Forward di-hadron correlations in d+Au collisions

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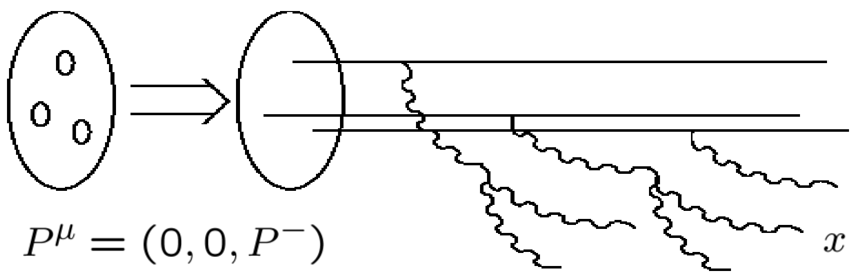
Parton saturation

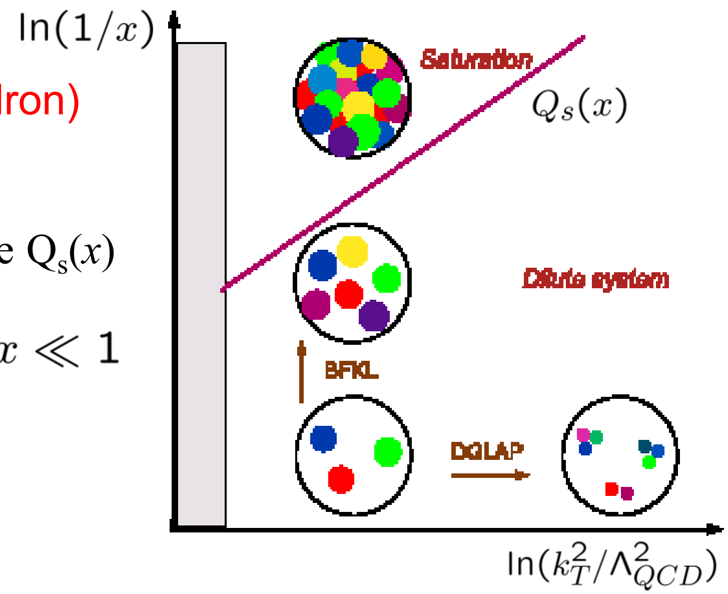


$P^{\mu} = (0, 0, P^{-})$ $\qquad x\ P^{-}, k_T$

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 a denser hadron)

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

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

$\rho \sim \dfrac{xf(x,k_\perp^2)}{\pi R^2}$ 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 $Q_s^2 = \dfrac{\alpha_s x f(x,Q_s^2)}{\pi R^2}$

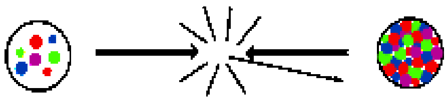
this regime is non-linear yet weakly coupled

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

Motivation

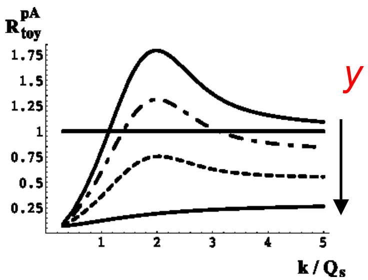
- after the first d+Au run at RHIC, there was a lot of new results on single inclusive particle production at forward rapidities

$\mathrm{d\ Au} \rightarrow \mathrm{h\ X}$



the spectrum $\dfrac{d\sigma^{dAu\rightarrow hX}}{d^2k\,dy}$ and

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



y increases

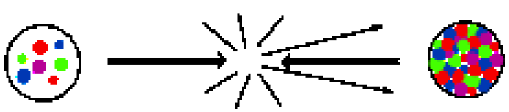
the suppressed production (R_{dA} < 1) was predicted in the Color Glass Condensate picture of the high-energy nucleus

