A–dependence in dilepton rapidity distributions: parton model and dipole approach analysis

M.B. Gay Ducati
beatriz.gay@ufrgs.br

High Energy Physics Phenomenology Group
Physics Institute
Universidade Federal do Rio Grande do Sul
Porto Alegre, Brazil

work with E.G. de Oliveira
Outline

- Motivation to dilepton production
- Improved parton model
- Color dipole approach
- Dipole cross section
- Nuclear PDFs
- Results
- Summary
Motivation to dilepton production at backward rapidities

- Dilepton \(\Rightarrow\) clean probe (electromagnetic interactions).
- Dilepton acts as a reference to hadron probes.
- \(p-p\) collisions: no nuclear effects.
- \(A-A\) collisions: nuclear effects with the formation of a dense medium.
- \(p-A\) collisions: nuclear effects \textit{without} the formation of a dense medium.
- Furthermore, saturation effects are studied at RHIC and LHC collisions.

We are interested in high density QCD (low-\(x\) physics) in high energy hadron collisions.
Motivation to dilepton production at backward rapidities

- p–A is an asymmetrical collision:

- Forward rapidities (proton direction):
  - Overlap in nucleus protons between parton saturation and nuclear effects such as shadowing.
  - High density of partons in the nucleus that can be described by dense systems (such as the Color Glass Condensate);

- Backward rapidities (heavy ion direction):
  - Saturation in the proton.
  - Nuclear effects in the heavy ion.

Therefore, backward rapidities is complementary in our understanding on nuclear collisions.

We compare how two different models take into account such effects: the improved parton model and the color dipole approach.
Improved parton model


- In this frame, the process is understood as the combination of two partons to create the virtual photon that splits into the dilepton (ignoring Z.)
Intrinsic transverse momentum

- Partons collinear to hadrons \( \Rightarrow \) experimental results of \( p_T \) distribution cannot be reproduced for small \( p_T \).


- We use a Gaussian intrinsic \( k_T \) distribution of a single parton as given by:

\[
\frac{1}{\pi \langle k_T^2 \rangle} \exp \left( -\frac{k_T^2}{\langle k_T^2 \rangle} \right)
\]

- Gaussian distribution of intrinsic \( k_T \) due to both partons:

\[
h(k_T^2) = \frac{1}{2\pi \langle k_T^2 \rangle} \exp \left( -\frac{k_T^2}{2 \langle k_T^2 \rangle} \right)
\]

- In a NLO study of pion production (P. Levai, G. Papp, G. G. Barnafoldi, and G. I. Fai, Eur. Phys. J. ST 155, 89 (2008)), \( \langle k_T^2 \rangle = 2.5 \) GeV was found to reproduce RHIC data even for low \( p_T \).
Improved parton model — Cross section

The Drell–Yan cross section at NLO is given by:

\[
\frac{d\sigma}{dM^2 dy d^2 p_T} = h(p_T^2) \frac{d\sigma}{dM^2 dy} + \int d^2 k_T \sigma_P(s, M^2, k_T^2) \left[ h((p_T - k_T)^2) - h(p_T^2) \right].
\]

R. D. Field, Applications of Perturbative QCD, Addison-Wesley (1989)

- NLO collinear double differential cross section \(d\sigma/dM^2 dy\) (no \(p_T\) dependence).
- Together with \(h(p_T^2)\), Gaussian dependence on \(p_T\).
- This \(p_T\) dependence is completely factorized.
- The first term is dominant at small \(p_T/\langle k_T \rangle\), while the second at high \(p_T/\langle k_T \rangle\).
Improved parton model — Cross section

- Only noncollinear subprocesses contribute to the second term: Compton scattering \( q + g \to q + \gamma^* \) and annihilation \( q + \bar{q} \to g + \gamma^* \).

