The STAR forward pion production in dAu collisions and the interplay of soft and hard dynamics in production of recoil jets

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Outline

1. BRAHMS effect - facts and interpretations
2. Leading twist expectations for leading pion production
3. Analysis of the STAR correlation data
FIG. 2 (color online). Nuclear modification factor for charged hadrons at pseudorapidities $\eta = 0, 1.0, 2.2, 3.2$. One standard deviation statistical errors are shown with error bars. Systematic errors are shown with shaded boxes with widths set by the bin sizes. The shaded band around unity indicates the estimated error on the normalization to $\langle N_{\text{coll}} \rangle$. Dashed lines at $p_T < 1.5$ GeV/$c$ show the normalized charged-particle density ratio $\frac{1}{\langle N_{\text{coll}} \rangle} \frac{dN/d\eta(Au)}{dN/d\eta(pp)}$.

Central (filled circles) and semicentral (empty circles) $R_{cp}$ ratios at pseudorapidities $\eta = 0, 1.0, 2.2, 3.2$. Systematic errors (~ 5%) are smaller than the symbols.
Evolution of the central /peripheral (filled circles) and semicentral /peripheral (empty circles) $R_{cp}$ ratios on pseudorapidity.
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 black disk limit

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 $N_{\text{part}}$, (ii) enhancement due to increase of $k_t$ of the small $x$ parton: $k_t \sim Q_s$. ➔ Overall dependence on $N_{\text{part}}$ is $(N_{\text{part}})^{0.5}$, collisions with high pt trigger are more central than the minimal bias events, no recoil jets in the kinematics expected in pQCD.
The STAR data appear to be consistent with pQCD calculations of Vogelsang et al. However they are sensitive to the gluon fragmentation which contributes even at the highest pion energies (next transparency)

The cross section at $p_t > 1.3$ GeV/c is dominated by

$pp \rightarrow \pi^0 X$ at RHIC - STAR
Relative contribution of gluons to the total yield in $pp \rightarrow h^+ X$. 

$\eta = 0$

$\eta = 2.2$

$\eta = 3.2$

$h^+ + h^-$

$K^-$

$h^-$

KKP ff

Kretzer ff

Kretzer ff
Strong flavor dependence is observed:

\[
\frac{\sigma^{pp\to \pi^-+X}}{dxF} \quad \frac{\sigma^{nN\to \pi^-+X}}{dxF} \quad \frac{\sigma^{pp\to \pi^-+X}}{dxF} \quad \frac{\sigma^{nN\to \pi^-+X}}{dxF}
\]

should be small at large \(x\) where scattering off u- and d-quarks dominates in the pion production.

Data from ISR: \(\frac{\pi^-}{\pi^+}\) for \(x>0.3\) is \(< 0.5\), weakly depends on \(p_T\) for \(p_t \leq 1.4\) GeV/c and reaches 0.2 for the highest \(x\).

For \(\eta=3.2\) (kinematics of the BRAHMS experiment) pQCD gives for the ratio in pp scattering 0.6 for \(p_t=2.15\) and 0.43 for \(p_t=3.45\) since quarks dominate and \(u/d > 3\).

Correction to convert from \(pp \to \pi^-\) to \(pN \to \pi^- + nN \to \pi^-\):

\[
2xF \frac{\sigma^{dA\to \pi^-+X}}{dxF} \quad \frac{\sigma^{nN\to \pi^-+X}}{dxF} \quad \frac{\sigma^{pN\to \pi^-+X}}{dxF} + xF \frac{\sigma^{pN\to \pi^-+X}}{dxF}
\]

is at least a factor of 1.5.
There appears to be some evidence for non LT effects at highest PT:

Requires $p/\pi^+ \sim 1$ impossible in LT pQCD
What values of \( x_2 \) (smaller of two \( x \)'s) are important in pQCD calculations?

\[ \sqrt{s} = 200\text{GeV}, \langle \eta \rangle = 3.8, p_t = 2\text{GeV/c} \]

Area under the curve illustrates relative contribution of different regions of \( x_2 \)

Median of the integral is \( x_2 \sim 0.013 \), however mean value of \( x_2 \) is substantially larger.
Fig. 2. Same as Fig. 1 but for the GRV [11] parton distributions. Besides $\eta = 3.2$ as relevant for BRAHMS, we have also extended the results to $\eta = 4.2$ which may be useful for future ex-
<η> = 3.2, \( P_T = 1.5 \text{ GeV/c} \)

