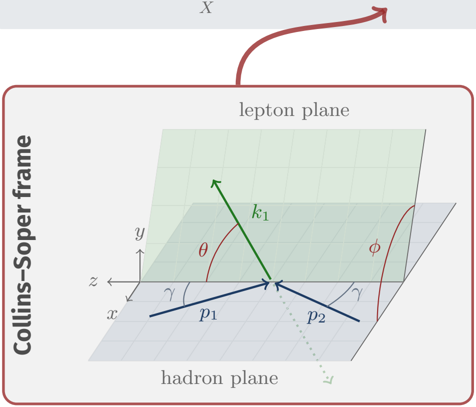
Setting the stage



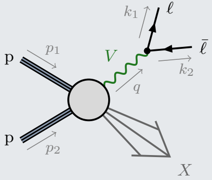
$$\mathrm{p}(p_1)\ \mathrm{p}(p_2) \ \to\ Z/\gamma^*(q)+X \ \to\ \ell^-(k_1)\ \ell^+(k_2)+X$$

lepton kinematics in the Z/γ^* (lepton-pair) rest frame:

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



Setting the stage



$$\mathrm{p}(p_1)\ \mathrm{p}(p_2)\ \to\ \mathrm{Z}/\gamma^*(q)+X\ \to\ \ell^-(k_1)\ \ell^+(k_2)+X$$

lepton kinematics in the Z/γ^* (lepton-pair) rest frame:

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

Decomposition in terms of spherical harmonics: $Y_{lm}(\theta,\phi),\ l = 0, 1, 2$

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

$A_i(q)$ $+\ \sigma^{\mathrm{unpol.}}$

production dynamics

$Y_{lm}(\theta,\phi)$

lepton kinematics

$l = 0:$	$m = 0$
$l = 1:$	$m = \pm1,\ 0$
$l = 2:$	$m = \pm2,\ \pm1,\ 0$
total:	9

Properties

Decomposition in terms of spherical harmonics: $Y_{lm}(\theta,\phi),\ l=0,1,2$

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

- dominant angular coefficients: $A_{0,\dots,4}$
- $A_{5,6,7}$ vanish at $\mathcal{O}(\alpha_s)$ and only small h.o. corrections
  $\hookrightarrow$ not discussed in the following
- parity even: $A_{0,1,2}$ $\rightsquigarrow$ probed by γ^* & Z exchange
- parity odd: $A_{3,4}$ $\rightsquigarrow$ sensitive to $\sin^2\theta_w$, $A_4 \leftrightarrow A_{FB}$

Experimental measurements

first measurements from fixed-target experiments

- NA10, E615 ['88, '89] (pions on tungsten and deuterium)
- FNAL E866/NuSea ['06, '08] (protons on deuterium and hydrogen)
- low-mass Drell–Yan $\rightsquigarrow$ γ^* exchange

  $\hookrightarrow$ sensitivity to $A_{0,1,2}$

measurements from hadron colliders

- Tevatron: CDF [arXiv:1103.5699]
- LHC: CMS [arXiv:1504.03512], ATLAS [arXiv:1606.00689]
- window around Z-resonance $\rightsquigarrow$ Z exchange

  $\hookrightarrow$ also sensitivity to $A_{3,4}$

Measurement by ATLAS & CMS @ 8 TeV

- first clear evidence for $A_0 - A_2 \neq 0$
- in tension with theory predictions

Theoretical predictions

Decomposition in terms of spherical harmonics: $Y_{lm}(\theta,\phi),\ l=0,1,2$

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

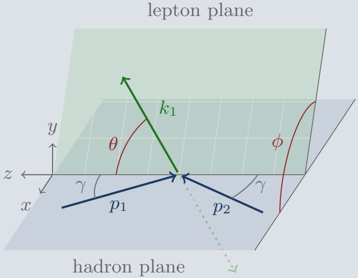
extraction of A_i though projections: $\int \mathrm{d}\Omega\ Y_{lm} Y^*_{l'm'} = \delta_{ll'}\,\delta_{mm'}$

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

$A_0 = 4 - 10\,\langle\cos^2\theta\rangle,\quad A_1 = 5\,\langle\sin^2\theta\cos(2\phi)\rangle,\quad A_2 = 10\,\langle\sin^2\theta\cos(2\phi)\rangle,$
$A_3 = 4\,\langle\sin\theta\cos\phi\rangle,\quad A_4 = 4\,\langle\cos\theta\rangle,\quad \ldots$

↪ **very** challenging numerics!

