Single particle distributions, leading twist and beyond

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Saturation, the Color Glass Condensate and Glasma: What have we learned from RHIC?

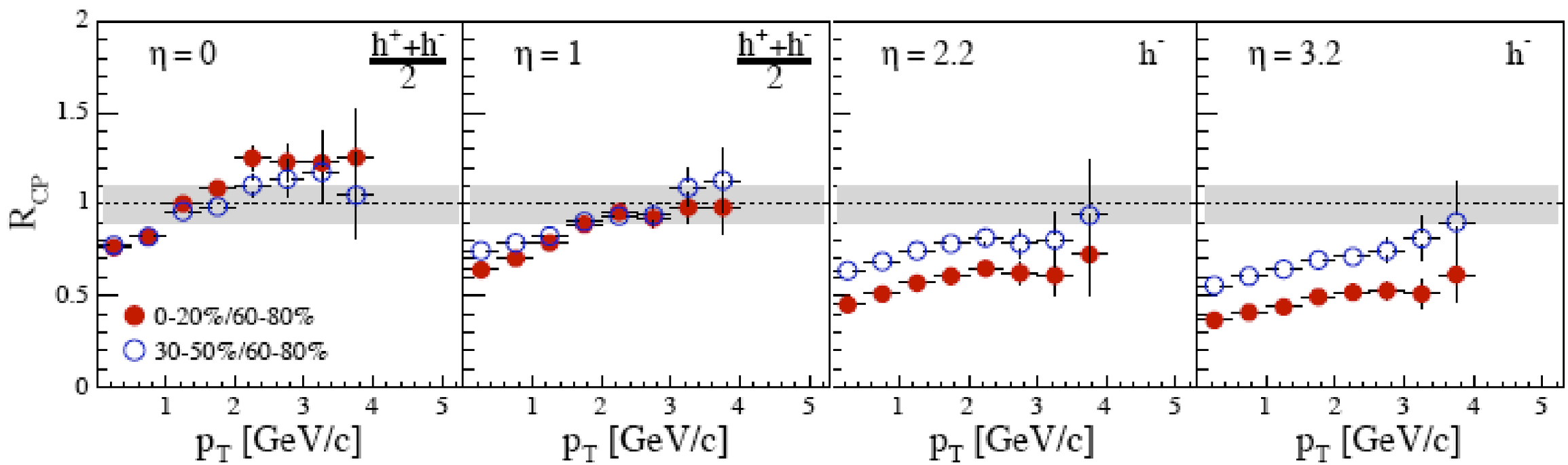
Nuclear effects in particle single inclusive particle production in RHIC d+Au collisions show two different regimes

$$R_{dAu} = \frac{1}{N_{coll}} \frac{\frac{dN_{dAu}}{dyd^2p_t}}{\frac{dN_{pp}}{dyd^2p_t}}$$

⇒ Central rapidities: Moderate Cronin enhancement for pt>2 GeV

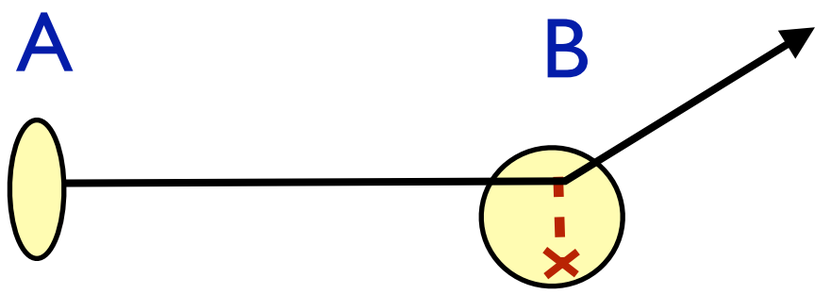
Moderate suppression for pt<2 GeV

⇒ Forward rapidities. Disappearance of Cronin peak and homogeneous suppression ∀ pt



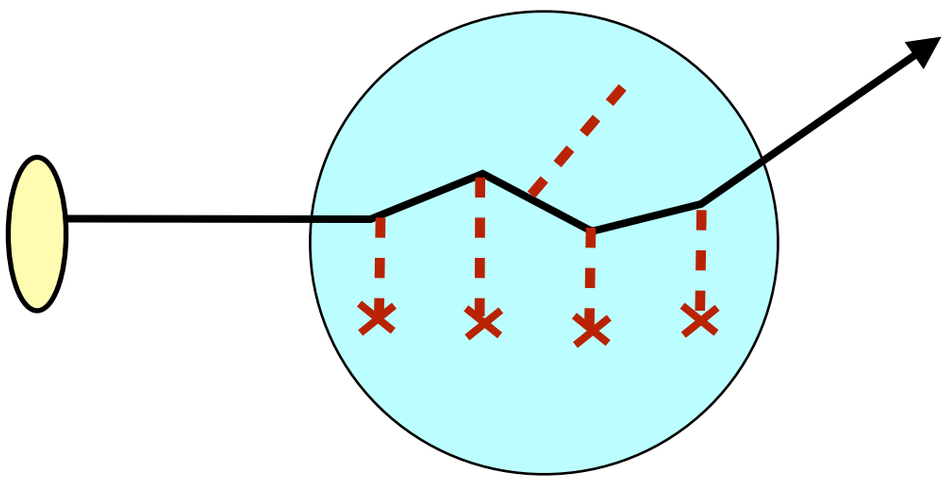
BRAHMS, PRL93, 242303

Particle production in p+p collisions: Collinear factorization



$$\frac{d\sigma^{AB\to hX}}{dyd^2k_t} \propto f_{a/A}(x_1,k_t^2)\, f_{b/B}(x_2,k_t^2) \otimes \frac{d\sigma^{ab\to cd}}{dyd^2k_t} \otimes D_{h/c}(z)$$

$$+\mathcal{O}(1/Q^2), \qquad Q \sim k_t$$

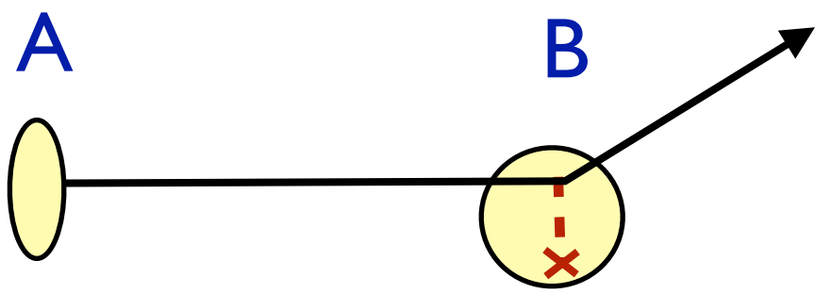


⇒ Multiple (elastic and inelastic) scattering:

Higher twists

Momentum broadening

Particle production in p+p collisions: Collinear factorization



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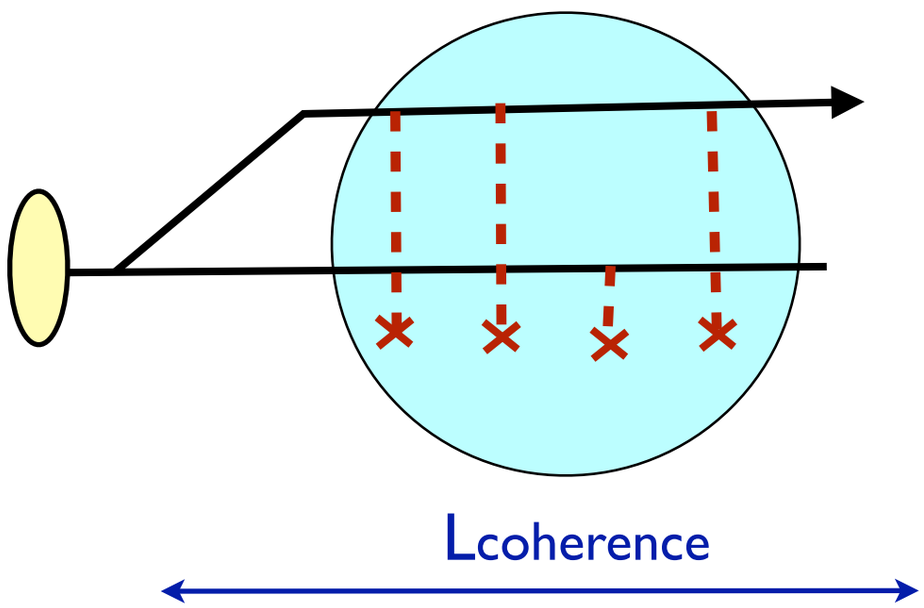


⇒ Multiple (elastic and inelastic) scattering:

Higher twists

Momentum broadening

⇒ Coherence effects:

Destructive interference, "Shadowing"

Color Glass Condensate description

$$L_{coh} \sim \frac{1}{2m_N x_2} \gtrsim R_A$$

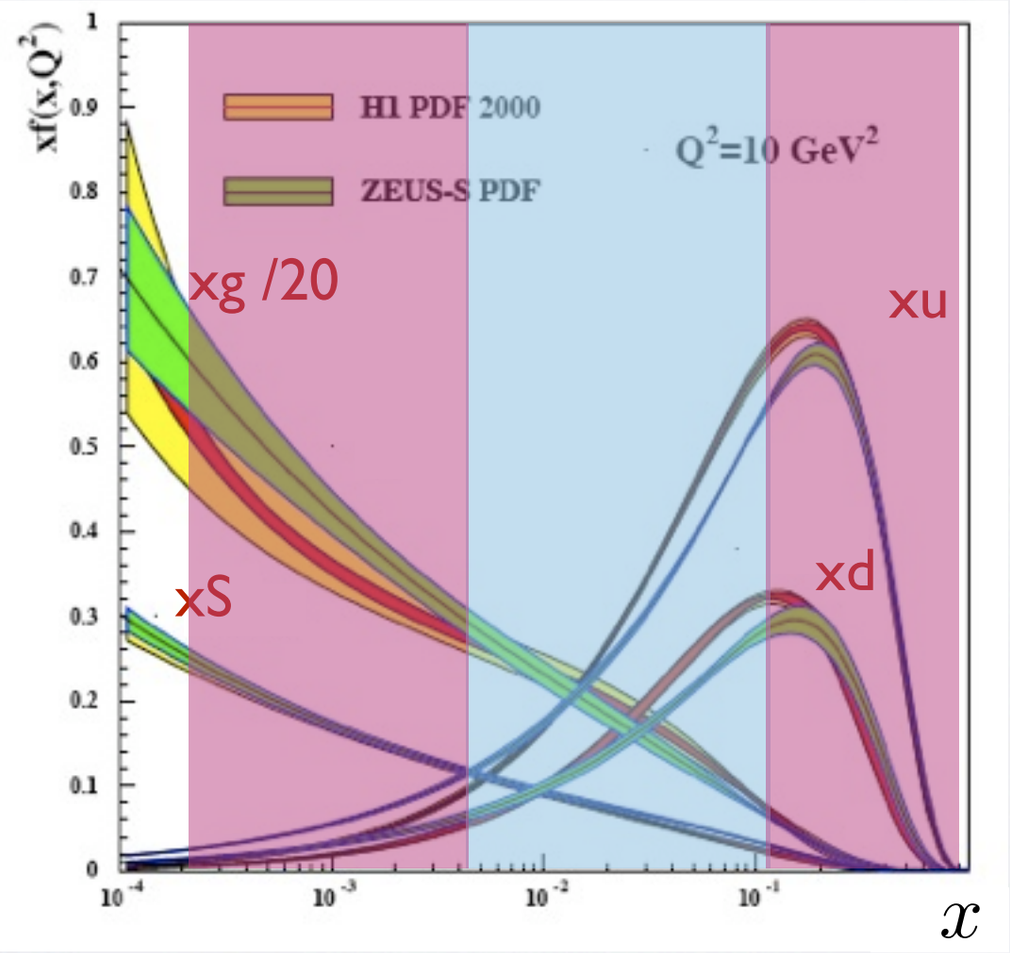
(approximate) RHIC Kinematics: $x_{1(2)} \sim \frac{m_t}{\sqrt{s}} \exp(\pm y_h)$

