High-Energy pA Collisions and Cosmic Ray Airshowers

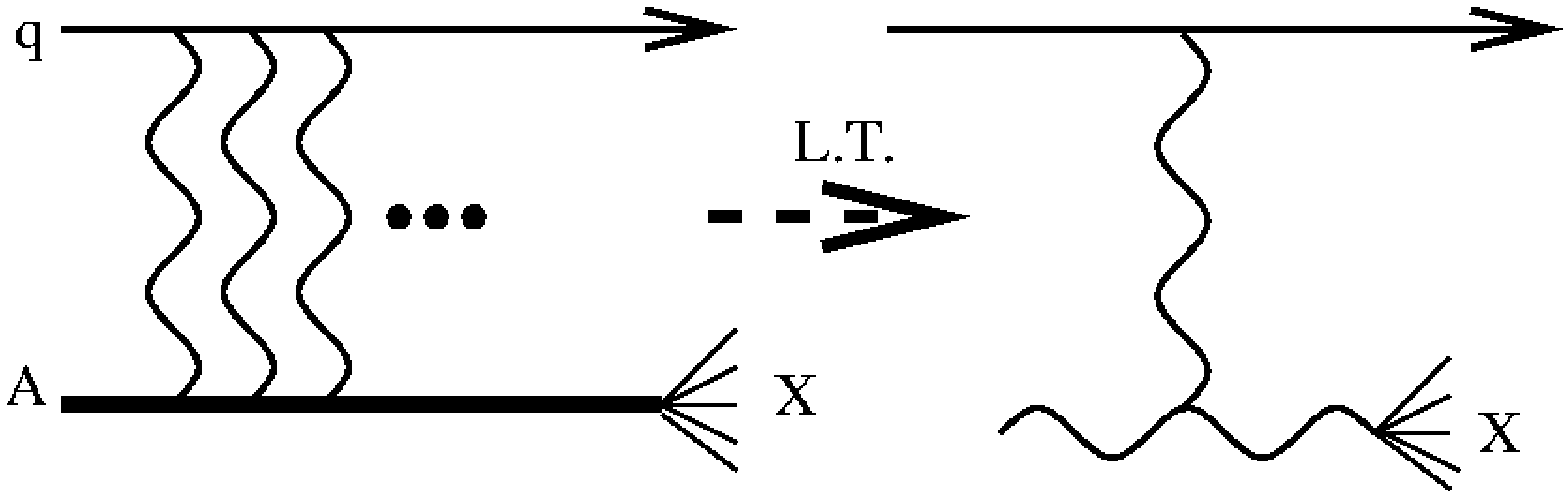
Adrian Dumitru (J.W. Goethe Univ., Frankfurt)

Collaborators: M. Strikman, H.-J. Drescher
hep-ph/0408073

- **qA Scattering**
- **Forward Hadron Production**
- **Qs (x)**
- **Application to Cosmic Ray Airshowers**
- **Summary**

Is there sensitivity to the evolution of Qs(x) ?

Quark-Nucleus Elastic Scattering



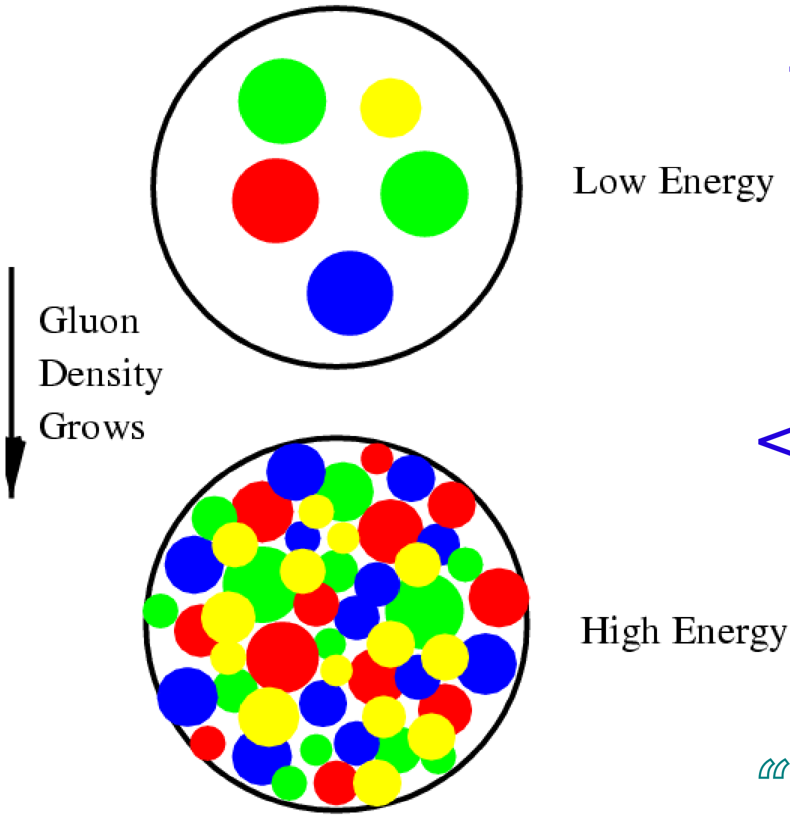
Quark Scattering Amplitude :

$$\langle q\ out \mid p\ in \rangle = \bar{u}(q)\ \tau(q,p)\ u(p)$$

with

$$\tau(q,p) \quad = \quad 2\pi\,\delta(p^- - q^-)\,\gamma^- \int \mathrm{d}^2 x_t\,[V(x_t) - 1]\ e^{i x_t (q_t - p_t)}$$

$$V(x_t) \quad = \quad \mathcal{P} \exp\left(-ig^2 \int_{-\infty}^{\infty} \mathrm{d}x^- \frac{1}{\partial_t^2}\,\rho^a(x^-, x_t)\,t^a \right)$$



