Small x physics and forward dynamics in pp/pA collisions

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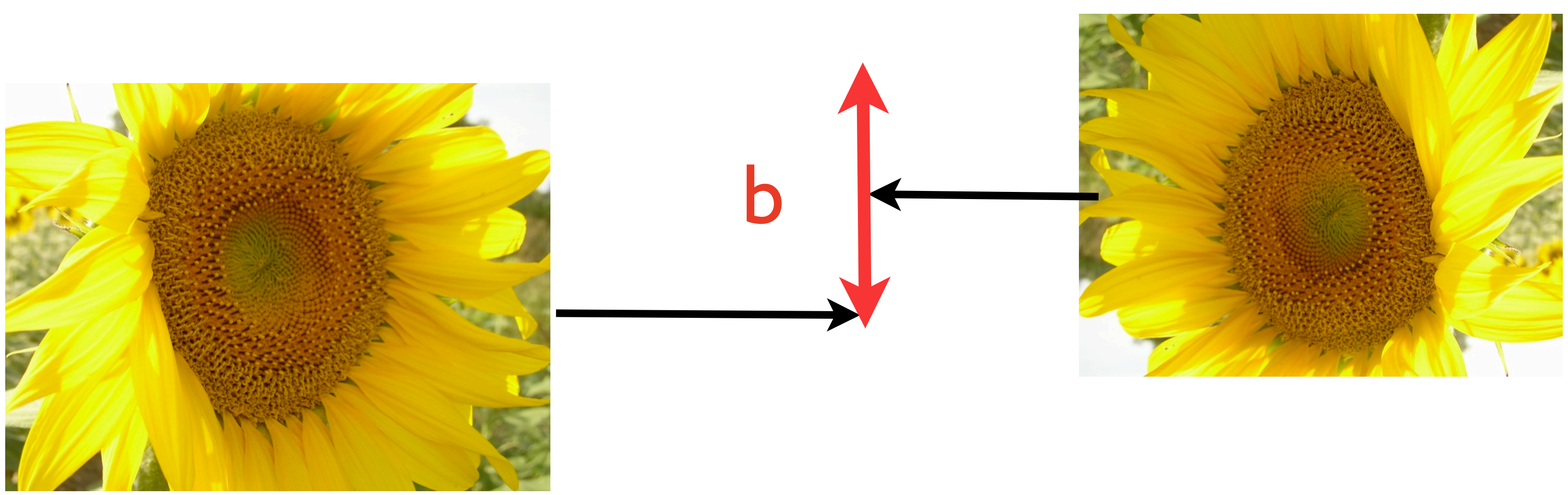
Outline

- *Three dimensional structure of high energy nucleon*
- *Onset of black regime for small dipole - nucleon/nucleus interaction*
- *Centrality trigger for pp collisions - modeling GZK p- air at LHC.*
- *Structure of inelastic final states in central pp/pA collisions.*

Two ingredients crucial for building a realistic description of pp/pA interactions at LHC energies and for cosmic rays:

Realistic implementation of information about transverse structure of the parton distributions in nucleon - generalized parton distributions - studied at HERA in exclusive processes.

Hard partons of the nucleon are close to its center, small x partons are spread much wider



Collisions of two composite objects should strongly depend on the impact parameter b

Breakdown of the leading twist approximation for the interaction of partons up to rather large virtualities (approach to the black disk limit). ***Problem*** *- current MC are forced to introduce a cutoff on minimal p_t of the jets which is a strong function of pp energy.*

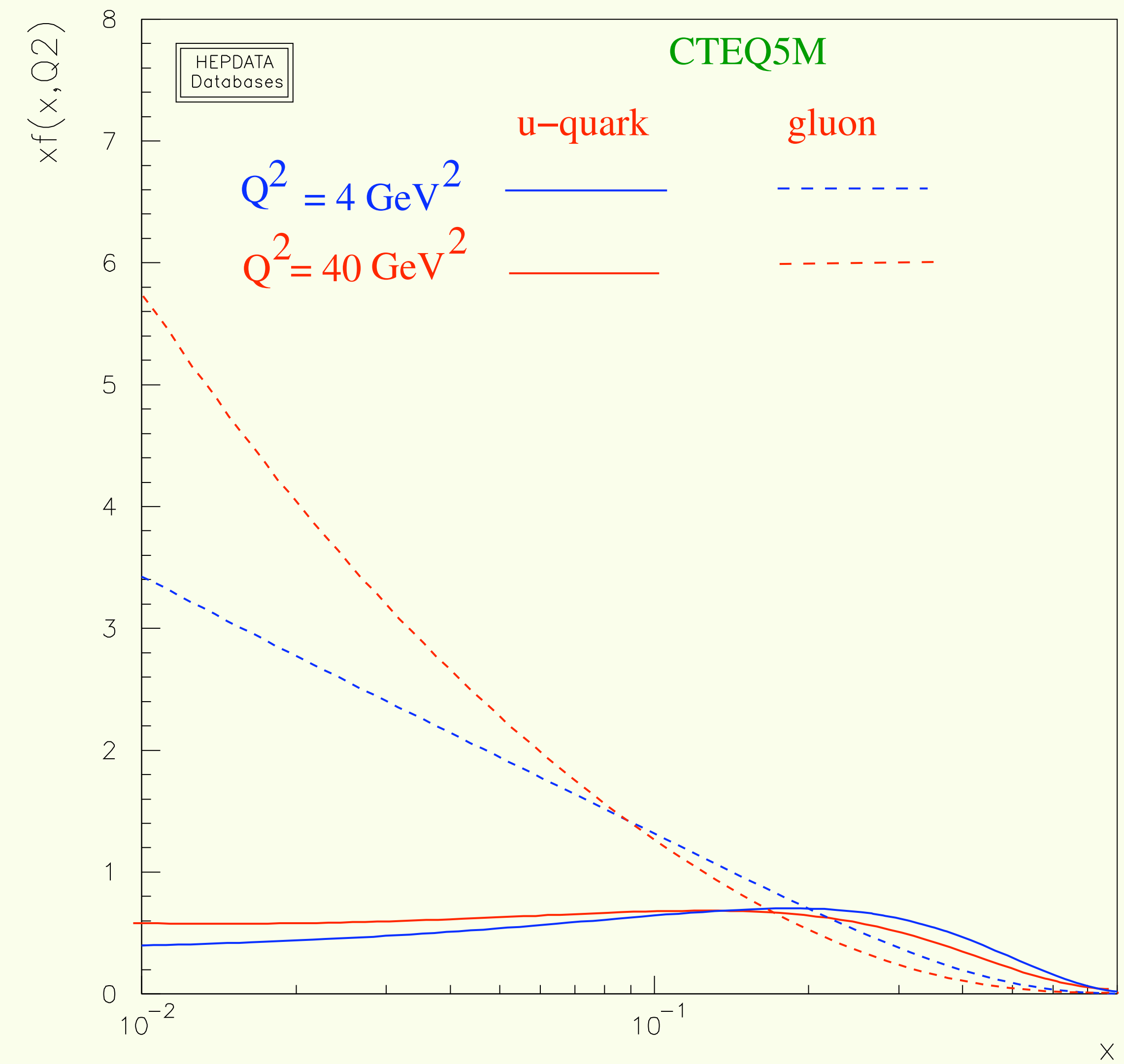
Another effect which maybe important:

transverse correlations between the partons

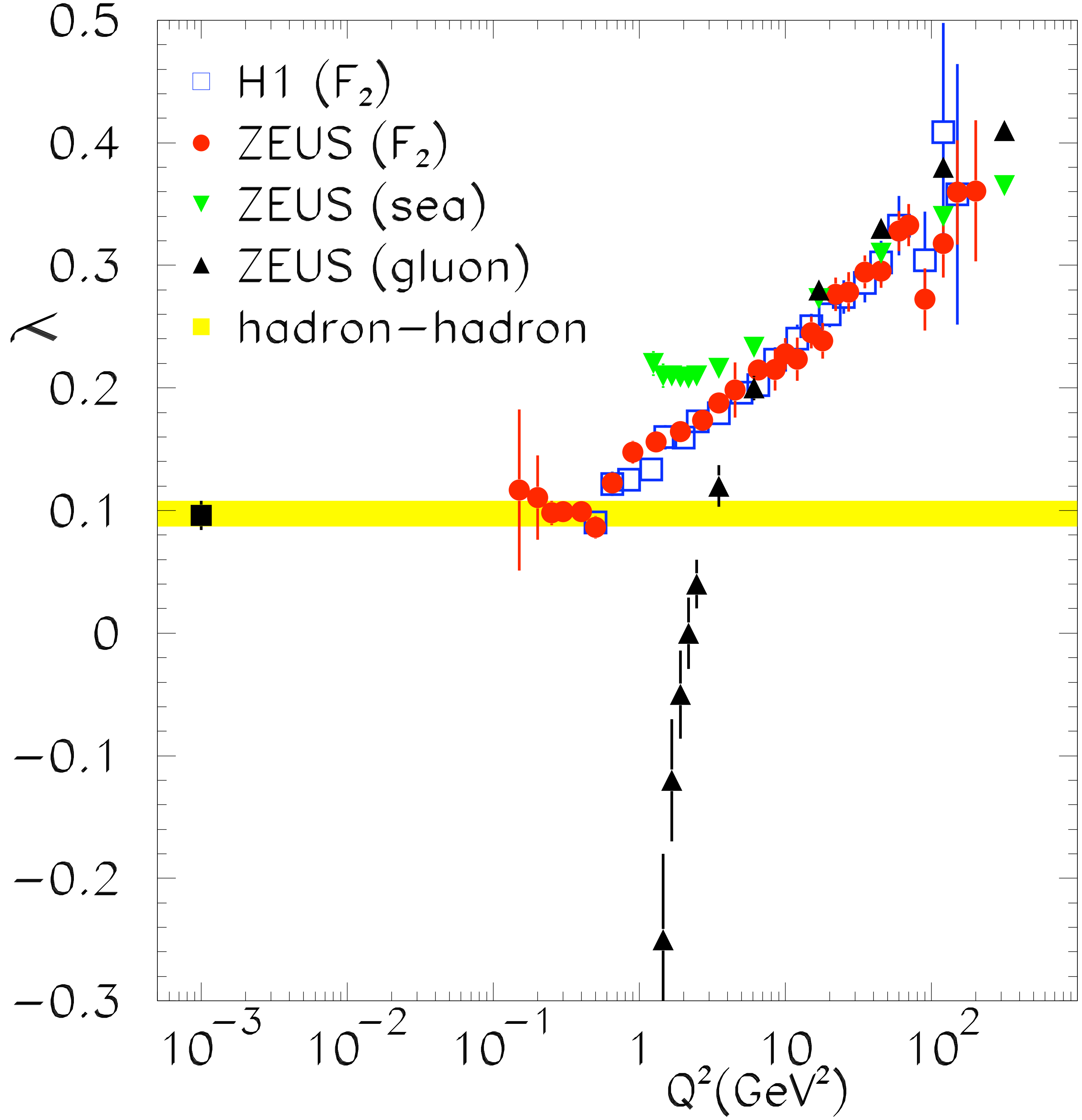
Key features of high energy QCD:

- Slow space-time evolution of the fast component of the high energy wave functions of colliding hadrons (Lorentz slow down)

- Already at a rather modest resolution of the probe, Q~ 2 GeV, nucleon consists of not simply three quarks and few gluons but of tens of constituents and the number of constituents rapidly grows with energy.

