Directions in pA studies

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- *New phenomena in the ultra forward region ($x > 0.1$)*

- *Looking for minijets using multiparton interaction processes*

EF06 TG meeting , June 17, 2020

New phenomena in the ultra forward region ($x > 0.1$)

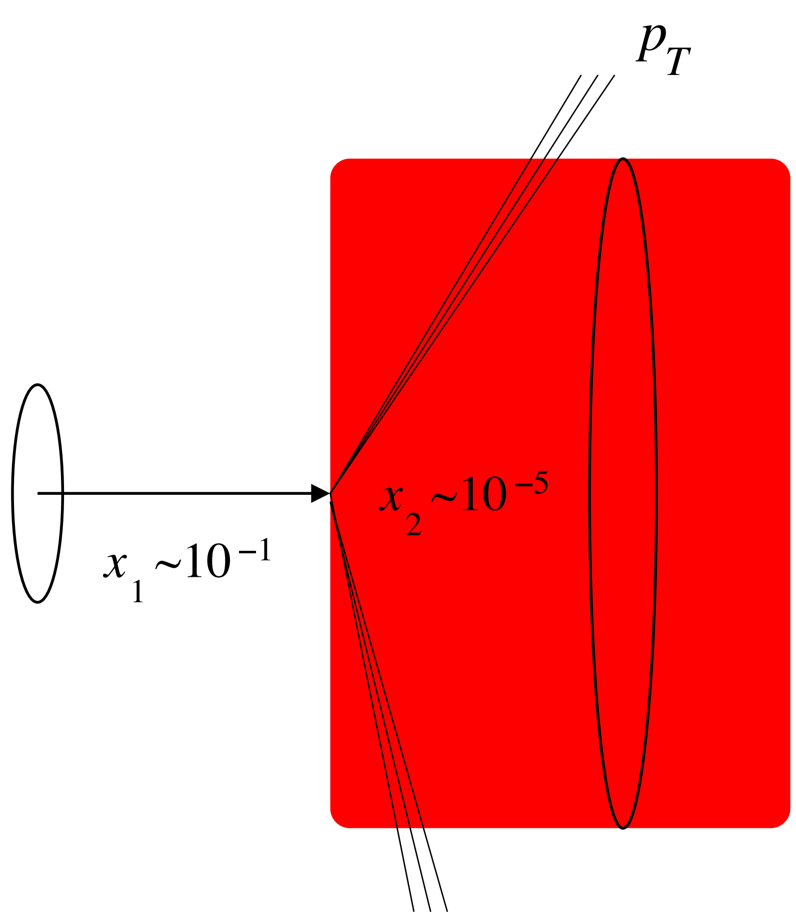
- Black disk limit (limit of 100% absorption) / saturation effects due to the small x effects: in proton - proton/nucleus collisions a parton with given x_1 resolves partons in another nucleon down to $x_2 = 4p_{\perp}^2/x_1 s$

At LHC $x_1 = 0.1, p_{\perp} = 2GeV/c \longrightarrow x_{2min} = 10^{-6}$

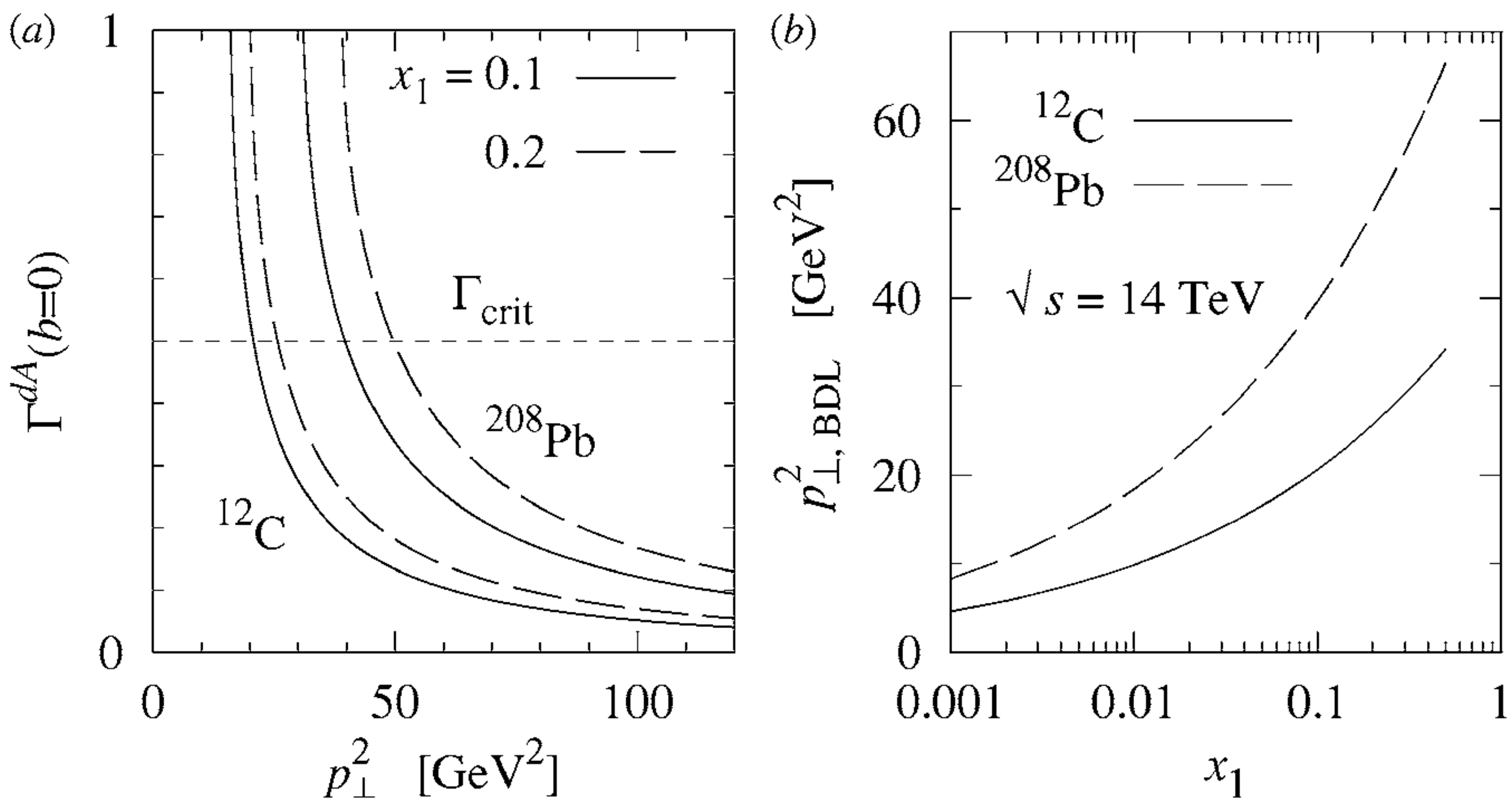
Near GZK $x_1 = 0.1, p_{\perp} = 2GeV/c \longrightarrow x_{2min} = 10^{-9}$