- 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



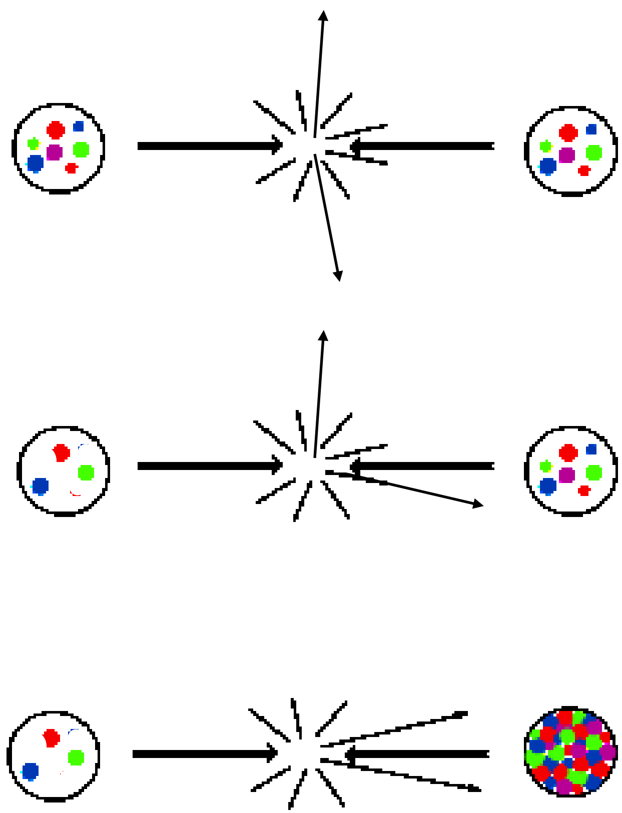
$\mathrm{d\ Au} \rightarrow \mathrm{h_1\ h_2\ X}$