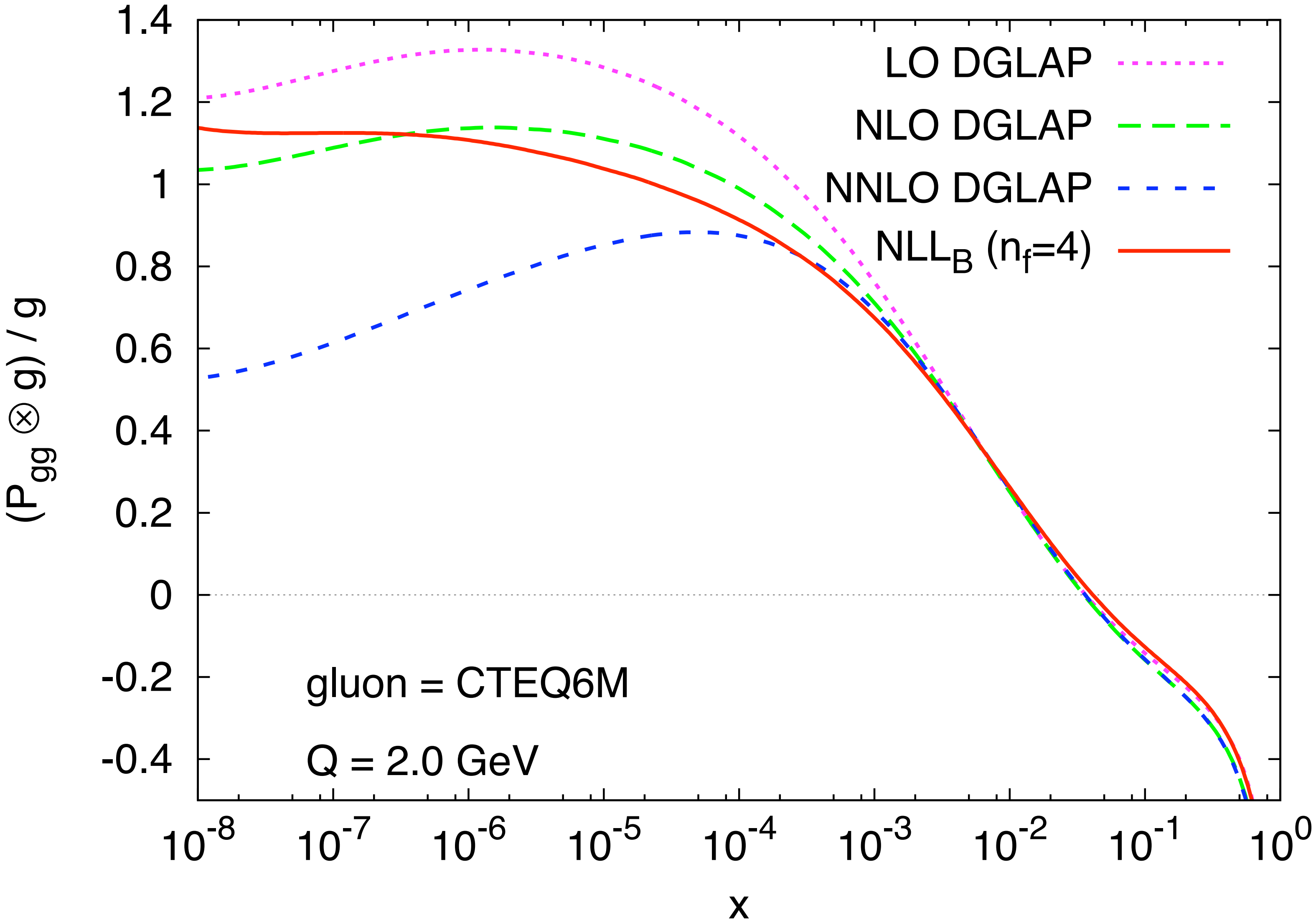


- Gluons carry   ~50% of the nucleon momentum at the resolution scales as low as $Q^2 \sim m_N^2$ (nonperturbative dynamics). Speeds up generation of strong gluon fields at small x.



Fits: $F_{2p}(x,Q^2) \propto x^{-\lambda}$ $x\bar{q}(x,Q^2) \propto x^{-\lambda}$

$$xg(x,Q^2) \propto x^{-\lambda}$$



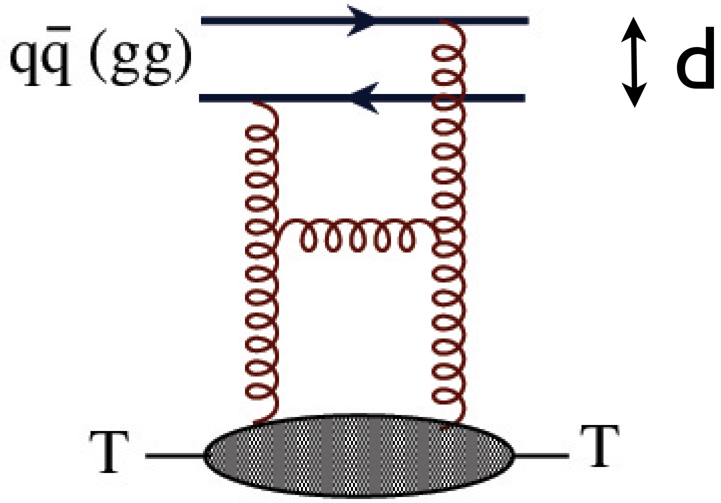
Scaling violation for gluons at small x
- from G.Salam study

Current studies of the perturbative QCD lead to expectation that the growth of the parton densities predicted by LO DGLAP is weakly modified when NLO is included and the attempt to sum various extra terms does not modify result noticeably down to smallest x relevant for GZK.

Can we trust pQCD prediction that the growth persist down to very small x?

NO!!!

Consider first "small dipole - hadron" cross section



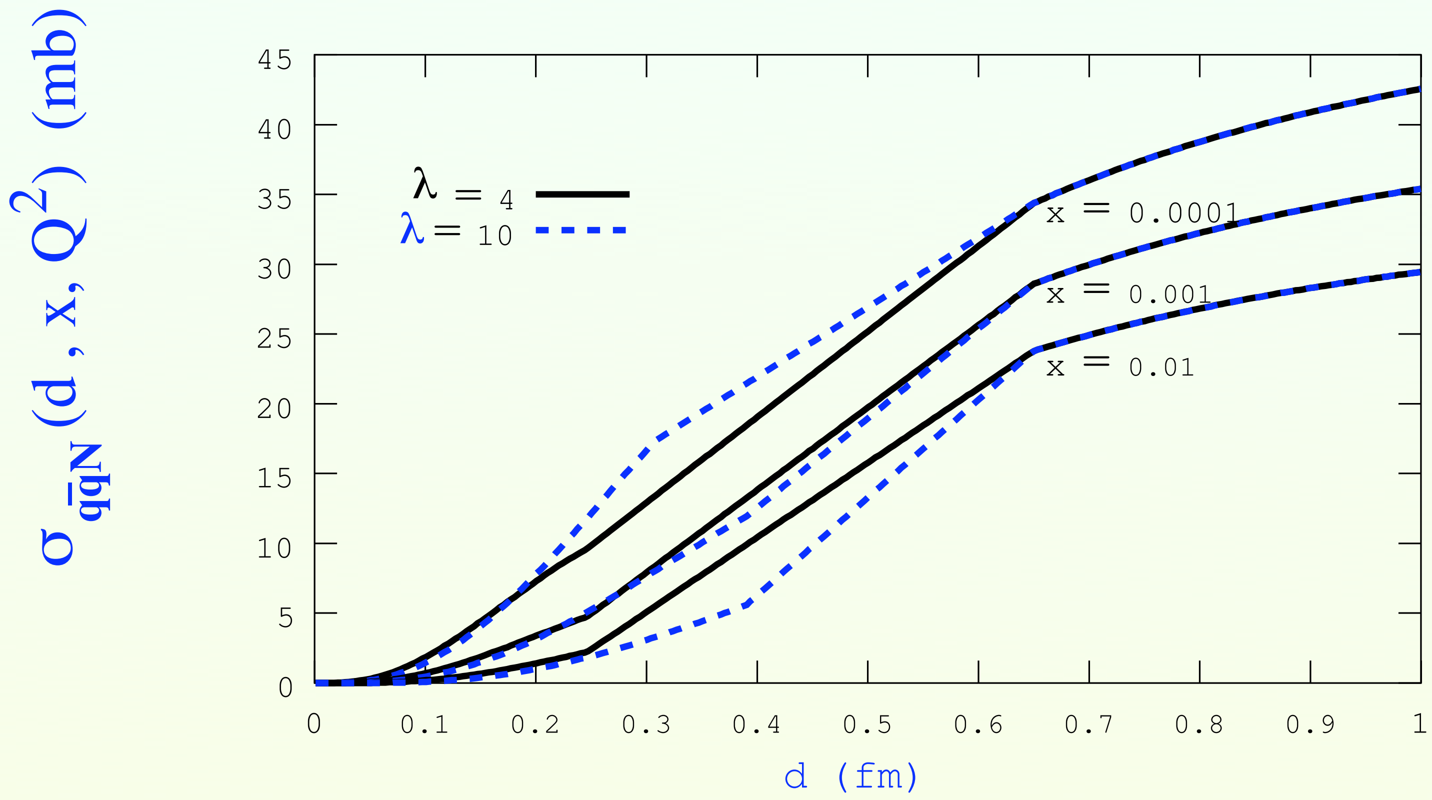
$$\sigma_{inel} = \frac{\pi^2}{3} F^2 d^2 \alpha_s(\lambda/d^2) x G_T(x.\lambda/d^2)$$

F^2 Casimir operator of color SU(3)

F^2 (quark) =4/3 F^2 (gluon)=3

Comment: This simple picture is valid only in LO. NLO would require introducing mixing of different components.

HERA data confirm increase of the cross sections of small dipoles predicted by pQCD