for CR protons

In central pA collisions



Black disk limit in central collisions: Leading partons in the proton, x_1, interact with a dense medium of small x_2 – gluons in the nucleus (shaded area), acquiring a large transverse momentum, $p_\perp$



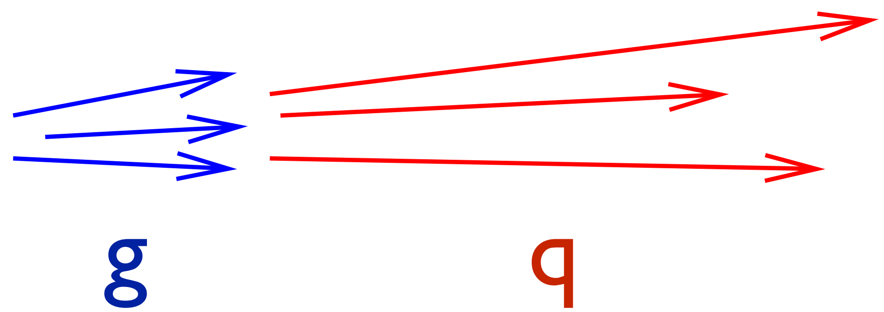
Impact factor Γ("gluon-gluon — dipole" - nucleus for LHC b=0

$$\Gamma(b) = 0.5 \rightarrow \text{Probability to interact} = 0.75$$

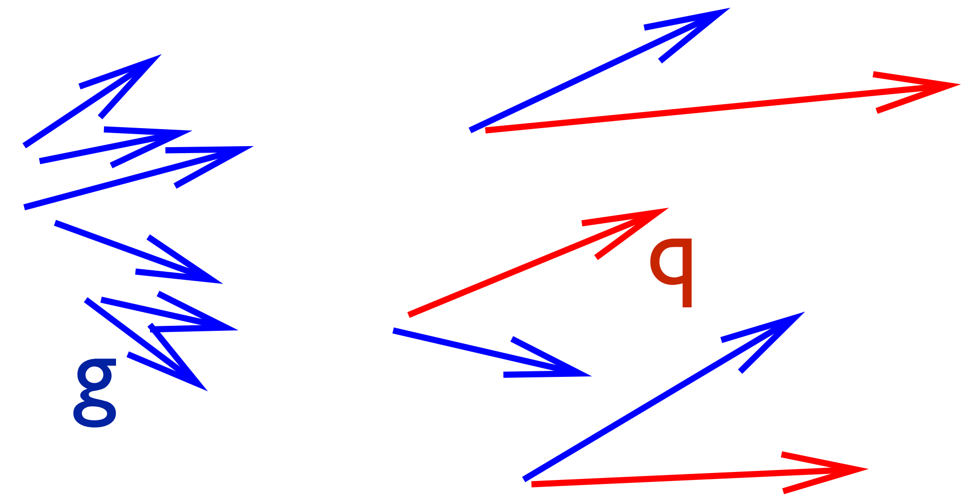
Black–disk limit in central collisions:
(a) The profile function for the scattering of a leading gluon in the proton (regarded as a constituent of a dipole) from the nucleus at zero impact parameter, , as a function of the transverse momentum squared,
(b) The maximum transverse momentum squared, BDL, for which the interaction of the leading gluon is "black" (for quarks it is a factor of two smaller).

$p^2_{\perp,\mathrm{BDL}}$ strongly depends on x, while cutoff in the MC's depends only on s!!!

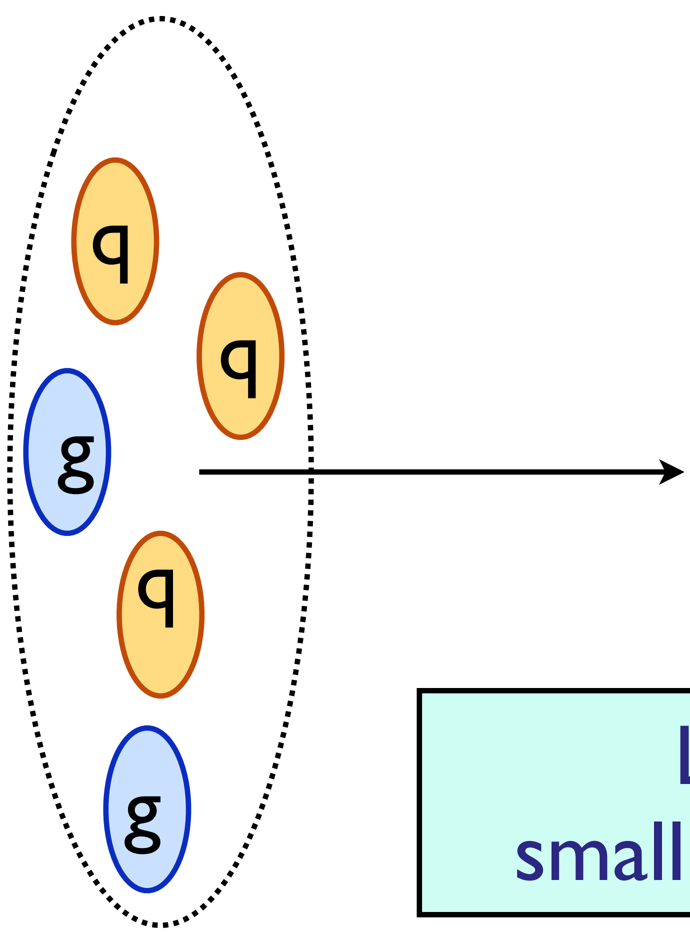
Characteristics of the nucleon fragmentation in the central pA(pp) collisions

