Electroweak corrections to the angular coefficients of finite-p_T Z-boson production at pp colliders[1]

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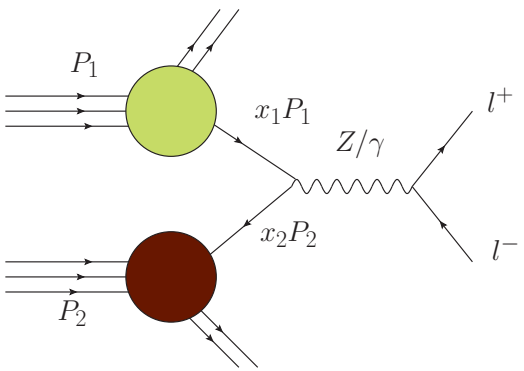
La Thuile (online),
March 11 2021

[1] R. Frederix, T. Vitos, arXiv:2007.08867

The (neutral current) Drell-Yan process



- At LHC: $pp \to Z/\gamma + X \to l^+l^- + X$
- Clear signature, large cross section $\to$ optimal for PDF fits
- **Measurements** with data:
  - pion beams [2]
  - $p\overline{p}$ at Tevatron [3][4]
  - pp at LHC [5][6]
- **Interesting for non-zero p_T** of Z-boson

Expansion for non-zero p_T

for some observable Σ:

$$\Sigma(\alpha, \alpha_S) = \underbrace{\alpha^2\alpha_S\Sigma_{2,1}}_{\text{LO}} + \underbrace{\alpha^2\alpha_S^2\Sigma_{2,2}}_{\text{NLO QCD}} + \underbrace{\alpha^3\alpha_S\Sigma_{3,1}}_{\text{NLO EW}} + \mathcal{O}(\alpha^4\alpha_S^2)$$

[2] Conway *et al.*, 10.1103/PhysRevD.39.92
[3] CDF Collaboration, arXiv:0908.3914
[4] D0 Collaboration, arXiv:hep-ex/0702025
[5] CMS Collaboration, arXiv:1504.03512
[6] ATLAS Collaboration, arXiv:1606.00689

Angular coefficients for the Drell-Yan process

- Expand the matrix element into **hadronic** and **leptonic tensor**

$$\mathscr{M} = H_{\mu\nu} L^{\mu\nu}$$

- Lepton (l^-) angular coordinates in the **Collins-Soper frame**: (θ, ϕ)
- **Differential cross section** in Z-boson kinematics expanded in **real spherical harmonics** $Y_{lm}(\theta, \phi)$:

$$\begin{aligned}\frac{\mathrm{d}\sigma}{\mathrm{d}p_{T,Z}\mathrm{d}y_Z\mathrm{d}m_{ll}\mathrm{d}\Omega} \propto \Bigg(& (1+\cos^2\theta) + A_0 \frac{1}{2}(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi \\ & + A_2 \frac{1}{2} \sin^2\theta \cos 2\phi + A_3 \sin\theta \cos\phi + A_4 \cos\theta \\ & + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi \Bigg)\end{aligned}$$

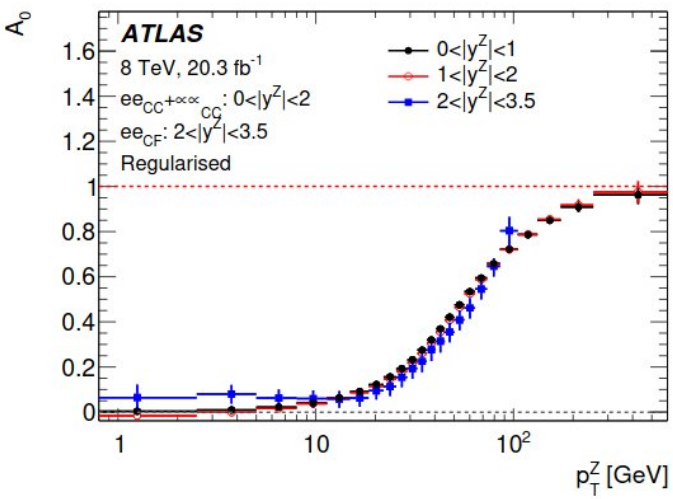
with eight **angular coefficients** $A_i(p_{T,Z}, y_Z, m_{ll})$

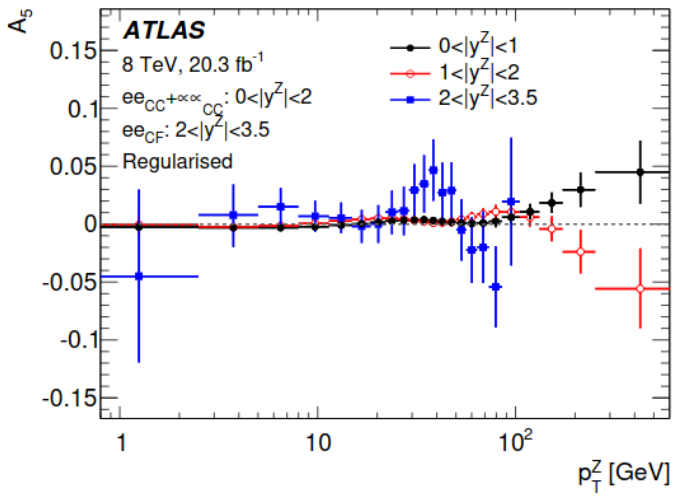
Angular coefficients for the Drell-Yan process

