

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

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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 **without** the formation of a dense medium.
- ▶ Furthermore, saturation effects are studied at RHIC and LHC collisions.

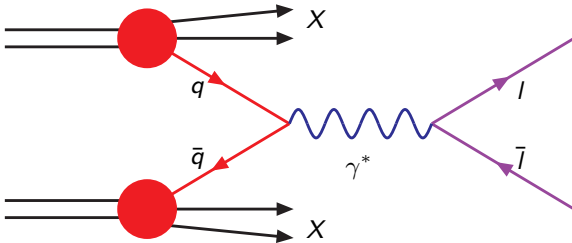
We are interested in high density QCD (low- x physics) in high energy hadron collisions.

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 the infinite momentum frame (IMF), both hadrons are understood as composed by partons in the Drell–Yan process: [Phys. Rev. Lett. 25, 316 \(1970\)](#); [Ann. Phys. 66, 578 \(1971\)](#).
- ▶ 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 .
- ▶ Introduce (two-dimensional) parton intrinsic transverse momentum **G.** Altarelli, G. Parisi, and R. Petronzio, *Phys. Lett.* B76, 351 (1978); *Phys. Lett.* B76, 356 (1978).
- ▶ We use a Gaussian intrinsic k_T distribution of a single parton as given by:

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

- ▶ $\langle k_T^2 \rangle = \frac{4}{\pi} \langle k_T \rangle^2$.
- ▶ 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)**), $\langle k_T^2 \rangle = 2.5 \text{ GeV}^2$ 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:

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

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

J. Raufeisen, J.-C. Peng, and G. C. Nayak, *Phys. Rev. D*66, 034024 (2002)

- ▶ 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 $q + g \rightarrow q + \gamma^*$ and annihilation $q + \bar{q} \rightarrow g + \gamma^*$.
- ▶ We have (R. D. Field, Applications of Perturbative QCD):

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

- ▶ $x_{1,2} = \sqrt{\frac{M^2 + p_T^2}{s}} e^{\pm y}$, 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 $x_{A\min} = (x_1 - M^2/s)/(1 - x_2)$.

Improved parton model and PDFs

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

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

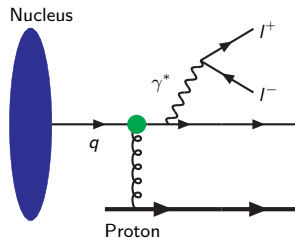
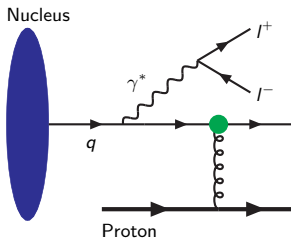
$$P_{qg}(x_A, x_B, M^2) = \sum_q e_q^2 (f_q(x_A) + f_{\bar{q}}(x_A)) f_g(x_B)$$

$$P_{gq}(x_A, x_B, M^2) = \sum_q e_q^2 f_g(x_A) (f_q(x_B) + f_{\bar{q}}(x_B)).$$

- ▶ 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:

$$\frac{d\sigma^{DY}}{dM^2 dy d^2 p_T} = \frac{\alpha_{em}^2}{6\pi^3 M^2} \int_0^\infty d\rho W(x_2, \rho, p_T) \sigma_{dip}(x_1, \rho),$$

- ▶ $\sigma_{dip}(x_1, \rho)$ is the **dipole cross section** and ρ is dipole size.
- ▶ The approach is phenomenologically valid for very backward rapidities y , i.e., small $x_1 = \sqrt{\frac{M^2 + p_T^2}{s}} e^y$.
- ▶ 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.
- ▶ α 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 ρ -sized dipole contribution to the cross section:

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

- ▶ 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:

$$Q_s^2(x) = Q_0^2 \left(\frac{x_0}{x} \right)^{\lambda/2} \qquad Q_0^2 = 1 \text{ GeV}^2.$$

- ▶ 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 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:
 - ▶ DHJ Dumitru, Hayashigaki, and Jalilian-Marian, Nucl. Phys. A765, 464 (2006); Nucl. Phys. A770, 57 (2006);
 - ▶ BUW Boer, Utermann, and Wessels, Phys. Rev. D77, 054014 (2008).
- ▶ 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 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?