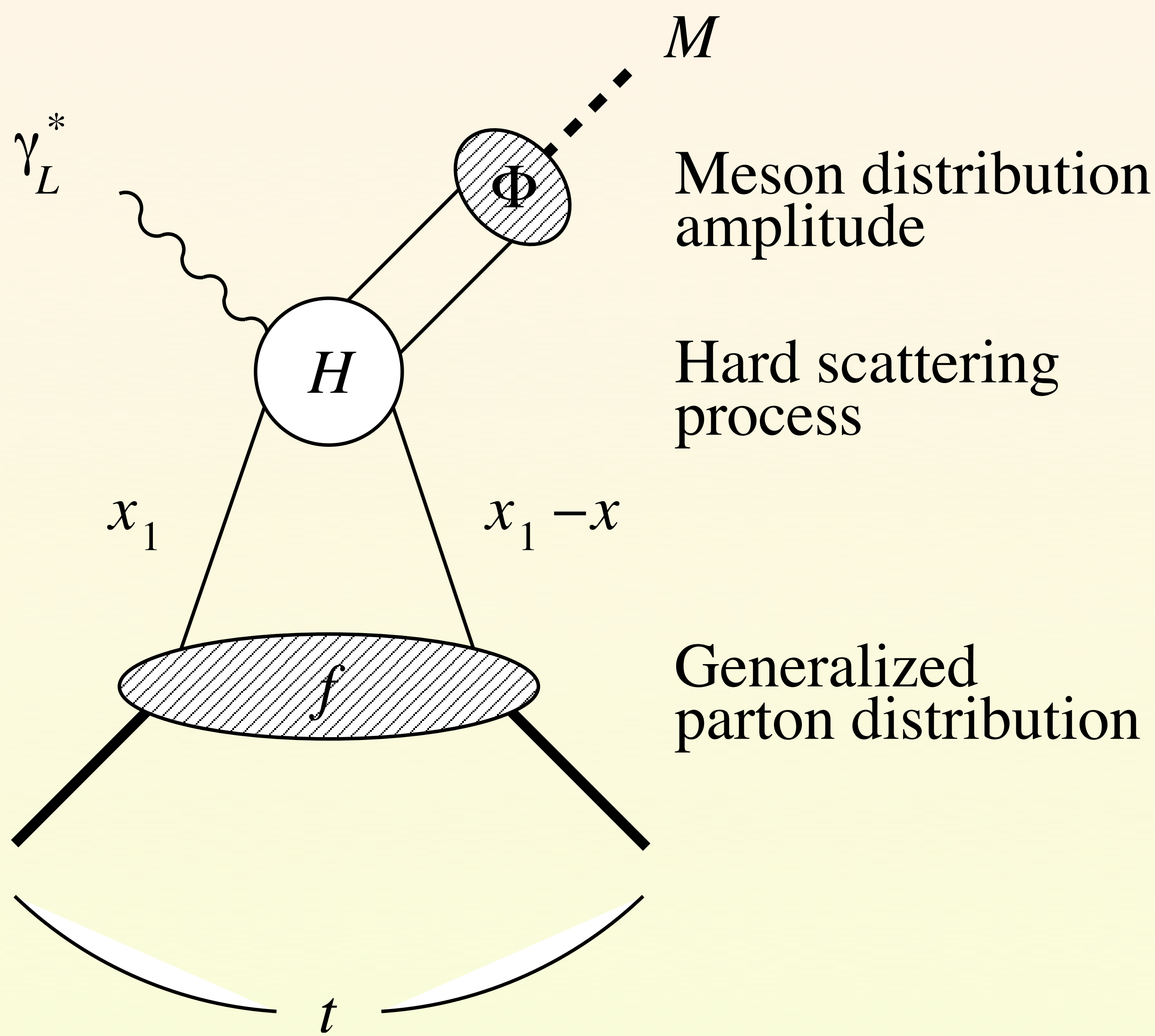


The interaction cross-section, $\hat{\sigma}$ for CTEQ4L, $x = 0.01, 0.001, 0.0001$, $\lambda = 4, 10$. Based on pQCD expression for $\hat{\sigma}$ at small d_t, soft dynamics at large b, and smooth interpolation. Provides a good description of F_{2p} at HERA and J/ψ photoproduction. Provided a reasonable prediction for σ_L

Frankfurt, Guzey, McDermott, MS 2000-2001

QCD factorization theorem for DIS exclusive processes

(Brodsky,Frankfurt, Gunion,Mueller, MS 94 - vector mesons, small x; general case Collins, Frankfurt, MS 97)



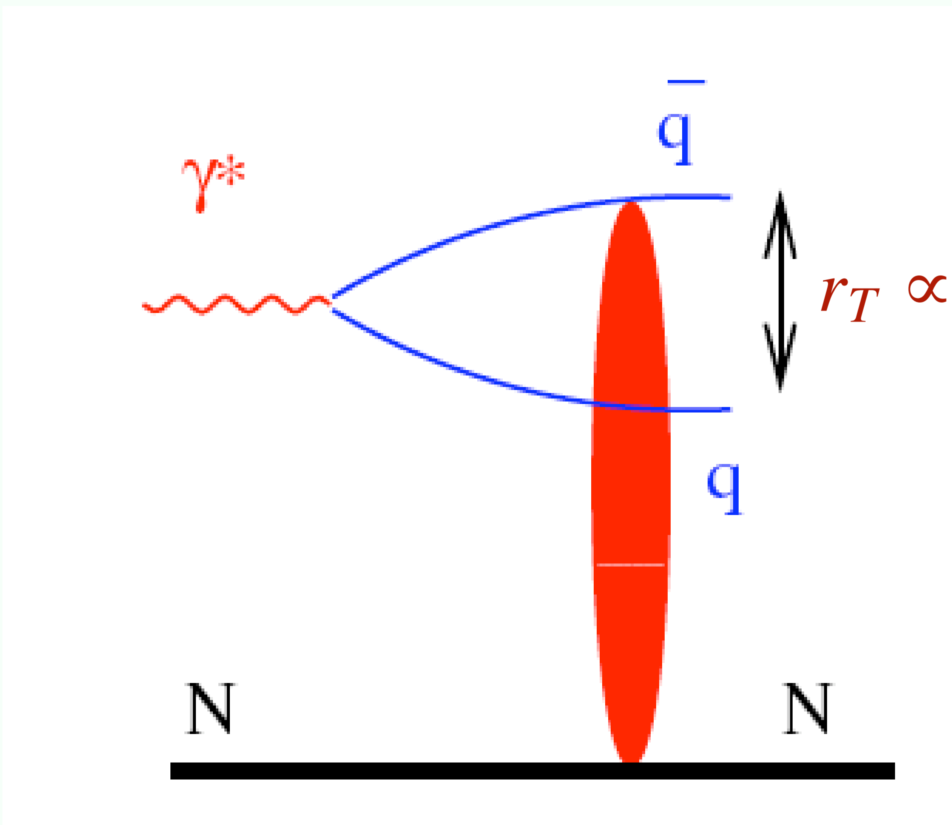
Extensive data on VM production from HERA support dominance of the pQCD dynamics. Numerical calculations including finite transverse size effects explain key elements of high Q^2 *data. The most important ones are:*

- Energy dependence of J/ψ production; absolute cross section of $J/\psi, \Upsilon$ production.

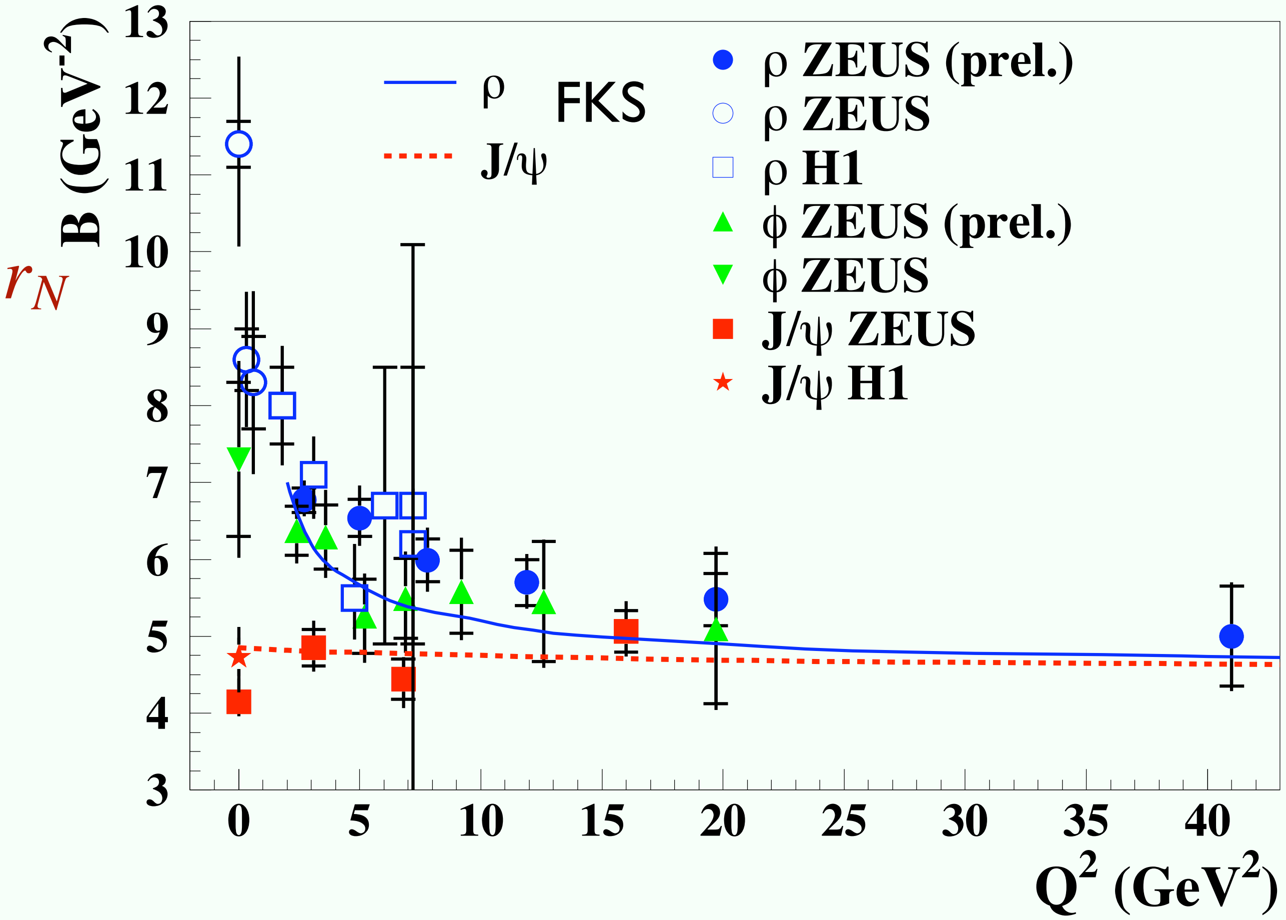
- Absolute cross section and energy dependence of ρ−meson production at $Q^2 \geq 20\ GeV^2$ Explanation of the data at lower Q^2 is more sensitive to the higher twist effects, and uncertainties of the low Q^2 gluon densities.

- Universal t-slope: process is dominated by the scattering of quark-antiquark pair in a small size configuration - t-dependence is predominantly due to the transverse spread of the gluons in the nucleon - two gluon nucleon form factor, $F_g(x,t)$. $d\sigma/dt \propto F_g^2(x,t)$.

  Onset of universal regime FKS[Frankfurt,Koepf, MS] 97.



$$r_T \propto \frac{1}{Q}\left(\frac{1}{m_c}\right) \ll r_N$$



Convergence of the t-slopes, B ($\frac{d\sigma}{dt} = A\exp(Bt)$,
of ρ-meson electroproduction to the slope of
J/ψ photo(electro)production.

⇒ Transverse distribution of gluons can be extracted from $\gamma + p \to J/\psi + N$

x-dependence of transverse distribution of gluons

$$F_g(x,t) = 1/(1-t/m_g(x)^2)^2, m_g^2(x=0.05) \sim 1GeV^2, m_g^2(x=0.001) \sim 0.6GeV^2.$$

For x=0.05 it is much harder than e.m. form factor (dynamical origin - chiral dynamics) $\Rightarrow$ more narrow transverse distribution of gluons than a naive expectation. (Frankfurt, MS , Weiss -02-03)

The gluon transverse distribution is given by the Fourier transform of the two gluon form factor as

$$F_g(x, \rho; Q^2) \equiv \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i(\Delta_\perp \rho)} F_g(x, t = -\Delta_\perp^2; Q^2)$$

It is normalized to unit integral over the transverse plane: $\int d^2\rho \, F_g(x, \rho; Q^2) = 1.$

$$F_g(x, \rho) = \frac{m_g^2}{2\pi} \left(\frac{m_g \rho}{2}\right) K_1(m_g \rho)$$

The Q^2 dependence is accounted using LO DGLAP evolution at fixed .

