Saturation effects in pA $\longrightarrow$

dilepton and photon production

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talk based on:

Saturation and shadowing in high-energy proton-nucleus dilepton production

in collaboration with A. H. Mueller and D. Schiff

Nucl. Phys. A 741 (2004) 358 (hep-ph/0403201)

related work by J. Jalilian-Marian:

Electromagnetic Signatures of the Color Glas Condensate: Dileptons

Nucl. Phys. A 739 (2004) 319 (nucl-th/0402014)

and by M. A. Betemps and M. B. Gay Ducati:

Dilepton low p_T suppression as evidence of the Color Glass Condensate

(hep-ph/0408097)

motivation

in $p(d)A$ and AA collisions
important initial- and final state effects
due to multi-gluon interaction in the nucleus

Ideal (additional) tool for exploring initial state:

production of real photons and dileptons

in $p(d)A$ collisions

no strong rescattering and no fragmentation function

references on production of photons/dileptons

1. S.J. Brodsky, A. Hebecker and E. Quack,
   Drell-Yan process and factorization in impact parameter space, PR D55 (1997) 2584
2. B.Z. Kopeliovich, A. Schäfer and A.V. Tarasov,
   Bremsstrahlung of a quark propagating through a nucleus, PR C59 (1999) 1609
3. J. Raufeisen, J.C. Peng and G.C. Nayak,
   Parton model versus color dipole formulation of the Drell-Yan process,
   PR D66 (2002) 034024
4. F. Gelis and J. Jalilian-Marian,
   Photon production in high energy proton-nucleus collisions, PR D66 (2002) 014021
5. F. Gelis and J. Jalilian-Marian,
   Dilepton production from the Color Glass Condensate, PR D66 (2002) 094014
6. for DIS, e.g. review by A.H. Mueller,
   Parton saturation - an overview, in *QCD Perspectives on Hot and Dense Matter*,
   eds. J.-P. Blaizot and E. Iancu, Kluwer Acad. Publ. (2002) p. 45 ff (hep-ph/0111244)

based on and aims for:

- exploring gluon properties at small x in nucleus
- dipole bremsstrahlung picture for
  quark + nucleus $--\ >$ dileptons $+X$ (- relation to DIS -)
  and related to nucleon (quark) + nucleus $--\ >$ hadrons (gluons) $+X$
- $k_{\perp}$ factorization and gluon saturation in large nucleus
- BFKL evolution and geometrical scaling by
  including non-linear evolution effects (BK equation)
  for large rapidity (energy) $Y = \ln(1/x)$
- for $Y >> 1$, i.e. large forward dilepton rapidities (RHIC energy) and at high energies (LHC energy)
  leading twist suppression/shadowing with respect to proton-proton collisions
  together with anomalous scaling behaviour with respect to A

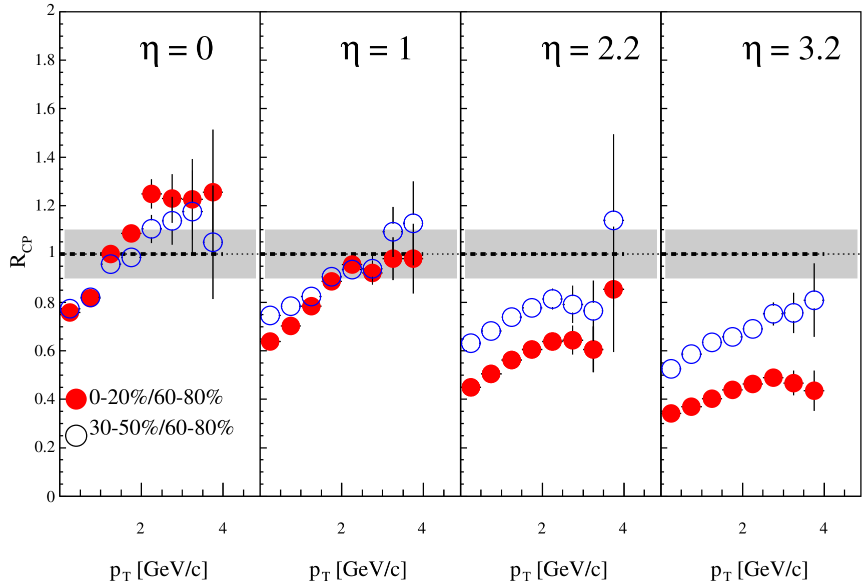
strong motivation due to

disappearence of Cronin like enhancement $\longrightarrow$

gradual suppression of hard (charged) particle yield at forward rapidities

- has been predicted

surprise: “quantum evolution” of gluon distribution dominates in the nucleus



ratios as a function of p_T , e.g. $[N_{central}/N_{coll,central}]/[N_{peripheral}/N_{coll,peripheral}]$

