HERA impact for QCD dynamics at LHC and beyond

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For a detailed review see Frankfurt, MS, C.Weiss - Annual Review in Nuclear and Particle Sciences, 05

DESY, July 11

Goal for LHC - realistic account of the transverse structure of the nucleon and of the onset of Black Disk Limit on the global structure of the events with Higgs, SUSY,...

For inclusive cross section at high virtuality transverse structure does not matter - convolution of parton densities

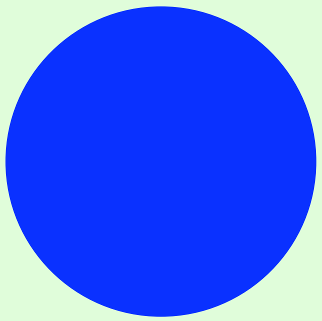
For multiple collisions - which have large probability at LHC - *rates scale as 1/(transverse area occupied by partons), depend on the shape of the transverse distribution and on the degree of the overlap*

Current MC's of pp collisions at LHC/ Tevatron do not include constrains on the transverse structure of the nucleon originating from HERA studies.

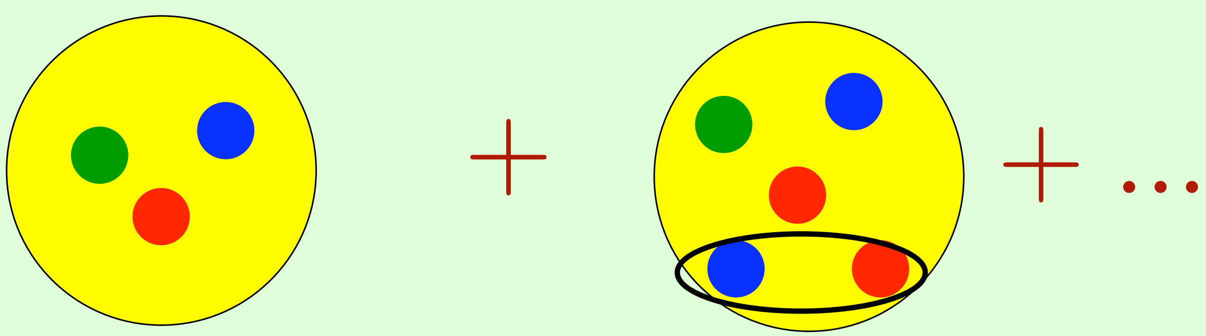
Outline

- Imaging a fast nucleon.
- Onset of black regime of interaction for small dipoles
- Centrality trigger for pp collisions.
- Forward hadron production - LHC & cosmic rays

Image of nucleon at different resolutions, q. Rest frame.



resolution 1 fm, $q < 300$ MeV/c

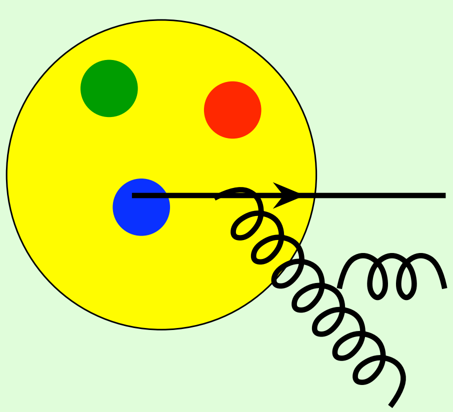


$q\bar{q}$ *pair in* π

resolution 1/3 fm

$1000 > q > 300$ MeV/c

Constituent quarks, pions (picture inspired by chiral QCD)



$q > 1000$ MeV/c

pQCD evolution

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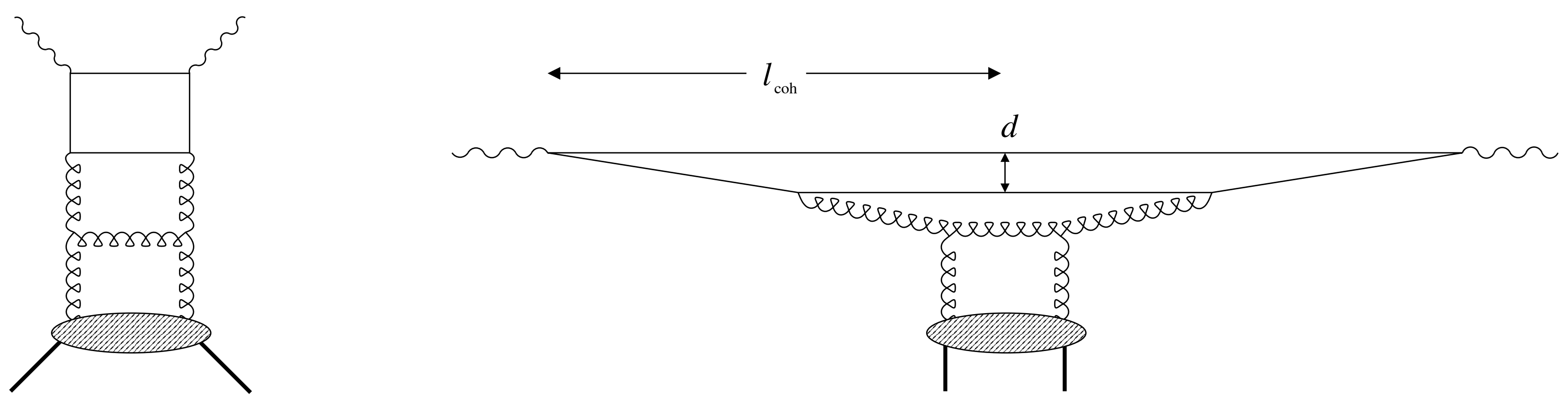
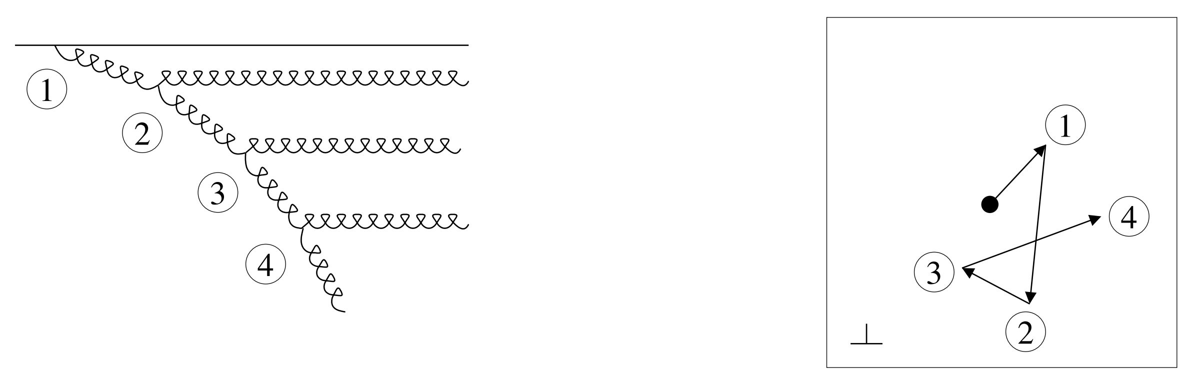
Image of nucleon at different resolutions, q. Fast frame.

Energy dependence of the transverse size of small x partons.



(a) (b)



(c) longitudinal momentum transverse coordinate

$$R^2(n) \approx \frac{n}{k_{t0}^2}$$

Random walk in b-space (Gribov 70). *(Drunken sailor walk)*

Length of the walk $\propto$ apidity, y as each step a change in rapidity of few units

$$n \propto y \implies R^2 = R_0^2 + cy \equiv R_0^2 + c' \ln s$$

Implications:

(a) The transverse size of the soft wee parton cloud should logarithmically grow wit energy.

Logarithmic increase of the t-slope of the elastic hadron-hadron scattering amplitude with energy:

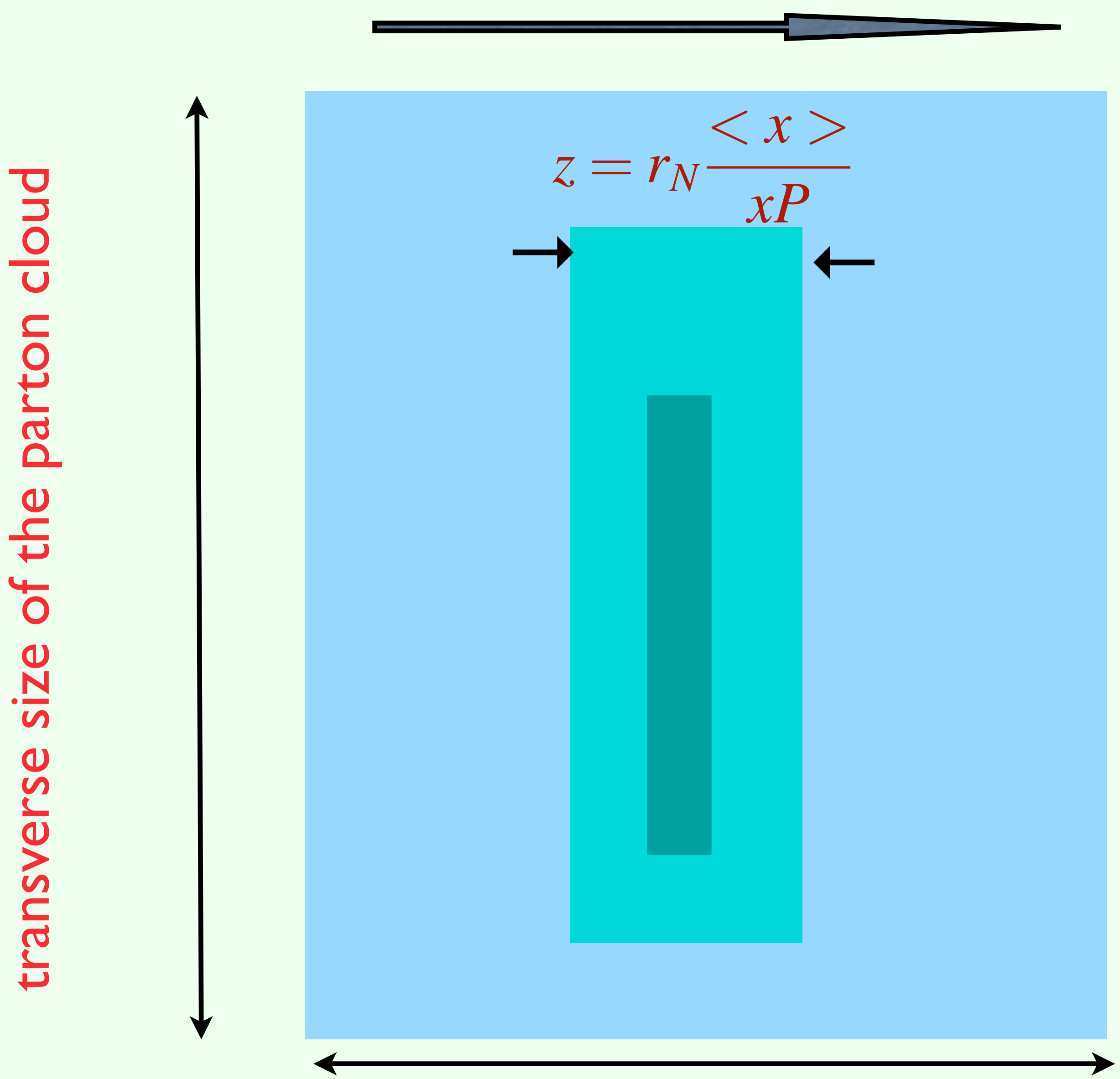
$$f(t) \propto \exp(Bt/2), \;\; B(s) = B_0 + 2\alpha' \ln(s/s_0)$$

$$\alpha' \propto 1/k_{t0}^2$$

z-x cut of the fast nucleon

the rate of increase of transverse size with x decreases with increase of the resolution scale

Momentum P in z direction



Transverse size of x>0.1 quarks and gluons is smaller than the average proton size predominantly due to the pion cloud effects - Frankfurt, MS, Weiss - will discuss later

wee parton are spread over 1 fm even at high energies

long.momentum/transverse Image at High resolution

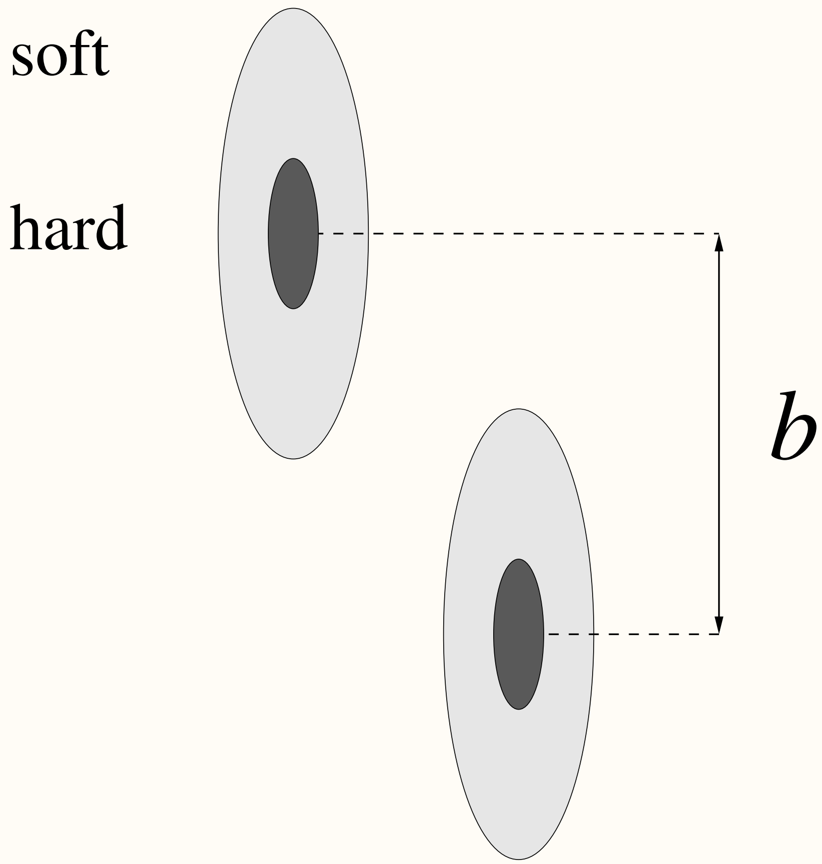
Gribov diffusion is much weaker as the transverse momenta in most of the decay ladder are much larger than the soft scale. Transverse size shrinks with increase of resolution scale!!! *No analogous effect in classical mechanics (brain images).*

Evidence: α' for the process $\gamma + p \rightarrow J/\psi + p$ is smaller than for soft processes by a factor of two.

