Initial Conditions: Theory status

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SEVENTH FRAMEWORK PROGRAMME

MARIE CURIE ACTIONS

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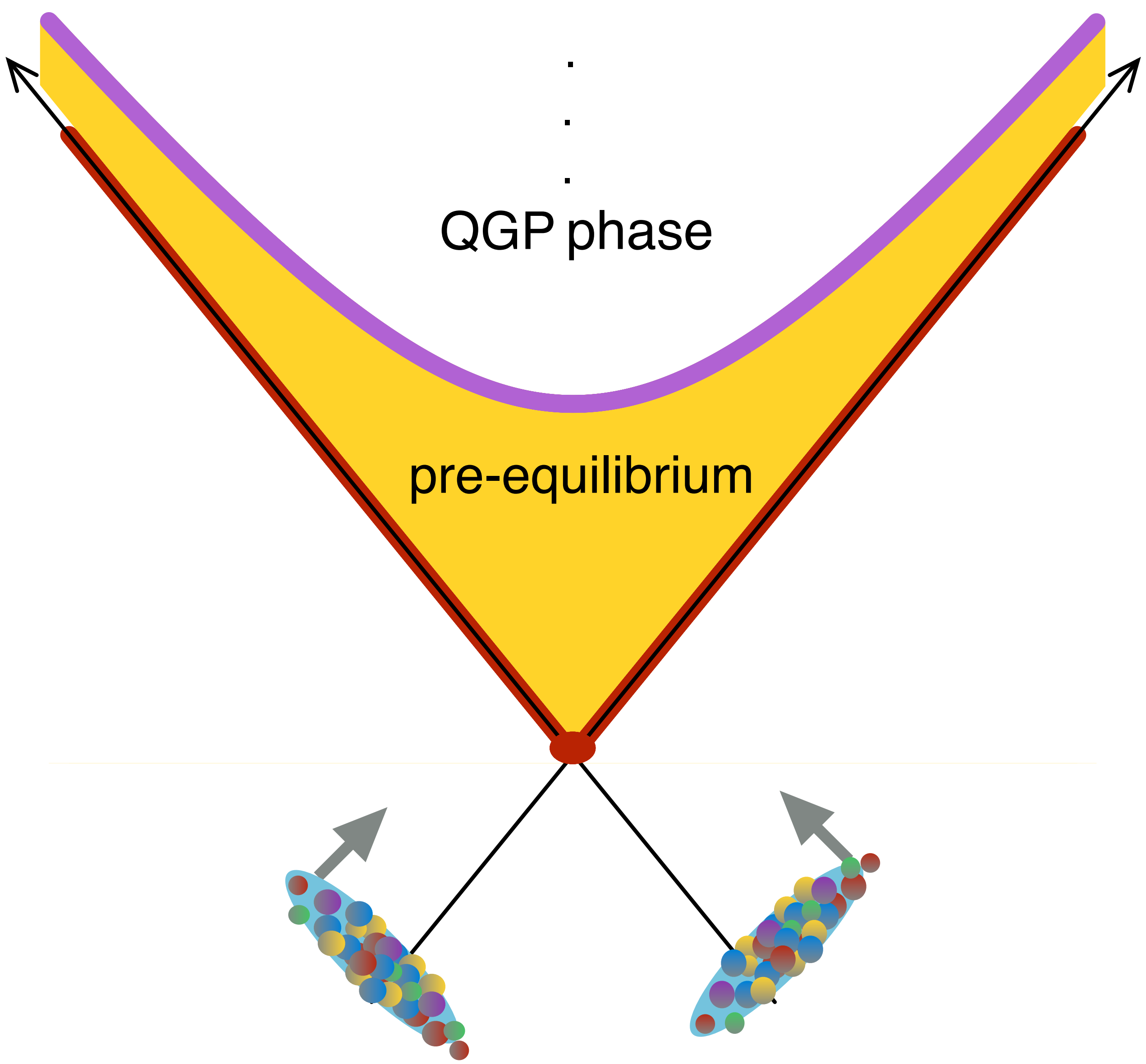
Outline

- 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

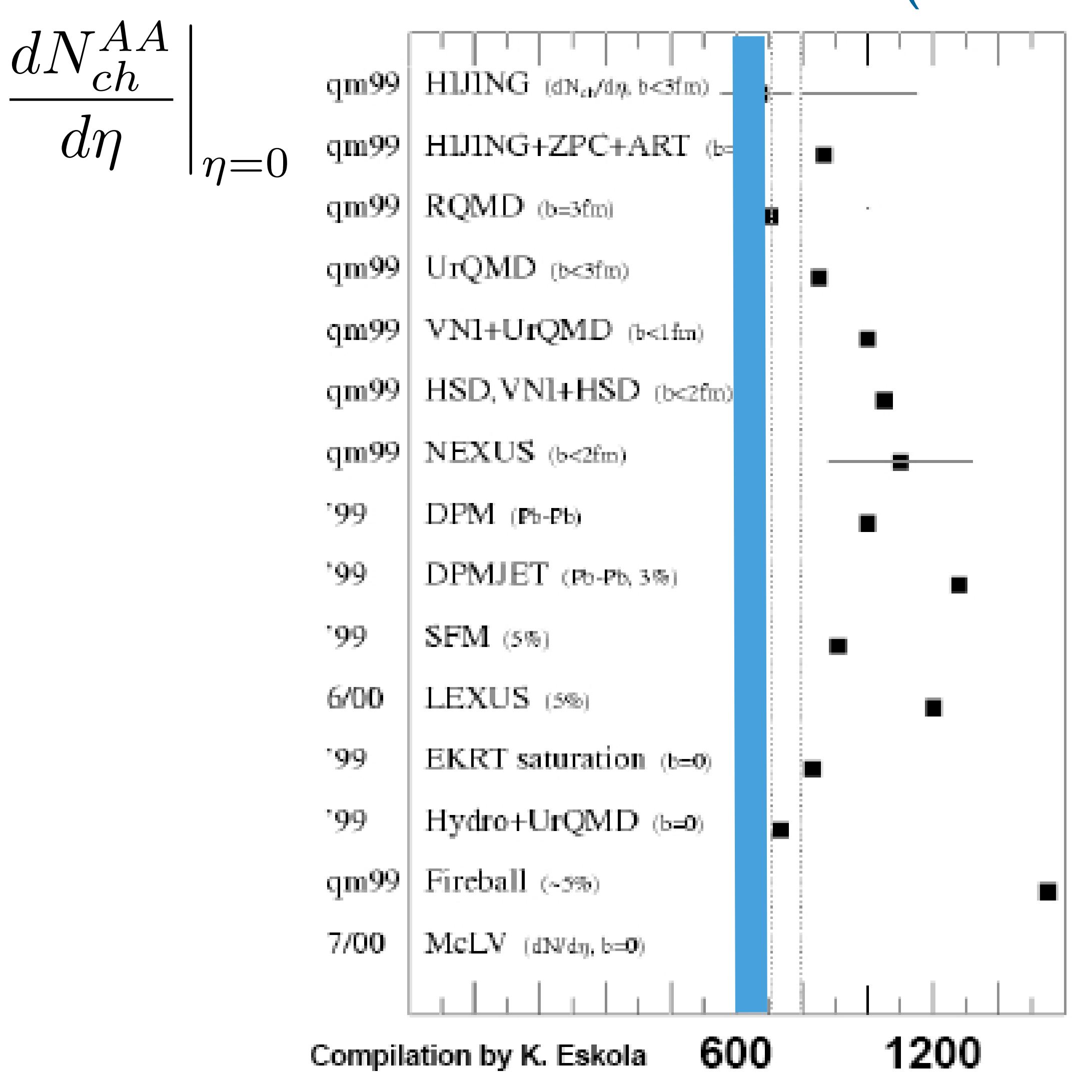
HIC behave very differently to a simple superposition of independent N-N collisions

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

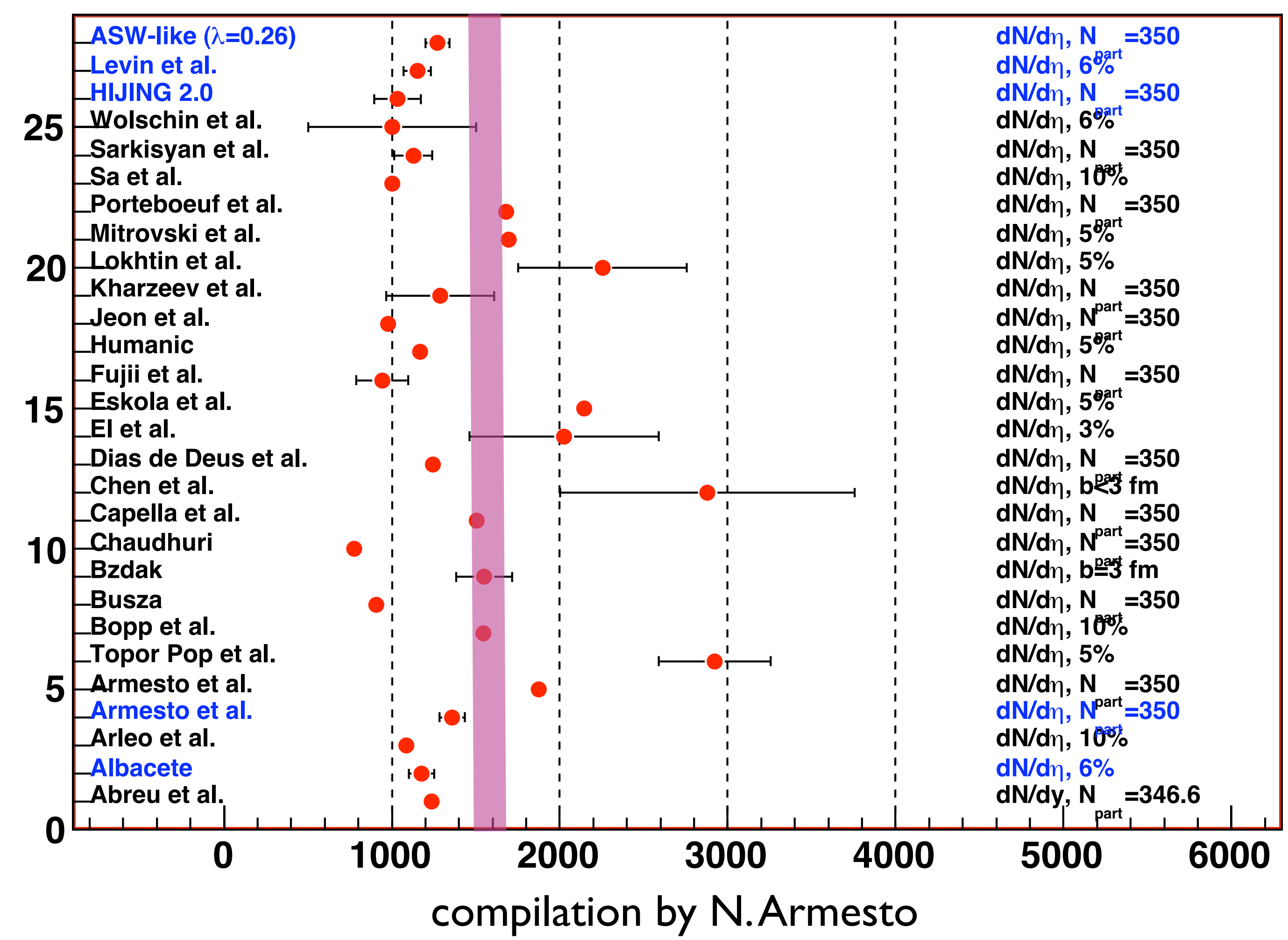
↓

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

RHIC: PHOBOS Au-Au (0.2 TeV)



