Probing BFKL effects with forward Drell-Yan productions

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Plan

- Drell -Yan process
- Mueller - Navelet jets
- Forward DY+jet and BFKL

Based on

KGB, L. Motyka, T.Stebel, JHEP 1812 (2018) 091

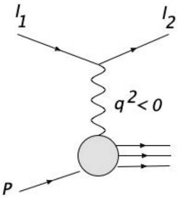
+ earlier papers

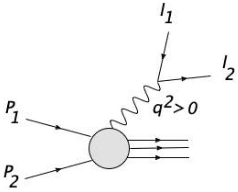
D. Brzemiński, L. Motyka, M. Sadzikowski, T. Stebel, JHEP 1701 (2017) 005
L. Motyka, M. Sadzikowski, T. Stebel, Phys.Rev. D95 (2017) 114025
L. Motyka, M. Sadzikowski, T. Stebel, JHEP 1505 (2015) 087
KGB, E. Lewandowska, A. Staśto, Phys.Rev. D82 (2010) 094010

Drell - Yan process

Drell - Yan lepton pair production

- Analog of inclusive DIS in hadronic scattering





- Cross section for lepton pair production in hadronic scattering

$$d\sigma_{DY} \sim \frac{1}{Q^4} L_{\mu\nu} W^{\mu\nu} \frac{d^3 l_1}{E_1} \frac{d^3 l_2}{E_2}$$

- Hadronic tensor

$$W^{\mu\nu} = \int d^4x \, \mathrm{e}^{iq\cdot x} \langle P_1 P_2 | \, J^\mu(x) J^\nu(0) \, | P_1 P_2 \rangle$$

- Two times bigger phase space and two times more structure functions.

DY structure function

- Using (q^μ, P^μ, p^μ) and $q_\mu W^{\mu\nu} = 0$, four structure functions

$$W^{\mu\nu} = (-g_T^{\mu\nu})\, W_1 + (P_T^\mu P_T^\nu)\, W_2 - \tfrac{1}{2}\,(P_T^\mu p_T^\nu + P_T^\nu p_T^\mu)\, W_3 + (p_T^\mu p_T^\nu)\, W_4$$

- Using photon polarization vectors (X^μ, Y^μ, Z^μ), helicity structure funct.

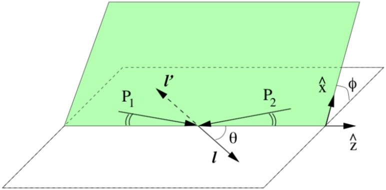
$$W^{\mu\nu} = (X^\mu X^\nu + Y^\mu Y^\nu)\, W_T + (Z^\mu Z^\nu)\, W_L - (X^\mu Z^\nu + Z^\mu X^\nu)\, W_{LT} - (X^\mu X^\nu - Y^\mu Y^\nu)\, W_{TT}$$

- Infinitely many choices of polarization vectors in photon rest frame where

$$X^\mu = (0, \hat{x})\,, \qquad Y^\mu = (0, \hat{y})\,, \qquad Z^\mu = (0, \hat{z})$$

- Each choice is called helicity frame.

Collins - Soper helicity frame ($q_\perp \neq 0$)



- Direction of lepton momentum $\vec{l}$ is given by spherical angles $\Omega = (\theta, \phi)$.

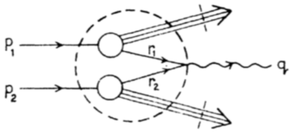
$$\frac{d\sigma^{DY}}{d^4q\, d\Omega} \sim L^{\mu\nu} W_{\mu\nu} \sim \Big[(1+\cos^2\theta)\, W_T + (1-\cos^2\theta)\, W_L + $$
$$+ (\sin 2\theta \cos\phi)\, W_{LT} + (\sin^2\theta \cos 2\phi)\, W_{TT}\Big]$$