On the properties of the coefficients

- A_0 and A_2 are an order of magnitude larger
- $\boldsymbol{A_{5,6,7}}$ **are zero at LO** and very small at NLO QCD
- All **even under parity except** $\boldsymbol{A_3, A_4}$ $\rightarrow$ sensitive to θ_w
- All **vanish except** $\boldsymbol{A_4}$ in the $\boldsymbol{p_{T,Z} \rightarrow 0}$ limit

- ATLAS measurements for A_0 and A_5[7]





[7] ATLAS Collaboration, arXiv:1606.00689

Lam-Tung relation

- Up to order $\alpha^2\alpha_S$ **(LO): Lam-Tung relation** $A_0 = A_2$
- Predictions available [8] at order $\alpha^2\alpha_S^3$ **(NNLO QCD)**
- LHC and Tevatron data all show **higher violation** of Lam-Tung than predicted by NNLO QCD at $p_{T,Z} \gtrsim 20$ GeV
- **NNLO QCD moves** SM prediction **closer to data**
- $\rightarrow$ Let us see the effects of NLO EW corrections!

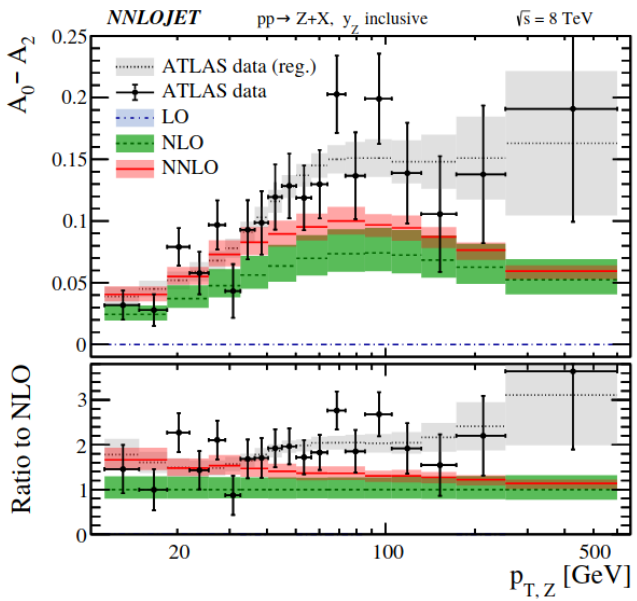


Figure: Figure from R. Gauld *et al.*

[8] R. Gauld, *et al.*, arXiv:1708.00008

Calculational setup

- **Fixed-order**: $pp \to l^+ l^- j$ at 8 TeV with MadGraph5_aMC@NLO
- Final state: e^+e^-, $\mu^+\mu^-$ and no jet requirements
- Lepton pair invariant mass window

$$m_{ll} \in [80.0, 100.0] \text{ GeV}$$

- **Photon recombination** with $R < 0.1$ (but results **insensitive** to this)
- Electroweak parameters: **complex G_μ-scheme** and complex mass scheme

On the θ_w

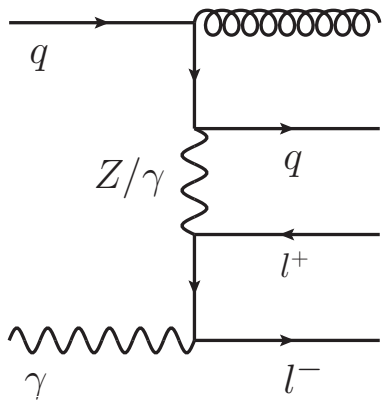
- High sensitivity to θ_w
- Include one-loop correction to **ρ-parameter** [9]