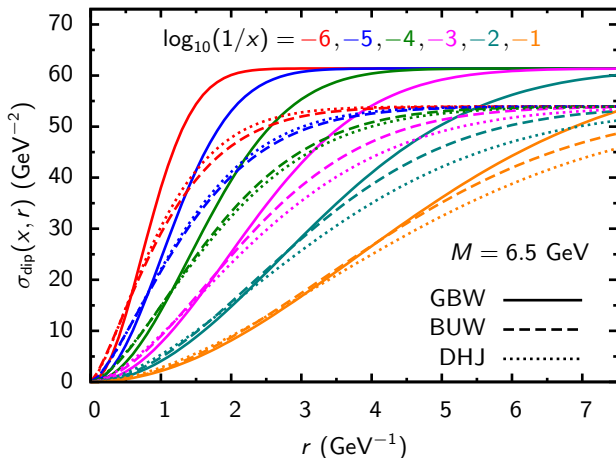
Dipole cross section — BUW

- ▶ Recently proposed by Boer, Utermann, and Wessels *Phys. Rev. D* **77**, 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



- BUW and DHJ share some similarity for small dipole sizes.

Nuclear PDFs

- ▶ Three parameterizations of the nuclear PDFs are used:
 - ▶ EKS *Nucl. Phys.* B535, 351 (1998); *Eur. Phys. J.* C9, 61 (1999); *JHEP* 05, 002 (2007)
 - ▶ 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: $f_q^{\text{proton}-A}(x, Q) = R_q^A(x, Q) f_q^P(x, Q)$.
- ▶ To obtain the nuclear neutron PDF, one relies on the isospin symmetry: $f_q^{\text{neutron}-A}(x, Q) = R_{q'}^A(x, Q) f_{q'}^P(x, Q)$; where, if q is up (or down), q' is down (or up).
- ▶ For example, the normalized total up distribution in a nucleus is

$$f_u^A = \frac{Z}{A} R_u^A(x, Q) f_u^P(x, Q) + \frac{A-Z}{A} R_d^A(x, Q) f_d^P(x, Q).$$

Nuclear PDF parameterizations

EKS

LO

Deep inelastic lepton-nucleus scattering and Drell-Yan dilepton production data

EPS08

LO

Deep inelastic lepton-nucleus scattering and Drell-Yan dilepton production data

+

RHIC BRAHMS inclusive high- p_T hadron production at high rapidities ($x \approx 10^{-4}$)

EPS09

NLO (and LO)

Deep inelastic lepton-nucleus scattering and Drell-Yan dilepton production data

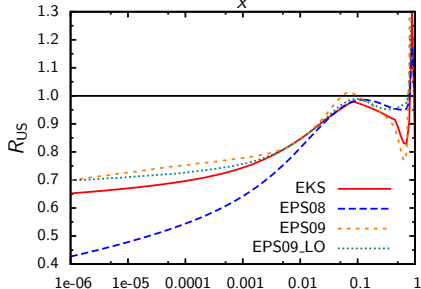
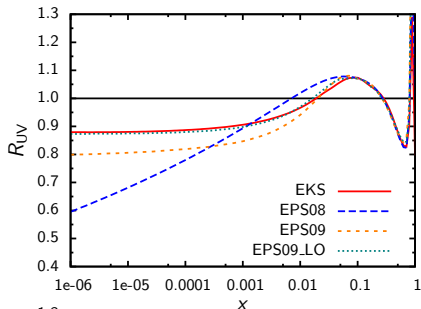
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RHIC PHENIX inclusive pion production at mid rapidities ($x \approx 10^{-2}$)

- ▶ 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.

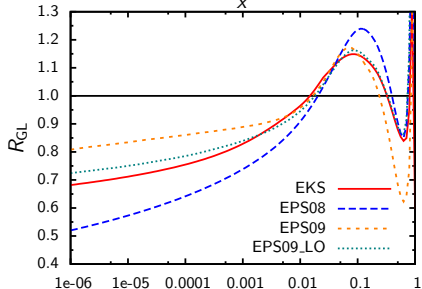
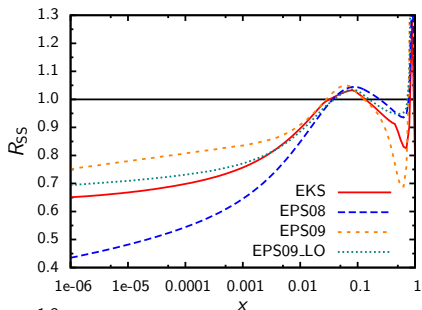
Nuclear PDFs — up quark

