

STAR's contribution to theoretical understanding of Cold QCD

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Where to begin ?

Excellent overview of Cold QCD results from RHIC experiments

The RHIC Cold QCD Program

White Paper

contribution to
the NSAC Long-Range Planning process

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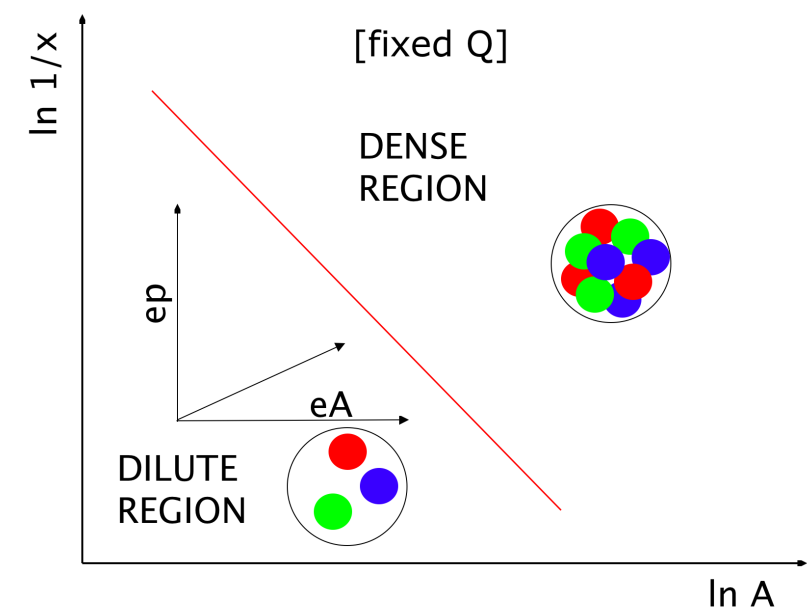
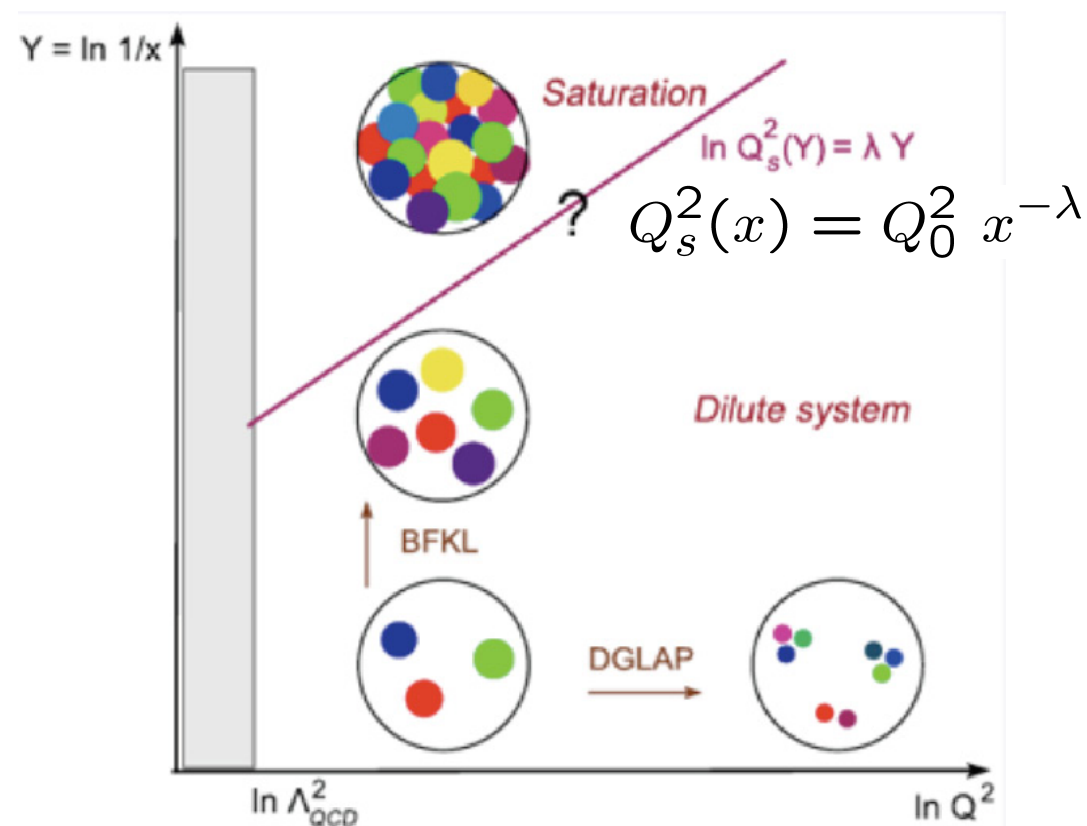
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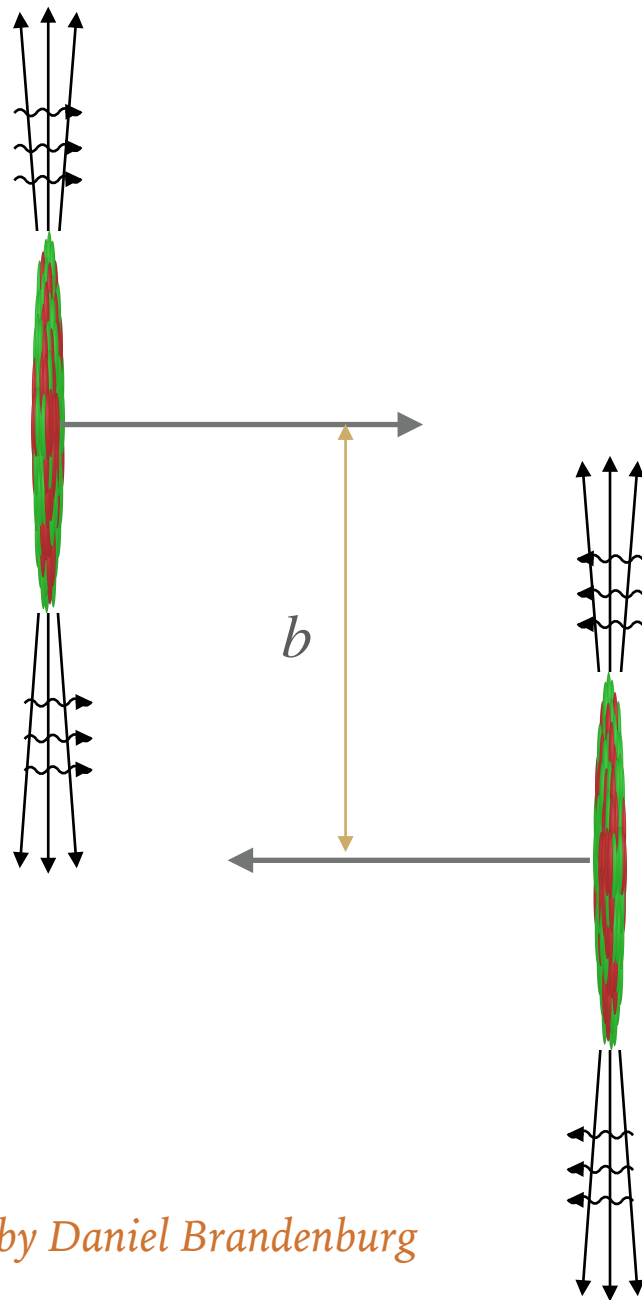
Big picture...

- What is nucleon structure in terms of quarks and gluons ?
- How these distributions get modified in nuclei ?
- What happens at very low x and/or high A ?
- Is there an onset of non-linear regime (saturation) ?



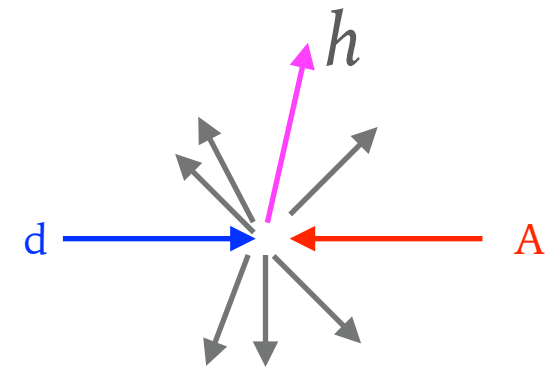
Examples of tests of cold QCD nuclear effects at STAR

UPC (eg. exclusive processes)

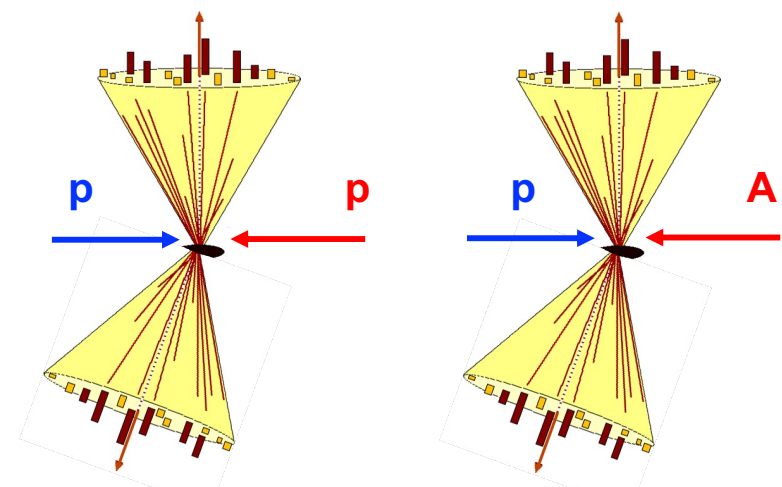


see also talk by Daniel Brandenburg

p_T spectra of hadrons in pp vs dA



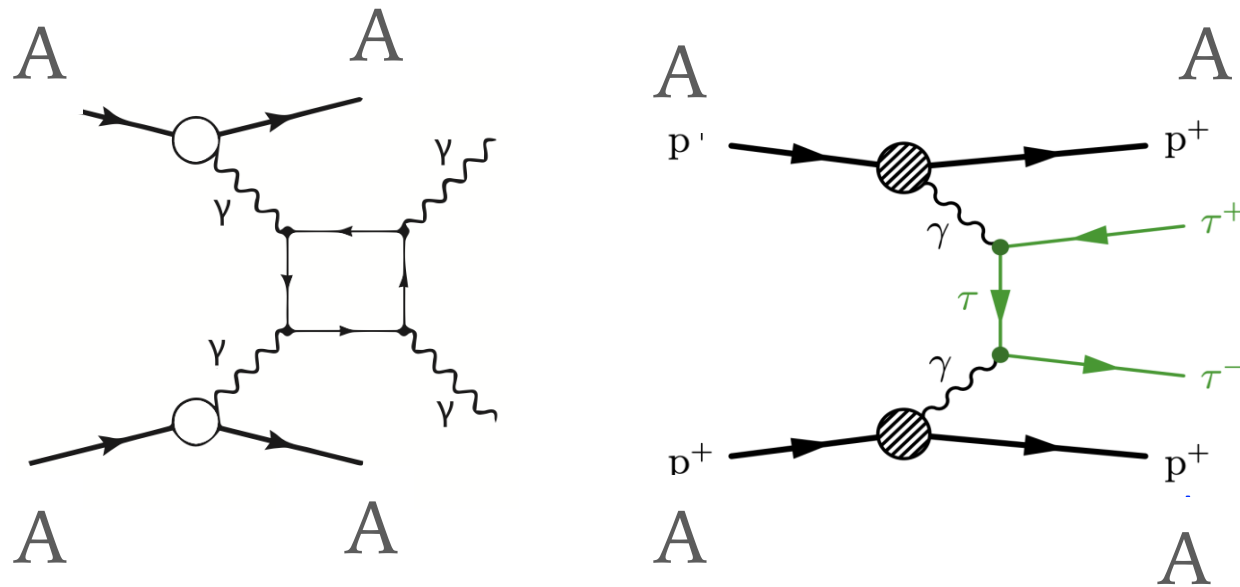
Di-hadron correlations



STAR has pioneered many of these measurements which are essential to explore cold nuclear effects

UPC physics

$\gamma\gamma$ physics

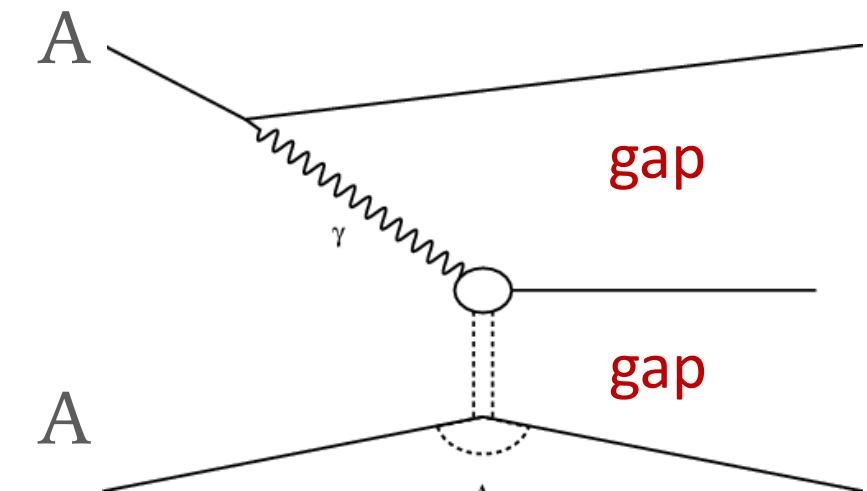


Testing QED

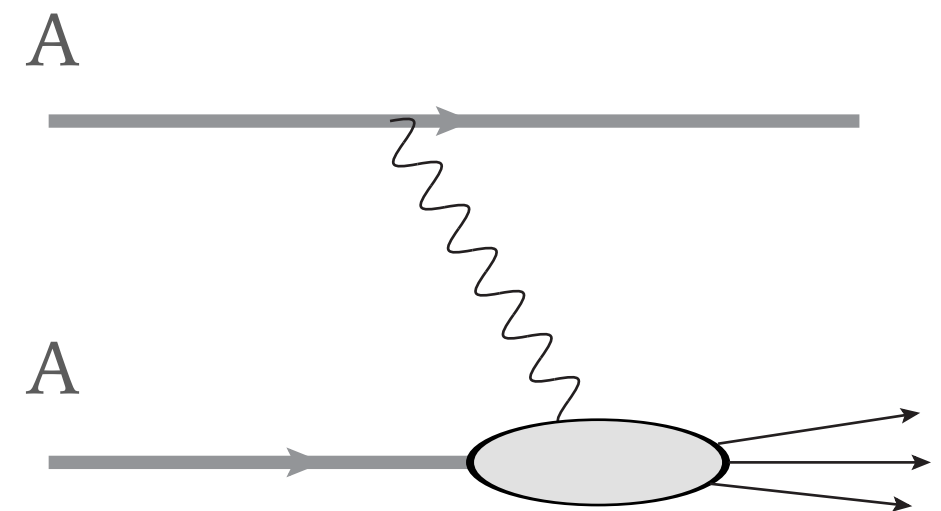
Testing SM in general

BSM and exotic searches

γA : photonuclear interactions



Exclusive production

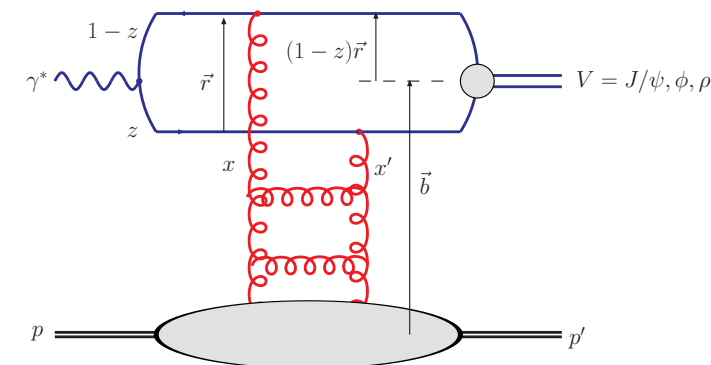
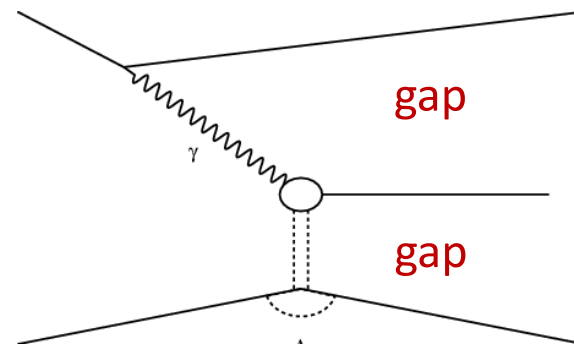


Inclusive: dijet, heavy quark production

Exclusive vector meson photo and electro-production

Weiler; Ryskin; Jung, Schuler, Terron; Nemchik, Nikolaev Zakharov...

