

## Drell-Yan plus jet production and BFKL evolution

---

**Krzysztof Golec-Biernat**<sup>\*†</sup>

*Institute of Nuclear Physics PAN, Kraków, Poland*

*E-mail:* [golec@ifj.edu.pl](mailto:golec@ifj.edu.pl)

**Leszek Motyka**

*Jagiellonian University, Kraków, Poland*

*E-mail:* [Leszek.Motyka@uj.edu.pl](mailto:Leszek.Motyka@uj.edu.pl)

**Tomasz Stebel**

*Institute of Nuclear Physics PAN, Kraków, Poland*

*E-mail:* [Tomasz.Stebel@ifj.edu.pl](mailto:Tomasz.Stebel@ifj.edu.pl)

The production of a forward Drell-Yan lepton pair accompanied by a jet separated by large rapidity interval is proposed to study the BFKL evolution at the LHC. Several observables to be measured are presented including the azimuthal angle dependence of the lepton pair which allows to determine the DY structure functions.

*XXVII International Workshop on Deep-Inelastic Scattering and Related Subjects - DIS2019*

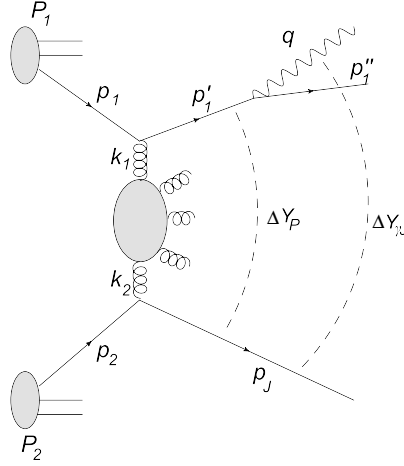
*8-12 April, 2019*

*Torino, Italy*

---

<sup>\*</sup>Speaker.

<sup>†</sup>A footnote may follow.



**Figure 1:** Kinematic variables relevant for the DY+jet production

## 1. Introduction

The Drell-Yan (DY) lepton pair production [1] is one of the most important processes which allow to study the QCD structure of the colliding hadrons. Of particular importance in this presentation are the high-energy QCD effects described by the Balitsky-Fadin-Kuraev-Lipatov (BFKL) evolution scheme [2] which is complementary to the commonly used collinear resummation schemes. A classical process to study the BFKL evolution in hadronic collisions, proposed by Mueller and Navelet (MN) [3], is a production of two jets with similar transverse momenta but with a large rapidity interval  $\Delta Y$  between them. In particular, it was proposed to look at the azimuthal decorrelation in the MN jets [4, 5]. Such studies were performed experimentally at the Fermilab [6, 7] and the LHC [8, 9] and analyzed theoretically in [10, 11] using the full NLO jet impact factors and the NLL BFKL kernels.

One of the MN jets can be replaced by a hadron [12]. We propose to replace it by a forward Drell-Yan lepton pair which has several advantages. (i) The experimental precision of DY measurements is usually very high. (ii) This process offers a broader range of parameters which may be scanned like the lepton pair mass  $M$  or its transverse momentum  $q_{\perp}$ . (iii) The lepton pair angular distribution allows to determine the DY structure functions [13] which show sensitivity to the underlying BFKL dynamics. (iv) Particularly interesting is the Lam-Tung combination of the DY structure functions [14] which is sensitive to partons' transverse momenta.

The forthcoming presentation is based on the paper [15] in which more details are provided.

## 2. Kinematics and cross sections

In Fig. 1 we show the relevant kinematic variables for the DY pair plus jet production with the BFKL ladder exchange. The most important is the large rapidity interval  $\Delta Y_{\gamma J}$  between the forward DY boson and the backward jet to be measured experimentally. The rapidity distance  $\Delta Y_P$  is purely theoretical since it is an argument of the BFKL kernel, related to  $\Delta Y_{\gamma J}$  through kinematics, see