Shape is nearly the same for different pion channels. It is also practically the same in LO and NLO. Median x is between 0.02 and 0.024.
If central collisions are suppressed due to some other mechanism scattering off periphery dominates where shadowing is even smaller effect.
Fig. 10. LO distributions in $\log_{10}(x_2)$ of the cross section $d\sigma/dp_{T,1}$ for $pp \rightarrow \pi^0\pi^0X$ and $dAu \rightarrow \pi^0\pi^0X$ production at $\sqrt{s} = 200$ GeV. The kinematic variables have been chosen as described in the text. Solid lines are for $pp$ collisions and histograms are for $dAu$, using “shadowing 1”. The higher-lying histograms are for the case of “arbitrary” (i.e., unconstrained) $\eta_2$, the lower ones are for $1.5 \leq \eta_2 \leq 4$. 
Our estimates indicate that interaction of large $x$ partons at RHIC energies is close to the black disk (complete absorption) limit at rather large transverse momenta up to 2 GeV/c. In the BDL quark propagates through large gluon field loosing through splitting and inelastic interactions finite fraction of its initial energy (Frankfurt et al 2001). Qualitative difference from the finite energy losses pQCD scenario.

Within this logic we start from pQCD subprocesses which are suppressed - most strongly at the central impact parameters due to large energy losses in the initial and final state - all together ~ 6% (GSW04) which is much larger than pQCD estimate as a result of parton propagation (at large energies corresponding to large $x_F$) through large gluon fields in nuclei. Correspondingly, the process is predominantly peripheral.
Analysis of the STAR data

FIG. 2: Inclusive $\pi^0$ 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).
FIG. 3: Nuclear modification factor \( (R_{dAu}) \) for minimum-bias d+Au collisions versus transverse momentum \( (p_T) \). The solid circles are for \( \pi^0 \) mesons. The open circles and boxes are for negative hadrons \( (h^-) \) at smaller \( \eta \) [10]. The error bars are statistical, while the shaded boxes are point-to-point systematic errors. (Inset) \( R_{dAu} \) for \( \pi^0 \) mesons at \( \langle \eta \rangle = 4.00 \) compared to the ratio of calculations shown in Figs. 2 and 1.
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 $\Delta \varphi = \varphi_{\text{to}} - \varphi_{\text{LCP}}$ for each event. This provides a coincidence probability $f(\Delta \varphi)$. It is fitted as a sum of two terms - a background term, $B/2\pi$, which is independent of $\Delta \varphi$ and the correlation term $\Delta \varphi$ which is peaked at $\Delta \varphi = \pi$. By construction,

$$\int_0^{2\pi} f(\Delta \varphi) d\Delta \varphi = B + \int_0^{2\pi} S(\Delta \varphi) d\Delta \varphi \equiv B + S \leq 1$$
To use information about central rapidities we need to summarize BRAHMS data for $y=0$ and compare them to Gribov-Glauber model as applied to $dA/AA$ (Kaidalov)

$$R^h = \frac{d\sigma^{d+A\rightarrow h+X}_{dyd^2p_T}}{2A d\sigma^{N+N\rightarrow h+X}_{dyd^2p_T}} = 1,$$

due to Abramovskii, Gribov, Kancheli cancelations provided NN multiplicity is energy independent. Experimentally in $pp$ multiplicity $\sim s^r$, $r\sim 0.2$

$$R^h = \left(\frac{N_{coll}}{2}\right)^{-r}$$

the factor of 2 because of deuteron

roughly consistent with the BRAHMS data at central rapidities for lower $p_t \sim p_{\text{min}}$

A reasonable fit for dependence of soft multiplicity on impact parameter independent of the AGK based interpretation.
FIG. 4: Coincidence probability versus azimuthal angle difference between the forward $\pi^0$ and a leading charged particle at midrapidity with $p_T > 0.5$ GeV/c. The left (right) column is $p+p$ ($d+Au$) data with statistical errors. The $\pi^0$ energy increases from top to bottom. The curves are fits described in the text, including the area of the back-to-back peak ($S'$).
Introduce $p_B$ - probability to produce a hadron within $p_T$ cuts of STAR in soft interactions, and $p_S$ - in hard interactions.

The $p_T$ cut of STAR is rather high (comparable to the momentum of the leading hadron in the recoiling jet for the trigger jet with $<p_T> \sim 1.3 \text{ GeV/c}$. 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 $p_{T_{min}}=0.5 \text{ GeV/c}$).

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

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

$$p_B = B_{pp} \left(1 + \frac{S_{pp}}{2 - B - S}\right), \quad p_S = S_{pp} \left(1 + \frac{B_{pp}}{2 - B - S}\right)$$
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: \(0.093 \pm 0.040\).

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.