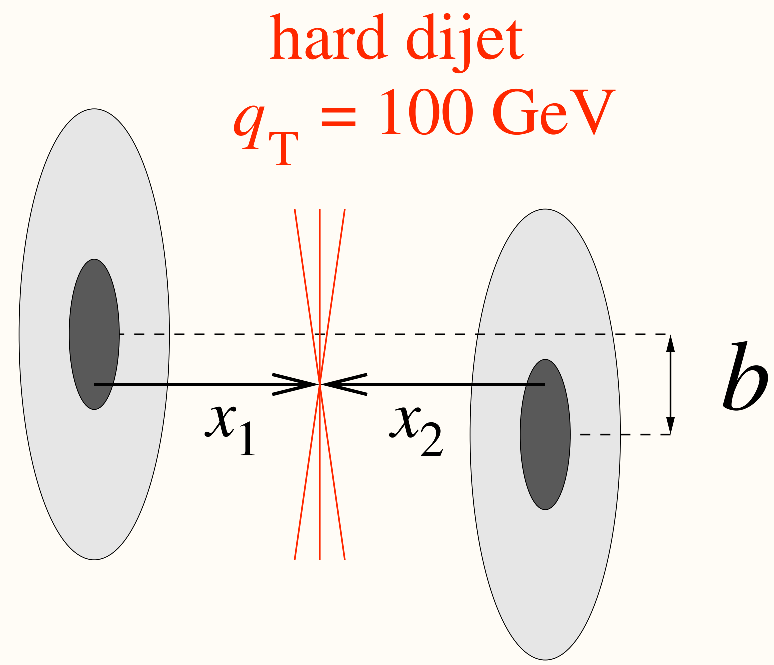
Confirms our prediction of 94 - BFGMS

Additional important effect: transverse distribution of $x \geq .05$ gluons in the nucleon is significantly smaller than a naive guess based on the e.m. radius of the nucleus.

Implication - hard processes correspond to collisions where nucleons overlap stronger & more partons hit each other - use hard collision trigger to study central collisions/ all new physics LHC craves to discover corresponds to central pp collisions.



"peripheral"
(dominate total cross section)



$$x_{1,2} = 2q_T/W \sim 10^{-2}$$

"central"

In proton-ion, ion-ion collisions collisions at small impact parameters are ***strongly different*** from the minimal bias events. Is this true also for pp collisions?

Why this is interesting/ important?

- Amplification of the small x effects: in proton - proton collisions a parton with given x_1 resolves partons in another nucleon with $x_2 = 4p_\perp^2/x_1 s$

At LHC $x_1 = 0.01, p_\perp = 2GeV/c \Rightarrow x_2 \sim 10^{-5}$

- Resulting strong difference between the semi-soft component of hadronic final states at LHC &Tevatron in events with production of Z, W, Higgs, SUSY,... and in minimal bias events.

$\Rightarrow$ ***Necessary to account for new QCD phenomena related to a rapid growth of the gluon fields at small x:*** **parton "1" propagates through the strong gluon field of nucleon "2".**

Hence, accumulation of higher twist effects and possible divergence of the perturbative series.

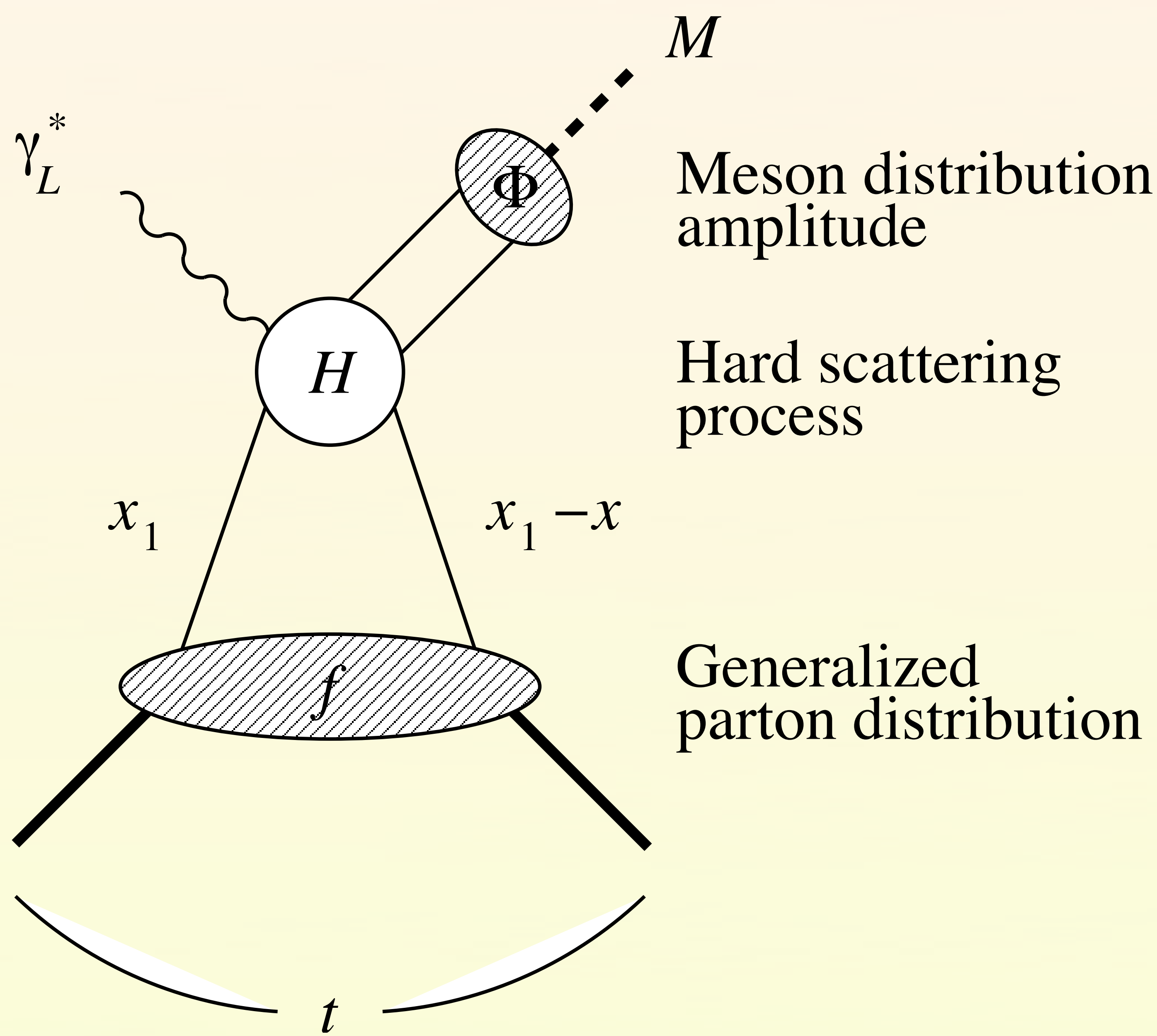
To quantify the difference of the impact parameters and the role of small x gluon field we can use theoretical analyses of the hard phenomena studied at HERA:

- Determination of the transverse distribution of gluons.

- Strength of of “small dipole”-nucleon interactions at high energies

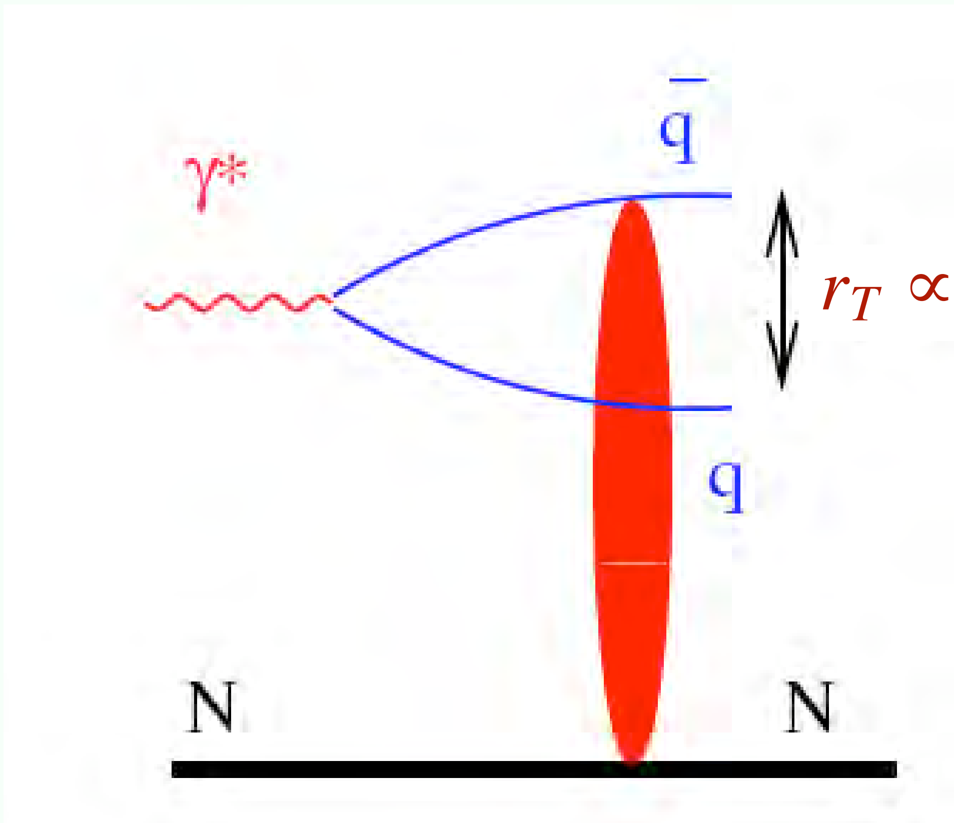
QCD factorization theorem for DIS exclusive processes