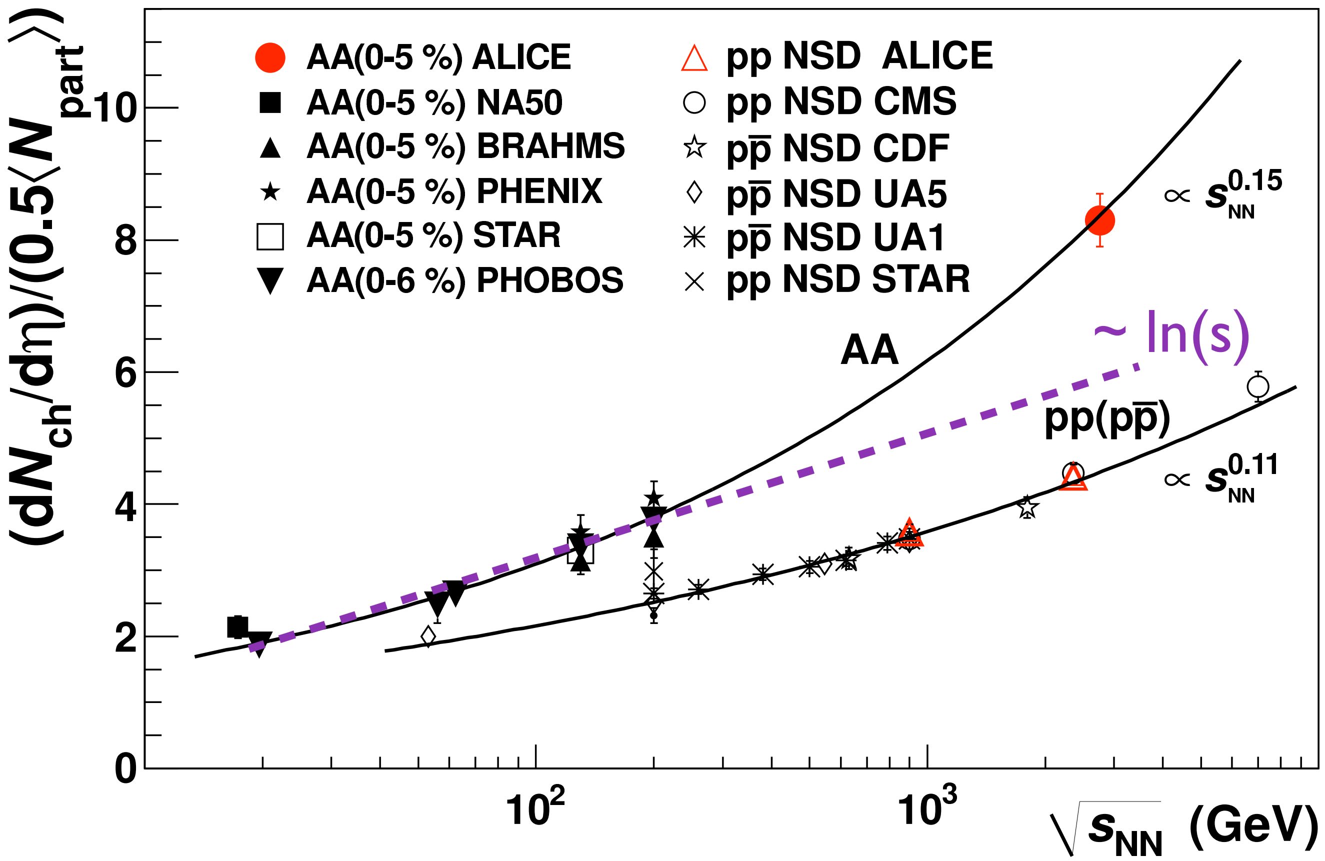
LHC: ALICE Pb-Pb (2.76 TeV)



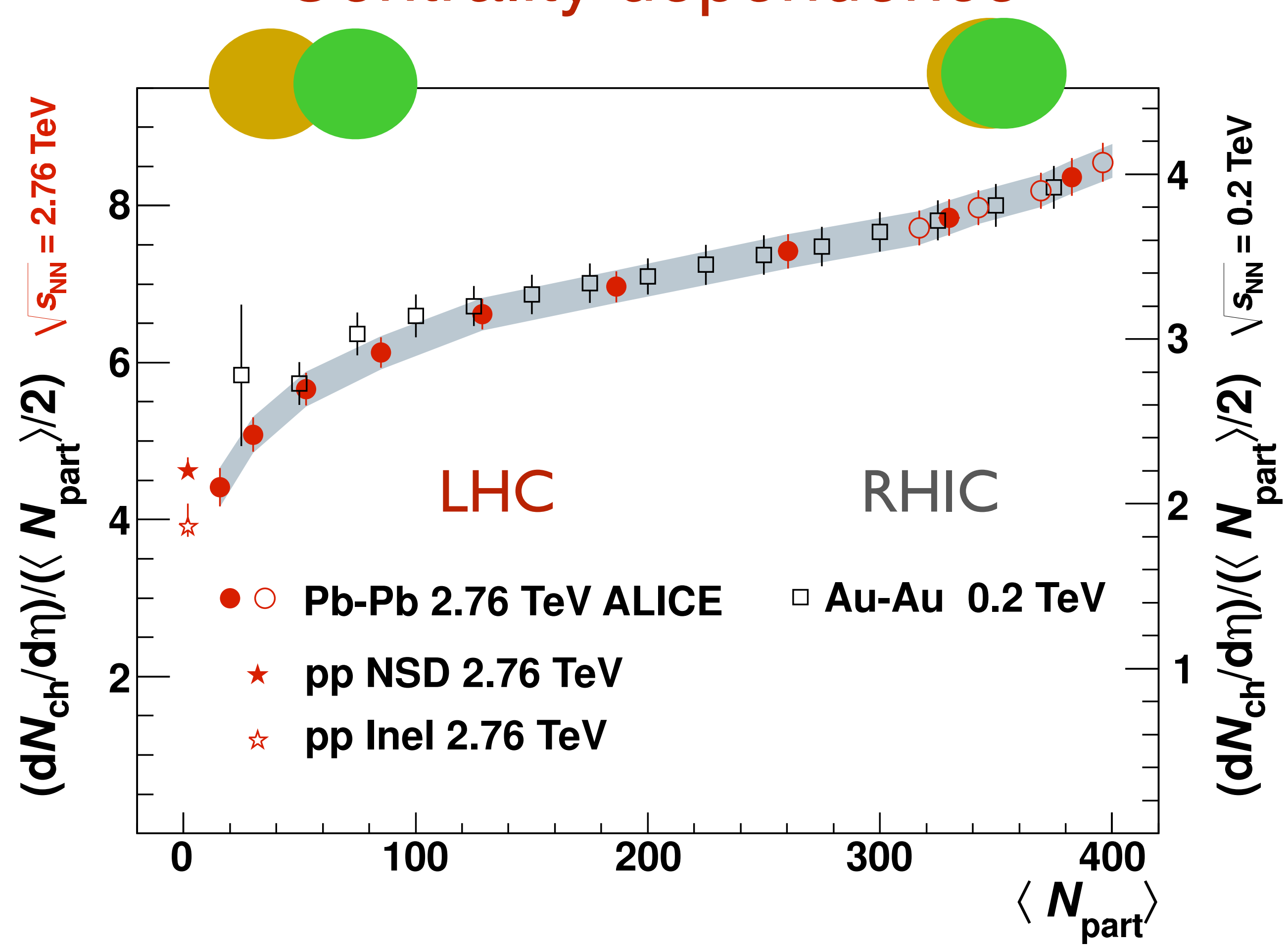
What are the relevant coherence effects and what is their dynamical description??

Lessons from data

Energy dependence



Centrality dependence

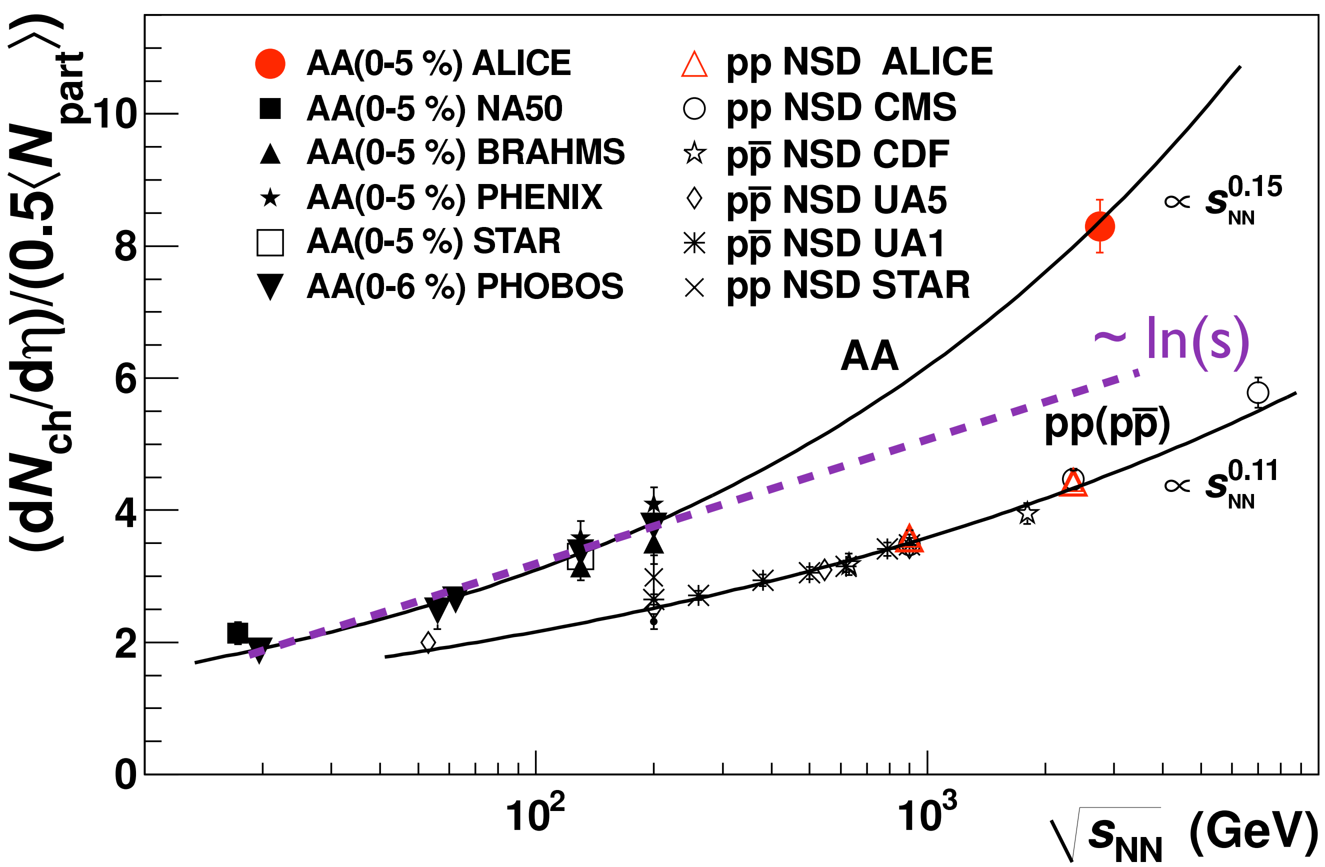


- Stronger energy dependence in A+A than in p+p?
- Factorization of energy and centrality dependence?

