Boosted saturation in colliding nuclei

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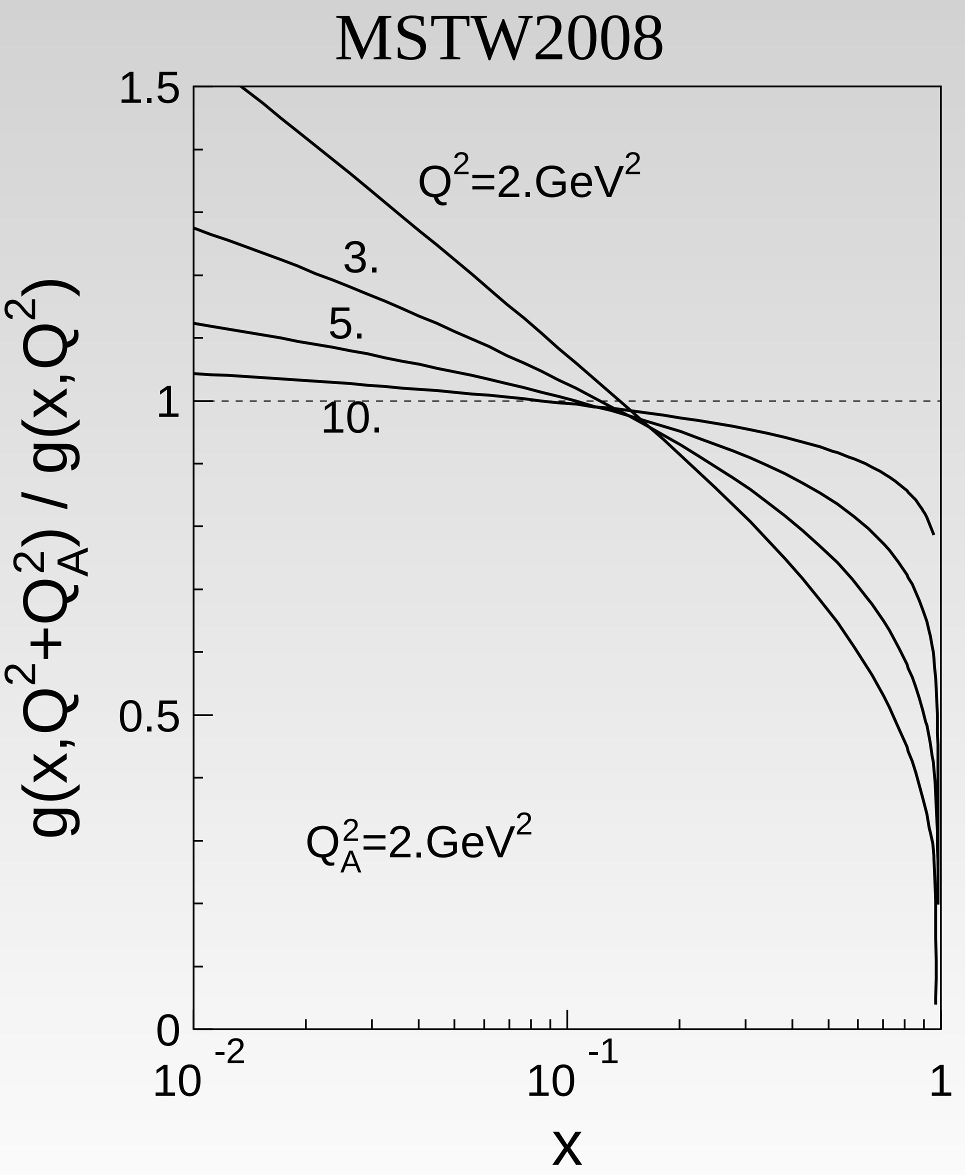
Proton modification in pA

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 higher value $Q^2 + Q^2_{sA}$.

The projectile gluon distribution is suppressed at large $x \to 1$, but enhanced at small x. This is a higher twist effect.



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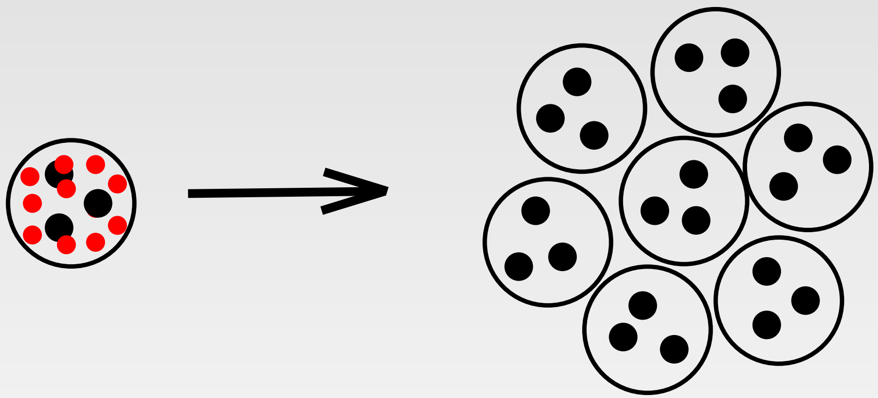
Proton modification in pA

There is an asymmetry in the properties of colliding nucleons in pA collisions: their PDFs correspond to different scales

- The PDF of the beam proton is modified to a state with a higher scale, $Q^2 + Q^2_{sA}$, and higher gluon density at small x than in NN collisions,



while the PDFs of the target bound nucleons remain unchanged and are controlled by the scale Q^2.