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

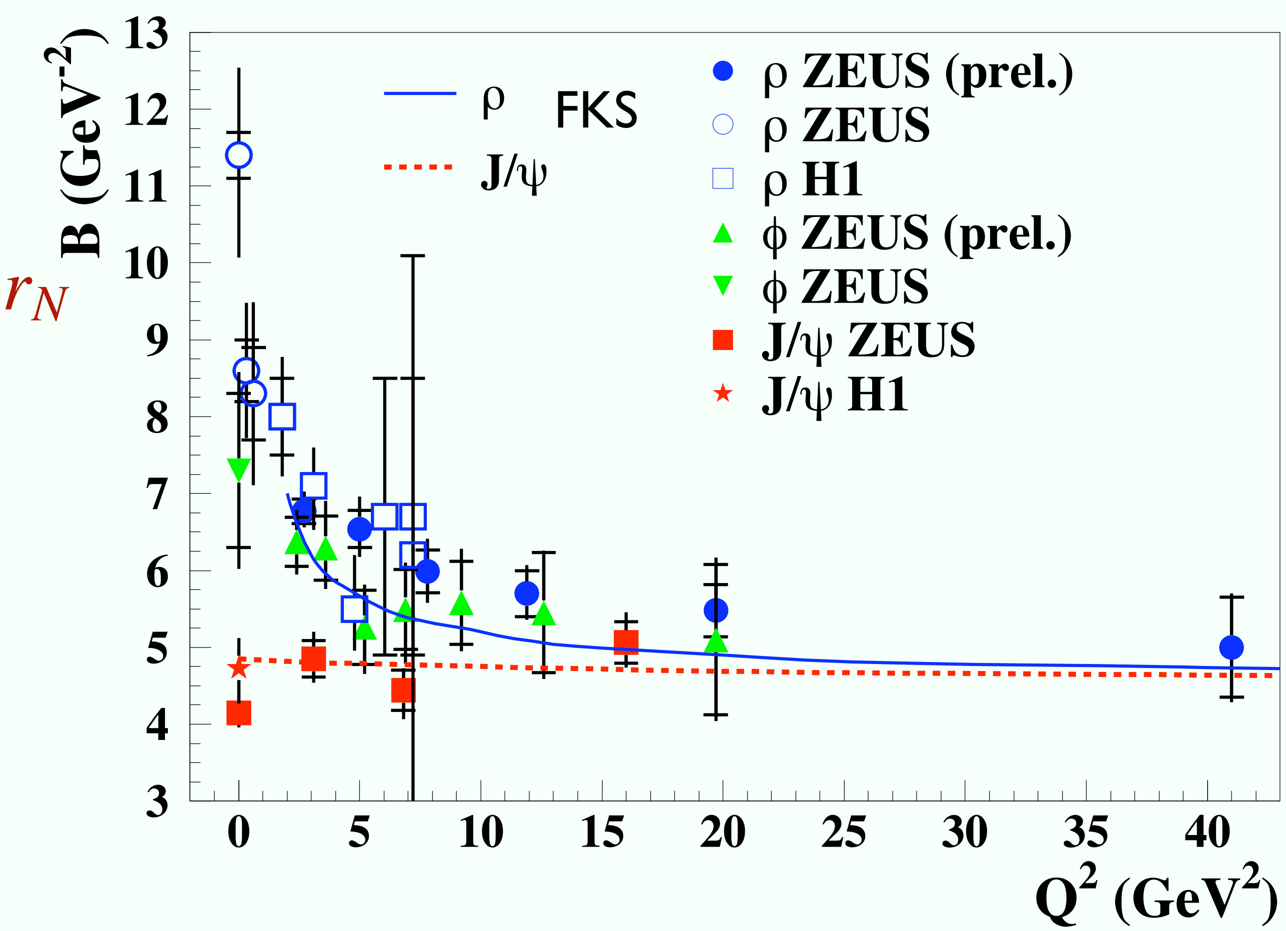


- Universal t-slope: process is dominated by the scattering of quark-antiquark pair in a small size configuration - t-dependence is predominantly due to the transverse spread of the gluons in the nucleon - two gluon nucleon form factor, $F_g(x,t)$. $d\sigma/dt \propto F_g^2(x,t)$.

  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 $\gamma + p \to J/\psi + N$

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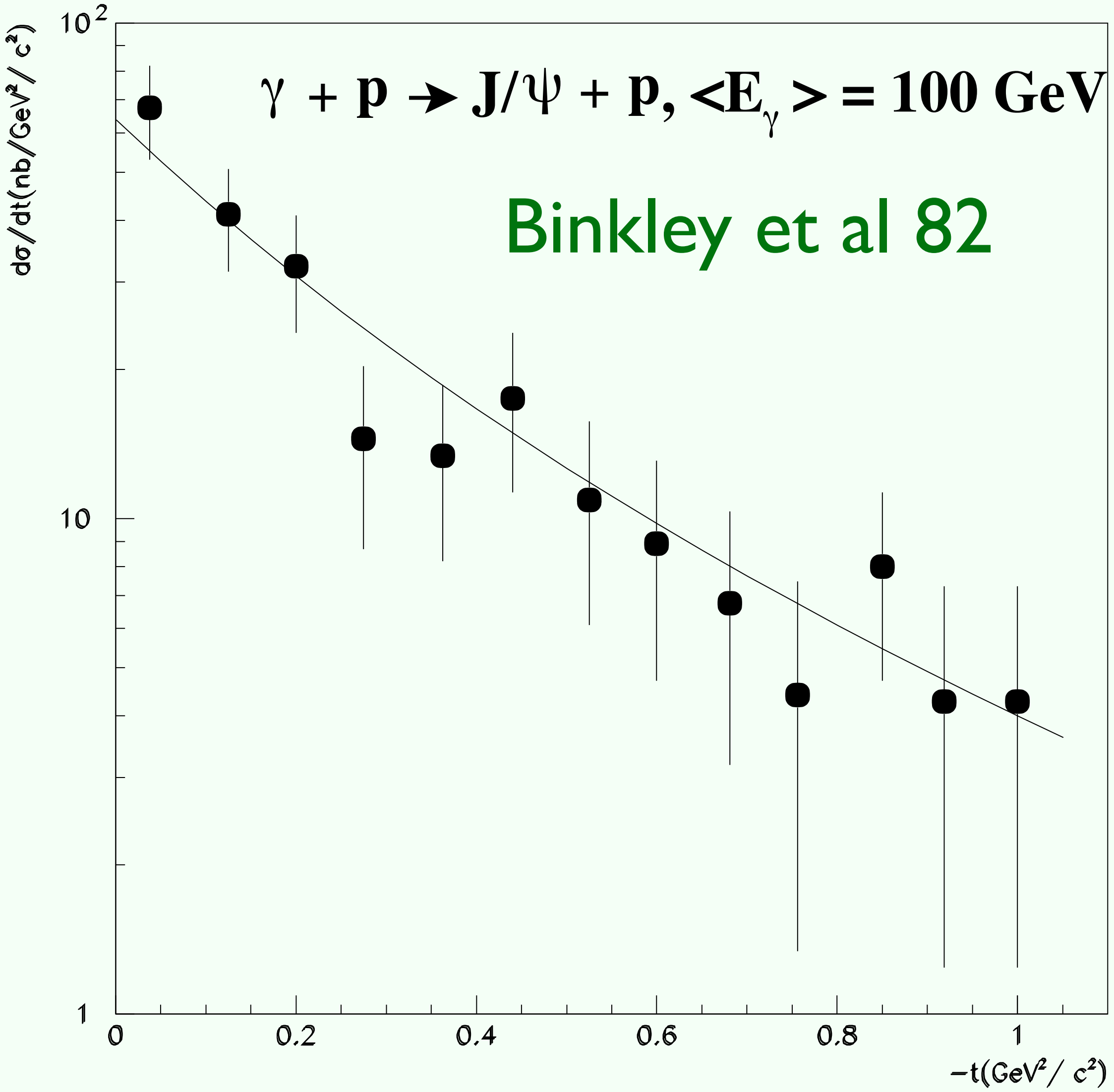


Theoretical analysis of J/ψ photoproduction at $100\ GeV \geq E_\gamma \geq 10\ GeV$ corresponds to the two-gluon form factor of the nucleon for $0.03 \leq x \leq 0.2,\ Q_0^2 \sim\ 3\ GeV^2, -t \leq 2\ GeV^2$

$$F_g(x, Q^2, t) = (1 - t/m_g^2)^{-2}.\ m_g^2 = 1.1\ GeV^2$$

which is larger than e.m. dipole mass

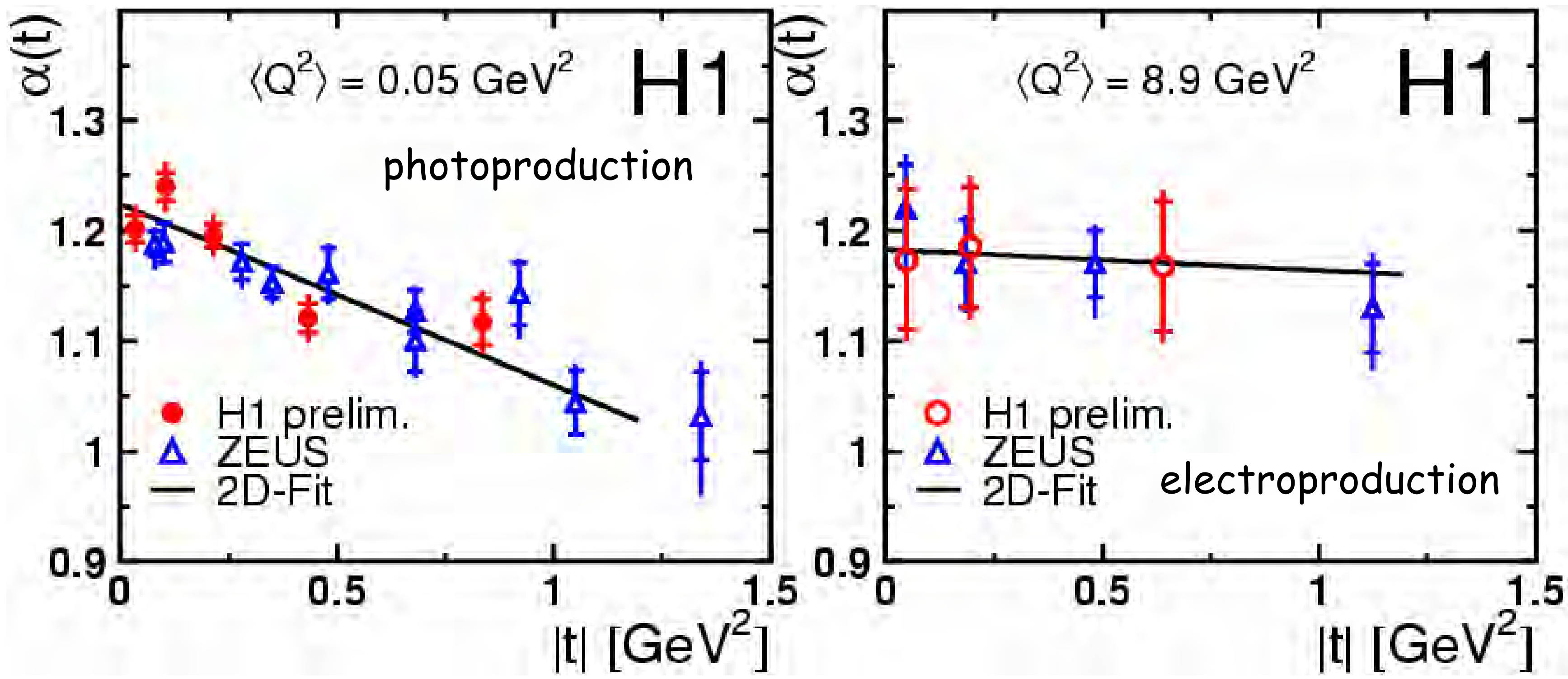
$$m_{e.m.}^2 = 0.7\ GeV^2.$$ (FS02)

The difference is likely due to the chiral dynamics - lack of scattering off the pion field at x>0.05 (Weiss &MS 03)

☝ ☝ ☝ Large difference between impact parameters of soft interactions and hard interactions especially for $x_{parton} > 0.01$.

Effective Pomeron Trajectory

2 dim. fit: $\alpha(t) = \alpha_0 + \alpha' t$



$$\frac{d\sigma}{dt} = f(t)\left(\frac{s}{s_0}\right)^{2\alpha(t)-1}$$

photoproduction:

$$\alpha(t) = (1.224 \pm 0.010 \pm 0.012) + (0.164 \pm 0.028 \pm 0.030)\ \text{GeV}^{-2}\ t$$

electroproduction:

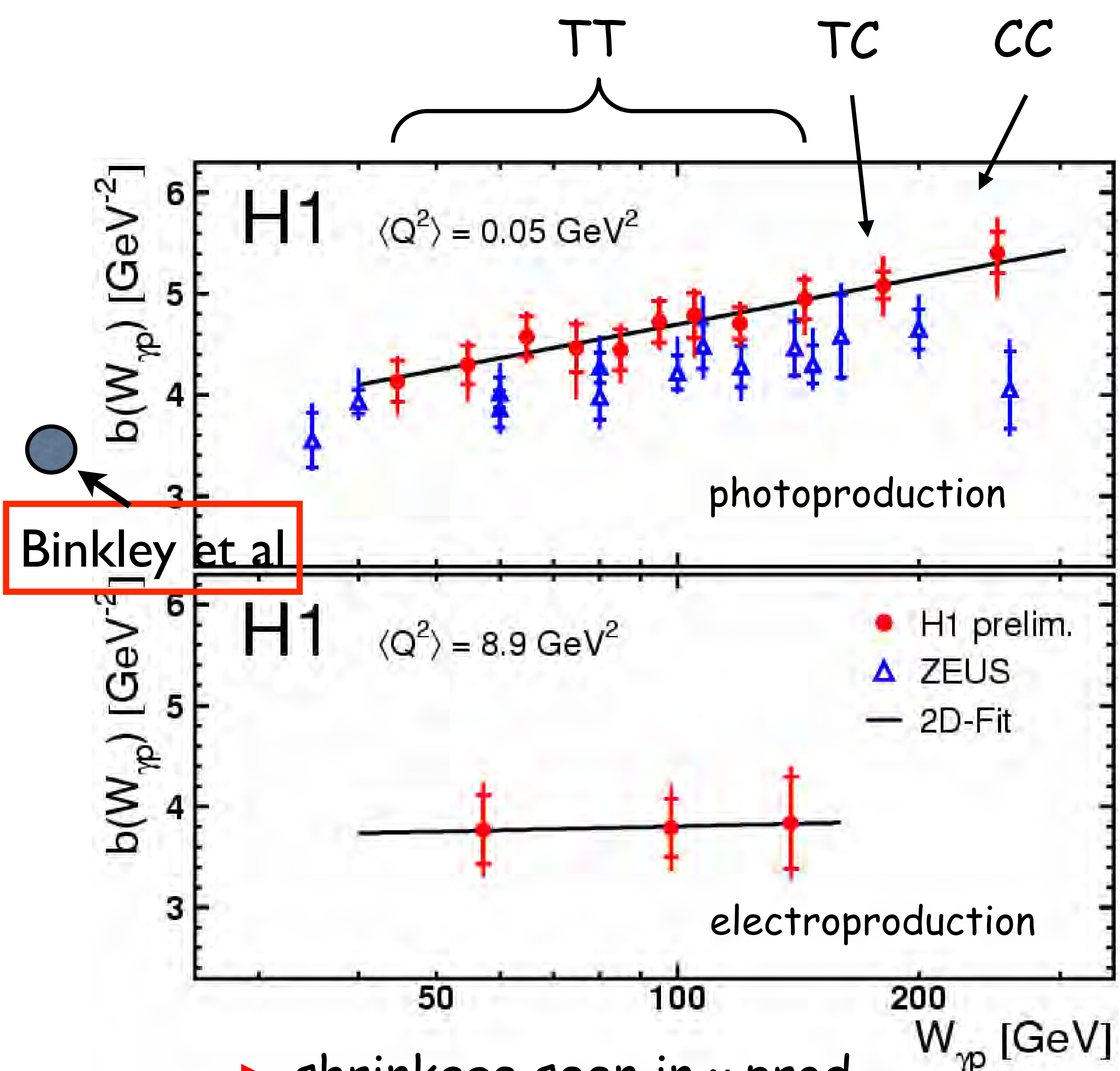
$$\alpha(t) = (1.183 \pm 0.054 \pm 0.030) + (0.019 \pm 0.139 \pm 0.076)\ \text{GeV}^{-2}\ t$$

