Status and future prospects of saturation in proton-nucleus collisions

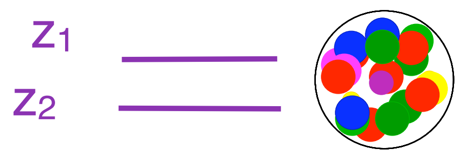
Javier L Albacete

IPN Orsay

Prospects of p-Pb collisions during the 2012 LHC HI run
CERN, October 17th 2011

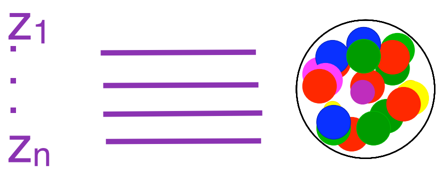
The Color Glass Condensate: Phenomenology tools

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

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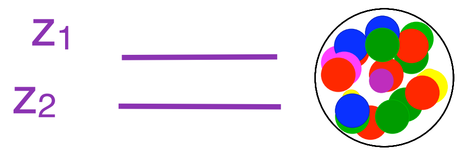

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2 SMALL-X EVOLUTION: Non-linear quantum BK-JIMWLK evolution equations: Predictive power is here!!!

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

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.

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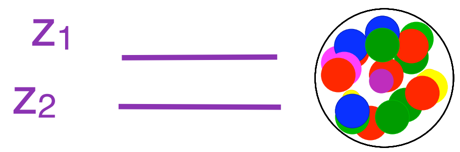

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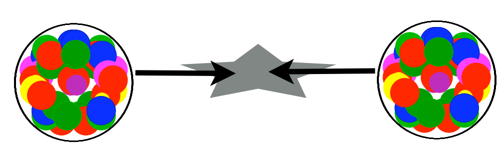
3 PARTICLE PRODUCTION:



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

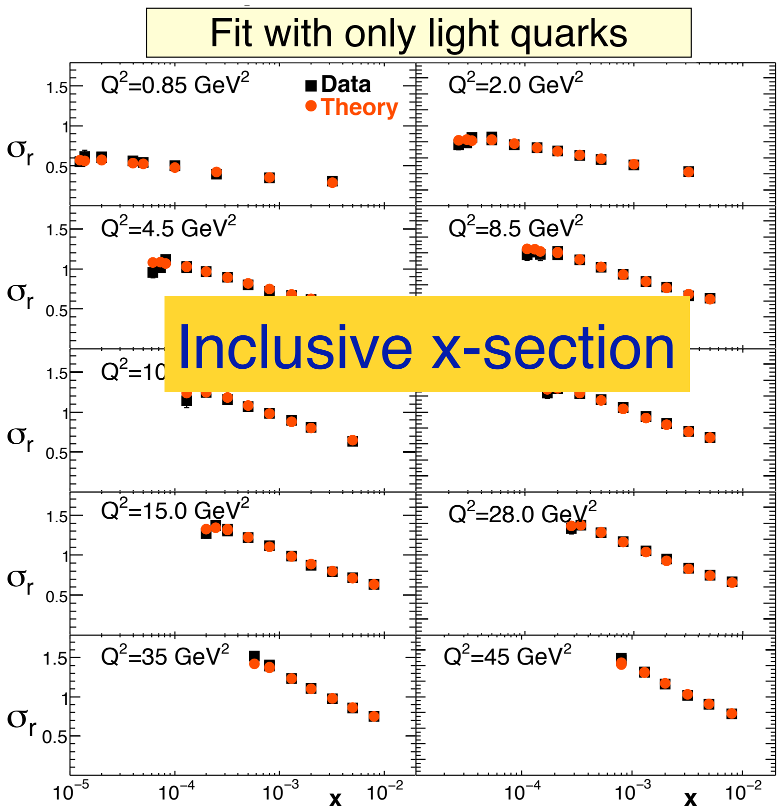
Factorization theorems only hold for certain, very inclusive observables
Most processes calculated only to LO accuracy

e+p data: proton as a building block for nuclei

[AAMQS, Kuokkanen, Rummukainen Weigert; Berger Stasto]

Succesful $(\chi^2/\mathrm{dof}\sim 1)$ global fits based on rcBK evolution

running coupling: $\mathbf{K^{run}}$



initial conditions

preasymptotic

$$\mathcal{N}(r,x_0) = 1 - \exp\left[-\frac{(r^2 Q_0^2)^\gamma}{4} \ln\left(\frac{1}{r\Lambda}\right)\right]$$

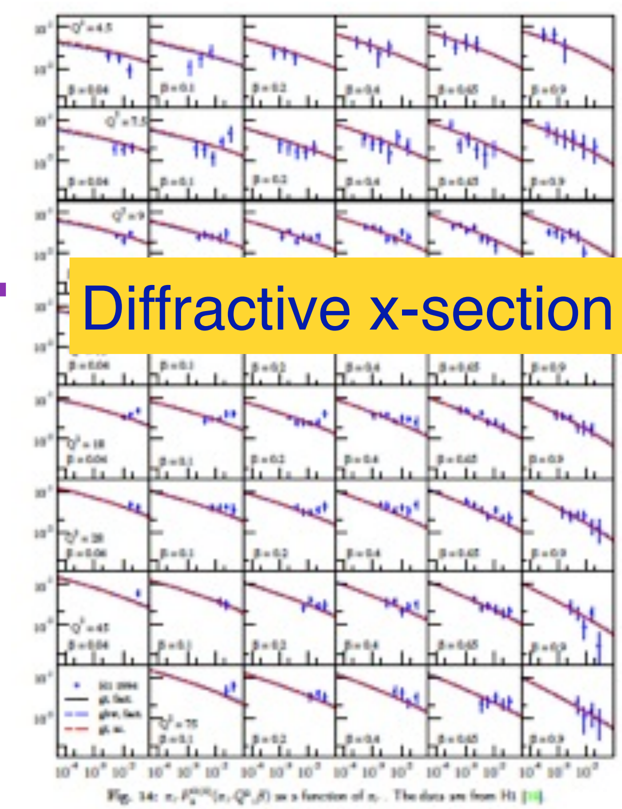
scaling

$$\mathcal{N}^{scal}(\tau_0 = r Q_{s0})$$

Fits stable for

$$[x < 10^{-2}, Q^2 < 50\,\mathrm{GeV}^2]$$

running coupling+ energy conservation: $\mathbf{K^{run}}\left(\mathbf{1} - \frac{\mathbf{d}}{\mathbf{dY}}\right)$



Relatively simple system, better understood theoretically. Abundant quality data down to $x\sim 10^{-6}$

ALL heavy ion phenomenological works use input from e+p

e+p data: proton as a building block for nuclei

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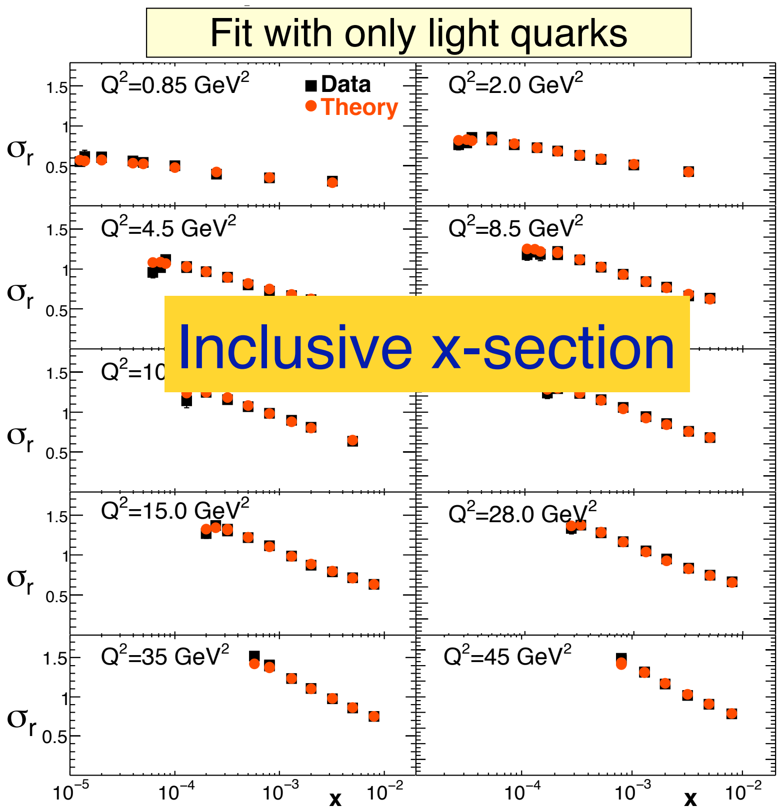

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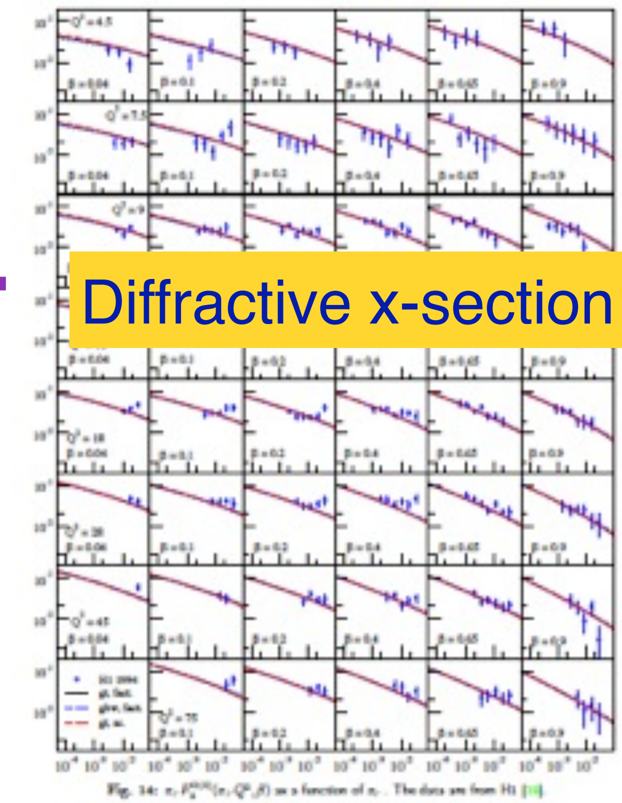


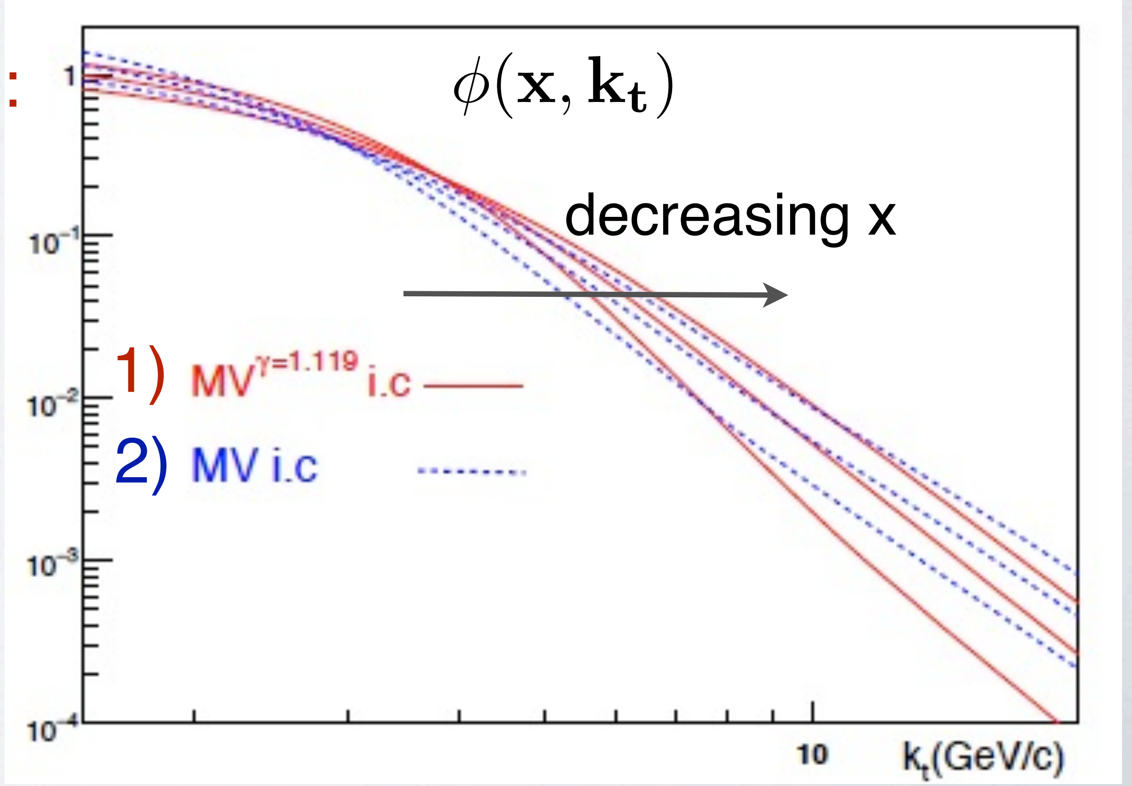
✕ Poor determination of the high-kt behavior of ugd's:

Differences persist in the relevant x-range for LHC predictions

$$\phi(\mathbf{x_0}, \mathbf{k_t} \gg \mathbf{Q_s}) \sim \frac{\mathbf{1}}{\mathbf{k_t^{2\gamma}}}, \quad \gamma \sim \mathbf{0.85 \div 1.28}$$

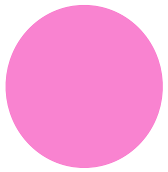
✕ Correlation between dynamical input and high-kt behavior (scaling vs pre-asymptotic fits)

✕ Fits with b-dependence: high sensitivity to gluon mass

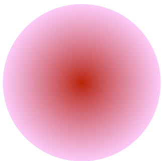


How to deal with b-dependence? Building nuclei from nucleons:

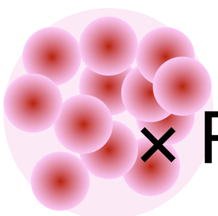
$$\phi^{\mathbf{A}}(\mathbf{x}, \mathbf{k_t}, \mathbf{B}) = \phi^{\mathbf{p}}(\mathbf{x}, \mathbf{k_t}, \mathbf{Q^2_{sp}} \to \mathbf{Q^2_{sA}}(\mathbf{B}))$$



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



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



× R

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

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

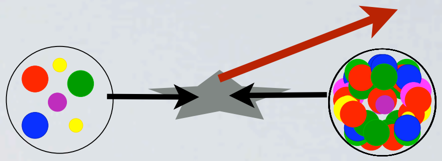
$$\varphi(x, k_t, R)$$

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?

Single Inclusive forward hadron production



$(p_t, y_h >> 0)$

pdf (proj) — CGC 2-point function — fragmentation

$$\frac{dN^{pA\to hX}}{d^2p_T d\eta} = \frac{K}{(2\pi)^2}\left[\int_{x_F}^{1}\frac{dz}{z^2}\left[x_1 f_g(x_1,Q^2) N_A(x_2,\frac{p_T}{z}) D_{h/g}(z,Q) + \Sigma_q x_1 f_q(x_1,Q^2) N_F(x_2,\frac{p_T}{z}) D_{h/q}(z,Q)\right]\right.$$
$$\left. + \int_{x_F}^{1}\frac{dz}{z^2}\frac{\alpha_s}{2\pi^2}\frac{z^4}{p_T^4}\int_{k_T^2<Q^2} d^2k_T k_T^2 N_F(k_T,x_2)\int_{x_1}^{1}\frac{d\xi}{\xi}\Sigma_{i,j=q,\bar{q},g} w_{i/j}(\xi) P_{i/j}(\xi) x_1 f_j(\frac{x_1}{\xi},Q) D_{h/i}(z,Q)\right]$$

Dumitru Jalilian-Marian; Kovner-Altinoluk

$$x_{1(2)} \sim \frac{m_t}{\sqrt{s}}\exp(\pm y_h)$$

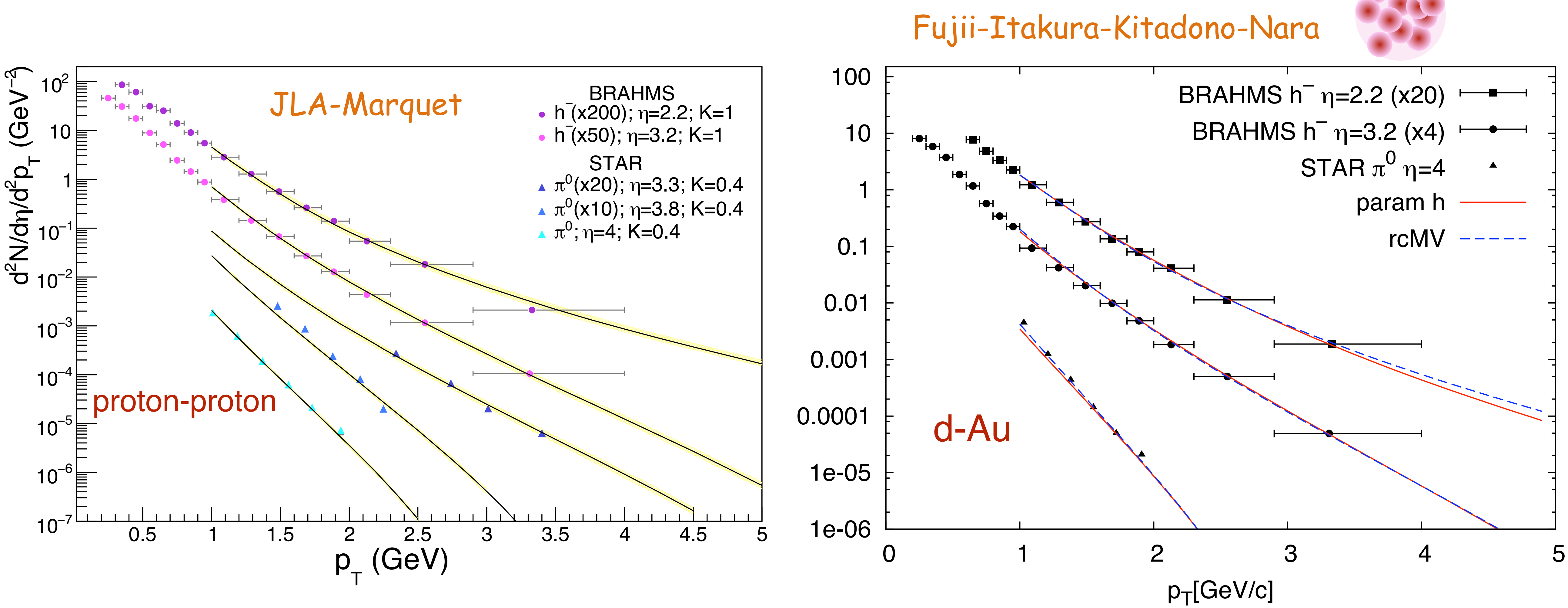
$$\tilde{N}_{F(A)}(x,k) = \int d^2\mathbf{r}\, e^{-i\mathbf{k}\cdot\mathbf{r}}\left[1-\mathcal{N}_{F(A)}(r, Y=\ln(x_0/x))\right]$$

Rapidity dependent K-factors allowed to account for the normalization

Recently calculated subleading in α_s corrections only included by Rezaeian and Jalilian Marian

In order to ensure $x_1 \geq x_0$, $x_2 \leq x_0$ with $x_0 \approx 0.01 \longrightarrow y_h \geq 2$

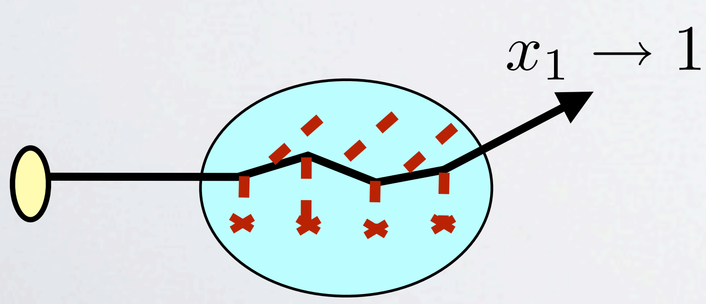
Comparison to RHIC data



RHIC data do not constrain initial conditions for evolution(MV, gamma>1...”everything works”)

Particle production close to the kinematic limit (x->1 in the projectile). K-factors ~ 0.3 for most forward rapidities

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

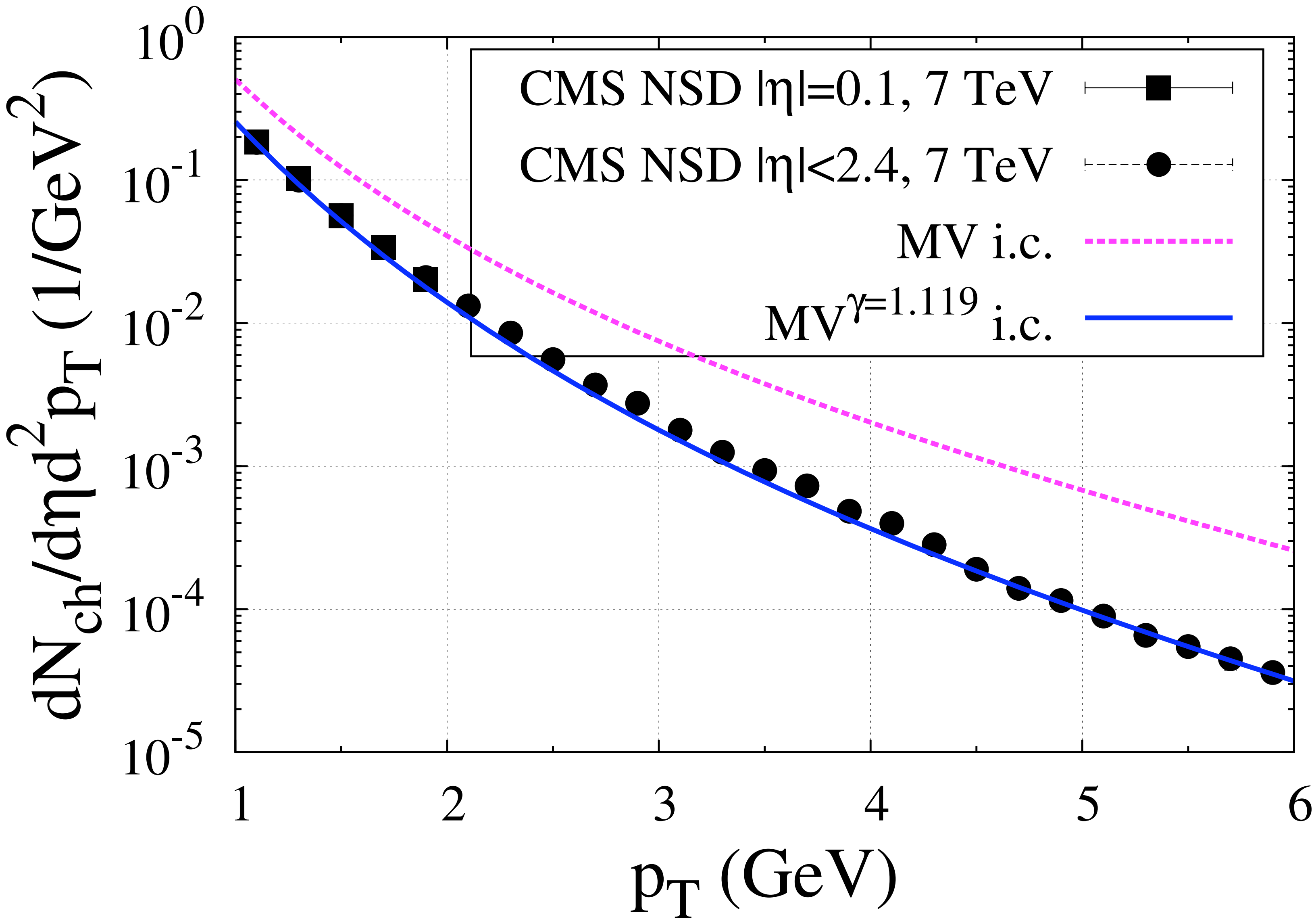


Probability of not losing energy:

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

Kopeliovich et al

Tips from p+p data @ LHC

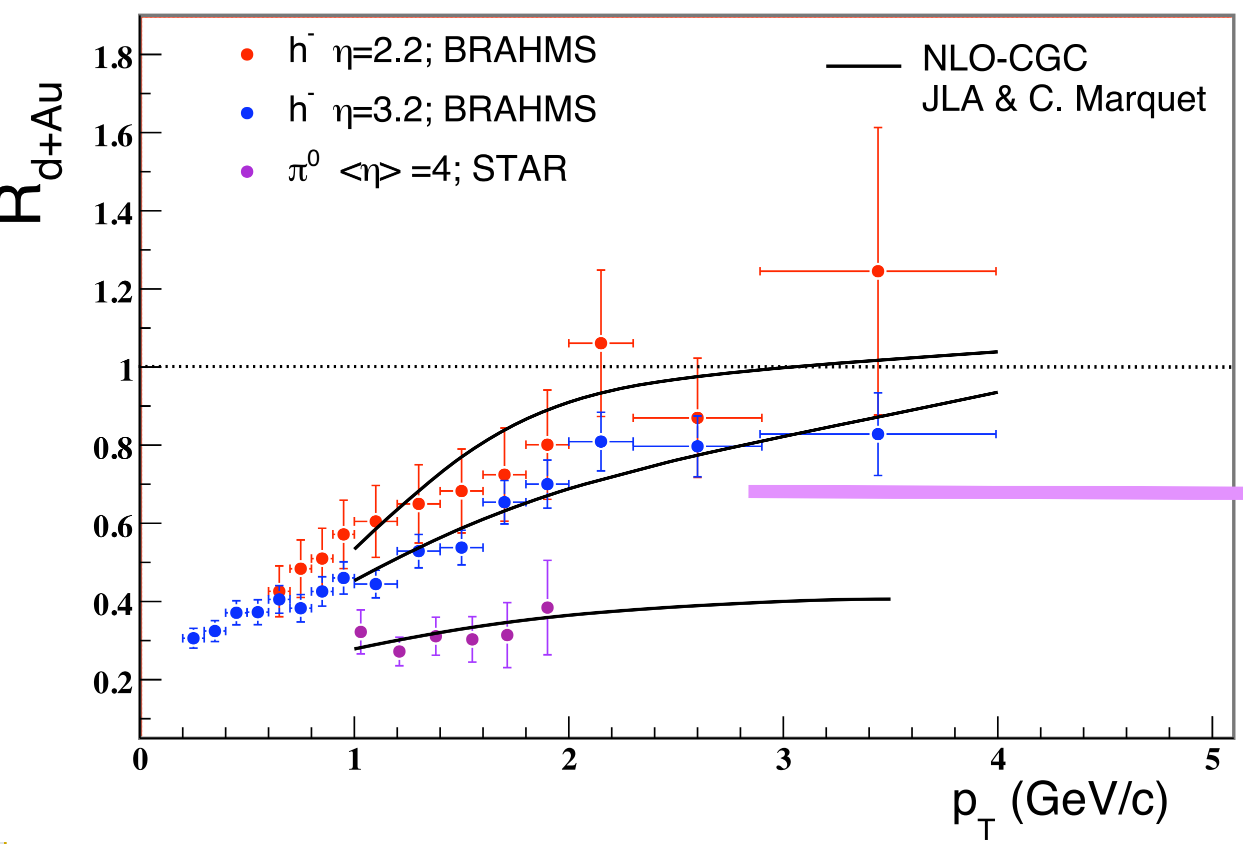


LHC p+p data seem to favor “steeper” initial conditions [2]

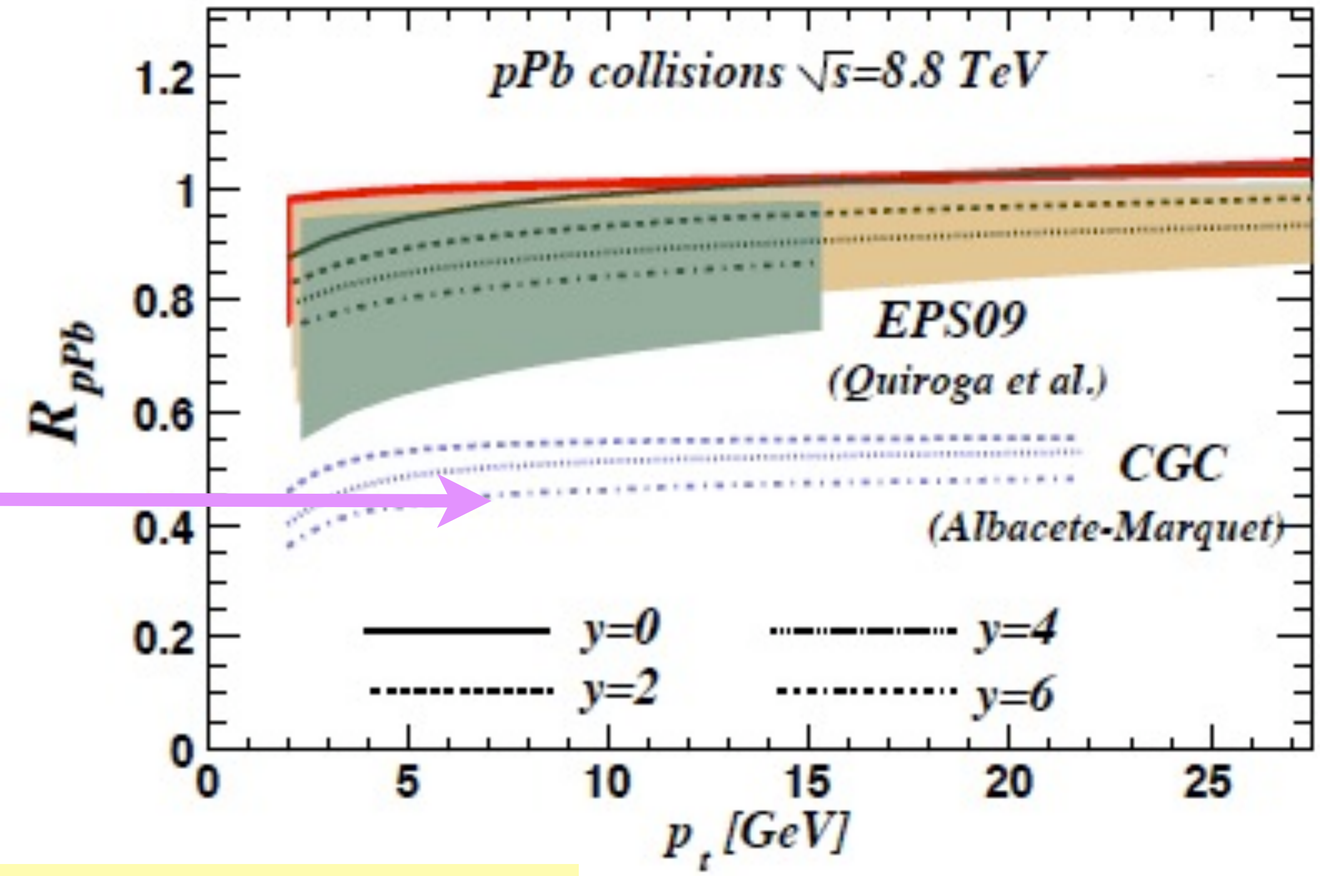
However: calculated using LO kt-factorization

Nuclear modification factors:

RHIC



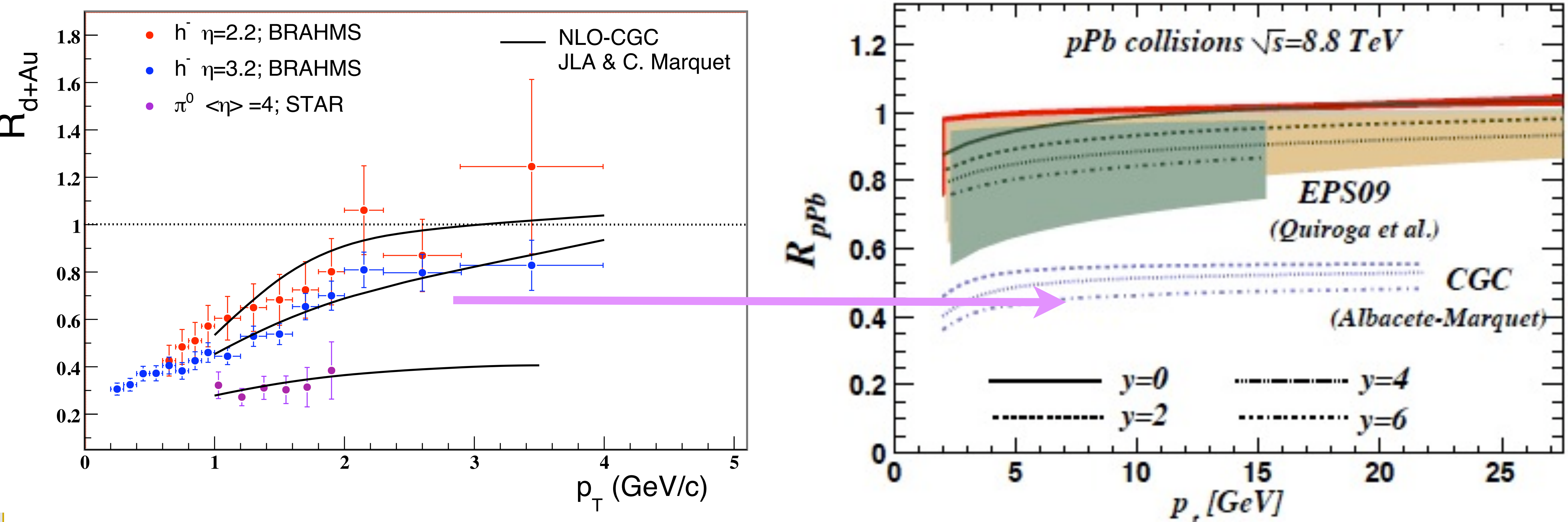
predictions for p+Pb @ LHC



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

Nuclear modification factors:

RHIC | predictions for p+Pb @ LHC



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

Normalization issue:
(lack of knowledge of
b-dependence)!!

$$R_{pA}^{CGC}(k_t >> 1) = \frac{1}{A}\frac{Q_{sA}^2}{Q_{sp}^2}\frac{\int^A d^2b}{\int^p d^2b} \to 1 \quad \text{if} \quad Q_{sA}^2 = A^{1/3}Q_{sp}^2$$