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

Di-hadron final-state kinematics

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

- 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

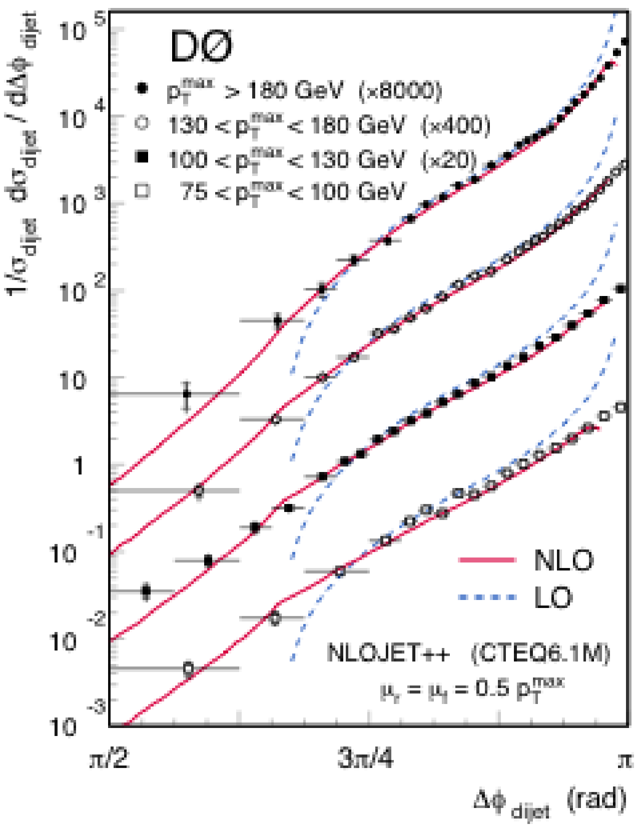
x_p ~ unchanged | x_A decreases

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

forward rapidities probe small x

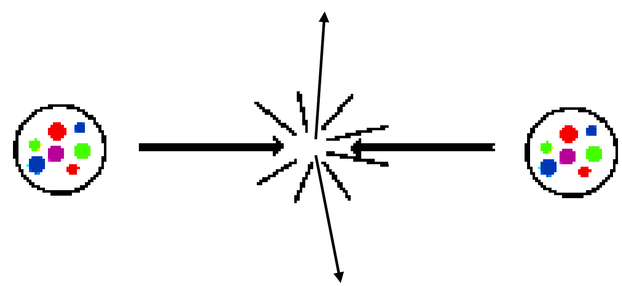
Dijets in standard pQCD

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

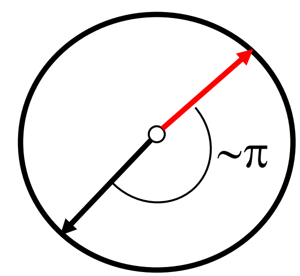


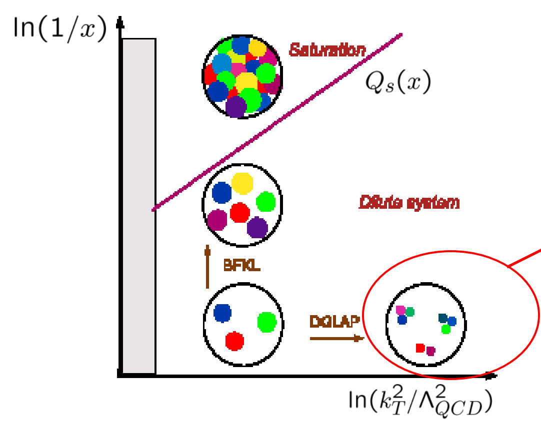
peak narrower with higher p_T

this is supported by Tevatron data with high p_T's



transverse view





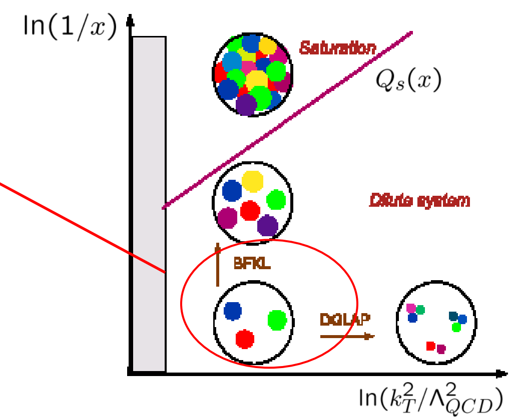
probing Λ_{QCD}/p_T <<1

power corrections are negligible

p_T broadening at large x

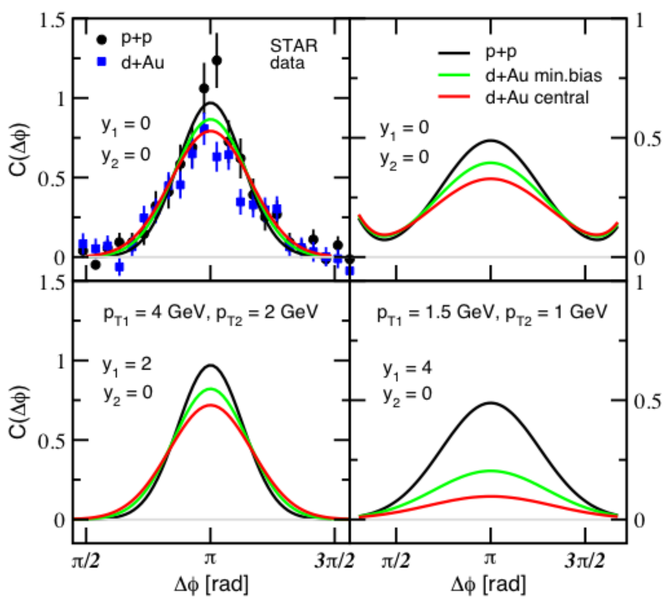
with lower transverse momenta, multiple scatterings become important