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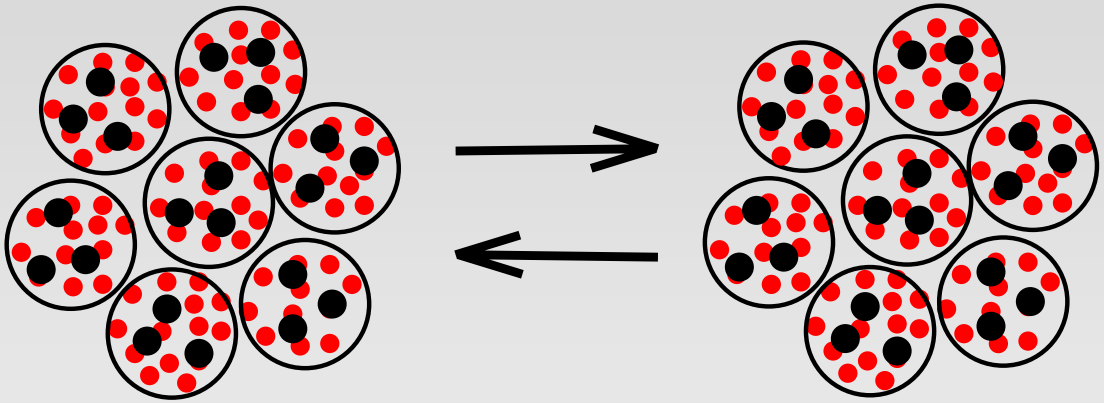
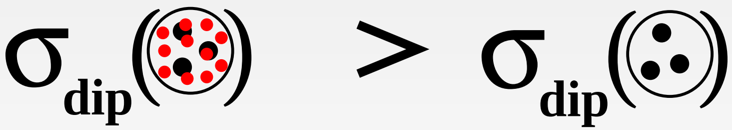
Mutual broadening in AA

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



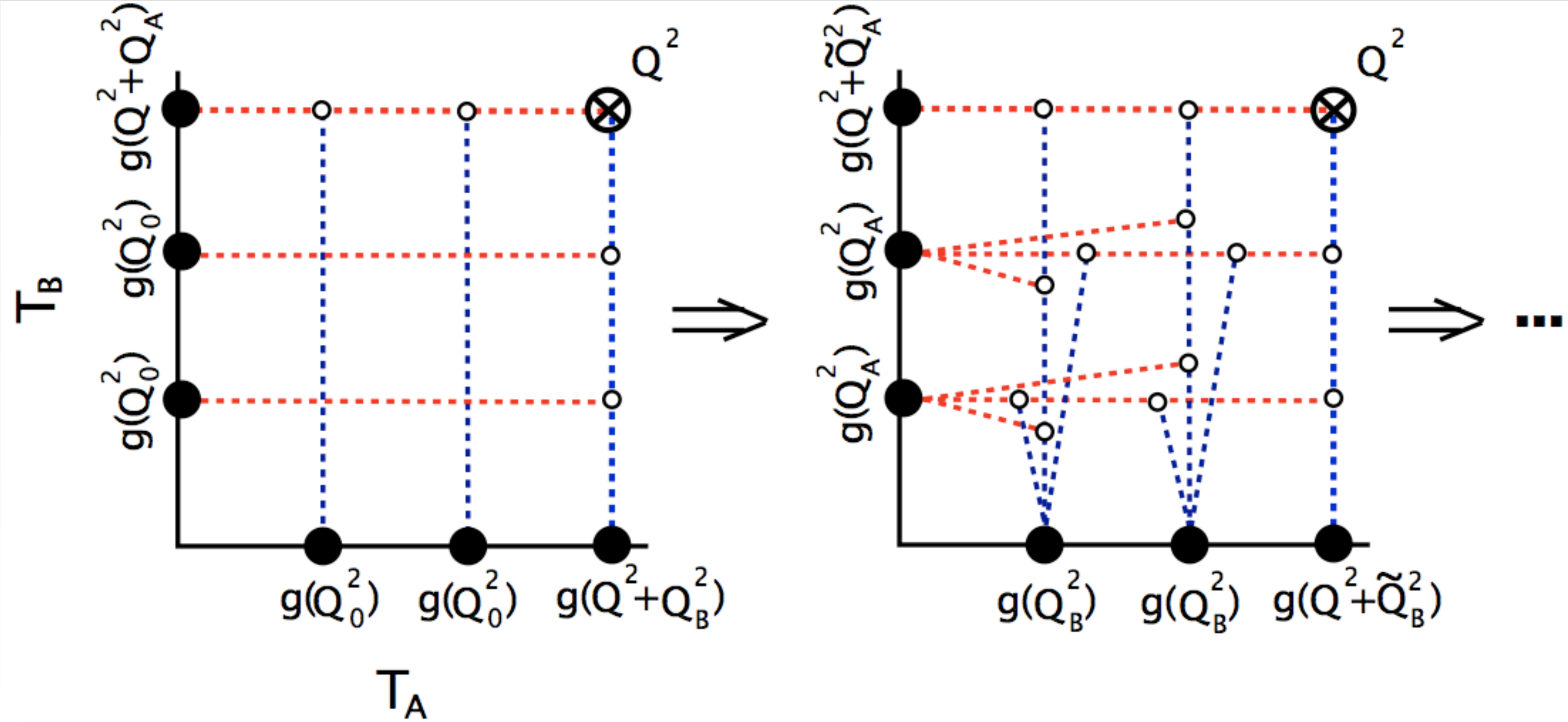
This in turn enhances broadening compared to pA, since the properties of the target nucleons change.