from R. Debbe (BRAHMS Collaboration), at QM2004, nucl-ex/0403052

references on initial state suppression

1. D. Kharzeev, E. Levin and L. McLerran, Phys. Lett. B561 (2003) 93
2. R. Baier, A. Kovner and U. A. Wiedemann, Phys. Rev. D68 (2003) 054009
3. D. Kharzeev, Y. V. Kovchegov and K. Tuchin, Phys. Rev. D68 (2003) 094013, and Phys. Lett. B599 (2004) 23
4. J. Jalilian-Marian, Y. Nara and R. Venugopalan, Phys. Lett. B577 (2003) 54
5. J. L. Albacete, N. Armesto, A. Kovner, C. A. Salgado and U. A. Wiedemann, Phys. Rev. Lett. 92 (2004) 082001
6. J. Jalilian-Marian, nucl-th/0402080, and J. Phys. G30 (2004) S751 (QM2004), references therein
7. E. Iancu, K. Itakura and D. N. Triantafyllopoulos, Nucl. Phys. A742 (2004) 182
8. J. P. Blaizot, F. Gelis and R. Venugopalan, Nucl. Phys. A743 (2004) 13, and Nucl. Phys. A743 (2004) 57
9. talks at this conference

propagating through a large nucleus: $qA \longrightarrow \gamma^* X$ (quark in a nucleon/deuteron)

cross section for massive γ^*, mass M, energy fraction z,
at medium and large p_T, and for massless quark q
(fixed impact parameter $\vec{b}$)

$$\frac{d\sigma}{dz d^2 k_\perp dM^2} = \frac{\alpha_{\rm em}}{3\pi M^2} \frac{d\sigma}{dz d^2 k_\perp}$$

restrict discussion to fixed QCD coupling α_s

kinematics for

$$parton_1 + parton_2 - - > photon^*$$

average momentum fractions:

$$x_1 = x_t \exp y\,,\; x_2 = x_t \exp(-y),\; x_t = \frac{M_\perp}{\sqrt{s}}\,,$$

e.g. for transverse mass $M_\perp = 5.0$ GeV ($M \sim 2.0,\ k_\perp \sim 4.5$ GeV)

and $y = 0$ (3.5) :

RHIC energy $\sqrt{s} = 200$ GeV

- gluon in nucleus - $x_2 = 2.5\ 10^{-2}\ \ (\underline{9.1\ 10^{-4}})$

LHC energy $\sqrt{s} = 5500$ GeV

- gluon in nucleus - $x_2 = \underline{7.5\ 10^{-4}}\ \ (2.7\ 10^{-5})$

i.e. fast quark $- >$ especially forward dileptons:

small x gluon in nucleus

$k_\perp$ factorized dipol formulation

$$\frac{d\sigma}{dz d^2 k_\perp d^2 b} =$$

$$\frac{\alpha_{\rm em}}{k_\perp^2 + (1-z)M^2} \int \frac{d^2 q_\perp}{q_\perp^2} H(k_\perp, z q_\perp, (1-z)M^2)\ \phi_G(\vec{q}_\perp, \vec{b}, Y)$$

unintegrated gluon distribution - $q\bar{q}$ ..dipole amplitude $N(\vec{x}_\perp, \vec{b}, Y)$:

$$\phi_G(\vec{q}_\perp, \vec{b}, Y) = \int d^2 x_\perp e^{i \vec{q}_\perp \cdot \vec{x}_\perp} \vec{\nabla}^2_{x_\perp} N(\vec{x}_\perp, \vec{b}, Y)$$