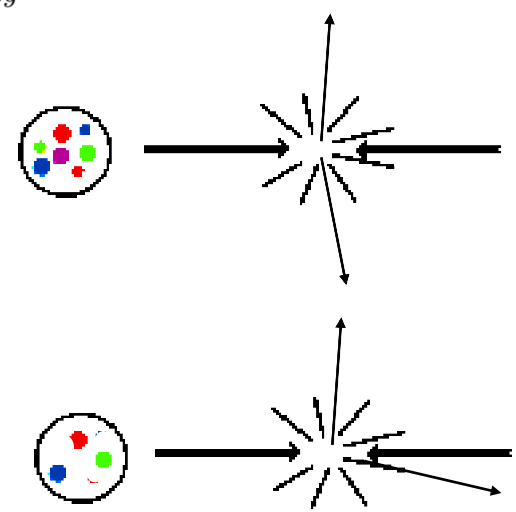
when p_T is not much higher than Λ_{QCD}
higher twists are important, especially with nuclei



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

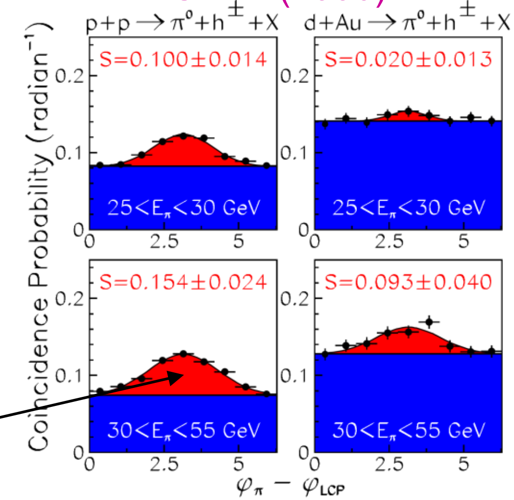
qualitative agreement with data, but quantitative ?

coincidence probability

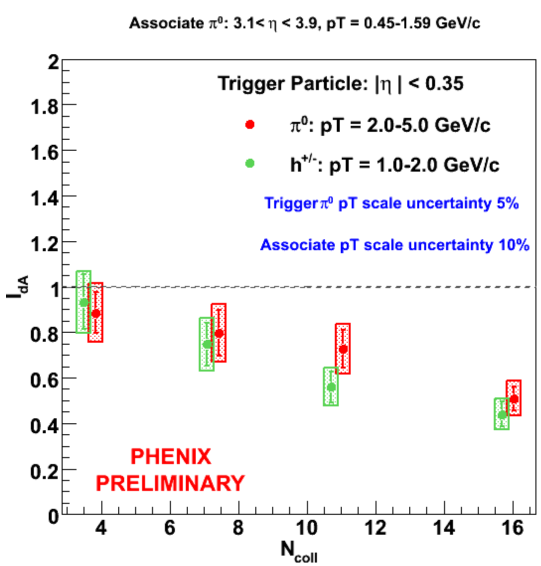
$$CP(\Delta\phi) = \frac{1}{N_{trigger}} \frac{dN_{pair}}{d\Delta\phi}$$