$\mathcal{O}(\alpha_s^3)$ predictions for A_i



Calculational setup

LHC @ $8\ \text{TeV}$: ATLAS [arXiv:1606.00689], CMS [arXiv:1504.03512], LHCb

region & accuracy: $p_{\mathrm{T,Z}} > 10\ \text{GeV}$ & $\mathcal{O}(\alpha_s^3)$ (using $\mathrm{Z}+\text{jet}$ @ NNLO)

PDF & α_s: `PDF4LHC15_nnlo_30` & $\alpha_s(M_Z) = 0.118$

scale choice: $\mu_0 \equiv E_{\mathrm{T,Z}} = \sqrt{m_{\ell\ell}^2 + p_{\mathrm{T},\ell\ell}^2}$

Scale variation

independent variation of μ_R & μ_R with $\frac{1}{2} \leq \mu_R/\mu_F \leq 2$ ⇝ 7 points

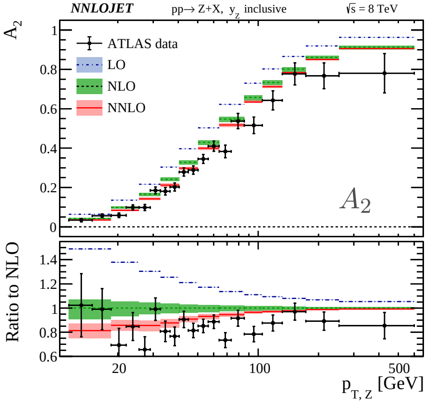
A_i defined through ratios:

$$\langle f(\theta,\phi)\rangle = \frac{\int \mathrm{d}\Omega\ \mathrm{d}\sigma(\mu_F^{\text{num.}}, \mu_R^{\text{num.}})\ f(\theta,\phi)}{\int \mathrm{d}\Omega\ \mathrm{d}\sigma(\mu_F^{\text{den.}}, \mu_R^{\text{den.}})}$$

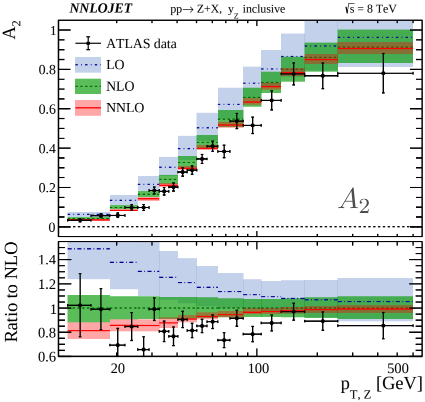
- **correlated:** $\mu_{F,R}^{\text{num.}} = \mu_{F,R}^{\text{den.}}$ ⇝ 7 points
- **uncorrelated:** $\frac{1}{2} \leq \mu_a^i/\mu_b^j \leq 2$ ⇝ 31 points

Ratios — correlated vs. uncorrelated

correlated:



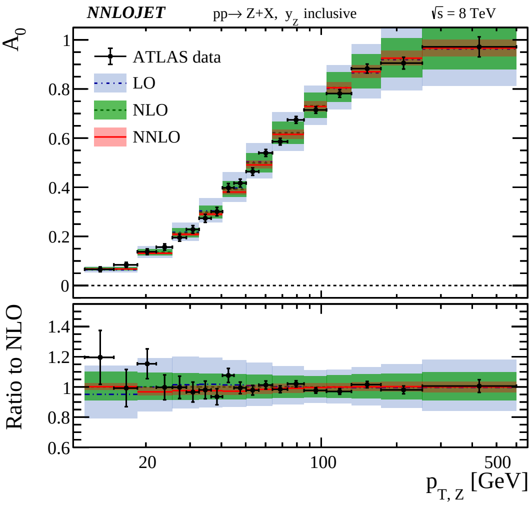
uncorrelated:



- **LO** α_s cancels in correlated case ⇝ almost no scale bands
- **NLO** substantial differences in correlated vs. uncorrelated
- **NNLO** similar uncertainty estimates

uncorrelated exhibits more realistic behaviour ⇝ default choice

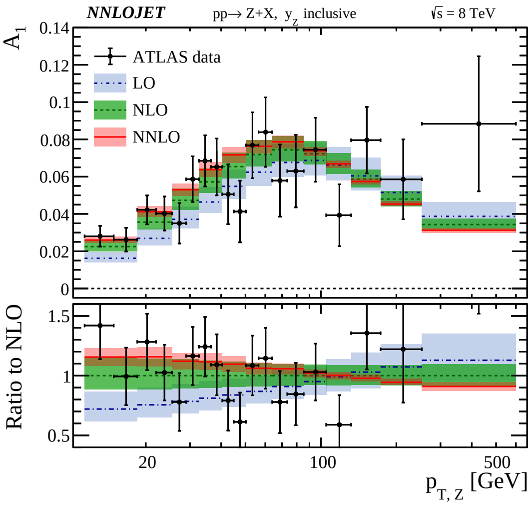
Data vs. prediction — ATLAS



A_0

- good pert. convergence:
  LO $\rightarrow$ **NLO** $\rightarrow$ **NNLO**
- small corrections
  NNLO $\lesssim 5\,\%$
- significant reduction of scale uncertainties

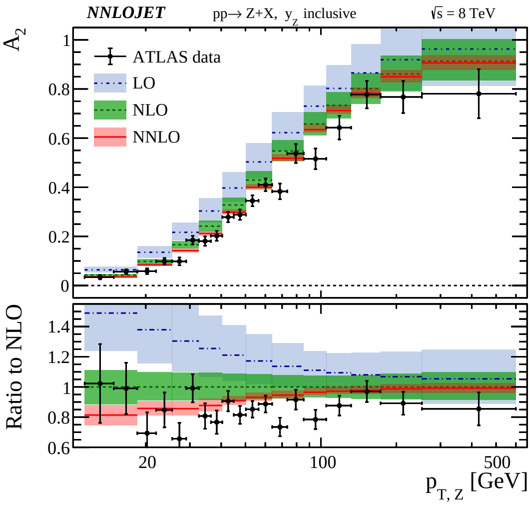
Data vs. prediction — ATLAS



A_1

- sizeable corrections
- shape distortion
  $+10\ \%$ @ low p_T
  $-5\ \%$ @ high p_T
- overlapping scale bands
  reduction: **NLO** → **NNLO**

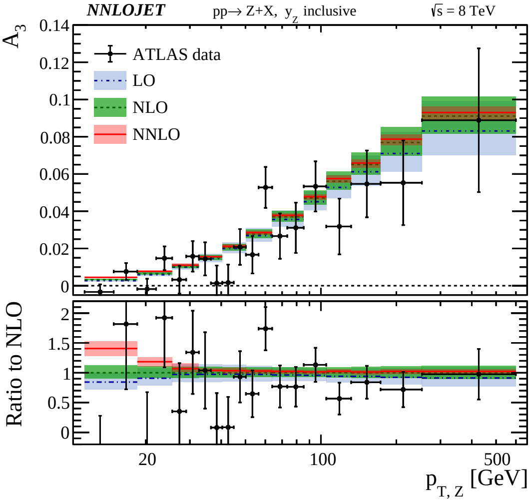
Data vs. prediction — ATLAS



A_2

- negative corrections
  most sizeable @ low p_T
  NNLO $\sim -20\ \%$
- overlapping scale bands
  reduction: **NLO** $\to$ **NNLO**
- data–theory comparison
  visible improvement