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

Mutual boosting of saturation scales

t-channel gluons in the rest frame of the nucleus $\boldsymbol{B}$, become s-channel gluons propagating through the nucleus $\boldsymbol{A}$ in its rest frame. So even gluonic exchanges experience broadening and participate in the boosting of the saturations scales.



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Reciprocity of saturation scales

As far as the properties of bound nucleons in nuclear collisions are modified compared to NN collision, the saturations scales in the colliding nuclei should be revised. The usual relations for the gluon saturation scales Q^2_{sA} (Q^2_{sB}) in $pA(pB)$ collisions, in the case of collision of two nuclei A and B are replaced by the system of reciprocity equations,

$$\tilde{Q}^2_{sB}(x_B) = \frac{3\pi^2}{2}\,\alpha_s(\tilde{Q}^2_{sA} + Q^2_0)\,x_B g_N(x_B, \tilde{Q}^2_{sA} + Q^2_0)\,T_B$$

$$\tilde{Q}^2_{sA}(x_A) = \frac{3\pi^2}{2}\,\alpha_s(\tilde{Q}^2_{sB} + Q^2_0)\,x_A g_N(x_A, \tilde{Q}^2_{sB} + Q^2_0)\,T_A$$

where $x_{A,B}$ are the fractional light-cone momenta of the radiated gluon relative to the colliding nuclei, $x_A x_B = k_T^2/s$; $Q^2_0 = 1.7\,\mathrm{GeV}^2$ is chosen to get the right infra-red behavior.

