Transverse-momentum Resummation effects on angular coefficients in Z and W boson hadroproduction

Gabriele Francesco Sala
In collaboration with S. Camarda, G. Ferrera, L. Rossi



UNIVERSITÀ DEGLI STUDI DI MILANO
FACOLTÀ DI SCIENZE E TECNOLOGIE

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Why the DY Angular Coefficients?

Impact of q_T-Resummation on DY Angular Coefficients:

Why?

Precision Physics

Theoretical predictions of DY angular coefficients have been used in the W mass extraction.

Polarization

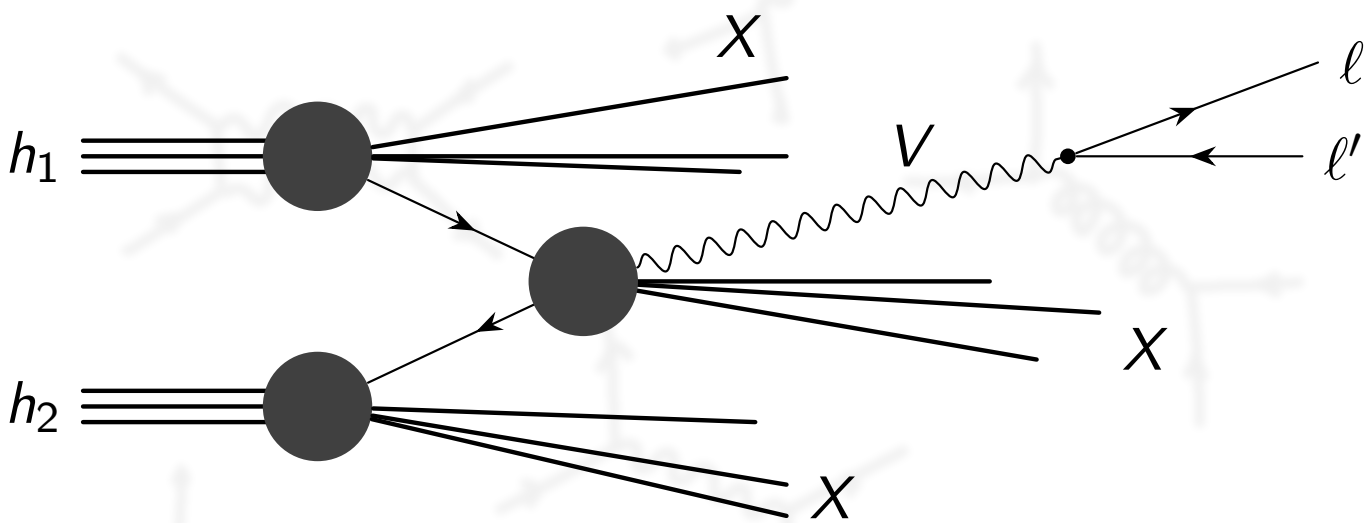
Lepton angular distributions probe vector-boson polarization and provide complementary information about QCD dynamics.

Theory Gap

At low q_T, large logarithmic corrections require resummation; its impact on angular coefficients is still not fully understood.

The Drell-Yan Process

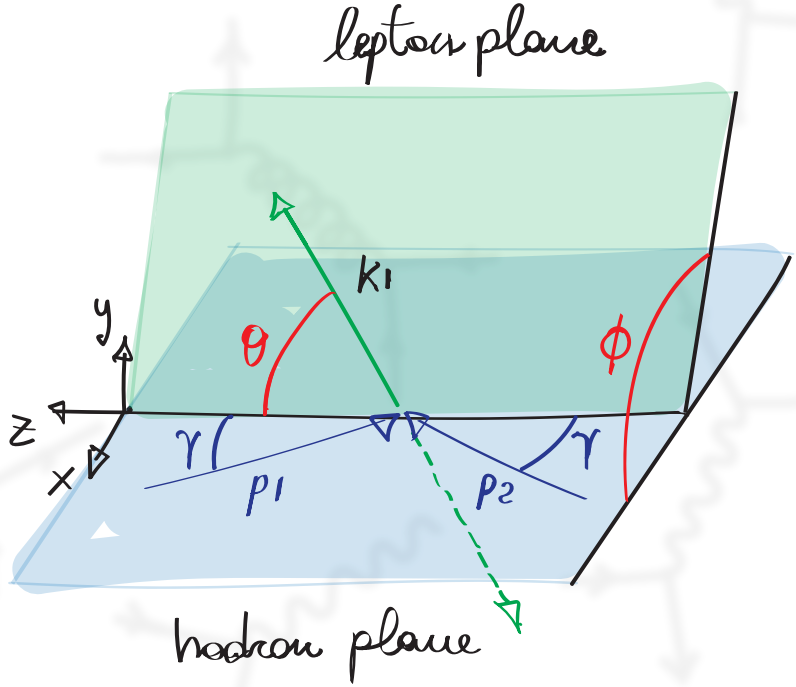
$$h_1(p_1) + h_2(p_2) \to V(q) + X \to \ell + \ell' + X$$



