Forward Drell-Yan Process as a Probe of Small x Dynamics

Recontres de Moriond QCD 2019

Leszek Motyka
Jagiellonian University, Krakow
27-03-2019
Overview

- Generalities

- Drell–Yan structure functions: effects of higher twists and parton $k_T$
  [Based on results obtained with M. Sadzikowski, T. Stebel and D. Brzemiński]

- Forward Drell–Yan + backward jet as a probe of QCD radiation
  [Based on results of recently completed work with K. Golec-Biernat and T. Stebel [arXiv:1811.04361 [hep-ph]]]

- Conclusions
Why forward Drell–Yan?

- Electroweak hard probe of strong interactions: expected high experimental precision and excellent theoretical control

- Highly tunable probe – variation possible of $M$ – mass of the dilepton system and virtual photon $q_T$

- Leptons’ angular distributions → four independent Drell – Yan structure functions may be measured providing stringent tests of theoretical framework

- Lam–Tung combination of DY structure functions was found to be extremely sensitive to kinematics of incoming partons – *a “gluon $kT$-meter”* [Sadzikowski, Stebel, LM, 2016]

- Inclusive Drell–Yan cross section at LHC well understood in BFKL framework → [Brzemiński, Sadzikowski, Stebel, LM, 2016], [Celiberto, Gordo Gomez, Sabio Vera, 2018]
Drell–Yan process and kinematics

\[ P_1 \]

\[ P_2 \]

\[ \gamma^*(q) \]

\[ x_F, q^2 = M^2, q_T \]

\[ k_1, k_2 \]

\[ (\theta, \phi) \]
Forward Drell–Yan at LHC: kinematic reach

- At LHC forward Drell–Yan may be used to measure parton densities down to \( x \sim 10^{-6} \) at \( M^2 \sim 10 \text{ GeV}^2 \)

- Unique opportunity to explore this kinematic region and to extend measurements of parton density functions
Theoretical interest in the forward Drell – Yan at LHC

- **Kinematical range:** 
  \[ x < 10^{-6} \text{ at } M^2 \sim 10 \text{ GeV}^2 \]

- **Expected strong effects of \( \log(1/x) \) resummation**

- If the mass is sufficiently small, multiple scattering and higher twists effects are expected to turn on: higher twist are suppressed by \( 1/M^2 \) but enhanced by \( x^{-\lambda} \)

- Higher twist effects should be estimated to avoid systematic errors of pdf determination, they are also interesting for deeper understanding of proton structure and dynamics of strong interactions
Gluon dominance in forward Drell – Yan

- Leading Order
- NLO
Gluon dominance in forward Drell–Yan

- Leading Order
- NLO

Gluon splitting to antiquark
Forward Drell–Yan scattering

- Asymmetric kinematics
  \[ \rightarrow \text{large } x_1 \gg \text{small } x_2 \]

- Dominance of gluons at small \( x_2 \) and valence quarks at \( x_1 \sim 1 \) => dominance of valence quark – gluon fusion channel

- Interesting to measure \( \rightarrow \) probe of gluon distribution at very small \( x \)
Standard picture: collinear QCD / DGLAP evolution and parton shower

- Single exchange → the leading twist in OPE
- Emissions ordered in transverse momenta
- Resummations of terms in perturbative expansion enhanced by powers of scale logarithms $\sim \log(M^2)$
Unordered emissions: BFKL / CCFM evolution and parton shower

DGLAP – $k_T$ ordered chain

BFKL – $k_T$ unordered chain
Balitsky–Fadin–Kuraev–Lipatov (BFKL) picture: kT-factorisation and small x resummation

- Partons’ transverse momenta kept at all stages of calculations
- Emissions unordered in transverse momenta
- Resummations of terms in perturbative expansion enhanced by powers of rapidity distance (or of $\log(1/x)$)
- Expected to provide dominant contributions for large rapidities and moderate scales
Very large gluon density at small $x \rightarrow$ multiple scattering

DGLAP / leading twist

Multiple scattering / higher twist

rapidity

scale
Two approaches to effects beyond collinear leading twist description of forward Drell–Yan process

- **BFKL description:** derived from QCD, based on resummation of energy logarithms
- Strong effects due to transverse momenta of the partons
- Higher twist effects extracted from singularities of the BFKL kernel in Mellin space, \( \chi(\gamma) \), at integer values of anomalous dimensions \( s \to \gamma \)
  
  \[
  \sigma(\gamma) \sim \exp(c \log(1/x) \, \alpha_s \, \chi(\gamma)) \\
  \chi(\gamma) = 2\psi(1) - \psi(\gamma) - \psi(1-\gamma) \sim \frac{1}{\gamma - n}
  \]
  