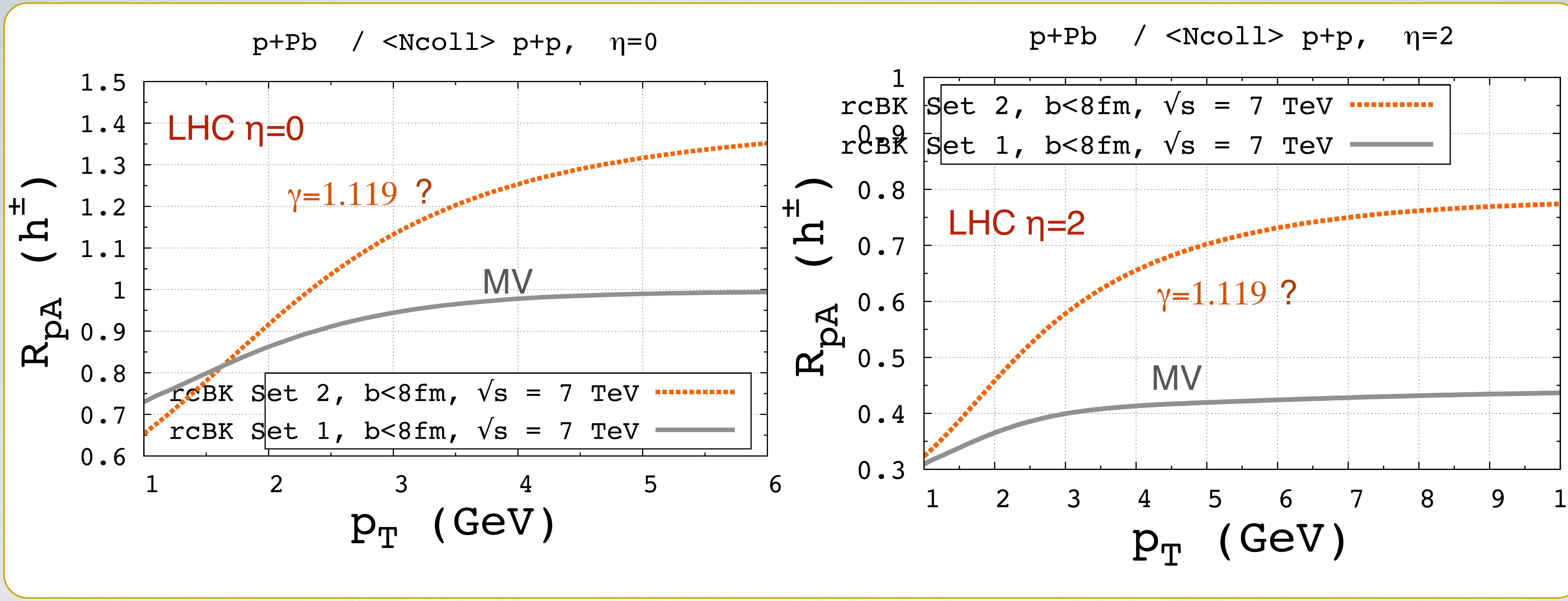
However, in the “trivial”
approach it’s found

$$\frac{Q_{0sA}^2}{Q_{0sp}^2} \sim 1.5 \div 4 < A^{1/3} \sim 6$$

JLA-Marquet
Jalilian Marian - Rezaeian

Problem cured when using Monte Carlo tools for geometry dependence (ensures self consistency)

Nuclear modification factors:



RpPb at y=0 uncertain due to sensitivity to i.c. and lack of information on b-dependence of Qs

Less sensitivity to i.c. at more forward rapidities: CGC predicts "on average"
- Larger suppression at small-pt and y=0 than nPDF approaches do
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A rapidity and centrality scan of yields in pPb collisions needed to discriminate both approaches and to fix the initial conditions for CGC evolution

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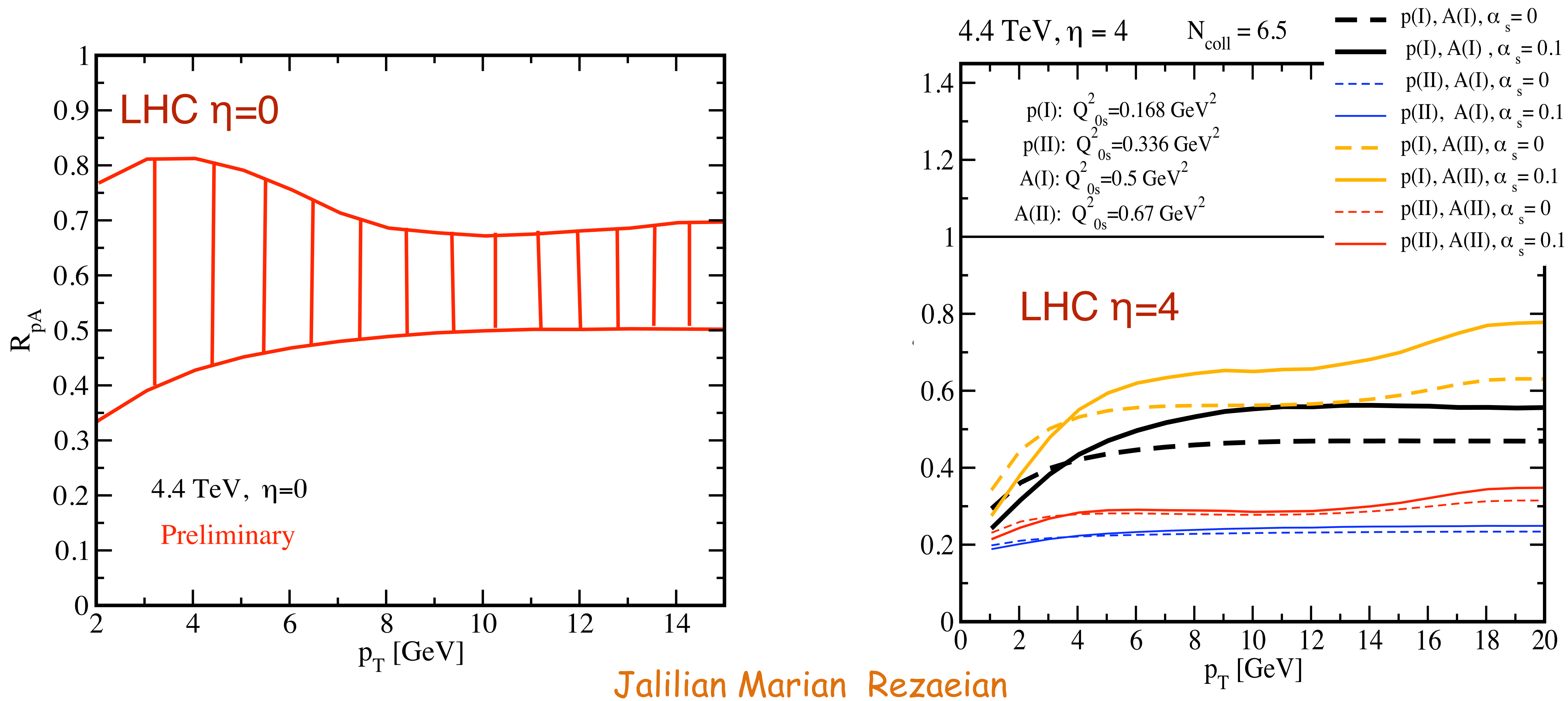

Jalilian Marian Rezaeian

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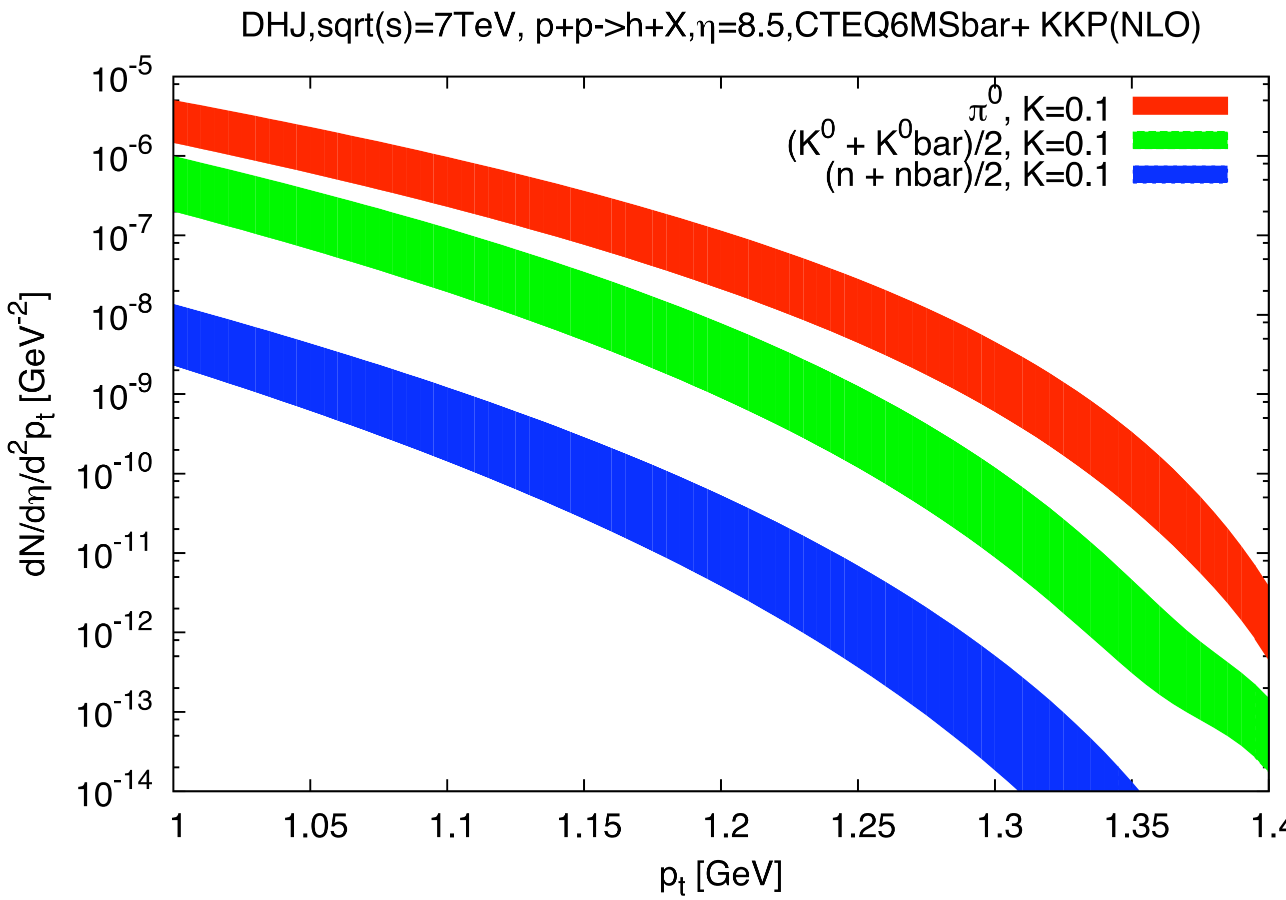
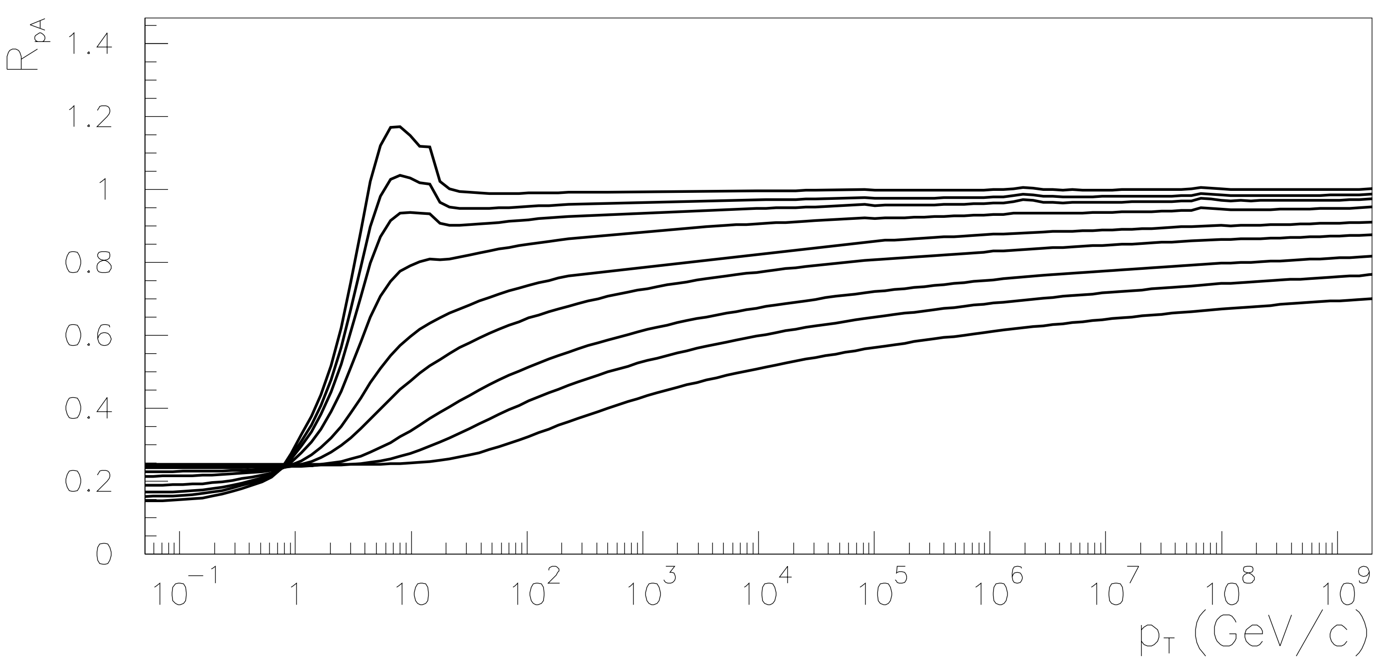
Going forward, towards LHCf

