Saturation and CGC in p+A collisions: from RHIC to AFTER

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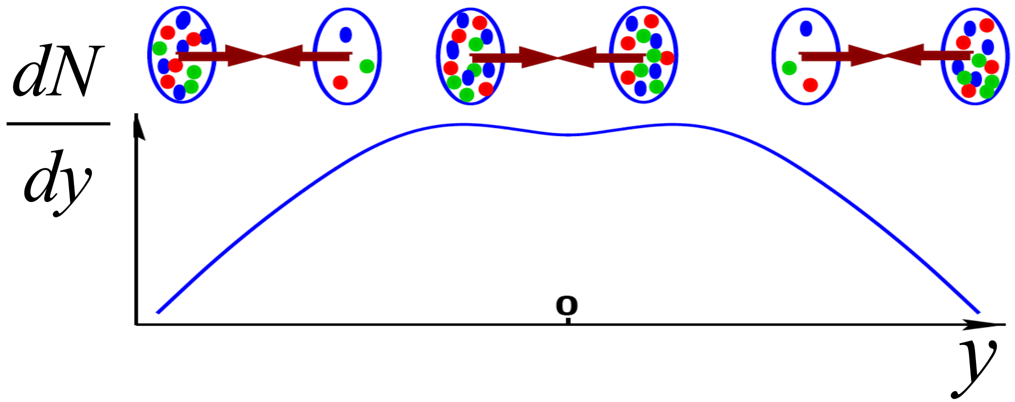
Single hadron production at RHIC (d+Au vs p+p)

Single hadron kinematics

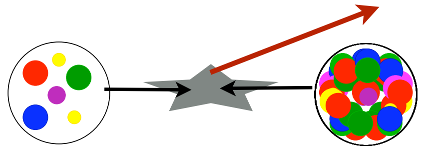
transverse momentum k_T, rapidity y

values of x probed
in the process:

$$x_1 = \frac{k_T\, e^{y}}{\sqrt{s}} \qquad x_2 = \frac{k_T\, e^{-y}}{\sqrt{s}}$$



cross section :



large-x parton from proj. (pdf)

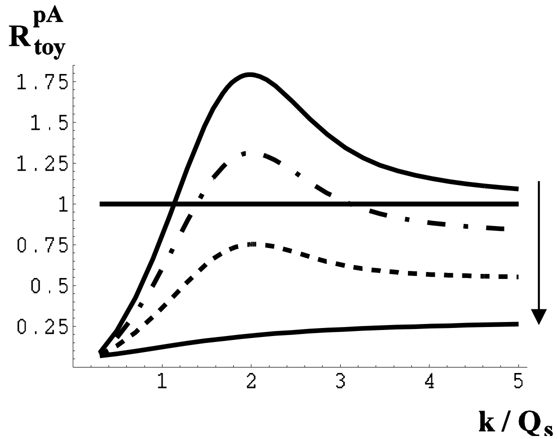
small-x glue from target (CGC)

$$\frac{dN_h}{dy_h\, d^2p_t} = \frac{K}{(2\pi)^2}\sum_q \int_{x_F}^{1} \frac{dz}{z^2}\left[x_1 f_{q\,/\,p}(x_1,p_t^2)\,\tilde{N}_F\left(x_2,\frac{p_t}{z}\right) D_{h\,/\,q}(z,p_t^2) + x_1 f_{g\,/\,p}(x_1,p_t^2)\,\tilde{N}_A\left(x_2,\frac{p_t}{z}\right) D_{h\,/\,g}(z,p_t^2)\right]$$

fragmentation

The suppression of R_{dA}

the suppression of R_{dA} was predicted



x_A decreases
(y increases)

$$R_{dA} = \frac{1}{N_{coll}} \frac{\dfrac{dN^{dA \to hX}}{d^2 k dy}}{\dfrac{dN^{pp \to hX}}{d^2 k dy}}$$

$R_{dA} = 1$ in the absence of nuclear effects, meaning if the gluons in the nucleus interact incoherently like in A protons

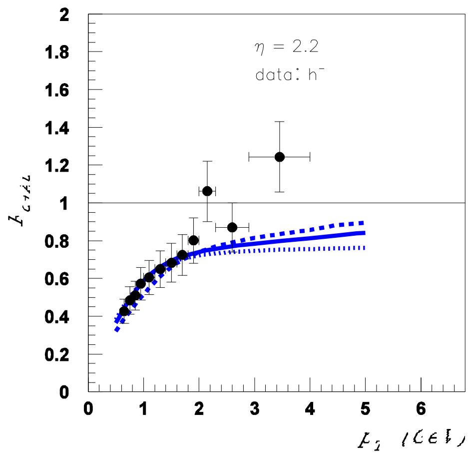
(which is the y=0 curve could not be predicted)