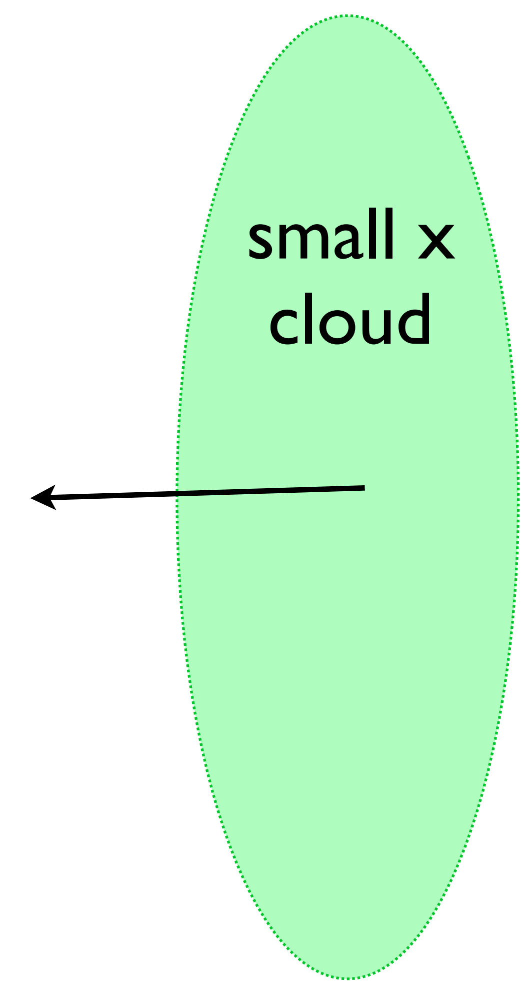


fast partons in a nucleon before collisions



fast partons in a nucleon after central collisions

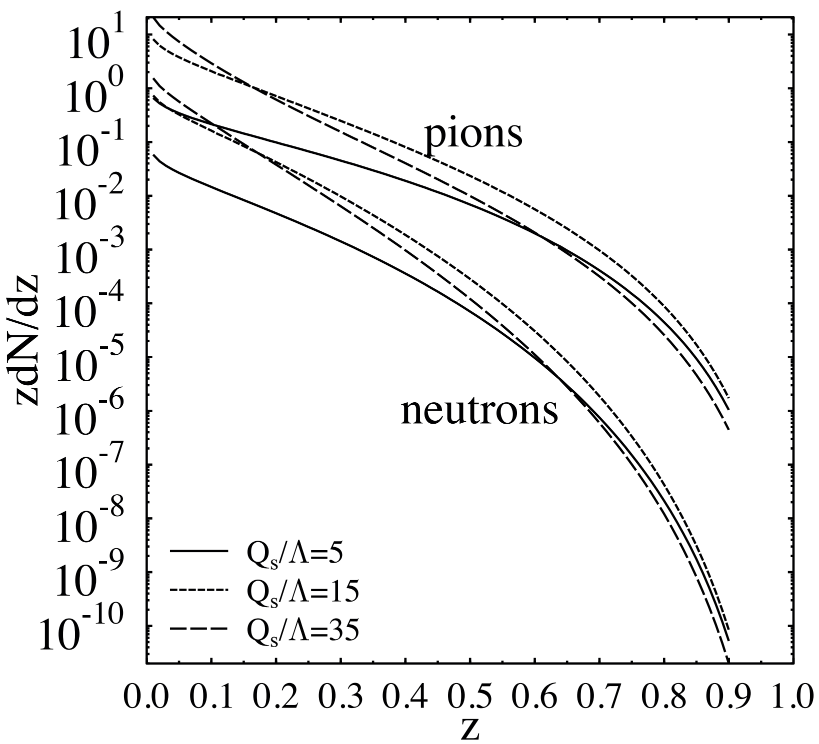


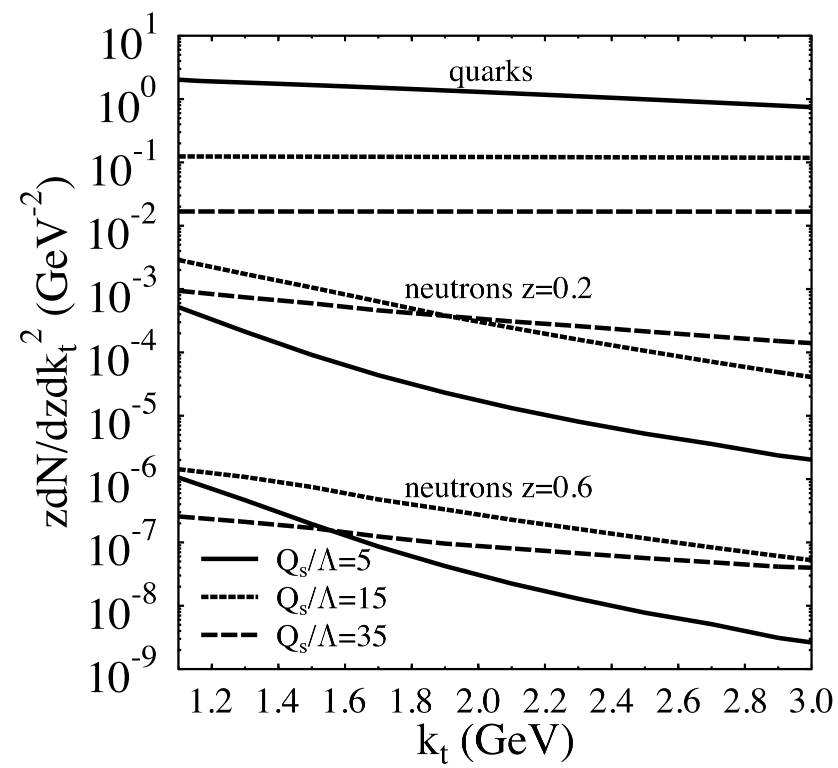


Large x partons burn
small holes in the small x cloud

The leading particle spectrum will be strongly suppressed compared to minimal bias events since each parton fragments independently and splits into a couple of partons with comparable energies. The especially pronounced suppression for nucleons: for $z \geq 0.1$ the differential multiplicity of pions should exceed that of nucleons. This model neglects additional suppression due to finite fractional energy losses in BDL

$$\frac{1}{N}\left(\frac{dN}{dz}\right)^{pA\to h+X} = \sum_{a=q,g}\int dx\, x f_a(x, Q^2_{eff}) D_{h/a}(z/x, Q^2_{eff})$$





Longitudinal (integrated over p_t) and transverse distributions in Color Glass Condensate model for central pA collisions. (Dumitru, Gerland, MS -PRL03). Spectra for central pp - the same trends.

Generic features expected in all model in which interaction strength is comparable with black disk regime:

- ☛ Strong suppression of the large z spectra at low p_t
- ☛ Broadening of the transverse momentum distribution at large z,

Both effects should become more and more pronounced with increase of collision energy and centrality of collision / increase of A.

LHCf / RHICf - inclusive measurements , could not remove contribution peripheral and ultraperipheral collisions (in pA UPC diffraction like events at LHC >> coherent diffractive events)