<-- Dilute Parton Gas

<-- `Saturated' Classical Color Field

"McLerran-Venugopalan Model"

- Small-x gluons evolve slowly
- Color averaging with static random sources :

$$\langle O \rangle = \int \mathcal{D}\rho \; O[\rho] \exp\left(- \int \mathrm{d}^2 x_t \mathrm{d}x^- \;\mathrm{tr}\; \rho^2/\mu^2 \right)$$

μ^2 is average color charge squared per area

- Field of nucleus : $[D_\mu, F^{\mu\nu}] = \delta(x^-)\,\delta^{\nu +}\, g\,\rho$

Color averaging with a Gaussian leads to

$$\langle V(x_t)\rangle_\rho = \exp -g^4 C\chi \int \mathrm{d}^2 z_t\, G_0^2(x_t - z_t)$$

$$\langle V(x_t)V^\dagger(\bar{x}_t)\rangle_\rho = \exp -g^4 C\chi \int \mathrm{d}^2 z_t\, \left[G_0(x_t - z_t) - G_0(\bar{x}_t - z_t)\right]^2$$

with $C = (N_c^2 - 1)/4N_c \quad , \quad G_0(x_t) = -\int \frac{\mathrm{d}^2 k_t}{(2\pi)^2} \frac{\exp ik_t x_t}{k_t^2}$

and

$$\chi(x^-, x_t) = \int_{x^-}^{x_A^-} \mathrm{d}z^- \mu^2(z^-, x_t) \rightarrow \frac{1}{\pi R_A^2} \frac{N_c}{N_c^2-1} \int dx\, g_A(x)$$

Defining the saturation momentum

$$Q_s^2 = 4\pi^2 \alpha_s^2 \frac{N_c^2-1}{N_c} \chi$$

--->

$$\frac{\mathrm{d}\sigma^{qA}}{\mathrm{d}q^- \mathrm{d}^2 q_t \mathrm{d}^2 b} = \delta(q^- - p^-)\; C(q_t)$$

$$C(q_t) \;=\; \int \frac{\mathrm{d}^2 r_t}{(2\pi)^2} e^{iq_t r_t} \left\{ \exp\left[-2Q_s^2 \int_\Lambda \frac{\mathrm{d}^2 p_t}{(2\pi)^2} \frac{1}{p_t^4} \left(1 - e^{ip_t r_t}\right) \right] \right.$$
$$\left. -2\exp\left[-Q_s^2 \int_\Lambda \frac{\mathrm{d}^2 p_t}{(2\pi)^2} \frac{1}{p_t^4} \right] + 1 \right\}$$

--->

$$\mathrm{d}\sigma^{\mathrm{el}}/\mathrm{d}^2 b = \left[1 - e^{-Q_s^2/4\pi\Lambda^2}\right]^2 \quad , \quad \mathrm{d}\sigma^{\mathrm{tot}}/\mathrm{d}^2 b = 2\left[1 - e^{-Q_s^2/4\pi\Lambda^2}\right]$$

AD + JJM: PRL 89 (2002)

Limits for qA cross section :

$$C(q_t) \;=$$

$$q_t \gg Q_s \;: \qquad \frac{1}{2\pi^2} \frac{Q_s^2}{q_t^4} \left[1 + \frac{4}{\pi} \frac{Q_s^2}{q_t^2} \log \frac{q_t}{\Lambda} + \mathcal{O}\left(\frac{Q_s^2}{q_t^2} \right) \right]$$

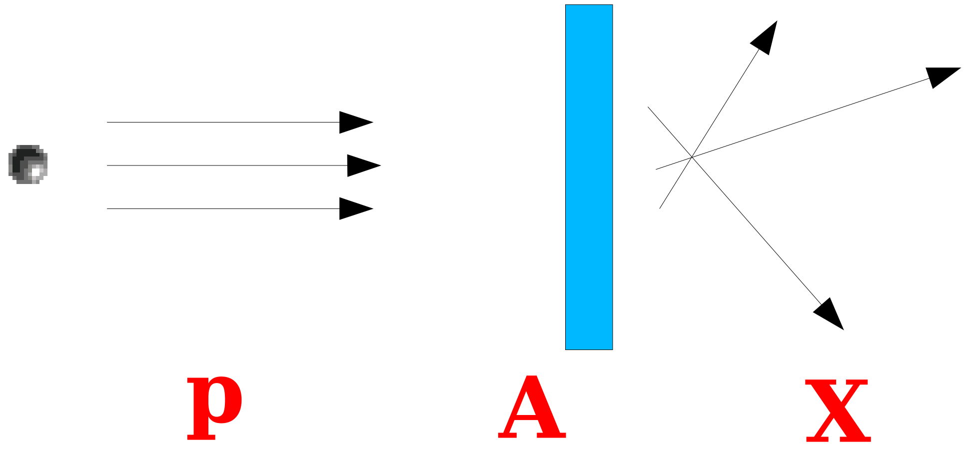
$$q_t \lesssim Q_s \;: \qquad \frac{1}{Q_s^2 \log Q_s/\Lambda} \exp\left(-\frac{\pi q_t^2}{Q_s^2 \log Q_s/\Lambda} \right)$$