At large rapidities (very small-x) the sensitivity to i.c is reduced (scaling regime)





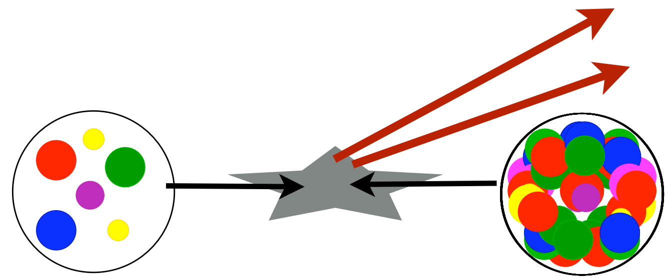
Hadron production (π^0 K^0 and n) at η =8.5 is being studied in this framework

Fujii-Itakura-Nara

RpPb should approach its universal limit at very forward rapidities suppression of forward di-hadron correlations in d-Au collisions:

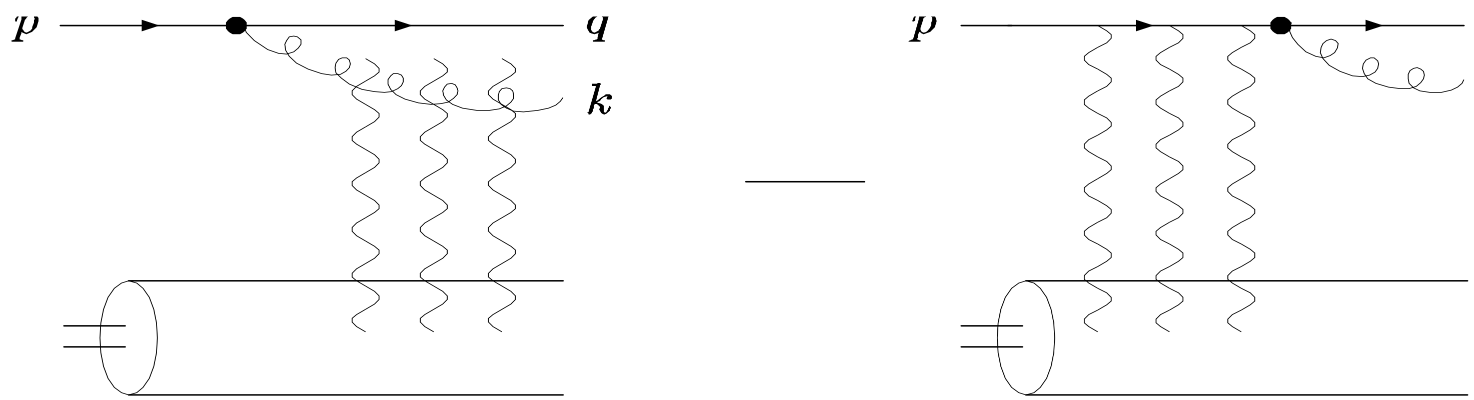
$$x_p = \frac{|k_1|e^{y_1} + |k_2|e^{y_2}}{\sqrt{s}}$$

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



$(k_1, y_1), (k_2, y_2)$

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)

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

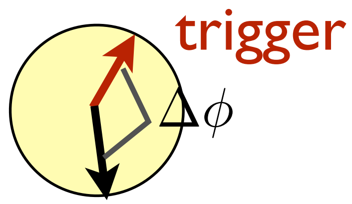
Scattering of the 2-parton system with the CGC target

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

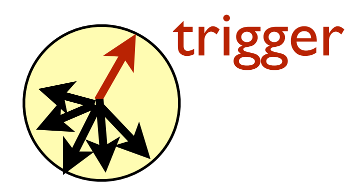
Involves more than 3 and 4 point functions. Calculated in the large Nc limit

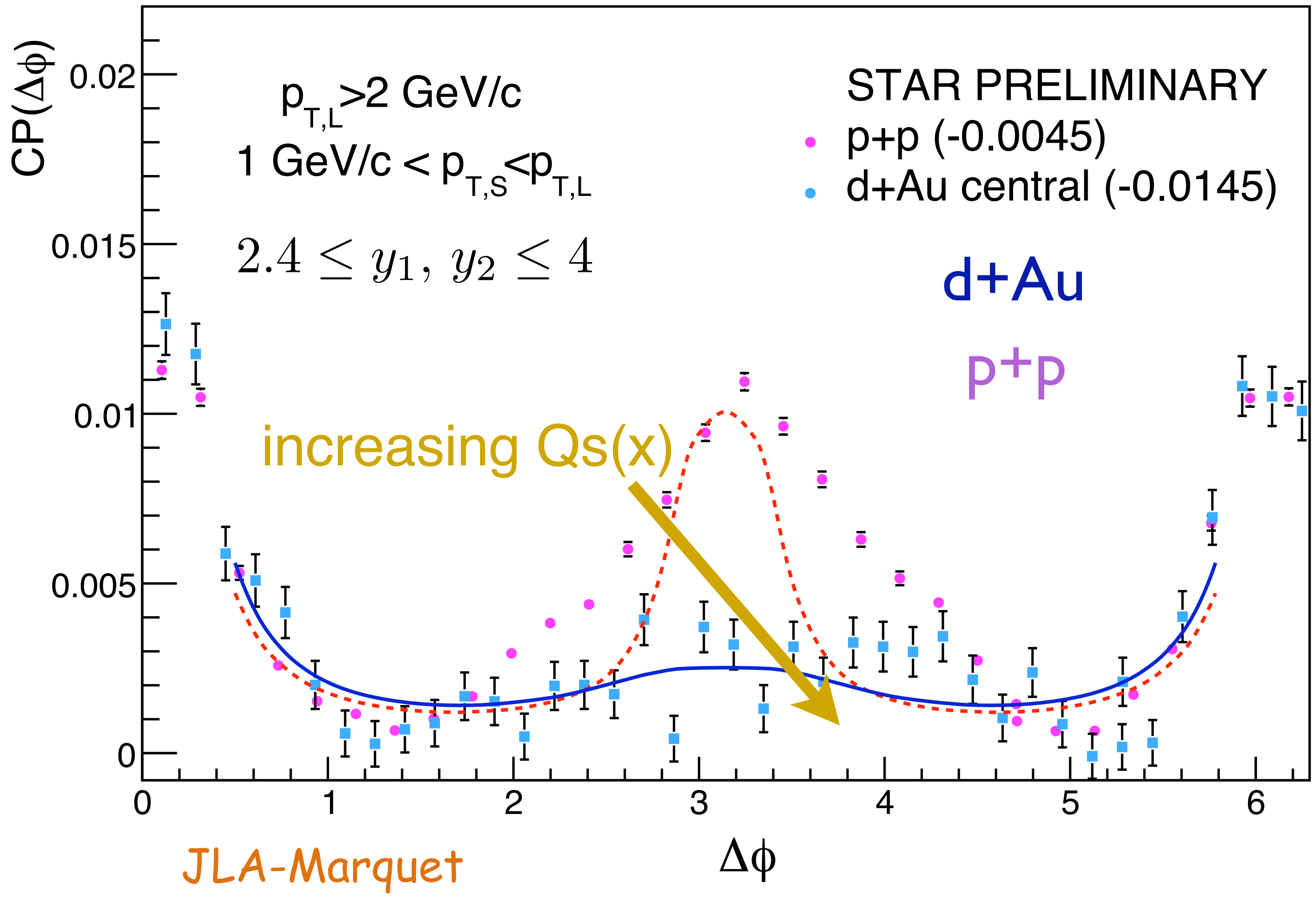
suppression of forward di-hadron correlations in d-Au collisions:

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):

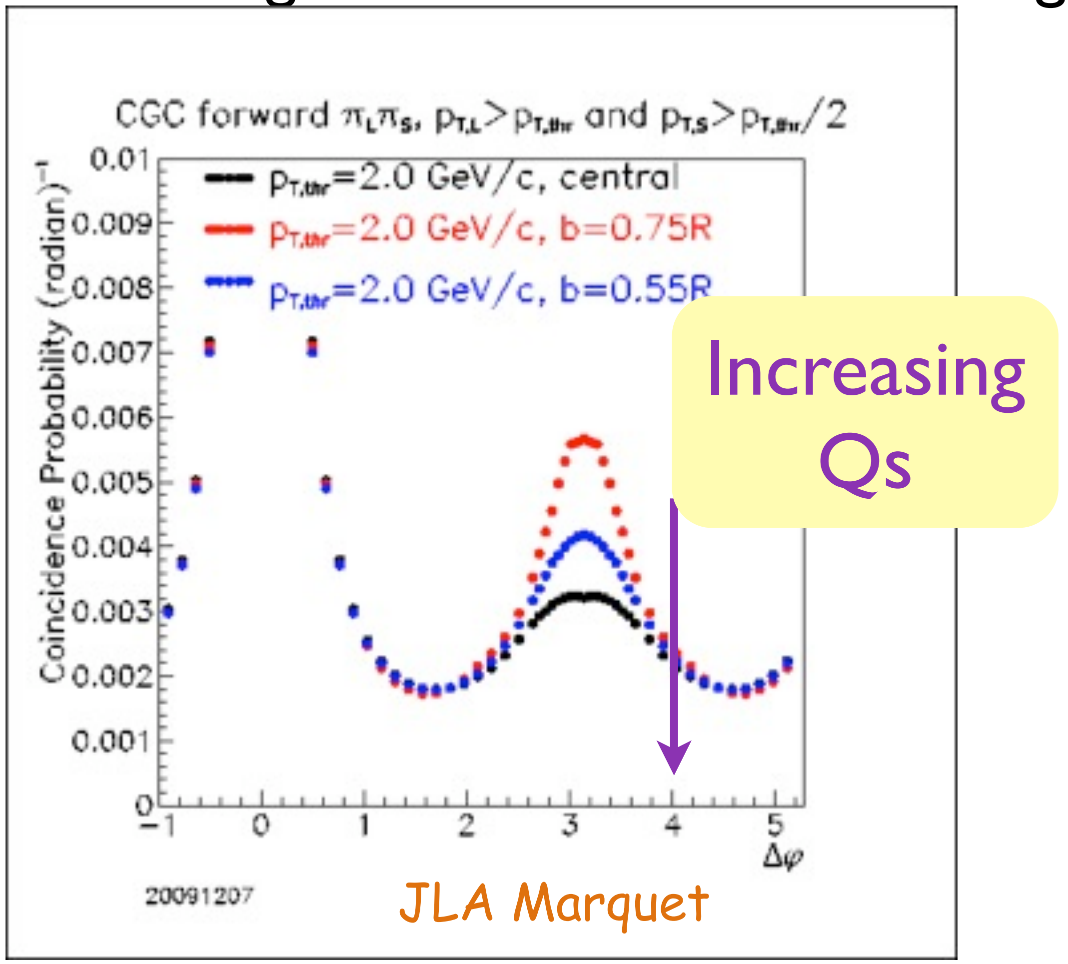
Dumitru et al (numerically)
Iancu -Triantafyllopoulos (analytically)