- W_{LT} and W_{TT} from azimuthal angle dependence. After integration over Ω

$$\frac{d\sigma^{DY}}{d^4q} \sim (2W_T + W_L)$$

QCD interpretation for $M^2 \gg \Lambda^2_{QCD}$

- In the lowest order: $q\bar{q} \to \gamma^*/Z \to l^+ l^-$



- Leading twist LO DY cross section integrated over lepton angles $d\Omega$

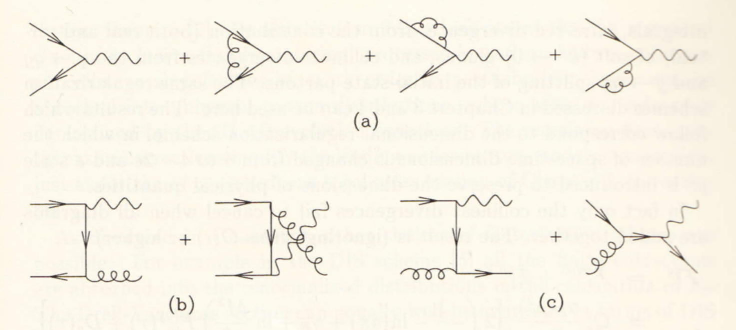
$$\frac{d\sigma^{DY}}{dY_\gamma dM^2 d^2 q_\perp} \sim \sum_{i=1}^{N_f} e_i^2 \left[q_i(x_1, M)\, \bar{q}_i(x_2, M) + (1 \leftrightarrow 2) \right] \delta^2(q_\perp)$$

where $x_{1,2} = (M_\perp/\sqrt{S})\, \mathrm{e}^{\pm Y_\gamma}$. Only $W_T \neq 0$.

- No photon transverse momentum $q_\perp$ in the LO collinear approach.
- DY cross section (integrated over $q_\perp$) can be used to extract PDFs.

Origin of $q_\perp$ dependence

- Higher order collinear corrections (NLO is large - 50%)

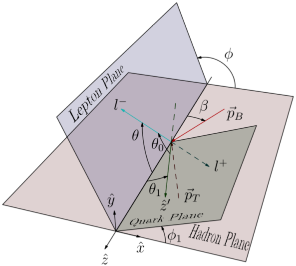


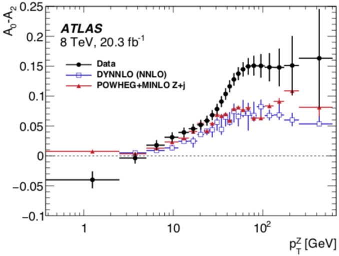
- Soft gluon resummation $q_\perp \ll M$ - TMDs
- Intrinsic parton transverse momentum $q_\perp \sim Q$ - UPDFs.

Lam - Tung relation

$$W_L - 2W_{TT} = 0$$

- Analog of Callan - Gross relation in DIS: $F_L = 0$.
- Satisfied in NLO in contrast to Callan - Gross relation.
- Violated when quark plane $\neq$ hadron plane





- Good indicator of non-zero parton transverse momentum.

Mueller - Navelet jets

High energy QCD

- High energy QCD describes scattering processes for which

$$S \gg Q^2 \gg \Lambda^2_{QCD}$$

- Large logarithms $Y = \log(S/Q^2)$ appear which must be resummed.
- BFKL equation resums powers

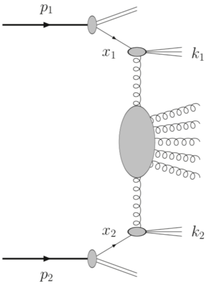
$$\alpha_s^n \log^n(S/Q^2) \quad \text{(LLA)}, \qquad\qquad \alpha_s^{n+1} \log^n(S/Q^2) \quad \text{(NLLA)}$$

- Mueller - Navelet jet production is a canonical process for BFKL studies.

Is DY process useful for high energy QCD studies?

MN jets

- Forward-backward jets separated by large rapidity $\Delta Y = \ln(\hat{S}/k_\perp^2) \gg 1$



- Initial partons are collinear - standard PDFs
- Gluon emissions in multi-regge kinematics

$$y_0 \gg y_1 \gg \ldots \gg y_{n+1}\,, \qquad\qquad |k_{i\perp}| \approx |k_\perp|$$

where $\Delta Y = y_0 - y_{n+1}$. Gives BFKL effects.