Shattering the proton

Probability for quark to be scattered to qt~0 (with color exchange !) :

$$\int_0^{\Lambda} \mathrm{d}^2 q_t \frac{\mathrm{d}\sigma^{\mathrm{in}}}{\mathrm{d}^2 b \mathrm{d}^2 q_t} \simeq 1 - \exp\left(-\frac{\pi\Lambda^2}{Q_s^2 \log Q_s/\Lambda}\right) \simeq \frac{\pi\Lambda^2}{Q_s^2 \log Q_s/\Lambda}$$

--> suppression of "beam-jet remnants" (soft physics) in the BBL



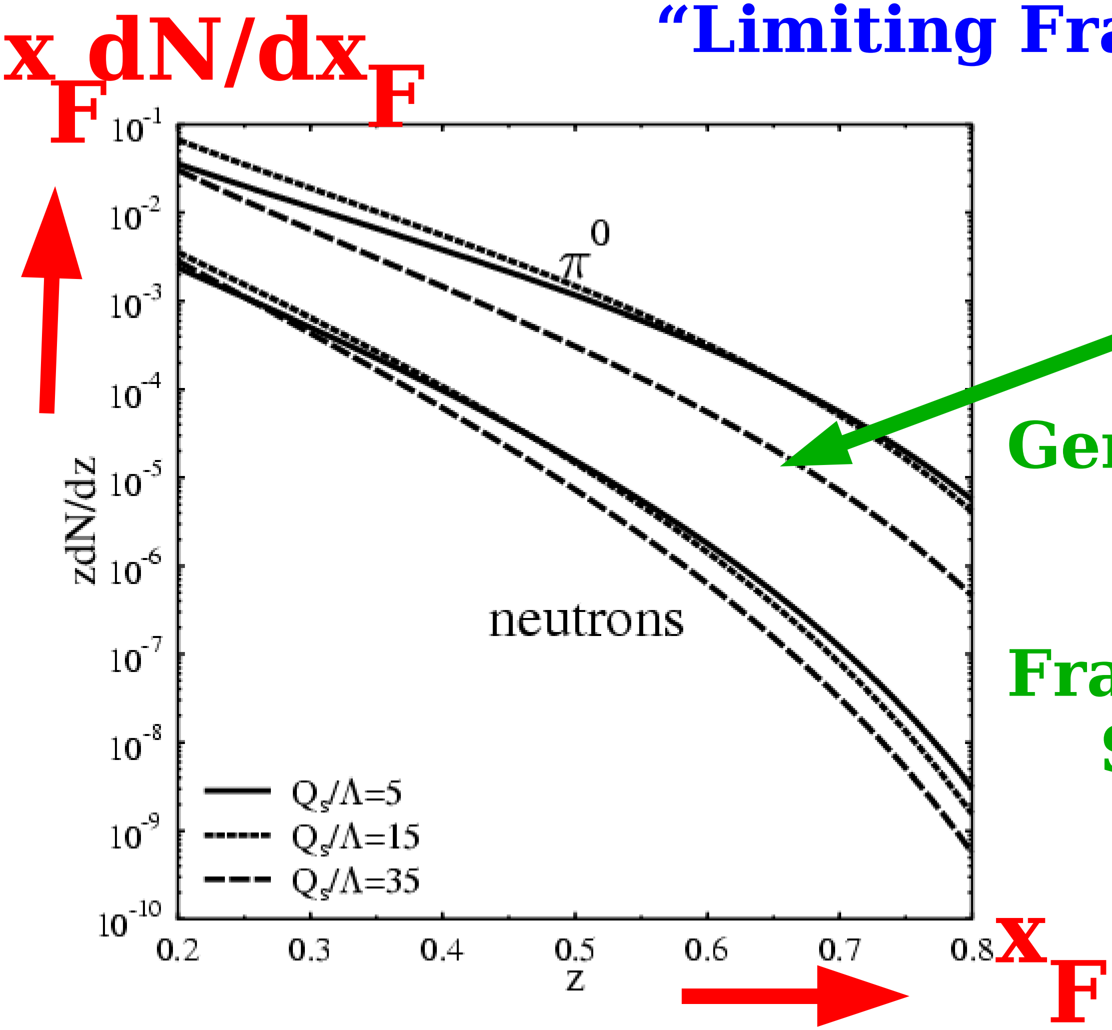
$$\langle q_t \rangle \sim Q_s$$

All partons resolved at scale Qs, coherence of proton destroyed completely.