formulae (2.9) and (2.10) in [15]. The DY+jet cross section reads

$$\begin{aligned} \frac{d\sigma^{\text{DY+j}}}{d\Pi d\Omega} &= (1 - \cos^2 \theta) \frac{d\sigma^{(L)}}{d\Pi} + (1 + \cos^2 \theta) \frac{d\sigma^{(T)}}{d\Pi} \\ &+ (\sin^2 \theta \cos 2\phi) \frac{d\sigma^{(TT)}}{d\Pi} + (\sin 2\theta \cos \phi) \frac{d\sigma^{(LT)}}{d\Pi}, \end{aligned} \quad (2.1)$$

where  $(\theta, \phi)$  are lepton spherical angles in the helicity frame,  $\Pi = (M^2, \vec{q}_\perp, \vec{p}_{J\perp}, \Delta Y_{\gamma J})$  are variables to be measured and the DY+j structure functions for four polarizations,  $\lambda = L, T, LT, TT$ , are given by

$$\begin{aligned} \frac{d\sigma^{(\lambda)}}{d\Pi} &= \frac{4\alpha_{\text{em}}^2 \alpha_s^2}{(2\pi)^4} \frac{1}{M^2 p_{J\perp}^2} \int_0^1 dx_1 \int_0^1 dx_2 \theta(1-z) f_q(x_1, \mu) f_{\text{eff}}(x_2, \mu) \\ &\times \int \frac{d^2 k_{1\perp}}{k_{1\perp}^2} \Phi^{(\lambda)}(\vec{q}_\perp, \vec{k}_{1\perp}, z) K_{\text{BFKL}}(\vec{k}_{1\perp}, \vec{k}_{2\perp} = -\vec{p}_{J\perp}, \Delta Y_P), \end{aligned} \quad (2.2)$$

where  $\Phi^{(\lambda)}$  are the DY impact factors and  $K_{\text{BFKL}}$  is the BFKL kernel given by the Fourier decomposition in the azimuthal angle  $\phi$  between  $\vec{k}_{1\perp}$  and  $\vec{k}_{2\perp}$

$$K_{\text{BFKL}}(\vec{k}_{1\perp}, \vec{k}_{2\perp}, \Delta Y_P) = \frac{2}{(2\pi)^2 |\vec{k}_{1\perp}| |\vec{k}_{2\perp}|} \left( I_0(\Delta Y_P) + \sum_{m=1}^{\infty} 2 \cos(m\phi) I_m(\Delta Y_P) \right) \quad (2.3)$$

More details on the BFKL are given in [15]. We only mention here that in our analysis  $K_{\text{BFKL}}$  is given in the leading logarithmic (LL) order with important part of the NLL corrections which are taken into account in the form of the kinematic constraint.

In the forthcoming presentation we will show the results for the helicity-inclusive cross section (2.1) integrated over the full spherical angle  $\Omega$  of the lepton pair,

$$\frac{d\sigma^{\text{DY+j}}}{d\Pi} = \frac{16\pi}{3} \left( \frac{d\sigma^{(T)}}{d\Pi} + \frac{1}{2} \frac{d\sigma^{(L)}}{d\Pi} \right). \quad (2.4)$$

