Saturation Physics

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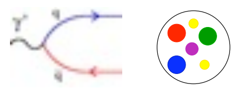
IPN Orsay

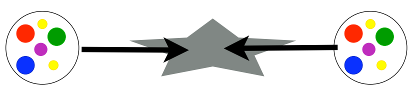
Fall meeting of the GDR PH-QCD: nucleon and nucleus structure studies with a LHC fixed-target experiment and electron-ion colliders, Oct 2011, IPN Orsay

OUTLINE

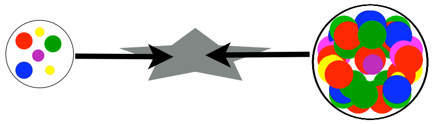
- Brief theory introduction
- Phenomenology:



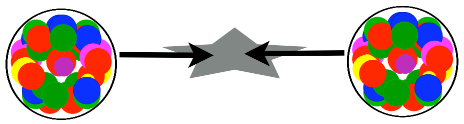
electron-proton (HERA)



proton-proton (RHIC, LHC)

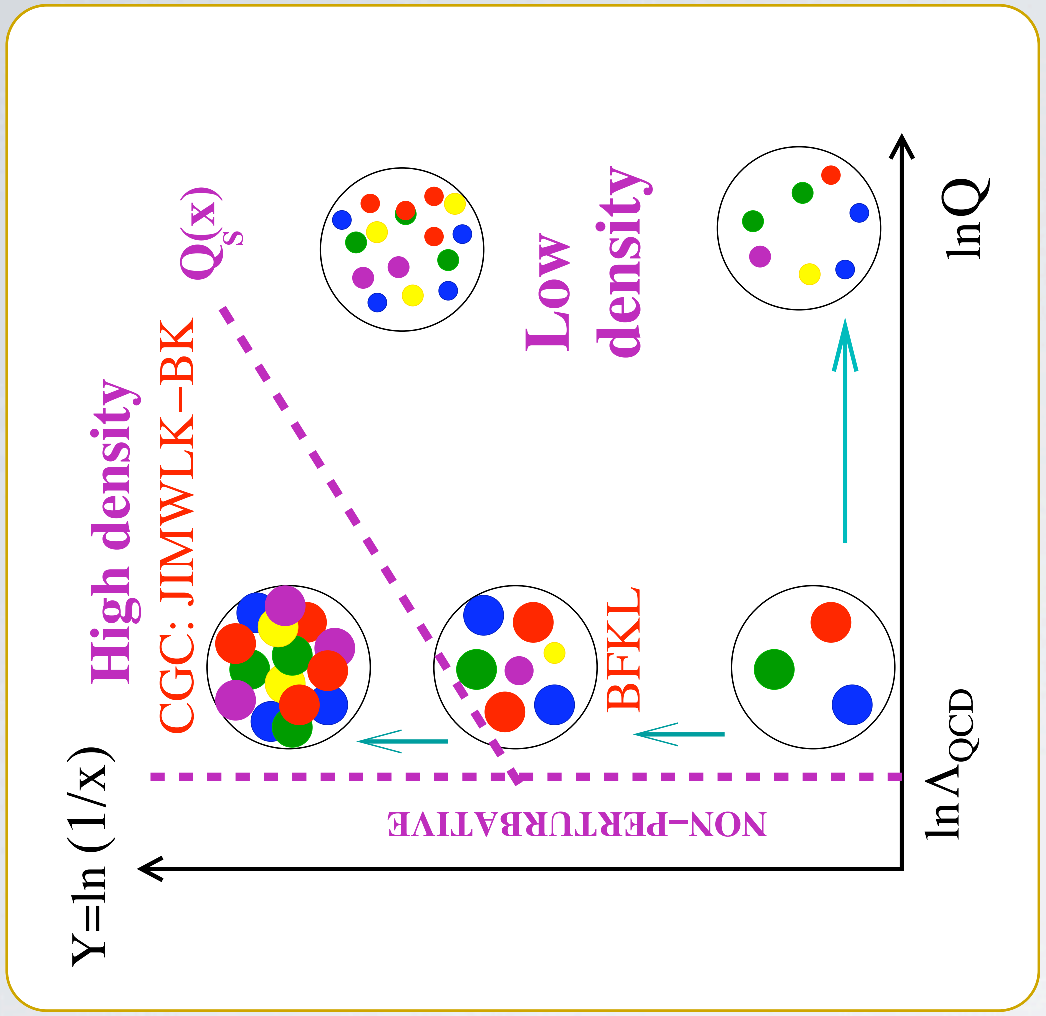


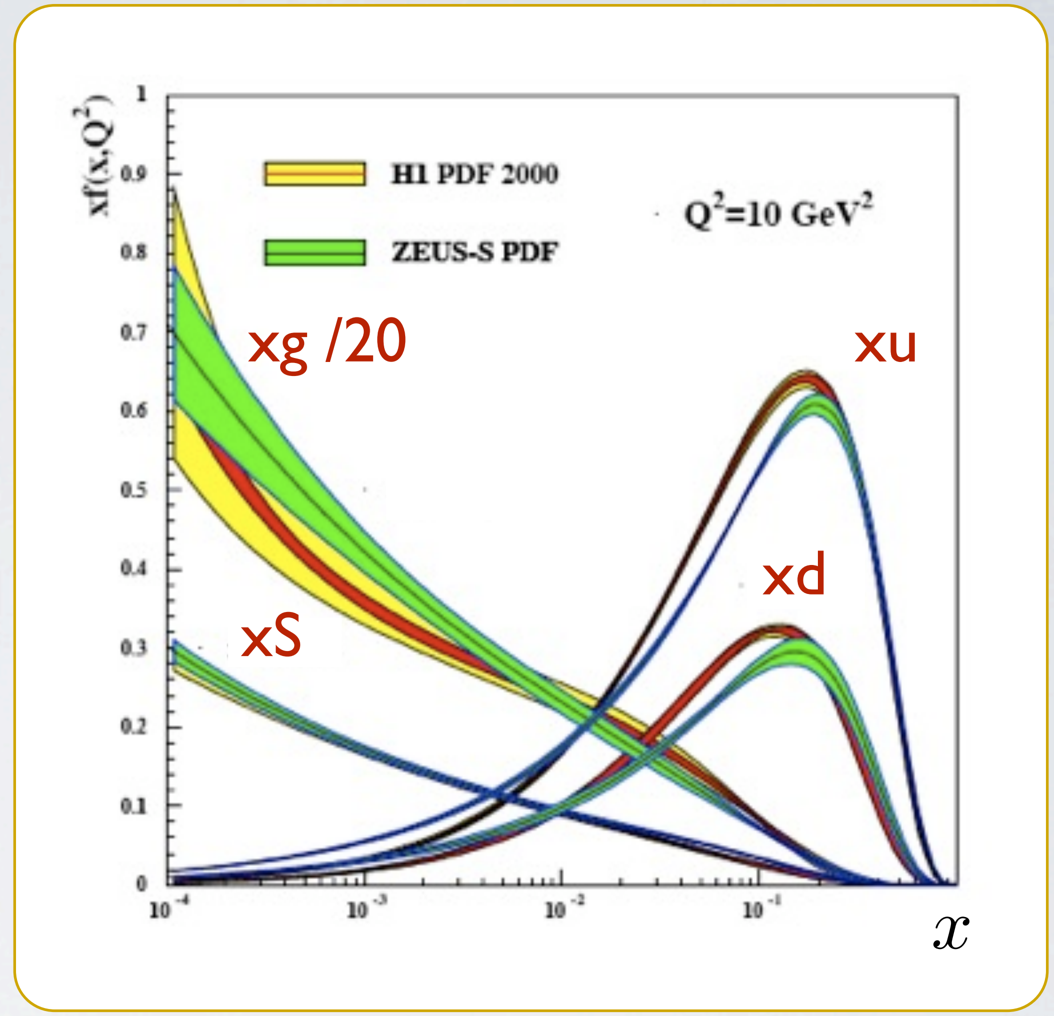
proton(d)-nucleus (RHIC)



nucleus-nucleus (RHIC, LHC)

Saturation: The small-x component of any energetic hadron is governed by high gluon densities

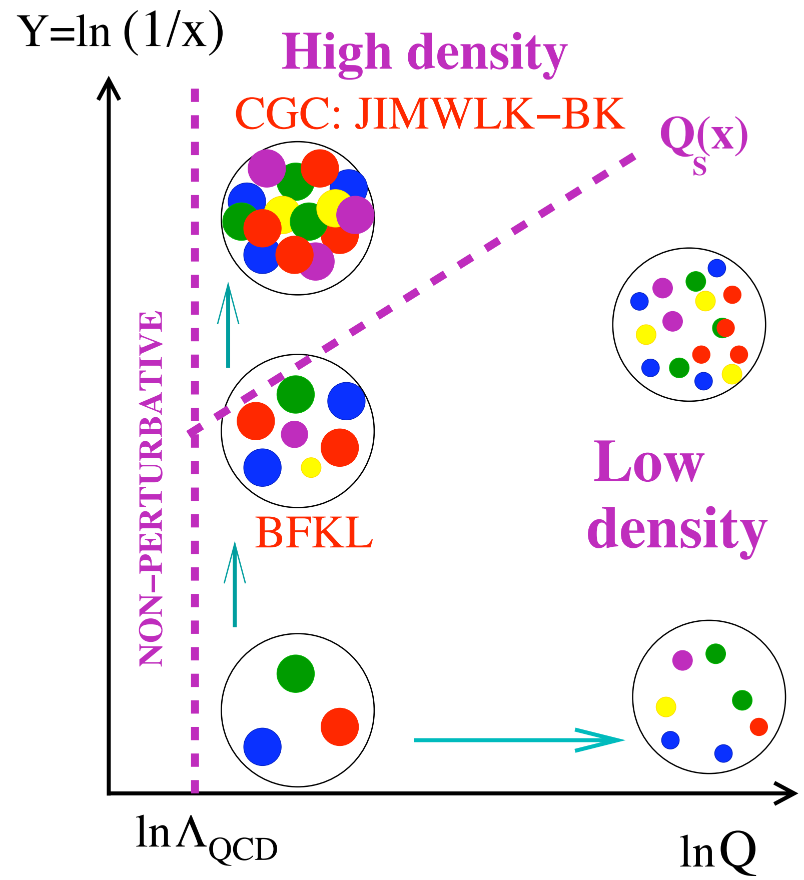


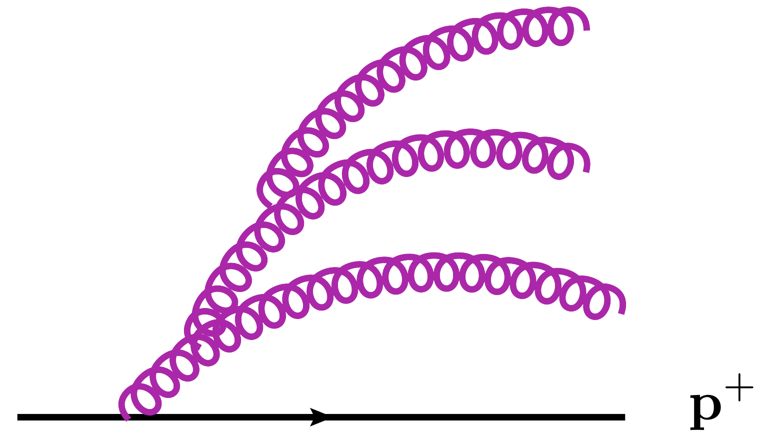


The Color Glass Condensate:

1 High gluon densities ~ Strong classical fields: $\mathcal{A}(\mathbf{k} \lesssim \mathbf{Q_s}) \sim \frac{\mathbf{1}}{\mathbf{g}}$

Saturation: The small-x component of any energetic hadron is governed by high gluon densities





"BK-JIMWLK"

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

↓

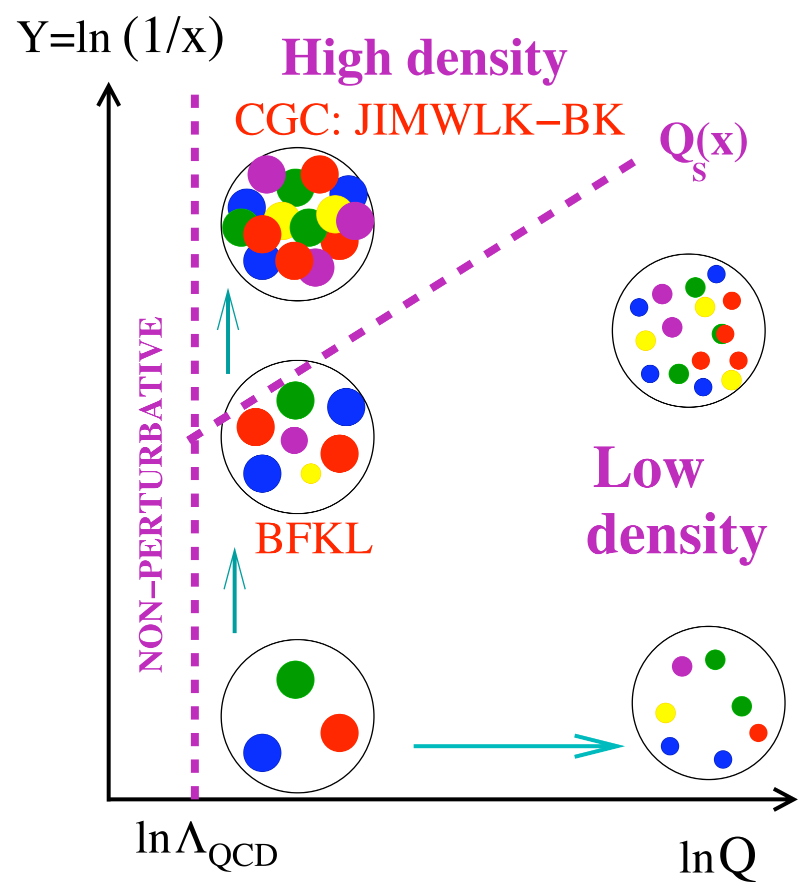
Non-linear *recombination* corrections are demanded by UNITARITY

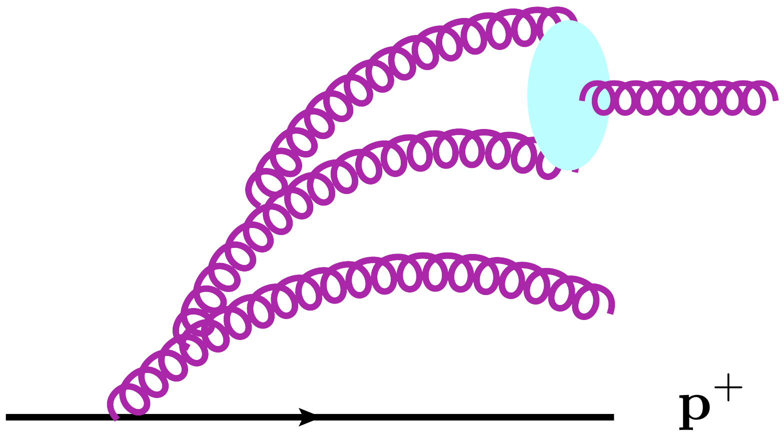
The Color Glass Condensate:

