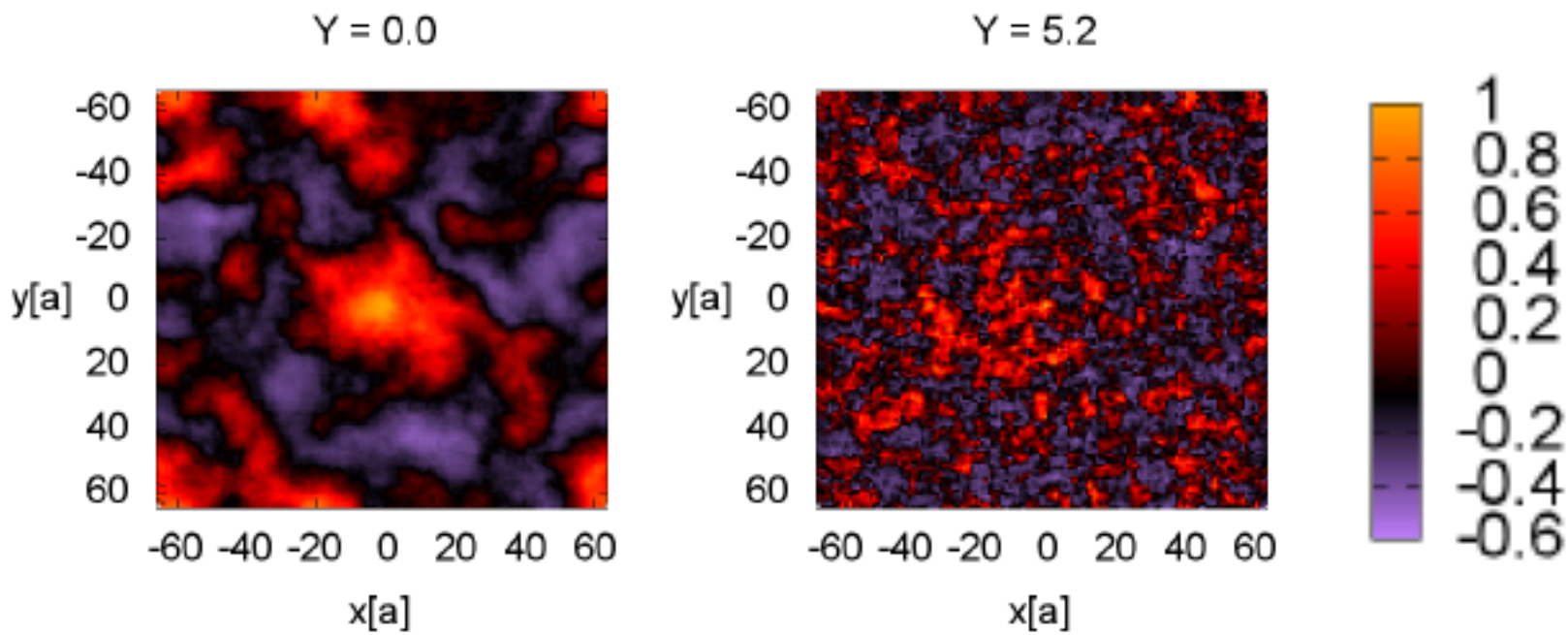
Recent PHENIX d+A results and the CGC

"Snapshots" of color charge fluctuations in a Color Glass Condensate, arXiv:1108.4764



Raju Venugopalan

BROOKHAVEN NATIONAL LABORATORY

PHENIX collaboration meeting, December 6, 2011

Talk outline

- A brief tale of asymptotia: Bjorken ("pQCD")
  vs. Regge ("saturation")

- Quantitative many-body QCD dynamics in the Regge limit:
  the CGC effective field theory

- Dilute (p) + Dense (A) dynamics in the CGC

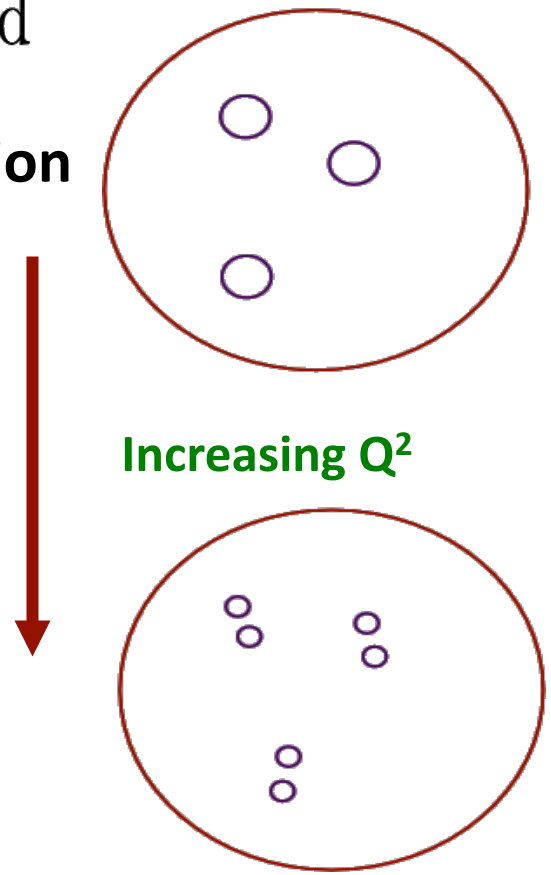
- Understanding PHENIX d+Au results

- What is to be done in theory and experiment ?

pQCD in the Bj limit

$$Q^2 \to \infty\,;\; s \to \infty\,;\; x_{\rm Bj} \approx \frac{Q^2}{s} = \text{fixed}$$

Resolving the hadron- DGLAP evolution



 # partons increases with Q^2,

phase space density (# partons / area / Q^2) *decreases*

- the proton/nucleus becomes more dilute…

pQCD in the Bj limit

- **Works great for inclusive, high Q^2 processes**

- **Higher twists important at lower Q^2 (will argue $\approx Q_S^2(x)$)**

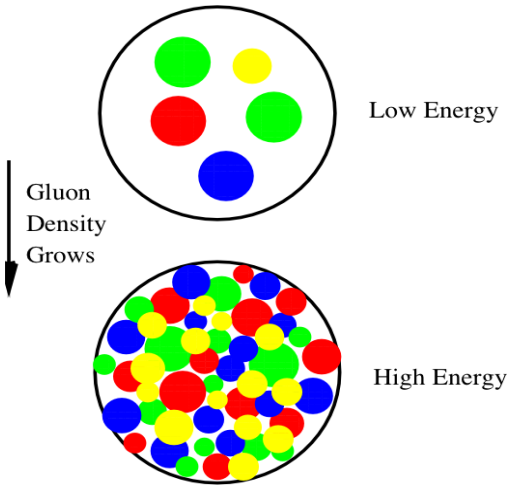
- **Formalism not designed to treat *collective phenomena*: shadowing, multiple scattering, diffraction, energy loss, impact parameter dependence, thermalization…**

