

Fractional energy losses in the black disk regime and BRAHMS effect

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*based on Frankfurt and Strikman (Phys.Lett.B645:412-421,2007);
Guzey, Strikman, Vogelsang (Phys.Lett.B603:173-183,2004)*

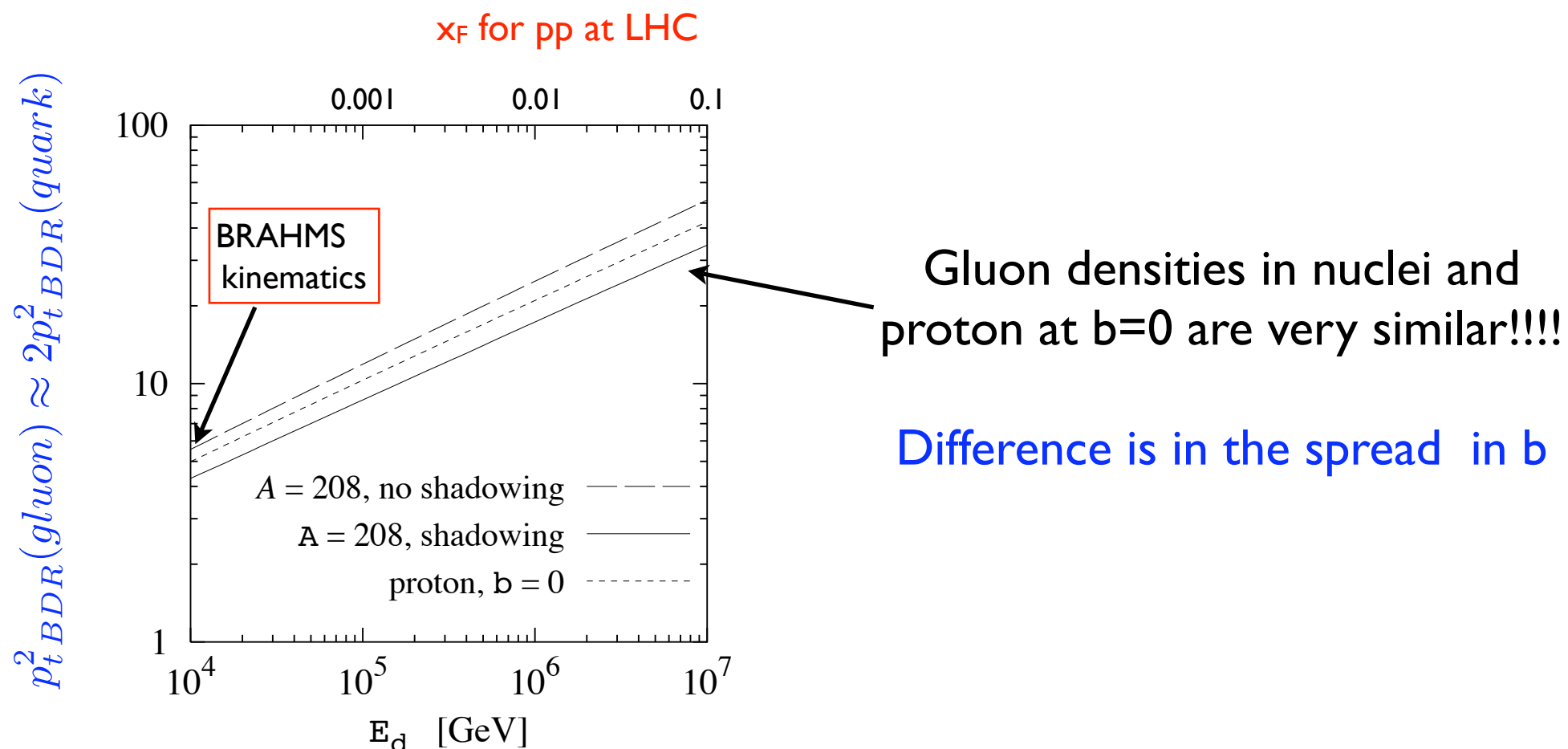
12th Diffractive Workshop, DESY, May24, 07

Outline

- ★ *Black disk regime and fractional energy losses*
- ★ *BRAHMS effect - facts and interpretations*
- ★ *Analysis of the STAR correlation data*
- ★ *Suggestions for future analyses*

BLACK DISK REGIME (BDR) - interaction reached
 maximal strength allowed by unitarity - impact factor $\Gamma(b)$
 approaches one

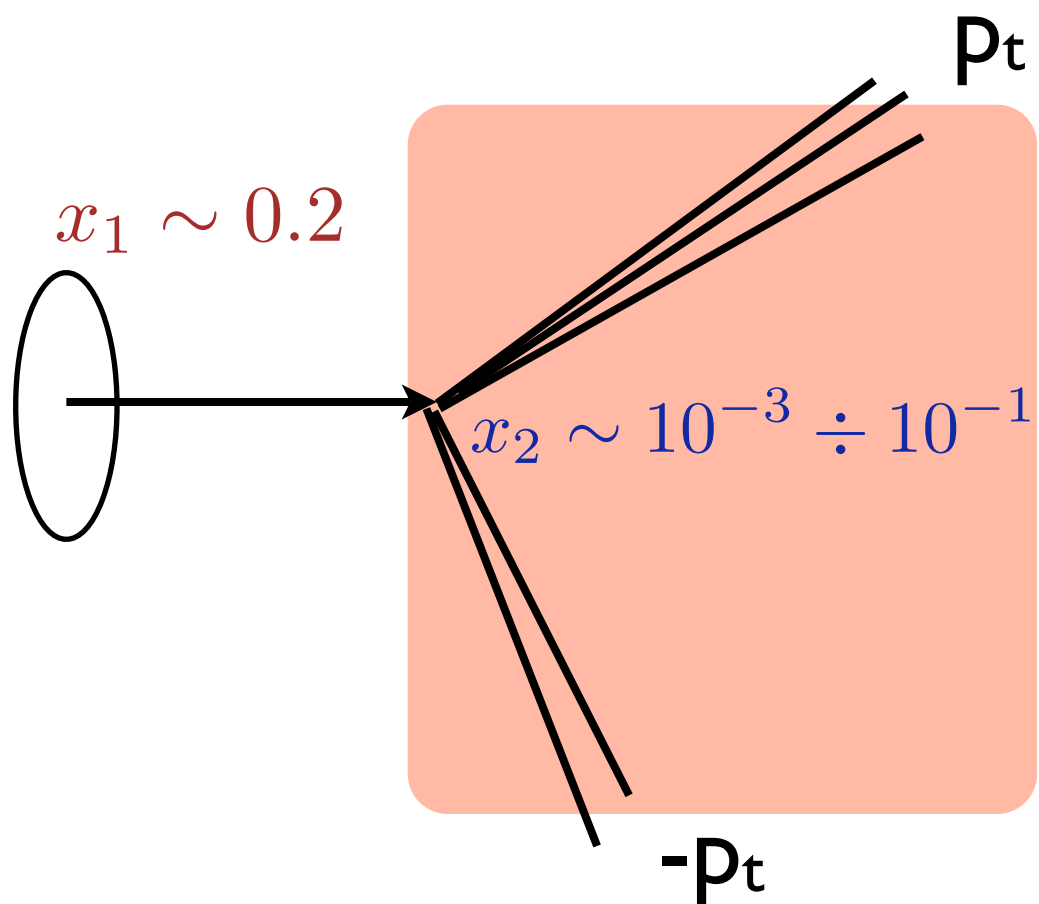
Onset of BDR for interaction of a small dipole - break down of LT
 pQCD approximation - natural definition of boundary: $\Gamma_d(b) = 1/2$ -
 corresponds for dipole to pass through the target at given b without
 interaction: $|1 - \Gamma_d(b)|^2 < 1/4 \implies p_{t\ BDR} \sim \frac{\pi}{2d_{BDR}}$



BDR - gross violation of Bj scaling $F_{2p} \sim Q^2 \ln^3(1/x)$, and suppression of the forward hadron spectrum violating QCD factorization

Frankfurt, Guzey,
McDermott, MS 91

BDR in central pA collisions: Leading partons in the proton, x_1 , interact with a dense medium of small x_2 – gluons in the nucleus (shaded area), losing fraction of its momentum and acquiring a large transverse momentum, $\gg p_t$ BDR



Parton cannot go through media in the BDR without interaction and getting a large transverse momenta.