$$\gamma^{(*)} p \rightarrow V p$$



Exclusive (photo)production of vector mesons

Mass of the heavy vector meson provides a hard scale

Process sensitive to **square of gluon density**

Explored at HERA collider

$$x = (Q^2 + M_{J/\psi}^2)/(W^2 + M_{J/\psi}^2)$$

$$\bar{Q}^2 = (Q^2 + M_{J/\psi}^2)/4,$$

Lowest order perturbative formula for electroproduction

Ryskin

$$\frac{d\sigma}{dt} (\gamma^* p \rightarrow J/\psi p) \Big|_{t=0} = \frac{\Gamma_{ee} M_{J/\psi}^3 \pi^3}{48\alpha} \left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} x g(x, \bar{Q}^2) \right]^2 \left(1 + \frac{Q^2}{M_{J/\psi}^2} \right)$$

Can test dynamics at low x and different A if nuclear targets are involved

Exclusive vector meson photoproduction

Measurements in ep

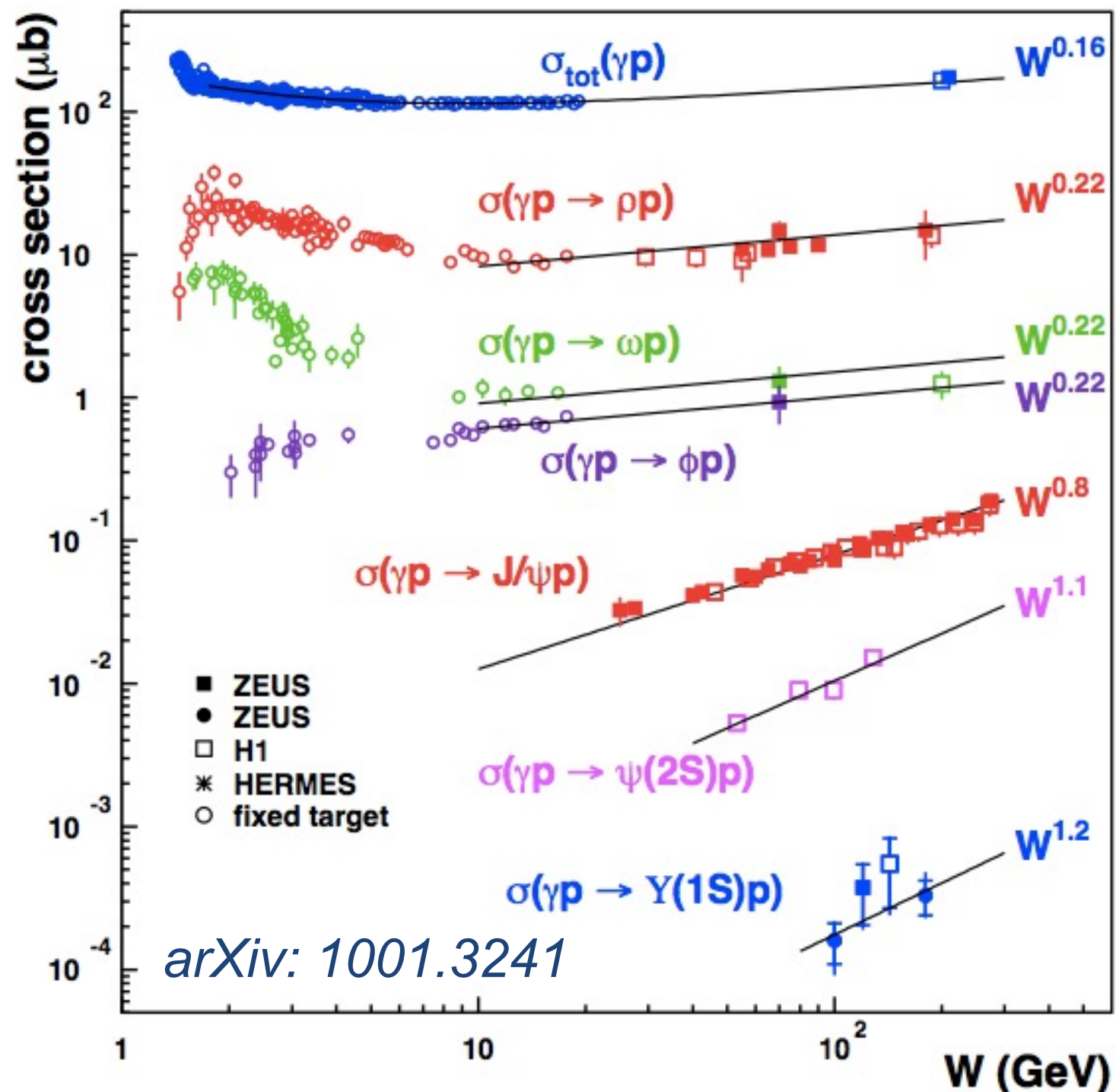
Rise in the slope of the
energy
with the scale of the process

$$\sigma \sim W^\delta$$

$$\delta \sim 4(\alpha_p(t) - 1)$$

$$\alpha_p(t) = \alpha_p(0) + \alpha' t$$

Transition from
soft to hard
phenomena



First observation of exclusive ρ^0 in AuAu UPC at STAR

First measurement of exclusive ρ^0 photoproduction in UPC AuAu

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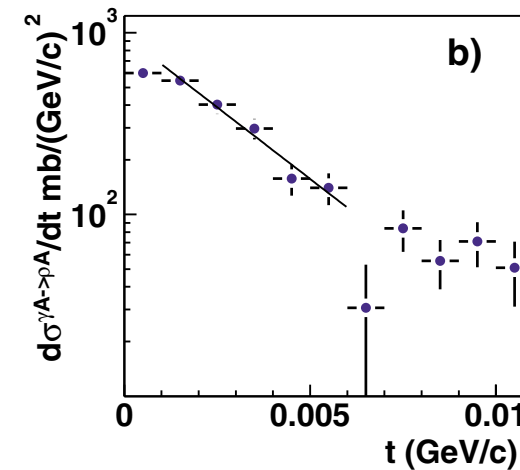
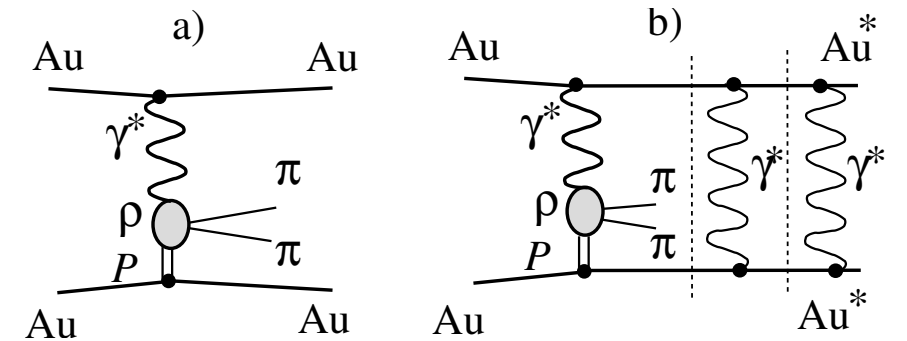
Coherent ρ^0 Production in Ultraperipheral Heavy-Ion Collisions

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(STAR Collaboration)

Abstract

The STAR Collaboration reports the first observation of exclusive ρ^0 photoproduction, $\text{AuAu} \rightarrow \text{AuAu}\rho^0$, and ρ^0 production accompanied by mutual nuclear Coulomb excitation, $\text{AuAu} \rightarrow \text{Au}^*\text{Au}^*\rho^0$, in ultraperipheral heavy-ion collisions. The ρ^0 have low transverse momenta, consistent with coherent coupling to both nuclei. The cross sections at $\sqrt{s_{NN}} = 130$ GeV agree with theoretical predictions treating ρ^0 production and Coulomb excitation as independent processes.



$$\frac{d\sigma^{\gamma A \rightarrow \rho A}}{dt} \sim \exp(bt)$$

$$R_{\text{Au}} = \sqrt{4b} = 7.5 \pm 2 \text{ fm}$$

More measurements of exclusive ρ^0 in AuAu UPC at STAR

PHYSICAL REVIEW C **77**, 034910 (2008)

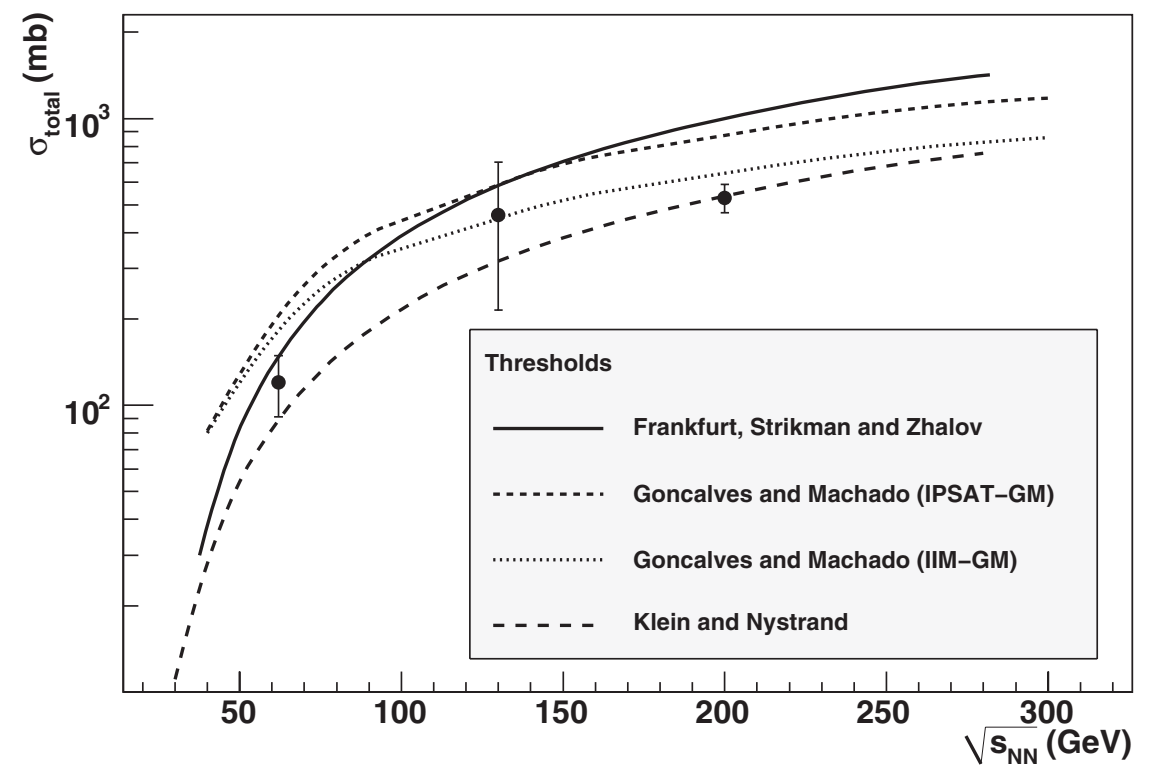
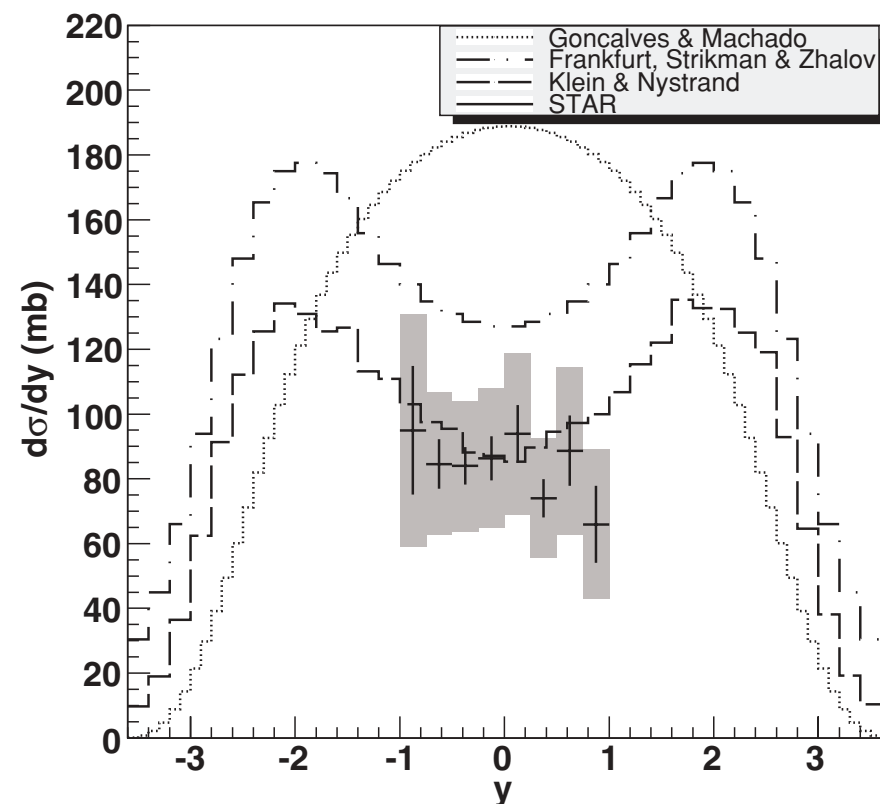
ρ^0 photoproduction in ultraperipheral relativistic heavy ion collisions at $\sqrt{s_{NN}} = 200$ GeV

PHYSICAL REVIEW C **85**, 014910 (2012)

ρ^0 photoproduction in AuAu collisions at $\sqrt{s_{NN}} = 62.4$ GeV measured with the STAR detector

(STAR Collaboration)

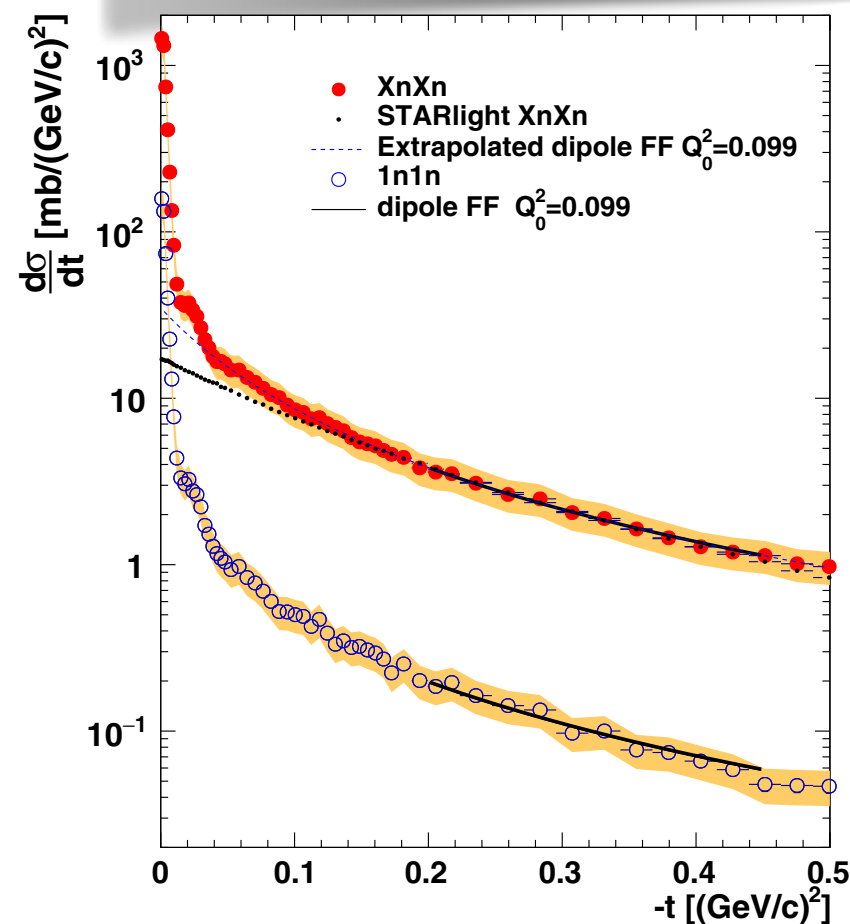
$\sqrt{s_{NN}} = 200$ GeV



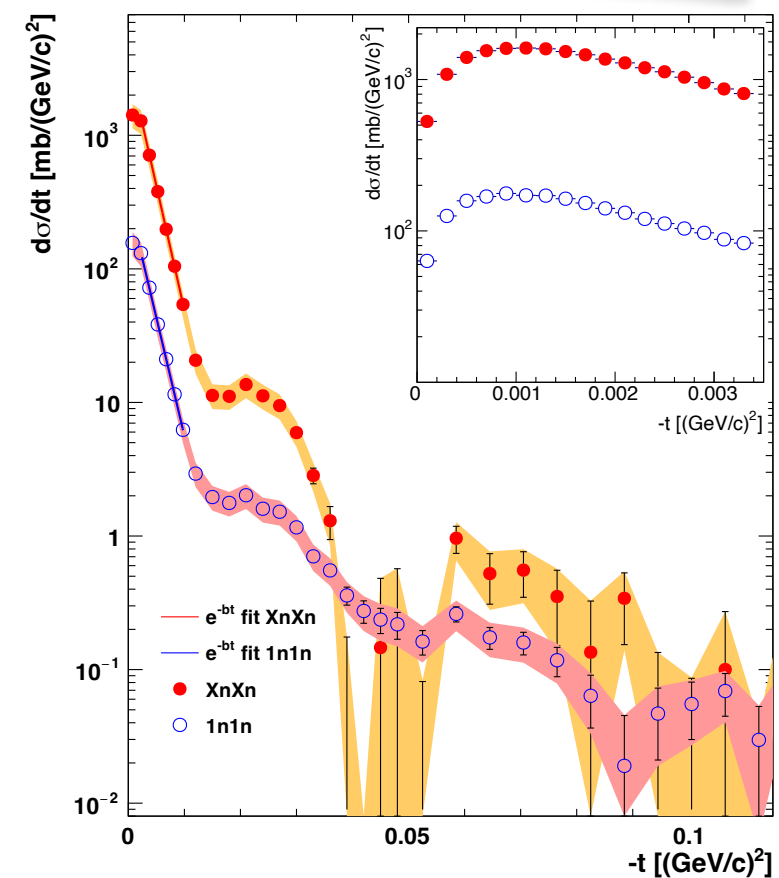
More measurements of exclusive ρ^0 in AuAu UPC at STAR

PHYSICAL REVIEW C **96**, 054904 (2017)

Coherent diffractive photoproduction of ρ^0 mesons on gold nuclei at 200 GeV/nucleon-pair at the Relativistic Heavy Ion Collider



t distribution photoproduction
with fit to incoherent tail



t distribution in coherent photoproduction
evidence for dips

We also measure the cross section $d\sigma/dt$ over a wide range and separate out coherent and incoherent components. The coherent contribution exhibits multiple diffractive minima, indicating that the nucleus is beginning to act like a black disk.