$$\Delta\rho = \frac{\sqrt{2}G_\mu}{16\pi} 3m_t^2$$

in the LO and NLO QCD calculations

[9] J Fleischer *et al.*, 10.1016/0370-2693(93)90810-5

Calculational setup: technicalities

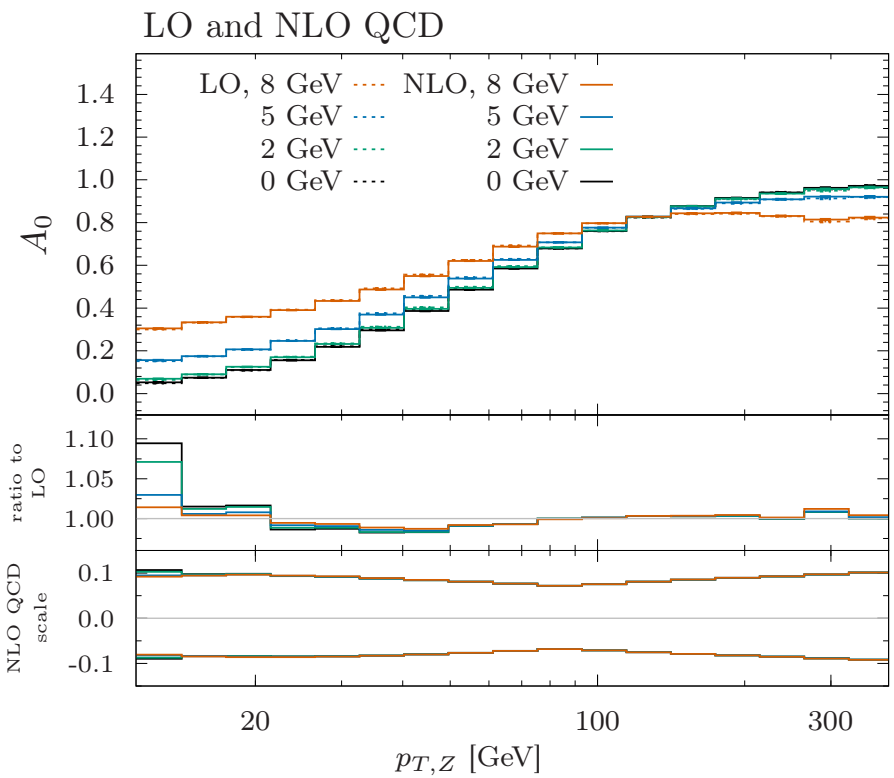


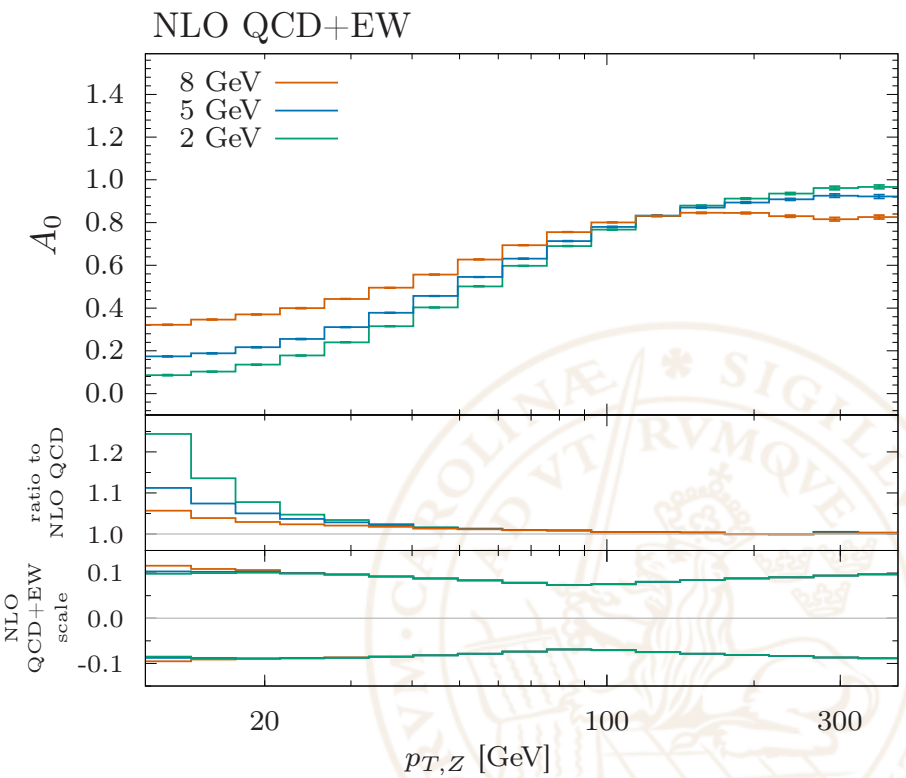
- **Double collinear singularity** for lepton + gluon
- Introduce massive leptons $\rightarrow$ large $log\,\frac{m_l^2}{\mu^2}$
- Introduce **single lepton p_T cut**
- Expansion in spherical harmonics then not valid
- $\rightarrow$ Extrapolate to the full phase-space by varying the cut value:

$$(p_T)_{\text{cut}} \in \{2.0, 5.0, 8.0\} \text{ GeV}$$

Angular coefficients: results

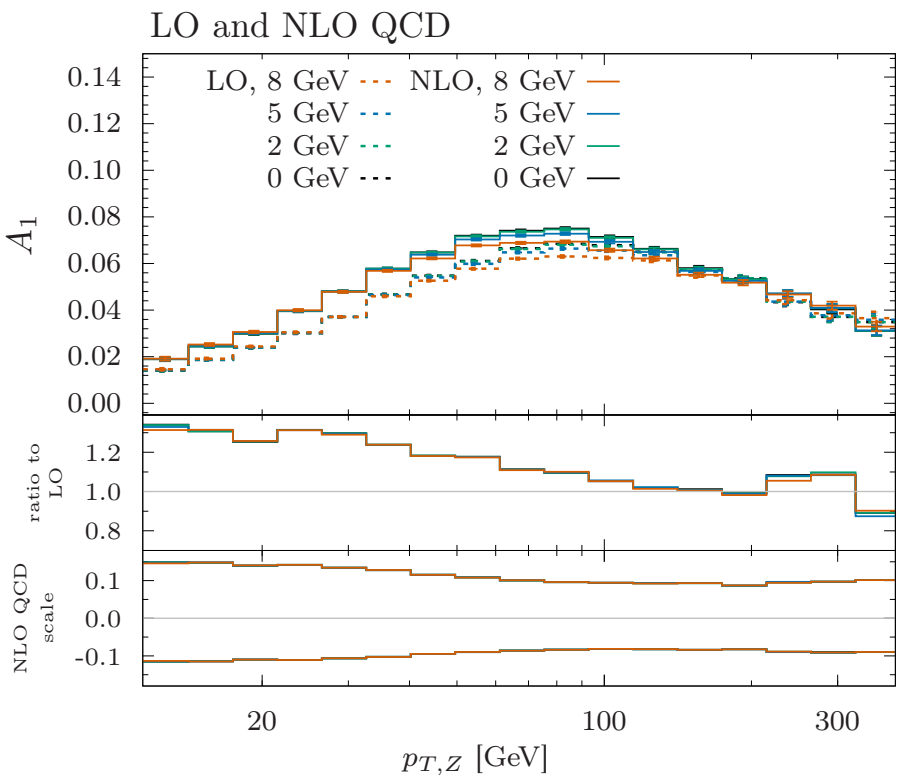
- Distributions for A_0
- No safe extrapolation in low-$p_{T,Z}$ region