- We have (R. D. Field, Applications of Perturbative QCD):

\[
\sigma_P(s, M^2, p_T^2) = \frac{1}{\pi^2} \frac{\alpha^2 \alpha_s}{M^2 s^2} \int_{x_{A_{\text{min}}}}^{1} dx_A \frac{x_B x_A}{x_A - x_1} \left\{ P_{q\bar{q}}(x_A, x_B, M^2) \frac{8}{27} \frac{2M^2 \hat{s} + \hat{u}^2 + \hat{t}^2}{\hat{t} \hat{u}} + P_{qg}(x_A, x_B, M^2) \frac{1}{9} \frac{2M^2 \hat{t} + \hat{s}^2 + \hat{u}^2}{-\hat{s} \hat{t}} \right\}.
\]

- \( x_{1,2} = \sqrt{\frac{M^2 + p_T^2}{s}} e^{\pm y} \), in which \( y \) is the virtual photon rapidity.

- Subprocess Mandelstam variables: \( \hat{s} = x_A x_B s \), \( \hat{t} = M^2 - x_A x_2 s \), and \( \hat{u} = M^2 - x_B x_1 s \).

- Parton momentum fractions: \( x_A \) and \( x_B = (x_A x_2 - M^2/s)/(x_A - x_1) \).

- The integration lower limit is \( x_{A_{\text{min}}} = (x_1 - M^2/s)/(1 - x_2) \).
Improved parton model and PDFs

- The functions $P_{q\bar{q},qg,gq}$ depend on the parton distribution functions:

\[
P_{q\bar{q}}(x_A, x_B, M^2) = \sum_q e_q^2 \left( f_q(x_A) f_{\bar{q}}(x_B) + \bar{q} \leftrightarrow q \right)
\]

\[
P_{qg}(x_A, x_B, M^2) = \sum_q e_q^2 \left( f_q(x_A) + f_{\bar{q}}(x_A) \right) f_g(x_B)
\]

\[
P_{gq}(x_A, x_B, M^2) = \sum_q e_q^2 f_g(x_A) \left( f_q(x_B) + f_{\bar{q}}(x_B) \right)
\]

- PDF parameterizations are needed.

- When it is the case, nuclear PDF parameterizations are used for the B hadron.
Color dipole approach

- In the color dipole approach, the same Drell–Yan process is studied in the target rest frame.
- At backward rapidities, the proton is the target and the nucleus is the projectile. M.A. Betemps, MBGD, E.G. de Oliveira; PRD 74 (2006) 094010
- Two diagrams are involved:
Color dipole approach — Cross section

- The Drell–Yan cross section in the color dipole picture arises as the interference of two diagrams:

\[
\frac{d\sigma_{DY}}{d M^2 dy d^2 p_T} = \frac{\alpha^2_{em}}{6\pi^3 M^2} \int_0^\infty d\rho W(x_2, \rho, p_T) \sigma_{dip}(x_1, \rho),
\]

- \( \sigma_{dip}(x_1, \rho) \) is the dipole cross section and \( \rho \) is dipole size.
- The approach is phenomenologically valid for very backward rapidities \( y \), i.e., small \( x_1 = \frac{\sqrt{M^2 + p_T^2}}{s} e^y \).
- \( x_2/A \) is the projectile momentum fraction carried by photon.
- \( x_2/A/\alpha > x_2/A \) is the projectile momentum fraction carried by the projectile parton.
- \( \alpha \) is the parton momentum fraction carried by the photon.
Dipole cross section — Cross section

- \( W(x_2, \rho, p_T) \) is the weight function and depends on the projectile composition.
- It weights each \( \rho \)-sized dipole contribution to the cross section:

\[
W(x_2, \rho, p_T) = \sum_q \int_{x_2}^1 \frac{d\alpha}{\alpha^2} e_q^2 \left[ \frac{x_2}{\alpha} f_q^A \left( \frac{x_2}{\alpha}, M^2 \right) + \frac{x_2}{\alpha} f_{\bar{q}}^A \left( \frac{x_2}{\alpha}, M^2 \right) \right] \\
\times \left\{ \left[ m_q^2 \alpha^4 + 2M^2(1 - \alpha)^2 \right] \left[ \frac{1}{p_T^2 + \eta_q^2} T_1(\rho) - \frac{1}{4\eta_q} T_2(\rho) \right] + \left[ 1 + (1 - \alpha)^2 \right] \left[ \frac{\eta_q p_T}{p_T^2 + \eta_q^2} T_3(\rho) - \frac{1}{2} T_1(\rho) + \frac{\eta_q}{4} T_2(\rho) \right] \right\},
\]