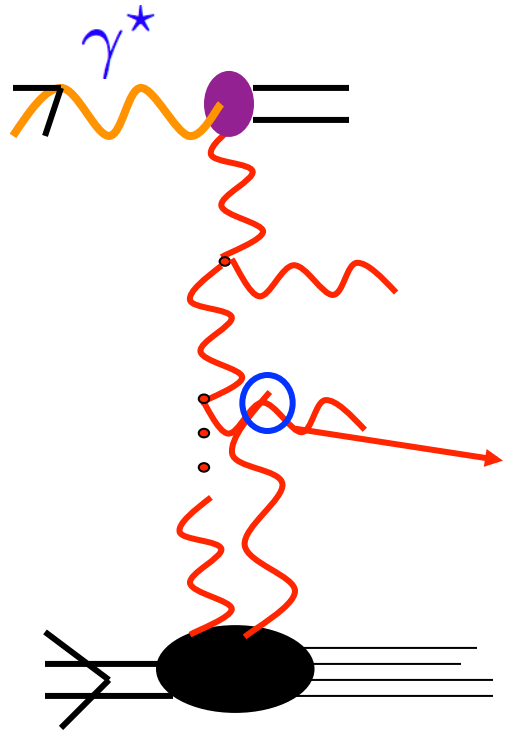
- **Extensions of "leading twist" formalism difficult…**
  Many-body dynamics is "parametrized away"…

Gluon saturation: the Regge-Gribov limit

Gribov,Levin,Ryskin
Mueller,Qiu

$$x_{Bj} \to 0;\ s \to \infty;\ Q^2(>> \Lambda^2_{QCD}) = \text{fixed}$$





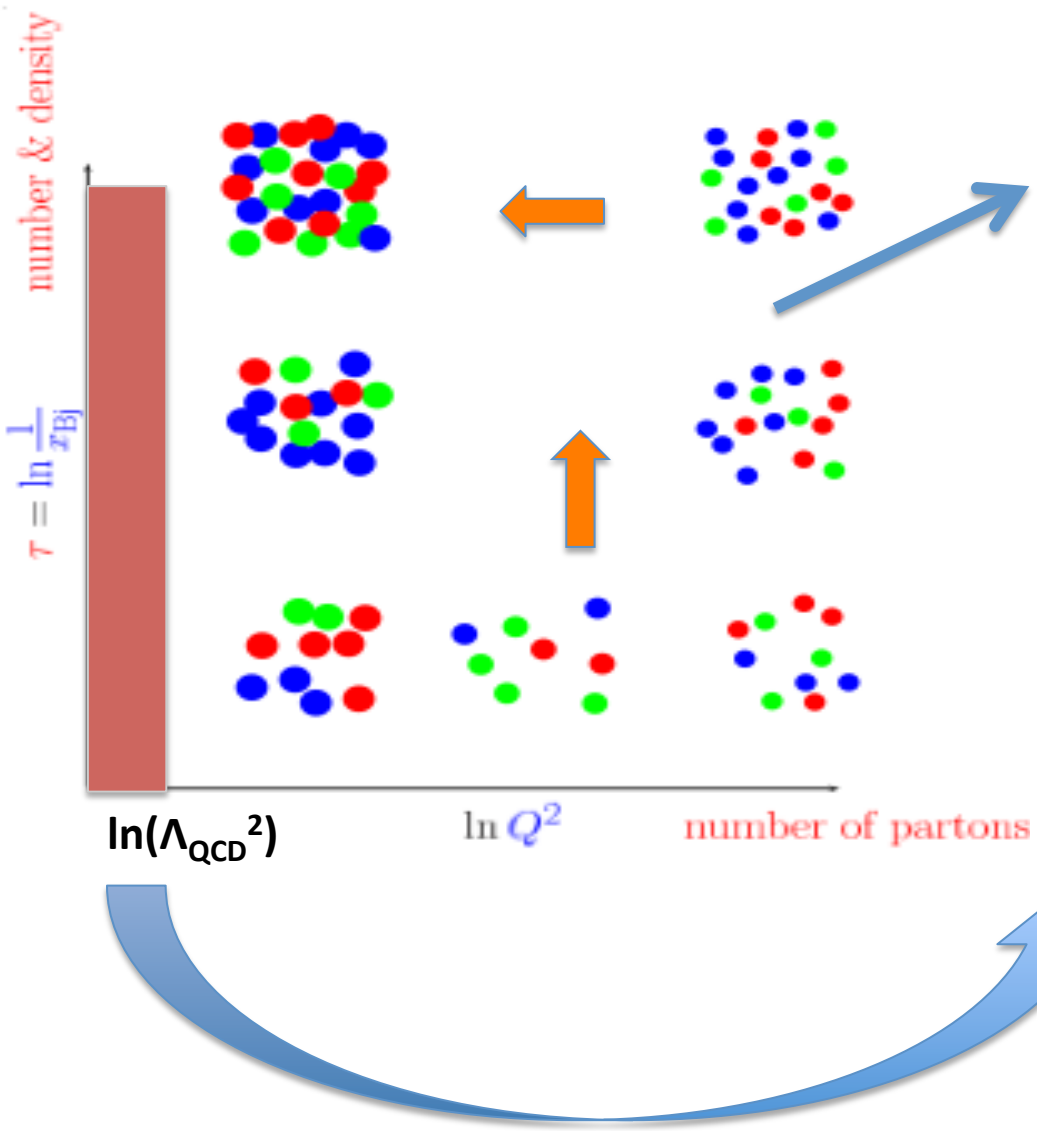
Large x - bremsstrahlung
linear evolution (DGLAP/BFKL)
$-\alpha_S \ln(Q^2) / \alpha_S \ln(x)$ resummation

Small x -gluon recombination
non-linear evolution
(BK/JIMWLK)

$Q_S(x)$ - transverse momentum scale below which non-linear ("higher twist") QCD dynamics is dominant

If $Q_S^2 >> \Lambda_{QCD}^2$, many-body color dynamics can be computed in weak coupling – quantitative comparison of QCD collective properties with experiment.

Many-body dynamics of universal gluonic matter



How does this happen ? What are the right degrees of freedom ?

How do correlation functions of these evolve ?

Is there a universal fixed point for the RG evolution of d.o.f

Does the coupling run with Q_s^2 ?

