Azimuthal correlations of forward di-hadrons in d+Au collisions at RHIC

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Based on : C.M., *Nucl. Phys.* **A796** (2007) 41-60
J.L. Albacete and C.M., arXiv:1005.4065

Outline

- Introduction to parton saturation

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

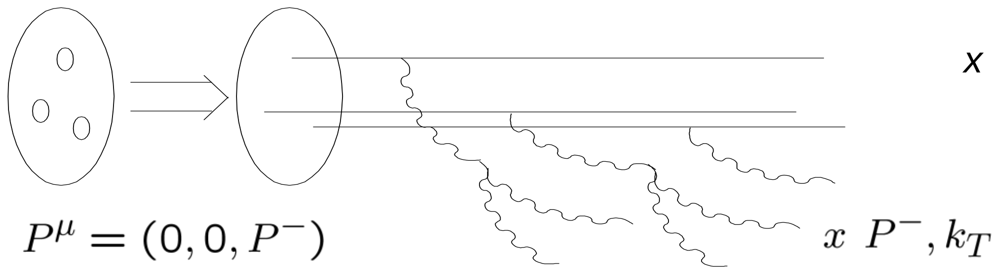
- Particle production in d+Au collisions at forward rapidities

  - the suppressed production was predicted by saturation physics
  - recent theoretical progress and new NLO predictions

- Two-particle correlations at forward rapidities

  - sensitive to multi-parton distributions
  - correlations in azimuthal angle show that monojets are produced

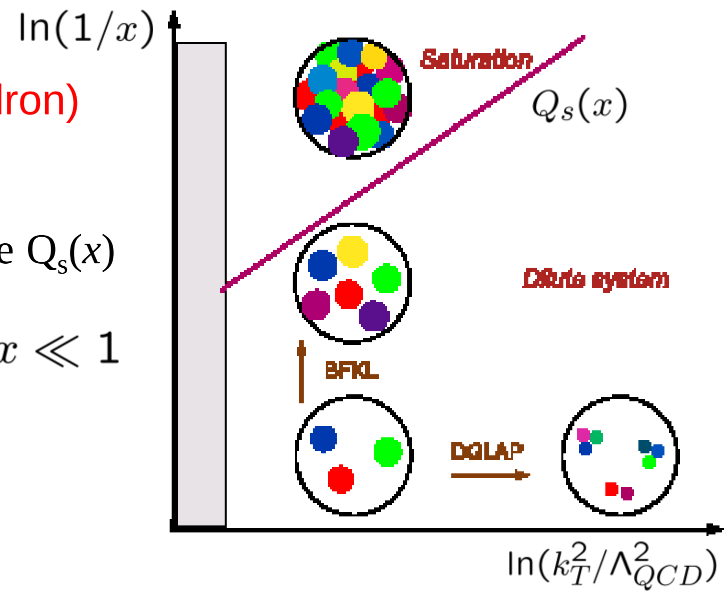
Parton saturation



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 $\rho\ \sigma_{rec} > 1$

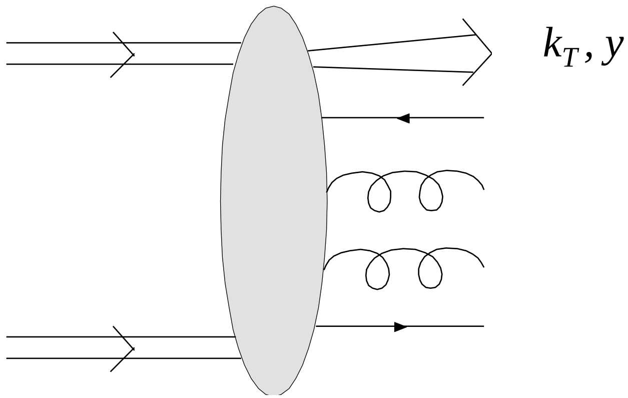
the saturation regime: for $k^2 < Q_s^2$ with $Q_s^2 = \frac{\alpha_s x f(x, Q_s^2)}{\pi R^2}$

this regime is non-linear yet weakly coupled $\alpha_s(Q_s^2) \ll 1$

Single particle production at forward rapidities

Forward particle production

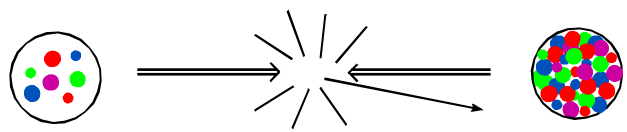
- forward rapidities probe small values of *x*



transverse momentum k_T, rapidity $y > 0$

values of x probed in the process:

