Single hadron spectra at forward rapidities in RHIC and the LHC from the Color Glass Condensate

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Orsay, 29 Janvier 2010

OUTLINE

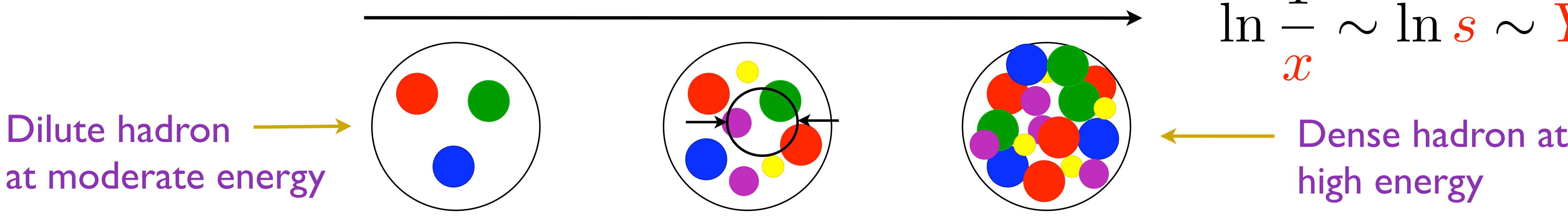
- Intro. Basic ideas and formalism

- Single particle production at forward rapidities at RHIC

- Nuclear modification ratios at the LHC

- Based on
  - JLA and Cyrille Marquet, 1001.1378 [hep-ph],
  - JLA, Phys.Rev.Lett.99:262301,2007
  - JLA and Yuri Kovchegov. Phys.Rev.D75:125021,2007

Saturation: At high energies (small Bjorken-x) the number of gluons in a hadron's wavefunction is large and recombination effects become important

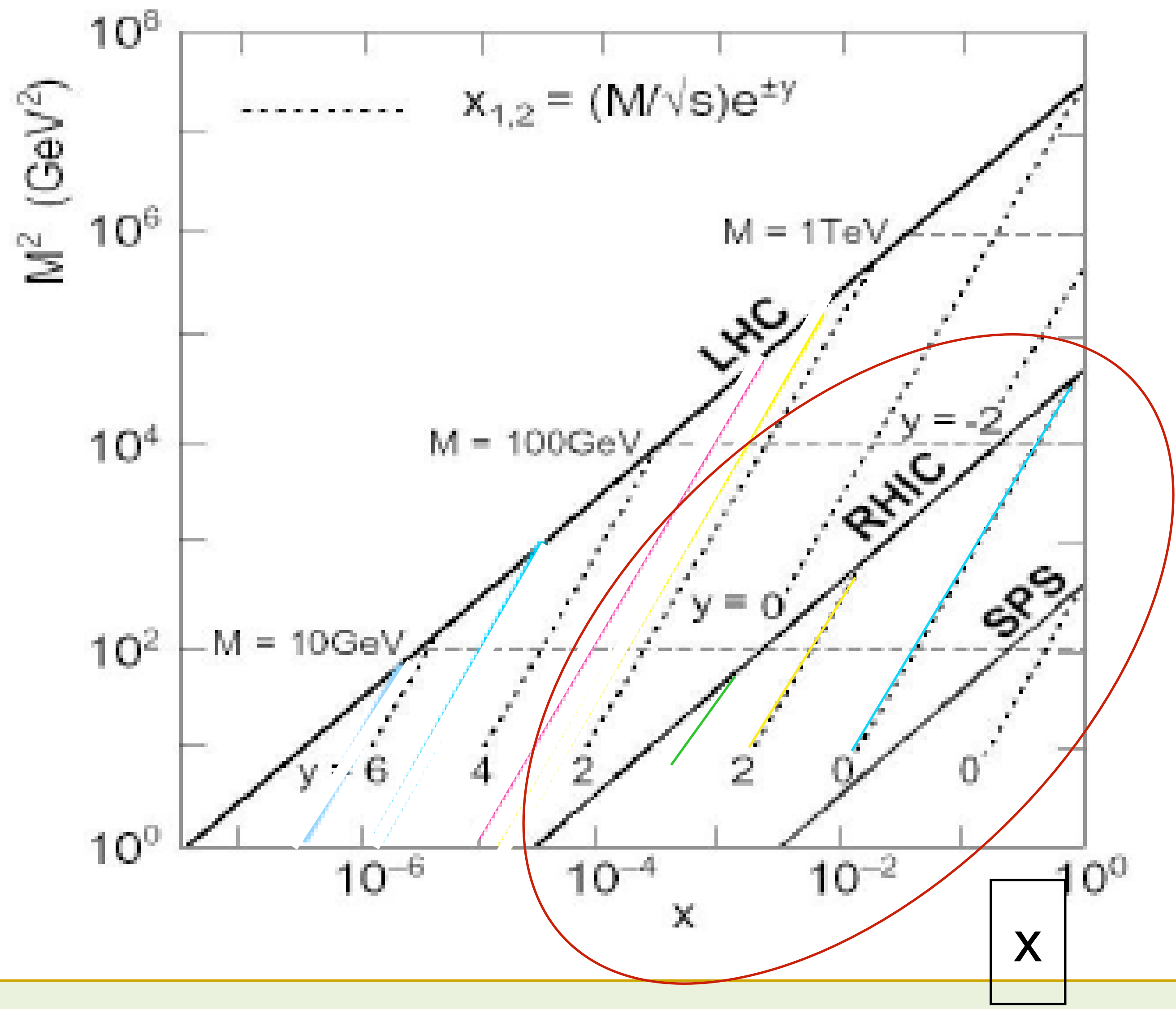


$$\ln\frac{1}{x} \sim \ln s \sim Y$$

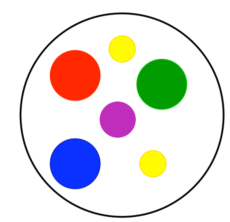
$\Rightarrow$ The saturation scale marks the onset of non-linear effects: $Q_s^2(Y) \sim Q_0^2 \exp \lambda\, Y$