→ trajectories similar within errors

$$\alpha_{I\!P} = (1.200 \pm 0.009) + (0.115 \pm 0.018)t$$ ZEUS photoproduction

$$\alpha_{I\!P} = (1.20 \pm 0.03) + (0.07 \pm 0.05)t$$ ZEUS electroproduction

Shrinkage of the Forward Peak



→ shrinkage seen in γ prod.

data point from 1D fits to $e^{-b|t|}$

line from a 2D Fit (W and t) :

$$b(W) = b_0 + 4\alpha' \ln \frac{W}{W_0}$$

photoproduction

$$b_0 = 4.630 \pm 0.060 \begin{array}{l} +0.043 \\ -0.163 \end{array}$$

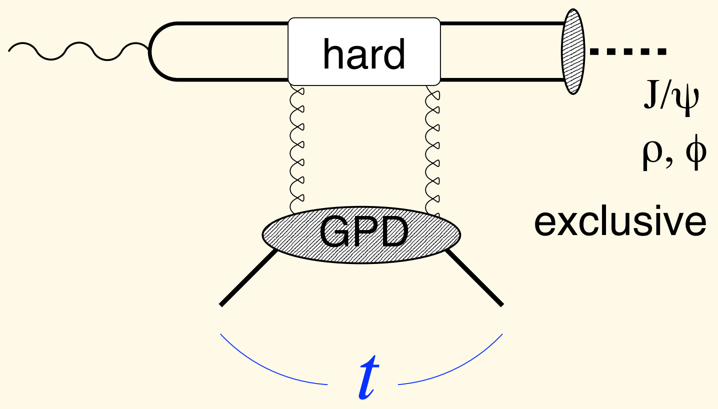
$$\alpha' = (0.164 \pm 0.028 \pm 0.030)\ \text{GeV}^{-2}$$

electroproduction

$$b_0 = 3.86 \pm 0.13 \pm 0.31$$

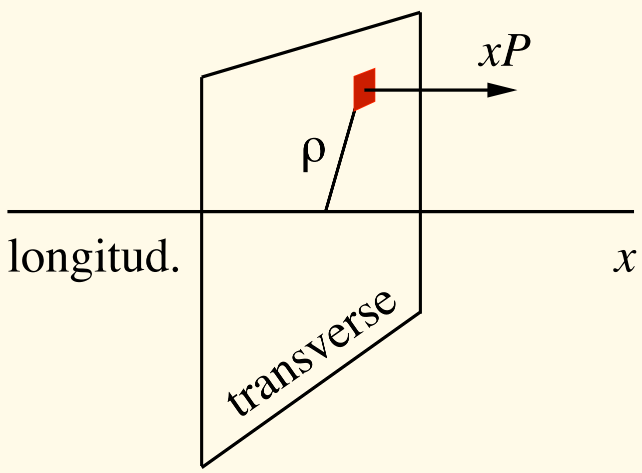
$$\alpha' = (0.019 \pm 0.139 \pm 0.076)\ \text{GeV}^{-2}$$

- Transverse spatial distribution of gluons



$$G(x, Q^2_{\text{eff}}; t) \;=\; G(x, Q^2_{\text{eff}}) \;\times\; F_g(x, Q^2_{\text{eff}}; t)$$

generalized gluon dist'n — two–gluon formfactor



$$F_g(x, t) \;=\; \int d^2\rho \, e^{-i\vec{\Delta}_\perp \cdot \vec{\rho}} \; F_g(x, \boldsymbol{\rho})$$

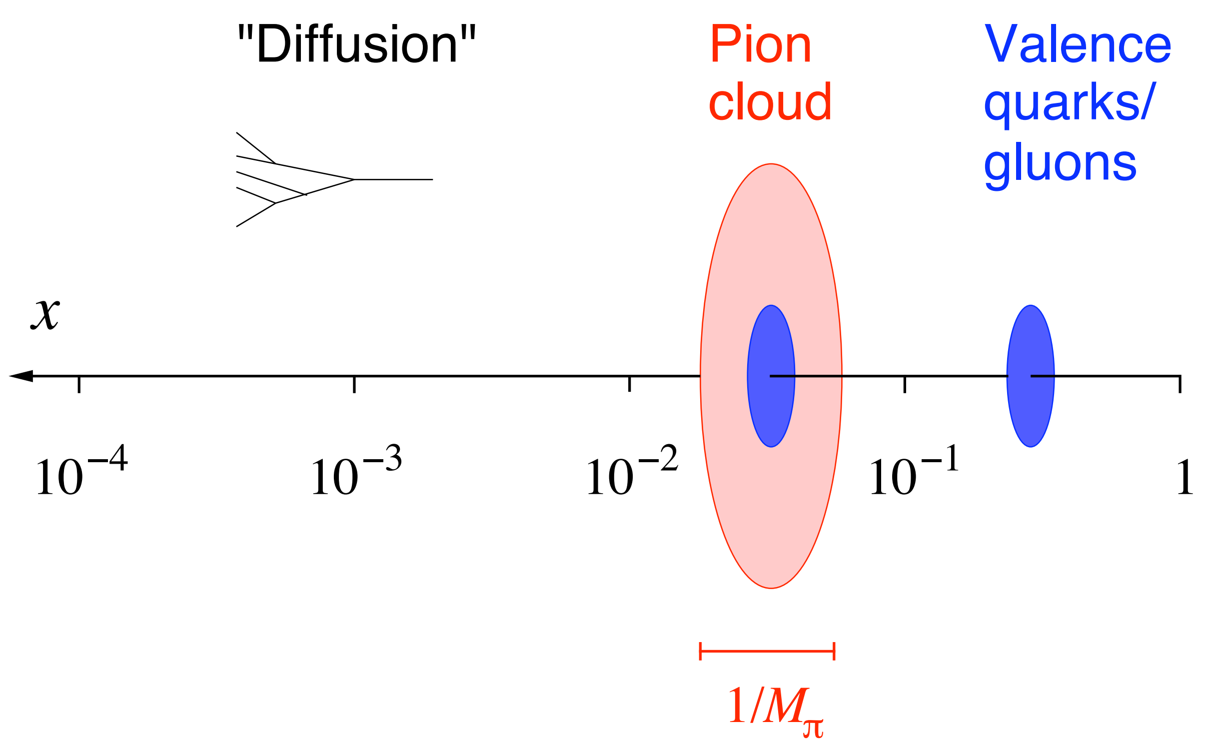
transverse spatial distribution of gluons

$$\langle \rho^2 \rangle_g \;=\; 4 \, \frac{\partial}{\partial t} \, F_g(x, t)$$

gluonic transverse size of nucleon, x–dependent!

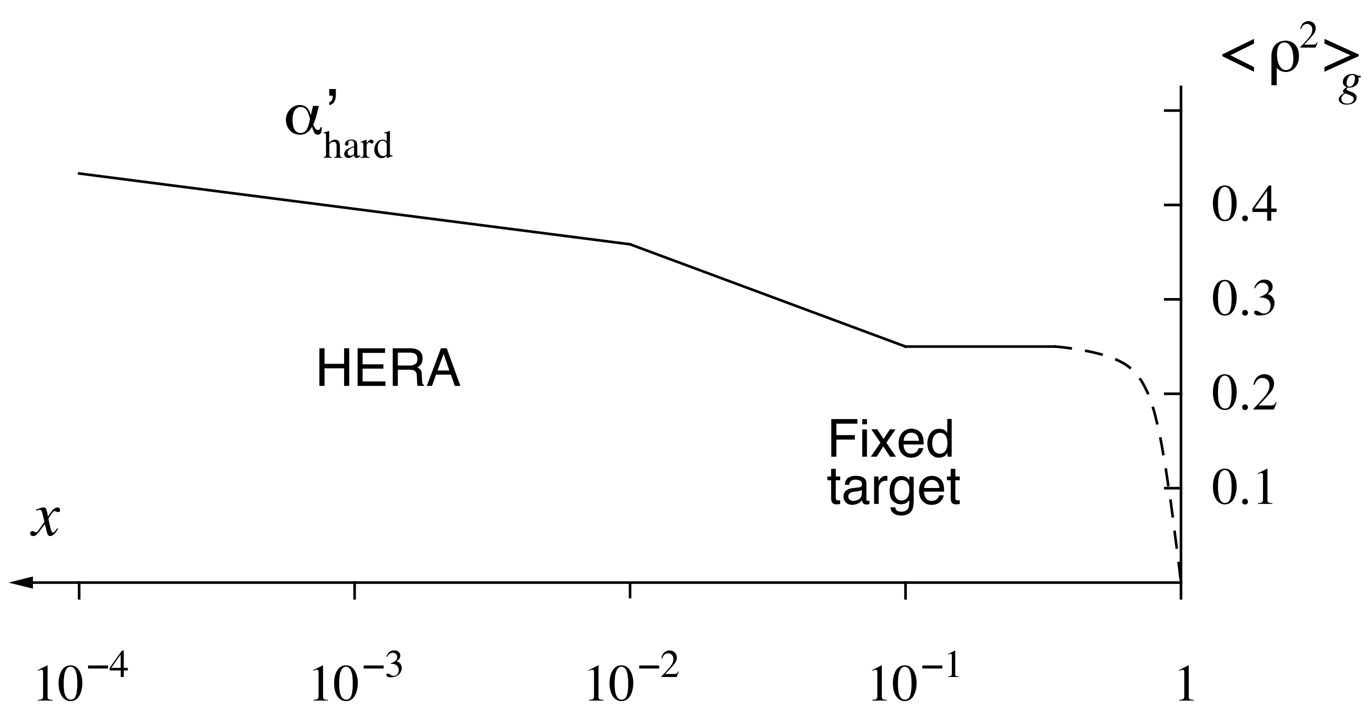
– Can be extracted from t–dependence of $\dfrac{d\sigma}{dt}(\gamma^* p \rightarrow V p)$

- Gluonic transverse size: x–dependence



Gluon transverse size decreases with increase of x

Pion cloud contributes for $x<M_\pi/M_N$ [MS &C.Weiss 03]