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



the large-x hadron should be described by standard leading-twist parton distributions

the small-x hadron/nucleus should be described by a Color Glass Condensate

the cross-section:

$$k_T^2 \frac{d\sigma}{d^2 k_T \, dy} \propto g(x_1, k_T^2) \, f(x_2, k_T^2)$$

single gluon production probes only the (unintegrated) gluon distribution

The non-linear QCD evolution

- the unintegrated gluon distribution $f_Y(k)$ $Y = \ln\left(\frac{1}{x}\right)$

Balitsky-Kovchegov *x* evolution $\frac{d}{dY} f_Y(k) = \bar{\alpha} \int \frac{dk'^2}{k'^2} \left[\frac{k'^2 f_Y(k') - k^2 f_Y(k)}{|k^2 - k'^2|} + \frac{k^2 f_Y(k)}{\sqrt{4k'^4 + k^4}} \right] - \bar{\alpha} f_Y^2(k)$

- BK equation in coordinate space $f_Y(k) = \int \frac{d^2r}{2\pi r^2} \, e^{ik.\mathbf{r}} N_Y(\mathbf{r})$

$$\frac{d}{dY} N_Y(\mathbf{x}-\mathbf{y}) = \frac{\bar{\alpha}}{2\pi} \int d^2z \, \frac{(\mathbf{x}-\mathbf{y})^2}{(\mathbf{x}-\mathbf{z})^2(\mathbf{z}-\mathbf{y})^2} \left[N_Y(\mathbf{x}-\mathbf{z}) + N_Y(\mathbf{z}-\mathbf{y}) - N_Y(\mathbf{x}-\mathbf{y}) - N_Y(\mathbf{x}-\mathbf{z}) N_Y(\mathbf{z}-\mathbf{y}) \right]$$

this is a leading-order equation in which the coupling doesn't run

- modeling the unintegrated gluon distribution

before

the numerical solution of the BK equation is not useful for phenomenology (because this is a leading-order calculation)

instead, saturation models are used for $f(x,k)$ (with a few parameters adjusted to reproduce the data)

now

BK evolution at NLO has been calculated Balitsky-Chirilli (2008)

one should obtain $f(x,k)$ from the evolution equation

BK evolution at NLO

- running coupling (RC) corrections to the BK equation

taken into account by the substitution

$$\alpha_s(\mathbf{r}^2) = \left[-\frac{11N_c - 2N_f}{12\pi}\ln\left(\mathbf{r}^2\Lambda_{QCD}^2\right)\right]^{-1}$$

$$\frac{\bar{\alpha}}{2\pi}\frac{(\mathbf{x}-\mathbf{y})^2}{(\mathbf{x}-\mathbf{z})^2(\mathbf{z}-\mathbf{y})^2} \xrightarrow[\text{Weigert}]{\text{Kovchegov}} \frac{N_c}{2\pi^2}\left[\frac{\alpha_s((\mathbf{x}-\mathbf{z})^2)}{(\mathbf{x}-\mathbf{z})^2} - 2\frac{\alpha_s((\mathbf{x}-\mathbf{z})^2)\alpha_s((\mathbf{z}-\mathbf{y})^2)}{\alpha_s((\mathbf{x}-\mathbf{y})^2)} + \frac{\alpha_s((\mathbf{z}-\mathbf{y})^2)}{(\mathbf{z}-\mathbf{y})^2}\right]$$

Balitsky ↓ (2007)

$$\frac{N_c\alpha_s((\mathbf{x}-\mathbf{y})^2)}{2\pi^2}\left[\frac{(\mathbf{x}-\mathbf{y})^2}{(\mathbf{x}-\mathbf{z})^2(\mathbf{z}-\mathbf{y})^2} + \frac{1}{(\mathbf{x}-\mathbf{z})^2}\left(\frac{\alpha_s((\mathbf{x}-\mathbf{z})^2)}{\alpha_s((\mathbf{z}-\mathbf{y})^2)} - 1\right) + \frac{1}{(\mathbf{z}-\mathbf{y})^2}\left(\frac{\alpha_s((\mathbf{z}-\mathbf{y})^2)}{\alpha_s((\mathbf{x}-\mathbf{z})^2)} - 1\right)\right]$$