What are the energy losses in BDR?

$$\Delta E = cE(L/3Fm) \quad c \approx 0.1$$

Qualitatively different pattern than at finite x - finite energy losses since in the initial moment no accompanying gluon field.

Single gluon exchange at high energies contributes very little because of gluon Reggeization

$$A_g \propto \alpha_s^2 s^{\beta(t)} (i + \tan(\pi\beta(t)/2))$$

where $\beta(t)$ is the gluon Regge trajectory with $\beta(t=0) < 1$.

inelastic cross section is calculable in terms of the probability of inelastic interaction, $P_{inel}(b)$ of a parton with a target at a given impact parameter b

$$\sigma_{inel} = \int d^2b P_{inel}(b, s, Q^2)$$

σ_{inel} is calculable in QCD

$$P_{inel}(b, x, Q^2) = \frac{\pi^2}{3} \alpha_s(k_t^2) \frac{\Lambda}{k_t^2} x G_A(x, Q^2, b)$$

where $x \approx 4k_t^2/s_{qN}$, $Q^2 \approx 4k_t^2$, $\Lambda \sim 2$ (for the gluon case $P_{inel}(b)$ is 9/4 times larger)

If $P_{\text{inel}}(b, x, Q^2)$ approaches one or exceeds one it means that average number of inelastic interactions, $N(b)$ becomes larger than one.

Denote as $G_{\text{cr}}(x, Q^2, b)$ value of G for which $P_{\text{inel}}(b, x, Q^2) = 1$

$$N(b, x, Q^2) = G_A(x, Q^2, b) / G_{\text{cr}}(x, Q^2, b)$$

Lower bound for energy losses for $P \sim l$

Loss of finite fraction of incident parton energy - ϵ , arises from the processes of parton fragmentation into mass M which does not increase with energy. For binary collision

$$M^2 = \frac{k_t^2}{\epsilon(1 - \epsilon)}$$

For small $\epsilon < 1/4$, $\epsilon = \frac{k_t^2}{M^2}$ where k_t is transverse momentum of parton after inelastic collision

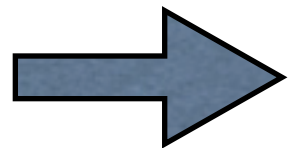
The spectrum over the masses in the single ladder approximation (NLO DGLAP and BFKL approximations)

$$d\sigma \propto \int dM^2 / M^2 (s/M^2)^\lambda \theta(M^2 - 4k_t^2)$$

where $\gamma \sim 0.25 - 0.3$

For contribution of small $\epsilon < 1/4$

$$\epsilon_N \equiv \langle \epsilon \rangle = \frac{\int_0^\gamma \epsilon d\epsilon / \epsilon^{1-\lambda}}{\int_0^\gamma d\epsilon / \epsilon^{1-\lambda}} = \gamma \frac{\lambda}{1-\lambda}$$



$$\epsilon_N \geq 8\%$$

In the multi ladder regime $\epsilon_A(b) \approx N(b)\epsilon_N$

We predict that in the kinematics when BDR is achieved in pA but not in pN scattering, the hadron inclusive cross section should be given by the sum of two terms - scattering from the nucleus edge which has the same momentum dependence as the elementary cross section and scattering off the opaque media which occurs with large energy losses:

$$\frac{d\sigma(d + A \rightarrow h + X)/dx_h d^2p_t}{d\sigma(d + p \rightarrow h + X)/dx_h d^2p_t} = c_1 A^{1/3} + c_2(A) A^{2/3}$$

Inclusive forward pion production

The BRHAMS data were reviewed in the Ditta Roehrich talk.

For pp - pQCD works both for inclusive pion spectra and for correlations (STAR)

Suppression of the pion spectrum for fixed p_t increases increase of η_N . Dynamical suppression effect for $\eta=3.2$ is even larger than the BRHAMS ratio (by a factor of 1.5) due isospin effect.