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

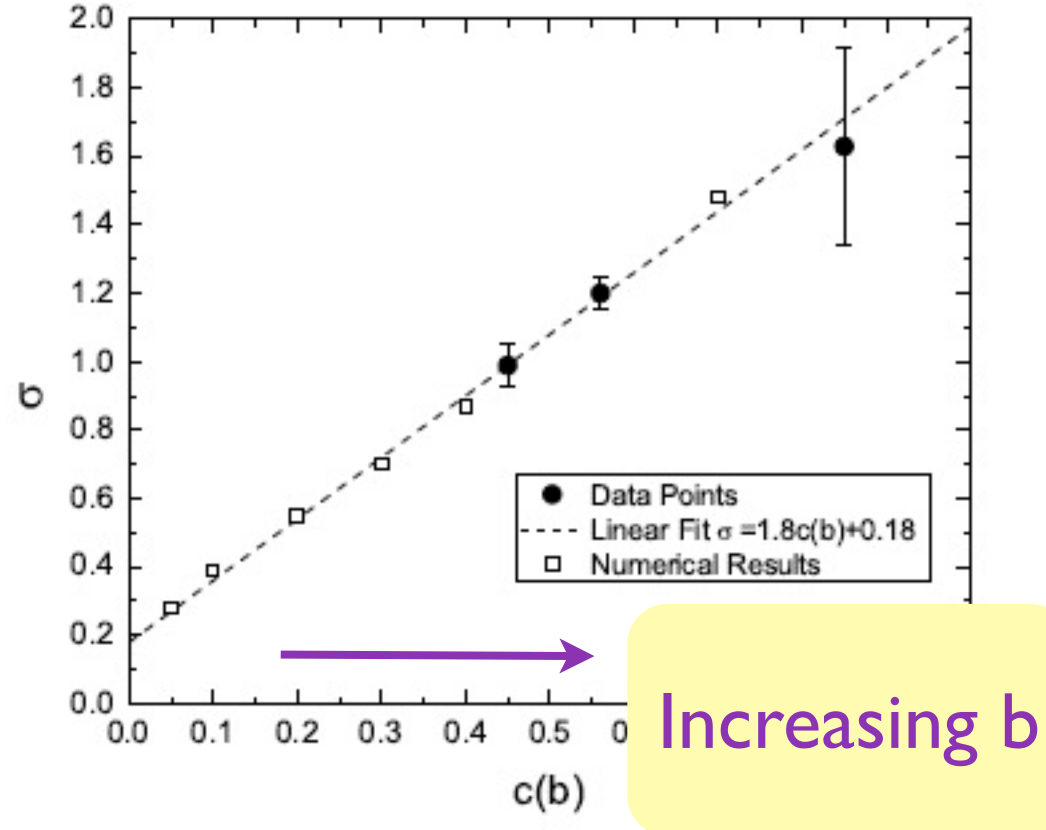
Dominance of double parton interactions ruled out by neutron-tagged measurements by STAR

decorrelation increases with

➡ Increasing the saturation scale of target:



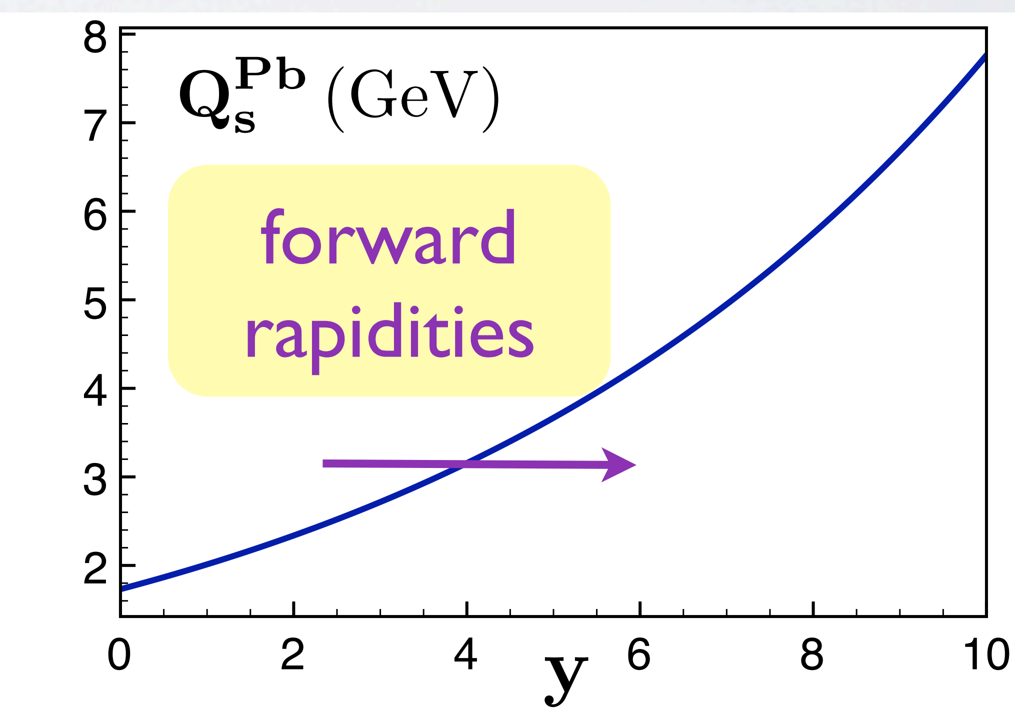
➡ Increasing collision centrality



Stasto, Xiao Yuan

A rapidity (central-central, central-forward and forward-forward) and centrality scan of of di-hadrons correlations at moderate pt (1-15 GeV) in pPb collisions at the LHC energies would:

1. Set strong constraints to the CGC evolution
2. Provide very valuable information on the b-dependence of the saturation scale



Initial gluon production in heavy ion collisions

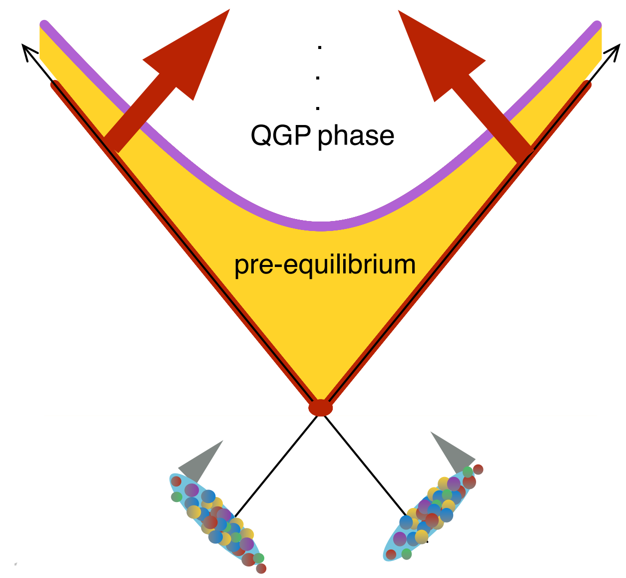
- Classical Yang-Mills EOM: $[\mathbf{D}_\mu \mathbf{F}^{\mu\nu}] = \mathbf{J}^\nu[\rho]$

  (Suplemented by JIMWLK evolution)

  Recent progress by T. Lappi

- kt-factorization (BK evolution)