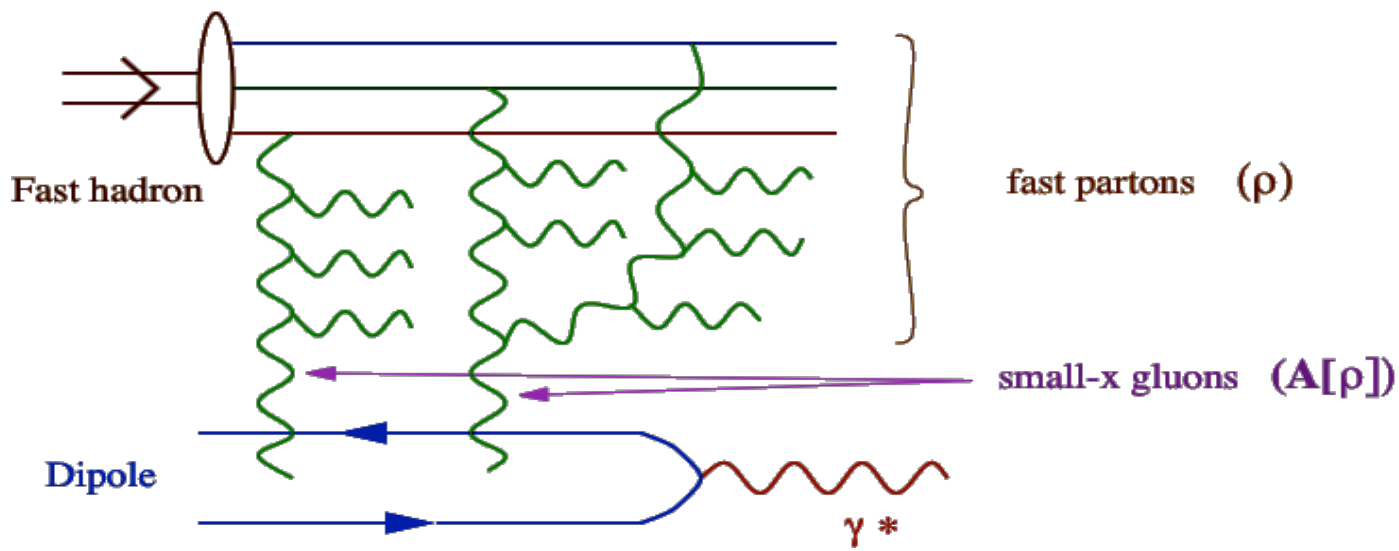
How does saturation transition to chiral symmetry breaking and confinement

CGC Effective Theory: B-JIMWLK hierarchy of correlators

$$\frac{\partial}{\partial Y} < O[\alpha] >_Y = < \frac{1}{2} \int_{x,y} \frac{\delta}{\delta \alpha^a_Y(x)} \chi^{ab}_{x,y} \frac{\delta}{\delta \alpha^b_Y(y)} O[\alpha] >_Y$$

"time"

"diffusion coefficient"

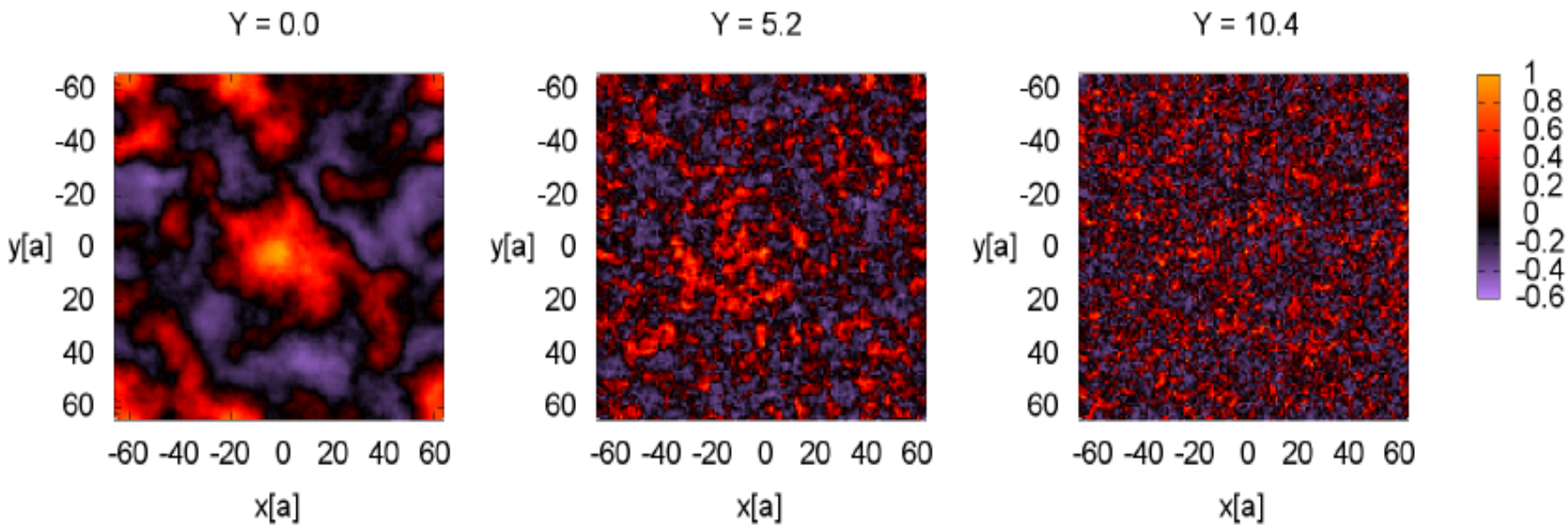


At high energies, the d.o.f that describe the frozen many-body gluon configurations are novel objects: dipoles, quadrupoles, …

Universal – appear in a number of processes in p+A and e+A; how do these evolve with energy ?

Functional Langevin solutions of JIMWLK hierarchy

Rummukainen,Weigert (2003)

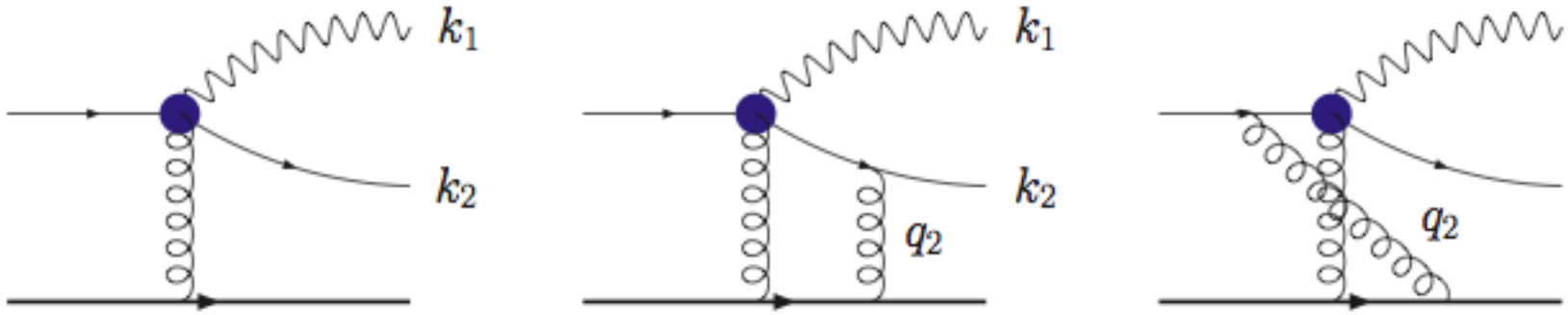


Dumitru,Jalilian-Marian,Lappi,Schenke,RV: arXiv:1108.1764

Multi-parton correlations in nuclear wavefunctions:

Event-by-event rapidity, number and impact parameter fluctuations

Universality: Di-jets in p/d-A collisions



Jalilian-Marian, Kovchegov (2004)
Marquet (2007)
Dominguez,Marquet,Xiao,Yuan (2011)

$$\frac{d\sigma^{qA\to qgX}}{d^3k_1 d^3k_2} \propto \int_{x,y,\bar{x},\bar{y}} e^{ik_{1\perp}\cdot(x-\bar{x})} e^{ik_{2\perp}\cdot(y-\bar{y})} \left[S_6(x,y,\bar{x},\bar{y}) - S_4(x,y,v) - \ldots\right]$$

$$\frac{N_c}{2C_F}\left\langle Q(x,y\,\bar{y},\bar{x})D(y,\bar{y}) - \frac{D(x,\bar{x})}{N_c}\right\rangle \qquad \frac{N_c}{2C_F}\left\langle D(x,y)D(\bar{y},\bar{x}) - \frac{D(x,\bar{x})}{N_c}\right\rangle$$

$$D(x,y) = \frac{1}{N_c}\langle \mathrm{Tr}(V_x V_y^\dagger)\rangle_Y$$

Dipoles: **Fundamental in high energy QCD, -ubiquitous in DIS and hadronic collisions**

$$Q(x,y;\bar{y},\bar{x}) = \frac{1}{N_c}\langle \mathrm{Tr}(V_x V_{\bar{x}}^\dagger V_{\bar{y}} V_y^\dagger)\rangle_Y$$

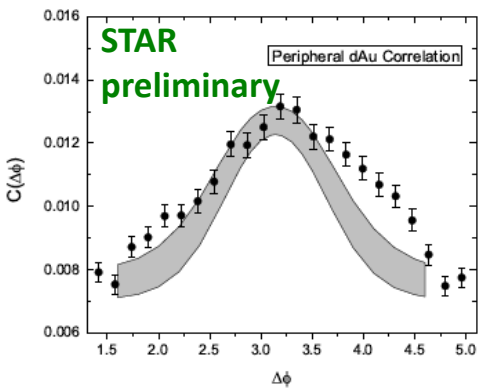
Quadrupoles: **also fundamental, appear in less inclusive processes**

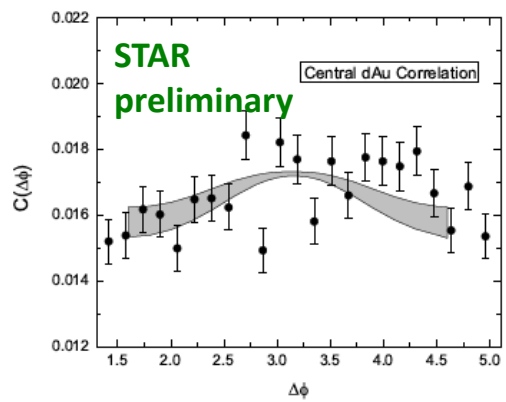
Higher point correlators accessible with more complex final states

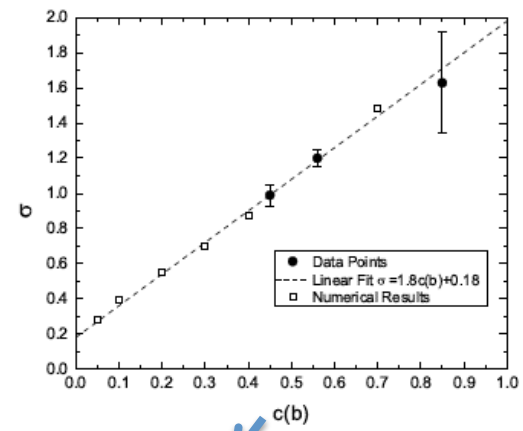
Saturation in p/D+A collisions ?

Marquet (2007); Albacete, Marquet (2010)
Tuchin (2010)

Forward di-hadron correlations- a measure of strong color fields
- disappearance of away-side peak predicted by Marquet







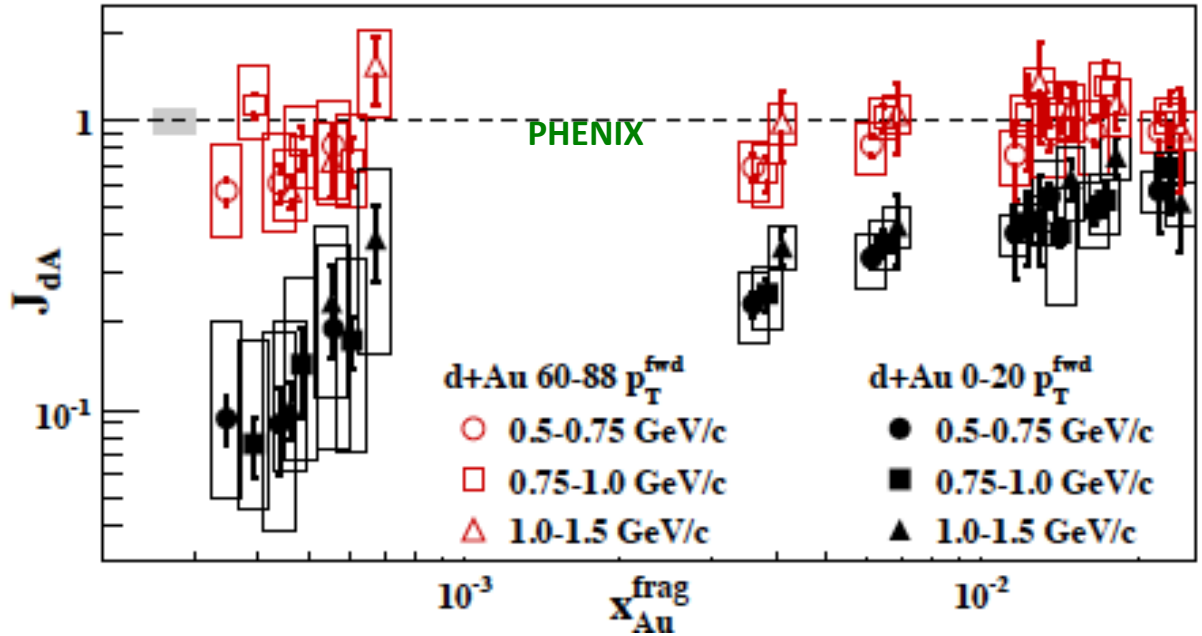
Stasto,Xiao,Yuan (2011)

$$Q_s^2(x,b) = c(b)\, A^{1/3}\, (x/x0)^{\lambda}$$

Recent computation includes Pedestal, Shadowing (color screening) and Broadening (multiple scattering) effects in CGC framework

Saturation in p/D+A collisions ?

