High pT Physics at RHIC

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PHOTONS AND GLUONS at RHIC
- some aspects -

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CONTENT

- MOTIVATION
- dipolebremsstrahlung picture of
  production of real and virtual photons

  discussion for quark + nucleus $-- >$ dileptons $(\gamma) + X$

- $k_\perp$ factorization - pQCD factorization
- gluon saturation
- BFKL evolution and geometrical scaling
- expectations/predictions for
  large forward photon rapidities
- work in progress in collaboration with

  A. H. Mueller and D. Schiff

Motivation

Disentangle

final versus initial state effects

due to multi gluon interaction in the nucleus

Ideal tool

real photons and dileptons

(also: no fragmentation function)

restrict discussion to:

- $qA \to \gamma(\gamma^*)X$

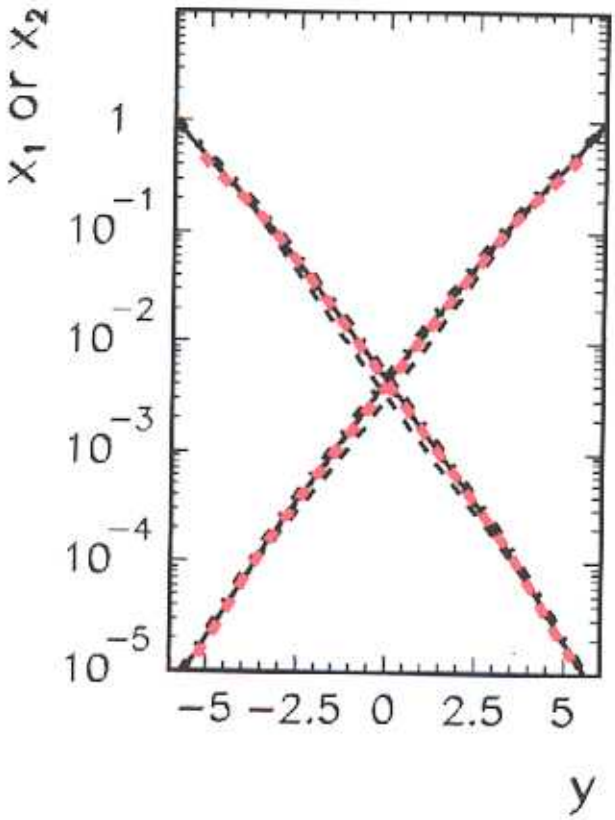
  at medium and large p_T,

  but large forward photon rapidities $\Longrightarrow$

  exploring the $x \to 0$ region in the nucleus
  at fixed energy

- fixed QCD coupling α_s

kinematics for $parton_1 + parton_2 - - > $ photon



average momentum fractions:

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

for $M_t > 0.5$ GeV and $\sqrt{s} = 200$ GeV

[taken from A. Szczurek (2003)]

and for $M_t = 3$ GeV and $y = 0\,(3.5)$: $x_2 = 1.5\ 10^{-2}\ (4.5\ 10^{-4})$

i.e. fast quark $- >$ forward photon: small x gluon

References on photons (a representative sample)

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 dipol formulation of the Drell-Yan process
   PR D66 (2002) 034024

4. F. Gelis and J. Jalilian-Marian,
   Photon propagation 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
   hep-ph/0111244

Bremsstrahlung of a quark
propagating through a large nucleus: $qA \to \gamma^* X$

cross section for massive γ^*, M and massless q

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

Dipoleformulation - impact parameter representation:
(cf. for DIS)

$$\frac{d\sigma}{dz d^2k_\perp d^2b} = \frac{2\alpha_{\rm elm}}{(2\pi)^4} \frac{1+(1-z)^2}{z} \int d^2x_\perp d^2y_\perp e^{i\vec{k}_\perp \cdot (\vec{x}_\perp - \vec{y}_\perp)}$$
$$\cdot \eta^2 \frac{\vec{x}_\perp \cdot \vec{y}_\perp}{x_\perp y_\perp} K_1(\eta x_\perp) K_1(\eta y_\perp) \left[N(z\vec{x}_\perp, \vec{b}) + N(z\vec{y}_\perp, \vec{b}) - N(z(\vec{x}_\perp - \vec{y}_\perp), \vec{b}) \right]$$

for transverse γ^*, $z = \frac{k_+}{p_+}$ (light cone momentum fraction) $= \frac{M_\perp e^{y_\gamma}}{\sqrt{s}}$,
$\eta^2 = (1-z)M^2$ and transverse mass $M_\perp$

$q\bar{q}$ ... dipole amplitude: $N(\vec{x}_\perp, \vec{b}) \equiv N_{q\bar{q}}(\vec{x}_\perp, \vec{b}, Y = \ln 1/x)$,
and $N(\vec{x}_\perp, \vec{b}) = 1 - S(\vec{x}_\perp, \vec{b})$

McLerran - Venugopalan model:

$$S(\vec{x}_\perp) = \exp(-L/2\lambda) = \exp(-x_\perp^2 \bar{Q}_s^2/4), \lambda = 1/\rho\sigma,$$

$$\bar{Q}_s^2 = \frac{C_F}{N_c} Q_s^2, \qquad Q_s^2(\vec{b}) = \frac{4\pi^2 \alpha_s N_c}{N_c^2 - 1} 2\rho \sqrt{R^2 - b^2} (xG(x, Q_s^2))$$