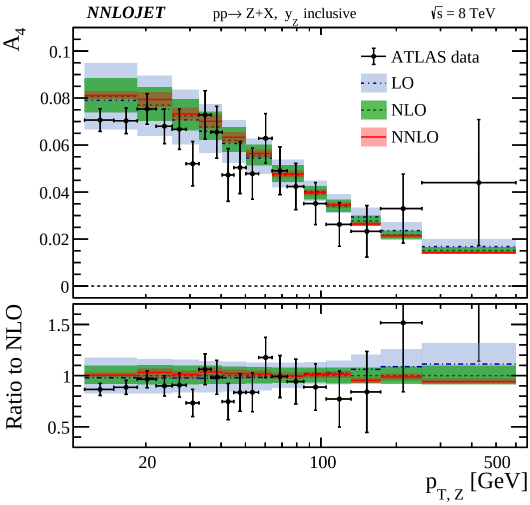
Data vs. prediction — ATLAS



A_3

- small corrections
  exception: very low p_T
- good pert. convergence:
  LO → **NLO** → **NNLO**
  reduced scale bands
- $\text{error}_{\text{exp.}} \gg$ **NNLO**
  phenom. unimportant

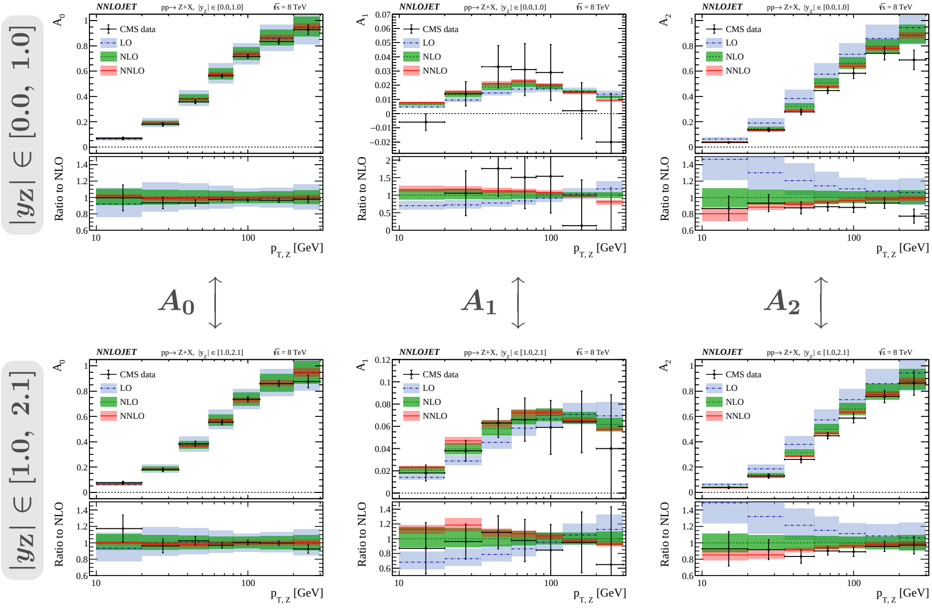
Data vs. prediction — ATLAS



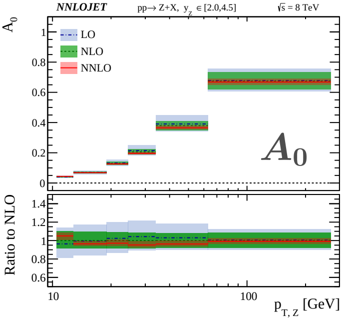
A_4

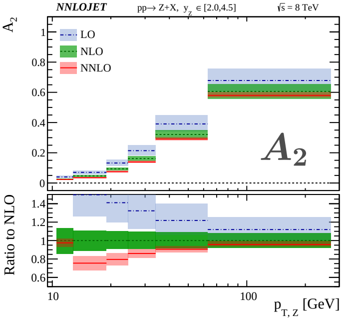
- very stable
  NLO → **NNLO**
- good pert. convergence
  & reduced scale bands
- $\text{error}_{\text{exp.}} \sim$ **NLO**
  phenom. unimportant