\(<\eta> = 0\) corresponds to \(x_A = 0.01\). Hence lack of suppression checks validity of pQCD mechanism below the median of median \(x_A\).
Account of the distribution over the number of the collisions

Define

\[ T(b) = \int_{-\infty}^{+\infty} dz \rho_A(\sqrt{b^2 + z^2}) \]

where \( \rho_A(r) \) is nuclear density normalized as

\[ \int d^3r \rho_A(r) = 1 \]

\[ \sigma_{in}^{pA} = \int d^2b (1 - (1 - T(b)\sigma_{in}^{NN})^A) \]

\[ \sigma_{in}^{pA} = \sum_{1}^{A} \sigma_m, \]

where

\[ \sigma_m = \int d^2b (T(b)\sigma_{in}^{NN})^m (1 - T(b)\sigma_{in}^{NN})^{A-m} \]

is cross sections of inelastic interactions with exactly \( m \) nucleons.
These partial cross sections satisfy the sum rule

$$\sum_{m=1}^{m=A} m\sigma_m = A\sigma_{NN}$$

To model distribution over the number of soft interactions, we need to introduce a suppression factor $SF(b)$ which is a function of the nuclear density per unit area at a given optical density which is given by $T(b)$. We choose two models inspired by the energy loss scenarios of linear and quadratic energy losses:

$$SF^{(1)}(b) = \frac{1}{1 + a_1 T(b)}, \quad SF^{(2)}(b) = \frac{1}{(1 + a_2 T(b))^2}$$

$$a_1 = 2.5, \quad a_2 = 1.63 \quad \text{fixed by} \quad \int T(b) SF^i(b) d^2b = R_{dAu}^{\pi^0} = 0.286$$

measured by STAR for the higher $p_T$ correlation bin corresponding to averaging over $30<E_{\pi}<55$ GeV

$$SF^{(1)}(b = 0) = \frac{1}{5.4}, \quad SF^{(2)}(b = 0) = \frac{1}{20}.$$
\[(1 - B - S) = \sum_{m=A}^{m=1} (1 - B - S)^m \text{collisions} \sigma_m(b) SF(b) d^2b \]

\[
\sum_{m=A}^{m=1} (1 - B - S)^m \text{collisions} \sigma_m(b) SF(b) d^2b
\]

\[
S = \sum_{m=1}^{m=A} S_m \text{collisions} \sigma_m(b) SF(b) d^2b
\]

\[
\sum_{m=1}^{m=A} S_m \text{collisions} \sigma_m(b) SF(b) d^2b
\]

We found that the two models of suppression give very similar results for the observables measured experimentally with the second model for \(SF(b)\) giving slightly larger values of \(S\) and \((1-B-S)\) since it yields a stronger suppression of scattering at the central impact parameters.
pAu - no energy conservation - soft multiplicity $\propto N_{\text{coll}}$

pAu - energy conservation soft multiplicity $\propto N_{\text{coll}}^{0.8}$

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.

$$(1 - B - S) = 0.1, \quad S' = 0.093 \pm 0.04$$

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 $x_p \sim 10^{-3}$
Probability distribution over the transverse distance between proton and neutron - a large tail to very large $b$ - large fraction of interactions where only one nucleon interacted. Can be used to learn more about impact parameter distributions - will discuss later.
Our estimate is a bit lower than the data - smaller number of interactions? Too rough model of the number of interactions of the second nucleon? Presence of the Color fluctuations?

Need for better observables
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 rapidites and transverse momenta:

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

where \( \phi \) is the angle between \( -p_{t f} \) and \( p_{t c} \). We can now introduce

\[ \Delta RR(y_f, |p_{t f}|, y_c, |p_{t c}|, \phi) = . \]

\[ = RR(y_f, |p_{t f}|, y_c, |p_{t c}|, \phi) - RR(y_f, |p_{t f}|, y_c, |p_{t c}|, -\phi) \]
We expect that only hard contribution to the central production depends on $\varphi$. Hence in the case of inclusive quantities like $\Delta RR$ 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 $\eta$ to study variation of $\Delta RR$ 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.

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 $\eta^{trig}$ 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]).
More challenging to extract dependence of the forward rate on impact parameter. More accurately calibrated dependence of multiplicity at $\eta=0$ on the number of collisions in generic collisions with subsequent use for collisions with trigger. First steps along this directions were done by BRAHMS.

Study of the rate of the leading pion production in correlation with central high pt pions for large soft multiplicities $\sim A^{1/3}$. 
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. Consistent with scenario of large energy losses in the regime of black disk limit.

Current STAR data do not indicate any suppression of the recoiling jets. A different analysis of these data may improve accuracy of this statement and look for possible suppression - nuclear shadowing will give some.