- ▶ 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

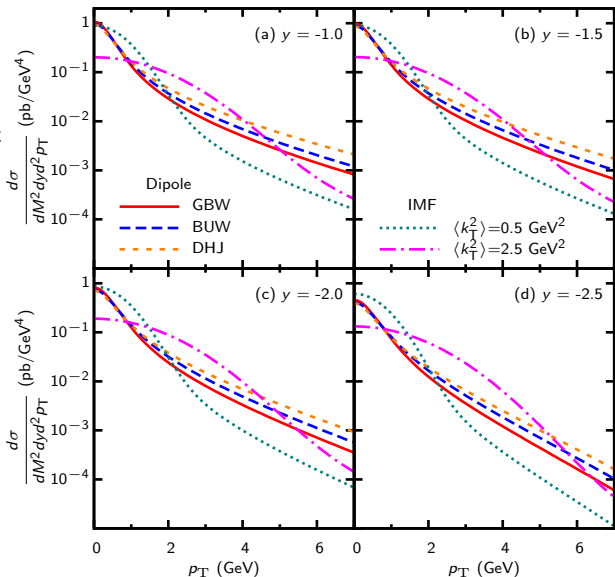
- ▶ Dilepton mass of 6.5 GeV.
- ▶ RHIC p-p and d-Au collisions at 200 GeV.
- ▶ LHC p-p and p-Pb collisions at 8.8 TeV.
- ▶ The **nuclear modification factor** is given by:

$$R_{pA} = \frac{d\sigma(pA)}{dp_{\perp}^2 dy dM} \bigg/ A \frac{d\sigma(pp)}{dp_{\perp}^2 dy dM}.$$

- ▶ 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 .

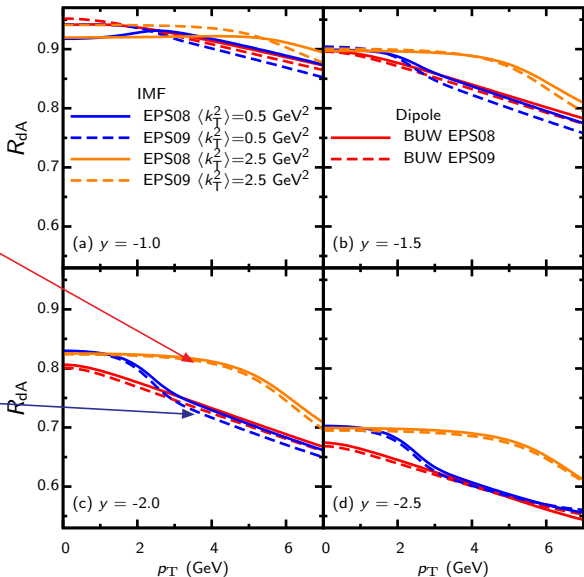
Results — p-p cross section (RHIC)

- ▶ Cross sections for RHIC p-p collisions at 200 GeV.
- ▶ Some disagreement among the σ_{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 σ_{dip} change.



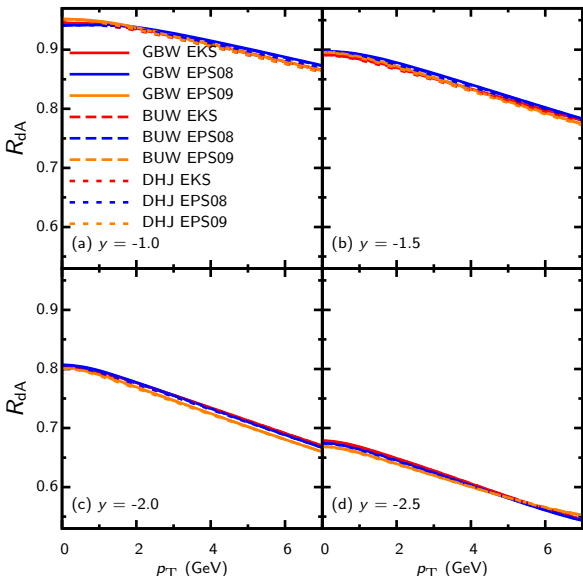
Results — R_{pA} (RHIC)

- ▶ 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.



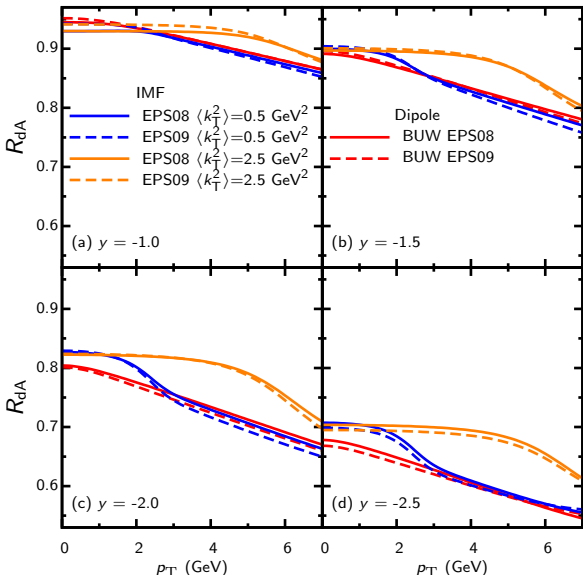
Results — GBW, BUW, and DHJ comparison

- ▶ 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.