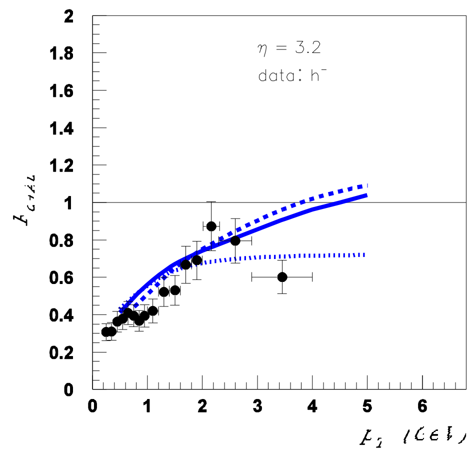
what we learned:

forward rapidities are needed to see the suppression

first comparisons to data:

Kharzeev, Kovchegov and Tuchin (2004)
Kharzeev, Levin and Nardi (2005)

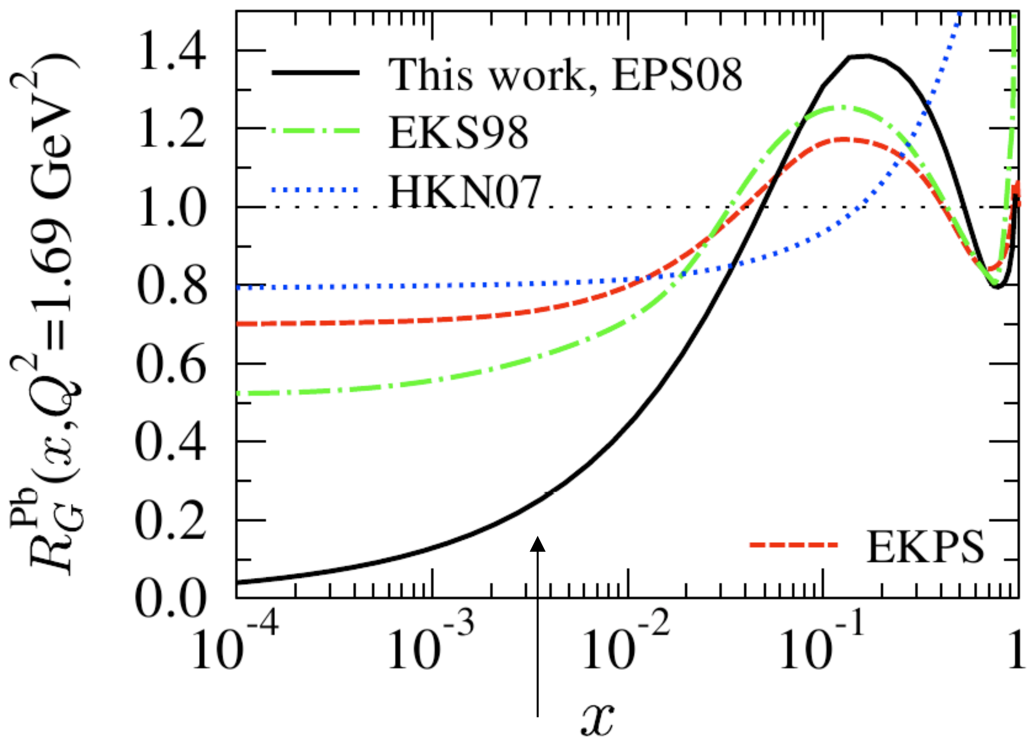




Nuclear PDF approach

there were attempts to describe the RHIC forward data in the "standard" QCD approach (linear evolution), this was abandoned

