Effects of saturation in high-multiplicity pp collisions

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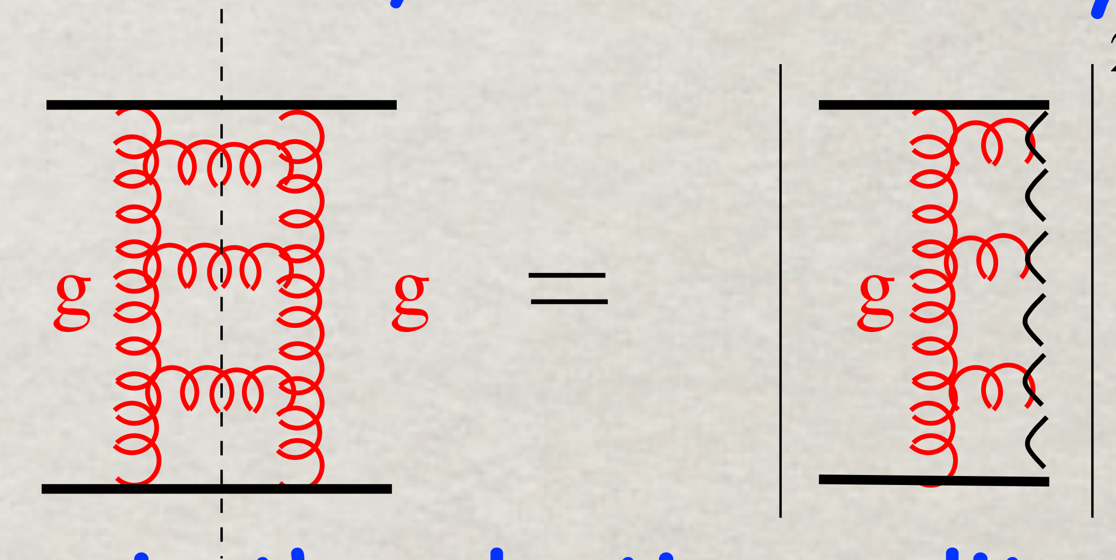
J/ψ in high multiplicity environment

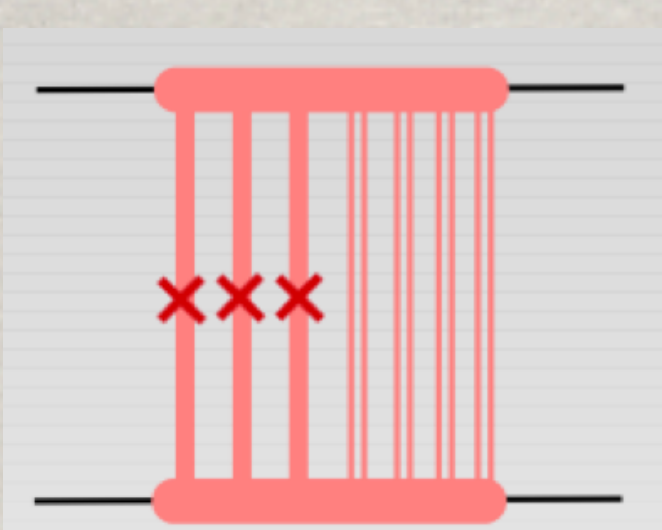
Mechanisms of multi-particle production in pp, pA and AA collisions are poorly understood and based on models involving numerous ad-hoc assumptions.

The popular eikonal or Glauber models provide information only about the elastic amplitude, which is related by unitarity with the total inelastic cross section, and do not say anything about the multiplicity distribution.

Example: unitarity cut of the Pomeron $\quad 2\,\mathrm{Im}\, f_{el} = $



The ambitious problem of relation between different terms in the elastic amplitude and inelastic processes was solved by Abramovsky, Gribov and Kancheli (AGK cutting rules). The main assumption is invariance of the multi-Pomeron vertex relative to different unitarity cuts.



The number of cut Pomerons, called number of collisions $\mathbf{N_{coll}}$ controls the hadron multiplicity

$$\langle \mathbf{n_h} \rangle \propto \mathbf{N_{coll}}$$

Uncut Pomerons play role of absorptive corrections, i.e. shadowing

Shadowing at high multiplicities

$$\frac{d\sigma_{in}}{d^2b} = e^{-N_{coll}} \sum_{k=1}^{\infty} \frac{[N_{coll}]^k}{k!} = 1 - e^{-N_{coll}}$$

The inelastic cross section is subject to shadowing. It does not need the AGK rules, but is derived directly from the eikonal (Glauber) model.

Such a formal expansion of the exponential should not be treated as sequential inelastic collisions of the projectile proton. A proton can do it only once. Multiple inelastic collisions must occur "in parallel", by involving multi-parton Fock components, otherwise one cannot cut several Pomerons simultaneously.

$$\frac{d\sigma_{incl}}{d^2b} = e^{-N_{coll}} \sum_{k=1}^{\infty} \frac{[N_{coll}]^k}{k!} k = N_{coll}$$

Mueller-Kancheli theorem:

Inclusive cross section is not affected by shadowing.

Thus, the inclusive cross sections and mean multiplicities of different particles are proportional to N_{coll}, and to each other.

This statement is fully based on AGK, in particular on independence of the hadron multi-Pomeron vertex of N_{coll}, which has not been proven in QCD.

AGK rules confront data

With notations for the normalized multiplicities of light hadrons and J/ψ

$$R_h \equiv \frac{dN_h/dy}{\langle dN_h/dy\rangle} \qquad R_{J/\Psi} \equiv \frac{dN_{J/\Psi}/dy}{\langle dN_{J/\Psi}/dy\rangle}$$

one would expect that the lack of shadowing leads to a simple relation $R_{J/\Psi} = R_h = N_{coll}$ strongly contradicting data

$R_h^{pA} = 1 + \beta_h (N_{coll} - 1)$ with $\beta_h \approx 0.55$, nearly independent of energy.