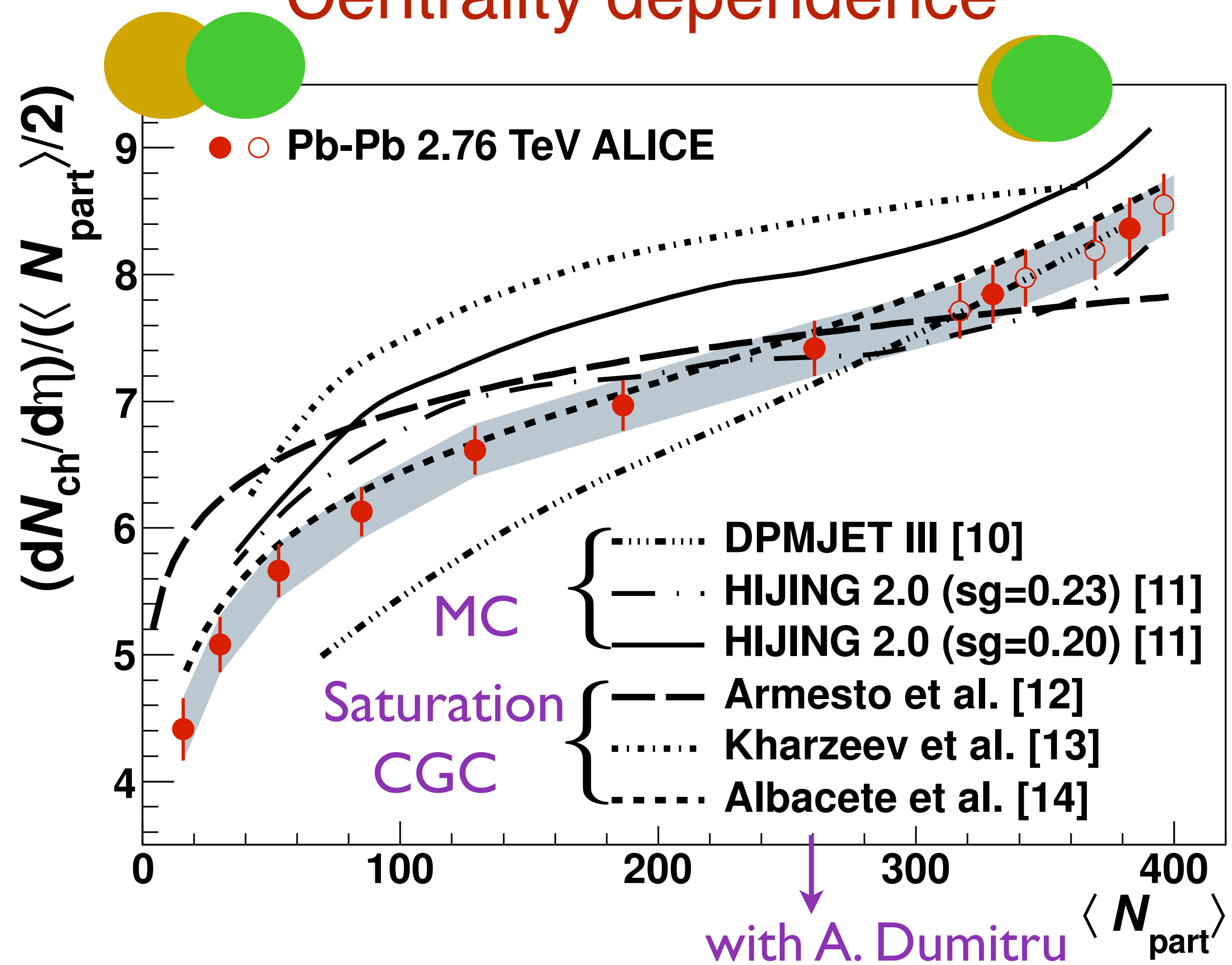
$$\left.\frac{dN^{ch}}{d\eta}\right|_{\eta=0} \approx \sqrt{s}^{0.3} \times f(N_{part})$$

Lessons from data

Energy dependence



Centrality dependence



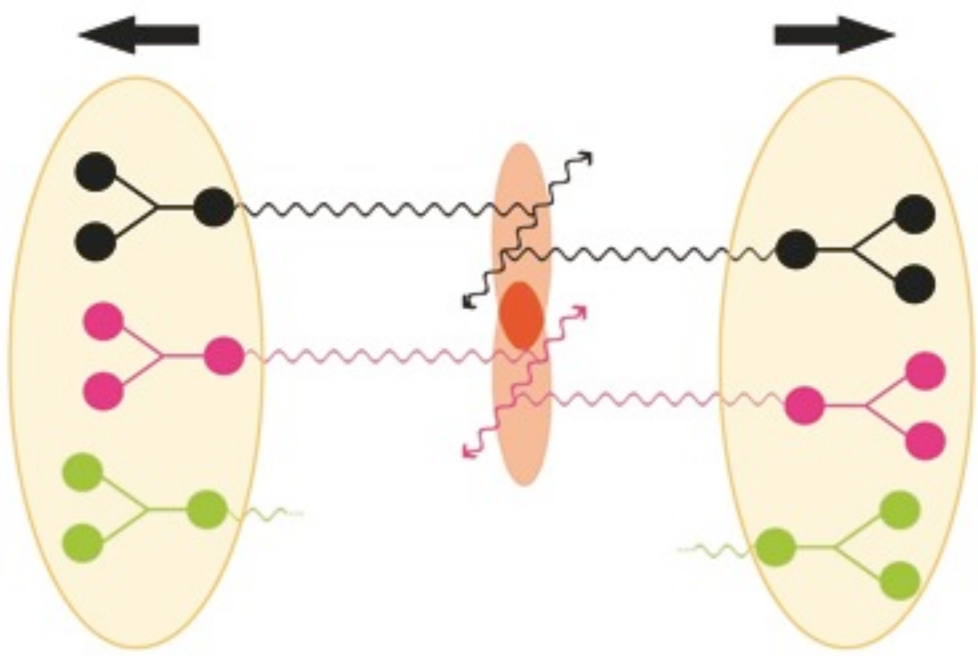
Different models reproduce data “well” (?)

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

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 — $p_0(s)$ → — HARD — p_t

SOFT	HARD
Strings, Dual Parton Model, RFT, hydro/thermal models...)	LO pQCD independent minijet production, eikonal approximation
$s^{\Delta_{soft}} \times \cancel{N_{coll}}$	$\frac{s^{\Delta_{hard}}}{p_0^2(s)} \times \cancel{N_{coll}}$
$\Delta_{soft} \approx 0.08$	$\Delta_{hard} \approx 0.3$

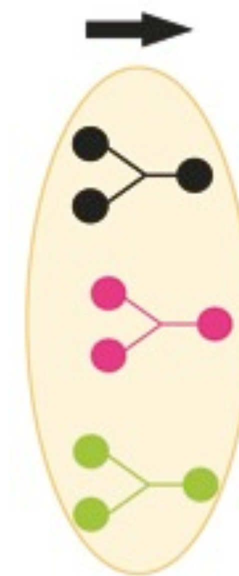
Coherence mechanisms in the Color Glass Condensate

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

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

radiation recombination

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



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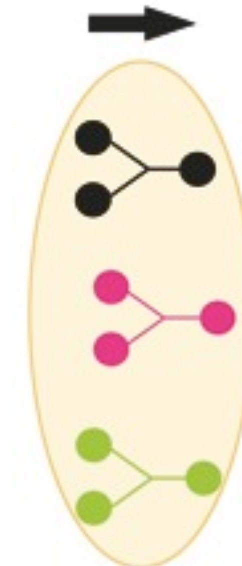

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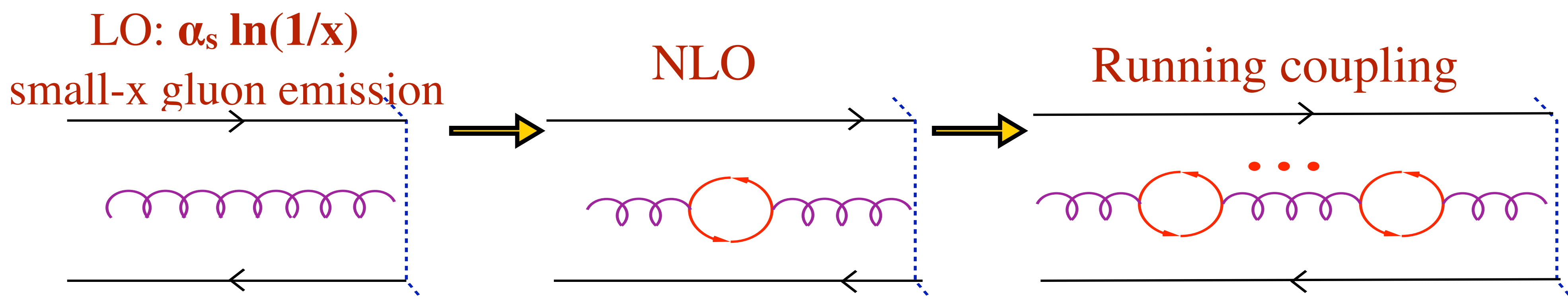
radiation recombination

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

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



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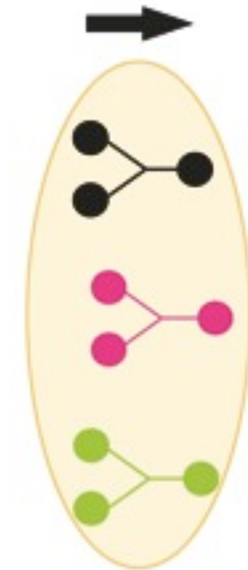
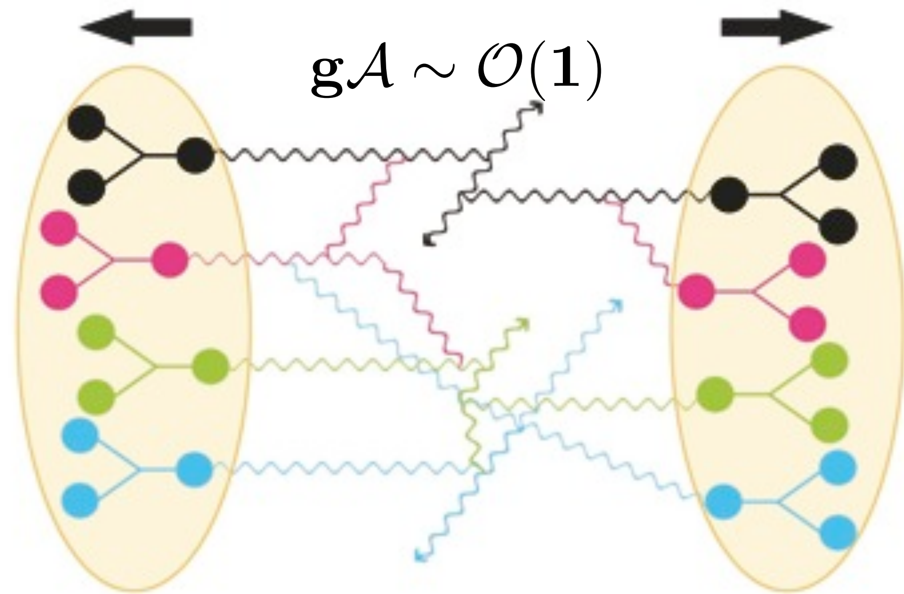
radiation — recombination



