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Z-boson pT-spectrum and lepton angular coefficients in the LO high-energy factorization with the real NLO corrections

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Inclusive Z-boson production

$$p + p \to Z/\gamma^* \to l^+ + l^-$$

- LO process: $Q + \bar{Q} \to Z/\gamma^* \to \mu^+ + \mu^-$.
- Drell-Yan processes are studied a long time.
- The effect of NLO $Q(\bar{Q}) + R \to Z/\gamma^* + q(\bar{q}) \to \mu^+ + \mu^- + q(\bar{q})$ is studied in the HEF approach.

Collinear Parton Model (CPM)

- On–shell initial states: $k_i^\mu = x_i P_i^\mu, \;\; {k_i}^2 = 0$
- Collinear factorization: $a(k_1) + b(k_2) \to \dots k(k_f)$

$$d\sigma = \sum_{a,\bar{b}} \int dx_1 f_{a/p}(x_1, \mu_F) \int dx_2 f_{b/p}(x_2, \mu_F) \times d\hat{\sigma}_{ab},$$

where $a, b \in \{g, q, \bar{q}\}$. Partonic cross-section:

$$d\hat{\sigma}_{ab}(t_1, t_2, k_f) = (2\pi)^4 \delta^{(4)}(k_1 + k_2 - \sum k_f) \frac{\overline{|\mathcal{A}(a\, b \to \dots)|^2}}{I} d\Phi(k_f)$$

with $I \simeq 2x_1 x_2 s$

- Framework: $\mu_F \sim p_T \gg \Lambda_{QCD}$.

Parton Reggeization Approach (PRA)

- Off–shell initial states: $k_i^\mu = x_i P_i^\mu + k_{Ti}^\mu, \;\; k_i^2 = -\mathbf{k}_{Ti}^2;$
- *Multi–Regge* kinematics: $a(k_1) + b(k_2) \to \ldots (k_f)$

$$d\sigma = \sum_{a,\bar{b}} \int \frac{dx_1}{x_1} \int dt_1 \int \frac{d\phi_1}{2\pi} \int \frac{dx_2}{x_2} \int dt_2 \int \frac{d\phi_2}{2\pi} \Phi_{a/p}(x_1, t_1, \mu^2) \Phi_{b/p}(x_2, t_2, \mu^2)$$

$\times d\hat{\sigma}_{ab}^{\mathrm{PRA}}$
where $t_i = -{k_{Ti}}^2$ and $a, b \in \{R, Q_q, \bar{Q}_q\}$. Partonic cross section:

$$d\hat{\sigma}_{ab}^{\mathrm{PRA}}(t_1, t_2, k_f) = (2\pi)^4 \delta^{(4)}(k_1 + k_2 - \sum k_f) \frac{\overline{|\mathcal{A}^{\mathrm{PRA}}(a\, b \to \ldots)|^2}}{I} d\Phi(k_f)$$

with $I \simeq 2x_1x_2$, $\overline{|\mathcal{A}^{\mathrm{PRA}}|^2}$ is calculated in the *Lipatov's EFT*. Exact normalization condition for the *modified unPDF*

$$\int_0^{\mu^2} dt_i \Phi_{a/p}(x_i, t_i, \mu^2) = x_i f_{a/p}(x_i, \mu^2)$$

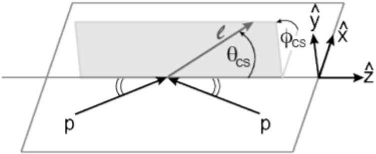
- Framework: $\mu_F \ll \sqrt{s}$ - ≪small≫ x physics.

Main PRA publications:

- M.A. Nefedov, V.A. Saleev and A.V. Shipilova, ≪Dijet azimuthal decorrelations at the LHC in the parton Reggeization approach≫, Phys. Rev. D 87 (2013) no.9, 094030;
- A.V. Karpishkov, M.A. Nefedov and V.A. Saleev, ≪$B\bar{B}$ angular correlations at the LHC in parton Reggeization approach merged with higher-order matrix elements≫, Phys. Rev. D 96 (2017) no.9, 096019;
- M. Nefedov and V. Saleev, ≪On the one–loop calculations with Reggeized quarks≫, Mod. Phys. Lett. A 32 (2017) no.40, 1750207;
- M.A. Nefedov, ≪Towards stability of NLO corrections in High–Energy Factorization via Modified Multi–Regge Kinematics approximation≫, JHEP 08 (2020), 055;
- M.A. Nefedov and V.A. Saleev, ≪High-Energy Factorization for Drell–Yan process in pp and $p\bar{p}$ collisions with new Unintegrated PDFs≫, Phys. Rev. D 102 (2020), 114018.