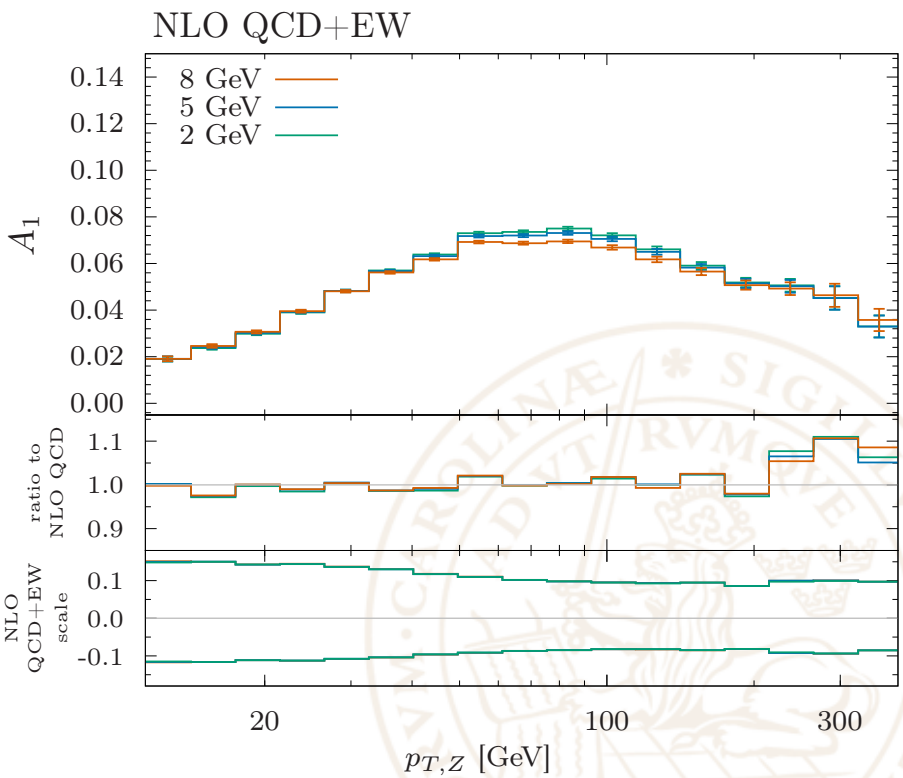




Angular coefficients: results

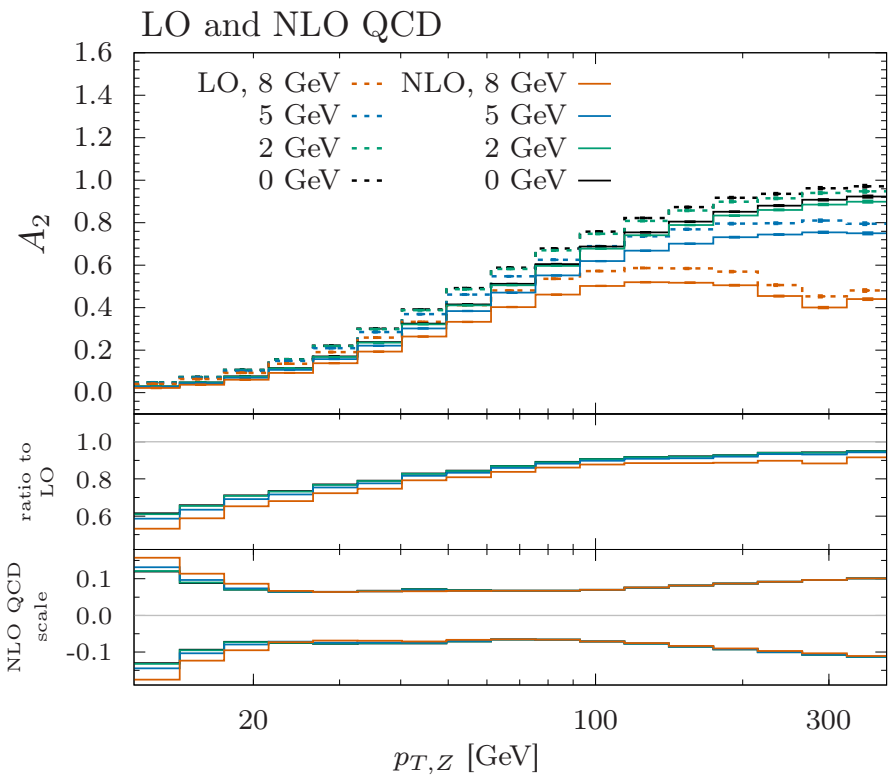
- Distributions for A_1
- Negligible electroweak corrections