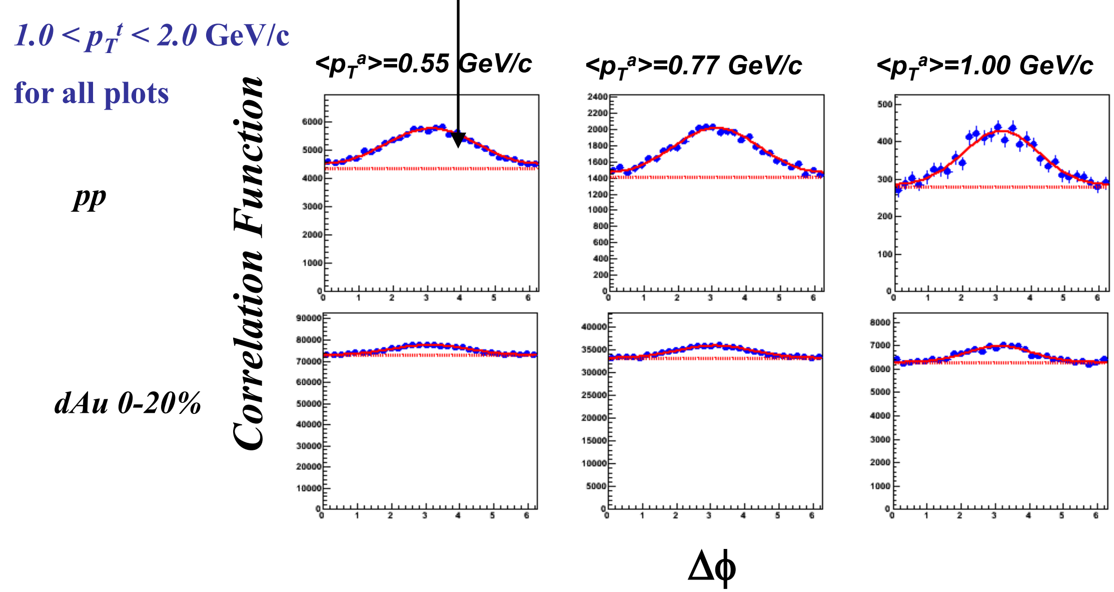
$$I_{dA} = \frac{S_{dAu}}{S_{pp}}$$

STAR (2006)



signal

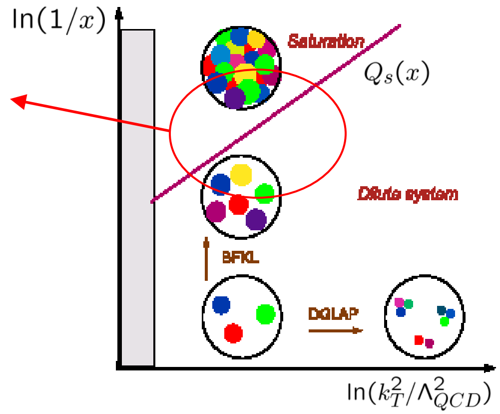




What changes at small x

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

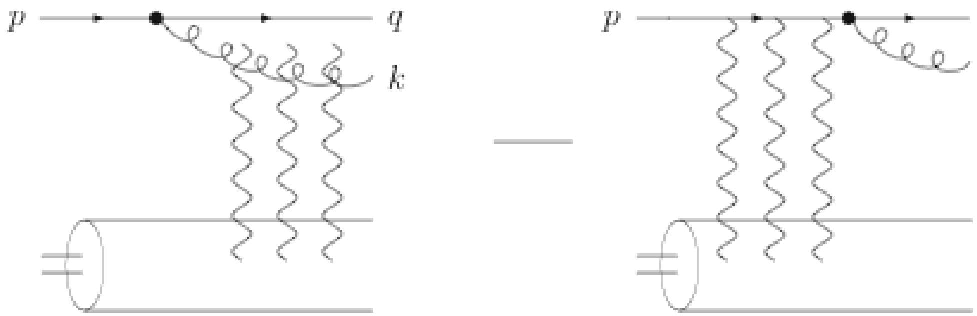
the CGC can be used to resum the expansion Q_S/p_T expansion

- 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 $q \rightarrow qg$ 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 in principle with JIMWLK evolution

gluon-initiated processes calculated recently

Dominguez, CM, Xiao and Yuan (2011)