1 High gluon densities ~ Strong classical fields: $\mathcal{A}(\mathbf{k} \lesssim \mathbf{Q_s}) \sim \frac{\mathbf{1}}{\mathbf{g}}$

2 Non-linear quantum evolution (BK-JIMWLK equations). $\mathbf{Q_s^2}(\mathbf{x}) \sim \mathbf{x}^{-\lambda}$

Saturation: The small-x component of any energetic hadron is governed by high gluon densities





"BK-JIMWLK"

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

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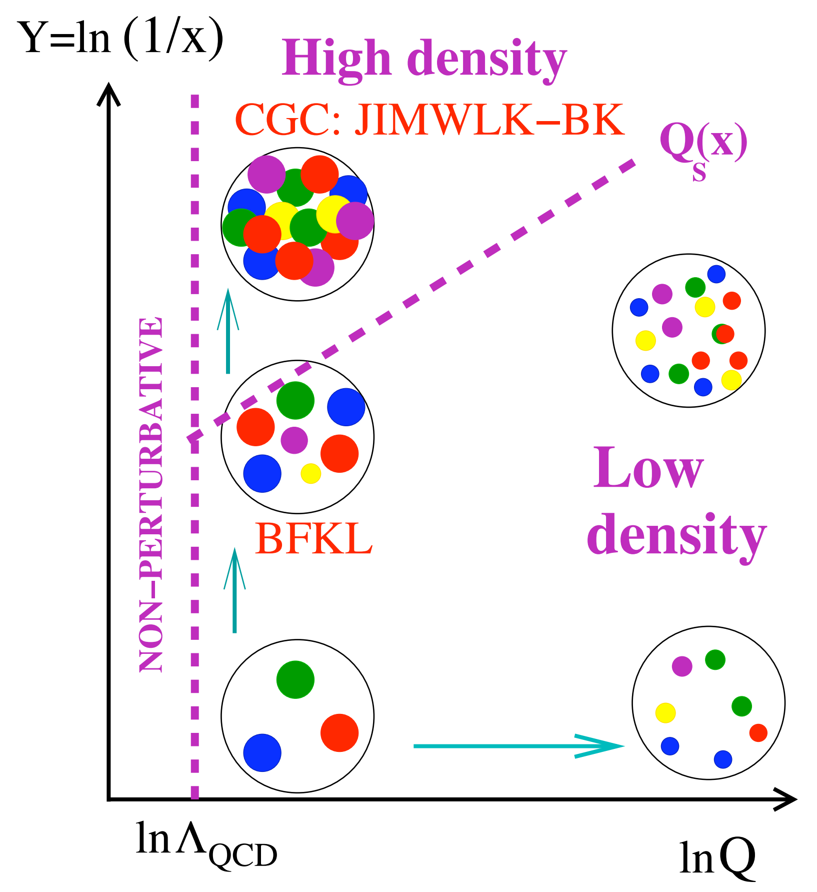
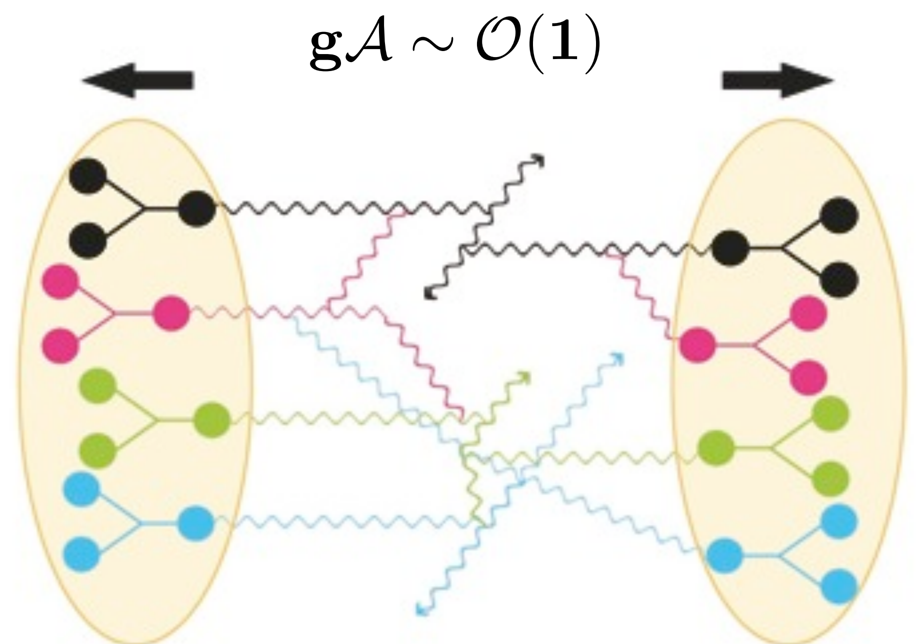




The Color Glass Condensate:

1 High gluon densities ~ Strong classical fields: $\mathcal{A}(\mathbf{k} \lesssim \mathbf{Q_s}) \sim \frac{1}{\mathbf{g}}$

2 Non-linear quantum evolution (BK-JIMWLK equations). $\mathbf{Q_s^2(x) \sim x^{-\lambda}}$

3 Rearrangement of perturbation series due to the presence strong fields

Evolution kernel: known up to full NLO accuracy. In practice BK with running coupling is used

"BK-JIMWLK"

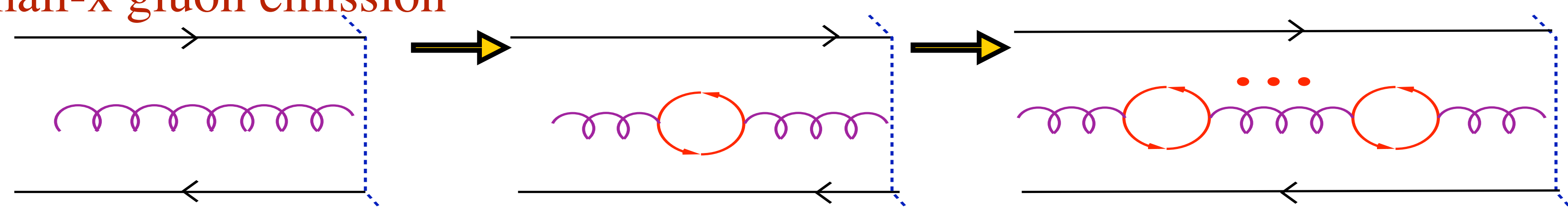
$$\frac{\partial \phi(\mathbf{x},\mathbf{k_t})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x},\mathbf{k_t}) - \phi(\mathbf{x},\mathbf{k_t})^2$$

radiation — recombination

LO: $\alpha_s \ln(1/x)$
small-x gluon emission

NLO

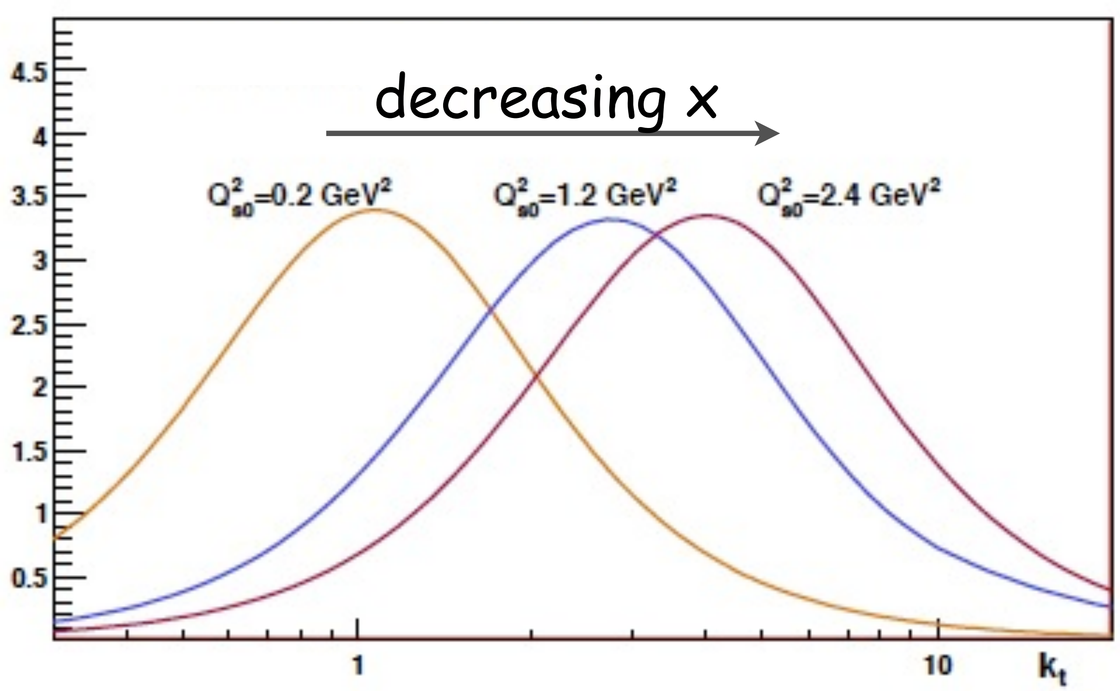
Running coupling



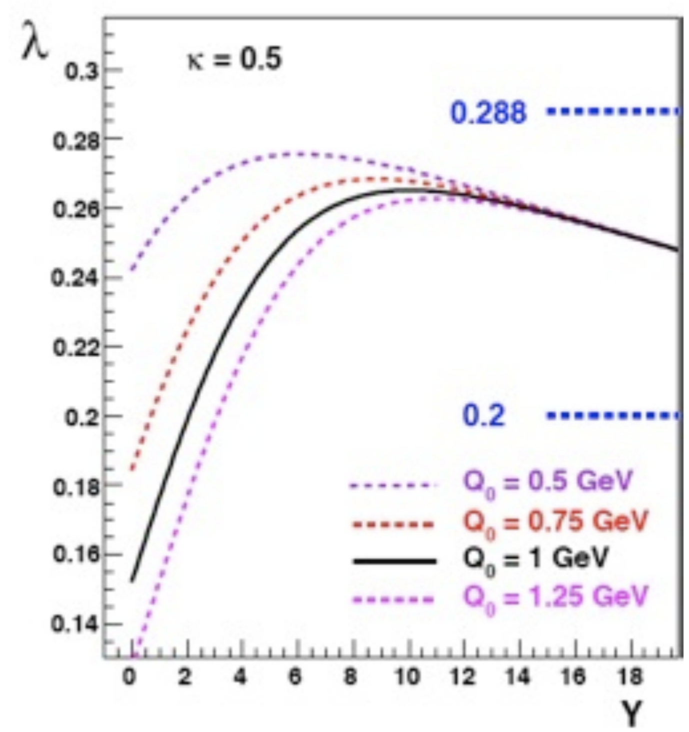
[Balitsky, , Gardi et at], Kovchegov-Weigert

$$K^{\rm run}(\mathbf{r},\mathbf{r_1},\mathbf{r_2}) = \frac{N_c\,\alpha_s(r^2)}{2\pi^2}\left[\frac{r^2}{r_1^2\,r_2^2} + \frac{1}{r_1^2}\left(\frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)} - 1\right) + \frac{1}{r_2^2}\left(\frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)} - 1\right)\right]$$

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



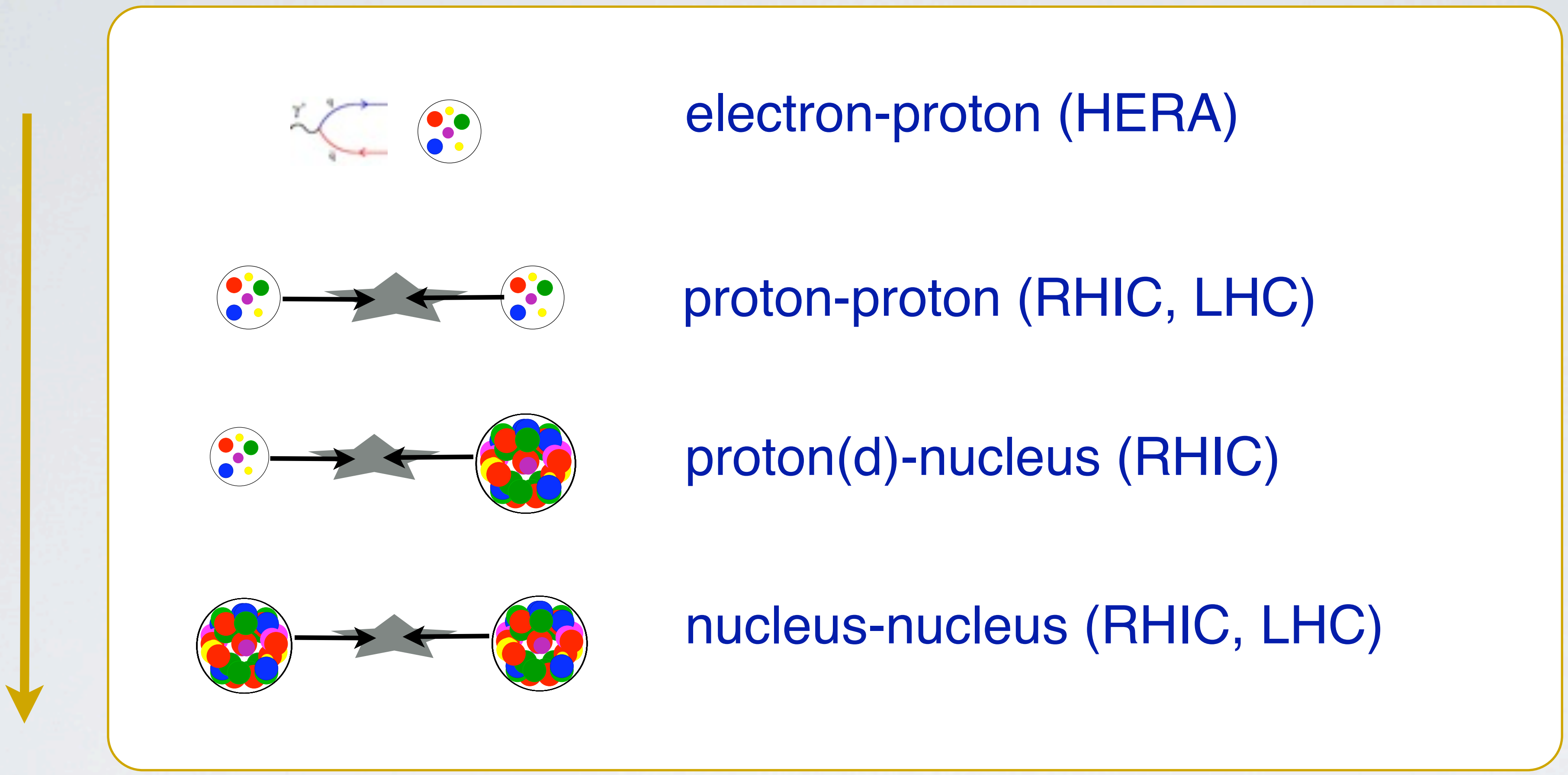
Running coupling corrections render evolution speed compatible with data!



Fits to
DIS
HIC

• Are saturation effects relevant in present high energy experiments?

