# *Multiplicities in Pb-Pb collisions at the LHC*

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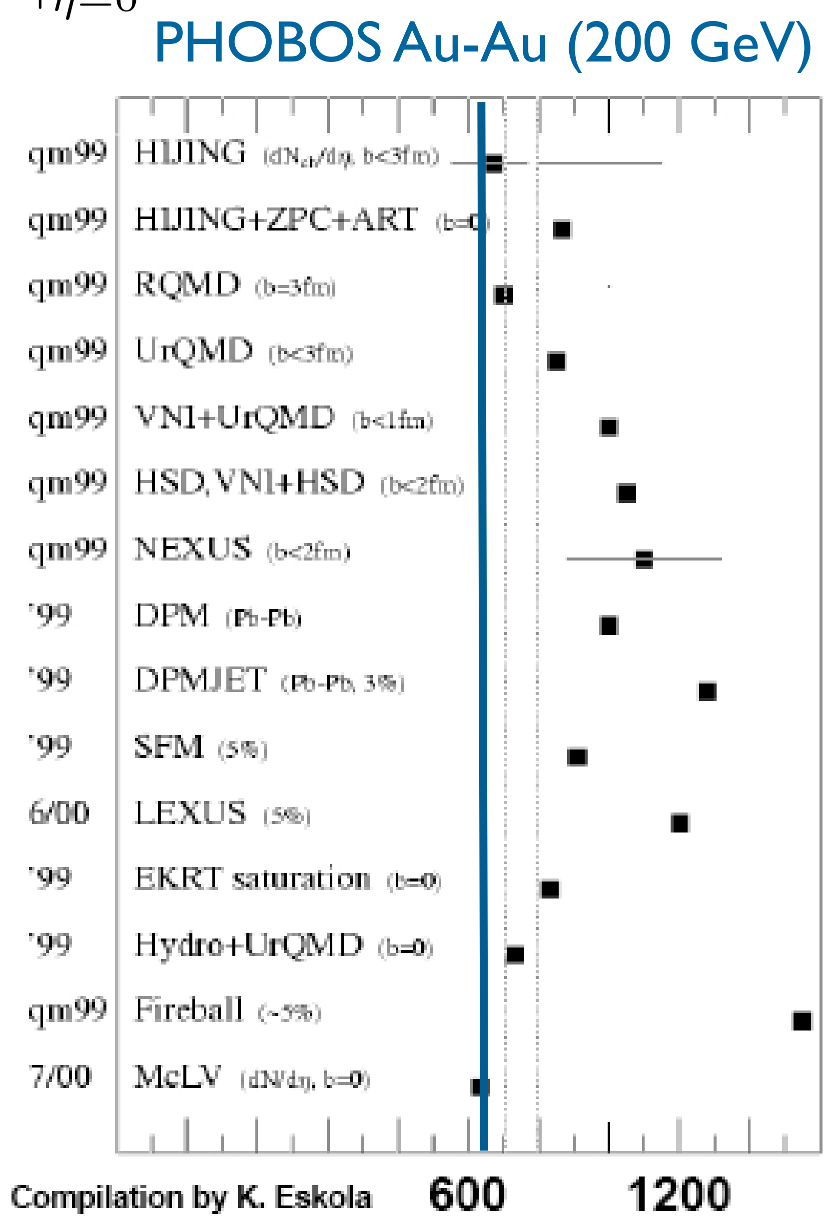
**Orsay, January 2011**

# 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

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



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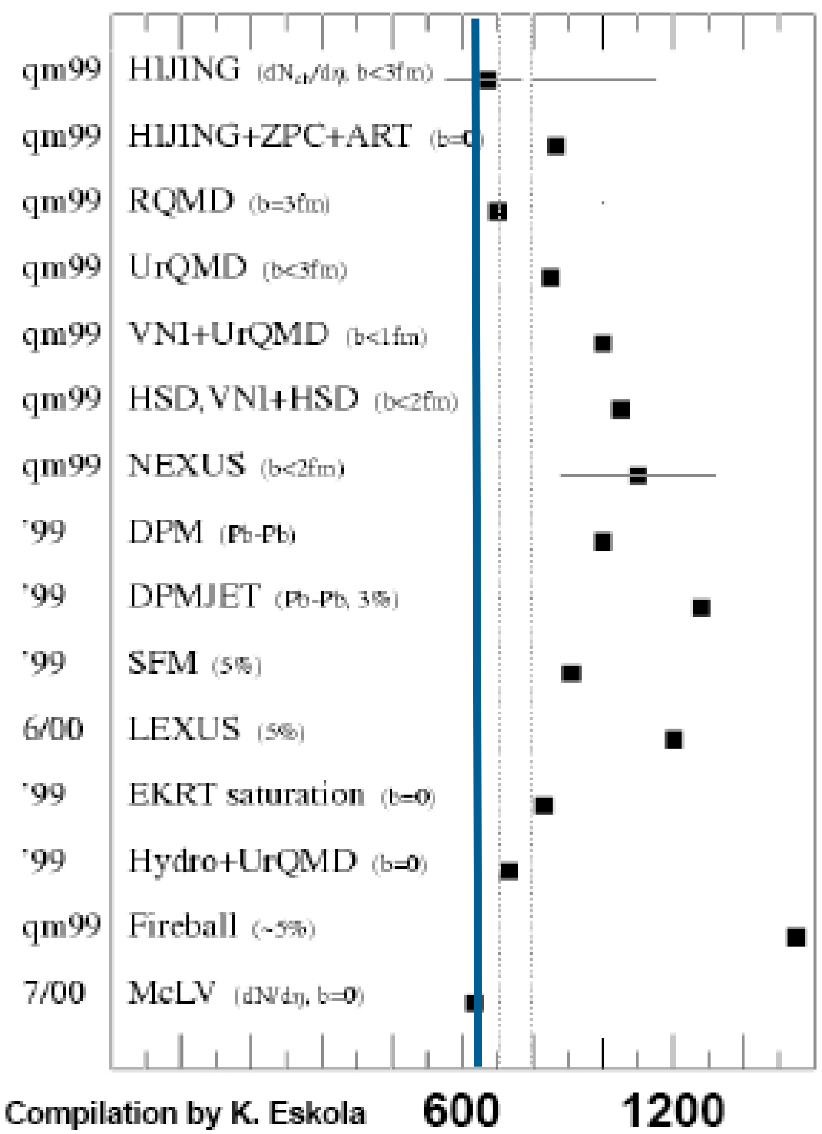
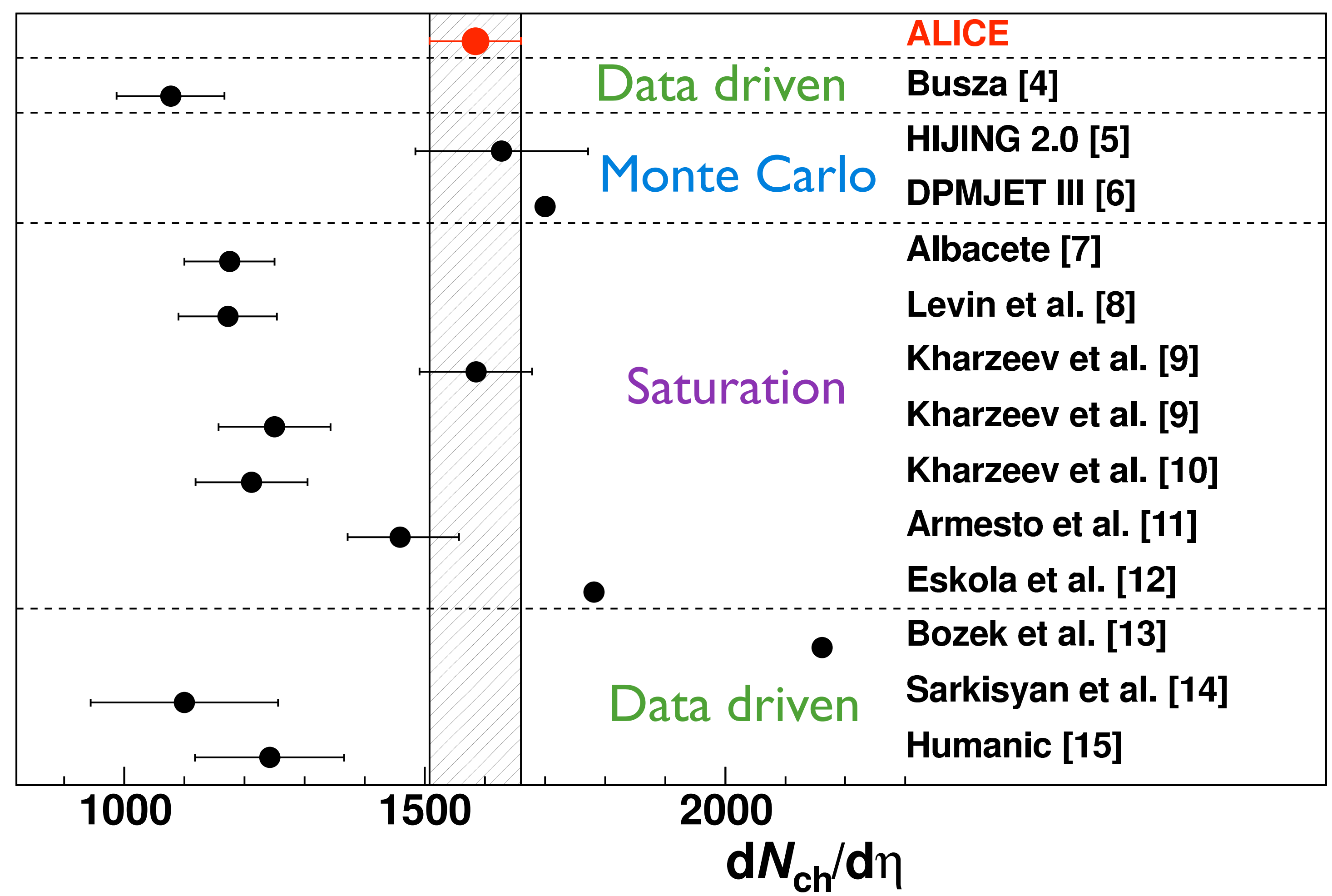