Modeling exclusive ρ^0 production

Photoproduction of ρ is difficult, due to low scale:
nonperturbative/soft physics

Calculations based on:

- vector meson dominance + Glauber *Klein, Nystrand*
- vector meson dominance + Gribov-Glauber *Frankfurt, Guzey, Strikman, Zhalov*
- dipole models *Goncalves, Machado*

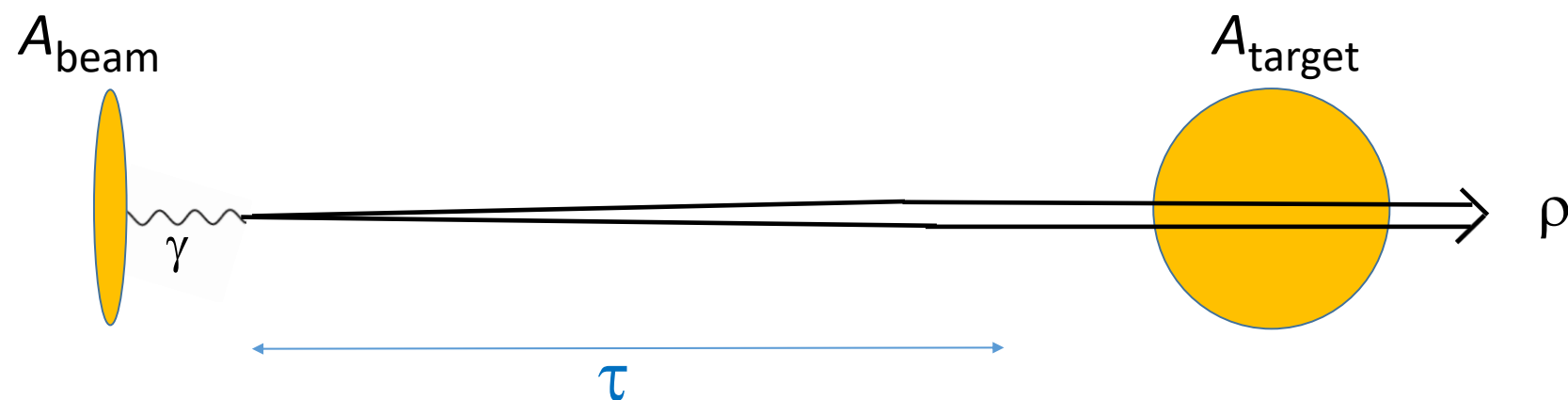


Fig. from:
Khoze, MartinRyskin

Figure 2: A sketch of the exclusive ρ production process in the rest frame of the target heavy ion. The $q\bar{q}$ pair is only able to form the ρ meson when its transverse separation becomes large enough (~ 0.5 fm). At high energies this results in a long formation time τ for the ρ meson.

Photon fluctuating into vector meson which then scatters elastically with the target

Large formation time τ for high energy

Example: VMD+Glauber model for ρ^0 production

Standard Glauber model for photoproduction on nuclei

Models by:

Klein, Nystrand

Frankfurt, Guzey, Strikman Zhalov

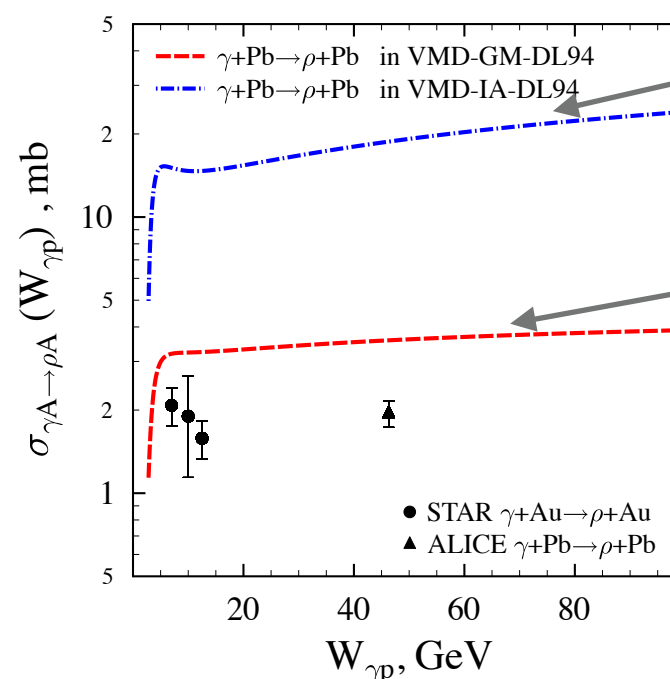
$$\sigma_{\gamma A \rightarrow \rho A} = \left(\frac{e}{f_\rho} \right)^2 \int d^2 \mathbf{b} \left(1 - e^{-\frac{1}{2} \sigma_{\rho N} T_A(b)} \right)^2$$

$\sigma_{\rho N}$ total rho-nucleon
cross section

f_ρ photon-meson
coupling

$T(b)$ nuclear
thickness

Interpretation: nuclear shadowing results from the multiple elastic scattering of vector meson along its trajectory



no-shadowing
(impulse approximation)

shadowing in VMD-GM

Shadowing by factor 4

Frankfurt, Guzey, Strikman Zhalov

Example: VMD+Gribov-Glauber model for ρ^0 production

Standard Glauber model for photoproduction on nuclei

$$\sigma_{\gamma A \rightarrow \rho A} = \left(\frac{e}{f_\rho} \right)^2 \int d^2\mathbf{b} \left(1 - e^{-\frac{1}{2}\sigma_{\rho N} T_A(b)} \right)^2$$

Modified model: Gribov-Glauber

$$\sigma_{\gamma A \rightarrow \rho A} = \left(\frac{e}{f_\rho} \right)^2 \int d^2\mathbf{b} \left| \int d\sigma P(\sigma) \left(1 - e^{-\frac{1}{2}\sigma T_A(b)} \right) \right|^2$$

Include the cross section **fluctuation** through additional function $P(\sigma)$

Interpretation: photon fluctuates into coherent superposition of eigenstates of scattering operator

Result summed over possible fluctuations with probability distribution

Model includes **inelastic diffractive intermediate states**

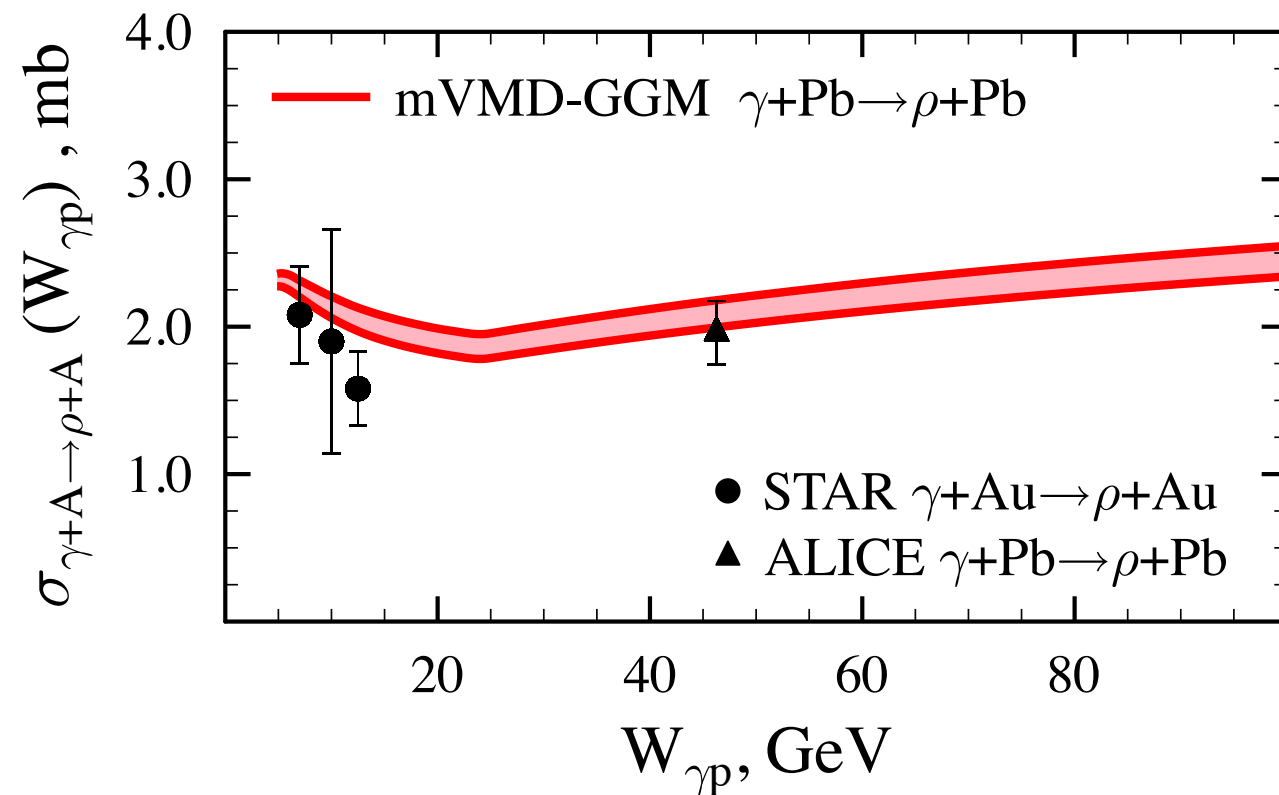
Frankfurt, Guzey, Strikman, Zhalov

$$\int d\sigma P(\sigma) = 1 \qquad \int d\sigma \sigma P(\sigma) = \langle \sigma \rangle = \sigma_{\rho N} \qquad \int d\sigma \sigma^2 P(\sigma) = \langle \sigma \rangle^2 (1 + \omega_\sigma)$$

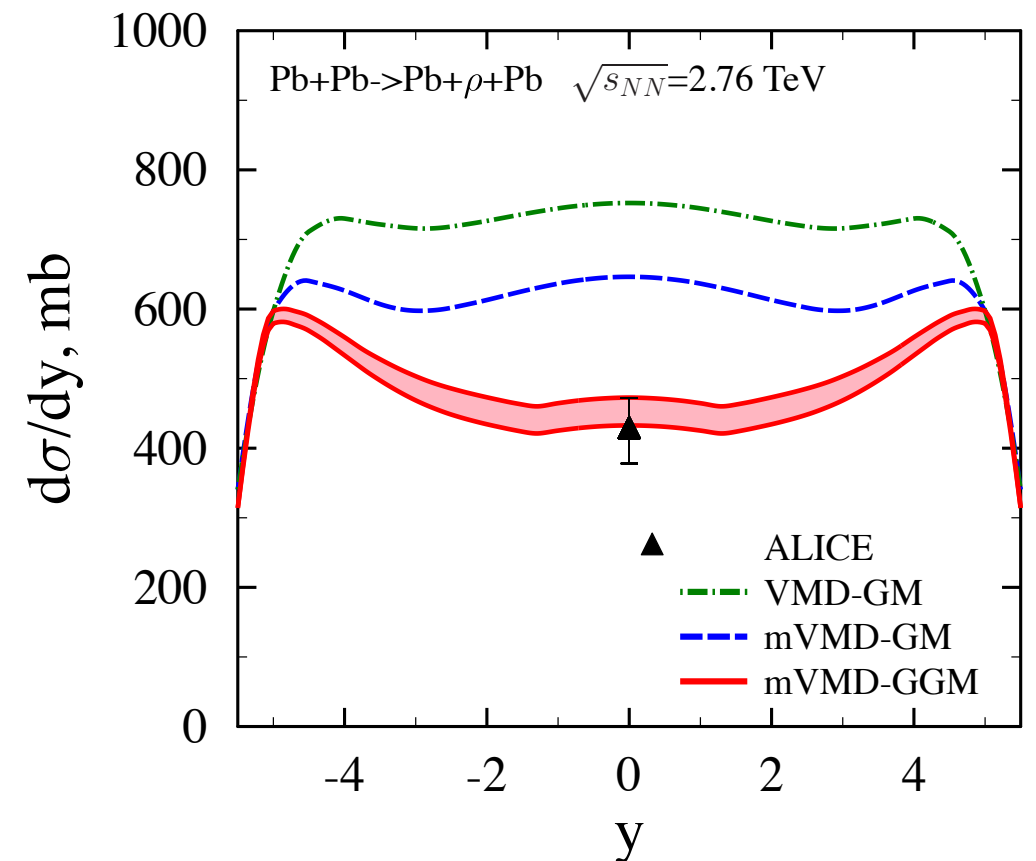
ω_σ parametrizes dispersion of distribution $P(\sigma)$

VMD+Gribov-Glauber

Energy dependence



Rapidity dependence



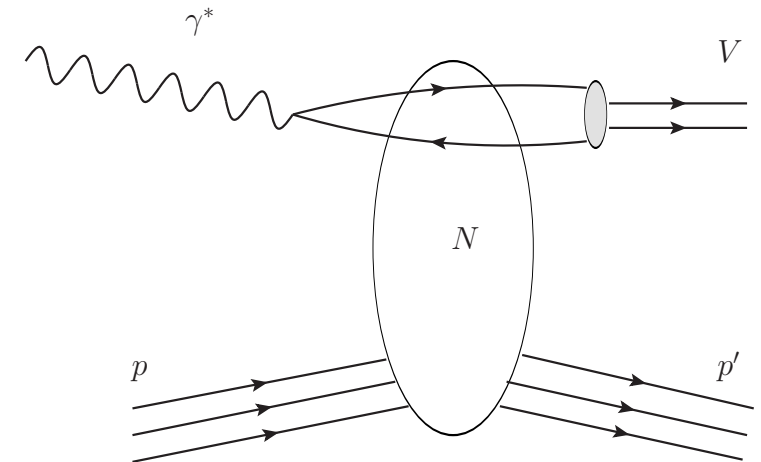
Frankfurt, Guzey, Strikman, Zhilov

VMD+GG leads to further suppression of cross section
Modification of shape in rapidity

VM production: dipole approach at high energy

Partonic interpretation : appropriate for higher scales
(**electroproduction** or **photoproduction** of heavy VM)

At high energy: **photon fluctuates** into
quark-antiquark pair and interacts with the target



Differential cross section

$$t = -\Delta^2 \quad \frac{d\sigma}{dt} = \frac{1}{16\pi} |A(x, \Delta, Q)|^2$$

Amplitude

$$A(x, \Delta, Q) = \sum_{h, \bar{h}} \int d^2\mathbf{r} \int dz \Psi_{h, h^*}(\mathbf{r}, z, Q^2) \mathcal{N}(x, \mathbf{r}, \Delta, z) \Psi_{\bar{h}, \bar{h}^*}^V(\mathbf{r}, z)$$

$$\mathcal{N}(x, \mathbf{r}, \Delta, z) = 2 \int d^2\mathbf{b} N(x, \mathbf{r}, \mathbf{b}) e^{i\Delta \cdot (\mathbf{b} - (1-z)\mathbf{r})}$$

Dipole amplitude

$$N(x, \mathbf{r}, \mathbf{b})$$

$\mathbf{r}$ dipole size
 $\mathbf{b}$ impact parameter

can be modeled/computed from QCD evolution equations (related to gluon density)