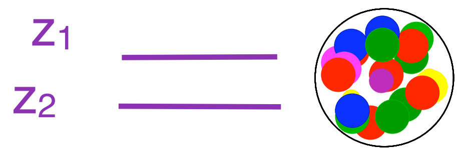
• Compelling indications from a variety of colliding systems:



ALL heavy ion phenomenology borrows information from electron-proton data!

The Color Glass Condensate: Phenomenology tools

1 INITIAL CONDITIONS: First principles calculation (MV model) or empirical determination of small-x component of hadronic wave functions at some initial scale $\mathbf{x_0}$



$$\phi(\mathbf{x_0}, \mathbf{k_t}, \mathbf{b}) = \mathrm{FT}\left[\mathbf{1} - \frac{\mathbf{1}}{\mathbf{N_c}}\left\langle \mathrm{tr}\left(\mathbf{U}(\mathbf{z_1})\mathbf{U}^\dagger(\mathbf{z_2})\right)\right\rangle_{\mathbf{x_0}}\right]$$

unintegrated gluon distr. ~ 2-point (dipole) amplitude

$$\phi^{\mathbf{n}}_{\mathbf{x_0}} \sim \mathrm{tr}\left(\mathbf{U}(\mathbf{z_1})\ldots\mathbf{U}^\dagger(\mathbf{z_n})\right)_{\mathbf{x_0}}$$

complete description: all n-point functions

2 SMALL-X EVOLUTION: Non-linear quantum BK-JIMWLK evolution equations. Predictive power is here!!!

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

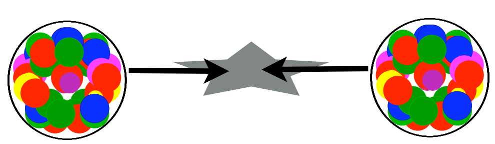
radiation — recombination

BK: evolution of the 2-point function

JIMWLK: (coupled) evolution of all n-point functions

Evolution kernels K known to NLO accuracy. In practice running coupling BK is used.
First steps of phenomenological implementation of JIMWLK very recent.

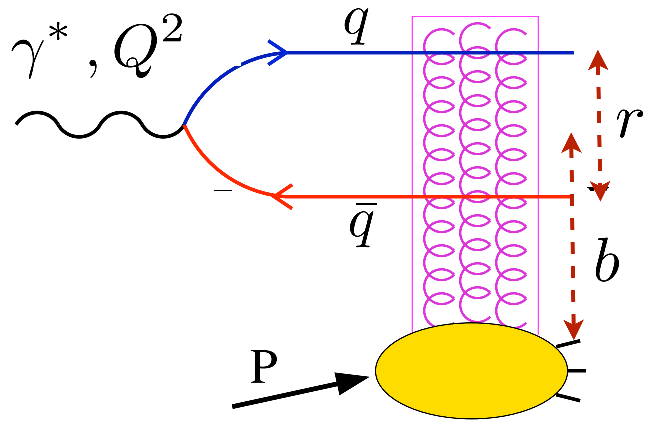
3 PARTICLE PRODUCTION:



$$\langle\mathcal{O}\rangle\left[\phi^{\mathbf{2}}, \ldots, \phi^{\mathbf{n}}\right]$$

Factorization theorems only hold for certain, very inclusive observables
Most processes calculated only to LO accuracy

Fits to e+p data: Global fits to structure functions and reduced x-section based on the use of running coupling BK equation provide a very good description of data



$$\sigma_{T,L}^{\gamma^* P}(x,Q^2) = \int_0^1 dz \int d^2\mathbf{r} \left|\Psi_{T,L}^{\gamma^*\to q\bar{q}}(z,Q,r)\right|^2 \sigma^{dip}(x,r)$$

$$\sigma^{dip}(x,r) = 2 \int d^2b\,\mathcal{N}(x,b,r)$$ → Dipole cross section. Strong interactions and x-dependence are here. Evolved with running coupling BK

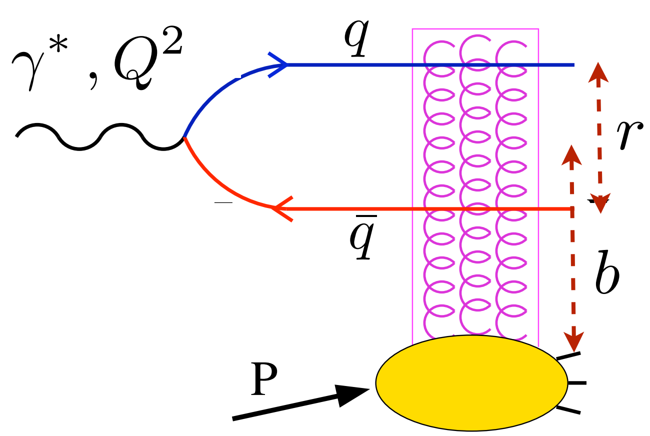
JLA-Armesto-Milhano, Quiroga-Salgado; Kuokkanen-Rumukainen-Weigert; Gonzalves et. al.

Fit parameters: initial condition for the evolution:

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

$$\phi(\mathbf{x_0}, \mathbf{k_t}) = \mathrm{F.T}[\mathcal{N}(x_0, r)]$$

Fits to e+p data: Global fits to structure functions and reduced x-section based on the use of running coupling BK equation provide a very good description of data



$$\sigma^{\gamma^* P}_{T,L}(x,Q^2) = \int_0^1 dz \int d^2\mathbf{r} \left|\Psi^{\gamma^*\to q\bar{q}}_{T,L}(z,Q,r)\right|^2 \sigma^{dip}(x,r)$$

$$\sigma^{dip}(x,r) = 2\int d^2b\,\mathcal{N}(x,b,r) \rightarrow$$

Dipole cross section.
Strong interactions and x-dependence are here. Evolved with running coupling BK

JLA-Armesto-Milhano, Quiroga-Salgado;
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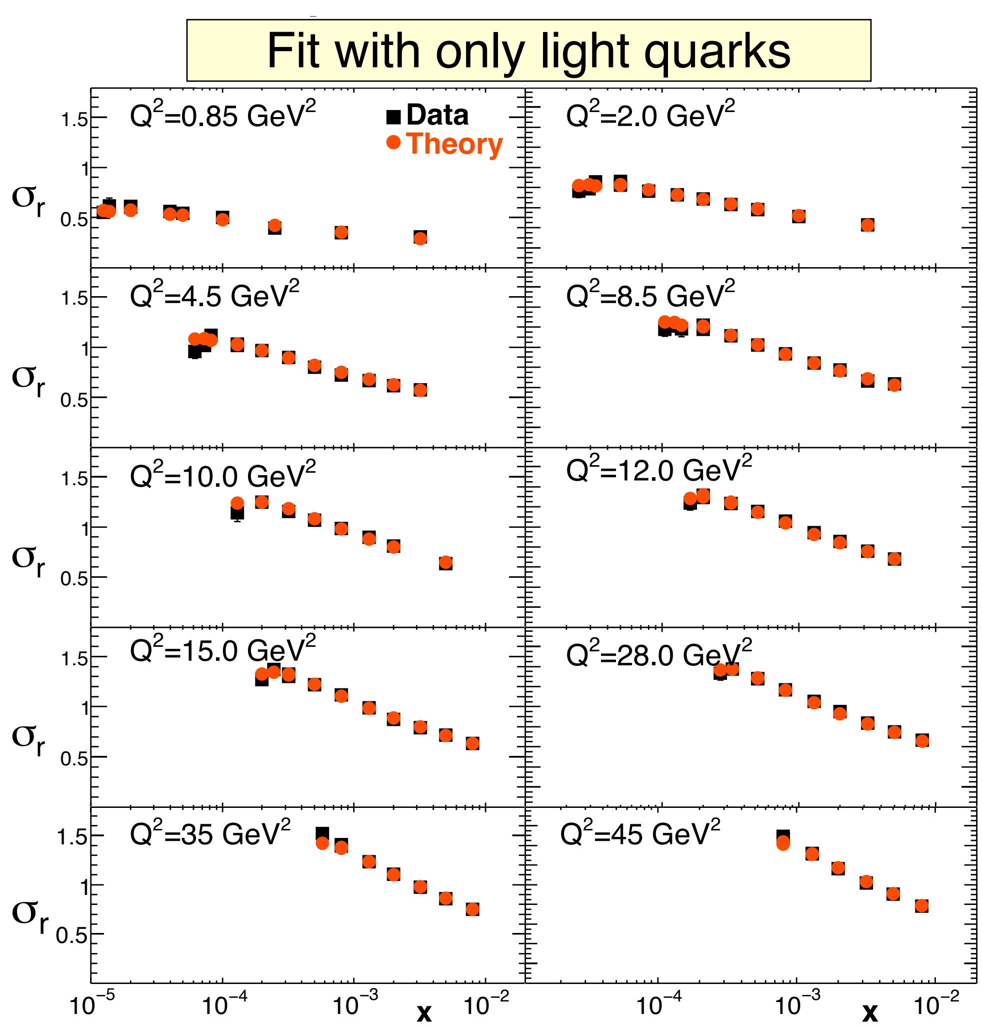
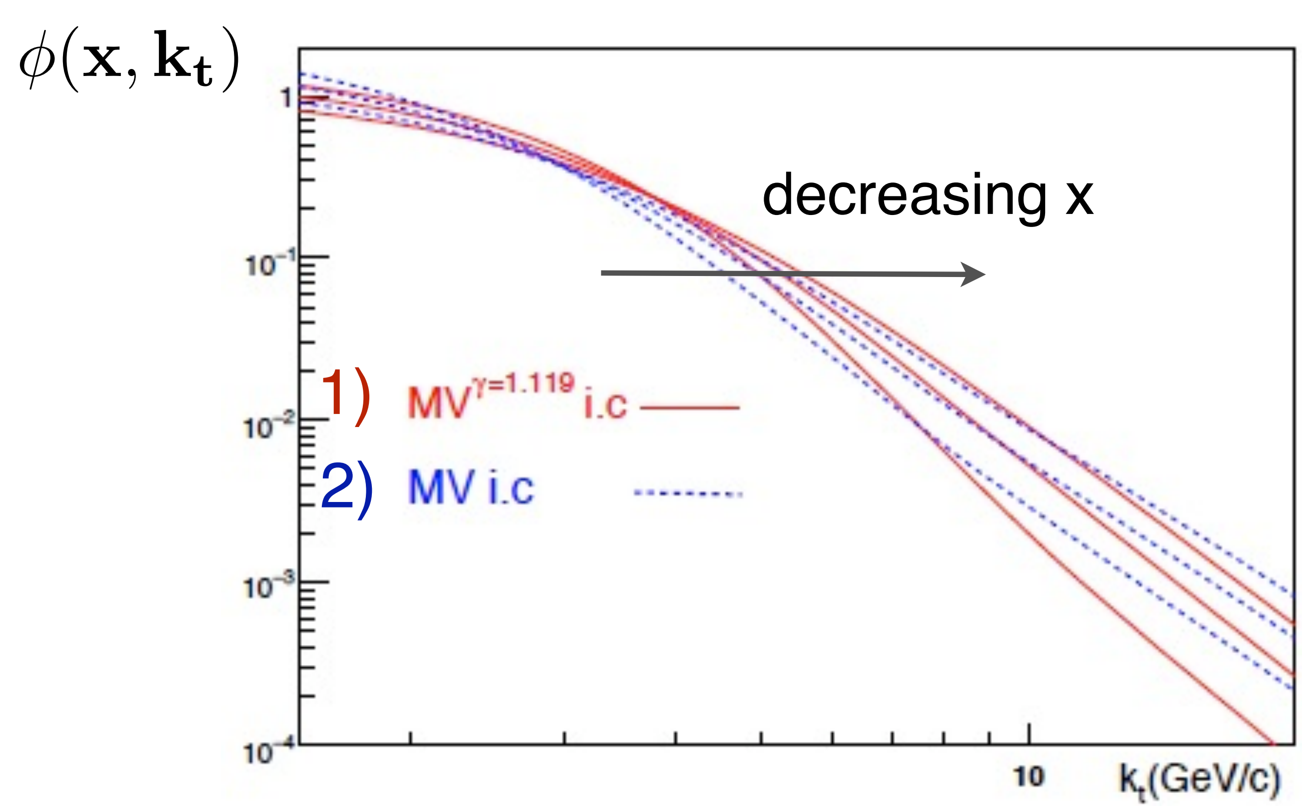


Data fitted is too inclusive to constrain the high-kt behavior of gluon u.g.d



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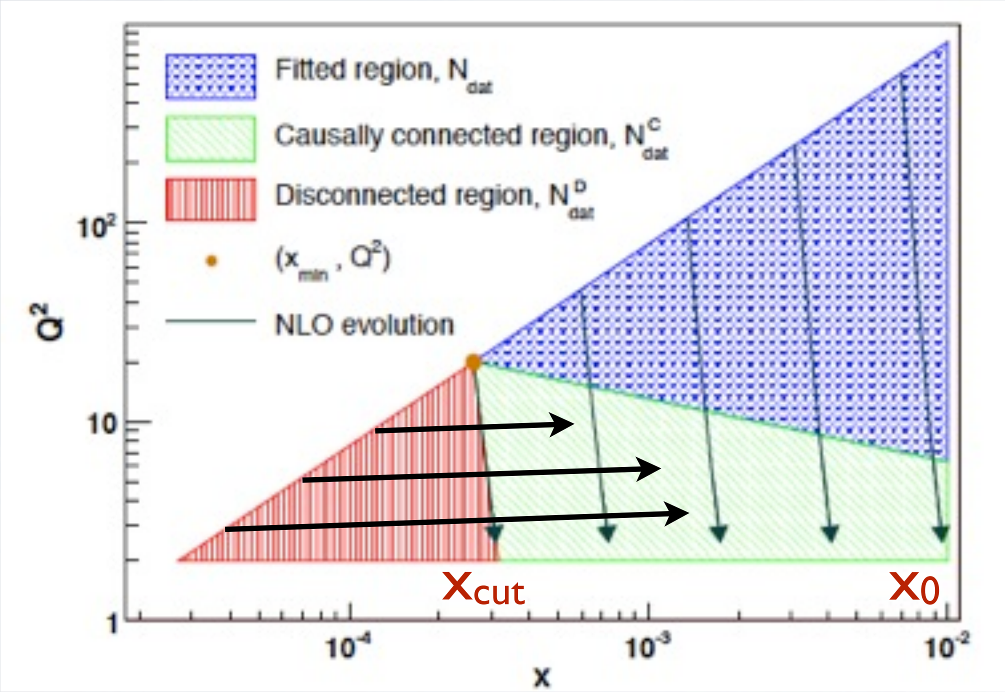
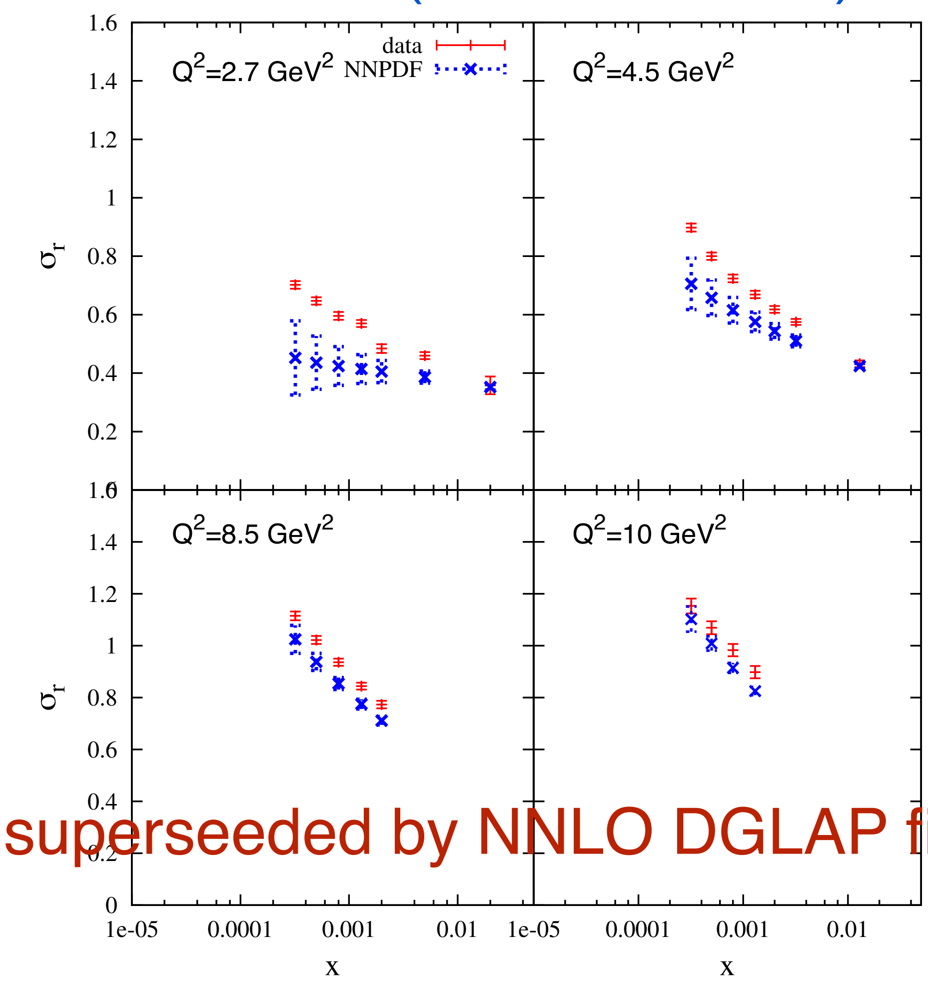