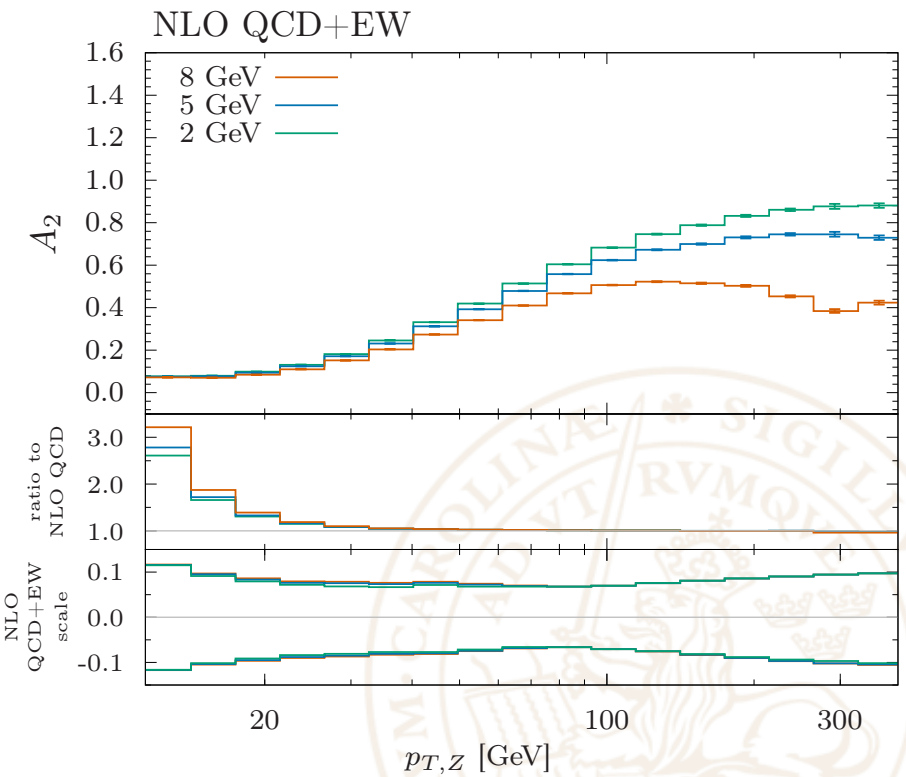




Angular coefficients: results

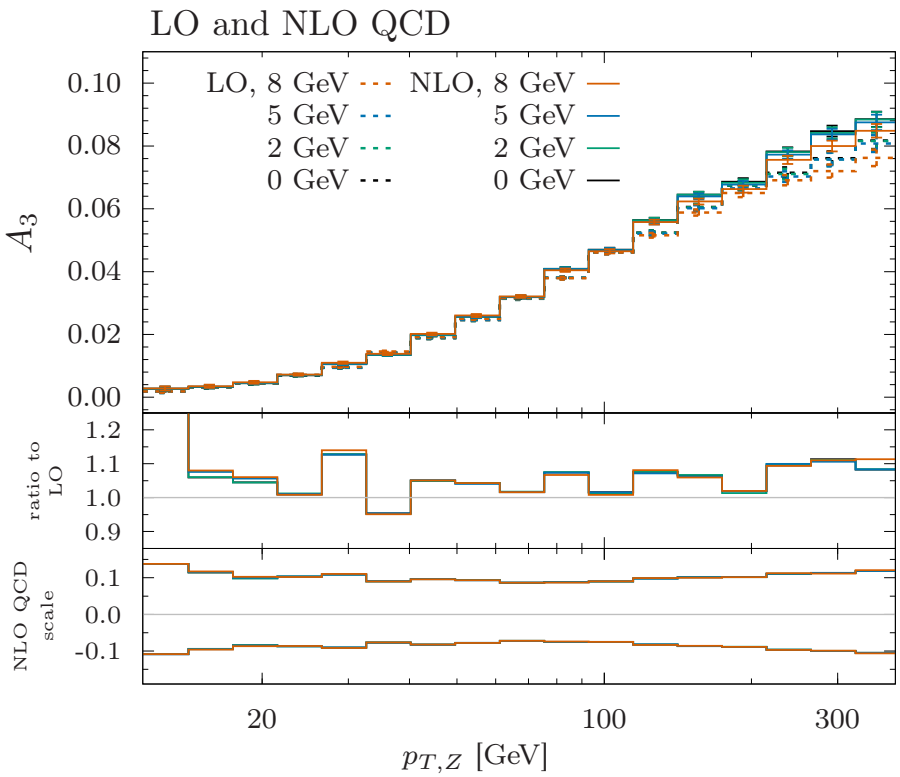
- Distributions for A_2

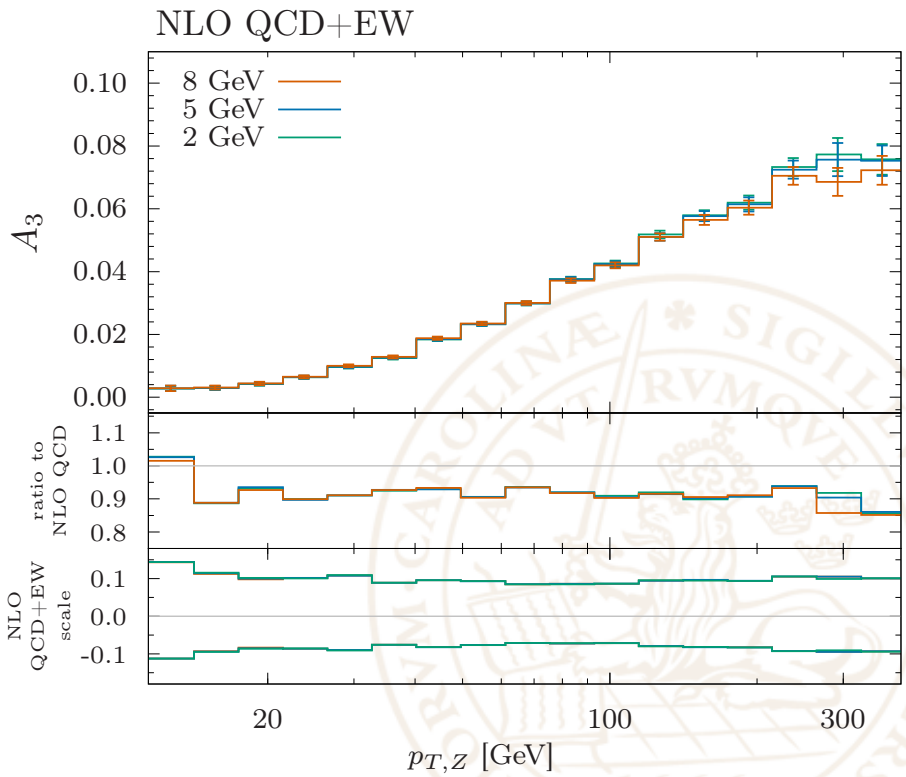