VM production in the dipole picture and nonlinear evolution

Balitsky-Kovchegov nonlinear equation for dipole amplitude at small x

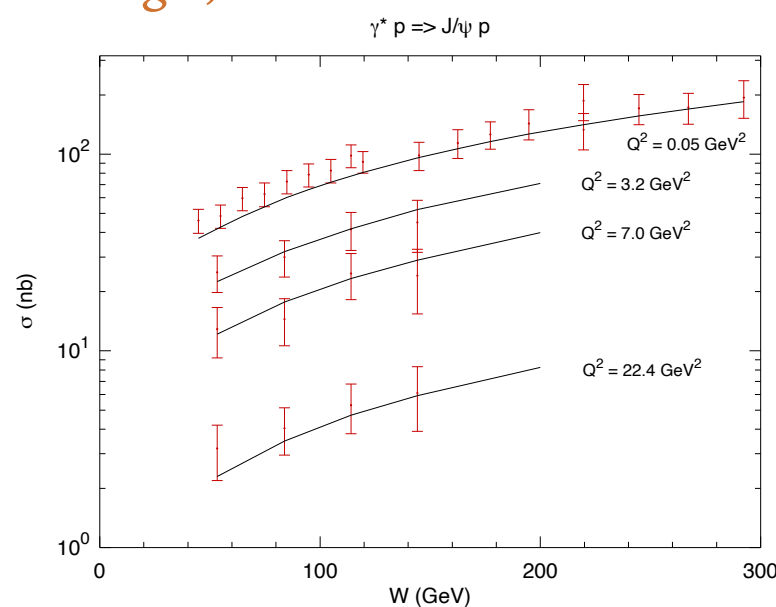
Balitsky; Kovchegov

$$\frac{\partial N_{\mathbf{x}_0\mathbf{x}_1}}{\partial Y} = \int \frac{d^2\mathbf{x}_2}{2\pi} \mathcal{K}(x_{01}, x_{12}, x_{02}; \alpha_s, m) [N_{\mathbf{x}_0\mathbf{x}_2} + N_{\mathbf{x}_2\mathbf{x}_1} - N_{\mathbf{x}_0\mathbf{x}_1} - N_{\mathbf{x}_0\mathbf{x}_2}N_{\mathbf{x}_2\mathbf{x}_1}]$$

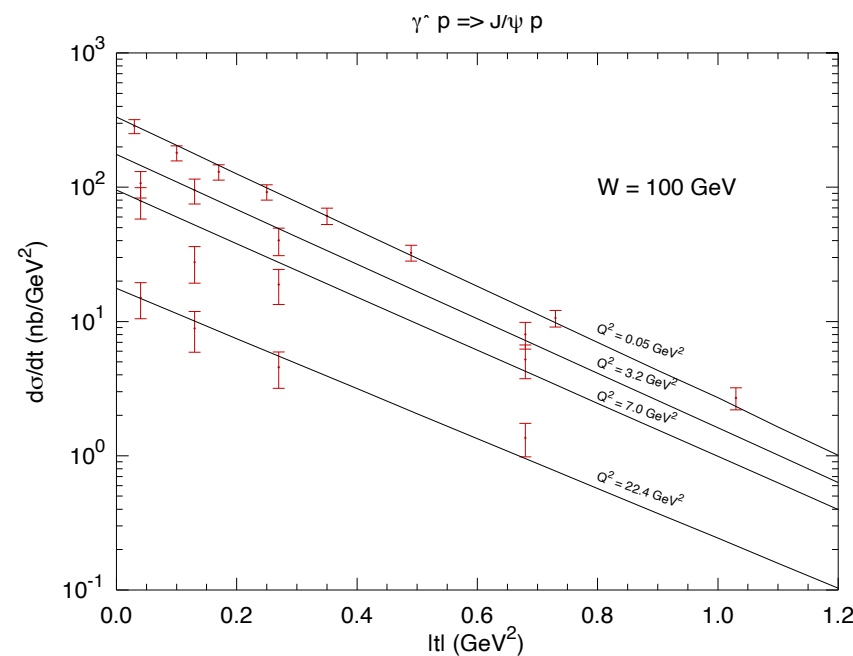
Can obtain good description of various features of the data on VM elastic photo- and electroproduction in electron - proton using impact parameter dependent BK

HERA data $\gamma^{(*)} p \rightarrow J/\psi p$

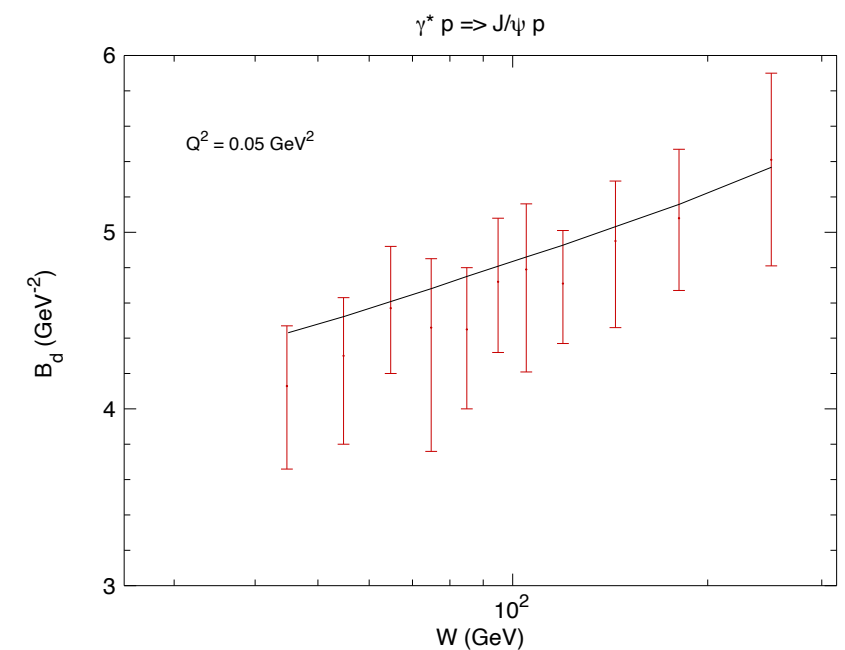
Berger, Stasto



energy dependence



t dependence



energy dependence of the slope

STAR measurement of exclusive J/ψ in UPC AA

PHYSICAL REVIEW LETTERS **133**, 052301 (2024)

Observation of Strong Nuclear Suppression in Exclusive J/ψ Photoproduction in Au + Au Ultraperipheral Collisions at RHIC

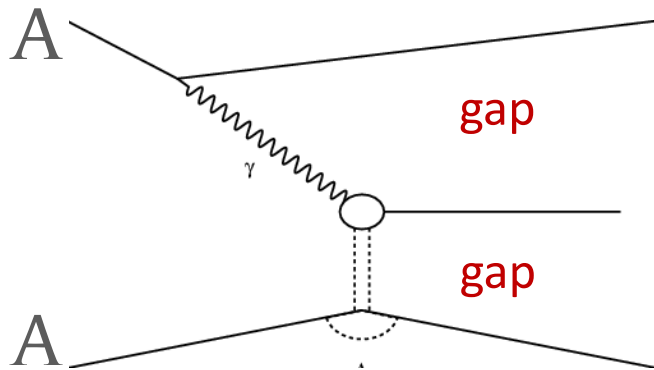
STAR Collaboration

We report a measurement of exclusive J/ψ and $\psi(2s)$ photoproduction in Au+Au ultra-peripheral collisions at $\sqrt{s_{NN}} = 200$ GeV using the STAR detector. For the first time, i) the $\psi(2s)$ photoproduction in midrapidity at the Relativistic Heavy-Ion Collider has been experimentally measured; ii) nuclear suppression factors are measured for both the coherent and incoherent J/ψ production. At average photon-nucleon center-of-mass energy of 25.0 GeV, the coherent and incoherent J/ψ cross sections of Au nuclei are found to be $71 \pm 10\%$ and $36 \pm 7\%$, respectively, of that of free protons. The stronger suppression observed in the incoherent production provides a new experimental handle to study the initial-state parton density in heavy nuclei. Data are compared with theoretical models quantitatively.

PHYSICAL REVIEW C **110**, 014911 (2024)

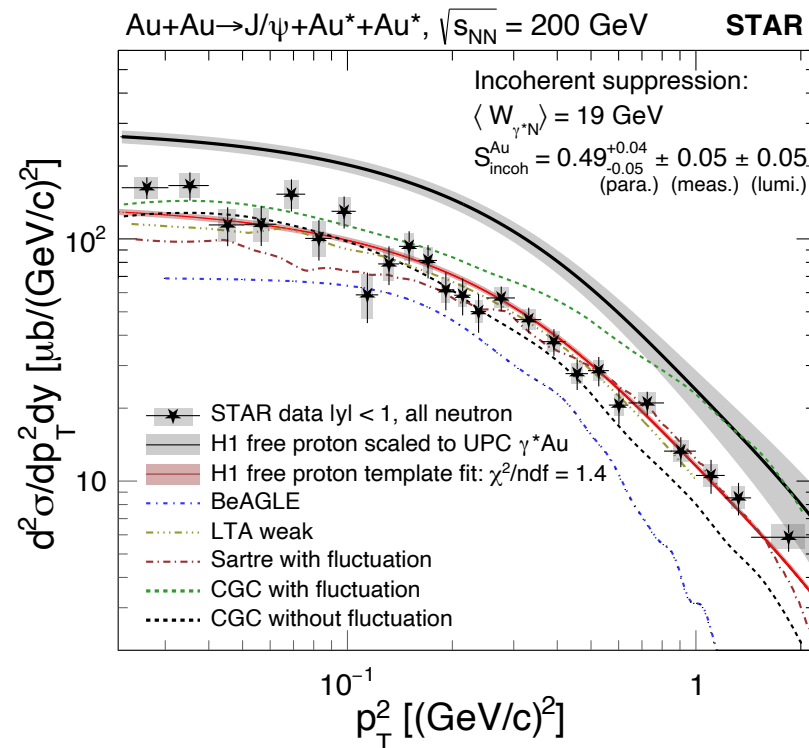
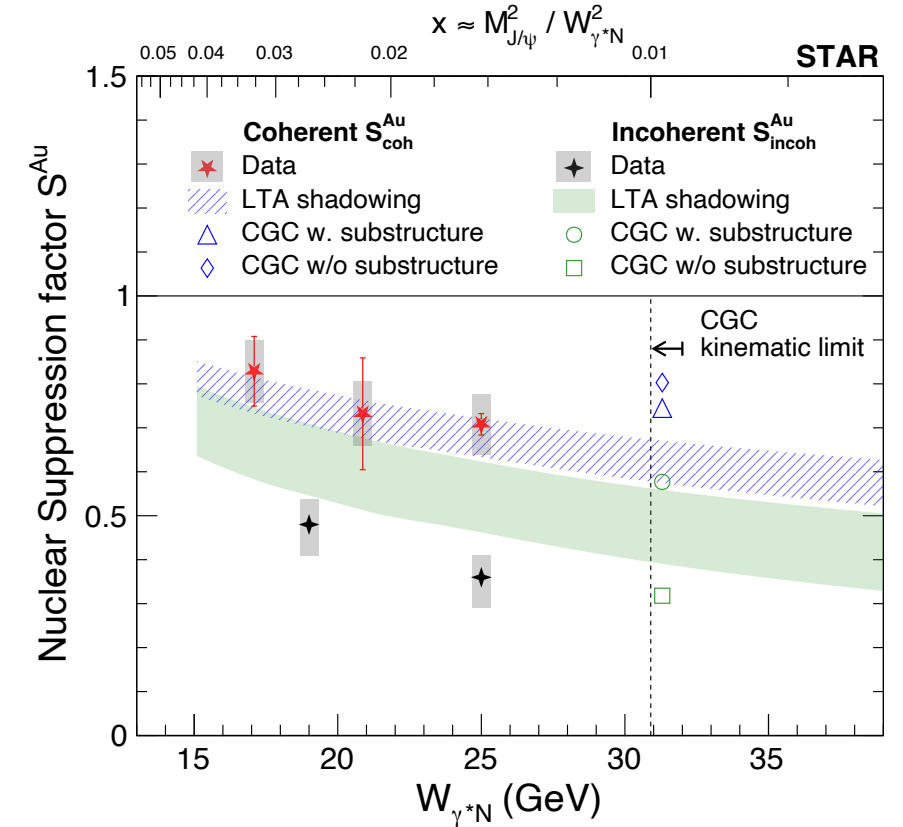
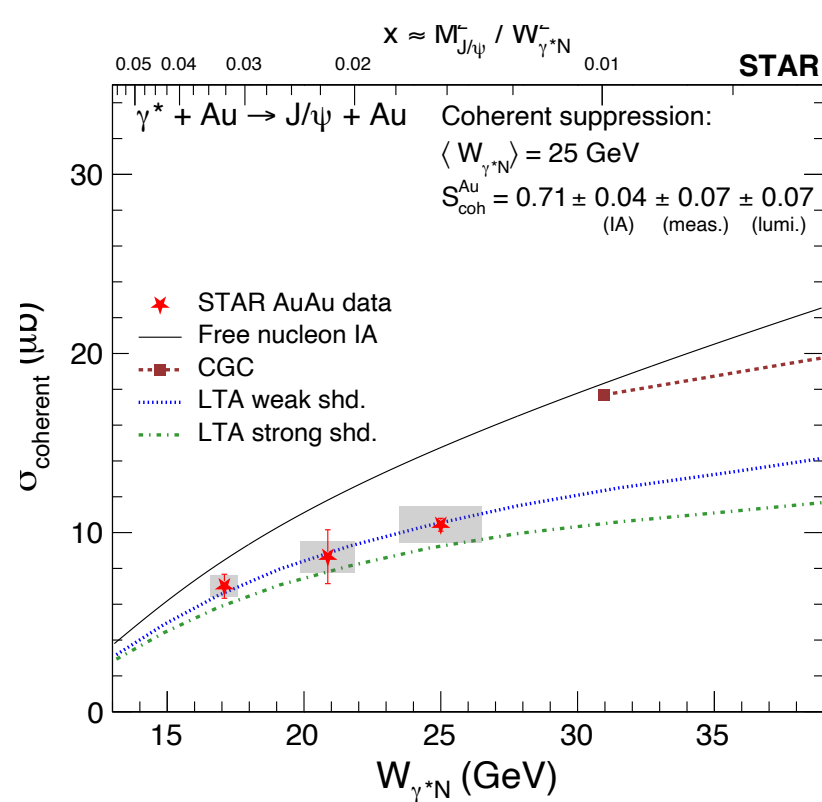
Exclusive J/ψ , $\psi(2s)$, and e^+e^- pair production in Au + Au ultraperipheral collisions at the BNL Relativistic Heavy Ion Collider

STAR Collaboration



Measurements of exclusive J/ψ , $\psi(2s)$, and electron-positron (e^+e^-) pair photoproduction in Au+Au ultra-peripheral collisions are reported by the STAR experiment at $\sqrt{s_{NN}} = 200$ GeV. We report several first measurements at the Relativistic Heavy-Ion Collider, which are i) J/ψ photoproduction with large momentum transfer up to 2.2 $[(\text{GeV}/c)^2]$, ii) coherent J/ψ photoproduction associated with neutron emissions from nuclear breakup, iii) the rapidity dependence of incoherent J/ψ photoproduction, iv) the $\psi(2s)$ photoproduction cross section at mid-rapidity, and v) e^+e^- pair photoproduction up to high invariant mass of $6 \text{ GeV}/c^2$. For measurement ii), the coherent J/ψ total cross section of $\gamma + \text{Au} \rightarrow J/\psi + \text{Au}$ as a function of the center-of-mass energy $W_{\gamma N}$ has been obtained without photon energy ambiguities. The data are quantitatively compared with the Monte Carlo models STARlight, Sartre, BeAGLE, and theoretical calculations of gluon saturation with color glass condensate, nuclear shadowing with leading twist approximation, Quantum Electrodynamics, and the Next-to-Leading Order perturbative QCD. At the photon-nucleon center-of-mass energy of 25.0 GeV, the coherent and incoherent J/ψ cross sections of Au nuclei are found to be $71 \pm 10\%$ and $36 \pm 7\%$, respectively, of that of free protons. These data provide an important experimental constraint for nuclear parton distribution functions and a unique opportunity to advance the understanding of the nuclear modification effect at the top RHIC energy.