$\eta = \mathbf{0}$ Intermediate values of x in projectile and target

$$p_t^{had} \sim 0.5 \div 10 \text{ GeV} \quad \Rightarrow \quad x \sim 0.005 \div 0.1$$

$\eta = \mathbf{3.2}$ Small-x gluons (nucleus) and valence quarks (deuteron) dominate

$$p_t^{had} \sim 0.5 \div 3.5 \text{ GeV} \quad \Rightarrow \quad \begin{array}{l} x_2 \sim 2 \cdot 10^{-4} \div 5 \cdot 10^{-3} \\ x_1 \sim 0.1 \div 0.9 \end{array}$$



Brief survey of approaches to particle production in d+Au collisions:

⇒ collinear factorization

$$\frac{d\sigma^{AB\to hX}}{dyd^2k_t} \propto f_{a/A}(x_1,k_t^2)\, f_{b/B}(x_2,k_t^2) \otimes \frac{d\sigma^{ab\to cd}}{dyd^2k_t} \otimes D_{h/c}(z)$$

⇒ nPDF's: All nuclear effects included in modification of collinear pdf's (EKS08, EPS09, HKN)

$$f_{a/Au}(x,Q^2) = f_{a/p}(x,Q^2)\, R_{a/Au}(x,Q^2)$$

⇒ Glauber-Eikonal multiple independent scatterings + unintegrated pdf's:

$$f_{a/A}(x,Q^2) \to F_{a/A}(x,Q^2,<k_T^2>) \quad \to F_{a/A}(x,Q^2,<k_T^2>+\Delta k_T^2(\sqrt{s},b,p_t))$$

intrinsic kt

momentum broadening

$$\frac{d\sigma^{iA}}{dyd^2k_t}(b) \sim \sum_{n=1}^{\infty}\frac{1}{n!}\int[d^2k]\frac{d\sigma^{iN}}{d^2k_1}T_A(b)\ldots\frac{d\sigma^{iN}}{d^2k_n}T_A(b)\,\exp\left[-\sigma_{in}(p_0)T_A(b)\right]\delta^2(\sum\vec{k}_i-\vec{k}_t)$$

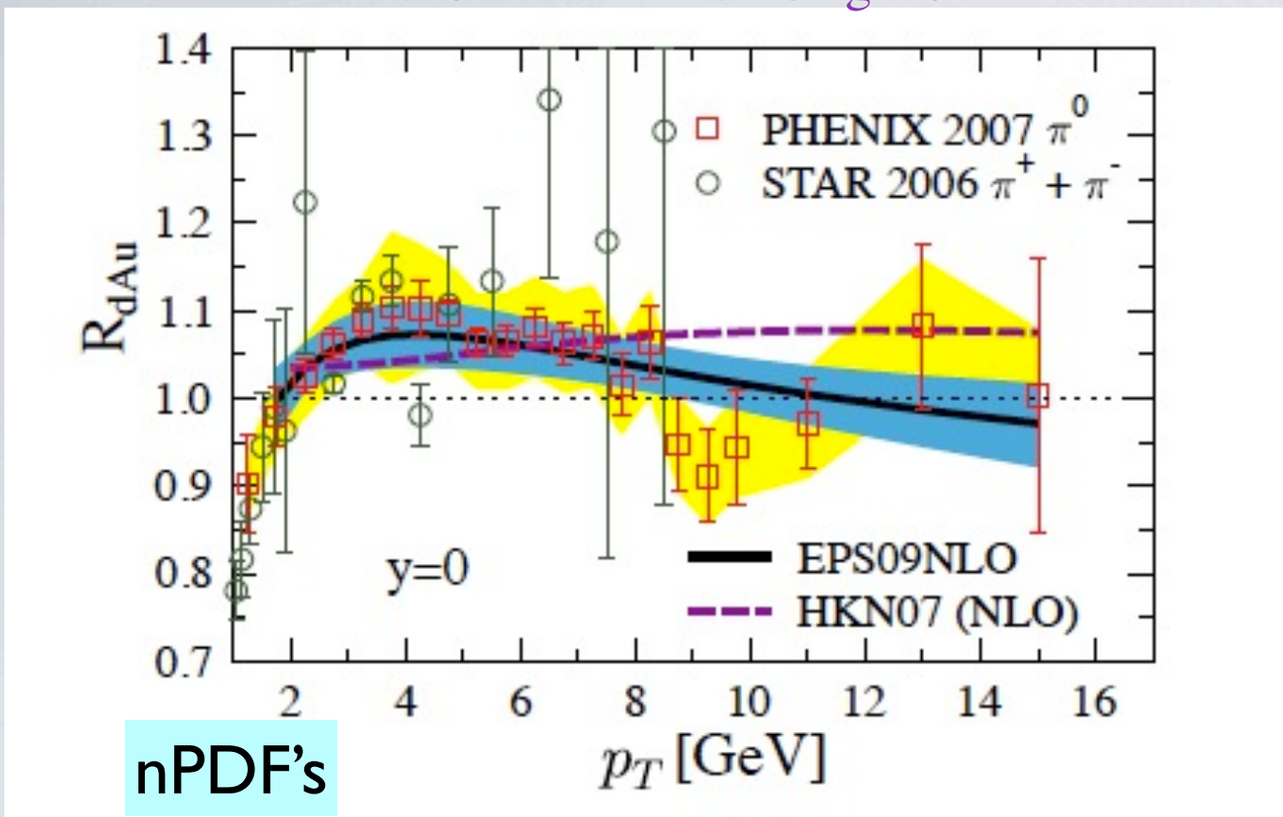
⇒ CGC: Full Coherence limit. Nucleus described as a saturated small-x glue ensemble

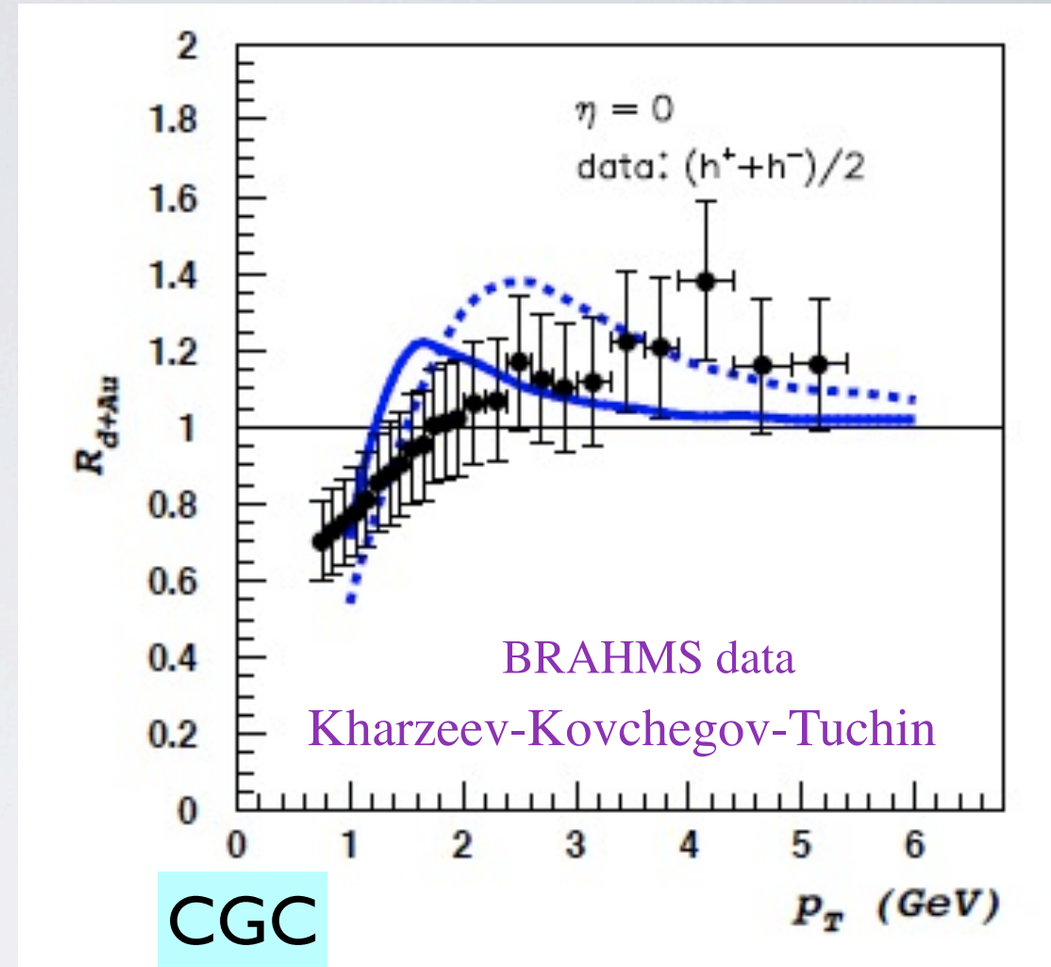
kt factorization for small-x gluon production + valence quark production

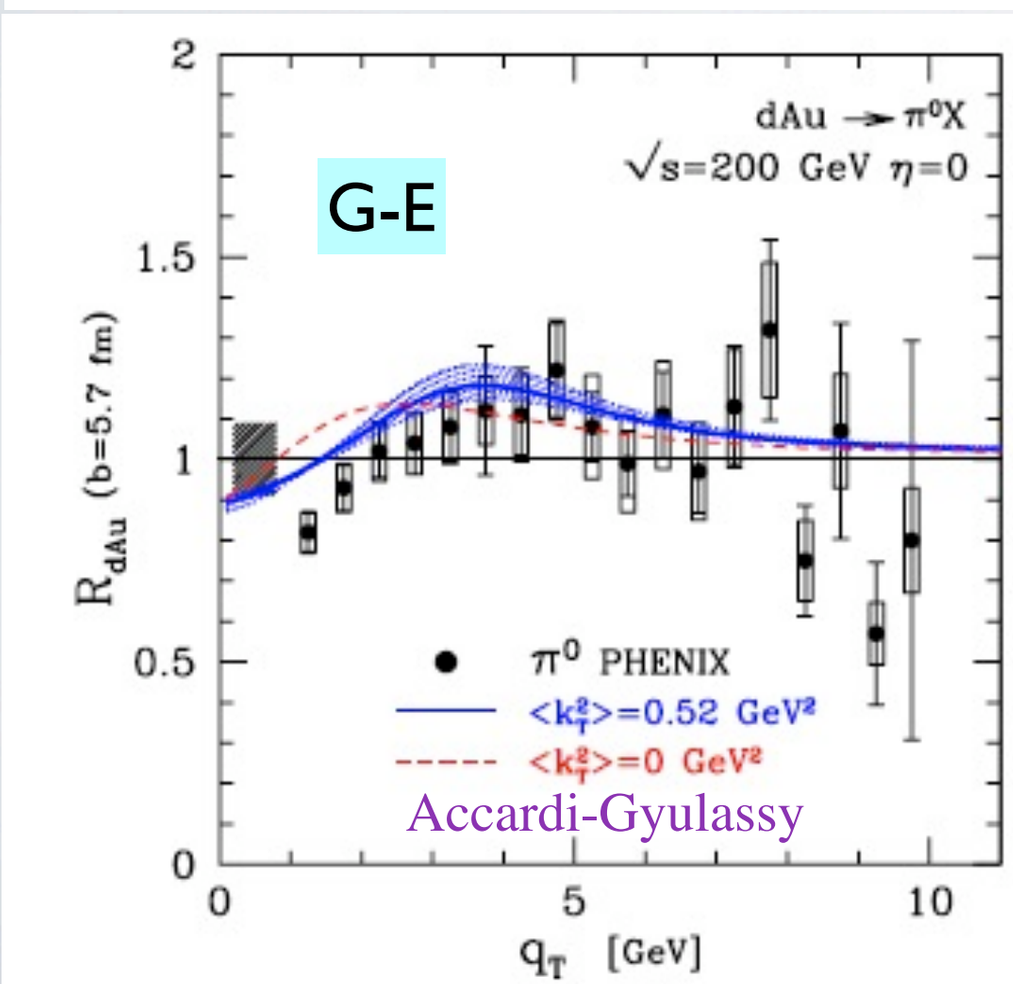
$$\frac{dN^{AB\to gX}}{dy\,d^2p_t} = \frac{S_A\,C_F}{\pi}\frac{\alpha_s}{p_t^2}\int d^2q\,\varphi_A(x_A,q)\,\varphi_B(x_B,p_t-q)$$