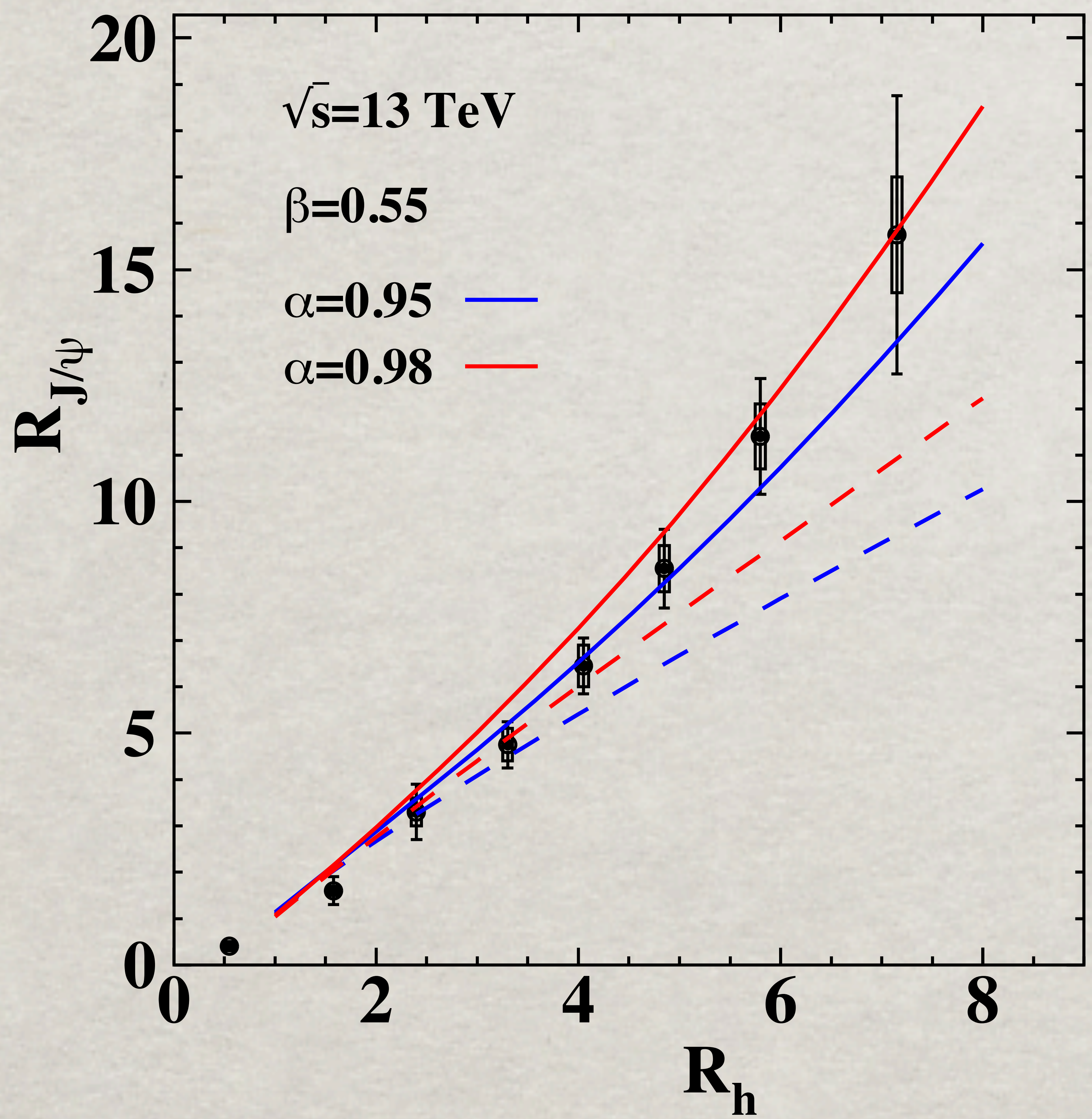
Similar, although smaller effect of suppression is observed for J/ψ production in pA, usually parametrized as $R^{pA}_{J/\Psi} = N_{coll} A^{\alpha-1}$, with α=0.95-0.98.
This can be also presented as

$R^{pA}_{J/\Psi} = 1 + \beta_{J/\psi}(N_{coll} - 1)$ with $\beta_{J/\psi} \approx 1 - (1-\alpha)\ln A$

Breakdown of AGK happens for several reasons, higher twist quark shadowing, analogous to shadowing in DIS on nuclei; coherence (gluon shadowing, Landau-Pomeranchuk effect)

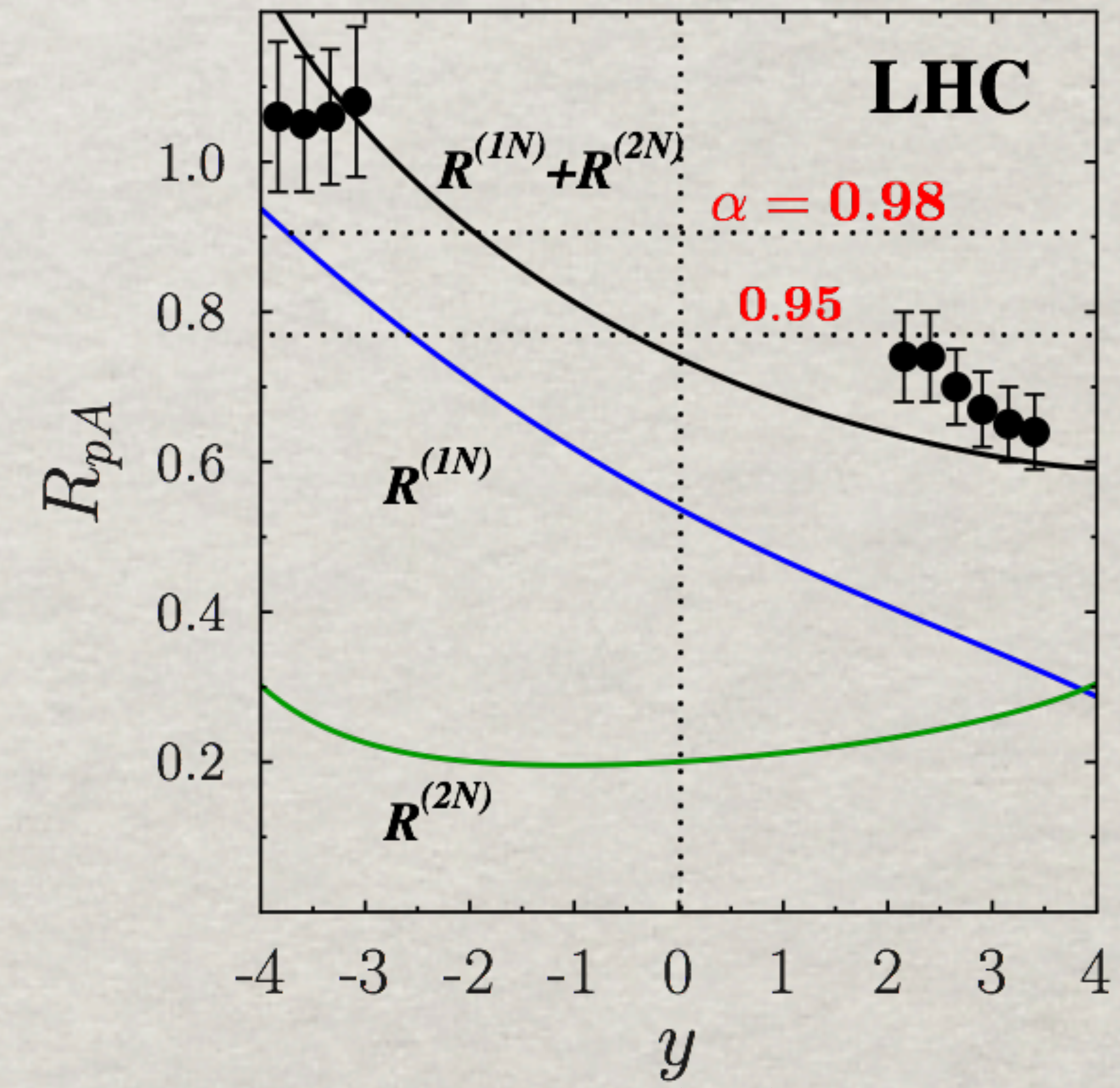
J/ψ vs pions

$$\frac{R^{pA}_{J/\Psi}-1}{R^{pA}_{h}-1}=\frac{\beta_{J/\psi}}{\beta_h}$$



BK, I.Potashnikova, H.J.Pirner & K.Reygers, PRD 88(2013)116002

The value of a has not been measured well at y=0.
Can be evaluated theoretically, but one hardly consider that as a reliable result