Suppression can be even stronger as in BDR quarks and gluons loose significant fraction of their energy - 10 —15 %.

MS & Frankfurt

Obvious violation of DGLAP expectations

May have been observed but not explored in sufficient detail at RHIC in forward pion production.

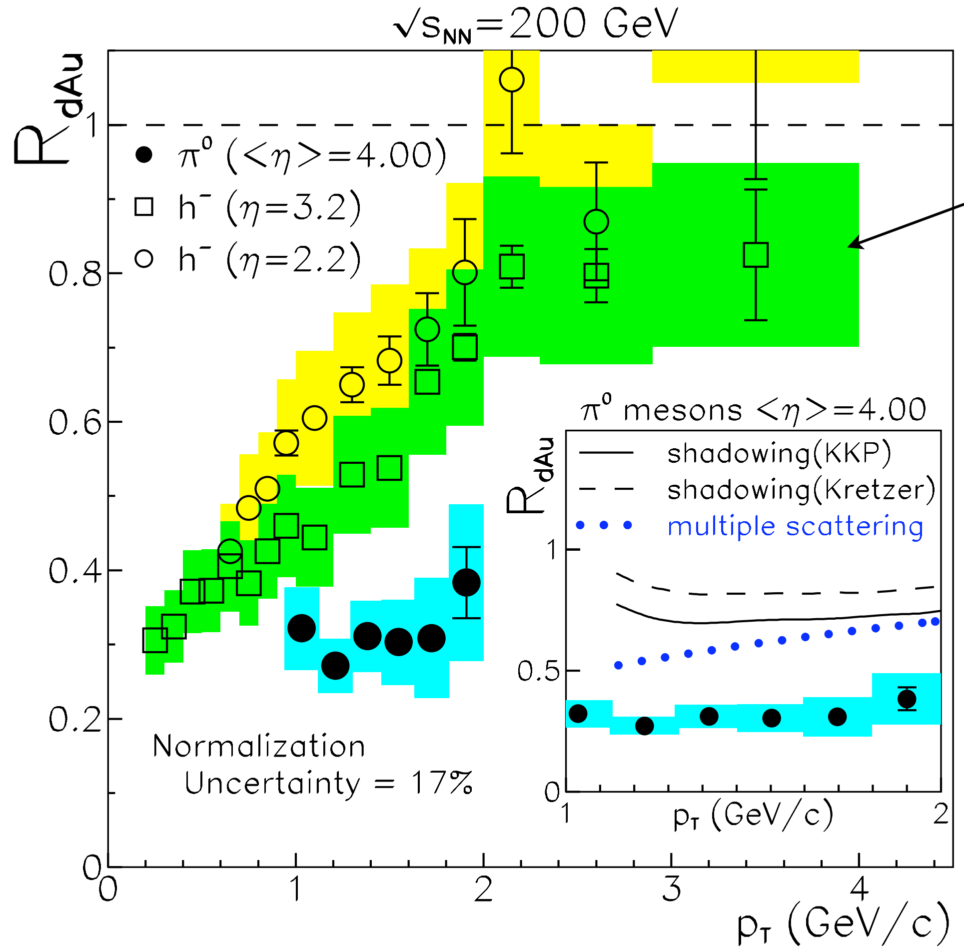
$pp \to \pi^0 + X$ **pQCD works well, essential xg for hard process ~ 0.01.**

$$g_A(x = .01)/g_N(x = .01) \approx 1.$$

pQCD

R_{dA}= 1

grossly violated



Significant nuclear suppression = $R_{dAu}/1.5$

BRAHMS and STAR are consistent when an isospin correction which reduces h- ration measured by BRAHMS by a factor ~ 1.5 (Guzey, MS,Vogelsang 04 =GSV04) is introduced

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.

Summary of the challenge

☞ For pp - pQCD works both for inclusive pion spectra and for forward - central rapidity correlations

☞ Suppression of the pion spectrum for fixed pt increases with increase of ηN. Pion production is mostly from peripheral collisions

The key question what is the mechanism of the suppression of the dominant pQCD contribution - scattering off gluons with $x_A > 0.01$ where shadowing effects are very small.

two scenarios: CGC& post-selection

CGC: leading pions from central collisions;
post-selection - pions from peripheral collisions ← supported by soft multiplicity data

Independent of details - the observed effect is a strong evidence for breaking pQCD approximation. Natural suspicion is that this is due to effects of strong small x gluon fields in nuclei as the forward kinematics sensitive to small x effects.

