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QCD Factorization at Forward Rapidities

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J. Nemchik, V. Petráček, I.K. Potashnikova and M. Š., **Phys. Rev. C78:025213, 2008**

J. Nemchik, M. Š., e-Print: **arXiv:0811.3837 [hep-ph]**

J. Nemchik, M. Š., **Nucl. Phys. A830:611C,2009**

J. Nemchik, M. Š., **PoS High-pT physics 09:042, 2009**

Forward physics: opportunities and dangers

- Light-front momentum fraction for projectile, target: $x_{1,2} = \frac{m_T}{\sqrt{s}} e^{\pm y}$
- Feynman variable: $x_F = x_1 - x_2 = \frac{2\, m_T}{\sqrt{s}} sinh(y)$
- In hadronic collisions minimal Bjorken x can be reached at forward rapidities $y \to y_{max}$ i.e. when $x_2 = x_1 - x_F \to 0$.
- Forward rapidity $\leftrightarrow$ the beam fragmentation region at large x_F:

  @RHIC projectile: $x_1 \approx 0.5 - 1$, mostly valence quarks contribute
  target: $x_2 < 0.01$, gluons dominate
- At large y, the target x_2 is e^y times smaller, than at mid-rapidities ($\sim 10^2$ at RHIC and $\sim 10^4$ at LHC)
- Opportunities to study interesting phenomena: parton saturation, Color Glass Condensate, ...
- Dangers to confuse the above phenomena with the effects of energy conservation

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Small-x physics ?

BRAHMS; Phys.Rev.Lett. 91, 072305 (2003)

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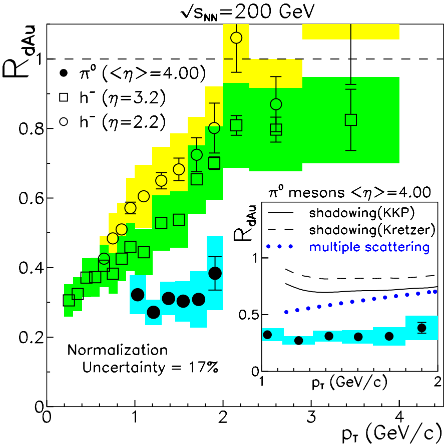

$$R^{Y}_{dAu} = \frac{\sigma^{pp}_{inel}}{<N_{bin}>\sigma^{dAu}_{hadr}} \frac{Ed^3\sigma/dp^3(d+Au \to Y+X)}{Ed^3\sigma/dp^3(p+p \to Y+X)}$$

- At small x_2, coherent phenomena (shadowing, CGC) are expected to suppress particle yields.
- No consensus so far on the strength of gluon shadowing and CGC. Data to be explained are just fitted. [D.Kharzeev et al., Phys.Lett.B599:23,2004]
- Saturation/CGC interpretation has problems: recent global LO analysis including besides DIS also this RHIC d+Au data [K. Eskola et al., JHEP 0807:102,2008. (EPS08)] leads to grossly exaggerated gluon shadowing.

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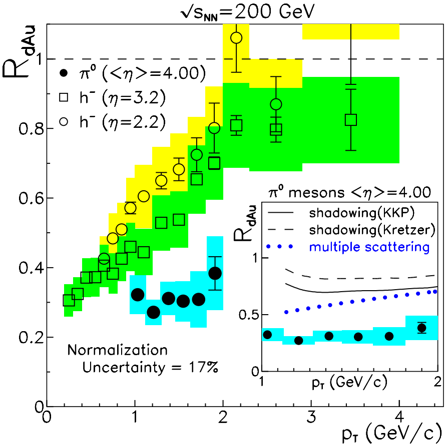

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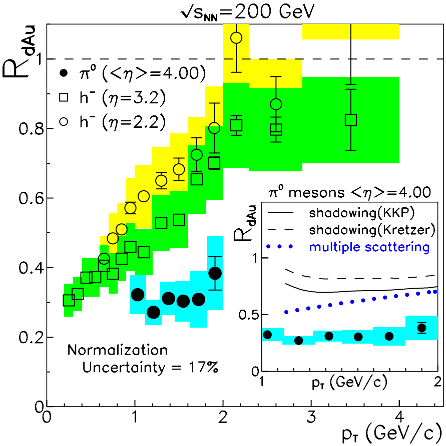