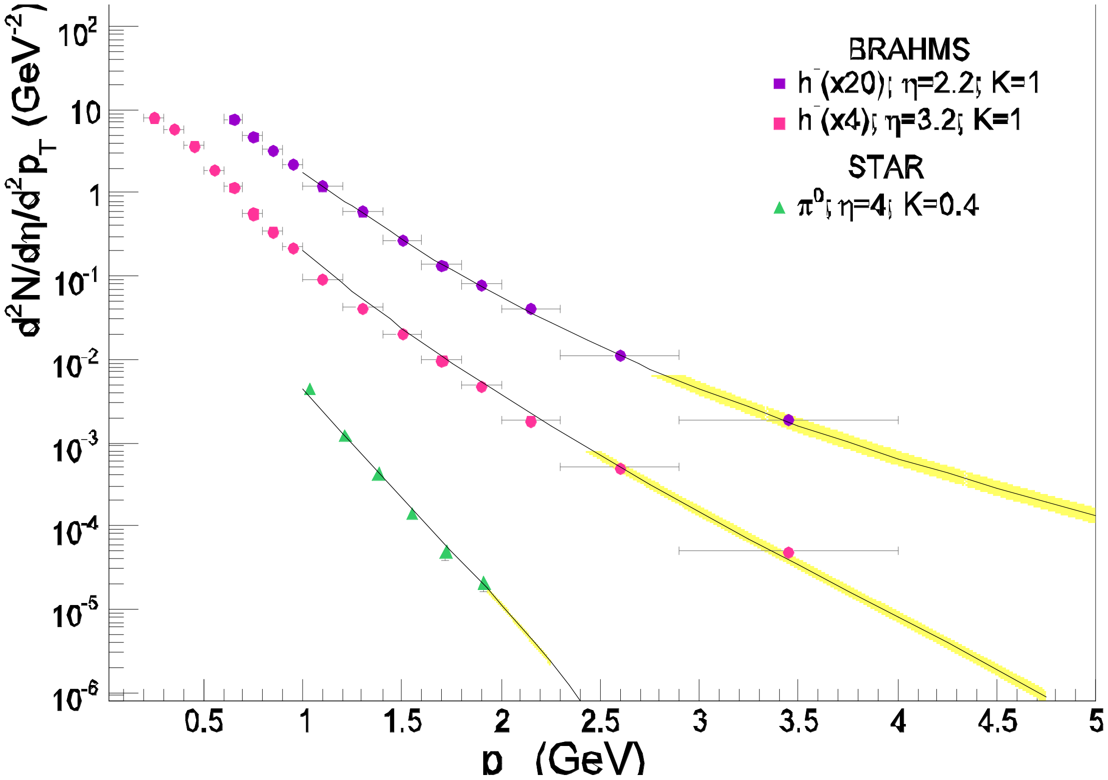
Eskola, Paukkunen, Salgado (2008)



if forward rapidity data are included in npdf fits, the resulting gluon distribution is over suppressed

rcBK description of d+Au data

2-parameter fit with most up-to-date non-linear QCD evolution



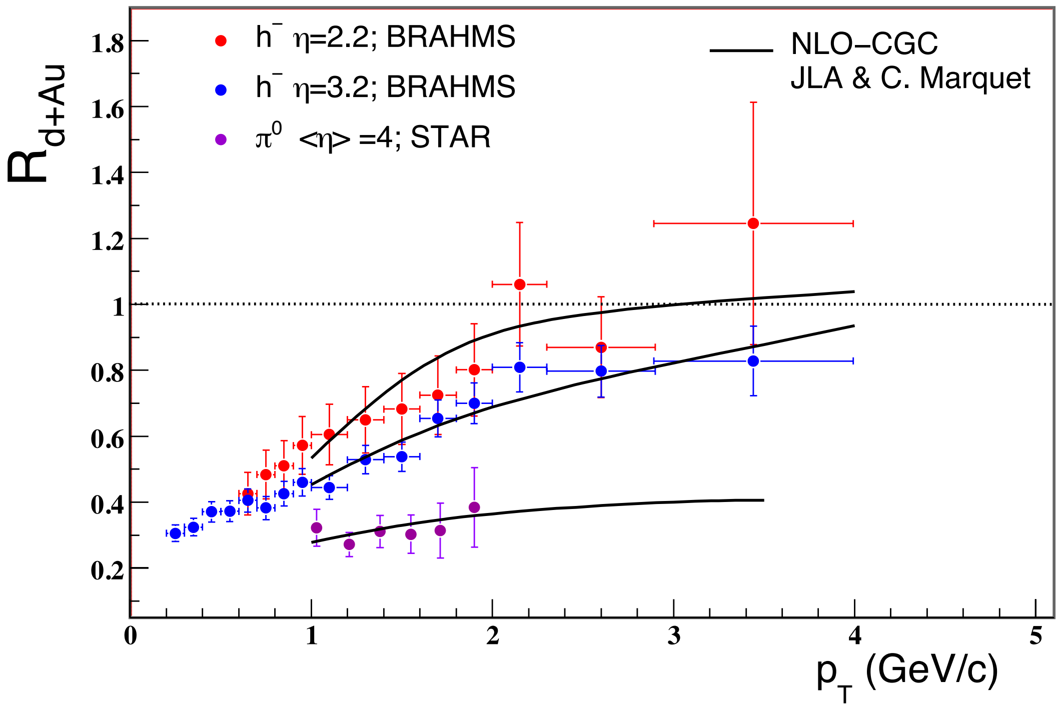
Albacete and C.M. (2010)

the speed of the x evolution and of the p_T decrease are predicted

the shapes and normalizations are well reproduced, except the π^0 normalization

Nuclear modification factor

NLO* CGC description



alternative descriptions

calculations including large-x effects (energy loss of high-x parton through cold nuclear matter) have been proposed