RHIC and LHC collisions provide access to the saturated region of the wavefunctions

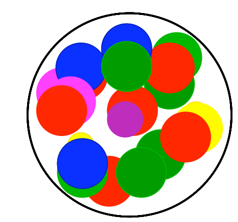
$2 \rightarrow 1$ kinematics in hadronic collisions: $$x_{1(2)} \sim \frac{m_t}{\sqrt{s}} \exp(\pm\, y_h)$$



Nuclear enhancement: large number of gluons in the nuclear wave function even at moderates energies



$$A^{1/3} \sim 6$$



$$\downarrow$$

$$Q^2_{sA}(x) \sim A^{1/3}\, Q^2_{sN}(x)$$

$$\downarrow$$

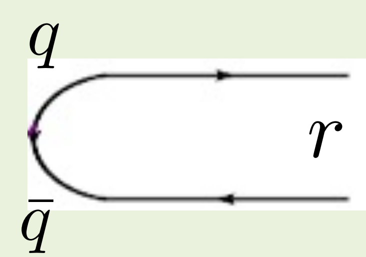
$$Q^2_{s\,Au}(\sqrt{s} = 130\,\mathrm{GeV})\Big|_{\eta=0} \approx 1\mathrm{GeV}^2$$

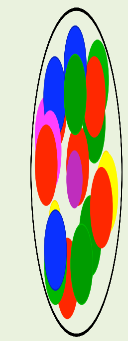
The abundant small-x gluons in the colliding nuclei feed the formation of a QGP

⇒ Non-linear QCD evolution: The Balitsky-Kovchegov (BK) equation

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

Evolution rapidity: $Y = \ln\,(x_0/x)$





Evolution kernel including running coupling corrections:

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

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

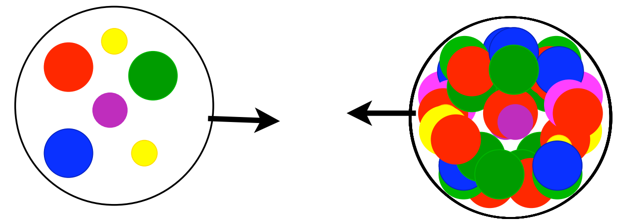
Dipole scattering amplitude ⇔ unintegrated gluon distribution

$$\varphi(x,k_t) = \int \frac{d^2 r}{2\pi\, r^2}\, e^{-i\,\vec{k}_t\cdot\vec{r}}\,\mathcal{N}(r,x) \quad \Rightarrow \quad \frac{\partial\,\varphi(x,k_t)}{\partial\, Y} \approx \tilde{K}\otimes\varphi - \varphi^2$$

radiation recombination

$\Rightarrow$ Particle Production in forward p-A and p-p collisions (Dumitru, Jalilian-Marian)

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



$$\frac{dN_h}{dy_h\, d^2p_t} = \frac{K}{(2\pi)^2} \sum_q \int_{x_F}^1 \frac{dz}{z^2} \left[x_1 f_{q\,/\,p}(x_1, p_t^2)\, \tilde{N}_F \left(x_2, \frac{p_t}{z} \right) D_{h\,/\,q}(z, p_t^2) \right.$$
$$\left. + \, x_1 f_{g\,/\,p}(x_1, p_t^2)\, \tilde{N}_A \left(x_2, \frac{p_t}{z} \right) D_{h\,/\,g}(z, p_t^2) \right]$$

