Forward di-hadron correlations in d+Au collisions

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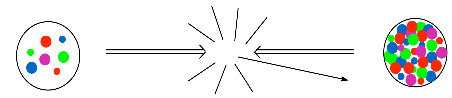
Motivation

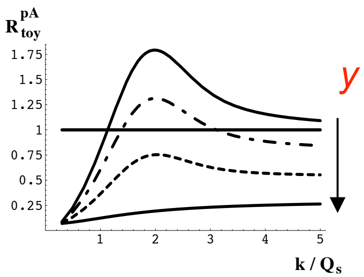
- after the first d+Au run at RHIC, there was a lot of new results on single inclusive particle production at forward rapidities

$d\,Au \rightarrow h\,X$



the spectrum $\frac{d\sigma^{dAu\rightarrow hX}}{d^2kdy}$ and

the modification factor $R_{dA} = \frac{1}{N_{coll}} \frac{dN^{dA\rightarrow hX}}{d^2kdy} \Big/ \frac{dN^{pp\rightarrow hX}}{d^2kdy}$ were studied



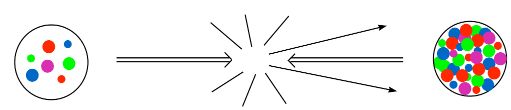
the suppressed production (R_{dA} < 1) was predicted in the Color Glass Condensate picture of the high-energy nucleus

- but single particle production probes limited information about the CGC

(only the 2-point function)

to strengthen the evidence, we need to study more complex observables

- focus on di-hadron azimuthal correlations



a measurement sensitive to possible modifications of the back-to-back emission pattern in a hard process

$d\,Au \rightarrow h_1\,h_2\,X$

Outline

- Introduction to parton saturation

  - the hadronic/nuclear wave function at small x
  - non-linear parton evolution in QCD and the saturation scale

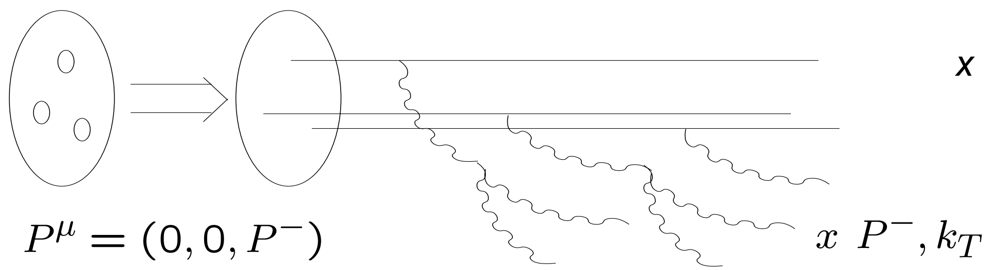
- Di-hadron correlation measurements

  - at high-p_T and central rapidities : leading-twist physics
  - at low-p_T and central rapidities : high-x p_T broadening physics
  - at low-p_T and forward rapidities : low-x saturation physics

- Forward/forward d+Au data and CGC predictions

  - forward di-pion correlations : monojets are produced in central d+Au
  - CGC: parameters fixed with single particle spectra
  - the CGC predictions reproduce the measured azimuthal correlations

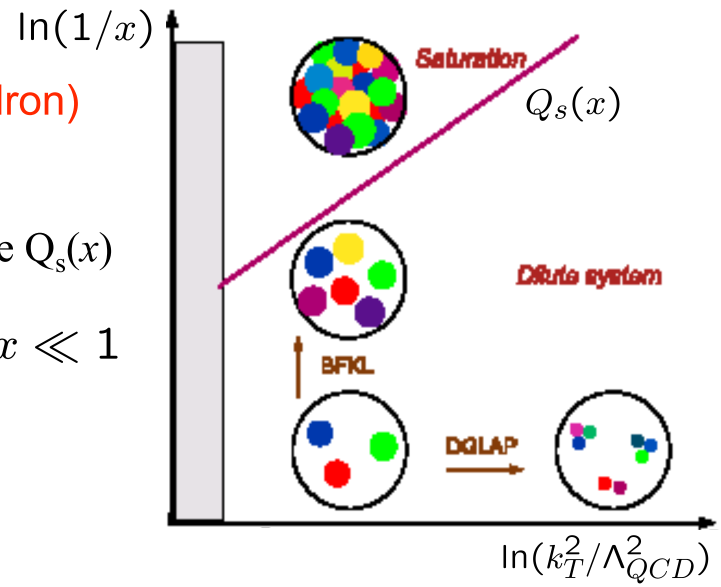
Parton saturation



x : parton longitudinal momentum fraction

k_T : parton transverse momentum

the distribution of partons as a function of x and k_T :



QCD linear evolutions: $k_T \gg Q_s$

DGLAP evolution to larger k_T (and a more dilute hadron)