Reminder: DIS - dipole model

[taken from A. H. Mueller (2001)]

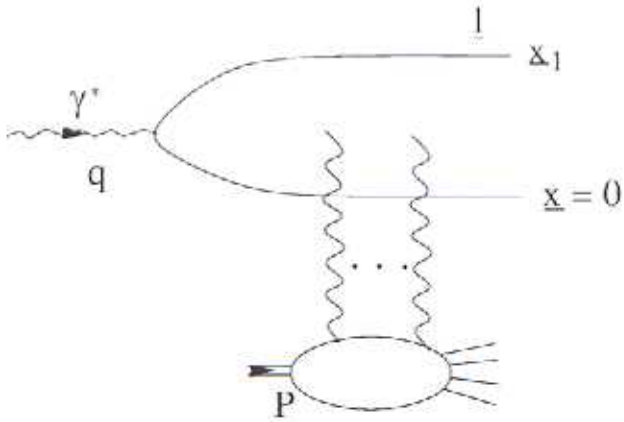
$$e_f^2 \frac{d(xq_f + x\bar{q}_f)}{dz d^2b d^2\underline{\ell}} = \frac{Q^2}{4\pi^2\alpha_{em}} \int \frac{d^2x_1 d^2x_2}{4\pi^2} \frac{1}{2} \sum_\lambda \psi^{f*}_{T\lambda}(\underline{x}_2, z, Q)\psi^f_{T\lambda}(\underline{x}_1, z, Q)$$

$$\cdot e^{-i\underline{\ell}\cdot(\underline{x}_1-\underline{x}_1)}[S^\dagger(\underline{x}_2)S(\underline{x}_1) - S^\dagger(\underline{x}_2) - S(\underline{x}_1) + 1],$$

γ^* wavefunction:

$$\psi^f_{T\lambda}(\underline{x}, z, Q) =$$

$$\{\frac{\alpha_{em}N_c}{2\pi^2} z(1-z)[z^2 + (1-z)^2]Q^2\}^{1/2} e_f K_1(\sqrt{Q^2\underline{x}^2 z(1-z)}) \frac{\underline{\epsilon}^\lambda \cdot \underline{x}}{|\underline{x}|}$$



$$S^\dagger(\underline{x}_2)S(\underline{x}_1) = S(\underline{x}_1 - \underline{x}_2).$$

$$e_f^2 \frac{d(xq_f + x\bar{q}_f)_A}{dz d^2\ell d^2b} = \frac{Q^2}{4\pi^2\alpha_{em}} \int \frac{d^2x_1 d^2x_2}{4\pi^2} \frac{1}{2} \sum_\lambda \psi^{f*}_{T\lambda}\psi^f_{T\lambda} e^{-i\underline{\ell}\cdot(\underline{x}_1-\underline{x}_2)}$$

$$\cdot[1 + S(\underline{x}_1 - \underline{x}_2) - S(\underline{x}_1) - S(\underline{x}_2)]$$

Dipolformulation - $k_\perp$ factorized representation

$$\frac{d\sigma}{dz d^2k_\perp d^2b} = \frac{2\alpha_{\rm elm}}{(2\pi)^4}\frac{1+(1-z)^2}{z}\int \frac{d^2q_\perp}{q_\perp^2}\phi(\vec{q}_\perp,\vec{b},Y)$$

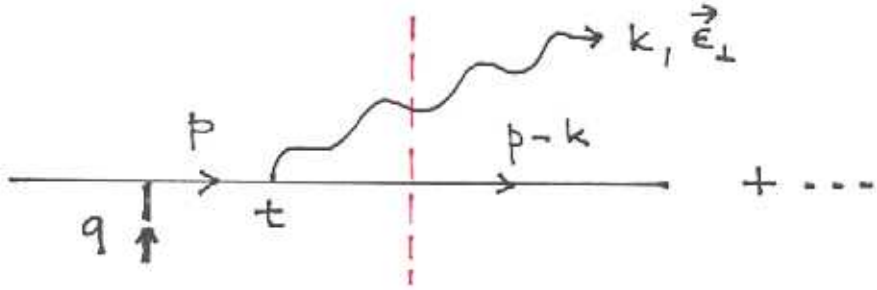
$$\cdot\left\{\frac{z^2q_\perp^2}{[k_\perp^2+\eta^2][(\vec{k}_\perp - z\vec{q}_\perp)^2+\eta^2]} - \eta^2\left[\frac{1}{k_\perp^2+\eta^2} - \frac{1}{(\vec{k}_\perp - z\vec{q}_\perp)^2+\eta^2}\right]^2\right\},$$

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

$$\text{Proof}: \frac{\vec{\epsilon}\cdot\vec{k}_\perp}{k_\perp^2+\eta^2} = i\int\frac{d^2x_\perp}{2\pi}e^{i\vec{k}_\perp\cdot\vec{x}_\perp}\vec{\epsilon}\cdot\vec{\nabla}_{x_\perp}K_0(\eta x_\perp)$$

$$= -i\eta\int\frac{d^2x_\perp}{2\pi}e^{i\vec{k}_\perp\cdot\vec{x}_\perp}\frac{\vec{\epsilon}\cdot\vec{x}_\perp}{x_\perp}K_1(\eta x_\perp)$$