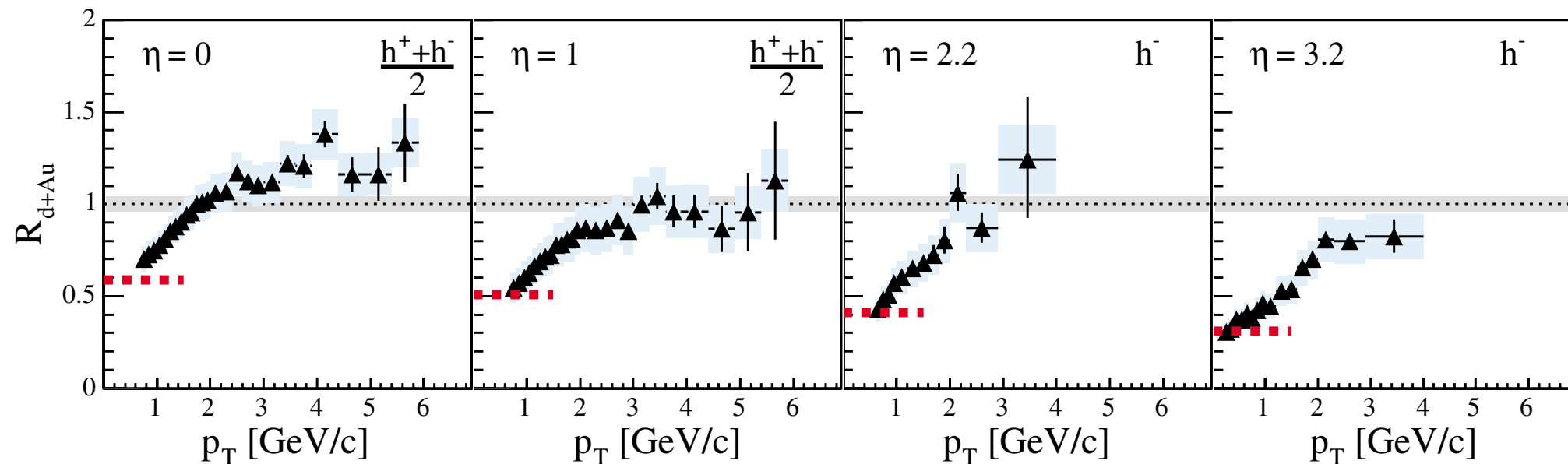
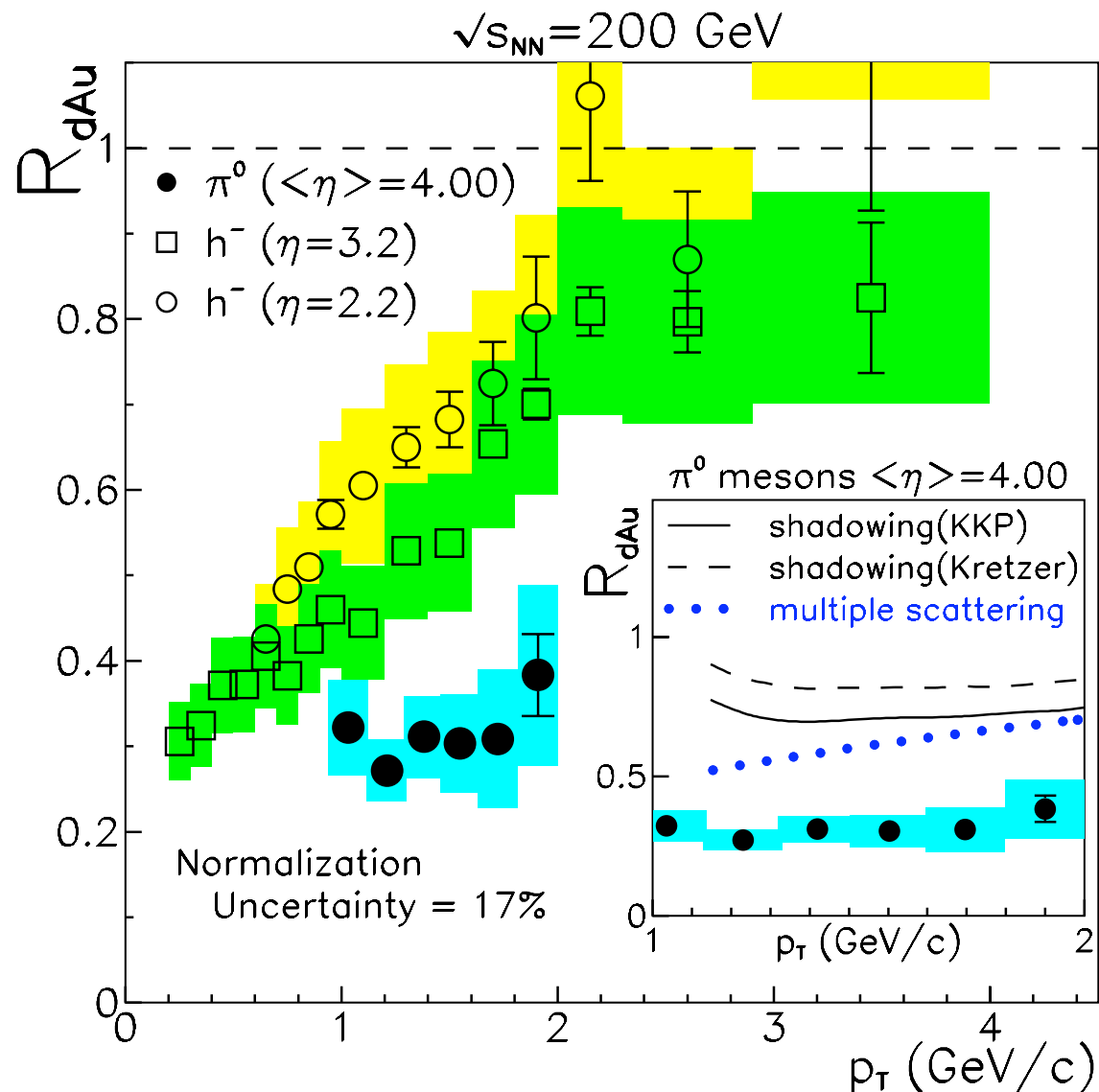


FIG. 2 (color online). Nuclear modification factor for charged hadrons at pseudorapidities $\eta = 0, 1.0, 2.2, 3.2$. On deviation statistical errors are shown with error bars. Systematic errors are shown with shaded boxes with widths set sizes. The shaded band around unity indicates the estimated error on the normalization to $\langle N_{coll} \rangle$. Dashed lines at $p_T < 1$ show the normalized charged-particle density ratio $\frac{1}{\langle N_{coll} \rangle} \frac{dN/d\eta(Au)}{dN/d\eta(pp)}$.



BRAHMS and STAR are
consistent when an isospin
effect in the BRAHMS data
is corrected for

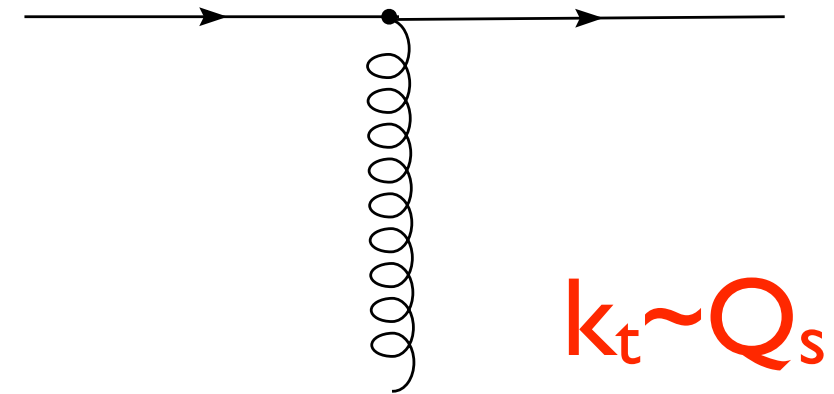
FIG. 3: Nuclear modification factor (R_{dAu}) for minimum-bias d+Au collisions versus transverse momentum (p_T). The solid circles are for π^0 mesons. The open circles and boxes are for negative hadrons (h^-) at smaller η [10]. The error bars are statistical, while the shaded boxes are point-to-point systematic errors. (Inset) R_{dAu} for π^0 mesons at $\langle\eta\rangle=4.00$ compared to the ratio of calculations shown in Figs. 2 and 1.

Suggested explanations

Energy losses - usually only finite energy losses discussed (BDMPS)
- hence a rather small effect for partons with energies 10^4 GeV in the second nucleus rest frame. Not true in BDR

Color Glass Condensate model

Assumes that the process is dominated both for a nucleus and nucleon target by the scattering of partons with minimal x allowed by the kinematics: $x \sim 10^{-4}$ in a $2 \rightarrow 1$ process.



Two effects - (i) density is smaller than for the incoherent sum of participant nucleons by a factor N_{part} , (ii) enhancement due to increase of k_t of the small x parton: $k_t \sim Q_s$. \rightarrow Overall dependence on N_{part} is $(N_{\text{part}})^{0.5}$, collisions with high p_t trigger are more central than the minimal bias events, no recoil jets in the kinematics expected in pQCD.

Key feature - dominant yield from central impact parameters

Challenge - in pQCD main contribution is from scattering off gluons with $\langle x \rangle > 0.01$ which are not screened

