Initial Conditions in heavy ion collisions: From RHIC to the LHC

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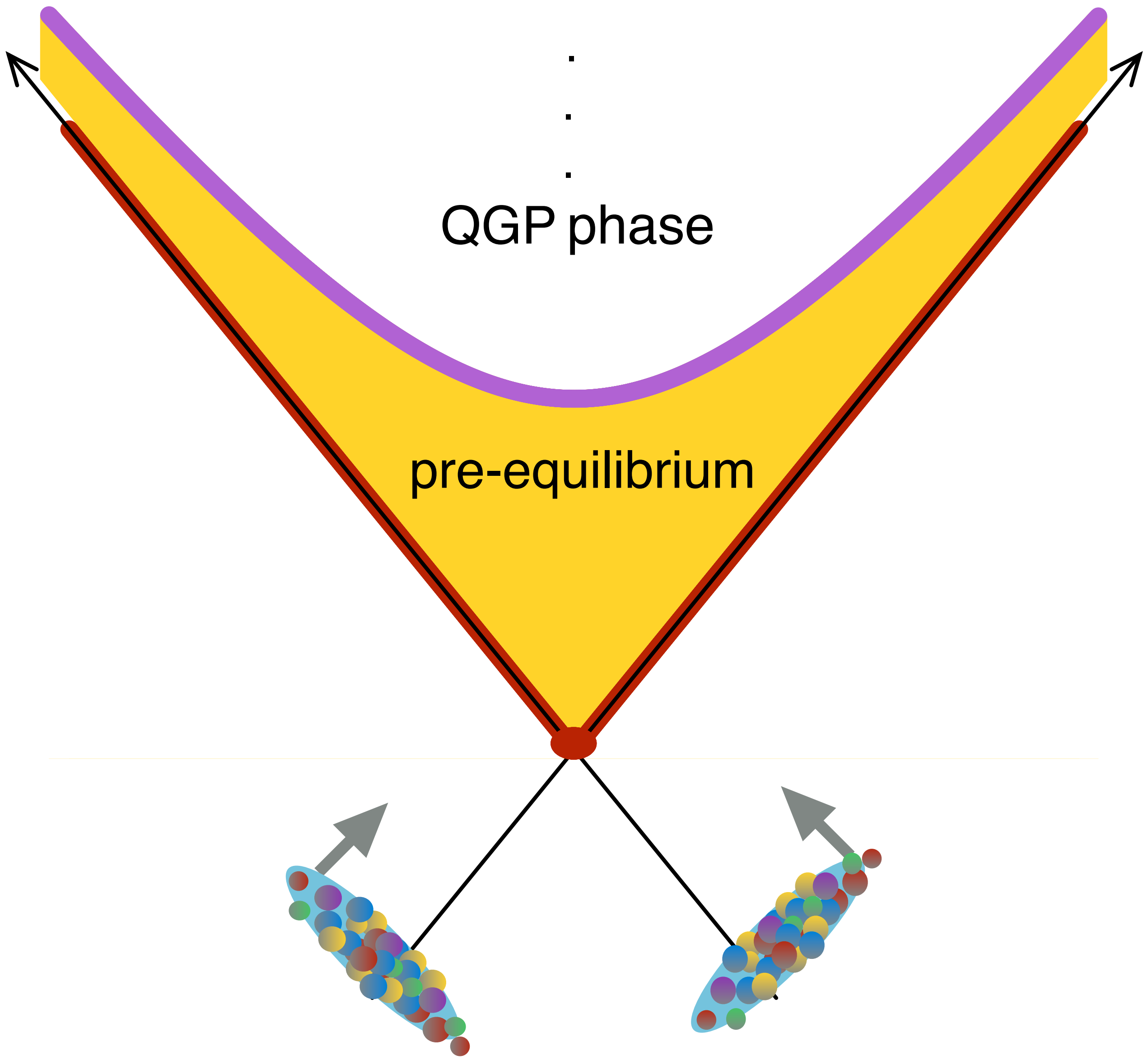
Outline

- Goal of initial-state studies: To characterize the system formed after the collision of two heavy ions and provide a description (and proof!) of the equilibration of the system



3. Equilibration dynamics
$0^+ < \tau < \tau_{eq}$

2. Initial production mechanism
$\tau = 0^+$

1. Nuclear wave function
$\tau < 0$

...mostly from a Color Glass Condensate perspective

Lessons from data

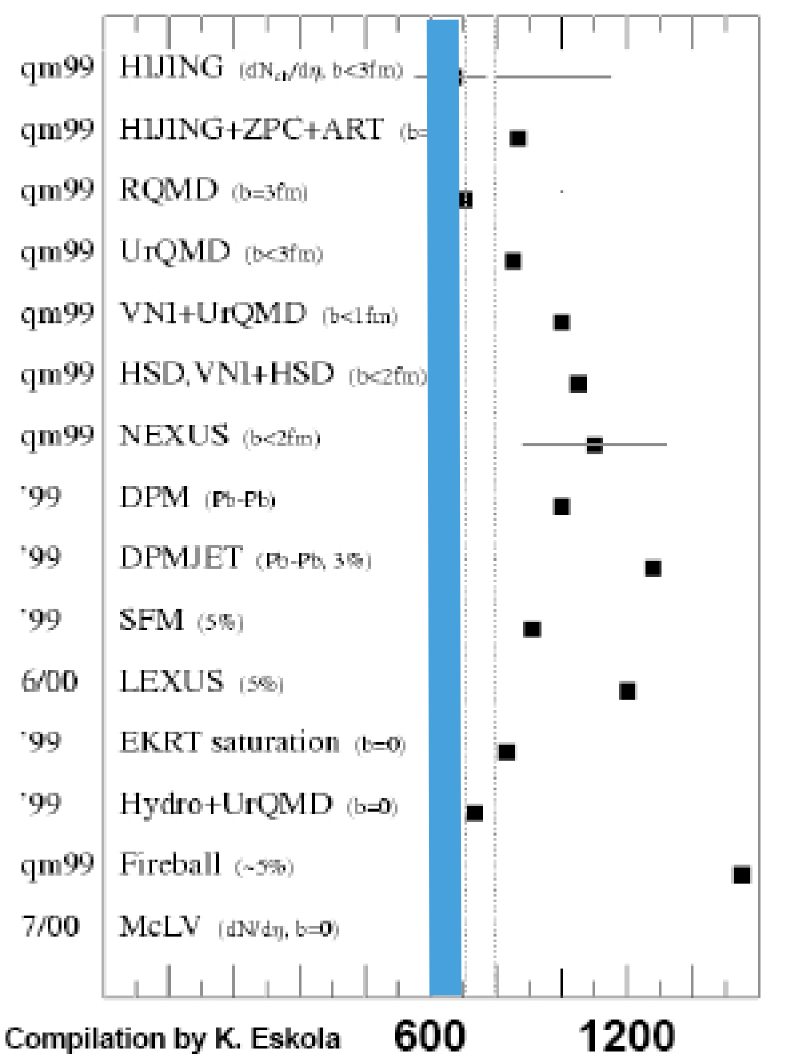
HIC behave very differently to a simple superposition of independent N-N collisions

$$\frac{dN^{AA}}{d\eta} \ll N_{coll} \frac{dN^{pp}}{d\eta}$$

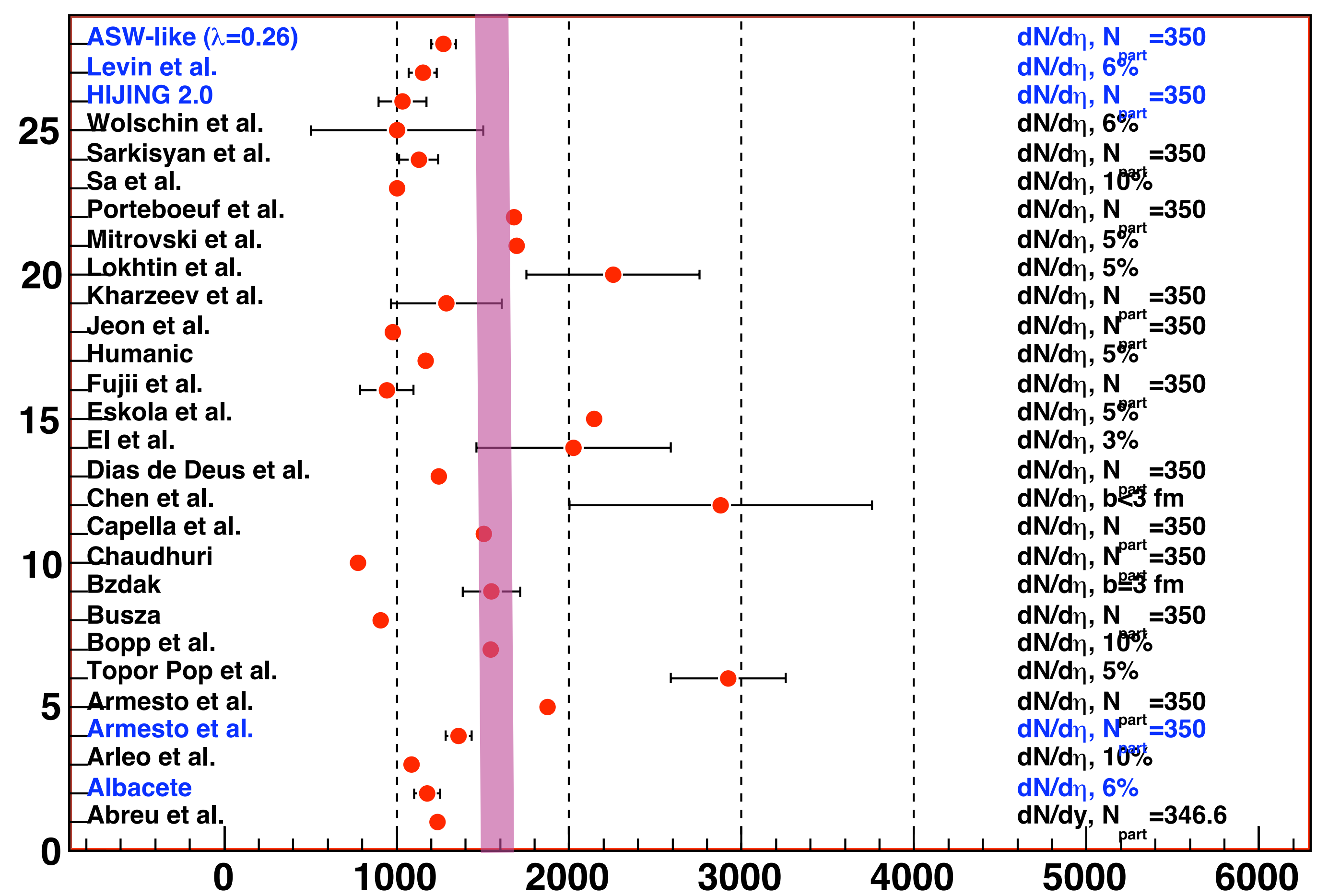
Strong coherence effects reduce the effective number of *sources* for particle production

$$\left.\frac{dN_{ch}^{AA}}{d\eta}\right|_{\eta=0}$$

RHIC: PHOBOS Au-Au (0.2 TeV)



LHC: ALICE Pb-Pb (2.76 TeV)