ALICE Pb-Pb (2.76 TeV, 5% central)



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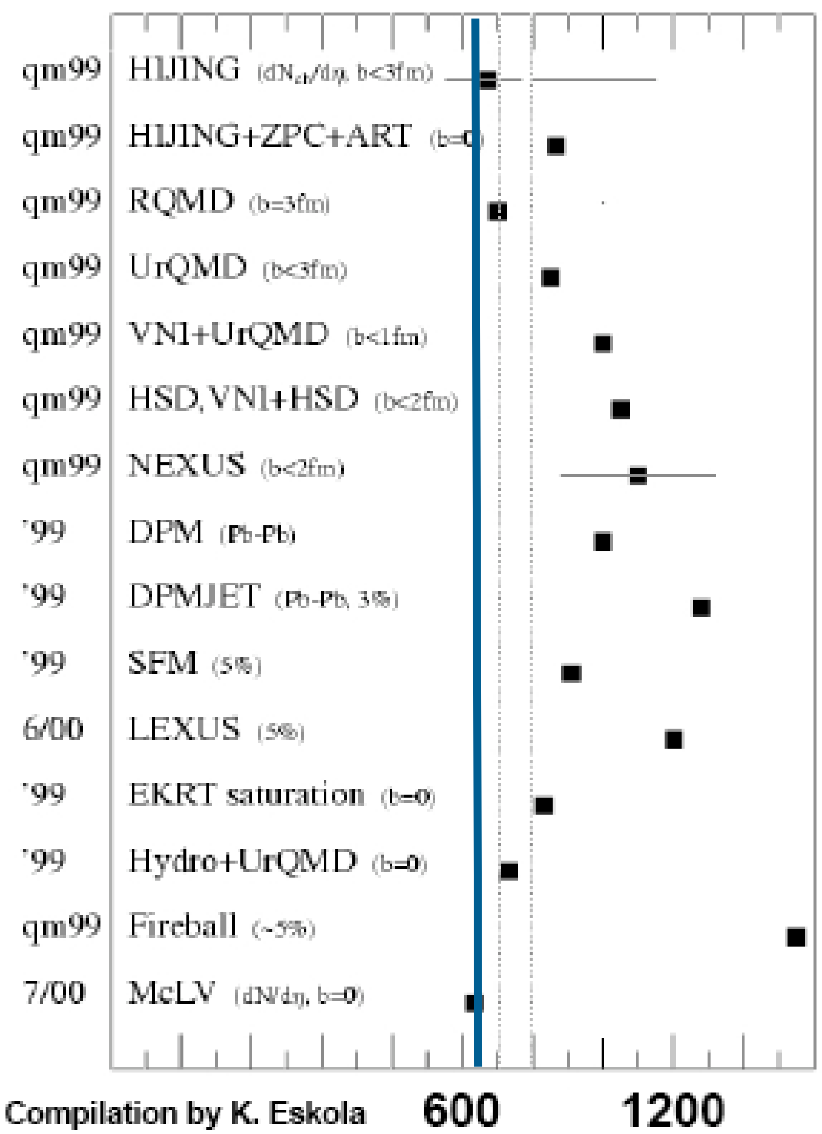
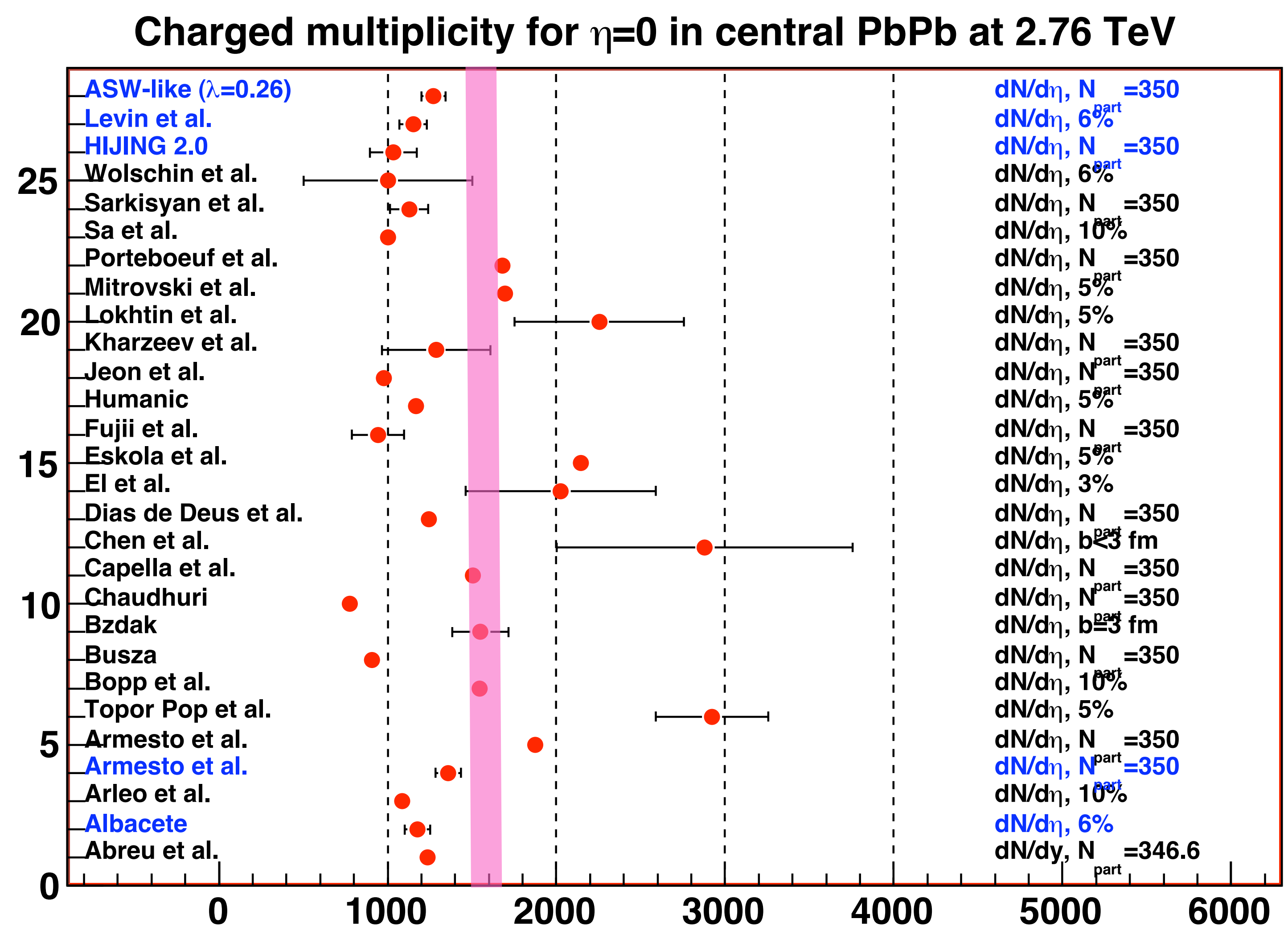