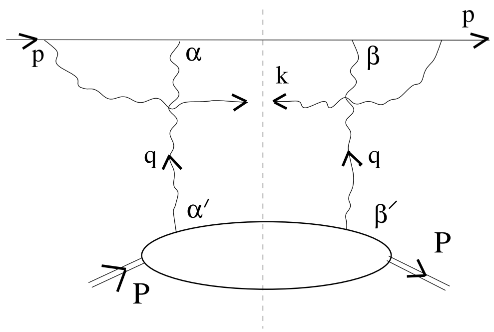
at $Y = 0$: McLerran - Venugopalan model (as initial conition)

$$N(\vec{x}_\perp, \vec{b}) = 1 - \exp(-x_\perp^2 Q_s^2(\vec{b})/4)\,,$$

saturation scale: $Q_s^2(\vec{b} = 0) \sim A^{1/3}$

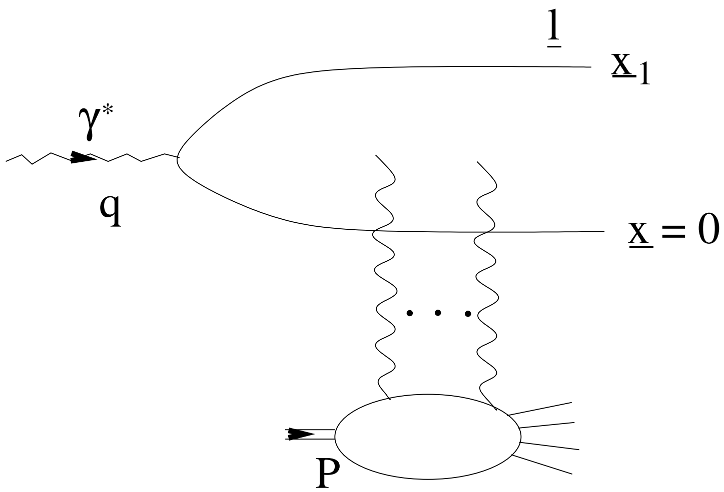
graphs

a typical $k_\perp$ factorized leading twist two gluon exchange graph



hard part H times unintegrated gluon distribution ϕ_G

relation to DIS:



gluon structure function

e.g. real ("isolated") photon production: $qA \longrightarrow \gamma X$

- $$\frac{d\sigma}{dz d^2k_\perp d^2b} = \frac{2\alpha_{\rm em}}{(2\pi)^4} \frac{1+(1-z)^2}{zk_\perp^2} \int d^2q_\perp \frac{\phi_G(\vec{q}_\perp, \vec{b})}{[\vec{q}_\perp - \vec{k}_\perp/z]^2}$$

- LO pQCD factorization: comparison with LO hard $k_\perp$ pQCD $2 \longrightarrow 2$ cross section for $qG \longrightarrow \gamma q$, when $k_\perp^2 \gg Q_s^2$,

$$\frac{d\sigma}{dz d^2k_\perp} = \frac{\alpha_{\rm em} z[1+(1-z)^2]}{k_\perp^4} \frac{\alpha_s}{N_c} xG_A\left(x = \frac{\mathrm{x}_T^2}{z(1-z)}, Q^2 \simeq k_\perp^2\right)$$

$$\frac{dxG_A(x,k_\perp^2)}{d^2b} = \int^{O(k_\perp^2)} \frac{d^2q_\perp}{\pi} \frac{N_c}{(2\pi)^3\alpha_s} \int d^2x_\perp e^{+i\vec{q}_\perp\cdot\vec{x}_\perp} \vec{\nabla}^2_{x_\perp} N(\vec{x}_\perp, \vec{b})$$

BFKL in presence of saturation

[Ya. Ya. Balitzky, V. S. Fadin, E. A. Kuraev, L. N. Lipatov (1976-1978)]

gives large number of gluons when $\alpha_s Y = \alpha_s \ln(1/x) >> 1$

due to quantum evolution - gluon radiation

- including non-linear Balitzky-Kovchegov type effects

[A. H. Mueller and D. N. Triantafyllopoulos (2002); also: S. Munier and R. Peschanski (2003)]

ϕ_G quickly scales as a function of scaling variable $\frac{q_\perp}{Q_s(Y)}$: ϕ_G maximal at $q_\perp = Q_s(Y)$

confirmed numerically by J. L. Albacete et al.