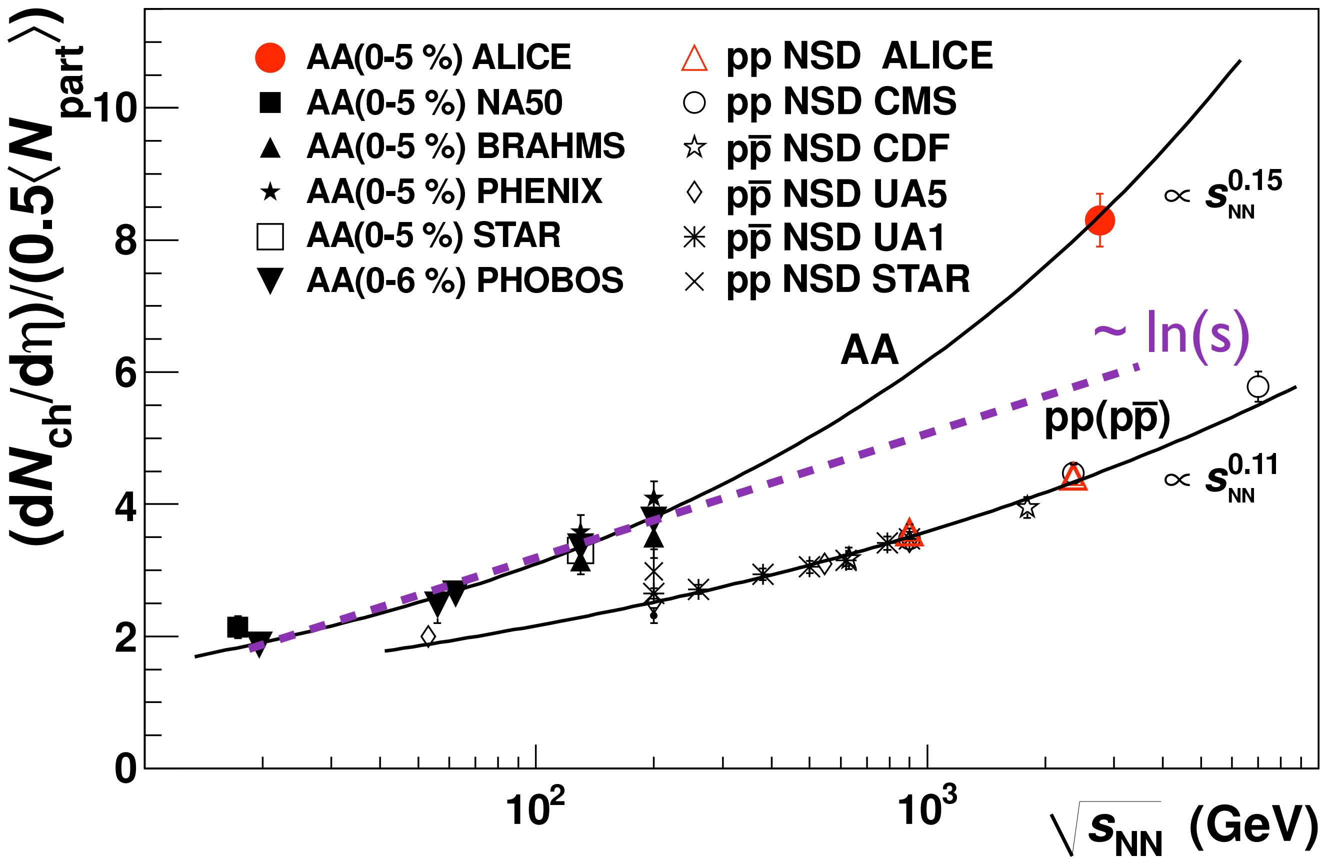


compilation by N. Armesto

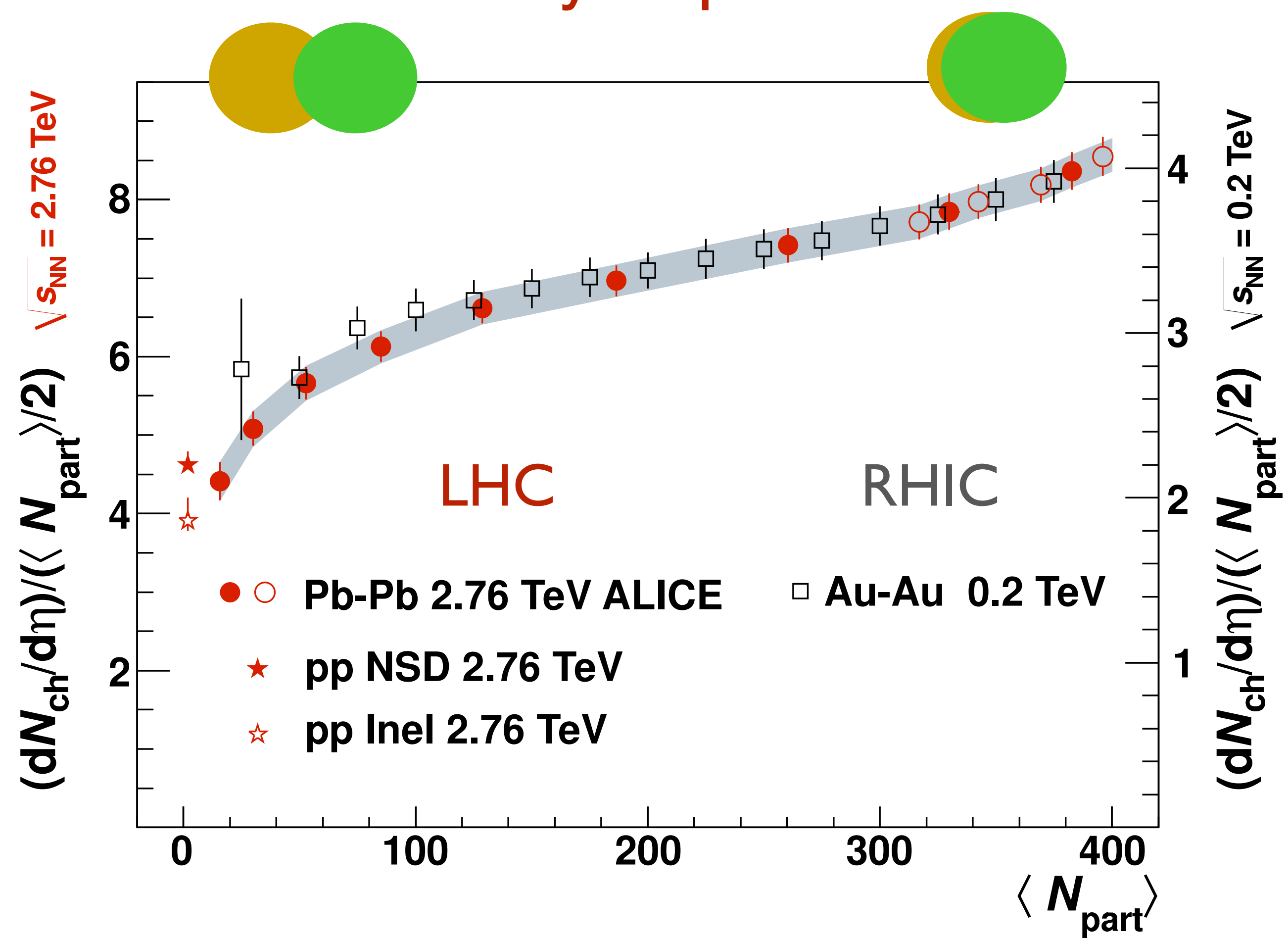
What are the relevant coherence effects and what is their dynamical description??

Lessons from data

Energy dependence



Centrality dependence

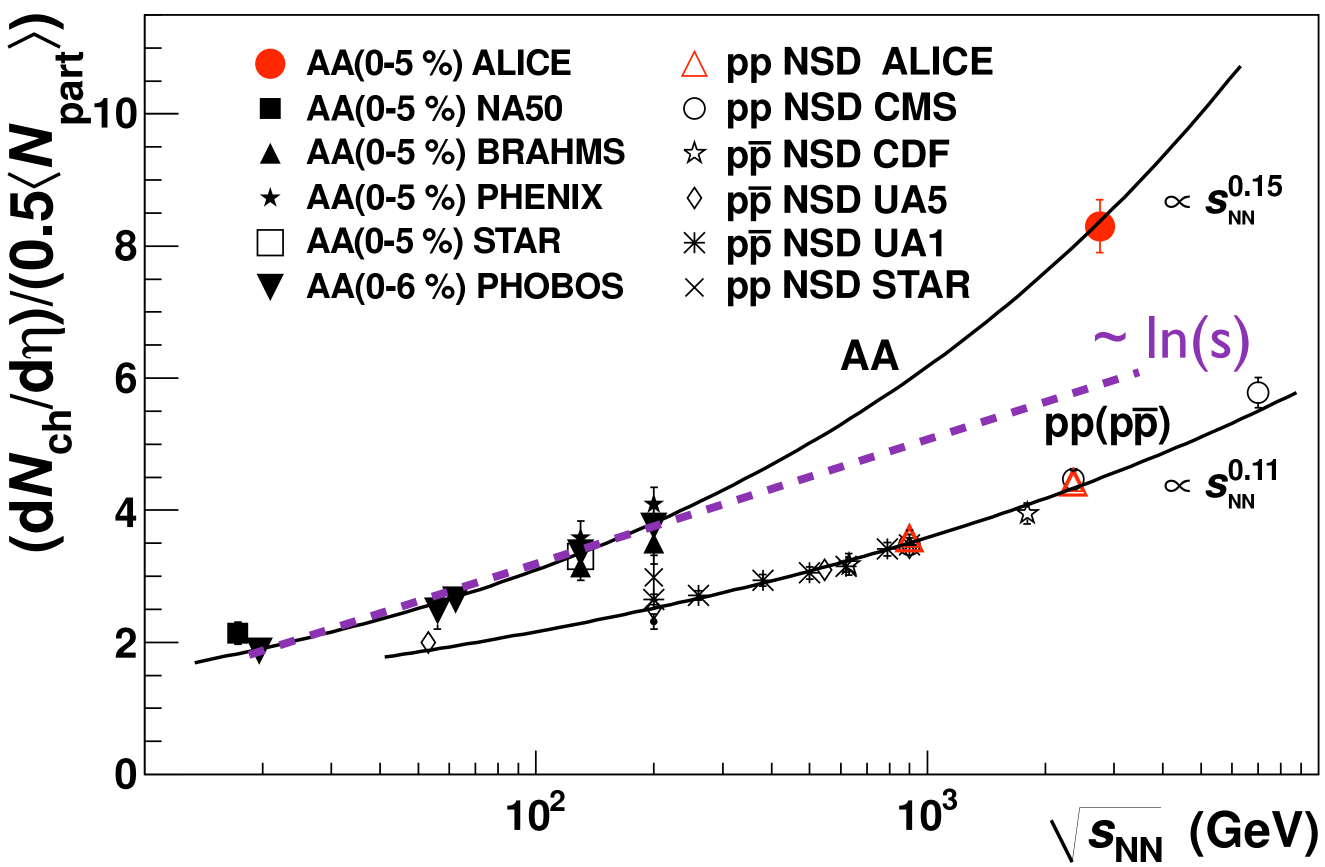


- Stronger energy dependence in A+A than in p+p?
- Factorization of energy and centrality dependence?

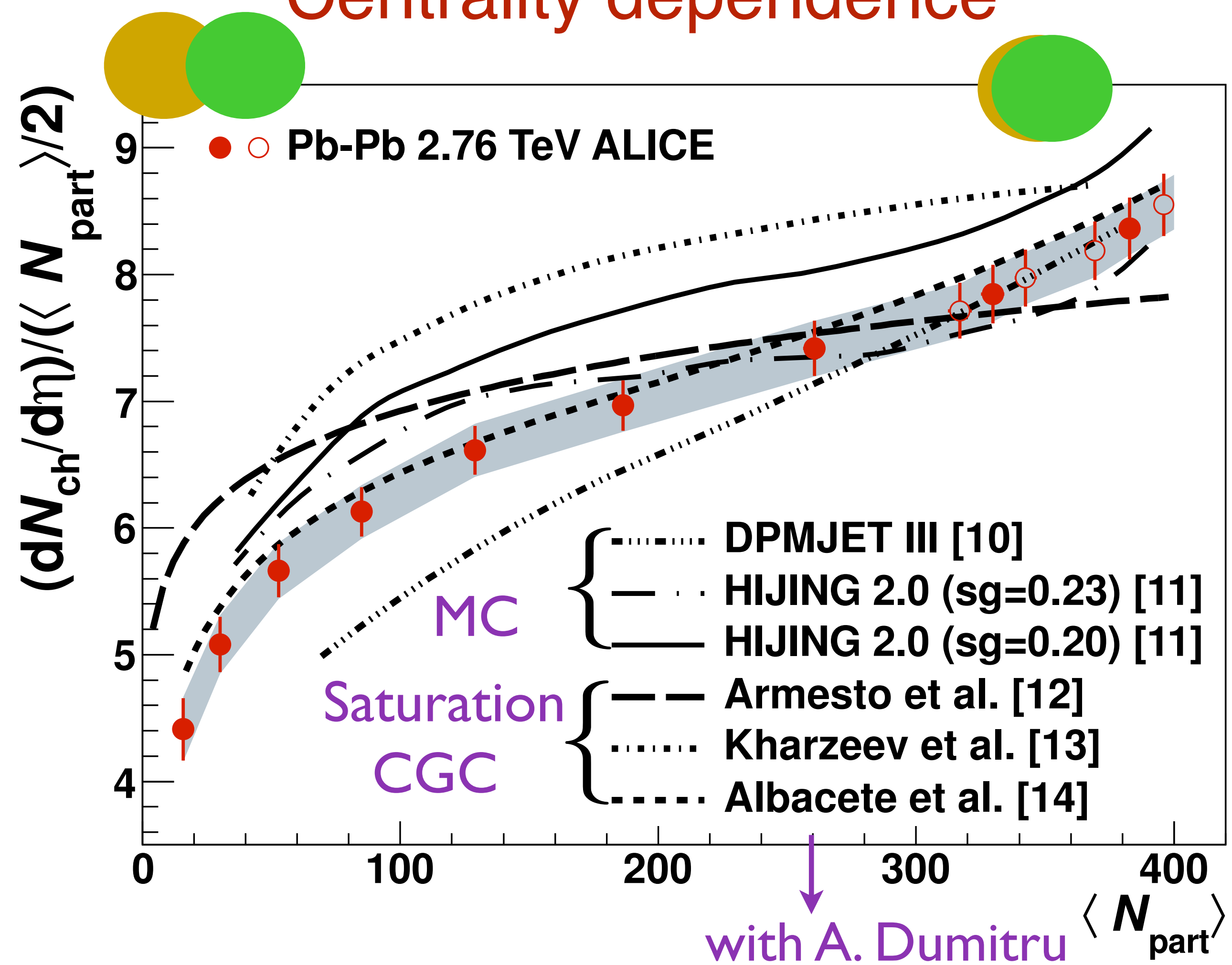
$$\left.\frac{dN^{ch}}{d\eta}\right|_{\eta=0} \approx \sqrt{s}^{0.3} \times f(N_{part})$$

Lessons from data

Energy dependence



Centrality dependence



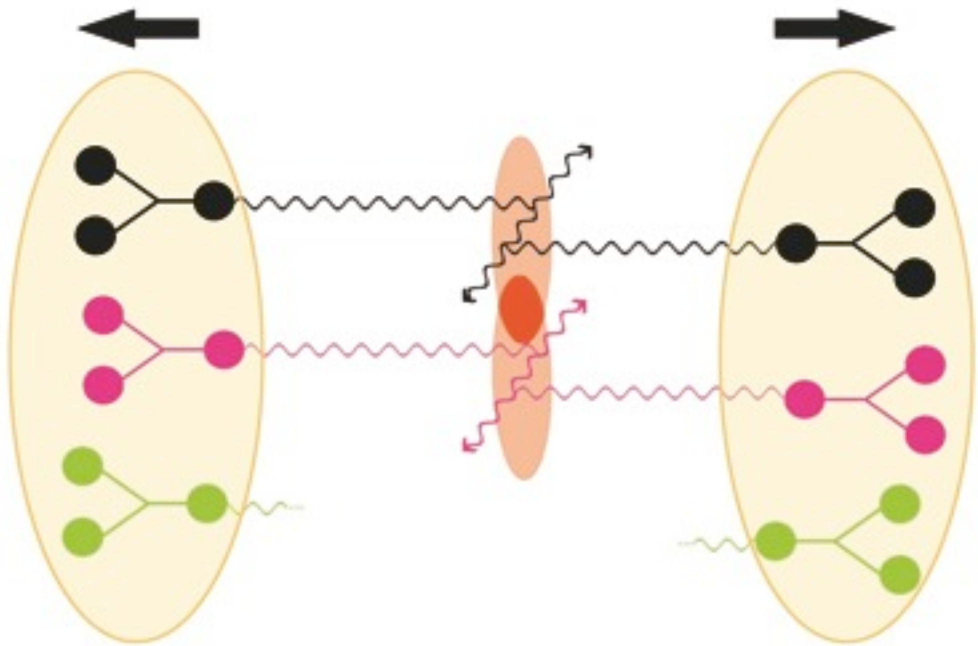
Different models reproduce data “well” (?)

$$\left.\frac{\mathrm{dN^{ch}}}{\mathrm{d}\eta}\right|_{\eta=0} \approx \sqrt{\mathrm{s}}^{0.3} \times \mathrm{f}(\mathrm{N_{part}})$$

Coherence mechanisms

Wave function:
- (b-dependent) Nuclear Shadowing
- String fusion -- percolation

Initial production: Breakdown of independent particle production: cutoff



Such mechanisms are implemented in (most of) A+A Monte Carlo event generators (HIJING, DPMJET, HYDJET, PACIAE, EPOS...)