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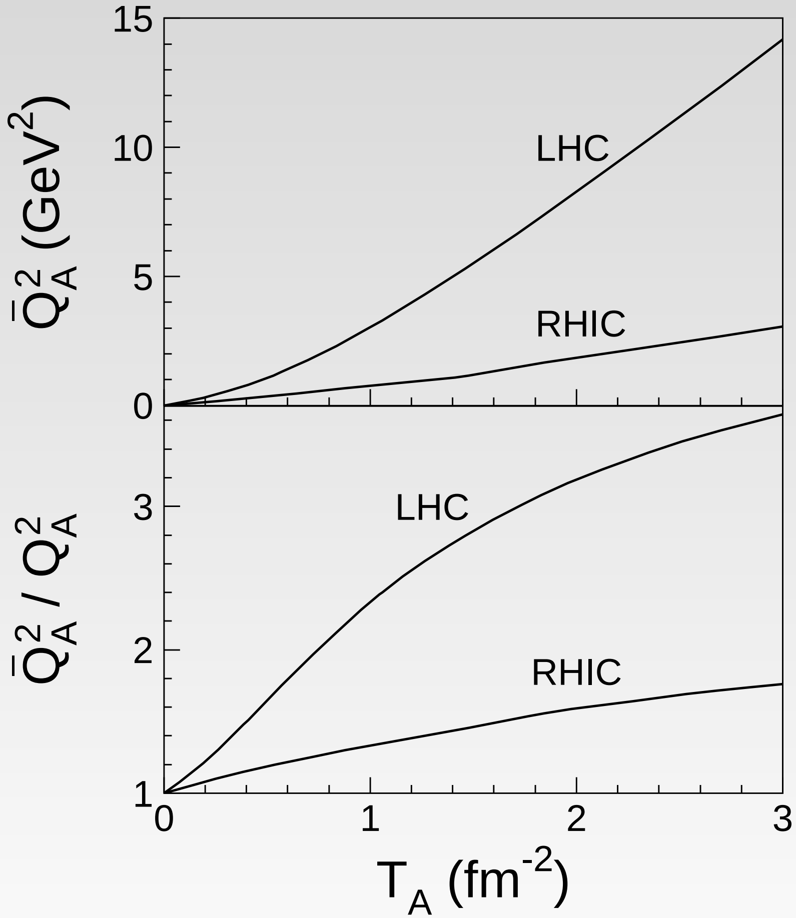
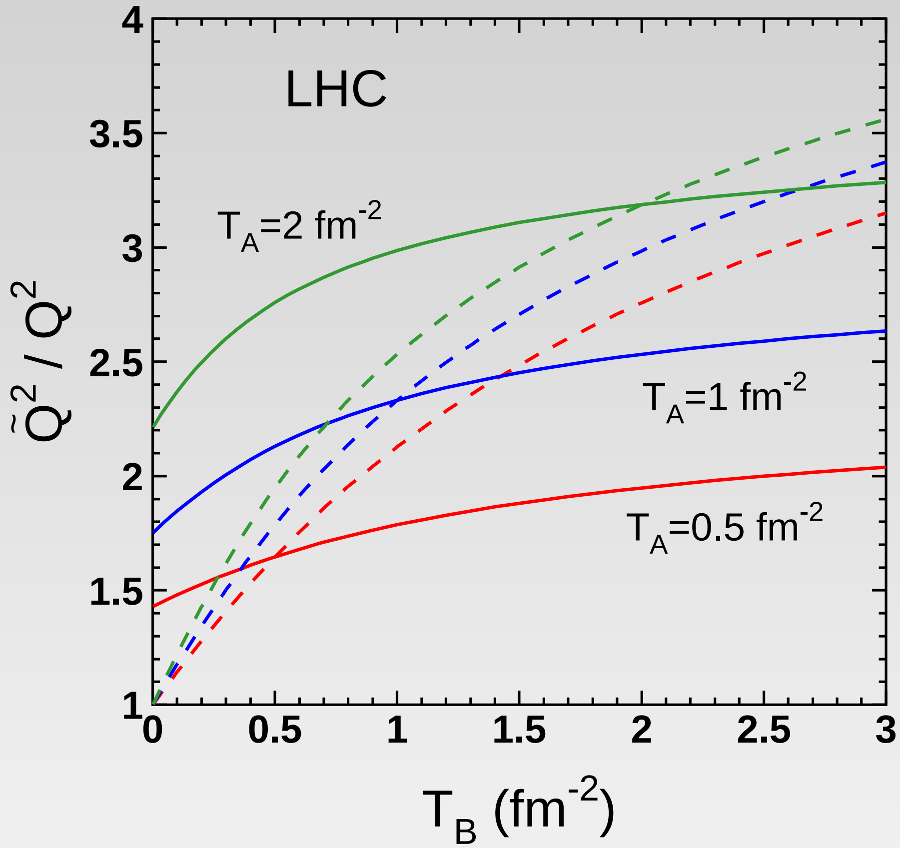
Saturation scale in AA vs pA

For central collisions $T_A = T_B$
the equations are easy to solve:





Non-central collisions, $T_A \neq T_B$

—— Q^2_B

—— Q^2_A

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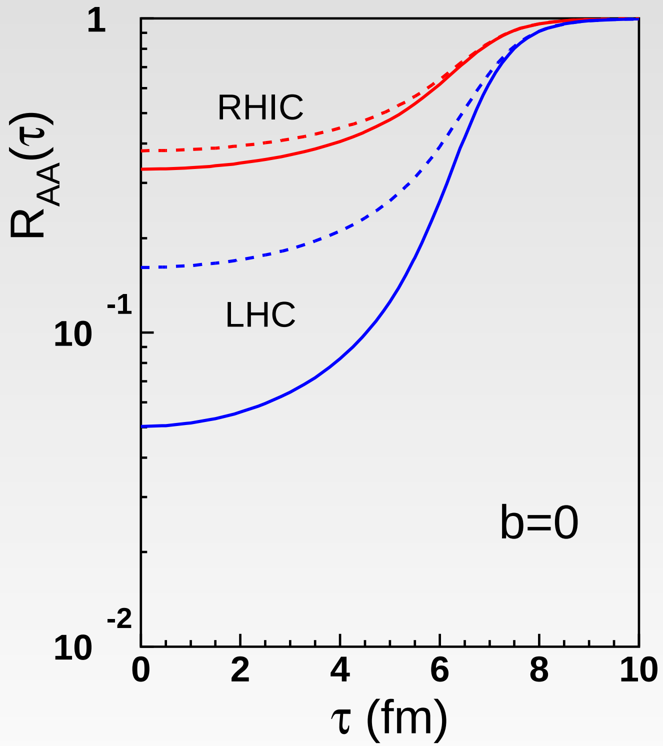
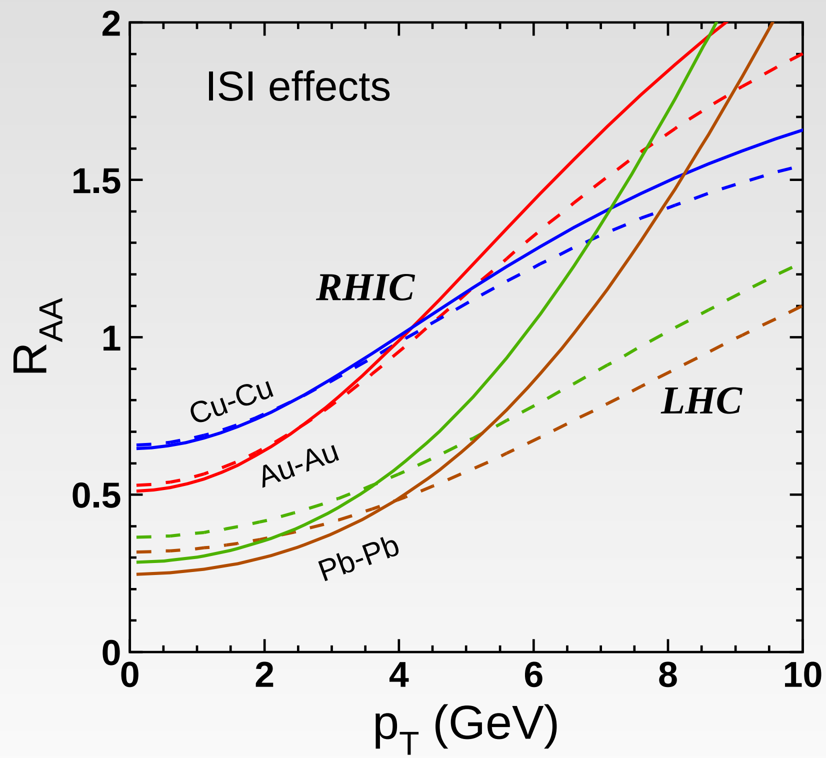
Boosted gluons in J/Ψ production