BFKL evolution to smaller x (and denser hadron)

dilute/dense separation characterized by the saturation scale $Q_s(x)$

QCD non-linear evolution: $k_T \sim Q_s$ meaning $x \ll 1$

$\rho \sim \frac{xf(x, k_\perp^2)}{\pi R^2}$ gluon density per unit area

it grows with decreasing x

$\sigma_{rec} \sim \alpha_s / k^2$ recombination cross-section

recombinations important when $\rho\ \sigma_{rec} > 1$

the saturation regime: for $k^2 < Q_s^2$ with $Q_s^2 = \frac{\alpha_s x f(x, Q_s^2)}{\pi R^2}$

this regime is non-linear yet weakly coupled

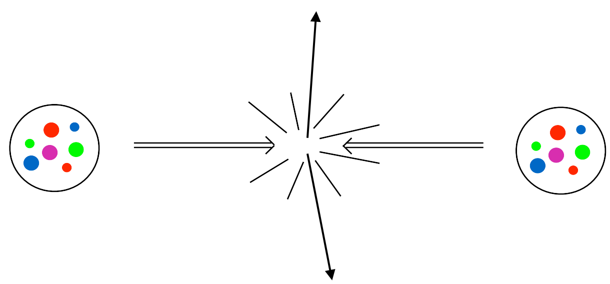
$\alpha_s(Q_s^2) \ll 1$

Di-hadron correlation measurements

Di-hadron final-state kinematics

final state : $k_1, y_1 \quad k_2, y_2$ $\qquad x_p = \dfrac{k_1\, e^{y_1} + k_2\, e^{y_2}}{\sqrt{s}} \qquad x_A = \dfrac{k_1\, e^{-y_1} + k_2\, e^{-y_2}}{\sqrt{s}}$