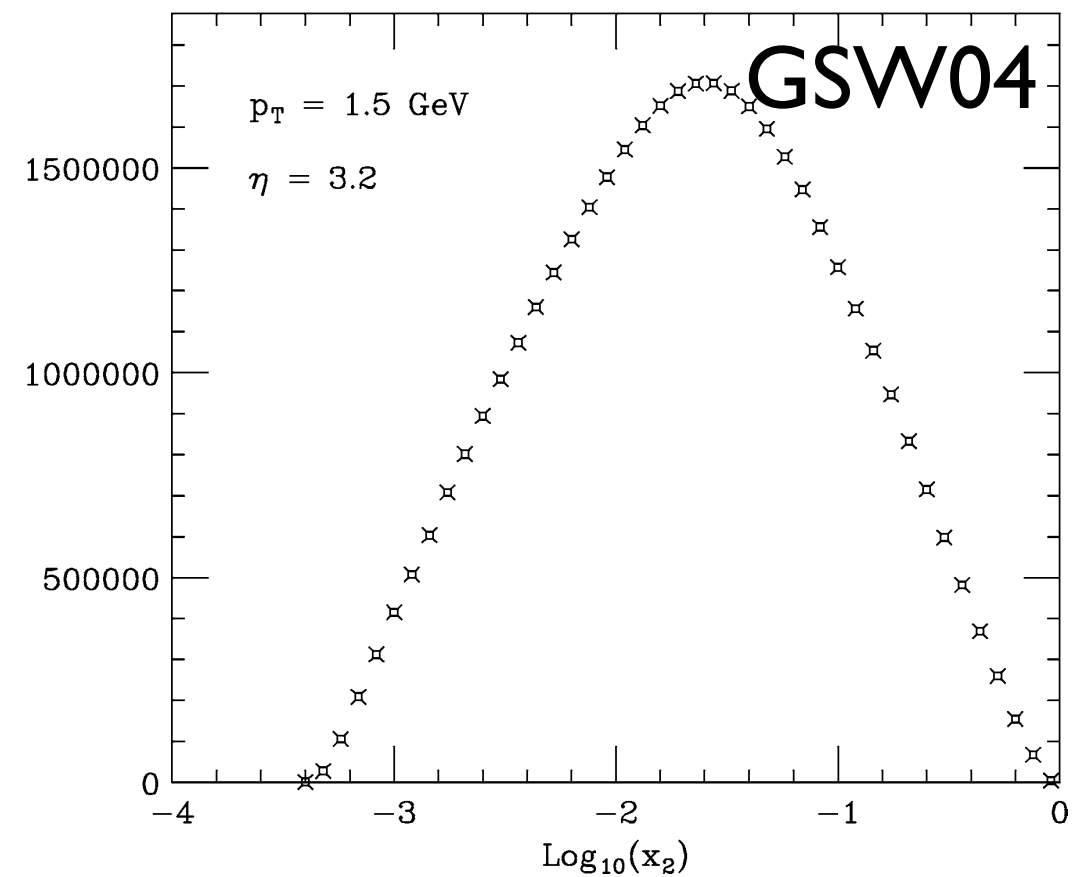


Fig. 1. Distribution in $\log_{10}(x_2)$ of the NLO invariant cross section $E d^3 \sigma / dp^3$ at $\sqrt{s} = 200 \text{ GeV}$, $p_T = 1.5 \text{ GeV}$ and $\eta = 3.2$.

CGC calculations which reproduce absolute yield due to scattering off $x=10^{-4}$ parton via coherent mechanism (Dumitru et al) - assume that there exists a unknown mechanism which kills $x > 0.005$ contribution

Analysis of the STAR data

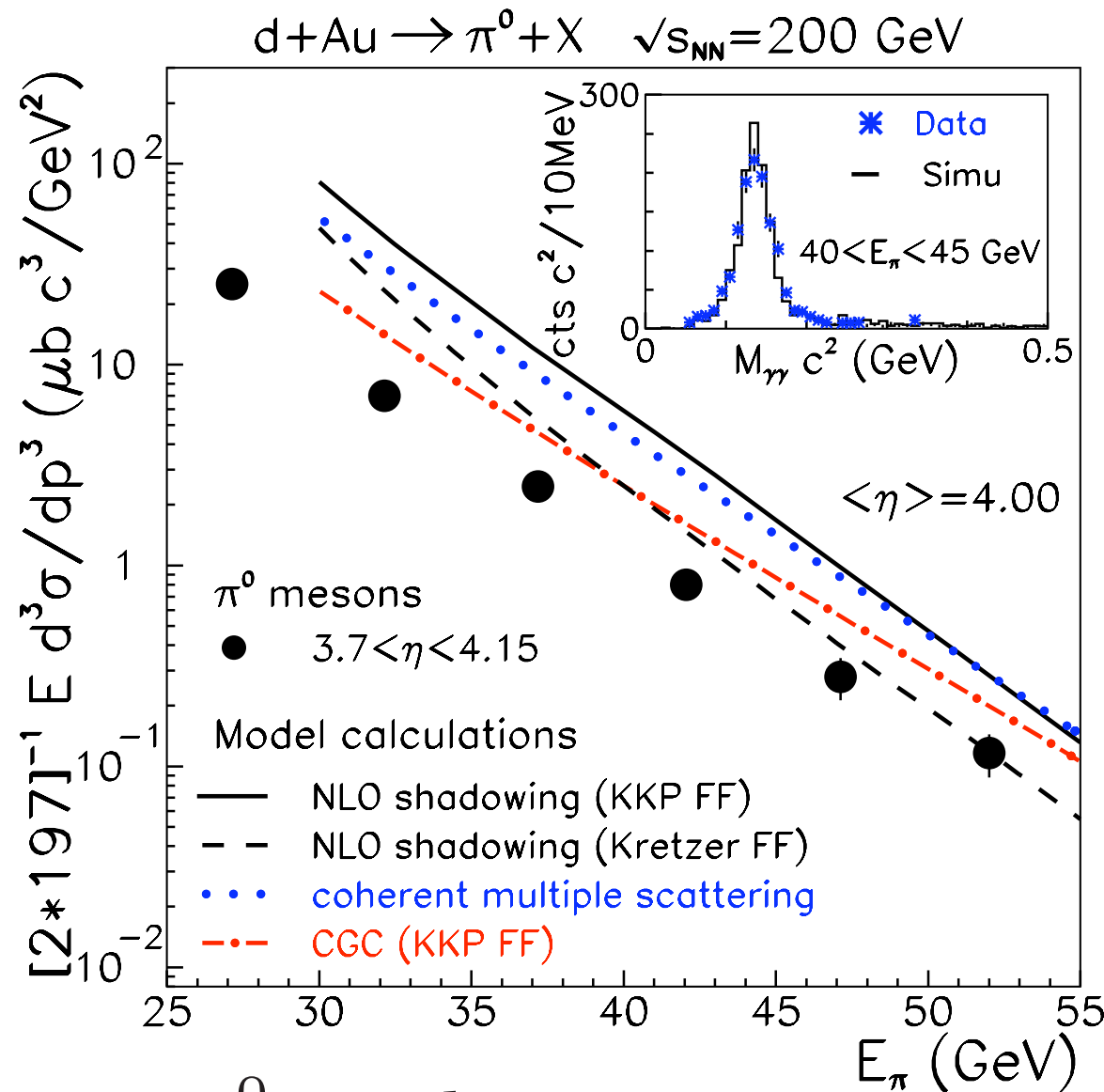
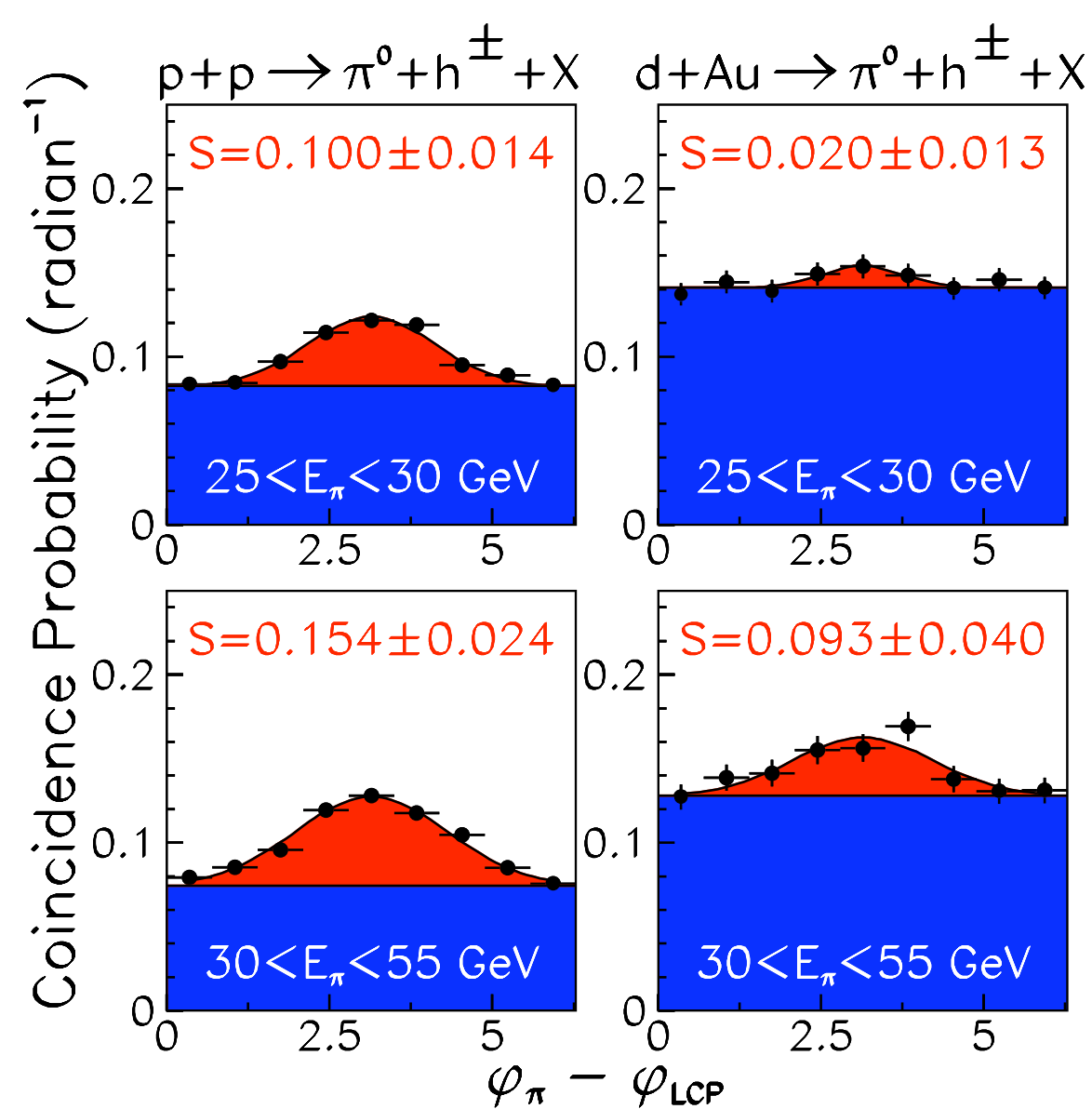


