Theoretical modeling of Pb+Pb minimum bias data

Javier L Albacete
IPhT CEA/Saclay

Winter workshop on recent QCD advances at the LHC
Les Houches, February 13-18 20011

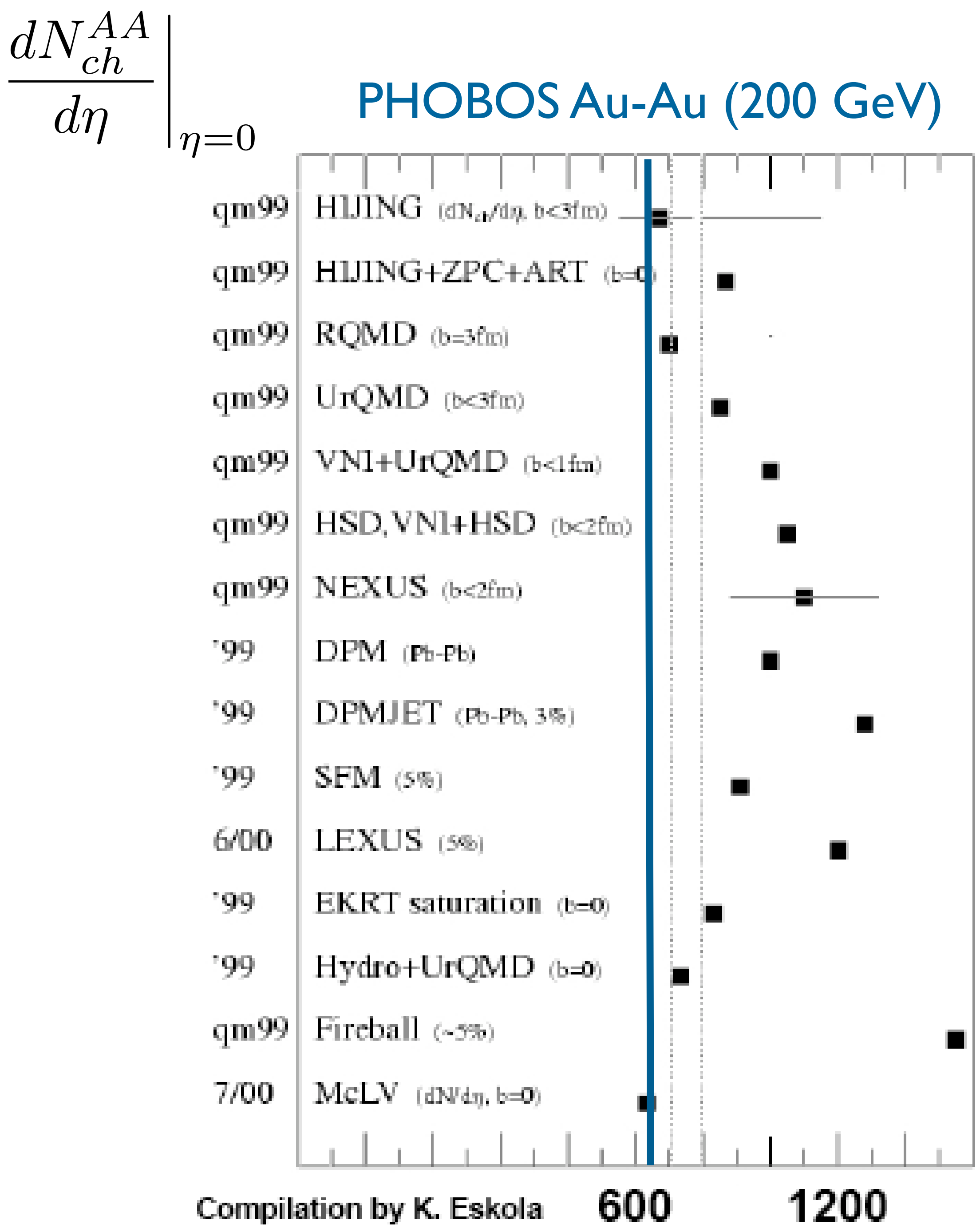
SEVENTH FRAMEWORK PROGRAMME
MARIE CURIE ACTIONS
IPhT cea saclay

OUTLINE

- A look at RHIC and LHC data on multiplicities
- Color Glass Condensate vs MC event generator approaches
- Recent advances in the CGC: rcBK Monte Carlo (in coll. with Adrian Dumitru)
- Outlook

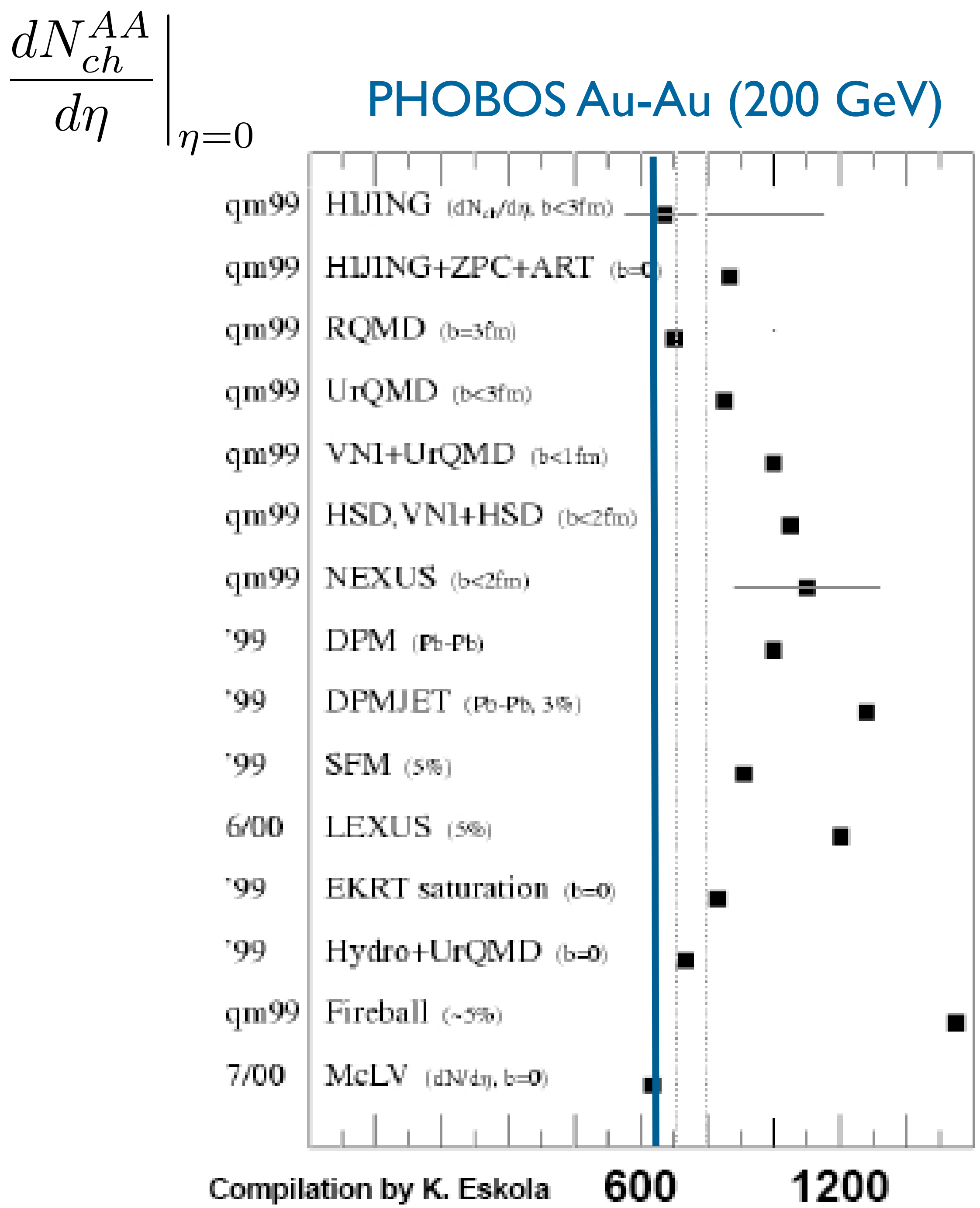
From RHIC to the LHC

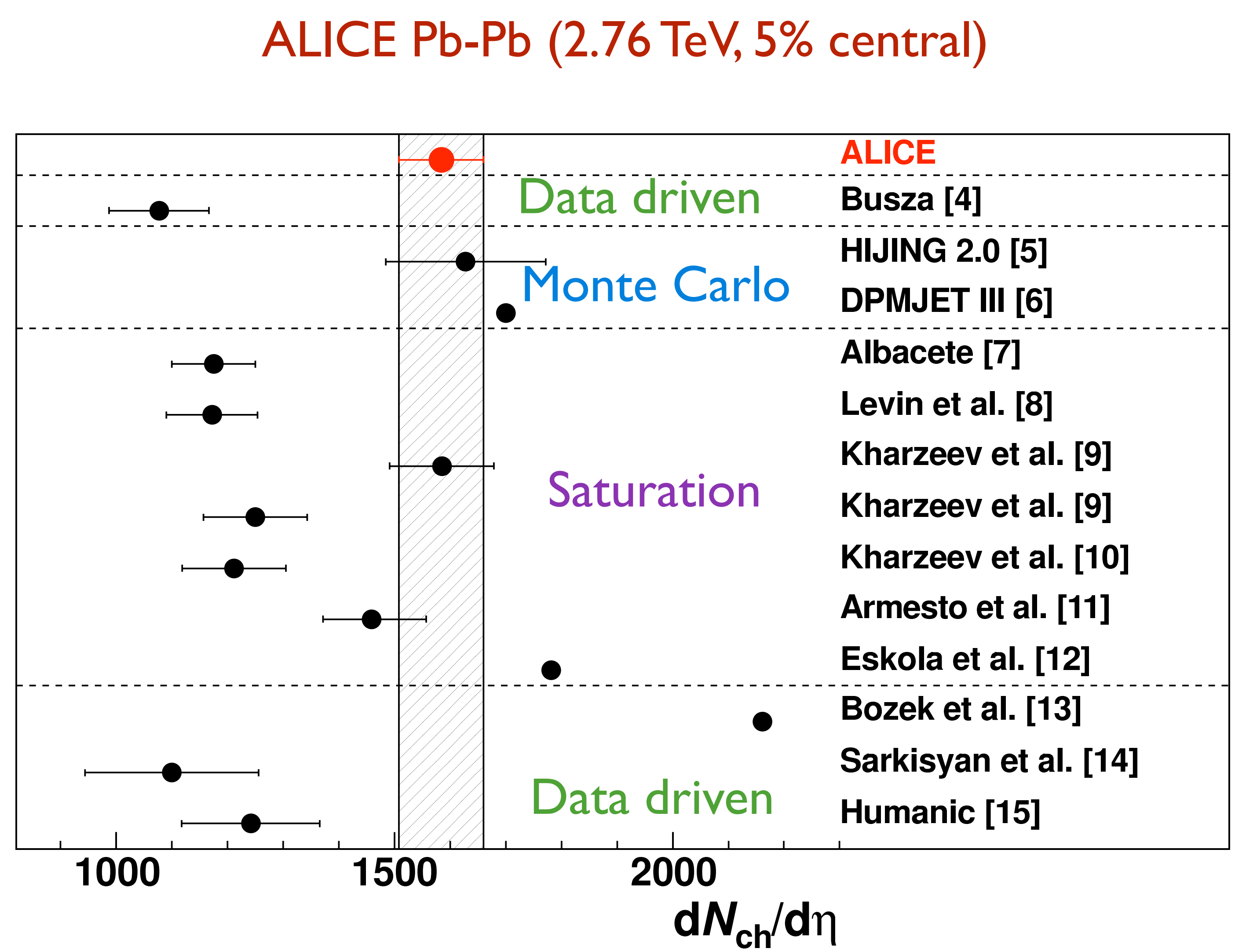
• RHIC multiplicities turned out much smaller than expected: Strong coherence effects reduce the effective number of sources (gluons, strings...) for particle production