SOFT $p_0(s) \longrightarrow$ HARD p_t

Strings, Dual Parton Model, RFT, hydro/thermal models...)

LO pQCD independent minijet production, eikonal approximation

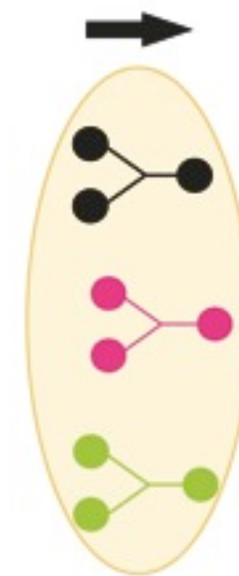
$$s^{\Delta_{soft}} \times \cancel{N_{coll}}$$

$$\Delta_{soft} \approx 0.08$$

$$\frac{s^{\Delta_{hard}}}{p_0^2(s)} \times \cancel{N_{coll}}$$

$$\Delta_{hard} \approx 0.3$$

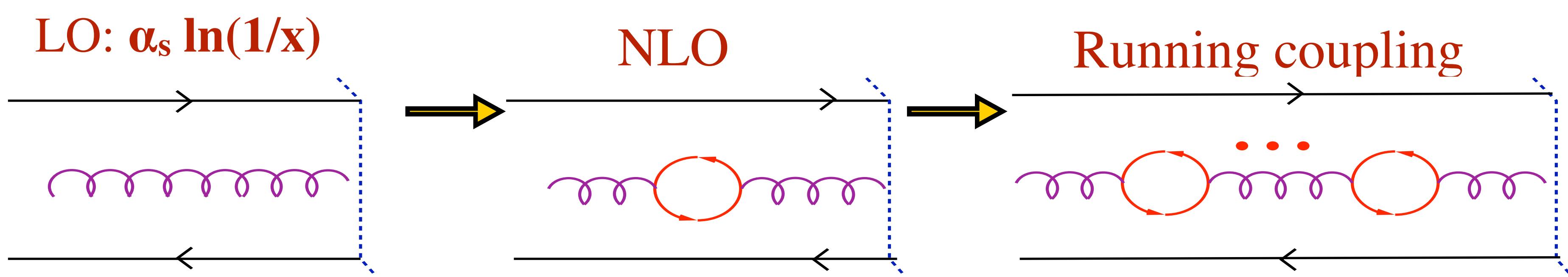
Coherence mechanisms in the Color Glass Condensate



Wave function: gluon recombination tame the growth of gluon densities towards small-x (high-energies)

“BK-JIMWLK” $$\frac{\partial \phi(\mathbf{x},\mathbf{k_t})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \underbrace{\mathcal{K}\otimes\phi(\mathbf{x},\mathbf{k_t})}_{\text{radiation}} - \underbrace{\phi(\mathbf{x},\mathbf{k_t})^{\mathbf{2}}}_{\text{recombination}}$$

Theory development!: Calculation of higher orders (full NLO and running coupling corrections) to the evolution kernel K [Balitsky, Kovchegov-Weigert, Gardi et at]:



Coherence mechanisms in the Color Glass Condensate

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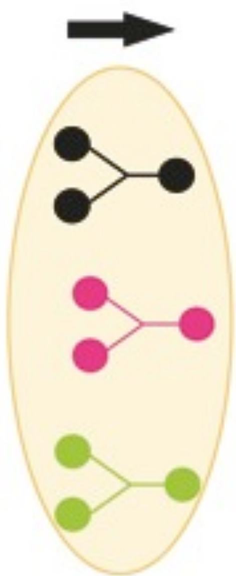
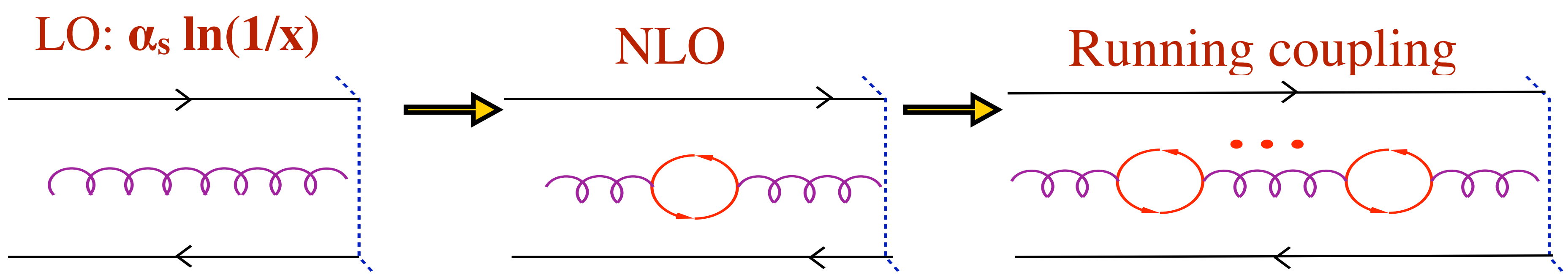
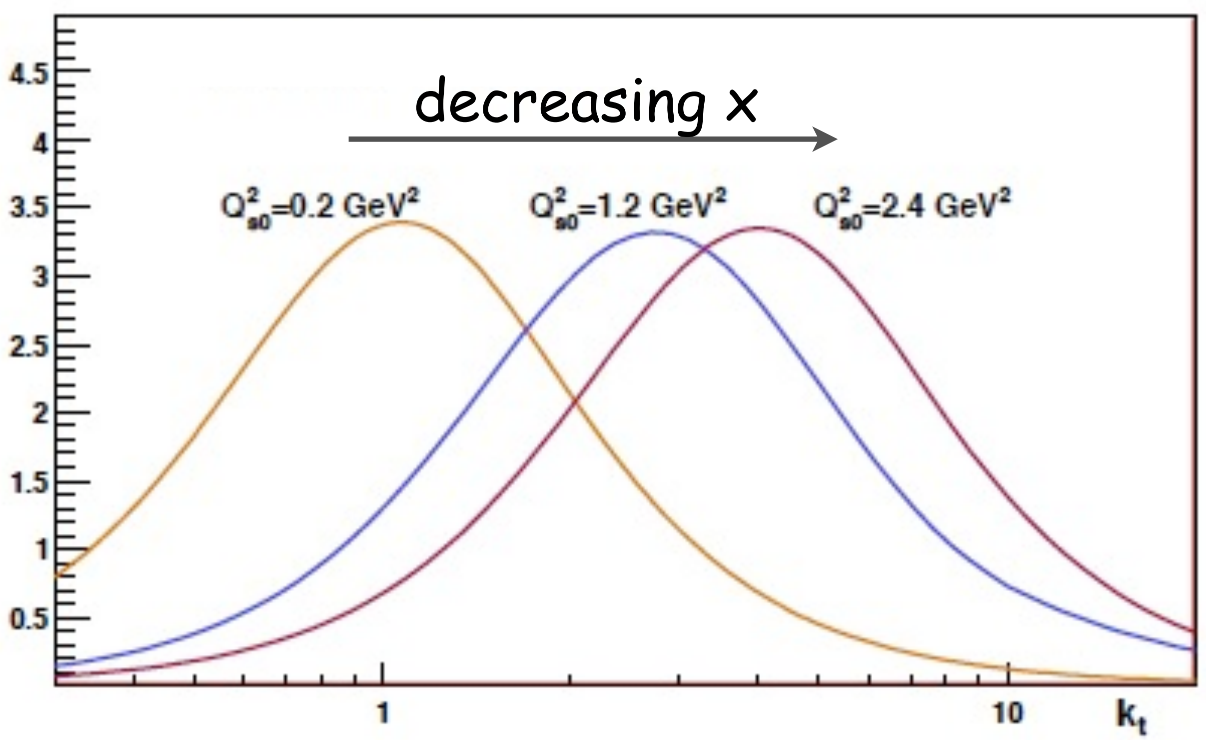


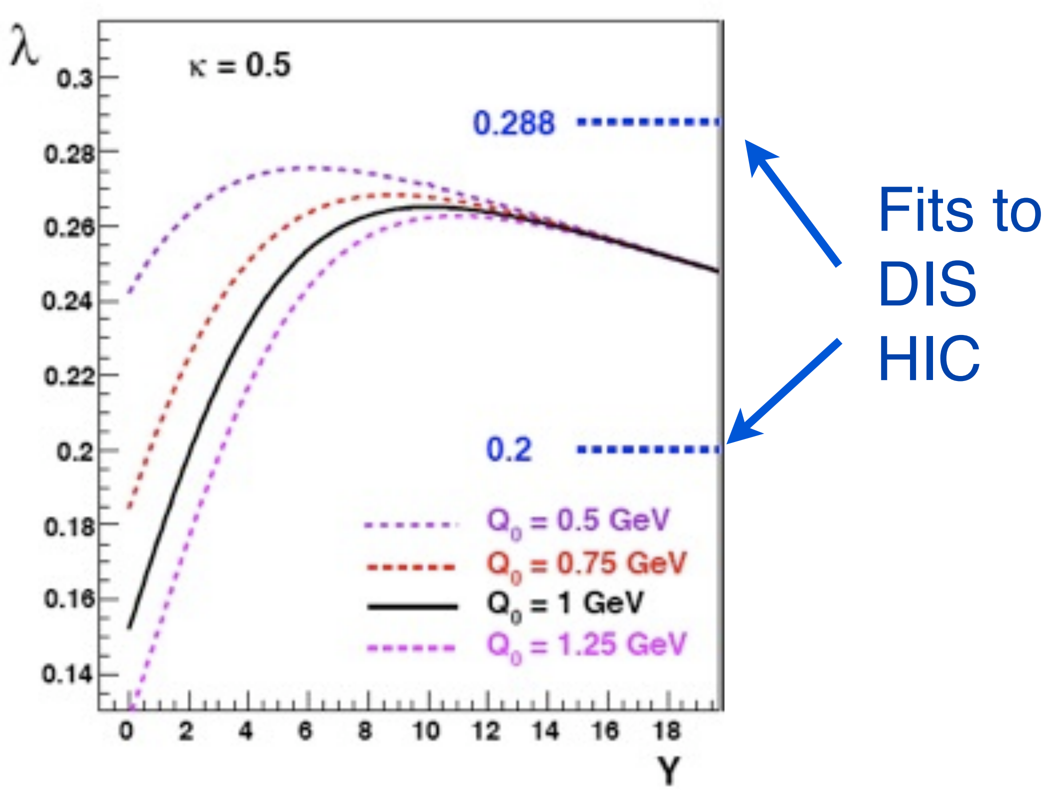
"BK-JIMWLK" $$\frac{\partial \phi(\mathbf{x}, \mathbf{k_t})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \underbrace{\mathcal{K} \otimes \phi(\mathbf{x}, \mathbf{k_t})}_{\text{radiation}} - \underbrace{\phi(\mathbf{x}, \mathbf{k_t})^2}_{\text{recombination}}$$



Saturation of gluons with: $\mathbf{k_t} \lesssim \mathbf{Q_s}(\mathbf{x})$



Running coupling corrections render evolution speed compatible with data!