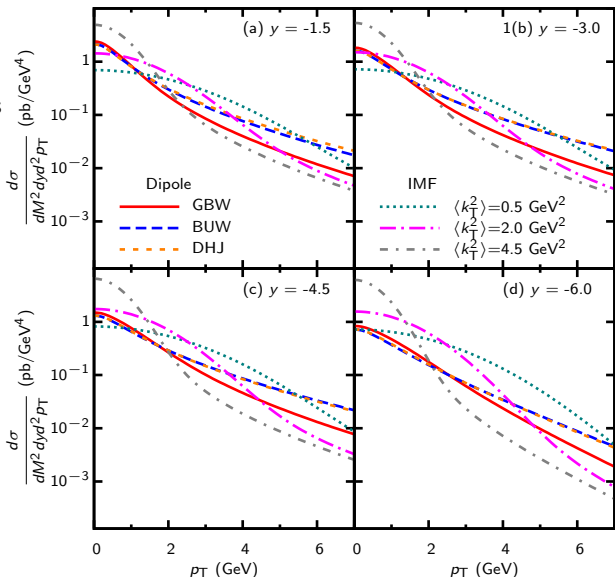
Results — EPS09 and EKS comparison

- ▶ R_{dA} for RHIC d–Au collisions at 200 GeV.
- ▶ EPS09 and EKS comparison.
- ▶ Both nPDFs give approximately the same results.



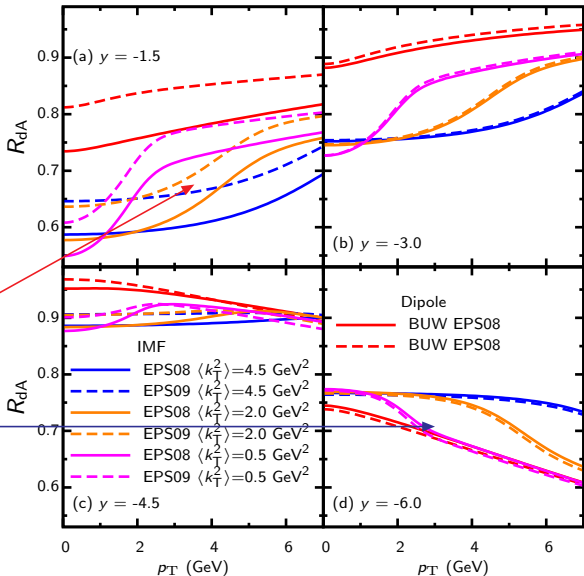
Results — p-p cross section (LHC)

- ▶ Cross sections for LHC p-p collisions at 8800 GeV.
- ▶ σ_{dip} DHJ and BUW models agree, while they disagree with GBW.
- ▶ $\langle k_{\text{T}}^2 \rangle = 0.5, 2.0, 4.5 \text{ GeV}^2$.
- ▶ Again, important effects due to intrinsic k_{T} .
- ▶ Again, cross sections are subject to variation as $\langle k_{\text{T}} \rangle$ and σ_{dip} change.



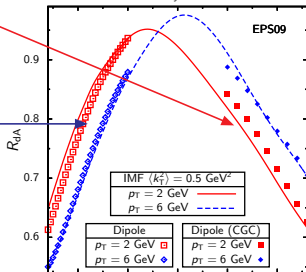
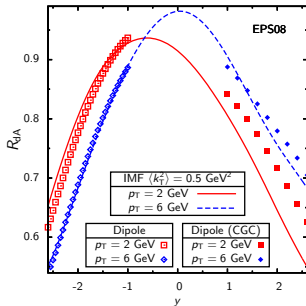
Results — R_{pA} (LHC)

- ▶ 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 $p_T/\langle k_T \rangle$.



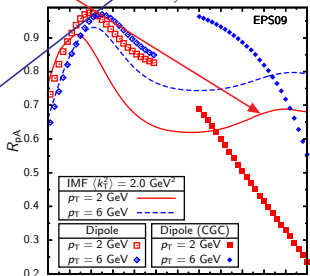
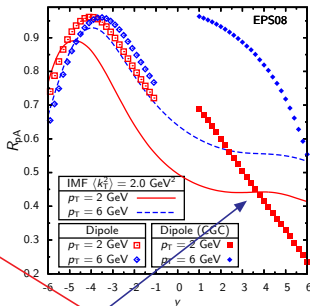
Results — Backward and forward rapidities (RHIC)

- ▶ CGC results at forward rapidities at RHIC energies (M. A. Betemps and M. B. Gay Ducati, *Phys. Rev. D*70, 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 .



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 ≈ 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.