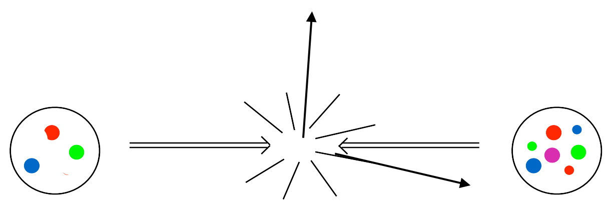
- scanning the wave-functions



$$x_p \sim x_A < 1$$

central rapidities probe moderate x

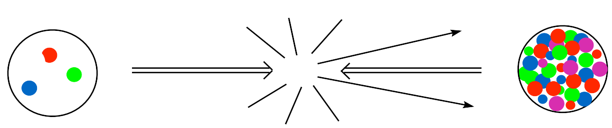
x_p increases | x_A ~ unchanged



$$x_p \sim 1,\, x_A < 1$$

forward/central doesn't probe much smaller x

x_p ~ unchanged | x_A decreases

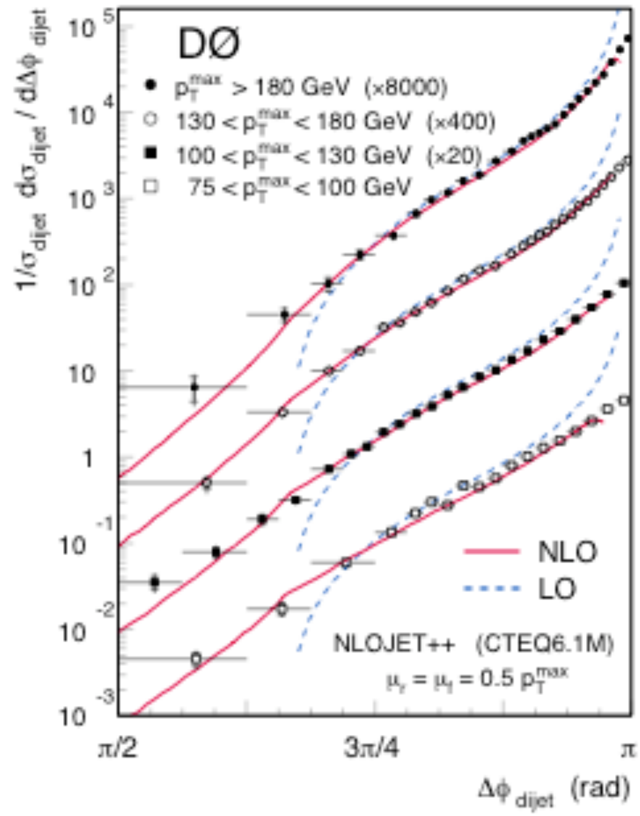


$$x_p \sim 1,\, x_A << 1$$

forward rapidities probe small x

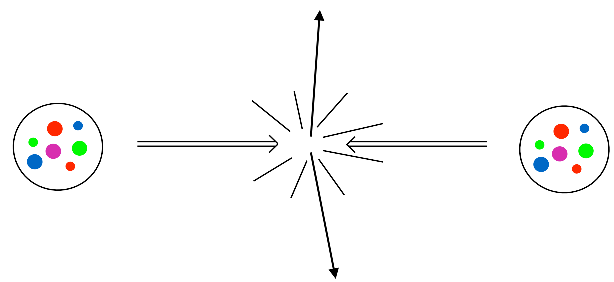
Dijets in standard pQCD

in pQCD calculations based on collinear factorization, dijets are back-to-back

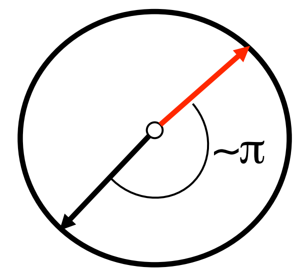


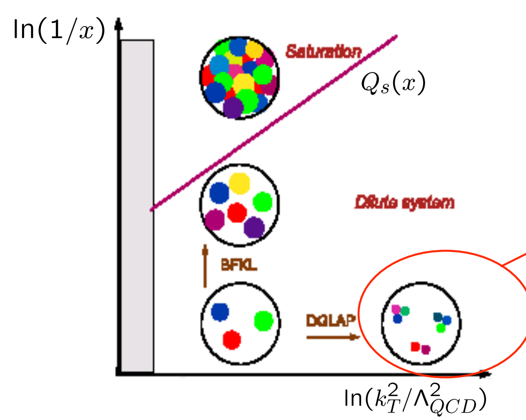
peak narrower with higher p_T

this is supported by Tevatron data with high p_T's



transverse view





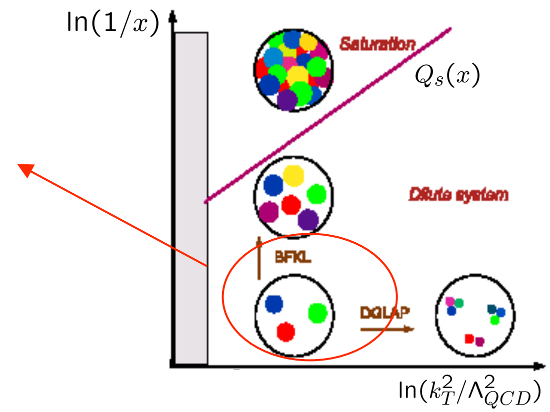
probing Λ_{QCD}/p_T <<1

power corrections are negligible

p_T broadening at large x

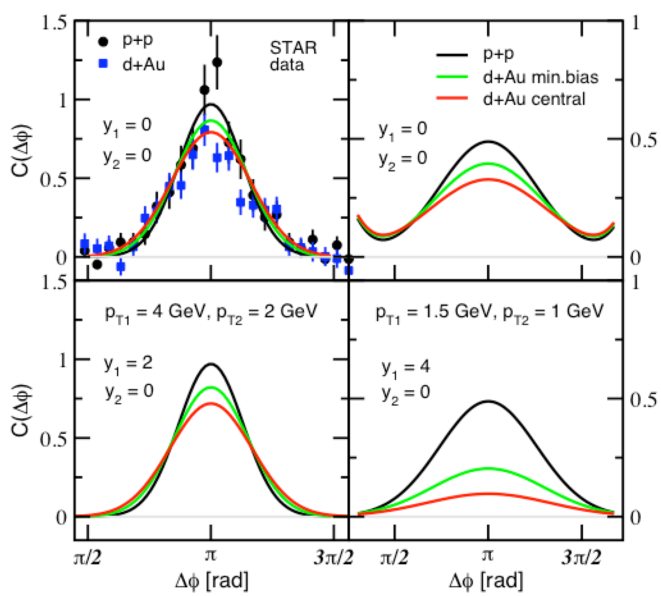
with lower transverse momenta, multiple scatterings become important

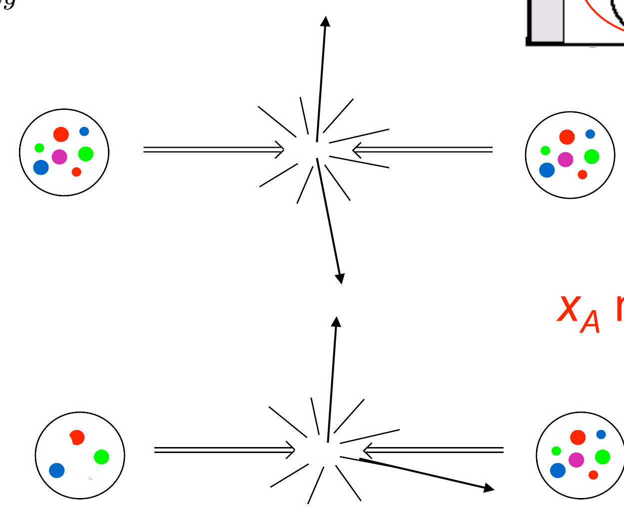
probing p_T not much higher than Λ_{QCD}
higher twists are important, especially with nuclei



a Gaussian model with $\sigma_{Away} \sim \hat{q}$

$$C(\Delta\phi) = \frac{A_{Near}}{\sqrt{2\pi}\sigma_{Near}} e^{-\frac{\Delta\phi^2}{2\sigma_{Near}}} + \frac{A_{Away}}{\sqrt{2\pi}\sigma_{Away}} e^{-\frac{\Delta\phi^2}{2\sigma_{Away}}}$$





x_A not small > 0.01

Qiu and Vitev (2006)   also Kharzeev, Levin, McLerran (2005)

forward/central data

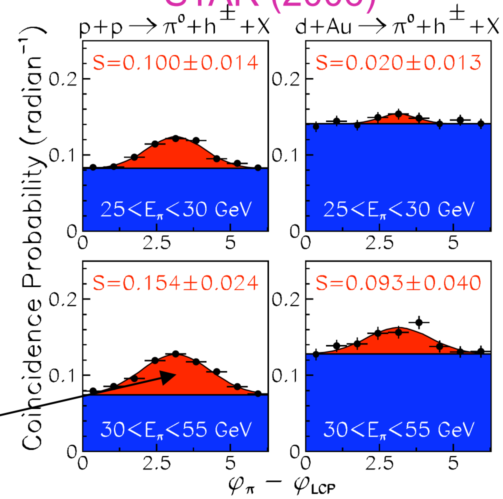
qualitative agreement with data, but quantitative ?