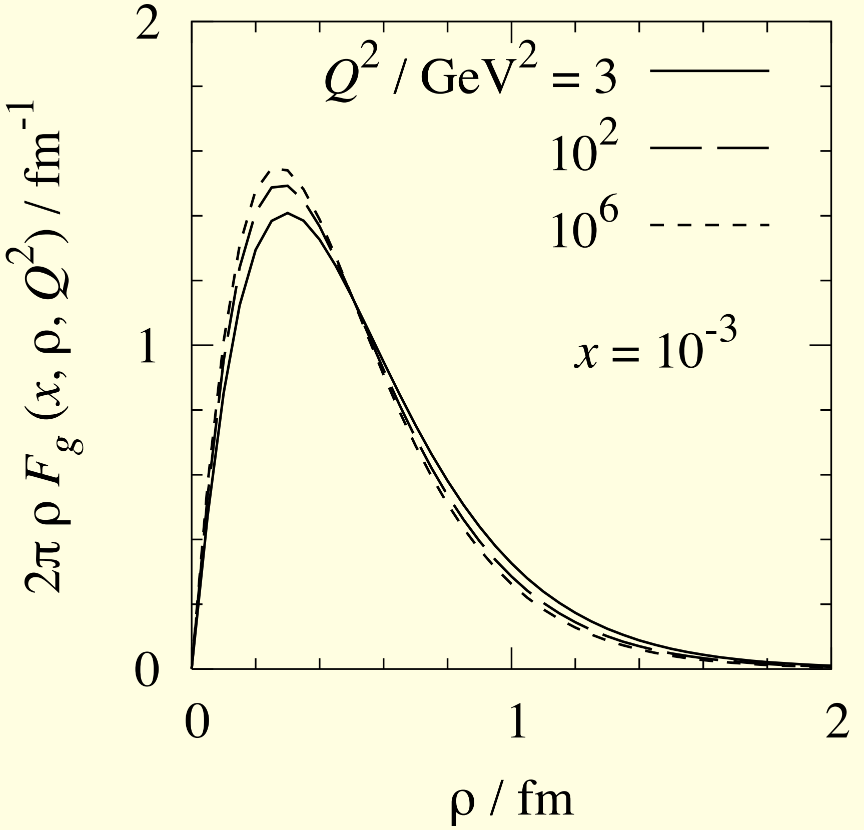


- Transverse size at large x much smaller than proton radius in soft interactions:

$$\langle\rho^2\rangle(x > 10^{-2}) \ll R^2_{\text{soft}}$$

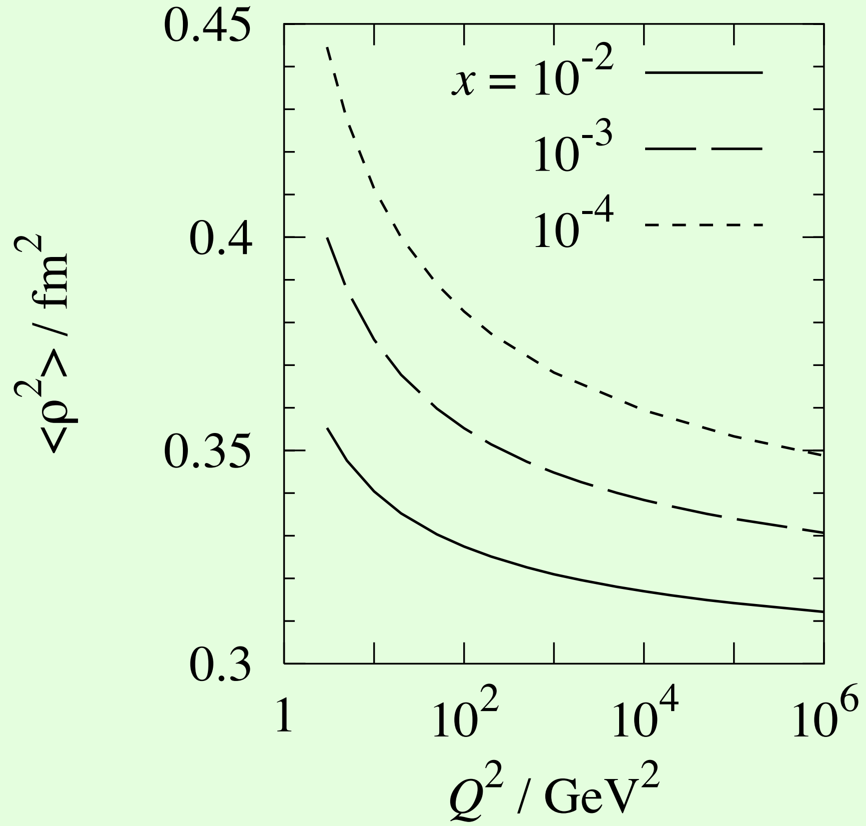
$\Downarrow$

Two scale picture



The change of the normalized ρ–profile of the gluon distribution, $F_g(x, \rho; Q^2)$, with Q^2, as due to DGLAP evolution, for $x = 10^{-3}$. The input gluon distribution is the GRV 98 parameterization at $Q_0^2 = 3\,GeV^2$, with a dipole–type b–profile.

M.Strikman



Change of <ρ²(Q²)> with x due to DGLAP evolution - leads to effective α′ which drops with Q but still remains finite even at very high Q.

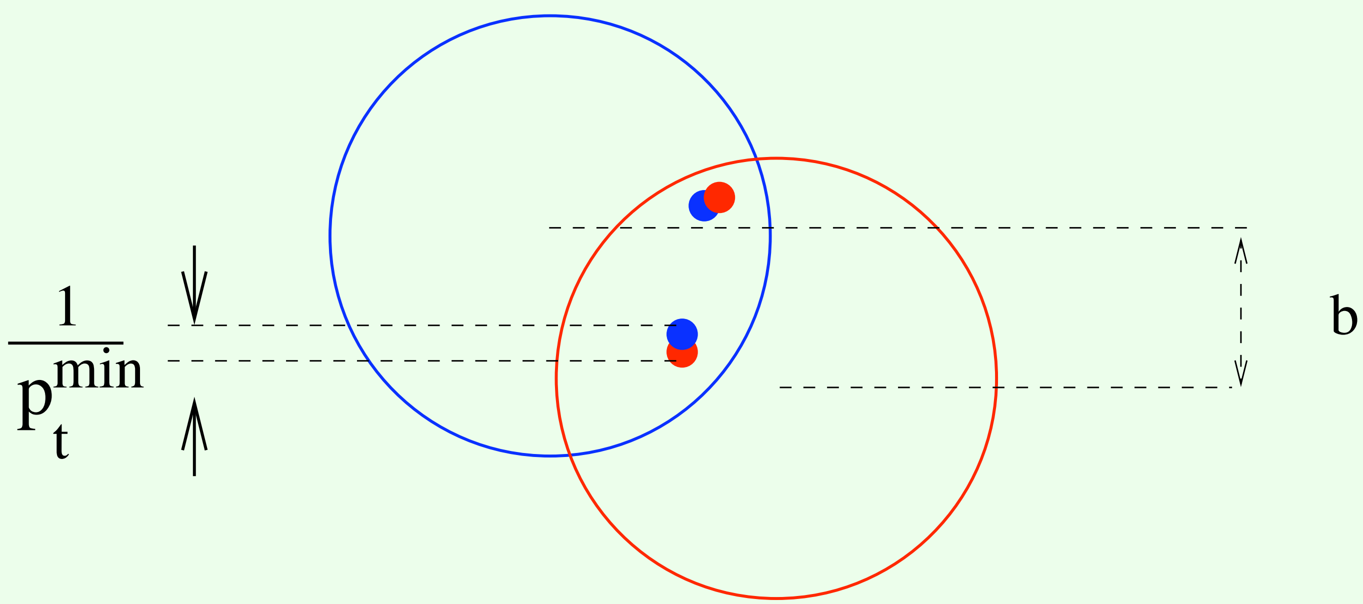
The change of the average transverse gluonic size squared, $\langle \rho^2 \rangle$, due to DGLAP evolution, for $x = 10^{-2}, 10^{-3}$ and 10^{-4}.

M.Strikman

Multi-jet production - study of parton correlations in nucleons

a) b)

Where is the infinite number of primordial 'sea' partons in the infinite momentum state of the proton: inside the constituent quarks (a) or outside (b) ?



A view of double scattering in the transverse plane.

At high energies, two (three ...) pairs of partons can collide to produce multi-jet events which have distinctive kinematics from the process two partons → four partons.

Note - collisions at points separated in b by ~ 0.5 fm
⇒ independent fragmentations

Experimentally one measures the ratio

$$\frac{\frac{d\sigma(p+\bar{p}\rightarrow jet_1+jet_2+jet_3+\gamma)}{d\Omega_{1,2,3,4}}}{\frac{d\sigma(p+\bar{p}\rightarrow jet_1+jet_2)}{d\Omega_{1,2}}\cdot\frac{d\sigma(p+\bar{p}\rightarrow jet_3+\gamma)}{d\Omega_{3,4}}} = \frac{f(x_1,x_3)f(x_2,x_4)}{\sigma_{eff}f(x_1)f(x_2)f(x_3)f(x_4)}$$

where $f(x_1,x_3), f(x_2,x_4)$ longitudinal light-cone double parton densities and

σ_{eff} is ``transverse correlation area".

CDF observed the effect in a restricted x-range: two balanced jets, and jet + photon and found $\sigma_{eff} = 14.5 \pm 1.7^{+\,1.7}_{-\,2.3}\, mb$ rather small - a naive expectation is σ_{eff} ~ 60 mb indicating high degree of correlations between partons in the nucleon in the transverse plane. No dependence of σ_{eff} on x_i was observed.

Possible sources of small σ_{eff} for CDF kinematics of x ~0.1-0.3 include:

☺ Small transverse area of the gluon field --accounts for 50 % of the enhancement $\sigma_{eff} \sim 30$mb (F&S & Weiss 03)

☺ Constituent quarks - quark -gluon correlations (F&S&W)

If most of gluons at low Q~ 1GeV scale are in constituent quarks of radius $r_q/r_N \sim 1/3$ found in the instanton liquid based chiral soliton model (Diakonov & Petrov) *the enhancement as compared to uncorrelated parton approximation is*

$$\frac{8}{9} + \frac{1}{9}\frac{r_N^2}{r_q^2} \sim 2$$

Hence, combined these two effects are sufficient to explain CDF data. (F&S&W)

☺ QCD evolution leads to "Hot spots" in transverse plane (A.Mueller). One observes that such hot spots do enhance multijet production as well. However this effect is likely not to be relevant in the CDF kinematics as x's of colliding partons are relatively large.

In order to analyze the strengths of interaction with the gluon fields at small x it is convenient to consider virtual photon - nucleon scattering in the nucleon rest frame.

Space-time picture of DIS, exclusive vector meson production - a three step process:

- transition $\gamma^* \to h$ where h are various $q\bar{q}, q\bar{q}g \ldots$ configurations long before the target:

$$l_{coh} \sim c(Q^2) q_0 / Q^2, c(Q^2) \leq 1$$

Slow evolution of this wave package.

- interaction of the evolved configurations with the target,

- formation of the final state.

Convenient to introduce a notion of the cross section of the interaction of a small dipole with the nucleon. Such a cross section can be legitimately calculated in the leading log approximation. One can also try to extend it to large size dipoles hoping that a reasonably smooth matching with nonperturbative regime is possible. Sensitive to m_q in nonperturbative regime - real photon size constrain → $m_q \sim$ 300 MeV for u & d quarks.

A delicate point: in pQCD the cross section depends both on the transverse separation between quark and antiquark and the off-shellness (virtuality) of the probe which produced the $q\bar{q}$ pair. In most of the models on the market this is ignored.

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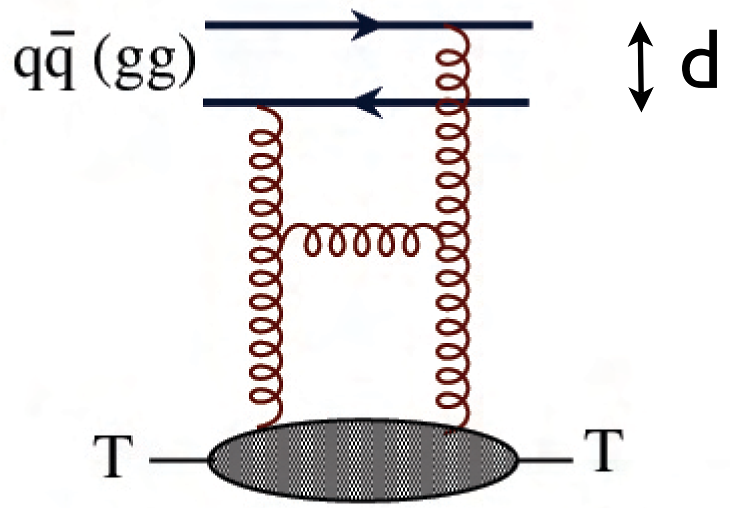
Consider first "small dipole - hadron" cross section



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

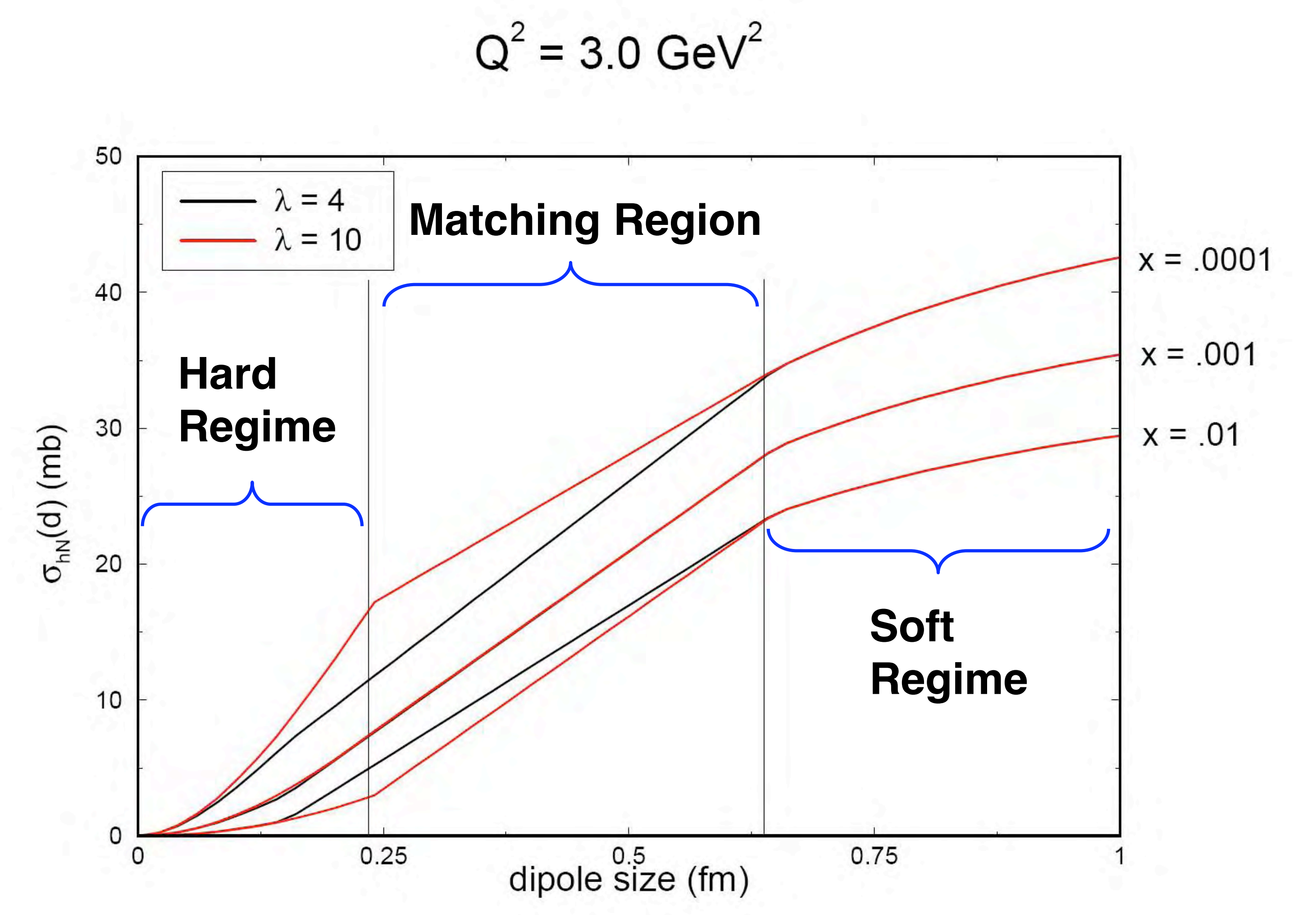
Baym et al 93

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. Also, in more accurate expression there is an integral over x, and and extra term due to quark exchanges