The boosted gluon density at small x in the colliding nuclei make the nuclear matter more opaques for color dipoles.



The shift of Q_s^2, i.e. of the mean transverse momentum, enhances the Cronin effect for J/Ψ.



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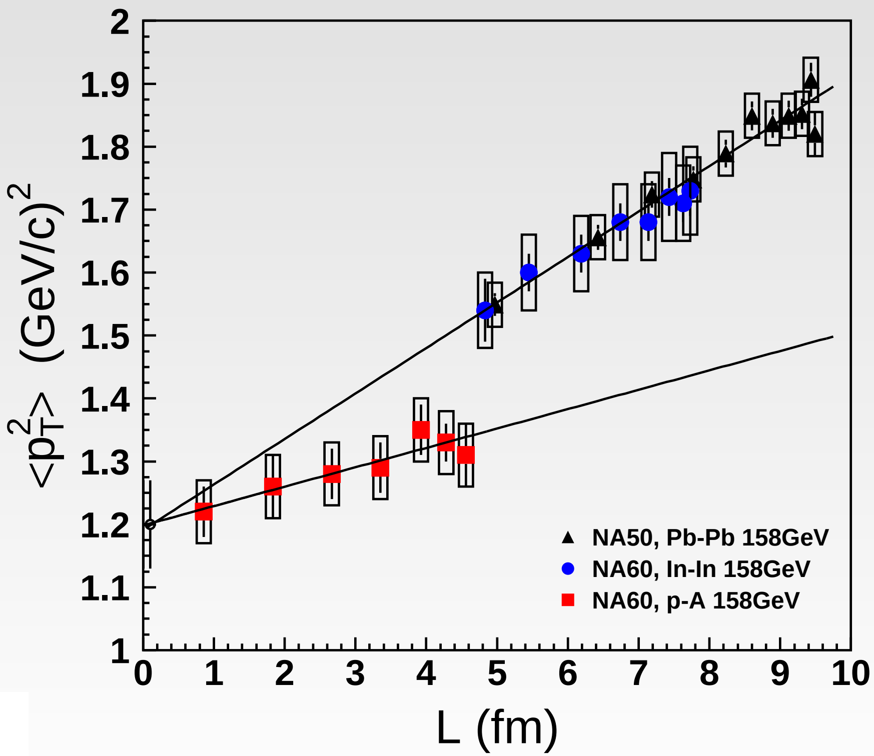
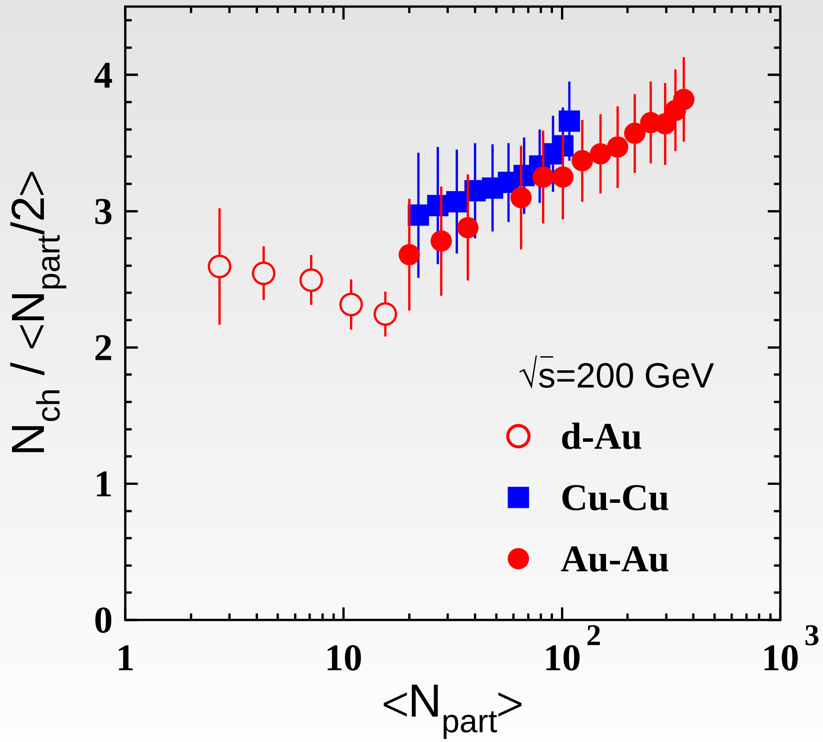
Other observables