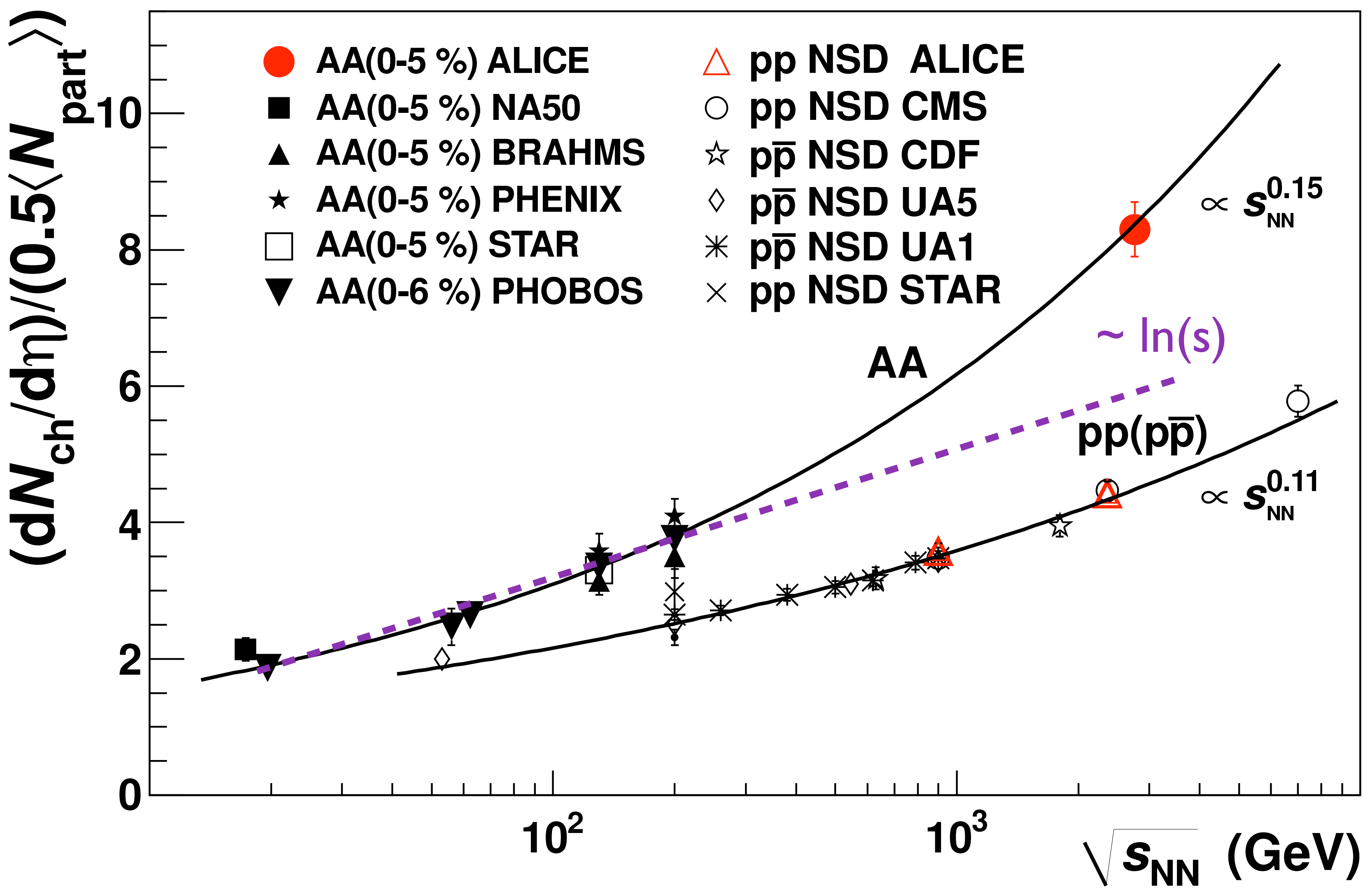




compilation by N. Armesto

# Energy dependence

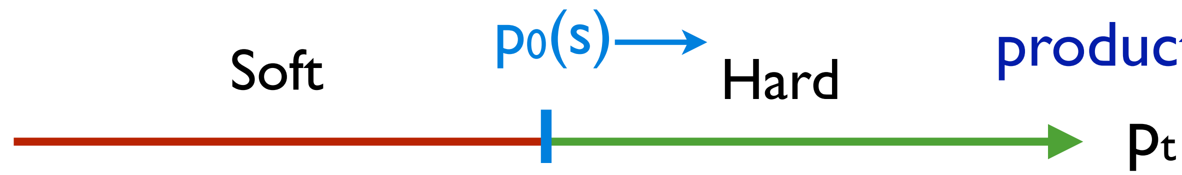
- Energy dependence of the multiplicities seems to obey a power-law. Logarithmic trends dictated by lower energy data seems to be ruled out by the LHC data

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



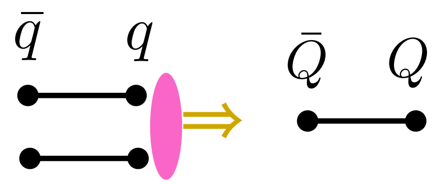
# Coherence mechanisms

Monte Carlo event generators: Soft (strings, DPM) + Hard (LO pQCD independent minijet production)




Breakdown of independent minijet production

String fusion



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

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

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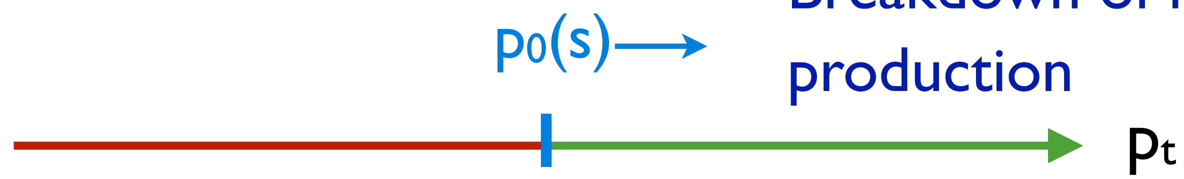


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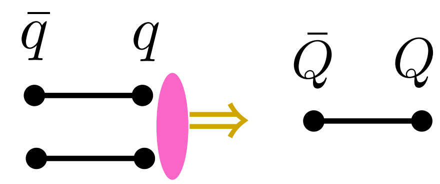


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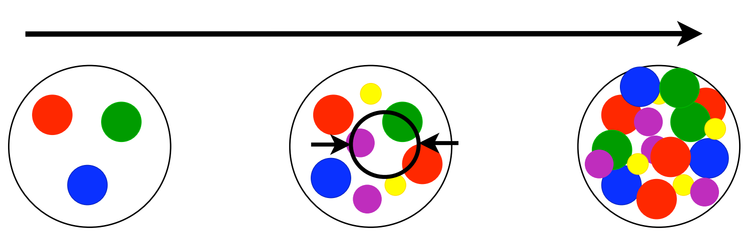
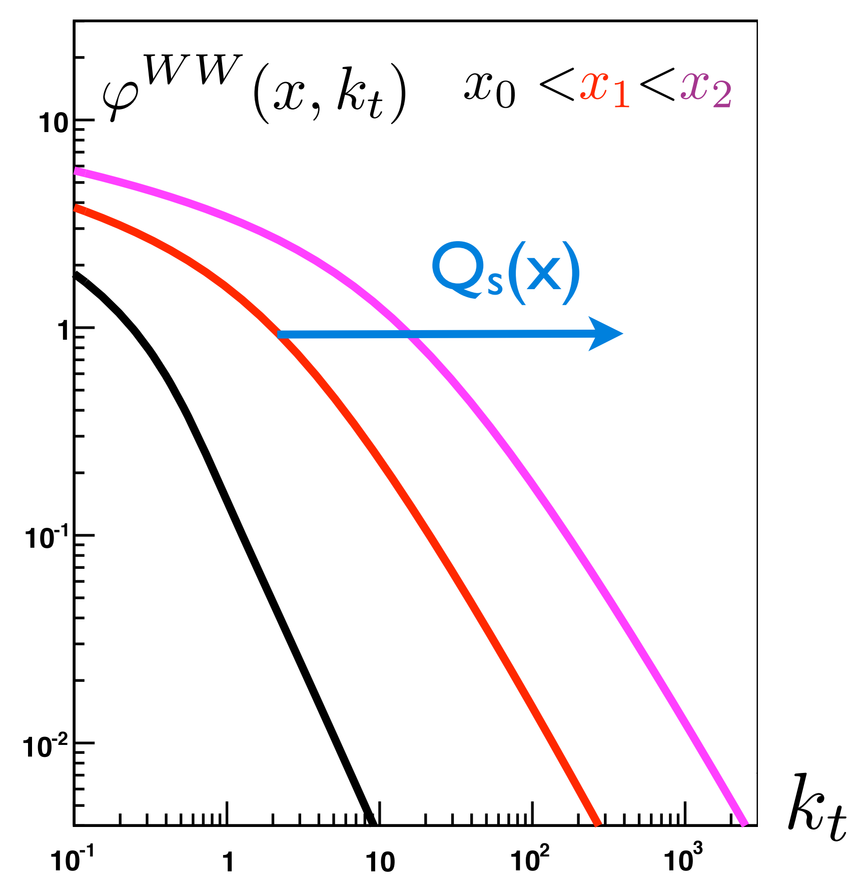
CGC: Non-linear recombination effects tame the growth of gluon densities with increasing energy




"BK-JIMWLK" equations

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

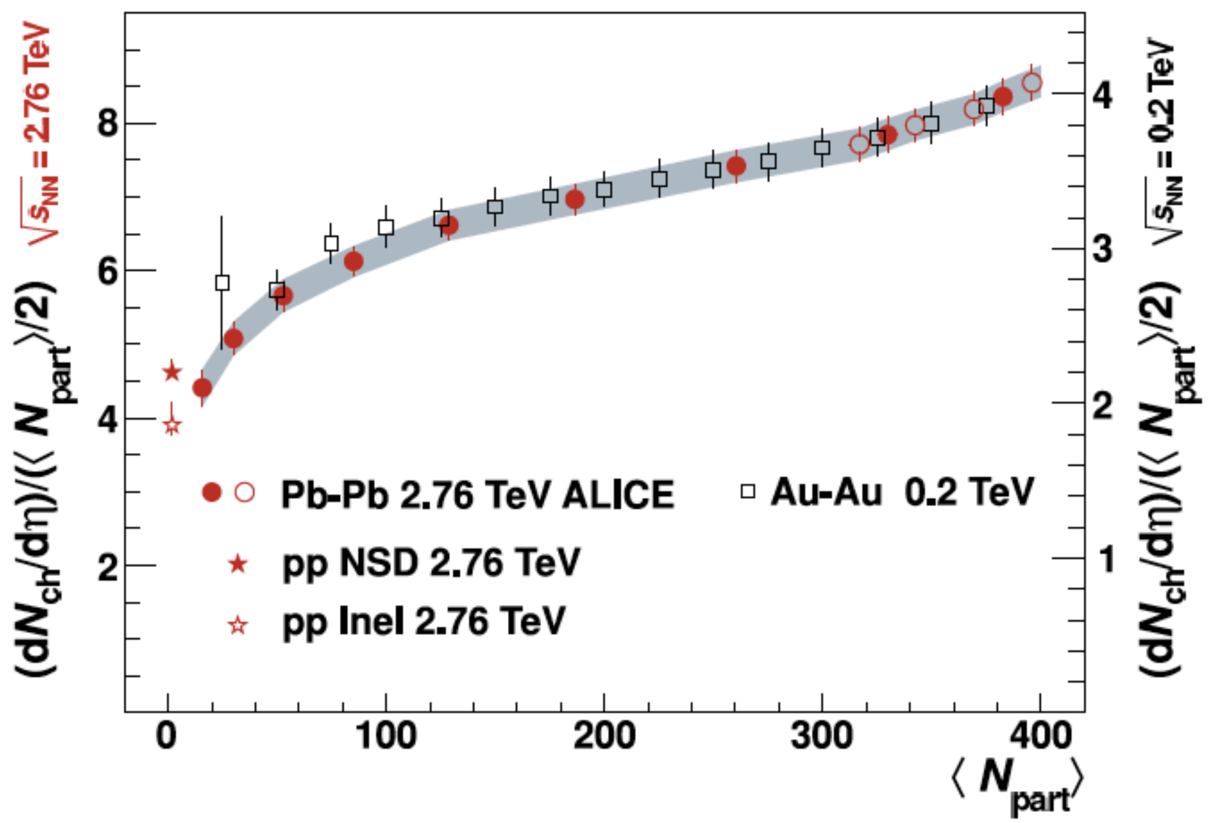
$$xG(x,Q^2) \sim \int^{Q^2} d^2k_t\, \varphi^{WW}(x,k_t)$$