Kopeliovich et al (2005), Frankfurt et al (2007)

Open issues

where perhaps AFTER can help ?

- species dependence: why the pion normalization is off ?
  additional large-x effect for pions only ? wrong fragmentation functions?
  problem with normalization of the data ?

- no J/Psi data at such forward rapidities
  would be nice to pinpoint when non-linear effects set in in that case,
  they are usually not taken into account

- amount of large x effects ?
  this suppression mechanism should contribute at some point,
  already at y=3 ? or only at y=4 ? species dependence ?

- transition to higher p_t (the LHC should answer that)
  the correct high-pt physics is not included in the formalism,
  when is it needed ? for p_t >5 ?

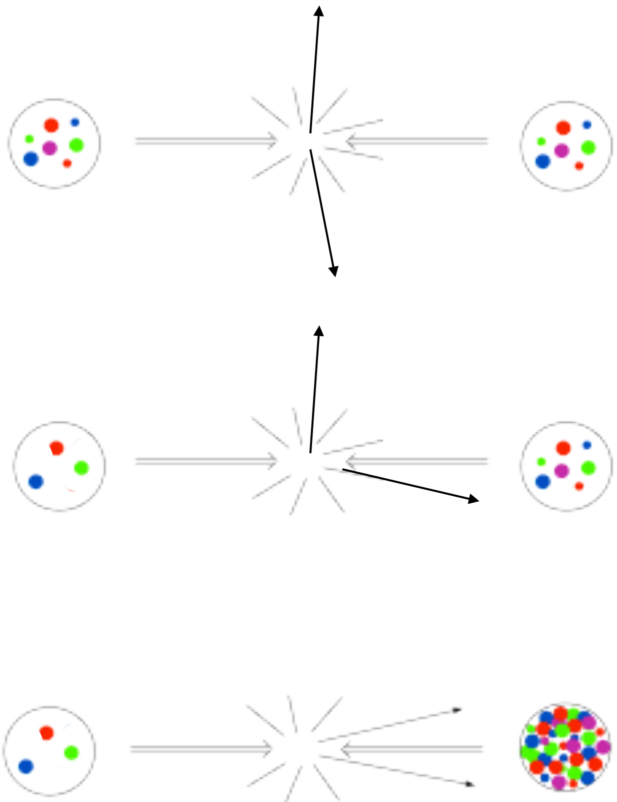
Di-hadron production at RHIC
(d+Au vs p+p)

Di-hadron final-state kinematics

final state : $k_1, y_1 \quad k_2, y_2$

$$x_p = \frac{k_1\, e^{y_1} + k_2\, e^{y_2}}{\sqrt{s}} \qquad x_A = \frac{k_1\, e^{-y_1} + k_2\, e^{-y_2}}{\sqrt{s}}$$

