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

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David Zaslavsky
Collaboration with Anna Staśto and Bo-Wen Xiao

Penn State University

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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

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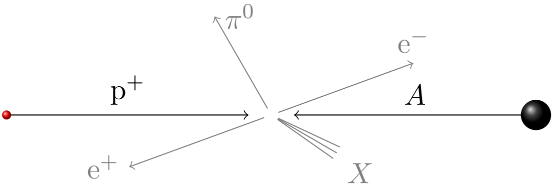
pA Collisions

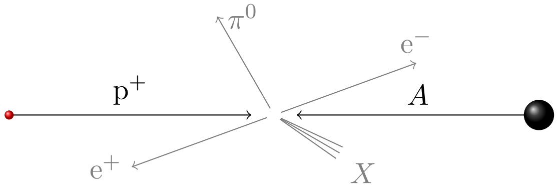


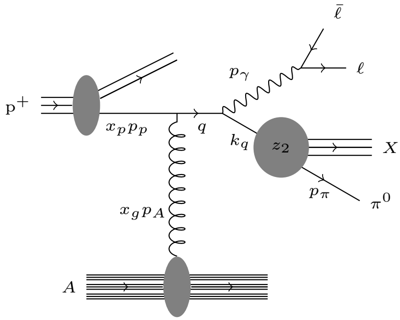
$p^+A \to \ell\bar{\ell}\pi^0 X$: lepton pair provides nearly direct access to gluon distribution and quark PDFs

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

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

$$\frac{\mathrm{d}\sigma^{pA\to\gamma^*\pi^0 X}}{\mathrm{d}Y_\gamma \mathrm{d}Y_\pi \mathrm{d}^2\mathbf{p}_{\gamma\perp}\mathrm{d}^2\mathbf{p}_{\pi\perp}\mathrm{d}^2 b} = \int_{\frac{z_{h2}}{1-z_{h1}}}^{1} \frac{\mathrm{d}z_2}{z_2^2}$$

$$\times \sum_f D_{\pi^0/f}(z_2,\mu) x_p q_f(x_p,\mu) \frac{\alpha_{\text{em}} e_f^2}{2\pi^2}(1-z) F_{x_g}(q_\perp)$$

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

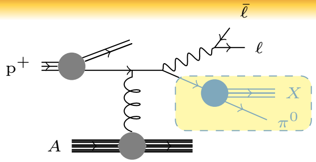
$$\left. - z^2(1-z)M^2 \left[\frac{1}{p_{\gamma\perp}^2+\epsilon_M^2} - \frac{1}{(\mathbf{p}_{\gamma\perp}-z\mathbf{q}_\perp)^2+\epsilon_M^2}\right]^2 \right\}$$

Essentially:

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

Inclusive Cross Section

Integrate over phase space of quark



$$\frac{d\sigma^{pA\to\gamma^* X}}{dY_\gamma d^2\mathbf{p}_{\gamma\perp} d^2 b} = \int_{z_{h1}}^{1} \frac{dz}{z} \int d^2\mathbf{q}_\perp \sum_f x_p q_f(x_p,\mu) \frac{\alpha_{\text{em}} e_f^2}{2\pi^2} F_{x_g}(q_\perp)$$

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

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

Correlation

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

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

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

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

GBW Model

- Phenomenological fit to DIS data
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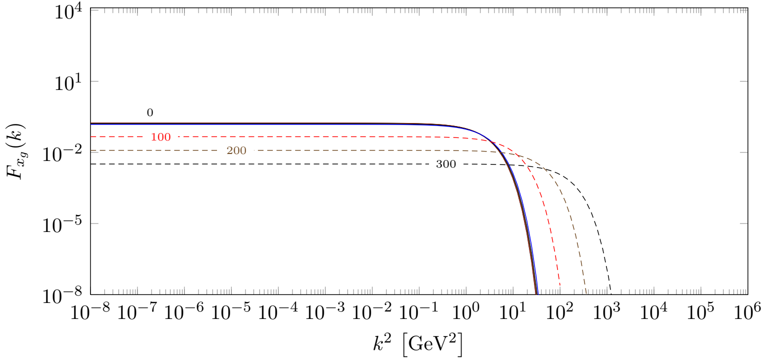