- $Y = \ln(1/x)$ dependent scale, increasing with Y

$$Q_s^2(Y) \approx \exp[\lambda\, Y]$$

- anomalous dimension $\lambda_0 = 0.372$:

$$\phi_G \approx A^{\frac{1-\lambda_0}{3}} \quad (\vec{b} = 0)$$

results: γ^* cross section at large Y

- parametric estimate for ratio

$$R_{pA}^{\gamma^*} = \frac{\sigma^{qA->\gamma^* X}(\vec{b})}{T(b)\ \sigma^{qp->\gamma^* X}}$$

- based on (scaling regions of A and p overlap)

$$\phi_G(k_\perp/Q_s(Y), \vec{b}\,) \approx (\frac{k_\perp^2}{Q_s^2(Y)})^{\lambda_0 - 1}$$

- since $\lambda_0 \neq 0$: anomalous suppression

$$R_{pA}^{\gamma^*}(\vec{b}=0) \approx \frac{T(b)|_p}{T(b)|_A}\,[\frac{Q_{s,A}^2}{Q_{s,p}^2}]^{1-\lambda_0} \approx A^{-\lambda_0/3}$$

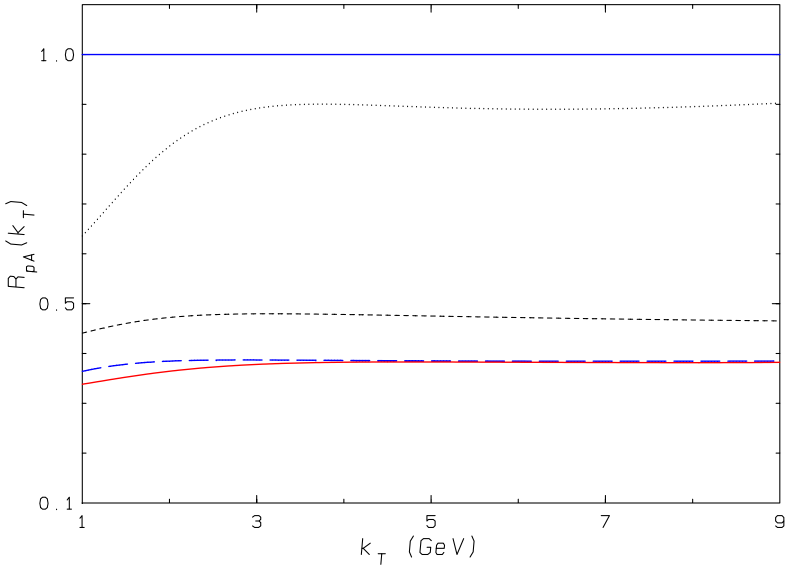
c.f. with R_{pA} for produced gluons

result: BFKL saturation model

as illustration, following K. Golec-Biernat and M. Wüsthoff:

$$Q_s^2(Y) \approx \exp[\lambda\, Y] : \ \lambda_{LO-BFKL} = 4.88 \frac{N_c \alpha_s}{\pi} \rightarrow \lambda_{BGW} \simeq 0.3$$

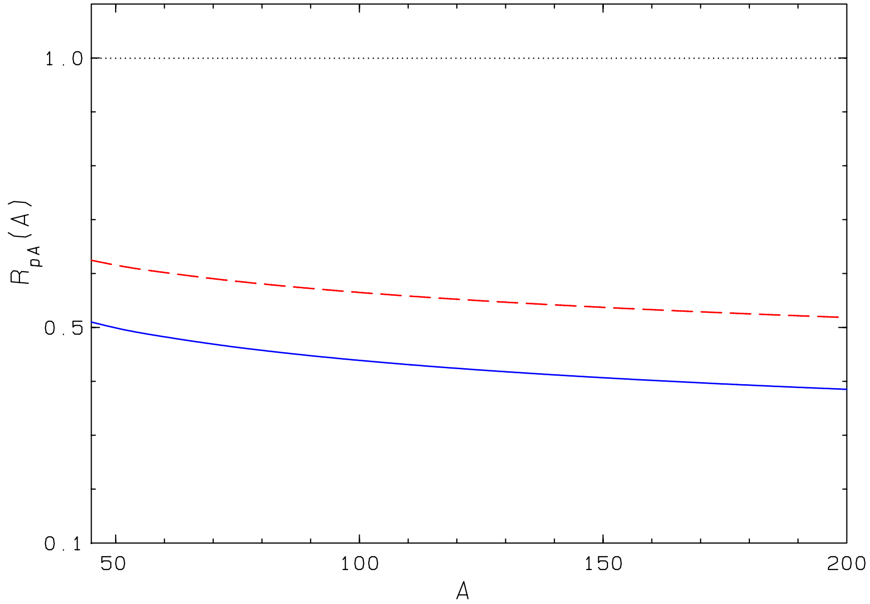
SUPPRESSION:



$M = 2$ GeV: $y_\gamma = 0.5$ (dotted), $y_\gamma = 1.5$ (short-dashed), $y_\gamma = 3.0$ (dashed blue)

$M = 4$ GeV and $y_\gamma = 3.0$ (red)

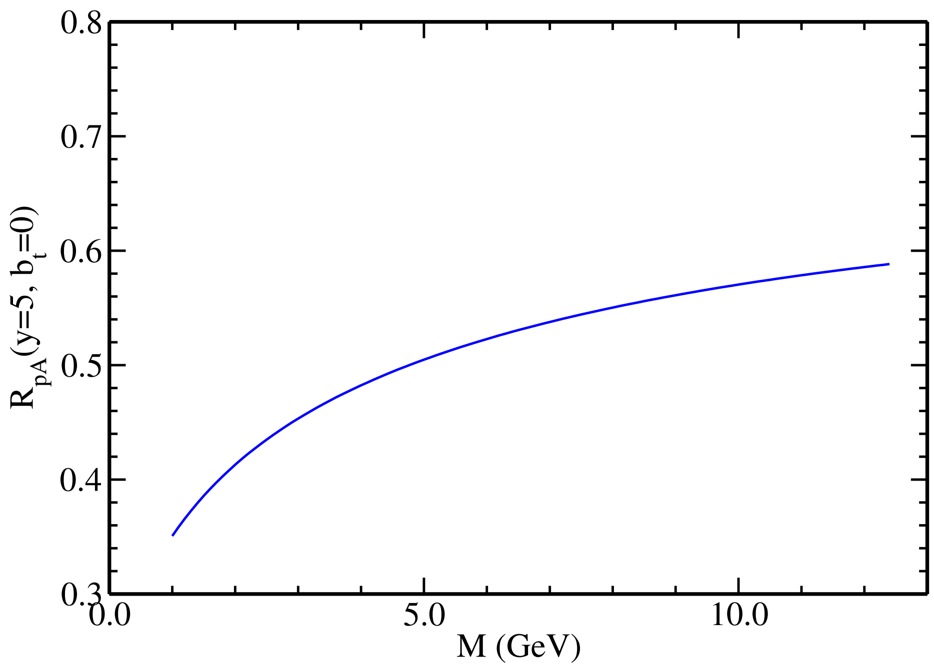
SUPPRESSION:



R_{pA} as a function of A for $k_\perp = 5$ GeV, $M = 2$ GeV and $y_\gamma = 3$ (blue)

compared with $A^{-\lambda_0/3}$ dependence (red)

SUPPRESSION:



$k_\perp$ integrated R_{pA} as function of dilepton mass for central collision at LHC: $y = 5$

[J. Jalilian-Marian (2004)]

summary

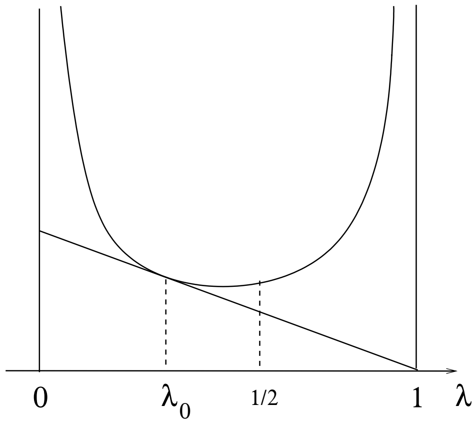
- hope: encouraging results for experimenters
  to measure in $p(d)A$ collisions at RHIC and LHC

  the (energy dependence of the) suppression at large rapidities
- for photons, dileptons and hadrons at moderate transverse momentum
- support of the saturation picture of gluon dynamics
  at high energies and small values of x
- detailed knowledge of the initial state is crucial to develop the theory,
  which describes finally the dynamics of the transition from the
  dense gluon state (CGC) to the (thermalized) QGP
  in $A - A$ collisions at highest energies
- extend analysis to running α_s and even beyond leading order BFKL

EXTRAS

saddle point conditions:

$$R = \frac{\ln Q^2/\mu^2}{2\bar{\alpha_s} Y} = \frac{\ln q_\perp^2/\bar{Q}_s^2}{2\bar{\alpha_s} Y}$$



anomalous dimension $\lambda_0 = 0.372$, $\lambda_c > \lambda_0$

for λ_0 :