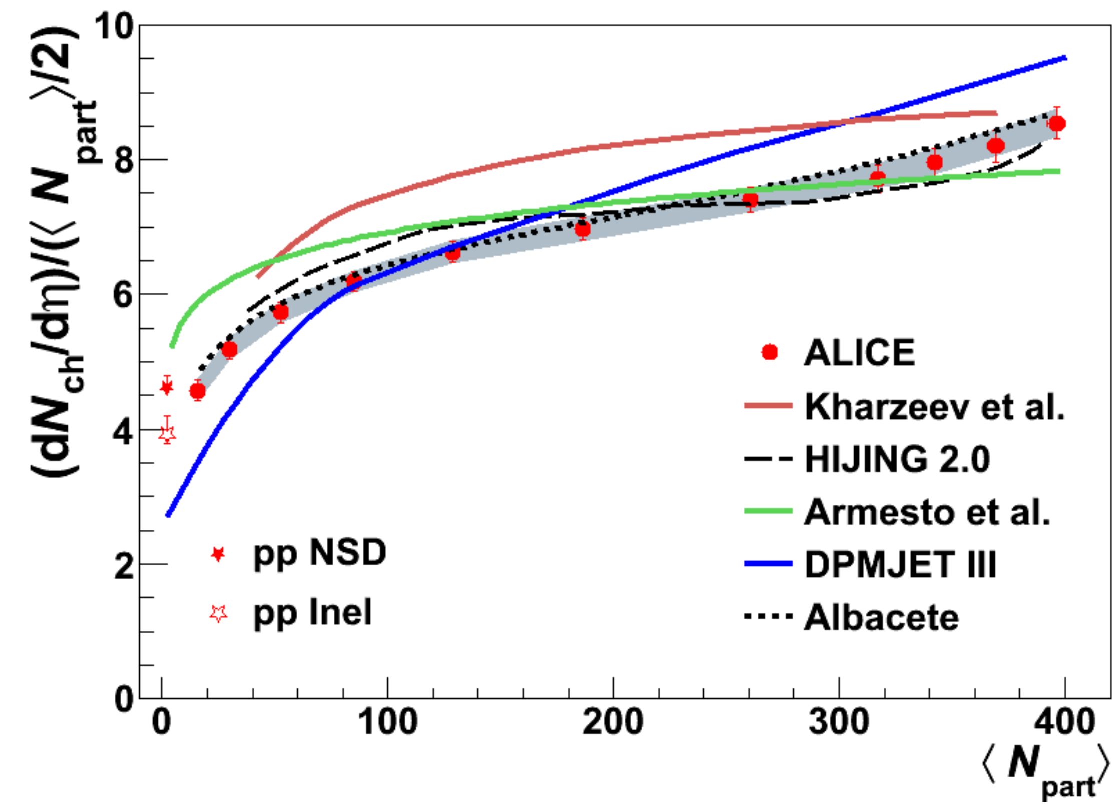


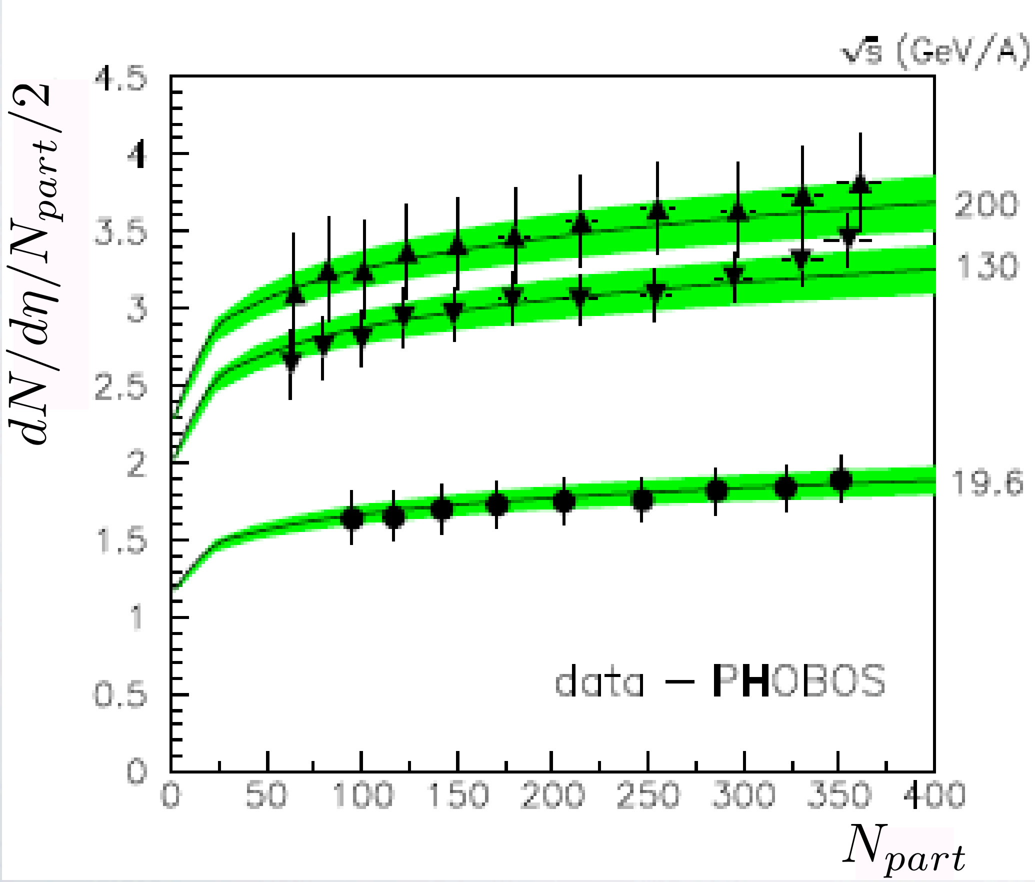
# Centrality dependence

The shape of the centrality dependence is very similar to the one observed at RHIC x 2.2

ALICE Collaboration arXiv:1012.1657



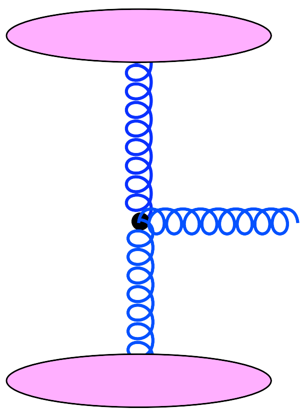



# Saturation models

All different saturation models rely on the use of kt-factorization to describe inclusive gluon production

$\varphi_A(x, p_t, b)$



$\varphi_B(x, p_t, b)$

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

unintegrated gluon distributions

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

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

Local Parton-Hadron Duality:
phase-space distribution of produced gluons at t=0 ~ hadrons at $t=t_{det}$