FIG. 2: Inclusive π^0 production cross section per binary collision for d+Au collisions, displayed as in Fig. 1. The curves are model calculations described in the text. (Inset) Uncorrected diphoton invariant mass ($M_{\gamma\gamma}$) spectrum for data with statistical errors (stars), normalized to simulation (histogram).

The STAR analysis: leading charge particle (LCP) analysis picks a midrapidity track with $|\eta_h| \leq 0.75$ with the highest $p_T \geq 0.5$ GeV/c and computes the azimuthal angle difference $\Delta\phi = \phi_{\pi^0} - \phi_{LCP}$ for each event. This provides a coincidence probability $f(\Delta\phi)$. It is fitted as a sum of two terms - a background term, $B/2\pi$, which is independent of $\Delta\phi$ and the correlation term $\Delta\phi$ which is peaked at $\Delta\phi = \pi$. By construction,

$$\int_0^{2\pi} f(\Delta\phi) d\Delta\phi = B + \int_0^{2\pi} S(\Delta\phi) d\Delta\phi \equiv B + S \leq 1$$



Coincidence probability versus azimuthal angle difference between the forward π^0 and a leading charged particle at midrapidity with $p_T > 0.5$ GeV/c. The left (right column in p+p (d+Au) data with statistical errors. The π^0 energy increases from top to bottom. The curves are described fits. **S is red area.**

Obvious problem for central impact parameter scenario of π^0 production is rather small difference between low p_T production in the $\eta=0$ region (**blue**), in pp and in dAu - (while for $b=0$, $N_{coll} \sim 13$)

To use information about central rapidities in a detailed way we used the relevant information from dAu BRAHMS analysis. Results are not sensitive to details.

Introduce p_B - probability to produce a hadron within p_T cuts of STAR in soft interactions, and p_S - in hard interactions.

p_T cut of STAR is rather high (comparable to the momentum of the leading hadron in the recoiling jet for the trigger jet with $\langle p_T \rangle \sim 1.3 \text{ GeV}/c$).

We will assume that in the pp events where both soft and hard mechanisms resulted in the production of a hadron (hadrons) within the STAR cuts there is an equal probability for the fastest hadron to belong to either the soft or hard component (this is essentially an assumption of a reasonably quick convergence of the integrals over p_T for $p_{T \text{ min}} = 0.5 \text{ GeV}/c$).

$$B_{pp} = p_B(1 - p_S/2), S_{pp} = p_S(1 - p_B/2)$$

Since S_{pp} is small to a very good approximation

$$p_B = B_{pp} \left(1 + \frac{S_{pp}}{2 - B - S} \right), p_S = S_{pp} \left(1 + \frac{B_{pp}}{2 - B - S} \right)$$

The probability that no hadrons will be produced in inelastic collision of a nucleon with m nucleons of the nucleus:

$$(1 - B - S)_{m \text{ collisions}} = (1 - p_B)^m (1 - p_S)$$

Using STAR data for $S + B$ we find $m = 2.8$.

$$S_{N \text{ collisions}} = p_S \cdot \sum_{m=0}^{m=N} \frac{C_N^m (1 - p_B)^{N-m} p_B^m}{(m + 1)}.$$

Taking $N \sim 3$ we find $S(dAu) \approx 0.1$ which agrees well with the data: 0.093 ± 0.040

Thus, the data consistent with no suppression of recoil jets. In CGC - 100% suppression - no recoil jets at all. Moreover for a particular observables of STAR dominance of central impact parameters in the CGC mechanism would lead to $(1 - B - S) < 0.01$, $S < 0.01$ since for such collisions $N_{\text{coll}} \sim 13$. This would be the case even if the central mechanism would result in a central jet.

$\langle \eta \rangle = 0$ corresponds to $x_A = 0.01$. Hence lack of suppression checks validity of pQCD mechanism below the median of median x_A .

In reality we took into account of the distribution over the number of the collisions, energy conservation in hadron production, different number of collisions with proton and neutron.

Our more detailed analysis confirms our initial conclusion that pion production is strongly dominated by peripheral collisions, and that there is no significant suppression of dijet mechanism.

For central impact parameters energy losses of $>10\%$ are necessary

Since the second jet has much smaller longitudinal momentum than the jet leading to the forward pion production it propagates in a much more pQCD like regime with much smaller energy losses, and hence does not affect the rate of correlation. If the energy losses were fractional but energy independent this would not be the case.