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

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:

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

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

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

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

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

- black disk limit -BDL

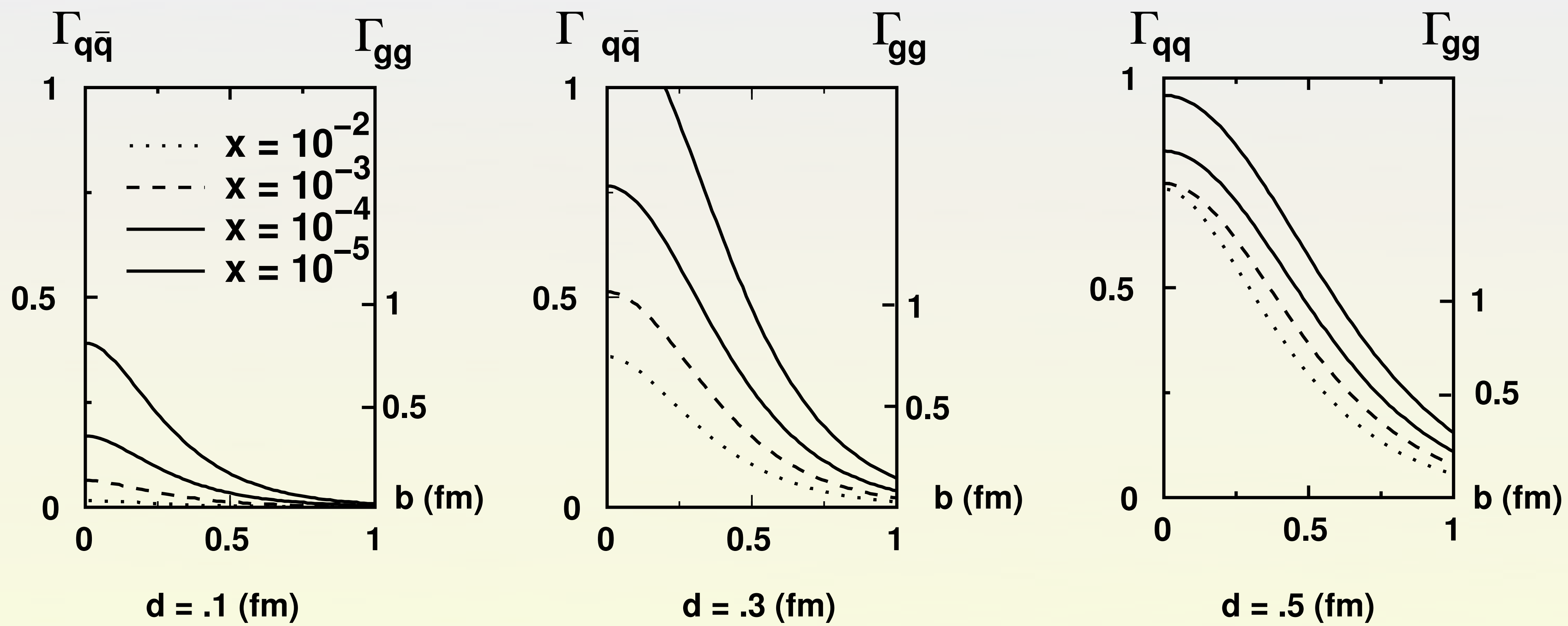
Note that elastic unitarity: $\frac{1}{2}ImA = |A|^2 + \ldots$ allows $\Gamma(b) \leq 2$

Using information on the exclusive hard processes we can also estimate t-dependence of the elastic dipole-nucleon scattering and hence estimate

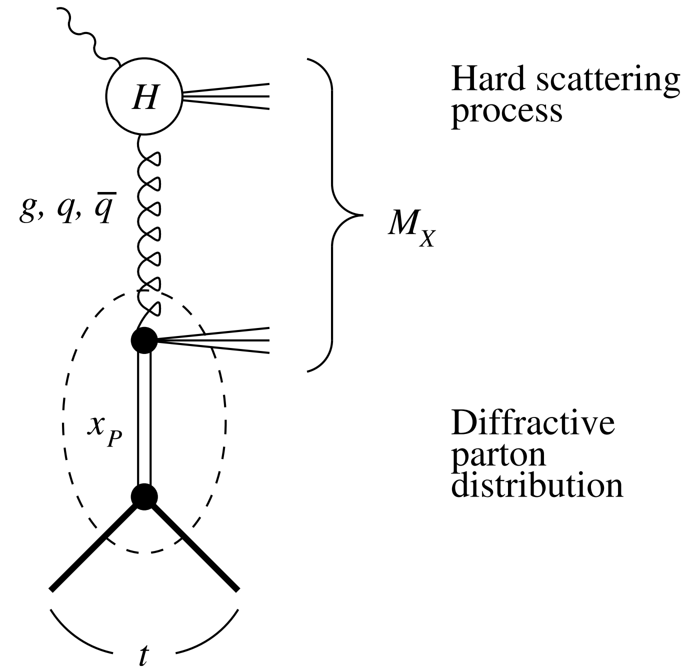
$\Gamma_{q\bar{q}}$ *from* $\sigma(q\bar{q}N)$.

In the case gg-N scattering we assume pQCD relation

$$\Gamma_{gg} = \frac{9}{4}\Gamma_{q\bar{q}}$$



Can use hard diffraction to check proximity to BDL



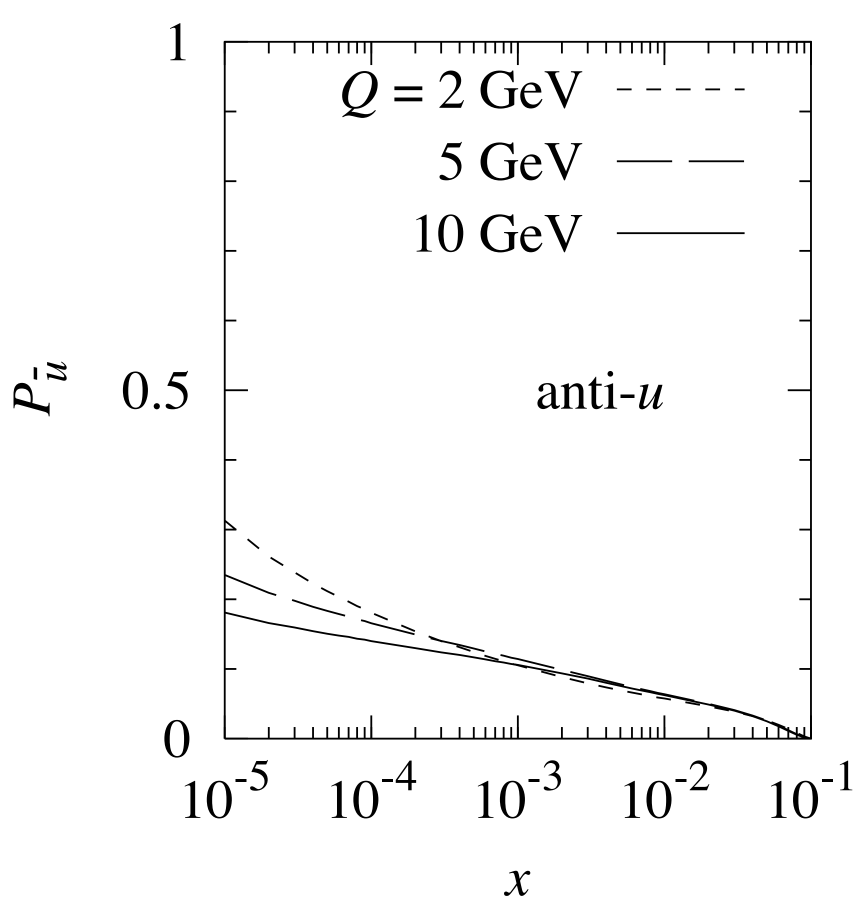
QCD factorization theorem for diffractive processes consistent with the data to define **universal** diffractive parton densities:

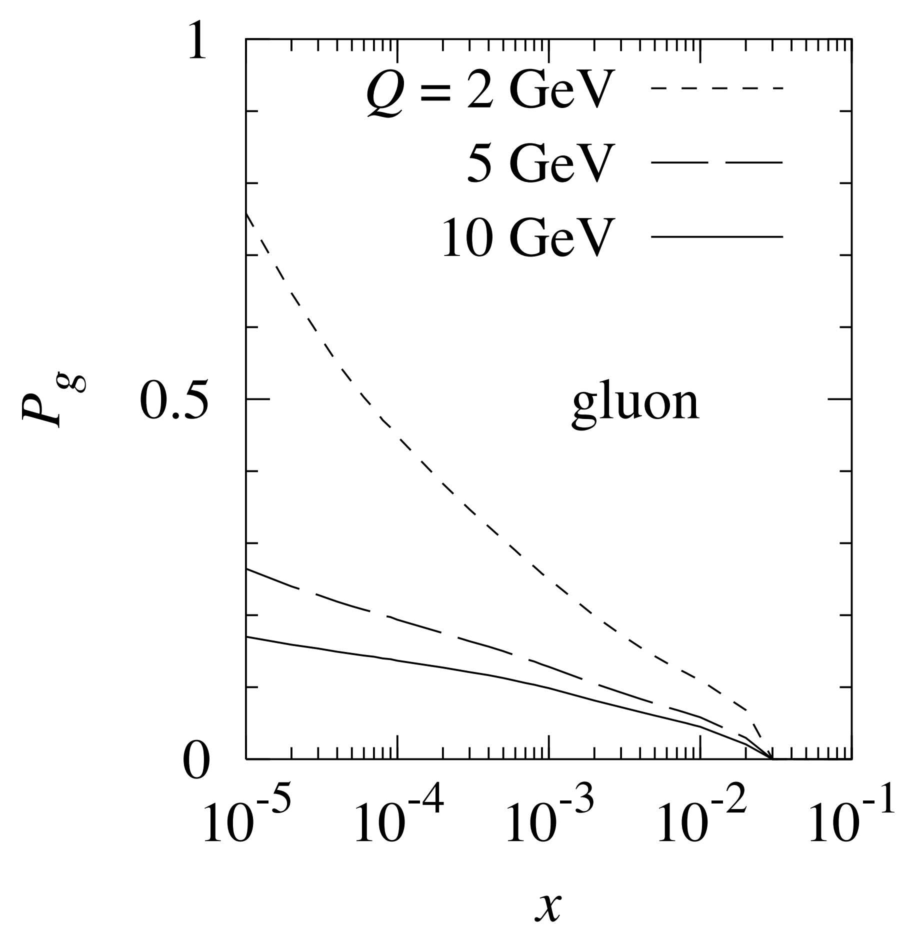
$$f_j^D(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t)$$

To test proximity to BDL 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 BDL