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

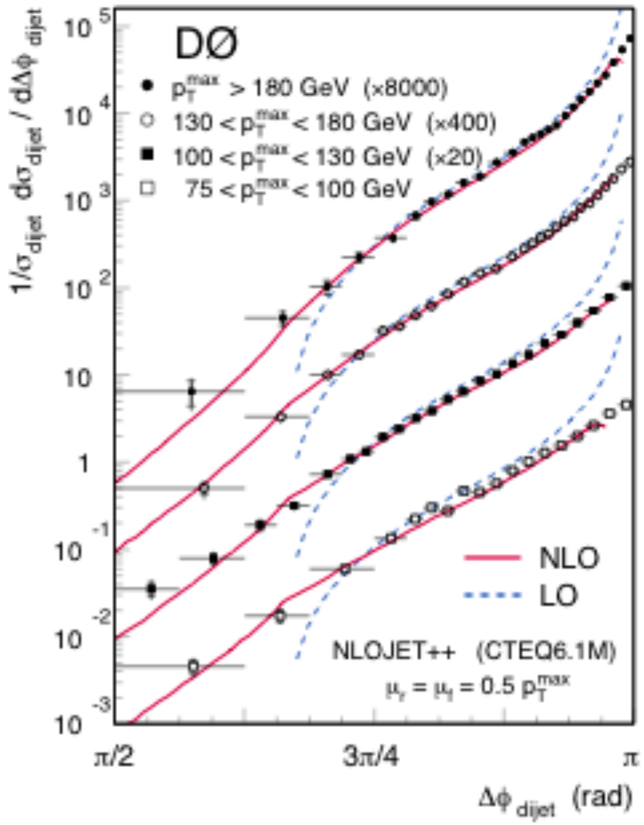
x_p ~ unchanged | x_A decreases

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

forward rapidities probe small x

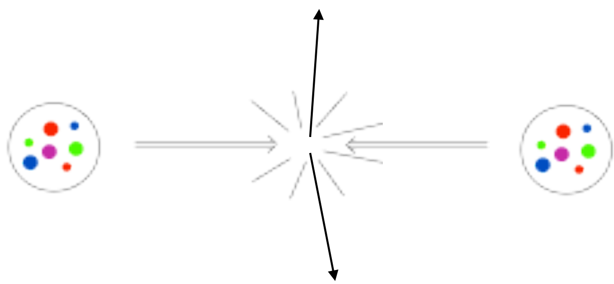
Dijets in standard pQCD

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

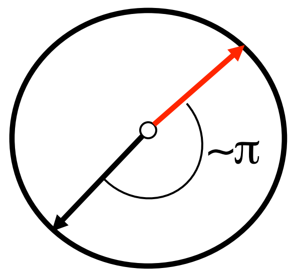


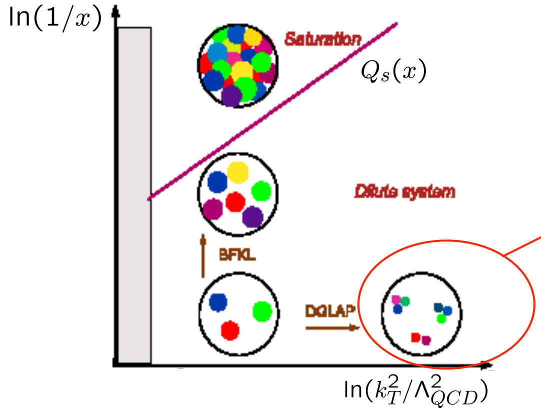
peak narrower with higher p_T

this is supported by Tevatron data with high p_T's



transverse view





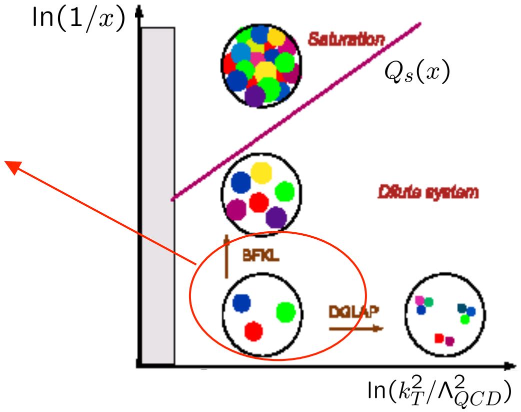
probing Λ_{QCD}/p_T <<1

power corrections are negligible

p_T broadening at large x

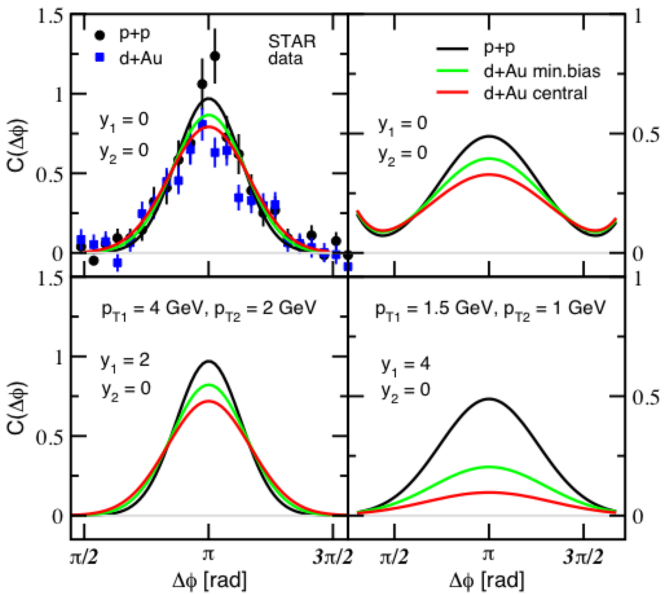
with lower transverse momenta, multiple scatterings become important