From RHIC to the LHC

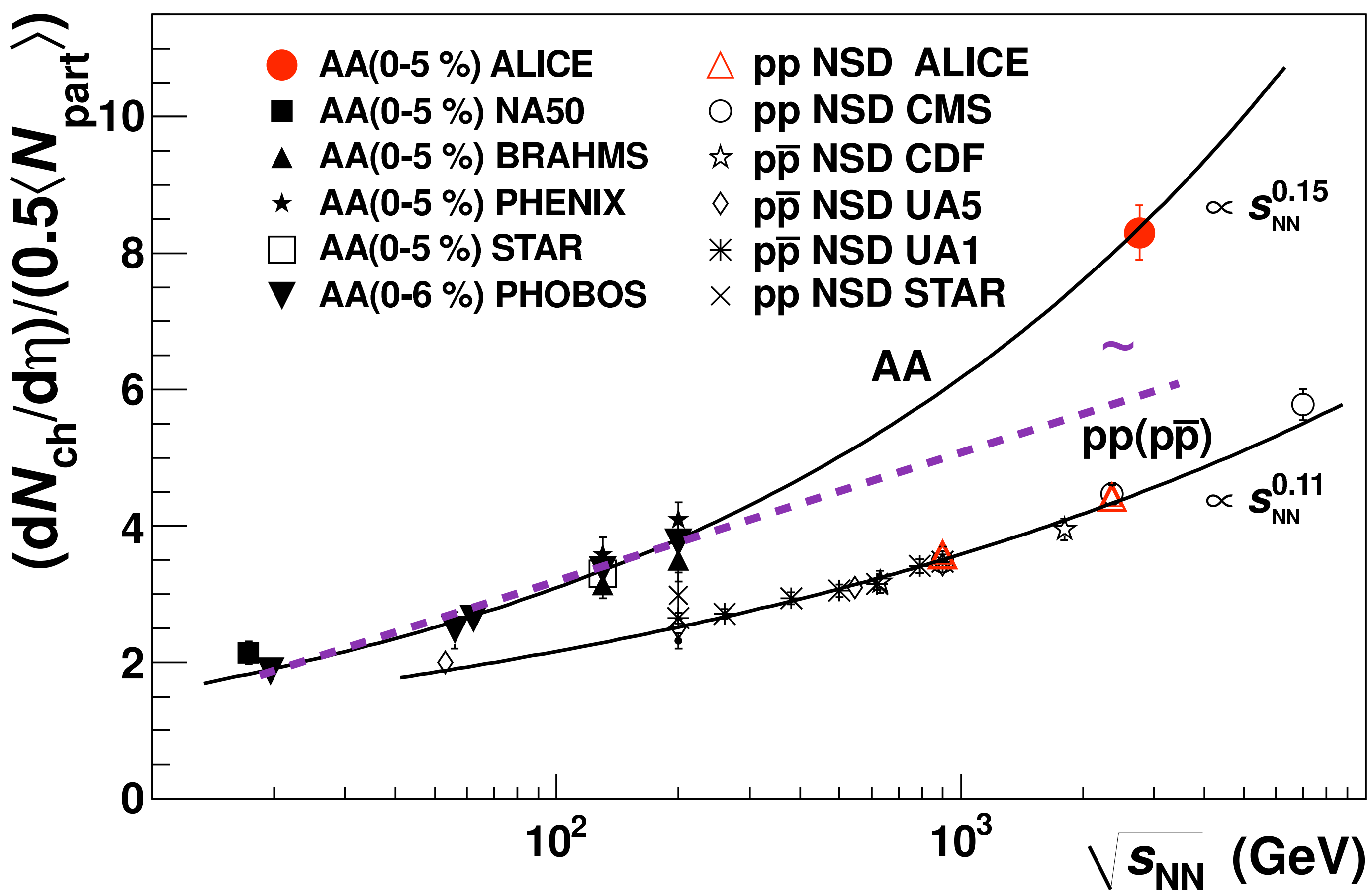
- RHIC multiplicities turned out much smaller than expected: Strong coherence effects reduce the effective number of sources (gluons, strings...) for particle production



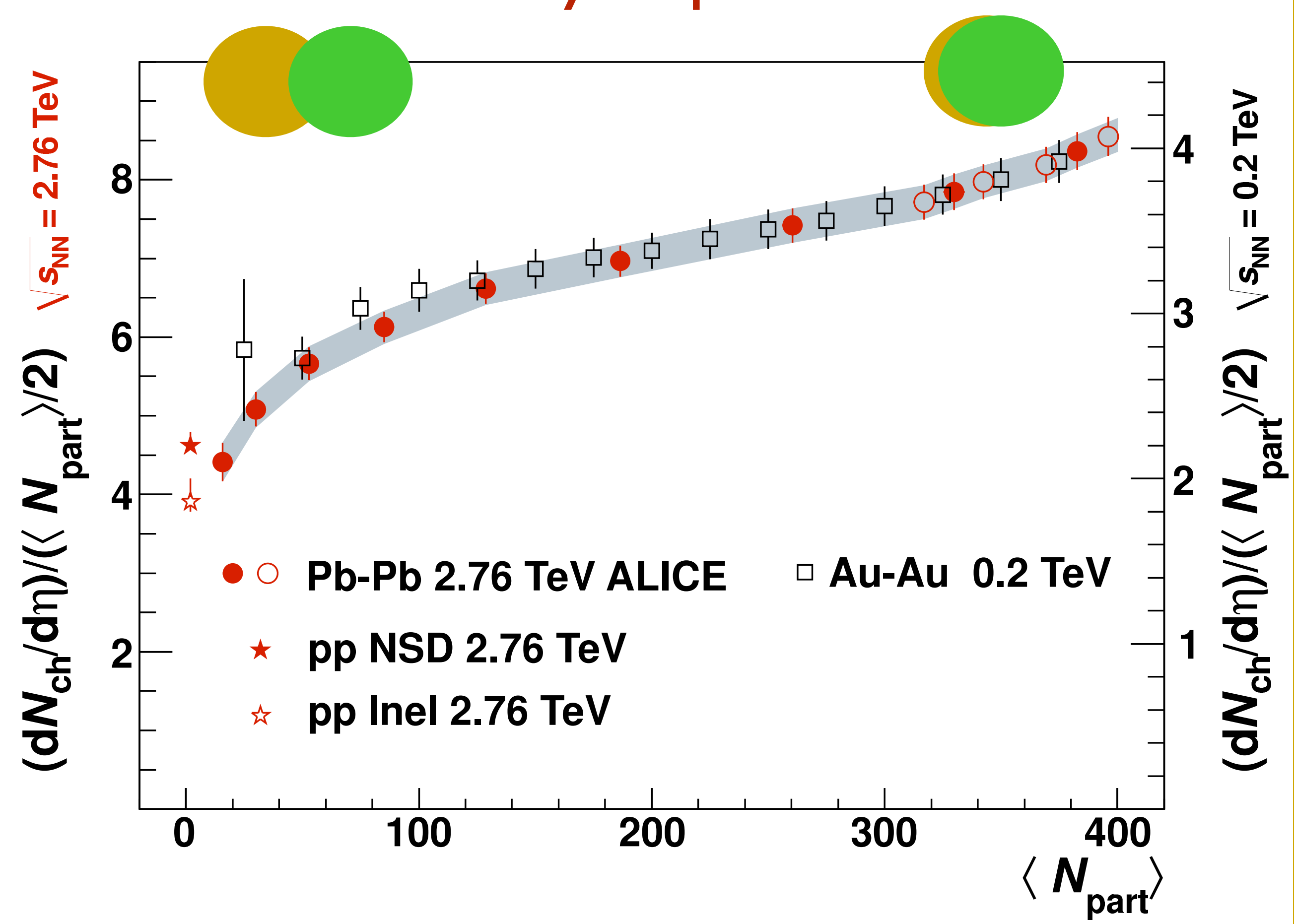


ALICE Pb-Pb data @ 2.76 TeV

Energy dependence



Centrality dependence

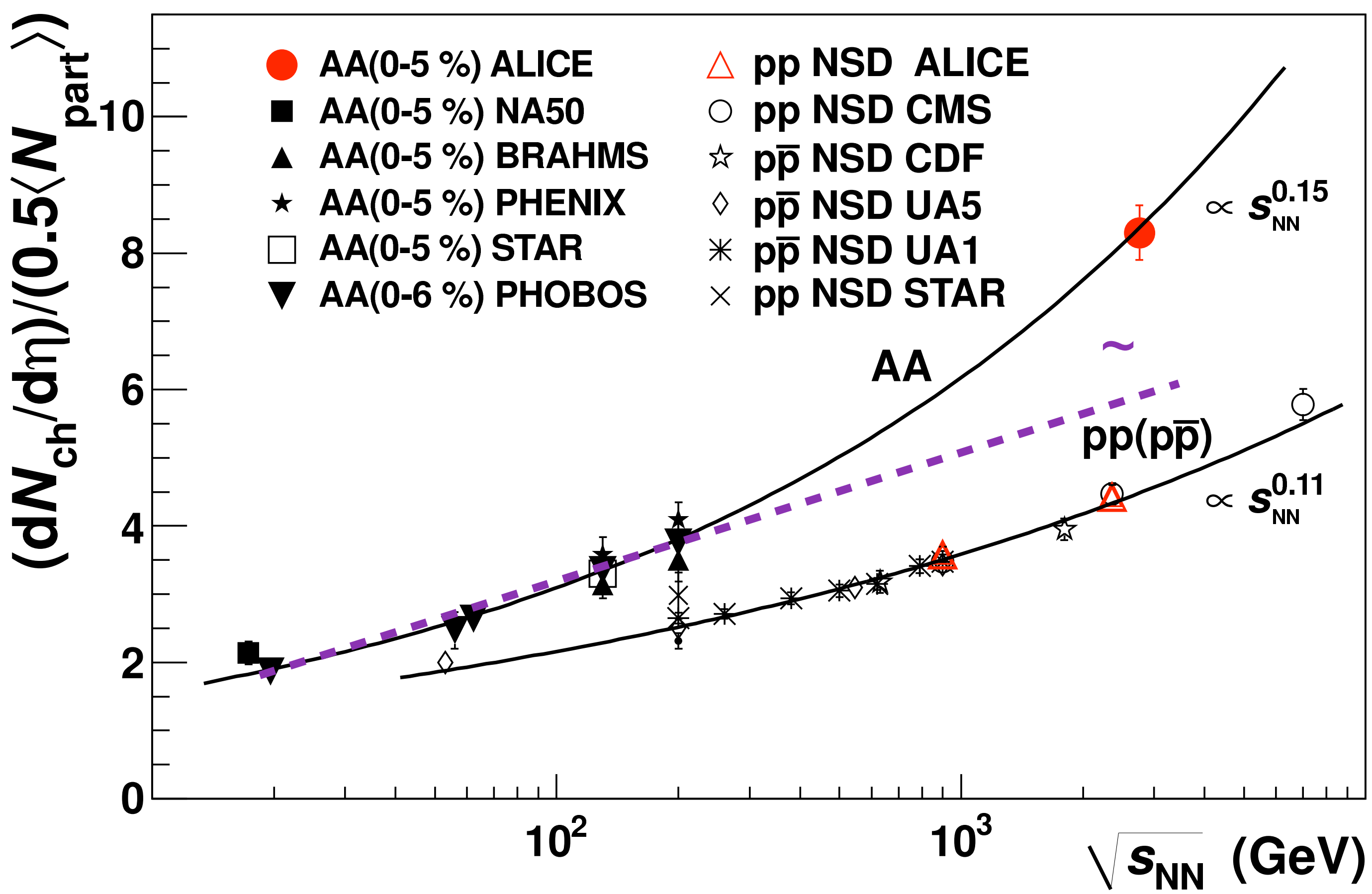


$$\frac{1}{N_{part}} \frac{dN_{ch}}{d\eta}\bigg|_{\eta=0} \propto s^{0.15} f(N_{part})$$