MN jet cross section

$$\frac{d\sigma^{MN}}{dy_1\,dy_2\,dk_{1\perp}^2\,dk_{2\perp}^2\,d\phi} = f_{\rm eff}(x_1, k_{1\perp}^2)\left[\frac{C_A\alpha_s}{k_{1\perp}^2}\right] K(\vec{k}_{1\perp}, -\vec{k}_{2\perp}, \Delta Y)\left[\frac{C_A\alpha_s}{k_{2\perp}^2}\right] f_{\rm eff}(x_2, k_{2\perp}^2)$$

- BFKL kernel

$$K(\phi, Y) \sim \left[I_0 + \sum_{m=1}^{\infty} 2\cos(m(\pi-\phi))\, I_m\right]$$

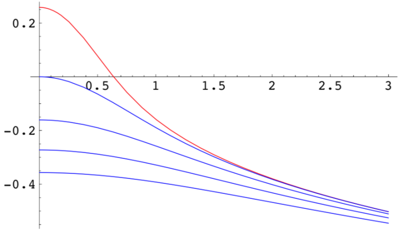
where ϕ is the azimuthal angle between jets and

$$I_m(\Delta Y) = \int_0^\infty d\nu\; \exp(\omega_m(\nu)\Delta Y)\cos(\nu\ln(k_1^2/k_2^2))$$

and the BFKL kernel eigenvalue in LLA

$$\omega_m(\nu) = \bar{\alpha}_s\left[2\psi(1) - \psi\left(\frac{m+1}{2} + i\nu\right) - \psi\left(\frac{m+1}{2} - i\nu\right)\right], \qquad \psi(z) = \frac{\Gamma'(z)}{\Gamma(z)}$$

Characteristic function $\omega_m(\nu)$



- $m = 0$ (red curve) gives dominant behaviour in Y (energy)

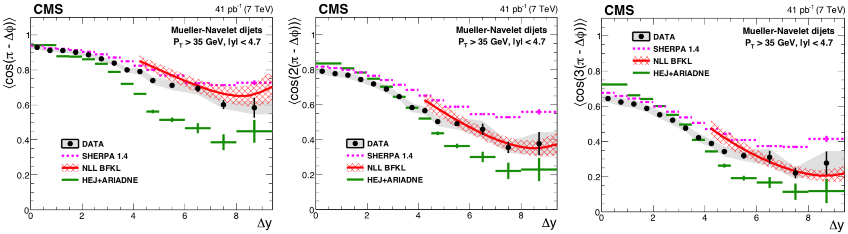
$$K(\Delta Y) \sim \exp(0.25\Delta Y) \sim S^{0.25}$$

- $m > 1$ (blue curves) give azimuthal angle dependence

Angular decorrelation - jets are no longer back-to-back due to gluon emissions

- Cross section measured by CMS collaboration

$$\frac{1}{\sigma^{MN}}\frac{d\sigma^{MN}}{d\phi}=\frac{1}{2\pi}\left\{1+2\sum_{m=1}^{\infty}\cos(m(\pi-\phi))\,\langle\cos(m(\pi-\phi))\rangle\right\}$$



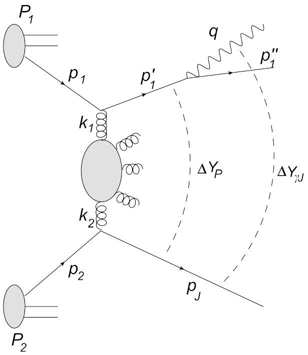
- Back-to-back jets: $\langle\cos(m(\pi-\phi))\rangle=1$

$$\frac{1}{\sigma^{MN}}\frac{d\sigma^{MN}}{d\phi}=\frac{1}{2\pi}\sum_{m=-\infty}^{\infty}e^{im(\pi-\phi)}=\delta(\pi-\phi)$$

- Red curves from BFKL calculations of Ducloué, Szymanowski and Wallon.