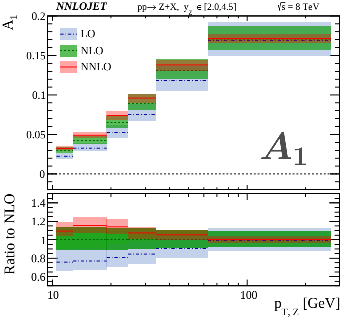
Data vs. prediction — CMS



Predictions — LHCb







LHCb: probe the forward regime

$\hookrightarrow |y_Z| \in [2.0,\ 4.5]$

- similar to central y_Z (ATLAS, CMS)

A_0 stable perturbative series

A_1 shape distortions

A_2 large corrections
@ low–medium p_T
(not captured by NLO bands)

The Lam–Tung relation

$$A_0 - A_2 \stackrel{?}{=} 0$$

Lam–Tung relation

Decomposition in terms of spherical harmonics: $Y_{lm}(\theta, \phi),\ l = 0, 1, 2$

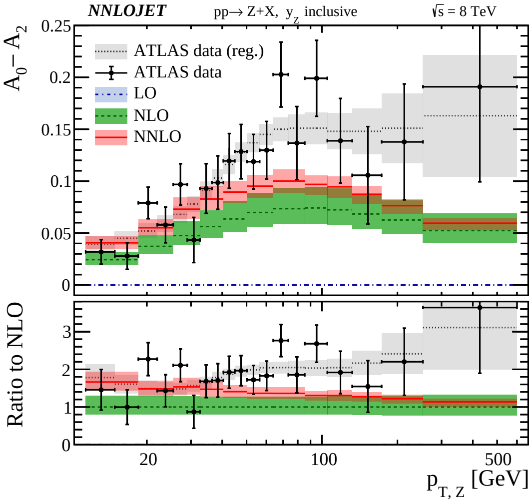
$$\frac{\mathrm{d}\sigma}{\mathrm{d}^4 q\ \mathrm{d}\cos\theta\ \mathrm{d}\phi} = \frac{3}{16\pi}\ \frac{\mathrm{d}\sigma^{\text{unpol.}}}{\mathrm{d}^4 q} \Big\{ (1+\cos^2\theta) + \frac{1}{2}\ A_0\ (1 - 3\cos^2\theta) + A_1\ \sin(2\theta)\cos\phi + \frac{1}{2}\ A_2\ \sin^2\theta\ \cos(2\phi) + A_3\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

Lam–Tung relation: $A_0 - A_2 = 0$

- ✓ @ $\mathcal{O}(\alpha_s^0)$ spin-$\frac{1}{2}$ nature of quarks $\leftrightarrow$ Callan–Gross $(F_2 = 2xF_1)$
- ✓ @ $\mathcal{O}(\alpha_s^1)$ vector coupling of spin-1 gluon
- ✗ @ $\mathcal{O}(\alpha_s^2)$ $\rightsquigarrow$ FEWZ / DYNNLO only **LO** prediction in $(A_0 - A_2)$!

$\mathcal{O}(\alpha_s^3)$ $\leftarrow$ shown here $\chi^2 = \sum_{i,j}^{N_{\text{dat.}}} (O^i_{\text{exp}} - O^i_{\text{th.}})\sigma^{-1}_{ij}(O^j_{\text{exp}} - O^j_{\text{th.}})$