Derivation: lightcone bremsstrahlung amplitudes



$$\Rightarrow \exp\left[it\left(\frac{k_\perp^2}{2k} + \frac{(\vec{p}_\perp - \vec{k}_\perp)^2}{2(p-k)} - \frac{p_\perp^2}{2p}\right)\right] = e^{it/t_{\rm form}} + \ldots$$

$$\Longrightarrow e\left[\frac{\vec{\epsilon}\cdot\vec{k}_\perp}{k_\perp^2+\eta^2} - \frac{\vec{\epsilon}\cdot(\vec{k}_\perp - z\vec{q}_\perp)}{(\vec{k}_\perp - z\vec{q}_\perp)^2+\eta^2}\right]$$

[e.g. BDMS (1998)]

Real ("isolated") photon production: $qA \to \gamma X$

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

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

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

$$\Longrightarrow xG_A(x,k_\perp^2) = \frac{N_c}{(2\pi)^3\alpha_s} \int^{O(k_\perp^2)} \frac{d^2q_\perp}{\pi} \int \phi(\vec{q}_\perp,\vec{b}) d^2b$$

or

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

in MV-model: rescale $x_\perp^2 \to N_c x_\perp'^2/C_F$, $\bar{Q}_s^2 \to Q_s^2$ etc.

$$\begin{aligned} \frac{dxG_A}{d^2b} &\equiv \int \frac{d^2q_\perp}{\pi} \phi_G(\vec{q}_\perp,\vec{b}), \\ \phi_G(q_\perp,\vec{b}) &\equiv \frac{C_F}{(2\pi)^3\alpha_s} \int d^2x_\perp e^{i\vec{q}_\perp\cdot\vec{x}_\perp} \vec{\nabla}^2_{x_\perp} [1-\exp(-x_\perp^2 Q_s^2/4)] \end{aligned}$$

- explicit LO check:

$$\phi^{\rm LO}(\vec{q}_\perp,\vec{b}) = q_\perp^2 \vec{\nabla}^2_{q_\perp} \int \frac{d^2x_\perp}{x_\perp^2}\, e^{i\vec{q}_\perp\cdot\vec{x}_\perp} \left[\frac{x_\perp^2\, Q_s^2(\vec{x}_\perp,\vec{b})}{4}\right]$$

$$= \frac{\bar{Q}^2_{so}}{4} q_\perp^2 \vec{\nabla}^2_{q_\perp} \int d^2x_\perp\, e^{i\vec{q}_\perp\cdot\vec{k}_\perp} \ln\frac{1}{x_\perp^2\lambda^2} = \frac{4\pi\bar{Q}^2_{so}}{q_\perp^2},$$

$$\bar{Q}^2_{so} = \bar{Q}_{so}(\vec{b}) = 2\pi C_F\ \alpha_s^2\ 2\rho\sqrt{R^2-b^2}.$$

with $\int d^2b 2\rho\sqrt{R^2-b^2} = A$ gives

$$xG_A^{\rm LO} = \frac{N_c C_F \alpha_s}{\pi} A \int^{O(k_\perp^2)} \frac{d^2q_\perp}{\pi q_\perp^2} \simeq A\frac{(N_c^2-1)\alpha_s}{2\pi}\ln\frac{k_\perp^2}{\Lambda^2}$$

$$= AxG^{\rm LO}(x,k_\perp^2)$$

i. e. confirms normalization factors etc.

Evolution of $\phi(\vec{q}_\perp, \vec{b}, Y)$.

- BFKL from $N(\vec{q}_\perp, \vec{b}, Y)$:

$$\phi = 16\pi \int_c \frac{d\lambda}{2\pi i} \frac{\Gamma(2-\lambda)}{4^\lambda} \exp\left[2\bar{\alpha}_s \chi(\lambda) Y - (1-\lambda) \ln \frac{q_\perp^2}{Q_{MV}^2}\right]$$

initial condition at $Y = 0$: MV distribution with scale

$$Q_{MV}^2 = \frac{\alpha_s^2 C_F}{2} \left(\frac{A}{R_A^2}\right)$$

saddle point solution: $\bar{\alpha}_s Y$ large and vanishing saddle point for $q_\perp = Q_0(Y)$