- Fully inclusive in QCD radiation
- $\{\ell, \ell'\} = \{\ell^+, \ell^-\}$: Z/γ^* production
- $\{\ell, \ell'\} = \{\ell^-, \bar{\nu}_\ell\}, \{\ell^+, \nu_\ell\}$: $W^\pm$ production

The Reference Frame

- Angular Coefficients are defined in a V-boson rest frame
- Different frames are related by rotations; all frames equivalent for $q_T \to 0$
- Collins-Soper frame: treats the two beams symmetrically and reduces sensitivity to the transverse motion of the partons



The Angular Coefficients

- In a V rest frame, the cross-section dependence on the $\ell\ell'$ pair's angular distribution $\mathbf{\Omega}$ is encoded in the **Angular Coefficients**

$$\frac{d\sigma}{d^2\mathbf{q}_T\, dy\, dM\, d\mathbf{\Omega}} = \frac{3}{16\pi}\frac{d\sigma}{d^2\mathbf{q}_T\, dy\, dM}\Big[(1+\cos^2\theta) + \frac{A_0}{2}(1-3\cos^2\theta) + A_1 \sin 2\theta\cos\phi + \frac{A_2}{2}\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big]$$

- For $q_T \to 0$, most Angular Coefficients are *power-suppressed*: only the **Forward-Backward Asymmetry** $A_{\rm FB} \propto A_4$ (sensitive to EW effects) survives

$$\frac{d\sigma}{d^2\mathbf{q}_T\, dy\, dM\, d\mathbf{\Omega}} \to \frac{3}{16\pi}\frac{d\sigma}{d^2\mathbf{q}_T\, dy\, dM}\Big[(1+\cos^2\theta) + A_4\cos\theta\Big]$$

The q_T-Resummation Formalism

- The hadronic cross-section σ is expressed as a *hard* (partonic) cross-section $\hat{\sigma}$ convoluted with the *Partonic Distribution Functions*

$$\frac{d\sigma_{h_1 h_2 \to ll'}}{d^2\mathbf{q}_T\, dM\, dy\, d\mathbf{\Omega}} = \sum_{a_1,a_2} \int_0^1 dx_1 \int_0^1 dx_2\, f_{a_1/h_1}(x_1)\, f_{a_2/h_2}(x_2) \times \frac{d\hat{\sigma}_{a_1 a_2 \to ll'}}{d^2\mathbf{q}_T\, dM\, d\hat{y}\, d\mathbf{\Omega}} (\mathbf{q}_T, M, \hat{y}, \hat{s}, \mathbf{\Omega})$$

- For $q_T \to 0$, $d\hat{\sigma} \sim \sum \alpha_S^n L_q^m / q_T^2$, $L_q = \ln q_T^2/M^2$
- Resummed to all orders after performing q_T-Resummation

The q_T-Resummation Formalism

- In impact parameter space, $\ln M^2/q_T^2 \to L = \ln M^2 b^2 >> 1$

$$\frac{d\hat{\sigma}_{a_1 a_2 \to ll'}}{d\mathbf{\Omega} dq_T dM d\hat{y}} = \frac{M^2}{\hat{s}} \int \frac{d^2\mathbf{b}}{4\pi} e^{i\mathbf{b}\cdot\mathbf{q}_T} \mathcal{W}_{a_1 a_2}(\mathbf{\Omega}, b, M, \hat{y}, \hat{s})$$