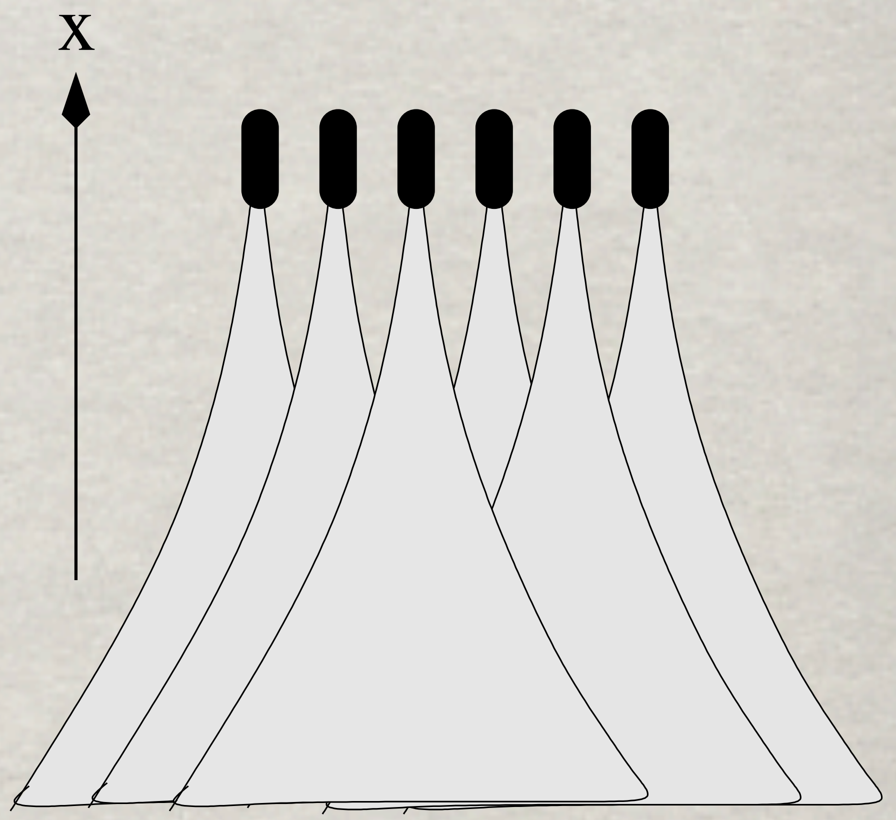
B.K., I.K.Potashnikova, M.Siddikov, I.Schmidt, PRC 95(2017)065203

Frame dependent parton model

Parton model description of high-energy hadronic interaction is not Lorentz invariant. It varies from frame to frame, while measurable observables must remain unchanged, i.e. are Lorentz invariant.

Example: DIS related to absorption of the virtual photon in the Bjorken frame, looks like photon splitting to q-qbar in the nuclear rest frame.

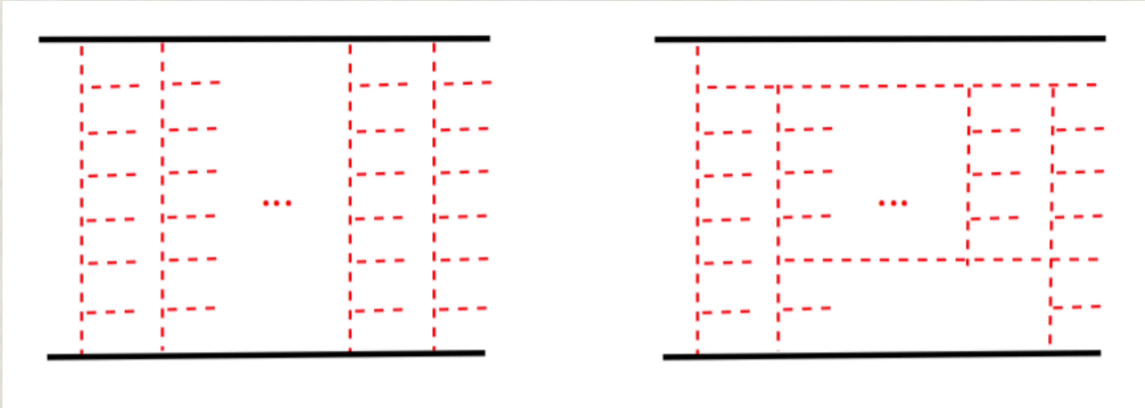
Another example: nuclear shadowing, which looks like optical analogy in the nuclear rest frame, is interpreted as fusion of overlapping parton clouds in the light-front frame.



Color-glass condensate (saturation): increase of the mean transverse momenta of nuclear partons in the light-front frame, looks like pT-broadening of a parton propagating through the nucleus in its rest frame.

Effects of parton saturation

Multiple coherent interactions in pp or nuclear collisions lead to broadening of transverse momenta calculated in a parameter free way within the dipole approach



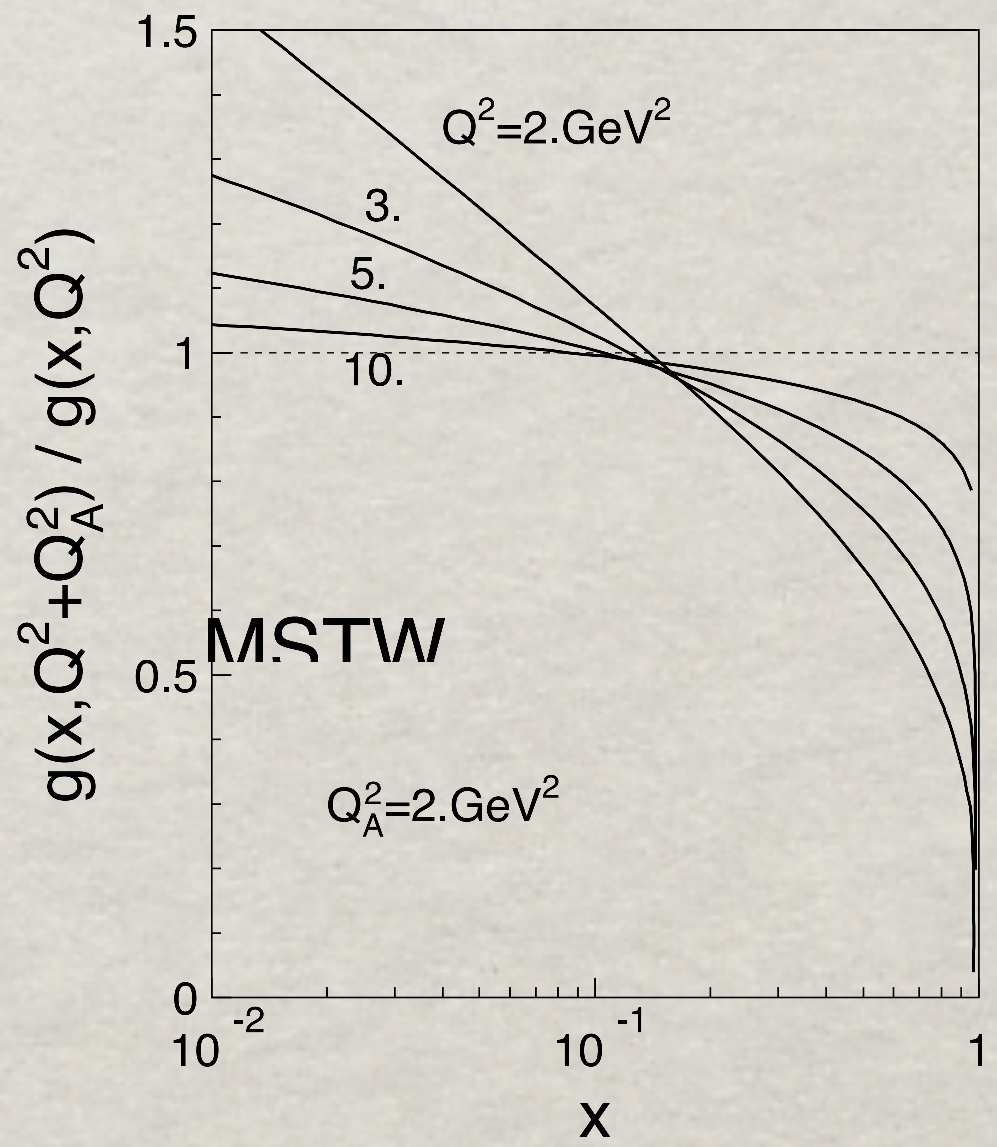
$$\Delta p_T^2 = \frac{9\,C(E)}{2\,\sigma_{in}^{pp}}\,(N_{coll}-1)$$ with