Angular coefficients: results

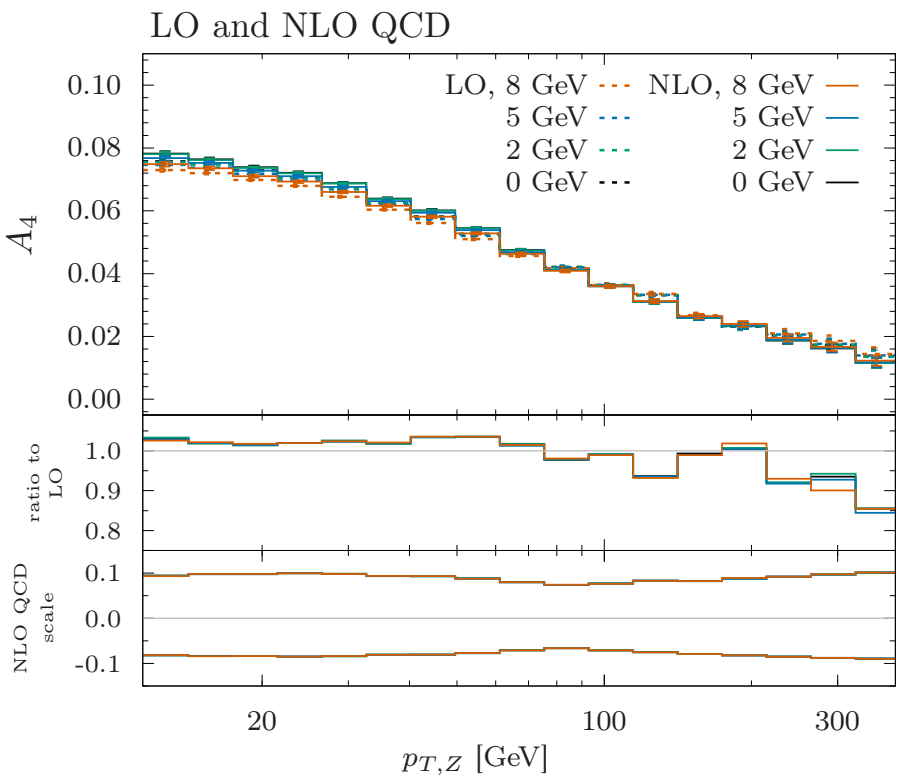
- Distributions for A_3
- Overall -10% electroweak corrections
- Would be **-30%** if **no one-loop** ρ-parameter in NLO QCD