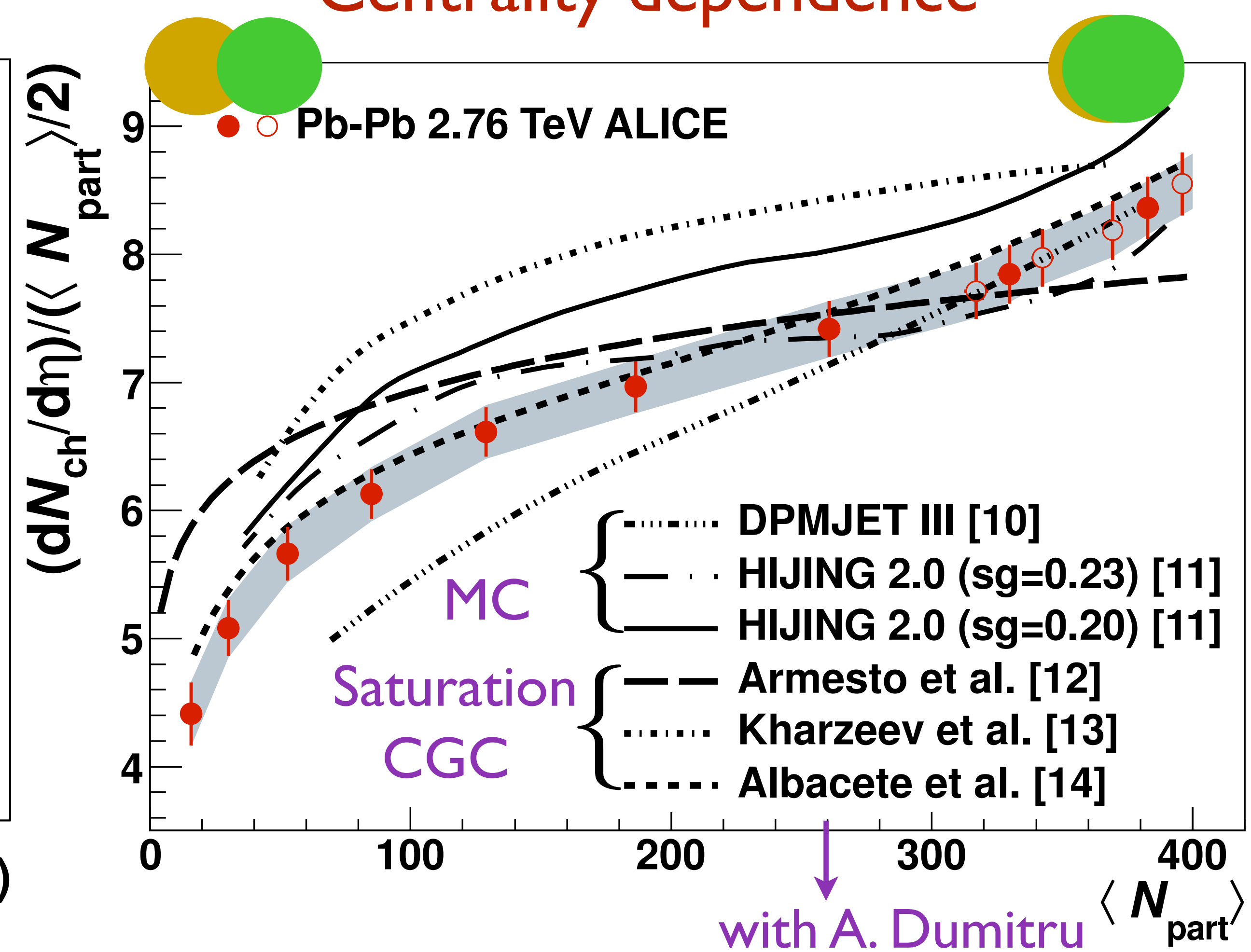
- Energy dependence of the multiplicities seems to obey a power-law. Logarithmic trends dictated by lower energy data seems to be ruled out by the LHC data
- Centrality dependence very similar to RHIC Au+Au data at 200 GeV
- Strong energy dependence in A+A coll. than in p+p??

ALICE Pb-Pb data @ 2.76 TeV

Energy dependence



Centrality dependence



$$\frac{1}{N_{part}} \frac{dN_{ch}}{d\eta}\bigg|_{\eta=0} \propto s^{0.15} f(N_{part})$$

- Energy dependence of the multiplicities seems to obey a power-law. Logarithmic trends dictated by lower energy data seems to be ruled out by the LHC data

- Centrality dependence very similar to RHIC Au+Au data at 200 GeV

- Strong energy dependence in A+A coll. than in p+p??

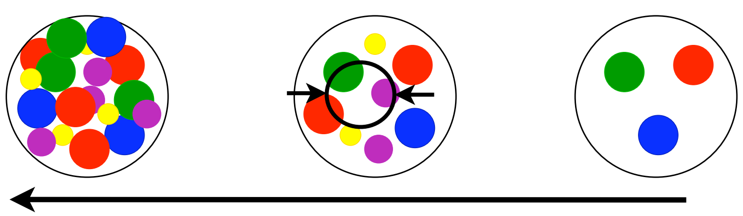
Saturation / Color Glass Condensate modeling of multiplicities

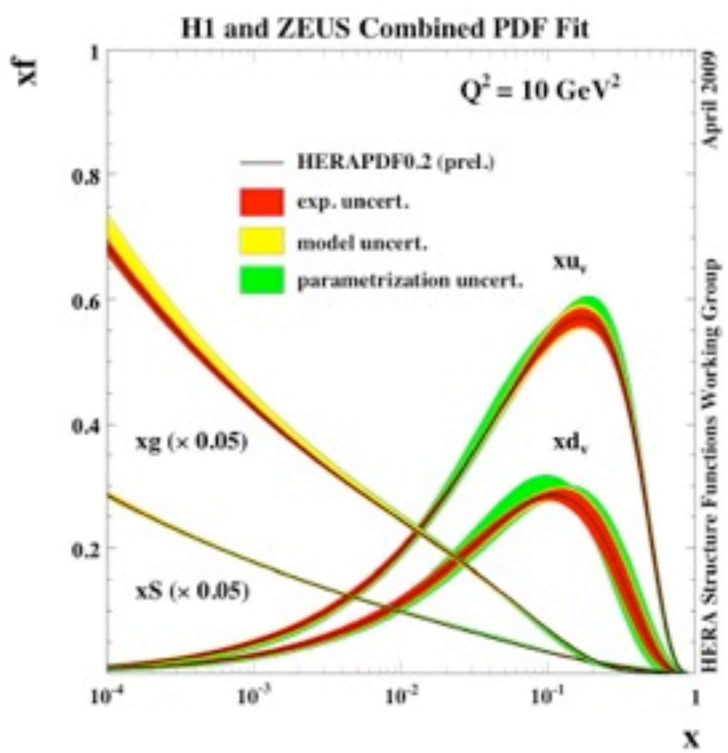
1. Semiclassical methods to approach hadron wavefunctions at small-x from first principles: MV model
2. Quantum corrections: Nonlinear renormalization group equations towards small-x: BK-JIMWLK
3. Calculation of production processes in dense partonic environments

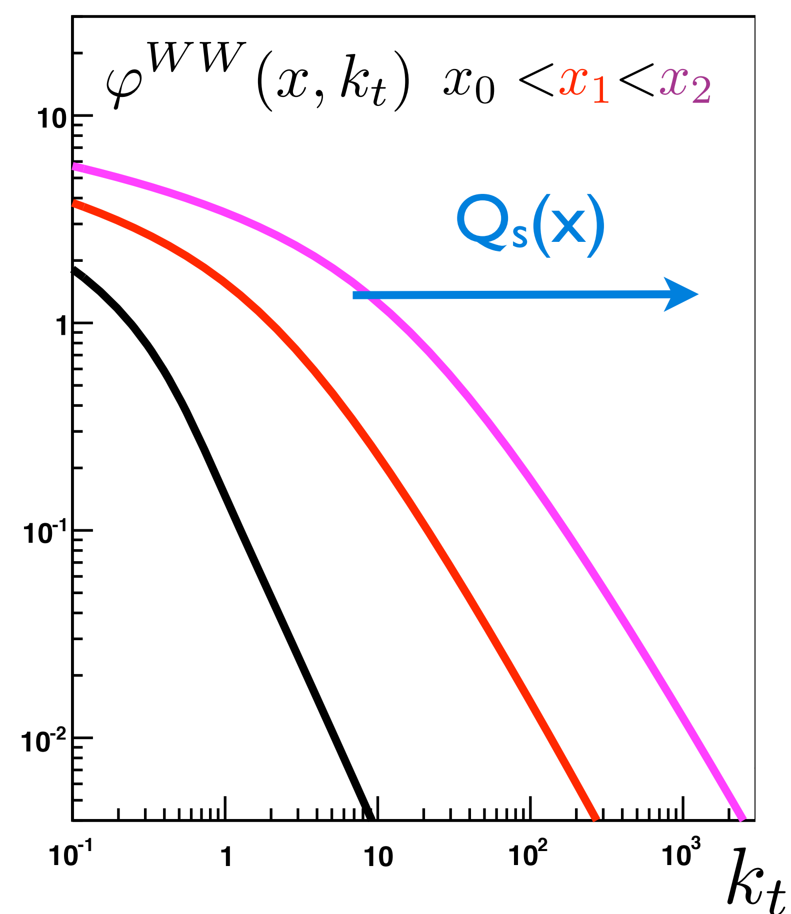
“BK-JIMWLK”:

$$\begin{cases} \dfrac{\partial \phi(\mathbf{x},\mathbf{k_t})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x},\mathbf{k_t}) - \phi(\mathbf{x},\mathbf{k_t})^{\mathbf{2}} \\ xG(x,Q^2) \sim \displaystyle\int^{Q^2} d^2k_t\, \varphi^{WW}(x,k_t) \end{cases}$$

$$\ln\frac{1}{x} \sim \ln s \sim Y$$

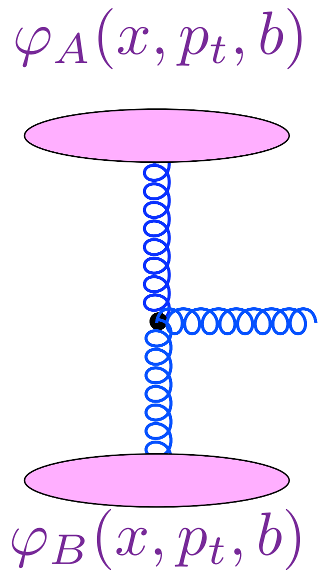






Saturation / Color Glass Condensate modeling of multiplicities

- Most of particles produced in the collision originate from small-x gluons in the saturation domain
- Other sources (genuinely soft processes, contribution from valence quarks etc) neglected
- Initial gluon production is calculated via kt-factorization and then mapped to final hadron spectra assuming local parton-hadron duality



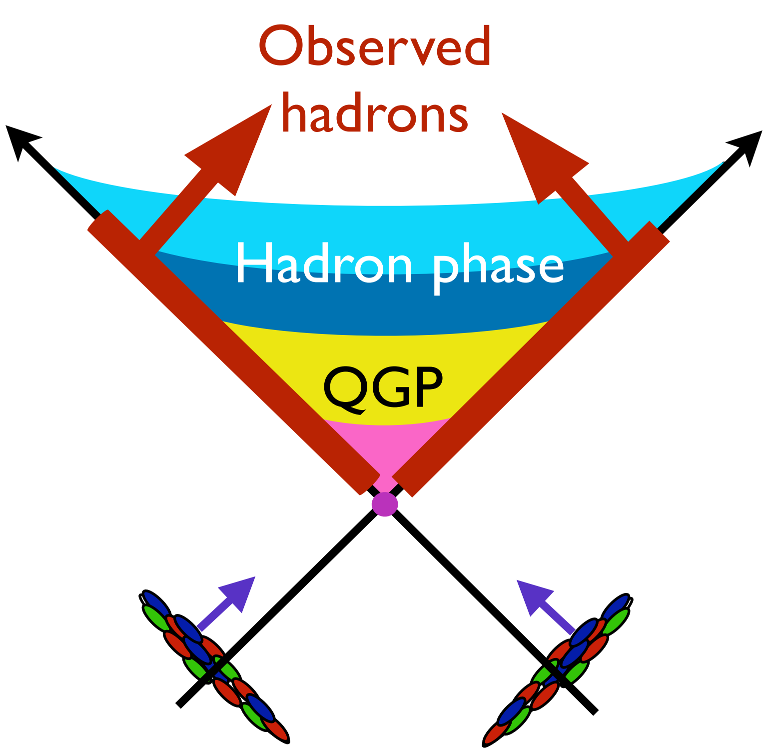
$$\frac{d\sigma^{A+B\to g}}{dy\, d^2p_t\, d^2R} = \kappa \frac{2}{C_F} \frac{1}{p_t^2} \int^{p_t} \frac{d^2k_t}{4} \int d^2b\, \alpha_s(Q)\, \varphi(\frac{|p_t + k_t|}{2}, x_1; b)\, \varphi(\frac{|p_t - k_t|}{2}, x_2; R - b)$$

$$x_{1(2)} = (p_t/\sqrt{s_{NN}}) \exp(\pm y)$$

unintegrated gluon distributions

"Leading order": N_part scaling

$$\left.\frac{dN_{AA}}{d\eta}\right|_{\eta=0} \propto Q_{sA}^2(\sqrt{s}, b) \sim \sqrt{s}^{\lambda}\, N_{part}$$ with $\lambda \sim 0.2 \div 0.3$