STAR measurement of exclusive J/ψ in UPC AA



Strong suppression (!):
 0.71 (coh), 0.36 (incoh)
 for moderate $0.01 < x < 0.1$

nuclear shadowing
 vs
 saturation model

Exclusive J/ψ in UPC AA from dipole model

Model for coherent and incoherent

Lappi, Mantysaari
Mantysaari, Schenke

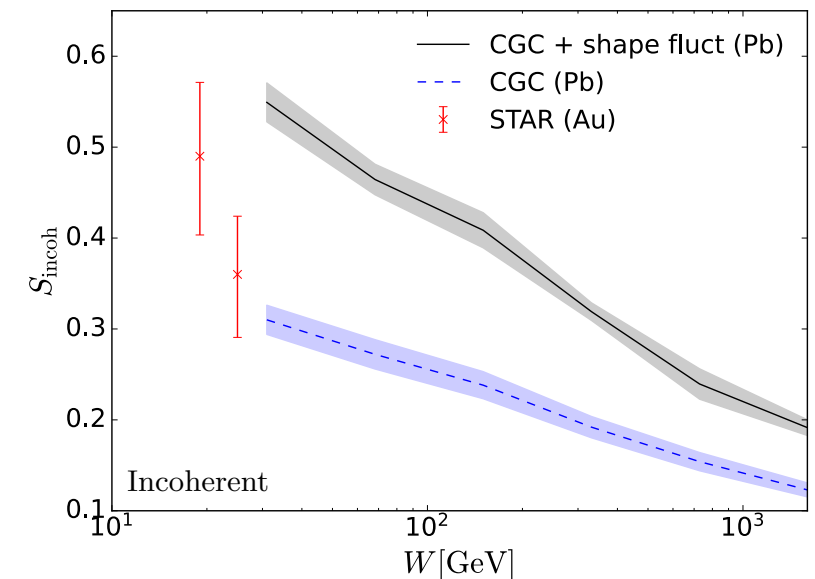
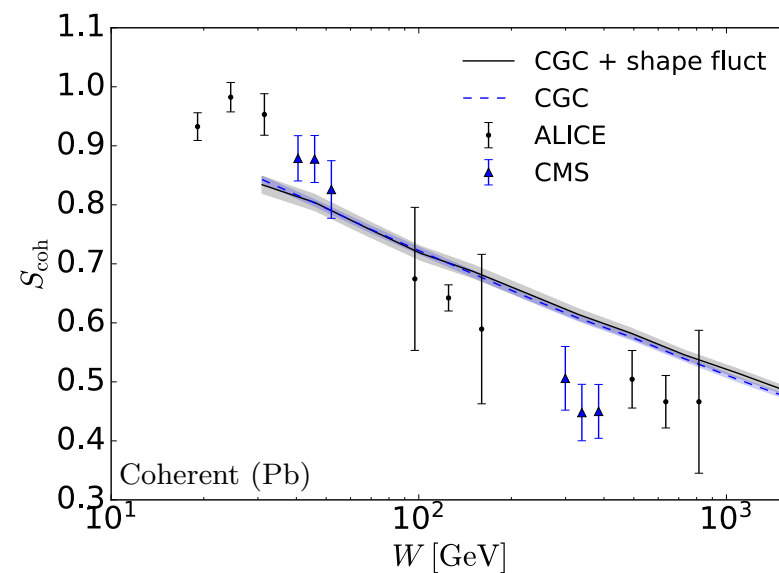
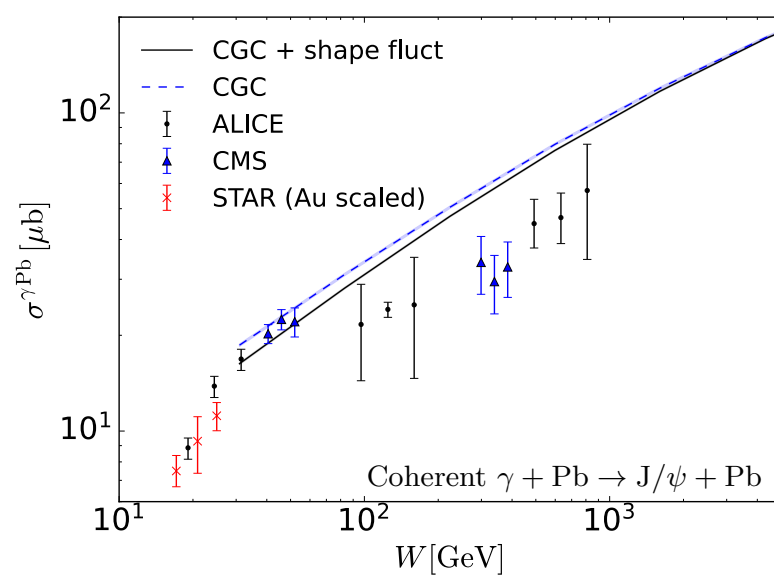
$$\frac{d\sigma}{dt} = \frac{1}{16\pi} |\langle A \rangle|^2$$

$$\frac{d\sigma}{dt} = \frac{1}{16\pi} [\langle |A|^2 \rangle - |\langle A \rangle|^2]$$

where

$$A(x, \Delta, Q) = \sum_{h, \bar{h}} \int d^2\mathbf{r} \int dz \Psi_{h, h^*}(\mathbf{r}, z, Q^2) \mathcal{N}(x, \mathbf{r}, \Delta, z) \Psi_{\bar{h}, \bar{h}^*}^V(\mathbf{r}, z)$$

$$\mathcal{N}(x, \mathbf{r}, \Delta, z) = 2 \int d^2\mathbf{b} N(x, \mathbf{r}, \mathbf{b}) e^{i\Delta \cdot (\mathbf{b} - (1-z)\mathbf{r})}$$



Mantysaari, Salazar, Schenke

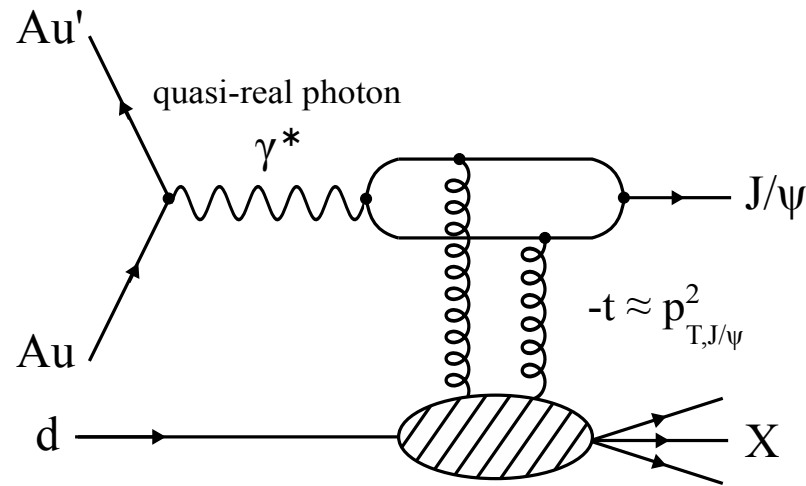
Strong suppression, also at low energies
dipole model: catches general trends
NLO corrections, wave function uncertainty...

Exclusive J/ψ in UPC dAu

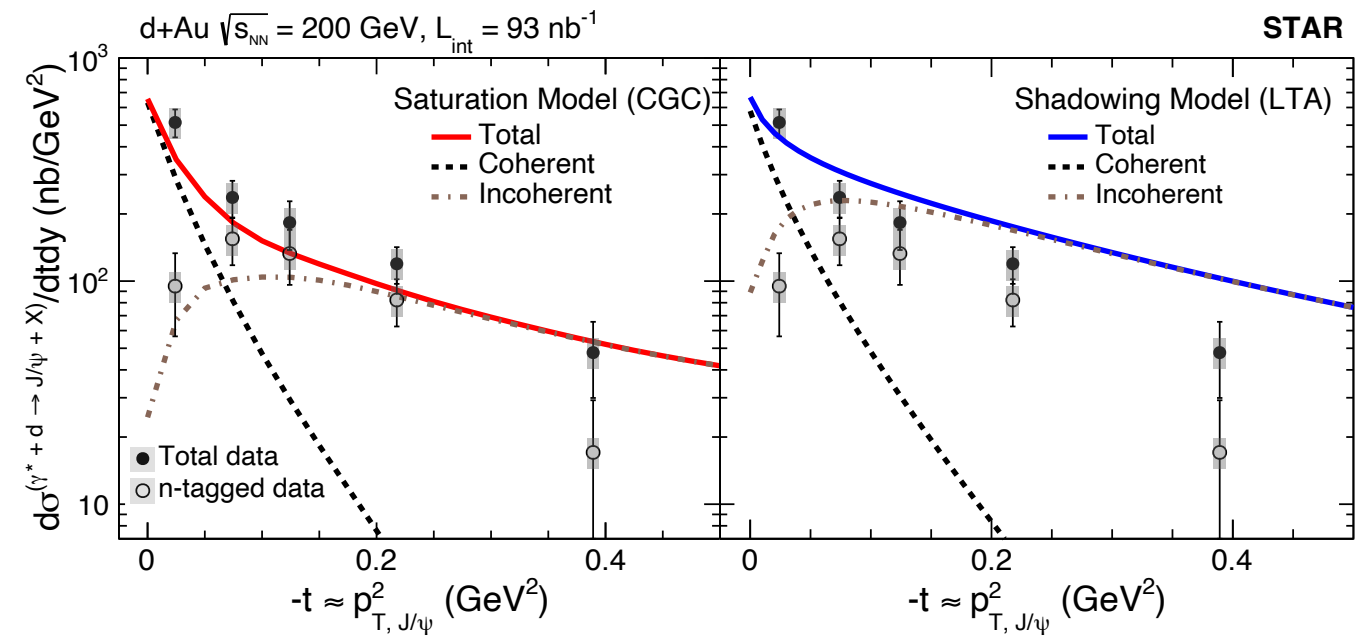
PHYSICAL REVIEW LETTERS 128, 122303 (2022)

Probing the Gluonic Structure of the Deuteron with J/ψ Photoproduction in $d + \text{Au}$ Ultraperipheral Collisions

(STAR Collaboration)



Understanding gluon density distributions and how they are modified in nuclei are among the most important goals in nuclear physics. In recent years, diffractive vector meson production measured in ultraperipheral collisions (UPCs) at heavy-ion colliders has provided a new tool for probing the gluon density. In this Letter, we report the first measurement of J/ψ photoproduction off the deuteron in UPCs at the center-of-mass energy $\sqrt{s_{NN}} = 200$ GeV in $d + \text{Au}$ collisions. The differential cross section as a function of momentum transfer $-t$ is measured. In addition, data with a neutron tagged in the deuteron-going zero-degree calorimeter is investigated for the first time, which is found to be consistent with the expectation of incoherent diffractive scattering at low momentum transfer. Theoretical predictions based on the color glass condensate saturation model and the leading twist approximation nuclear shadowing model are compared with the data quantitatively. A better agreement with the saturation model has been observed. With the current measurement, the results are found to be directly sensitive to the gluon density distribution of the deuteron and the deuteron breakup process, which provides insights into the nuclear gluonic structure.



- Coherent and incoherent production was measured
- Comparison with dipole saturation and shadowing model
- Moderate values of x explored

$$W_{\gamma N} \sim 25 \text{ GeV}$$

$$M_{J/\psi}^2 / W_{\gamma N}^2 \sim 0.015$$

VM photoproduction over range of energies

Exclusive measurements of VM
Explosion in popularity at the LHC: pp, pA and AA

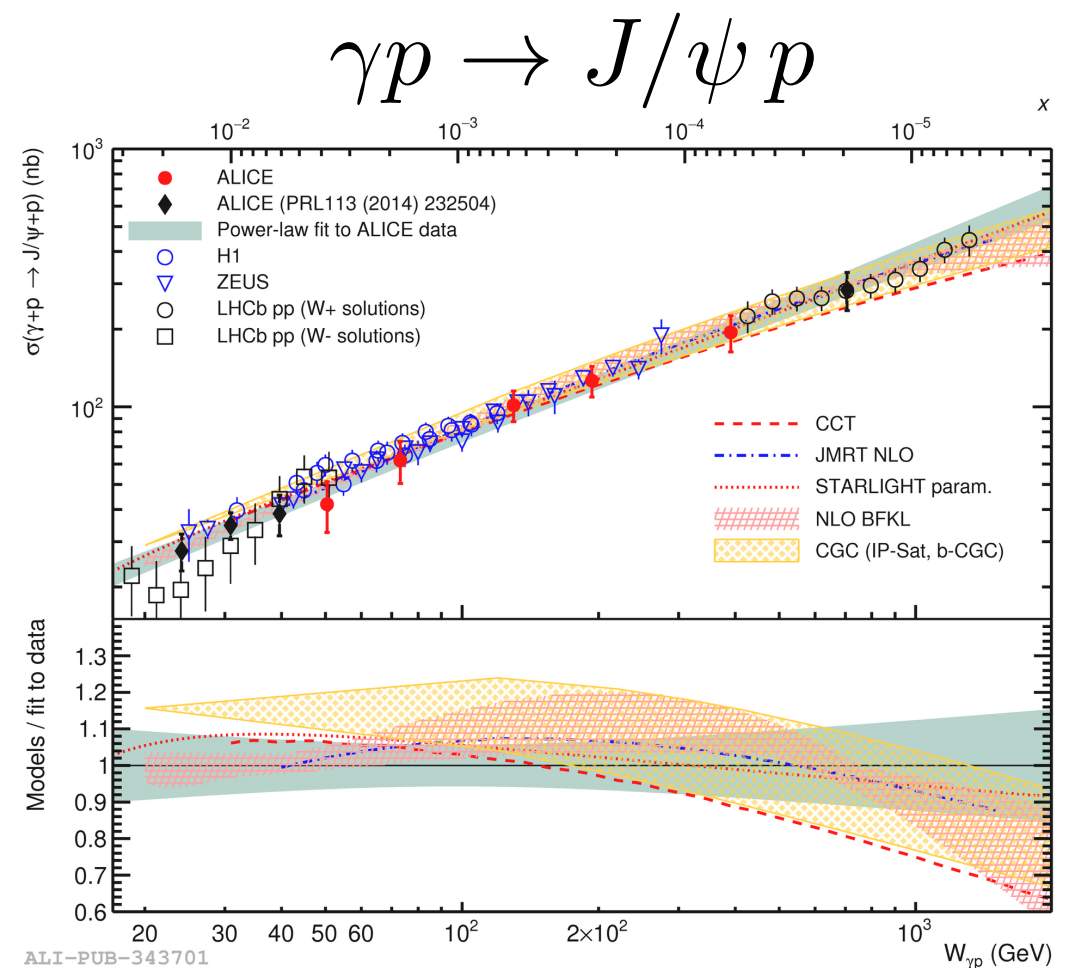
Large energy range together with
HERA measurements

Can test **evolution** and **gluon
density** at moderate scales

NLO collinear

NLO BFKL (small x evolution)

Nonlinear BK evolution



LHC continues exploration of UPC physics.

STAR has been at the forefront of the exclusive VM measurements in UPC

Identified hadron spectra in pp and dAu



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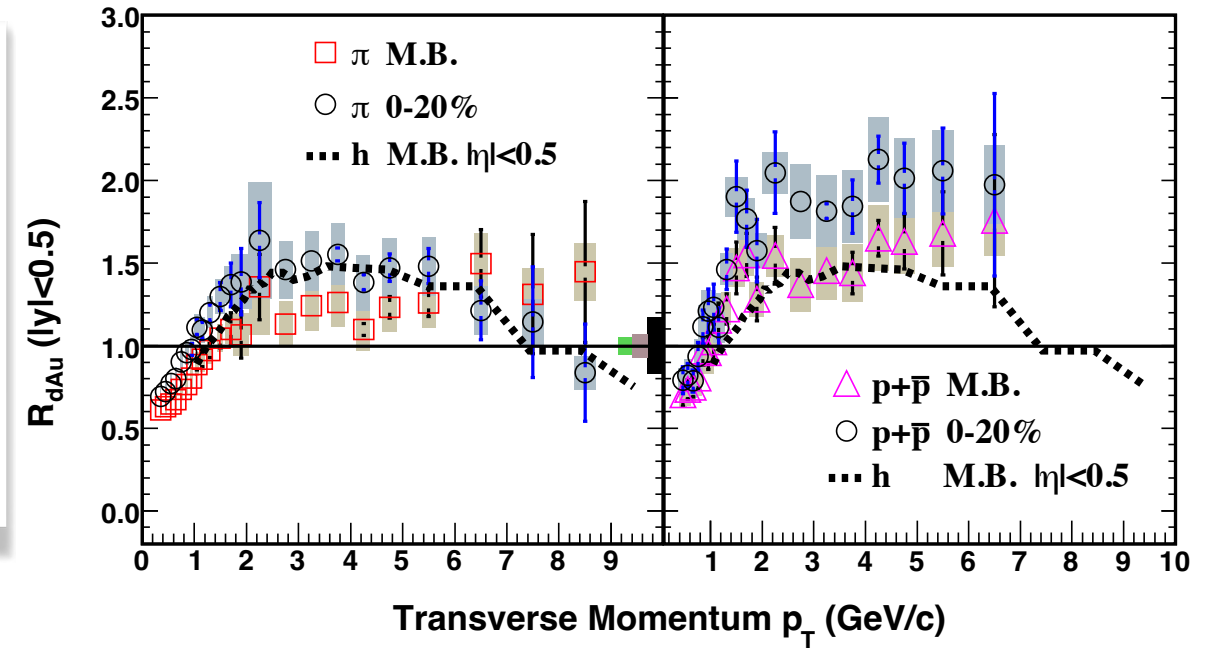
PHYSICS LETTERS B

Physics Letters B 637 (2006) 161–169

www.elsevier.com/locate/physletb

Identified hadron spectra at large transverse momentum in $p + p$ and $d + \text{Au}$ collisions at $\sqrt{s_{\text{NN}}} = 200 \text{ GeV}$