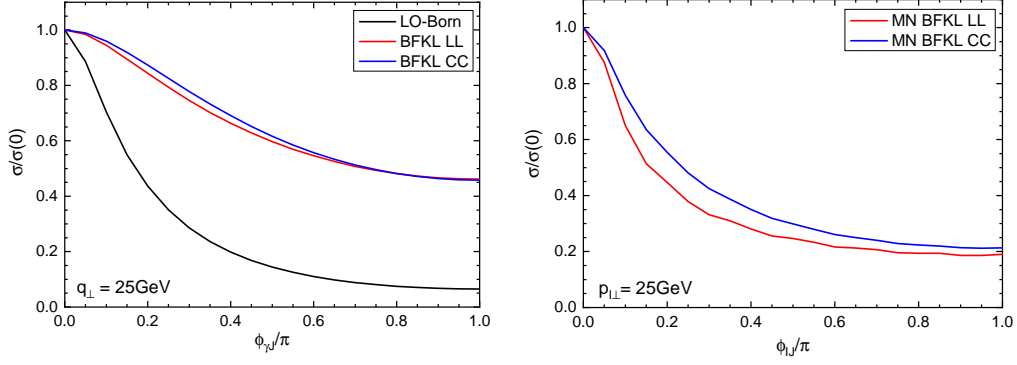
### 3. Azimuthal angle dependence

The first quantity to study is the dependence of (2.4) on the azimuthal angle  $\phi_{\gamma J}$  between the photon transverse momentum  $\vec{q}_\perp$  and jet momentum  $\vec{p}_{J\perp}$ , see Fig. 2 where the normalized formula (2.4) is shown as a function of  $\phi_{\gamma J}$ . The BFKL effects in the DY+jet case (left) lead to stronger decorrelation in the azimuthal angle in comparison to the LO-Born (two gluon) exchange and also to the MN jet case (right).

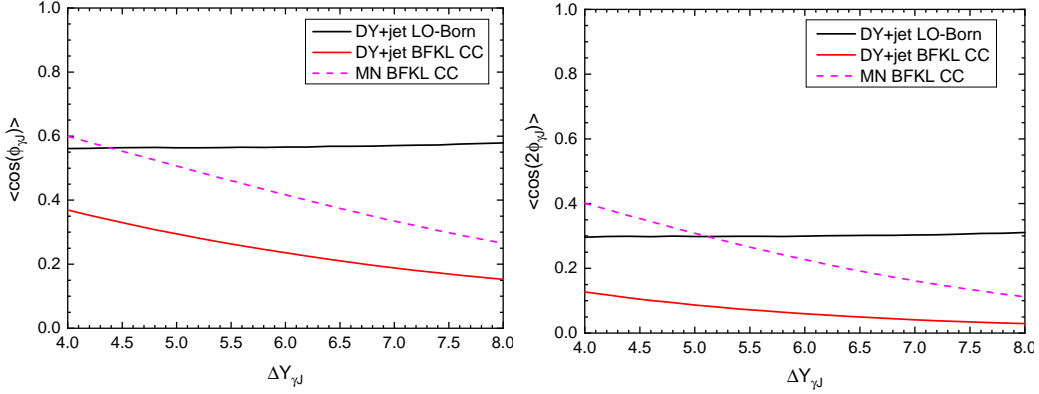
In Fig. 3 we show the comparison between the DY+jet (solid lines) and MN jet (dashed lines) processes in terms of the mean cosine

$$\langle \cos(n\phi_{\gamma J}) \rangle = \frac{\int_0^{2\pi} d\phi_{\gamma J} \frac{d\sigma^{\text{DY+j}}}{dM d\Delta Y_{\gamma J} d q_\perp d p_{J\perp} d\phi_{\gamma J}} \cos(n\phi_{\gamma J})}{\int_0^{2\pi} d\phi_{\gamma J} \frac{d\sigma^{\text{DY+j}}}{dM d\Delta Y_{\gamma J} d q_\perp d p_{J\perp} d\phi_{\gamma J}}} \quad (3.1)$$

We study this quantity as a function of the rapidity difference  $\Delta Y_{\gamma J}$  for  $n = 1$  and  $n = 2$ . In both cases, we see stronger decorrelation for the DY+jet production than for the MN jet case. Note that the mean cosine values equal one for the MN jet process in the Born approximation, when both jets have the same transverse momentum, which gives the strongest possible correlation.



**Figure 2:** The azimuthal angle dependence of the normalized helicity cross sections for the DY+jet (right) and MN jets (left) processes for  $q_{\perp} = 25 \text{ GeV}$ ,  $p_{J\perp} = 30 \text{ GeV}$ ,  $M = 35 \text{ GeV}$  and  $\Delta Y_{\gamma J} = \Delta Y_{IJ} = 7$ .



**Figure 3:** The mean cosine  $\langle \cos(n\phi_{\gamma J}) \rangle$  as a function of rapidity difference  $\Delta Y_{\gamma J}$  for  $n = 1$  (left) and  $n = 2$  (right) for the DY+jet (solid lines) and MN jets (dashed lines) processes with  $q_{\perp} = p_{J\perp} = 25 \text{ GeV}$ ,  $p_{J\perp} = 30 \text{ GeV}$  and  $M = 35 \text{ GeV}$ .