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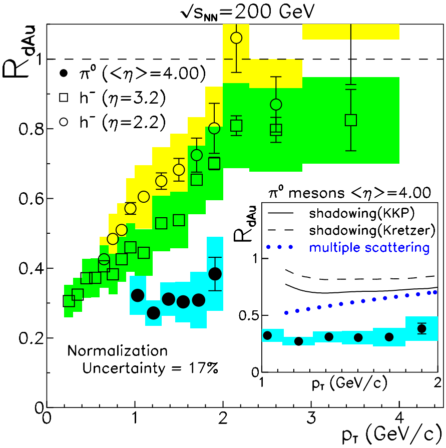

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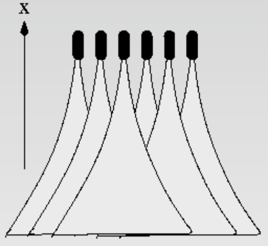
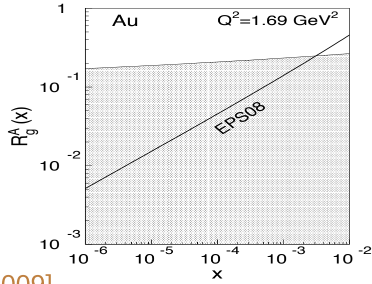
Unitarity bound for gluon shadowing

- Gluon clouds of different nucleons undergo a weaker Lorentz contraction at small, than at large x. They may overlap and fuse, leading to reduction of the gluon density at small x in a nucleus - gluon shadowing.
- Although they overlap in the longitudinal direction, most of them are still well separated in the transverse plane and therefore cannot fuse.

$\Rightarrow$ Gluon shadowing is constrained from below by a unitarity bound which corresponds to full fusion of overlapping gluons .





[B.Kopeliovich et al., Phys.Rev.C79:064906,2009]

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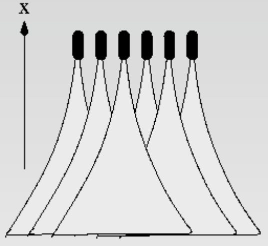
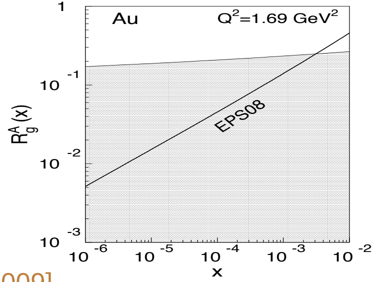
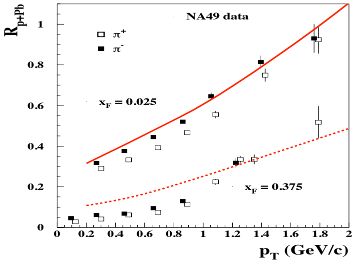


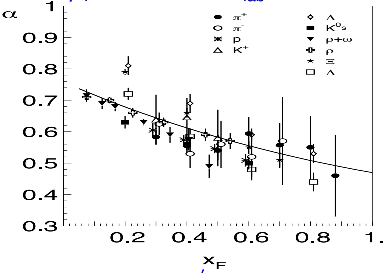


p+A fixed target reactions at forward rapidities

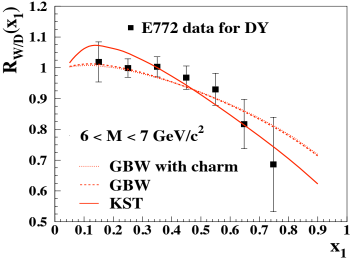
p+Pb at $E_{lab} = 158 GeV$



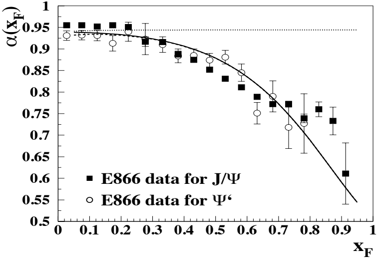
Small-p_T hadrons, A^α, $E_{lab} = 70 - 400 GeV$