Implications for LHC: even larger energy losses for fragmentation region - $x > 0.2$, losses comparable to those needed to explain STAR and BRAHMS data for $x_p \sim 10^{-3}$

Suggestions for future analyses and measurements

Let us consider the ratio of the double inclusive and single inclusive cross sections for production of a particle in forward and in central kinematics which are characterized by their rapidities and transverse momenta:

$$RR(y_f, |p_{t\,f}|, y_c, |p_{t\,c}|, \phi) = \frac{\frac{d\sigma(y_f, p_{t\,f}, y_c, p_{t\,c})}{dy_f dp_{t\,f} dy_c dp_{t\,c}}}{\frac{d\sigma(y_f, p_{t\,f})}{dy_f dp_{t\,f}}},$$

where ϕ is the angle between $-p_{t\,f}$ and $p_{t\,c}$. We can now introduce

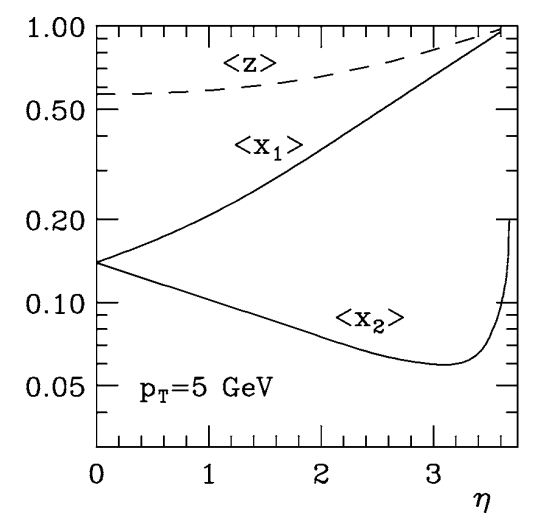
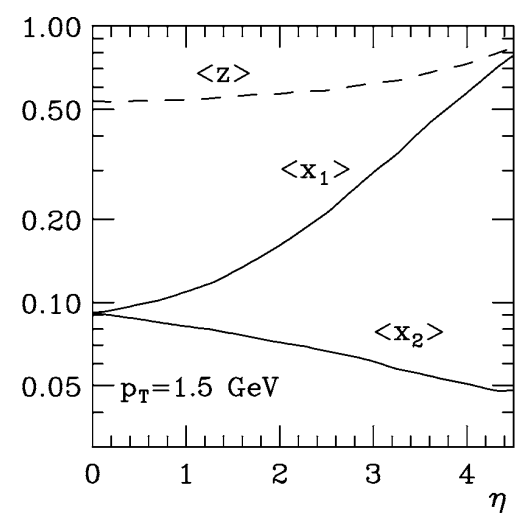
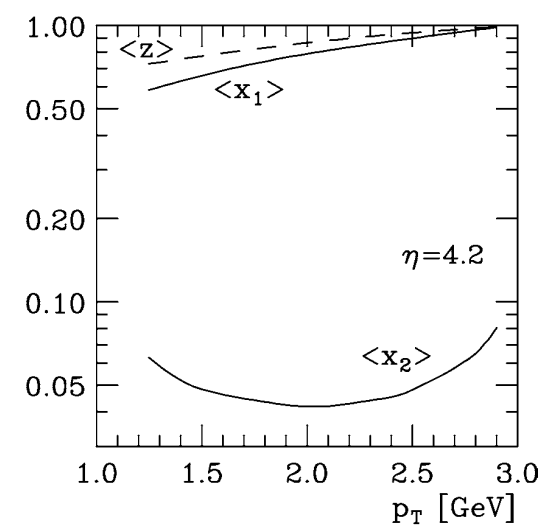
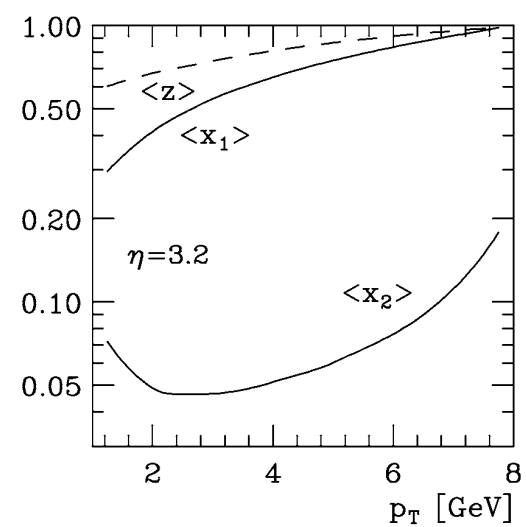
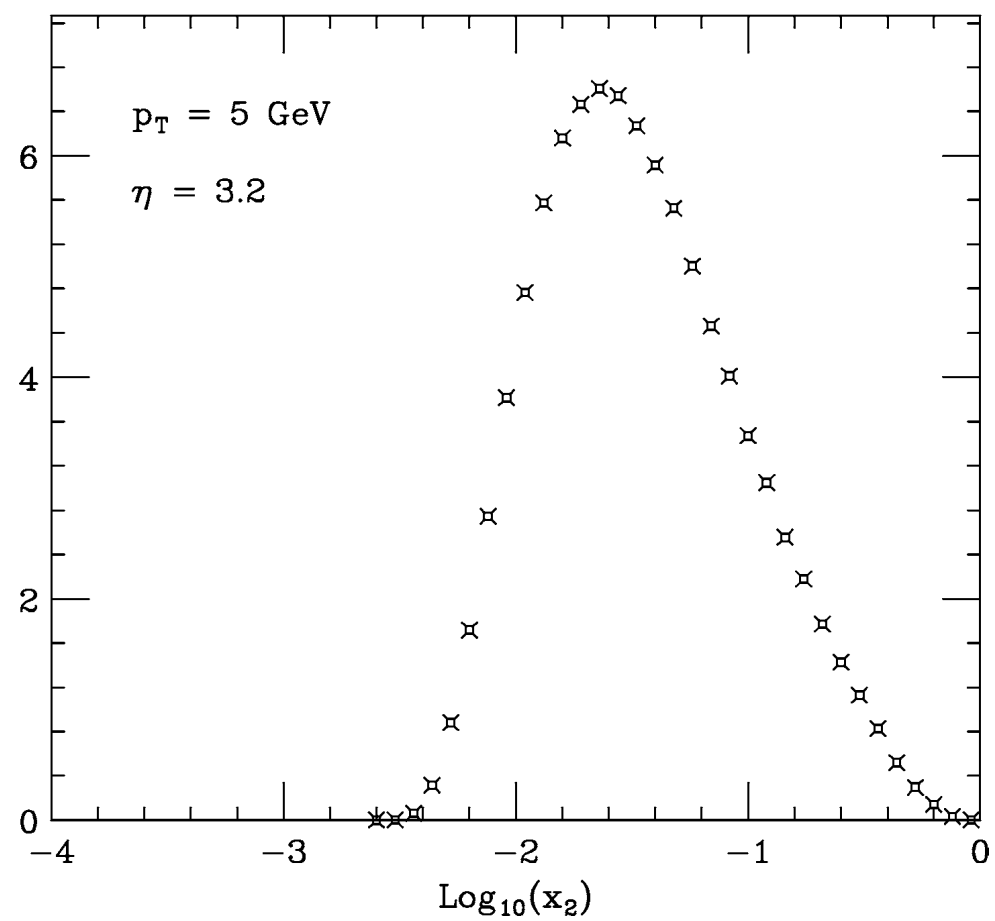
$$\begin{aligned} \Delta RR(y_f, |p_{t\,f}|, y_c, |p_{t\,c}|, \phi) &= \\ &= RR(y_f, |p_{t\,f}|, y_c, |p_{t\,c}|, \phi) - RR(y_f, |p_{t\,f}|, y_c, |p_{t\,c}|, -\phi) \end{aligned}$$

We expect that only hard contribution to the central production depends on φ . Hence in the case of inclusive quantities like ΔRR the soft interaction are canceled, while this is not the case for the quantities considered by STAR which started with similar logic but used different observables. Our procedure would allow to integrate over the angles and hence would allow to study A-dependence of bins in η to study variation of ΔRR in the $0.005 < x < 0.02$ range. Similar procedure to study the A-dependence of the shape of the recoil jets - pt dependence for fixed parameters of the trigger, two particles in the recoil jet, etc.