– diffusion into saturation regime $q_\perp < Q_0(Y)$

– Y dependence even for $q_\perp = Q_0(Y)$, $\phi \sim 1/\sqrt{\alpha_s Y}$

- BFKL in presence of saturation - including non-linear BK-type effects

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

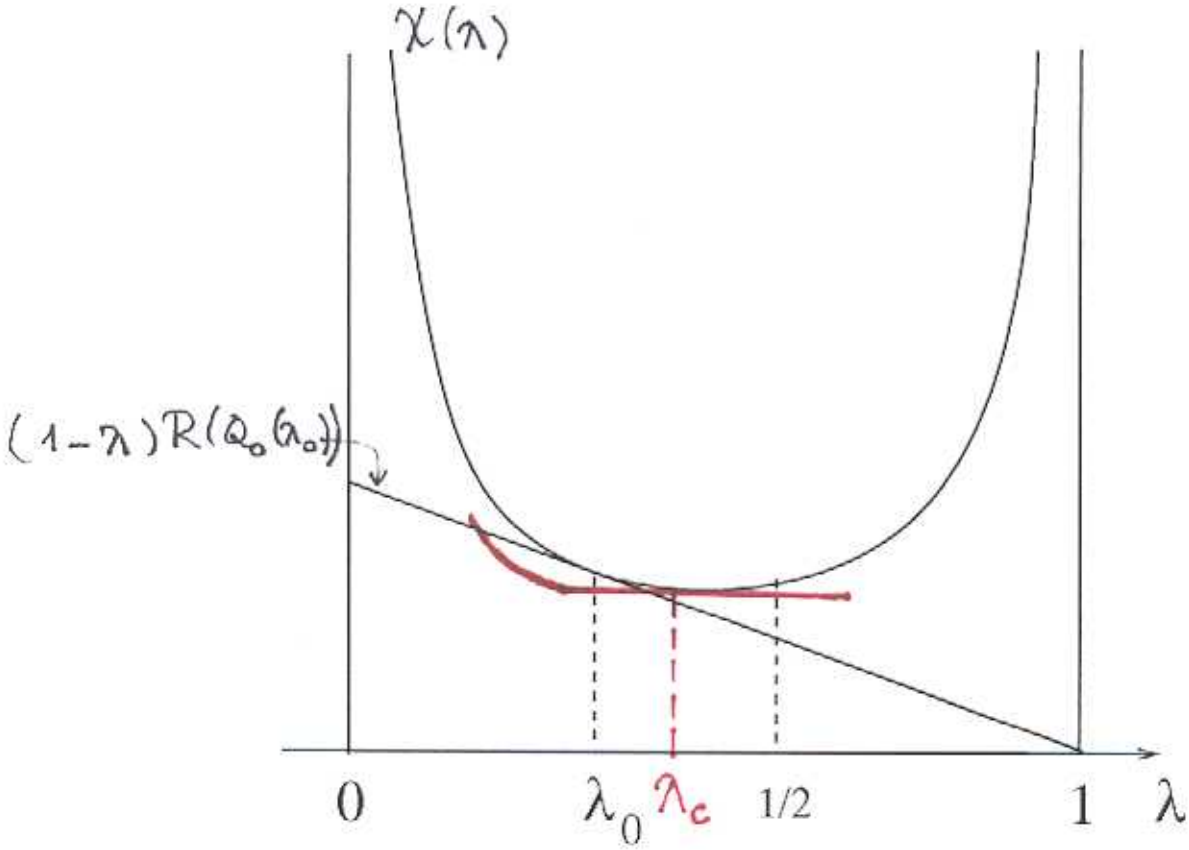
$\Longrightarrow$ successfull comparison with numerical solutions of the Balitzky-Kovchegov equation

TALK BY

[J. I. Albacete, N. Armesto, A. Kovner, C. A. Salgado, U. A. Wiedemann (2003)]

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

saddle point conditions: $R = \frac{\ln Q^2/\mu^2}{2\bar{\alpha}_s Y} = \frac{\ln 4q_\perp^2/Q_{MV}^2}{2\bar{\alpha}_s Y}$



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

for λ_0 :

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

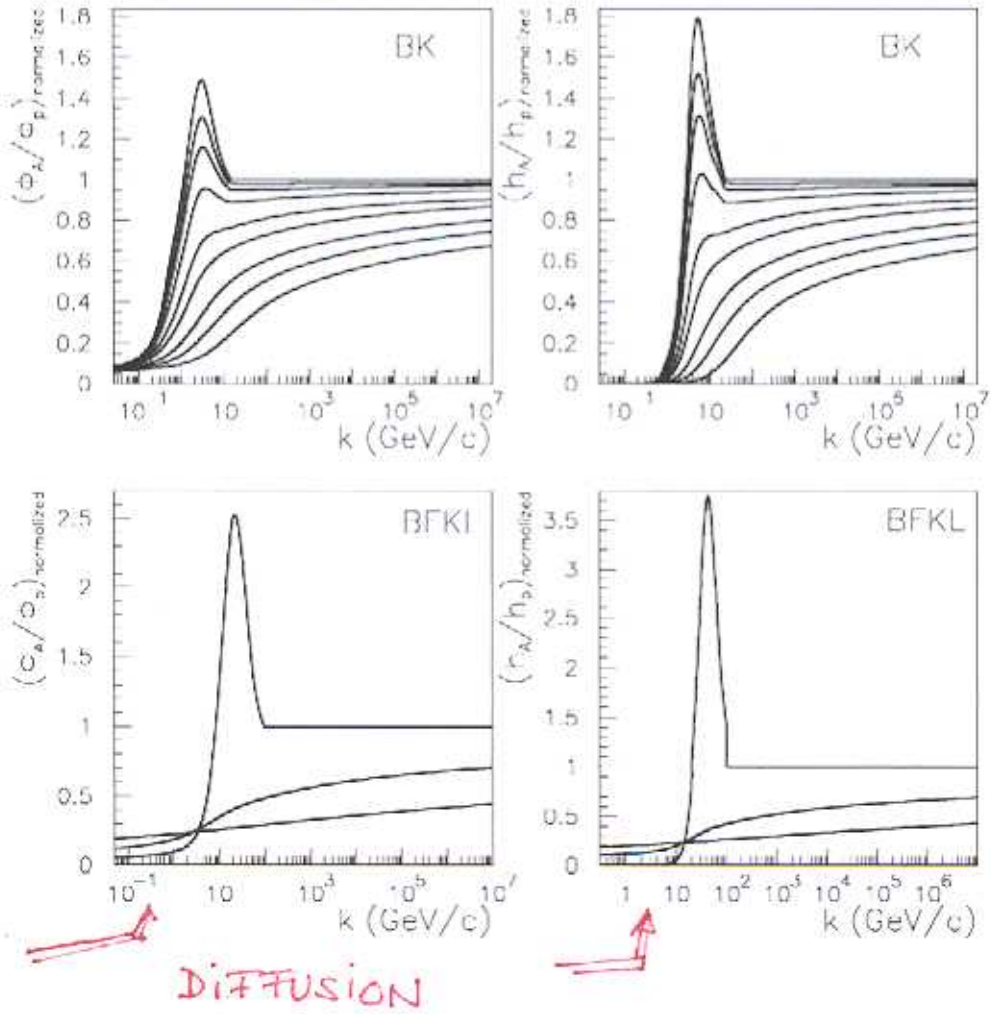
for λ_c :