  → essential singularities of cross-section in Mellin space

- **Golec-Biernat – Wusthoff (GBW) saturation model:** eikonal multiple gluon ladder exchange → twist-2n contributions enhanced by \( (1/x)^{n^2} \) at small gluon \( x \)
- Model consistent with known results on evolution of higher twist quasipartonic operators in QCD and with bulk of HERA data
Drell–Yan structure functions
Drell–Yan structure functions

- Leptons’ angular distributions
  → four independent Drell–Yan structure functions may be measured providing stringent tests of the theoretical framework

\[
\frac{d\sigma^{\text{DY}+j}}{d\Pi d\Omega} = (1 - \cos^2 \theta) \frac{d\sigma^{(L)}}{d\Pi} + (1 + \cos^2 \theta) \frac{d\sigma^{(T)}}{d\Pi} + \\
+ (\sin^2 \theta \cos 2\phi) \frac{d\sigma^{(TT)}}{d\Pi} + (\sin 2\theta \cos \phi) \frac{d\sigma^{(LT)}}{d\Pi}
\]

- Interpretation: virtual photon helicity density matrix accessed by interference of produced leptons
Lam–Tung relation

- DY helicity structure functions: projections of DY amplitudes on virtual photon polarization states
- Lam–Tung relation: vanishing combination of DY structure functions at leading twist up to NNLO
- in collinear QCD

\[ W_L - 2W_{TT} = 0 \]

- Lam–Tung relation is broken by higher order QCD effects related to parton \( k_T \)

- At twist 4 – non-zero contribution to LT combination → enhanced relative higher twist contributions
Forward Drell–Yan cross-section within $kT$-factorisation: partons carry transverse momenta.

\[ \frac{d\sigma}{dxFdM^2d\Omega d^2q_T} = \frac{\alpha_{em}}{(2\pi)^2(P_1 \cdot P_2)^2 M^2 x_F^2 (1 - z)} L^{\sigma \sigma'}(\Omega) \int_0^1 dz \varphi(x_F/z) \]

\[ \times \int d^2k_T \frac{2\pi\alpha_s}{3} \frac{f(x_g, k_T^2)}{k_T^4} \tilde{\Phi}_{\sigma \sigma'}(q_T, k_T, z) \]
Results: DY at LHC: forward Drell – Yan structure functions from BFKL vs GBW

- $A_i = W_i / W_{tot}$, $M^2 = 20 \text{ GeV}^2$, $Y = 7$

Clear differences between BFKL and GBW approaches

For $M^2 = 20 \text{ GeV}^2$ higher twist corrections are important below $q_T = 5 \text{ GeV}$

[M. Sadzikowski, T. Stebel, D. Brzemiński, LM]
Lam–Tung relation from GBW and BFKL

- Striking difference in Lam–Tung relation breaking
- Subleading twist effects in GBW vs leading twist effects in BFKL
- Importance of parton $k_T$ effects in BFKL

$M^2 = 5 \text{ GeV}^2$  \quad $\sqrt{s} = 14 \text{ TeV}$  \quad $M^2 = 20 \text{ GeV}^2$
Forward Drell–Yan + backward jet: why?

- Intriguing case of Mueller–Navelet jets: jets with similar pT, but separated by a large distance in rapidity (forward – backward jets)

- Classical probe of Balitsky–Fadin–Kuraev–Lipatov dynamics: suppression of hard scale logarithms, enhancement of energy logarithms – expected dominance of small x resummation effects

- Particularly interesting observable: azimuthal angle decorrelation of jet directions due to gluon radiation in between the jets

- Surprise: NLO / NLL BFKL calculations give much too strong decorrelation
  
  → good description of data requires application of Brodsky – Lepage – Mackenzie scale fixing procedure, which leads to very large renormalisation scale – closer to collision energy, than to pT of the jet

- Need to probe the dynamics with different processes
Forward Drell–Yan + backward jet
Azimuthal decorrelation:
Mueller–Navelet jets vs forward DY + jet
Kinematics of DY + jet

\[
P_1 \longrightarrow p_1 \rightarrow p'_1 \rightarrow q \rightarrow p''_1
\]

\[
P_2 \rightarrow p_2 \rightarrow k_1 \rightarrow k_2 \rightarrow p_J \rightarrow \Delta Y_P \rightarrow \Delta Y_{JJ}
\]
Results: photon* – jet azimuthal decorrelation

- Photon* helicity inclusive cross sections
- Backward jet $p_T = 30$ GeV, photon* – jet rapidity distance $Y = 7$, $M = 35$ GeV