coincidence probability

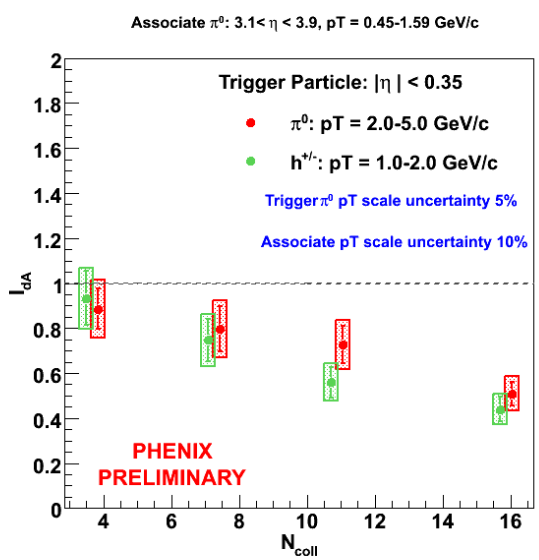
$$CP(\Delta\phi) = \frac{1}{N_{trigger}} \frac{dN_{pair}}{d\Delta\phi}$$

$$I_{dA} = \frac{S_{dAu}}{S_{pp}}$$

STAR (2006)



signal

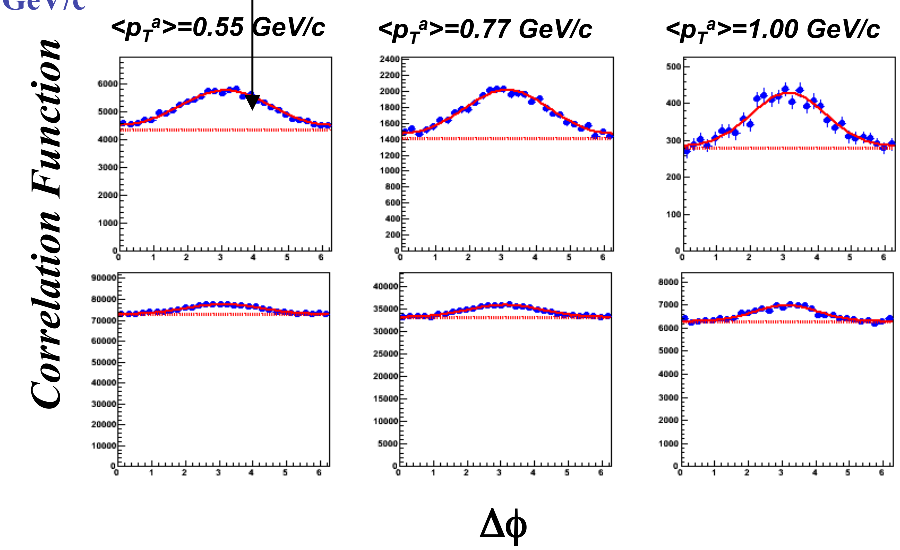


$1.0 < p_T^t < 2.0$ GeV/c

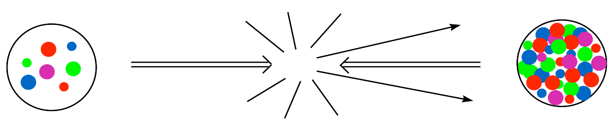
for all plots

pp

dAu 0-20%



Forward/forward correlations

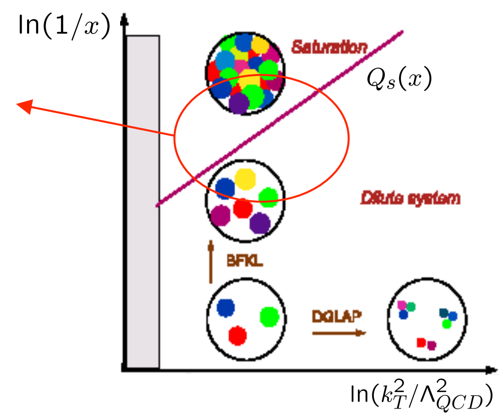


What changes at small x

at small x, multiple scatterings are characterized by Q_S (not Λ_{QCD} anymore)

$\hat{q}$ or intrinsic k_T , or whatever is introduced to account for higher twists in the OPE becomes ~ Q_S

in addition, when $p_T \sim Q_S$ and therefore multiple scatterings are important, so is parton saturation



the OPE approach is not appropriate at small x, because all twists contribute equally starting from the leading twist result and calculating the next term is not efficient

when x is large, we don't know a better way,
but when x is small (such that $Q_S >> \Lambda_{QCD}$), we do