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

$$\lambda_c = \lambda_0 + \mathcal{O}\left(\frac{\ln Y}{Y}\right)$$

Balitzky-Kovchegov equation - numerical solution

[J. I. Albacete, N. Armesto, A. Kovner, C. A. Salgado, U. A. Wiedemann (2003)]



Ratio of distributions ϕ^{WW} and $h = \phi$ in nucleus and proton, normalized to 1 at $k \to \infty$. *Upper plots*: BK evolution, with MV as initial condition with $Q_s^2 = 0.1$ GeV^2 for p and 2 GeV^2 for A. Lines from top to bottom correspond to $Y = 0$, 0.05, 0.1, 0.2, 0.4, 0.6, 1, 1.4 and 2. *Lower plots*: BFKL evolution, with MV as initial condition with $Q_s^2 = 4$ GeV^2 for p and 100 GeV^2 for A. Lines from top to bottom correspond to $Y = 0$, 1 and 4.

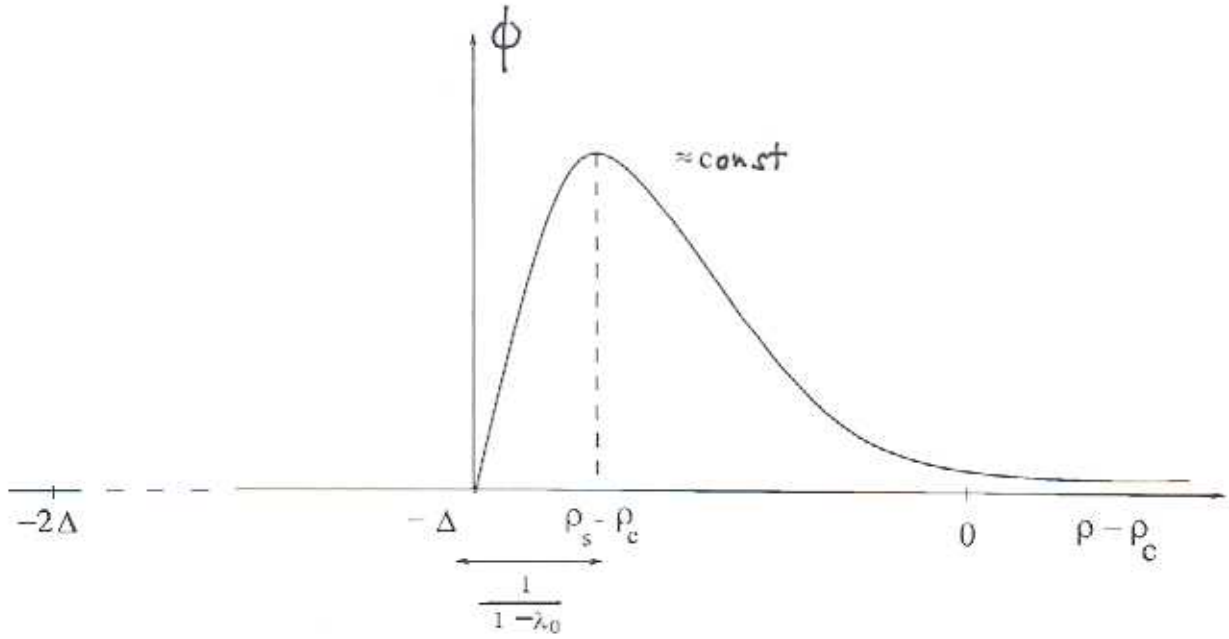
cutting out diffusion into saturation region, i.e.
require ϕ to vanish close to the saturation boundary

scaling "solution"