[K. Golec-Biernat, T. Stebel, LM]
Drell–Yan plus jet vs Mueller – Navelet jets

- Backward jet $p_T = 30$ GeV, rapidity distance $Y = 7$, $M = 35$ GeV
- Similar pattern to Mueller – Navelet jets at large $Y$
Results: azimuthal decorrelation continued

- Backward jet $p_T = 30$ GeV, rapidity distance $Y = 7$, $M = 35$ GeV

  DY + jet

  Mueller – Navelet jets

![](image-url)
Impact of BFKL radiation on DY + jet structure functions

- Drell – Yan structure functions integrated over photon – jet angle
Conclusions

- Forward Drell Yan process is of great interest for determination of parton density functions at small x, studies of small x resummation and higher twist effects.

- Higher twist effects found to be important for $M^2 > 10 \text{ GeV}^2$.

- Sensitivity of DY structure functions to transverse momenta of partons, in particular to the Lam–Tung combination.

- Forward photon – backward jet azimuthal decorrelation pattern is similar to Mueller – Navelet jets.

- The Drell – Yan + jet structure functions also sensitive to BFKL radiation effects – particularly high sensitivity found for Lam–Tung combination of the structure functions.

THANKS!
Composition of DY + jet

- Forward DY impact factor
- Known for all structure functions at the LO
Composition of DY + jet

- Collinear quark density
- Collinear quark or gluon density
Composition of DY + jet

- Jet impact factor
- Known at NLO
Composition of DY + jet

- Gluon radiation:
  BFKKL evolution

- LL, NLL, NLL with collinear improvement
DY + jet: formalism

- Drell – Yan + jet structure functions:

\[
\frac{d\sigma^{(\lambda)}}{dM^2 \, d\Delta Y_{\gamma J} \, dq_{\perp} \, dp_{J\perp}} = \frac{4\alpha_{em}^2 \alpha_s^2}{(2\pi)^4} \int_0^1 dx_1 \int_0^1 dx_2 \, \theta(1 - z) \, f_q(x_1, \mu) f_{\text{eff}}(x_2, \mu) \times
\]
\[
\times \frac{1}{M^2 p_{J\perp}^2} \int \frac{d^2k_{1\perp}}{k_{1\perp}^2} \Phi^{(\lambda)}(\vec{q}_{\perp}, \vec{k}_{1\perp}, z) \, K(\vec{k}_{1\perp}, \vec{k}_{2\perp} = -\vec{p}_{J\perp}, \Delta Y_P)
\]

- Selected impact factors

\[
\Phi^{(L)}(\vec{q}_{\perp}, \vec{k}_{\perp}, z) = 2 \left[ \frac{M(1 - z)}{D_1} - \frac{M(1 - z)}{D_2} \right]^2
\]
\[
\Phi^{(T)}(\vec{q}_{\perp}, \vec{k}_{\perp}, z) = \frac{1 + (1 - z)^2}{2} \left[ \frac{\vec{q}_{\perp}}{D_1} - \frac{\vec{q}_{\perp} - z\vec{k}_{\perp}}{D_2} \right]^2
\]
BFKL Green’s function

[Following Kwieciński, Martin, Outhwaite, LM,2001]

- Fourier decomposition of Green’s function (conformal spins)

\[ K(\vec{k}_1, \vec{k}_2, \Delta Y_P) = \frac{2}{(2\pi)^2 |\vec{k}_1| |\vec{k}_2|} \left( I_0(\Delta Y_P, \rho) + \sum_{m=1}^{\infty} 2\cos(m\phi)I_m(\Delta Y_P, \rho) \right) \]

- Scale invariance of LL BFKL: integral representation by inverse Mellin transform

\[ I_m(\Delta Y_P, \rho) = \int_0^{\infty} d\nu R_m^A(\nu) \exp(\omega_m^A(\nu)\Delta Y_P) \cos(\rho \nu) \]

- LL BFKL kernel

\[ \omega^\text{LL}_m(\nu) = \chi_m(0, \nu) = \bar{\alpha}_s \left[ 2\psi(1) - \psi \left( \frac{m + 1}{2} + i\nu \right) - \psi \left( \frac{m + 1}{2} - i\nu \right) \right] \]

- BFKL kernel with consistency condition: collinear resummation of leading higher order corrections

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

- Strong coupling constant adjusted to give Pomeron intercept ~0.27 (GBW value)
Similar behavior of $W_T$ and $W_L$ in BFKL and GBW, but significant differences in “interference” structure functions $W_{TT}$ and $W_{LT}$.
Azimuthal decorrelation: Fourier components

- Backward jet $p_T = 30$ GeV, rapidity distance $Y = 7$, $M = 35$ GeV