Future: analysis of the A-dependence/centrality of pion production data at wide range of energies. Production of leading mesons in pp collisions with centrality trigger - like multijet production.

Looking for minijets using multiparton interaction processes

☛ **Do few GeV minijets exist?**

hard (minijet) collisions with p_t ~ few GeV main source of σ_{inel} (pp)

HERWIG, Pythia

puzzle: Suppression factor grows rather rapidly with s

What is mechanism of energy dependence of the suppression of minijets in pp and pA scattering?

explanation (?) saturation - black disk regime - problem similar suppression in peripheral and central pp collisions & present for collisions at x ~ 10^{-2} — 19^{-3}

Need to understand multiparton interactions — sensitive to transverse geometry of colliding hadrons, parton - parton correlations in hadrons

Experimentally one measures the ratio

$$\frac{\frac{d\sigma(p+\bar{p}\to jet_1+jet_2+jet_3+\gamma)}{d\Omega_{1,2,3,4}}}{\frac{d\sigma(p+\bar{p}\to jet_1+jet_2)}{d\Omega_{1,2}}\cdot\frac{d\sigma(p+\bar{p}\to jet_3+\gamma)}{d\Omega_{3,4}}} = \frac{1}{\sigma_{eff}}\,\frac{f(x_1,x_3)f(x_2,x_4)}{f(x_1)f(x_2)f(x_3)f(x_4)}$$

where $f(x_1,x_3), f(x_2,x_4)$ longitudinal light-cone double parton densities and σ_{eff} is ``transverse correlation area". A priori longitudinal correlations contribute as well.

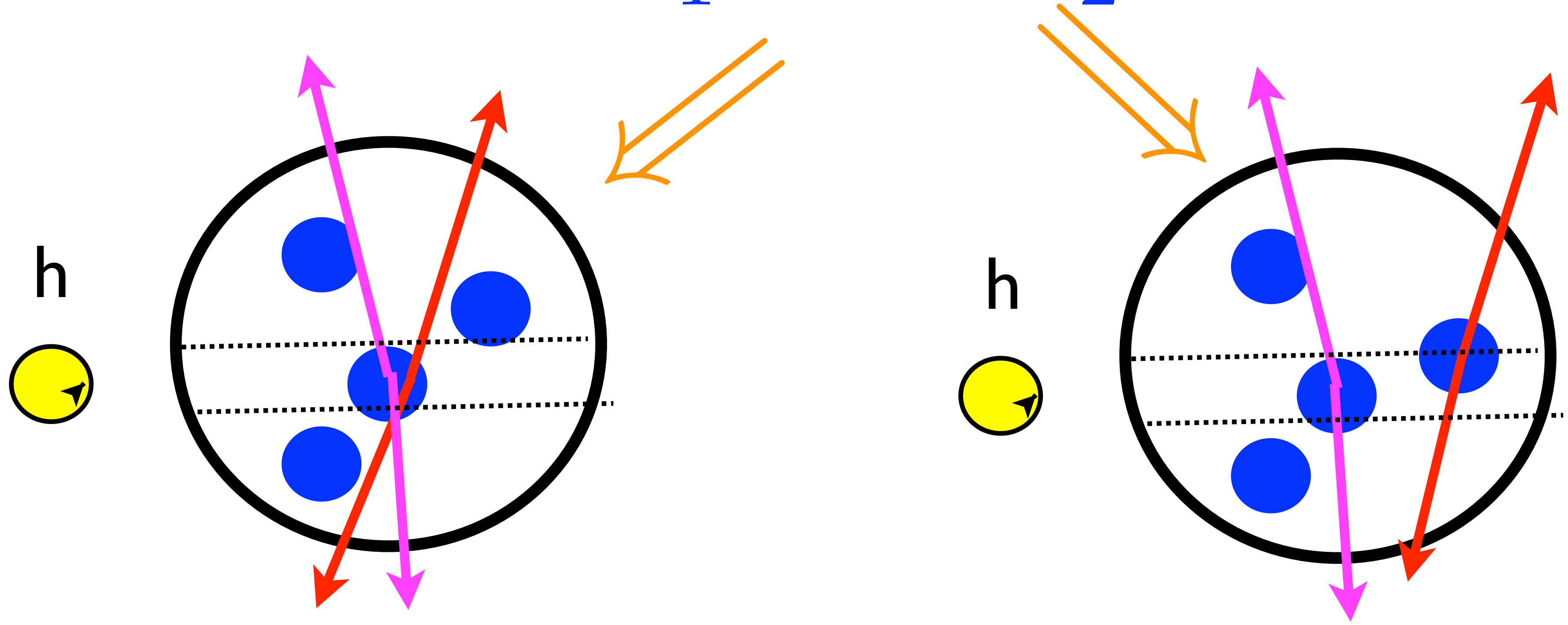
One tries to select kinematics where $2 \to 4$ contribution is small.

Experimental studies - major problem to distinguish higher order pQCD processes like 2 —> 4 and double parton interactions 4 —> 4

DPS in pA - tool to observe DPS, and probe nucleon structrue

MS & Treleani 95 - PRL 2002

$$\sigma = \sigma_1 \cdot A + \sigma_2$$



$$R \equiv \frac{\sigma_2}{\sigma_1 \cdot A} \approx \frac{(A-1)}{A^2} \cdot \sigma_{eff} \int T^2(b)\, d^2b \approx 1.0 \cdot \left(\frac{A}{12}\right)^{0.39} \Big|_{A \geq 12, \sigma_{eff} \sim 20mb}$$

$$T(b) = \int_{-\infty}^{\infty} dz \rho_A(z,b), \int T(b) d^2b = A.$$

"Antishadowing effect": For A=200, and σ_{eff}=20 mb, R=4.0. QCD evolution induced correlation enhance R by ~a factor 1.2

Blok, MS ,Wiedemann 2013: QCD analysis - small correction to the parton model result.