ρ

$\Rightarrow$ Possible to model elastic dipole - nucleon/nucleus amplitude for which one can formulate S-channel unitarity condition

Impact parameter distribution in "h"(dipole)p interaction

Study of the elastic scattering allows to determine how the strength of the interaction depends on the impact parameter, b:

$$\Gamma_h(s,b) = \frac{1}{2is}\frac{1}{(2\pi)^2}\int d^2\vec{q}e^{i\vec{q}\vec{b}}A_{hN}(s,t); \;\; ImA = s\sigma_{tot}\exp(Bt/2)$$

$$\sigma_{tot} = 2\int d^2b\,\mathrm{Re}\Gamma(s,b)$$

$$\sigma_{el} = \int d^2b|\Gamma(s,b)|^2$$

$$\sigma_{inel} = \int d^2b(1-(1-\mathrm{Re}\Gamma(s,b))^2 - [\mathrm{Im}\Gamma(s,b)]^2)$$

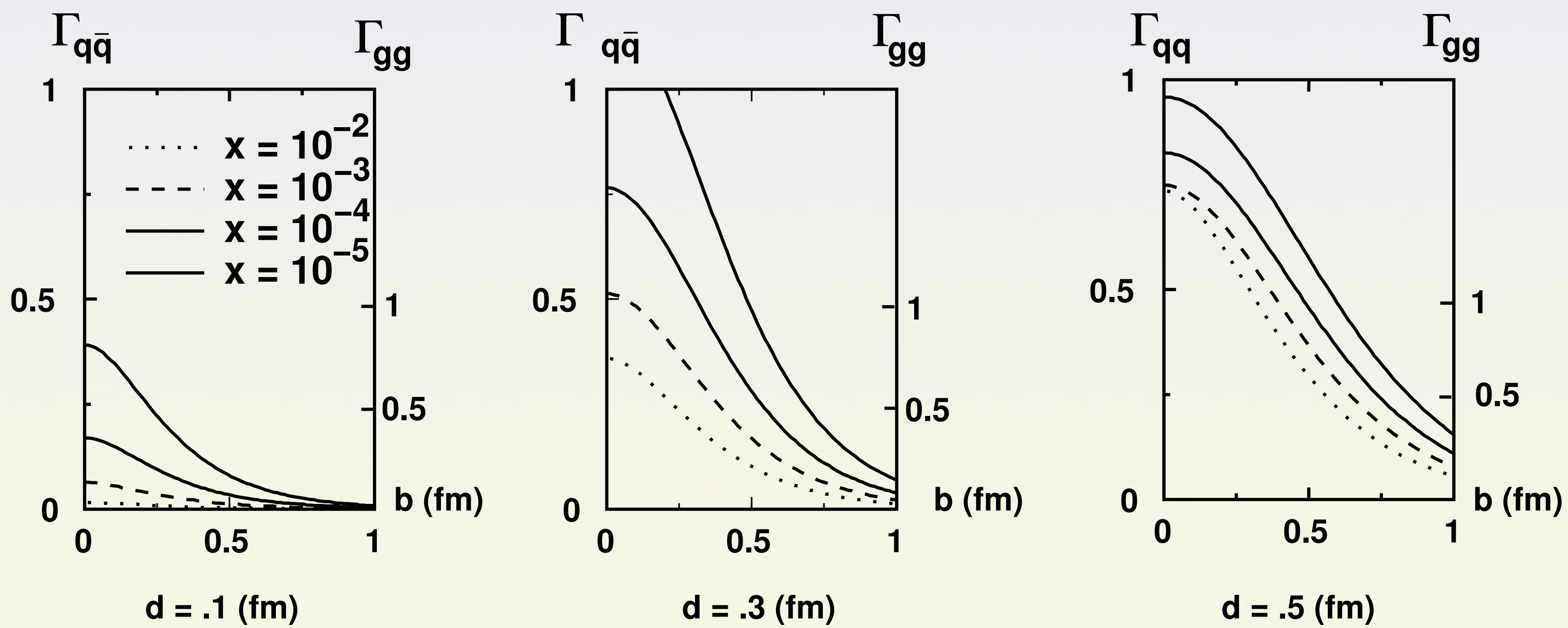
$$\Gamma(b) = 1 \;\equiv\; \sigma_{inel} = \sigma_{el}$$

- black disk limit(BDL)

Note that elastic unitarity: $\frac{1}{2}ImA = |A|^2 + \ldots$ allows $\Gamma(b) \leq 2$

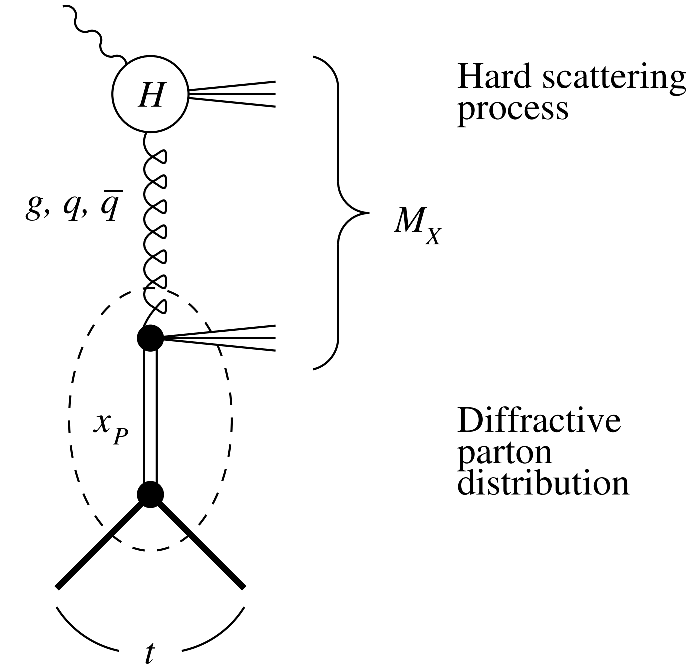
Using information on the t-dependence of the exclusive hard processes and cross section of dipole-nucleon scattering we can estimate $\Gamma_{\bar{q}q}(b)$

In the case gg-N scattering we assume pQCD relation $\Gamma_{gg} = \frac{9}{4}\Gamma_{q\bar{q}}$



This analysis indicates that gg-N interaction is close to the BDL for dipoles of size d> 0.3 fm, corresponding to Q<2 GeV

Can use hard diffraction to check proximity to BDL



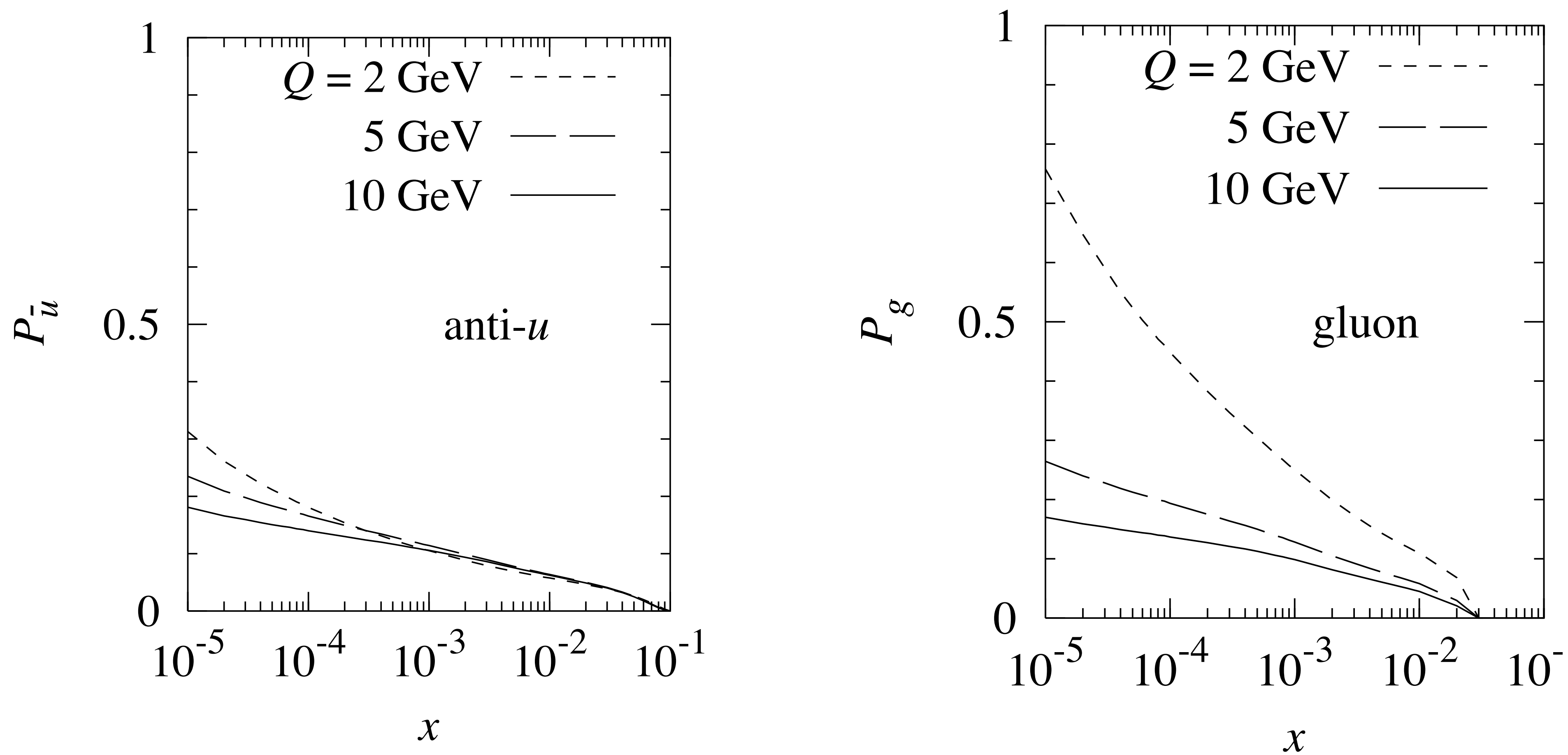
QCD factorization theorem for diffractive processes consistent with the data to define **universal** diffractive parton densities:

$$f_j^D\left(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t\right)$$

To test proximity to BBL it is useful to define and calculate the probability of diffractive scattering depending on the type of parton coupling to the hard probe

$$P_j(x,Q^2) = \int dt \int dx_{I\!P}\, f_j^D(x/x_{I\!P},Q^2,x_{I\!P},t) \Big/ f_j(x,Q^2)$$

If $P_j(x,Q^2)$ is close to 1/2 interaction of "j" parton approaches BBL



$$P_g(x \leq 3\cdot 10^{-4}, Q^2 = 4\,GeV^2) \geq 0.4 \;!!!$$

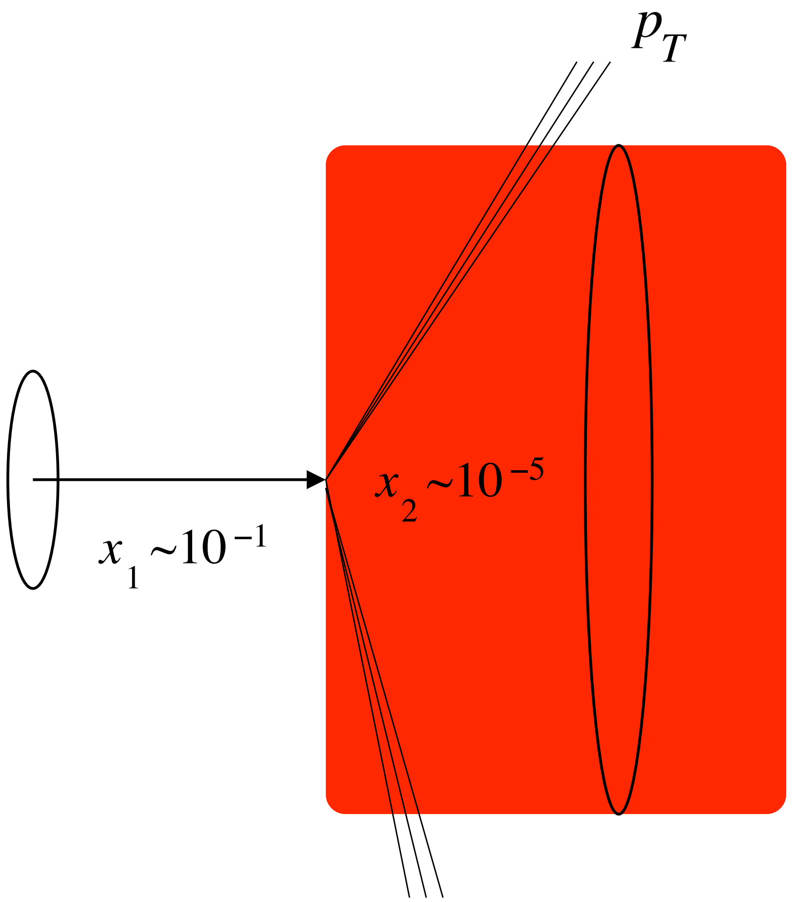
FS98

$\Rightarrow$ *Incident partons which have large enough energies to resolve $x \sim 10^{-4}$ -- 10^{-5} in the target nucleon and which pass at impact parameters < 0.5 fm, interact with the nucleon in a regime which is close to the black body limit.*

Implications for LHC - impact parameters for collisions with new particle production vs generic inelastic collisions

New hard dynamics for fragmentation in pA and AA collisions

First consider central pA collisions



Black body limit in central collisions: Leading partons in the proton, x_1, interact with a dense medium of small x_2– gluons in the nucleus (shaded area), acquiring a large transverse momentum, $p_\perp$.