- $\chi'(\lambda_0) + R(Q_0) = 0, \;\; \chi(\lambda_0) - (1-\lambda_0)R(Q_0) = 0$

scaling solution for λ_c :

- $\chi'(\lambda_c) + R(Q_c) = 0$
- $\chi(\lambda_c) - (1-\lambda_c)R(Q_c) = 3/2 \ln(4\bar{\alpha_s}\chi''(\lambda_c)Y)/(2\bar{\alpha_s}Y)$

[A. H. Mueller and D. N. Triantafyllopoulos (2002)]

cutting out diffusion

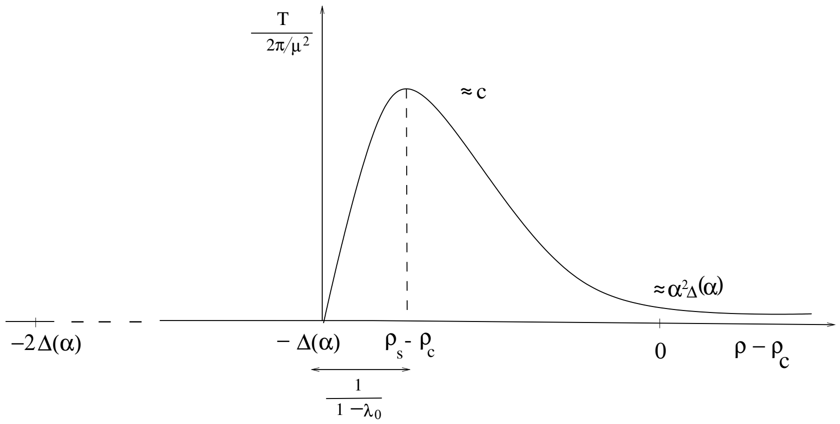
into saturation region: requires ϕ_G to vanish close to the saturation boundary

geometric scaling solution in terms of the scaling variable $q_\perp / Q_s(Y)$:

$$\phi_G = \phi_{max}\,(1-\lambda_0)\,[\ln\frac{q_\perp^2}{Q_s^2(Y)} + \frac{1}{1-\lambda_0}]\,\exp[-(1-\lambda_0)\ln\frac{q_\perp^2}{Q_s^2(Y)}]$$

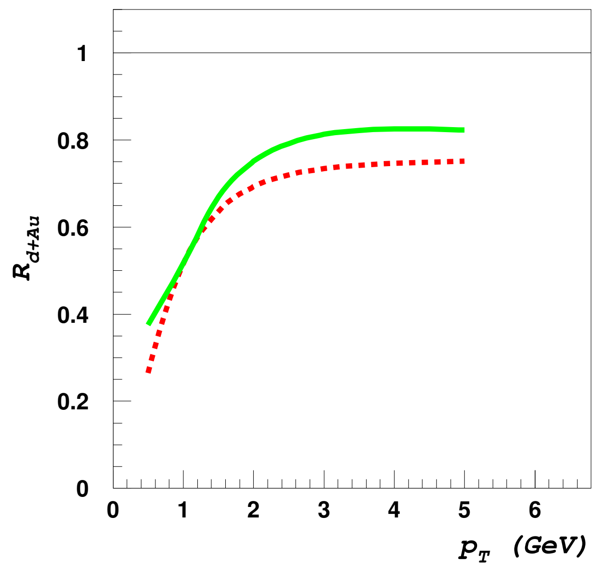
(with $\phi_G = \phi_{max} =$ const at $q_\perp = Q_s(Y)$)
i.e. $\phi_G \approx A^{\frac{1-\lambda_0}{3}}$ at $\vec{b} = 0$ and energy dependent scale

$$Q_s^2(Y) \simeq Q_c^2(Y) = \bar{Q}_s^2 \frac{\exp[2\bar{\alpha}_s \frac{\chi(\lambda_0)}{1-\lambda_0} Y]}{[4\bar{\alpha}_s \chi''(\lambda_0) Y]^{3/[2(1-\lambda_0)]}}$$



LHC prediction, cont.

hadroproduction [D. Kharzeev et al. (2004)]:



R_{pA} of charged particles at LHC energies at $\eta = 0$ (dashed) versus R_{dAu} at RHIC at $\eta = 3.2$ –

quite similar predictions, since effective values of Bjorken x are quite similar,

but stronger suppression at LHC at forward rapidities expected