"Antishadowing effect": For A=200, and σ_{eff}=14 mb [25 mb low Q]

$$\frac{\sigma_{pA}}{A\sigma_{pp}} \approx 3$$

σ_{eff}=14 mb

$$\frac{\sigma_{pA}}{\sigma_{pp}} \approx 3.8$$

σ_{eff}=20 mb

LHC large Q

$$\frac{\sigma_{pA}}{A\sigma_{pp}} \approx 4.5$$

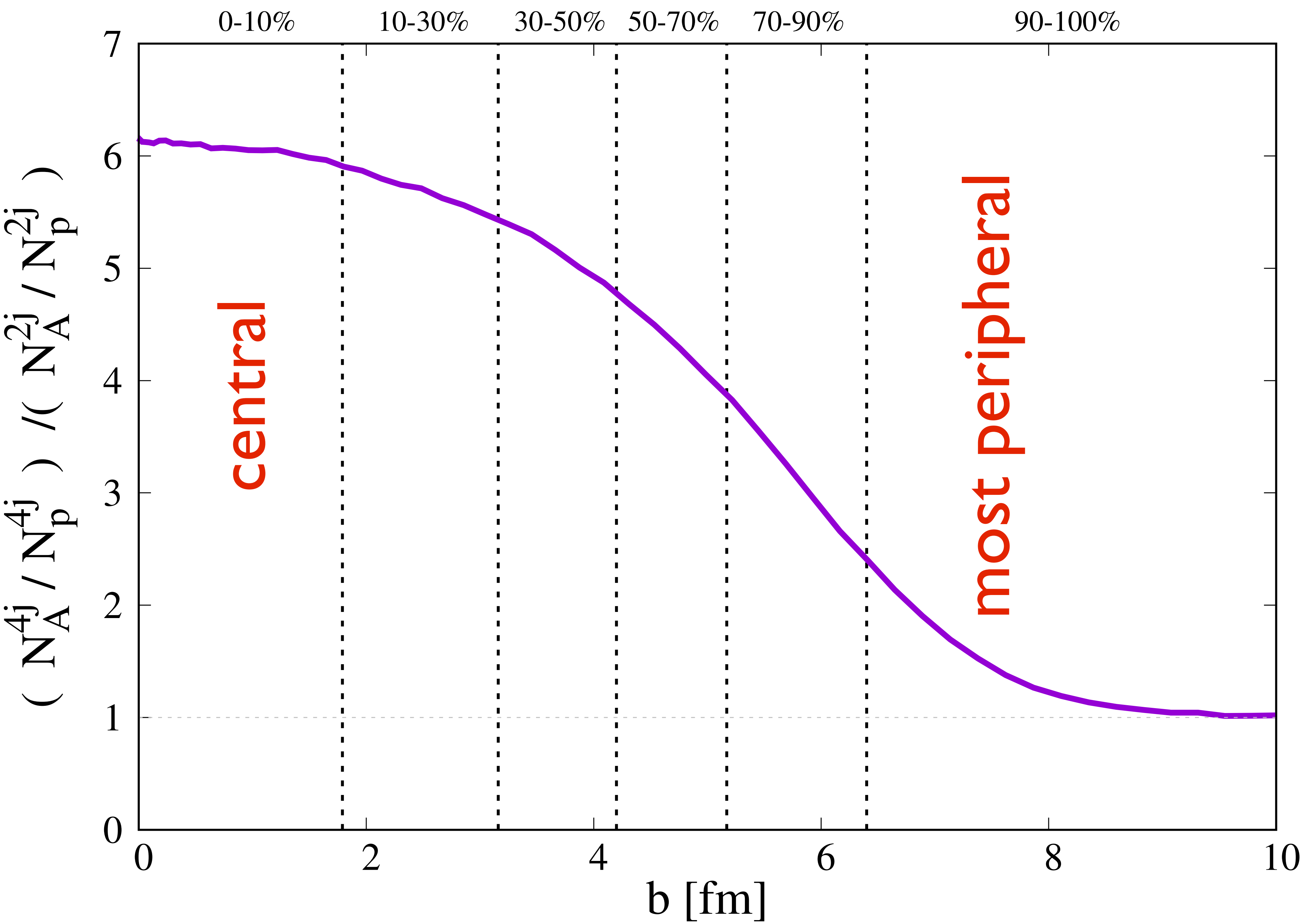
σ_{eff}=25 mb

low Q

Measurement of R=σ_2 /Aσ_1 allows to separate longitudinal and transverse correlations of partons as it measures

$$R \propto \frac{f(x_1, x_2)}{f(x_1)f(x_2)}$$

$$\frac{\left.\frac{DPS(b)}{SPS(b)}\right._A}{\left.\frac{DPS}{SPS}\right._p}$$



Alvioli & MS

Strategy for observing DPS: consider build double ratios :of the rate of candidate DPS events and SPS events in central and peripheral collisions. Expect - a fast increase of the ratio with centrality since all competing 2 --> 4 processes are linear in T(b)..

Idea in nutshell

if no 2—> 3, 4 and and impact parameter b is known for each event

$$R_{DPS/LT}(b) = \sigma_{eff} T(b)$$

also

$$\frac{d\sigma_{pA}^{(DPS)}}{d^2b} = \sigma_{pN} T_A(b) + \sigma_1 \sigma_2 T^2(b)$$

total including LT

model independent prediction for b - dependence of DPS in terms of the elementary (DPS+LT) pp cross section, σ_1,σ_2 and T(b).

No need to separate LT!!!

Nuclear pdf / nucleon pdf =1 for high p_t kinematics for leading pair of jets

Procedure to observe DPI/ MPI in pA

Three contributions to the final state:
(i) the leading twist contribution
(ii) DPS due to the interaction with one nucleon
(iii) DPS due to the interaction with two nucleons.