- In Mellin space w.r.t $z = M^2/\hat{s}$ the logs exponentiate

$$\mathcal{W}_{N,a_1 a_2}(\mathbf{\Omega}, b, M, \hat{y}) = \left[d\hat{\sigma}^{(0)}_{q\bar{q}\to ll'}/d\mathbf{\Omega}\right] \mathcal{H}_{N,q\bar{q}}(\alpha_S) \times \exp\left(\mathcal{G}_{N,a_1 a_2}(\alpha_S, L)\right)$$

- $\mathcal{H}, \mathcal{G}$ can be directly related to TMDs

$$\frac{d\sigma^{(\mathrm{res.})}}{dq_T} = \frac{M^2}{\hat{s}} \hat{\sigma}^{(0)}_{q\bar{q}} H_q(\alpha_S(M^2)) \sum_{a_1,a_2} \int \frac{d^2\mathbf{b}}{2\pi} e^{i\mathbf{b}\cdot\mathbf{q}_T} S_q(M, b)$$
$$\times \int_{x_1}^1 \frac{dz_1}{z_1} C_{q a_1}(z_1; \alpha_S(b_0^2/b^2)) f_{a_1/h_1}(x_1/z_1, b_0^2/b^2) \int_{x_2}^1 \frac{dz_2}{z_2} C_{\bar{q} a_2}(z_2; \alpha_S(b_0^2/b^2)) f_{a_2/h_2}(x_2/z_2, b_0^2/b^2)$$

$$\tilde{F}_{q/h}(x, b, M) = \sum_a \int_x^1 \frac{dz}{z} \sqrt{S_q(M, b)} C_{q\,a}(z; \alpha_S(b_0^2/b^2)) f_{a/h}(x/z, b_0^2/b^2)$$

The Matched Cross-Section

- the *matched* Cross-Section smoothly interpolates between Resummed and FO predictions

$$d\hat{\sigma}_{a_1 a_2 \to l l'} = d\hat{\sigma}^{(\mathrm{res.})}_{a_1 a_2 \to l l'} + d\hat{\sigma}^{(\mathrm{fin.})}_{a_1 a_2 \to l l'}$$

Log-enhanced contributions

$$\sum_q d\hat{\sigma}^{(0)}_{q\bar{q}\to l l'} \; (1 + \sum_n \alpha_S^n \mathcal{H}^{(n)}_{q\bar{q}}) \times \exp(L g^{(1)} + \sum_n \alpha_S^n g^{(n+2)})$$

Where $g^{(n)} = g^{(n)}(\alpha_S L)$
$N^k LL + N^{k-1} LO$ Accuracy:
$\mathcal{G}$ up to $g^{(k-1)}$, $\mathcal{H}$ up to $\mathcal{H}^{(k)}$

Finite terms from FO

$$\Big[d\hat{\sigma} \Big]_{\mathrm{f.o.}} - \Big[[d\hat{\sigma}^{(\mathrm{res.})}]_{\mathrm{l.a.}} \Big]_{\mathrm{f.o.}}$$

The requirement of no double-counting determines which order must be matched to $N^k LL$

q_T-Resummation and the Angular Coefficients

- Angular Coefficients can be obtained by ratios of cross-sections:

$$A_i \sim \frac{\int d\mathbf{\Omega}\, \omega_i(\mathbf{\Omega})\, d\hat{\sigma}/dq_T d\mathbf{\Omega}}{\int d\mathbf{\Omega}\, d\hat{\sigma}/dq_T d\mathbf{\Omega}}$$

- Born angular dependence* enters the numerator in $d\hat{\sigma}^{(\mathrm{res.})}$: **only the denominator is resummed**
- *: Partonic Born kinematics need to be modified to account for $q_T \neq 0$: some contributions from the Recoil Prescription



$$\frac{d\hat{\sigma}^{(0)}}{d\mathbf{\Omega}} = \hat{\sigma}^{(0)}(M^2)\, F(\mathbf{q}_T; M^2, \mathbf{\Omega})$$

Methodology

- **The objective:** Compute DY Angular Coefficients at NLO & NNLL+NLO and compare with experimental data