If one assumes indep. fragm. of scattered partons :

$$x_F \frac{d\sigma^{pA\to hX}}{dx_F d^2k_t d^2b} = \underbrace{\int_{x_F}^{1} dx \frac{x}{x_F} f_{q/p}(x,Q_s^2) D_{h/q}(\frac{x_F}{x},Q_s^2) \frac{d\sigma^{qA}}{d^2q_t d^2b}}$$

"Limiting Fragmentation" curve in BBL



Long. distribution steepens

Gerland, A.D., Strikman PRL 90 (2003)

see also

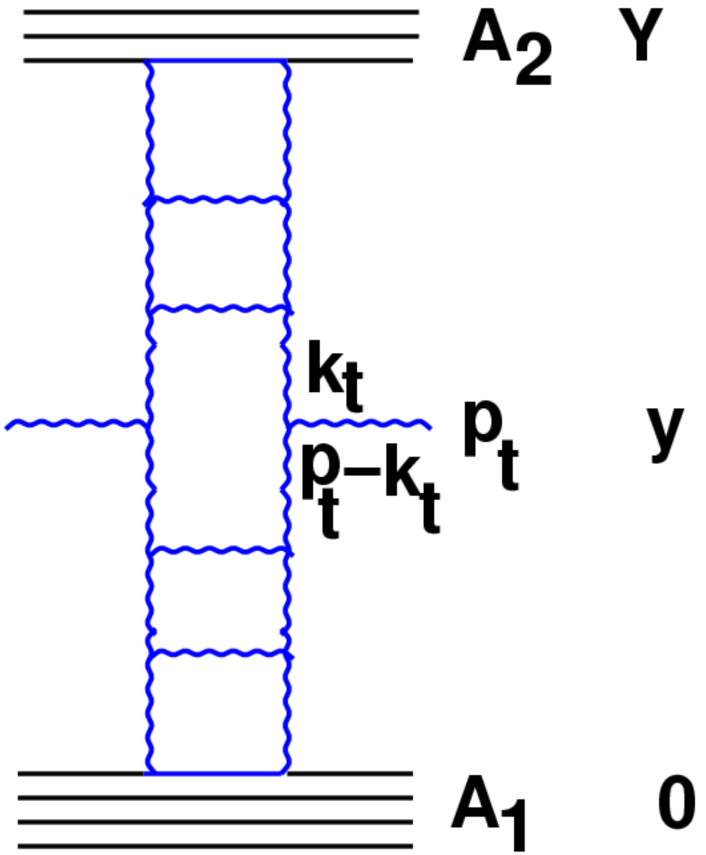
Frankfurt, Guzey, McDermott, Strikman: PRL 87 (2001)

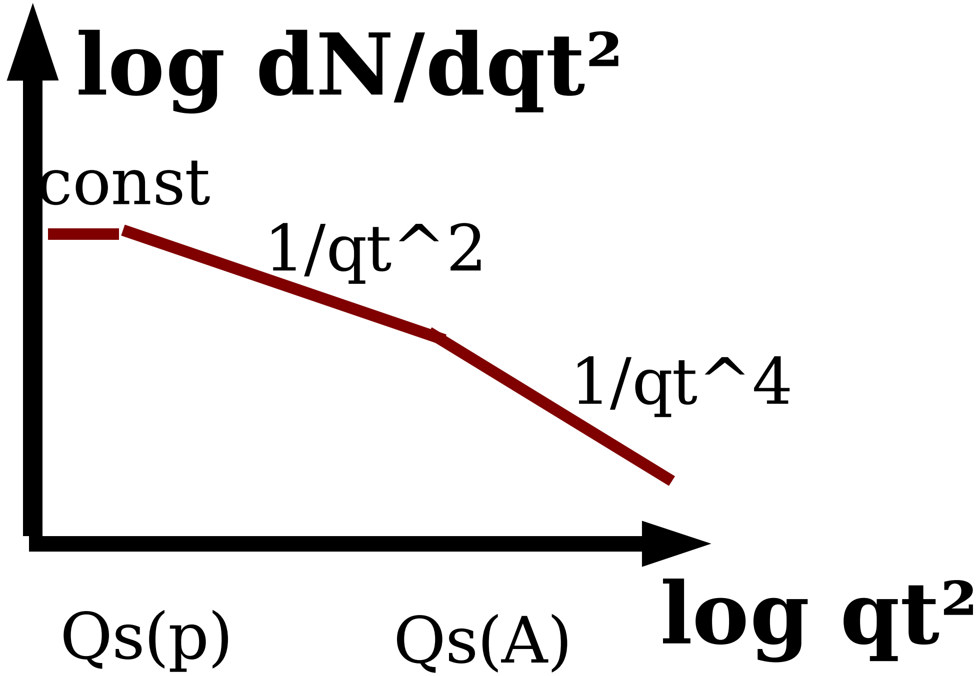
Gluon radiation

$$\frac{dN^g}{dy\,dq_t^2} = 4\pi\alpha_s \frac{N_c}{N_c^2-1}\frac{1}{q_t^4}$$
$$x_2\, g_A(x_2, q_t^2)\; x_1\, g(x_1, q_t^2)$$