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

FS98

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$\Sigma\Sigma$

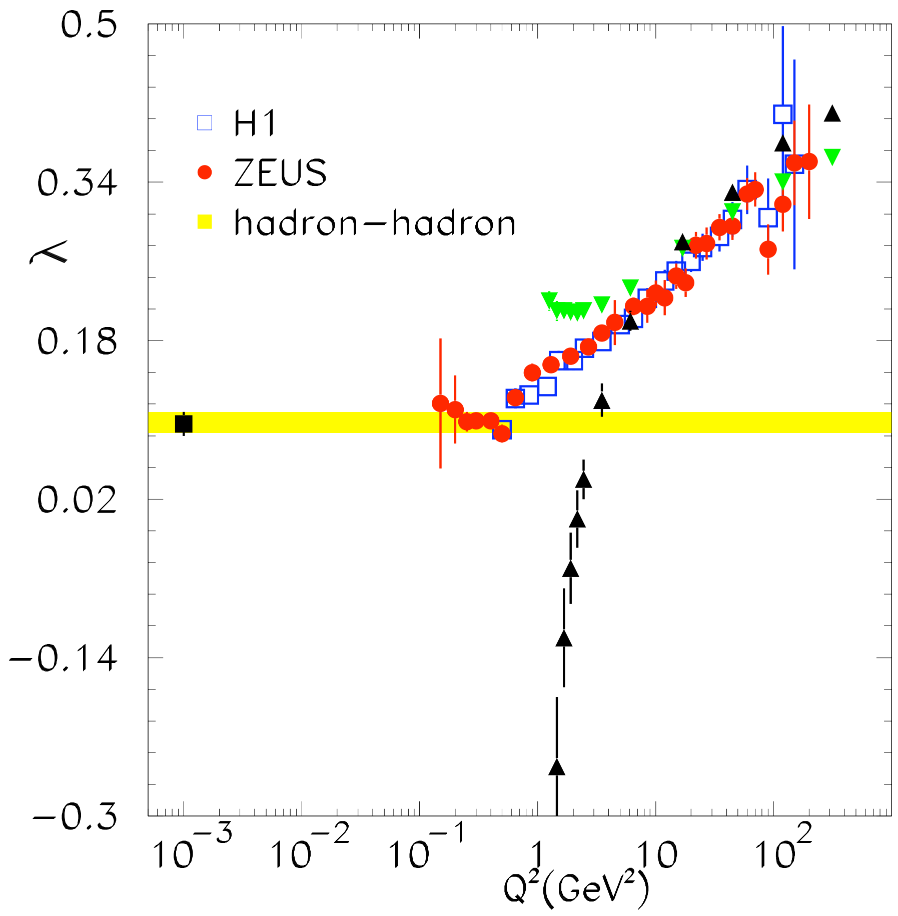
- Large ratio of diffraction/ total for gluon channel

- Large value of Γ(b~0) for "gluon dipole" -nucleon interaction for d >0.3 fm, x~10^{-4}

⇒ At HERA interaction of gluons is close to BDL for $Q^2 \leq 4GeV^2$

Two additional evidences:

- Pattern of scaling violation for small Q and small x

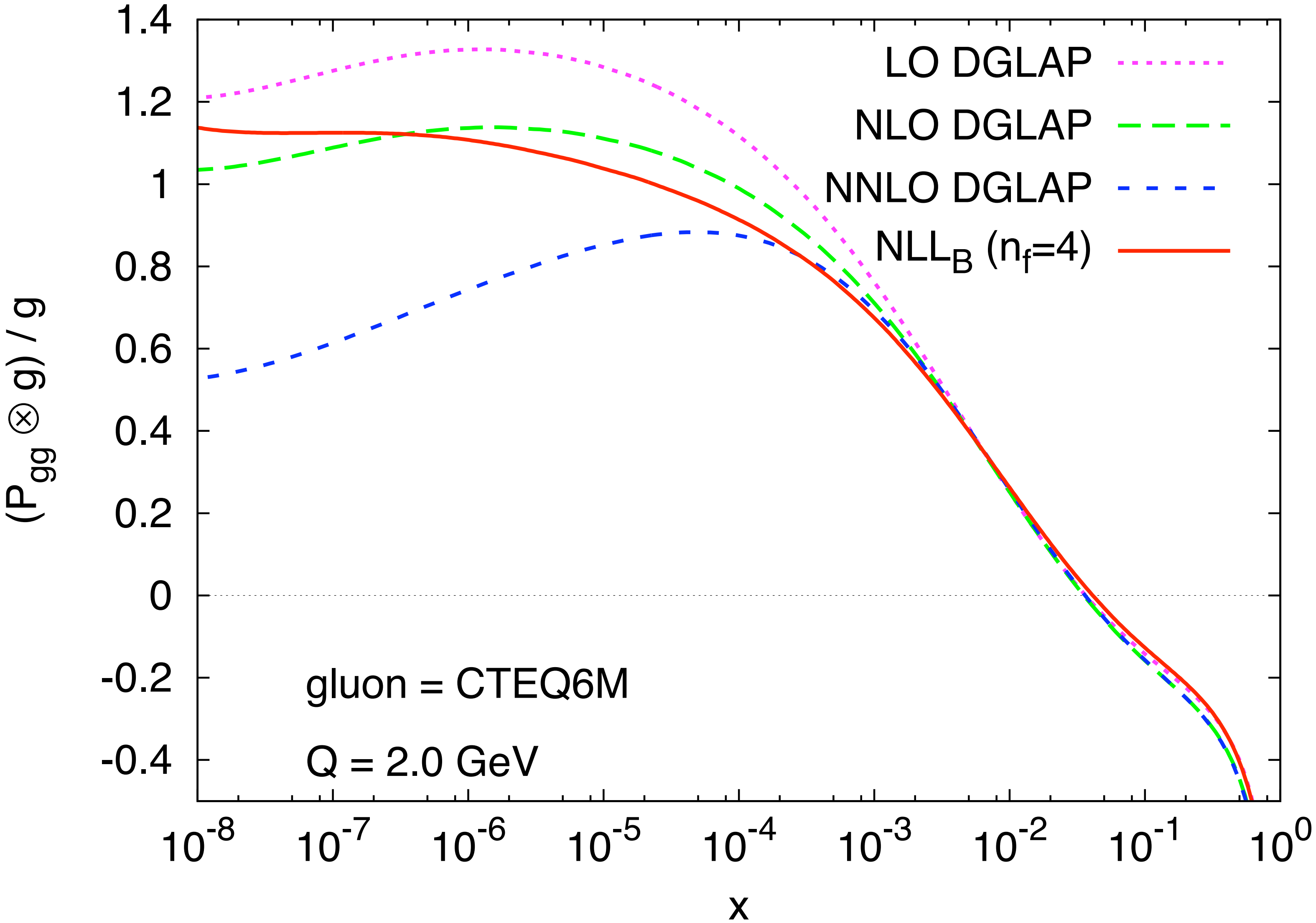


Fits:

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

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

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



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?

Depends on transverse size of the system. As we argued above - in practical situation answer is NO !!! already in the region where log x effects are moderate and could be accounted for by NLO

$\Gamma_{q\bar{q}\,N}$(d ~0.3 fm, b<0.5 fm , x ~ 10^{-4}) ~ 0.5

↓ enhancement factor ~0.5 $A^{1/3}$

$\Gamma_{q\bar{q}\,A\sim 200}$(d ~0.3 fm, b<3 fm , x ~ $2\cdot 10^{-4}$) ~ 1

Based on HERA data, we expect for RHIC validity of BDL for virtualities 1-2 GeV^2 for interaction of leading quarks with heavy nuclei

⇓

✺ Large fractional energy losses in pA for central impact parameters (F&S01) .

Explains pattern of suppression of leading pions and correlations observed at RHIC which is in contradiction with the CGC predictions.

Conclusion

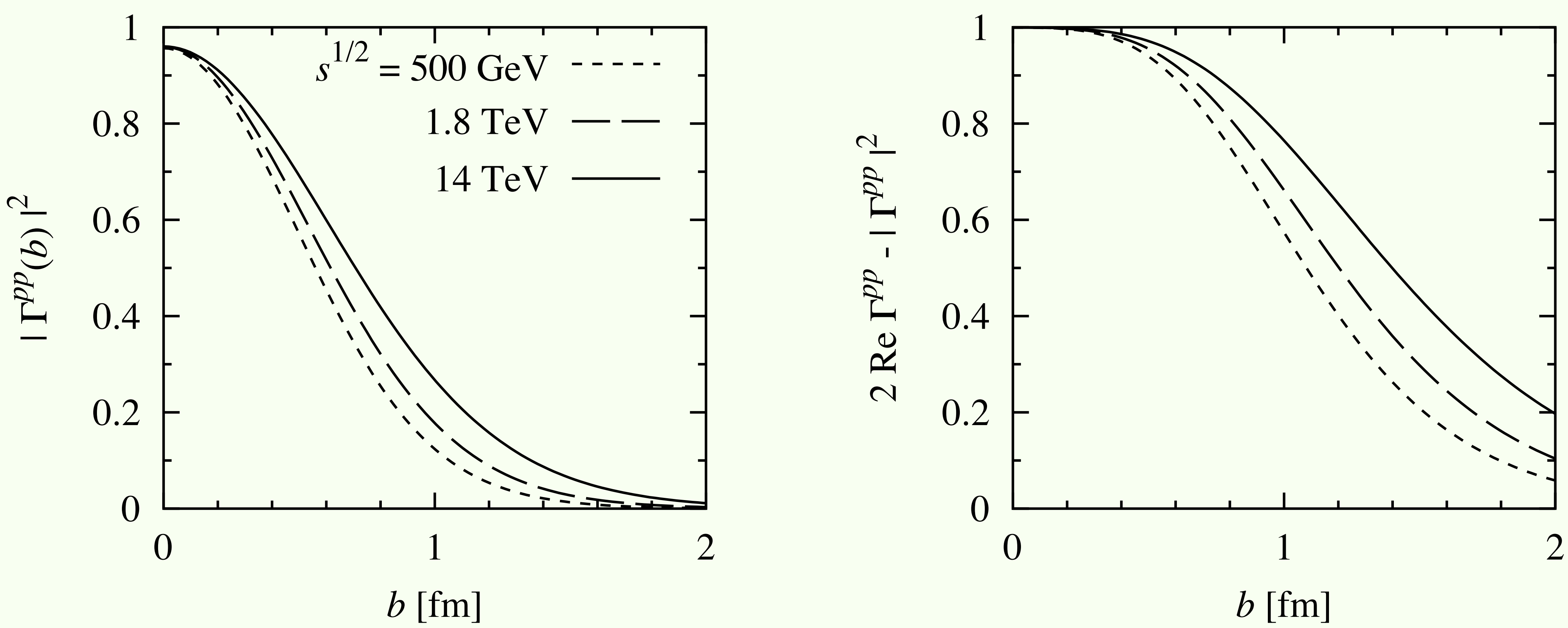
Incident partons which have large enough energies to resolve $x \sim 10^{-4} \div 10^{-5}$ in the target nucleon and wh disk ass close enough $b \leq 0.5 fm$ from the nucleon, interact with the nucleon in a regime which is likely to be close to the black body regime.

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

(i) Impact parameter distribution in pp interaction

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

$$\Gamma_h(s,b) = \frac{1}{2is}\frac{1}{(2\pi)^2}\int d^2\vec{q}e^{i\vec{q}\vec{b}}A_{hN}(s,t)$$



Calculation uses model of Islam et al

Probability of inel. interaction: $P(b) = 2\,Re\Gamma(b) - |\Gamma(b)|^2$

Broadening of the distribution over b is primarily a result of Gribov diffusion.

$\Gamma(b) = 1 \equiv \sigma_{inel} = \sigma_{el}$ - black disk limit (BDL).

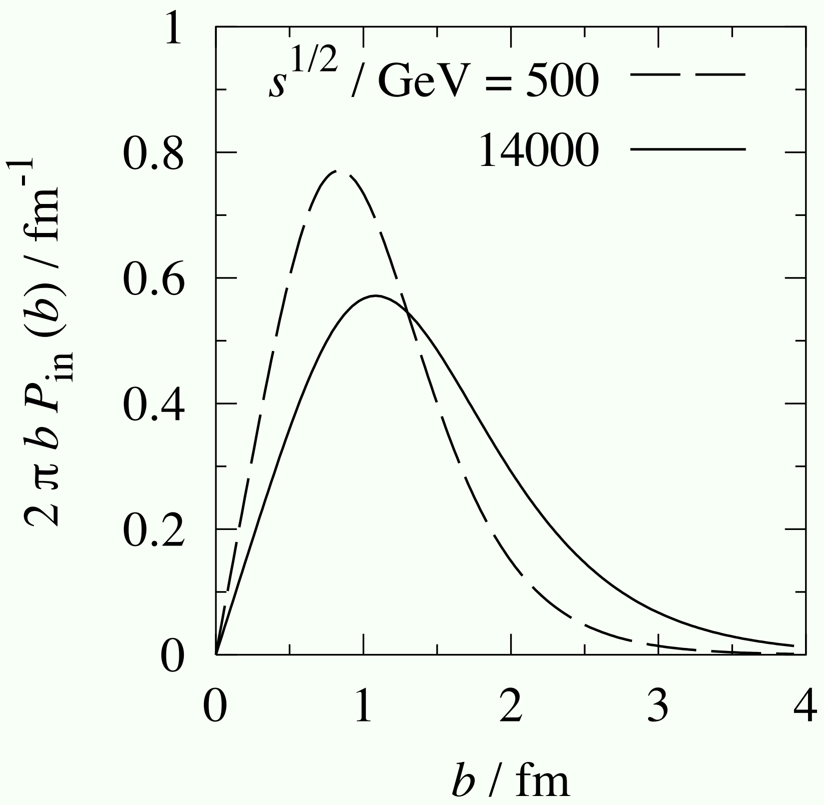
Warning: relation between Γ(s,b) and the scattering amplitude seems to indicate that elastic scattering occurs at small impact parameters. In fact this is the wave goes around the target which survived nearly complete absorption at small b. Relevant for suppression of hard diffraction at colliders.