- **The program:** The `DYTurbo` public code provides numerical calculation for FO and matched DY cross-sections:
  - Fully-exclusive in the leptonic kinematics
  - Non-perturbative effects in the low-q_T region
  - Fast integration (with quadrature methods) for azimuthally-averaged cross-section
  - Modified logs $L \to \tilde{L} = \ln\left(1 + \frac{M^2 b^2}{b_0^2}\right)$ improve matching and enforce unitarity

Methodology

- The value for the **Angular Coefficient** A_i within a q_T-bin can be computed by

$$\langle A_i \rangle_{\text{bin}} \propto \frac{\int_{\text{bin}} dq_T \int d\mathbf{\Omega}\, \omega_i(\mathbf{\Omega})\, d\hat{\sigma}/dq_T d\mathbf{\Omega}}{\int_{\text{bin}} dq_T \int d\mathbf{\Omega}\, d\hat{\sigma}/dq_T d\mathbf{\Omega}}$$

Smearing effect

- χ^2 **Test** for each dataset d to quantitatively assert improvement (availability of Correlation Matrix V_d varies...)

$$\chi^2 = \left(\vec{D}_d - \vec{P}_d\right)^T V_d^{-1} \left(\vec{D}_d - \vec{P}_d\right)$$

Methodology

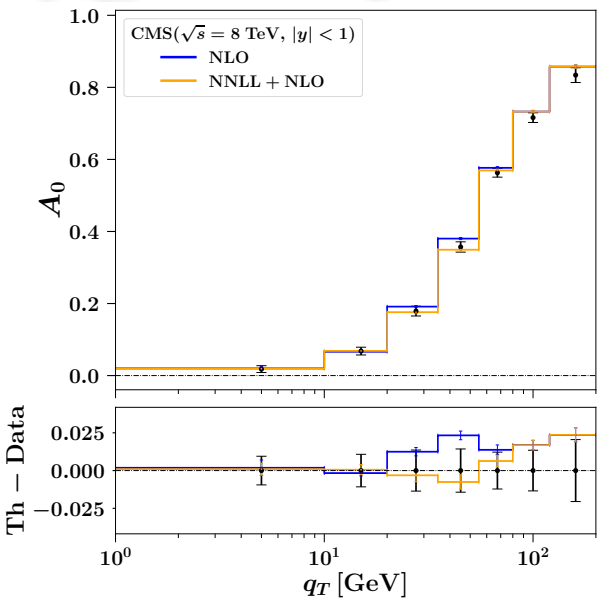
Wide range of analyzed datasets

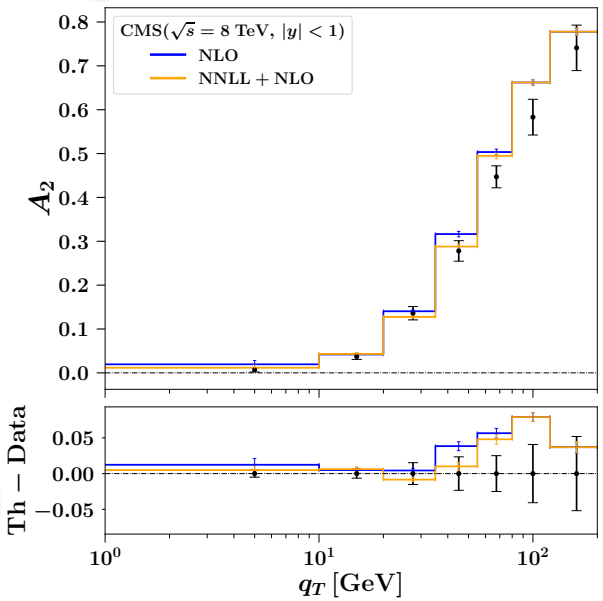
Experiment	Exchanged boson	N_{dat}	$\sqrt{s}$ [GeV]	y cut
CDF	Z	5	1960	Inclusive
CMS	Z	7	8000	$\lvert y\rvert < 1$
ATLAS	Z	19	8000	$\lvert y\rvert < 1$
LHCb	Z	6	13000	$y > 2$
CDF	W^-	4	1800	Inclusive
ATLAS	W^+	10	13000	Inclusive
ATLAS	W^-	10	13000	Inclusive