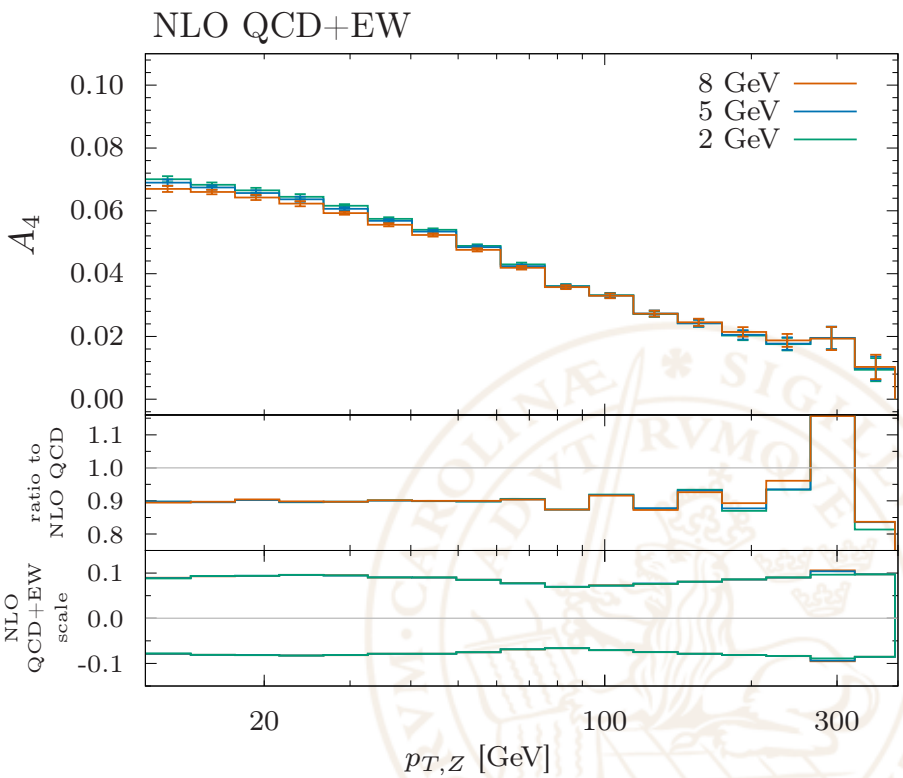




Angular coefficients: results

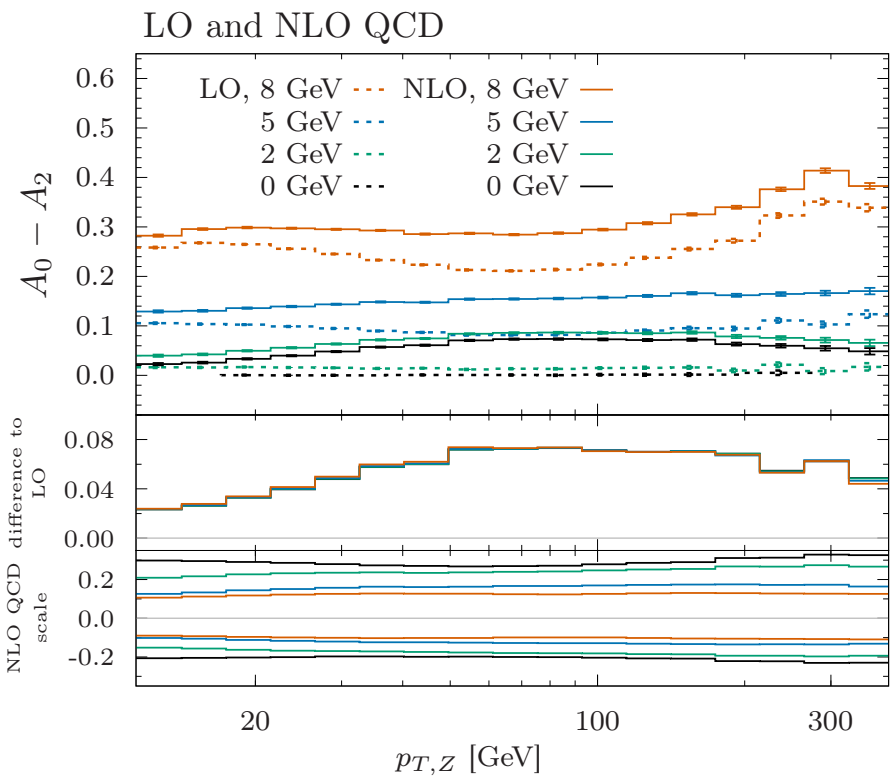
- Distributions for A_4
- Same -10% electroweak corrections