Conclusions

- ★ We put forward arguments for presence of large fractional energy losses in BDR and argued that forward pion production data at RHIC is consistent with these expectations.
- ★ STAR data strongly indicate dominance of a peripheral mechanism of the forward pion production with a strong suppression of the production at central impact parameters.
- ★ Current STAR data do not indicate any suppression of the recoiling jets *in qualitative contradiction* with predictions of CGC models. We suggested a different analysis of these data which may improve accuracy of this statement.
- ★ Need to build a system of cross calibration of measurements of N_{coll} - *central backward multiplicities, neutron spectators* - to study dependence of the suppression on impact parameter, and look for possible effects of color fluctuations in the nucleon
- ★ Much larger effects at LHC both in AA and in pp.

Few more slides - supplementary



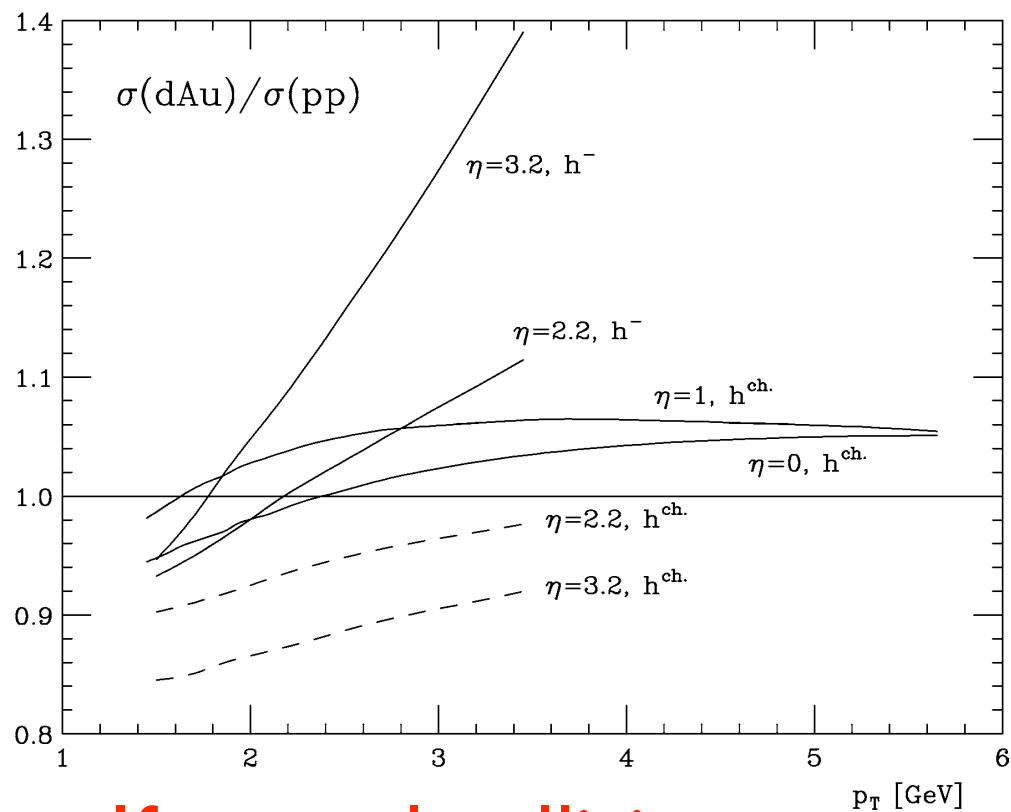
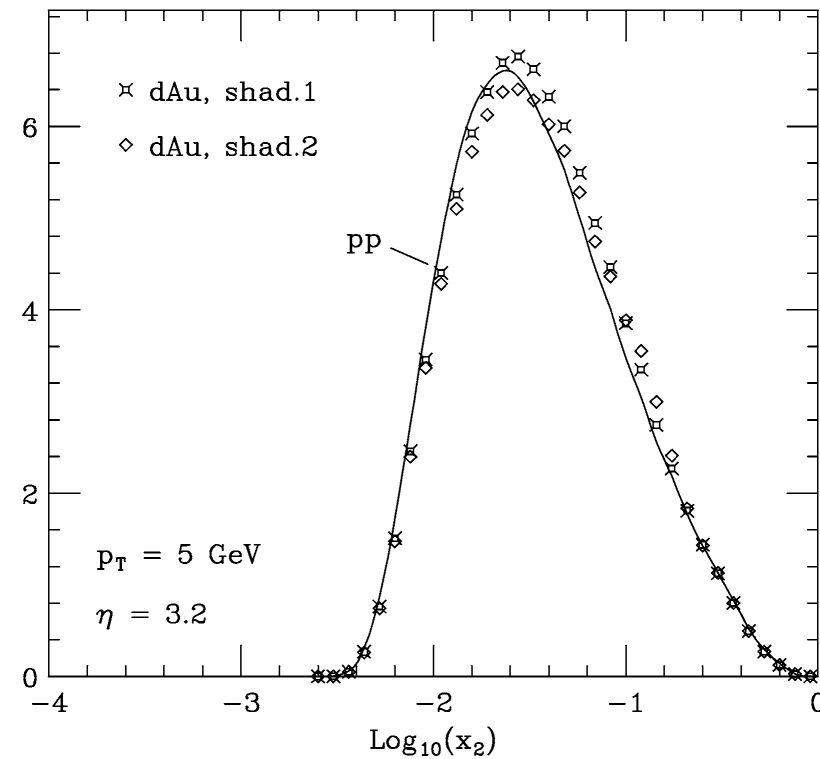
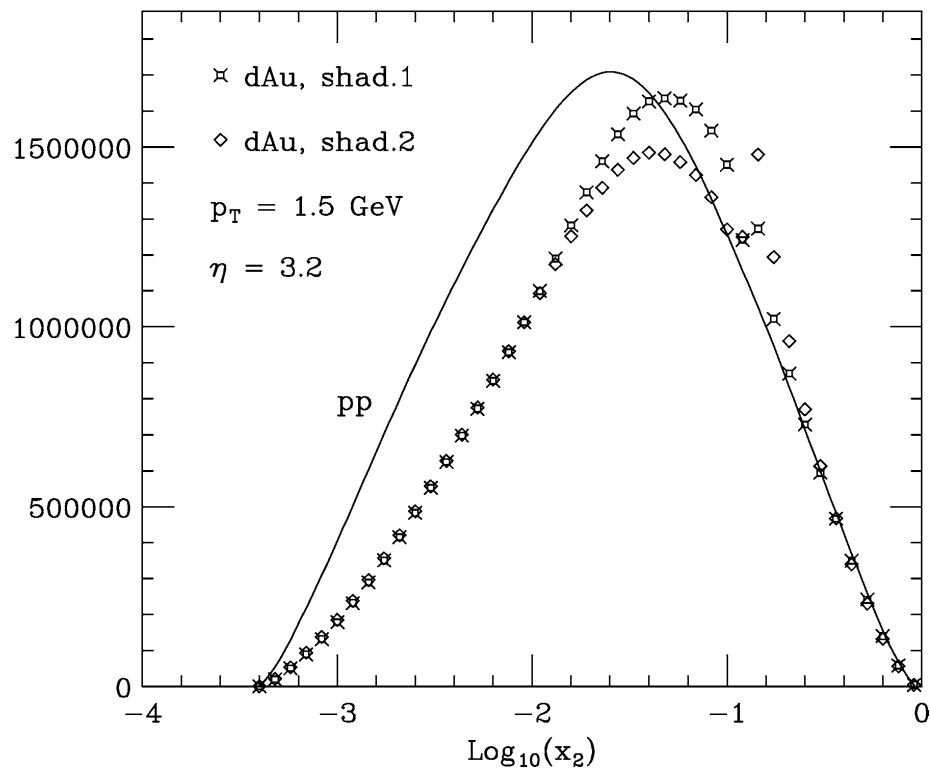


Fig. 9. Ratio R_{dA} of cross sections for $\text{dAu} \rightarrow hX$ and $pp \rightarrow hX$ as a function of transverse momentum at various rapidities relevant to the BRAHMS experiment. As in experiment, we have considered production of *summed* charged hadrons, $h^{\text{ch.}} \equiv (h^+ + h^-)/2$ for $\eta = 0, 1$ and *negatively* charged hadrons h^- for $\eta = 2.2$ and 3.2 . For comparison, the dashed lines show the result for summed charged hadrons at $\eta = 2.2$ and 3.2 . We have used the “shadowing 1” nPDFs for the gold nucleus. The fragmentation functions are from [24]; we have found that for the case of summed charged hadrons using the set of [10] does not alter our results by more than a few percent.