Coherence mechanisms in the Color Glass Condensate

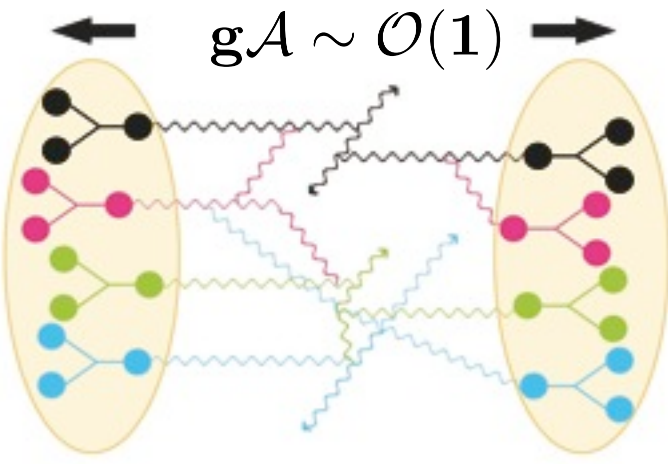
Initial production: Rearrangement of perturbation series due to strong color fields

- Classical Yang-Mills EOM: $[\mathbf{D}_\mu \mathbf{F}^{\mu\nu}] = \mathbf{J}^\nu[\rho]$

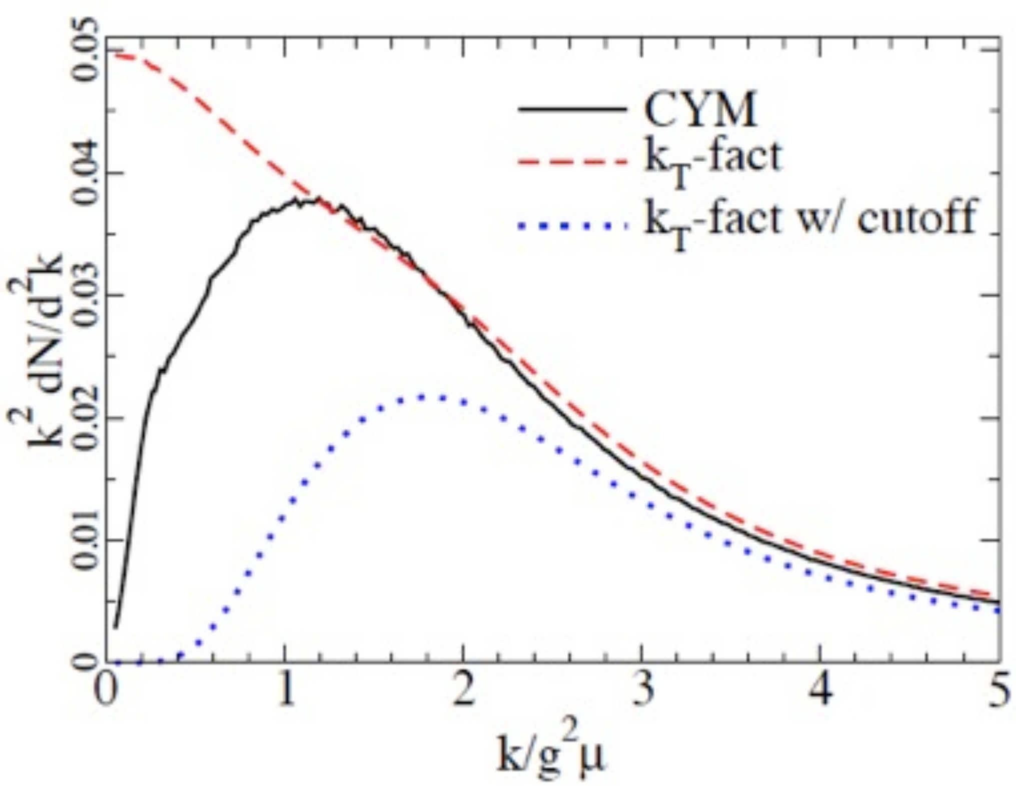
  (Suplemented by JIMWLK evolution)

- kt-factorization: $\frac{\mathbf{dN^g}}{\mathbf{d\eta d^2 p_t}} \sim \phi(\mathbf{x_1}, \mathbf{k_t}) \otimes \phi(\mathbf{x_2}, \mathbf{k_t} - \mathbf{pt})$

  (BK evolution)

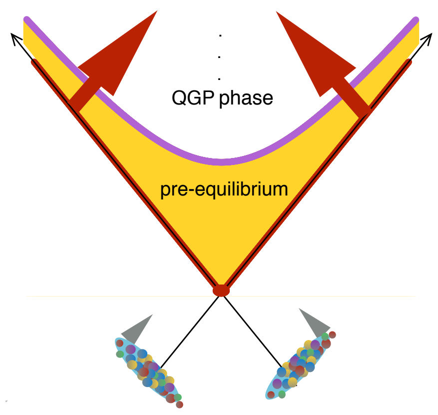


Big differences for small kt gluons...



Blaizot-Lappi-Mehtar Tani

Total multiplicities: local parton-hadron duality



$$\left.\frac{\mathbf{dN^{ch}}}{\mathbf{d\eta}}\right|_{\eta=\mathbf{0}} = \frac{\mathbf{2}}{\mathbf{3}} \mathbf{K} \left.\frac{\mathbf{dN^g}}{\mathbf{d\eta}}\right|_{\eta=\mathbf{0}}$$

- Gluon to hadron conversion
- Contribution from valence and sea partons
- jet fragmentation
- k-factor for higher order corrections
- Truly soft contribution (peripheral collisions)
- ...

Total multiplicities

LO kt-factorization (running coupling corrections now available Horowitz-Kovchegov):

$$\lambda \approx 0.24 \div 0.3$$

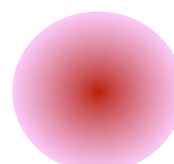
$$\left.\frac{\mathrm{d}N^g}{\mathrm{d}\eta\, \mathrm{d}^2b}\right|_{\eta=0} \propto \int \frac{\mathrm{d}^2p_t}{p_t^2}\int \mathrm{d}^2k_t\, \mathrm{d}^2B\, \alpha_s\, \phi(x_1,k_t,B)\,\phi(x_2,|p_t-kt|,b-B) \quad \sim Q_s^2(\sqrt{s},b)\sim \sqrt{s}^{\lambda} N_{part}$$

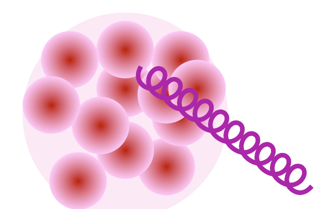
energy-centrality factorization

(x, kt)-dependence "RHIC" $\longrightarrow$ "LHC"

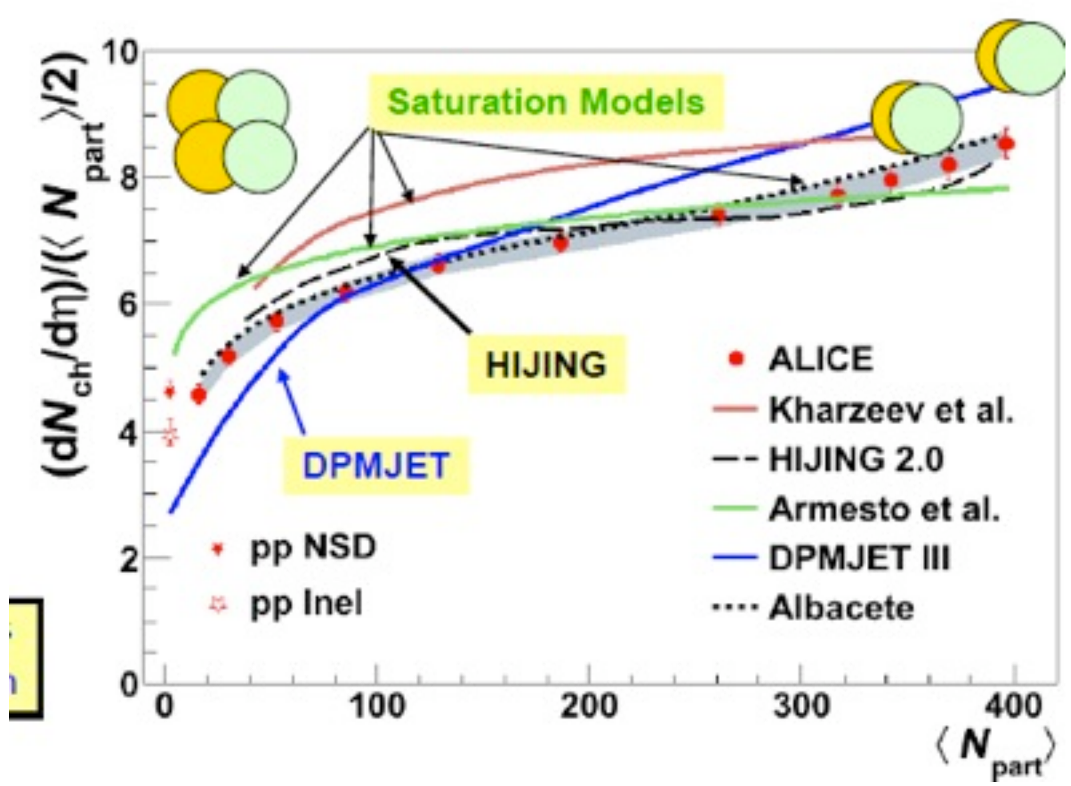
Empiric information from e+p coll.
+ analytical models
[KLN, ASW, Razeian-Levin...]

- Solutions of running coupling BK equation
[JLA-Dumitru-Nara]

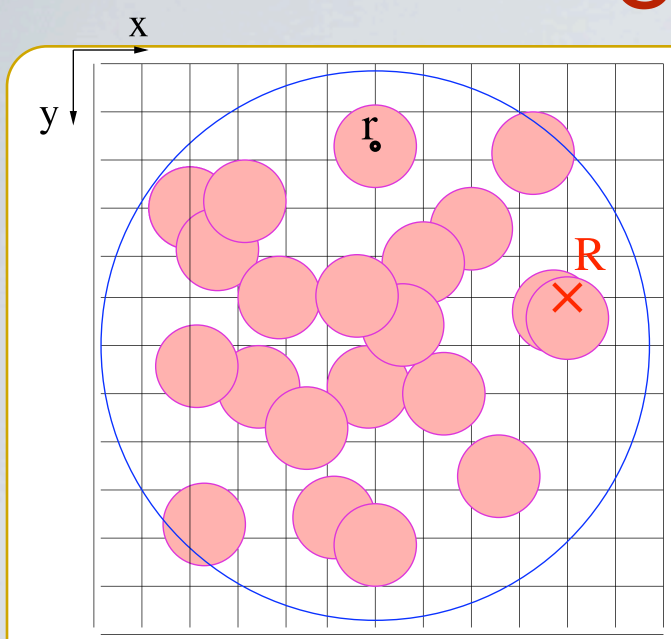
b-dependence: - Mean field 

-Monte-Carlo 

Fundamental (non-perturbative) problem: Convoluting evolution and b-dependence?



CGC Monte Carlo: MC-KLN and rcBK



1. Initial conditions for the evolution (x=0.01)

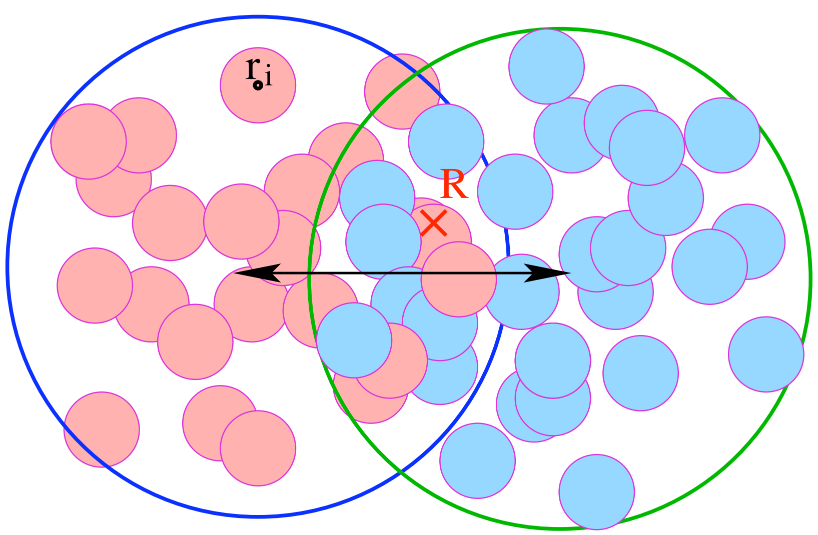
$$N(\mathbf{R}) = \sum_{i=1}^{A} \Theta\left(\sqrt{\frac{\sigma_0}{\pi}} - |\mathbf{R} - \mathbf{r_i}|\right) \longrightarrow Q_{s0}^2(\mathbf{R}) = N(\mathbf{R})\, Q_{s0,\,\mathrm{nucl}}^2$$

$$\varphi(x_0 = 0.01, k_t, R)$$

2. Solve local running coupling BK evolution at each transverse point

rcBK equation or KLN model

$$\varphi(x, k_t, R)$$



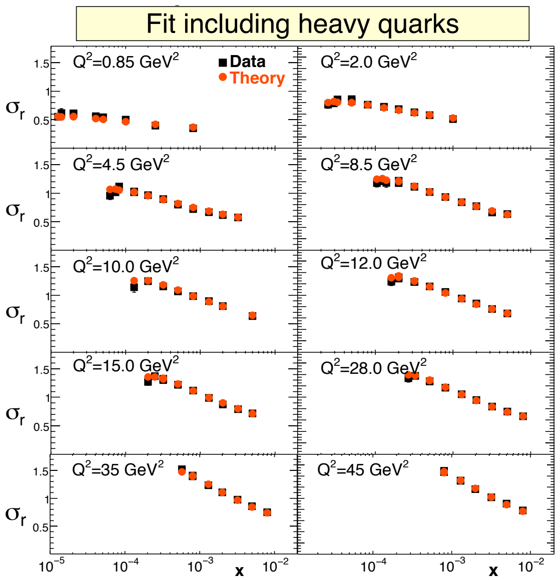
3 Calculate gluon production at each transverse point according to kt-factorization