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

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

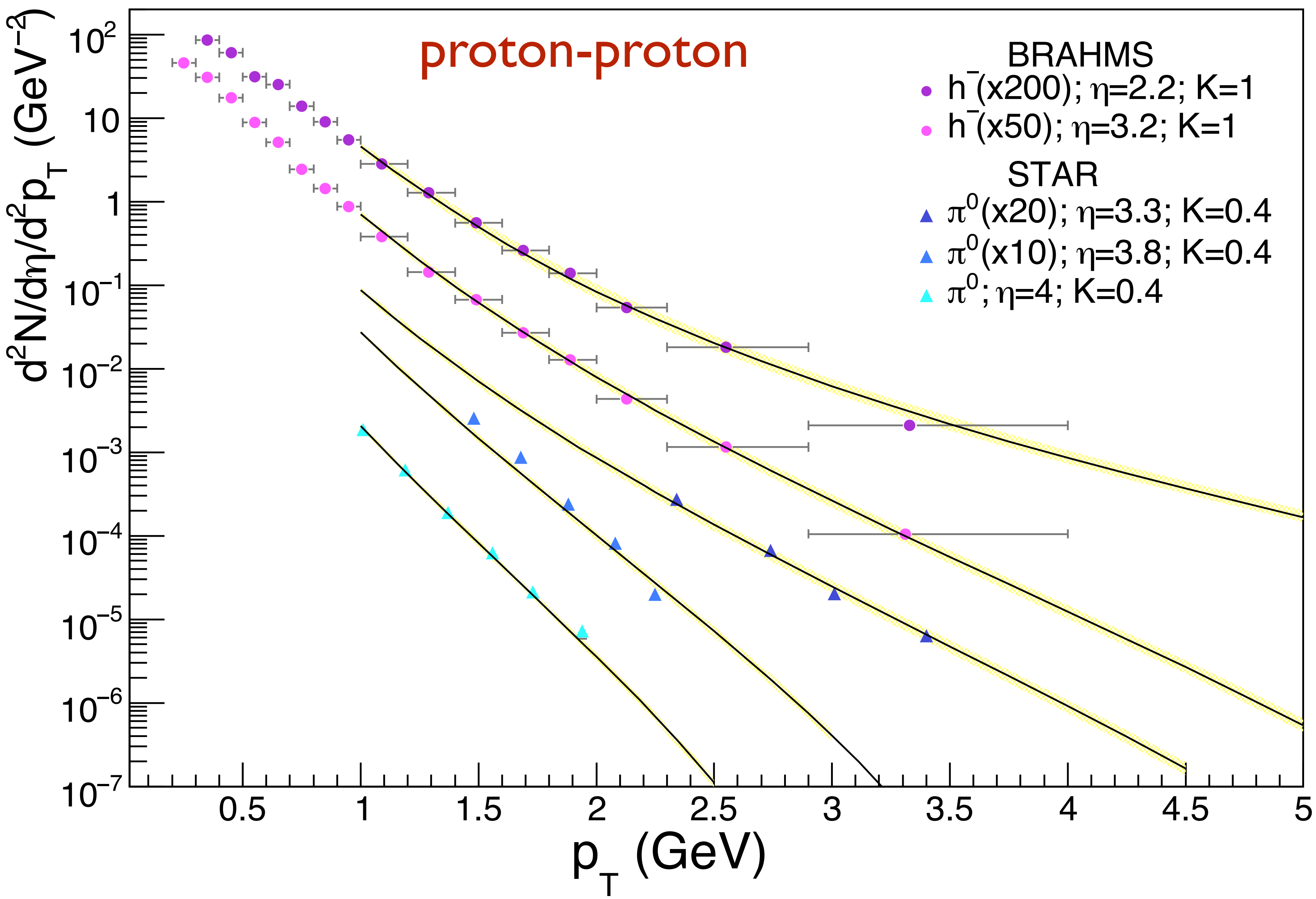
Previous work need rapidity dependent K-factors to account for the normalization

We use CTEQ6 pdf's and de Florian-Sassot ff's

Comparison with RHIC p-p data

- Very good descriptions of forward yields!
- No K-factor needed for negative charged hadrons!
- Rapidity independent K=0.4 for neutral pions