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

with $\phi = \phi_{max} = \text{const}$ at $q_\perp = Q_s(Y)$, and

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

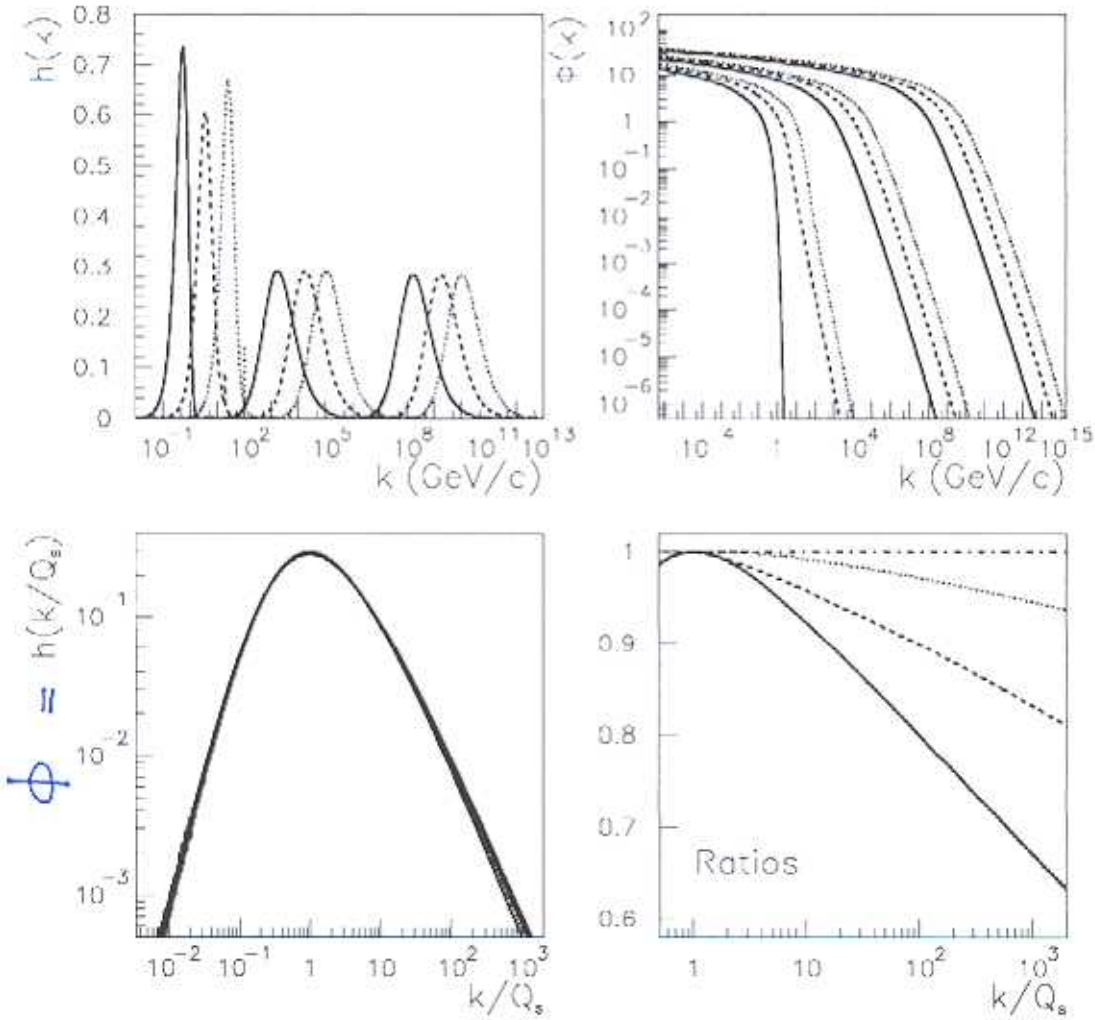


here: $\rho = \ln\frac{q_\perp^2}{Q_{MV}^2}$, $\rho_c = \ln\frac{Q_c^2(Y)}{Q_{MV}^2}$

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

Balitzky-Kovchegov equation - numerical solution

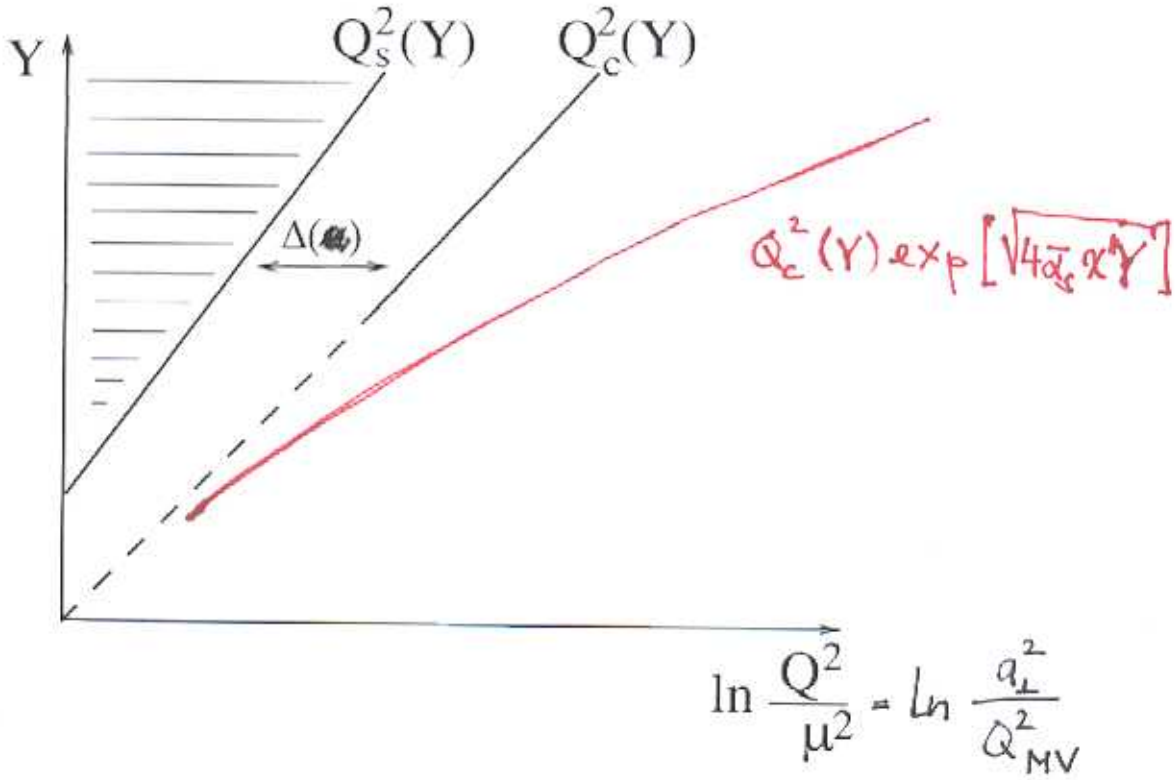
[J. I. Albacete, N. Armesto, A. Kovner, C. A. Salgado, U. A. Wiedemann (2003)]