#### 4. Angular coefficients

In the inclusive DY process, it is useful to define normalized structure functions. We follow this approach and define the following coefficients for the DY+jet process

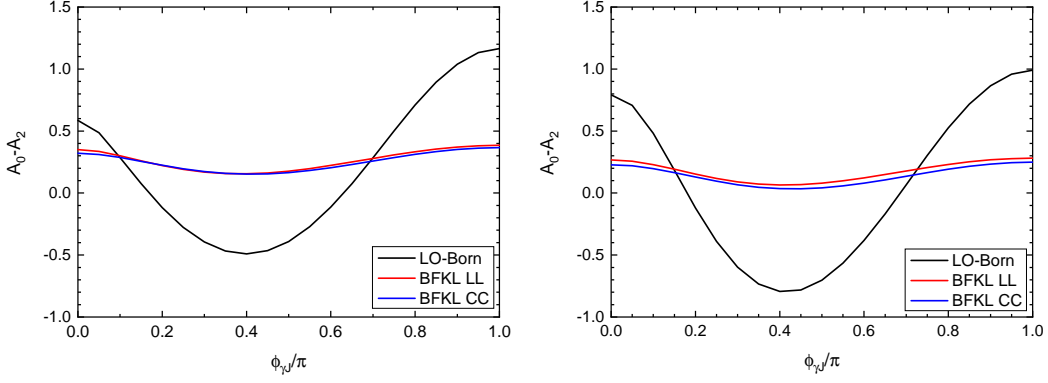
$$A_0 = \frac{d\sigma^{(L)}}{d\sigma^{(T)} + d\sigma^{(L)}/2}, \quad A_1 = \frac{d\sigma^{(LT)}}{d\sigma^{(T)} + d\sigma^{(L)}/2}, \quad A_2 = \frac{2d\sigma^{(TT)}}{d\sigma^{(T)} + d\sigma^{(L)}/2}. \quad (4.1)$$

Of particular interest is to study the Lam-Tung relation

$$d\sigma^{(L)} - 2d\sigma^{(TT)} = 0 \quad \text{or} \quad A_0 - A_2 = 0. \quad (4.2)$$

which is valid at the LO and NLO for the DY  $qg$  channel in the leading twist collinear approximation [1, 14]

As it was shown in [16], the combination  $A_0 - A_2$  is sensitive to partons' transverse momenta. In Fig. 4 we show this combination as a function the photon-jet azimuthal angle  $\phi_{\gamma J}$ . We see a dramatic difference between the full BFKL result, which is almost independent of the angle, and the LO-Born approximation (two gluon exchange) in which we find strong dependence on the



**Figure 4:** The Lam-Tung difference of angular coefficients,  $A_0 - A_2$ , as a function the azimuthal photon-jet angle  $\phi_{\gamma J}$  for  $q_{\perp} = 25$  GeV (left) and  $q_{\perp} = 60$  GeV (right) while  $p_{J\perp} = 30$  GeV,  $\Delta Y_{\gamma J} = 7$  and  $M = 35$  GeV.

angle  $\phi_{\gamma J}$ . A similar pattern can be found for the coefficients  $A_0, A_1$  and  $A_2$ , separately. This shows that for leptons' angular coefficients, the decorrelation coming from the BFKL emission is almost complete.

## 5. Conclusions

We proposed a new process to study the BFKL evolution in high energy hadronic collisions at the LHC – the Drell-Yan plus jet production. In this process, the DY photon with large rapidity difference with respect to the backward jet should be tagged through the lepton pair. The presented numerical results show a significant angular decorrelation with respect to the Born approximation for the BFKL kernel. The found decorrelation is also stronger than for the Mueller-Navelet jets due to more complicated final state with one more particle, being the DY photon. We also presented numerical results on the angular coefficients of the DY lepton pair which provide an additional experimental opportunity to test the effect of the BFKL evolution in the proposed process. Of particular interest is the Lam-Tung relation which is sensitive to partons' transverse momenta.

The future studies should include the full NLL BFKL kernel as well as the NLO photon plus jet impact factors. Although the first element is known, the NLO impact factors have not been computed yet.