Semiclassical MV multiple scatterings + quantum corrections

Eskola-Paukkunen-Salgado





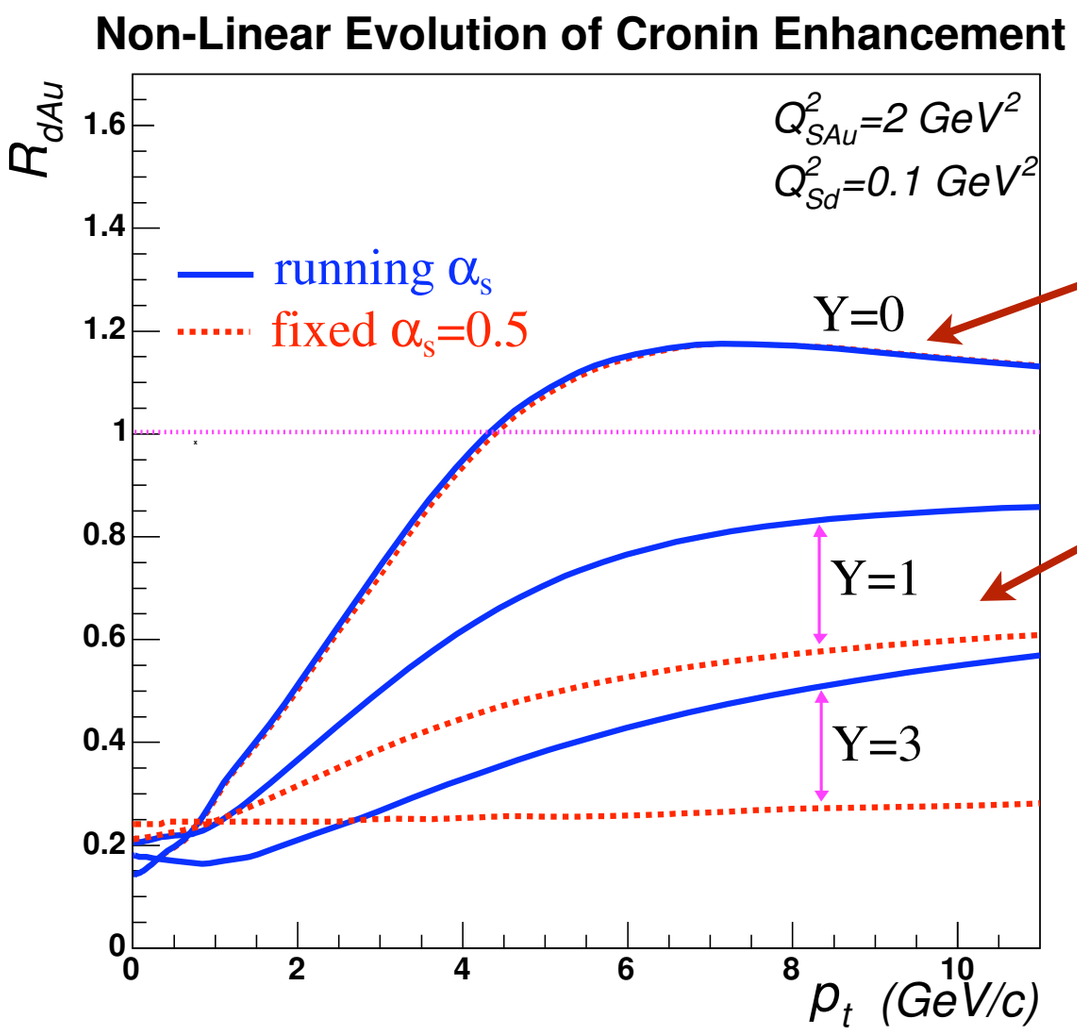


- Comparable description of data from different approaches
- nPDF's studies do not access the pt<2 Gev region (suppression)
- Both CGC and GE calculation invoke some intrinsic "non-perturbative" transverse scale ~ 1 GeV

⇒ Forward spectra. Qualitative expectations

⇒ CGC-based calculations correctly predicted forward hadron suppression: (2003)

JLA-Armesto-Kovner-Salgado-Wiedemann; Kovchegov-Kharzeev-Tuchin.



Semiclassical MV model always yield a Cronin-peak (i.e, MV has unitarity but no shadowing)

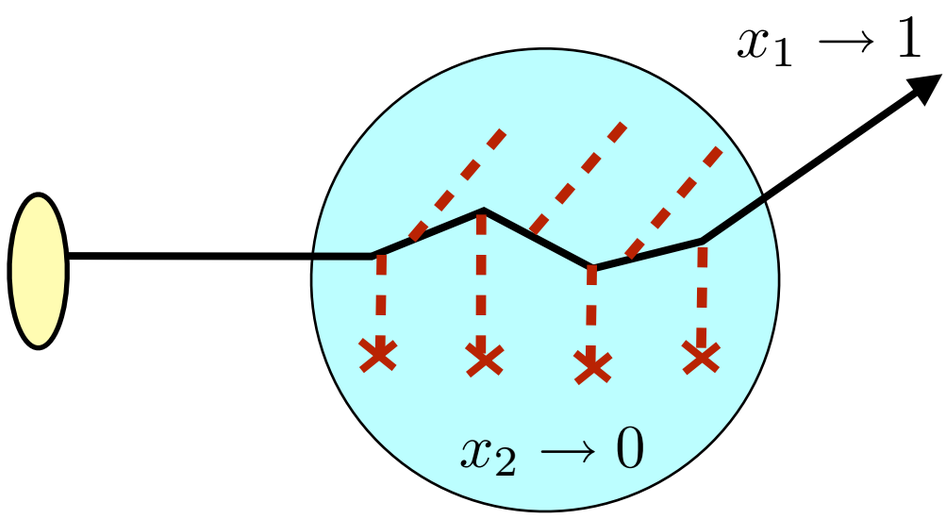
Forward suppression originates in the dynamical shadowing generated by the quantum non-linear BK-JIMWLK evolution equations

$$\frac{\partial \varphi(x)}{\partial \ln(x_0/x)} \approx \tilde{K} \otimes \varphi - \varphi^2$$

⇒ Forward spectra. Qualitative expectations

Forward production implies large-xF

⇒ Energy conservation. Kopeliovich et al; Frankfurt-Strickman.



Eikonal propagation implicit in the CGC neglects recoil in the parton propagation through target

Interaction with the target induces gluon bremstahlung and energy loss, which is stronger in nuclei than in proton.

Probability of not losing energy:

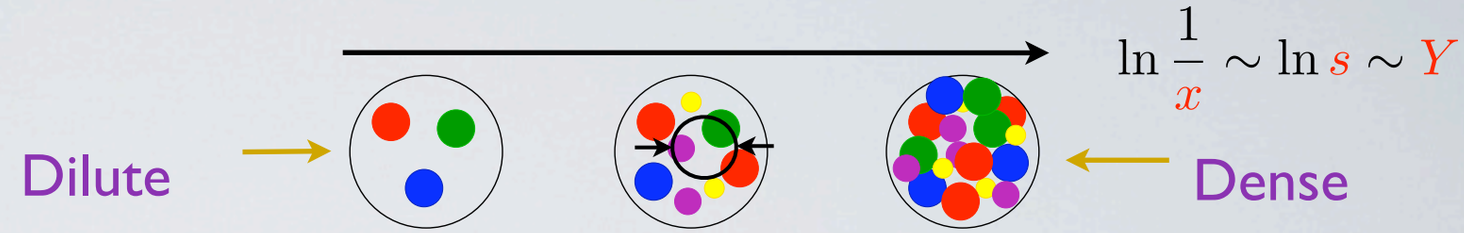
$$P(\Delta y) \approx e^{-n_G(\Delta y)} \approx (1 - x_F)^{\#}$$

#nucleus > #proton

Small if $x_F \to 1$ forward rapidity

Effective parton distributions depend on the target: breakdown of factorization.

CGC evolution at NLO



✓ NLO corrections to BK-JIMWLK equations have been calculated recently. Balitsky-Chirilli; Kovchegov-Weigert, Gardi et al.

✓ Phenomenological tool: The BK equation including only running coupling corrections in Balitsky's scheme grasps most of the NLO corrections (JLA-Kovchegov)

BK eqn:

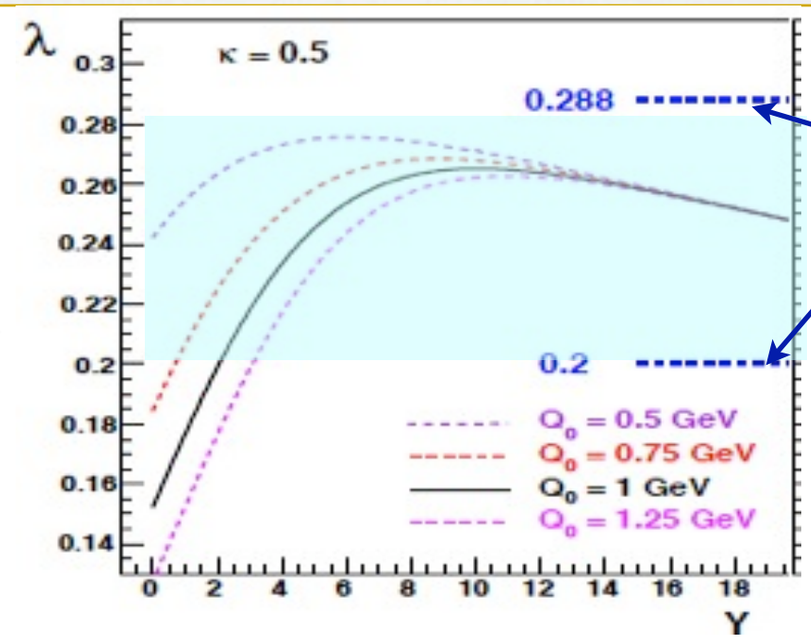
$$\frac{\partial \mathcal{N}(r,x)}{\partial \ln(x_0/x)} = \int d^2 r_1\, K(r,r_1,r_2)\,[\mathcal{N}(r_1,x)+\mathcal{N}(r_2,x)-\mathcal{N}(r,x)-\mathcal{N}(r_1,x)\mathcal{N}(r_2,x)]$$

Running coupling kernel:

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

NLO corrections are large:

$$\lambda(Y) = \frac{d\ln Q_s(Y)}{dY}$$

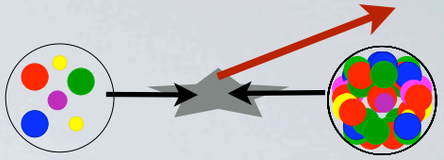


values compatible with data

$$\lambda^{LO} \approx 4.8\,\alpha_s$$

⇒ Forward hadron production in the CGC

(Dumitru, Jalilian-Marian)



large-x parton from proj. (pdf)

small-x glue from target (CGC)

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

fragmentation

Unintegrated gluon from running coupling BK

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

MV Initial conditions:

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

JLA & C. Marquet 10

Two free parameters: (x_0, Q_0)

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

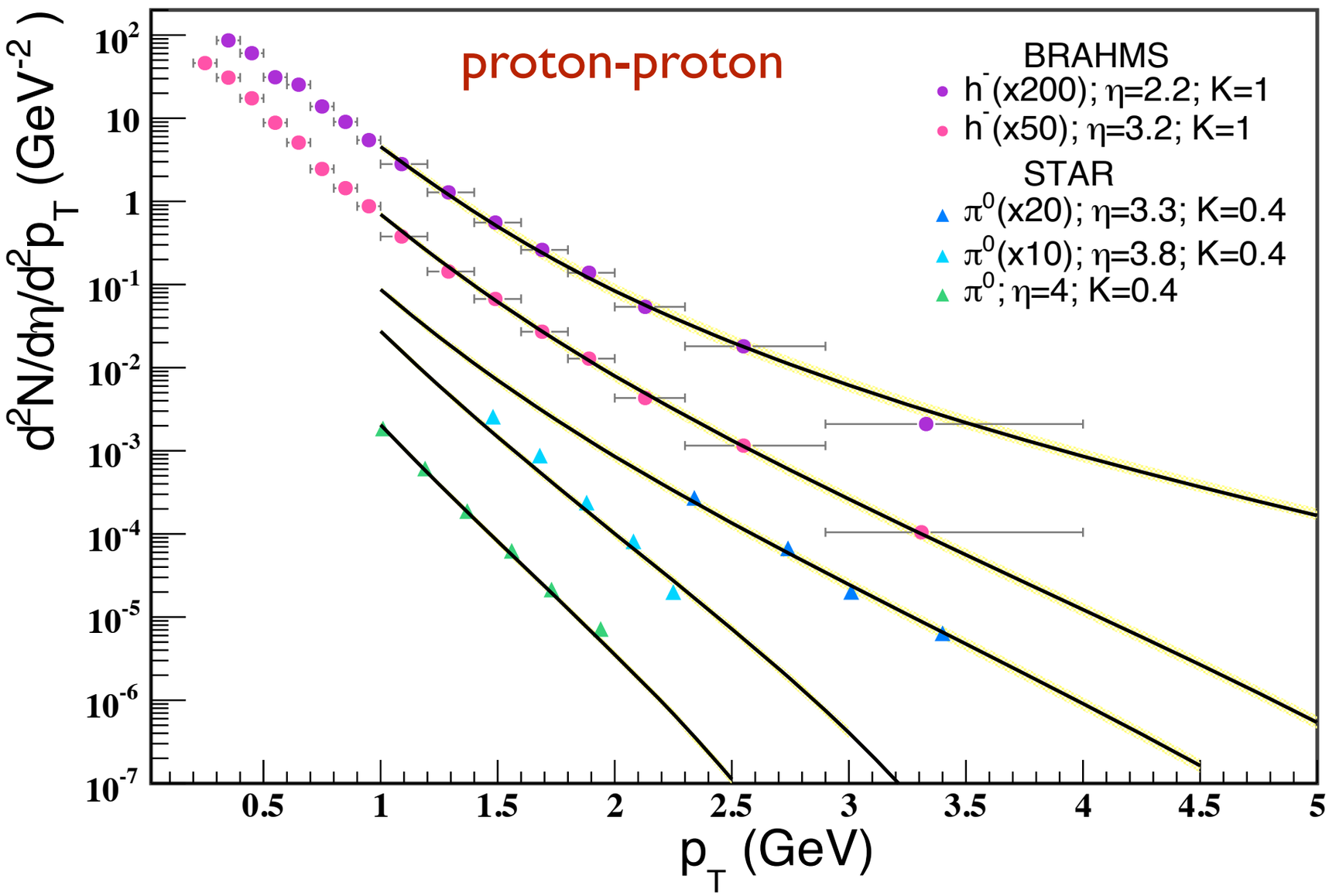
Alternative approaches: Modelization of quantum corrections

(Dumitru-JalilianMarian-Hayashigaki; De Boer-Utermann-Wessels; Goncalves et al; Kharzeev-Kovchegov-Tuchin)

- Very good description of forward yields in proton+proton collisions. (NLO analysis in EPS09 fails to describe data)

- K=1 for h^-. K=0.4 for neutral pions (?)

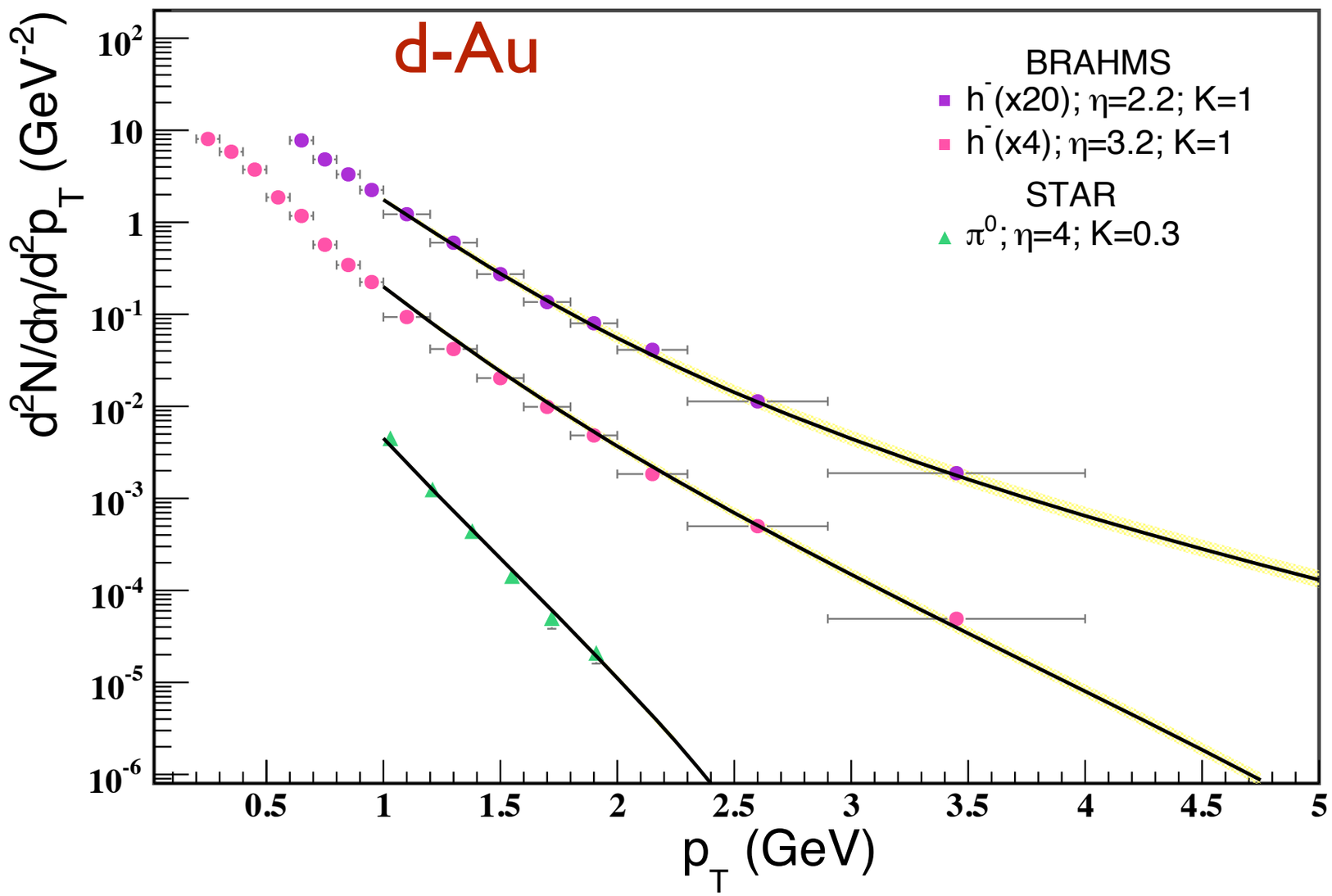
$$0.005 \leq x_0 \leq 0.01 \qquad Q_{s0}^2 = 0.2\,\mathrm{GeV}^2$$



- Very good description of forward yields in d+Au collisions
- K=1 for h^-. K=0.4 for neutral pions (?)

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

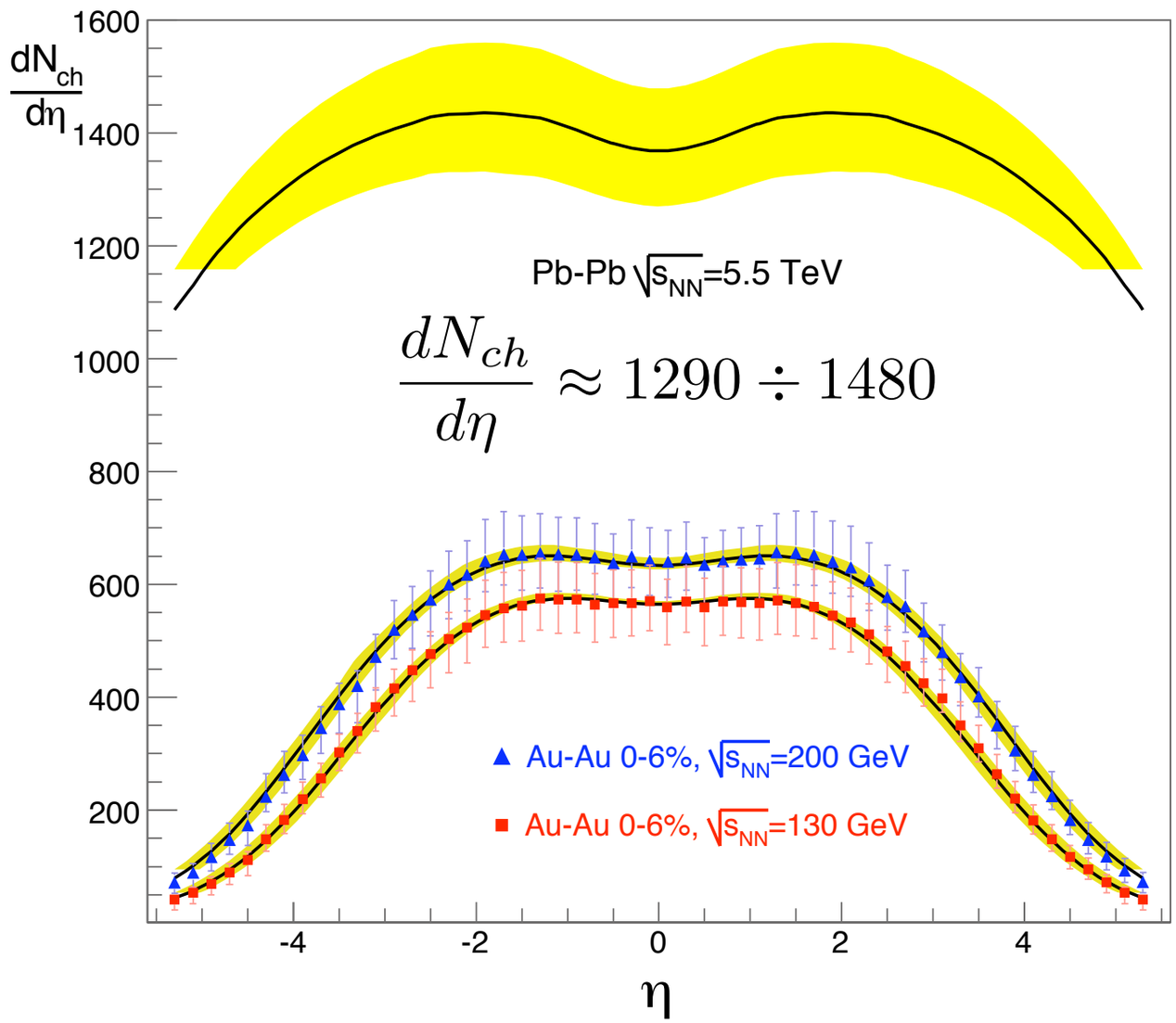
$$0.005 \leq x_0 \leq 0.01 \qquad Q^2_{s0} = 0.5\,\mathrm{GeV}^2 \longrightarrow Q^2_{s0,\,gluon} = 1.125\,\mathrm{GeV}^2$$