DY + jet

Forward Drell - Yan and backward jet



- ΔY_P is an argument of the BFKL kernel while $\Delta Y_{\gamma J}$ is measured

$$\Delta Y_P = \ln\left(\frac{z(1-z)\,x_1 x_2 S}{M^2(1-z) + q_T^2 + z(k_{1\perp}^2 - 2\vec{k}_{1\perp}\cdot\vec{q}_T)}\right), \qquad z = \frac{p_{J\perp}\,M_\perp}{x_1 x_2 S}\,\mathrm{e}^{\Delta Y_{\gamma J}}$$

- Theoretical ΔY_P depends on measured $\Delta Y_{\gamma J}$

- For DY+jet helicity structure functions for $\lambda = T, L, TT, LT$

$$W_\lambda \equiv \frac{d\sigma_\lambda^{DY}}{d^4q} \quad \to \quad W_\lambda^{DY+j} \equiv \frac{d\sigma_\lambda^{DY+j}}{d^4q\, d^2p_{J\perp}}$$

and $d^4q = \frac{1}{2} dY_{\gamma J} dM^2 dq_\perp^2 d\phi_{\gamma J}$.

- Explicitly

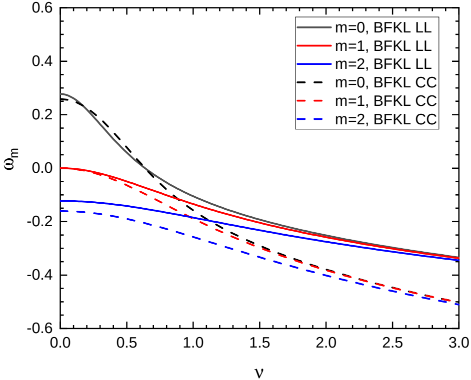
$$W_\lambda^{DY+j} = \frac{4\alpha_{em}^2\alpha_s^2}{(2\pi)^4} \frac{1}{M^2 p_{J\perp}^2} \int dx_1 \int dx_2\, f_{q\bar{q}}(x_1, M_\perp)\, f_{\text{eff}}(x_2, M_\perp)\, \theta(1-z)$$
$$\times \int \frac{d^2k_{1\perp}}{k_{1\perp}^2}\, \Phi_{(\lambda)}^{\gamma J}(q_\perp, k_{1\perp}, z)\, K(\vec{k}_{1\perp}, -\vec{p}_{J\perp}, \Delta Y_P)$$

where $\Phi_{(\lambda)}^{\gamma J}$ is the LO photon/jet impact factor and K is the BFKL kernel.

BFKL kernel eigenvalues $\omega_m(\nu)$

- BFKL kernel with consistency condition (CC) (part of NLLA corrections)
- Eigenvalues $\omega = \omega_m(\nu)$ from equation

$$\omega = \bar{\alpha}_s \left[2\psi(1) - \psi\left(\frac{\omega+m+1}{2} + i\nu\right) - \psi\left(\frac{\omega+m+1}{2} - i\nu\right) \right]$$



Angular decorrelation in DY+jet process

- Cross section integrated over over lepton angles - combination $T + \frac{1}{2}L$

$$\sigma(\phi_{\gamma J}) \equiv \frac{d(\sigma_T + \sigma_L/2)}{dp_{J\perp}^2 \underbrace{(dM^2 d\Delta Y_{\gamma J} dq_\perp^2 \, d\phi_{\gamma J})}_{photon}}$$

- For LHC energy $\sqrt{S} = 13 \text{ TeV}$ and

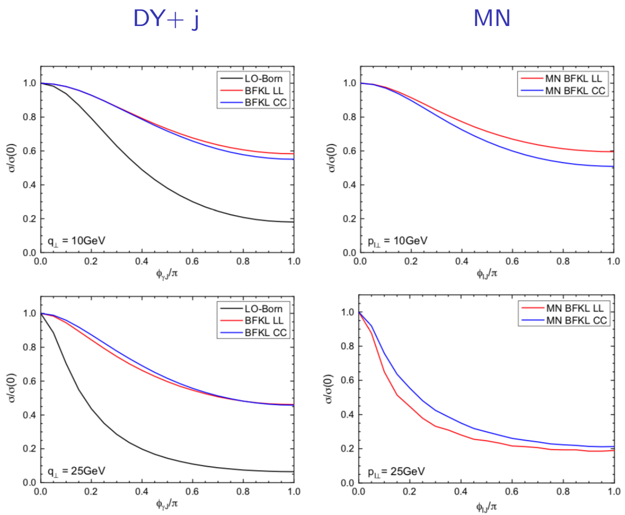
$$p_{J\perp} = 30 \text{ GeV}\,, \qquad M = 35\,\text{GeV}\,, \qquad \Delta Y_{\gamma J} = \Delta Y_{MN} = 7$$