The boosted "cold" nuclear medium in AA collisions, also increases J/Ψ broadening. This is an example of a "cold" nuclear medium, which is rather "hot".

The saturation scale also controls the multiplicity $dn/d\eta \propto Q_s^2/\alpha_s(Q_s^2)$. The boosting, $\tilde{Q}_s^2 > Q_s^2$, should lead to a mismatch of multiplicities in pA and AA collisions.





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Summary

- Multiple interactions in pA collisions significantly modify the gluon PDF in the projectile proton, enhancing small, but suppressing large x. However, the PDFs of the target nucleons remain unchanged.

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Summary

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- The "cold" nuclear medium in AA collisions is not really cold. The PDFs in both nuclei are affected by multiple interactions. Their saturation scales are boosted up to the values significantly higher than in pA collisions.

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- The nuclear medium in AA is more opaque for color dipoles (J/Ψ) than in pA collisions. No simple extrapolation from J/Ψ suppression in pA to the ISI effects in AA is possible.
- Measurement of p_T-broadening of J/Ψ in pA and AA collisions would be a straightforward test of the boosting effect.

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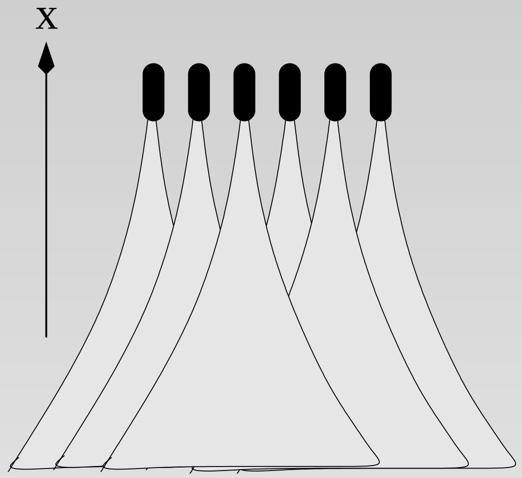
LP principle and saturation

Lorentz contruction does not affect parton clouds of bound nucleons at small x in the nuclear infinite momentum frame, so they overlap in longitudinal direction.

[O. Kancheli, 1973]



This leads to a dense packing of radiated gluons in the phase space. However, according to the LP principle [L. Landau & I.Pomeranchuk, 1953] multiple interactions do not generate multiple radiation of identical gluons, if the coherence time of radiation is large, $l_c \gg R_A$. So the amount of gluon radiation should saturate at small x.

The density of radiated gluons is maximal at small k_T, where it saturates, but it is getting dilute above the saturation scale $k_T \gtrsim Q_A$, where the Bethe-Heitler regime takes over.

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Measuring the saturation scale