(i) & (ii) $\propto$ T(b)

(iii) $\propto$ T^2(b)

$$R^{double/inclusive} = N(dijet + pion/jet)/N(dijet) = c_1 + c_2 T(b)$$

No need to model LT contribution

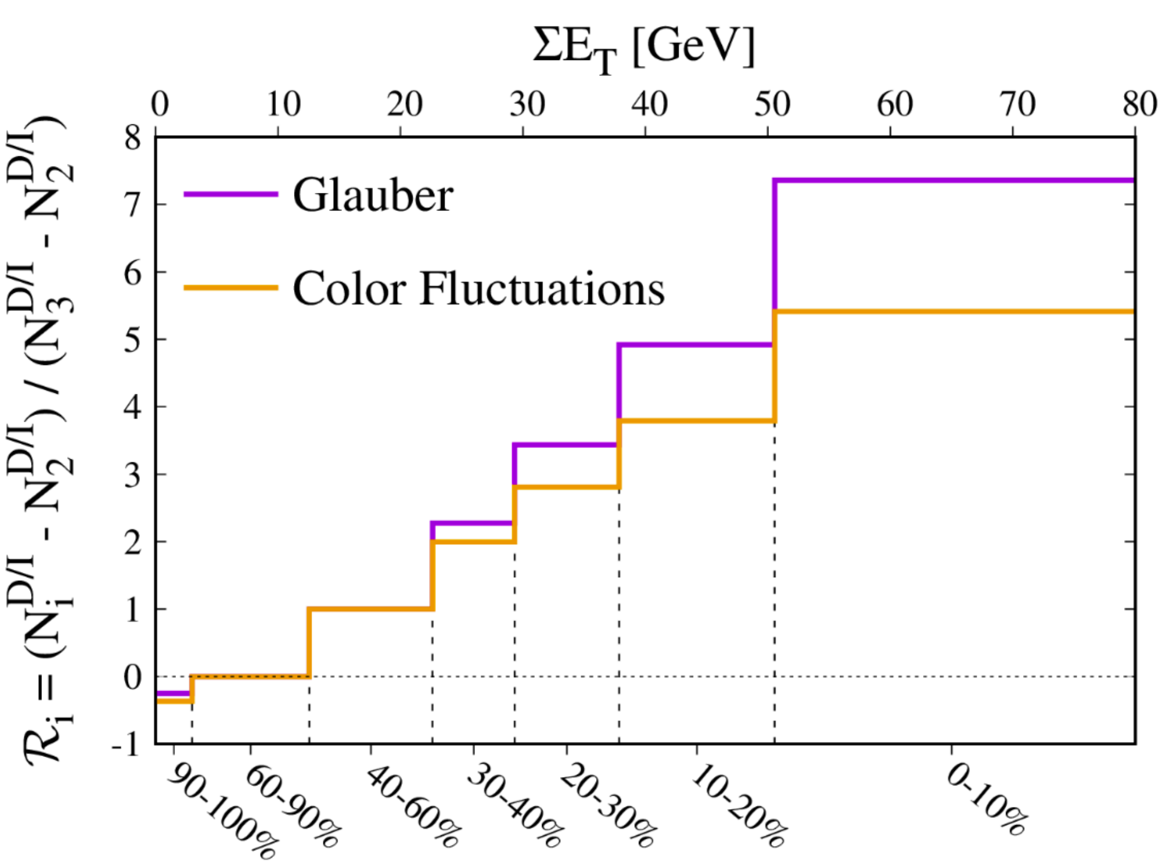
Numerical studies for Z(W)+ dijet, 4 jets of c1, c2 — Blok & Ceccopieri

A bit more advanced procedure

Define N_i = multiplicity of second pair of jets / high p_t pion in the event belonging to a bin of ΣE_T

$$R_i = \frac{N_i - N_2}{N_3 - N_2}$$

Main requirement for using a particular process: process is due to LT plus DPS that is Dependence of N_i on centrality is due to hard scatterings. σ_{eff} cancels in the ratio R. For different pt of jets, pions universal function. We use N_2 to avoid super peripheral collisions where diffraction, etc maybe important. We avoid using information from pp - but can compare N_1,N_2 with pp.



Centrality dependence of DPS multiplicity enhancement as a function of $\sum E_T$ measured in $-3.2 \geq \eta \geq -4.9$ (along the nucleus direction) which corresponds centrality bins denoted in the plot.

Conclusions

pA have a tremendous potential for study novel features of QCD

- **multiparton nucleon structure (+global transverse structure via color fluctuations (Cole's talk)**

- **Superfast quarks(x> 1) in nuclei**

- **Interaction in the high density limit**

- **fruitful interfaces with the physics of ultraperiphral collisions**

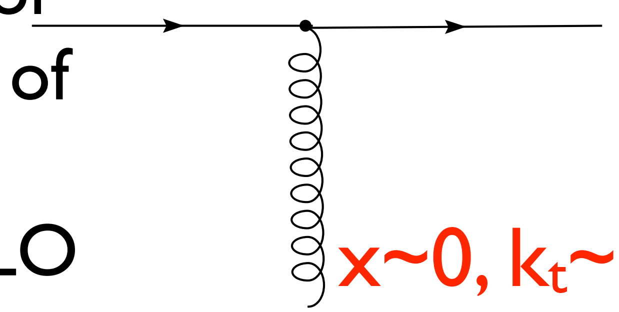
Critical to have data with one or two nuclei in addition to Pb to cross check centrality dynamics.

Supplementary slides

Two possible explanations of d-Au data both based on presence of strong small x gluon fields

✔ *Color Glass Condensate inspired models*

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 $2 \to 1$ process. Plus NLO emissions from quark and gluon lines.



Two effects - (i) gluon 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: $k_t \sim Q_s$

➔ Overall dependence on N_{part} is $(N_{part})^{0.5}$. Hence collisions with high p_t trigger are more central than the minimal bias events, no recoil jets in the kinematics where such jets are predicted in pQCD.