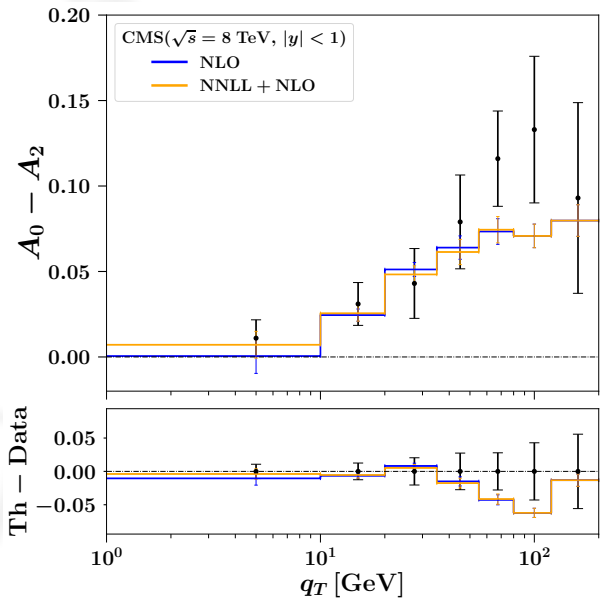
Results

Z-boson: Moderate but systematic improvement around $q_T \sim 20 - 50\text{GeV}$

χ^2 (CMS, $\sqrt{s} = 8\text{TeV}$, $\lvert y\rvert < 1$)		
	NLO	NNLL+NLO
A_0	1.05	0.47
A_2	1.92	1.30
$A_0 - A_2$	0.78	0.70