Comparison with data into a kinematic region excluded from the fits: The non-linear rcBK approach is more stable than NLO DGLAP at small (x,Q^2).

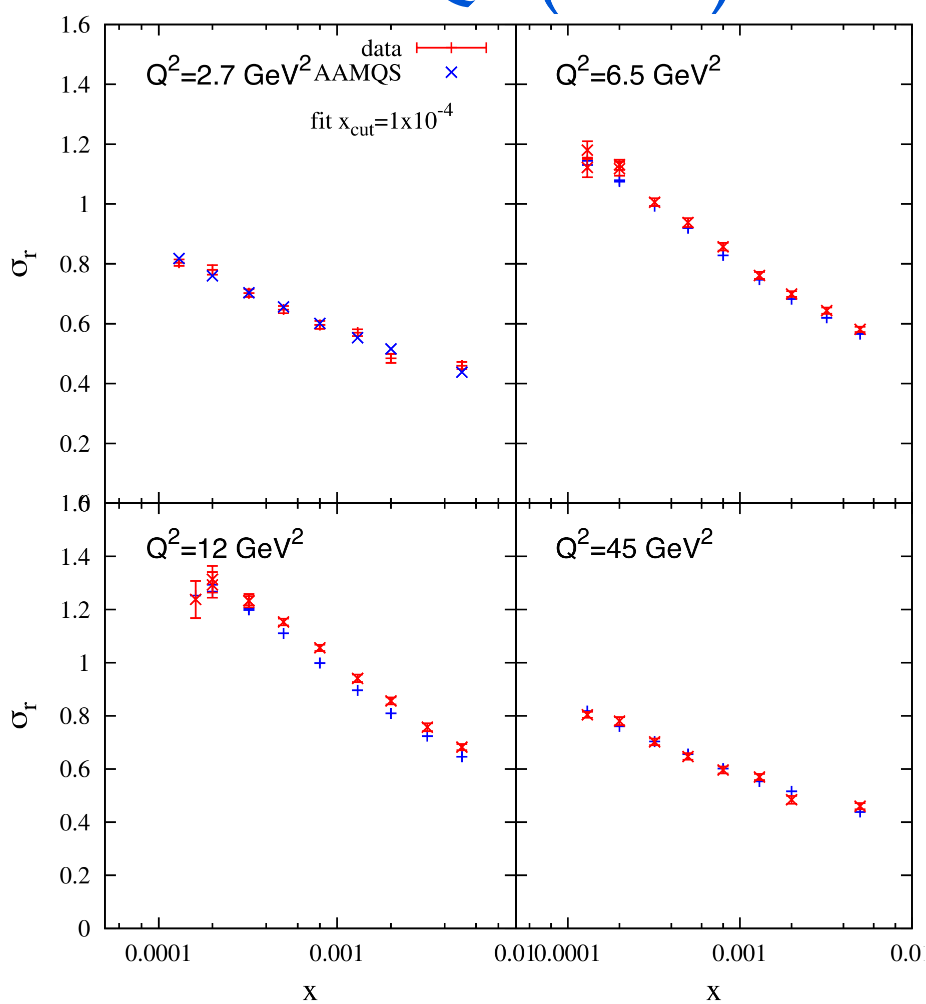
JLA, Milhano, Quiroga, Rojo (in preparation)

NNPDF (NLO DGLAP)



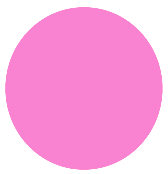
superseeded by NNLO DGLAP fits!!

AAMQS (rcBK)

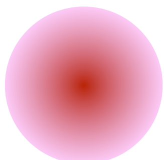


How to deal with b-dependence? Building nuclei from nucleons:

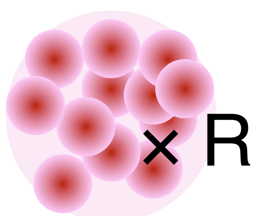
$$\phi^{\mathbf{A}}(\mathbf{x}, \mathbf{k_t}, \mathbf{B}) = \phi^{\mathbf{p}}(\mathbf{x}, \mathbf{k_t}, \mathbf{Q^2_{sp}} \to \mathbf{Q^2_{sA}}(\mathbf{B}))$$



1. Trivial: $\bar{\mathbf{Q}}_{\mathbf{s}}^{\mathbf{2,A}} \sim \mathbf{A^{1/3}}\, \mathbf{Q}_{\mathbf{s}}^{\mathbf{2,N}}$



2. Mean field: $\mathbf{Q}_{\mathbf{s}}^{\mathbf{2,A}}(\mathbf{B}) \sim \mathbf{T_A}(\mathbf{B})\, \mathbf{Q}_{\mathbf{s}}^{\mathbf{2,N}}$



3. Monte Carlo (realistic i.c for heavy ion collisions)

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

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

$$\downarrow$$

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

b) Solve **local** rcBK evolution at each transverse point

$$\downarrow \quad \text{rcBK equation or KLN model}$$

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

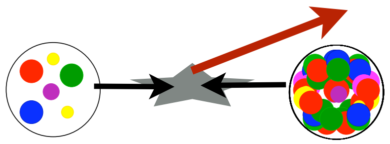
Nucleons can be regarded as disks ( ) or gaussian ( ) or ...

Is using the same functional form for proton and nuclei u.g.d a good idea?

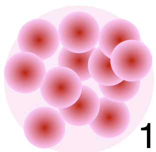
Is diffusion in the transverse plane negligible?

Forward suppression in p(d)-A collisions:

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

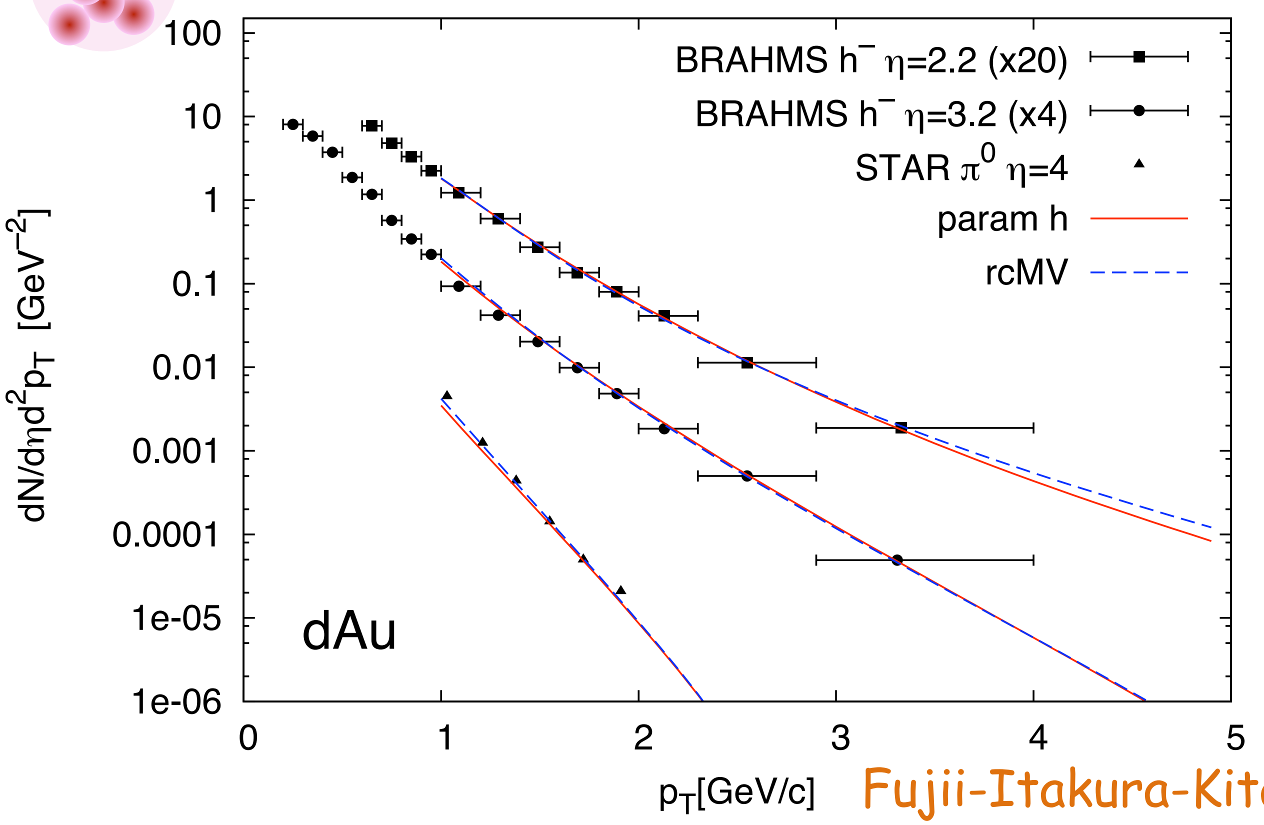


$$\mathrm{pdf}(\mathbf{x_1}, \mathbf{k_t}) \otimes \phi(\mathbf{x_2}, \mathbf{k_t}) \qquad x_{1(2)} \sim \frac{m_t}{\sqrt{s}} \exp(\pm y_h)$$

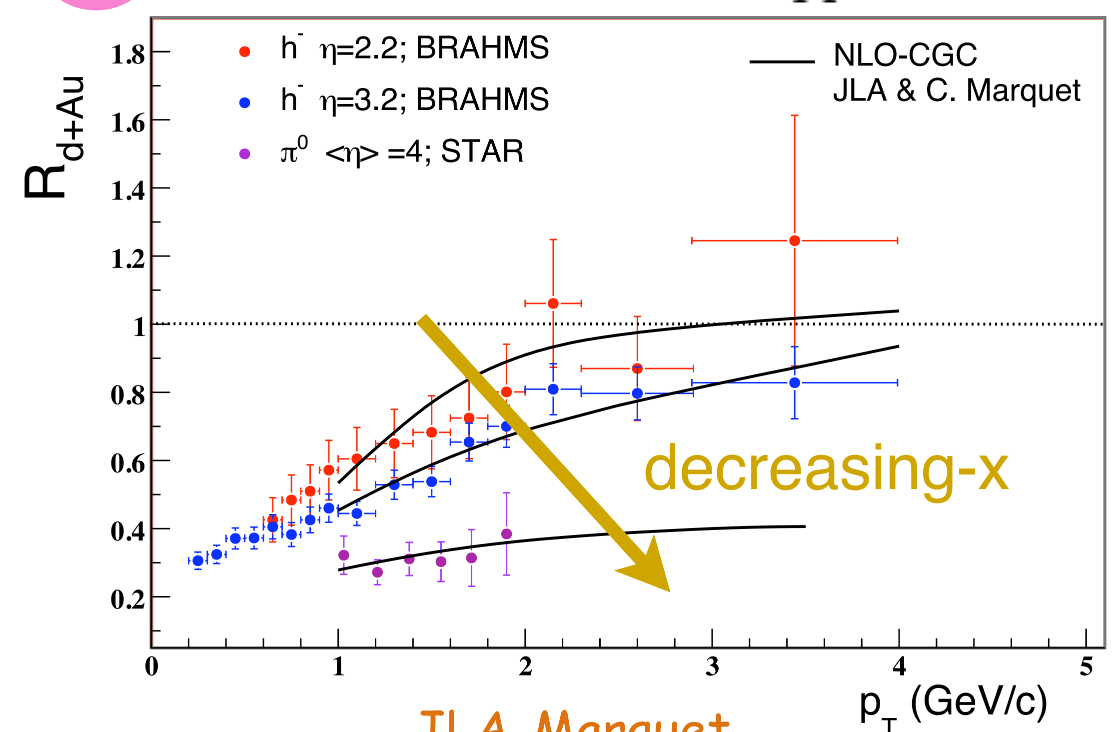


single inclusive yields in dAu

$$\mathbf{R_{dAU}} = \frac{\mathbf{1}}{\mathbf{A}} \frac{\text{Yield in d+Au}}{\text{Yield in pp}}$$



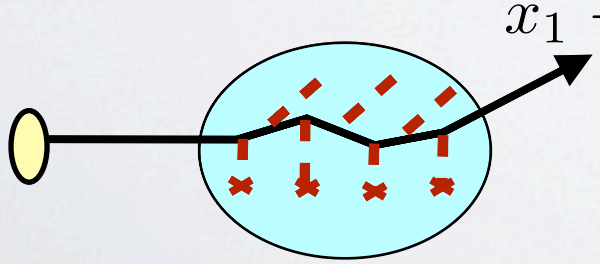
Fujii-Itakura-Kitadono-Nara



JLA-Marquet

Measurements very close to the kinematic limit (K-factor ~ 0.3 for forward pions?)