What happens when a parton goes through strong gluon fields? It will be resolved to its constituents if interaction is strong. To estimate the transverse momenta of the resolved system use a second parton as a regularization - consider the propagation of a small dipole of transverse size d, which interacts in LO pQCD with cross section: $\sigma_{inel} = \frac{\pi^2}{3} F^2 d^2 \alpha_s(\lambda/d^2) x G_T(x.\lambda/d^2)$

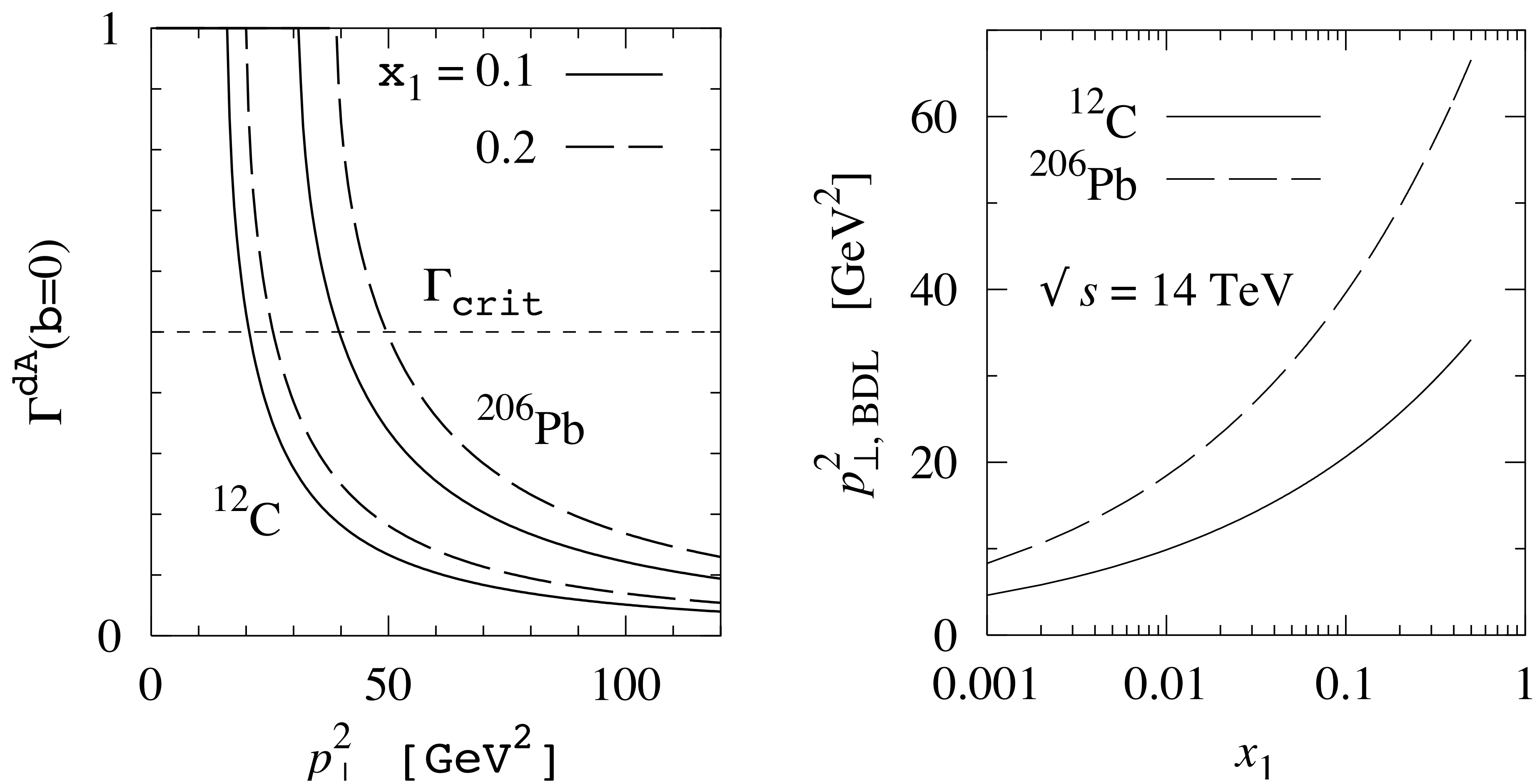
To estimate the maximum transverse momentum for interactions close to the BBL, we can treat the leading parton as one of the constituents of a small dipole scattering from the target. This "trick" allows us to apply the results of our study of the dipole –hadron scattering. In this analogy, the effective scale in the gluon distribution is $Q^2_{eff} \sim 4p^2_\perp$ corresponding to an effective dipole size of $d \approx 3/2p_\perp$

Criterion of proximity to BDL:

$$\Gamma^{"dipole"A}(b=0) \geq \Gamma_{crit} \sim 0.5$$

corresponding to probability of inelastic collision of

$$1 - |1-\Gamma|^2 \geq 0.75$$



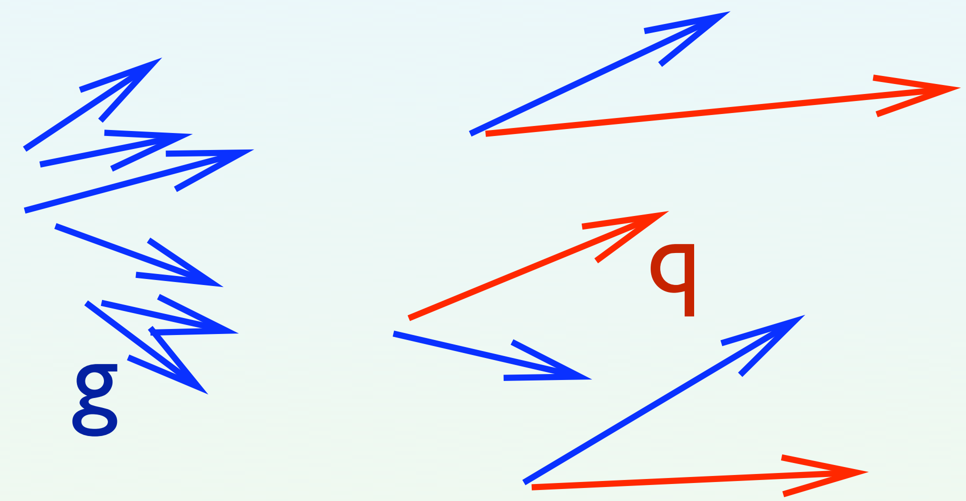
Black–disk limit in central collisions:

(a) The profile function for the scattering of a leading gluon in the proton (regarded as a constituent of a dipole) from the nucleus at zero impact parameter, , as a function of the transverse momentum squared,

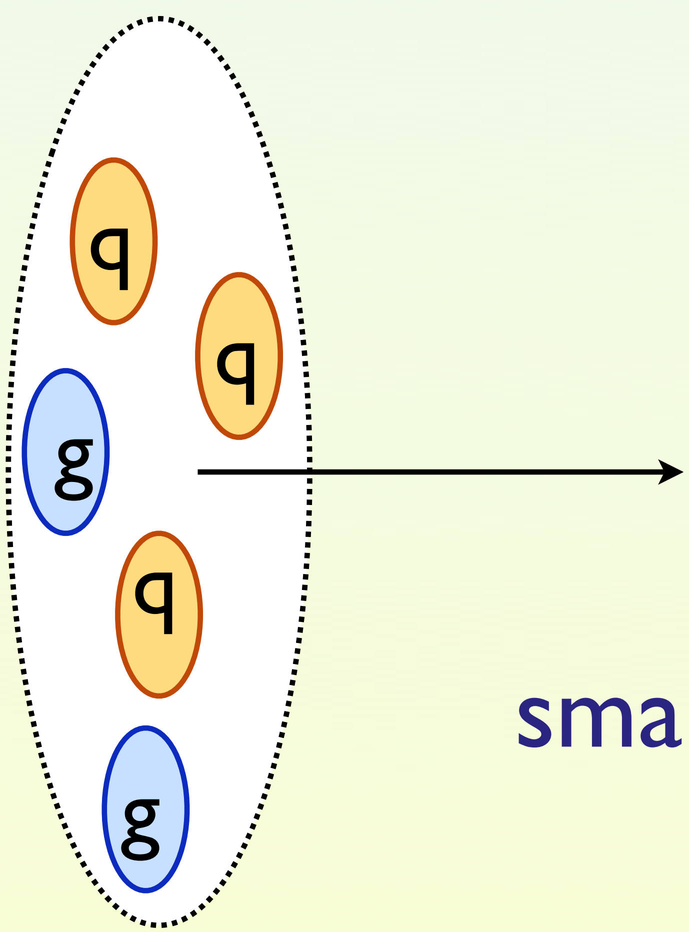
(b) The maximum transverse momentum squared, BDL, for which the interaction of the leading gluon is "black" (for quarks it is a factor of two smaller).