- with \( \eta_q^2 = (1 - \alpha)M^2 + \alpha^2 m_q^2 \) and:

\[
T_1(\rho) = \frac{\rho}{\alpha} J_0 \left( \frac{p_T \rho}{\alpha} \right) K_0 \left( \frac{\eta \rho}{\alpha} \right) \\
T_2(\rho) = \frac{\rho^2}{\alpha^2} J_0 \left( \frac{p_T \rho}{\alpha} \right) K_1 \left( \frac{\eta \rho}{\alpha} \right) \\
T_3(\rho) = \frac{\rho}{\alpha} J_1 \left( \frac{p_T \rho}{\alpha} \right) K_1 \left( \frac{\eta \rho}{\alpha} \right).
\]
Dipole cross section

- Dipole cross section in DIS is the cross section between the color dipole component of the virtual photon and the target.

- Golec–Biernat and Wüsthoff modeled Phys. Rev. D59, 014017 (1999) the dipole cross section data as:

\[ \sigma_{\text{dip}}(x, r) = \sigma_0 \left[ 1 - \exp \left( -\frac{1}{4} r^2 Q_s^2(x) \right) \right], \]

with:

\[ Q_s^2(x) = Q_0^2 \left( \frac{x_0}{x} \right)^{\frac{\lambda}{2}} \]

\[ Q_0^2 = 1 \text{GeV}^2. \]

- A recent fit (H. Kowalski, L. Motyka, and G. Watt, Phys. Rev. D74, 074016 (2006)) to DIS data found \( \sigma_0 = 23.9 \text{ mb} \ (61.38 \text{ GeV}^{-2}) \), \( x_0 = 1.11 \times 10^{-4} \), and \( \lambda = 0.287 \).

- The model reproduces color transparency for small \( r \) (\( \sigma_{\text{dip}}(x, r) \propto r^2 \) and saturation for large \( r \) (\( \sigma_{\text{dip}}(x, r) \approx \sigma_0 \)).

- The property of \( \sigma_{\text{dip}}(x, r) = \sigma_{\text{dip}}(rQ_s(x)) \) leads the DIS cross section for small \( x \) to depend only on \( Q/Q_s(x) \) and is called geometric scaling.
Dipole cross section

- Two recently proposed models of our interest:

- Both models were used to fit forward d–Au RHIC hadron production data in the context of the Color Glass Condensate.

- The original dipole scattering amplitudes represent quark and gluon interactions with the medium.

- They can be rewritten to represent a dipole cross section.

- Both models start with the following expression:

\[
\sigma_{\text{dip}}(x, r) = \sigma_0 N_{\gamma} = \sigma_0 \left[ 1 - \exp \left( -\frac{1}{4} (r^2 Q_s^2)^{\gamma(M, x)} \right) \right]
\]

- If \( \gamma(M, x) \) is set to 1, BUW and DHJ models reduce to the GBW model with parameters \( \sigma_0 = 23 \text{ mb} \ (59.07 \text{ GeV}^{-2}) \), \( x_0 = 3 \times 10^{-4} \), and \( \lambda = 0.3 \).
Dipole cross section — DHJ

In DHJ model the anomalous dimension reads:

\[ \gamma(M, x) = \gamma_s + (1 - \gamma_s) \frac{|\log(M^2/Q_s^2)|}{\lambda Y + d\sqrt{Y} + |\log(M^2/Q_s^2)|}, \]

with \( Y = \log 1/x \) and \( \gamma_s = 0.628 \).

The parameter \( d = 1.2 \) was fitted to data.

The additional dependence on \( x \) not through \( M^2/Q_s^2 \) breaks the geometric scaling.

It is not possible to observe geometric scaling directly from hadron collision data (the opposite is truth in the case of DIS).

Therefore, one can ask: geometric scaling is needed to describe hadron collision data?
Dipole cross section — BUW

- Recently proposed by Boer, Utermann, and Wessels Phys. Rev. D77, 054014 (2008), BUW model makes the anomalous dimension do not depend on $x$ separately, but only on the variable $w = \sqrt{M^2/Q_s^2(x)}$:

$$\gamma(w) = \gamma_s + (1 - \gamma_s) \frac{w^a - 1}{(w^a - 1) + b}.$$  

- The best BUW fit to the data gives $a = 2.82$ and $b = 168$.