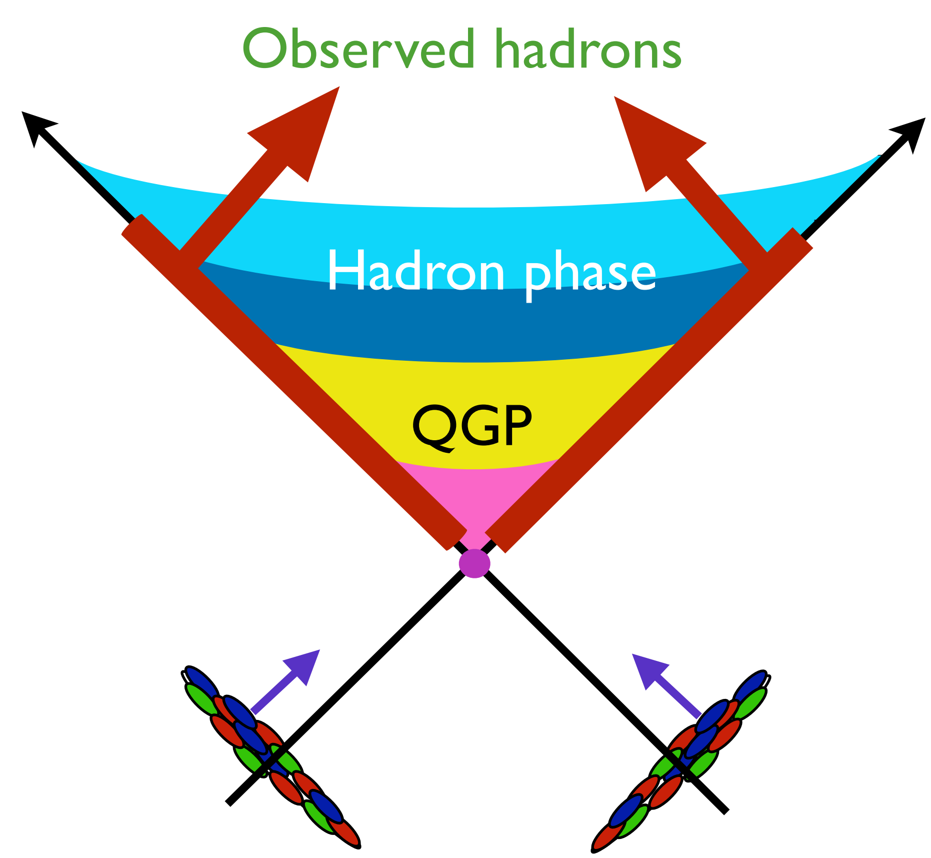
+

eta/y transformation

$$y(\eta, p_t, m) = \frac{1}{2} \ln \left[ \frac{\sqrt{\frac{m^2+p_t^2}{p_t^2} + \sinh^2\eta} + \sinh\eta}{\sqrt{\frac{m^2+p_t^2}{p_t^2} + \sinh^2\eta} \quad \sinh\eta} \right]$$

+

Implementation details...



# Saturation models

KLN (Kharzeev-Levin-Nardi, NPA 747 609). Model of unintegrated gluon distributions and running coupling effects

ASW (Armesto-Salgado-Wiedemann PRL94 022002). Data driven. Extension of geometric scaling observed in e+p and e+A collisions to p+A and A+A collisions

$$\phi\left(\frac{k_t}{Q_s(x)}\right) \qquad Q_{sA}^2(x) = A^{1/(3\delta)}\, Q_{sp}^2(x)$$

$$Q_s^2(x) \sim Q_0^2 \left(\frac{x_0}{x}\right)^\lambda \Rightarrow \frac{1}{N_{part}} \frac{dN_{AB}^g}{d^2b\, d\eta}\bigg|_{\eta=0} = \begin{cases} \sqrt{s}^\lambda \ln\left(\sqrt{s}^\lambda N_{part}\right) \;; & \text{KLN} \\ \sqrt{s}^\lambda\, N_{part}^{\frac{1-\delta}{3\delta}} \;; & \text{ASW} \end{cases}$$

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Running coupling BK (JLA 07 and JLA & Dumitru 10). (x,kt)-dependence of gluon densities calculated by solving the running coupling BK equation. Free parameters associated to the initial conditions fixed at RHIC

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

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

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

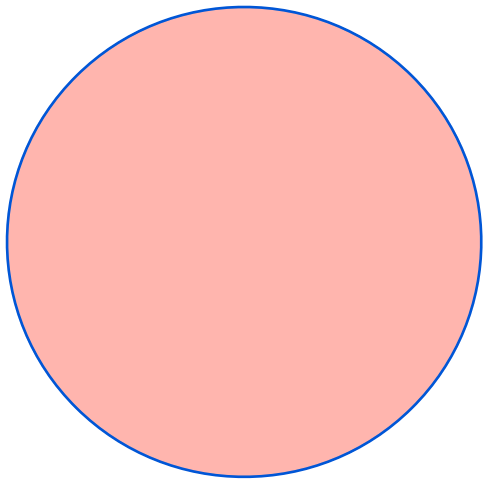
$$\varphi(k,x,b) = \frac{C_F}{\alpha_s(k)\,(2\pi)^3}\int d^2\mathbf{r}\; e^{-i\mathbf{k}\cdot\mathbf{r}}\, \nabla^2_{\mathbf{r}}\mathcal{N}_G(r, Y = \ln(x_0/x), b)\,. \qquad \mathcal{N}_G(r,x) = 2\,\mathcal{N}(r,x) - \mathcal{N}^2(r,x)$$