Characteristics of the final state in the central pA(pp) collisions

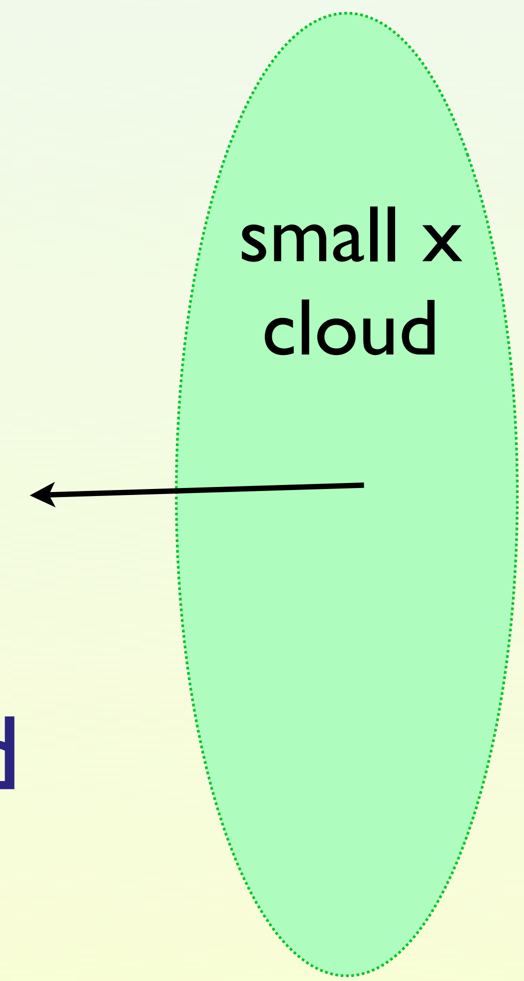
fast partons in a nucleon before collisions



fast partons in a nucleon after central collisions

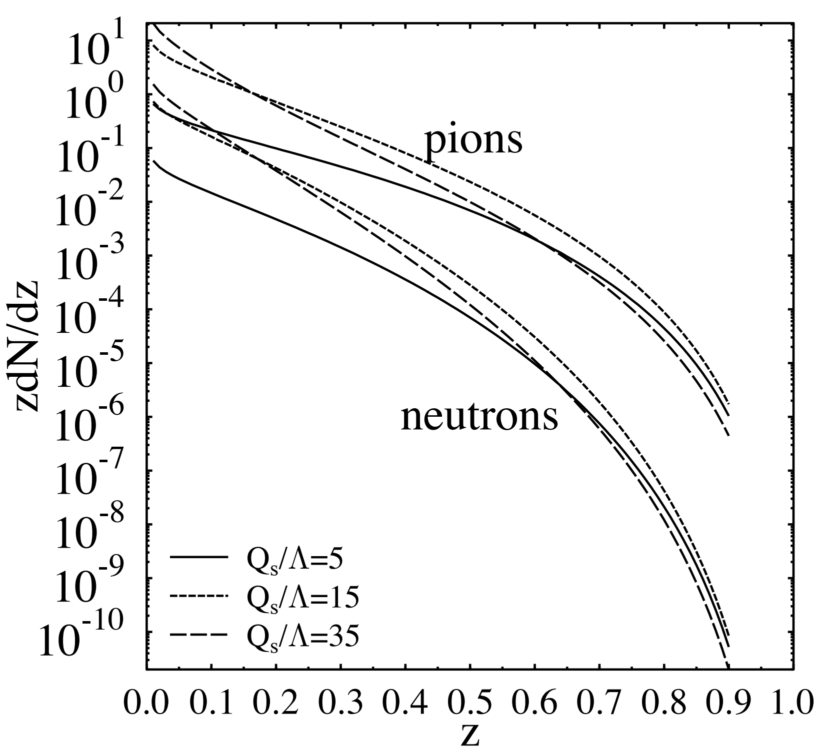


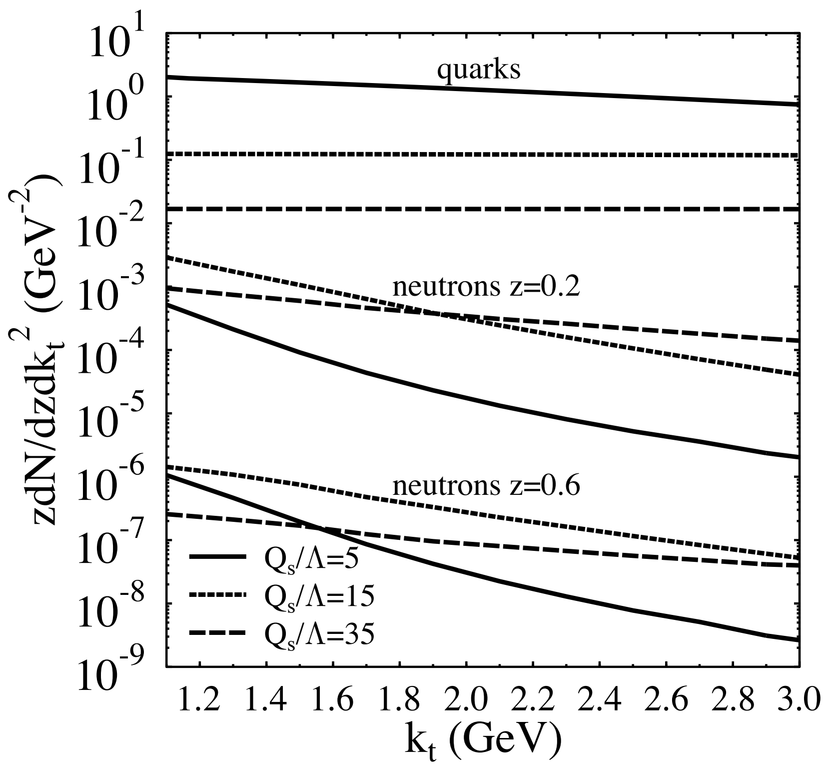
Large x partons burn small holes in the small x cloud



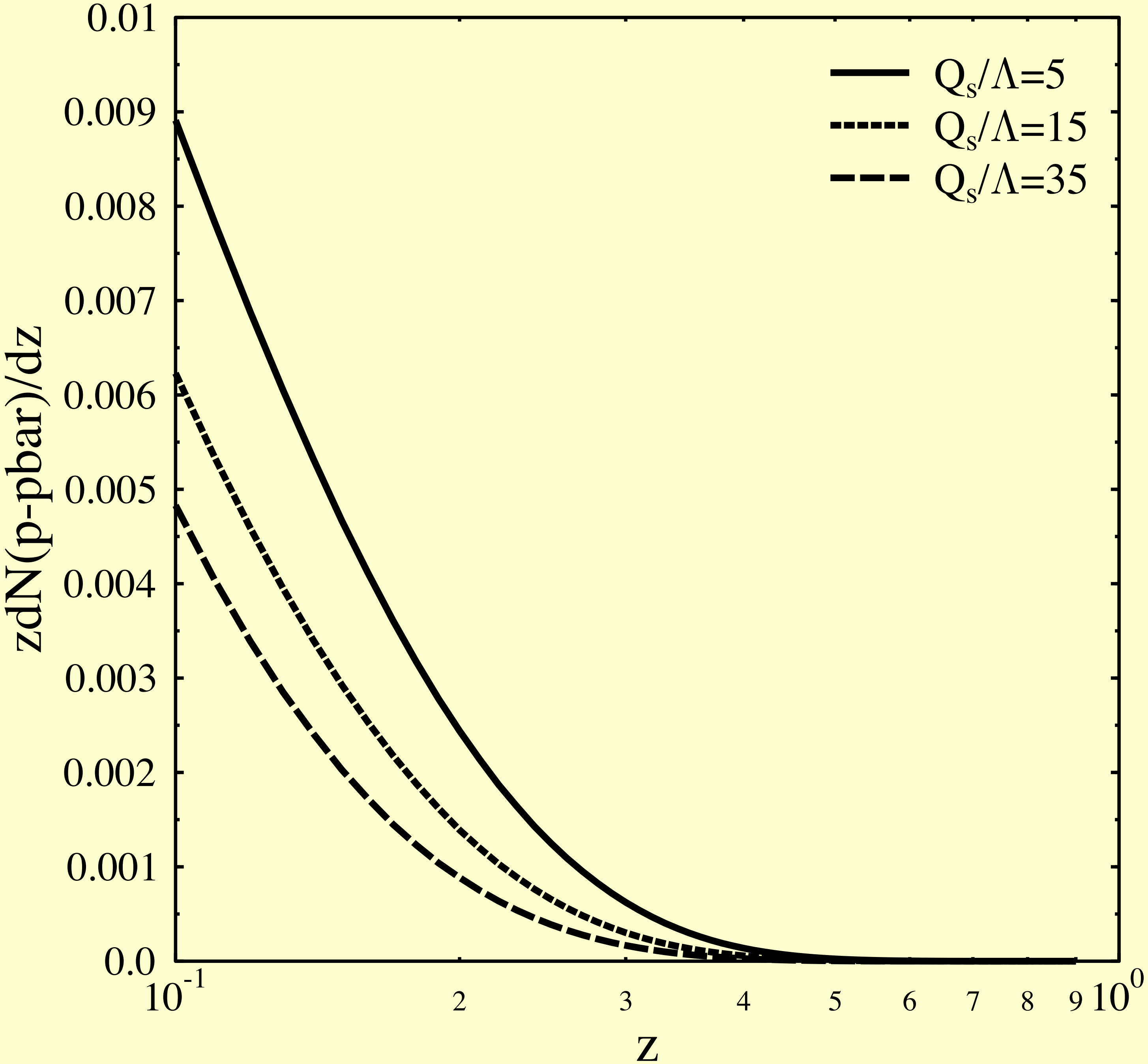
The leading particle spectrum will be strongly suppressed compared to minimal bias events since each parton fragments independently and splits into a couple of partons with comparable energies. The especially pronounced suppression for nucleons: for $z \geq 0.1$ the differential multiplicity of pions should exceed that of nucleons.

$$\frac{1}{N}\left(\frac{dN}{dz}\right)^{pA\to h+X} = \sum_{a=q,g}\int dx\, x f_a(x, Q^2_{eff}) D_{h/a}(z/x, Q^2_{eff})$$





Longitudinal (integrated over p_t) and transverse distributions in Color Glass Condensate model for central pA collisions. (Dumitru, Gerland, MS -PRL03). Spectra for central pp - the same trends.



Longitudinal distribution of net protons

Note for moderate Q_s coalecense becomes important for moderate z enhancing the proton yields

Cosmic rays of ultrahigh energies: $s \leq 10^{11}\ GeV^2 = 1000\ s_{LHC}$

Interpretation is very sensitive to the forward physics - number of leading particles,...

Important characteristics - "penetration depth", X_{max}, - measured by Hires stereo. Stronger energy losses of primary interacting particle, smaller X_{max}.

Drescher, Dumitru and MS (PRL 2004) modified cosmic ray code Sybill to include the discussed effects.

Two versions:

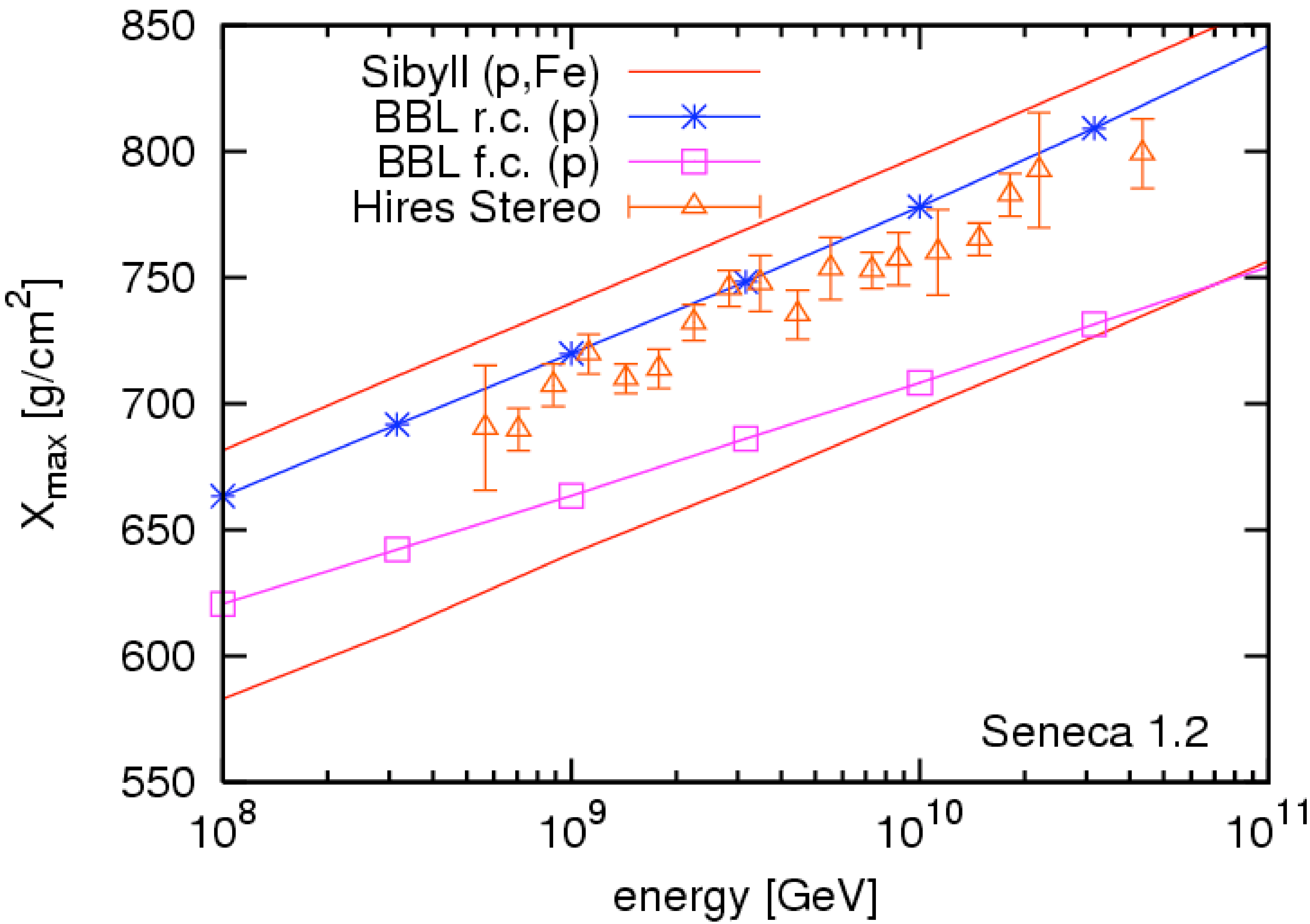
(a) power law increase of the gluon densities to the BBL. Contradicts to the data: too large reduction of X_{max}.

