

Drell-Yan Lepton-Pair-Jet Correlation in pA Collisions

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Gluon Distributions

Two unintegrated gluon distributions relevant at small- x

Weizsäcker-Williams distribution

- Gluon number density in light-cone gauge
- Measurable by dihadron correlations in deep inelastic scattering

Dipole gluon distribution

- No probabilistic physical interpretation
- Measurable by lepton pair-hadron correlations in Drell-Yan scattering

Gluon Distributions

Two unintegrated gluon distributions relevant at small- x

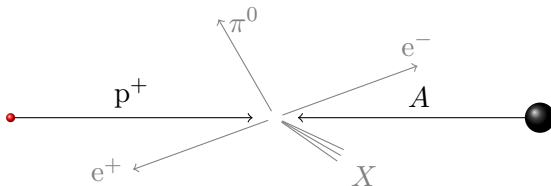
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Dipole gluon distribution

- No probabilistic physical interpretation
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pA Collisions

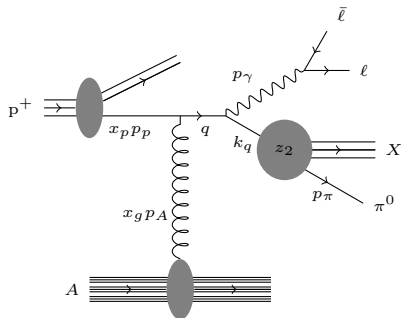
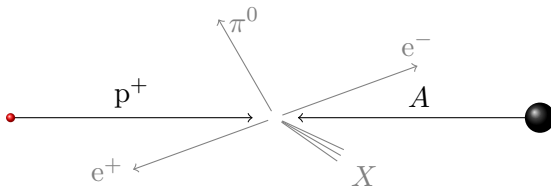


$p^+ A \rightarrow \ell \bar{\ell} \pi^0 X$: lepton pair provides nearly direct access to gluon distribution and quark PDFs

- No final-state interactions on γ
- No fragmentation in $\gamma \rightarrow \ell \bar{\ell}$

Consequence: correlation can be calculated exactly for all angles

pA Collisions



RHIC:

- Gold nuclei, $A = 197$
- $\sqrt{s_{NN}} = 200 \text{ GeV}$

LHC:

- Lead nuclei, $A = 208$
- $\sqrt{s_{NN}} = 5 \text{ TeV}$

Exclusive Cross Section

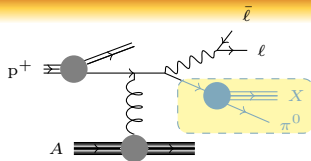
$$\begin{aligned}
 \frac{d\sigma^{pA \rightarrow \gamma^* \pi^0 X}}{dY_\gamma dY_\pi d^2\mathbf{p}_{\gamma\perp} d^2\mathbf{p}_{\pi\perp} d^2b} &= \int_{\frac{z_{h2}}{1-z_{h1}}}^1 \frac{dz_2}{z_2^2} \\
 &\times \sum_f D_{\pi^0/f}(z_2, \mu) x_p q_f(x_p, \mu) \frac{\alpha_{\text{em}} e_f^2}{2\pi^2} (1-z) F_{x_g}(q_\perp) \\
 &\times \left\{ [1 + (1-z)^2] \frac{z^2 q_\perp^2}{[p_{\gamma\perp}^2 + \epsilon_M^2] [(\mathbf{p}_{\gamma\perp} - z\mathbf{q}_\perp)^2 + \epsilon_M^2]} \right. \\
 &\quad \left. - z^2(1-z) M^2 \left[\frac{1}{p_{\gamma\perp}^2 + \epsilon_M^2} - \frac{1}{(\mathbf{p}_{\gamma\perp} - z\mathbf{q}_\perp)^2 + \epsilon_M^2} \right]^2 \right\}
 \end{aligned}$$