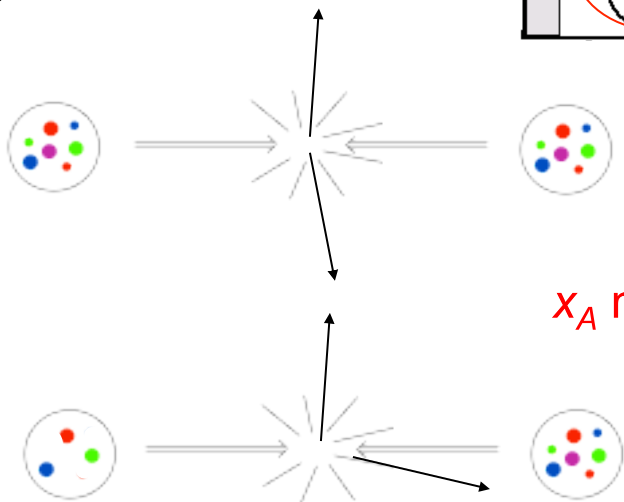
when p_T is not much higher than Λ_{QCD}
higher twists are important, especially with nuclei



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)

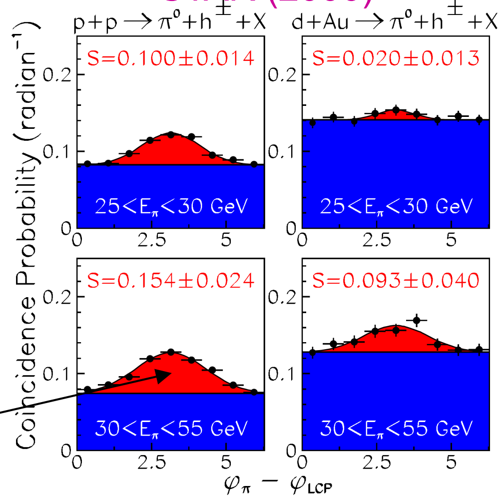
Forward/central data

qualitative agreement with data, but quantitative ?

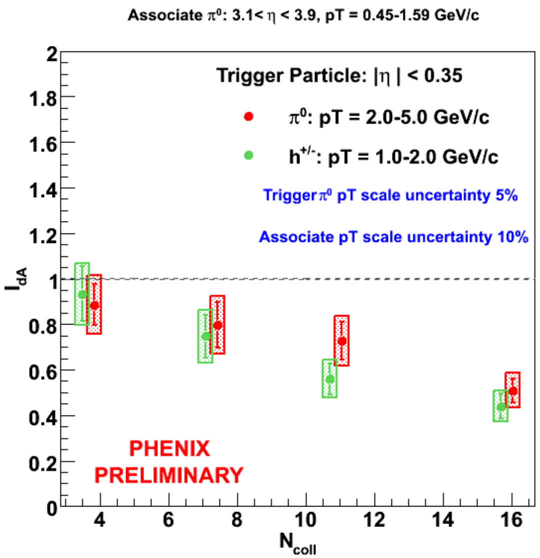
coincidence probability
$$CP(\Delta\phi) = \frac{1}{N_{trigger}} \frac{dN_{pair}}{d\Delta\phi}$$

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

STAR (2006)