Collins-Soper frame (CS)

- The rest of $l\,\bar{l}$ frame.



$$\frac{d\sigma}{dQd\mathbf{q}_T dy d\Omega_l} = \frac{3}{16\pi}\frac{d\sigma}{dQd\mathbf{q}_T dy}[(1+\cos^2\theta_l) + \frac{A_0}{2}(1-3\cos^2\theta_l) + A_1\sin 2\theta_l\cos\phi_l$$

$$+ \frac{A_2}{2}\sin^2\theta_l\cos 2\phi_l + A_3\sin\theta_l\cos\phi_l + A_4\cos\theta_l$$

$$+ A_5\sin^2\theta_l\sin 2\phi_l + A_6\sin 2\theta_l\sin\phi_l + A_7\sin\theta_l\sin\phi_l]$$

MC parton-level event generator KaTie

- The approach to obtaining gauge invariant amplitudes with off-shell initial state partons in scattering at high energies was proposed in the Ref. [A. van Hameren, P. Kotko, and K. Kutak, JHEP 01, 078 (2013), 1211.0961].
- This formalism for numerical amplitude generation is equivalent to amplitudes built according to Feynman rules of the Lipatov EFT at the level of tree diagrams. It has been tested numerically at least for $2 \to 2$ and $2 \to 3$.
- The accuracy of our numerical calculations using KaTie for total proton-proton cross sections is equal to 0.05%.

Method of moments

- After integrating the angular distribution in CS with a specific function m we can explicitly express A_i:

$$< m >= \frac{\int d\sigma(q_T, y, \theta, \phi)\, m\, d\cos\theta d\phi}{\int d\sigma(q_T, y, \theta, \phi) d\cos\theta d\phi} \to \frac{\sum_{i=1}^{N_{\rm ev}} W(\theta_l^i, \phi_l^i) m(\theta_l^i, \phi_l^i)}{\sum_{i=1}^{N_{\rm ev}} W(\theta_l^i, \phi_l^i)}$$

$$< \tfrac{1}{2}(1 - 3\cos^2\theta) >= \tfrac{3}{20}(A_0 - \tfrac{2}{3}), \qquad < \sin 2\theta \cos\phi >= \tfrac{1}{5} A_1$$

$$< \sin^2\theta \cos 2\phi >= \tfrac{1}{10} A_2 \qquad < \sin\theta \cos\phi >= \tfrac{1}{4} A_3$$

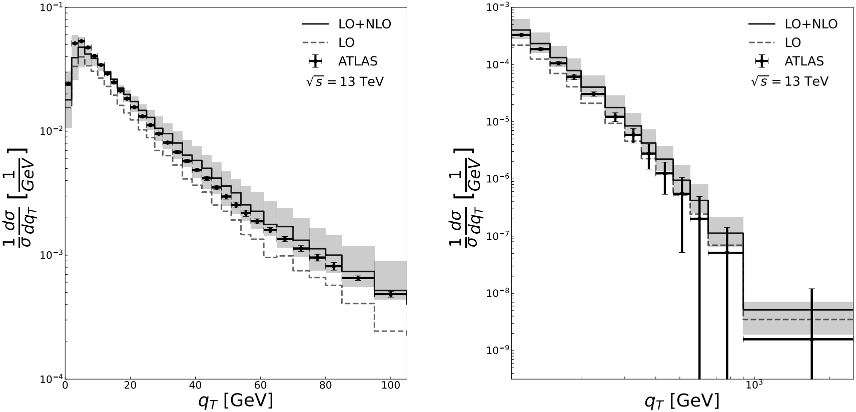
Cross section

- Calculation of cross section with NLO correction.