INPUT: $\varphi(\mathbf{x} = \mathbf{0.01}, \mathbf{k_t})$ FOR A SINGLE NUCLEON:

NOTE: rcBK Monte Carlo is built as an upgrade of MC-KLN, by Drescher and Nara

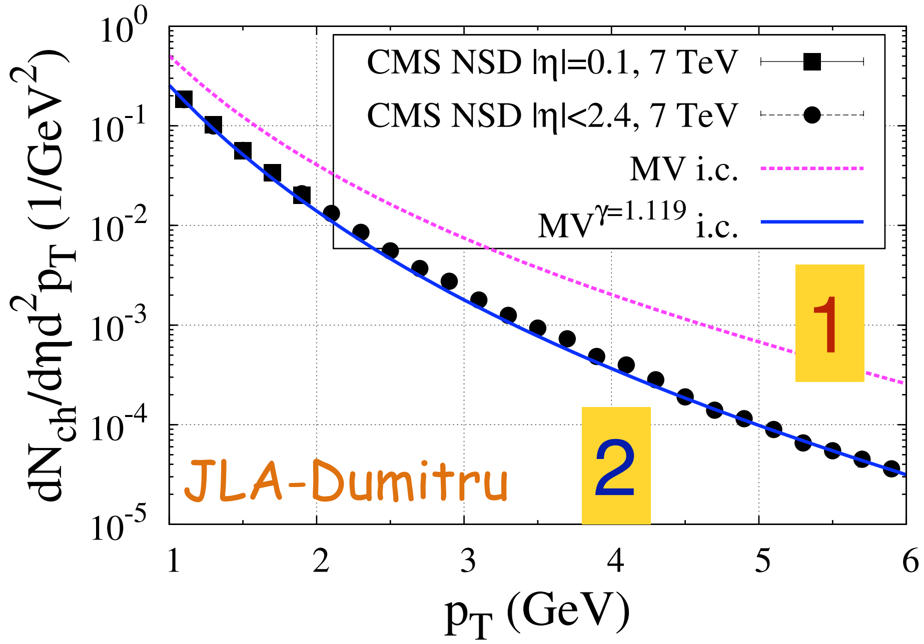
Learning from proton data: Initial Conditions for rcBK

Global fits to e+p (HERA)

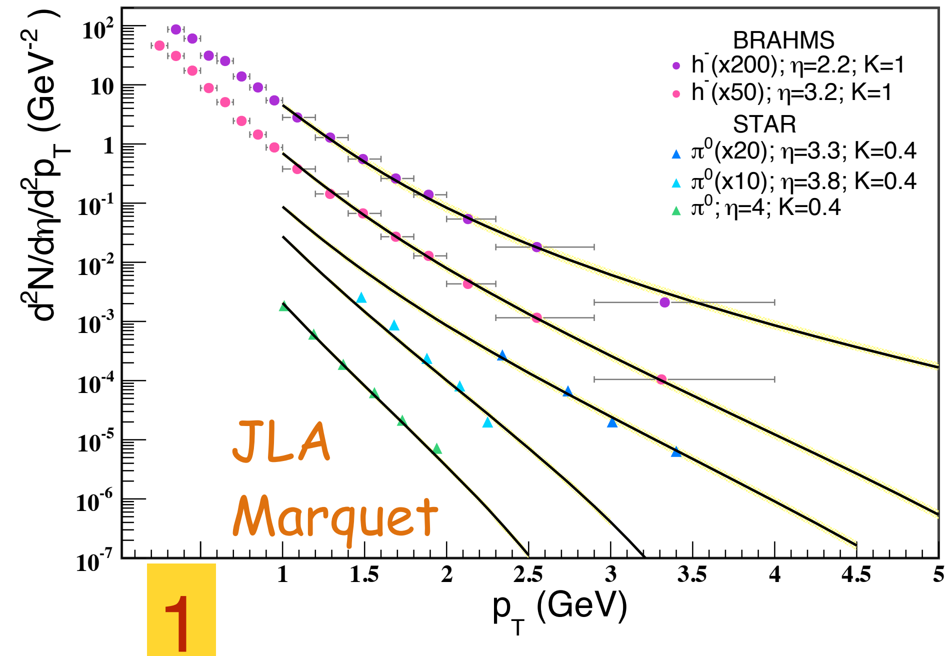


AAMQS Collaboration 2

p+p yields @ LHC



forward p+p yields (RHIC)

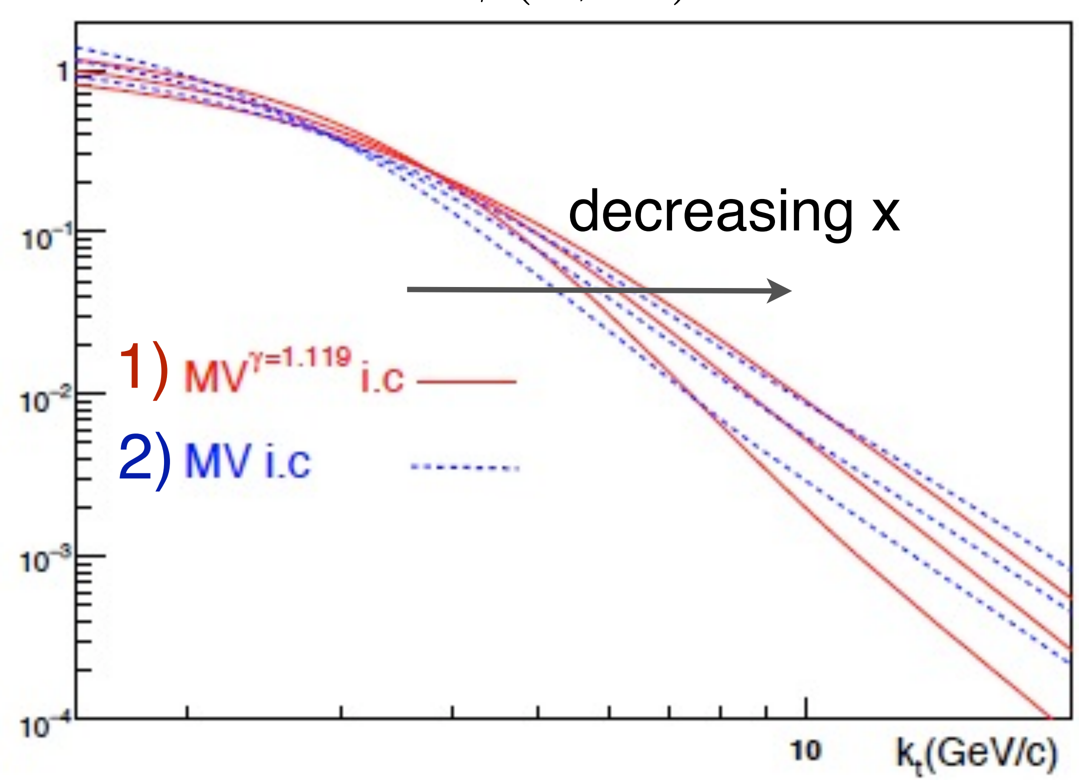


Such analyses do not suffice to unambiguously determine the initial conditions for the evolution

$$\phi(\mathbf{x} = \mathbf{x_0} \approx \mathbf{0.01}, \mathbf{k_t})$$

Differences persist after the evolution:

$$\phi(\mathbf{x}, \mathbf{k_t})$$



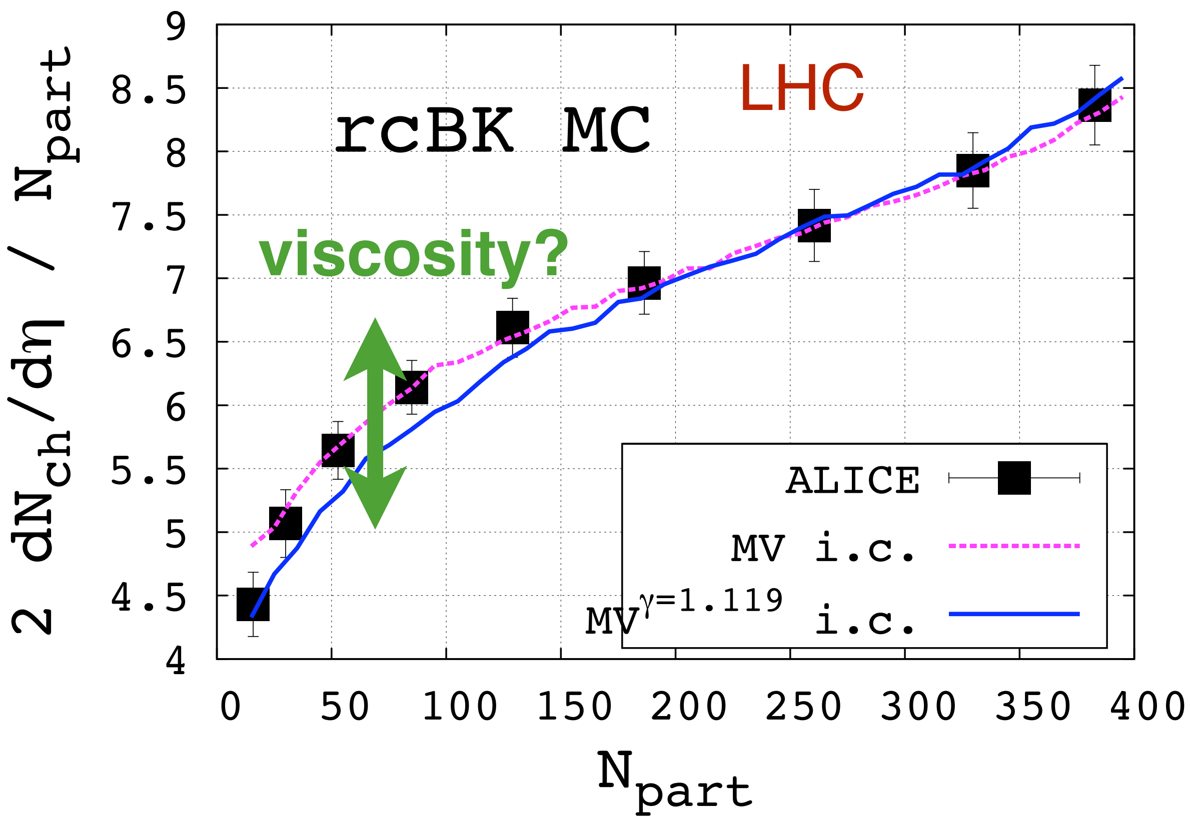
I.C: Variants of the MV model

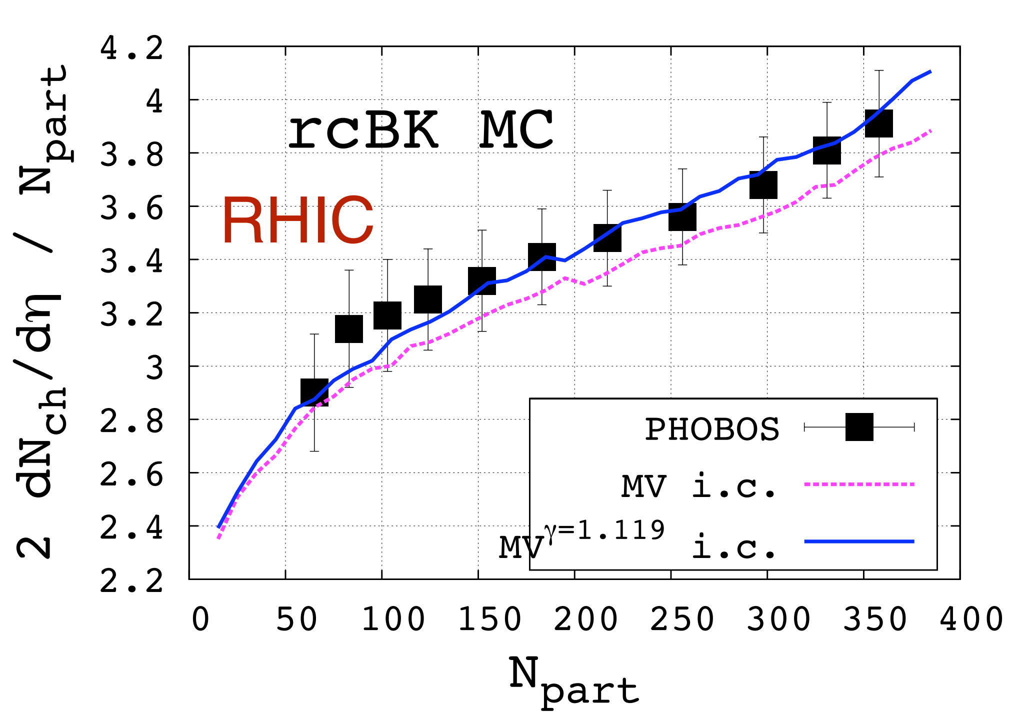
$$\mathcal{N}^{MV}(r, x_0 = 10^{-2}) = 1 - \exp\left[-\left(\frac{r^2\, Q_{s0}^2}{4}\right)^{\gamma} \ln\left(\frac{1}{r\,\Lambda_{QCD}}\right)\right]$$