# Nuclear geometry in rcBK approaches

## JLA 2007

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

$Q_{sA}^2$

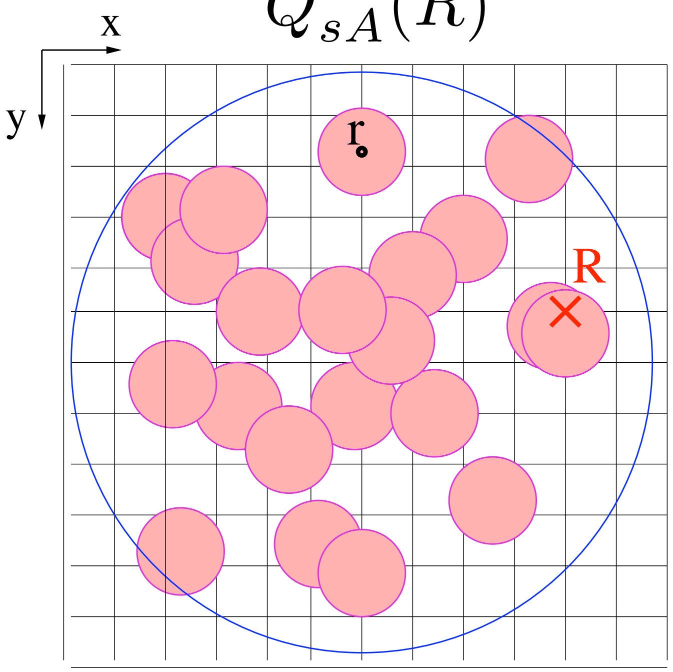


This approach underestimates data

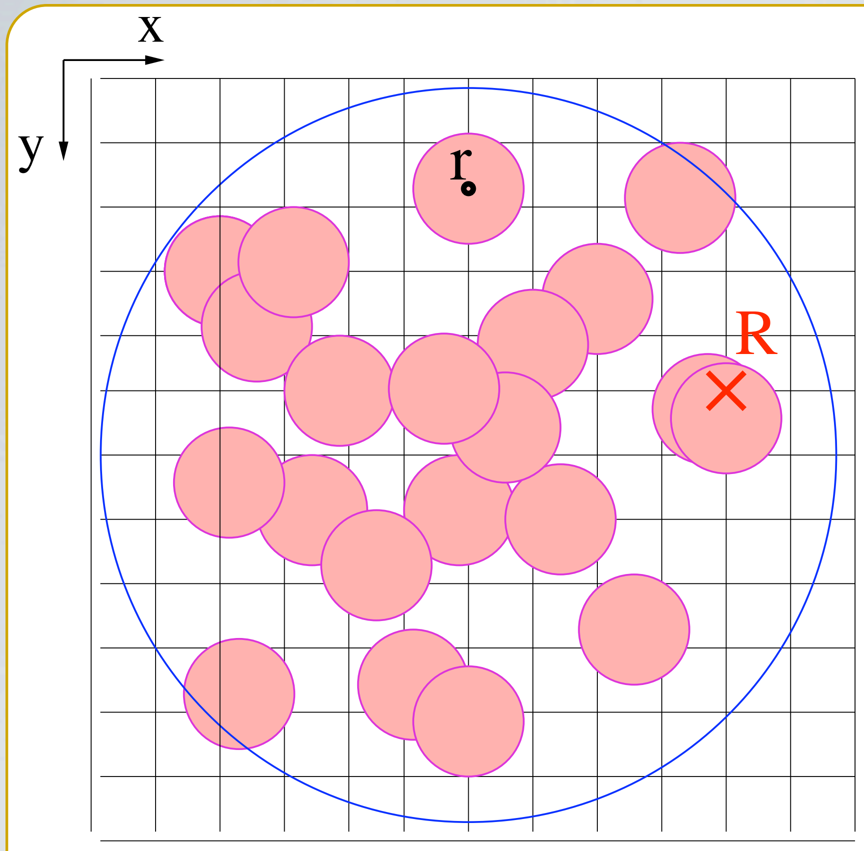
## JLA & Dumitru 2010

Monte Carlo treatment of nuclear geometry

$Q_{sA}^2(R)$



# 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:

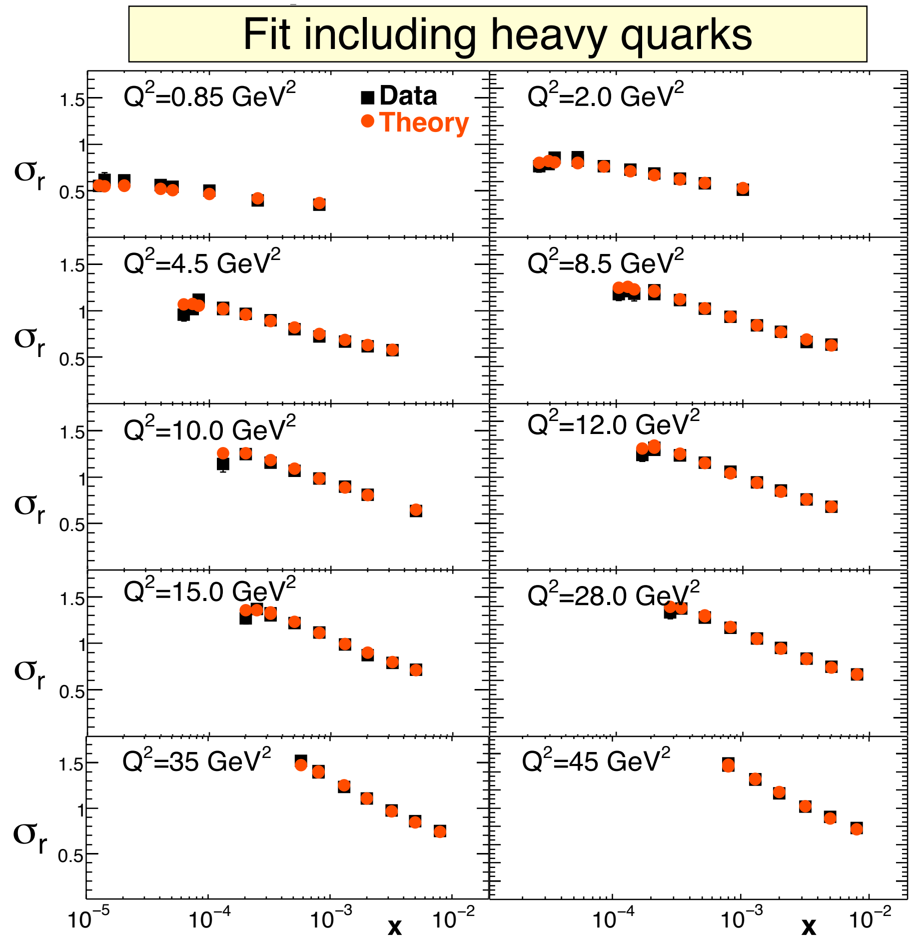
$$Q^2_{s0}(\mathbf{R}) = N(\mathbf{R})\, Q^2_{s0,\,\mathrm{nucl}} \qquad Q^2_{s0,\,\mathrm{nucl}} = 0.2 \text{ GeV}^2;$$

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

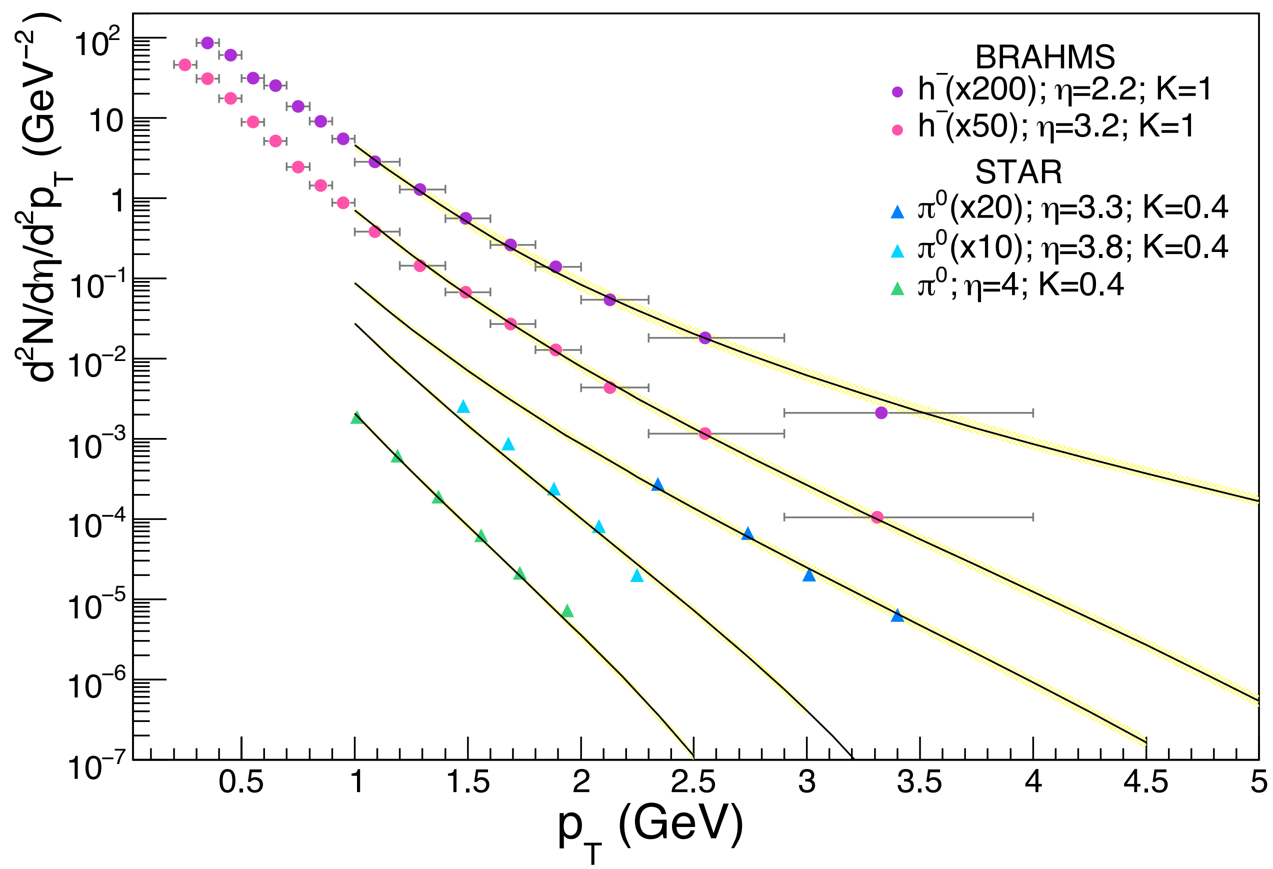
# Outline

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)



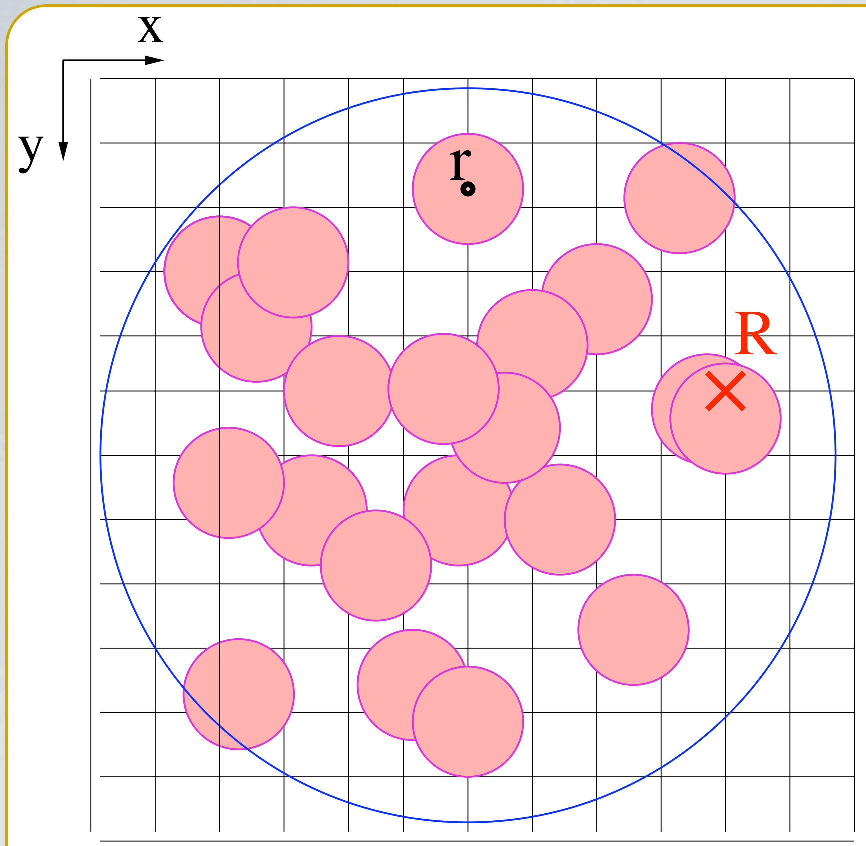

Forward single inclusive spectra in p+p collisions at RHIC (JLA-Marquet)




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

$$Q_{s0,\,\rm nucl}^2 = 0.2\ \mathrm{GeV}^2,$$

# rcBK Monte Carlo

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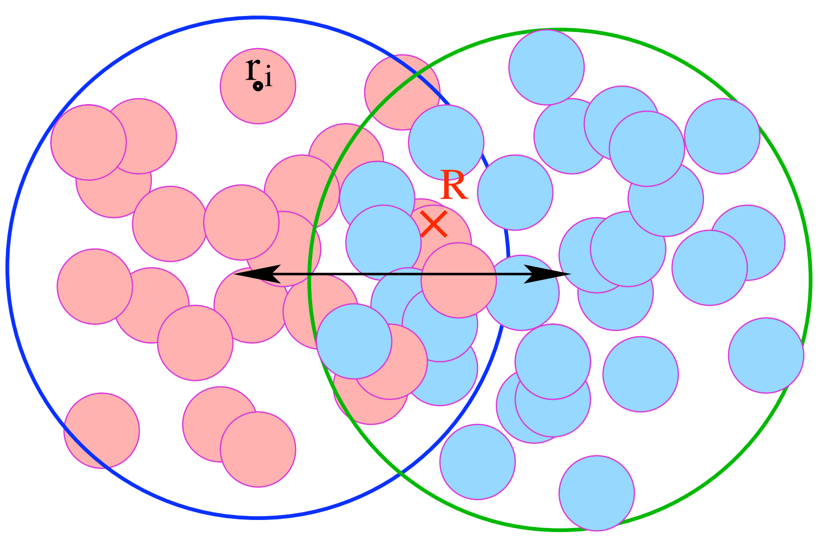
$$\varphi(x_0 = 0.01, k_t, R) \xrightarrow{\text{rcBK equation}} \varphi(x, k_t, R)$$