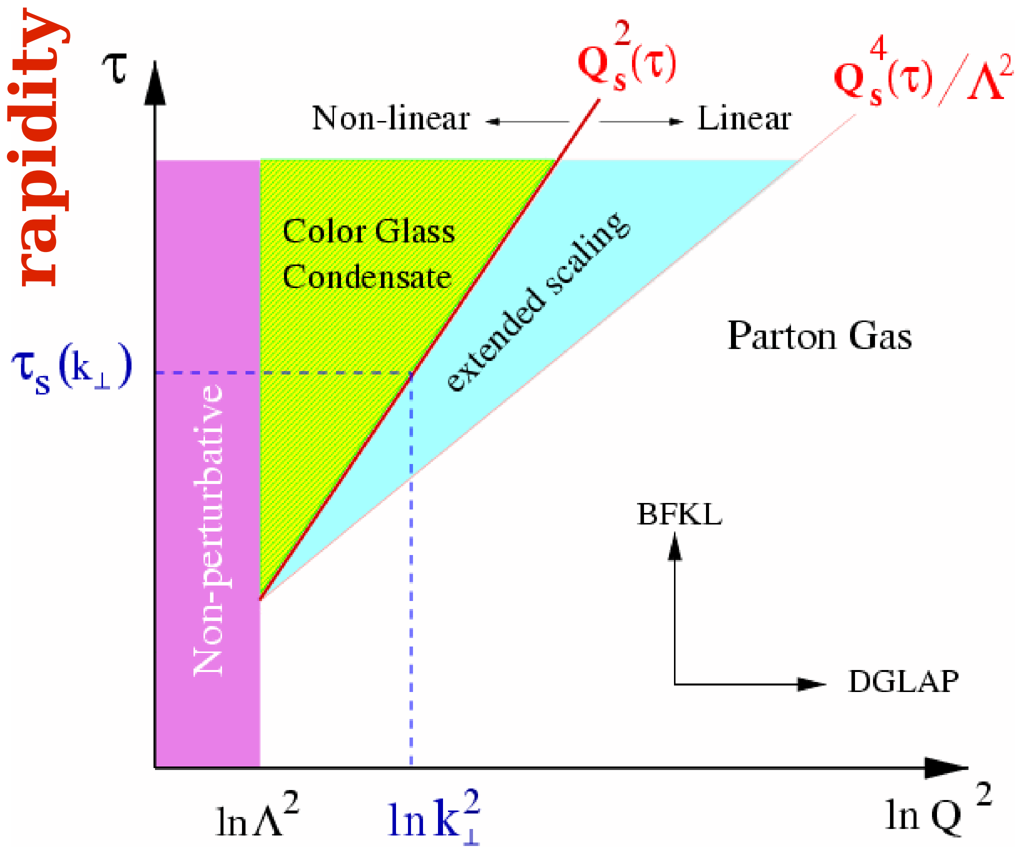
$$xg(x, q_t^2) \propto \frac{1}{\alpha_s}\min(q_t^2, Q_s^2(x))\;(1-x)^4$$

(Kharzeev, Levin, Nardi, NPA 2004)





Evolution of Qs



Iancu, Venugopalan
hep-ph/0303204

determine Qs(x) from BFKL

fixed coupl. BFKL:

$$Q_s^2(y, A) = Q_0^2 \exp c\bar{\alpha}_s y \rightarrow Q_s^2(x) = Q_0^2\, (x_0/x)^\lambda$$

GB-W: λ~0.28 Initial condition : $Q_0^2 \sim A^{1/3} \log A$

Factorized A- and x-dependence !

running coupl BFKL : $\bar{\alpha}_s(Q^2) = b_0/\log Q^2/\Lambda^2$

$$Q_s^2 = \Lambda^2 \exp\left(\log(Q_0^2/\Lambda^2)\sqrt{1 + 2\,c\,\bar{\alpha}_s\,y}\right)$$

$$y \to 0: \quad \to \quad Q_0^2 \exp\left(\bar{\alpha}_s\,c\,y\,\log Q_0^2/\Lambda^2\right) \stackrel{!}{=} Q_0^2 \exp\lambda y$$

$$\to Q_s^2 = \Lambda^2 \exp\sqrt{\log(Q_0^2/\Lambda^2)\,(2\lambda y + \log Q_0^2/\Lambda^2)}$$

$$y \to \infty: \quad \to \quad \Lambda^2 \exp\sqrt{2\lambda y\,\log Q_0^2/\Lambda^2}$$

	RHIC	LHC	GZK
yP	10.7	17.3	26.1
Qs r.c.	1.1 GeV	2.4 GeV	5.9 GeV
Qs f.c.	1.4 GeV	4.5 GeV	19.2 GeV