$$0.005 \le x_0 \le 0.01 \qquad Q_{s0}^2 = 0.2\,\mathrm{GeV}^2$$

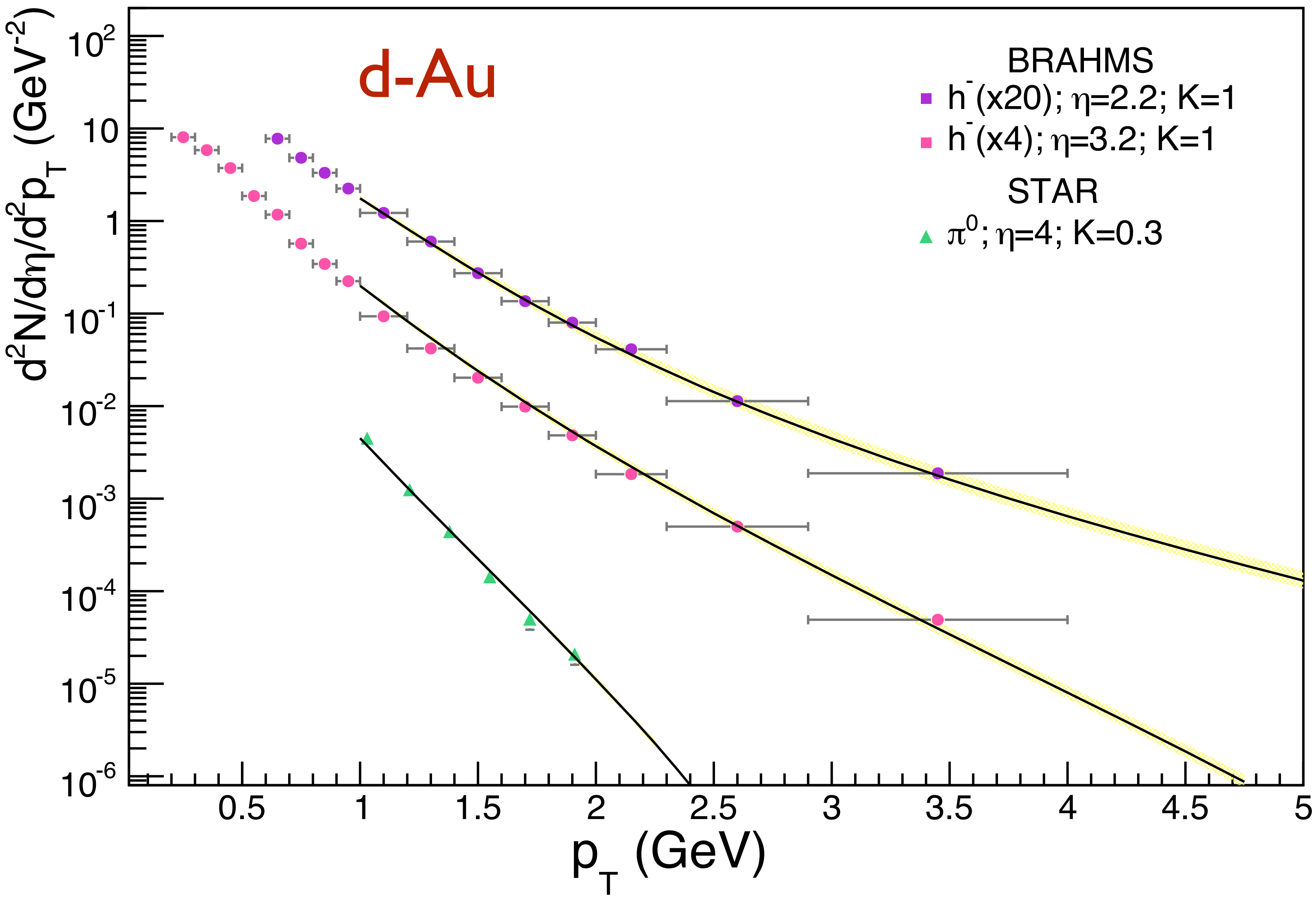


Comparison with RHIC d-Au data

- K=1 for negative charged hadrons and K=0.3 for neutral pions
- This is minimum bias data. Qs is larger in the center of the nucleus

$$0.01 \leq x_0 \leq 0.025 \qquad Q_{s0}^2 = 0.4\,\mathrm{GeV}^2 \longrightarrow Q_{s0\,gluon}^2 = 0.9\,\mathrm{GeV}^2$$

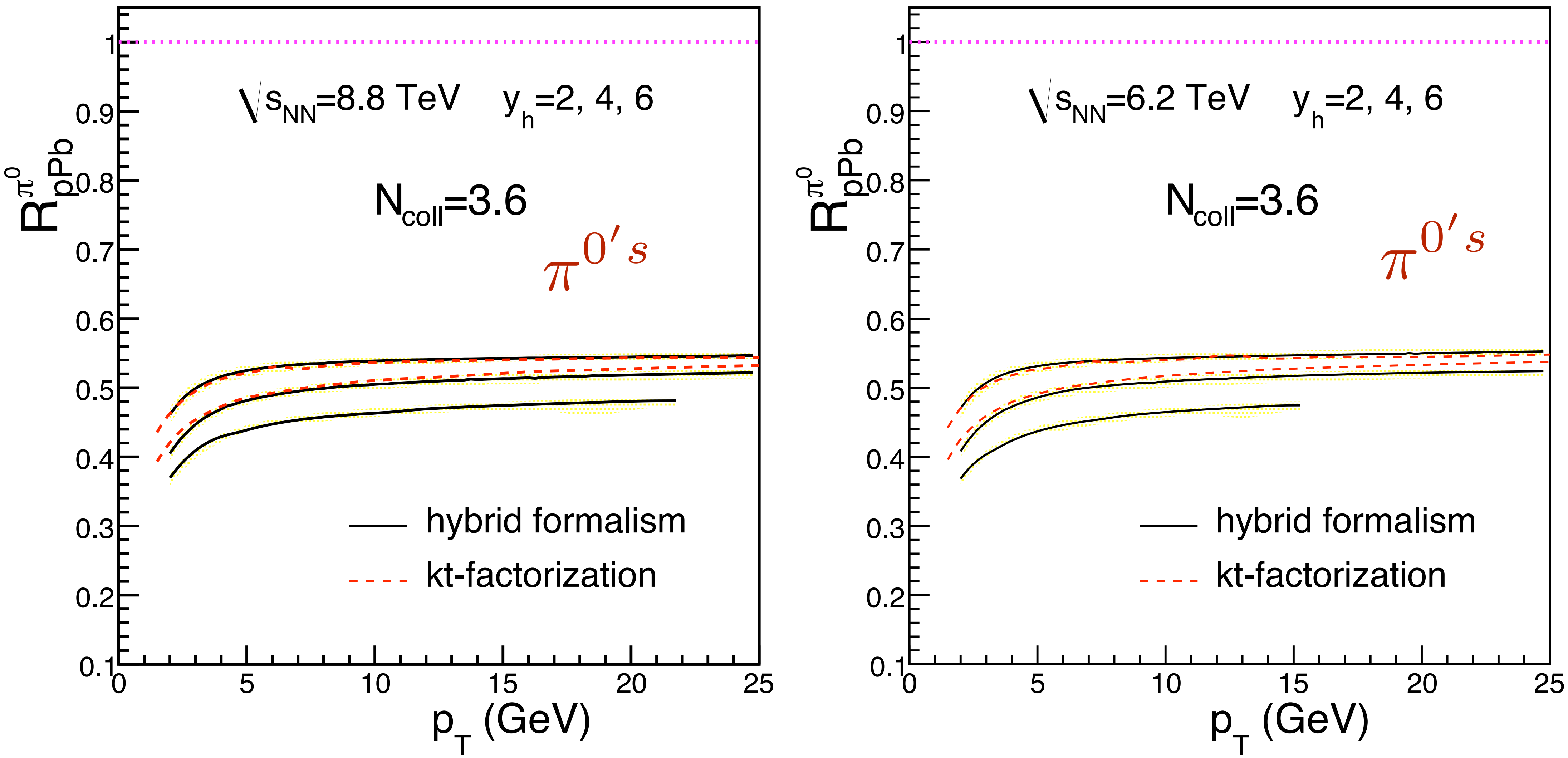
$$0.005 \leq x_0 \leq 0.01 \qquad Q_{s0}^2 = 0.5\,\mathrm{GeV}^2 \longrightarrow Q_{s0,\,gluon}^2 = 1.125\,\mathrm{GeV}^2$$