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

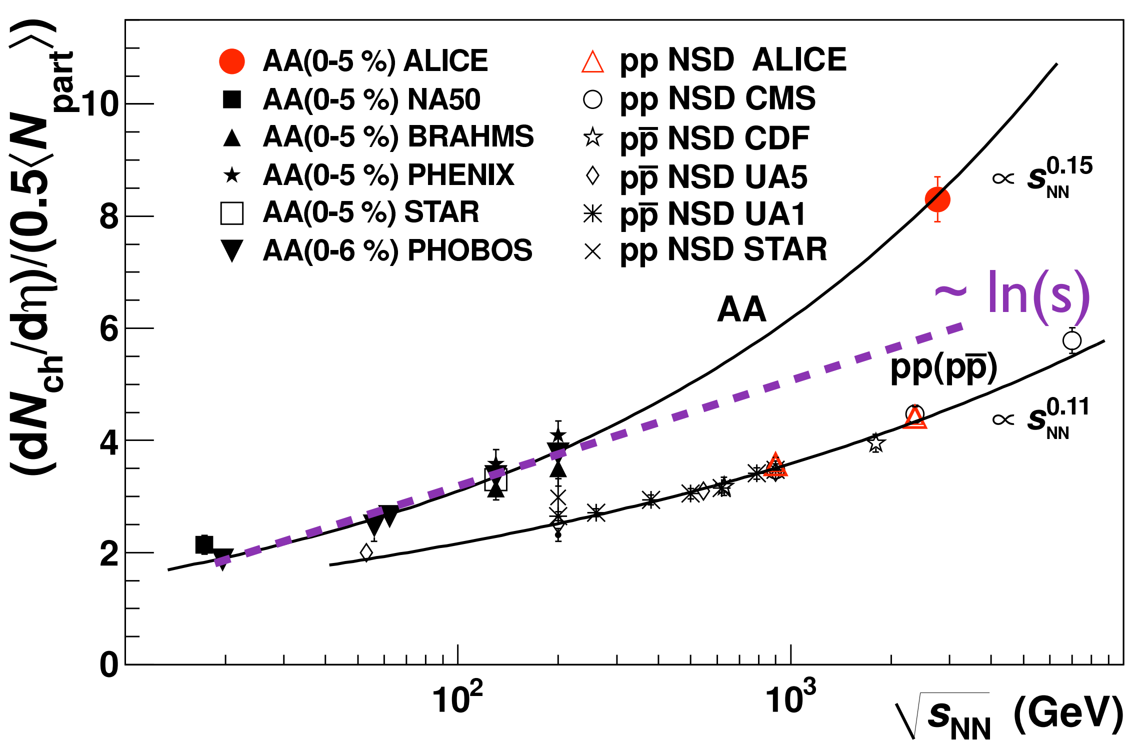


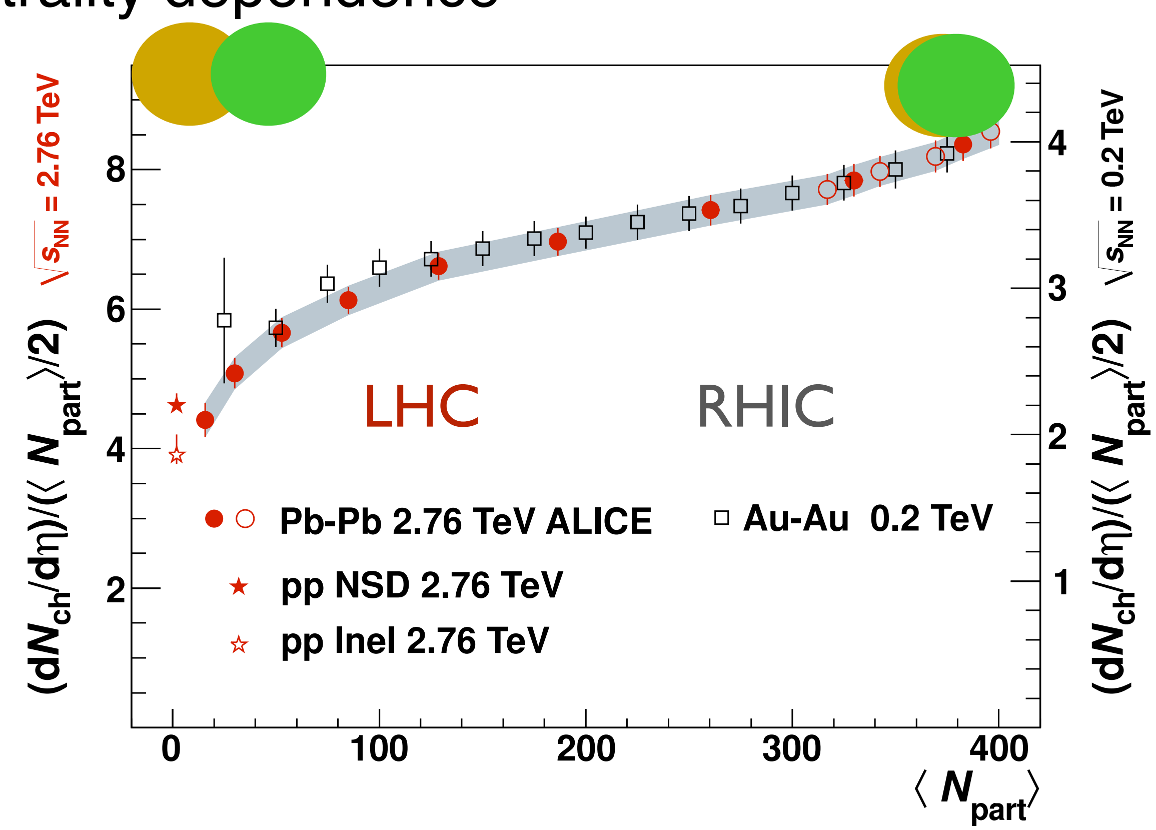
$$\left.\frac{\mathbf{dN^{ch}}}{\mathbf{d\eta}}\right|_{\eta=0} = \frac{2}{3}\mathbf{K}\left.\frac{\mathbf{dN^g}}{\mathbf{d\eta}}\right|_{\eta=0}$$

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

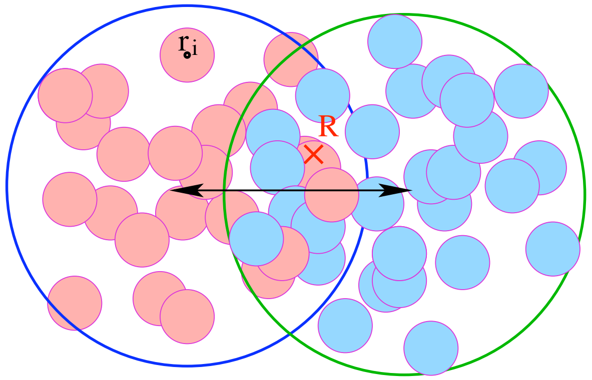
DATA:

- Strong coherence effects: $\frac{\mathbf{dN^{AA}}}{\mathbf{d\eta}} \ll \mathbf{N_{coll}} \frac{\mathbf{dN^{pp}}}{\mathbf{d\eta}}$
- Approximate factorization of energy and centrality dependence