$$C(E) = \frac{1}{2}\,\tilde{\nabla}_{r_1}\cdot\tilde{\nabla}_{r_2}\,\sigma_{\bar{q}q}(\tilde{r}_1-\tilde{r}_2,E)\Big|_{\tilde{r}_1=\tilde{r}_2}.$$

M.Johnson, B.K., A.Tarasov PRC638(2001)0352203

The dipole cross section $\sigma_{\bar{q}q}(r,x)$ is fitted to DIS data from HERA.

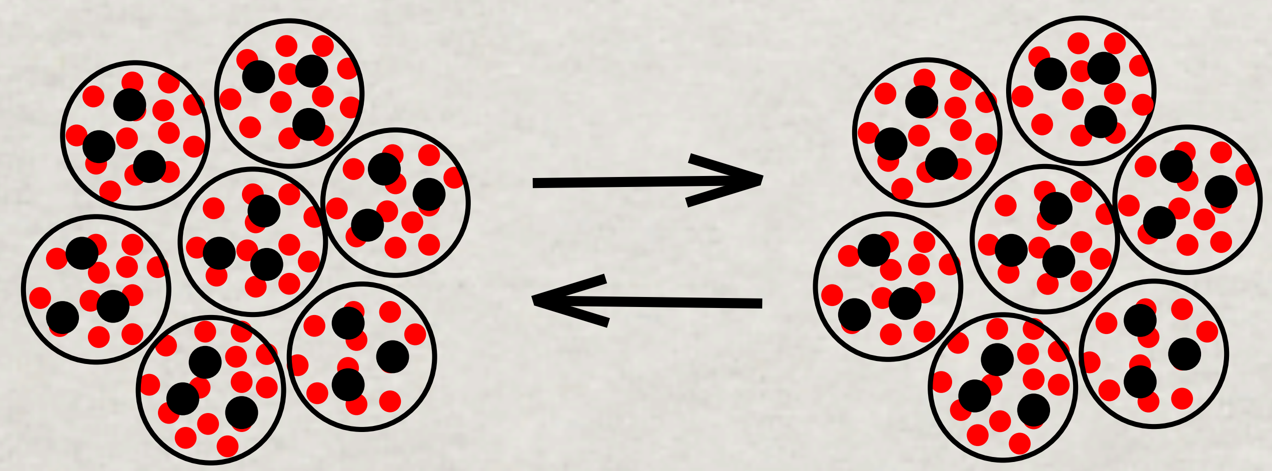
Due to broadening the nuclear target probes the parton distribution in the beam hadron with a higher resolution, so in a hard reaction the effective scale Q^2 for the beam PDF drifts to a highervalue $Q^2+Q_A^2$. More gluons at small x.



Thus, the rate of J/ψ is increased by saturation.

Mutual broadening in AA

In nuclear collisions the PDFs of bound nucleons in both nuclei are drifting towards higher scales.



This, in turn, enhances broadening compared to **pA**, since the properties of the target nucleons change.