If central collisions are suppressed due to some other mechanism scattering off periphery dominates where shadowing is even smaller effect.

$S=0.068 \ \& \ .075$; $(1-B-S)=0.070 \ \& \ 0.086$. pAu - no energy conservation -
soft multiplicity $\propto N_{\text{coll}}$

$S=0.085 \ \& \ .090$; $(1-B-S)=0.11 \ \& \ 0.12$. pAu - energy conservation
soft multiplicity $\propto N_{\text{coll}}^{0.8}$

$S=0.067 \ \& \ .072$; $(1-B-S)=0.066 \ \& \ 0.079$. dAu - energy conservation

In the dAu case we used $N_{\text{coll}}(\text{dAu})/N_{\text{coll}}(\text{pAu}) \approx 1.5$ and corrected for this difference in average.

$$(1 - B - S) = 0.1, S = 0.093 \pm 0.04 \quad \text{STAR data}$$

Our more detailed analysis confirms our initial conclusion that pion production is strongly dominated by peripheral collisions, and that there is no significant suppression of dijet mechanism.

Implications for LHC: even larger energy losses for fragmentation region - $x > 0.2$, losses comparable to those needed to explain STAR and BRAHMS data for $x_p \sim 10^{-3}$

Very recent analysis of PHENIX along similar lines, though at relatively small rapidities of up to 2 corresponding to $0.01 < x_p < 0.1$

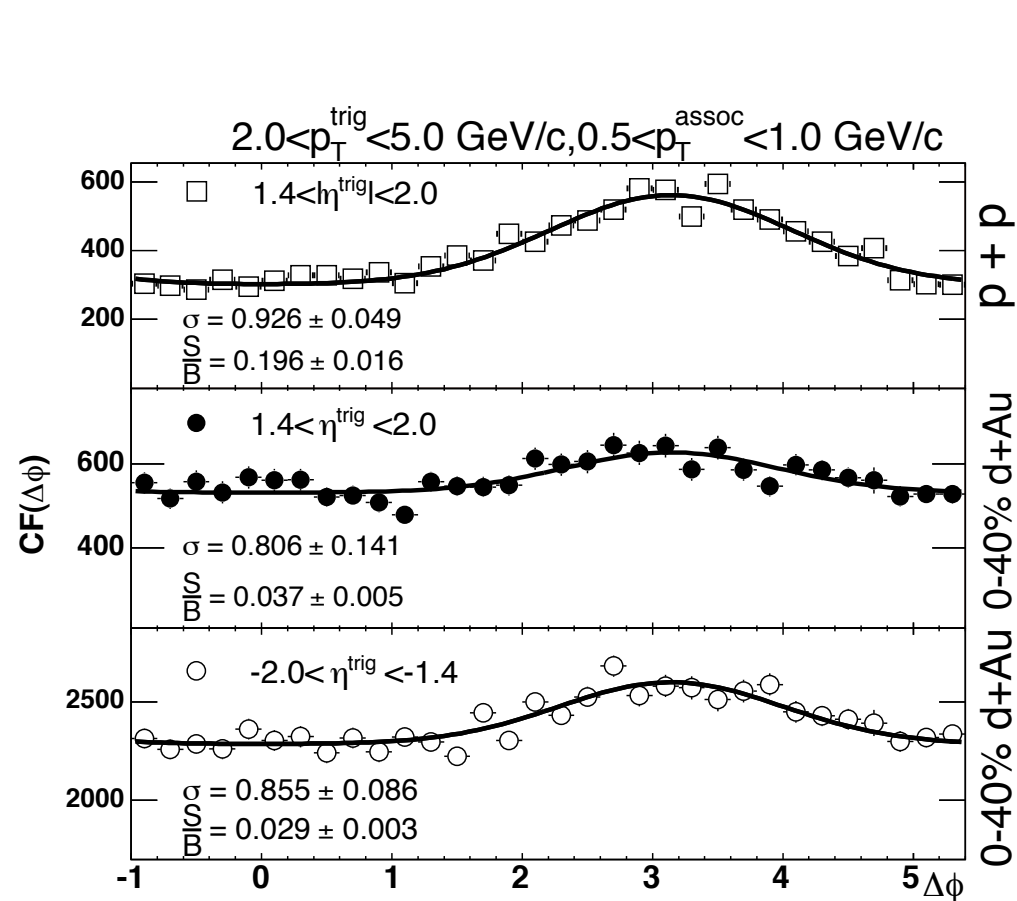


FIG. 1: Azimuthal angle correlation functions. On the plots, the Gaussian widths from the fits and the signal to background ratio integrated over $\pi - 1 < \Delta\phi < \pi + 1$ are shown. Note that the y -axis is zero-suppressed on the middle and bottom panels.

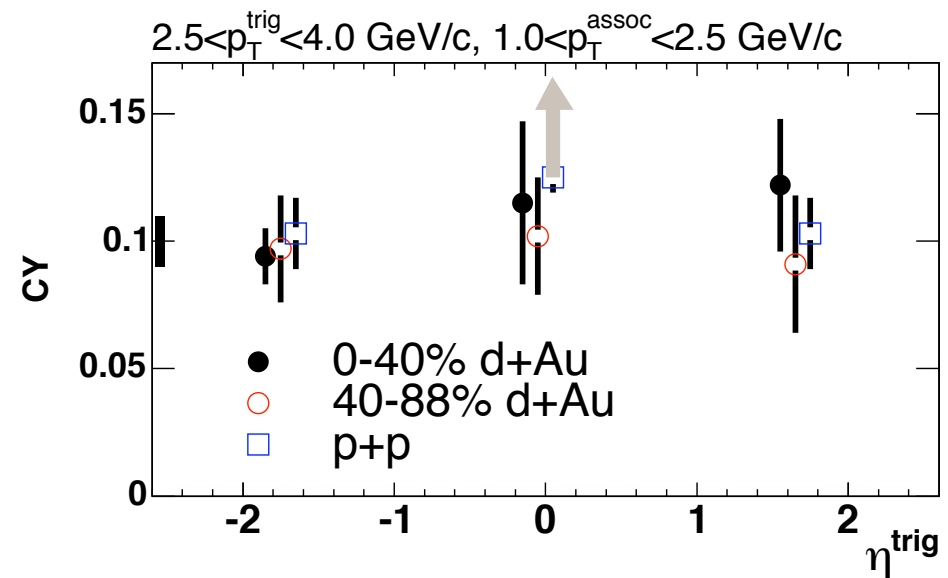


FIG. 2: Conditional yields are shown as a function of trigger particle pseudorapidity. The data points at mid-rapidity for $d + Au$ collisions are from [14]. To increase visibility, we artificially shift the data points belonging to the same η^{trig} bin. The errors on each points are statistical errors. The black bar around 0.1 on the left of the plot indicates a 10% common systematic error for all the data points due to the determination of associated particle efficiency. There is an additional +0.037 systematic error on the mid-rapidity $p+p$ point from jet yield extraction, which is shown as the arrow on that point (similar analysis as [16]).