bottom-left The scaled function $h(\rho) = \Phi$ versus $\rho = k/Q_s$ for $Y = 4, 6, 8, 10$ and the same initial conditions and conventions (lines cannot be distinguished). *bottom-right*: Ratio of $h(Y, \rho)/h(Y, \rho = 1)$ over $h(Y = 10, \rho)/h(Y = 10, \rho = 1)$ for $Y = 4$ (solid line), 6 (dashed line), 8 (dotted line) and 10 (dashed-dotted line), and initial condition MV with $Q_s^2 = 4$ GeV^2.

Range of scaling behaviour for $\phi(\vec{q_\perp}, Y)$

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



$(\mu = Q_{MV})$

valid at large rapidity Y for:

$$q_\perp = Q > Q_c : \ln(Q^2/Q_c^2) << \sqrt{4\bar{\alpha}_s\chi''(\lambda_0)Y}$$

$$q_\perp = Q < Q_c : \ln(Q_c^2/Q^2) << \Delta(\alpha_s)$$

γ^* cross section at large Y

- replace

$$\phi \to \frac{(2\pi)^3 \alpha_s}{N_c} \phi(q_\perp / Q_s(Y), \vec{b}\ )$$

- $$\frac{d\sigma^{qA->\gamma^* X}}{d^2 b} - (k^2{}_\perp + \eta^2) \frac{d\sigma}{d(\ln z) d^2 k_\perp d^2 b} =$$
$$= \int \frac{d^2 q_\perp}{\vec{q}_\perp^2} H(\vec{k}_\perp, z\vec{q}_\perp, z)\, \phi(q_\perp / Q_s(Y), \vec{b})$$

  (for $\eta < k_\perp$)

- $$H(\vec{k}_\perp, \vec{q}_\perp, z) - \frac{\alpha_{elm} \alpha_s}{\pi N_c} [1 + (1-z)^2] \frac{\vec{q}_\perp^2}{(\vec{k}_\perp - \vec{q}_\perp)^2 + \eta^2}$$

- for $k_\perp$.. hard scale $\to$ SCALING

$$\frac{d\sigma^{qA->\gamma^* X}}{d^2 b} = \phi(k_\perp / (z Q_s(Y)), \vec{b}\ )\, F[\ln(k_\perp / z Q_s(Y)), \eta / k_\perp, z]$$

prediction for large Y

- parametric estimate for ratio

$$R_{pA}^{\gamma^*} = \frac{d\sigma^{qA->\gamma^* X}}{A\ d\sigma^{qp->\gamma^* X}}$$

- based on

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

(scaling regions of A and p overlap)

and

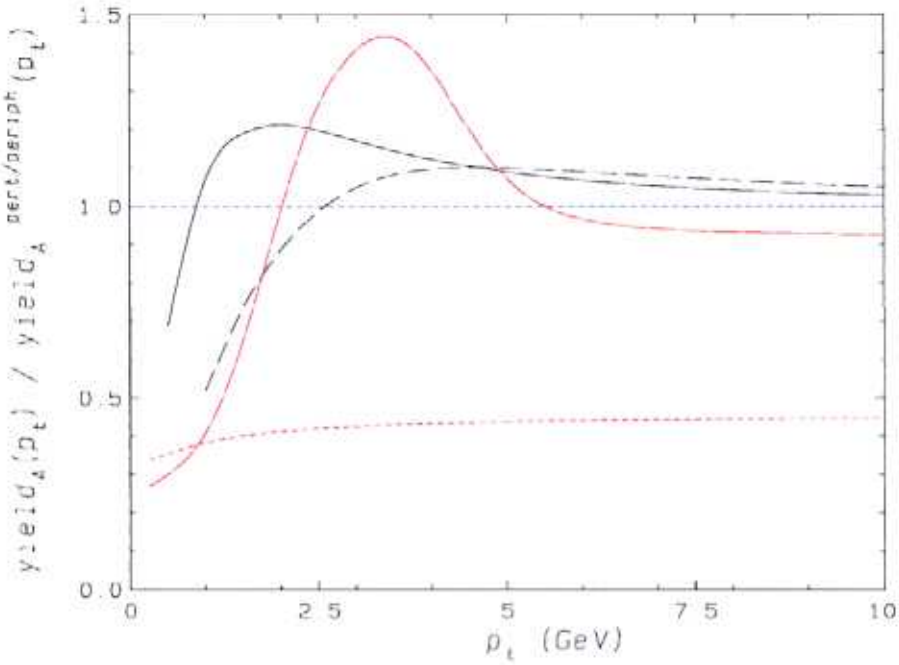
$$\frac{Q_s^2(Y)|_A}{Q_s^2(Y)|_p} = \frac{AR_p^2}{R_A^2} \approx A^{1/3}$$