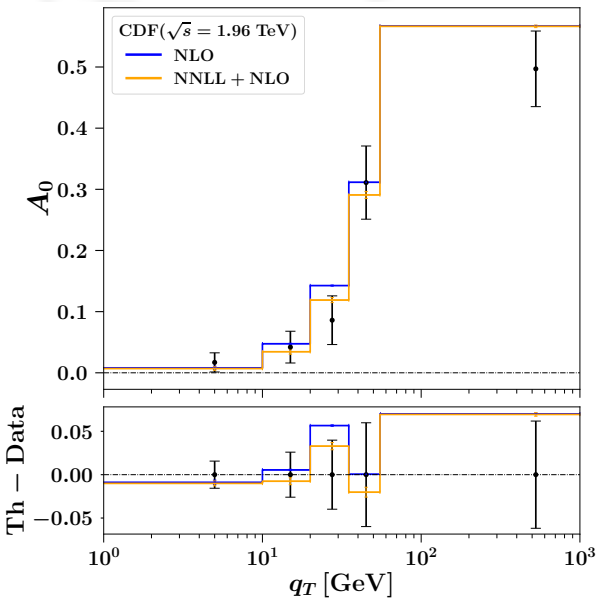


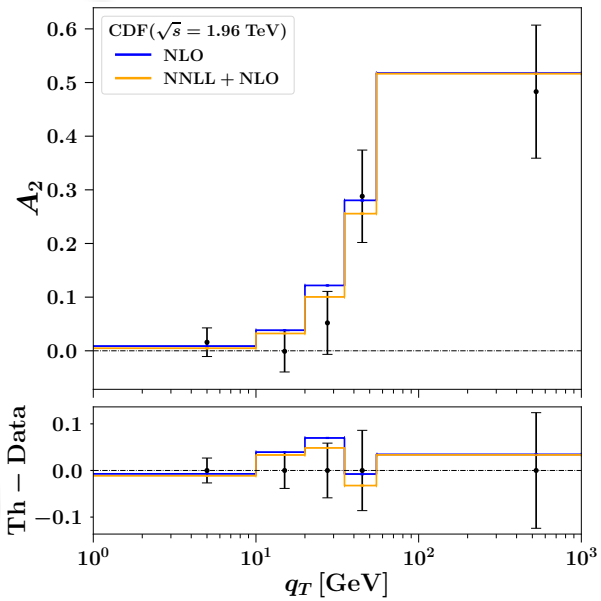


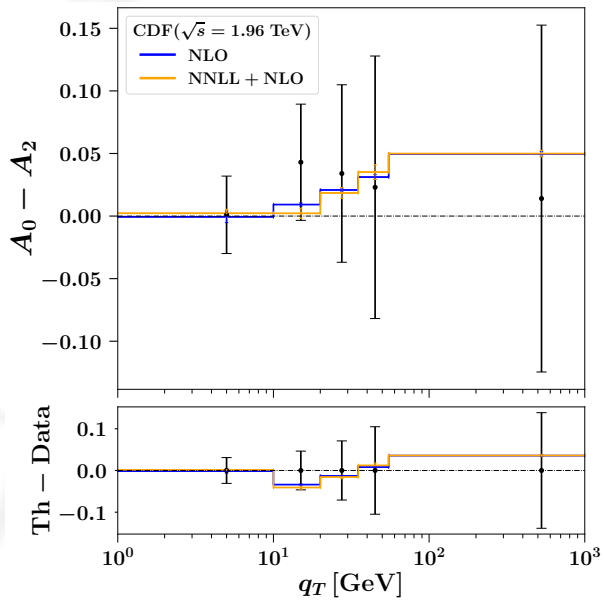
Results

Z-boson: Moderate but systematic improvement around $q_T \sim 20 - 50\text{GeV}$

χ^2 (CDF, $\sqrt{s} = 1.96\text{TeV}$)		
	NLO	NNLL+NLO
A_0	0.73	0.51
A_2	0.52	0.36
$A_0 - A_2$	0.13	0.18