Fit parameters consistent with NLO-CGC analyses of other observables:

Multiplicities in RHIC Au+Au

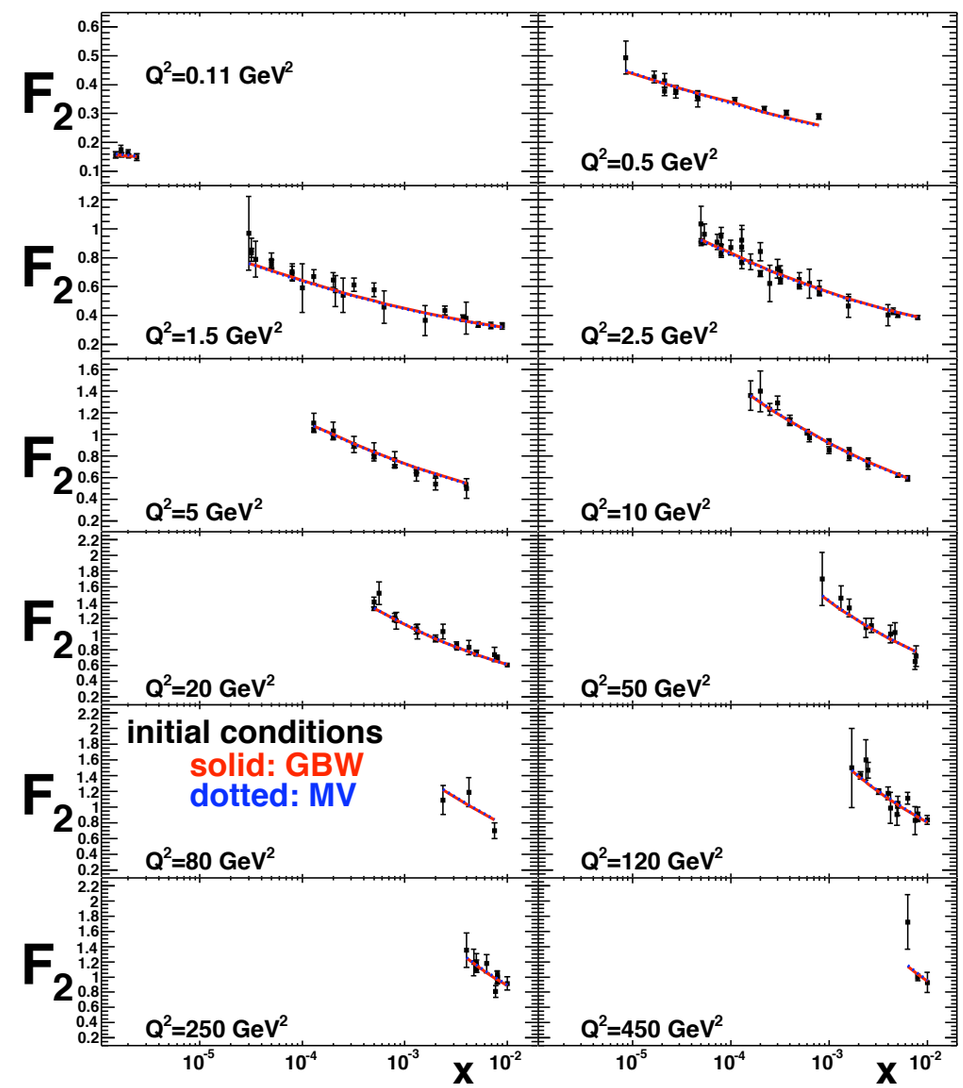
JLA



$$\frac{dN_{ch}}{d\eta} \approx 1290 \div 1480$$

F_2, F_L and F_D in e+p HERA collisions

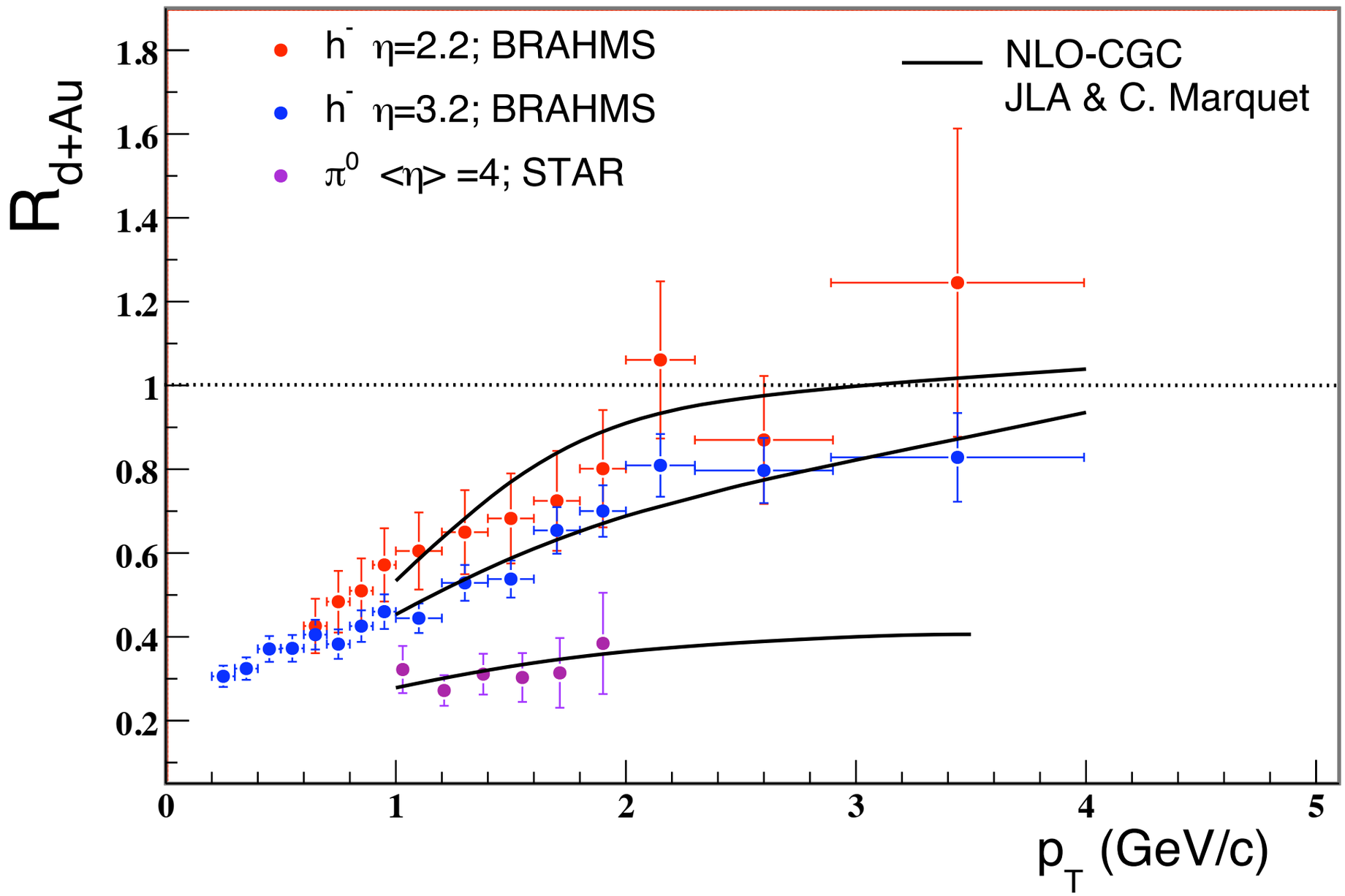
JLA-Armesto-Milhano-Salgado
Goncalves et al.