Essentially:

nonperturbative $\otimes$ dipole gluon distribution $\otimes$ kinematic factor

Inclusive Cross Section

Integrate over phase space of quark



$$\frac{d\sigma^{pA \rightarrow \gamma^* X}}{dY_\gamma d^2\mathbf{p}_{\gamma\perp} d^2b} = \int_{z_{h1}}^1 \frac{dz}{z} \int d^2\mathbf{q}_\perp \sum_f x_p q_f(x_p, \mu) \frac{\alpha_{\text{em}} e_f^2}{2\pi^2} F_{x_g}(q_\perp) \times \left\{ [1 + (1-z)^2] \frac{z^2 q_\perp^2}{[p_{\gamma\perp}^2 + \epsilon_M^2] [(\mathbf{p}_{\gamma\perp} - z\mathbf{q}_\perp)^2 + \epsilon_M^2]} - z^2(1-z)M^2 \left[\frac{1}{p_{\gamma\perp}^2 + \epsilon_M^2} - \frac{1}{(\mathbf{p}_{\gamma\perp} - z\mathbf{q}_\perp)^2 + \epsilon_M^2} \right]^2 \right\}$$

integrate nonperturbative $\otimes$ dipole gluon distribution $\otimes$ kinematic factor

Correlation

The correlation is the angle-dependent ratio of the two cross sections

$$C^{\text{DY}}(\Delta\phi) = \frac{\int \cdots \int_{p_{\{\gamma,\pi\}\perp} > p_{\perp\text{cut}}} d^2\mathbf{p}_{\gamma\perp} d^2\mathbf{p}_{\pi\perp} \frac{d\sigma^{pA \rightarrow \gamma^* \pi^0 X}}{dY_{\gamma} dY_{\pi} d^2\mathbf{p}_{\gamma\perp} d^2\mathbf{p}_{\pi\perp} d^2b}}{\int_{p_{\gamma\perp} > p_{\perp\text{cut}}} d^2\mathbf{p}_{\gamma\perp} \frac{d\sigma^{pA \rightarrow \gamma^* X}}{dY_{\gamma} d^2\mathbf{p}_{\gamma\perp} d^2b}}$$

$$C^{\text{DY}}(\Delta\phi) = \frac{\sigma^{pA \rightarrow \gamma^* \pi^0 X}}{\sigma^{pA \rightarrow \gamma^* X}}$$

- Parton distributions: MSTW 2008 NLO
- Fragmentation functions: DSS (2007)

GBW Model

- Phenomenological fit to DIS data
- Exponential fall at high momentum

$$\phi(k^2, Y) = \frac{1}{2} \Gamma\left(0, \frac{k^2}{Q_{sA}^2(Y)}\right)$$
$$F_{x_g}(k^2, Y) = \frac{1}{\pi Q_{sA}^2(Y)} e^{-k^2/Q_{sA}^2(Y)}$$

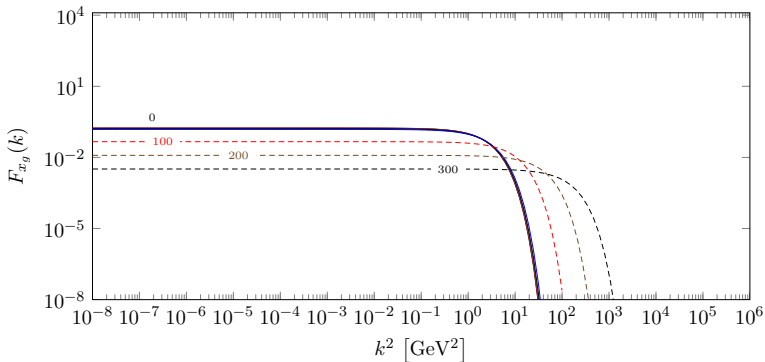
where

$$Q_{sA}^2 = Q_{s0}^2 \left(\frac{x_0}{x}\right)^\lambda$$

Here $Q_{s0} = 1 \text{ GeV}$, $\lambda = 0.288$, $x_0 = 3.04 \times 10^{-4}$

GBW Model

- Phenomenological fit to DIS data
- Exponential fall at high momentum



BK Equation: Fixed Coupling

- Disagreement with DIS data
- Inverse power fall at high momentum

$$\frac{\partial \phi(k, Y)}{\partial Y} = \bar{\alpha}_s K \otimes \phi(k) - \bar{\alpha}_s \phi^2(k)$$