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

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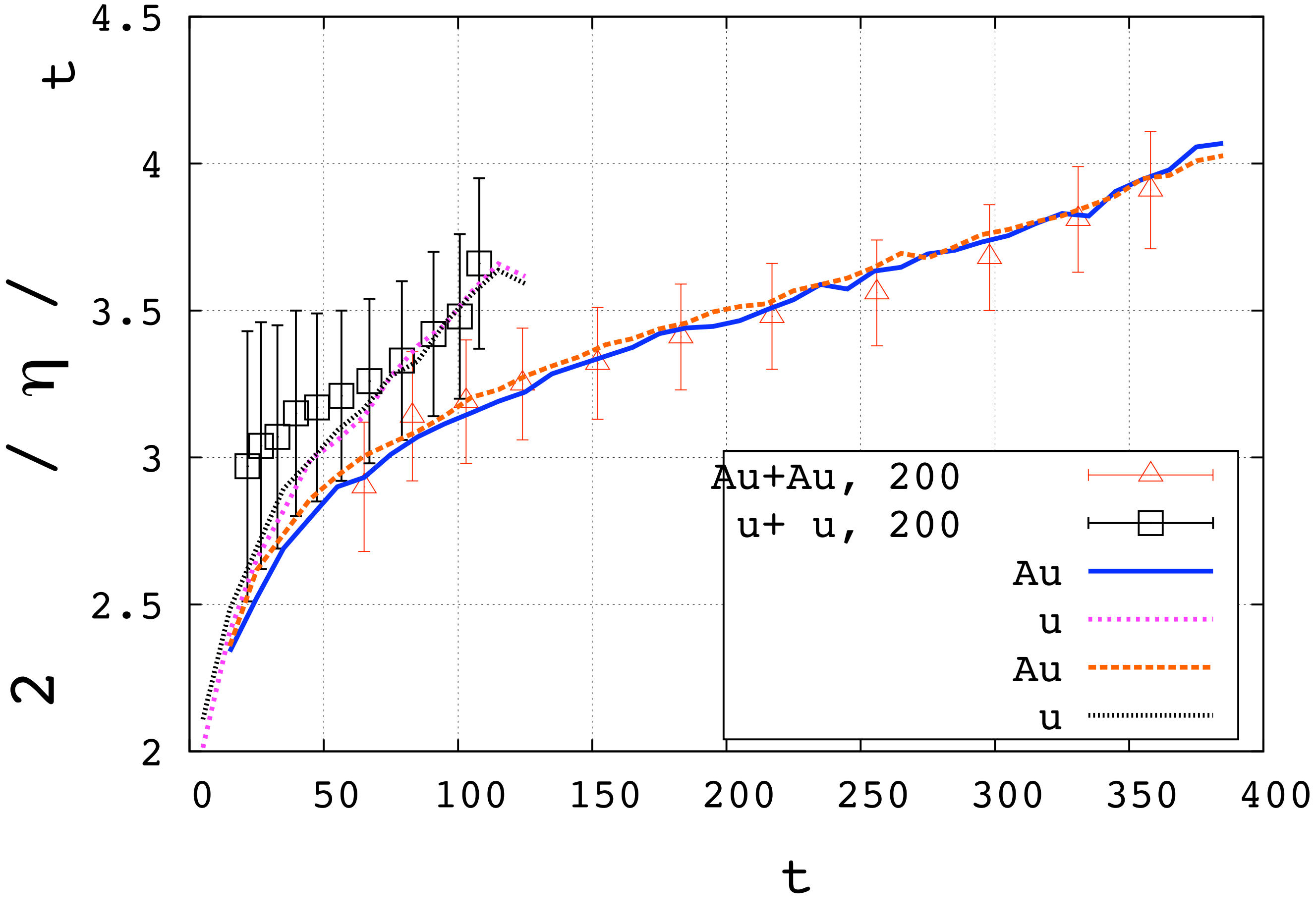
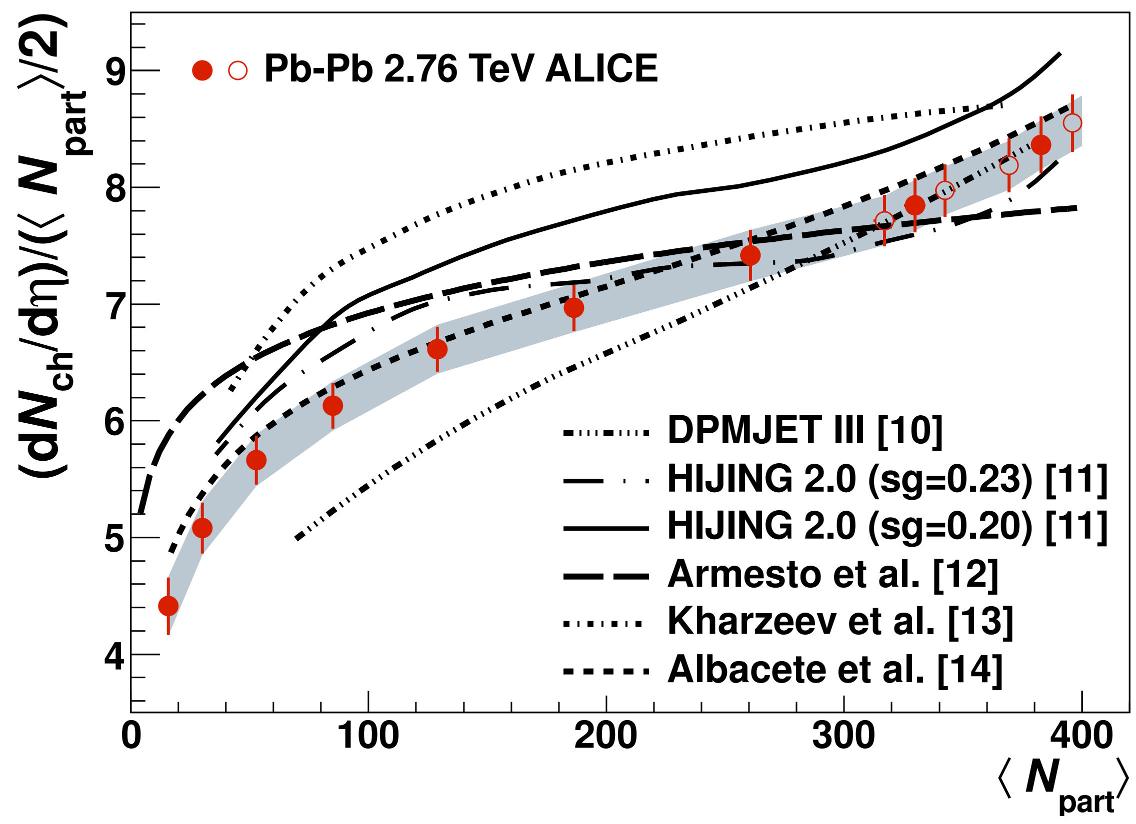
$$\frac{dN_{\mathrm{ch}}}{d\eta} = \frac{\cosh\eta}{\sqrt{\cosh^2\eta + m^2/P^2}}\frac{dN_{\mathrm{ch}}}{dy} \qquad m = 350 \text{ MeV and } P = 400 \text{ MeV}$$