Drell-Yan at $E_{lab} = 800 GeV$



A^α: J/Ψ and Ψ' at $E_{lab} = 800 GeV$



Any reaction observed so far at any energy is nuclear suppressed

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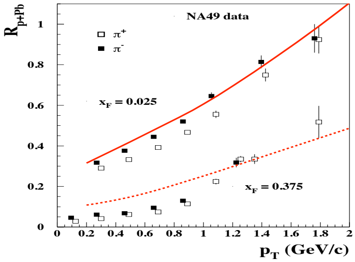

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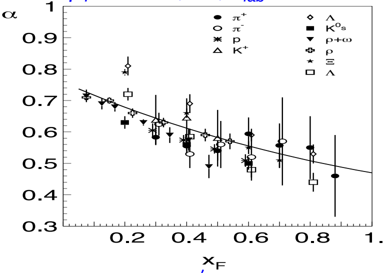

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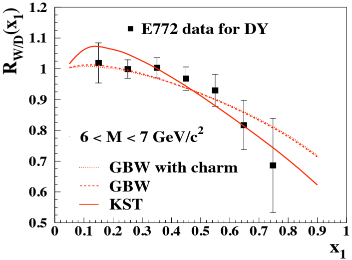

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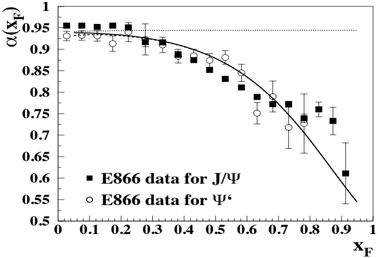

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Energy loss in nuclear matter

- All those fixed target experiments have too low energy for the coherent effects in gluon radiation to occur.
  x_2 isn't small enough and so the coherence length $\ell_c \propto 1/(x_2 m_N)$ is still shorter than the mean inter-nucleon spacing.

  What is the mechanism of nuclear suppression?

- The projectile hadron and its debris dissipate energy when propagating through the nucleus. As a result, the probability of production of a particle carrying the substantial fraction x_F of the initial momentum decreases compared to a free proton target case. [B.Kopeliovich et al., Phys.Rev.C72:054606,2005].
- This can be equivalently viewed as:
  - Reduced survival probability for LRG processes in nuclei
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Two types of energy loss

- Energy loss proportional to energy
  Compared to the proton target the nuclear target (via multiple interactions) resolves higher multiparton Fock components of the projectile hadron and thus produces more intense gluon radiation $\Rightarrow$ the suppression is a consequence of induced energy loss.
  - Energy loss caused by on-mass-shell production of such partons rises with energy, $dE/dz \propto E$.
  - Nuclear suppression is energy independent and scales with x_F.

- Energy loss independent of energy
  A parton in a medium loses its energy on induced gluon radiation with a rate $dE/dz = const.$ independent of its energy [F.Niedermayer, Phys.Rev.D34, 3494(1986), S.Brodsky&P.Hoyer, Phys.Lett.B296,165(1993)].
  - Energy independence results from $dn/d\omega_g \sim 1/\omega_g$.
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E-loss and AGK cutting rules

- For the nuclear target the leading parton distribution involves higher multiparton Fock states and thus must fall off steeper at $x_F \to 1$ than in the proton target case..
  [R. Blankenbecler, S. Brodsky, Phys.Rev.D10, 2973 (1974)]
- Each of multiple interactions produces an extra suppression factor $S(x_F)$, the weight factors are given by the AGK cutting rules:

$$\frac{d\sigma_A}{dx_F d^2b} = \frac{d\sigma_N}{dx_F} T_A(b) e^{-[1-S(x_F)]\sigma_{in} T_A(b)}$$

  and $S(x_F) \approx (1 - x_F)$ is survival probability of a large rapidity gap.
- The effective PDF of the beam hadron is target-dependent