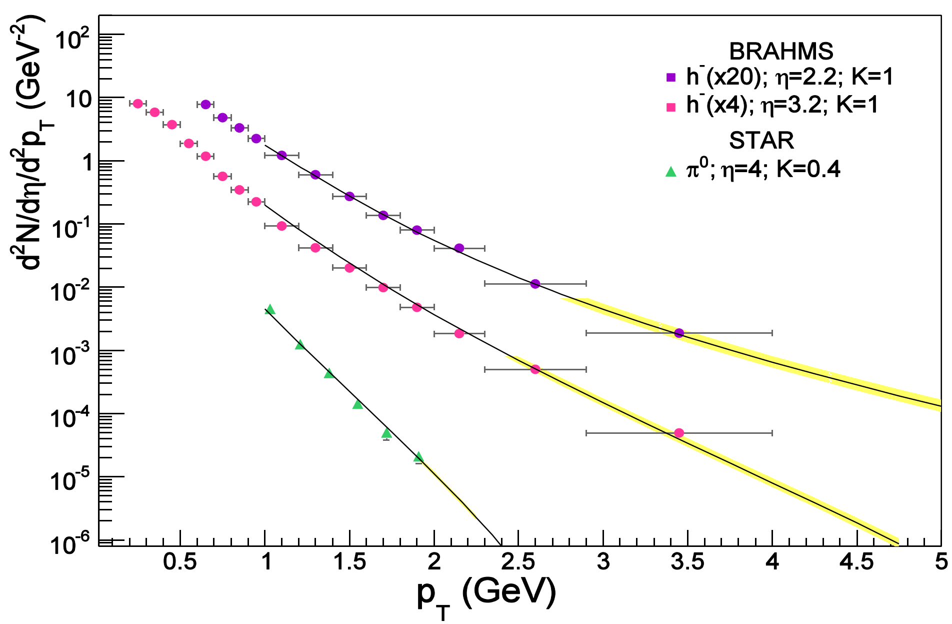
RC corrections represent most of the NLO contribution

- the begining of saturation phenomenology at NLO

first numerical solution Albacete and Kovchegov (2007)

first phenomenological implementation Albacete, Armesto, Milhano and Salgado (2009)
to successfully describe the proton structure function F_2 at small x

NLO-BK description of d+Au data



Albacete and C.M. (2010)

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

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

this fixes the two parameters of the theory:

- the value of *x* at which one starts to trust (and therefore use) the CGC description
- and the saturation scale at that value of *x* $Q_s^2(x_0) = 0.4\ \mathrm{GeV}^2$ $x_0 = 0.02$

in very forward particle production in p+p collisions at RHIC (where NLO DGLAP fails), using this formalism to describe the (small-x) proton also works

Betemps, Goncalves, de Santana Amaral (2009)

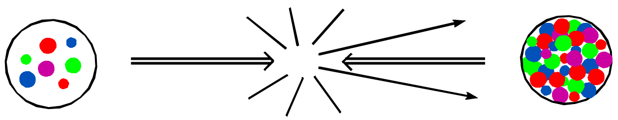
Two-particle correlations at forward rapidities

Final-state kinematics

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

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

- the ideal situation



two hadrons close in rapidity
both in the same forward direction

C. M. (2007)

at forward rapidities in order to probe small x

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

- a good test for the theory

the saturation regime is better probed compared to single particle production

$$\frac{d\sigma^{pA\to h_1h_2X}}{d^2k_1dy_1d^2k_2dy_2}$$

is sensitive to multi-parton distributions,
and not only to the gluon distribution