$\sigma_{dip}($  $) > \sigma_{dip}($  $)$

Therefore, broadening, i.e. the saturation momentum, increases

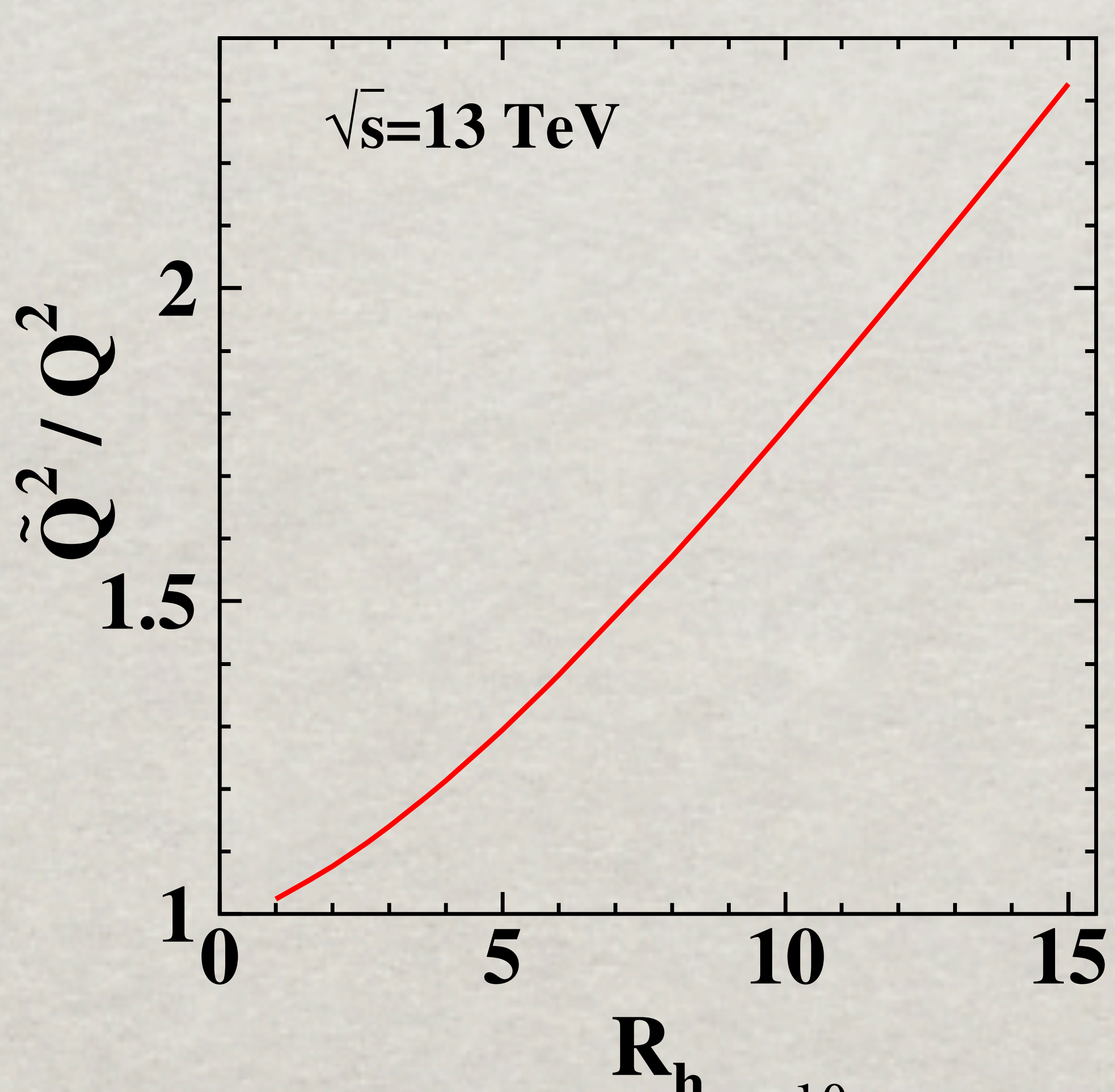
Mutual boosting of the saturation scale

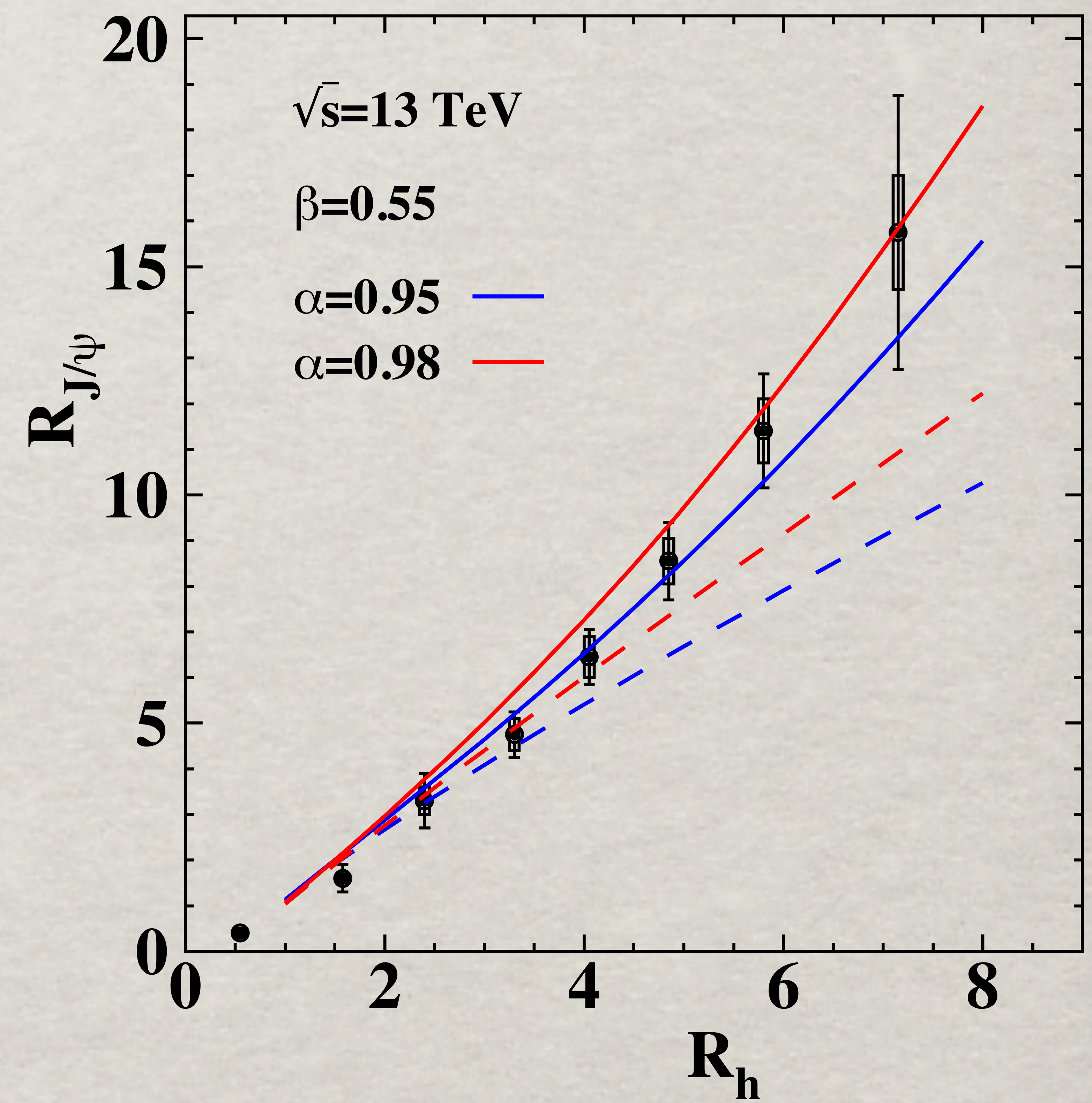
In pA collisions only the projectile proton undergoes multiple interactions, which modify its PDF, while the PDFs of bound nucleons remain unchanged. In the case of AA, or high multiplicity pp collisions, the interaction becomes symmetric, both assembles of colliding constituents are subject to multiple interactions, increasing their partonic content at small x.

$$\tilde{Q}^2_{sA}(x) = \frac{3\pi^2}{2}\,\alpha_s(\tilde{Q}^2_{sA}+Q^2_0)\,xg_N(x,\tilde{Q}^2_{sA}+Q^2_0)\,\frac{N_{coll}}{\sigma^{pp}_{tot}}$$