$\Rightarrow$ ***interaction with a nuclear target does not obey factorization!!!***

- The lack of factorization does not disappear with increasing scale $\Rightarrow$ the factorization is violated via leading twist effect.
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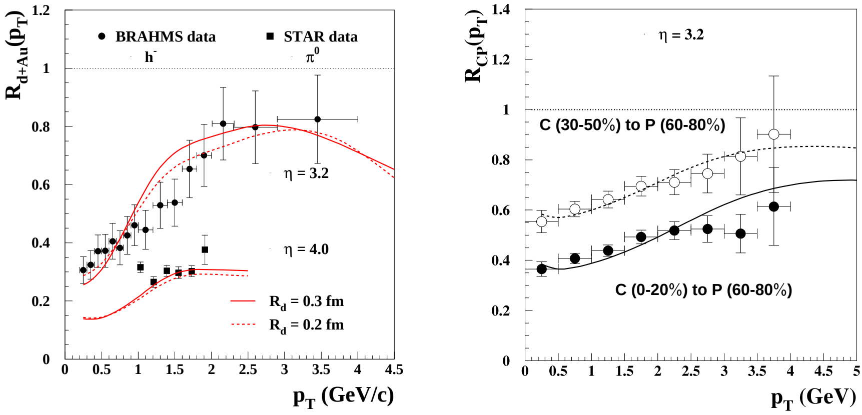
Large-p_T, forward rapidity: d+Au at RHIC

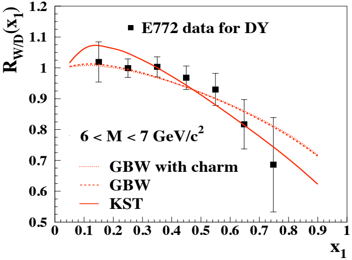
d+Au at $\sqrt{s_{NN}} = 200 GeV$



- The description is parameter-free.
- No other model has been able so far to explain the sharp drop of the cross section between the rapidities η = 3.2 - 4

Forward rapidity: p+A at FNAL and SPS

Drell-Yan at $\sqrt{s} = 38.3 GeV$



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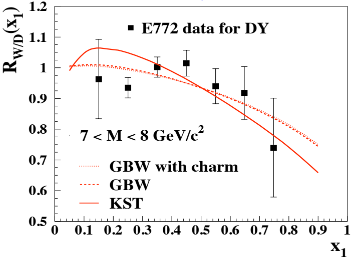
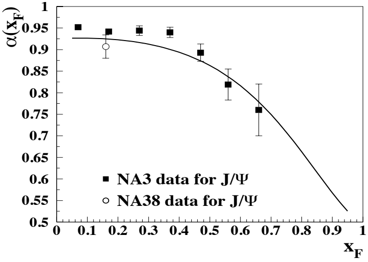
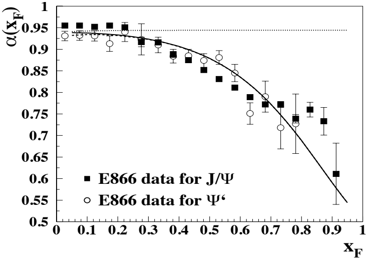


A^{α}: J/Ψ at $\sqrt{s} = 17.3 GeV$

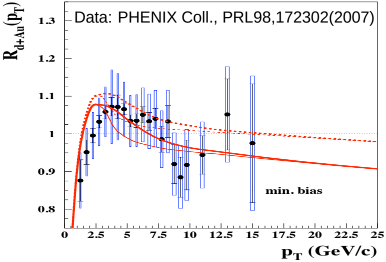


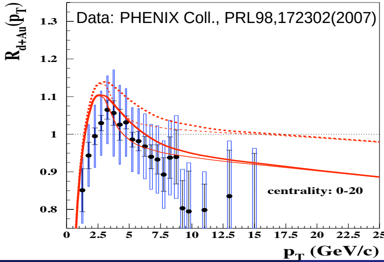
A^{α}: J/Ψ and Ψ' at $\sqrt{s} = 38.3 GeV$



Large-p_T, mid-rapidity: d+Au at RHIC

One can approach the kinematic limit increasing either $x_F = \frac{2\,m_T}{\sqrt{s}}\,sinh(y)$ or $x_T = \frac{2\,p_T}{\sqrt{s}}$. In both cases the energy constraints lead to nuclear suppression.