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

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

$$\mathcal{A}(\mathbf{k} \lesssim \mathbf{Q_s}) \sim \frac{\mathbf{1}}{\mathbf{g}}$$



- Classical Yang-Mills EOM: $[\mathbf{D}_\mu \mathbf{F}^{\mu\nu}] = \mathbf{J}^\nu[\rho]$
  (Suplemented by JIMWLK evolution)

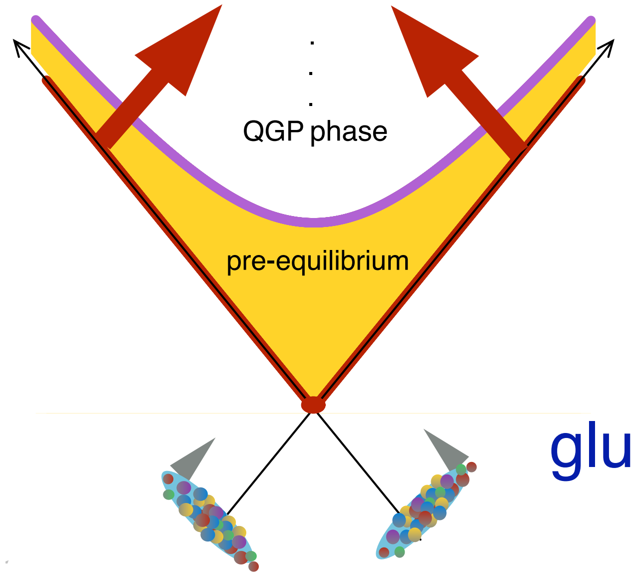
- kt-factorization: $$\frac{\mathbf{dN^g}}{\mathbf{d}\eta \mathbf{d^2p_t}} \sim \phi(\mathbf{x_1}, \mathbf{k_t}) \otimes \phi(\mathbf{x_2}, \mathbf{k_t} - \mathbf{pt})$$
  only for (p+A)
  (BK evolution)

$\mathbf{Q_s}(\mathbf{x}) \gg \Lambda_{\mathbf{QCD}}$:A purely perturbative analysis is possible

$$\mathbf{Q_s^{Pb}}(\mathbf{LHC}) \sim \mathbf{1.5} \div \mathbf{4}\,\mathrm{GeV}$$

Color Glass Condensate models

charged particles ~ # small-x gluons in the wave functions of the colliding nuclei



LO kt-factorization: $$\left.\frac{dN^g}{d\eta\, d^2p_t}\right|_{\eta=0} \propto \frac{1}{p_t^2}\int d^2k_t\, \alpha_s\, \phi(x_1, k_t)\, \phi(x_2, |p_t - kt|)$$

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

gluon-hadron duality: $$\left.\frac{dN^{ch}}{d\eta}\right|_{\eta=0} = \frac{2}{3} K \left.\frac{dN^g}{d\eta}\right|_{\eta=0} \propto Q_s^2(\sqrt{s}, b) \sim \sqrt{s/s_0}^{\lambda} N_{part}$$

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

Color Glass Condensate models

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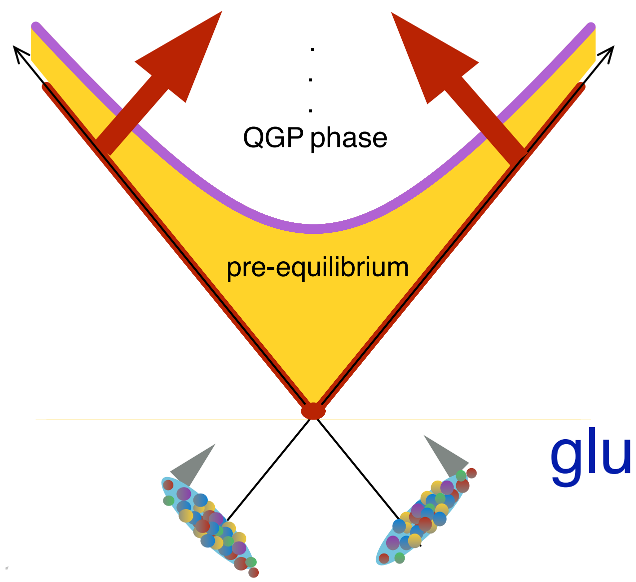

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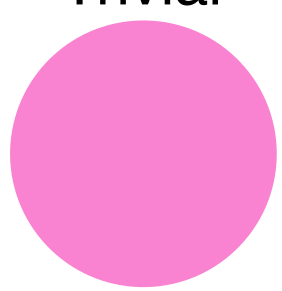
Energy dependence:
- Empiric information from e+p collisions [KLN, ASW, Razeian-Levin]
- Solutions of running coupling BK equation [JLA-Dumitru]

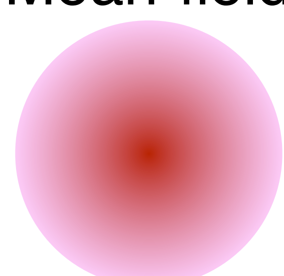
Centrality dependence:

Trivial



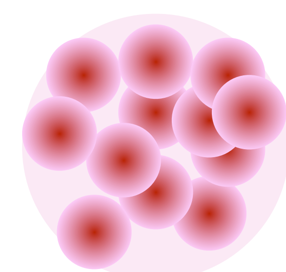
$\bar{Q}_{sA}$

Mean-field



$Q^2_{sA}(b) \sim T_{part}(b)$

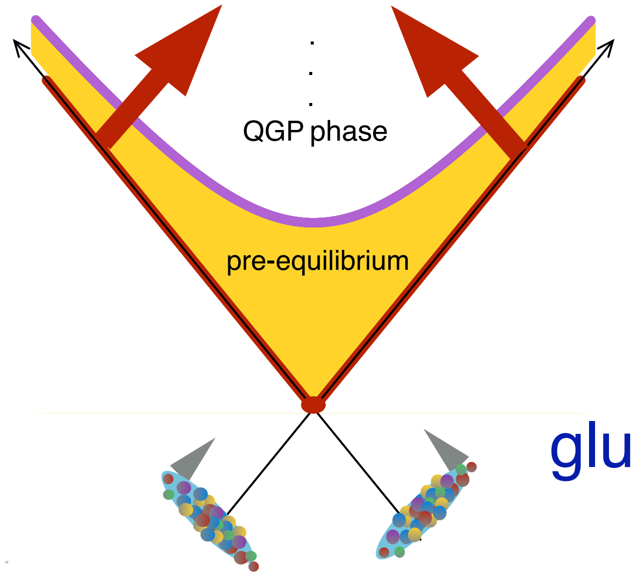
Monte-Carlo



$Q^2_{sA}(b) \sim N_{part}(b)\, Q^2_{s0,nucleon}$

Color Glass Condensate models

charged particles ~ # small-x gluons in the wave functions of the colliding nuclei



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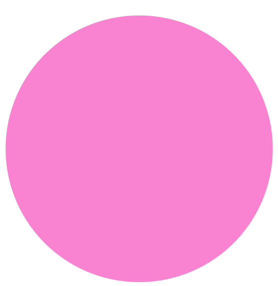

$\bar{Q}_{sA}$

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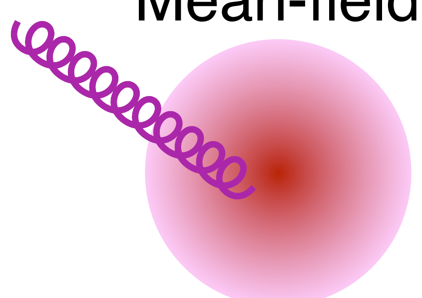

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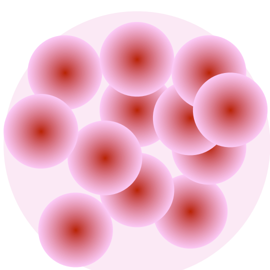
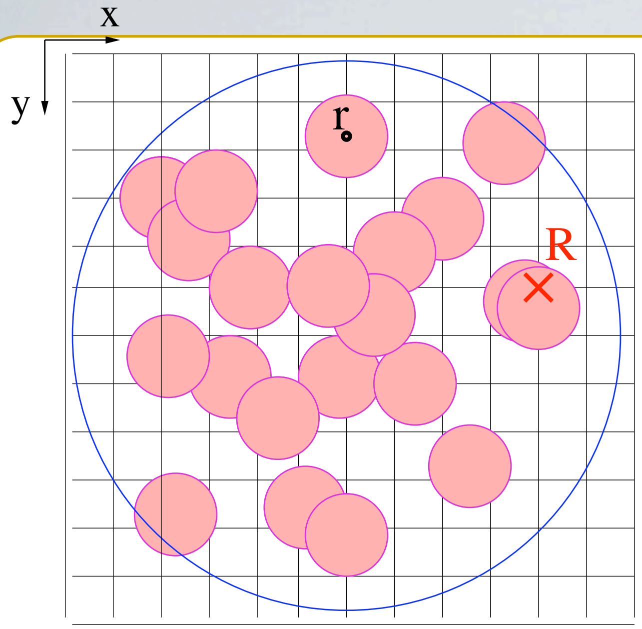


$Q_{sA}^2(b) \sim N_{part}(b)\, Q_{s0,nucleon}^2$

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

Ansatz: Solving b-independent rcBK evolution at each transverse point

CGC Monte Carlo: MC-KLN and rcBK



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

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

$$\downarrow$$

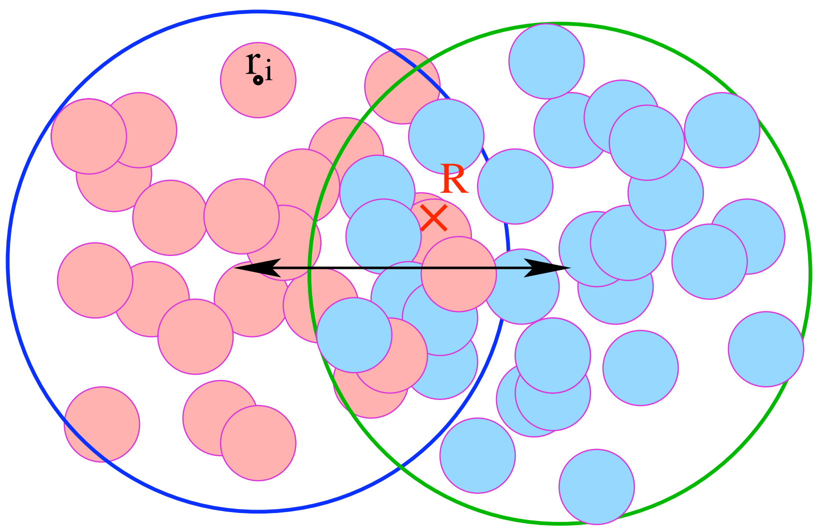
$$\varphi(x_0 = 0.01, k_t, R)$$

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

rcBK equation or KLN model

$$\downarrow$$

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



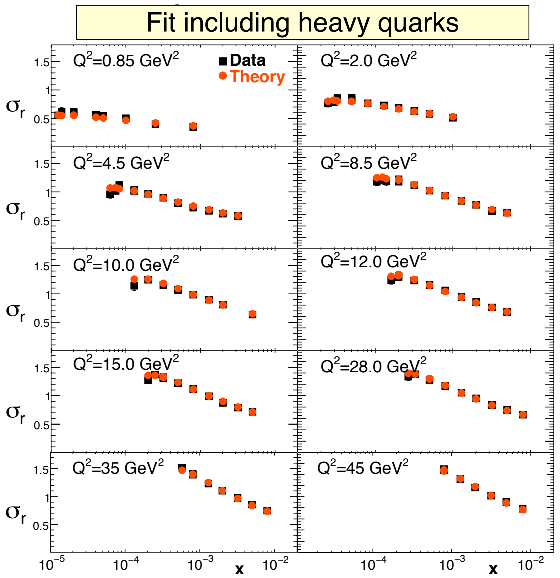
3 Calculate gluon production at each transverse point according to kt-factorization