- plotted ratio

$$\frac{\sigma(\phi_{\gamma J})}{\sigma(0)}$$

- γJ decorrelation - flat distribution in $\phi_{\gamma J}$

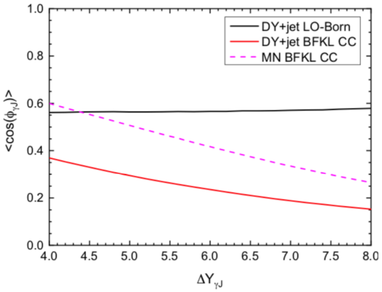
Angular decorrelation in DY+jet process

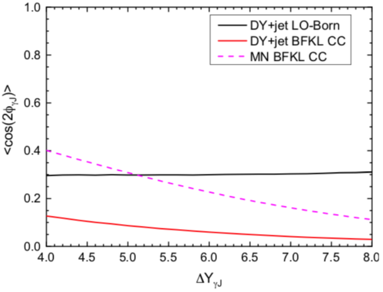


- Stronger decorrelation for DY+j than for MN jets.

Angular decorrelation as a function of $\Delta Y_{\gamma J}$

- Given in terms of mean cosines $\langle \cos(m\phi_{\gamma J}) \rangle$
- γJ decorrelation $=>$ $\langle \cos(m\phi_{\gamma J}) \rangle < 1$





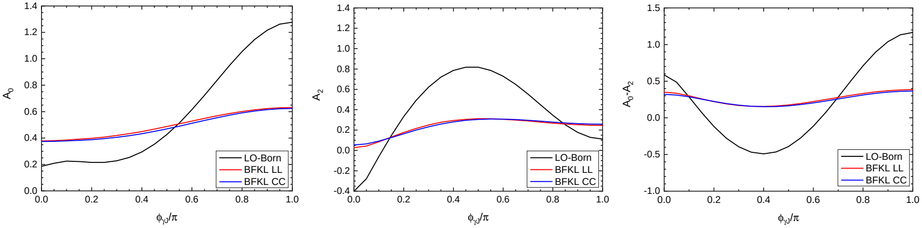
$q_\perp = p_{l\perp} = 25\,\mathrm{GeV}$ $p_{J\perp} = 30\,\mathrm{GeV}$ $M = 35\,\mathrm{GeV}$

- Stronger decorrelation for DY+j than for MN jets.

- From angular dependence of DY lepton pair helicity structure functions for $DY + j$

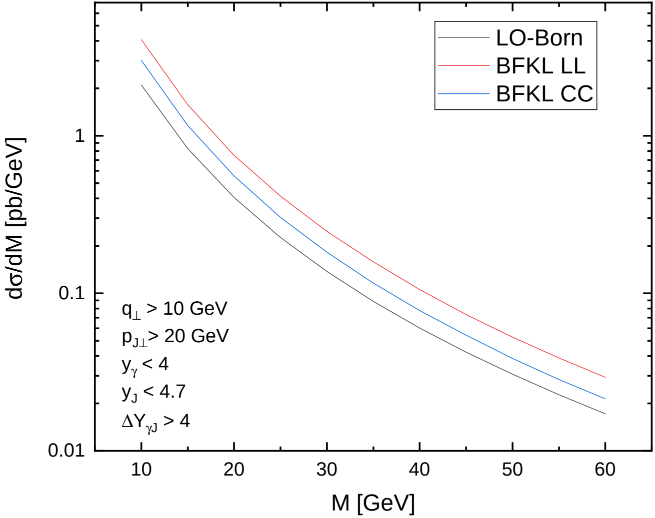
$$A_0 = \frac{W_L}{W_T + W_L/2}\,, \qquad A_1 = \frac{W_{LT}}{W_T + W_L/2}\,, \qquad A_2 = \frac{2W_{TT}}{W_T + W_L/2}$$

- Lam-Tun relation: $A_0 - A_2 = 0$



- Additional information about BFKL effects.

Total cross section



Summary

- DY $+$ jet process was proposed to test BFKL effects.
- More observables than for MN jets and cleaner experimental signal.
- Stronger angular decorrelation than for MN jets.
- Helicty structure functions are sensitive to BFKL dynamics.

Best wishes for all women today!