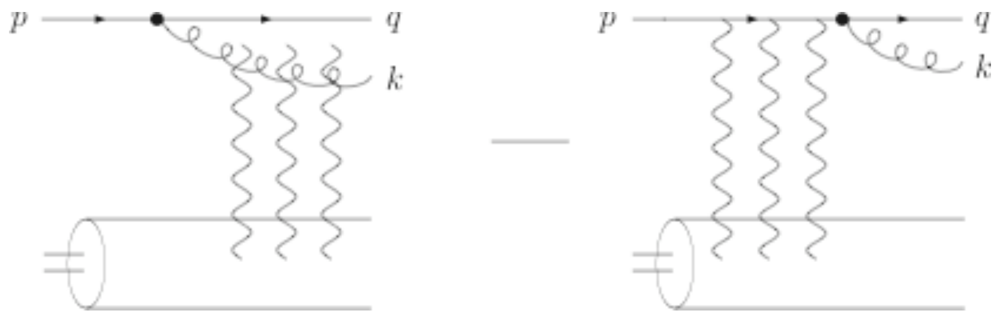
the CGC can be used to resum the expansion Q_S/p_T expansion

- forward dijet production

calculations with different levels of approximations

Jalilian-Marian and Kovchegov (2005)
Baier, Kovner, Nardi and Wiedemann (2005)
Nikolaev, Schafer, Zakharov and Zoller (2005)
C.M. (2007)

Forward di-jet production



b: quark in the amplitude
x: gluon in the amplitude
b': quark in the conj. amplitude
x': gluon in the conj. amplitude

collinear factorization of quark density in deuteron

Fourier transform $k_\perp$ and $q_\perp$ into transverse coordinates

$$\frac{d\sigma^{dAu\to qgX}}{d^2k_\perp dy_k d^2q_\perp dy_q} = \alpha_S C_F N_c\, x_d q(x_d,\mu^2) \int \frac{d^2x}{(2\pi)^2}\frac{d^2x'}{(2\pi)^2}\frac{d^2b}{(2\pi)^2}\frac{d^2b'}{(2\pi)^2}\, e^{ik_\perp.(\mathbf{x}'-\mathbf{x})} e^{iq_\perp.(\mathbf{b}'-\mathbf{b})}$$

$$\left|\Phi^{q\to qg}(z,\mathbf{x}-\mathbf{b},\mathbf{x}'-\mathbf{b}')\right|^2 \Big\{ S^{(4)}_{qg\bar{q}g}[\mathbf{b},\mathbf{x},\mathbf{b}',\mathbf{x}';x_A] - S^{(3)}_{qg\bar{q}}[\mathbf{b},\mathbf{x},\mathbf{b}'+z(\mathbf{x}'-\mathbf{b}');x_A]$$

$$-S^{(3)}_{\bar{q}gq}[\mathbf{b}+z(\mathbf{x}-\mathbf{b}),\mathbf{x}',\mathbf{b}';x_A] + S^{(2)}_{q\bar{q}}[\mathbf{b}+z(\mathbf{x}-\mathbf{b}),\mathbf{b}'+z(\mathbf{x}'-\mathbf{b}');x_A]\Big\}$$

pQCD $q \to qg$ wavefunction

interaction with hadron 2 / CGC

$$z = \frac{|k_\perp|e^{y_k}}{|k_\perp|e^{y_k} + |q_\perp|e^{y_q}}$$

n-point functions that resums the powers of $g_S A$ and the powers of $\alpha_S \ln(1/x_A)$

computed with JIMWLK evolution at NLO (in the large-Nc limit), and MV initial conditions   no parameters

CGC predictions

with a large-Nc approximation to practically handle to 4-point function

C.M. (2007) $S^{(4)}$ and $S^{(3)}$ expressed as non-linear functions of $S^{(2)}$

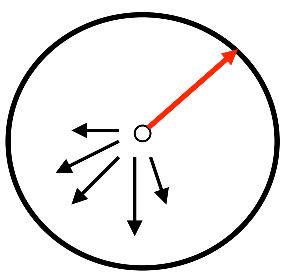
even though the knowledge of $S^{(2)}$ is enough to predict the forward dihadron spectrum, there is no k_T factorization: the cross section is a non-linear function of the gluon distribution

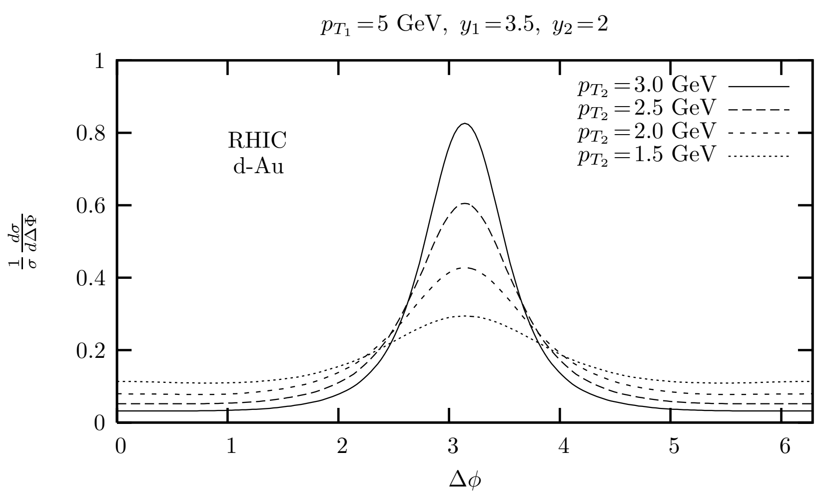
- some results for $(1/\sigma)\, d\sigma/d\Delta\Phi$

$$k_1 = 5 \text{ GeV},\ y_1 = 3.5,\ y_2 = 2$$

k_2 is varied from 1.5 to 3 GeV

as k_2 decreases, it gets closer to Q_S and the correlation in azimuthal angle is suppressed