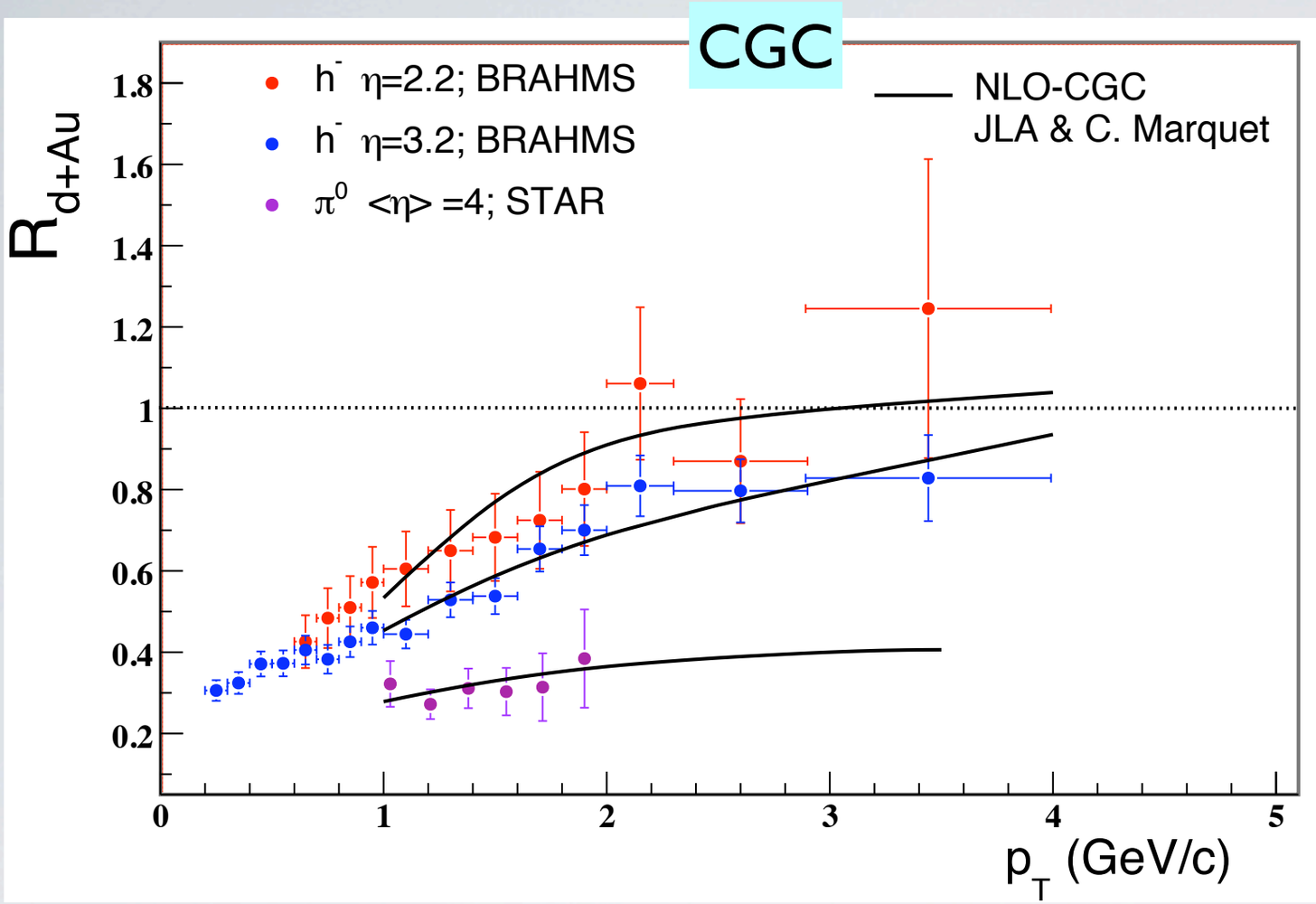


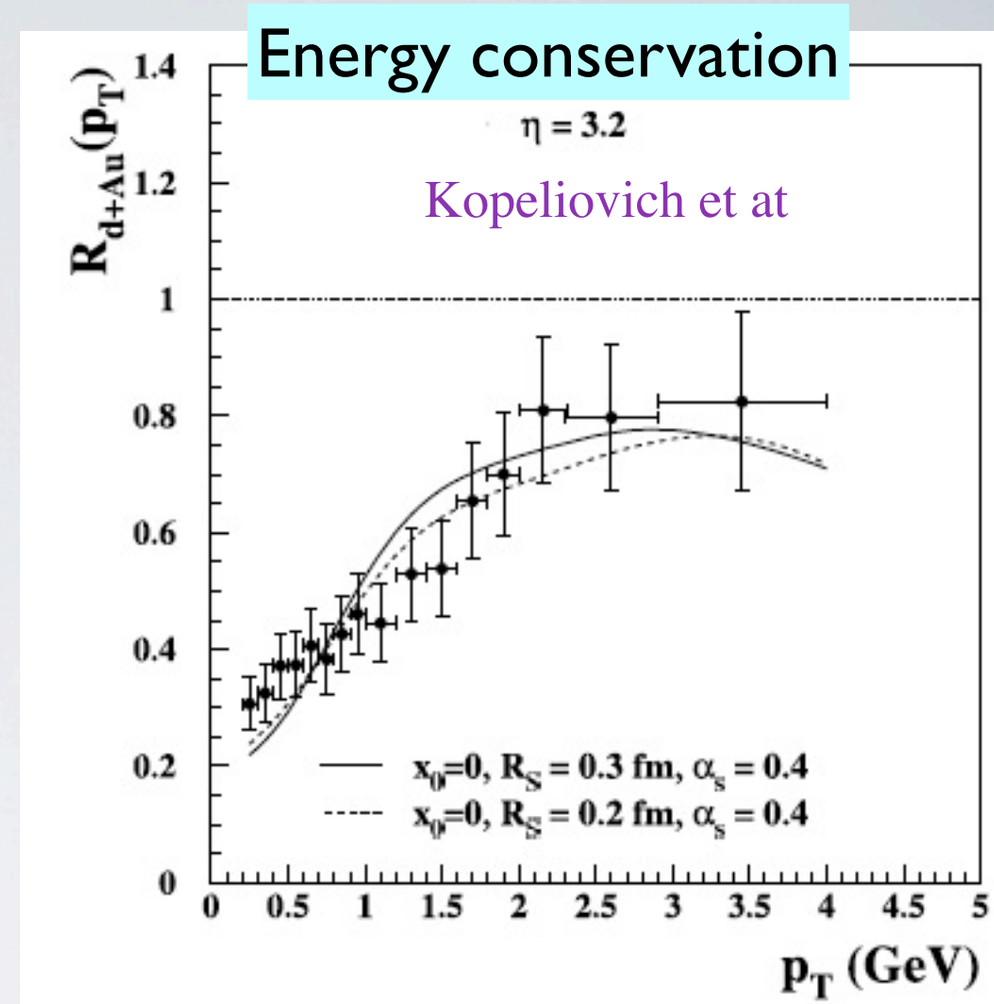
$$\frac{Q^2_{0A}}{Q^2_{0proton}} \sim 2 \div 2.5 = cA^{1/3}$$ compatible with e+A data. K. Dusling et al

Two-particle correlations in forward d+Au at RHIC (Cyrille Marquet's talk)

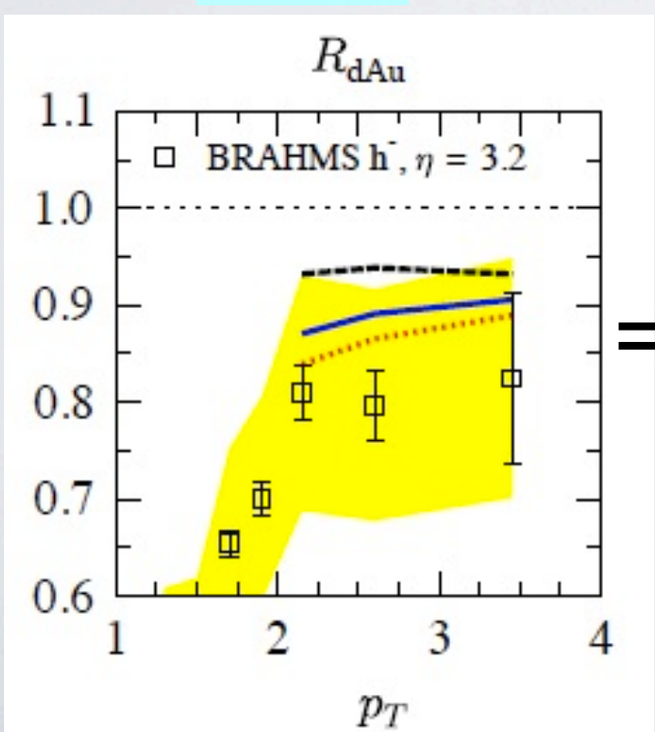
- ...by simply taking the ratio of d+Au and p+p spectra we get a good description of the nuclear modification factor (not a trivial statement!!)







nPDF's Eskola-Paukkunen-Salgado



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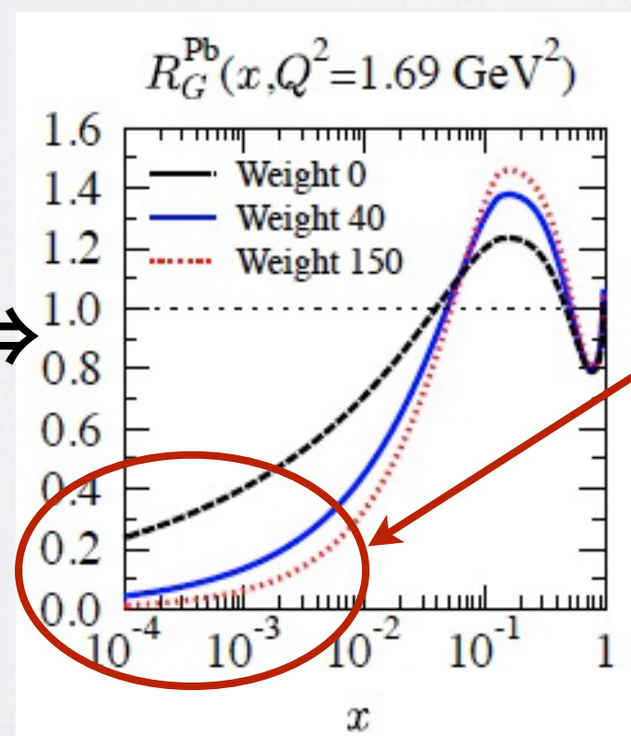
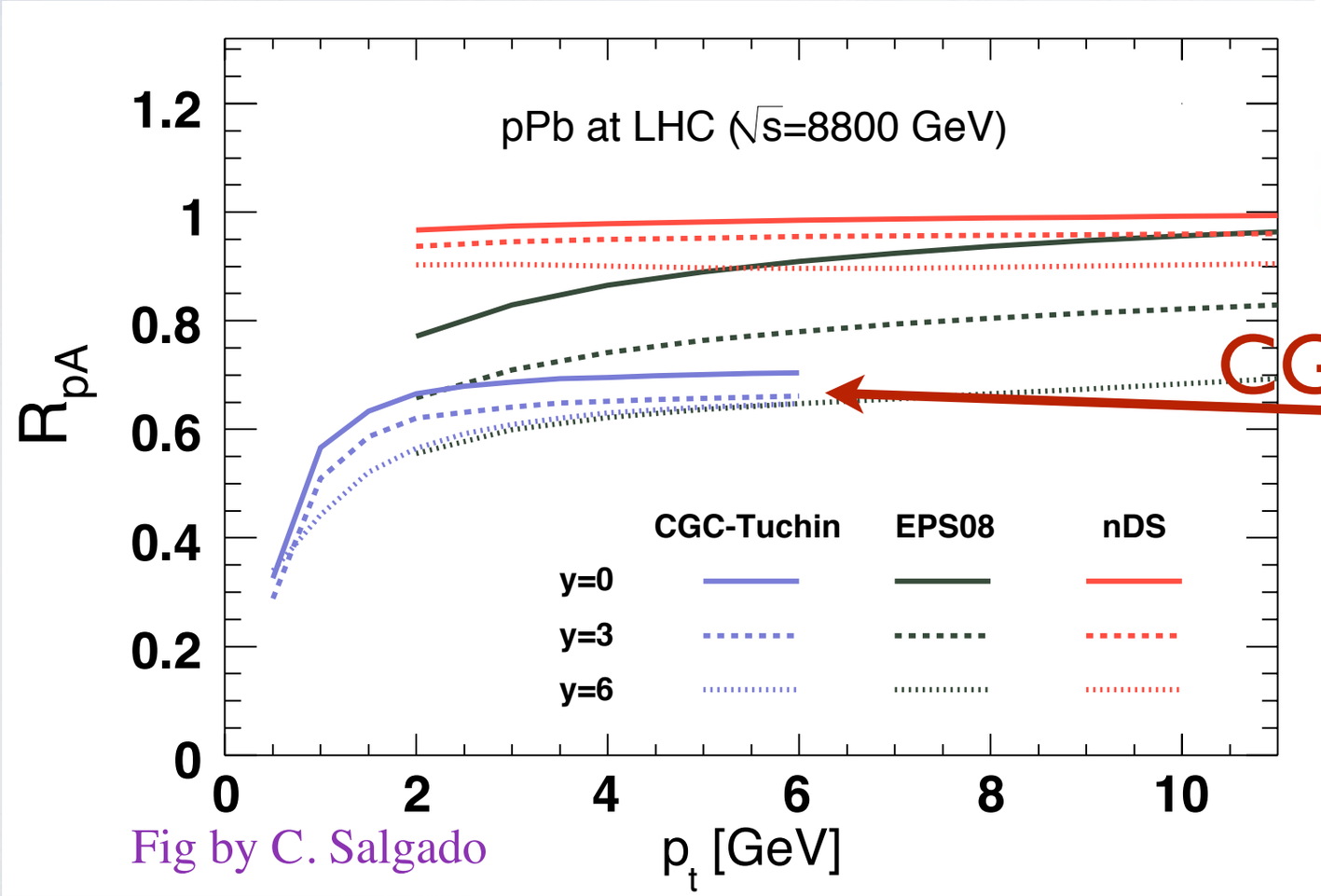
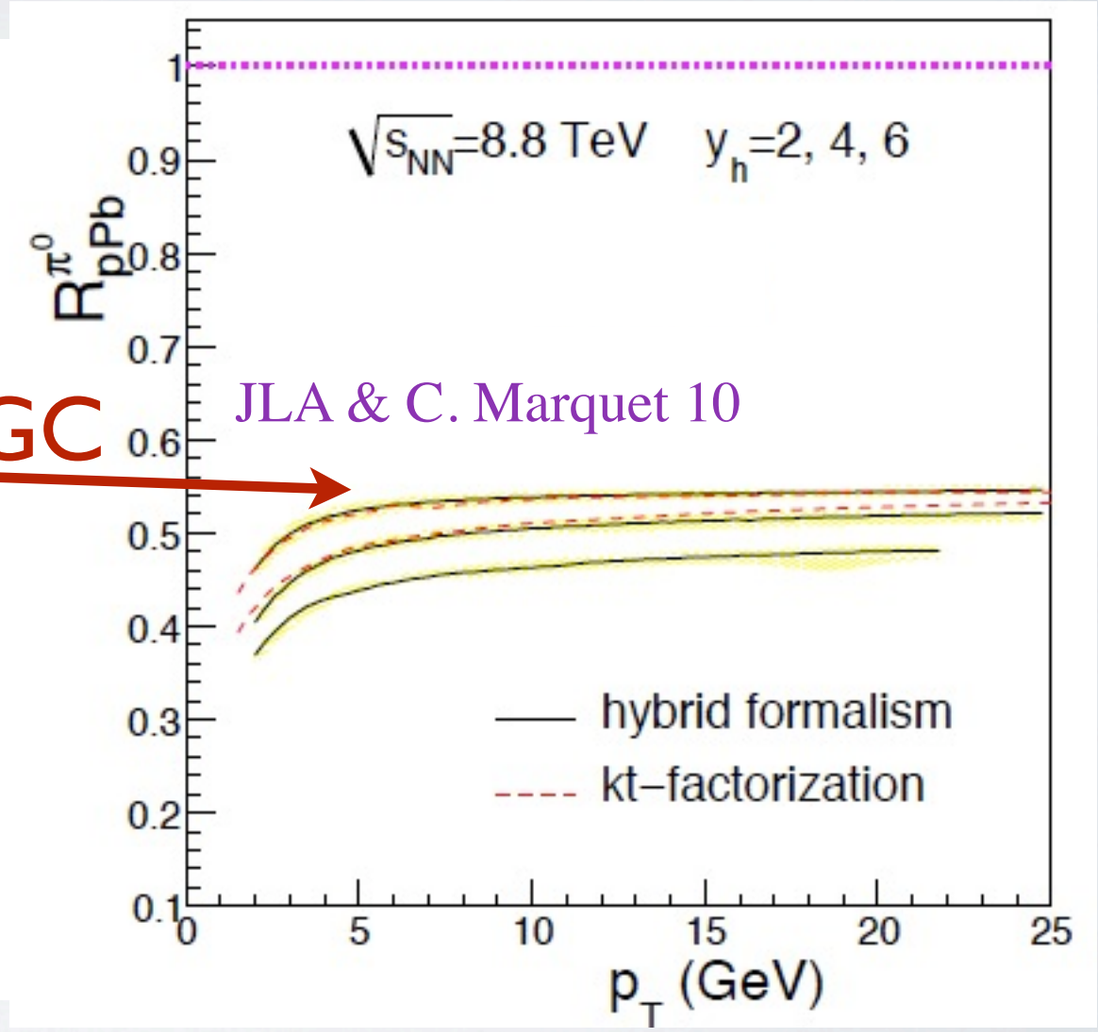