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



$x_1 \to 1$

Probability of not losing energy:

$$P(\Delta y) \approx e^{-n_G(\Delta y)} \approx (1 - x_F)^{\#}$$

Kopeliovich et al

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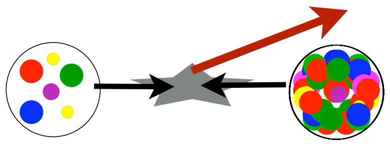

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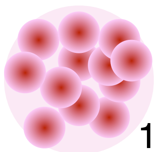
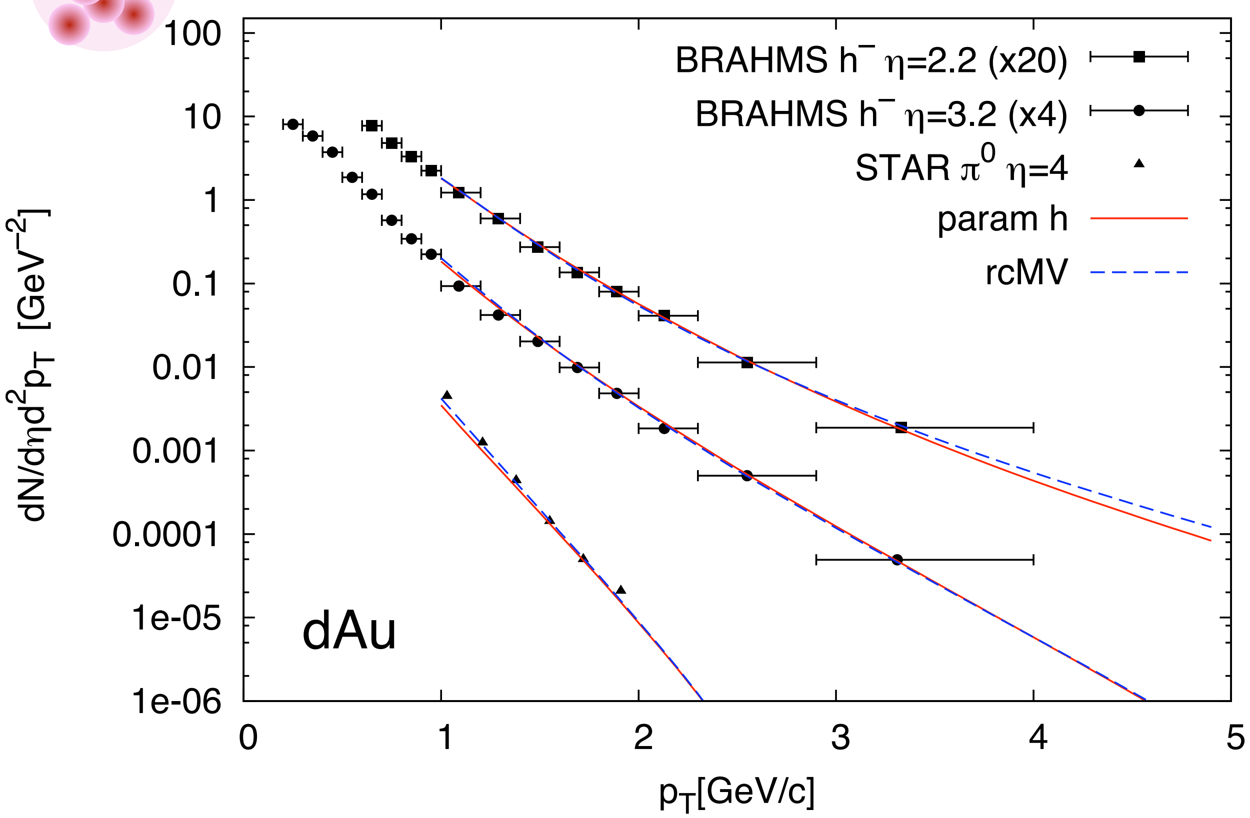
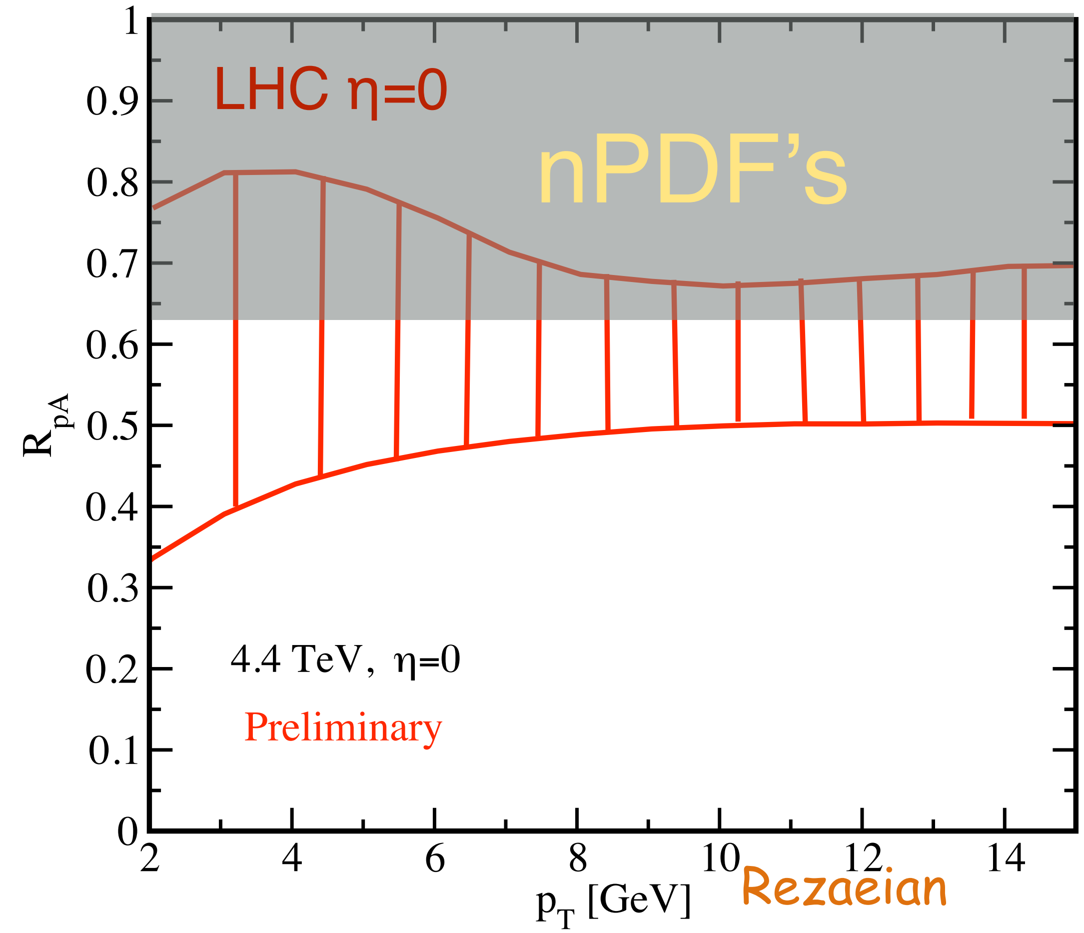


single inclusive yields in dAu



Fujii-Itakura-Kitadono-Nara

R_{pPb} at the LHC



Rezaeian
Jalilian Marian

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

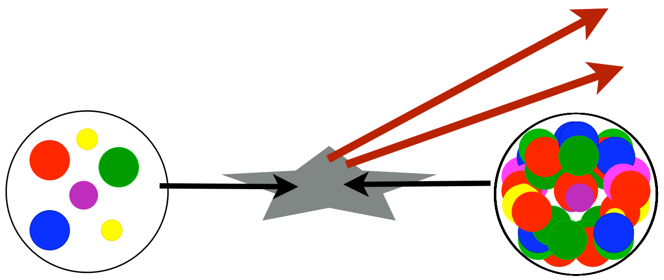
Measurements very close to the kinematic limit (K-factor ~ 0.3 for forward pions?)

Related R_{pPb} measurement at the LHC may clarify the origin of RHIC forward suppression, though large systematics uncertainties from poor knowledge of initial conditions

suppression of forward di-hadron correlations in d-Au collisions:

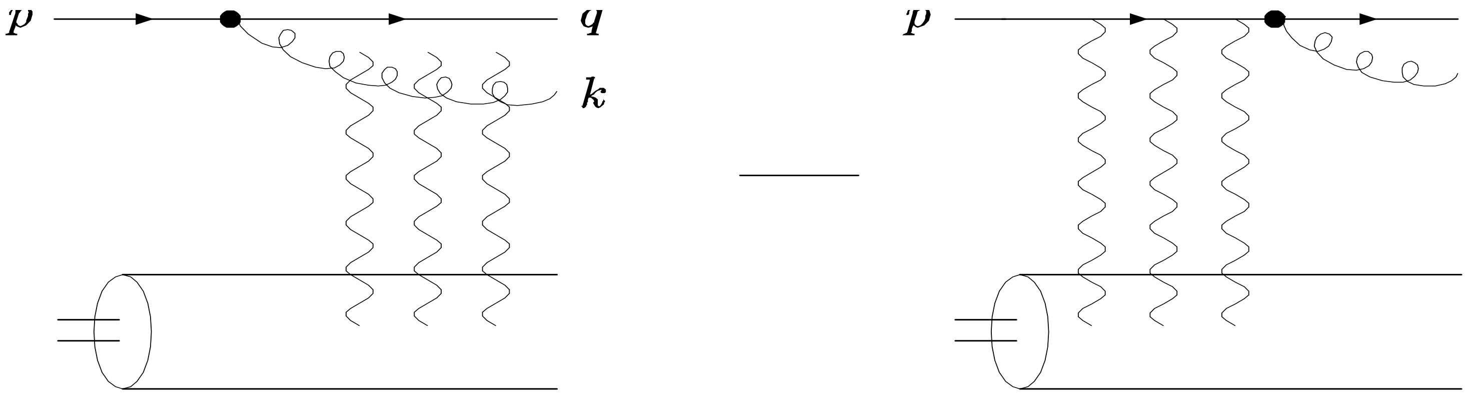
$$x_p = \frac{|k_1|e^{y_1} + |k_2|e^{y_2}}{\sqrt{s}}$$

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



(k1, y1), (k2, y2)

C. Marquet;
Dominguez et al (gluon channel)



hard quark initiating scattering

Fourier transfrom coordinate space to momentum

$$\frac{d\sigma^{dAu\to qgX}}{d^2k_\perp dy_k d^2q_\perp dy_q} = \alpha_S C_F N_c\, x_d q(x_d,\mu^2) \int \frac{d^2x}{(2\pi)^2}\frac{d^2x'}{(2\pi)^2}\frac{d^2b}{(2\pi)^2}\frac{d^2b'}{(2\pi)^2}\, e^{ik_\perp.(\mathbf{x}'-\mathbf{x})} e^{iq_\perp.(\mathbf{b}'-\mathbf{b})}$$

$$\left|\Phi^{q\to qg}(z,\mathbf{x}-\mathbf{b},\mathbf{x}'-\mathbf{b}')\right|^2 \Big\{ S^{(4)}_{qg\bar{q}g}[\mathbf{b},\mathbf{x},\mathbf{b}',\mathbf{x}';x_A] - S^{(3)}_{qg\bar{q}}[\mathbf{b},\mathbf{x},\mathbf{b}'+z(\mathbf{x}'-\mathbf{b}');x_A]$$

q-> qg splitting (pQCD)

$$-S^{(3)}_{\bar{q}gq}[\mathbf{b}+z(\mathbf{x}-\mathbf{b}),\mathbf{x}',\mathbf{b}';x_A] + S^{(2)}_{q\bar{q}}[\mathbf{b}+z(\mathbf{x}-\mathbf{b}),\mathbf{b}'+z(\mathbf{x}'-\mathbf{b}');x_A]\Big\}$$

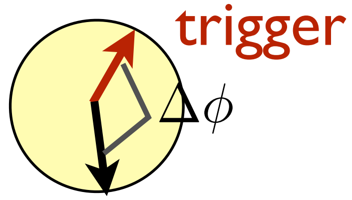
Scattering of the 2-parton system with the CGC target

$$z = \frac{|k_\perp|e^{y_k}}{|k_\perp|e^{y_k} + |q_\perp|e^{y_q}}$$

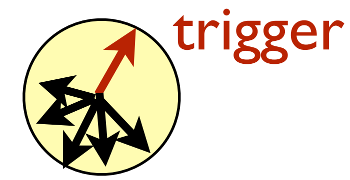
Involves more than 3 and 4 point functions. Calculated in the large Nc limit

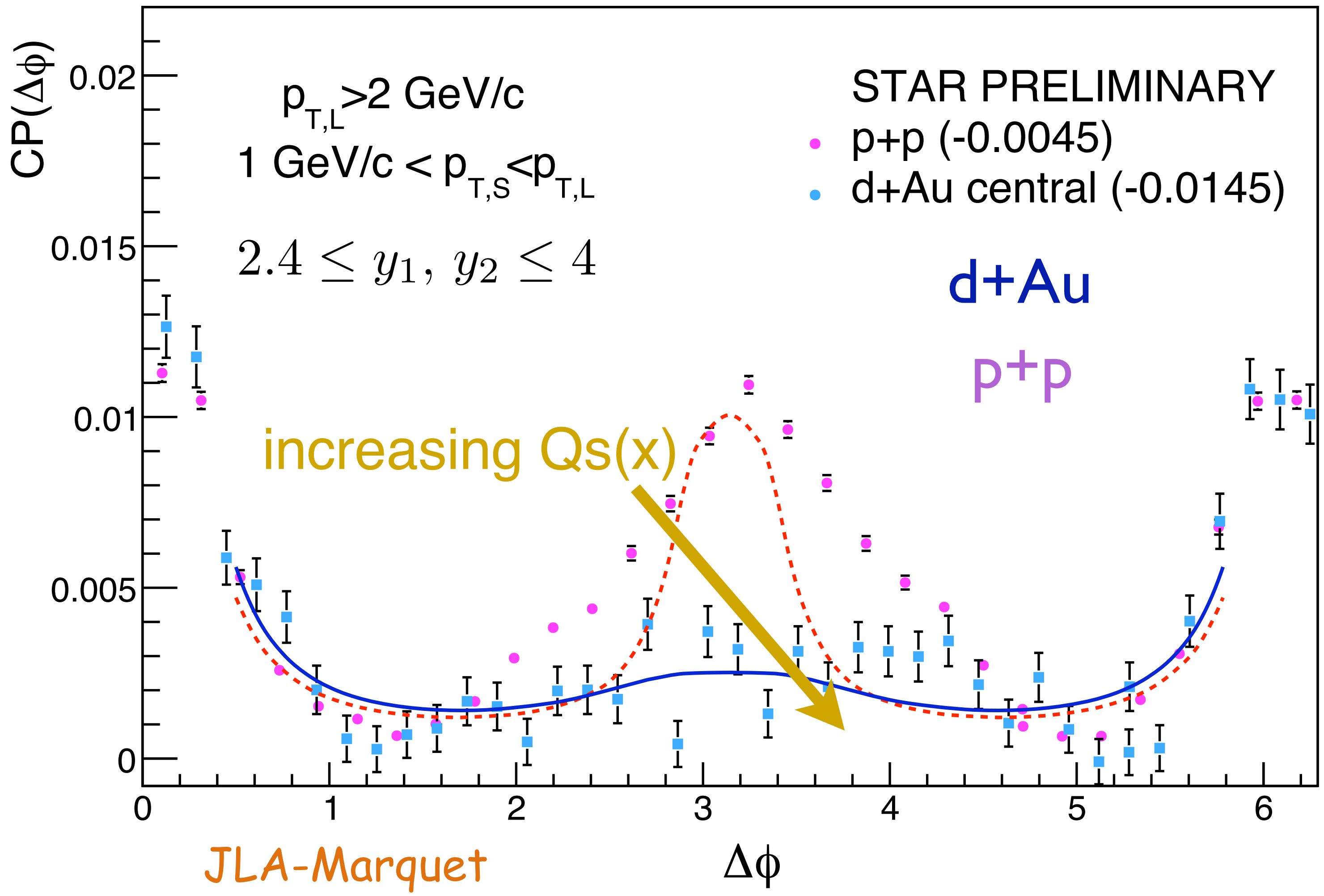
suppression of forward di-hadron correlations in d-Au collisions:

Presence of “monojets” well explained qualitative and quantitatively by the presence of a dynamical, semi-hard saturation scale:



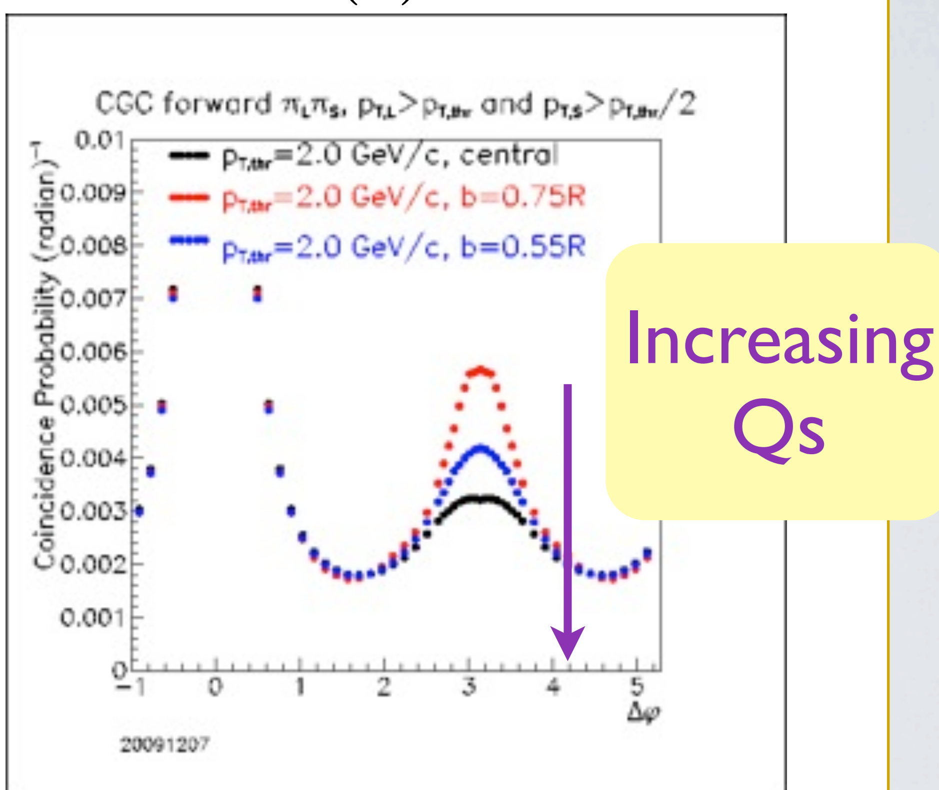
$$CP(\Delta\phi) = \frac{1}{N_{trig}} \frac{dN_{pair}}{d\Delta\phi}$$





Decorrelation happens if

$$p_{t1(2)} \lesssim Q_s$$



Knowledge of 4 and 6 point correlators needed (i.e solving JIMWLK): Dumitru et al (numerically) Iancu -Triantafyllopoulos (analytically)

Inclusion of gluon channel recently carried out by Stasto et al.

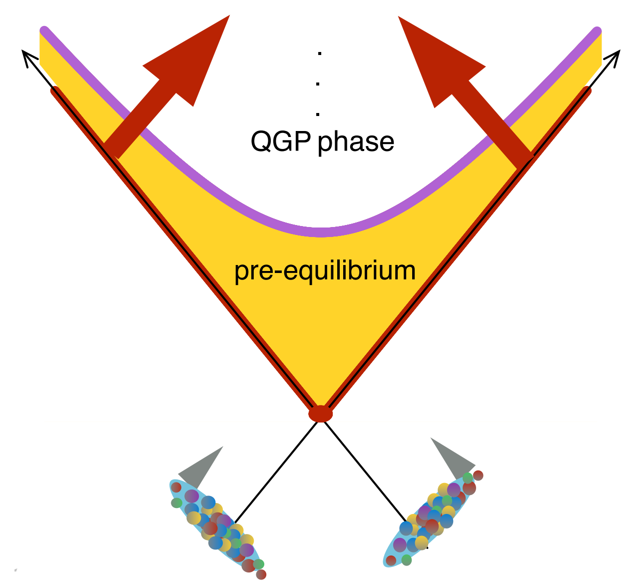
Dominance of double parton interactions ruled out by neutron-tagged measurements by STAR

Initial gluon production in heavy ion collisions

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

- kt-factorization (BK evolution)

$$\frac{dN^g}{d\eta d^2b} \propto Q_s^2(x,b) \sim \sqrt{s}^\lambda N_{part}$$



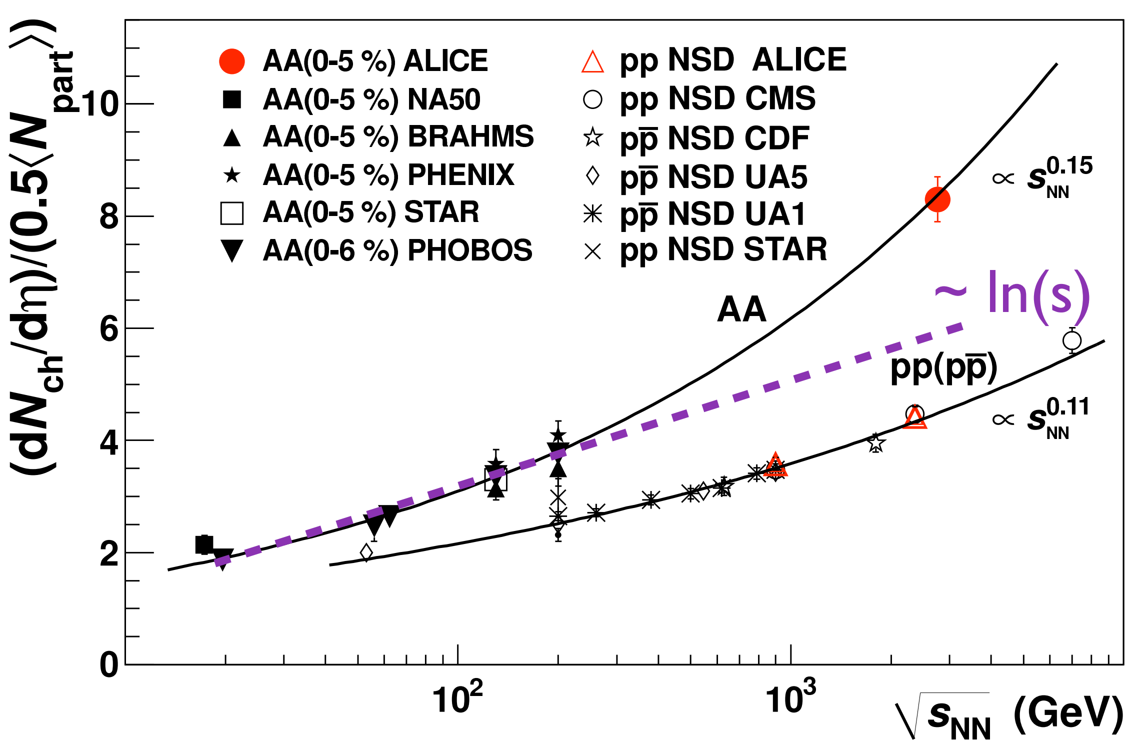
$$\left.\frac{dN^{ch}}{d\eta}\right|_{\eta=0} = \frac{2}{3} K \left.\frac{dN^g}{d\eta}\right|_{\eta=0}$$

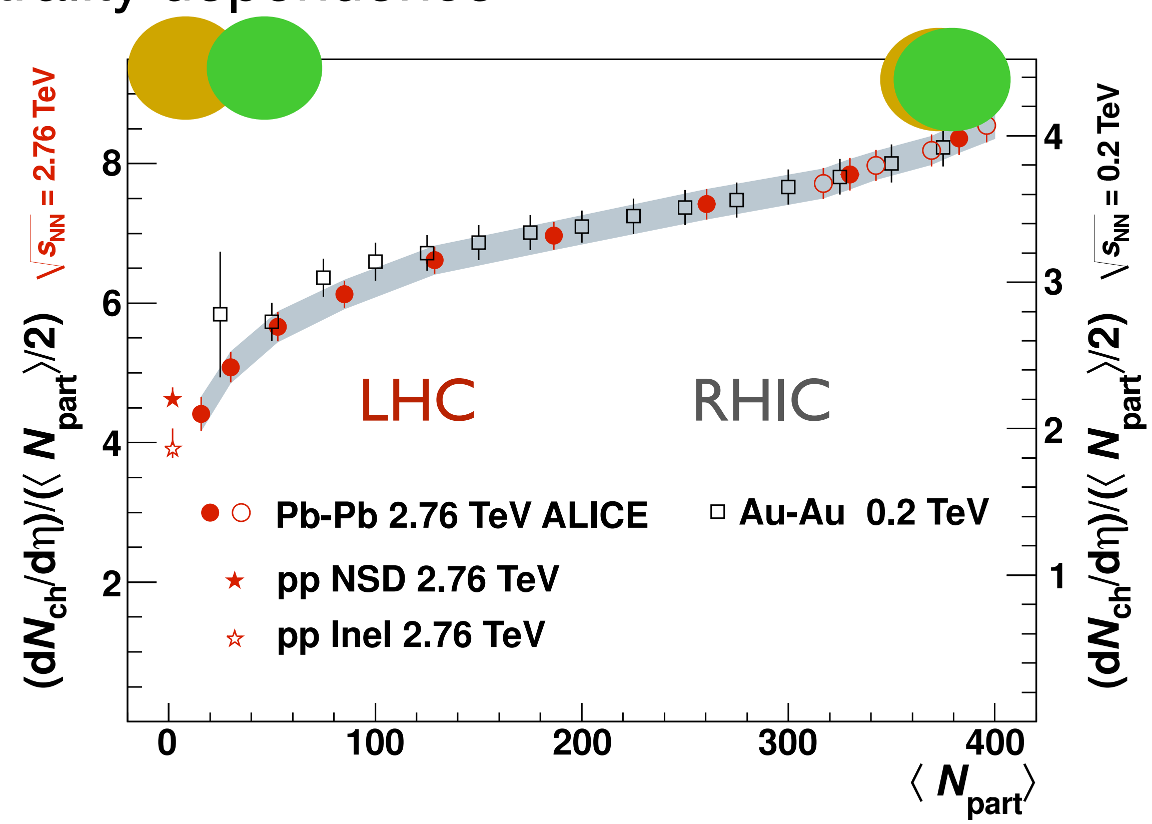
- Gluon to hadron conversion
- Quark contribution
- jet fragmentation
- k-factor for higher order corrections
- Truly soft contribution
- ...

DATA:

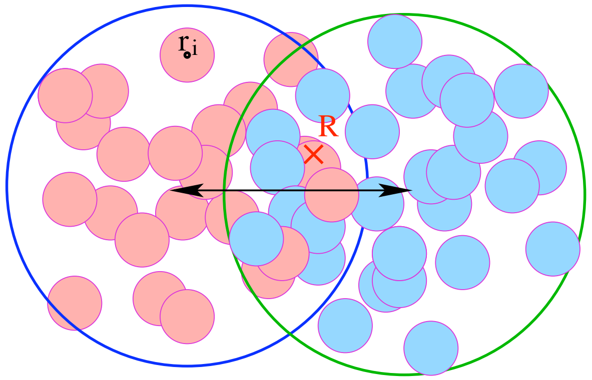
- Strong coherence effects: $\frac{dN^{AA}}{d\eta} \ll N_{coll}\frac{dN^{pp}}{d\eta}$

- Approximate factorization of energy and centrality dependence





CGC Monte Carlo: MC-KLN and rcBK

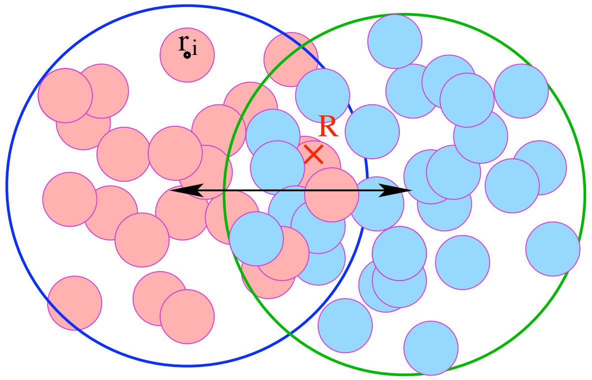


- kt-factorization + running coupling BK evolution [JLA-Dumitru-Nara]

$$\frac{d\sigma^{A+B\to g}}{dy\,d^2p_t\,d^2R} = \kappa\,\frac{2}{C_F}\frac{1}{p_t^2}\int^{p_t}\frac{d^2k_t}{4}\int d^2b\,\alpha_s(Q)\,\varphi(\frac{|p_t+k_t|}{2},x_1;b)\,\varphi(\frac{|p_t-k_t|}{2},x_2;R-b)$$

$$\frac{dN^{A+B\to g}}{dy\,d^2p_t\,d^2R} = \frac{1}{\sigma_s}\frac{d\sigma^{A+B\to g}}{dy\,d^2p_t\,d^2R}$$