Phenomenological models:

$$\frac{1}{N_{part}} \left.\frac{dN_{AB}^g}{d^2b\, d\eta}\right|_{\eta=0} = \begin{cases} \sqrt{s}^{\lambda}\, \ln\left(\sqrt{s}^{\lambda} N_{part}\right); \\ \sqrt{s}^{\lambda}\, N_{part}^{\frac{1-\delta}{3\delta}}; \end{cases}$$

- Scaling violations from running coupling, KLN model (Kharzeev-Levin-Nardi, NPA 747 609)

$$Q_{sA}^2(x) = A^{1/(3\delta)}\, Q_{sp}^2(x)$$

- Data driven ASW model ASW (Armesto-Salgado-Wiedemann PRL94 022002)

A+A MC event generators (HIJING, DPMJET, HYDJET, PACIAE, EPOS...)

SOFT — p_0 — HARD → p_t

No Coherence

$$\left.\frac{\mathbf{dN}}{\mathbf{d}\eta}\right|_{\eta=\mathbf{0}} (\sqrt{\mathbf{s}} \gg, \mathbf{b}) \propto$$

SOFT

- Strings, Dual Parton Model, Regge Field Theory, hydro/thermal models...)

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

$$\Delta_{soft} \approx 0\ 08$$

HARD

LO pQCD independent minijet production, eikonal approximation

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

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

At high energies independent particle production (soft and hard) leads to Ncoll scaling

At high energies the hard dominates

A+A MC event generators (HIJING, DPMJET, HYDJET, PACIAE, EPOS...)

break-down of independent minijet production (also in p+p)

SOFT $p_0(s) \longrightarrow$ HARD p_t

Coherence Mechanims

$$\left.\frac{\mathbf{dN}}{\mathbf{d}\eta}\right|_{\eta=\mathbf{0}} (\sqrt{\mathbf{s}} \gg, \mathbf{b}) \propto$$

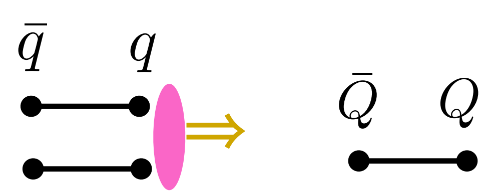
SOFT

- Strings, Dual Parton Model, Regge Field Theory, hydro/thermal models...)

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

$$\Delta_{soft} \approx 0\ 08$$

String fusion - percolation



HARD

LO pQCD independent minijet production, eikonal approximation

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

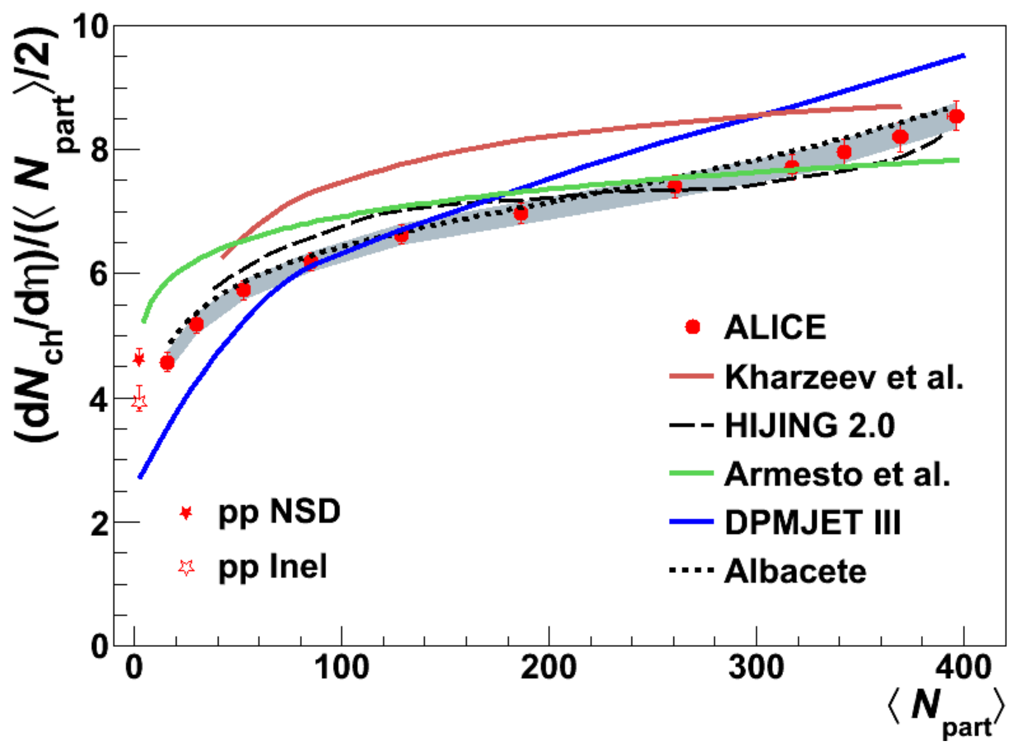
$$\Delta_{hard} \approx 0.3$$

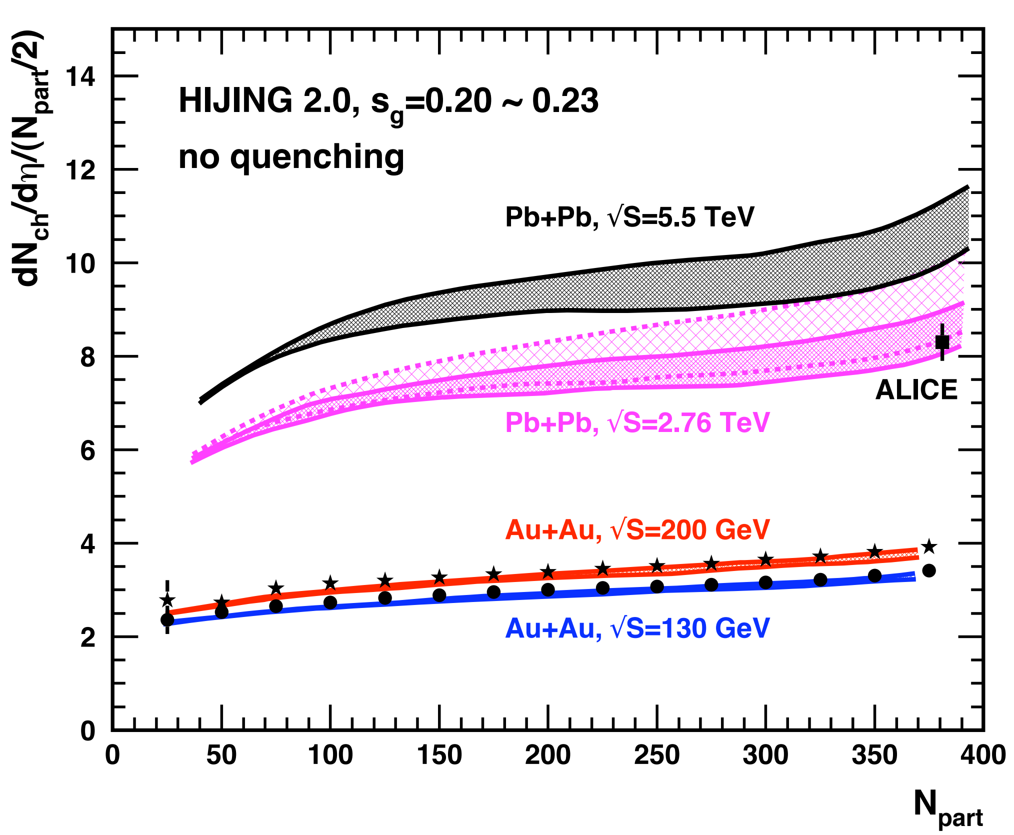
Nuclear Shadowing

$$f_{i/A}(x, Q^2, b) = A\, R_{i/A}(x, Q^2, b)\, f_{i/N}(x, Q^2)$$

$$R_{i/A}(x \lesssim 0.01, Q^2) < 1$$

HIJING 2.0 and DPMJET III





- HIJING 2.0: Tuned to LHC p+p data and Pb+Pb 5% central data. Energy dependent cutoff:

$$p_0 = 2.62 - 1.084\log(\sqrt{s}) + 0.299\log^2(\sqrt{s}) - 0.0292\log^3(\sqrt{s}) + 0.00151\log^4(\sqrt{s}),$$

- Strong b-dependent, Q^2-independent gluon shadowing adjusted to RHIC data

$$R_g^A(x,b) = 1.0 + 1.19\log^{1/6}A\,(x^3 - 1.2x^2 + 0.21x) - s_g(b)\,(A^{1/3}-1)^{0.6}(1 - 1.5x^{0.35}) \times \exp(-x^2/0.004),$$

$$s_a(b) = s_a\frac{5}{3}(1 - b^2/R_A^2),$$

- DPMJET uses standard Wood-Saxons profiles $T_A(b)$, yielding a much stronger centrality dependence

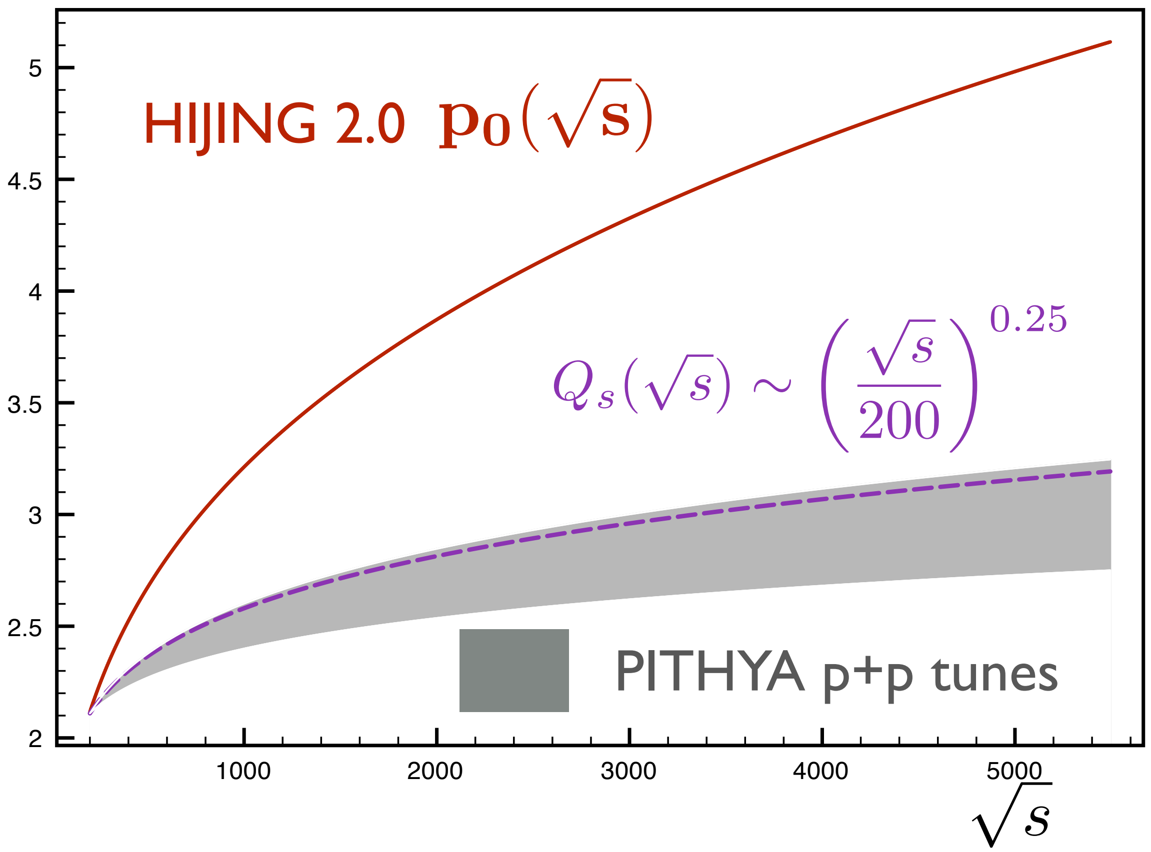
- My impression: At high energies the hard part dominates over the soft one, leading to Ncoll scaling of the multiplicities

$$\left.\frac{dN_{ch}^{AA}}{d\eta}\right|_{\eta=0} = \left.\frac{dN_{ch}^{NN}}{d\eta}\right|_{\eta=0}\left[\frac{1-x}{2}N_{part} + xN_{coll}\right],$$