The partial dipole-nucleus amplitude at impact parameter b reads,

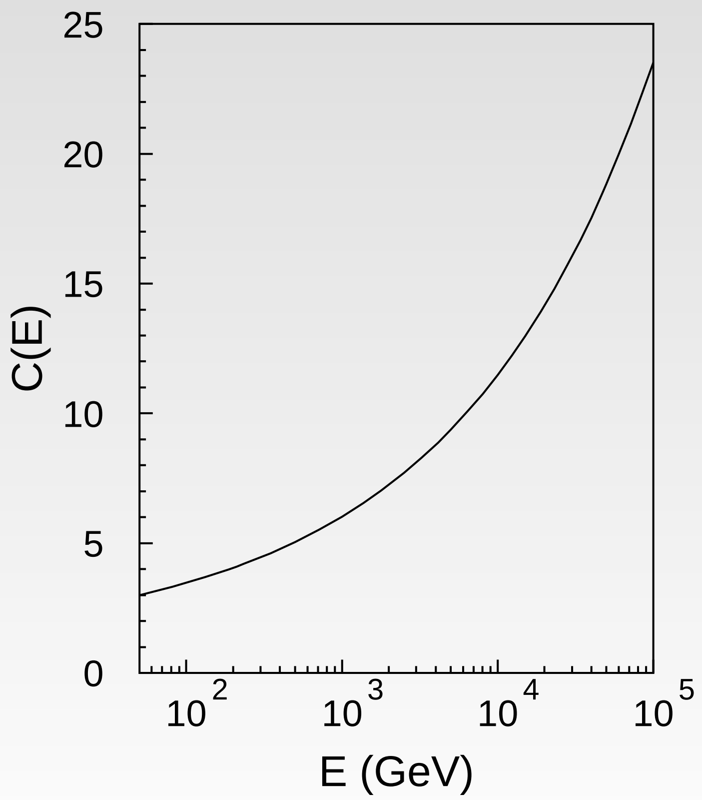
$$f^A_{dip}(b) = 1 - e^{-\frac{1}{2}\sigma^N_{dip}(r_T,E)\,T_A(b)} = 1 - e^{-\frac{1}{4}r_T^2\,Q_A^2(b,E)}$$

Calculation of Q_A^2 from the first principles looks pretty hopeless, but one can get it from phenomenology.

A parton propagating through a nucleus experiences broadening, which turns out to be exactly the saturation scale

$$\Delta p_T^2 = 2C(E)T_A$$

$$C(E) = \frac{1}{2}\vec{\nabla}^2\sigma_{dip}\Big|_{r_T=0}$$



Dolejsi, Hüfner, B.K. (1993)
BDMPS (1997)
Johnson, B.K., Tarasov (2000)

$$\Delta p_T^2 = Q_A^2$$

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Gluon shadowing

So far broadening was calculated in the LO approximation. However, gluon radiation from different sources interfere resulting in a suppression of broadening (gluon shadowing).

$$\widetilde{C}_q(E,b) = \frac{\pi}{3}\int d^2k\,\frac{\alpha_s(k^2)}{k^2}\,\mathcal{F}(x,k^2)\,S_A(E,k^2,b)$$

$\mathcal{F}(x,k^2)$ is the unintegrated gluon density.
$S_A(x,k^2,b)$ is the LPM suppression factor, which is known at $k^2 \ll Q_A^2$, or $k^2 \gg Q_A^2$.

$$S_A(E,k^2,b) = 1 - \frac{\sigma_{eff}T_A(b)}{1+\sigma_{eff}T_A(b)}\,e^{-k^2/Q_{gA}^2(E,b)}$$

$\sigma_{eff} = \frac{9}{4}C(E)\,r_0^2$ is the cross section for a glue-glue dipole.
The size $r_0 \approx 0.3$ fm is dictated by $pp \to pX$ diffraction data.

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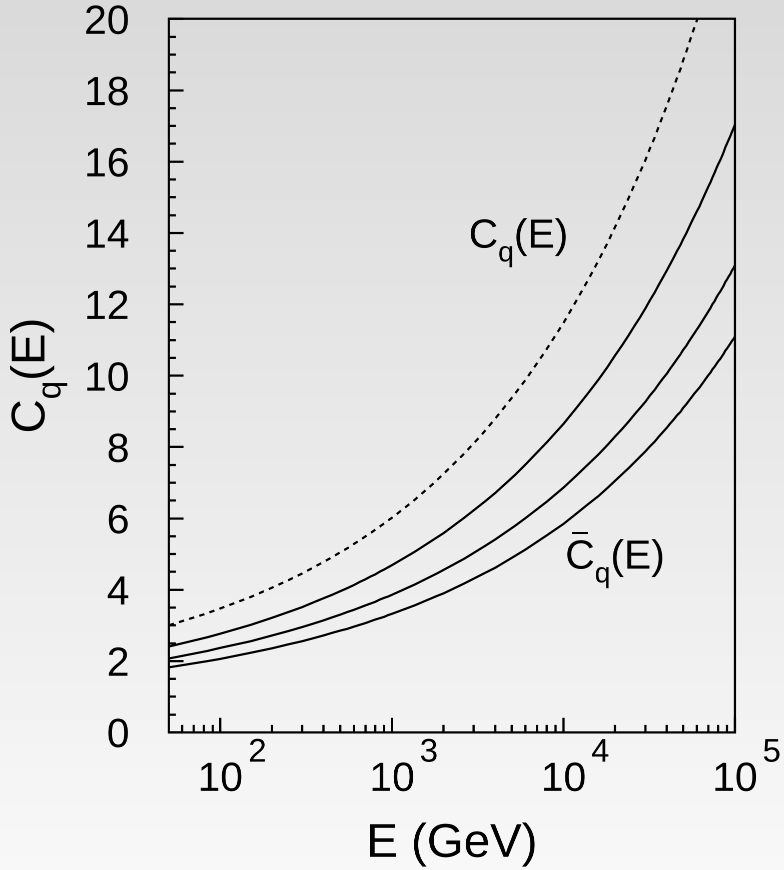
Self-quenching of shadowing