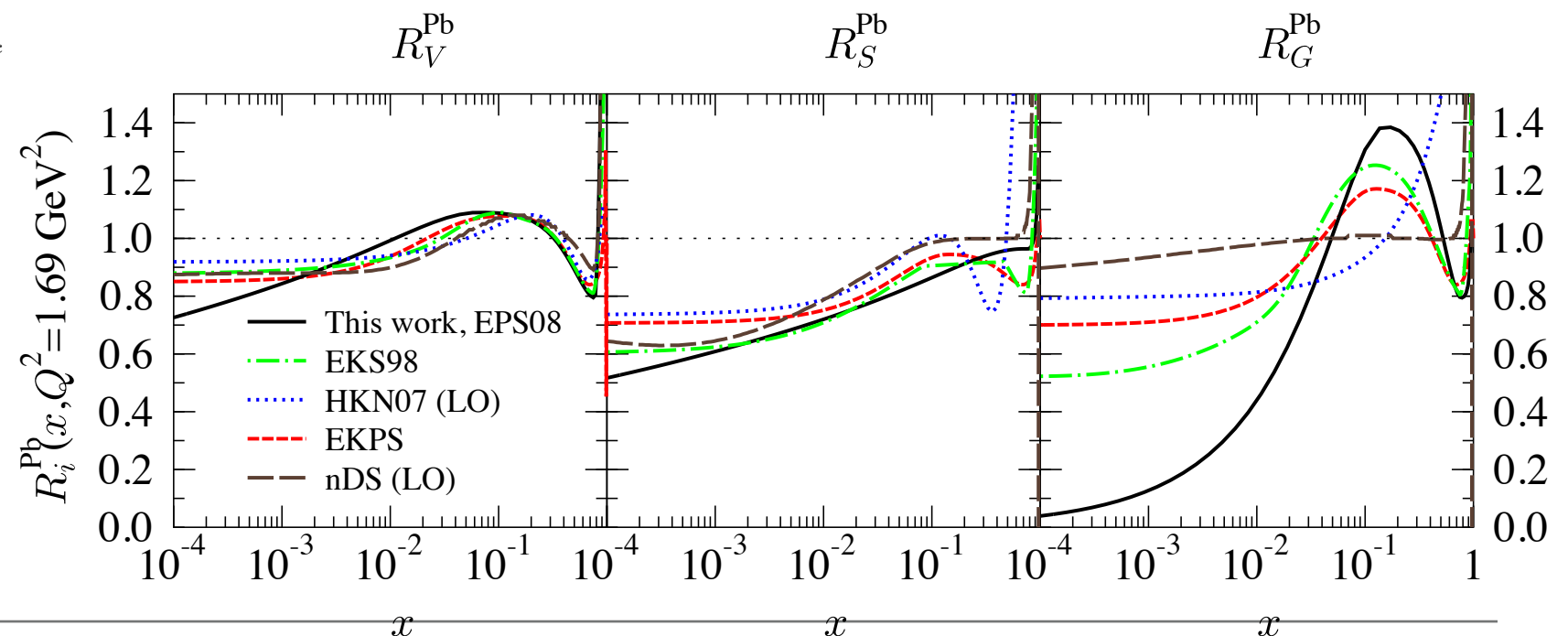
STAR Collaboration



An improved global analysis of nuclear parton distribution functions including RHIC data

Kari J. Eskola,^{ab} Hannu Paukkunen^{ab} and Carlos A. Salgado^c

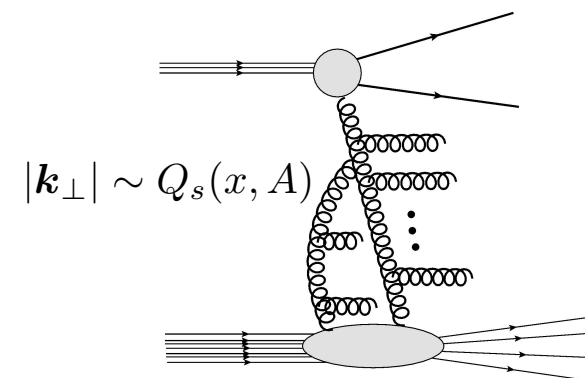
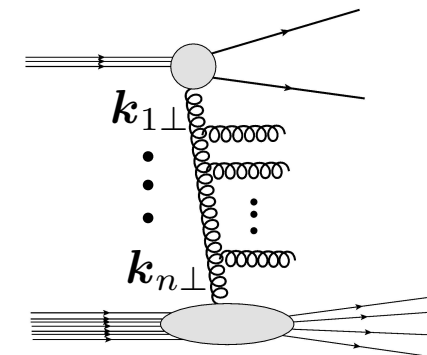
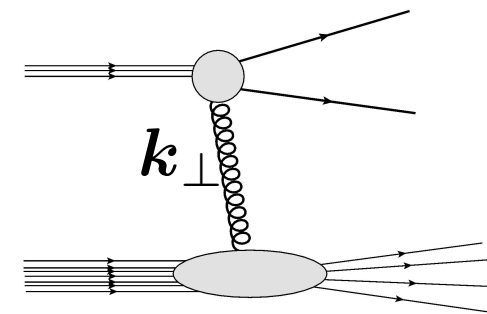
Inclusive hadron production from pp and dAu included in the global nPDF analysis



Angular correlations in small x/CGC physics

- **Transverse momentum** from the target can lead to the modification of **angular correlation** between the two produced hadrons/jets (at forward rapidities)
- **Broadening** of angular correlation should be present even in linear BFKL due to the **diffusion** of the transverse momenta at low x
- In the dense regime **decorrelation** due to multiple scatterings and the **saturation scale** being dependent on x and A

Marquet; Albacete, Marquet



Angular (de)correlations in forward production

single inclusive cross section (at LO) for forward production

$$\frac{d\sigma^{pA \rightarrow hX}}{d^2b d^2p_\perp dy_h} = \int_{z_h}^1 \frac{dz_1}{z_1^2} \left[D_{h/q}(z_1) x_p q_f(x_p) F_{x_g}(k_\perp) \right. \\ \left. + x_p g_f(x_p) \tilde{F}_{x_g}(k_\perp) D_{h/g}(z_1) \right] ,$$

differential cross section for two-particle production

$$\frac{d\sigma_{\text{corr.}}^{(pA \rightarrow h_1 h_2)}}{dy_{h_1} dy_{h_2} d^2p_{1\perp} d^2p_{2\perp}} = \int \frac{dz_1}{z_1^2} \frac{dz_2}{z_2^2} \frac{\alpha_s^2}{\hat{s}^2} \left[x_p q(x_p) \mathcal{F}_{qg}^{(i)} \right. \\ \times H_{qg}^{(i)} (D_{h_1/q}(z_1) D_{h_2/g}(z_2) + D_{h_2/q}(z_1) D_{h_1/g}(z_2)) \\ \left. + x_p g(x_p) \mathcal{F}_{gg}^{(i)} H_{gg}^{(i)} D_{h_1/g}(z_1) D_{h_2/g}(z_2) \right] ,$$

$g(x), q(x)$ collinear PDFs in the projectile

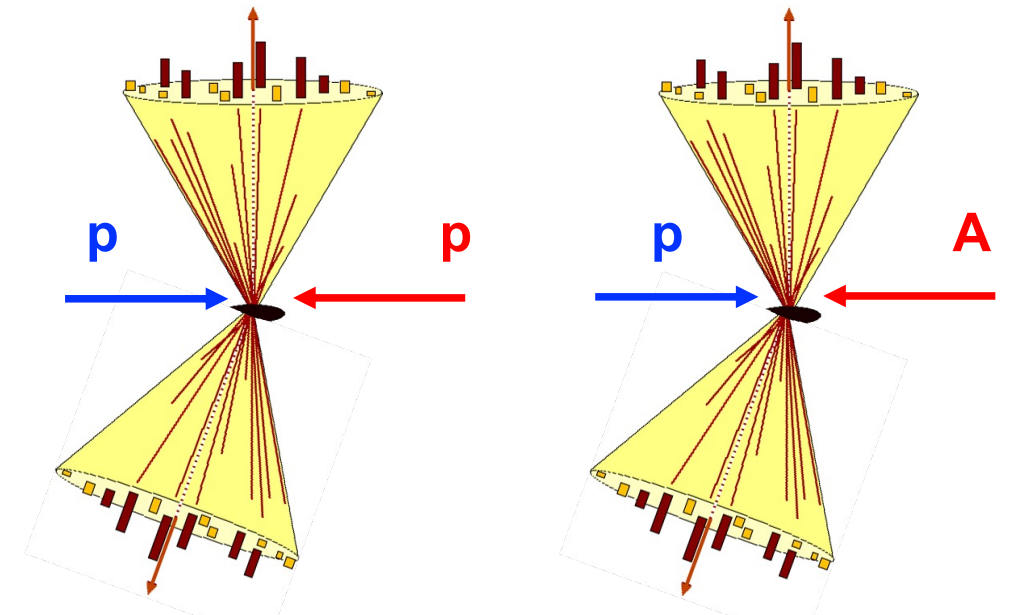
$F_{x_g}(k_T), \tilde{F}_{x_g}(k_T)$ gluon distributions in the target

$D_{h/q}(z), D_{h/g}(z)$ fragmentation functions

di-hadron correlation

$$C(\Delta\phi) = \frac{\int_{|p_{1\perp}|, |p_{2\perp}|} \frac{d\sigma^{pA \rightarrow h_1 h_2}}{dy_1 dy_2 d^2p_{1\perp} d^2p_{2\perp}}}{\int_{|p_{1\perp}|} \frac{d\sigma^{pA \rightarrow h_1}}{dy_1 d^2p_{1\perp}}}$$

Test in dA or pA collisions



picture from STAR collaboration

Suppression and correlations in pp and dA

PRL **97**, 152302 (2006)

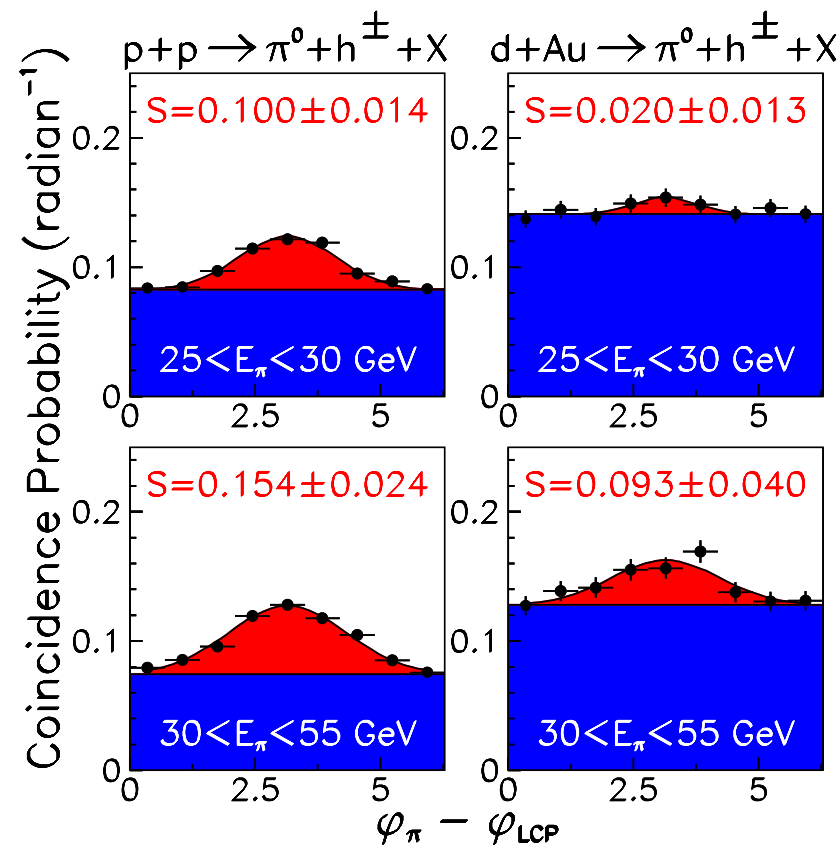
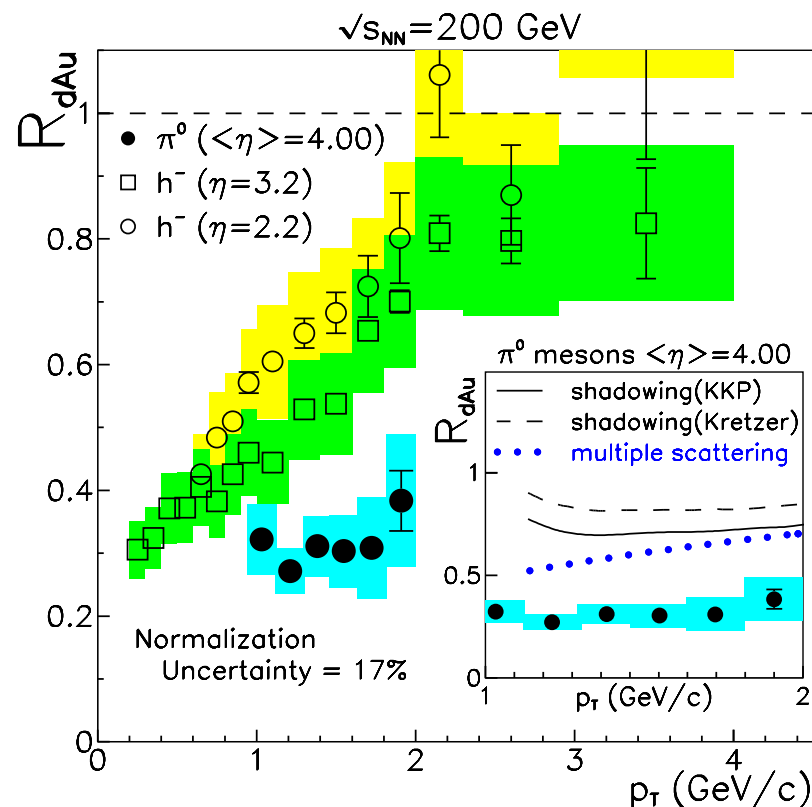
PHYSICAL REVIEW LETTERS

week ending
13 OCTOBER 2006

Forward Neutral Pion Production in $p + p$ and $d + \text{Au}$ Collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$

Measurements of the production of forward π^0 mesons from $p+p$ and $d+\text{Au}$ collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$ are reported. The $p+p$ yield generally agrees with next-to-leading order perturbative QCD calculations. The $d+\text{Au}$ yield per binary collision is suppressed as η increases, decreasing to $\sim 30\%$ of the $p+p$ yield at $\langle\eta\rangle = 4.00$, well below shadowing expectations. Exploratory measurements of azimuthal correlations of the forward π^0 with charged hadrons at $\eta \approx 0$ show a recoil peak in $p+p$ that is suppressed in $d+\text{Au}$ at low pion energy. These observations are qualitatively consistent with a saturation picture of the low- x gluon structure of heavy nuclei.

STAR Collaboration



azimuthal correlations
show suppression of
peak in dA compared
with pp

Angular (de)correlations in dA

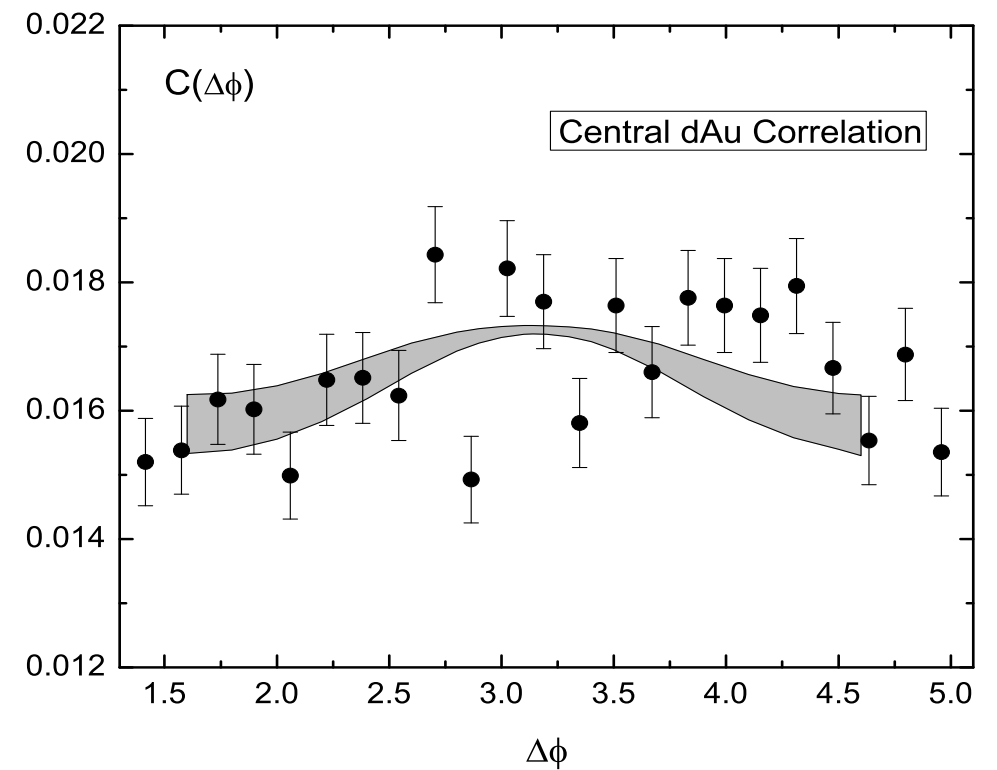
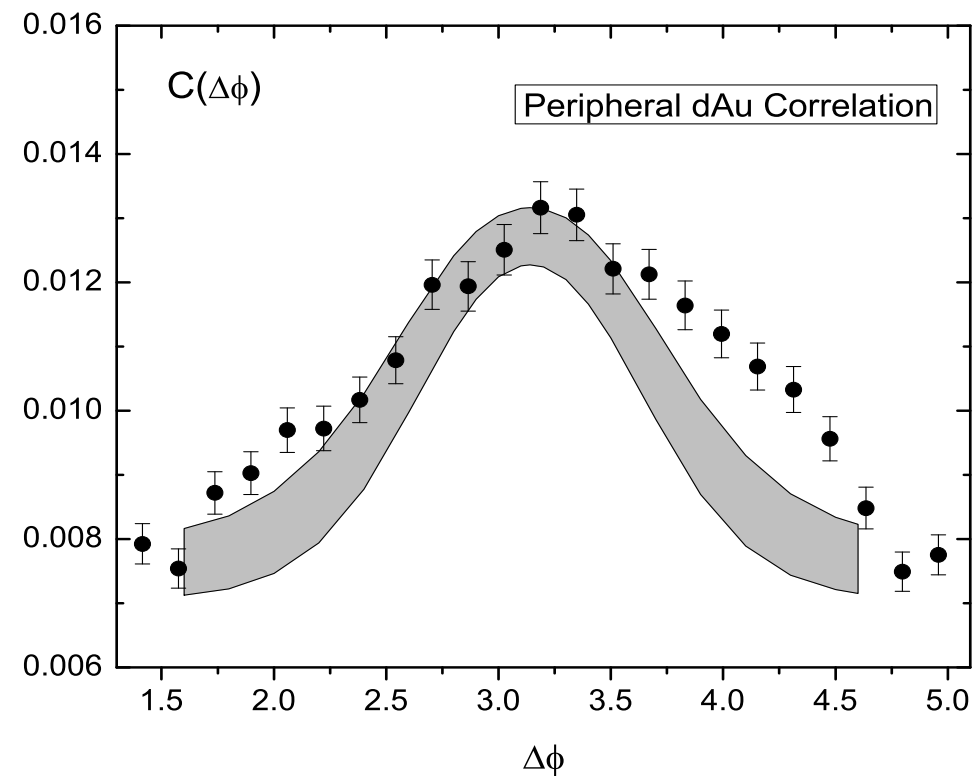
Used GBW model for the target gluon density