- Both models were used to fit forward d–Au RHIC hadron production data, the difference being that DHJ violates geometric scaling, while BUW does not.

- Both DHJ and BUW model can explain RHIC results at small $x$, but at larger $x$ DHJ model deviates from data.

- At LHC energies, the predictions differ even at small $x$. 
Dipole cross section — Comparison

\[
\log_{10}(1/x) = -6, -5, -4, -3, -2, -1
\]

\[\sigma_{\text{dip}}(x, r) \text{ (GeV}^{-2}\text{)}\]

\[M = 6.5 \text{ GeV}\]

- GBW
- BUW
- DHJ

 BUW and DHJ share some similarity for small dipole sizes.
Nuclear PDFs

- Three parameterizations of the nuclear PDFs are used:
  - EPS08 JHEP 07, 102 (2008)
  - EPS09 JHEP 04, 065 (2009)

- The parameterizations give the nuclear proton PDF as the free proton PDF multiplied by a factor: $f_{qA}^{\text{proton}}(x, Q) = R_{q}^{A}(x, Q)f_{q}^{p}(x, Q)$.

- To obtain the nuclear neutron PDF, one relies on the isospin symmetry: $f_{qA}^{\text{neutron}}(x, Q) = R_{q'}^{A}(x, Q)f_{q'}^{p}(x, Q)$; where, if $q$ is up (or down), $q'$ is down (or up).

- For example, the normalized total up distribution in a nucleus is

$$f_{uA} = \frac{Z}{A} R_{u}^{A}(x, Q)f_{u}^{p}(x, Q) + \frac{A - Z}{A} R_{d}^{A}(x, Q)f_{d}^{p}(x, Q).$$
## Nuclear PDF parameterizations

<table>
<thead>
<tr>
<th></th>
<th>EKS</th>
<th>EPS08</th>
<th>EPS09</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>LO</td>
<td>LO</td>
<td>NLO (and LO)</td>
</tr>
<tr>
<td>Data</td>
<td>Deep inelastic lepton-nucleus scattering and Drell–Yan dilepton production data</td>
<td>Deep inelastic lepton-nucleus scattering and Drell–Yan dilepton production data</td>
<td>Deep inelastic lepton-nucleus scattering and Drell–Yan dilepton production data</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>RHIC BRAHMS inclusive high-$p_T$ hadron production at high rapidities ($x \approx 10^{-4}$)</td>
</tr>
</tbody>
</table>

- The authors of EPS09 did not use BRAHMS data because they concluded that baseline $p$–$p$ predictions were not accurate enough.
- As free proton PDF parameterization, we use CTEQ6.1.
Nuclear PDFs — up quark

- $R_{UV}$ and $R_{US}$: factors of valence and sea up quark.

- Nuclear effects:
  - shadowing ($x \lesssim 0.01$),
  - antishadowing ($0.01 \lesssim x \lesssim 0.3$),
  - EMC effect ($0.01 \lesssim x \lesssim 1$), and
  - Fermi motion ($x \approx 1$).

- Stronger shadowing in EPS09.

- EPS09 LO very similar to EKS.
Nuclear PDFs — strange quark and gluon

- $R_{SS}$ and $R_{GL}$: factors of strange quark and gluon.

- EPS08 shows a very strong shadowing.

- In EPS09 shows the less strong shadowing.

- EPS09_LO very similar to EKS.
Results

- Dilepton mass of 6.5 GeV.
- RHIC p–p and d–Au collisions at 200 GeV.
- LHC p–p and p–Pb collisions at 8.8 TeV.
- The nuclear modification factor is given by:

\[ R_{pA} = \frac{d\sigma(pA)}{dp_T^2dydM} \div A \frac{d\sigma(pp)}{dp_T^2dydM}. \]

- If there were no nuclear effects, \( R_{pA} = 1 \).
- Therefore, the nuclear modification factor tells how different is a collision between two free protons from a collision of a free proton and a bound nucleon.
- In the case of d–A collisions, deuteron nuclear effects are neglected and the ratio is divided by two times \( A \) instead of only \( A \).
Results — p–p cross section (RHIC)