(b) Slower increase at very small x as suggested in Altarelli et al, Ciafaloni et al estimates. - Leads to modest reduction of X_{max} - agrees with the data.

Cosmic Ray Airshowers

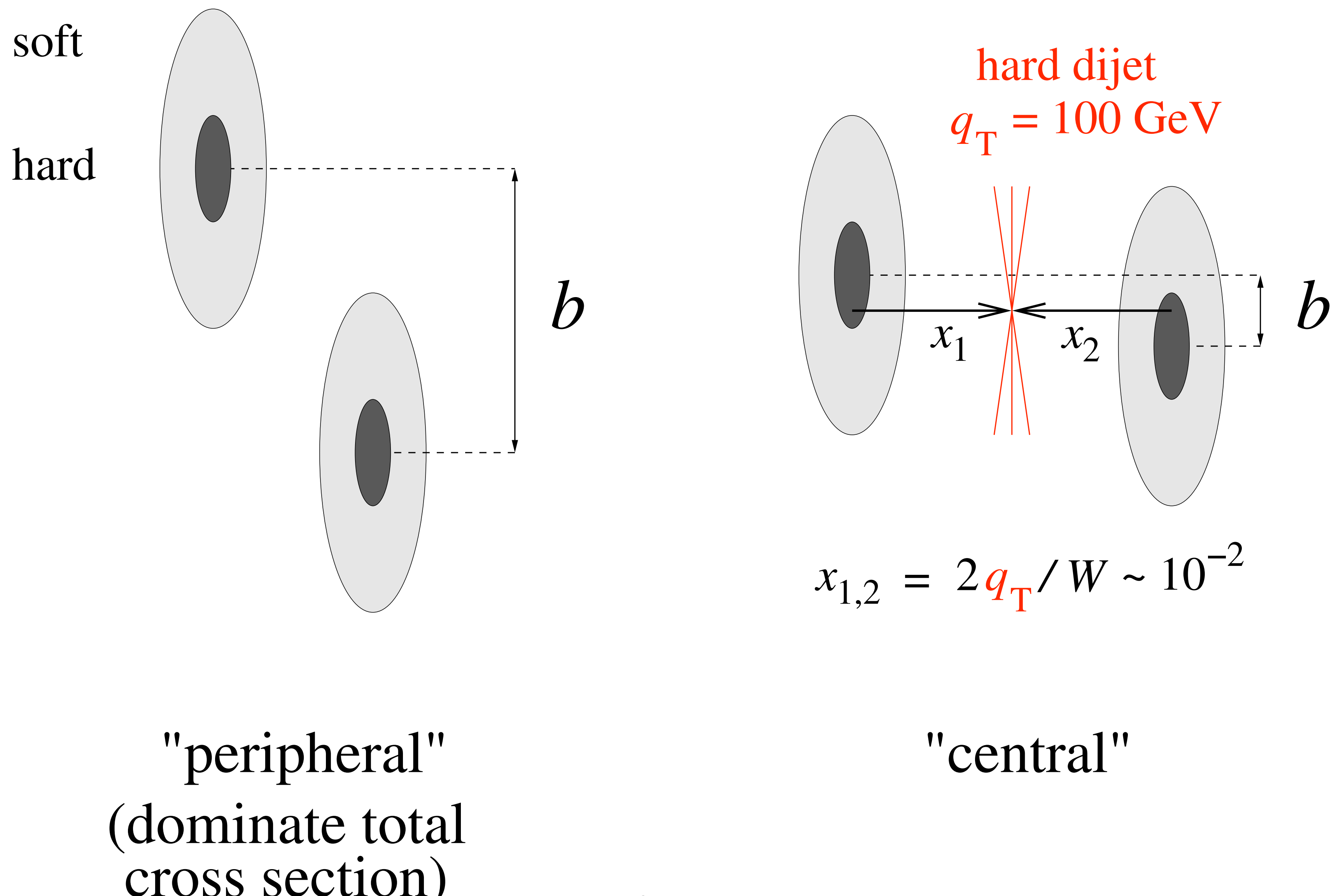
H.J. Drescher

“penetration depth”



Can one study the same effects in pp?

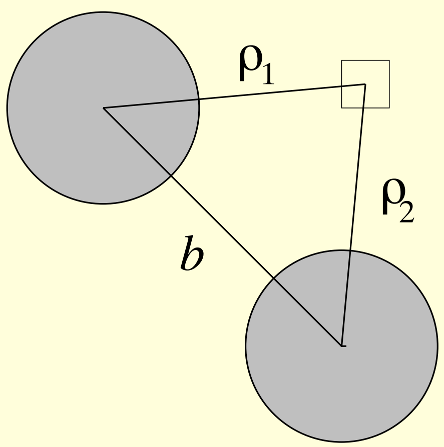
Main idea/Qualitative expectation: hard partons are more localized in transverse plane - ***gluon density in a nucleon at small impact parameters is comparable to that in nuclei at small b.*** Hence in events with hard interaction spectator partons experience much stronger gluon fields.



Impact parameter distribution for a hard multijet trigger.

For simplicity take $x_1 = x_2$ for colliding partons producing two jets with $x_1 x_2 = 4q_\perp^2/s$. Answer is not sensitive to a significant variation of x_i for fixed $q_\perp$.

The overlap integral of parton distributions in the transverse plane, defining the b–distribution for binary parton collisions producing a dijet follows from the figure:



Hence the distribution of the cross section for events with dijet trigger over the impact parameter b is given by

$$P_2(b) \equiv \int d^2\rho_1 \int d^2\rho_2\ \delta^{(2)}(\boldsymbol{b} - \boldsymbol{\rho}_1 + \boldsymbol{\rho}_2) F_g(x_1, \rho_1)\ F_g(x_1, \rho_2),$$

where $x_1 = 2q_\perp/\sqrt{s}$. Obviously $P_2(b)$ is automatically normalized to 1.

For a dipole parameterization:

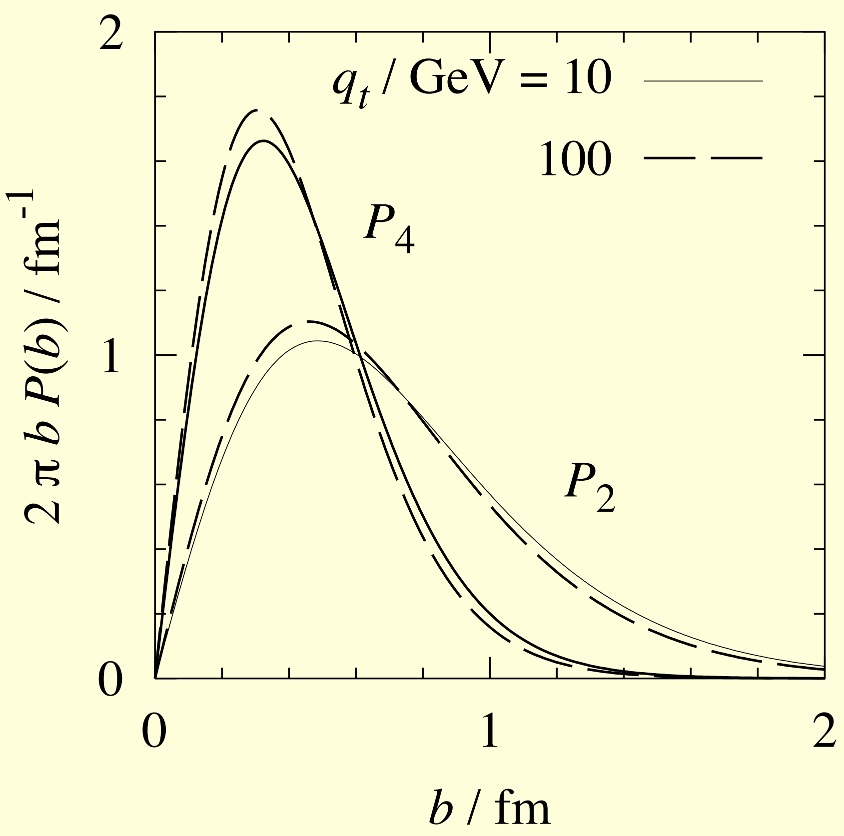
$$P_2(b) \ = \ \frac{m_g^2}{12\pi}\left(\frac{m_g b}{2}\right)^3 K_3(m_g b)$$

For two binary collisions producing four jets *assuming no correlation between gluons in the transverse plane*:

$$P_4(b) \ = \ \frac{P_2^2(b)}{\displaystyle\int d^2b\ P_2^2(b)}; P_4(b) \ = \ \frac{7\,m_g^2}{36\pi}\left(\frac{m_g b}{2}\right)^6 \left[K_3(m_g b)\right]^2.$$

More realistic estimate for 4 jet case using information from the analysis of the CDF data gives:

$$P_{4,corr}(b) \approx P_2(b)\ \frac{\sigma_{eff}(model) - \sigma_{eff}(CDF)}{\sigma_{eff}(model)} + P_4(b)\ \frac{\sigma_{eff}(CDF)}{\sigma_{eff}(model)}$$



The b–distribution for the trigger on hard dijet production, $P_2(b)$, obtained with the dipole form of the gluon b–profile, for $\sqrt{s} = 14000\, GeV$ and $q_\perp = 10\, GeV$ and $100\, GeV$. The plots show the "radial" distributions in the impact parameter plane, $2\pi b\, P_2(b)$. Also shown is the corresponding distribution for a trigger on double dijet production, $P_4(b)$, with the same $p_\perp$.