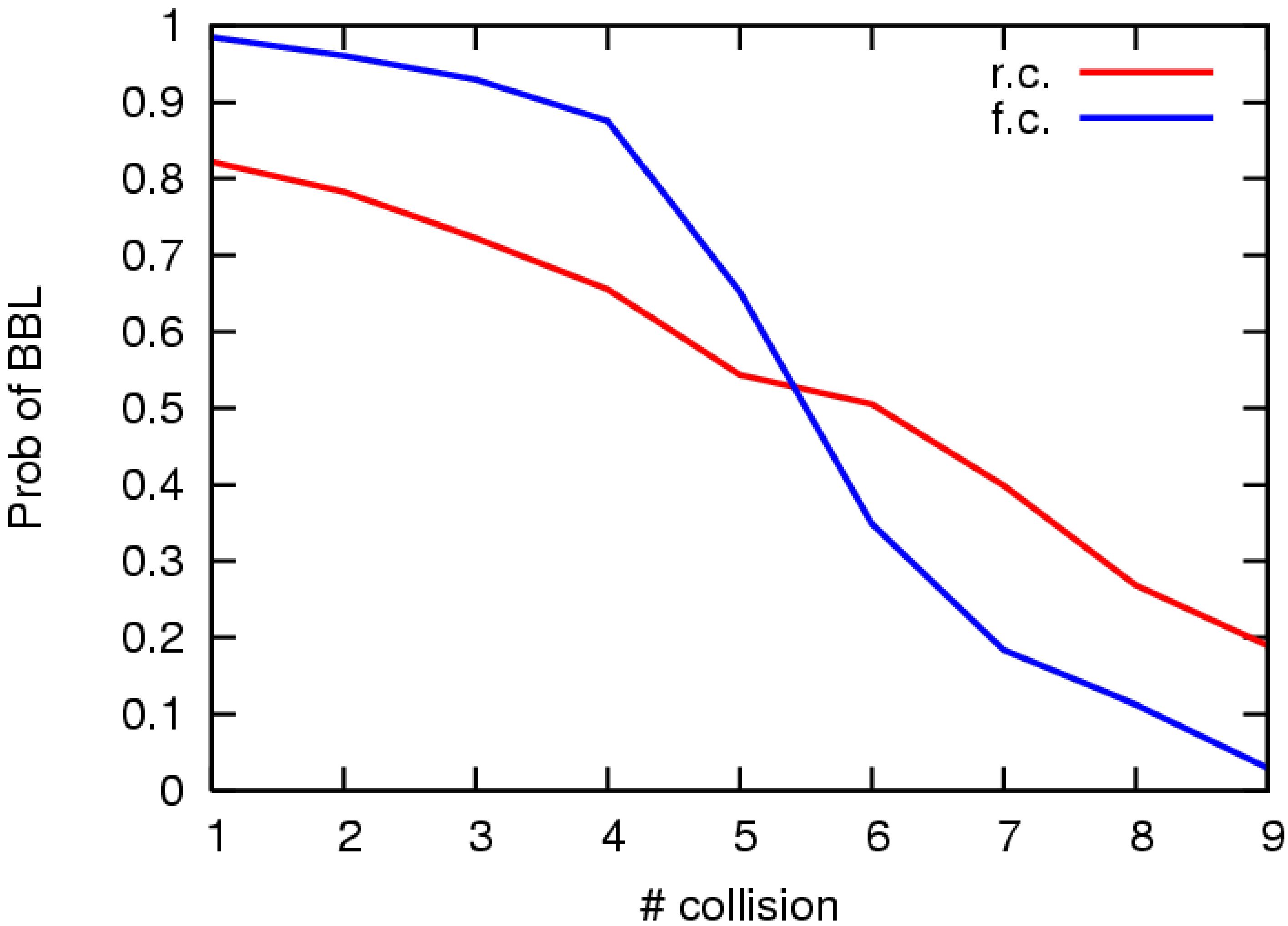
λ=**0.28; central "p+N"; (Q0/Λ)^2~Nval/3**

BBL 1.0 : hA MC for high energies

- Distributions of produced partons in full phase space (complete event, central+forward regions)
- Conserves energy and momentum
- Connects partons (val q and bremsstr. g) by strings --> “absorption” of collinear g
- Fragmentation via standard PYTHIA / JETSET
- Realistic transv. density profile for target nucleus
- Low-energy / peripheral collisions handled by any other model for L.T. + soft hadronic interactions, for example Lund string models (here: SIBYLL)