- $$R_{pA}^{\gamma^*} \approx (\frac{R_A^2}{AR_p^2})^{\lambda_0} \approx A^{-\lambda_0/3}$$

i.e. suppression, independent on $k_\perp$ and Y

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

[R. Baier, A. Kovner, U. A. Wiedemann (2003)]



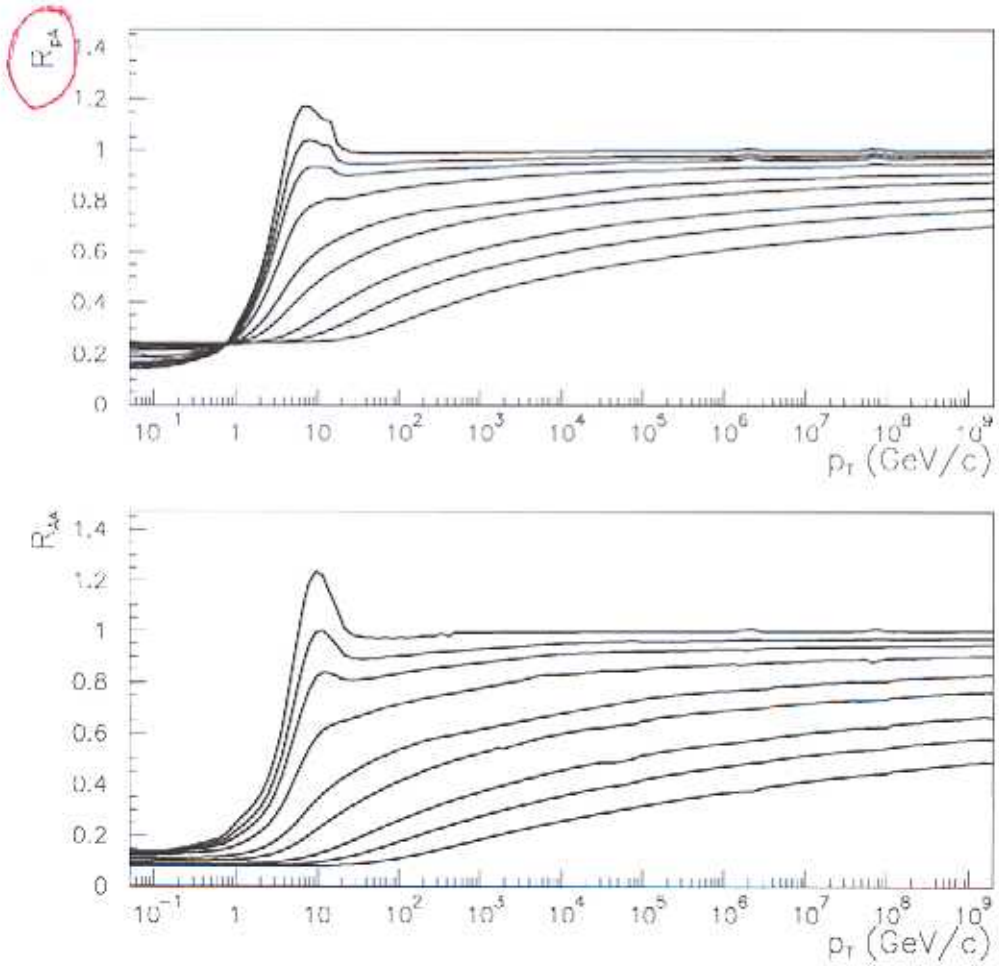
Gluon yield produced in p-A collisions, normalized to the perturbative yield for the MV gluon and to the peripheral yield for the evolved gluon distributions. The different curves are for the quasi-classical expression (dashed curve), the k_t-factorized spectrum with MV gluon (solid curve), and with evolved gluon distributions

$$\phi_A^{WW}(k_t) = \frac{N_c^2 - 1}{4\pi^3 \alpha_s N_c} \left(\frac{\hat{Q}_s^2}{k_t^2 + \hat{Q}_s^2} \right)^{\gamma(k_t)}$$

(dot-dashed curve: $\gamma = 0.64$) and (short-dashed curve: $\gamma(k_t)$), respectively.

Balitzky-Kovchegov equation - numerical solution

[J. I. Albacete, N. Armesto, A. Kovner, C. A. Salgado, U. A. Wiedemann (2003)]



Ratios R_{pA} and R_{AA} of gluon yields in p–A (upper plot) and A–A (lower plot) for BK evolution, with MV as initial condition with $Q_s^2 = 0.1$ GeV^2 for p and 2 GeV^2 for A. Lines from top to bottom correspond to $Y = 0, 0.05, 0.1, 0.2, 0.4, 0.6, 1, 1.4$ and 2.