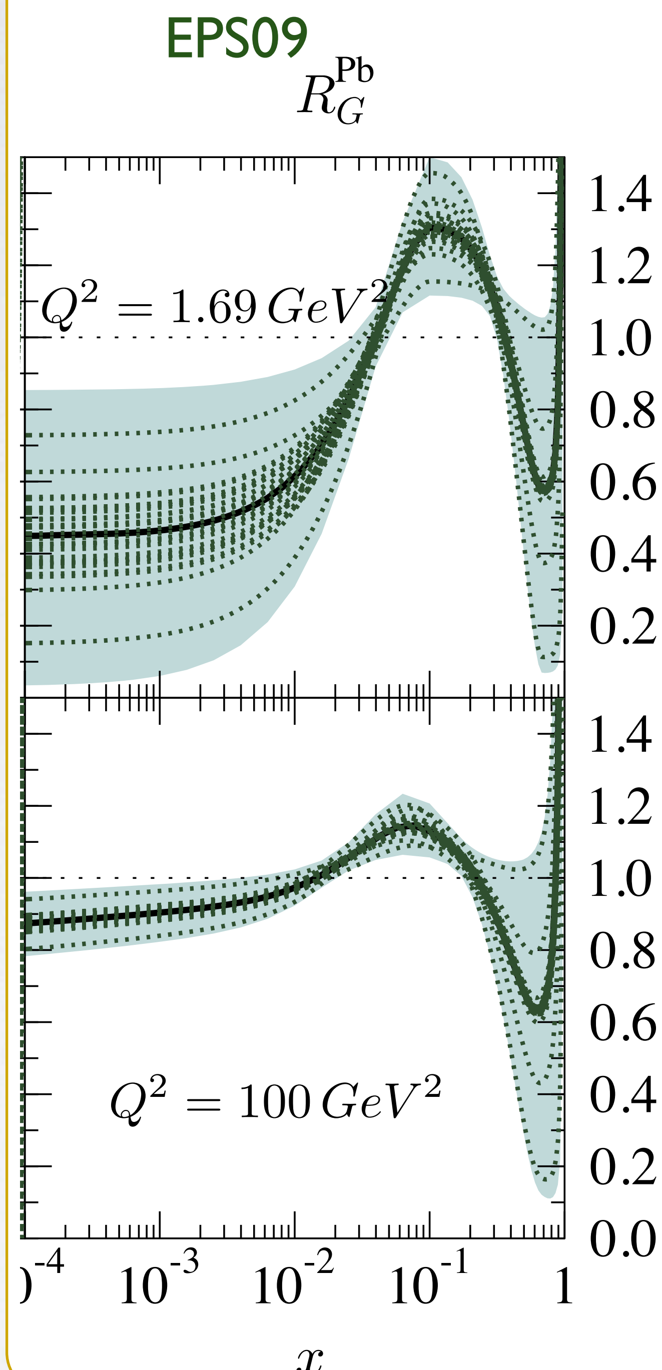
HIJING 2.0

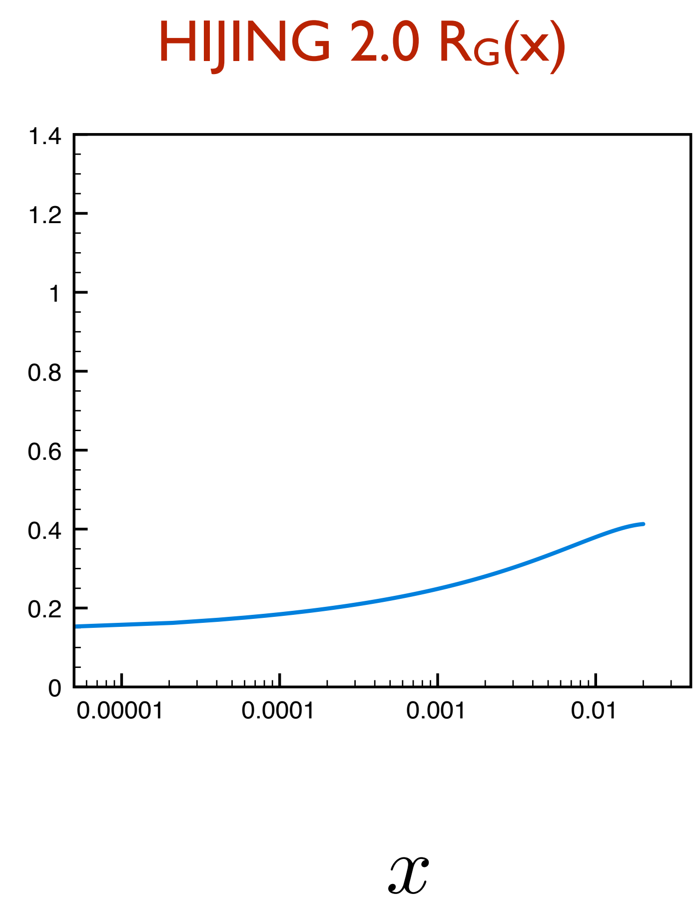
Energy dependent cutoff:

$$p_0 = 2.62 - 1.084\log(\sqrt{s}) + 0.299\log^2(\sqrt{s}) - 0.0292\log^3(\sqrt{s}) + 0.00151\log^4(\sqrt{s}),$$



- Strong b-dependent gluon shadowing





The assumption of independent pQCD minijet production has to be strongly corrected through coherence mechanisms in order to agree with data

✓ rcBK approach: (x,kt)-dependence of gluon densities calculated by solving the running coupling BK eqn

BK eqn:

$$\frac{\partial \mathcal{N}(r,x)}{\partial \ln(x_0/x)} = \int d^2 r_1 \, K(r,r_1,r_2) \, [\mathcal{N}(r_1,x) + \mathcal{N}(r_2,x) - \mathcal{N}(r,x) - \mathcal{N}(r_1,x)\mathcal{N}(r_2,x)]$$

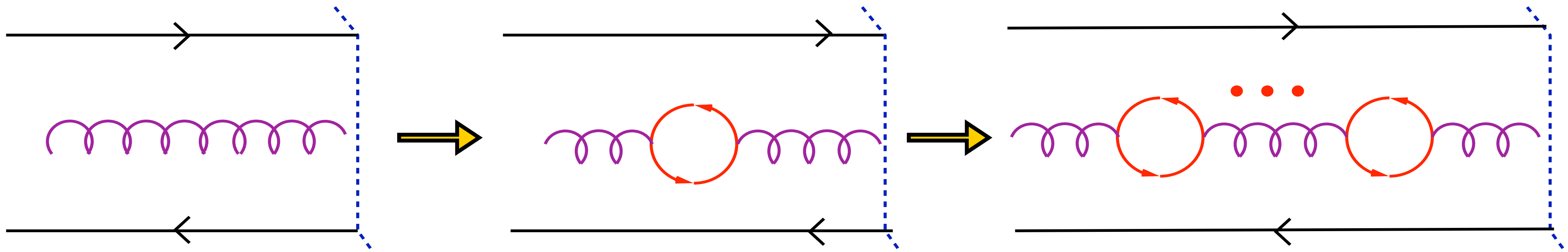
Running coupling kernel:

Balitsky-Chirilli; Kovchegov-Weigert, Gardi et al).

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

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

"NLO": $\alpha_s N_f$
Quark loops resummed to all orders



Gluon contribution: $N_f \rightarrow -6\pi\beta_2$

✓ rcBK approach: (x,kt)-dependence of gluon densities calculated by solving the running coupling BK eqn

BK eqn:

$$\frac{\partial \mathcal{N}(r,x)}{\partial \ln(x_0/x)} = \int d^2 r_1\, K(r,r_1,r_2)\, [\mathcal{N}(r_1,x) + \mathcal{N}(r_2,x) - \mathcal{N}(r,x) - \mathcal{N}(r_1,x)\mathcal{N}(r_2,x)]$$

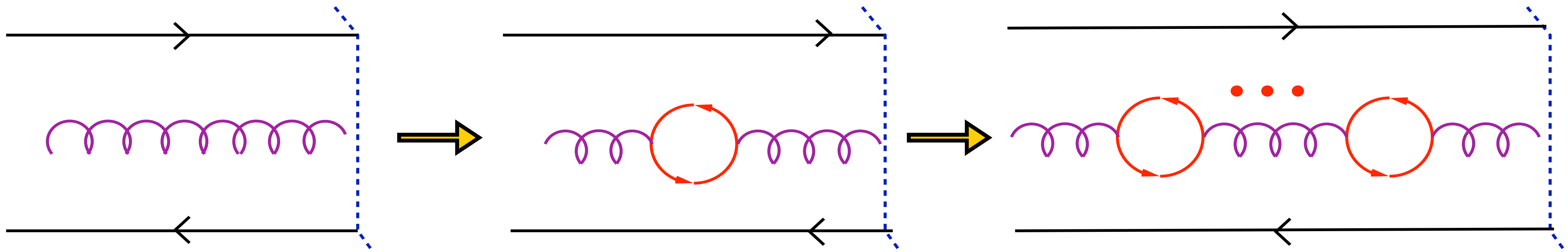
Running coupling kernel:

Balitsky-Chirilli; Kovchegov-Weigert, Gardi et al).