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

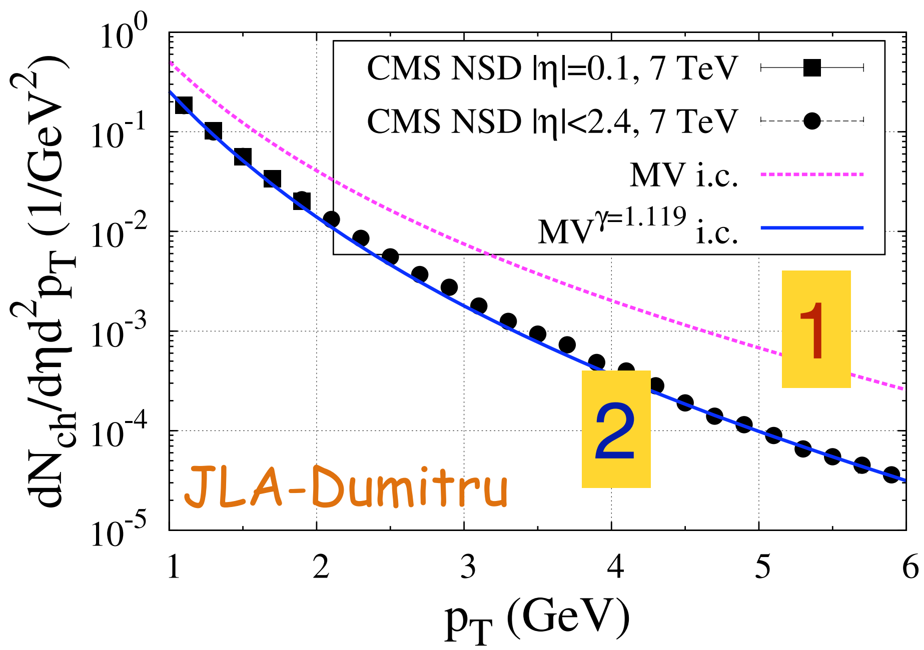
Learning from proton data: Initial Conditions for rcBK

AAMQS Fits to e+p (HERA)

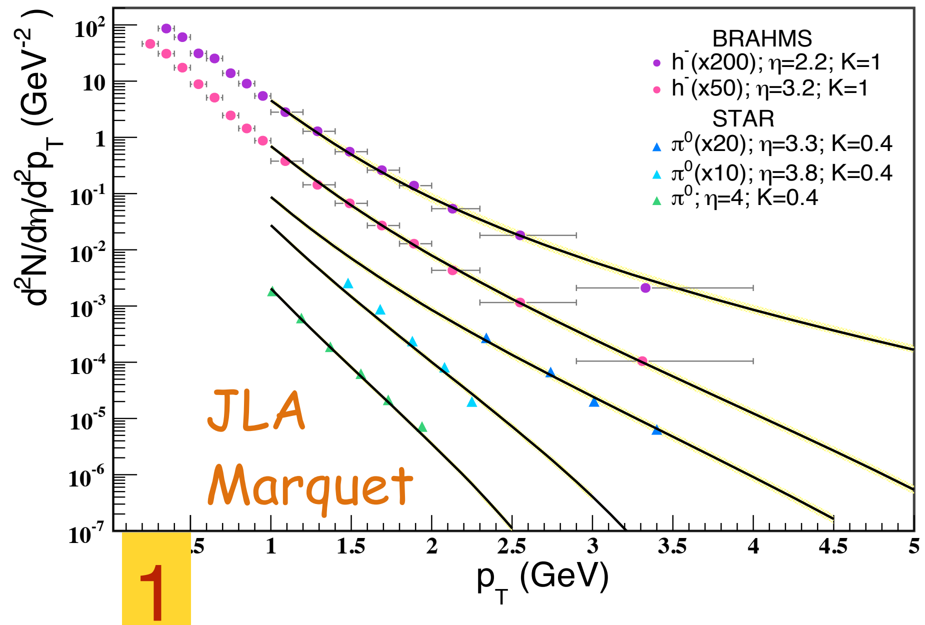


Talk by P. Quiroga 2

p+p yields @ LHC



forward p+p yields (RHIC)



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

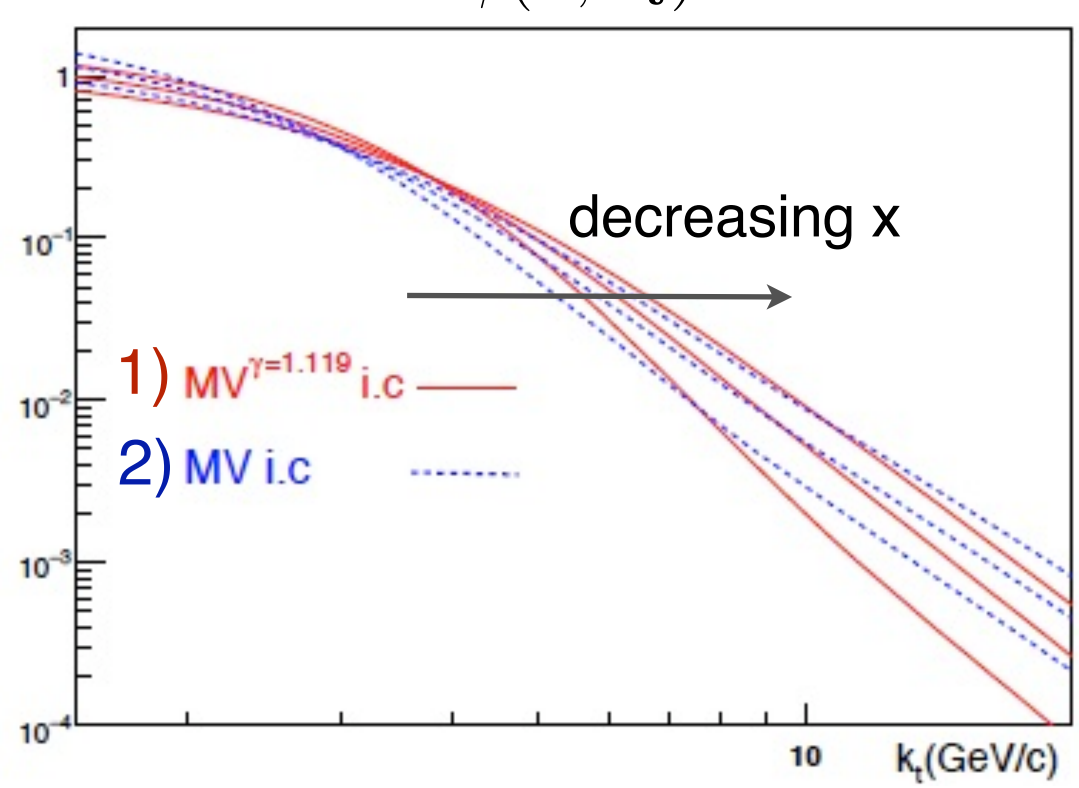
$$\phi(\mathbf{x} = \mathbf{x_0} \approx \mathbf{0.01}, \mathbf{k_t})$$

Differences persist after the evolution:

I.C: Variants of the MV model

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

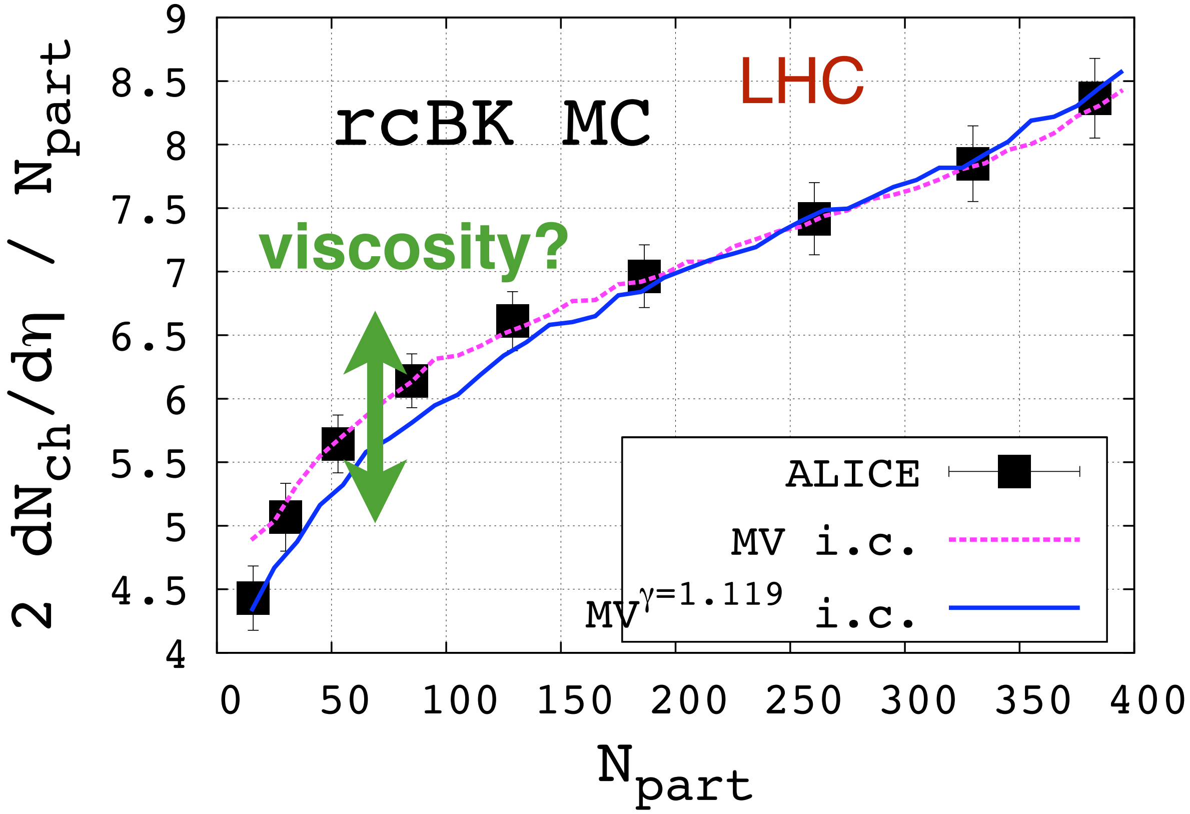
$\phi(\mathbf{x}, \mathbf{k_t})$

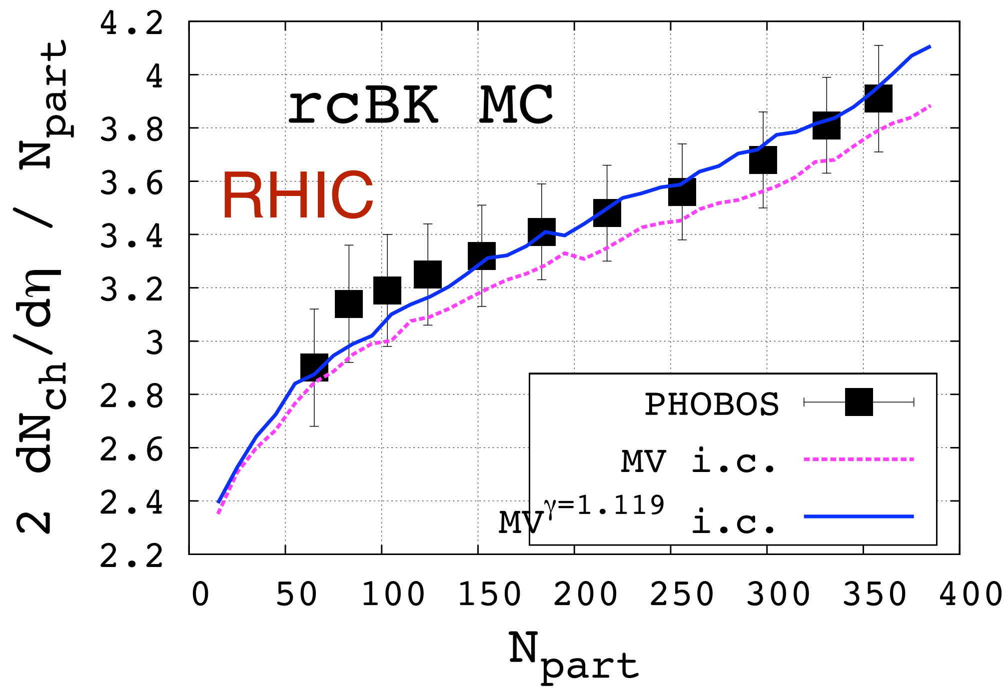


Learning from proton data: Initial Conditions in rcBK

Little effect on multiplicity distributions

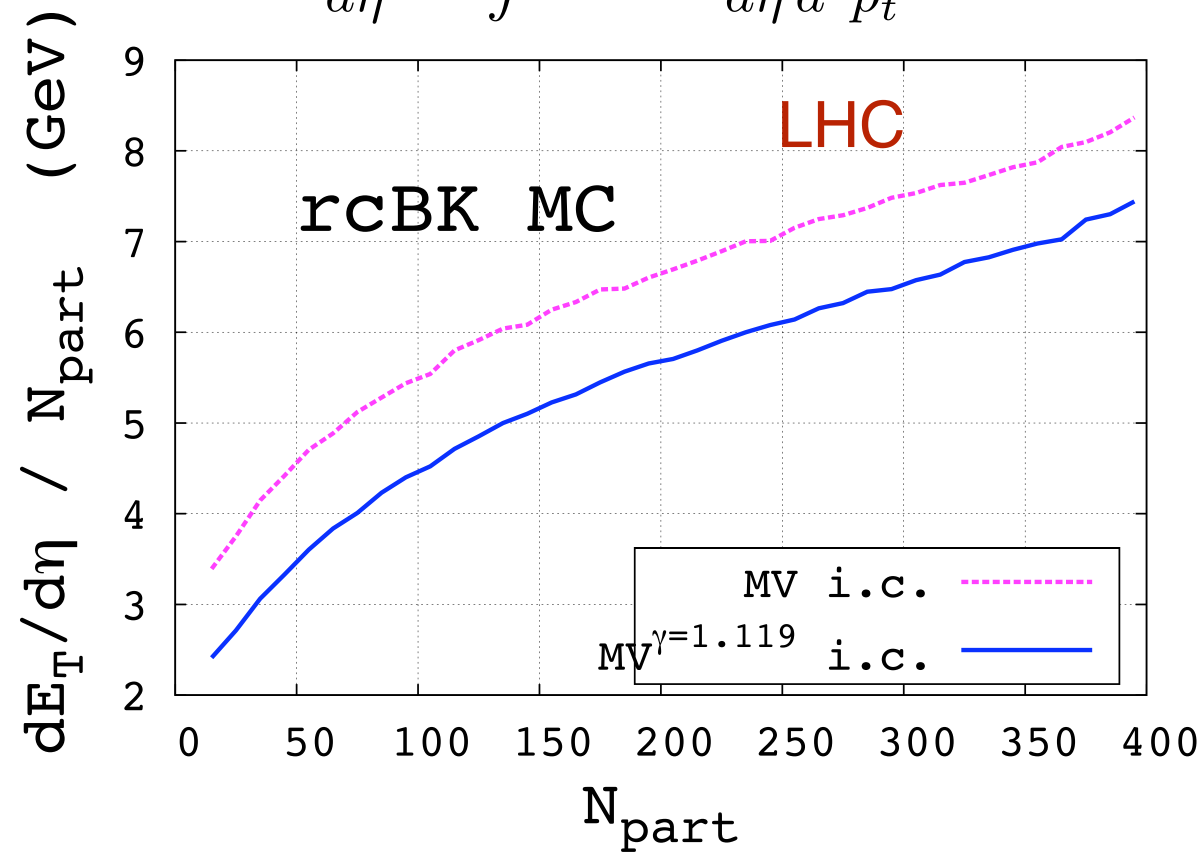
$$\frac{dN}{d\eta} \sim \int d^2p_t \frac{dN}{d\eta\, d^2p_t}$$