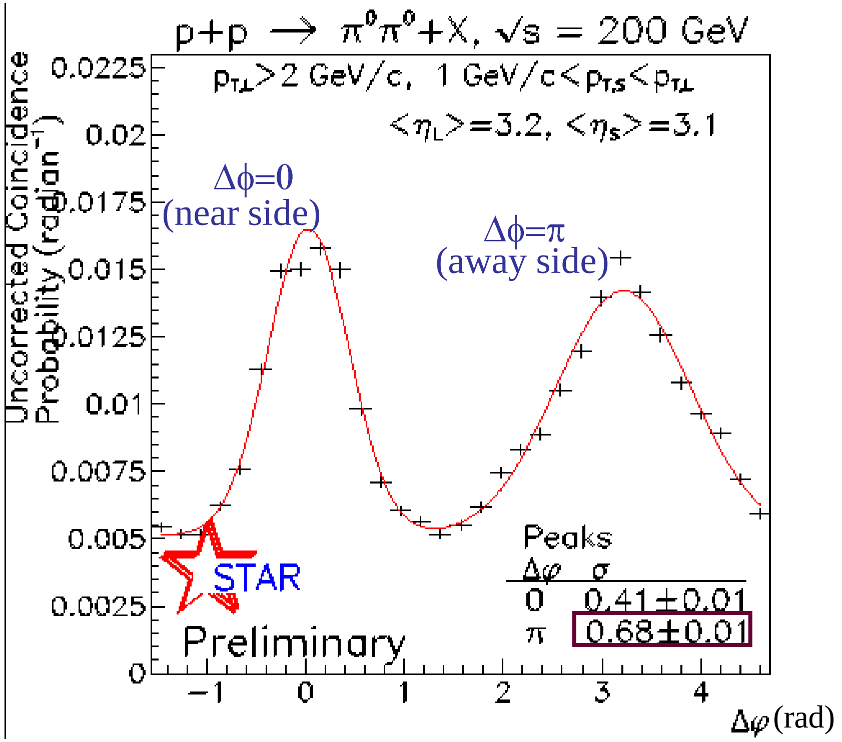
Azimuthal correlations in p+p

typical measurement in p+p collisions at RHIC:

coincidence probability

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

at RHIC this is done with low-p_T pions



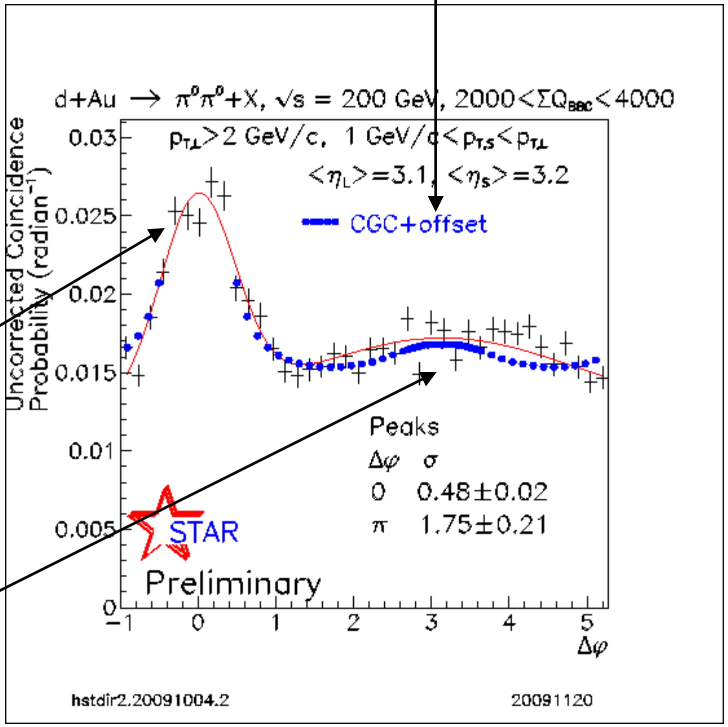
a measurement sensitive to possible modifications of the back-to-back emission pattern in a hard process

No back-to-back pattern in d+Au

- in central collisions where Qs 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