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

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

"NLO": $\alpha_s N_f$
Quark loops resummed to all orders



Gluon contribution: $N_f \to -6\pi\beta_2$

✓ The only freedom comes from the choice of initial conditions for the evolution:

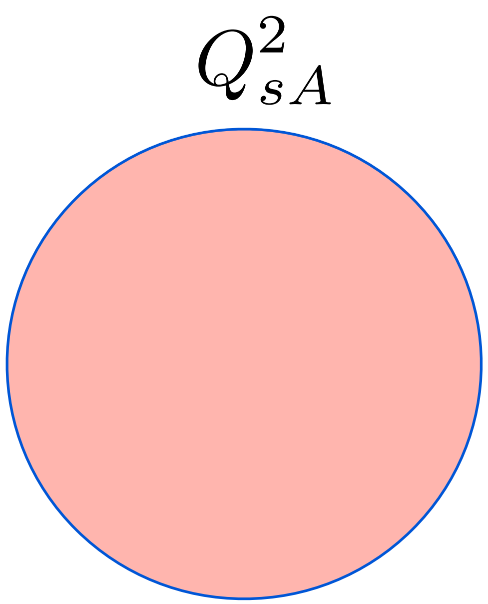
$$\mathcal{N}(r, x=x_0) = 1 - \exp\left[-\frac{r^2\, Q_0^2}{4}\ln\left(\frac{1}{r\,\Lambda} + e\right)\right]$$

$$\varphi(k,x,b) = \frac{C_F}{\alpha_s(k)\,(2\pi)^3}\int d^2\mathbf{r}\; e^{-i\mathbf{k}\cdot\mathbf{r}}\, \nabla_{\mathbf{r}}^2 \mathcal{N}_G(r, Y = \ln(x_0/x), b)\,. \qquad \mathcal{N}_G(r,x) = 2\,\mathcal{N}(r,x) - \mathcal{N}^2(r,x)$$

Nuclear geometry in rcBK approaches

JLA 2007

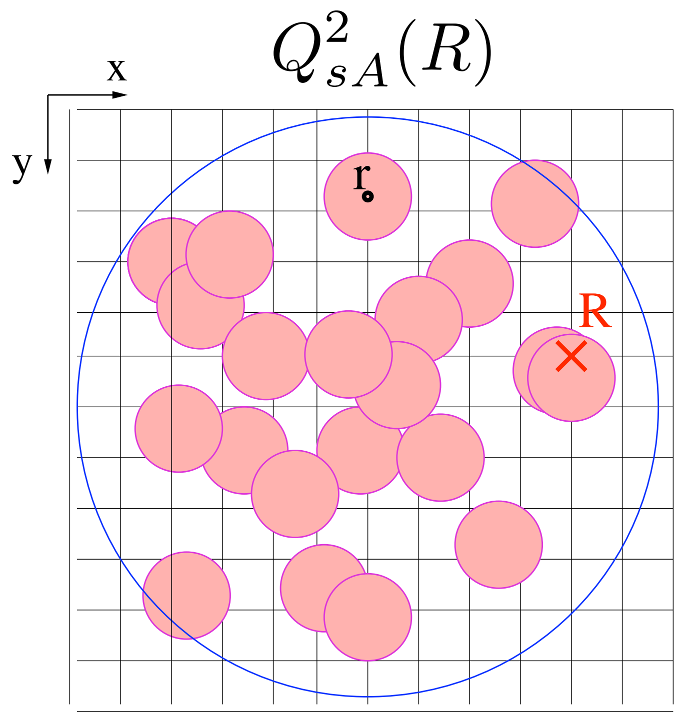
Homogeneous "disk" nucleus characterized by a single initial saturation scale, $Q_s^2 \sim 1\ \mathrm{GeV}^2$, adjusted to reproduce RHIC most central data



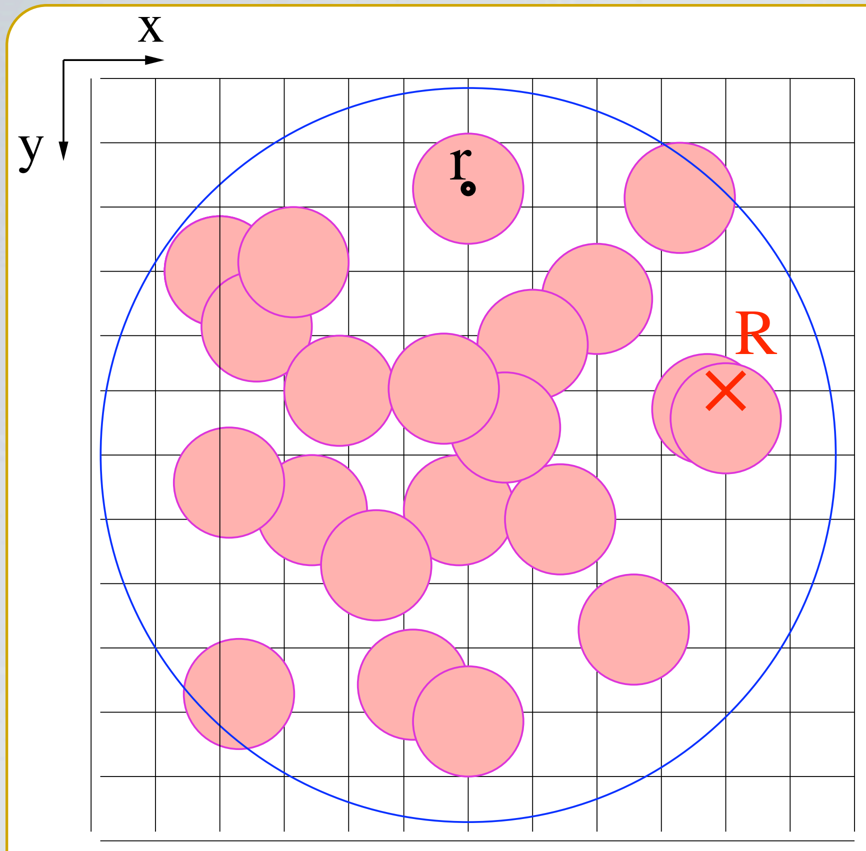
This approach underestimates data

JLA & Dumitru 2010

Monte Carlo treatment of nuclear geometry



rcBK Monte Carlo (JLA & Dumitru 2010)



1. Generate configurations for the positions of nucleons in the transverse plane (r_i, $i=1...A$). Wood-Saxons thickness function $T_A(R)$
2. Count the number of nucleons at every point in the transverse grid, R.

$$N(\mathbf{R}) = \sum_{i=1}^{A} \Theta\left(\sqrt{\frac{\sigma_0}{\pi}} - |\mathbf{R} - \mathbf{r_i}|\right) \qquad \sigma_0 \simeq 42 \text{ mb}$$

3. Assign a local initial ($x=x_0=0.01$) saturation scale at every point in the transverse grid, R:

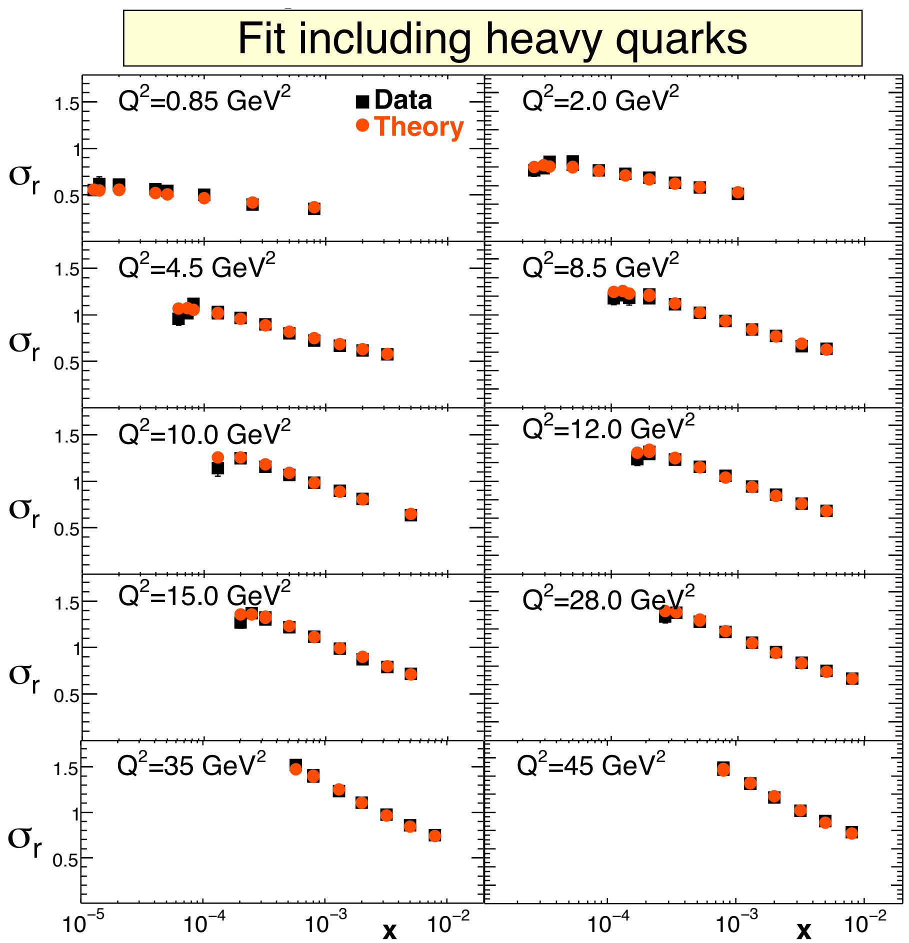
$$Q_{s0}^2(\mathbf{R}) = N(\mathbf{R})\, Q_{s0,\,\mathrm{nucl}}^2 \qquad Q_{s0,\,\mathrm{nucl}}^2 = 0.2 \text{ GeV}^2;$$

$$\varphi(x_0 = 0.01, k_t, R) \xrightarrow{\text{rcBK equation}} \varphi(x, k_t, R)$$

The proton u.g.d is constrained by analysis of e+p and p+p data using a similar running coupling BK approach

Fits to reduced cross sections in e+p HERA collisions

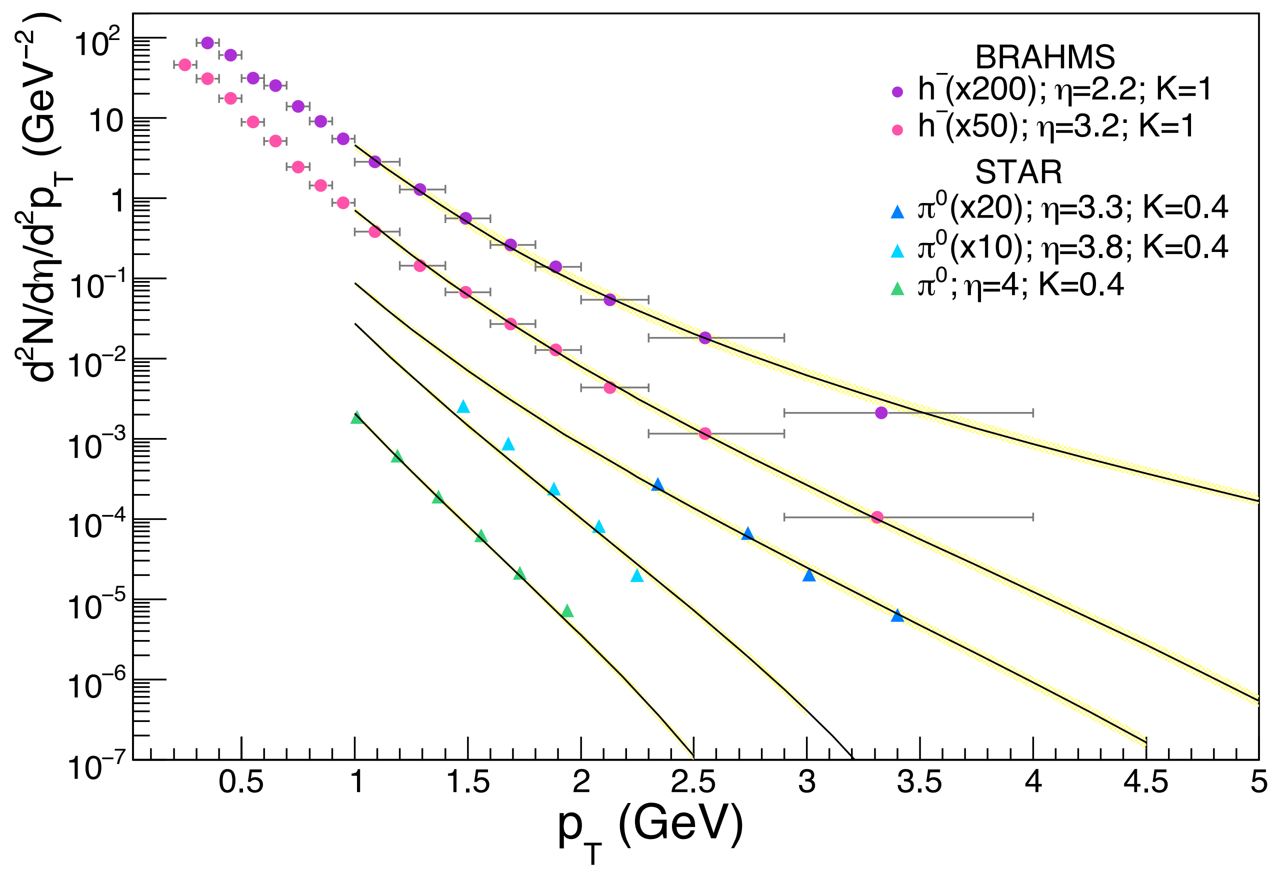
(JLA-Armesto-Milhano-Quiroga-Salgado)