# rcBK Monte Carlo

Good description of Npart dependence of
RHIC Au+Au and Cu+Cu multiplicities



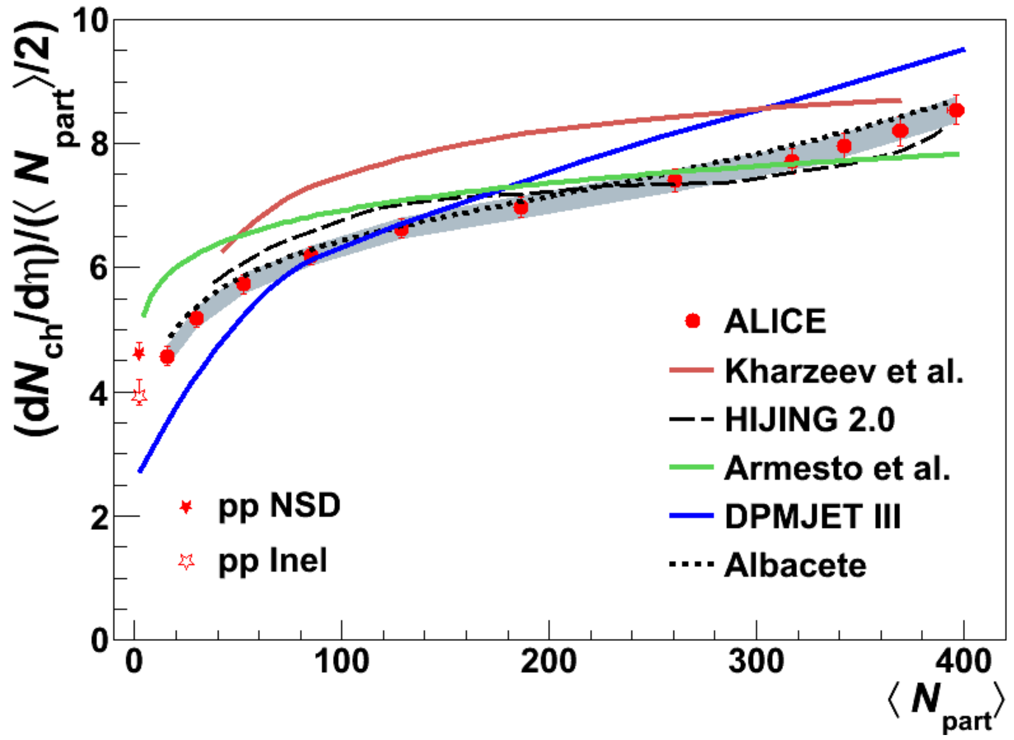



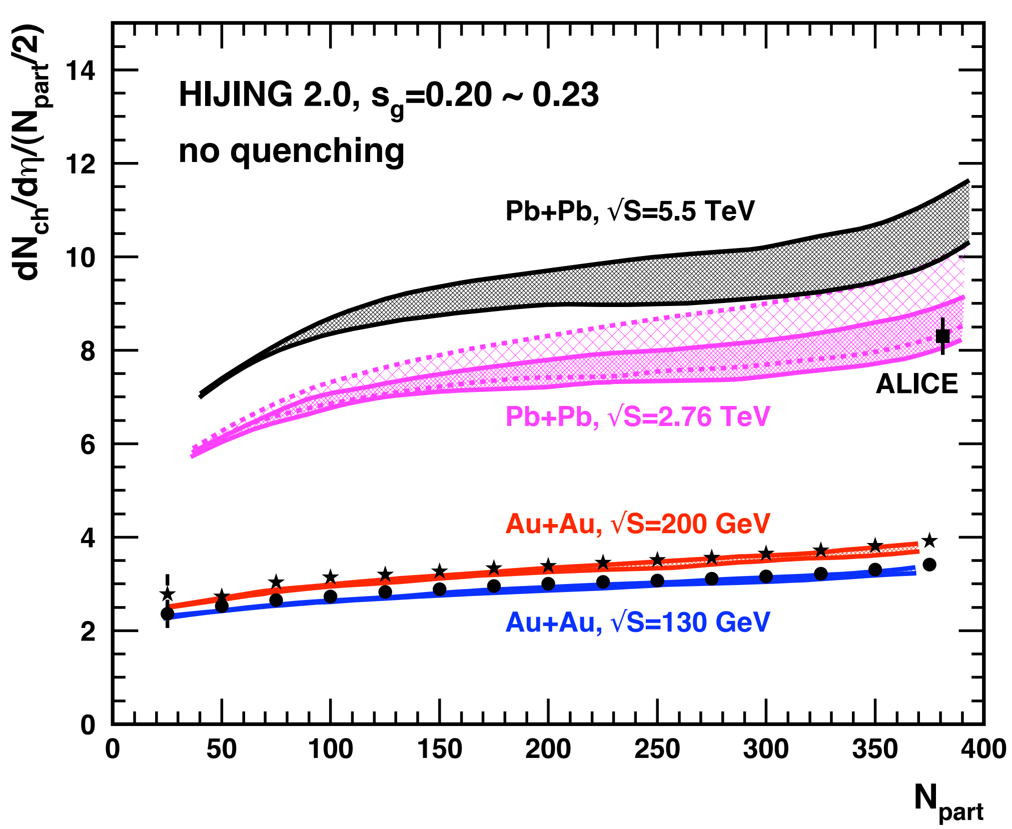

My to do list:

- 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

# 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

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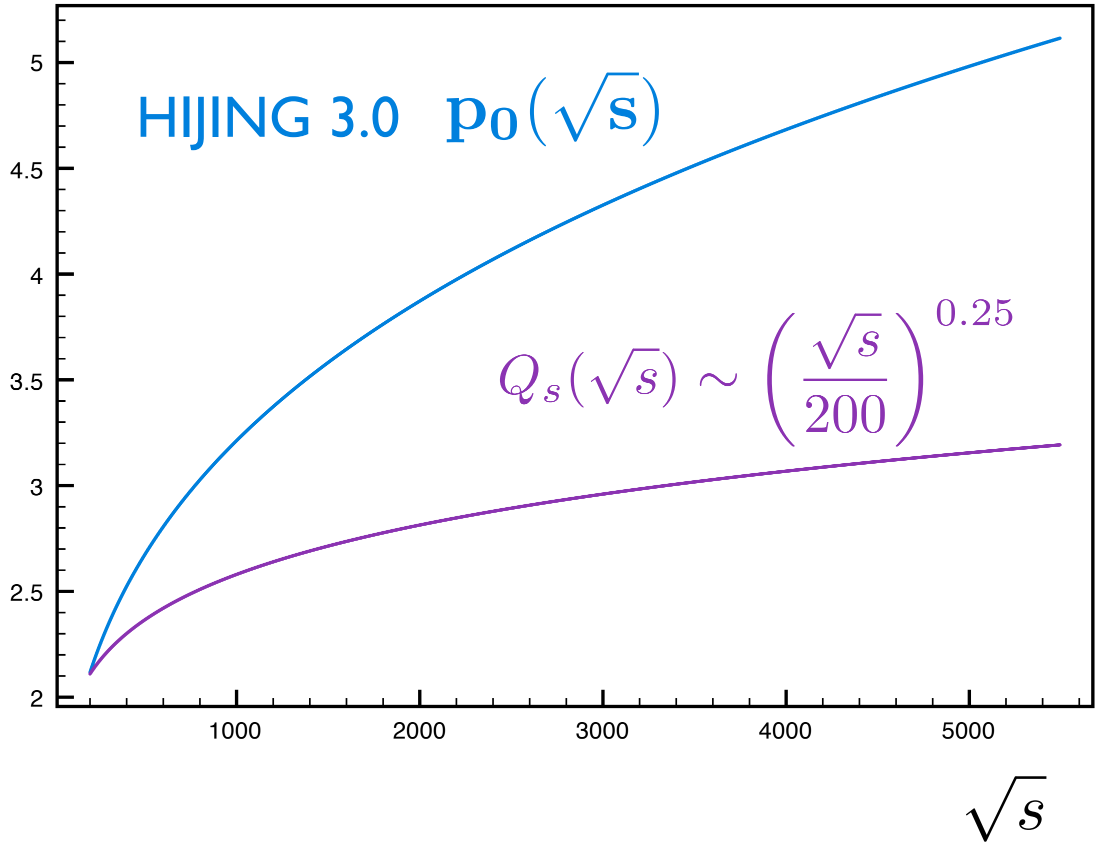
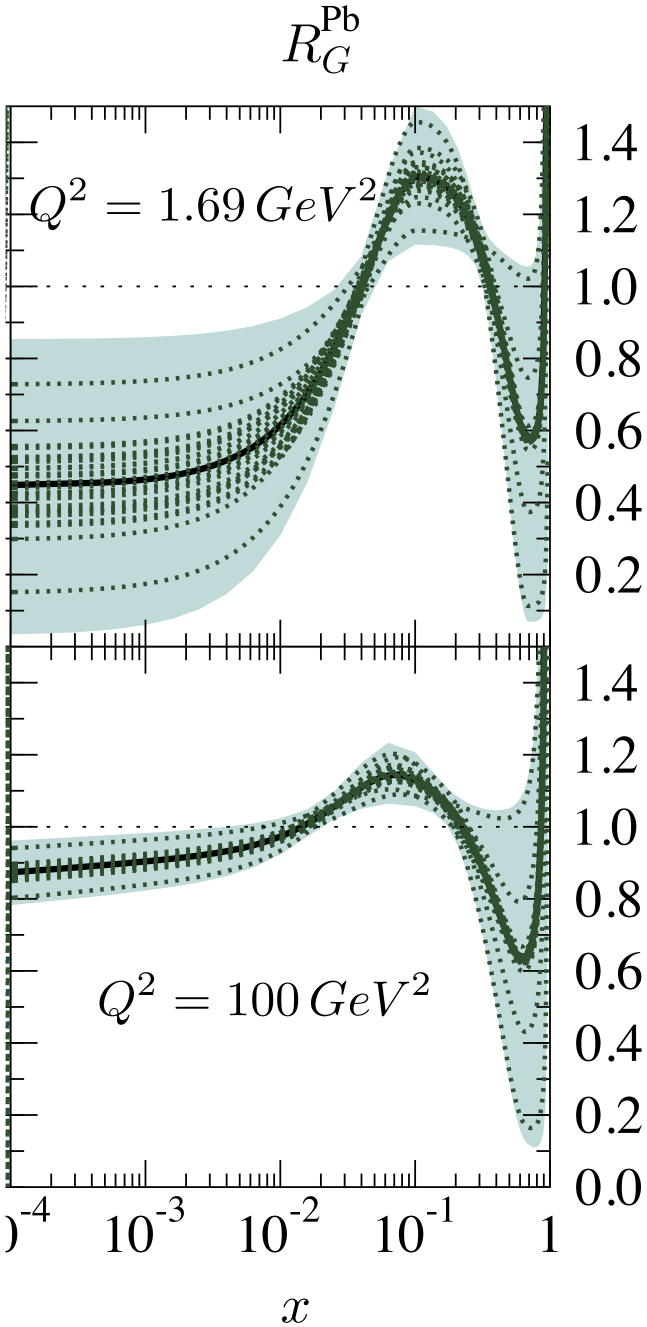



- Strong b-dependent gluon shadowing

EPS09




HIJING 3 $R_G(x)$