- At small-medium p_T the ratio $\mathrm{R_{d+Au}}$ at $\eta = 0$ was first described by B. Z. Kopeliovich et al.; PRL 88, 232303-1(2002). Vital for correct description of the Cronin effect is inclusion of gluon multiple rescattering.
- Solid/dashed (thick/thin) lines correspond to calculations with/without energy conservation restrictions in multiple parton rescatterings, (with/without finite coherence length correction), respectively.
- With QCD factorization one expects at large transverse momenta $\mathrm{R_{d+Au}} \rightarrow 1$ (with a small corrections for isotopic effects).
- Energy conservation leads to a considerable suppression, which seems to be confirmed by the data.

Midrapidity production of direct photons in Au+Au

T. Isobe *et al.*, (PHENIX Coll.), J. Phys. G34:S1015(2007)

- Prompt photons produced in a hard reaction are not expected to have any final state interaction, either energy loss, or absorption. Besides Cronin enhancement and small isotopic corrections no nuclear effects are expected.
- So far no explanation of observed suppression has been given.
- Production of prompt photons with large p_T is again subject to energy sharing constraints.
- Isospin effects lead to the value $R_{Au+Au} \to 0.8$.

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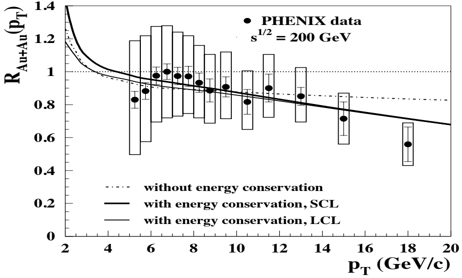

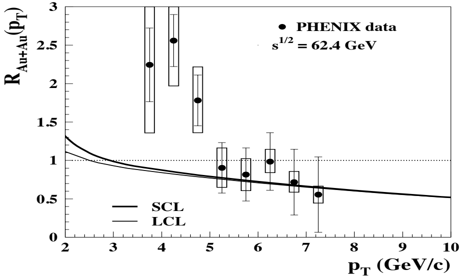

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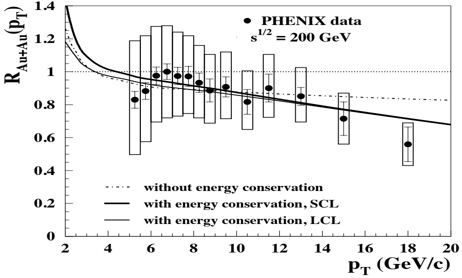

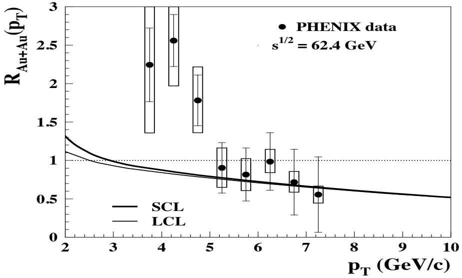

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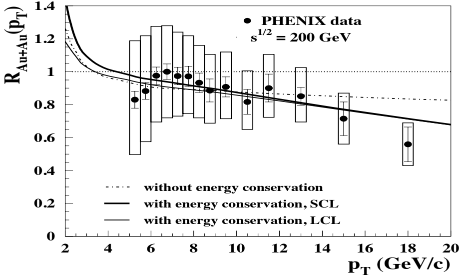