$$\frac{3\pi^2}{2}\,\alpha_s(Q^2_0)\,xg(x,Q^2_0) = C(E),$$

BK, I.Potashnikova, H.J.Pirner & I.Schmidt, PLB 697(2011)333





B. Kopeliovich, Clermont Ferrand 2018

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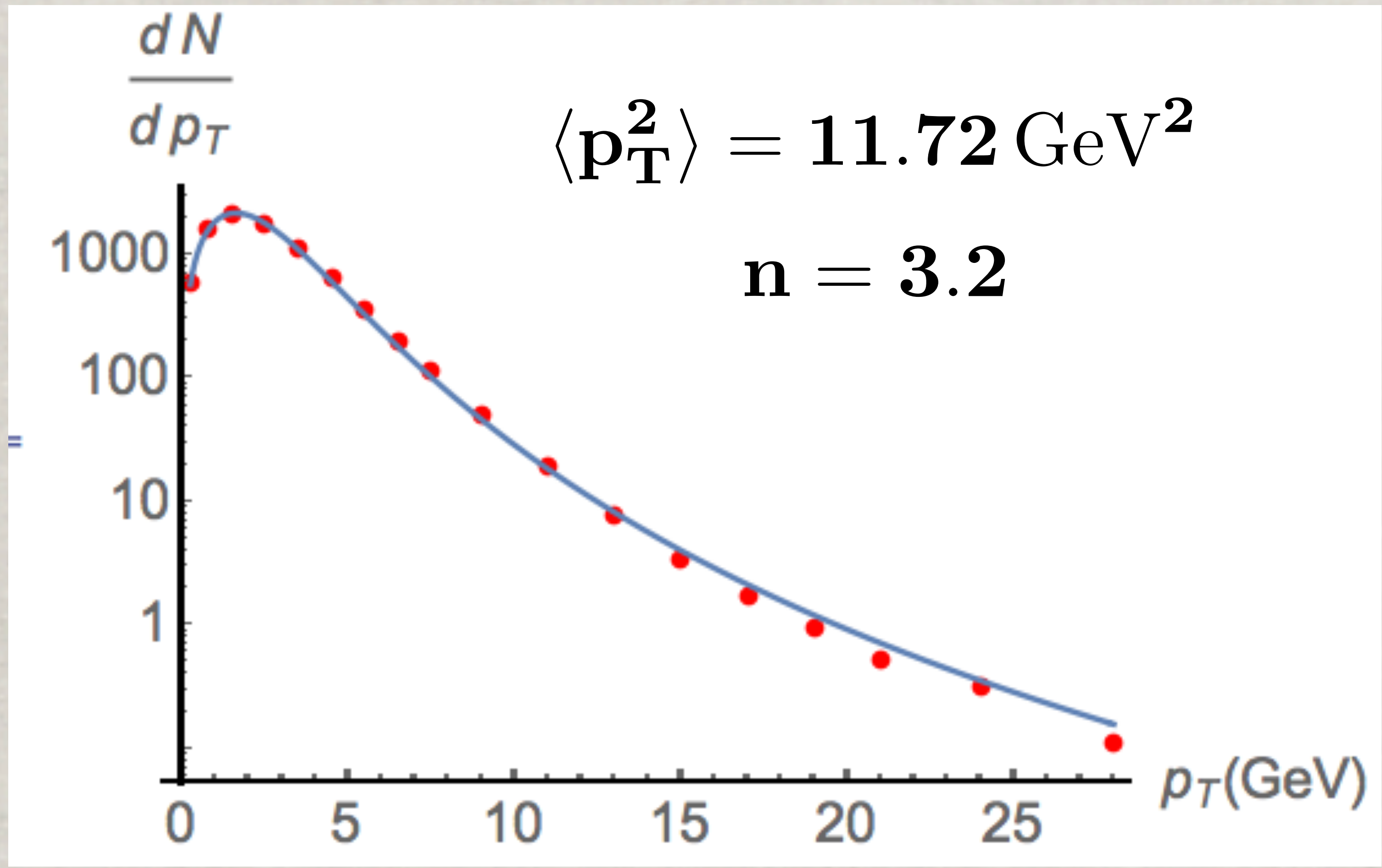
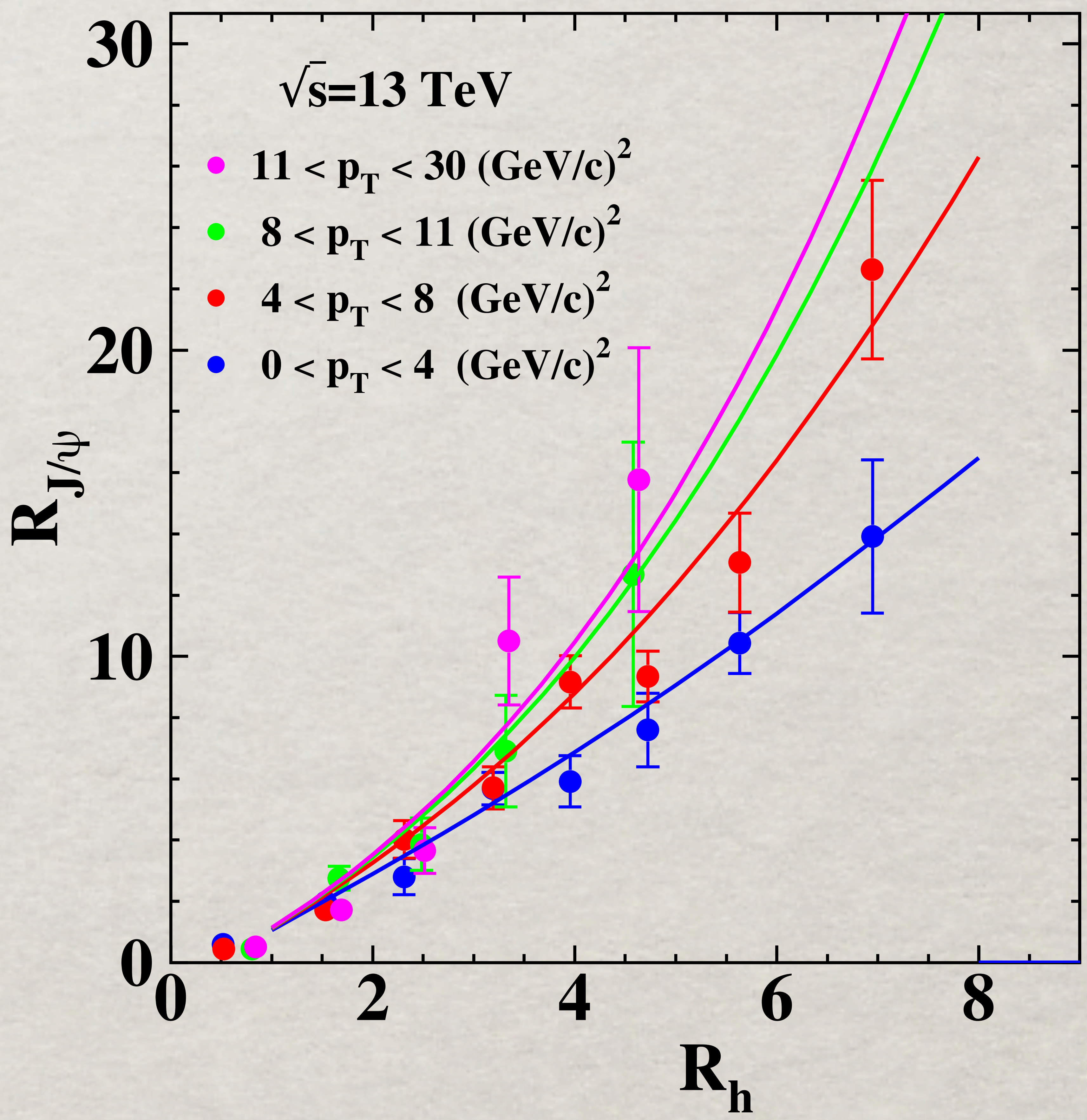
Effects of parton saturation in pT intervals