Results from rcBK MC

Little effect on multiplicity distributions

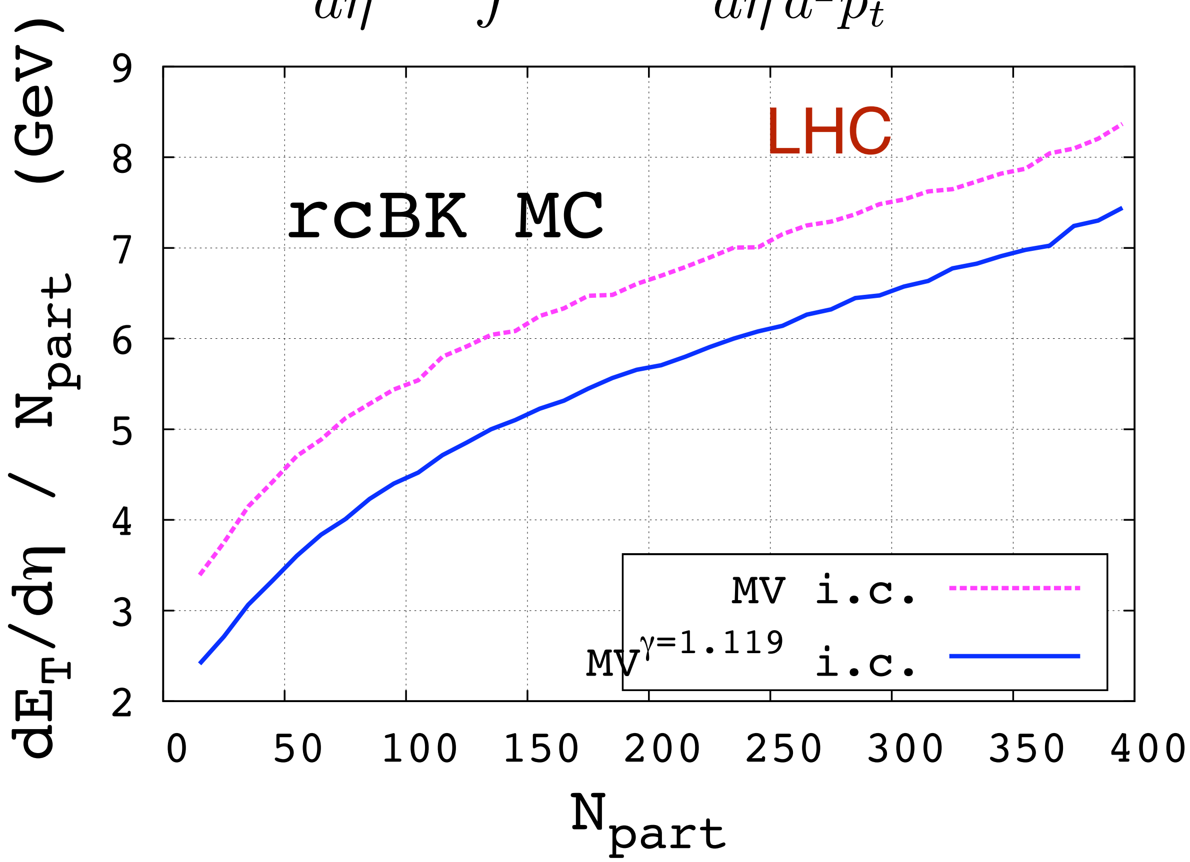
$$\frac{dN}{d\eta} \sim \int d^2p_t \frac{dN}{d\eta\, d^2p_t}$$

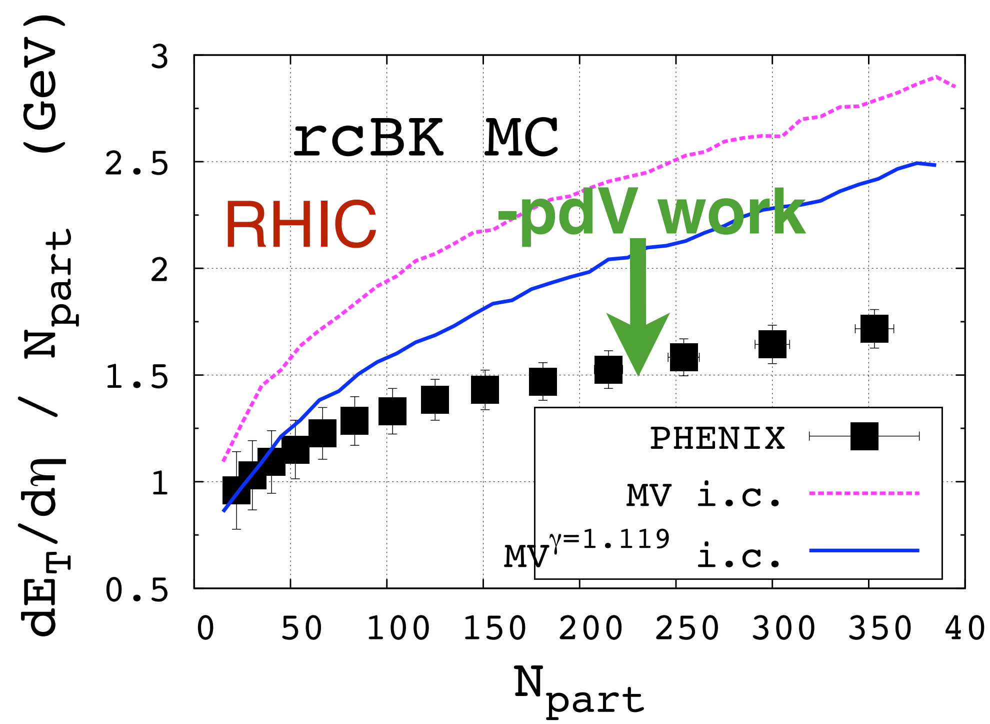




Larger effect on transverse energy distributions

$$\frac{dE_t}{d\eta} \sim \int d^2p_t\, p_t \frac{dN}{d\eta\, d^2p_t}$$

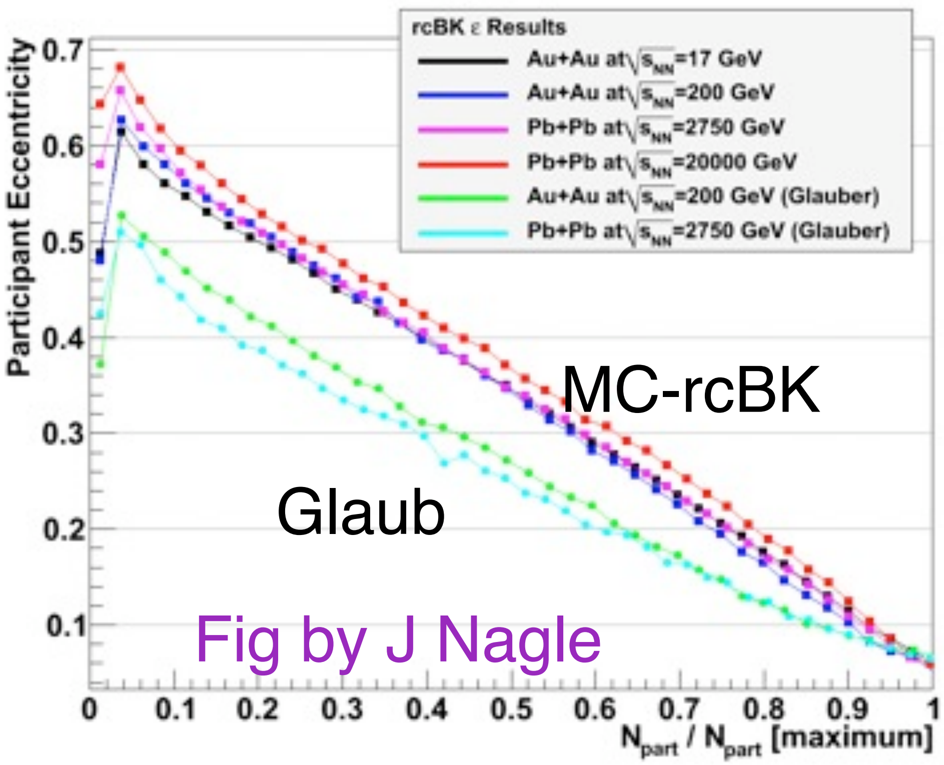


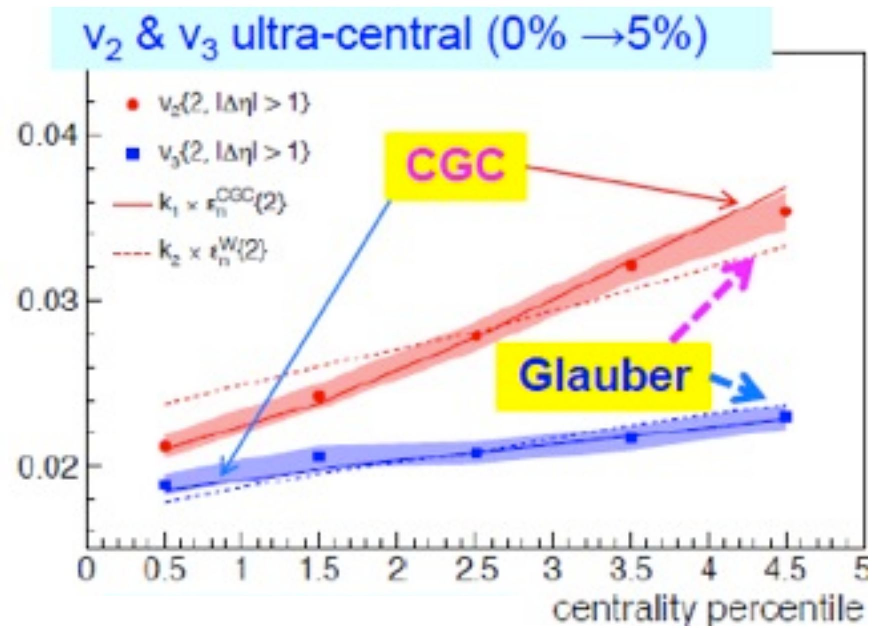


Initial state anisotropy

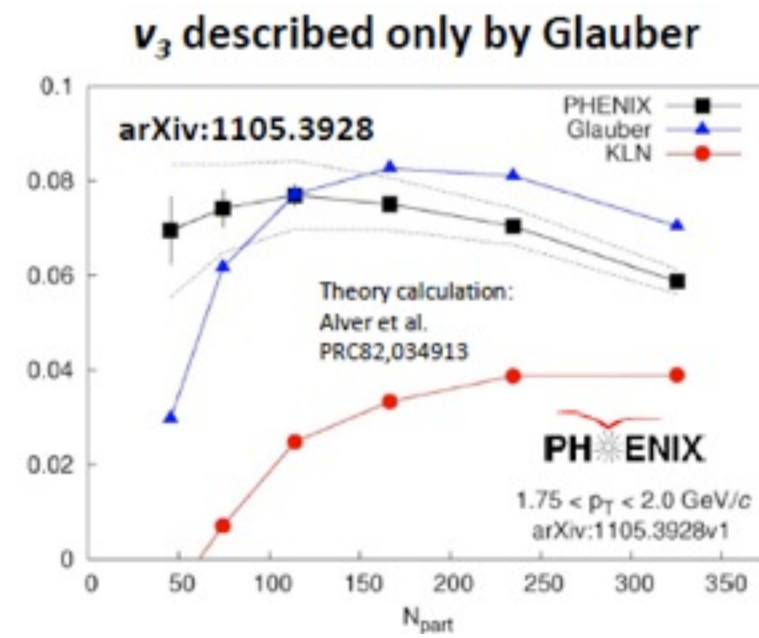
v2 measurements can be accommodated both for Glauber and MC-CGC i.c

higher harmonics: v3. Current CGC-MC underestimate initial state fluctuations





ALICE's talk at QM2011



PHENIX talk at QM2011

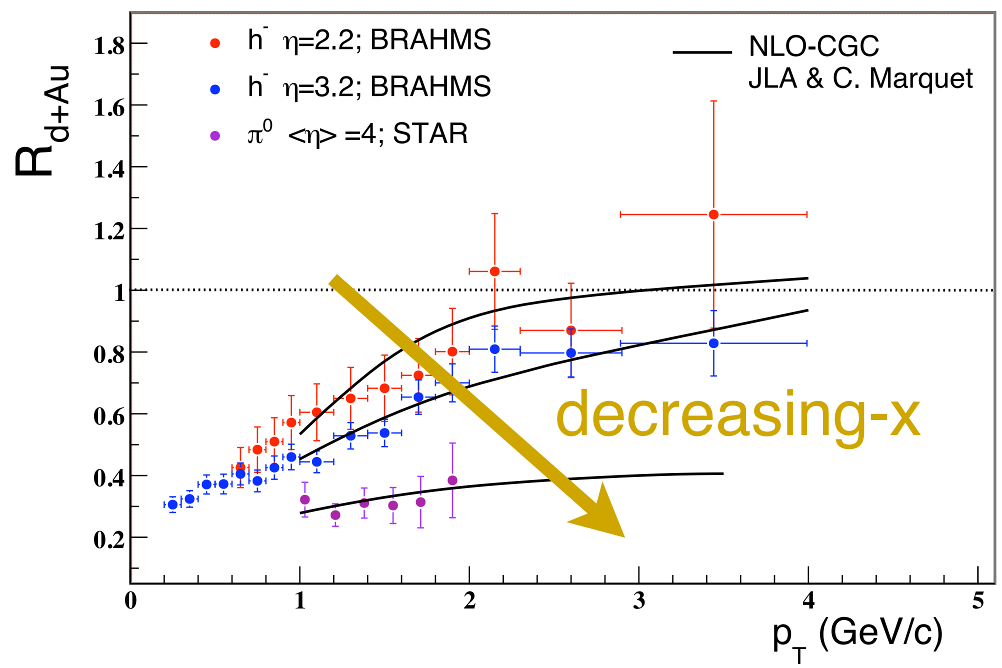
WARNING!!