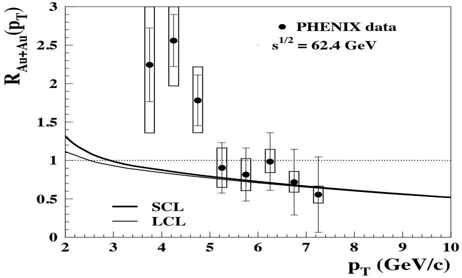

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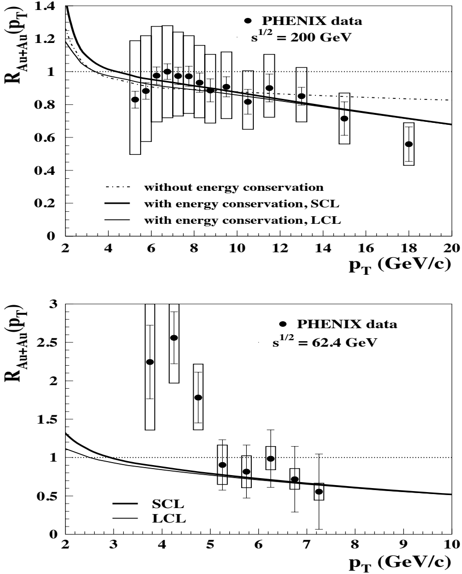

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Jet quenching in heavy ion collision

- Suppression of high-p_T hadrons produced in ultra-relativistic heavy ion collisions does not vanish even at $p_T > 10\text{GeV}$ but remains constant. This is in apparent conflict with the QCD factorization which would demand $\mathrm{R_{AA}}$ to rise with p_T.
- In the limit of a very dense medium the mean free path of produced (pre)hadron vanishes, and $\mathrm{R_{AA}}$ is completely controlled by the production length ℓ_c. $\mathrm{R_{AA}} = \langle \ell_c^2 \rangle / \mathrm{R_A^2}$, where $\ell_c = z(1-z)E_{jet}/p_T^2$ and R_A is the nuclear radius. This should cause considerable suppression at large p_T.

B.Z. Kopeliovich *et al.*, arXiv:0707.4302 [nucl-th]

$R_{AA}(p_T)$ of pions in central AA collisions ($A \approx 200$) at $\sqrt{s} = 200GeV$ (solid) and $\sqrt{s} = 5500GeV$ (dashed line).

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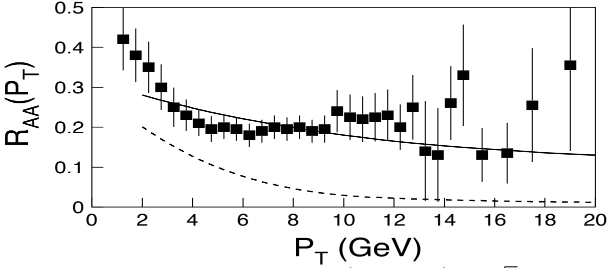

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Summary (1/2)

- Although measurement at forward rapidities allow to access smallest Bjorken x, one should be careful with interpretation. Assuming that suppression at RHIC is due to gluon saturation only, one arrives at astonishingly small amount of gluons in nuclei and conflict with unitarity.
- Factorization requires the nucleus to be an universal filter for different Fock components of the projectile hadron. This is not the case in the vicinity of the kinematic limit where sharing of energy between the constituents becomes an issue. Higher Fock components are resolved better, so the projectile parton distribution becomes softer.
- This effect can be treated as an effective energy loss proportional to energy. The nonperturbative fluctuations resolved by the nucleus carry finite fractions of the total momentum, and this is the source of energy loss which is proportional to energy.

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- $dE/dz \propto E$ leads to a nuclear suppression at any energy and predicts x_F-scaling of the suppression. This explains why any high-energy reaction is at large x_F nuclear suppressed and solves the long-standing puzzle of the x_F-scaling in J/Ψ suppression.
- One can also approach the kinematic limit in p_T, e.g. at $\eta = 0$. Effects of energy conservation now show up when the Cronin enhancement at medium-high p_T switches to nuclear suppression at larger p_T approaching the $A^{-1/3}$-behavior. This unexpected behavior is signaled by the RHIC data on pion production in d+Au collisions and even by direct high-p_T photons from Au+Au.
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