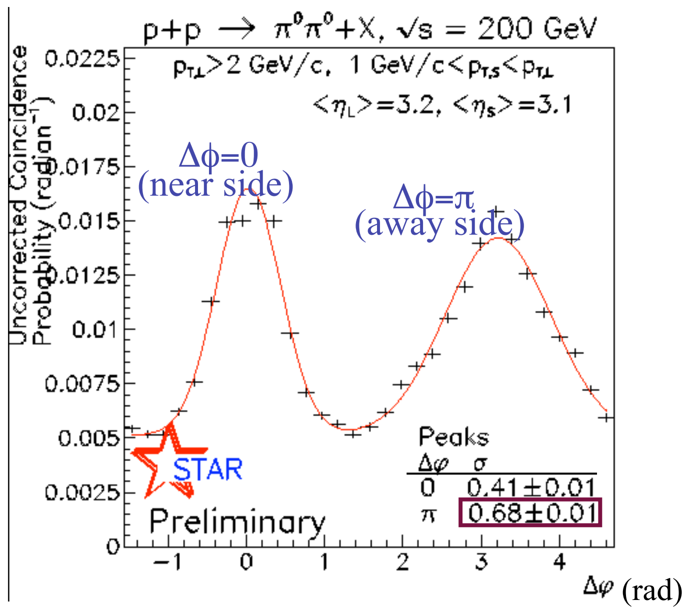




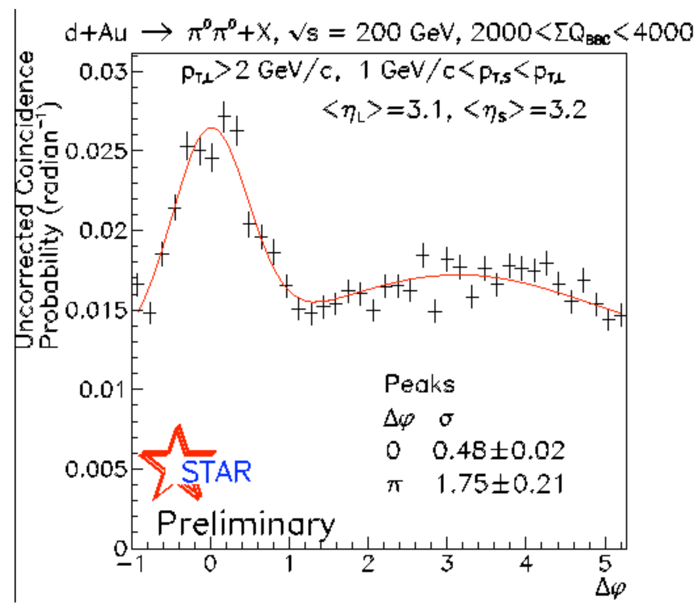
azimuthal correlations are only a small part of the information contained in $\dfrac{d\sigma^{pA\to h_1 h_2 X}}{d^2k_1 dy_1 d^2k_2 dy_2}$