- nPDF's description of forward suppression involves a huge nuclear shadowing at small-x
- Forward RHIC data not included in most recent NLO parametrizations (EPS09)

- So, is RHIC forward suppression a small-x_2 (CGC) or a large-xF (energy conservation) effect??
- p-Pb collisions at the LHC probe both the target and the projectile at small-x
- CGC calculations agree to predict a sizable suppression (~0.5) at y=0 in pPb at the LHC





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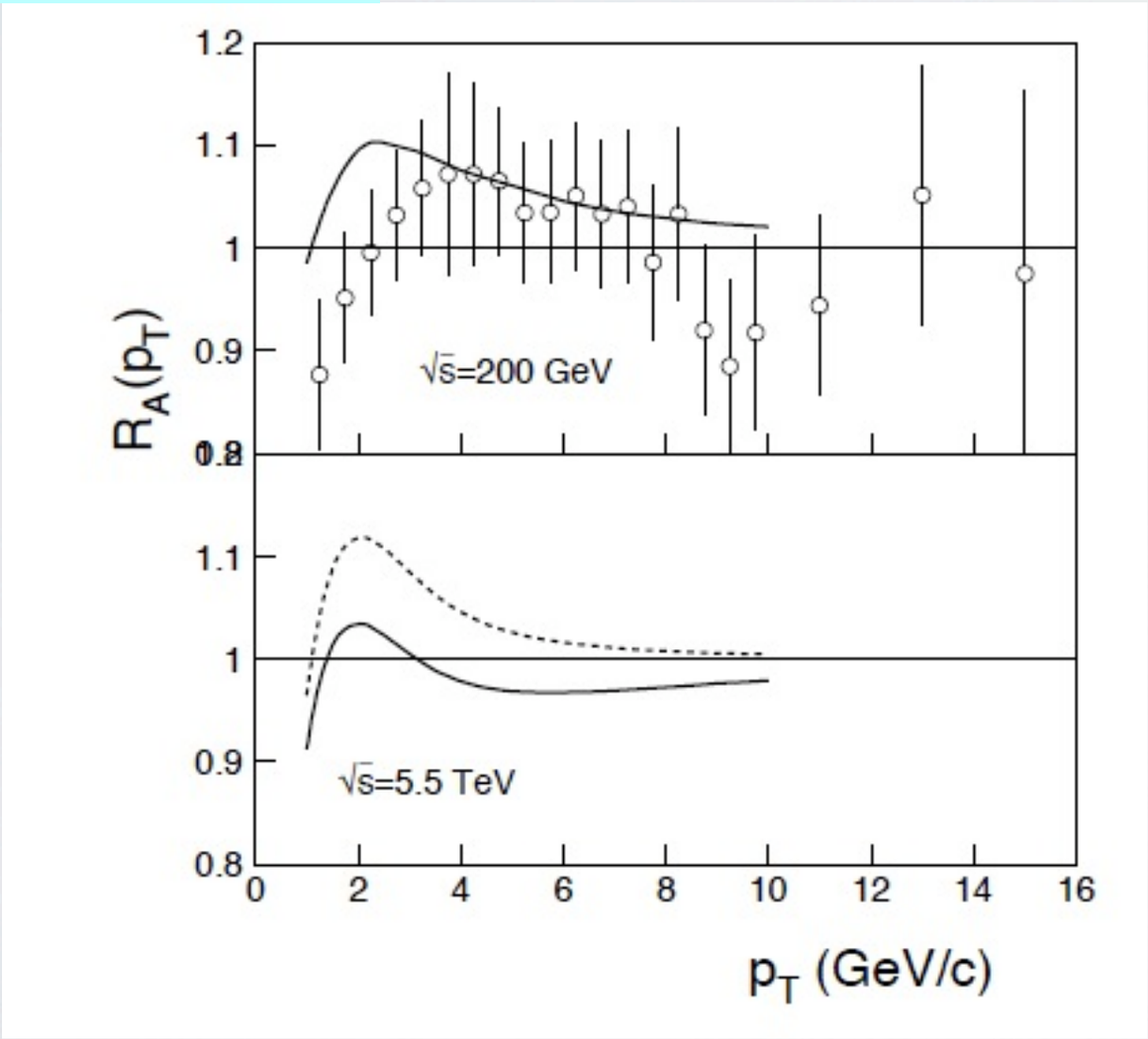
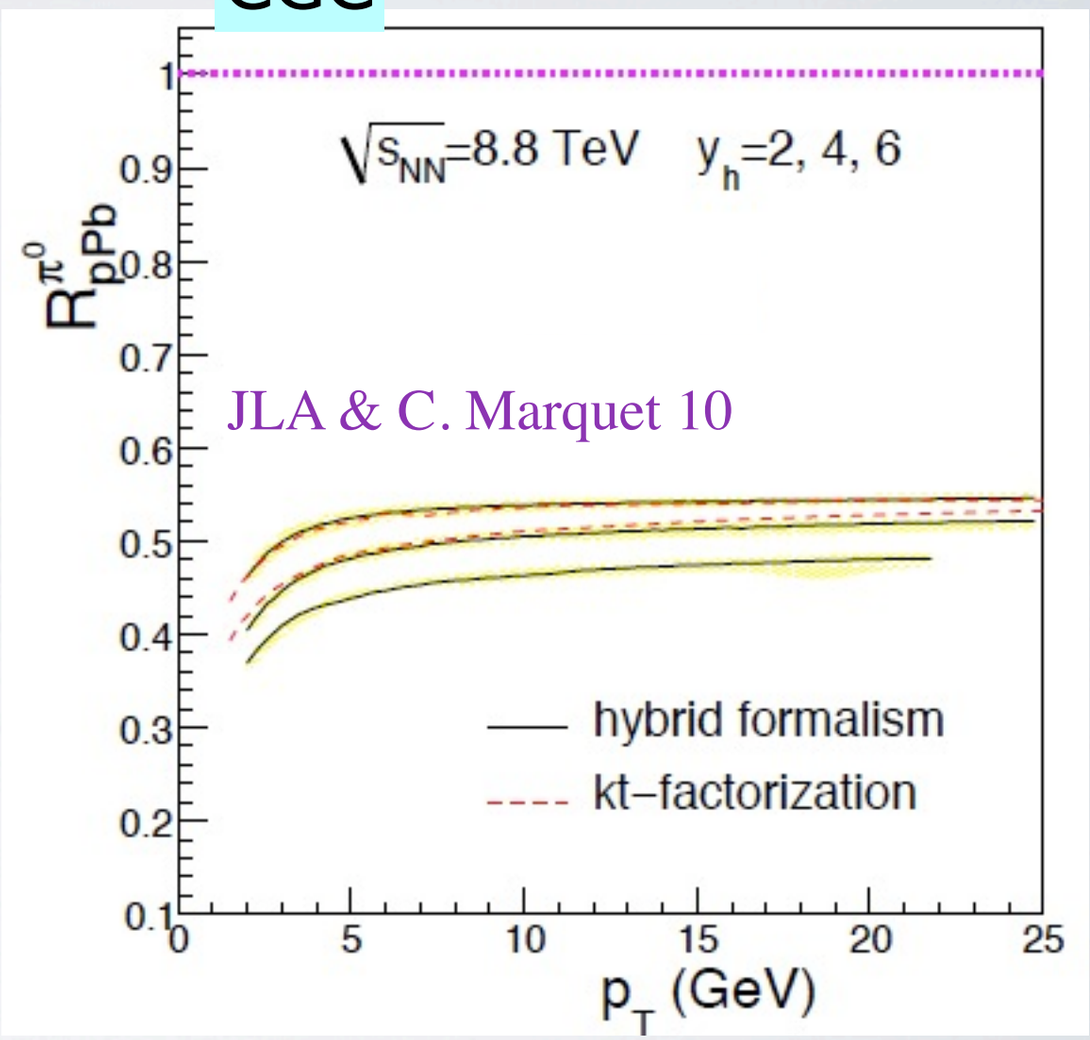
- p-Pb collisions at the LHC probe both the target and the projectile at small-x
- CGC calculations agree to predict a sizable suppression (~0.5) at y=0 in pPb at the LHC
- Energy-loss is not expected to be relevant in that kinematic region