here: Qs (b, xF=0.001) >~ 1 GeV

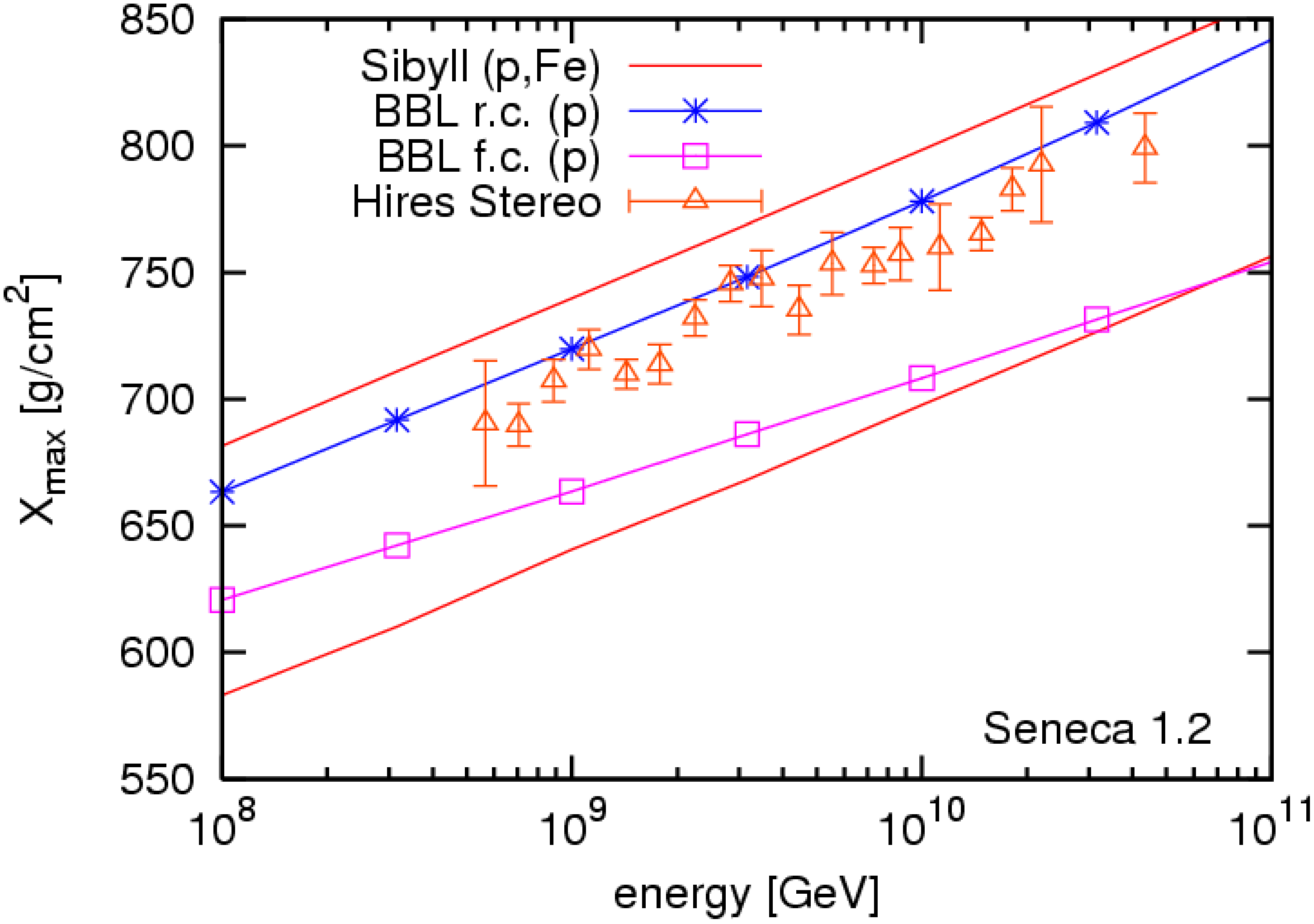
Area of "black disc" seen by leading hadron in n-th collision within one airshower