Adare et al., Phys. Rev. Lett. 107, 172301 (2011)



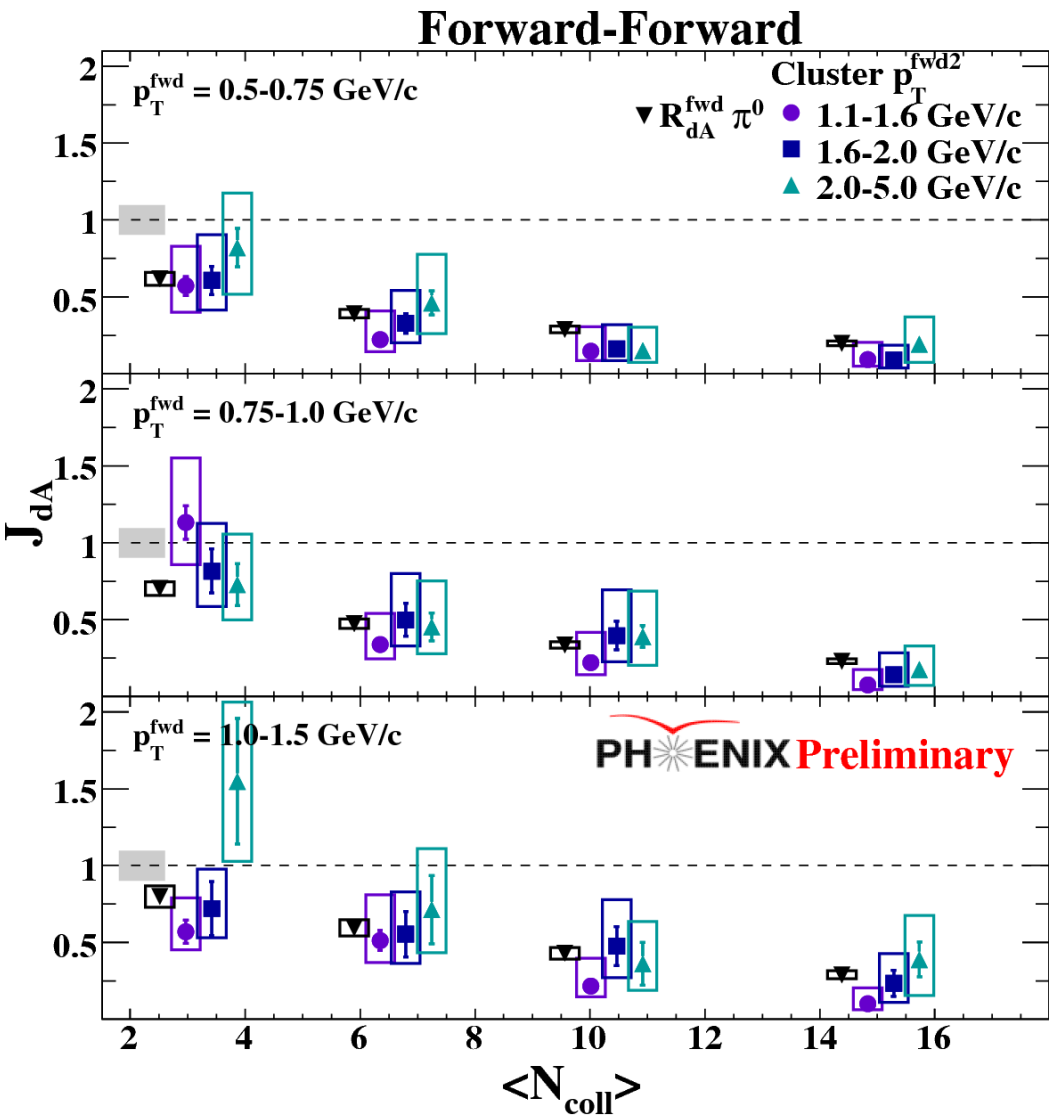
In CGC, Q_S^2 grows with decreasing x and increasing centrality

When both produced partons are forward, they are coherent enough to receive a common Q_S^2 kick from nuclear color field

The kick decorrelates (and broadens) pair with x and centrality

Saturation in p/D+A collisions ?

Adare et al., Phys. Rev. Lett. 107, 172301 (2011)

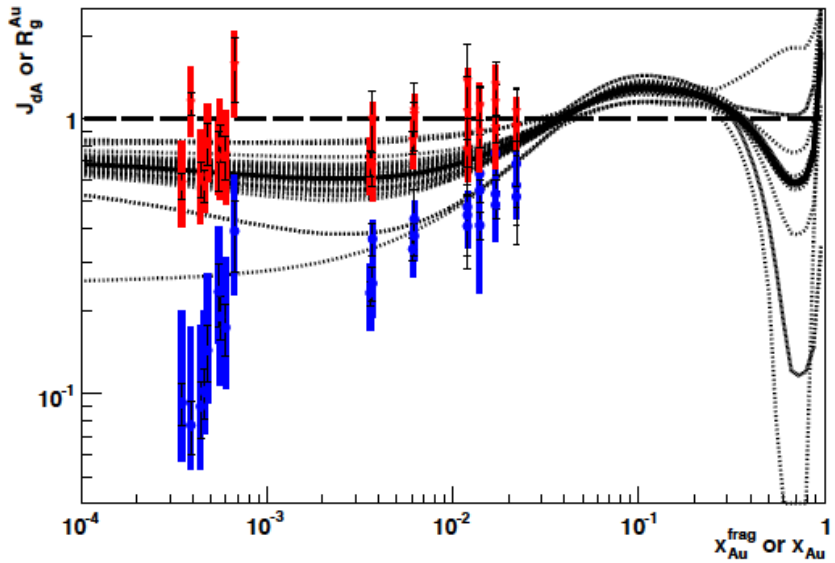


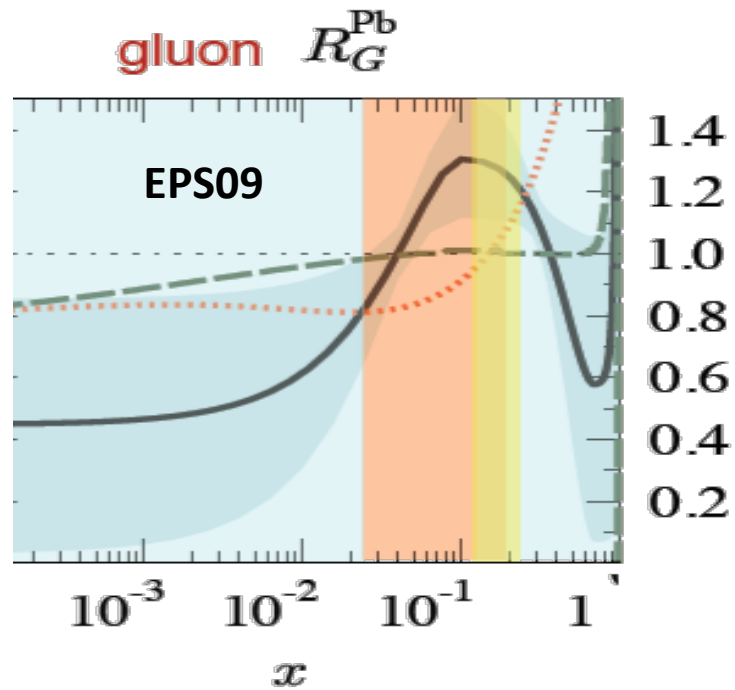
Though the eye may be deceptive, apparently more N_{coll} suppression at lower p_T

- also qualitatively anticipated in CGC picture

Saturation in p/D+A collisions ?