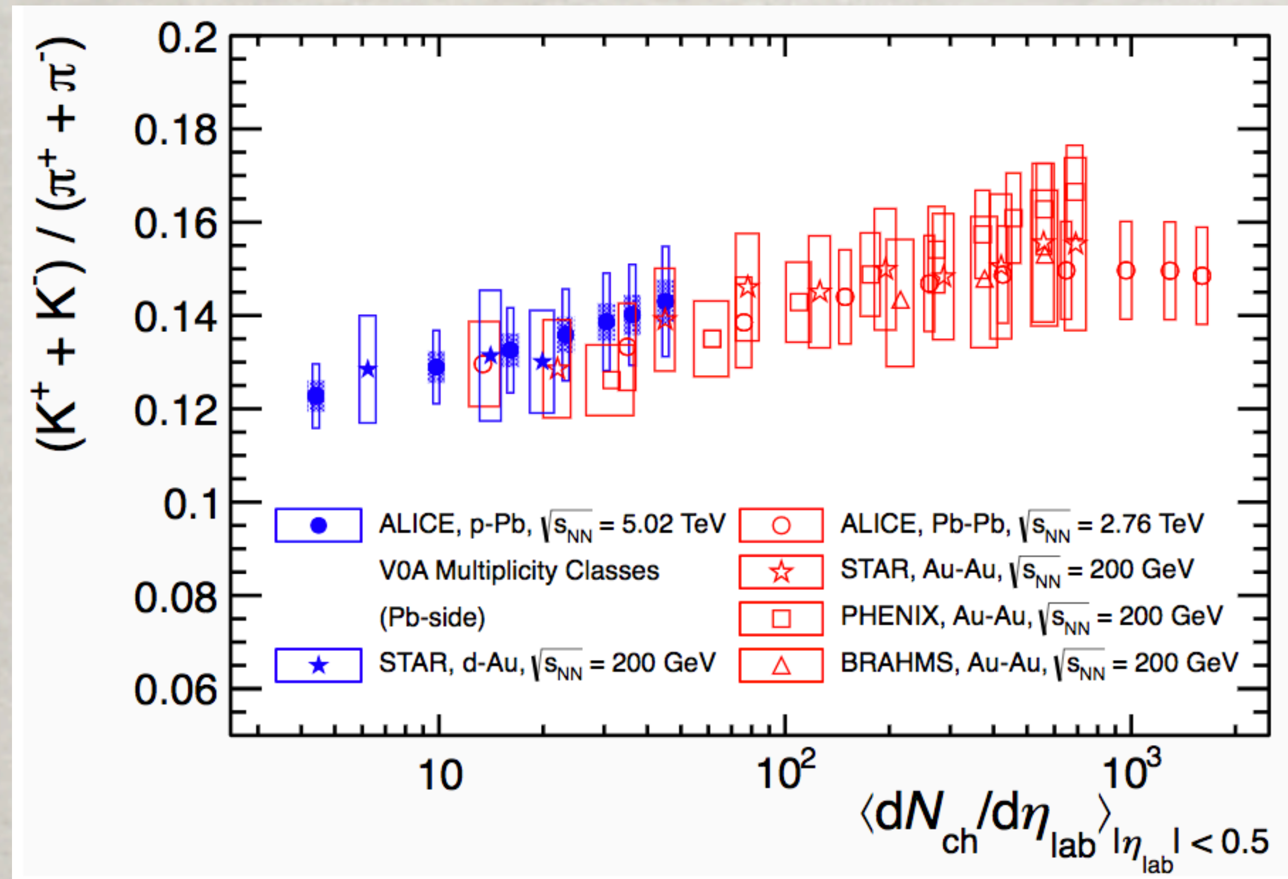
$$\mathbf{R_{J/\psi}(p_T) = \frac{\int_{p_T^{min}}^{p_T^{max}} dp_T p_T \, dN^{pp}_{J/\psi}(R_h)/dyd^2p_T}{\int_{p_T^{min}}^{p_T^{max}} dp_T p_T \left\langle dN^{pp}_{J/\psi}/dyd^2p_T \right\rangle}}$$

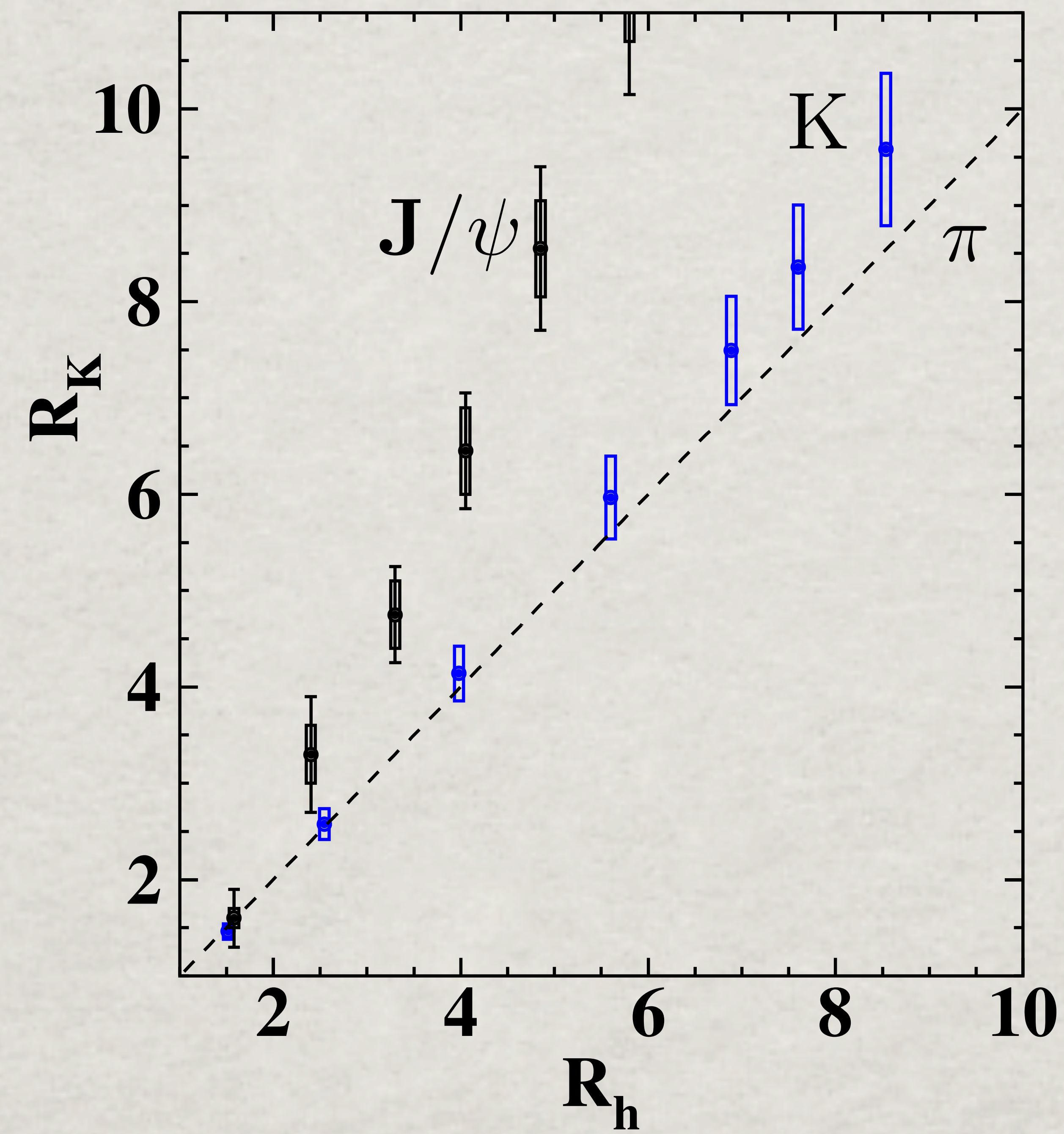
$$\mathbf{\frac{dN^{pp}_{J/\psi}}{dyd^2p_T} = \frac{dN^{pp}_{J/\psi}}{dy} \frac{1}{\langle p_T^2 \rangle} \left(1 + \frac{p_T^2}{(n-2)\langle p_T^2 \rangle}\right)^{-n}}$$