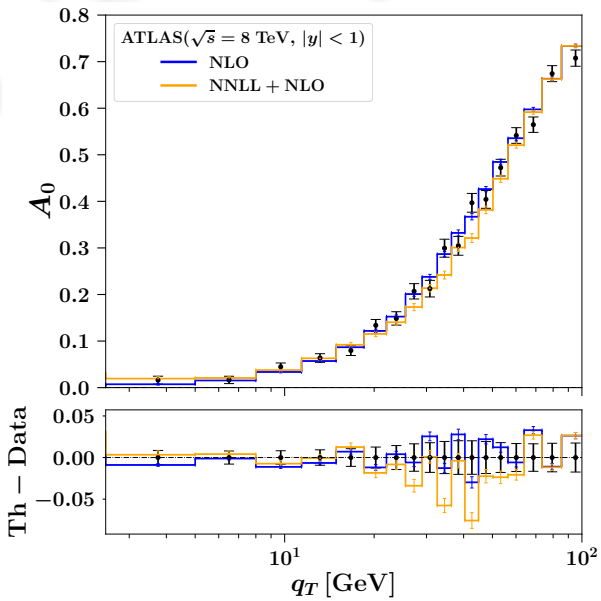


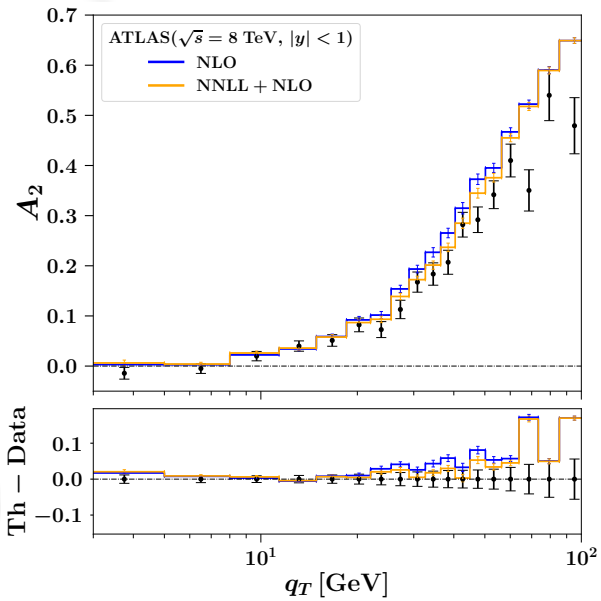


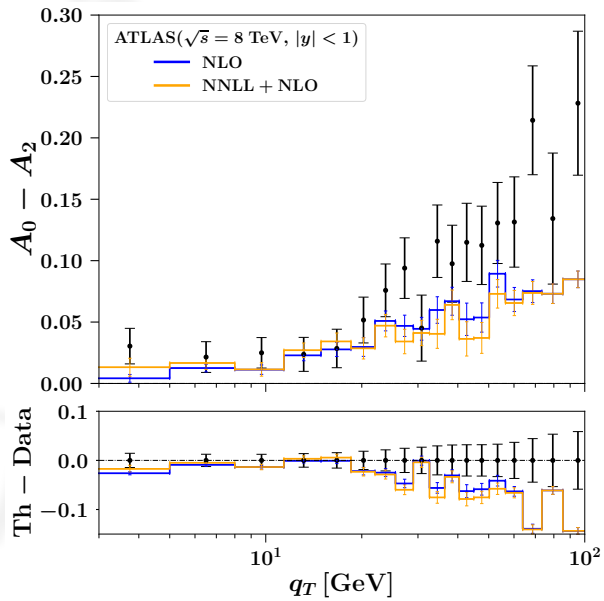
Results

Z-boson: Moderate but systematic improvement around $q_T \sim 20 - 50\text{GeV}$

χ^2 (ATLAS, $\sqrt{s} = 8\text{TeV}$, $\lvert y\rvert < 1$)		
	NLO	NNLL+NLO
A_0	0.70	1.40
A_2	3.64	2.42
$A_0 - A_2$	2.24	2.61