## Acknowledgments

This work was supported by the National Science Center, Poland, Grants No. 2015/17/B/ST2/01838, DEC-2014/13/B/ST2/02486 and 2017/27/B/ST2/02755.

## References

- [1] C. S. Lam and W.-K. Tung, *A Systematic Approach to Inclusive Lepton Pair Production in Hadronic Collisions*, *Phys. Rev.* **D18** (1978) 2447.
- [2] L. N. Lipatov, *Small  $x$  physics in perturbative QCD*, *Phys. Rept.* **286** (1997) 131–198, [[hep-ph/9610276](#)].

- [3] A. H. Mueller and H. Navelet, *An Inclusive Minijet Cross-Section and the Bare Pomeron in QCD*, *Nucl. Phys.* **B282** (1987) 727–744.
- [4] V. Del Duca and C. R. Schmidt, *Dijet production at large rapidity intervals*, *Phys. Rev.* **D49** (1994) 4510–4516, [hep-ph/9311290].
- [5] W. J. Stirling, *Production of jet pairs at large relative rapidity in hadron hadron collisions as a probe of the perturbative pomeron*, *Nucl. Phys.* **B423** (1994) 56–79, [hep-ph/9401266].
- [6] D0 collaboration, S. Abachi et al., *The Azimuthal decorrelation of jets widely separated in rapidity*, *Phys. Rev. Lett.* **77** (1996) 595–600, [hep-ex/9603010].
- [7] D0 collaboration, B. Abbott et al., *Probing BFKL dynamics in the dijet cross section at large rapidity intervals in  $p\bar{p}$  collisions at  $\sqrt{s} = 1800$  GeV and 630-GeV*, *Phys. Rev. Lett.* **84** (2000) 5722–5727, [hep-ex/9912032].
- [8] ATLAS collaboration, G. Aad et al., *Measurements of jet vetoes and azimuthal decorrelations in dijet events produced in  $pp$  collisions at  $\sqrt{s} = 7$  TeV using the ATLAS detector*, *Eur. Phys. J.* **C74** (2014) 3117, [1407.5756].
- [9] CMS collaboration, V. Khachatryan et al., *Azimuthal decorrelation of jets widely separated in rapidity in  $pp$  collisions at  $\sqrt{s} = 7$  TeV*, *JHEP* **08** (2016) 139, [1601.06713].
- [10] B. Ducloue, L. Szymanowski and S. Wallon, *Evidence for high-energy resummation effects in Mueller-Navelet jets at the LHC*, *Phys. Rev. Lett.* **112** (2014) 082003, [1309.3229].
- [11] F. Caporale, D. Yu. Ivanov, B. Murdaca and A. Papa, *Mueller-Navelet jets in next-to-leading order BFKL: theory versus experiment*, *Eur. Phys. J.* **C74** (2014) 3084, [1407.8431].
- [12] A. Dafne Bolognino, F. G. Celiberto, M. Fucilla, D. Yu. Ivanov, B. Murdaca and A. Papa, *Inclusive production of two rapidity-separated heavy quarks as a probe of BFKL dynamics*, in *27th International Workshop on Deep Inelastic Scattering and Related Subjects (DIS 2019) Torino, Italy, April 8-12, 2019*, 2019. 1906.05940.
- [13] D. Brzeminski, L. Motyka, M. Sadzikowski and T. Stebel, *Twist decomposition of Drell-Yan structure functions: phenomenological implications*, *JHEP* **01** (2017) 005, [1611.04449].
- [14] C. S. Lam and W.-K. Tung, *A Parton Model Relation Without QCD Modifications in Lepton Pair Productions*, *Phys. Rev.* **D21** (1980) 2712.
- [15] K. Golec-Biernat, L. Motyka and T. Stebel, *Forward Drell-Yan and backward jet production as a probe of the BFKL dynamics*, 1811.04361.
- [16] L. Motyka, M. Sadzikowski and T. Stebel, *Lam-Tung relation breaking in  $Z^0$  hadroproduction as a probe of parton transverse momentum*, *Phys. Rev.* **D95** (2017) 114025, [1609.04300].