$$Q_{sA}^2 = c(b) A^{1/3} Q_s^2(x)$$

c(b) fit parameter for central and peripheral

Width and magnitude depends on Q_s

STAR



AS, Xiao, Yuan

Overall great description of the data.

But, is this the whole story ?

Impact of the nonlinear evolution

Albacete, Giacalone, Marquet, Matas

Used running coupling Balitsky-Kovchegov nonlinear equation for the target gluon density

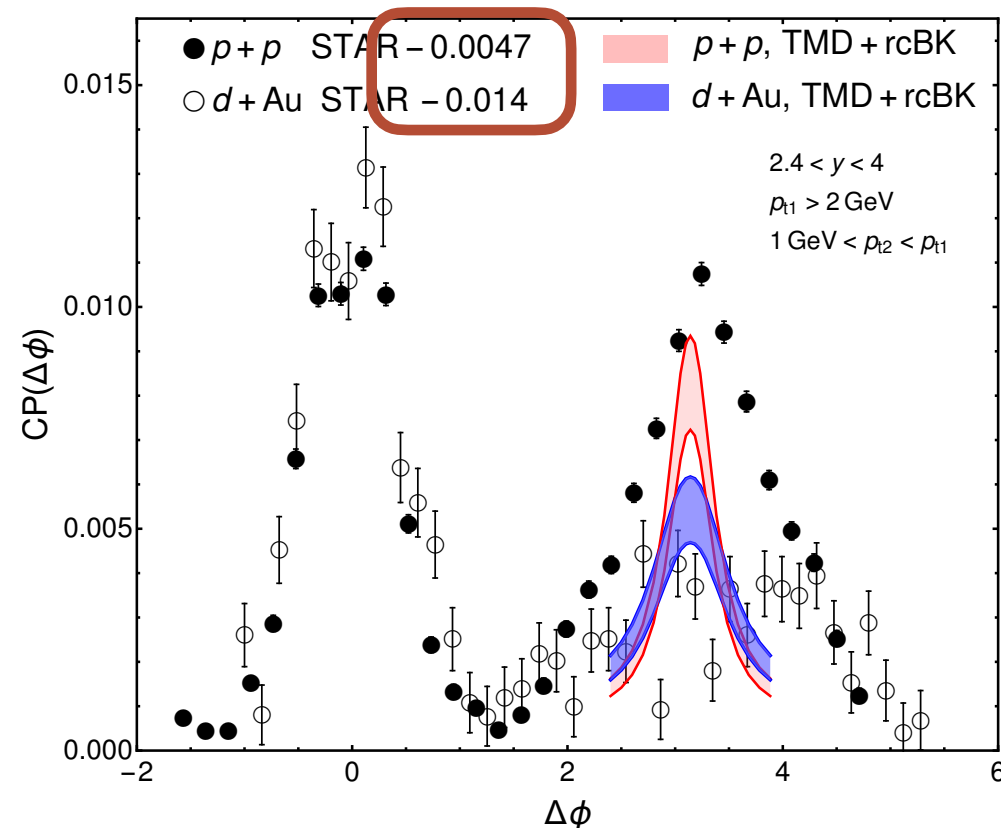
$$\frac{d\sigma_{\text{corr.}}^{(pA \rightarrow h_1 h_2)}}{dy_{h_1} dy_{h_2} d^2 p_{1\perp} d^2 p_{2\perp}} = \int \frac{dz_1}{z_1^2} \frac{dz_2}{z_2^2} \frac{\alpha_s^2}{\hat{s}^2} \left[x_p q(x_p) \mathcal{F}_{qg}^{(i)} \right. \\ \times H_{qg}^{(i)} (D_{h_1/q}(z_1) D_{h_2/g}(z_2) + D_{h_2/q}(z_1) D_{h_1/g}(z_2)) \\ \left. + x_p g(x_p) \mathcal{F}_{gg}^{(i)} H_{gg}^{(i)} D_{h_1/g}(z_1) D_{h_2/g}(z_2) \right] ,$$

$$\mathcal{F}_{\alpha\beta}^{(i)} \quad \text{related to} \quad N_{\mathbf{x}_0 \mathbf{x}_1} = N(Y; \mathbf{x}_0, \mathbf{x}_1)$$

Obtained from BK equation

$$\frac{\partial N_{\mathbf{x}_0 \mathbf{x}_1}}{\partial Y} = \int \frac{d^2 \mathbf{x}_2}{2\pi} K(\mathbf{x}_0, \mathbf{x}_1, \mathbf{x}_2; \alpha_s) [N_{\mathbf{x}_0 \mathbf{x}_2} + N_{\mathbf{x}_1 \mathbf{x}_2} - N_{\mathbf{x}_0 \mathbf{x}_1} - N_{\mathbf{x}_0 \mathbf{x}_2} N_{\mathbf{x}_1 \mathbf{x}_2}]$$

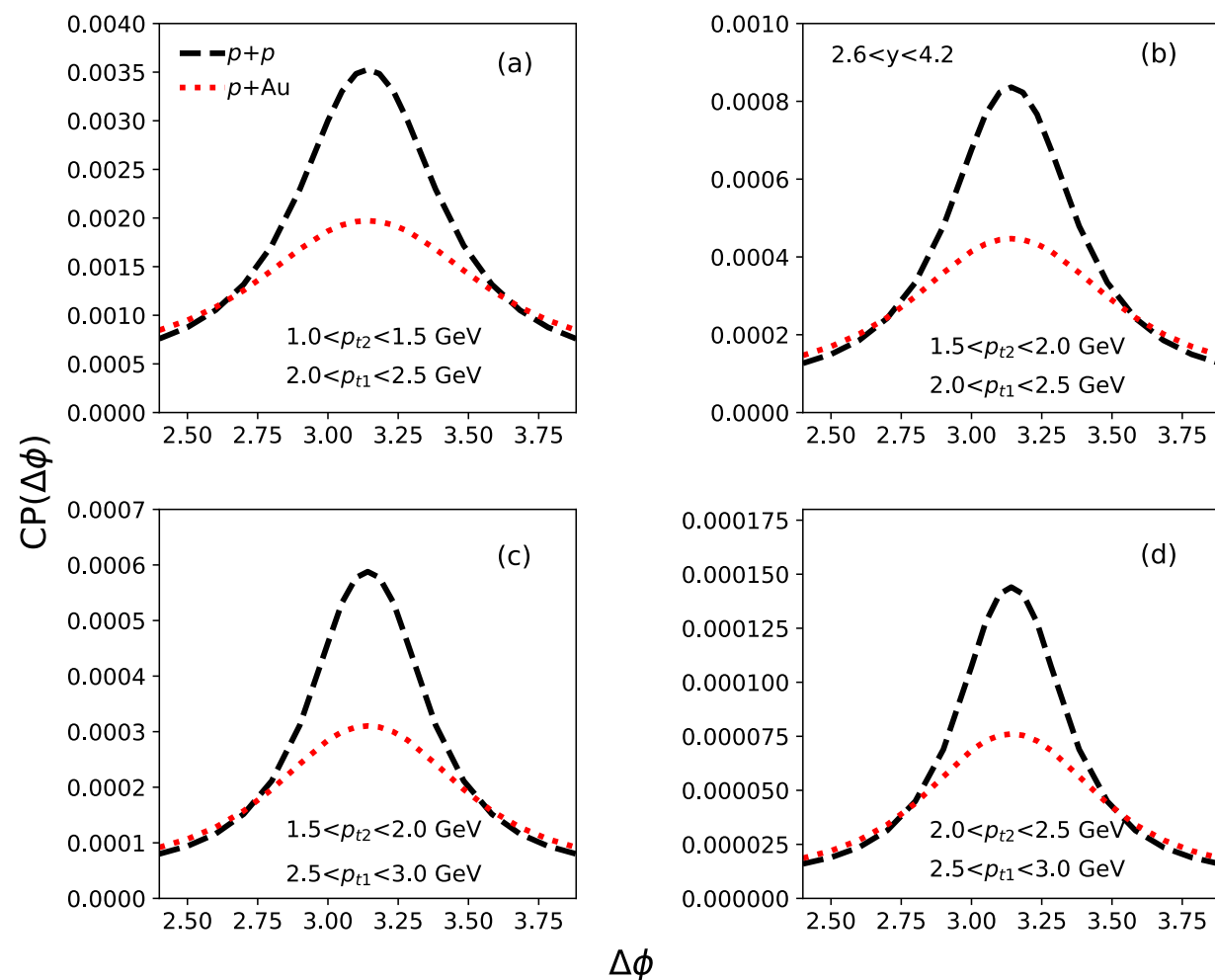
offset to data to push to 0 at minimum



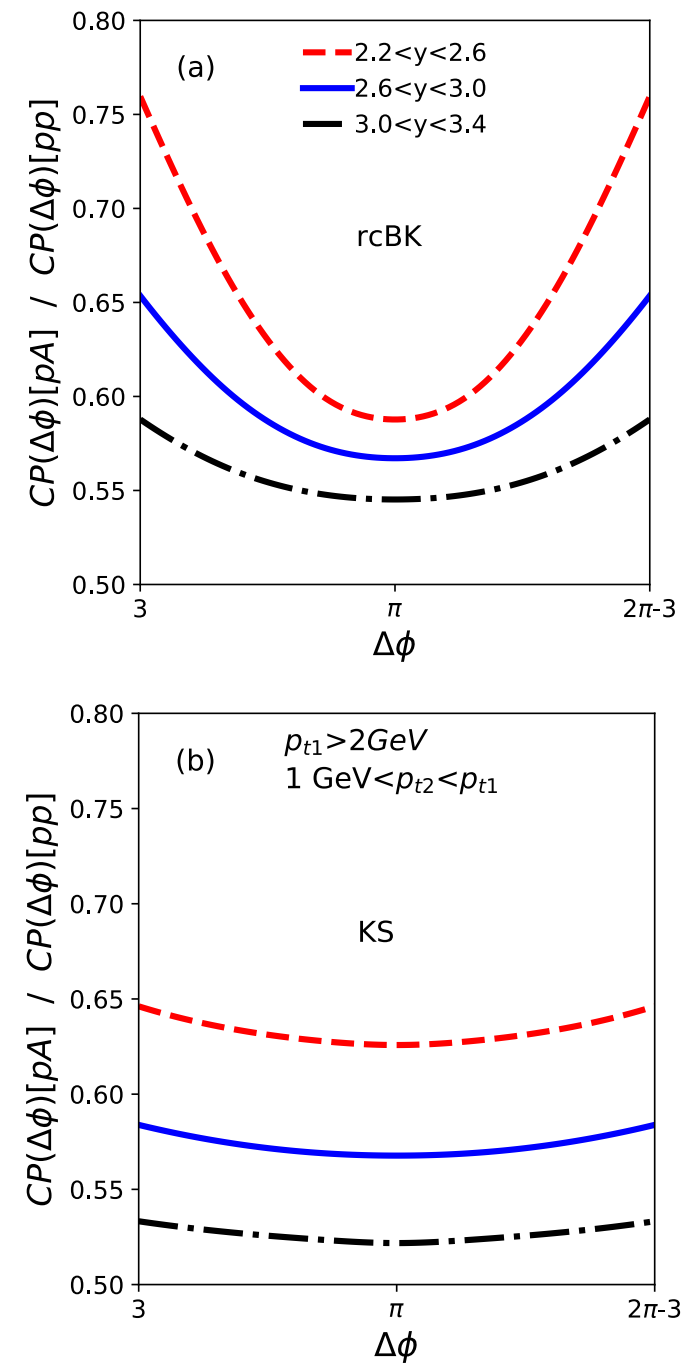
- The trend of the data reproduced by the calculation with rcBK
- The width is not captured, particularly in pp

Impact of the nonlinear evolution: predictions for pA

Predictions for pA



Albacete, Giacalone, Marquet, Matas



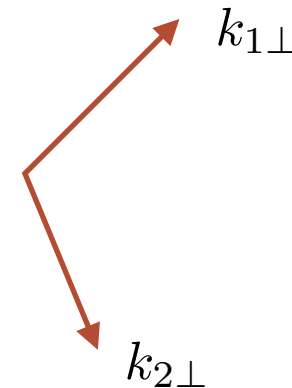
- **Suppression** of the away side peak in pA w.r.t. pp by factor 2. Mostly independent of p_T
- Distinct **rapidity** dependence of the suppression. Sensitive to the **model** of the **gluon** density in the target

Dihadron correlations: saturation and Sudakov included

Including Sudakov effects in CGC calculations:

Mueller, Xiao, Yuan

$$\frac{d\sigma_{\text{corr.}}^{(pA \rightarrow h_1 h_2)}}{dy_{h_1} dy_{h_2} d^2 p_{1\perp} d^2 p_{2\perp}} = \int \frac{dz_1}{z_1^2} \frac{dz_2}{z_2^2} \frac{\alpha_s^2}{\hat{s}^2} [x_p q(x_p) \mathcal{F}_{qg}^{(i)} \times H_{qg}^{(i)} (D_{h_1/q}(z_1) D_{h_2/g}(z_2) + D_{h_2/q}(z_1) D_{h_1/g}(z_2)) + x_p g(x_p) \mathcal{F}_{gg}^{(i)} H_{gg}^{(i)} D_{h_1/g}(z_1) D_{h_2/g}(z_2)] ,$$



Transverse mom. imbalance

$$k_{\perp} = k_{1\perp} + k_{2\perp}$$

Relative transverse mom.