CGC predictions

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

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

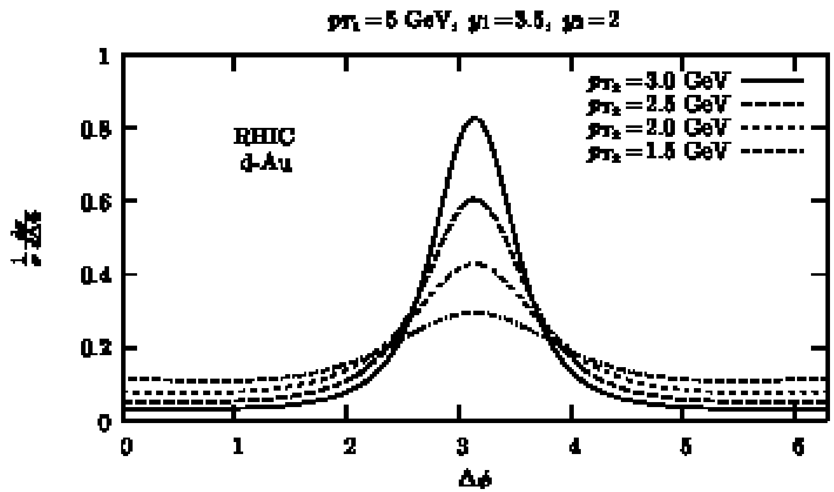
even though the knowledge of $S^{(2)}$ is enough to predict the forward dihadron spectrum, there is no k_T factorization: the cross section is a non-linear function of the gluon distribution

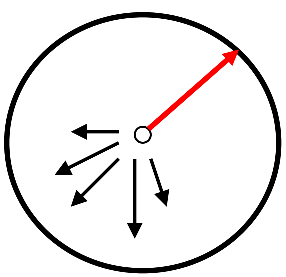
- some results for $(1/\sigma)\, d\sigma/d\Delta\Phi$

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

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

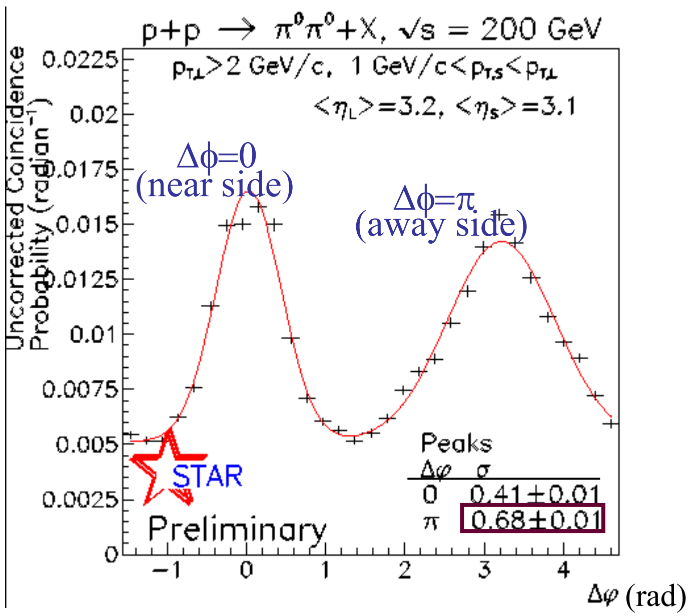




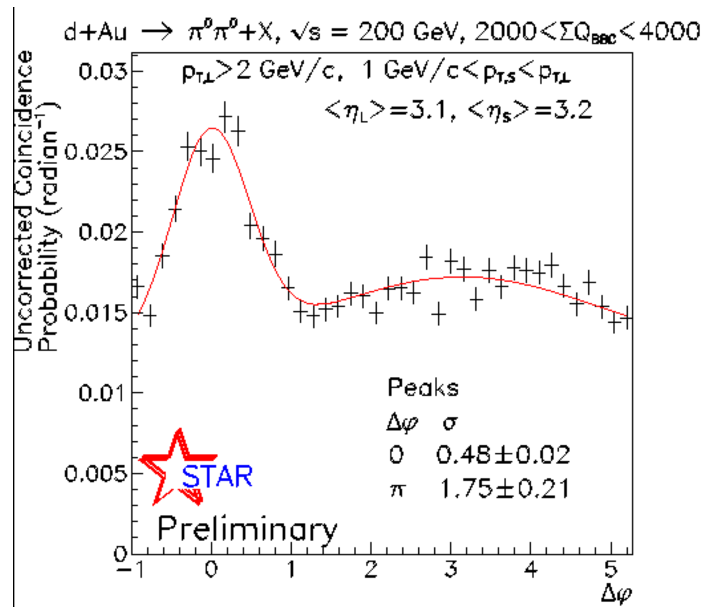
azimuthal correlations are only a small part of the information contained in $\frac{d\sigma^{pA\to h_1 h_2 X}}{d^2k_1 dy_1 d^2k_2 dy_2}$