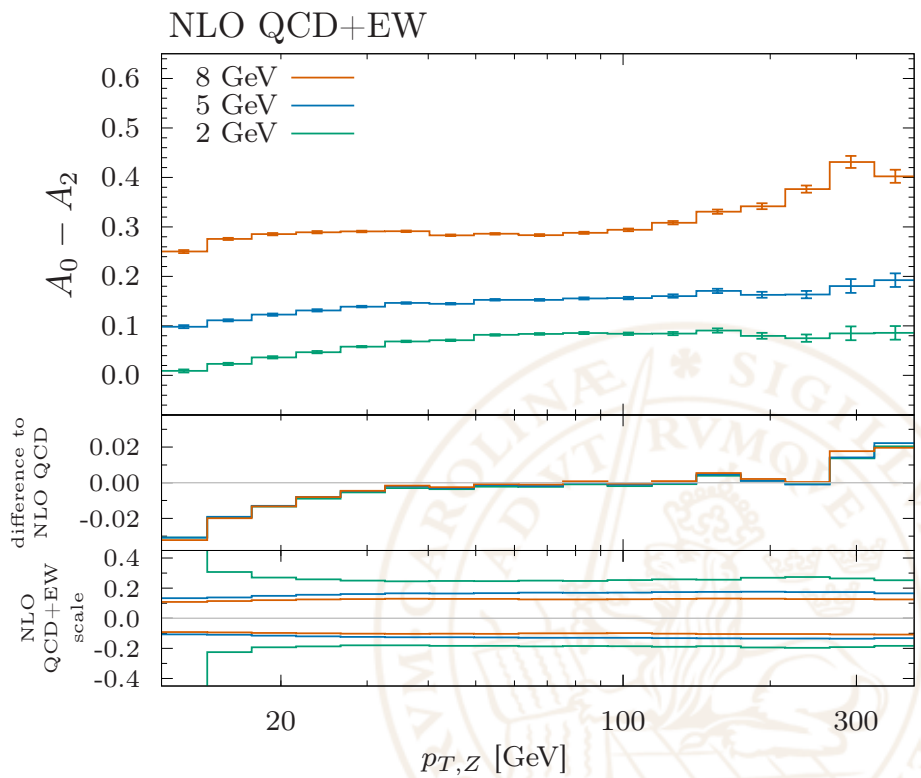




Angular coefficients: results

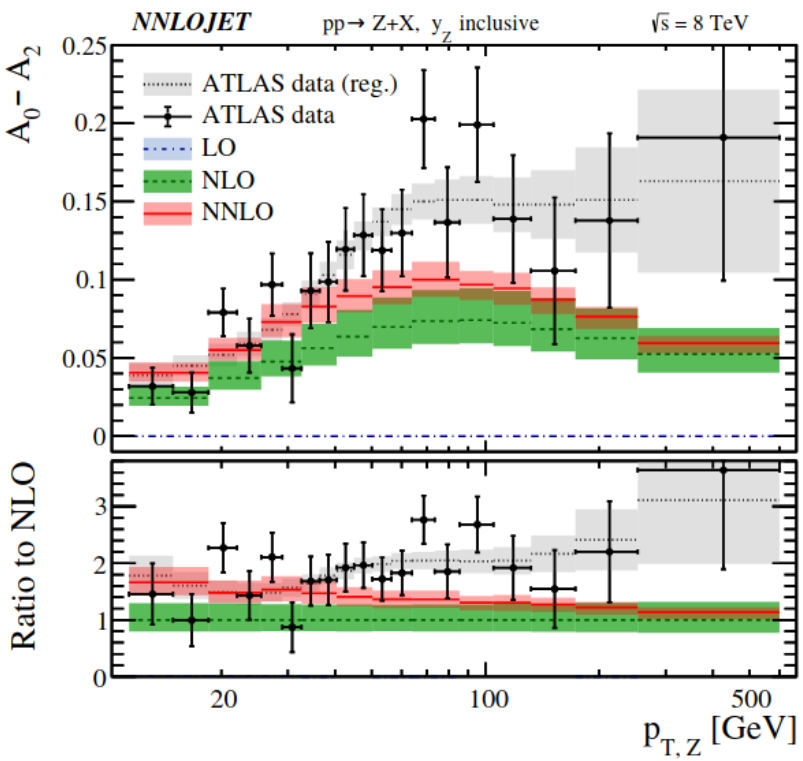
- Lam-Tung relation $A_0 - A_2$
- **Difference** rather than ratio as ***K*-factor**

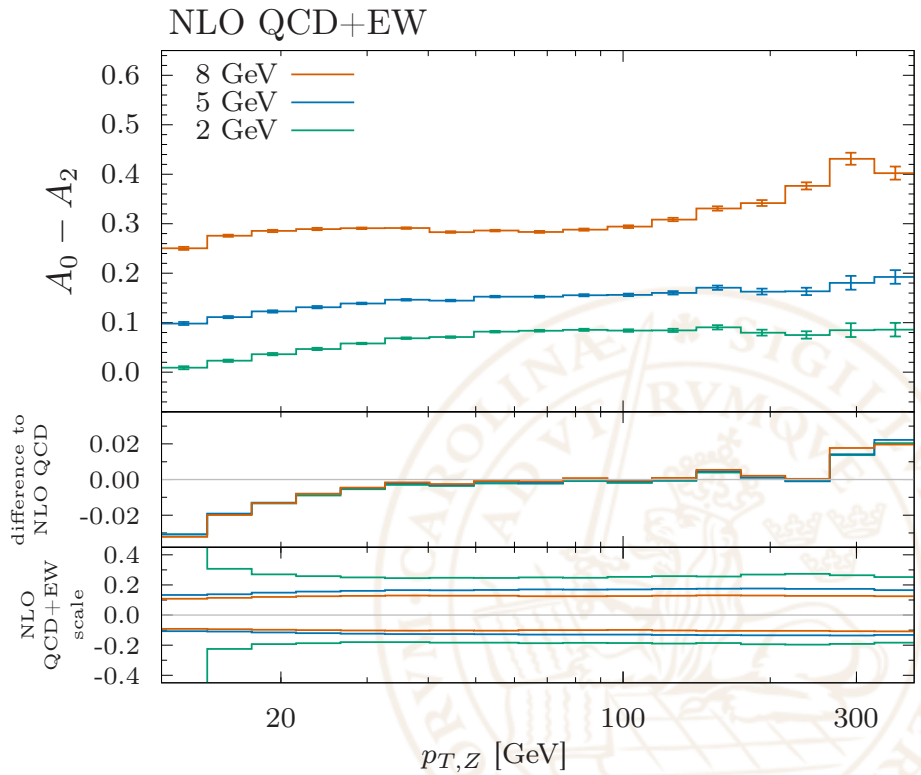




Angular coefficients: results

- Lam-Tung relation $A_0 - A_2$
- **Difference** rather than ratio as ***K*-factor**
- **Qualitative comparison** to **ATLAS** data and **NNLO QCD** prediction[10]





[10] R. Gauld, *et al.*, arXiv:1708.00008

Summary

Technical cut

K-factors: negligible dependence on single lepton $p_T$cut
Lam-Tung relation difference: no dependence on the cut

Low-p_T range

Found sizeable effect on the Lam-Tung relation for $p_{T,Z} \lesssim 20$ GeV

High-p_T range

No electroweak effect for $p_{T,Z} \gtrsim 20$ GeV
$\rightarrow$ elecrtoweak logs are not expected to contribute largely

Thank you for listening!