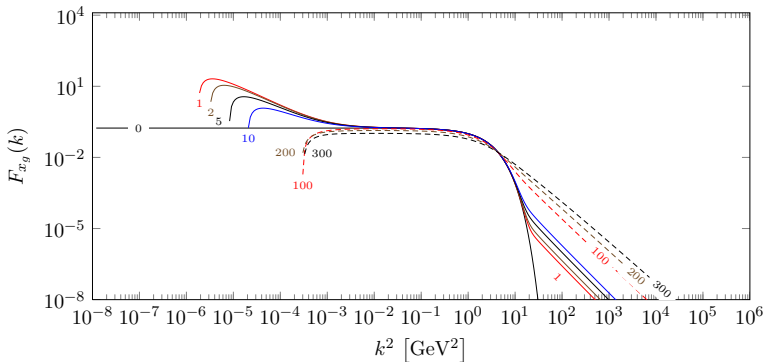
with

$$K \otimes \phi(k) = \int_0^\infty \frac{dk'^2}{k'^2} \left[\frac{k'^2 \phi(k') - k^2 \phi(k)}{|k^2 - k'^2|} + \frac{k^2 \phi(k)}{\sqrt{4k'^4 + k^4}} \right]$$

then $F_{x_g} = \frac{1}{2\pi} \nabla_{\mathbf{k}}^2 \phi$

BK Equation: Fixed Coupling

- Disagreement with DIS data
- Inverse power fall at high momentum



BK Equation: Running Coupling

- Agrees with DIS data
- Inverse power fall at high momentum

$$\frac{\partial \phi(k, Y)}{\partial Y} = \bar{\alpha}_s K \otimes \phi(k) - \bar{\alpha}_s \phi^2(k)$$

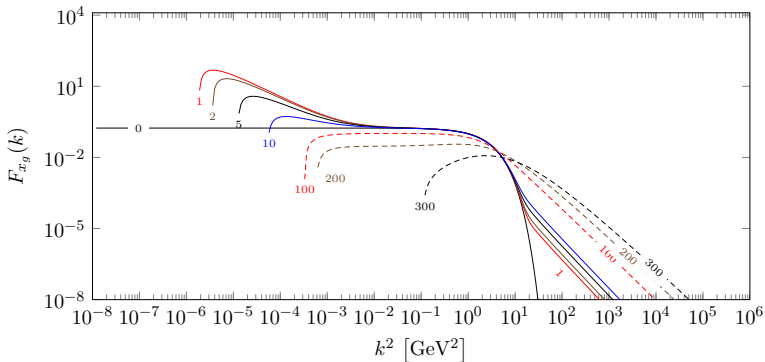
as before, but now the coupling is not fixed

$$\bar{\alpha}_s(k^2) = \frac{1}{\beta \ln \frac{k^2 + \mu^2}{\Lambda_{\text{QCD}}^2}}$$

Evolution with rapidity is slower with running coupling

BK Equation: Running Coupling

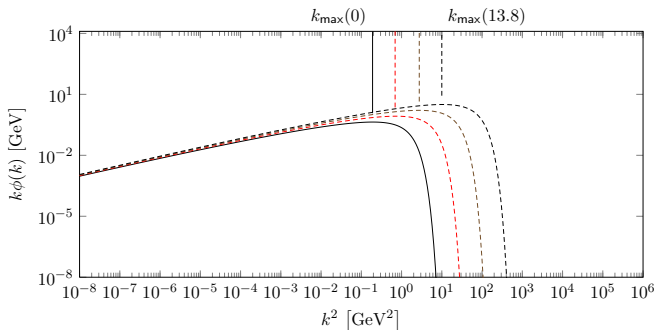
- Agrees with DIS data
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Saturation scale