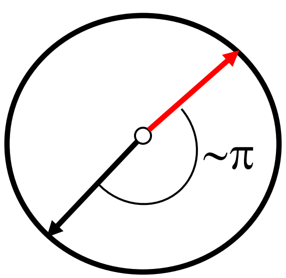
Evidence of monojets

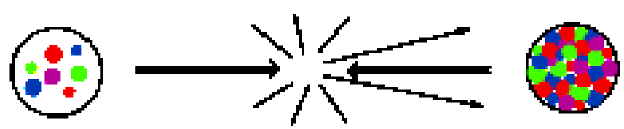
p+p

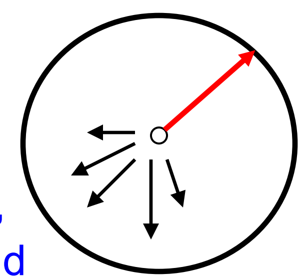


d+Au central









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

Monojets in central d+Au

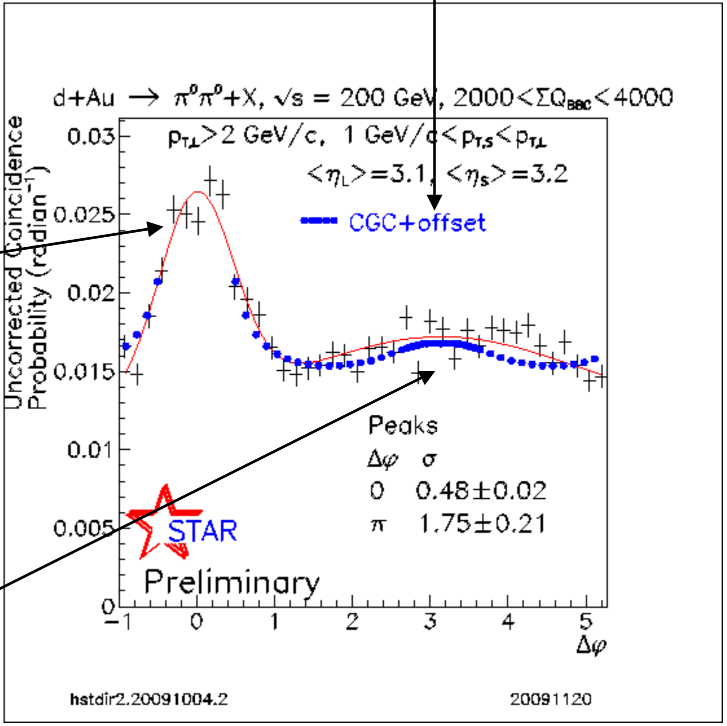
- in central collisions where Q_S is the biggest

an offset is needed to
account for the background

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

Albacete and CM, (2010)

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

About the CGC calculation

- in the large-Nc limit, the cross section is obtained from

[redacted] and [redacted]

the 2-point function is fully constrained
by e+A DIS and d+Au single hadron data

- in principle the 4-point function should be obtained from an evolution equation (equivalent to JIMWLK + large Nc)

Jalilian-Marian and Kovchegov (2005)