LHC data and rcBK CGC Monte Carlo



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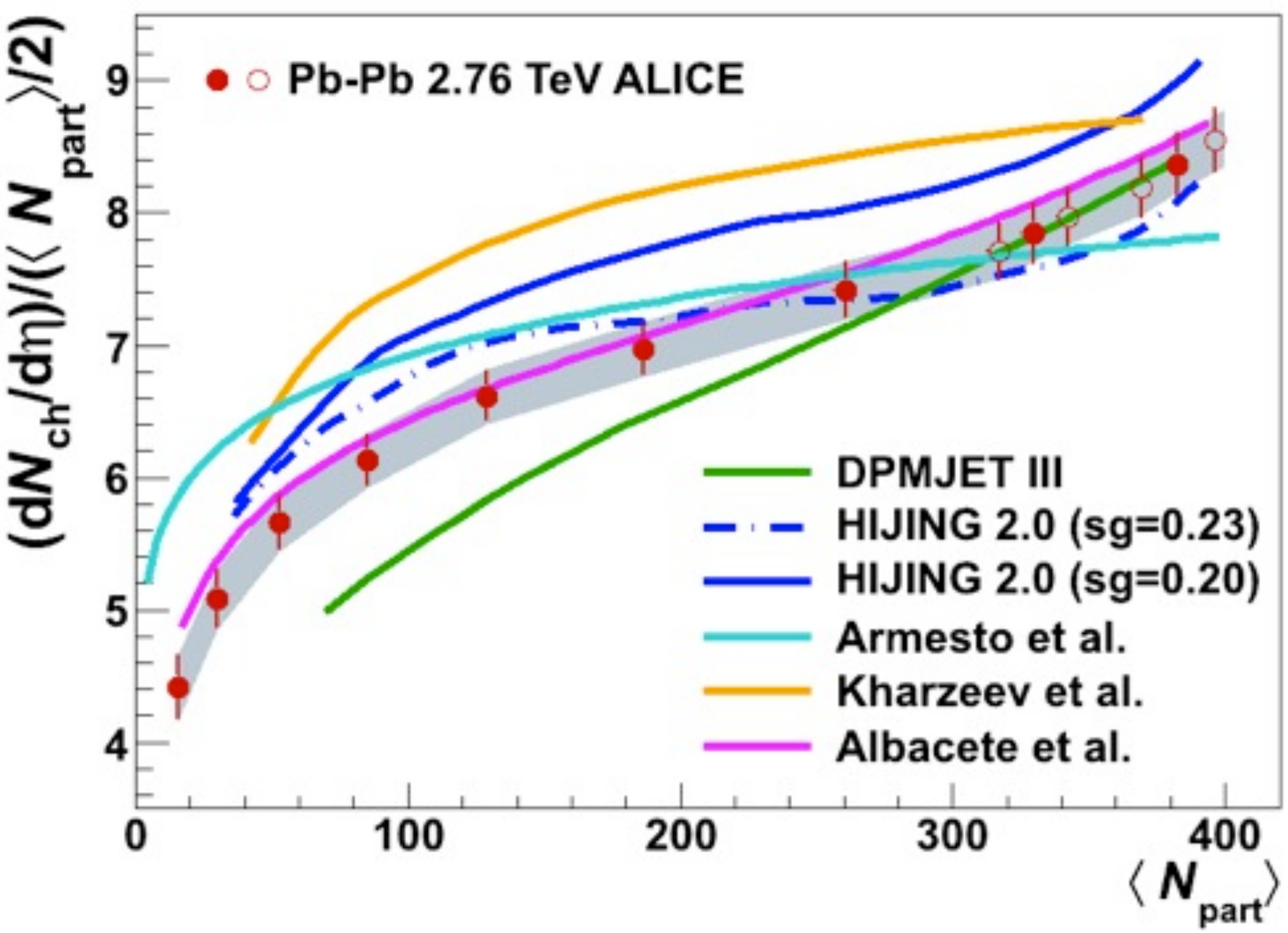
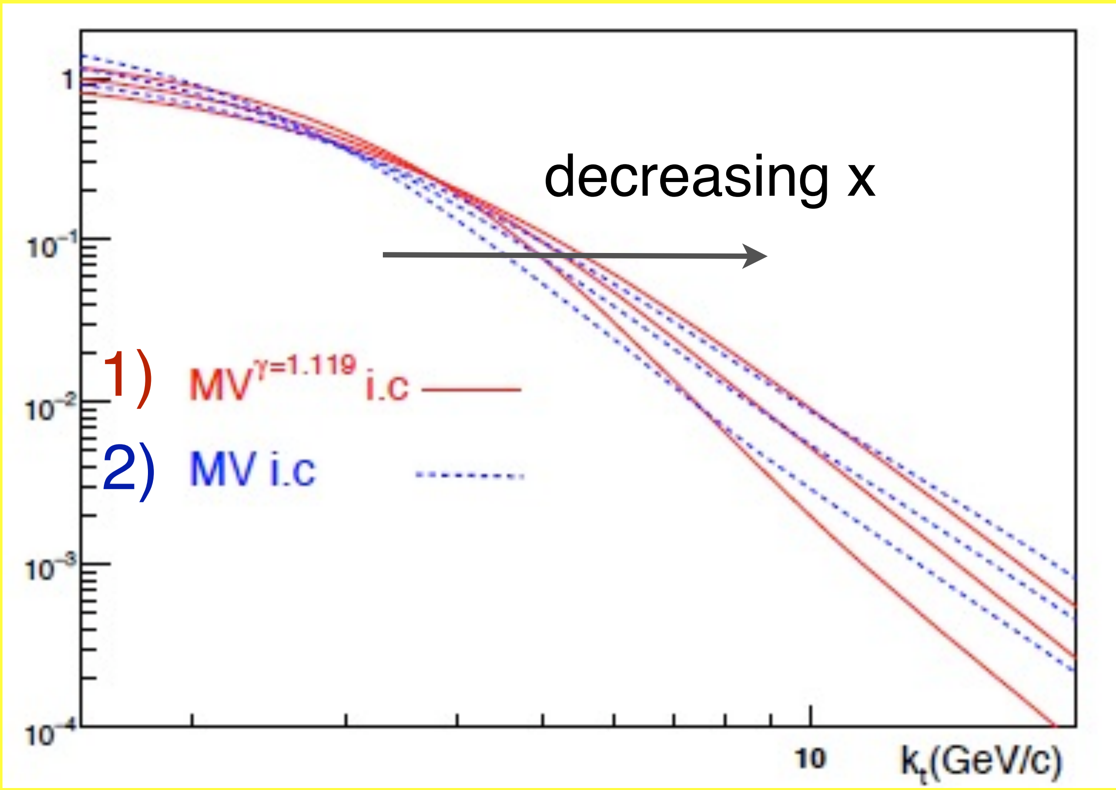


NOTE: rcBK Monte Carlo is built as an upgrade of MC-KLN, by Drescher and Nara

Sensitivity of MC-CGC models for the initial state of HIC to high-kt uncertainties

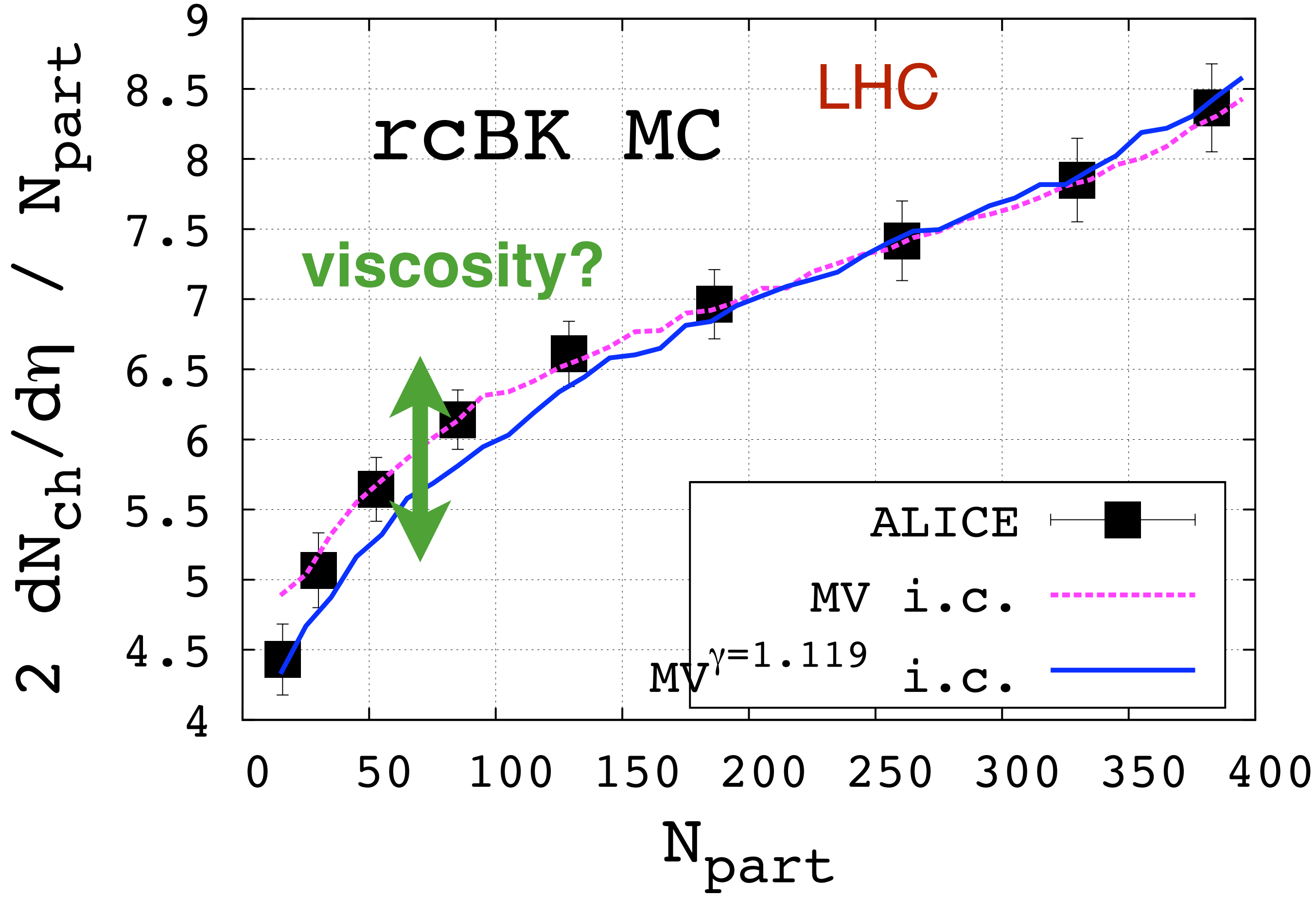
Reminder: e+p, d+Au and Pb+Pb (multiplicities) data are compatible with u.g.d with rather different high-kt behavior:



Sensitivity of MC-CGC models for the initial state of HIC to high-kt uncertainties

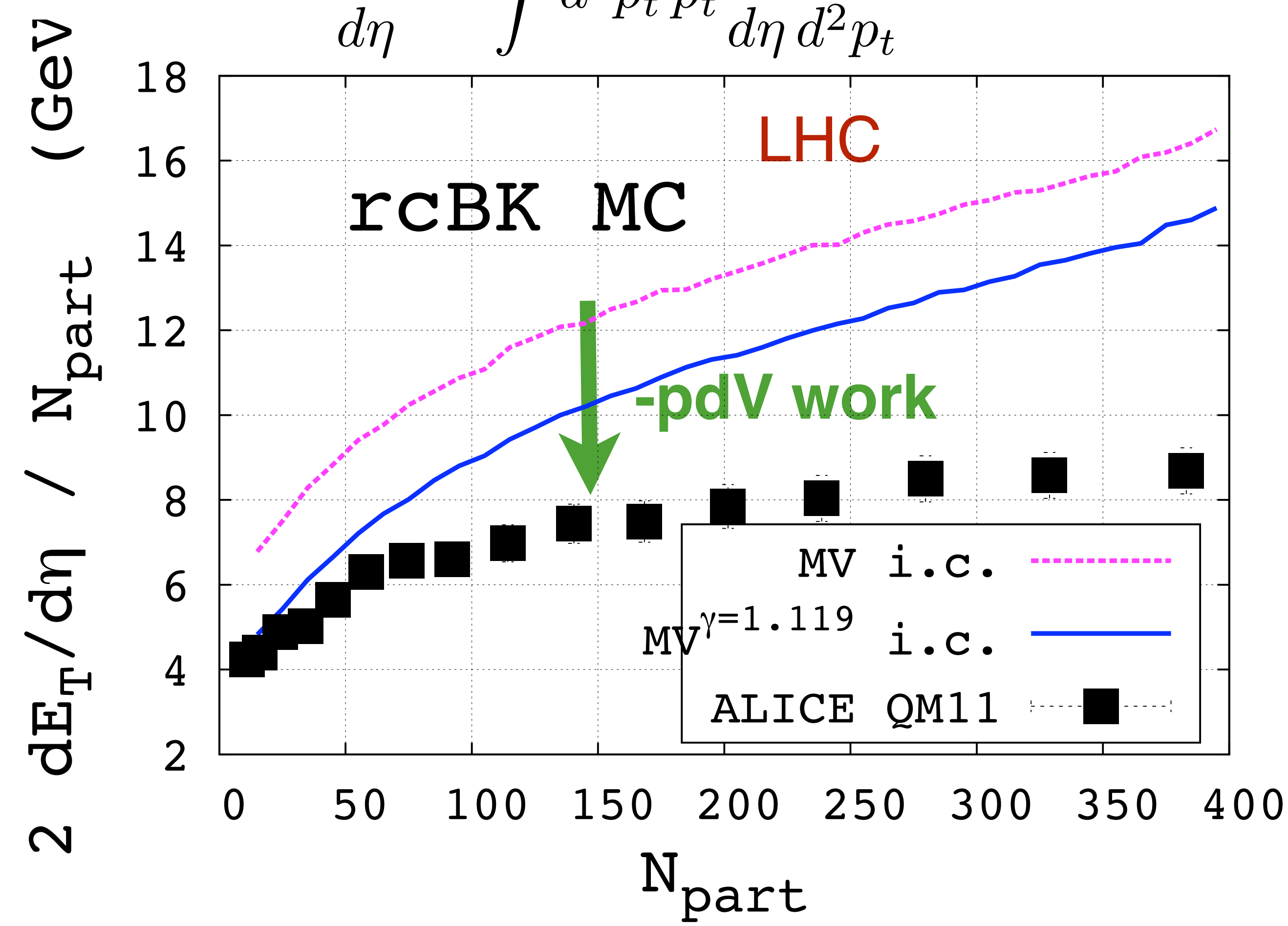
~ 10% effect on multiplicity distributions

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



Larger (x2) effect on transverse energy distributions!