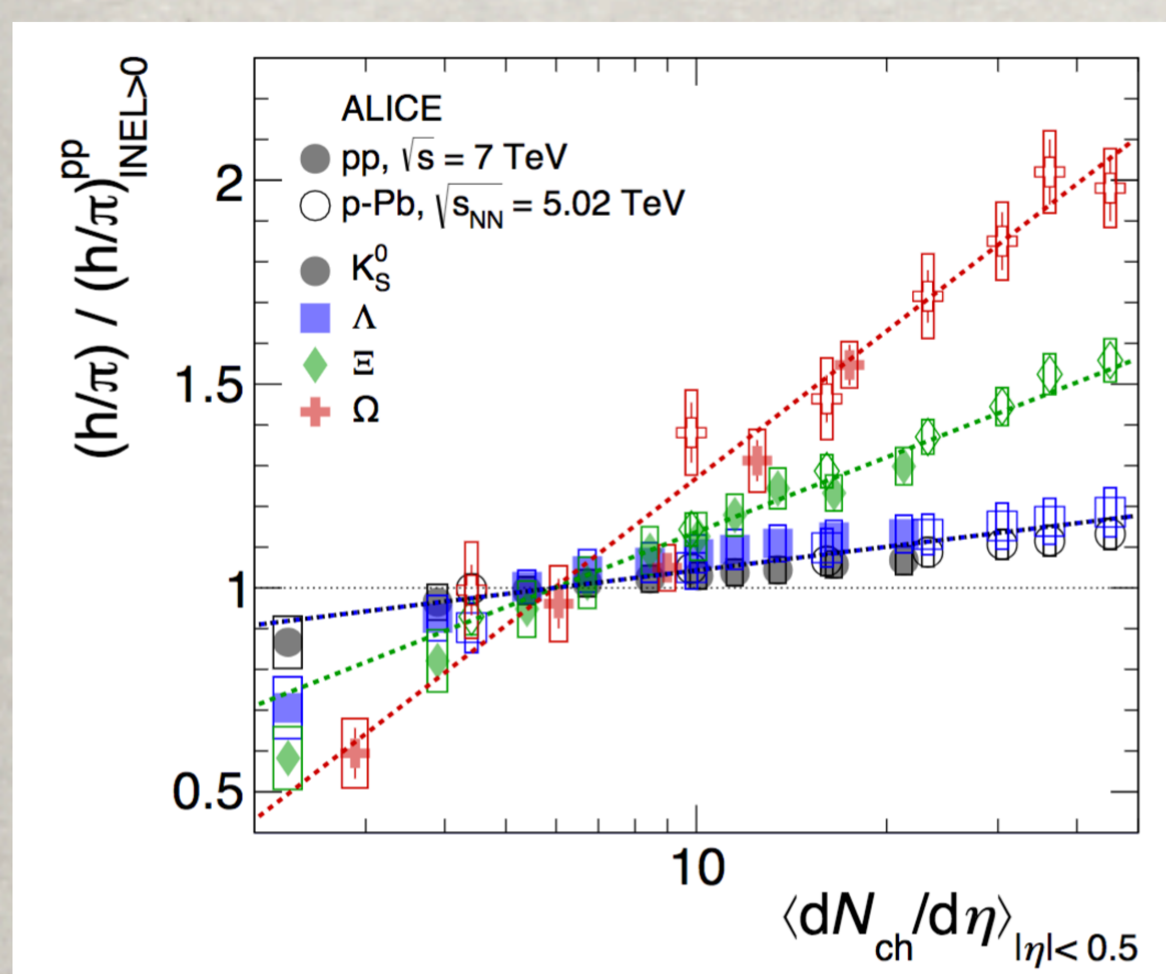


Enhancement of strangeness

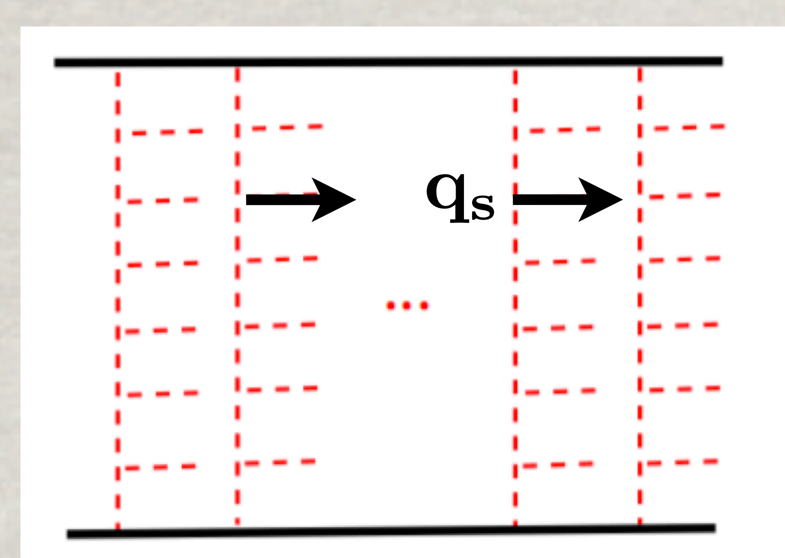




Kaons rise steeper than pions, but less than J/ψs



Multi-strange hyperons are enhanced more due to simultaneous production from several parton chains



enhanced by $N_{coll}(N_{coll} - 1)/2$

or by $N_{coll}(N_{coll} - 1)(N_{coll} - 2)/3$

$$N_{coll} = 1 + (R_h - 1)/\beta_h$$

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Summary

- Multiplicity distribution in pp and pA collisions are described basing on the AGK cutting rules. The main (poorly proven) idea is equivalence of different unitarity cuts of the multi-Pomeron vertex. It allows to make a bridge to the Glauber/eikonal model.

- AGK rules are broken by the coherence effects and higher-twist quark shadowing, more for light than for heavy quarks. This is why J/Ψs rise with multiplicity faster than kaons. Reliable evaluation of AGK breaking effects is difficult (nonperturbative physics), so we rely on available experimental information.

- Coherence leads to pT broadening in high-multiplicity events, which is equivalent to the effect of parton saturation.Appearance of the saturation scale leads to a DGLAP enhancement of low-x gluons. Mutual enhancement of low-x gluons in the two colliding hadrons (pp, AA) results in a rather strong boost of the saturation scales.