Predictions for the LHC are now entirely driven by the small-dynamics.

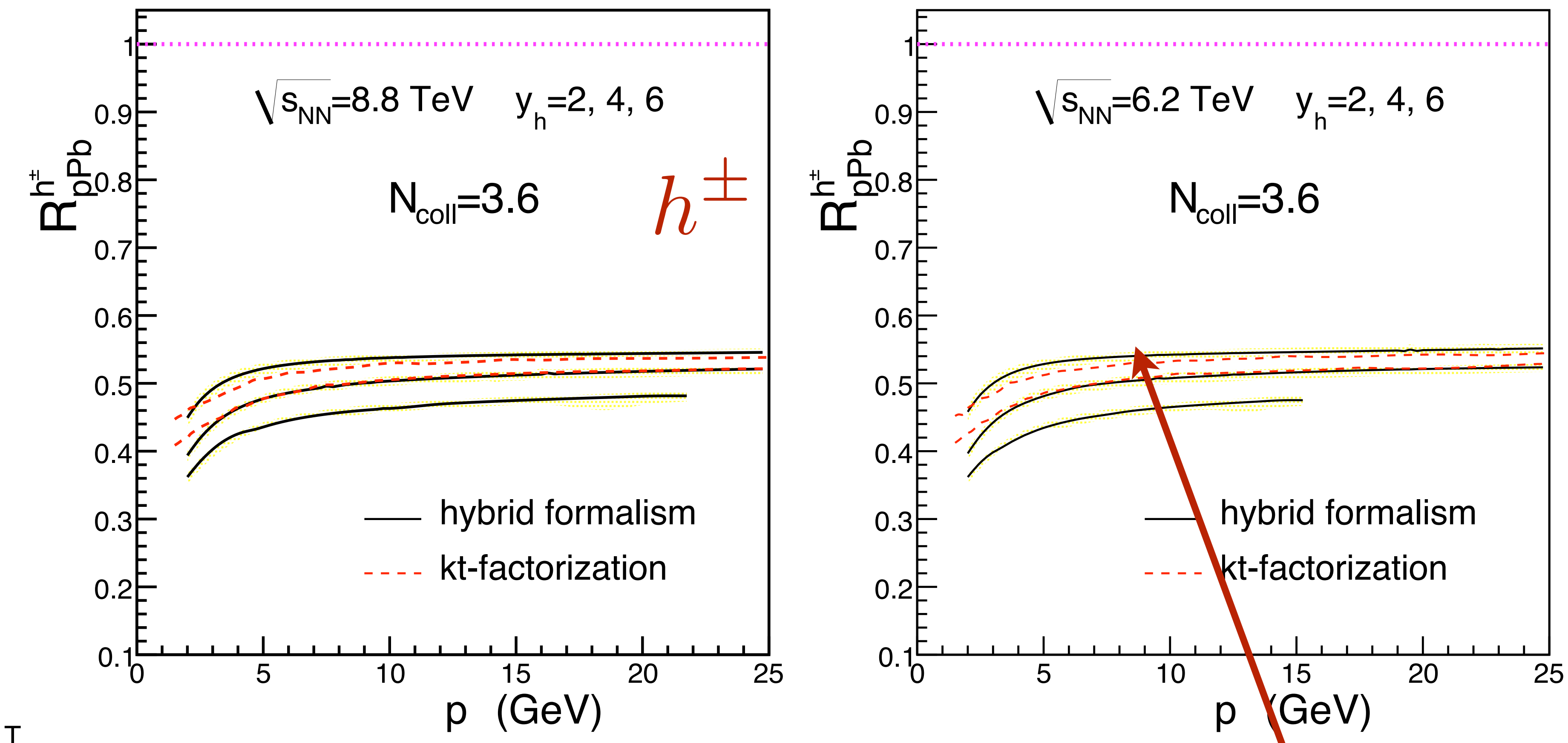
Nuclear modification factor: in p+Pb collisions

$$R_{pPb} = \frac{1}{N_{\rm coll}} \frac{dN_h^{pPb}}{dy_h\, d^2p_t} \Big/ \frac{dN_h^{pp}}{dy_h\, d^2p_t}$$