$\Downarrow$

dominant yield from central impact parameters

✔ *Post-selection (effective energy losses) in proximity to black disk regime* - usually only finite energy losses discussed (BDMPS) (QCD factorization for LT) - hence a very small effect for partons with energies 10^4 GeV in the rest frame of second nucleus. Not true in BDR - post selection - energy splits before the collision - effectively 10- 15 % energy losses decreasing with increase of k_t. Large effect on the pion rate since x_q's, z's are large,

$\Downarrow$

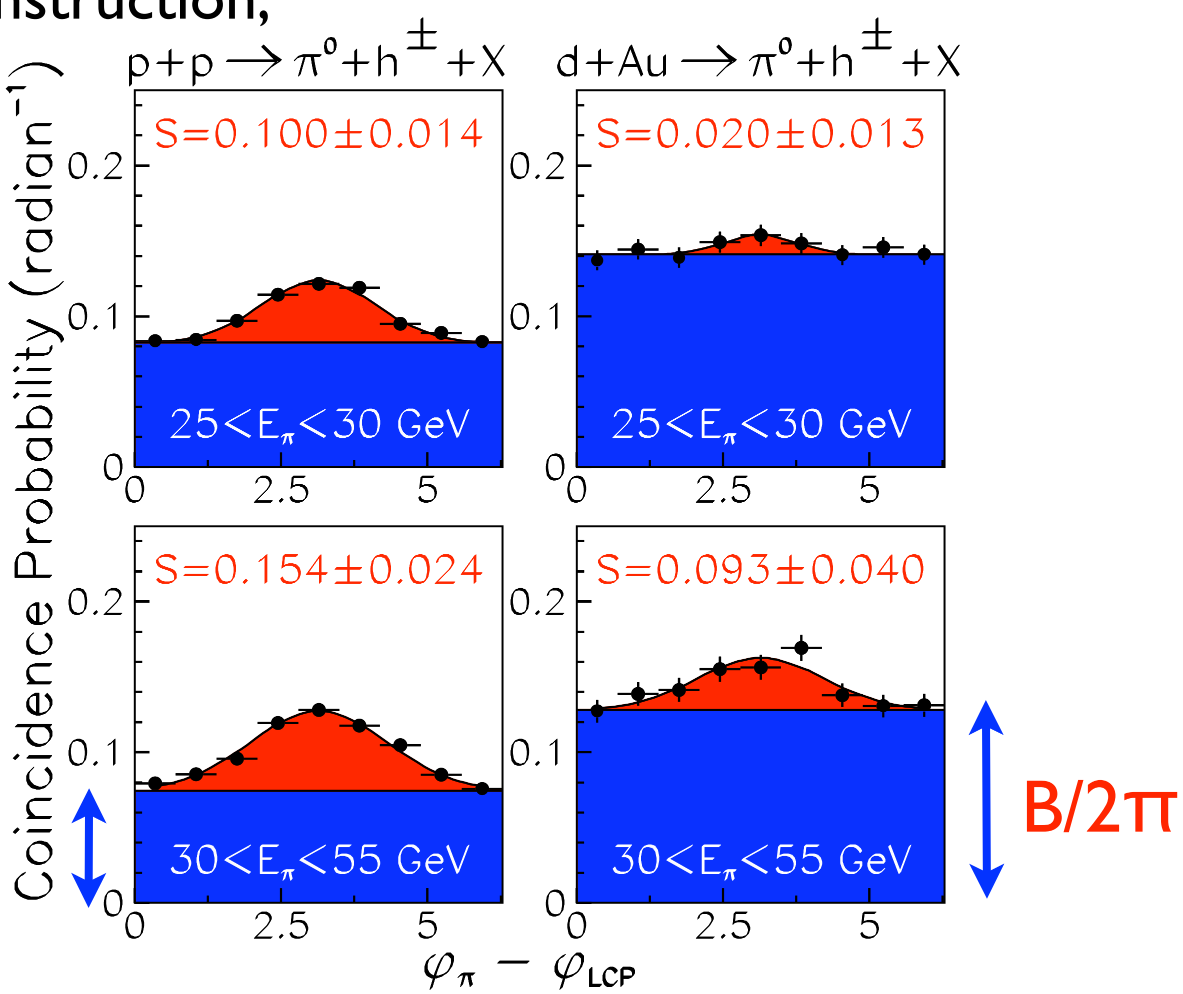
dominant yield from scattering at peripheral impact parameters

Analysis of the STAR correlation data of 2006

Forward central correlations - kinematics corresponding to $x_A \sim 0.01$ - main contribution in $2\to2$

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 $\Delta\varphi=\varphi_{\pi^0}-\varphi_{LCP}$ 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,

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



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 curves are fits of the STAR. 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, $N_{coll} \sim 16$)

Detailed analysis using BRAHMS result: central multiplicity $\propto N^{0.8}$. Our results are not sensitive to details though 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.

average number of wounded nucleons in events with leading pion: $\langle N \rangle \cong 3$

We find $S(dAu) \approx 0.1$ assuming no suppression of the second jet. Data: $S(dAu) = 0.093 \pm 0.040$

Thus, the data are consistent with no suppression of recoil jets. PHENIX analysis which effectively subtracts the soft background - similar conclusion. 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 $(1\text{-}B\text{-}S) < 0.01$, $S < 0.01$ since for such collisions $N_{coll} \sim 13$. This would be the case even if the central mechanism would result in a central jet.

Test of our interpretation - ratio, R, of soft pion multiplicity at $y \sim 0$ with π^0 trigger and in minimal bias events.

In CGC scenario R ~ 1.3

In BDR energy loss scenario we calculated R ~ 0.5

STAR - R ~0.5 Gregory Rakness - private communication

$\langle \eta \rangle = 0$ corresponds to $x_A = 0.01 \Rightarrow$ lack of suppression proves validity of $2 \rightarrow 2$ for dominant x_A region.

Correlation data appear to rule out CGC $2 \rightarrow 1$ mechanism as a major source of leading pions in inclusive setup $\Rightarrow$ NLO CGC calculations of inclusive yield grossly overestimates $2 \rightarrow 1$ contribution.