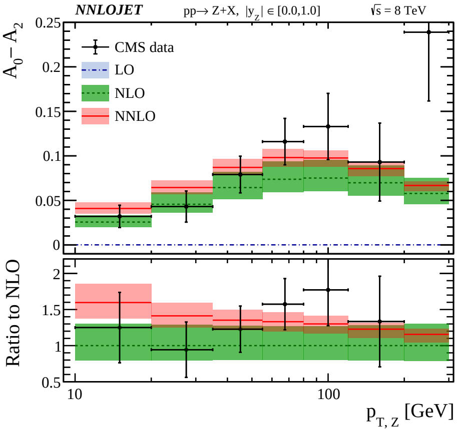
Lam–Tung violation — ATLAS

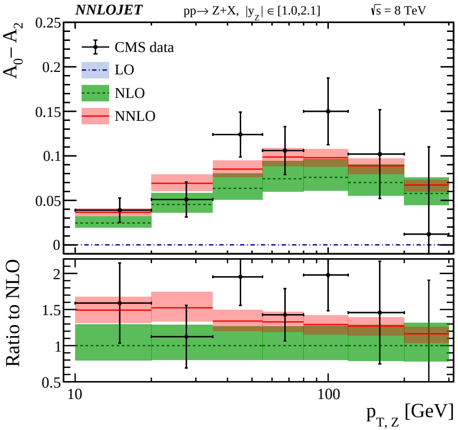


NLO (ATLAS) $\chi^2/N_{\mathrm{data}} = 185.8/38 = 4.89$

NNLO (ATLAS) $\chi^2/N_{\mathrm{data}} = 68.3/38 = 1.80$

Lam–Tung violation — CMS

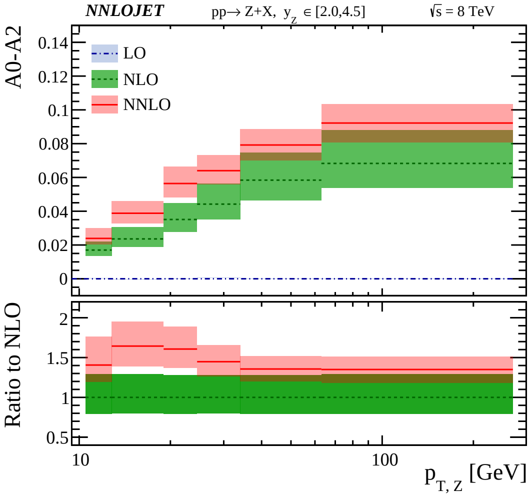




NLO (CMS) $\chi^2/N_{\mathrm{data}} = 24.5/14 = 1.75$

NNLO (CMS) $\chi^2/N_{\mathrm{data}} = 14.2/14 = 1.01$

Lam–Tung violation — LHCb



- sizeable **NNLO** corrections: $30\ \% - 60\ \%$
- important to include in data vs. theory comparison!

Summary — tl;dr

- angular coefficients A_i directly probe production dynamics
- NNLO corrections at $\mathcal{O}(\alpha_s^3)$ presented for $p_T > 10$ GeV
  - ↪ good perturbative convergence (uncorrelated scales)
    & reduction of scale uncertainties
  - ↪ important impact on A_0, A_1, and A_2
  - ↪ shape of A_1 and A_2 altered by sizeable corrections
  - ↪ corrections to A_3 and A_4 small
- first clear evidence of Lam–Tung violation $A_0 - A_2 \neq 0$ (ATLAS & CMS)
  - ↪ NNLO substantially improves agreement with data

- important to measure A_i & Lam–Tung violation @ LHCb
  - ↪ test pQCD in very different kinematic regime $|y_Z| > 2.0$

Summary — tl;dr

- angular coefficients A_i directly probe production dynamics
- NNLO corrections at $\mathcal{O}(\alpha_s^3)$ presented for $p_T > 10$ GeV
  - ↪ good perturbative convergence (uncorrelated scales) & reduction of scale uncertainties
  - ↪ important impact on A_0, A_1, and A_2
  - ↪ shape of A_1 and A_2 altered by sizeable corrections
  - ↪ corrections to A_3 and A_4 small
- first clear evidence of Lam–Tung violation $A_0 - A_2 \neq 0$ (ATLAS & CMS)
  - ↪ NNLO substantially improves agreement with data

- important to measure A_i & Lam–Tung violation @ LHCb
  - ↪ test pQCD in very different kinematic regime $|y_Z| > 2.0$

Thank you