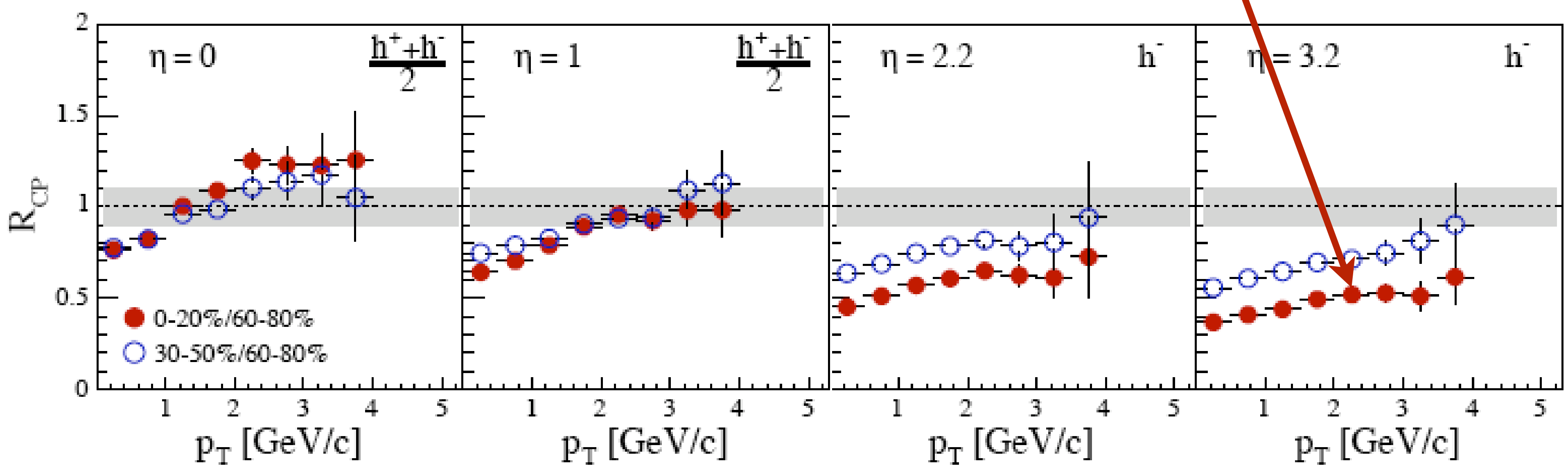


A similar suppression is expected at y=0

- We get similar results for charged hadrons:



BRAHMS, PRL93, 242303

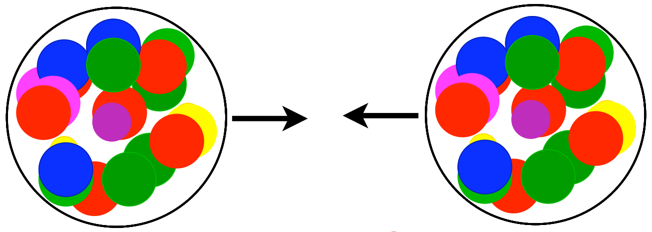


- Our results agree with the expectation that forward suppression at RHIC should be similar to mid and mid-forward suppression at the LHC.

What about Pb-Pb collisions??

The suppression predicted for pPb collisions is rooted in the nuclear wavefunction.
At a qualitative level, one expects a suppression which is, roughly, the one in pPb collisions squared

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



$y_h = 0$

- Small-x effects in both projectile and system
- At midrapidity it is a symmetric system. Hybrid formalism not well-suited

Phenomenological approach: Use of kt-factorization

$$\frac{dN^{AB\to gX}}{d\eta\, d^2p_t} = \frac{C_F}{\pi}\frac{\alpha_s}{p_t^2}\int d^2b d^2q\; \varphi_A(x_A,q,b)\,\varphi_B(x_B,p_t-q,B_t-b)$$