$$P_{\perp} = \frac{1}{2} |k_{1\perp} - k_{2\perp}|$$

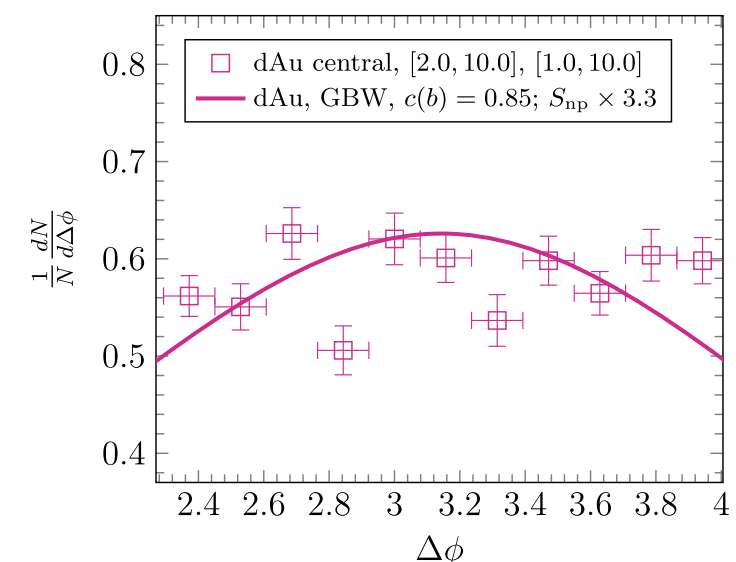
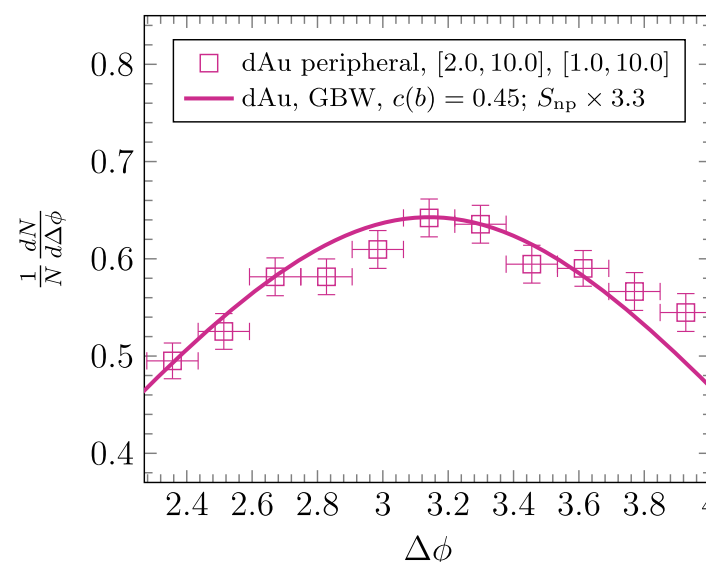
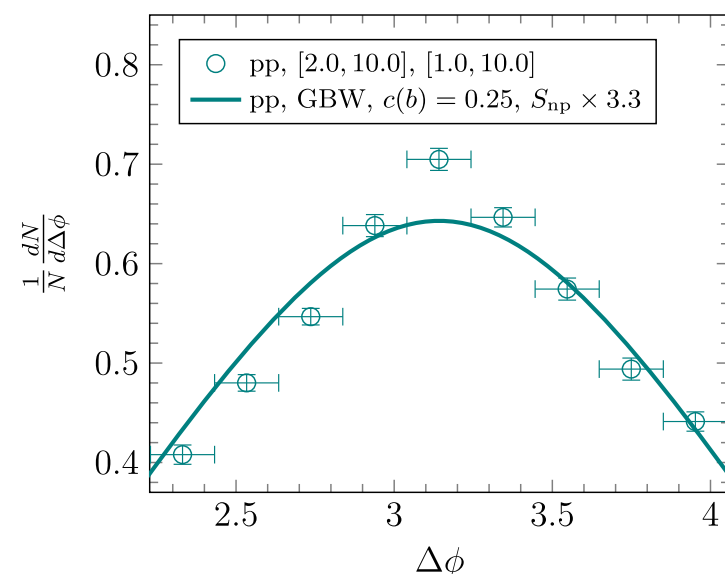
Large logarithms:

$$\alpha_s \ln^2(P_{\perp}^2 / k_{\perp}^2)$$

Sudakov effects factorize

Modify functions $\mathcal{F}_{\alpha\beta}^{(i)}$

Normalized forward dihadron angular correlation compared with the STAR data (also normalized)



In pp Sudakov effects are very important

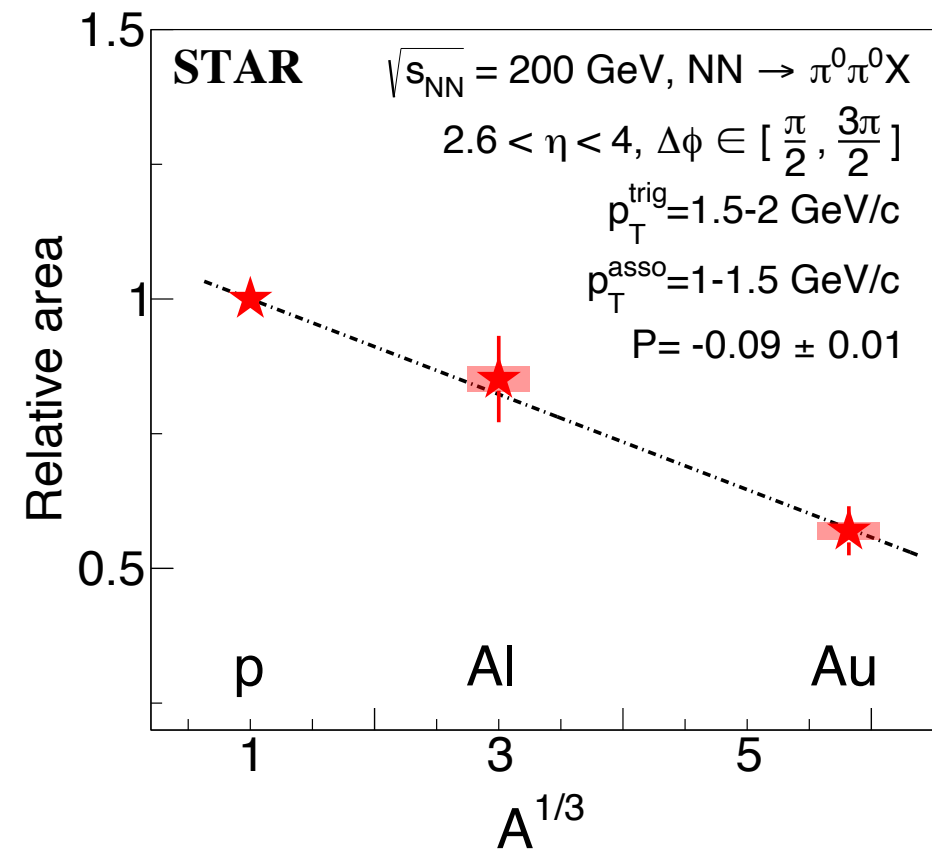
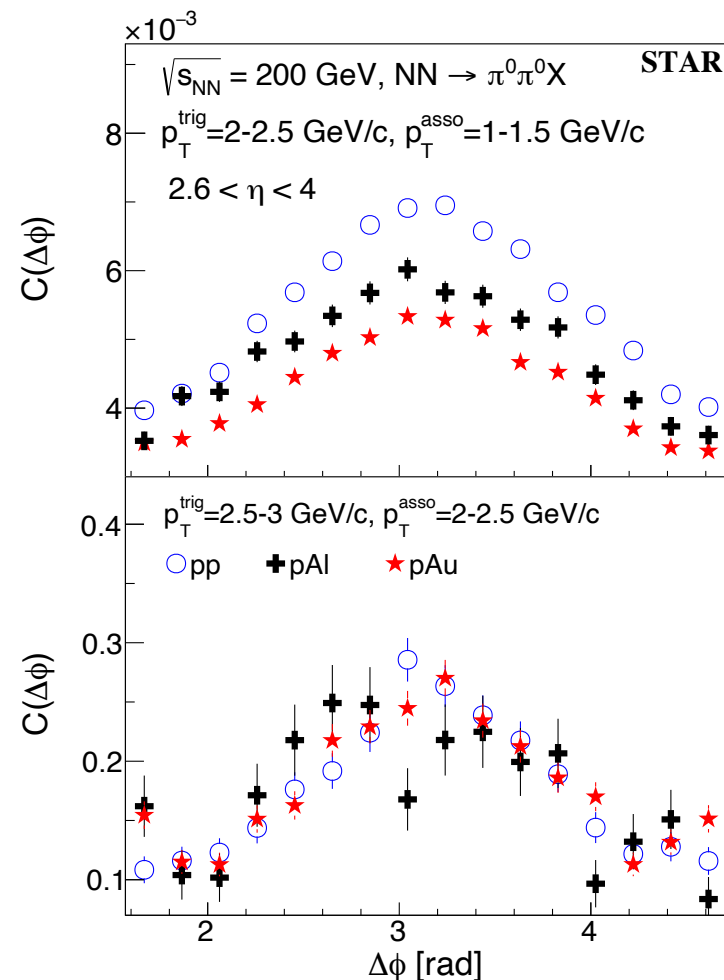
AS, Wei, Xiao, Yuan

Di-hadron correlations in pp,pAl,pAu

PHYSICAL REVIEW LETTERS **129**, 092501 (2022)

Evidence for Nonlinear Gluon Effects in QCD and Their Mass Number Dependence at STAR

The STAR Collaboration reports measurements of back-to-back azimuthal correlations of di- π^0 s produced at forward pseudorapidities ($2.6 < \eta < 4.0$) in $p + p$, $p + \text{Al}$, and $p + \text{Au}$ collisions at a center-of-mass energy of 200 GeV. We observe a clear suppression of the correlated yields of back-to-back π^0 pairs in $p + \text{Al}$ and $p + \text{Au}$ collisions compared to the $p + p$ data. The observed suppression of back-to-back pairs as a function of transverse momentum suggests nonlinear gluon dynamics arising at high parton densities. The larger suppression found in $p + \text{Au}$ relative to $p + \text{Al}$ collisions exhibits a dependence of the saturation scale Q_s^2 on the mass number A . A linear scaling of the suppression with $A^{1/3}$ is observed with a slope of -0.09 ± 0.01 .



Clear suppression observed in pA, scales with A

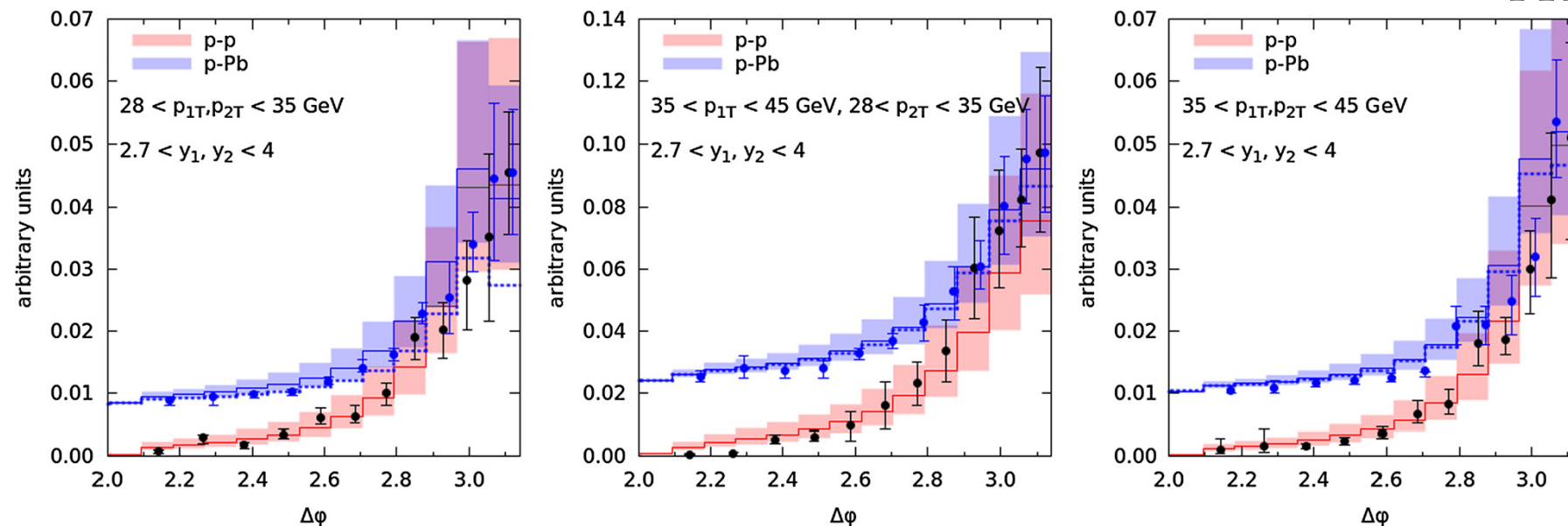
Correlations in dijets at the LHC

van Hameren, Kotko, Kutak, Sapeta

Calculation using **improved TMD** factorization with **saturation** effects in the TMD (unintegrated) gluon density and the **Sudakov** effects

$$\frac{d\sigma^{pA \rightarrow j_1 j_2 + X}}{d^2q_T d^2k_T dy_1 dy_2} = \sum_{a,c,d} x_p f_{a/p}(x_p, \mu) \sum_{i=1}^2 \mathcal{K}_{ag^* \rightarrow cd}^{(i)}(q_T, k_T; \mu) \times \Phi_{ag \rightarrow cd}^{(i)}(x_A, k_T, \mu),$$

ATLAS dijet data

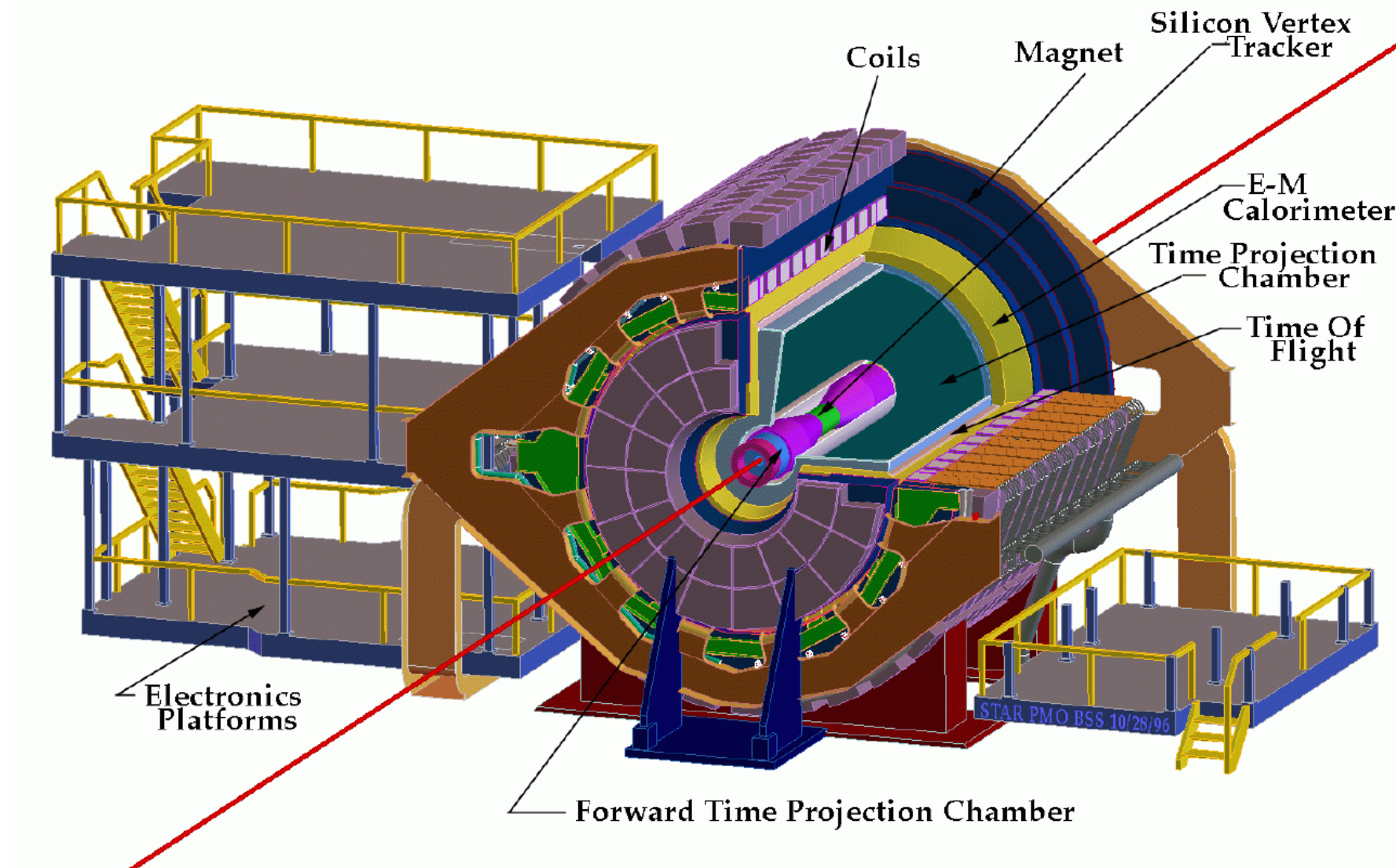


- Change the normalization : shift (pedestal) is added to the data to match pp and pPb at the peak.
- Broadening observed in pPb.
- What is interpretation of this procedure ?

Summary

- ★ **STAR has been a pioneer of exploration of cold nuclear matter in AA, dA, pA**
- ★ Examples of important measurements:
 - ★ exclusive vector meson production in UPC
 - ★ inclusive charged particle production
 - ★ forward particle production
 - ★ dihadron correlations
- ★ **Motivated many theoretical developments:**
 - ★ constraints on the nuclear PDFs, phenomenological models including saturation, description of coherent and incoherent diffraction, nonlinear evolution, impact parameter dependence, NLO and resummation corrections, dihadron, dijet correlations, forward production, Sudakov resummation...
- ★ Similar measurements performed at LHC : many UPC measurements, dijet correlations
- ★ **Theory and experimental exploration of cold QCD :
to be continued at the EIC !**

STAR Detector



*Thank you STAR for 25 years of extraordinary performance
and fantastic physics results !!!*