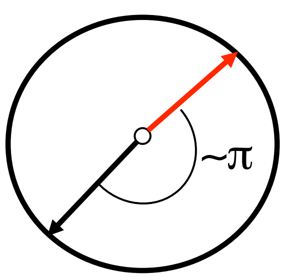
Evidence of monojets

p+p

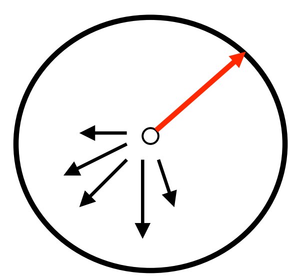


d+Au central





transverse view



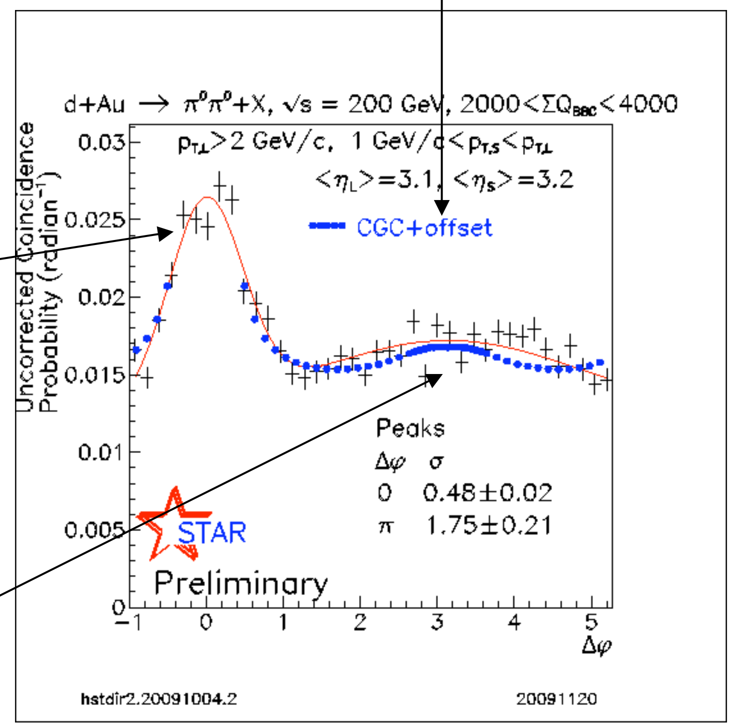
Monojets in central d+Au

- in central collisions where Q_S is the biggest

there is a very good agreement of the saturation predictions with STAR data

Albacete and C.M., to appear

an offset is needed to account for the background



to calculate the near-side peak, one needs di-pion fragmentation functions

- the focus is on the away-side peak

where non-linearities have the biggest effect

suppressed away-side peak

standard (DGLAP-like) QCD calculations cannot reproduce this

The centrality dependence

it can be estimated by modifying the initial condition for NLO-BK evolution

for a given impact parameter,
the initial saturation scale used is

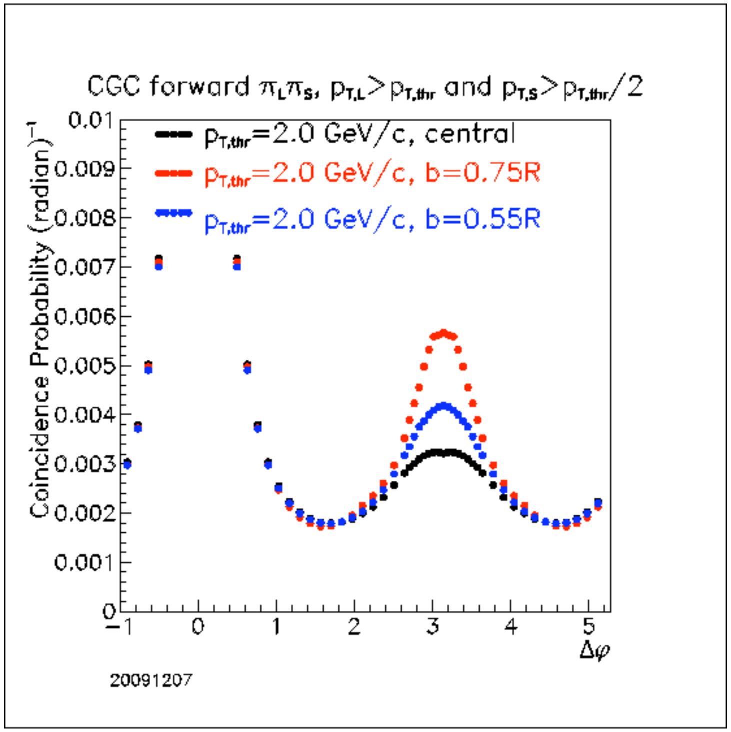
$$Q_s^2(b) = Q_s^2(0)\sqrt{1 - b^2/R^2}$$

peripheral collisions are like p+p collisions

the away-side peak is reappearing
when decreasing the centrality

the near-side peak is unchanged

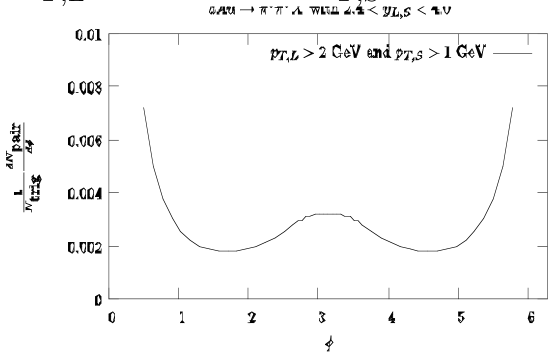
data not binned in centrality yet, but soon