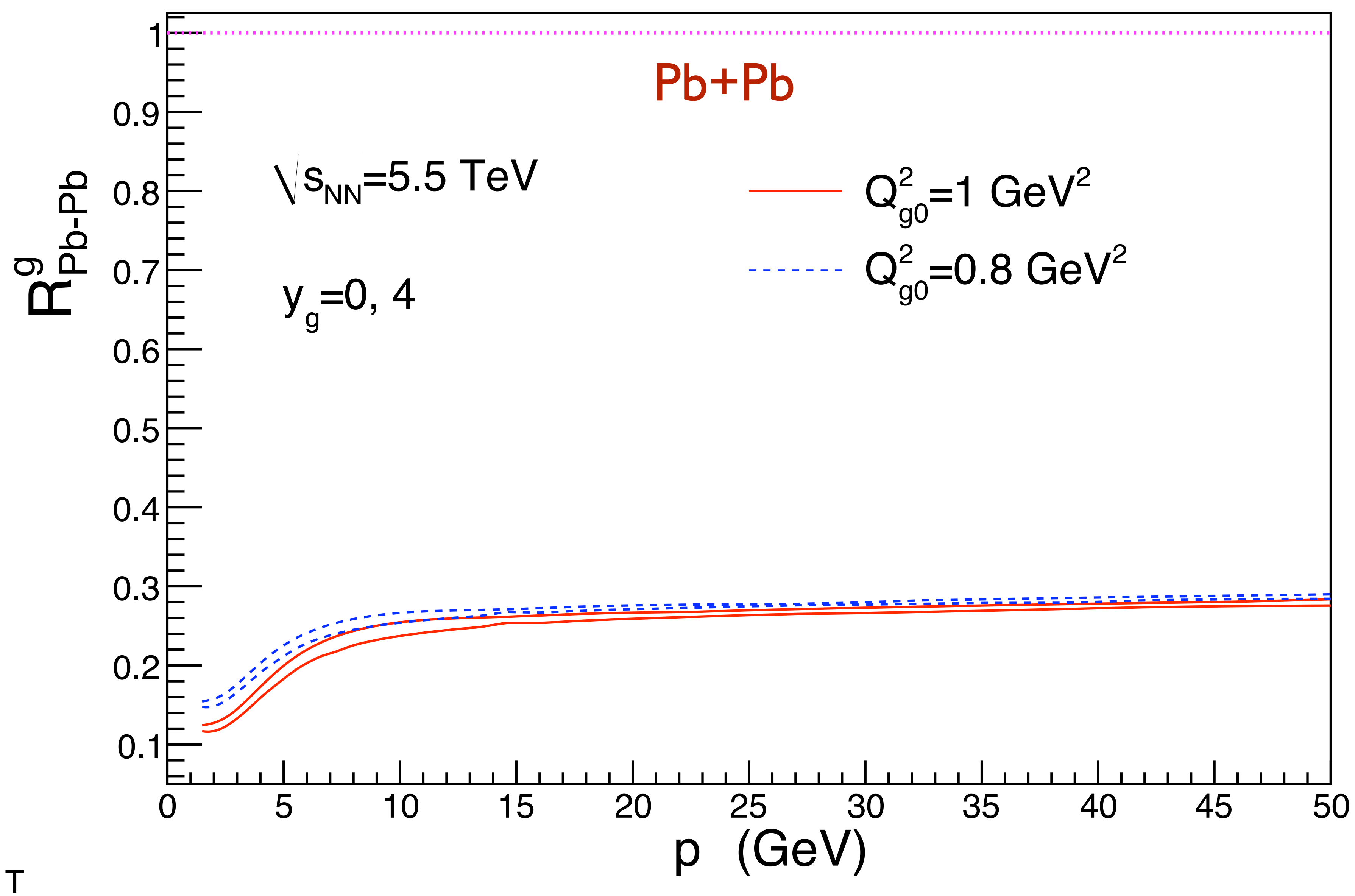
$$\varphi(x,k,b) = \int d^2\mathbf{r}\, e^{-i\mathbf{k}\cdot\mathbf{r}}\,\nabla^2_{\mathbf{r}}\mathcal{N}(r,Y=\ln(x_0/x),b) = k^2\,\tilde{N}(x,k,b)$$

- It is valid when x is small in projectile and target, but has only been proven for p(e)-A collisions (dilute-dense scattering)
- However, phenomenologically it seems to work rather well...

We predict a large suppression of gluon production in PbPB collisions originating purely from initial state effects.

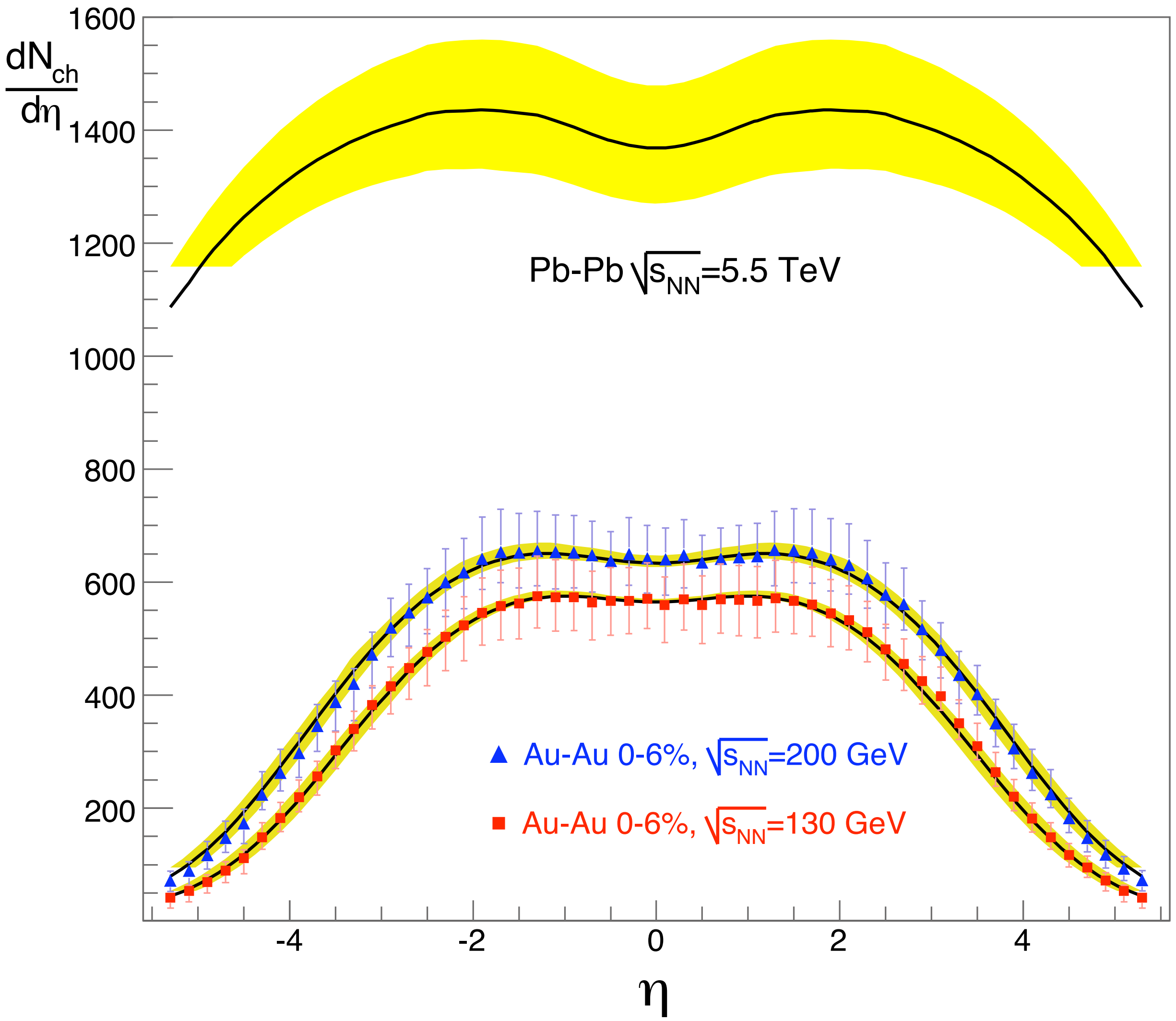
Our results should are valid at $t=0^+$. They should be convoluted with final state (QGP) and hadronization effects to get the total R_{PbPb}