"Energy-loss" Kopeliovich et al

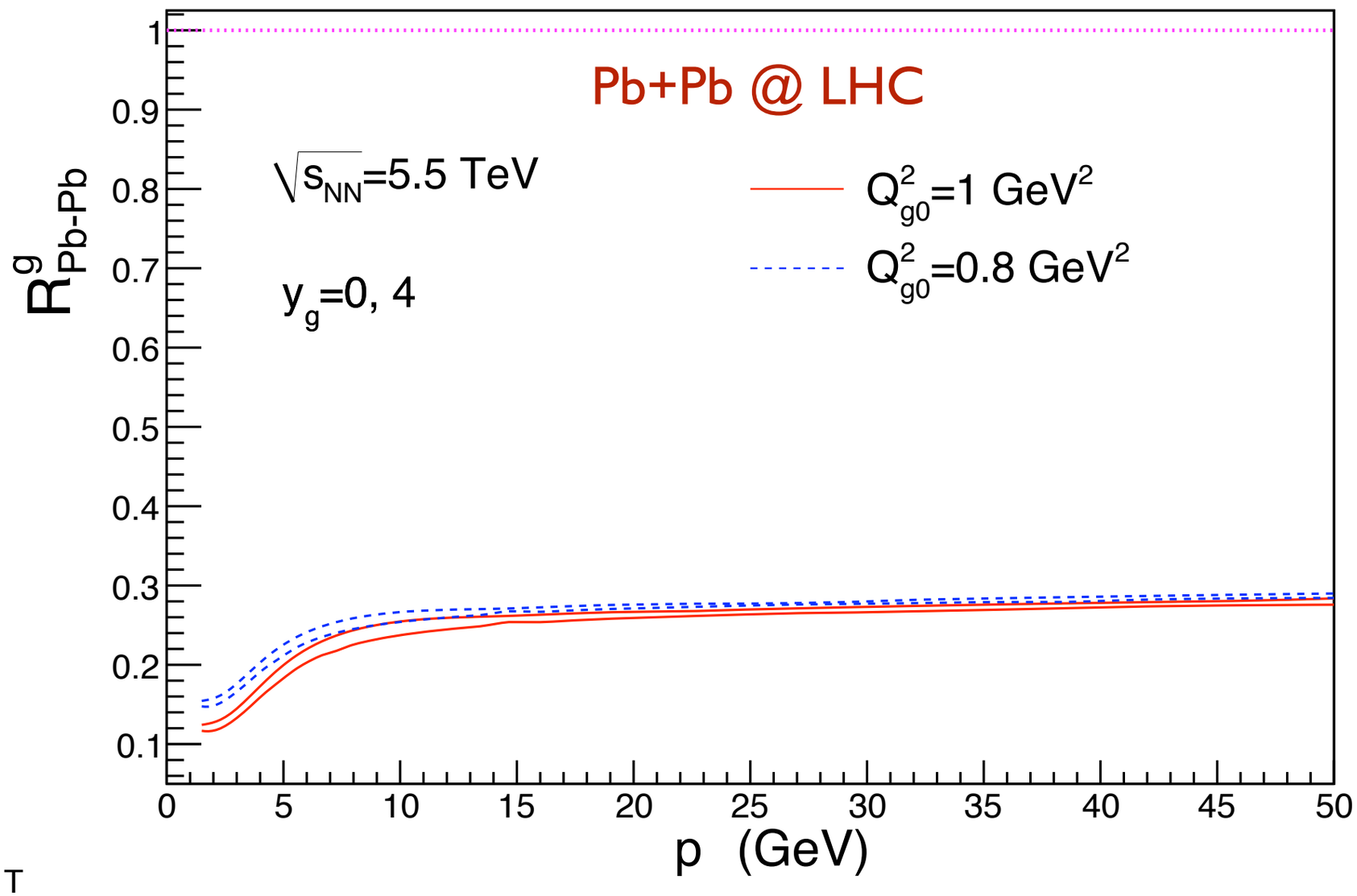


CGC



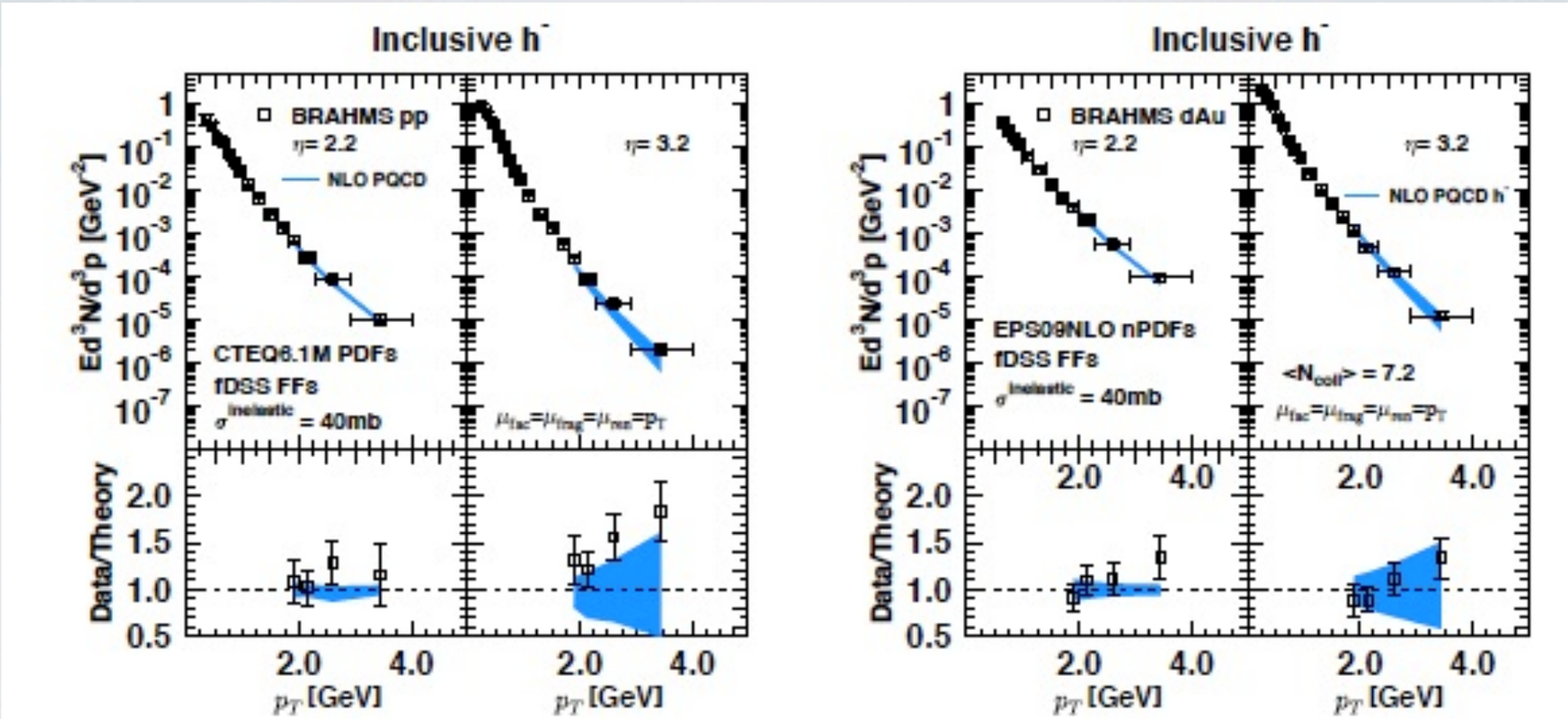
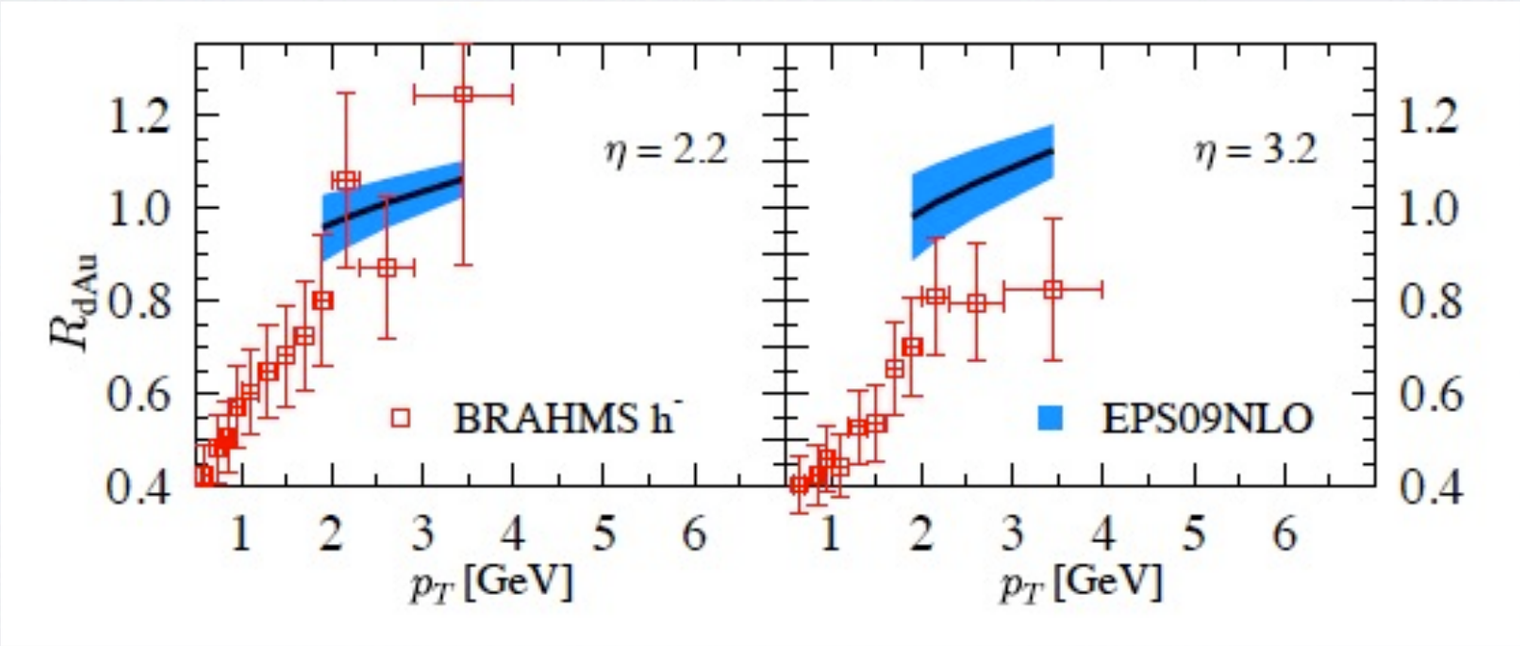
Small-x effects would also lead to strong suppression of initial gluon production in Pb+Pb collisions @ LHC:

"Naked" n.m.f. $$R^g_{PbPb} = \frac{1}{N_{\rm coll}} \frac{dN_h^{PbPb}}{dy_h\, d^2p_t} \Big/ \frac{dN_h^{pp}}{dy_h\, d^2p_t}$$



Summary

- RHIC data for inclusive hadron production in d+Au and p+p collisions probe moderate to small values of x in the target wave function. Onset of CGC description is expected
- Mid-rapidity data does not allow to discriminate between different approaches (CGC, Glauber-Eikonal, npdf's...)
- Very good description of forward data in p+p and d+Au collisions based on CGC @ NLO.
- Energy-momentum conservation corrections (missing in the CGC description) have been argued to lead to a comparable suppression of forward yields as the one stemming from CGC analyses
- The study of more exclusive observables is needed
- The p+Pb program at the LHC may shed light on the problem

Back up slides

Eskola-Paukkunen-Salgado (EPS08)