- in practice one uses an approximation that allows to express $S^{(4)}$ as a (non-linear) function of $S^{(2)}$

C.M. (2007)

this approximation misses some leading-Nc terms Dumitru and Jalilian-Marian (2010)

the evolution of higher point functions (~ multi-gluon distribution)
is different from that of the 2-point function (single gluon distribution)
it is equally important to understand it

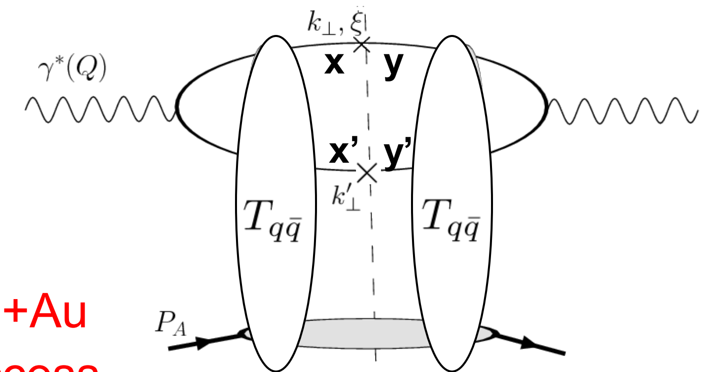
Di-hadron correlations in DIS

unlike most observables considered in DIS, di-hadrons probe more than the dipole scattering amplitude, it also probes the 4-point function

- the di-hadron cross section in the CGC picture

$$\frac{d\sigma_{T,L}^{\gamma^* p\to q\bar{q}X}}{d^2k_\perp d^2k'_\perp} = \int \frac{d^2x}{2\pi}\frac{d^2y}{2\pi}\frac{d^2x'}{2\pi}\frac{d^2y'}{2\pi}\, e^{-ik_\perp\cdot(\mathbf{x}-\mathbf{y})}e^{-ik'_\perp\cdot(\mathbf{x}'-\mathbf{y}')}\int d\xi\, \Phi_{T,L}(\xi,\mathbf{x}-\mathbf{x}',\mathbf{y}-\mathbf{y}';Q^2)$$
$$\times[T_{q\bar{q}}(\mathbf{x}-\mathbf{x}',x_B)+T_{q\bar{q}}(\mathbf{y}-\mathbf{y}',x_B)-T_{q\bar{q}\bar{q}q}(\mathbf{x},\mathbf{x}',\mathbf{y}',\mathbf{y},x_B)]$$

we expect to see the same effect in e+A vs e+p than the one seen in d+Au vs p+p collisions at RHIC



the same 4-point function is involved as in the d+Au case but the e+A process gives a more direct access

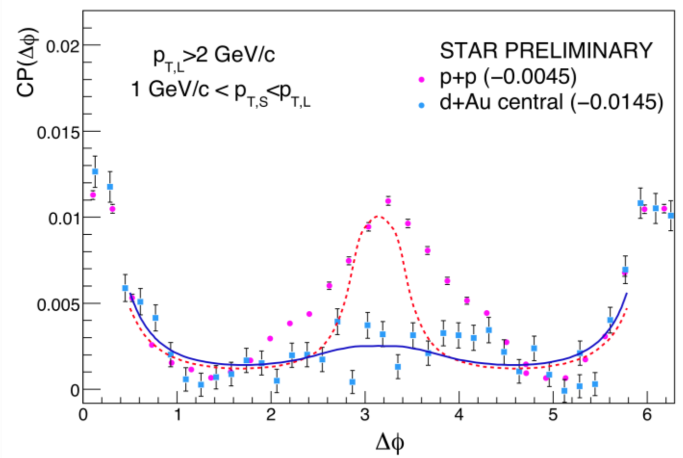
the connection between the 4-point function and TMDs can be established when [redacted]

Dominguez, Xiao and Yuan (2010)

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 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