With this form of the LP suppression factor we arrive at the equation for $R_g(E,b) = \widetilde{C}(E,b)/C(E,b)$

$$R_g = 1 - \frac{R_g^2\, n_0^2\, n_{eff}}{(1 + R_g\, n_0)^2 (1 + n_{eff})}$$

$$n_{eff}(E,b) = \sigma_{eff}(E)\, T_A(b)$$
$$n_0(E,b) = \frac{9}{8}\, \sigma_0(E)\, T_A(b)$$

Since gluon shadowing occurs due to multiple rescatterings of the radiated gluons, which is reduced by gluon shadowing, gluon shadowing is quenching itself.



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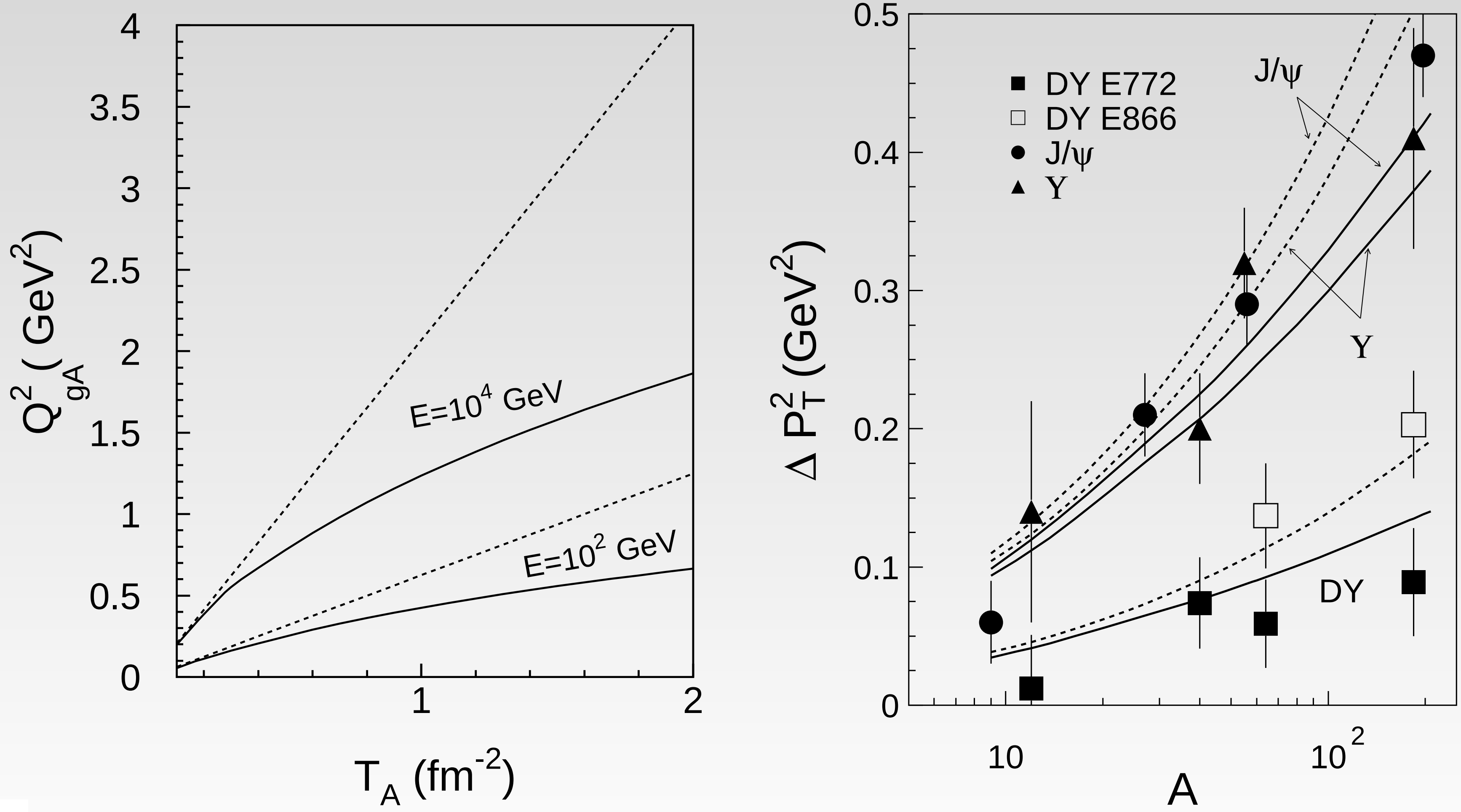
Gluon shadowing

The T_A-dependence of the saturation momentum saturates and levels off at large T_A.



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