BK Equation: Fixed Coupling

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

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

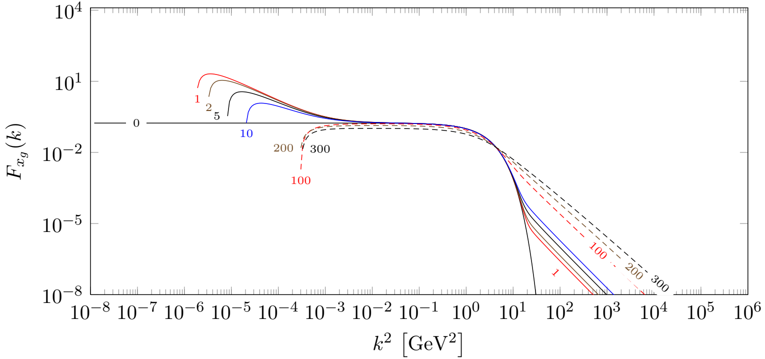
with

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

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

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

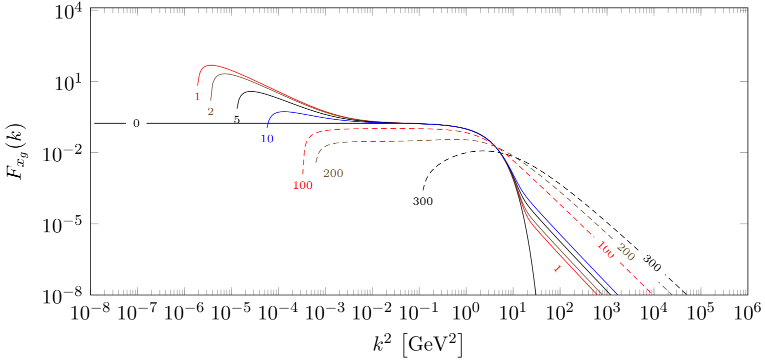
as before, but now the coupling is not fixed

$$\bar{\alpha}_{\mathsf{s}}(k^2) = \frac{1}{\beta \ln \frac{k^2+\mu^2}{\Lambda^2_{\mathsf{QCD}}}}$$

Evolution with rapidity is slower with running coupling

BK Equation: Running Coupling

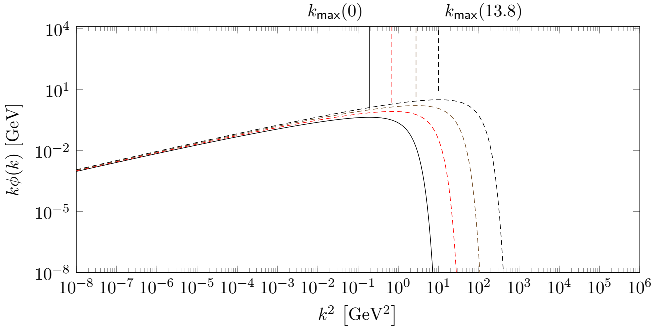
- Agrees with DIS data
- Inverse power fall at high momentum



Saturation scale

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

Example: GBW model

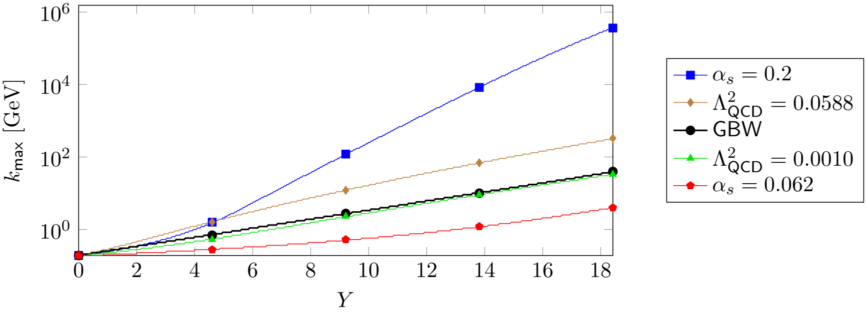


and take $Q_s(Y) \propto k_{\text{max}}(Y)$

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
- $\Lambda^2_{QCD} = 0.001\,\mathrm{GeV}^2$ for running-coupling BK

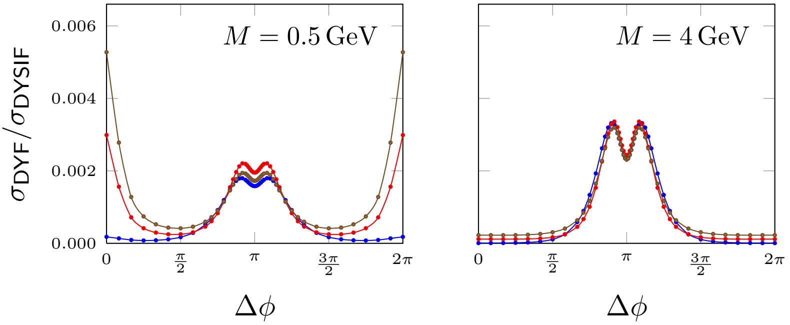


Parameter choices

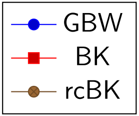
For the results presented in the paper and the following slides:

		RHIC	LHC
virtual photon mass	M	$0.5\,\text{GeV}, 4\,\text{GeV}$	$4\,\text{GeV}, 8\,\text{GeV}$
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	$\sqrt{s_{NN}}$	$200\,\text{GeV}$	$8800\,\text{GeV}$
transverse momentum cut	$p_{\perp\text{cut}}$	$1.5\,\text{GeV}$	$3\,\text{GeV}$
projectile type		deuteron	proton

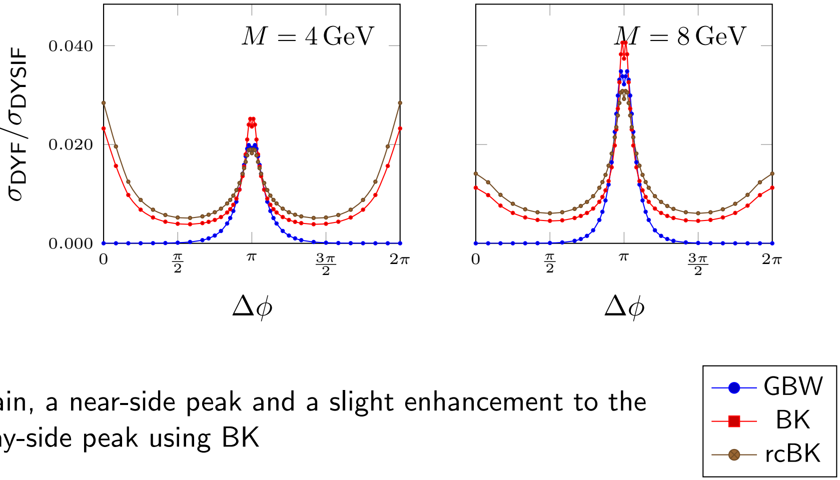
RHIC Predictions



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

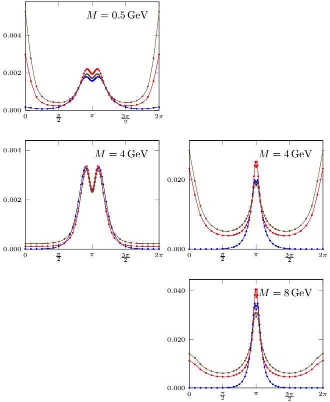


LHC Predictions



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:

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

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.

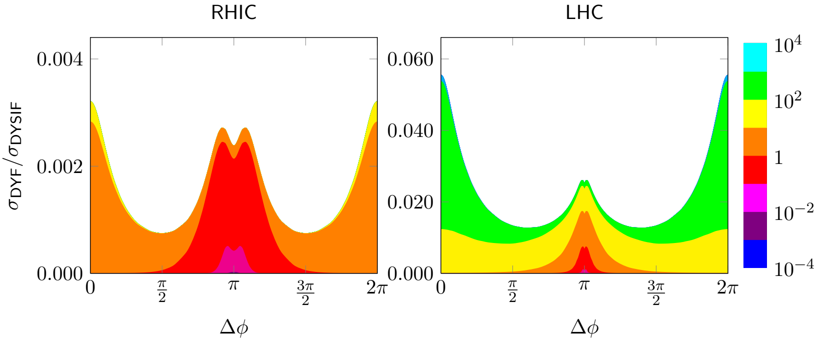
- Double peak appears on the away side, related to fragmentation
- GBW model is not sufficient to predict correlation at all angles

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

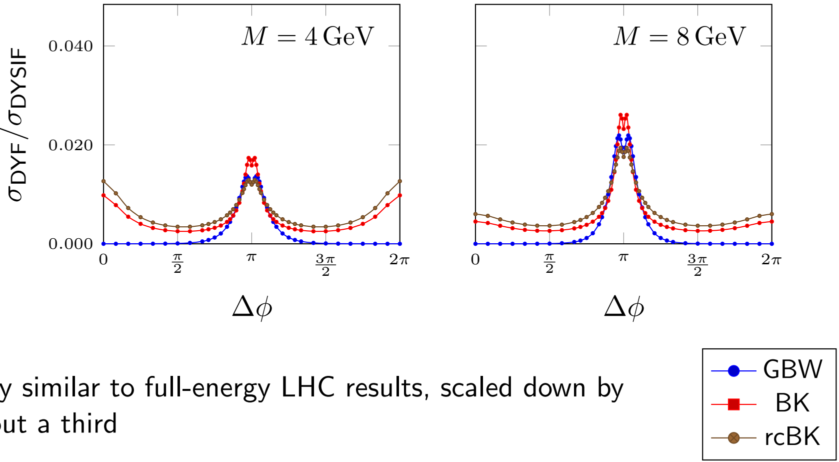
Breakdown of the contributions to the correlation function from each region of transverse momentum



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