B. Meredith, ECT* talk June 2011
M. Chiu, arXiv:1109.2133



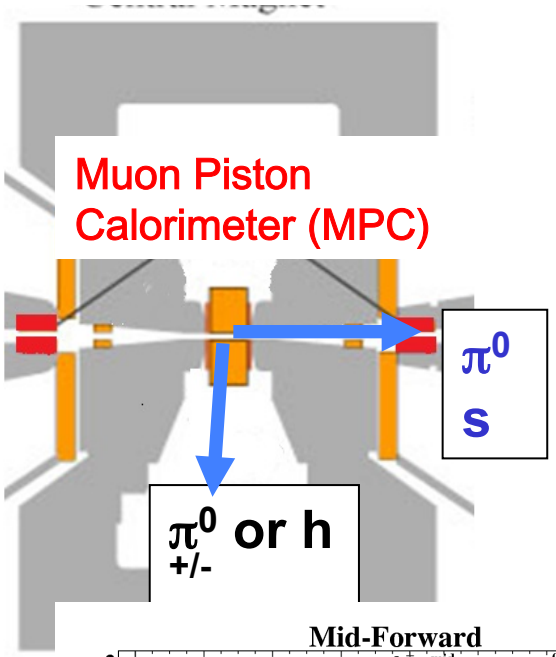


$$J_{\rm dAu} \approx \frac{f_d^a(x_d^a) \otimes f_{\rm Au}^b(x_{\rm Au}^b) \otimes \hat{\sigma}^{ab\to cd} \otimes \mathcal{D}(z_c, z_d)}{\langle N_{\rm coll}\rangle f_p^a(x_p^a) \otimes f_p(x_p^b) \otimes \hat{\sigma}^{ab\to cd} \otimes \mathcal{D}(z_c, z_d)} \approx \frac{f_{\rm Au}^b}{\langle N_{\rm coll}\rangle f_p(x_p^b)}$$

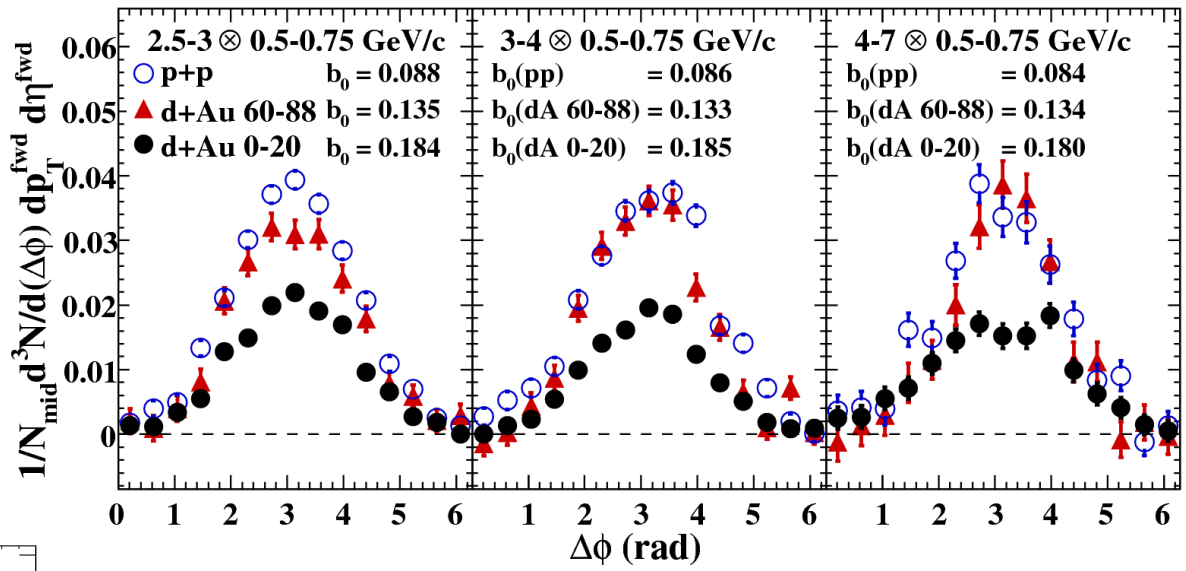
Difficult to explain as usual (a la EPS) shadowing…

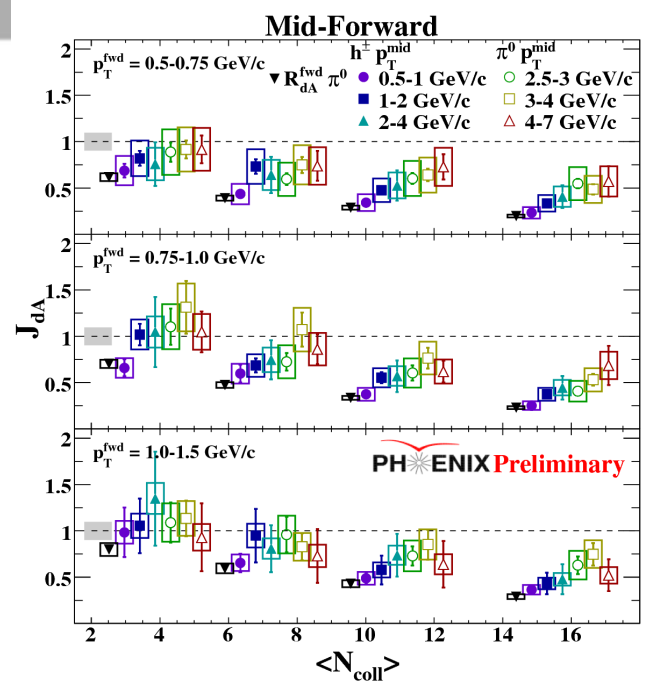
Caveat: EPS09 is min. bias.

Forward-mid-rapidity correlations



$|\eta^{mid}| < 0.35$, $\eta^{fwd} = 3.0\text{-}3.8$





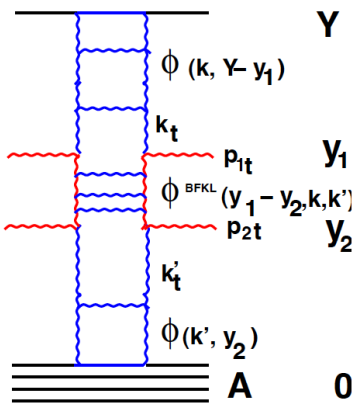
More suppression with decreasing p_T^{mid}, p_T^{fwd}, increasing N_{coll}

But claim is that no broadening is seen…

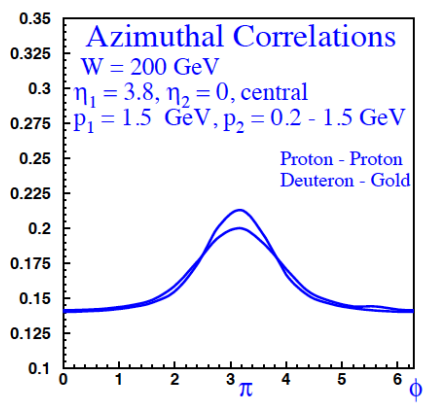
Forward-mid-rapidity correlations

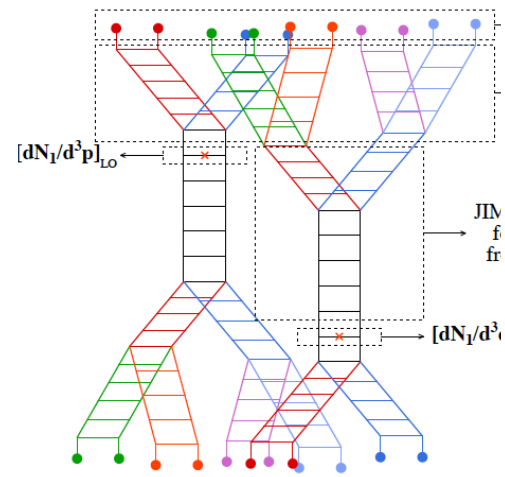
Two types of contributions:

Kharzeev,Levin,McLerran, NPA748 (2005) 627
Tuchin, NPA846 (2010) 83

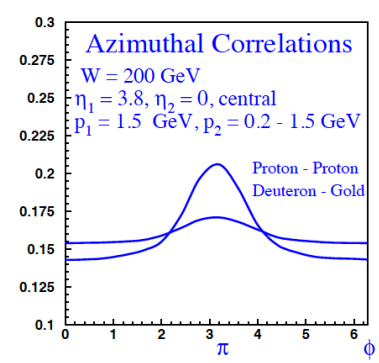


Same ladder emission





Independent ladder emission

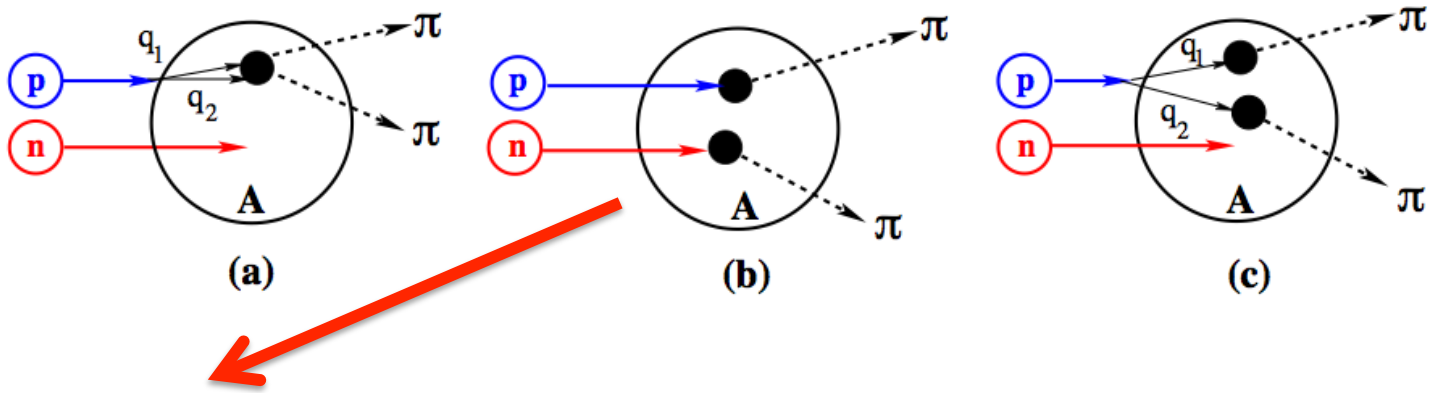


My claim: for forward-central kinematics, same ladder emission dominant in p+A won't give much broadening but instead depletion of strength.
Quantitative computation needs NLO

What about the pedestal ?

Strikman,Vogelsang, PRD83 (2011) 034029

"Double scattering" contribution



Dominant contribution, especially at forward rapidities – absent in p+A

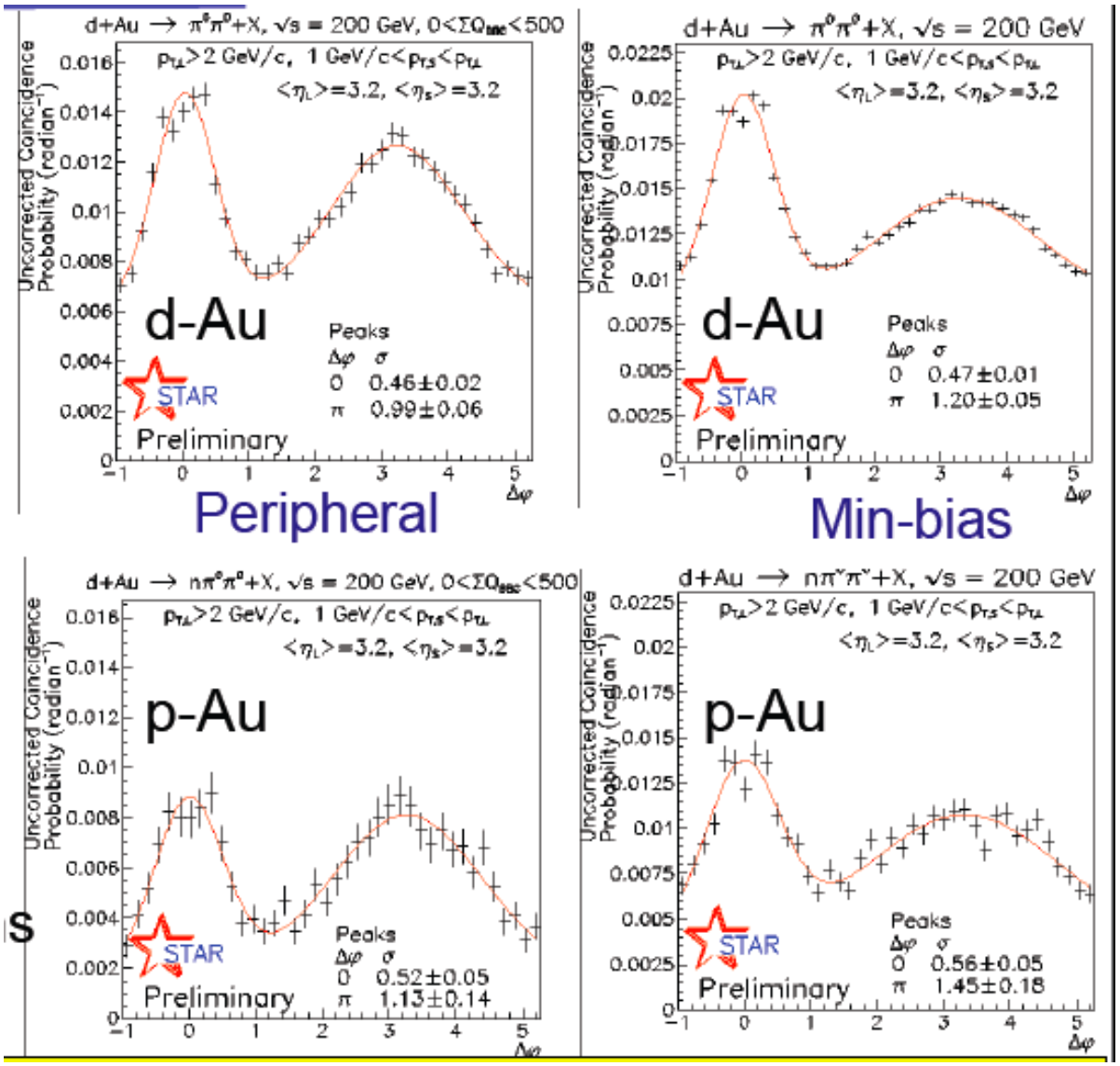
ΔΦ independent pedestal could be larger in d+A explaining suppression

However…

No change seen in near side from p+p to d+Au; should also be affected by pedestal – requires fine tuning of fragmentation functions

What about the pedestal ?