Need to build a system of cross calibration of measurements of $N_{\text{coll}}$ - 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.

pAu measurements would help a lot.
Few more slides - supplementary
Use of information from ZDC

(a) Number of neutrons in the nucleus fragmentation is less sensitive to effects of energy splitting between “Pomerons”. Still need cross calibration with soft multiplicity data at central rapidities. Best for selection of events when both nucleons hit Au at small b. Is suppression in this case a factor of 5 as compared to the impulse approximation or 20?

(b) Use of neutron spectators. i) rate of the spectators is larger if collisions are peripheral - can study distribution over number of collisions for such interactions - scan of SF(b) for moderate T(b), ii) imposing cuts on the spectator momentum - smaller b - larger transverse momenta and vice versa (characteristic transverse momentum 150 MeV/c - is this doable with current ZDC. If better energy resolution, one can use $AE_n/(E_A)>1.3$ cut to select situations when both nucleons were close.

Clean way to look for color fluctuations/ color transparency:
Pick two bins with same $R^h$ for say $x=0.2$ and $x=0.3$ (different $p_t$) and look for a drop of $N_{coll}$ for $x=0.5$
If one can reach regime of high transverse momenta where cross section is \( \propto A \) analysis at least for pA would be simple:

\[
N_{\text{coll}}(\text{large } x \text{ trigger}) = 1 + \frac{A - 1}{A} \sigma_{\text{eff}}(x) \int d^2b T^2(b)
\]

presence of the second nucleon would complicate analysis a bit.
Our estimate is a bit lower than the data - smaller number of interactions? Too rough model of the number of interactions of the second nucleon? Presence of the Color fluctuations?

Need for better observables - change of $N_{\text{coll}}$ by 50% led to a rather small change of $B,S$.

*Color fluctuations* - in this case configurations with $x >> 0.3$ correspond to nucleon configurations of smaller transverse size which interact with $\sigma_{\text{eff}} << \sigma_{\text{in}}^{\text{NN}}$ (FS85) and hence lead to smaller $N_{\text{coll}}$ than Gribov-Glauber model.

$$N_{\text{coll}}(\text{large } x \text{ trigger}) = 1 + \frac{A - 1}{A} \sigma_{\text{eff}}(x) \int d^2bT^2(b)$$
Color fluctuations in the nucleon wave function & 3-dimensional mapping of the nucleon

\[ |N\rangle = (3q) + (3qg) + (3q+ \pi) + \]

Fluctuations of interaction strength are likely to be correlated with quark content of the hadron. Smallest configurations are most likely the minimal Fock state ones.

**Important feature of QCD:** QCD sum rules, form factors at large $Q$, chiral dynamics.

**Experimental evidence:** Pion diffraction into two jets, inelastic coherent diffraction off nuclei.

At RHIC energies the variance of the interaction strength is still large $\omega_\sigma \sim 0.25 \div 0.3$

At LHC it is expected to drop to $\omega_\sigma \sim 0.06$
Comment: Fluctuations of strength of nucleon interaction lead to strong modifications of the distribution over the number of wounded nucleons (Baym, LF, MS 93)

Guzey and MS 05
The inelastic small $t$ coherent diffraction off nuclei provides one of the most stringent tests of the presence of the fluctuations of the strength of the interaction in $NN$ interactions. The answer is expressed through $P(\sigma)$ - probability distribution for interaction with the strength $\sigma$. (Miller & FS 93)

$$\sigma_{diff}^h = \int d^2b \left( \int d\sigma P_h(\sigma) |\langle h|F^2(\sigma, b)|h\rangle| - \left( \int d\sigma P(\sigma) |\langle h|F(\sigma, b)|h\rangle| \right)^2 \right).$$

Here $F(\sigma, b) = 1 - e^{-\sigma T(b)/2}$, $T(b) = \int_{-\infty}^{\infty} \rho_A(b, z) dz$, and $\rho_A(b, z)$ is the nuclear density.
\[ \sigma_{DD} \equiv \sigma(pA \rightarrow X + A) \]

Guzey and MS 05

e.m. int. = inelastic interaction of protons with the Coulomb field of the nucleus
The cross section of coherent diffraction dissociation of protons and neutrons on nuclei as a function of the atomic number $A$. The solid lines are the theoretical prediction based on the above eqn. Total cross section data are from the FNAL emulsion and $^4\text{He}$ jet target experiments. The FNAL data on the reaction $n + A \rightarrow p\pi^- + A$ a small fraction of the total diffractive cross section is presented as stars have similar $A$-dependence for all masses and provide a good indication of the overall trend of the $A$-dependence. The theoretical prediction for coherent diffraction on $^4\text{He}$ is given by the dashed lines.