At each rapidity, determine the peak $k_{\max}$ of $k\phi(k, Y)$

Example: GBW model

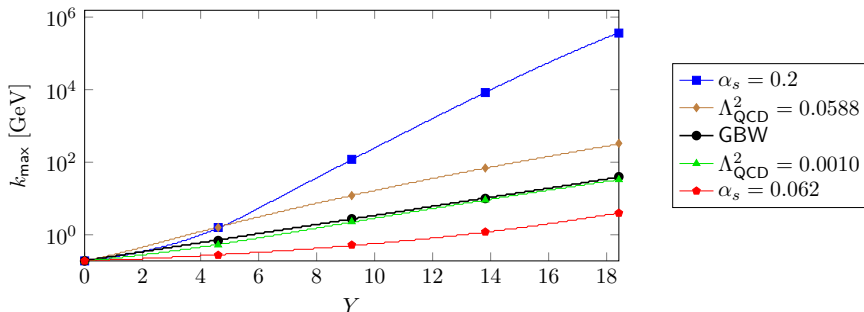


and take $Q_s(Y) \propto k_{\max}(Y)$

Evolution Matching

For $10 \lesssim Y \lesssim 20$, the best match to $\frac{\partial Q_s}{\partial Y}$ in the GBW model is found with

- $\alpha_s = 0.062$ for fixed-coupling BK
- $\Lambda_{QCD}^2 = 0.001 \text{ GeV}^2$ for running-coupling BK

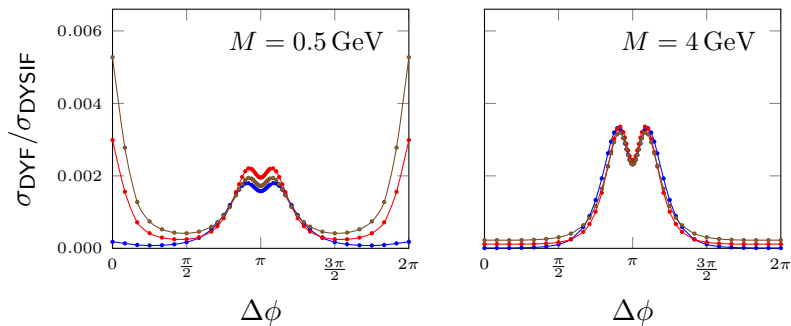


Parameter choices

For the results presented in the paper and the following slides:

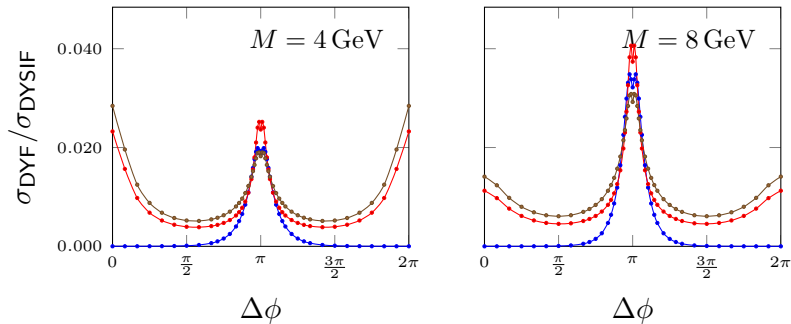
		RHIC	LHC
virtual photon mass	M	0.5 GeV, 4 GeV	4 GeV, 8 GeV
photon rapidity	Y_γ	2.5	4
pion rapidity	Y_π	2.5	4
centrality coefficient	c	0.85	0.85
mass number	A	197	208
CM energy per nucleon	$\sqrt{s_{NN}}$	200 GeV	8800 GeV
transverse momentum cut	$p_{\perp cut}$	1.5 GeV	3 GeV
projectile type		deuteron	proton

RHIC Predictions



Using the BK equation we find a near-side peak at low M that is not present with the GBW model, and a slight enhancement to the away-side peak