$\sqrt{S}$ TeV	σ^{exp} [nb]	σ^{LO} [nb]	σ^{NLO} [nb]	σ^{theor} [nb]
7	$0.396^{+0.026}_{-0.026}$	0.303	0.155	$0.458^{+0.052}_{-0.059}$
8	$0.410^{+0.030}_{-0.030}$	0.311	0.164	$0.476^{+0.056}_{-0.064}$
13	$0.731^{+0.027}_{-0.027}$	0.569	0.349	$1.023^{+0.104}_{-0.230}$

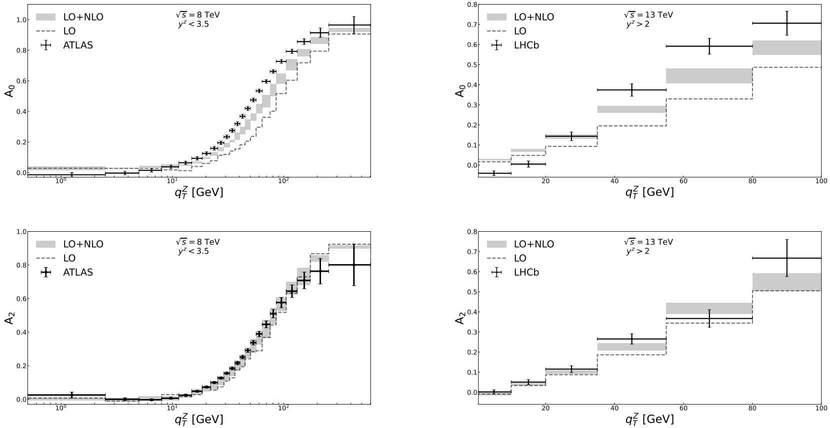
- Markers:

$$\sigma^{\text{LO}} = \sigma(Q\bar{Q} \to Z/\gamma^* \to l\ \bar{l})$$
$$\sigma^{\text{NLO}} = \sigma(Q(\bar{Q})R \to q(\bar{q})\ Z/\gamma^* \to q(\bar{q})\ l\ \bar{l})$$
$$\sigma^{\text{theor}} = \sigma^{\text{LO}} + \sigma^{\text{NLO}}$$



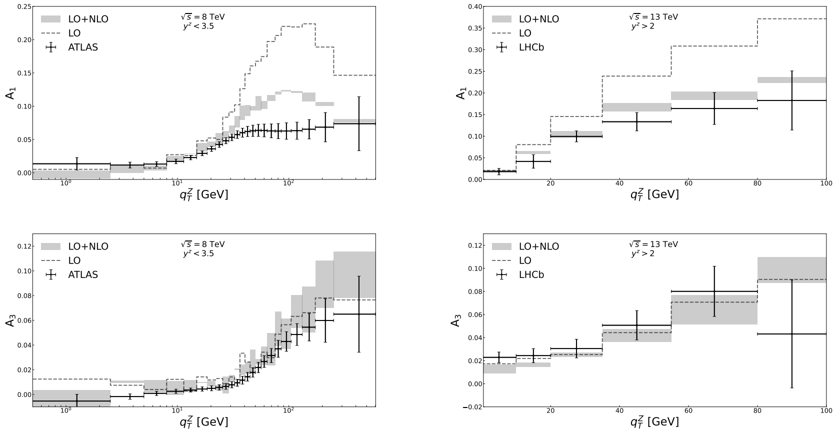
Spectra of inclusive Z-boson production on transverse momentum q_T^Z where lepton rapidities $|y_l| < 2.5$ with NLO correction in PRA[1].

[1] The data are from ATLAS Collaboration



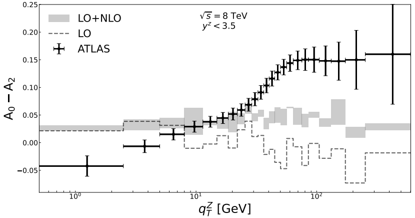
A_0 and A_2 as functions q_T^Z with NLO correction in PRA[2].

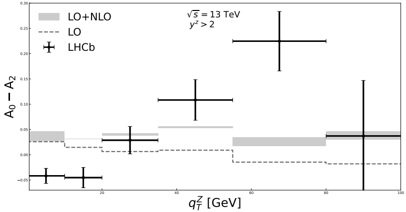
[2] The data are from ATLAS and LHCb Collaborations



A_1 and A_3 as functions q_T^Z with NLO correction in PRA.

Results





$A_0 - A_2$ as functions q_T^Z with NLO correction in PRA. For LO $A_0 - A_2 \simeq 0.004$, with NLO correction $A_0 - A_2 \simeq 0.04$

Conclusions

- MC generator KaTie is used to calculate and lepton angular coefficients A_n for the first time.
- The first correction of NLO by α_s improves the description of angular coefficients.
- For angular coefficients calculated in HEF accounting NLO fundamentally important.
- More accurate study is needed, y^Z-dependence.

Thank you for your attention!