signal

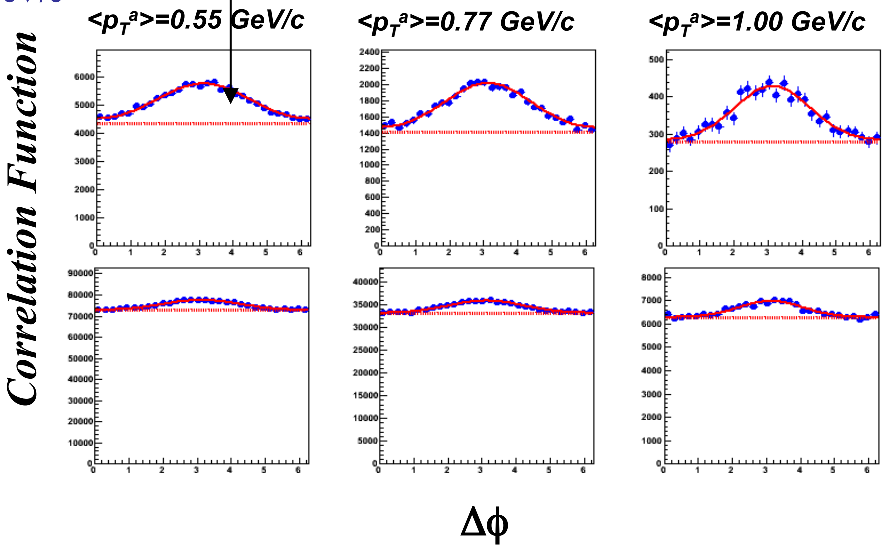


$1.0 < p_T^t < 2.0$ GeV/c

for all plots

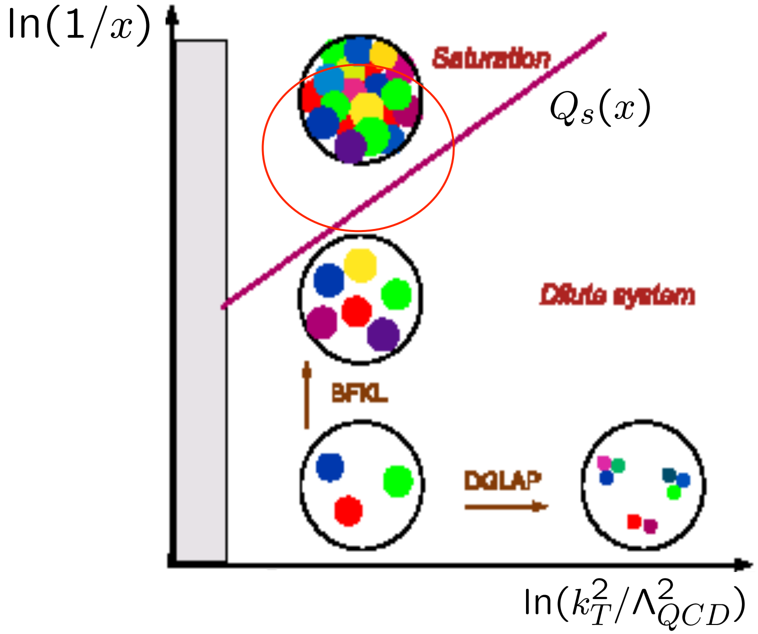
pp

dAu 0-20%



What changes at small x

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



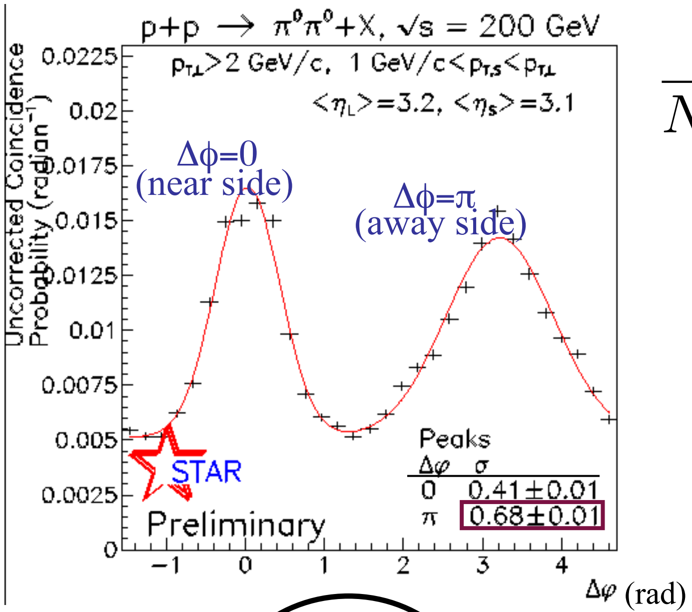
$\hat{q}$ or intrinsic k_T (or whatever is introduced to account for higher twists) becomes ~ Q_S