Cosmic Ray Airshowers

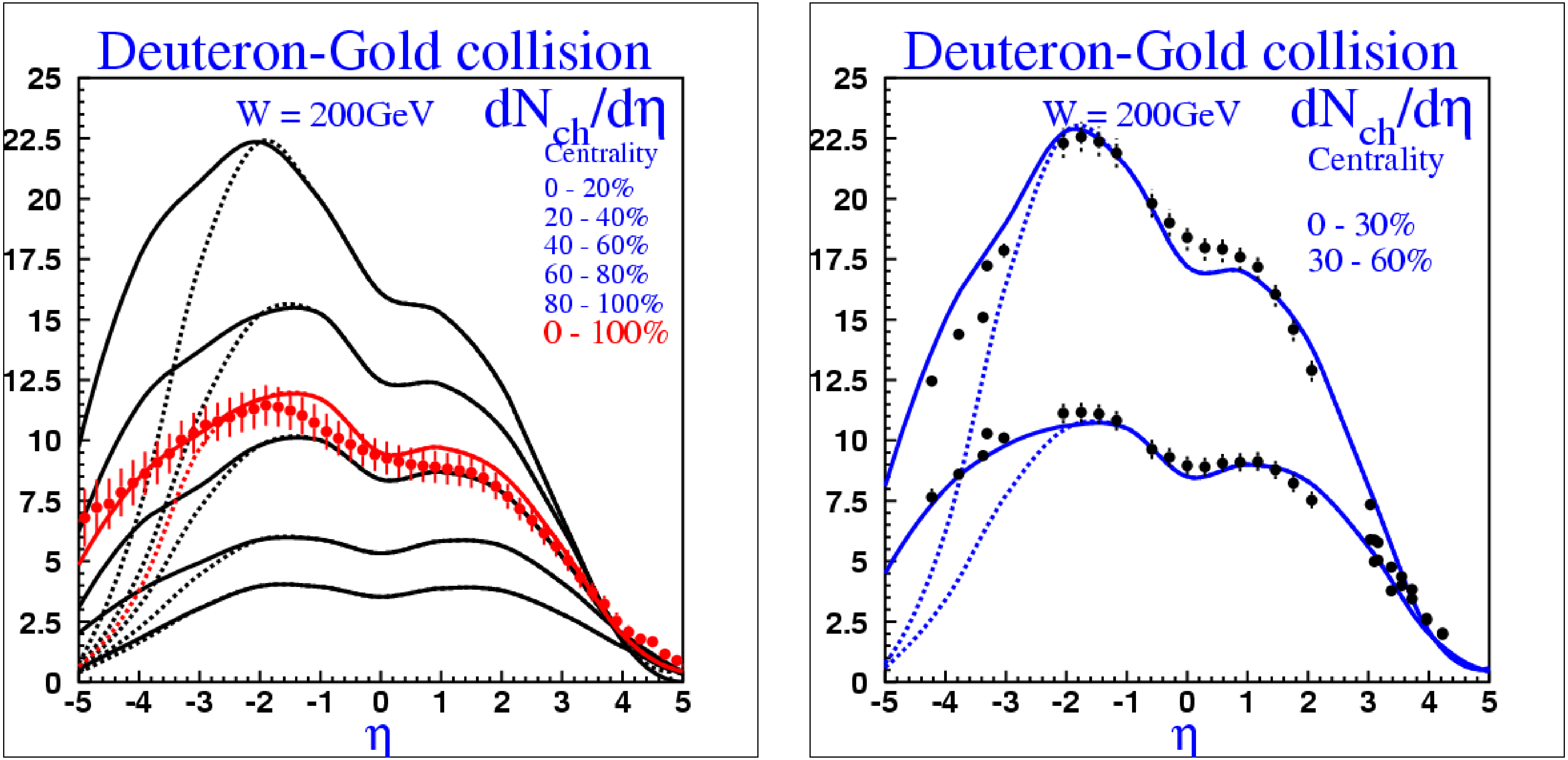
hep-ph/0408073

"penetration depth"



=> Sensitive to evolution of Qs !!

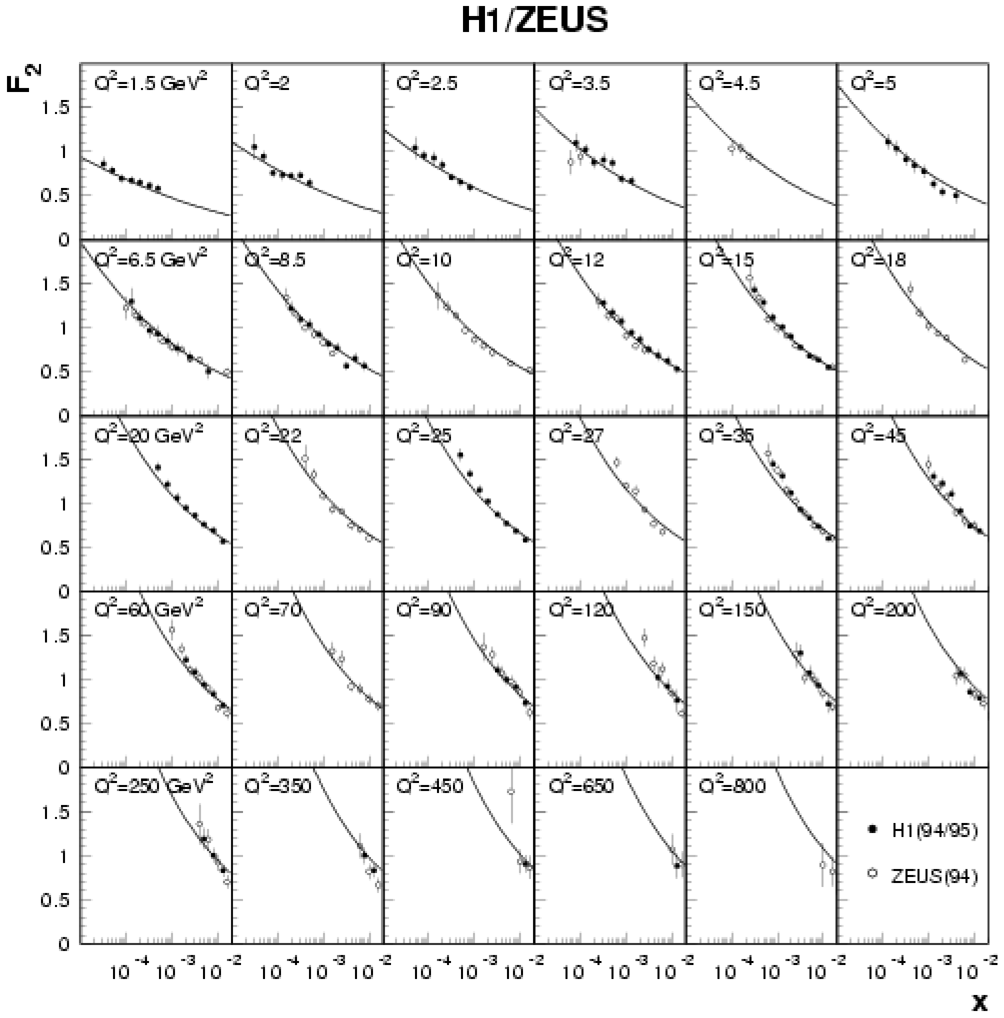
Fixed-Coupl / GB-W evolution at HERA & RHIC



KLN: hep-ph/0212316

GB-W: hep-ph/9903358

DIS on protons: F_2



=> for RHIC and HERA energies, f.c. evolution of Qs works fine

Summary

- **High-energy pA is of great interest for understanding the high-density non-linear regime of QCD at small x: gluon saturation, unitarity ?**

- **Would be very interesting physics @ LHC!**
  (especially in the forward region)

- **Cosmic ray airshowers are sensitive to QCD evolution scenario. Indications for a less rapid growth of Qs(x) as compared to RHIC or HERA.**