- 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

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

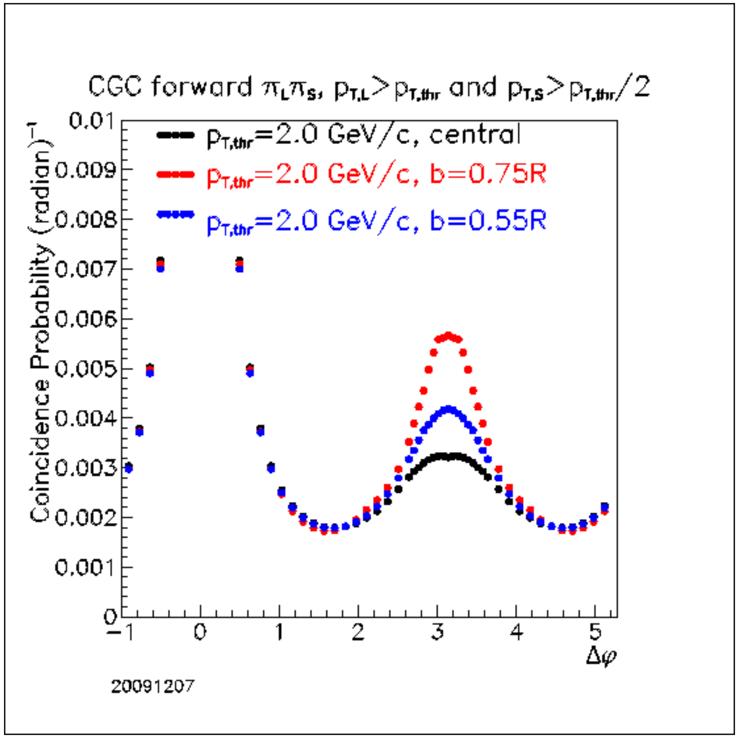
for a given impact parameter,
the initial saturation scale used is

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

peripheral collisions are like p+p collisions

the away-side peak is reappearing
when decreasing the centrality

no data yet,
but hopefully soon

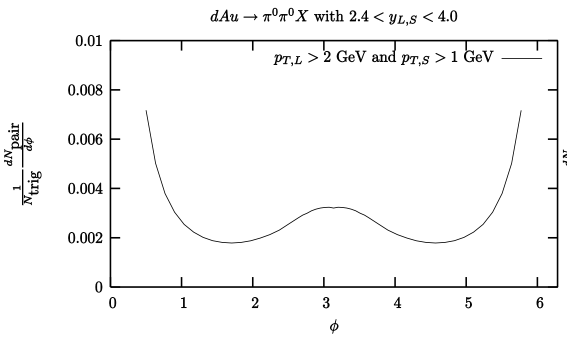


The p_T dependence

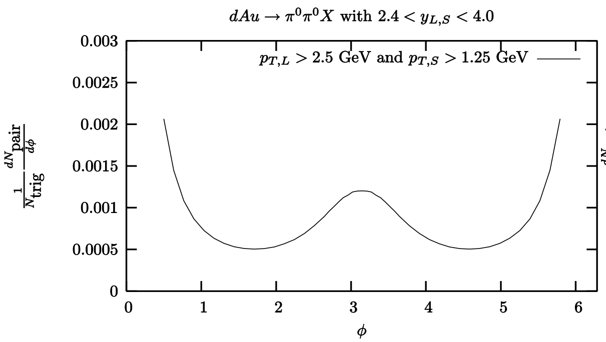
with higher p_T, one goes away from the saturation regime

the away-side peak is restored at higher p_T

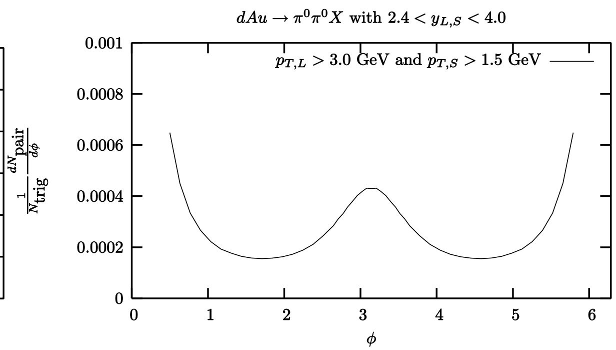
$p_{T,L} > 2$ GeV and $p_{T,S} > 1$ GeV



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



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



so far, only p+p data have been shown

Conclusions

- Single particle production at forward rapidities in d+Au collisions

  - the suppressed production at forward rapidities was predicted
  - there is a good agreement with saturation calculations
  - now that NLO-BK is known, one should stop using models

- Two-particle correlations at forward rapidities

  - probe the theory deeper than single particle measurements
  - mono-jets seen in central d+Au collisions
  - first theory(CGC)/data comparison successful, more coming

- Can p+p(Pb) collisions at the LHC see these saturation effects ?

  - need p_T ~ Qs, so maybe jets cannot be used
  - particle identification at forward rapidities would be good