LHC Predictions



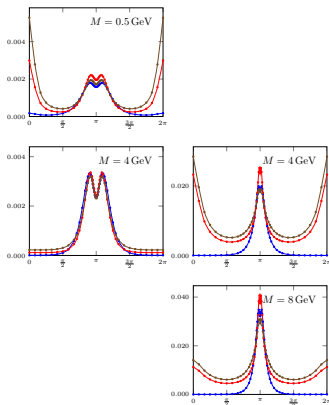
Again, a near-side peak and a slight enhancement to the away-side peak using BK

Features

Key feature: *double peak* structure around $\Delta\phi = \pi$, unique to Drell-Yan

Recall kinematic factor:

$$[1 + (1 - z)^2] \frac{z^2 q_{\perp}^2}{[p_{\gamma\perp}^2 + \epsilon_M^2][(\mathbf{p}_{\gamma\perp} - z\mathbf{q}_{\perp})^2 + \epsilon_M^2]} - z^2(1 - z)M^2 \left[\frac{1}{p_{\gamma\perp}^2 + \epsilon_M^2} - \frac{1}{(\mathbf{p}_{\gamma\perp} - z\mathbf{q}_{\perp})^2 + \epsilon_M^2} \right]^2$$



This is equal to 0 at $q_{\perp} = 0$, so the partonic cross section goes to zero at $\Delta\phi = \pi$. Fragmentation “blurs” this somewhat but not enough to eliminate the minimum.

Summary

Drell-Yan lepton-pair-jet events provide a direct probe of the dipole gluon distribution.

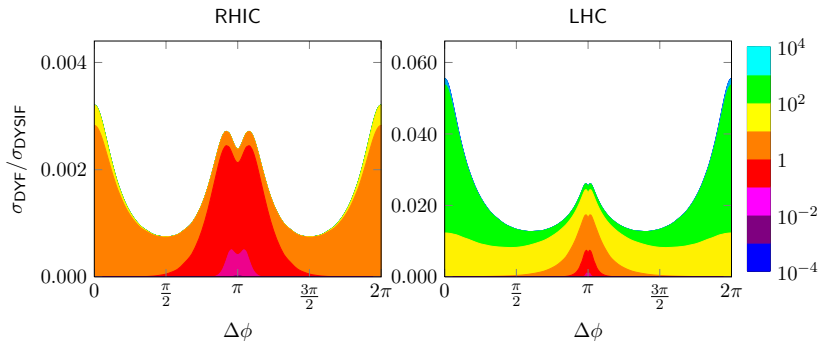
- Double peak appears on the away side, related to fragmentation
- GBW model is not sufficient to predict correlation at all angles

Results from this simulation (with appropriate parameters) can be compared to data to be collected in the 2013 p-Pb run at the LHC and the planned 2017 d-Au run at RHIC.

Supplemental slides

k_T distribution

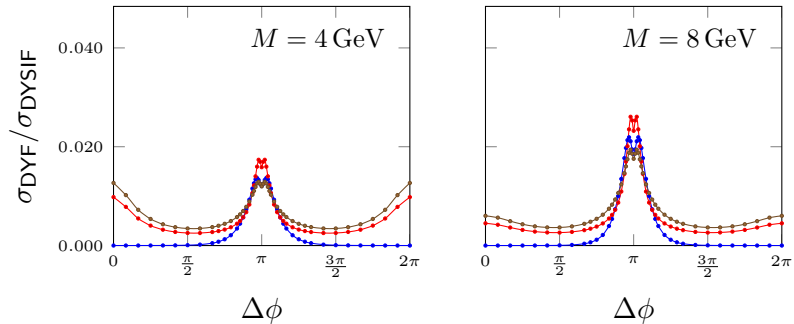
Breakdown of the contributions to the correlation function from each region of transverse momentum



Momentum ranges are in GeV

5 TeV predictions

These are predictions for the LHC run beginning later this year (not “vetted for publication”)



Very similar to full-energy LHC results, scaled down by about a third