- Not clear to what extent such difference is rooted in the use of kt-factorization
- Initial anisotropies very sensitive to particle production in the (dilute) periphery
- Some differences arise due to implementation details: nucleon size, nucleon spread, sources of fluctuations etc...

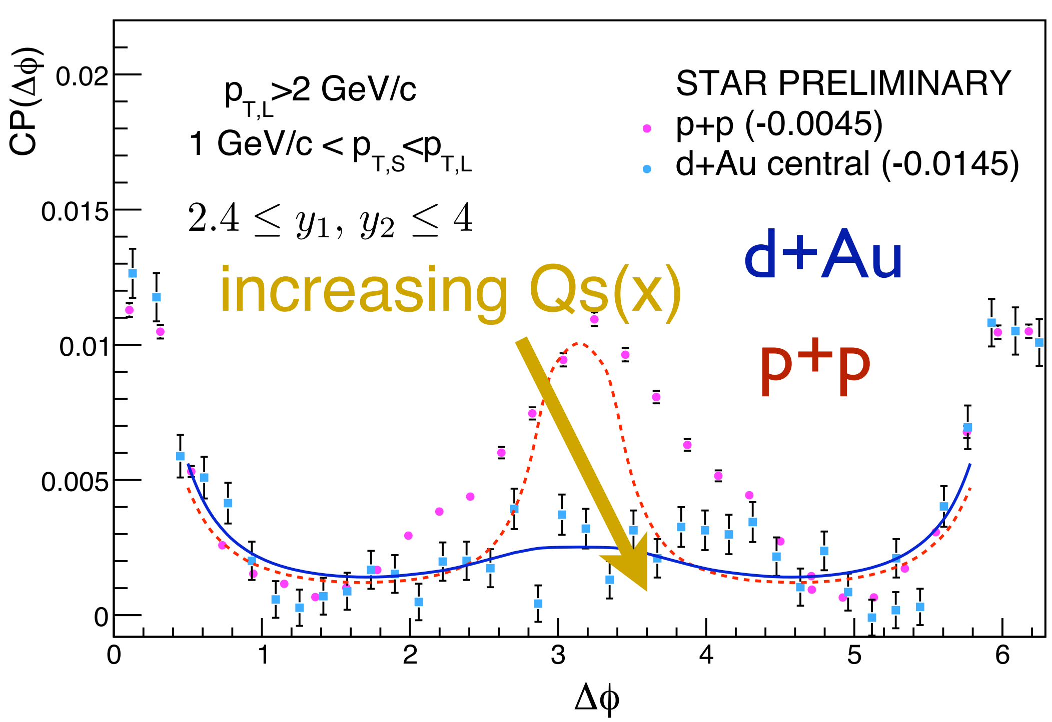
forward suppression in p-A collisions:

Forward (i.e x<0.01) RHIC suppression well described by rcBK CGC calculations.

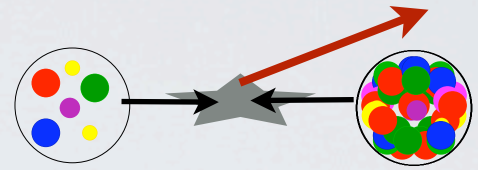
• single inclusive



• central d+Au di-hadron correlations in Δϕ



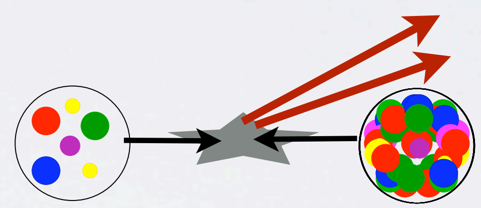
multi-parton interactions?



$\mathrm{pdf}(x_1) \otimes N^{2)}(x_2, k_t)$

Are large-x energy loss effects (not included in the CGC) the cause of the suppression?

K-factor ~ 0.3 for forward pions?



$\mathrm{pdf}(x_1) \otimes F[N^{2)}(x_2,k_t), N^{4)}(x_2,k_t,..), N^{6)}(x_2,kt,...)]$

Some leading-Nc terms missing:
$N^4 \sim N^2\, N^2 + O(Nc)$

Multi-parton interactions enhanced in d+Au collisions at large-x?

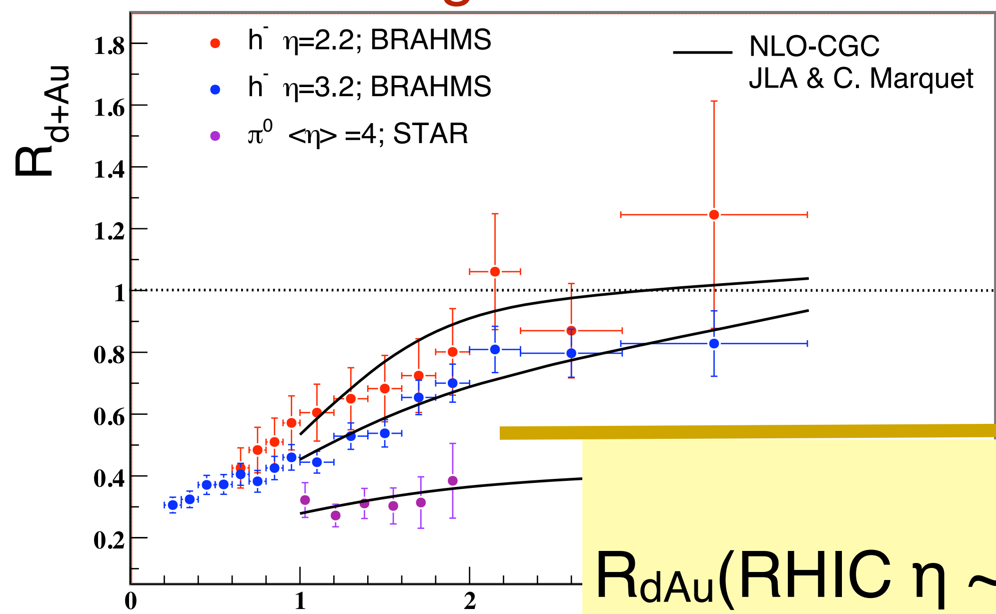
NOTE: Calculations done in the trivial b-dependence scheme

$\bar{Q}_{sA}$

p-A collisions:

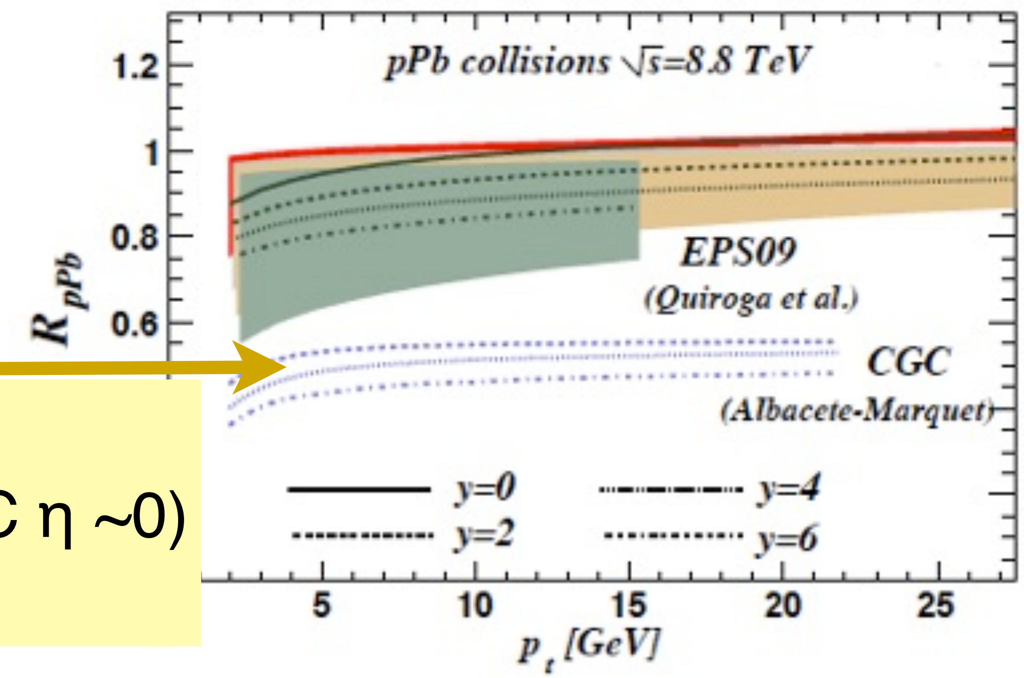
Forward RHIC suppression well described by rcBK CGC calculations

- single inclusive



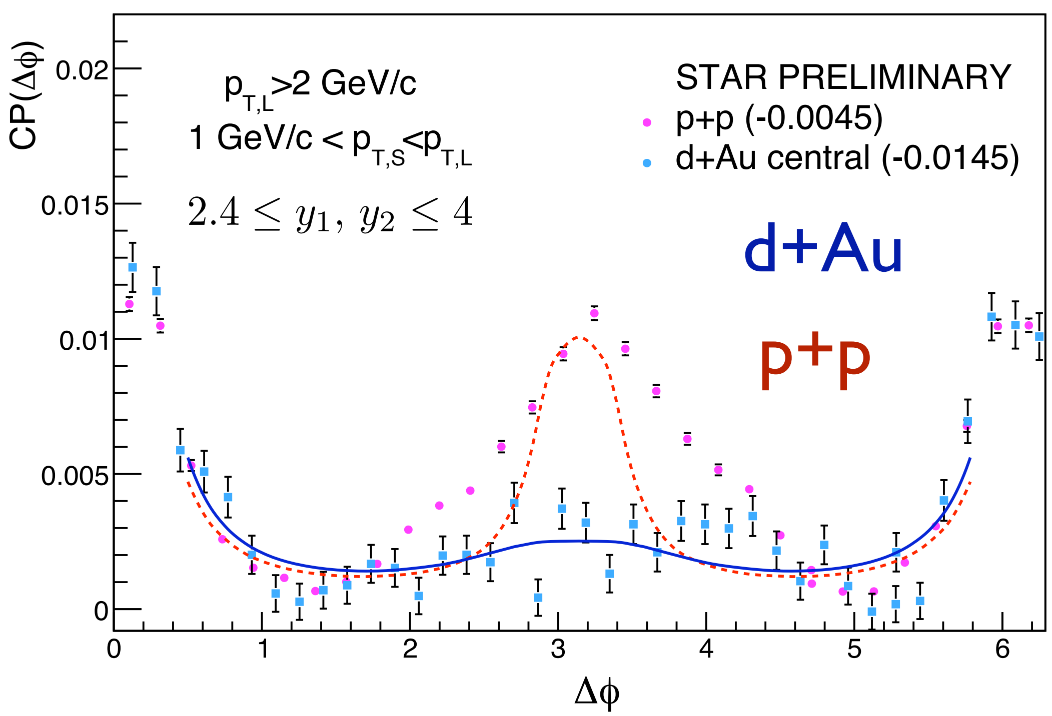
Large-x energy los

predictions for p+Pb @ LHC



R_{dAu}(RHIC η ~ 3)~ R_{pPb}(LHC η ~0)

- central d+Au di-hadron correlations in Δϕ



multi-parton interactions?

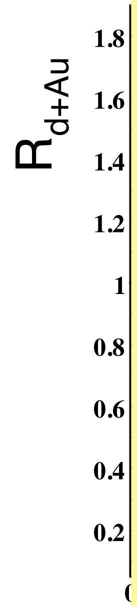
?? Sensitivity to non-perturbative input (initial conditions, b-dependence) and normalization issues remain to be tested...

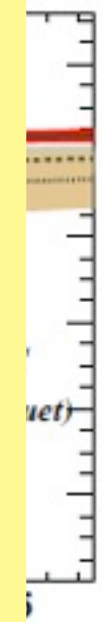
Calculation needs to be redone using MC-CGC methods to ensure proper normalization!!

p+Pb run: extremely useful **also** to constrain CGC models for bulk particle production

p-A collisions:

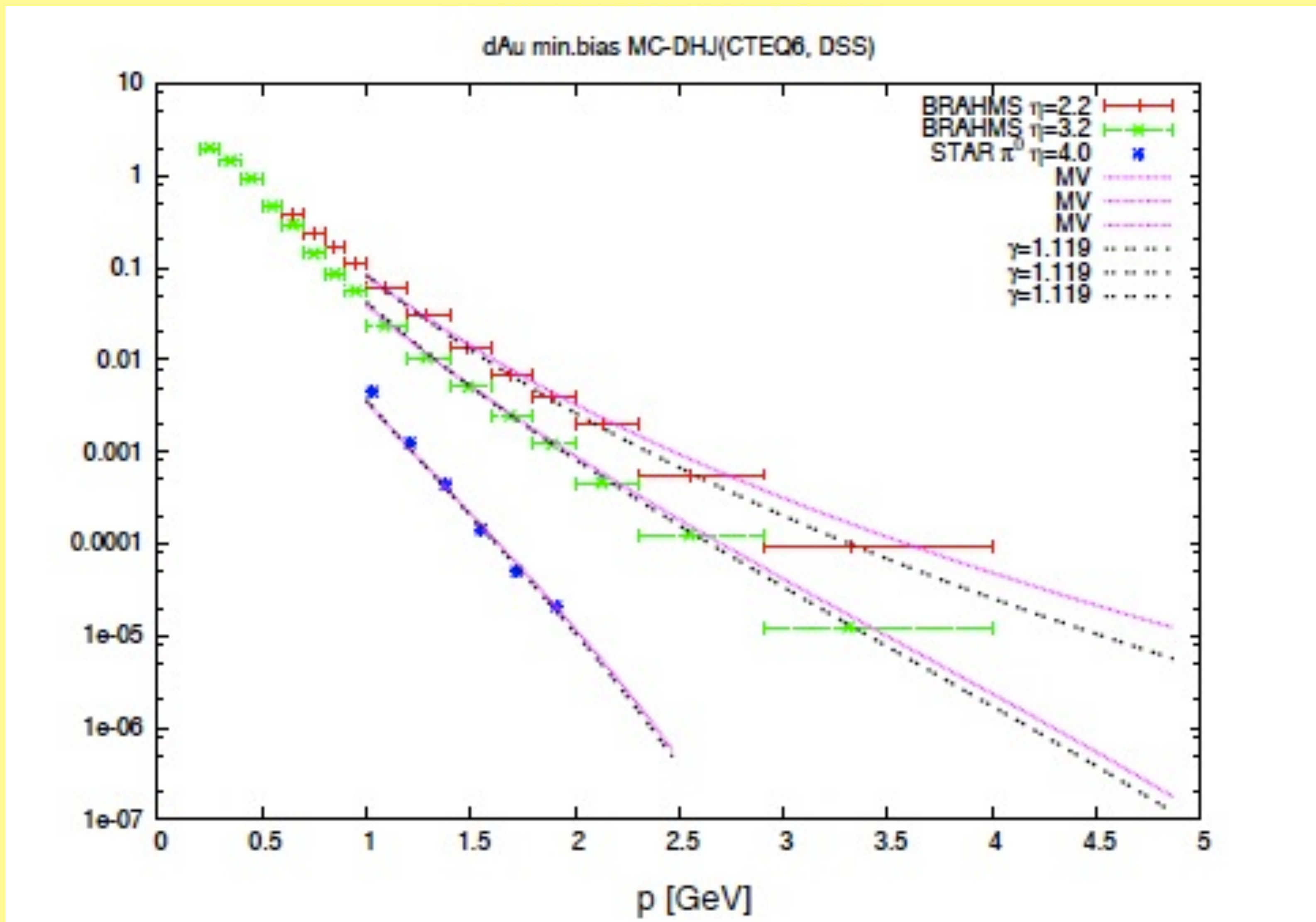
Forward RHIC suppression well described by rcBK CGC calculations





First step in that direction: MC-DHJ/rcBK by Fujii et at.

Good description of forward hadron yields in RHIC d+Au collisions



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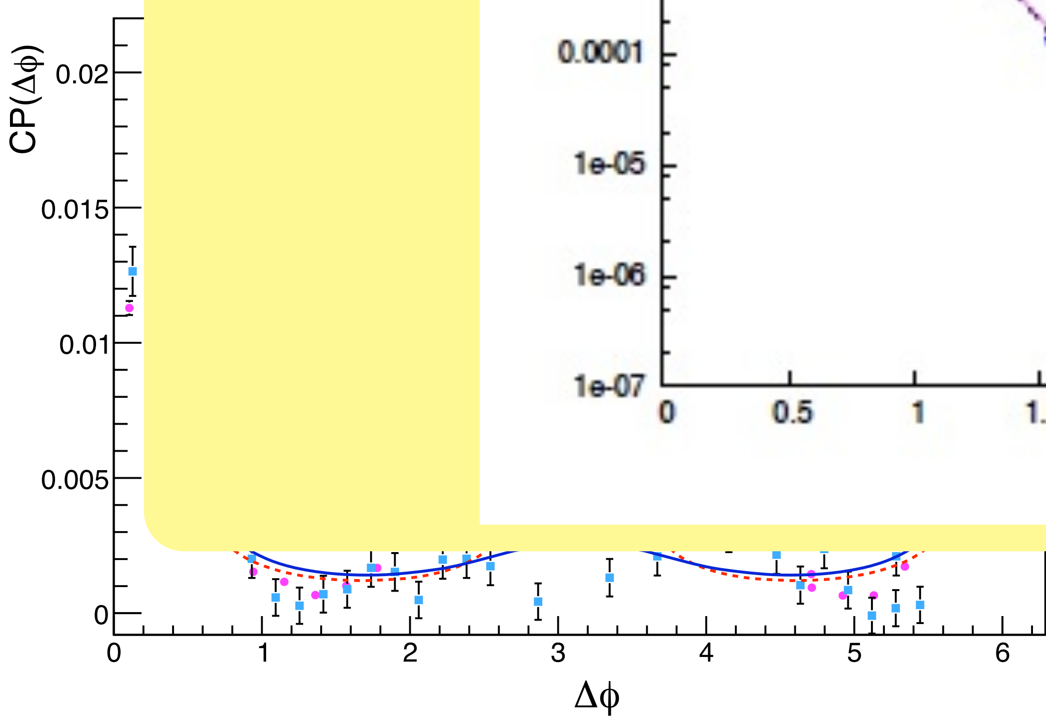
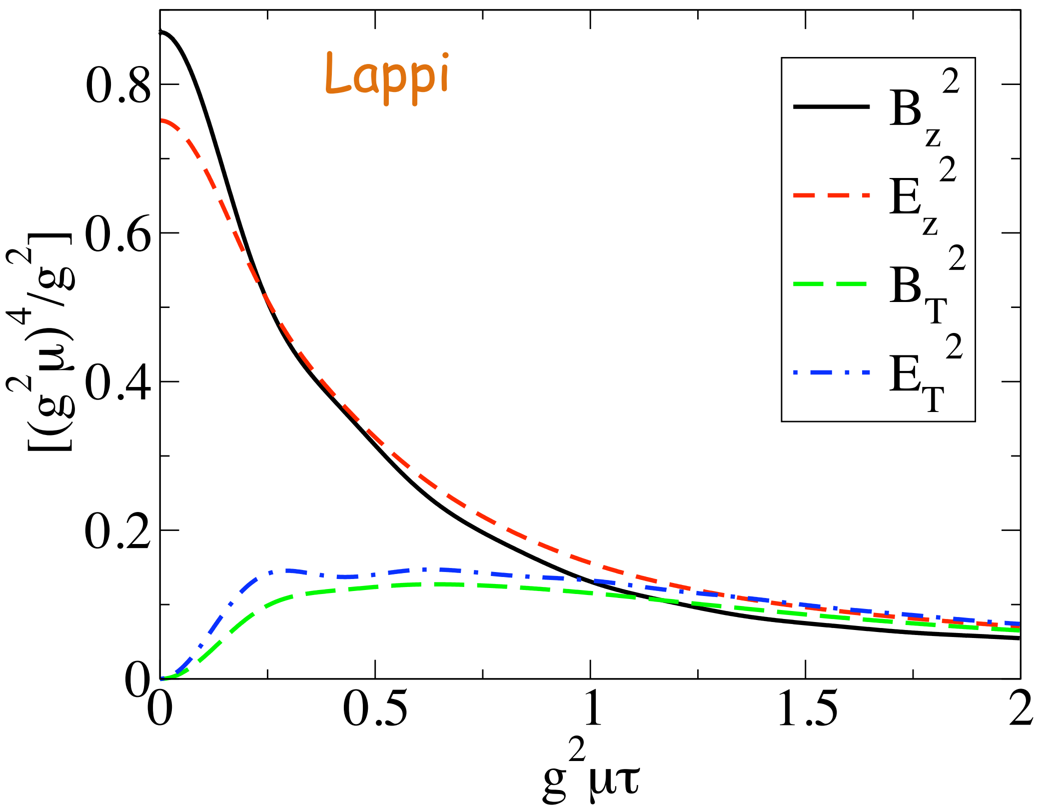


multi-parton interactions?

p+Pb run: extremely useful **also** to constrain CGC models for bulk particle production

CGC at very early times

Solution of classical Yang-Mills EOM: (A+A): Electric and magnetic fields are longitudinal:



Correlated over rapidity intervals $\Delta\eta \sim \frac{1}{\alpha_s}$

Correlated over transverse sizes $\Delta R_\perp \sim \frac{1}{Q_s}$

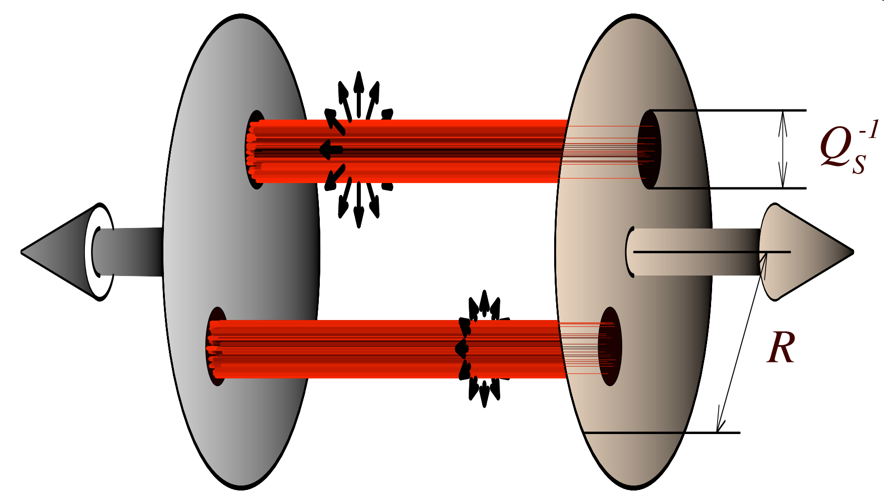


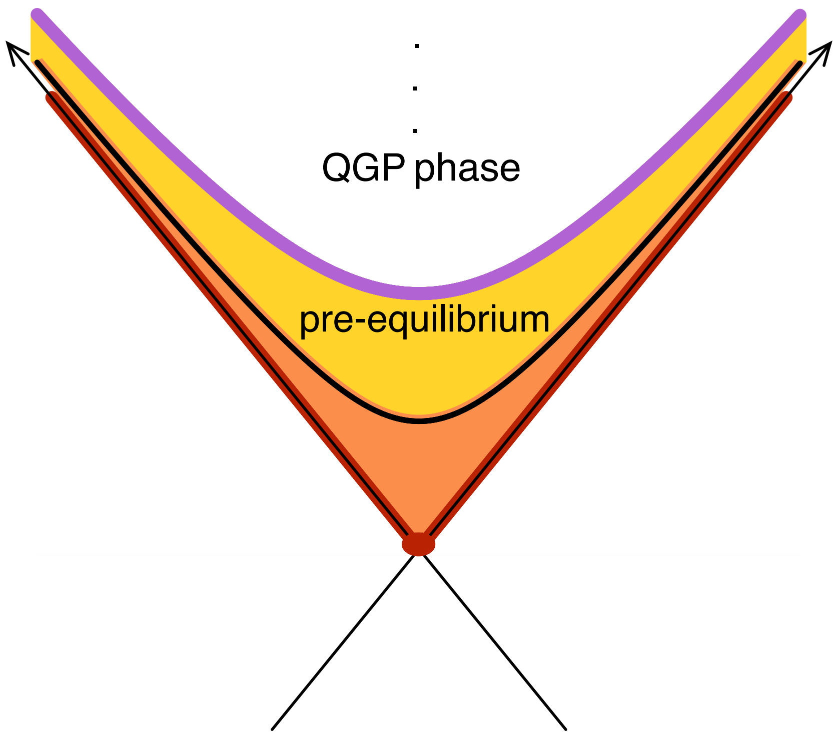
Fig by F Gelis

Imply the presence of long-range in rapidity correlations, which must be generated at early times.

Several attempts to describe current correlation data based on CGC+ radial flow exist [Gavin, McLerran, Dusling et al]

...however, phenomenological description of the demands accounting for flow effects triggered by initial state fluctuations

The thermalization conundrum



The energy-momentum tensor after the collision is maximally anisotropic:

$$T^{\mu\nu}_{LO} = \mathrm{diag}\left(\epsilon, \epsilon, \epsilon, -\epsilon\right) \qquad \tau = \mathbf{0}^{+}$$

$$T^{\mu\nu}_{iso} = \mathrm{diag}\left(\epsilon, p, p, p\right) \qquad \tau_{\mathbf{th}} \sim \mathbf{1}\,\mathrm{fm/c}$$

How does the transition to an (quasi) isotropic EMT happen over such short times?

CGC/ weak coupling approaches:

Bottom-up approach: large estimates of thermalization time [Baier et al]

Resummation of Feynmann diagrams leads to free streaming (pz=0) [Kovchegov]

Resummation of unstable secular terms may speed up the thermalization dynamics [Romatchske-Venugopalan, Dusling et al]

Strong coupling? AdS/CFT studies suggest a rapid thermalization
Chesler-Yaffe, Lin-Shuryak, Mue, JLA-Kovchegov-Taliotis, Balasubramanian et al]
How to match them with weak coupling/CGC at earlier times?

No conclusive proof of thermalization yet...the elephant remains in the room

Conclusions / Outlook

- ✔ LHC reach on small-x physics is unprecedented.
- ✔ Important steps have been taken in promoting GCG to an useful quantitative tool
  - Theoretical calculation of higher order corrections (running coupling)
  - Phenomenological effort to systematically describe data from different systems (e+p, e+A, p+p, d+Au, Aa+Au and Pb+Pb) in an unified framework
  - Devise & maintenance of Monte Carlo methods to input hydro/transport calculation
  -... but more work is still needed!
- ✔ First HI LHC data on multiplicities compatible with CGC models (and others)
- ✔ Most urgent tasks:
  - Putting together b-dependence and evolution
  - Matching with high-x, high-Q^2 physics (valence quarks ,DGLAP evolution)
  - Improve non-perturbative modeling in MC-CGC
- ✔ A p+Pb run would be extremely useful for the calibration of initial-state effects for hard probes, but also to further constrain models for bulk particle production

THANK YOU!!