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

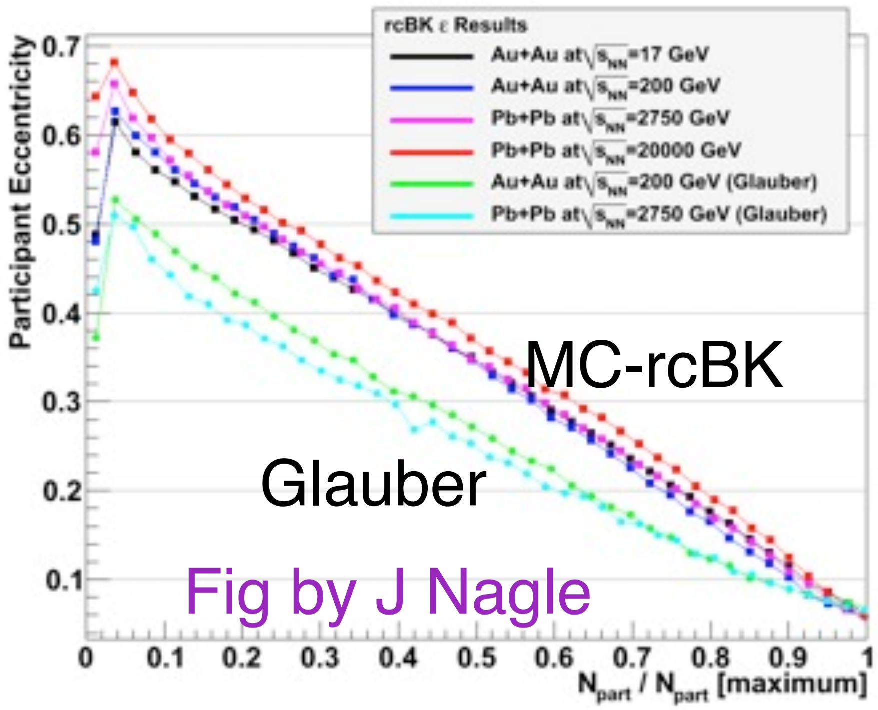


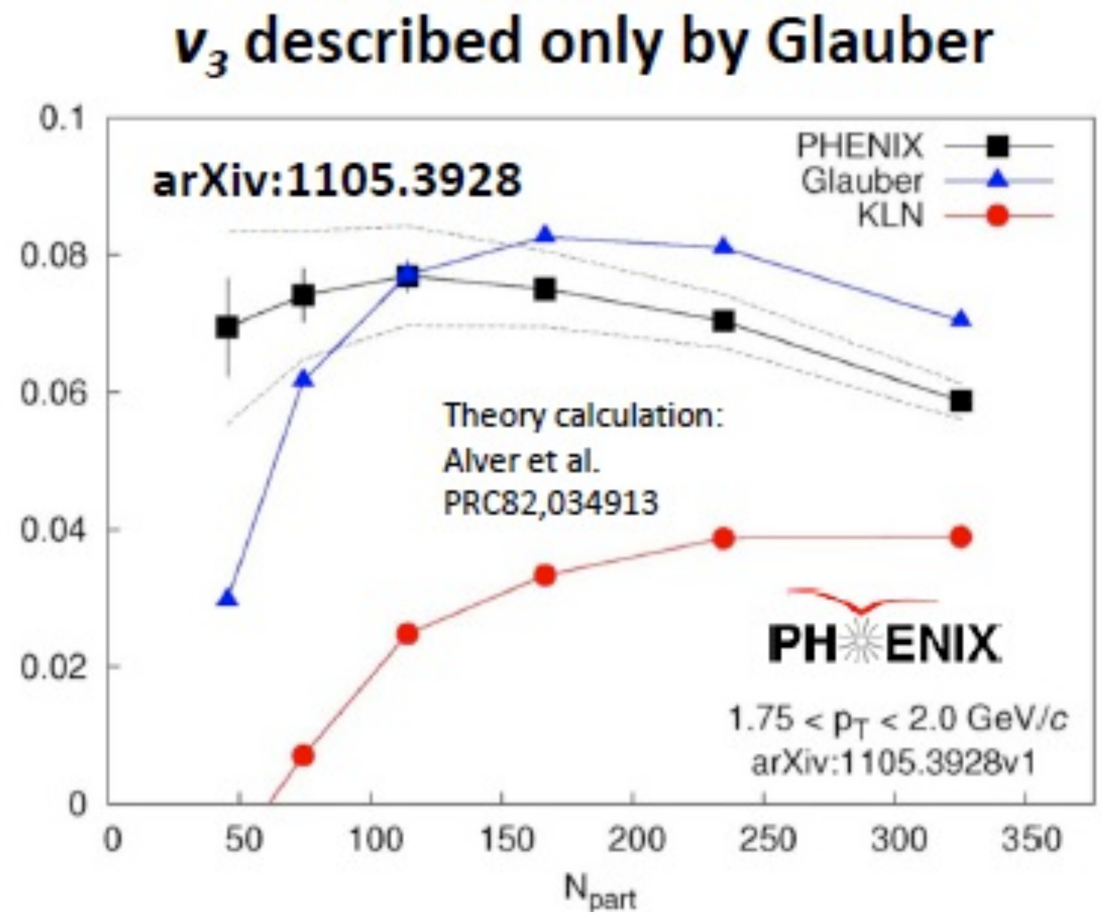
These uncertainties translate to the extraction of transport coefficients (shear viscosity...) when these model are used as i.c. for hydro evolution

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”





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...

Conclusions / Outlook

- ✔ 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!

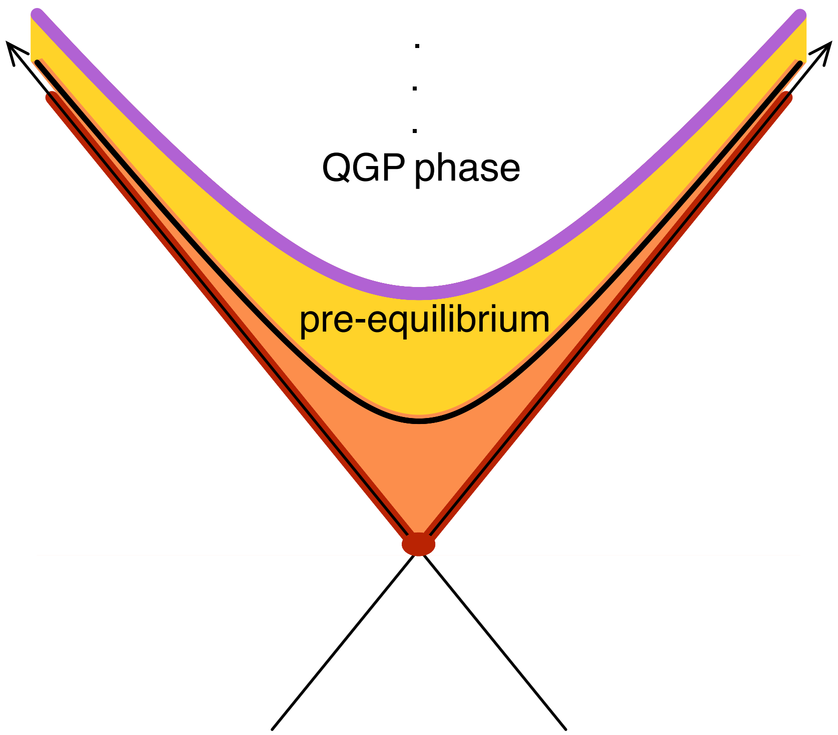
- ✔ First HI LHC data on multiplicities compatible with CGC models

- ✔ 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!!

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]

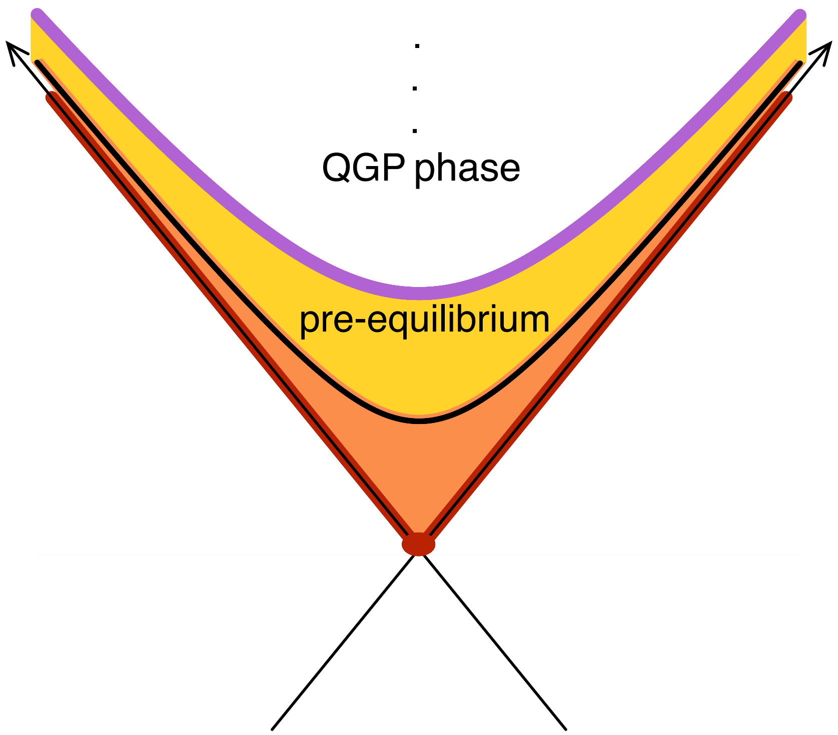
Strong coupling? AdS/CFT studies suggest a rapid thermalization

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

The thermalization conundrum



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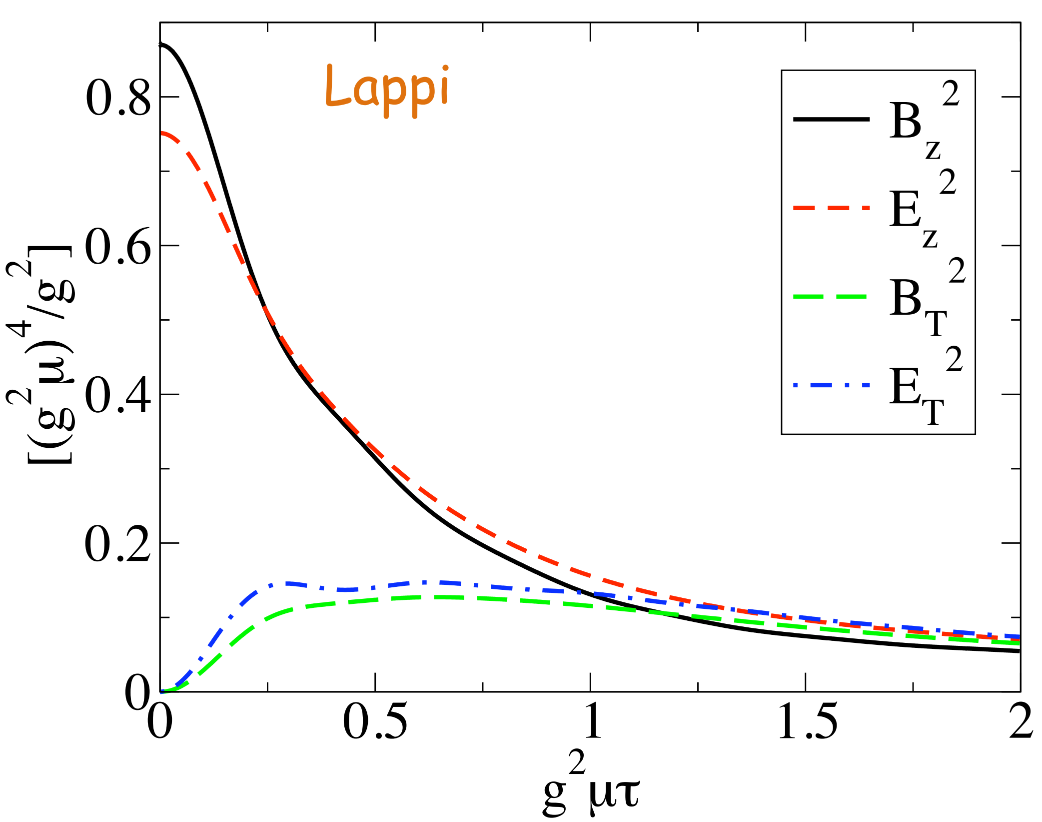
CGC at very early times

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

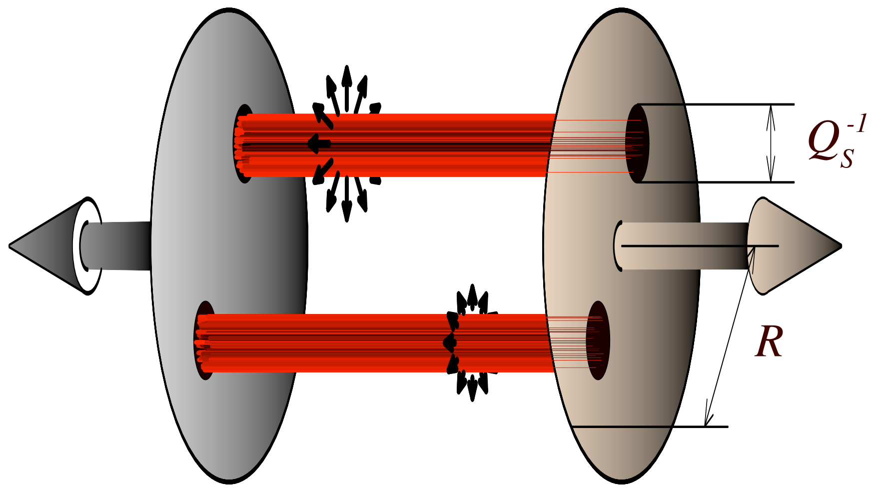


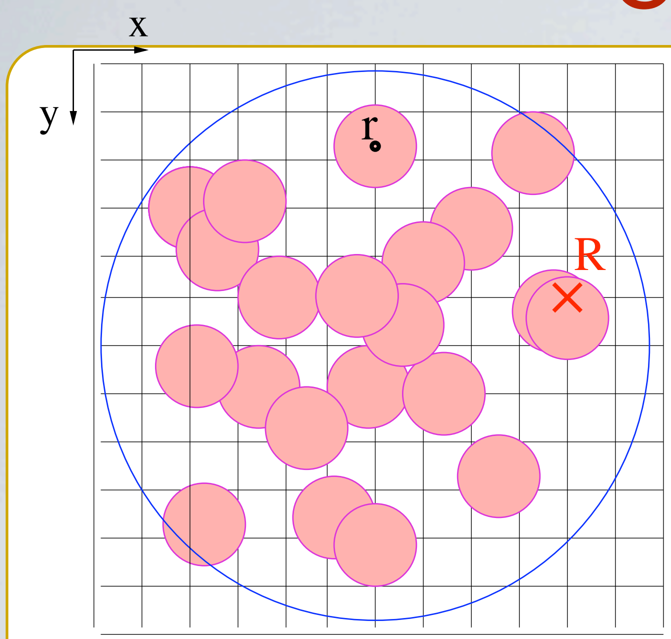
Fig by F Gelis

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

CGC Monte Carlo: MC-KLN and rcBK



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

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

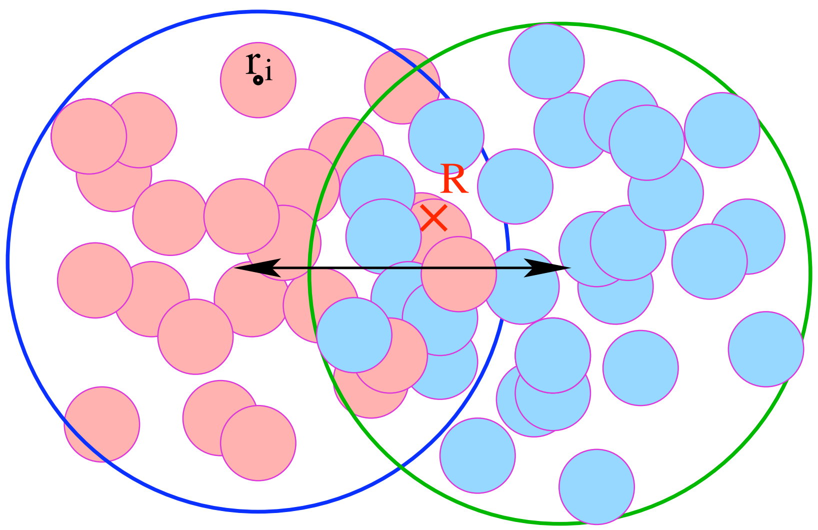
$$\downarrow$$

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

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

rcBK equation or KLN model

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



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