$$\mathcal{N}(r, Y=0) = 1 - \exp\left[-\frac{\left(r^2\, Q_0^2\right)^{\gamma}}{4} \ln\left(\frac{1}{r\,\Lambda} + e\right)\right]$$

$$\gamma = 1.119 \qquad Q^2_{s0,nucl} = 0.168\,\mathrm{GeV}^2$$

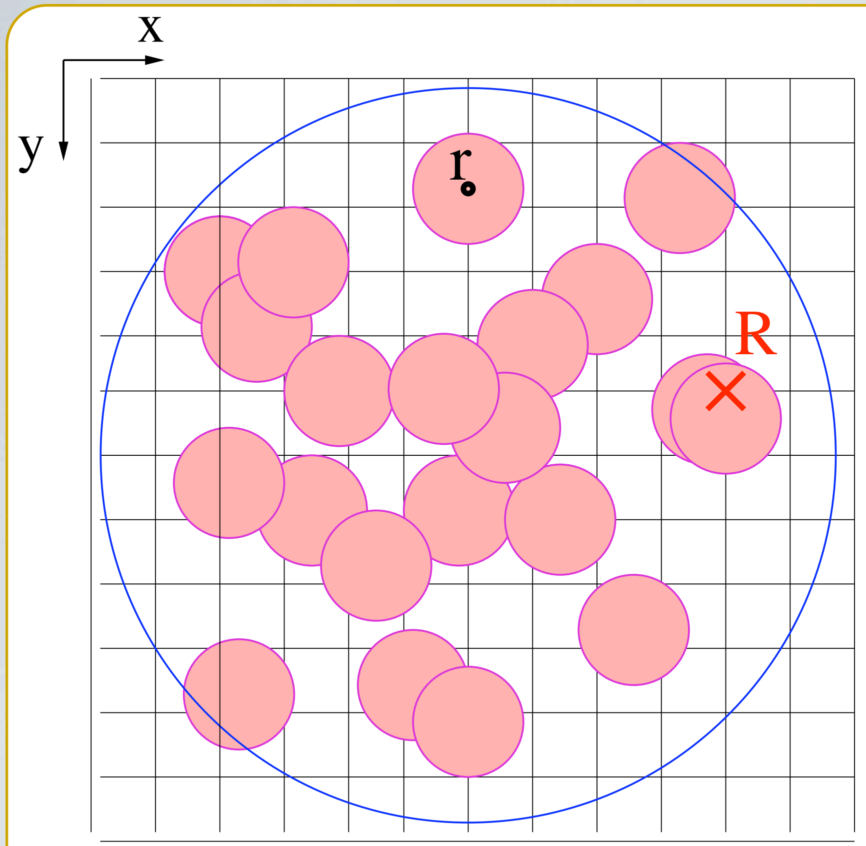
Forward single inclusive spectra in p+p collisions at RHIC (JLA-Marquet)



$$\mathcal{N}(r, Y\!=\!0; R) = 1 - \exp\left[-\frac{r^2\, Q_{s0}^2(R)}{4} \ln\left(\frac{1}{\Lambda\, r} + e\right)\right]$$

$$Q^2_{s0,\,\mathrm{nucl}} = 0.2\ \mathrm{GeV}^2$$

rcBK Monte Carlo



1. Generate configurations for the positions of nucleons in the transverse plane (r_i, i=1...A). Wood-Saxons thickness function $T_A(R)$
2. Count the number of nucleons at every point in the transverse grid, R.

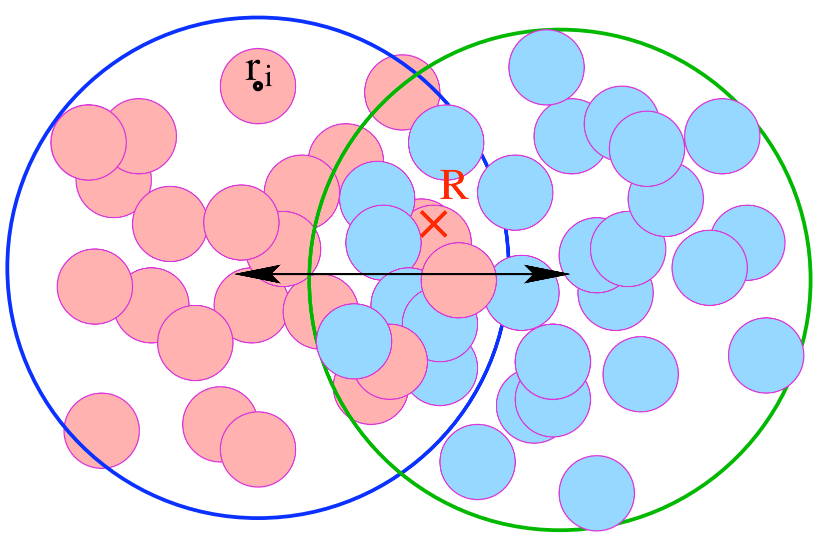
$$N(\mathbf{R}) = \sum_{i=1}^{A} \Theta\left(\sqrt{\frac{\sigma_0}{\pi}} - |\mathbf{R} - \mathbf{r_i}|\right) \qquad \sigma_0 \simeq 42 \text{ mb}$$

3. Assign a local initial ($x=x_0=0.01$) saturation scale at every point in the transverse grid, R:

$$Q_{s0}^2(\mathbf{R}) = N(\mathbf{R})\, Q_{s0,\,\mathrm{nucl}}^2 \qquad Q_{s0,\,\mathrm{nucl}}^2 = 0.2 \text{ GeV}^2;$$

$$\varphi(x_0 = 0.01, k_t, R) \xrightarrow{\text{rcBK equation}} \varphi(x, k_t, R)$$

4. Gluon production is calculated at each transverse point according to kt-factorization

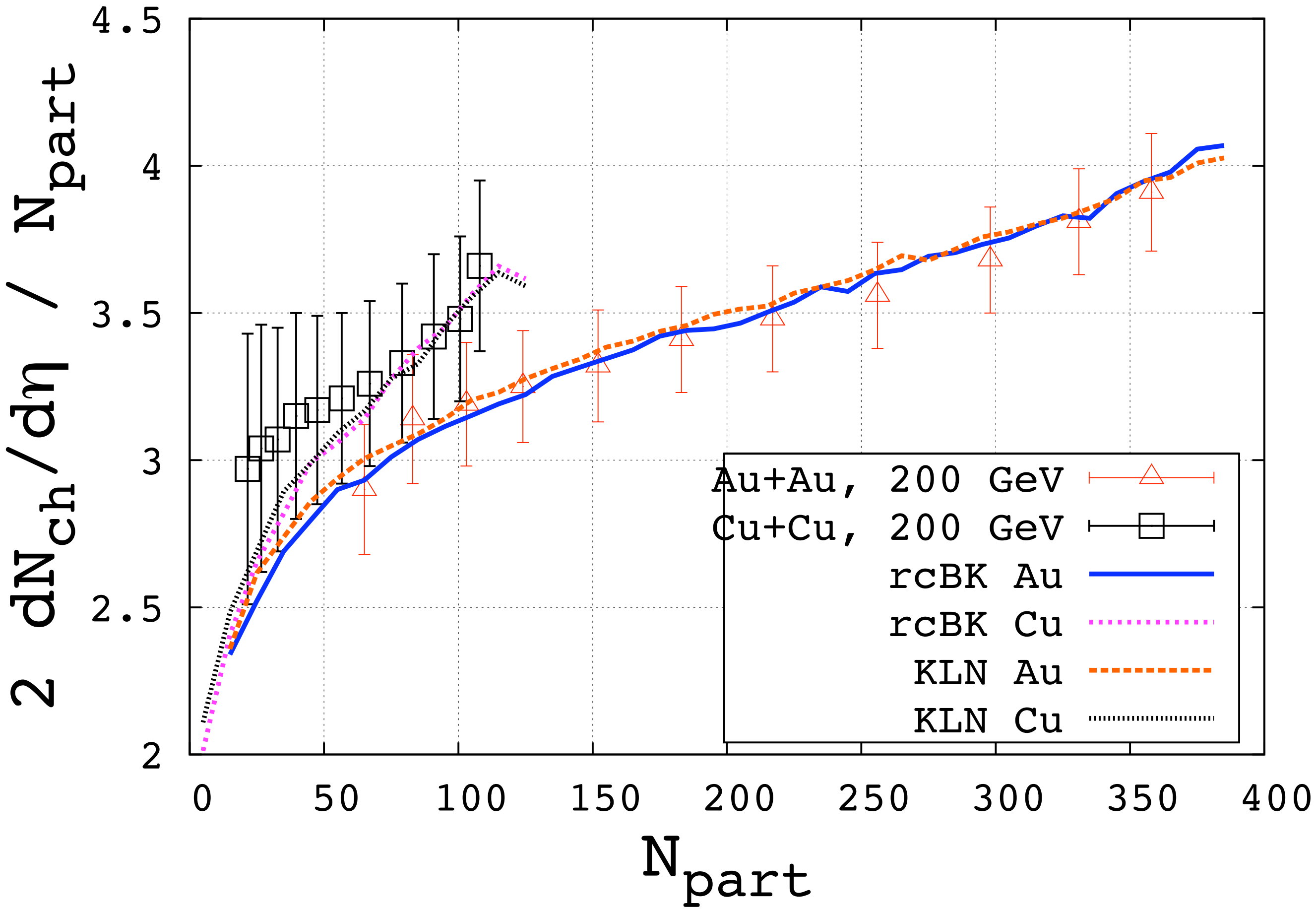


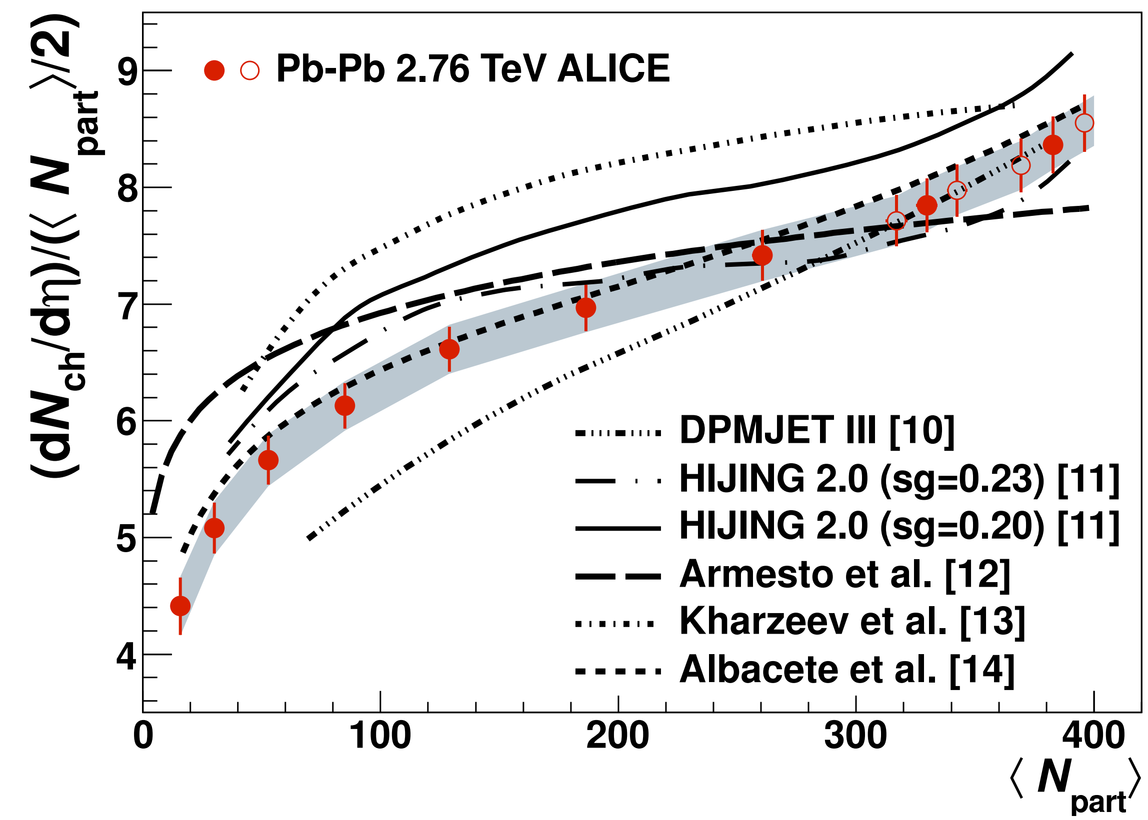
$$\frac{d\sigma^{A+B\to g}}{dy\, d^2p_t\, d^2R} = \kappa \frac{2}{C_F} \frac{1}{p_t^2} \int^{p_t} \frac{d^2k_t}{4} \int d^2b\, \alpha_s(Q)\, \varphi\left(\frac{|p_t + k_t|}{2}, x_1; b\right) \varphi\left(\frac{|p_t - k_t|}{2}, x_2; R - b\right)$$

$$\frac{dN_{\mathrm{ch}}}{d\eta} = \frac{\cosh\eta}{\sqrt{\cosh^2\eta + m^2/P^2}} \frac{dN_{\mathrm{ch}}}{dy} \qquad m = 350 \text{ MeV and } P = 400 \text{ MeV}$$

rcBK Monte Carlo

MV initial conditions: Good description of Npart dependence of RHIC Au+Au and Cu+Cu and LHC Pb+Pb multiplicities:



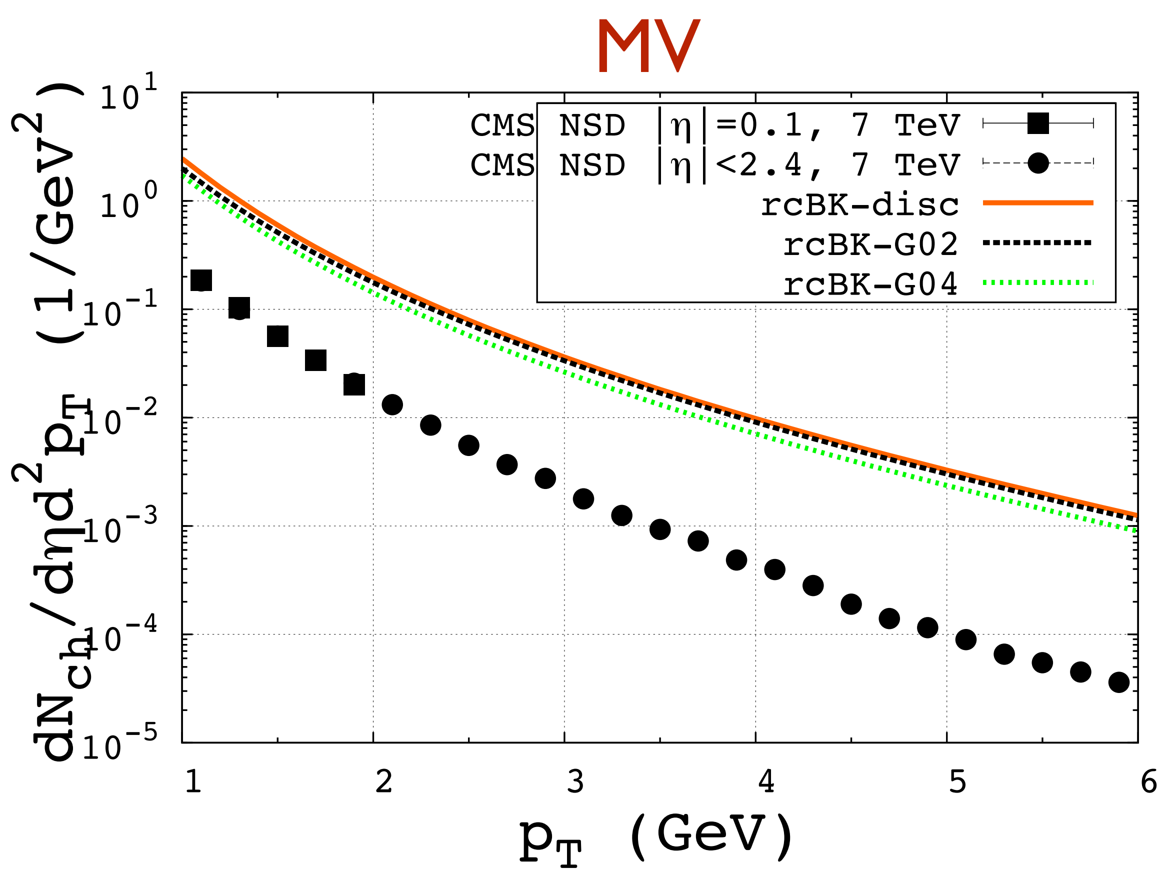


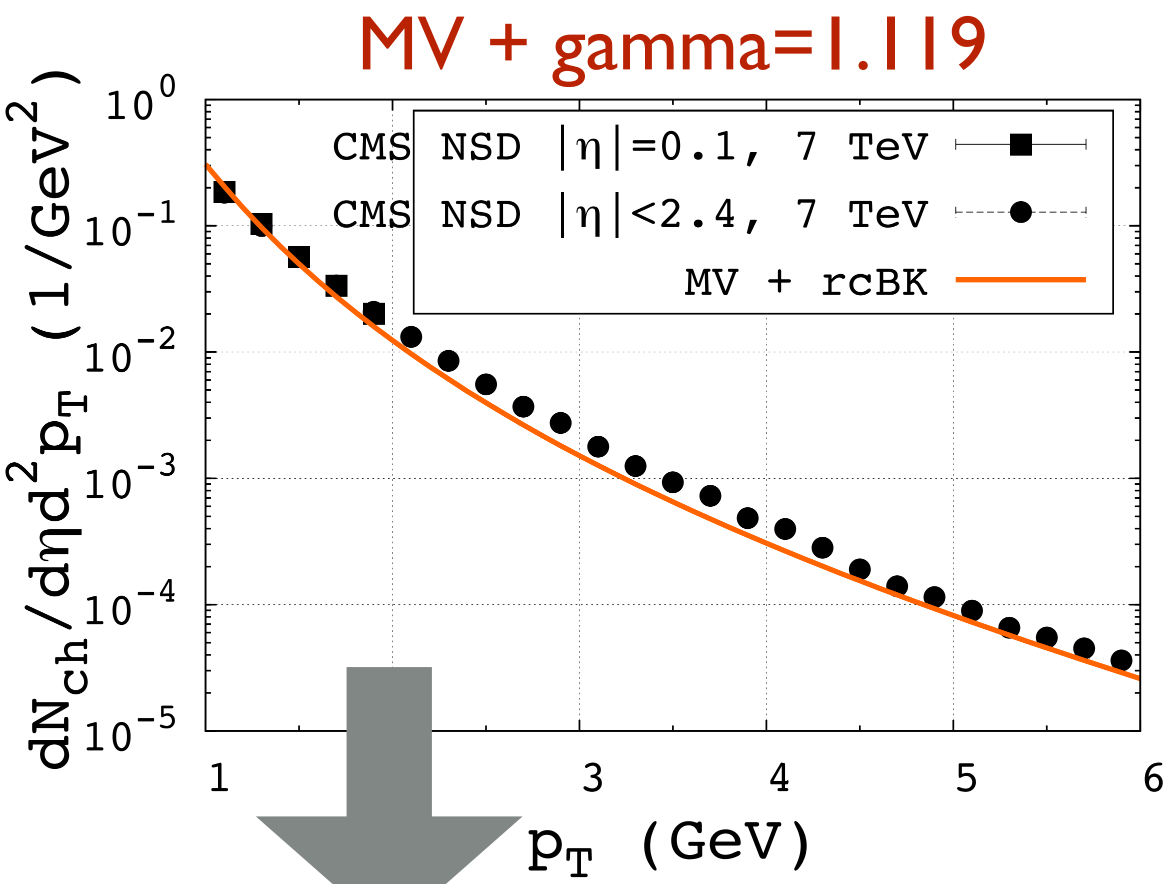
- Systematics: Changing the model parameters (average hadron mass, pt-cutoff ...) yield an equally good description of RHIC and LHC data by just adjusting the normalization (i.e the gluon to hadron ratio)

$$\kappa \approx 4.5 \div 7$$

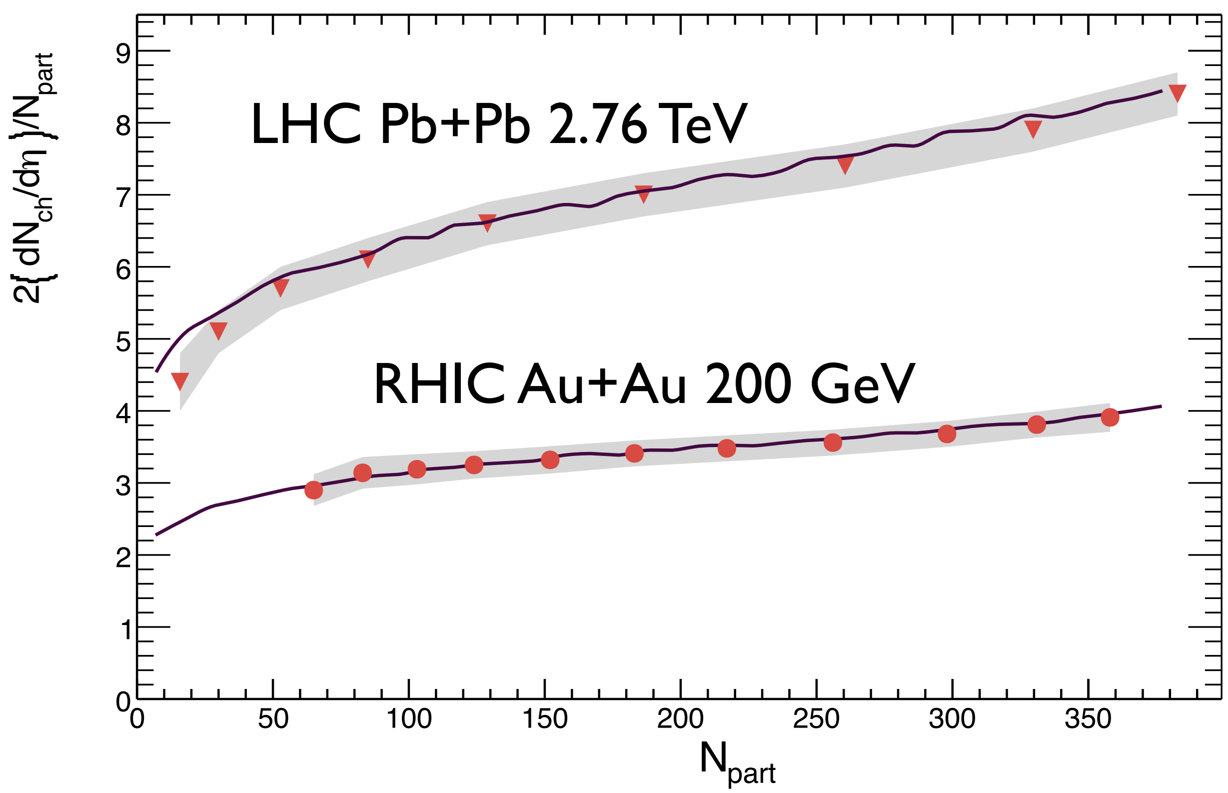
Constraining the initial conditions: p+p yields at the LHC

Steeper initial conditions than the MV model are needed to get a good description of p+p yields





Steeper initial conditions also provide a good description of RHIC and LHC multiplicity data:



OUTLOOK

- CGC approaches and MC generators both provide a good description of the energy and centrality dependence of the charged hadron multiplicities measured at RHIC and the LHC

- They both include, albeit through rather different implementation, strong coherence effects

My to do list for the rcBK MC:

- Complete study of the systematics (model parameters and initial conditions)
- Take into account nucleon geometry and fluctuations
- Eventually, improve the description of particle production, maybe resorting to classical Yang-Mills calculations suplemented with information on the solutions of the evolution
- Use rcBK as initial condition for hydro simulations. Code available at:

http://physics.baruch.cuny.edu/node/people/adumitru/res_cgc