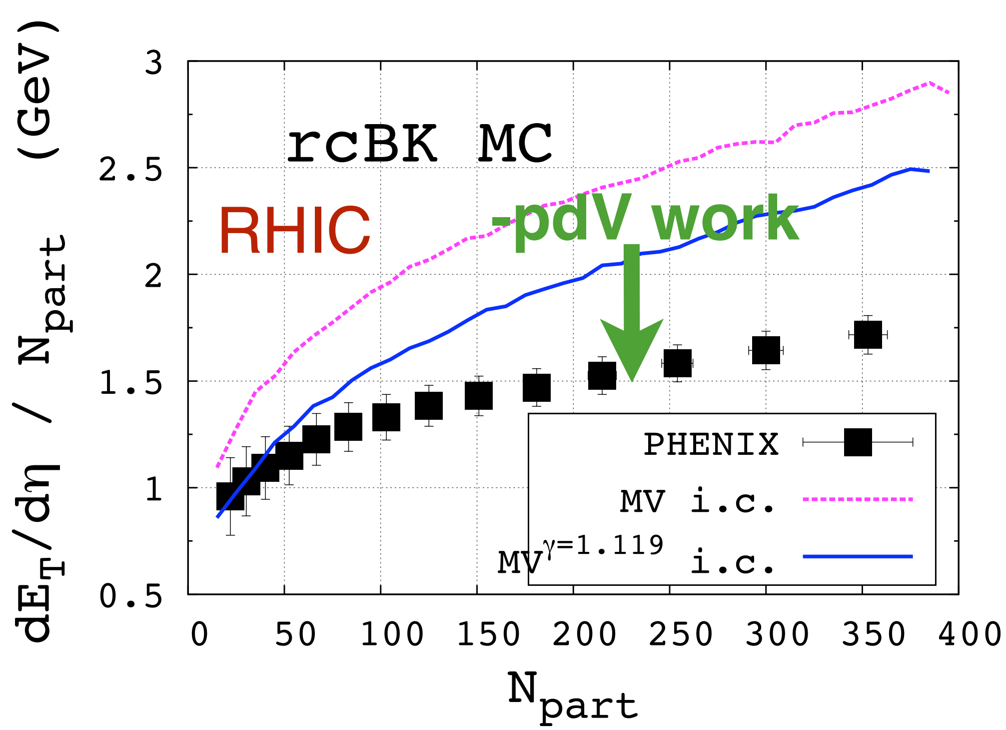




Larger effect on transverse energy distributions

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

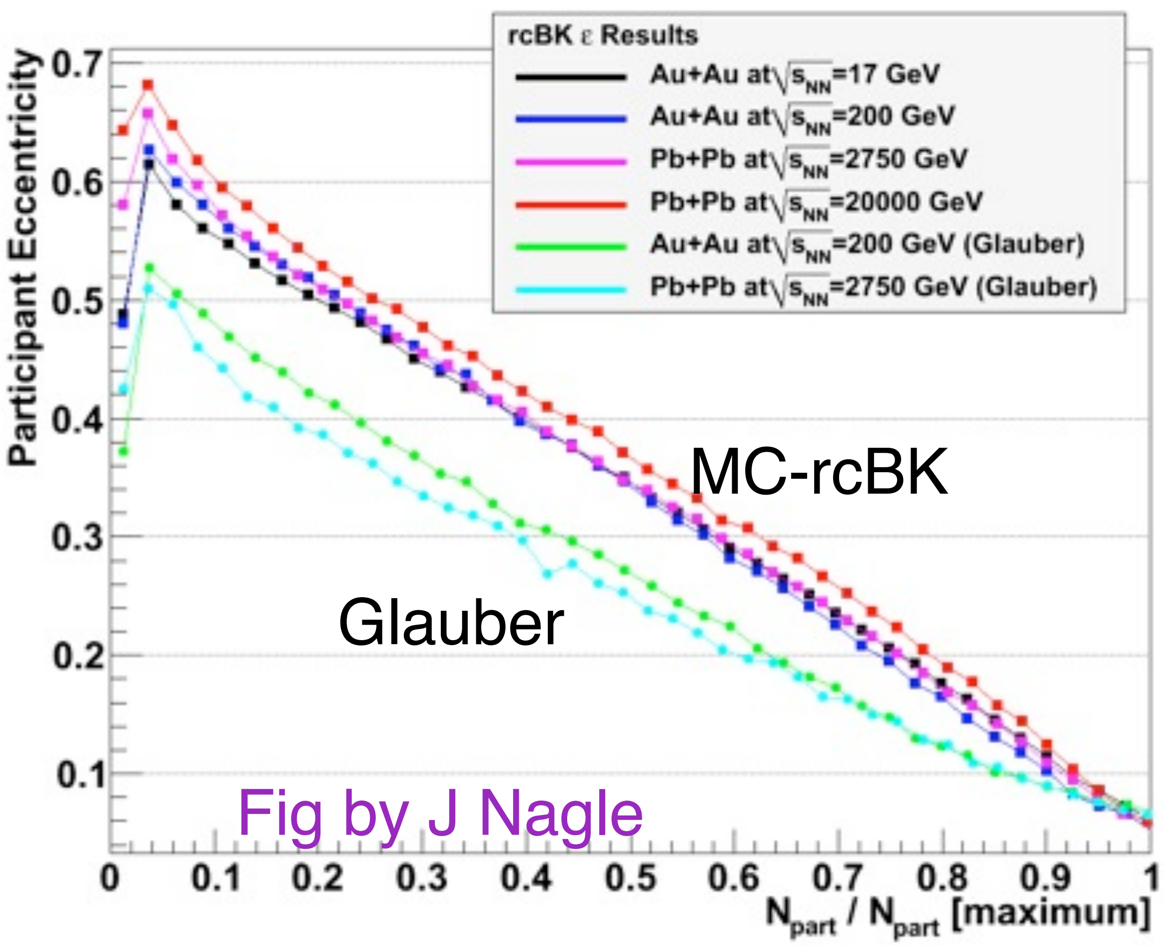


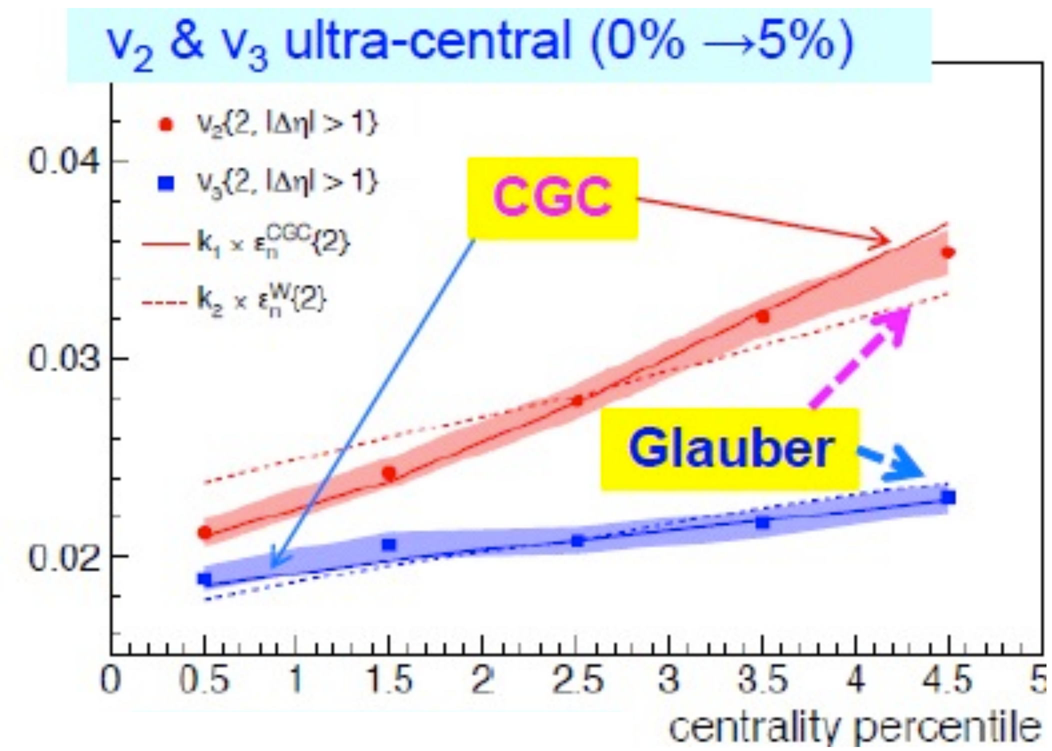


Initial state anisotropy

CGC (MC-KLN or rcBK) yield larger eccentricites than Glauber calculations

Study of higher harmonics may set further constraints on models for the initial state





from ALICE's talk yesterday

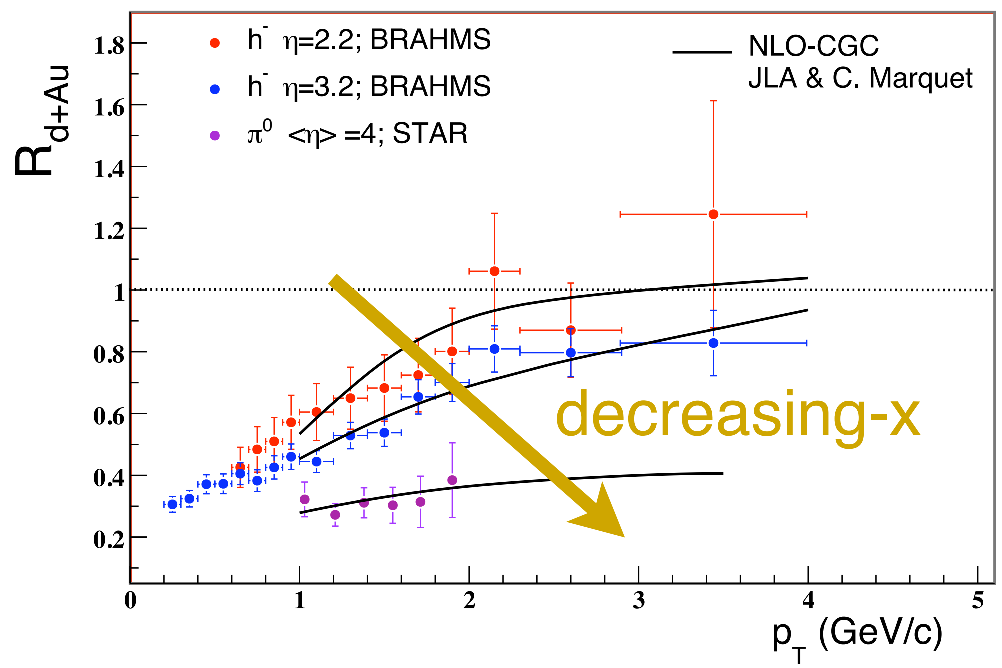
WARNIG!!

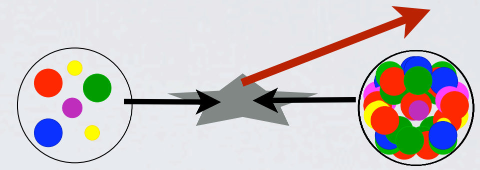
- Not clear to what extent such difference is rooted in the use ok kt-factorization [Lappi-Venugopalan]
- Some differences arise due to implementation details: nucleon size, spread etc..

p-A collisions:

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

- single inclusive

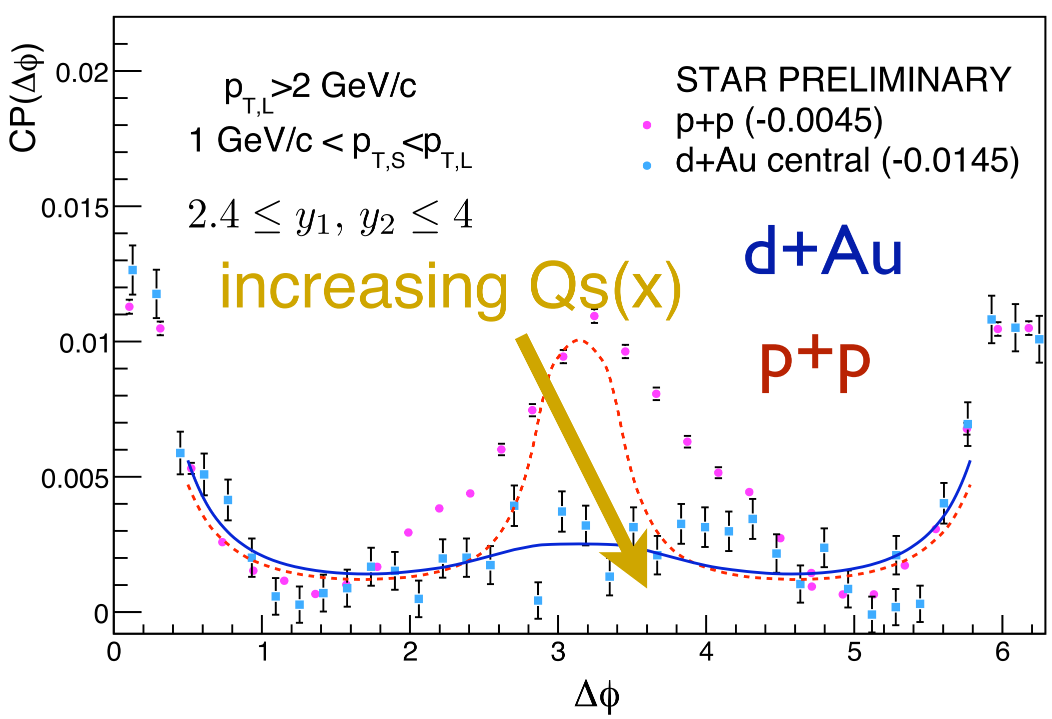




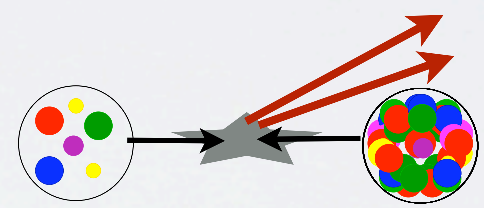
Large-x energy loss effects?

K-factor ~ 0.3 for forward pions?

- central d+Au di-hadron correlations in Δϕ



multi-parton interactions?



Some leading-Nc terms missing

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

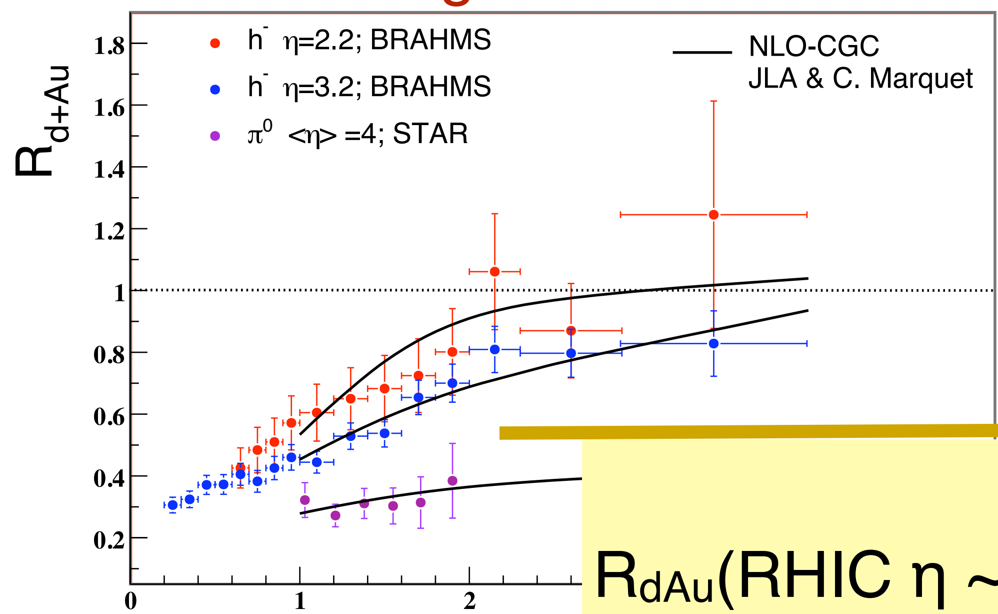
NOTE: Calculations done in the trivial b-dependence scheme

$\bar{Q}_{sA}$

p-A collisions:

Forward RHIC suppression well described by rcBK CGC calculations

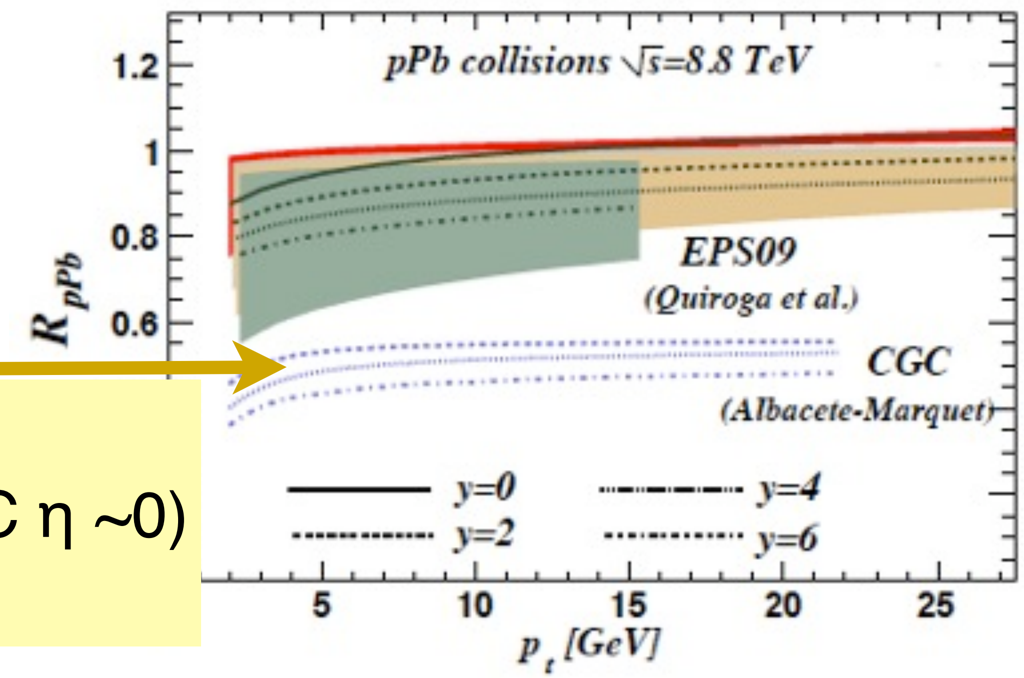
- single inclusive



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

Large-x energy los

predictions for p+Pb @ LHC



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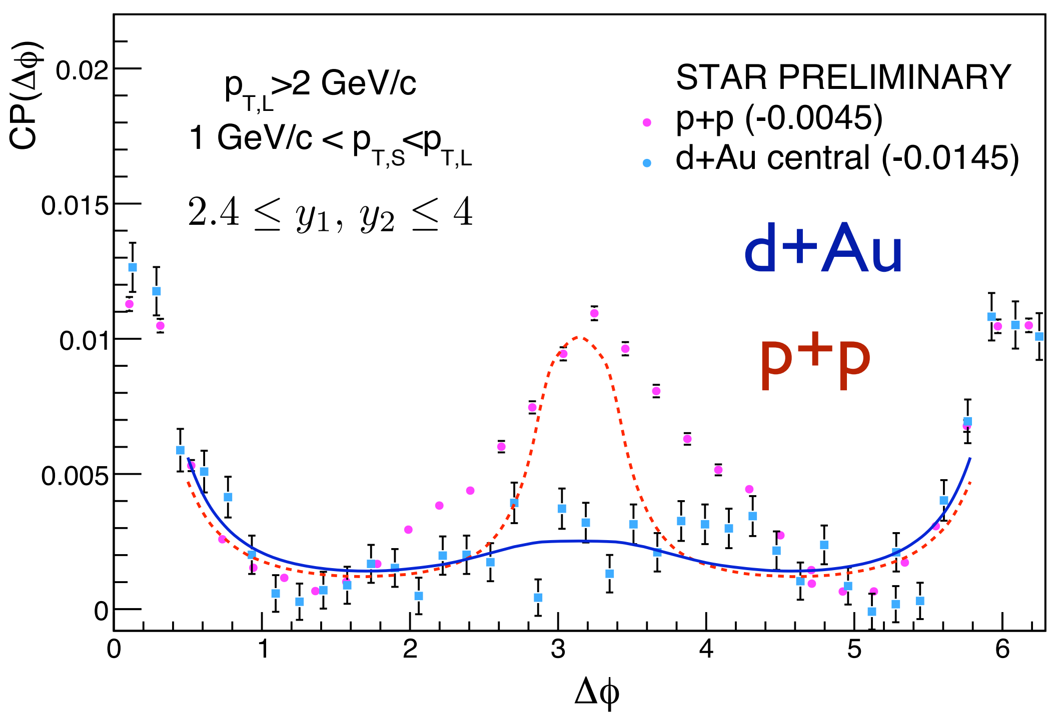


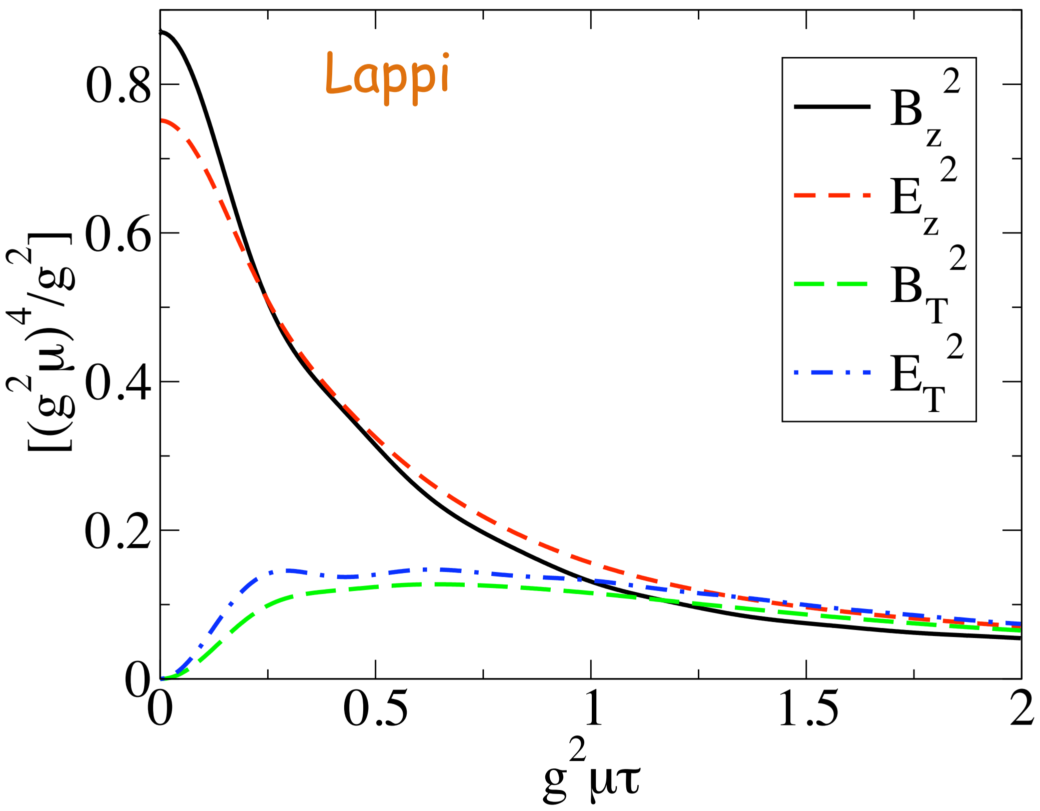
multi-parton interactions?

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

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 $\Delta R_\perp \sim \frac{1}{Q_s}$

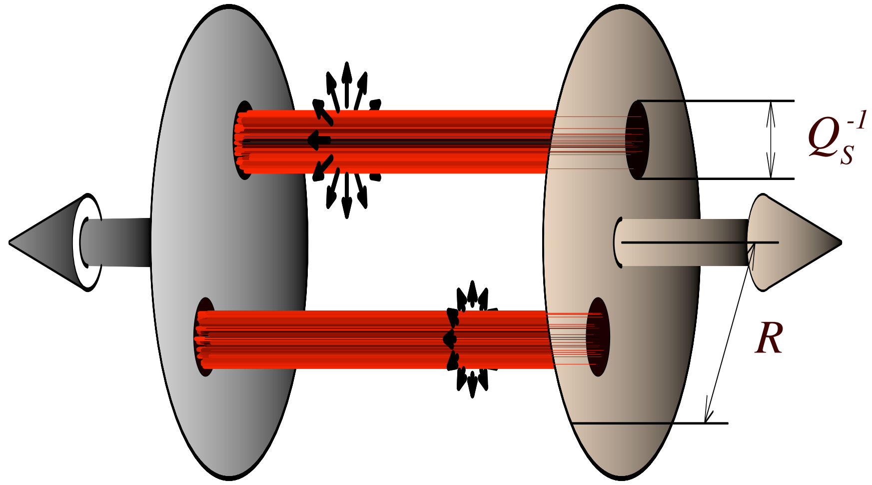


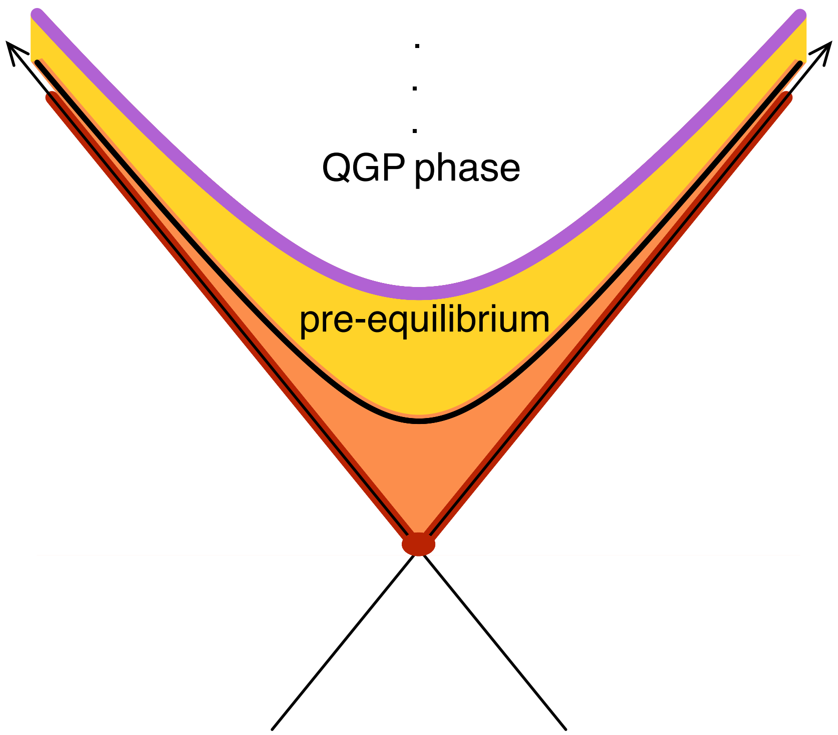
Fig by F Gelis

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:

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

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

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

GGC: Short list of theoretical developments

Evolution Equations BK-JIMWLK: $$\frac{\partial\,\phi(x,k)}{\partial\,\ln(1/x)} = \mathcal{K}\otimes\phi(x,k) - \phi^2(x,k)\ ; \quad \frac{\partial\,W[\rho]}{\partial\,Y} = \ldots$$

- ✓ -Running coupling corrections [Balitsky, Kovchegov-Weigert, Gardi et at]
- ✗ -Full NLO kernel [Balitsky]
- ✗ -High-Q^2 effects (CCFM + saturation) [Avsar-Iancu]
- ✗ -Kinematic constraints & b-dependence in BK evolution [Berger-Stasto]
- ✗ - Subleading-N(c) corrections [kovchegov-Weigert]
- - ...

Production processes: $$\frac{dN^{AB\to X}}{d^3p_1\ldots}\left[\phi(x,k); W_Y[\rho]\right]$$

- ✓ - Factorization of multiparticle production processes [Gelis-Lappi-Venugopalan]
- ✗ - Analytic solutions to Yang-Mills EOM [Blaizot-Mehtar Tani-Lappi]
- ✗ - Running coupling corrections to kt-factorization [Kovchegov-Horowitz]
- ✗ - DIS NLO photon impact factors [Balitsky-Chirilli]
- ✓ - Di-hadron correlations [Dumitru-Jalilian Marian, Dominguez et al]
- ✗ - Progress in the hybrid formalism (CGC+pdf's) [Altinoluk-Kovner]
- ✗ - New observables beyond the large-Nc limit [Marquet-Weigert]
- - ...

Used in phenomenological works? ✓ Yes ✗ No ✓A bit :)

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)
- ✔ 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!!