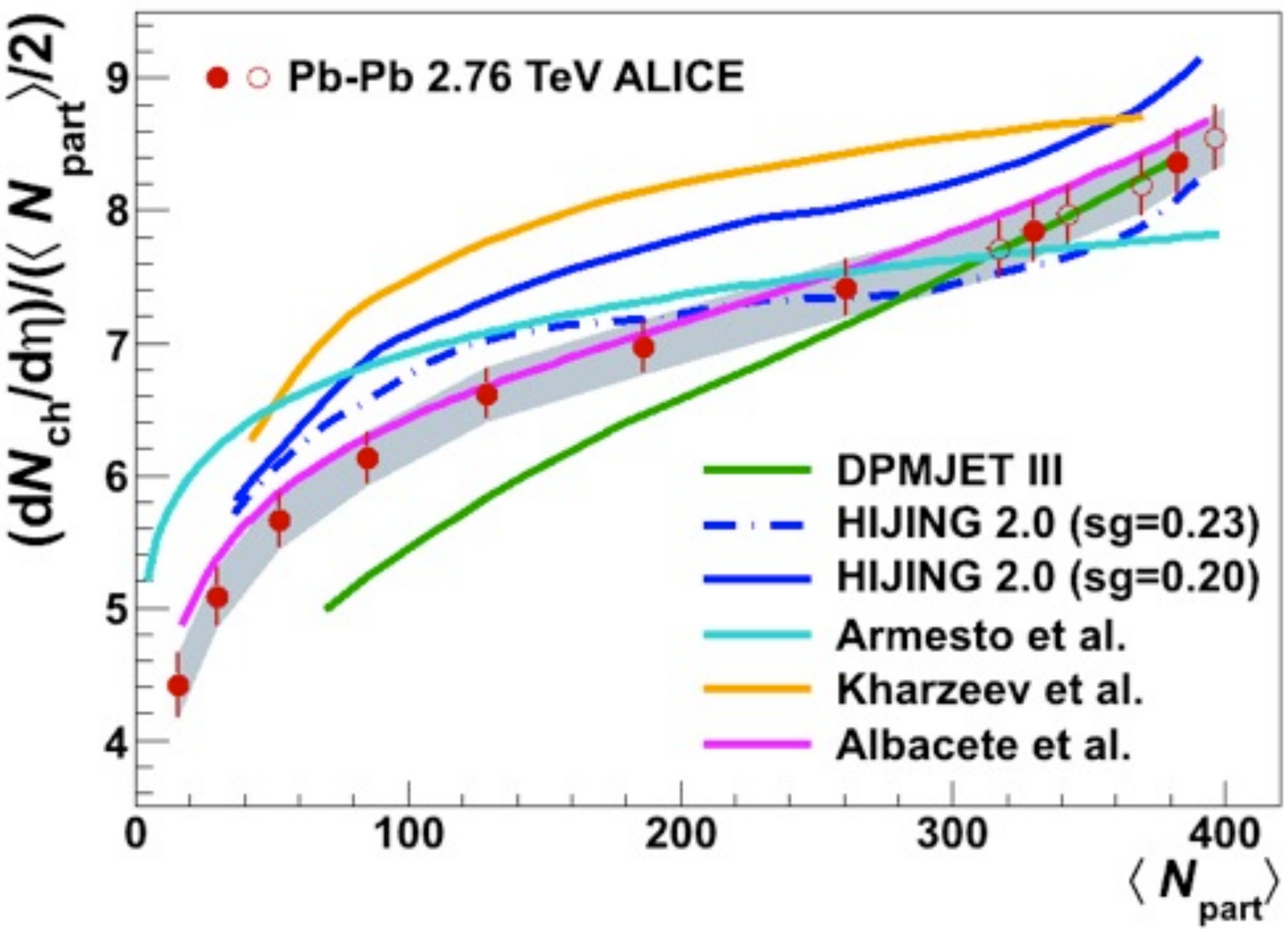
LHC data and rcBK CGC Monte Carlo



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

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

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

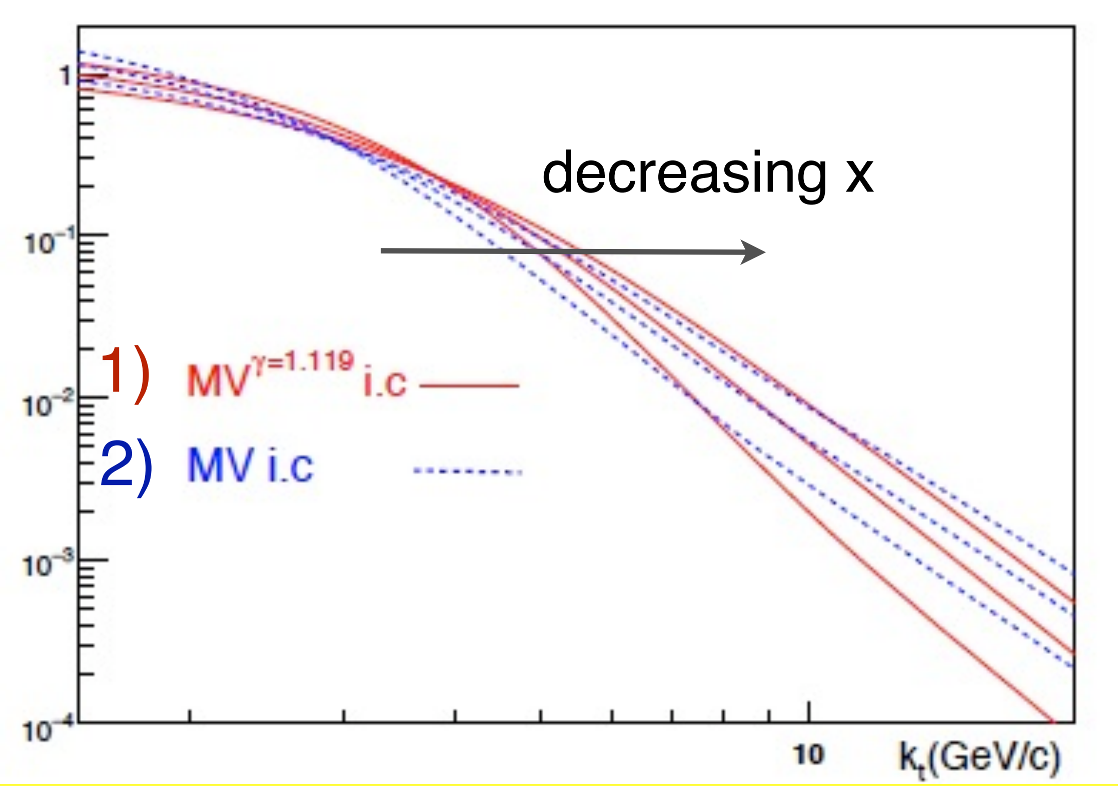


Good description of Pb+Pb data

CGC models for multiplicities can also be tested in a p+Pb run

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

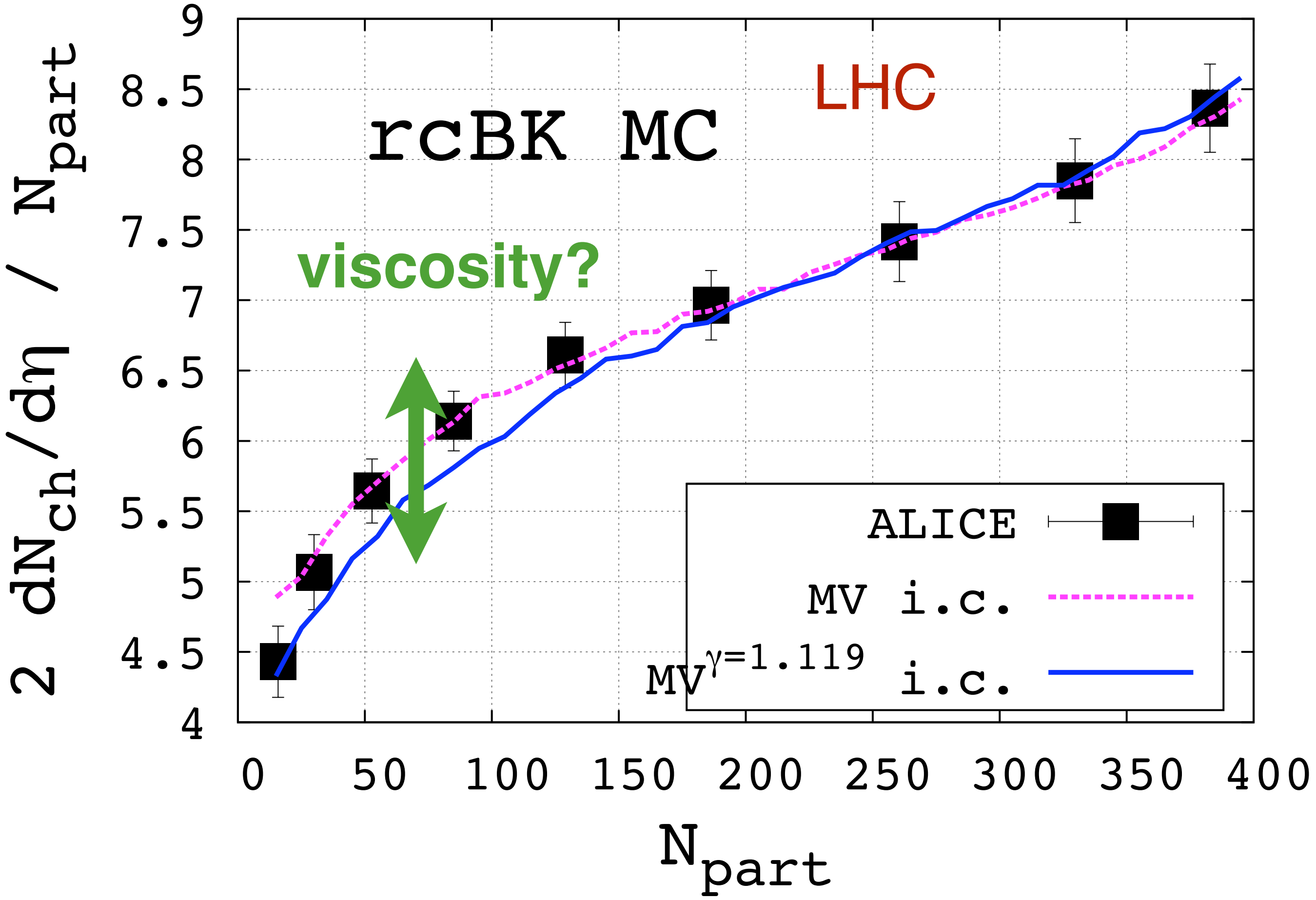
Reminder: e+p, d+Au and Pb+Pb (multiplicities) data are compatible with u.g.d with rather different high-kt behavior:



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

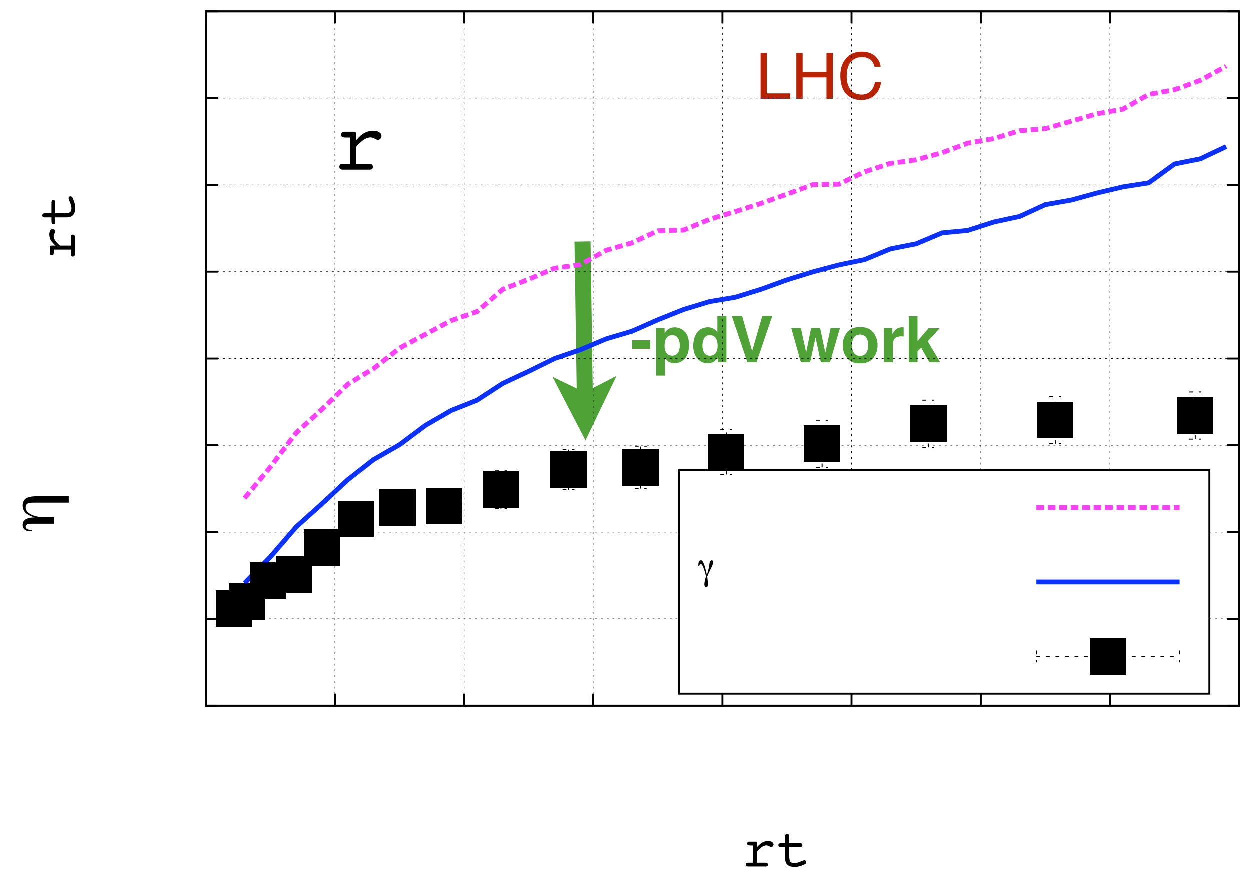
~ 10% effect on multiplicity distributions

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



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

Information on the moderate to high kt behaviour of Pb ugd's from a pPb run would ALSO have a positive impact on CGC models for bulk particle production !!!

Conclusions / Outlook

✔ CGC can **consistently** describe data at small-x collected in different collision systems (e+p, p+p, d+Au, Au+Au) at energies lower than the LHC

✔ First LHC data on bulk properties of HIC in agreement with CGC expectations

✔ Predictive power of the CGC limited due to the lack of small-x data on nuclear reactions able to constrain the initial conditions for the evolution (b,kt)-dependence

✔ Relatively simple measurements (multiplicities and transverse energy distributions, single inclusive hadron spectra and di-hadron correlations) in a p +Pb run at the LHC at relatively low momentum (pt < 10~20 GeV) A p-Pb run at the LHC would be **most useful** for:

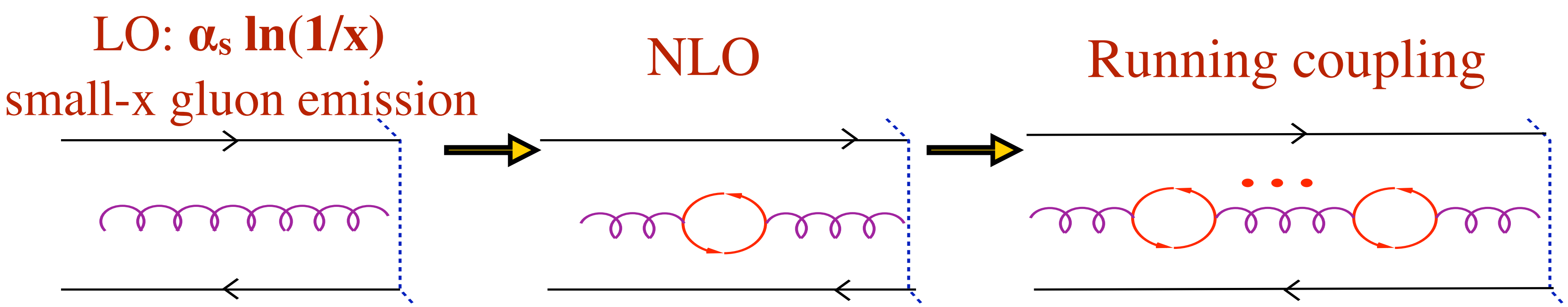
1. Testing the formalism at its present degree of accuracy
2. Establishing reliable references for initial state effects in hard probes production in HIC (photons, drell-yan, heavy quarks...)

✔ A p+Pb run would ALSO be extremely useful to further constrain models for bulk particle production, thus reducing systematic uncertainties for hydro studies.

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

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

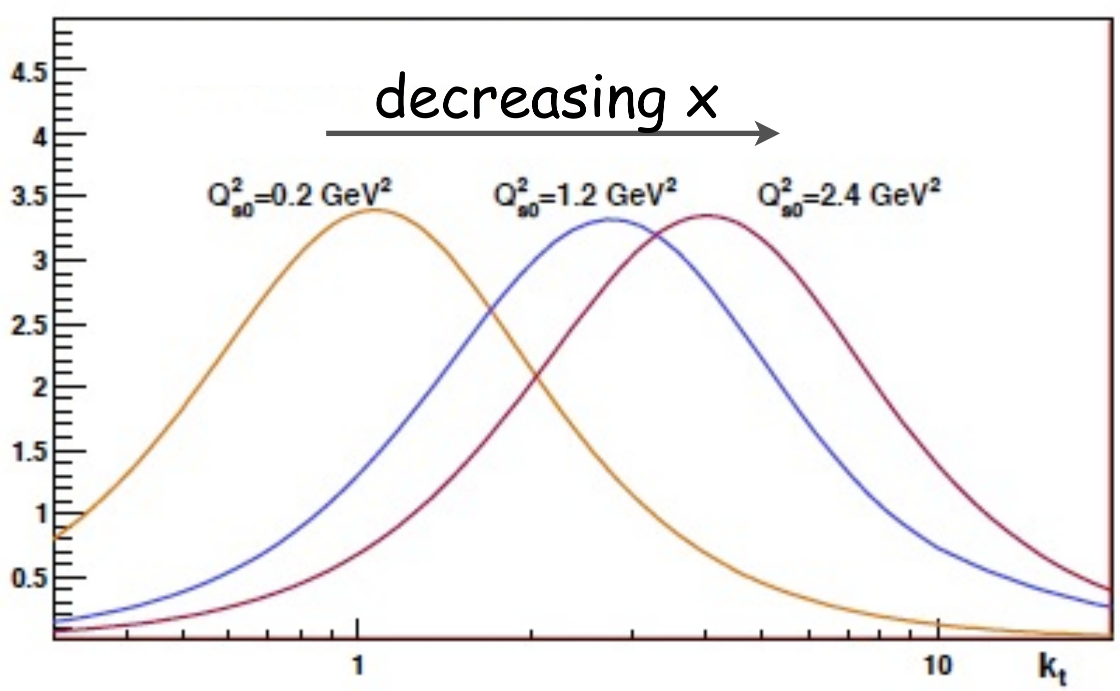
radiation recombination



[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!