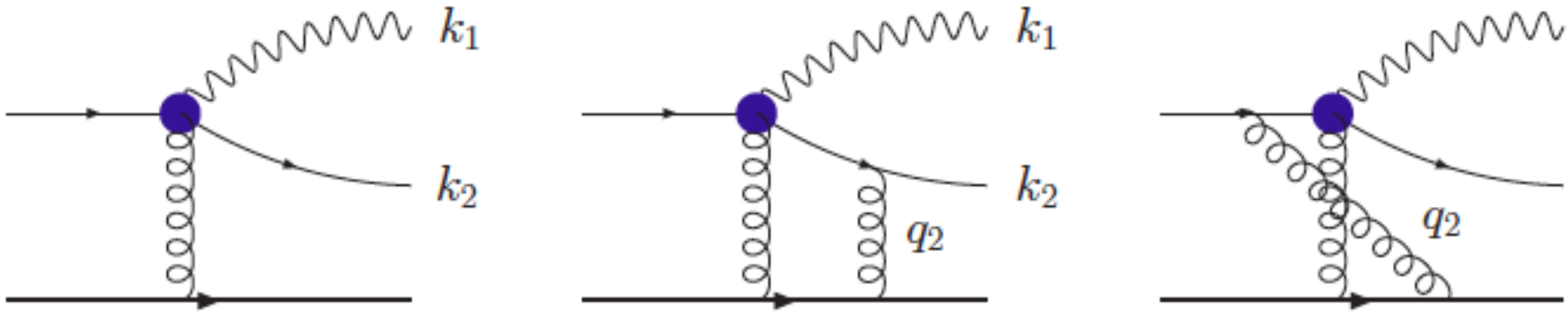
H. Caines, QM 2011
C.Perkins, DIS2011



Preliminary STAR data on tagged neutrons show no reduction in the away-side width expected from MPI claim

Important to verify this!

Forward photon-jet production in d+A



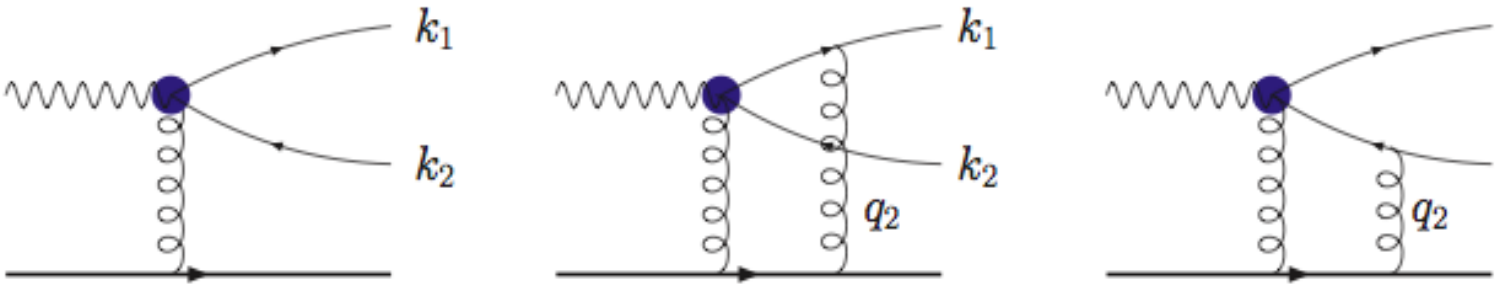
$$\frac{d\sigma^{qA\to q\gamma X}}{d^3k_1 d^3k_2} \propto \sum_f x_p q_f(x_p) \otimes D$$

Dipole cross-section

Much weaker broadening in this case

CGC prediction: J_{pA} more suppressed at LHC at forward rapidities

Semi-inclusive DIS: quadrupole evolution



Dominguez,Marquet,Xiao,Yuan (2011)

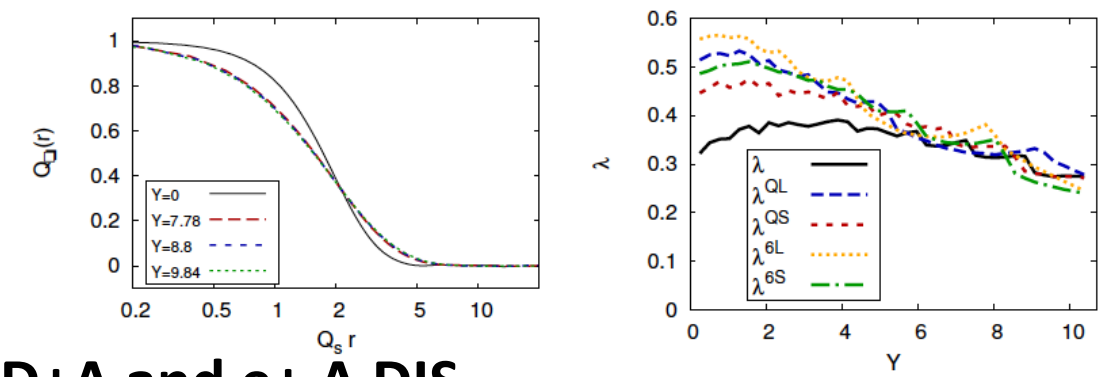
$$\frac{d\sigma^{\gamma^*_{\mathrm{T,L}} A \to q\bar{q}X}}{d^3k_1 d^3k_2} \propto \int_{x,y,\bar{x}\bar{y}} e^{ik_{1\perp}\cdot(x-\bar{x})} e^{ik_{2\perp}\cdot(y-\bar{y})} \left[1 + Q(x,y;\bar{y},\bar{x}) - D(x,y) - D(\bar{y},\bar{x})\right]$$

$$D(x,y) = \frac{1}{N_c}\langle \mathrm{Tr}(V_x V_y^\dagger)\rangle_Y \qquad Q(x,y;\bar{y},\bar{x}) = \frac{1}{N_c}\langle \mathrm{Tr}(V_x V_{\bar{x}}^\dagger V_{\bar{y}} V_y^\dagger)\rangle_Y$$

RG evolution provides fresh insight into multi-parton correlations

Dumitru,Jalilian-Marian,Lappi,Schenke,RV: arXiv:1108.1764

Quadrupoles, like Dipoles, exhibit Geometrical Scaling



- **New opportunity in p/D+A and e+ A DIS**

Summary

PHENIX forward di-hadron results are very suggestive of strong color field dynamics in d+Au collisions

Consistent with intepretation of PHENIX R_{dA} results in saturation framework

Neutron tagging will help rule out (or in) pedestal arguments. E&M probes add an important new dimension

<u>Theory improvements:</u>

Quantitative effects of pedestal in d+Au, relative to p+A

Improved computation of forward-central decorrelation needed

Several groups working on systematics of forward-forward J_{dA}