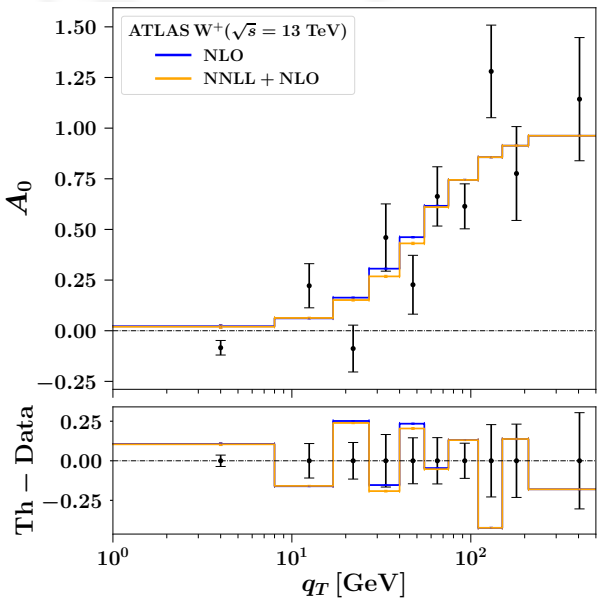


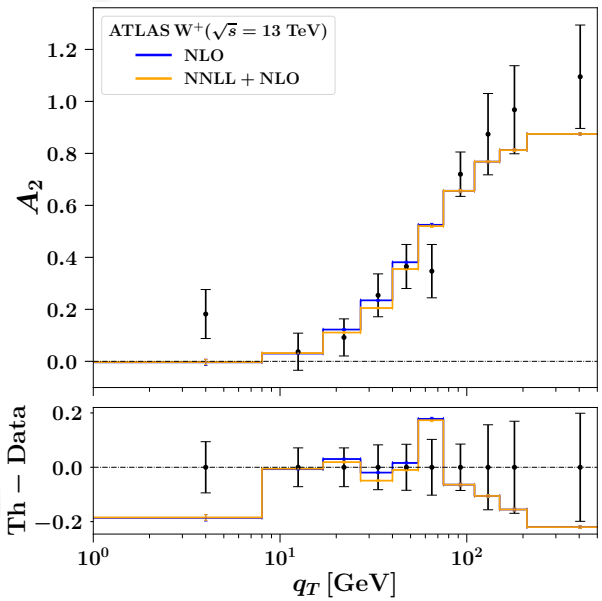


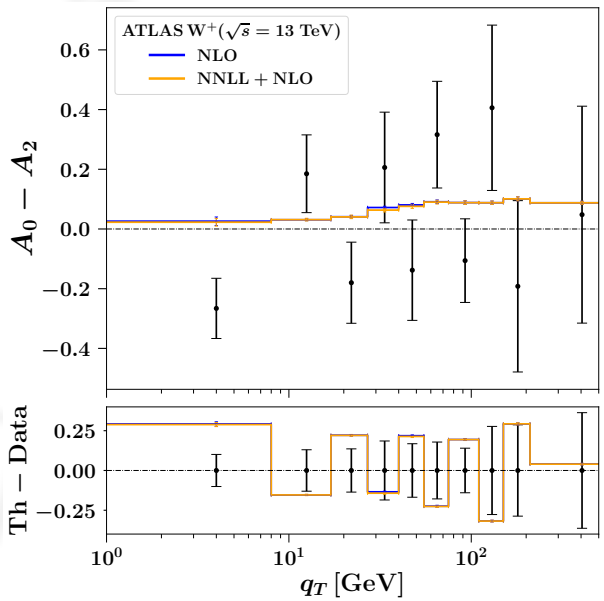
Results

W-boson: Visible modification in the intermediate-q_T region
More precise data is required

χ^2 (ATLAS, W^+, $\sqrt{s} = 13$TeV)	NLO	NNLL+NLO
A_0	2.43	2.34
A_2	1.02	1.01
$A_0 - A_2$	2.03	2.01



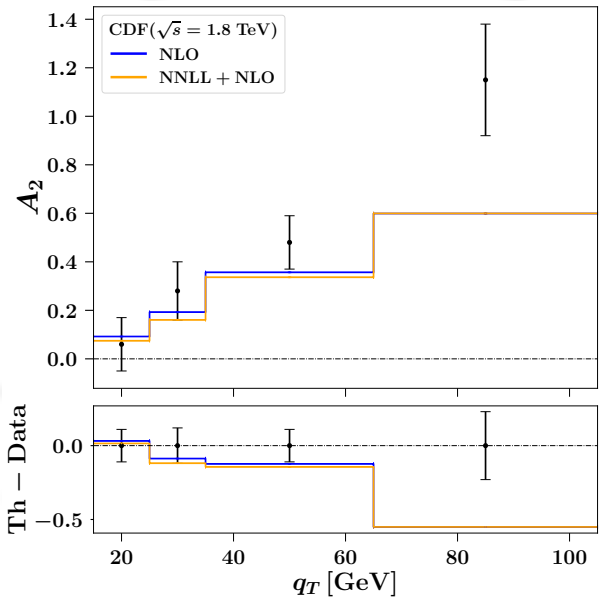


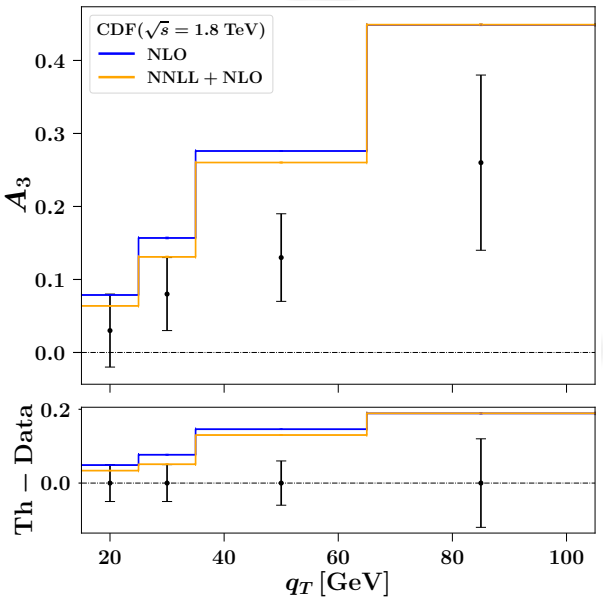


Results

W-boson: Visible modification in the intermediate-q_T region
More precise data is required

χ^2 (CDF, W^-, $\sqrt{s} = 1.8$TeV)	NLO	NNLL+NLO
A_2	1.90	2.10
A_3	2.93	2.17





Conclusions

- **What we did:** Comprehensive analysis of the impact of q_T-resummation on DY Angular Coefficients
- **How we did it:** NLO & NNLL+NLO theoretical predictions computed with `DYTurbo` public code and comparisons with experimental data backed up by χ^2 test
- **What we found:** Slight but consistent improvement for Z-boson data, inconclusive results for W-boson data

Thank you!

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The Recoil Prescription

Potentially large impact of Recoil Prescription?