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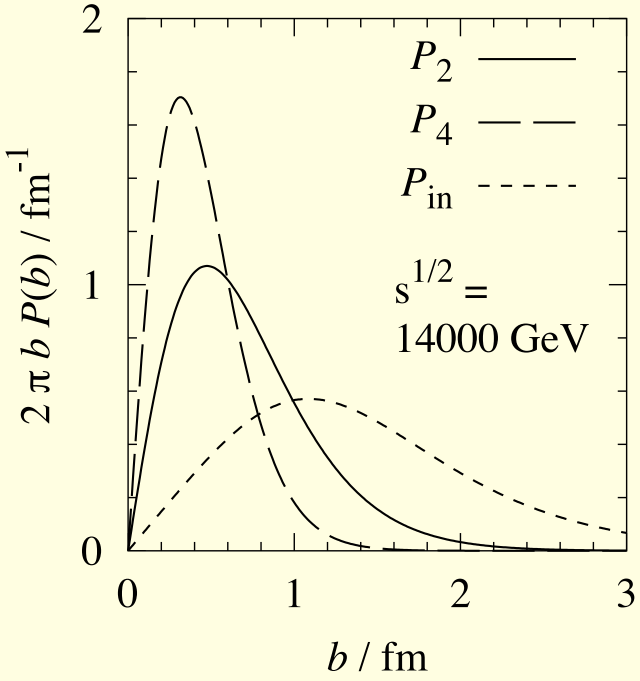
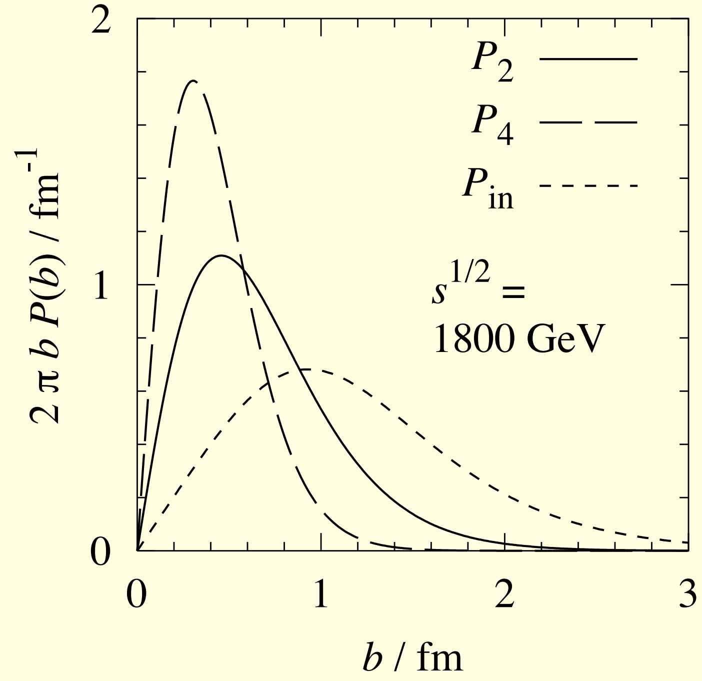
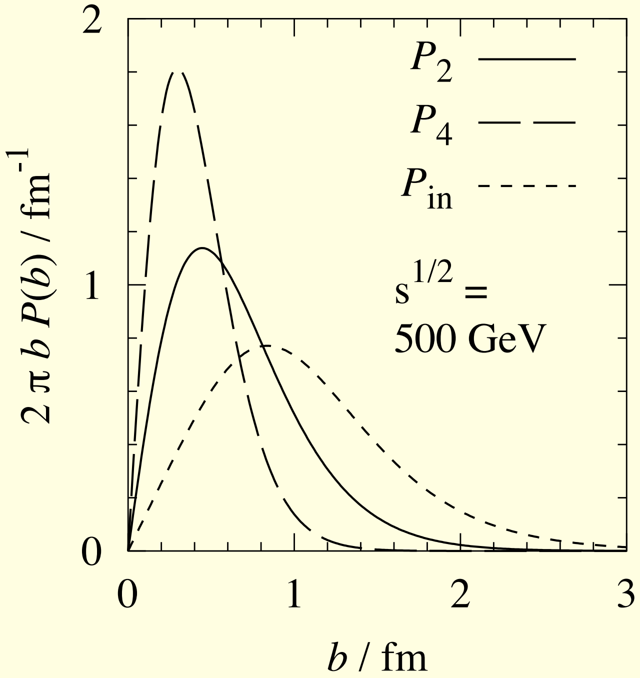






Difference between b-distributions for minimal bias and dijet, four jet events strongly increases with increase of incident energy. *Solid lines:* b–distributions for the dijet trigger, $P_2(b)$, with $q_\perp = 25\,GeV$, as obtained from the dipole–type gluon ρ–profile. *Long–dashed line:* b–distribution for double dijet events, $P_4(b)$. *Short–dashed line*: b–distribution for generic inelastic collisions.

Let us estimate what average transverse momenta are obtained by a parton in the collision at a fixed b and next take into account distribution over b .

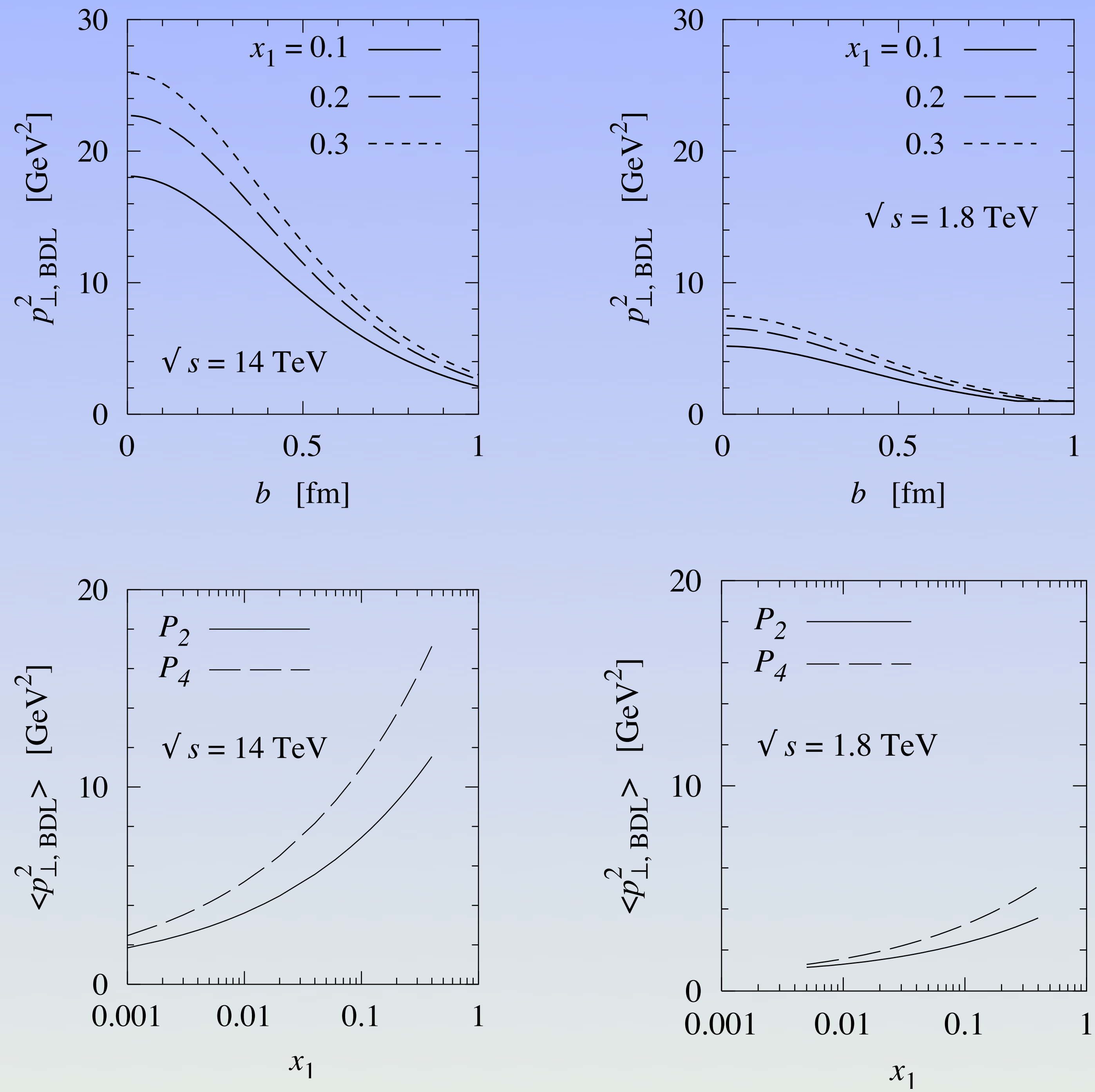
- Fixing fast parton's x (x_1) resolved by collision with partons in other proton

- Determining what minimal x are resolved in the second proton for given virtuality $x = \frac{4p_\perp^2}{x_1 s}, Q^2 = 4p_\perp^2$ $small\, x \leftrightarrow large\, x_1$

- for given ρ – distance of the parton from the center of another nucleon – determining maximum virtuality - minimal size of the dipole- d, for which Γ =0.5.

- converting from d to average $< p_\perp^2 >$

$p_\perp$ acquired by a spectator parton	$\approx$	Maximal $p_\perp$ for which interaction remains black for given x_1



Note: gluon densities at b~ 0 for pp and pPb are similar !!!

The critical transverse momentum squared, below which the interaction of a leading gluon with the other proton is close to the black body limit, as a function b (x_1)

For leading quarks, the values of $p^2_{\perp,\mathrm{BDL}}$ are about half of those for gluons.

Also, a spectator parton in the BDL regime loses a significant fraction of its energy *similar to electron energy loss in backscattering of laser off a fast electron beam. Very different from eikonal type picture (scattering off the classical field)*

Qualitative predictions for properties of the final states with dijet trigger

- The leading particle spectrum will be strongly suppressed compared to minimal bias events since each parton fragments independently and splits into a couple of partons with comparable energies. The especially pronounced suppression for nucleons: for $z \geq 0.1$ the differential multiplicity of pions should exceed that of nucleons.

- A large fraction of the dijet tagged events will have no particles with $z \geq 0.02 - 0.05$. This suppression will occur simultaneously in both fragmentation regions, corresponding to the emergence of long--range rapidity correlations between the fragmentation regions ⇒ **large energy release at rapidities y= 4 - 6.**

- Average transverse momenta of the leading particles $\geq 1\ GeV/c$

Many similarities with expectations for spectra of leading hadrons in central pA collisions.

Implications for the searches of new heavy particles at LHC.

- Background cannot be modeled based on study of minimal bias events.

- Events with production of heavy particles should contain a significant fraction of hadrons with transverse momenta $p_\perp \sim p_{\perp,BBL}$ originating from fragmentation of partons which passed through by the strong gluon field. Transverse momenta of these hadrons are unrelated to the transverse momenta of the jets. Strong increase of multiplicity at central rapidities: a factor ~2 increase observed at FNAL, much larger at LHC.

$\Longrightarrow$ Difficult to identify jets, isolated leptons,... unless $p_\perp\,(jet) \gg p_{\perp,BBL}$

$\Longrightarrow$ Significant corrections to the LT approximation results for total cross sections and small $p_\perp \leq p_{\perp,BBL}$ differential cross setions of new particle production.

Conclusions

- ★ *Small x physics is an unavoidable component of the new particle physics production at LHC. Significant effects already for Tevatron.*
- ★ *Forward physics for cosmic rays sensitive to small x physics - connection between pPb at LHC and GZK cosmic rays*
- ★ *Significant corrects for the LT predictions especially for moderate transverse momenta.*
- ★ *Many of the discussed effects are not implemented or implemented in a very crude way in the current MC for LHC and cosmic rays*
- ★ *Minijet activity in events with heavy particles should be much larger than in the minimum bias events or if it is modeled based on soft extrapolation from Tevatron.*