- Cross sections for RHIC p–p collisions at 200 GeV.
- Some disagreement among the $\sigma_{\text{dip}}$ is seen, specially at high $p_T$, when larger dipole sizes become important.
- $\langle k_T^2 \rangle = 0.5, 2.5 \text{ GeV}^2$.
- The effects of intrinsic $k_T$ are easily seen.
- Cross sections are prone to variation as $\langle k_T \rangle$ and $\sigma_{\text{dip}}$ change.
Results — $R_{pA}$ (RHIC)

- $R_{dA}$ for RHIC d–Au collisions at 200 GeV.
- Nuclear effects seen: antishadowing and EMC effect.
- Nuclear effects are very dependent on the intrinsic $k_T$.
- At high $p_T/\langle k_T \rangle$, dipole approach and the IMF agree, since intrinsic $k_T$ plays a minor role. (Compton scattering is the dominant subprocess.)
- EPS09 and EPS08 show good agreement.
Results — GBW, BUW, and DHJ comparison

- \( R_{dA} \) for RHIC d–Au collisions at 200 GeV.
- Only dipole approach.
- GBW, BUW, and DHJ comparison.
- Nuclear effects in these results do not distinguish among dipole cross section parameterizations.
- This despite p–p cross section differences.
Results — EPS09 and EKS comparison

- $R_{dA}$ for RHIC d–Au collisions at 200 GeV.
- EPS09 and EKS comparison.
- Both nPDFs give approximately the same results.
Results — p–p cross section (LHC)

- Cross sections for LHC p–p collisions at 8800 GeV.
- $\sigma_{\text{dip}}$ DHJ and BUW models agree, while they disagree with GBW.
- $\langle k_T^2 \rangle = 0.5, 2.0, 4.5$ GeV$^2$.
- Again, important effects due to intrinsic $k_T$.
- Again, cross sections are subject to variation as $\langle k_T \rangle$ and $\sigma_{\text{dip}}$ change.
Results — $R_{pA}$ (LHC)

- $R_{pA}$ for LHC p–Pb collisions at 8800 GeV.
- Nuclear effects seen: shadowing, antishadowing, and EMC effect.
- EPS09 and EKS have good agreement, as well as GBW, BUW, and DHJ have (not shown here).
- EPS08 and EPS09 disagree when shadowing is important.
- Again, nuclear effects are very dependent on the intrinsic $k_T$.
- Dipole approach and the IMF agree at high $p_T/\langle k_T \rangle$.
Results — Backward and forward rapidities (RHIC)

- CGC results at forward rapidities at RHIC energies (M. A. Betemps and M. B. Gay Ducati, Phys. Rev. D70, 116005).
- The three ways to calculate the dilepton production agree pretty well; even the transverse momentum dependence is the same.
- Forward rapidities: $R_{pA}$ increases with $p_T$, due to a necessary increase in the parton momentum fraction, reducing the effect of shadowing.
- At backward rapidities, there is no shadowing but the antishadowing effect, leading to a decrease of $R_{pA}$ with $p_T$. 

![Graph showing dilepton rapidity distributions for CGC and Dipole approaches at different $p_T$ values.](image-url)
Results — Backward and forward rapidities (LHC)

- At LHC energies, forward rapidity results disagree.
- Only the qualitative $p_T$ dependence is kept.
- From mid to forward rapidities, less annihilation and more Compton scattering subprocess become important.
- EPS09 has an increase at forward rapidities as $y$ increases.
- This happens because quark shadowing is stronger than gluon shadowing and shadowing is not sufficiently enhanced as $x \rightarrow 0$.
- In EPS08, shadowing is enhanced very fast, therefore the nuclear modification factor always decreases for $y > 0$. 
Summary

We studied the nuclear effects in the improved parton model and the color dipole approach through the nuclear modification factor.

- Nuclear effects at $y$ are not sensitive to different dipole cross sections (no hint about geometric scaling).
- Introduction of the intrinsic transverse momentum can change $R_{pA}$ of $\approx 0.1$.
- Color dipole approach misses the changes in nuclear effects due to intrinsic $k_T$.
- At RHIC, different models qualitatively agree.
- At LHC, forward models qualitatively disagree due to the interplay of quark and of gluon shadowing.

Dileptons bring a lot of information on nuclear effects.