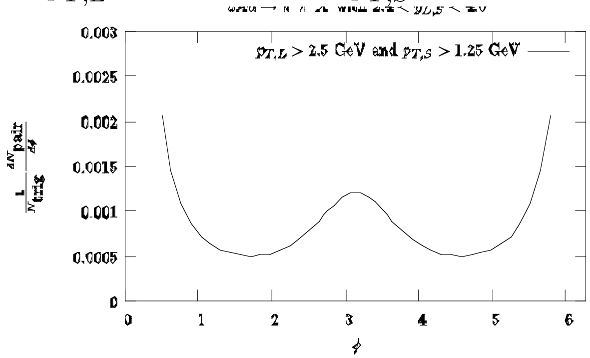
The p_T dependence

with higher p_T, one goes away from the saturation regime

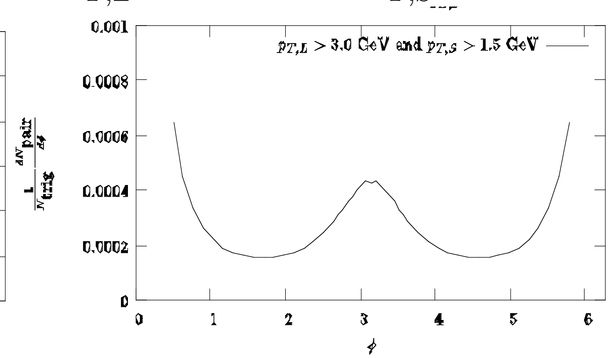
$p_{T,L} > 2$ GeV and $p_{T,S} > 1$ GeV



$p_{T,L} > 2.5$ GeV and $p_{T,S} > 1.25$ GeV



$p_{T,L} > 3$ GeV and $p_{T,S} > 1.5$ GeV



the away-side peak is restored at higher p_T, since this means larger x

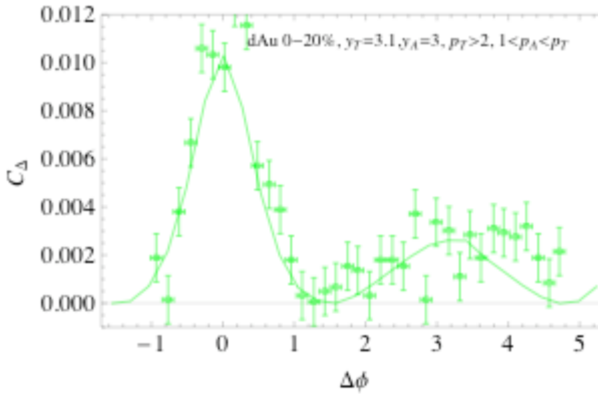
Alternatives to CGC ?

Tuchin (2010)

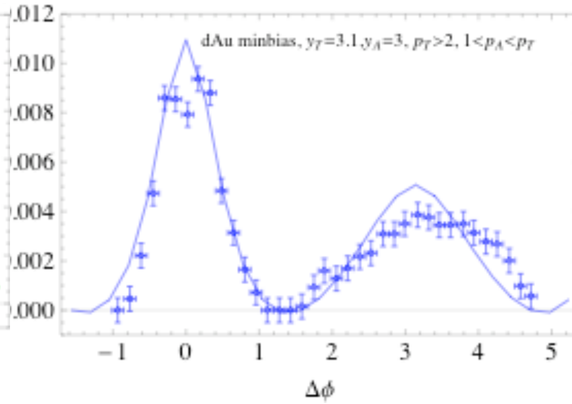
I am aware of one, but saturation is still a crucial ingredient

model assuming k_T factorization, neglecting fragmentation, and using KLN evolution

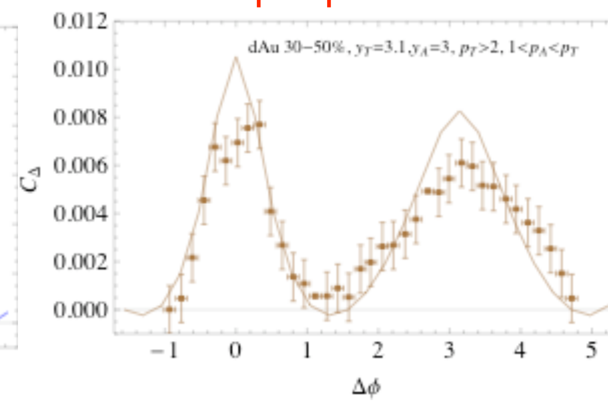
central



minimum-bias



peripheral



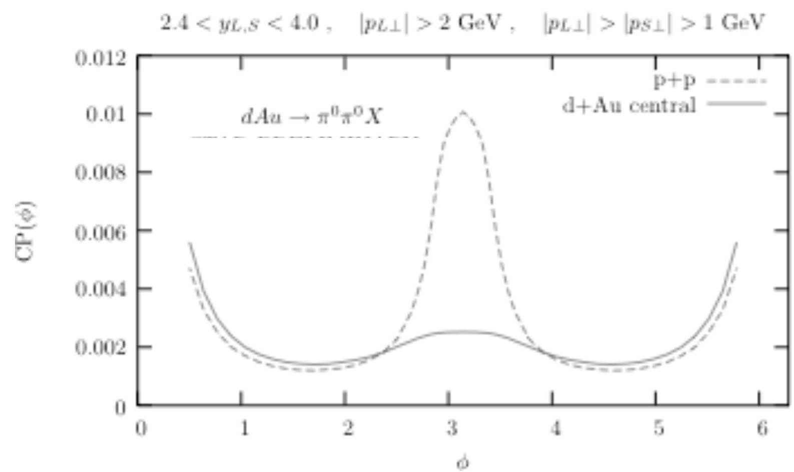
centrality of data not determined yet, but qualitatively right

can the alternative scenarios that explain the suppressed R_{pA} without saturation explain this ?

Conclusions

the magnitude of the away-side peak, compared to that of the near-side peak, decreases from p+p to d+Au central

this happens at forward rapidities, but at central rapidities, the p+p and d+Au signal are almost identical



$\Rightarrow$ the suppression of the away-side peak occurs when Q_S increases

this was predicted, in some cases quantitatively with no parameter adjustments

so far all di-hadron correlations measured in d+Au vs. p+p are consistent with saturation

now one should try to quantify this better, to further develop our understanding of the CGC