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

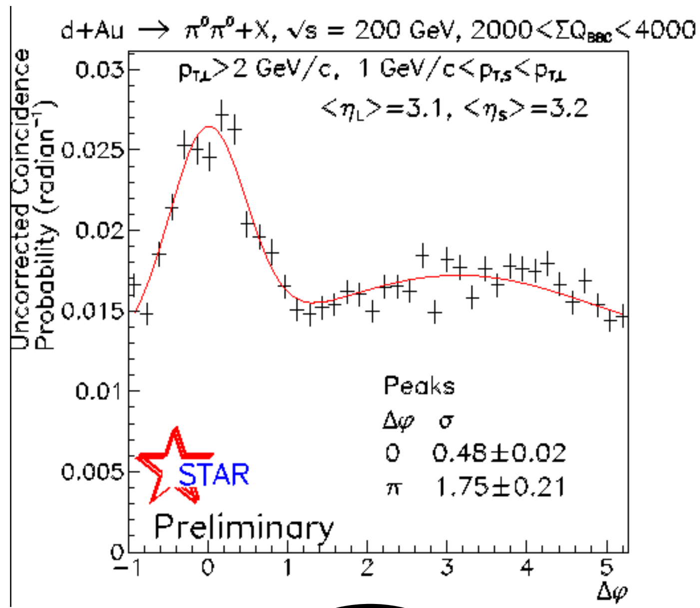
Forward/forward data

comparison between d Au → h_1 h_2 X and p+p → h_1 h_2 X

p+p collisions

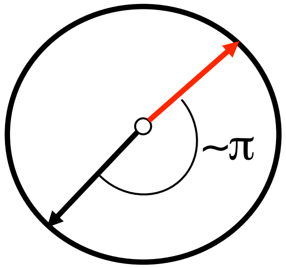


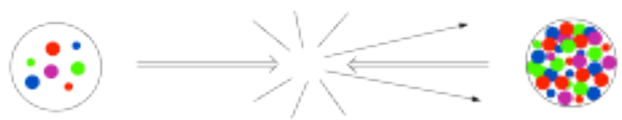
central d+Au collisions

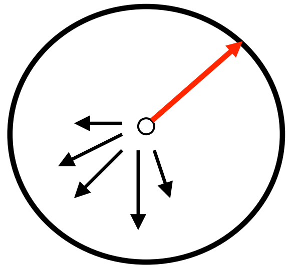


$$\frac{1}{N_{trig}} \frac{dN_{pair}}{d\Delta\varphi}$$

$$x_A = \frac{k_1\, e^{-y_1} + k_2\, e^{-y_2}}{\sqrt{s}} << 1$$







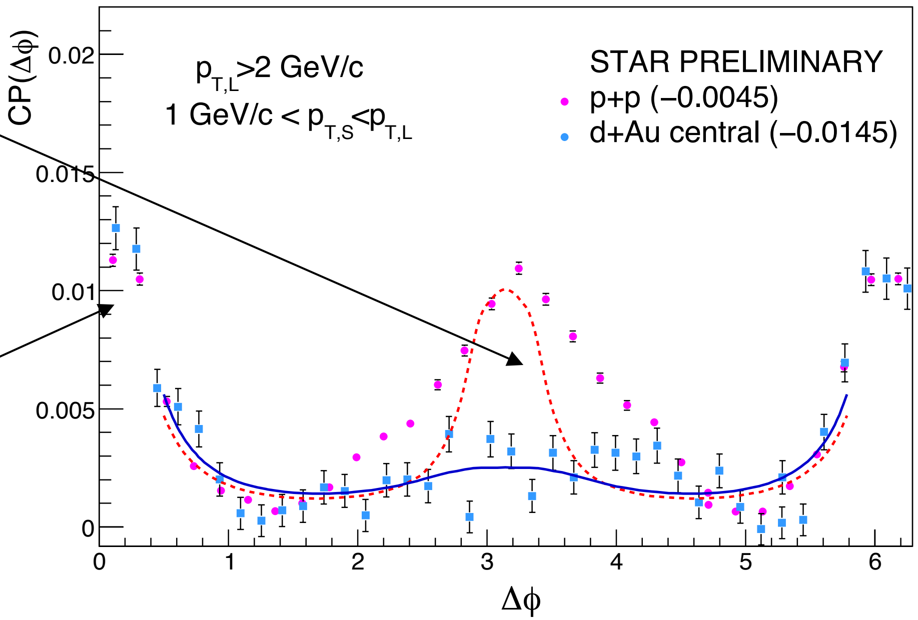
this happens at forward rapidities, but at
central rapidities, the p+p and d+Au signal are almost identical

Comparison with CGC

Albacete and C.M. (2010)

the focus is on the away-side peak where non-linearities have the biggest effect

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



the magnitude of the away-side peak, compared to that of the near-side peak, decreases from p+p to d+Au central (and from forward/central to forward/forward)

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

this was predicted, and even though accurate calculations are still out of reach, the experimental signal is so stricking that it confirmed the effect

Open issues

where perhaps AFTER can help ?

- quantitative computations are still out of reach
  will RHIC (LHC?) data be enough to constrain the initial multi-gluon distributions ?
- p_t dependence of the away-side peak presence/suppression
  when multiple scatterings become incoherent (no saturation anymore) ?
- A dependence
  the A dependence of Qs is usually modeled (it is not predicted by perturbative calculations like the x dependence), it would be nice to be able to extract it from data