$$R^g_{PbPb} = \frac{1}{N_{\rm coll}} \frac{dN_h^{PbPb}}{dy_h\, d^2p_t} \Big/ \frac{dN_h^{pp}}{dy_h\, d^2p_t}$$

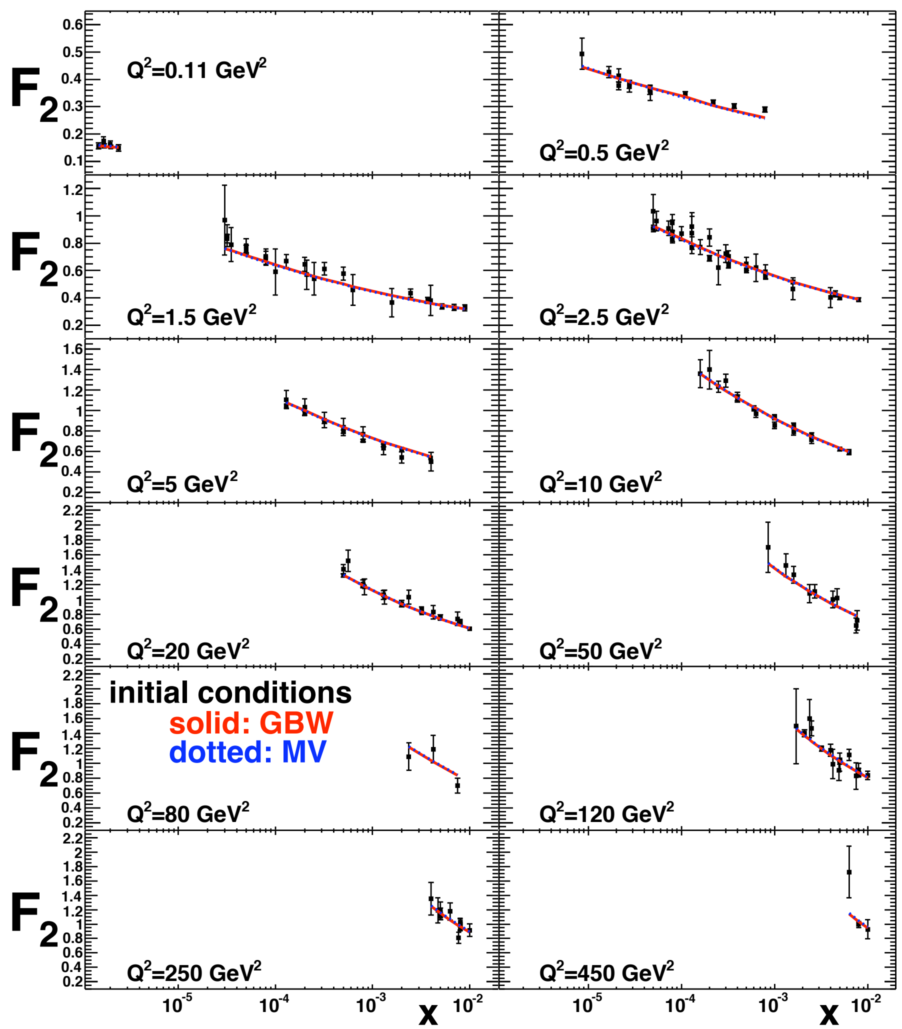


The wavefunctions used here also yield a very good description of other observables

Multiplicities in RHIC Au+Au



F_2, F_L and F_D in e+p HERA collisions



$$\frac{Q^2_{0,A}}{Q^2_{0proton}} = 2 \div 2.5 = c\,A^{1/3}$$ compatible with e+A data. Francois Gelis et al

Also two-particle correlations in forward d+Au at RHIC (Cyrille will tell us about that)

Conclusions

A very good description of forward hadron yields in d+Au collisions at RHIC is possible within the CGC

We use the most up-to-date theoretical tools to describe the x-dependence (energy and rapidity) of the nuclear wavefunctions: BK including running coupling corrections.

We predict a large suppression (~1/2) of forward hadron yields in p+Pb collisions @ LHC and an even larger suppression for mid-rapidity initial gluon production on Pb+Pb collisions

Together with the study of other observables,

We should (and shall) extend these studies to more differential observables (correlations, photons...)