Answer is the same as using Eq. from the previous slide – complementarity principle: diffraction off the hole and absorptive disk of the same shape are the same.

Quiz: consider scattering of a deuteron off a large absorptive nucleus so that $\sigma_{inel}(pA) = \sigma_{el}(pA)$.

Select events where one nucleon went through the center (centrality trigger). What is probability that the second nucleon scatters elastically?

- ○ 10 %
- ○ 50 %
- ○ 0 %

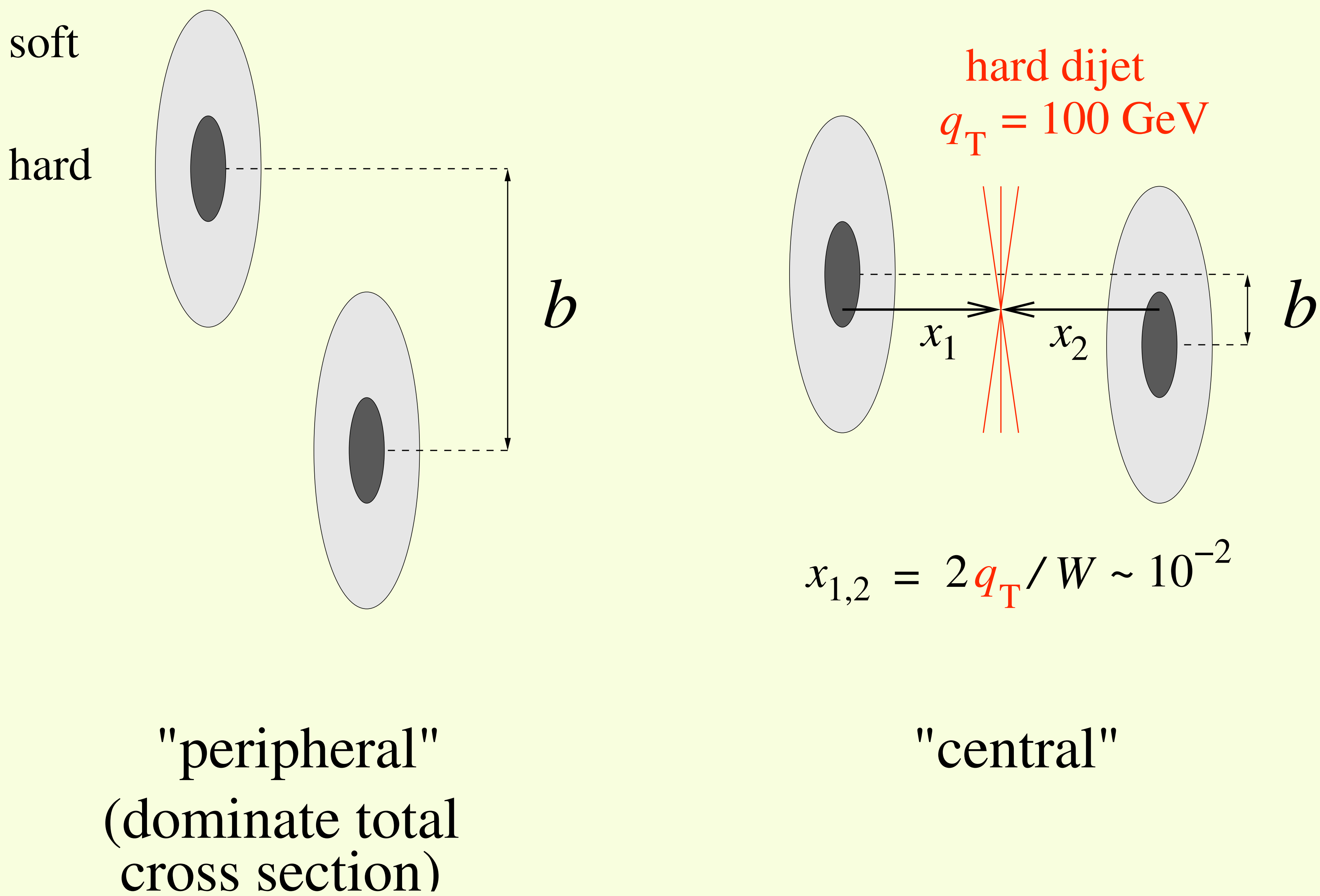


$$P_{in}(s,b) \;=\; \frac{2Re\,\Gamma^{pp}(s,b) - |\Gamma^{pp}(s,b)|^2}{\sigma_{in}(s)}$$

The normalized impact parameter distribution for generic inelastic collisions, $P_{in}(s,b)$, obtained with the parameterization of the elastic pp amplitude of Islam *et al.* ("diffractive" part only). The plot shows the "radial" distribution in the impact parameter plane, $2\pi b\, P_{in}(s,b)$. The energies are $\sqrt{s} = 500\, GeV$ (RHIC) and $14000\, GeV$ (LHC).

M.Strikman

Impact parameter distribution for dijet trigger.

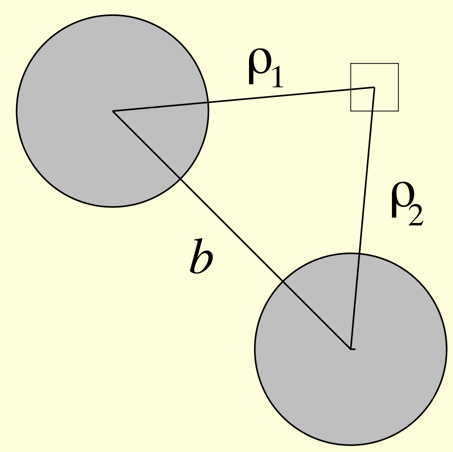


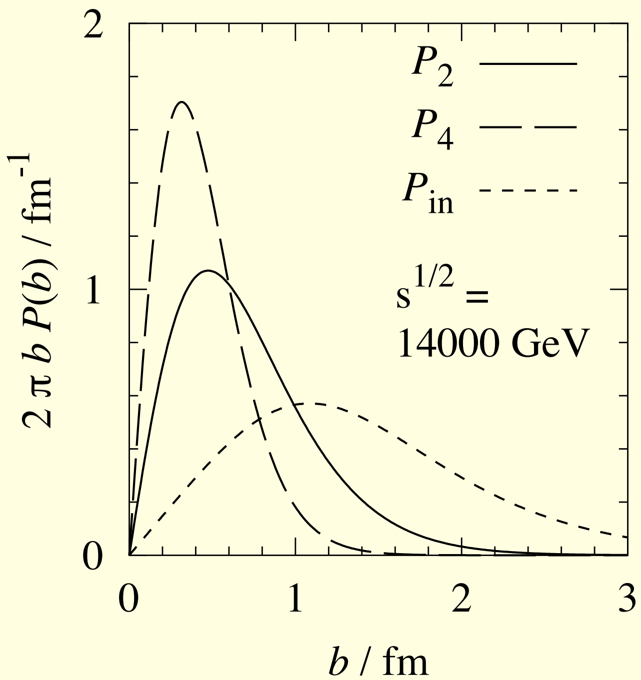
Main idea/Qualitative expectation: hard partons are more localized in transverse plane. Hence in events with hard interaction spectator partons experience much stronger gluon fields.

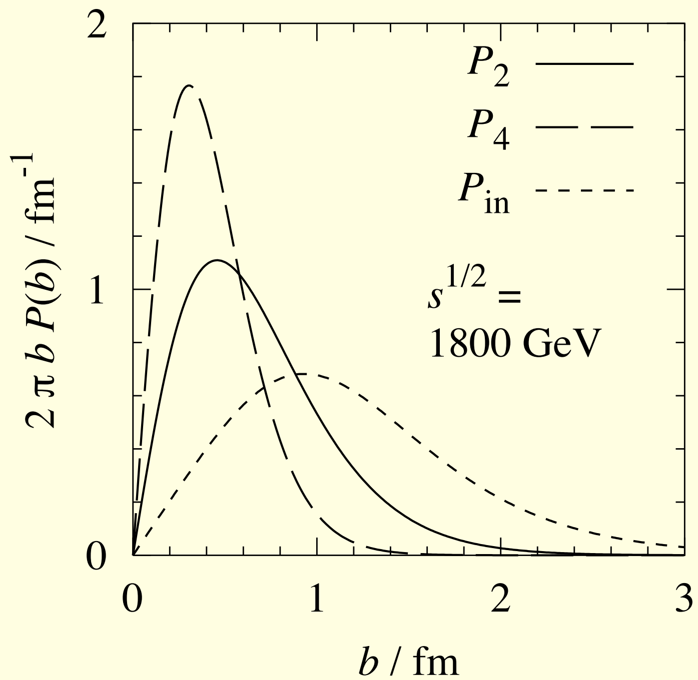
Impact parameter distribution for a hard multijet trigger.

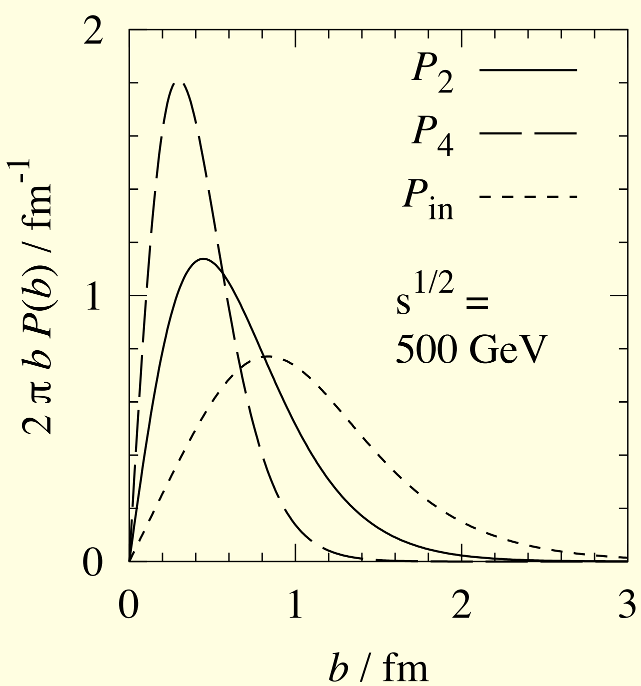
For simplicity take $x_1 = x_2$ for colliding partons producing two jets with $x_1 x_2 = 4q_\perp^2/s$. Answer is not sensitive to a significant variation of x_i for fixed $q_\perp$.

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:









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.

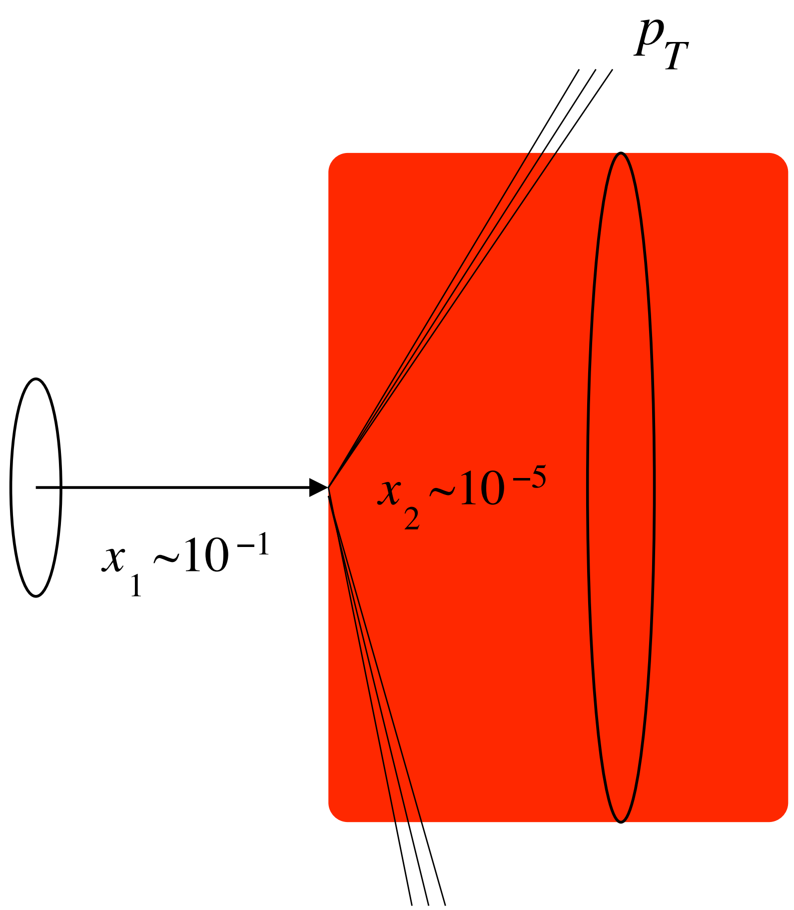
What happens when a parton goes through strong gluon fields? It will be resolved to its constituents if interaction is strong. To estimate the transverse momenta of the resolved system use a second parton as a regularization - consider the propagation of a small dipole of transverse size d, which interacts in LO pQCD with cross section:

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

F^2 Casimir operator of color SU(3)

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

First consider central pA collisions



Black disk 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, $p_\perp$

To estimate the maximum transverse momentum for interactions close to the BDL, we can treat the leading parton as one of the constituents of a small dipole scattering from the target. This regularization "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

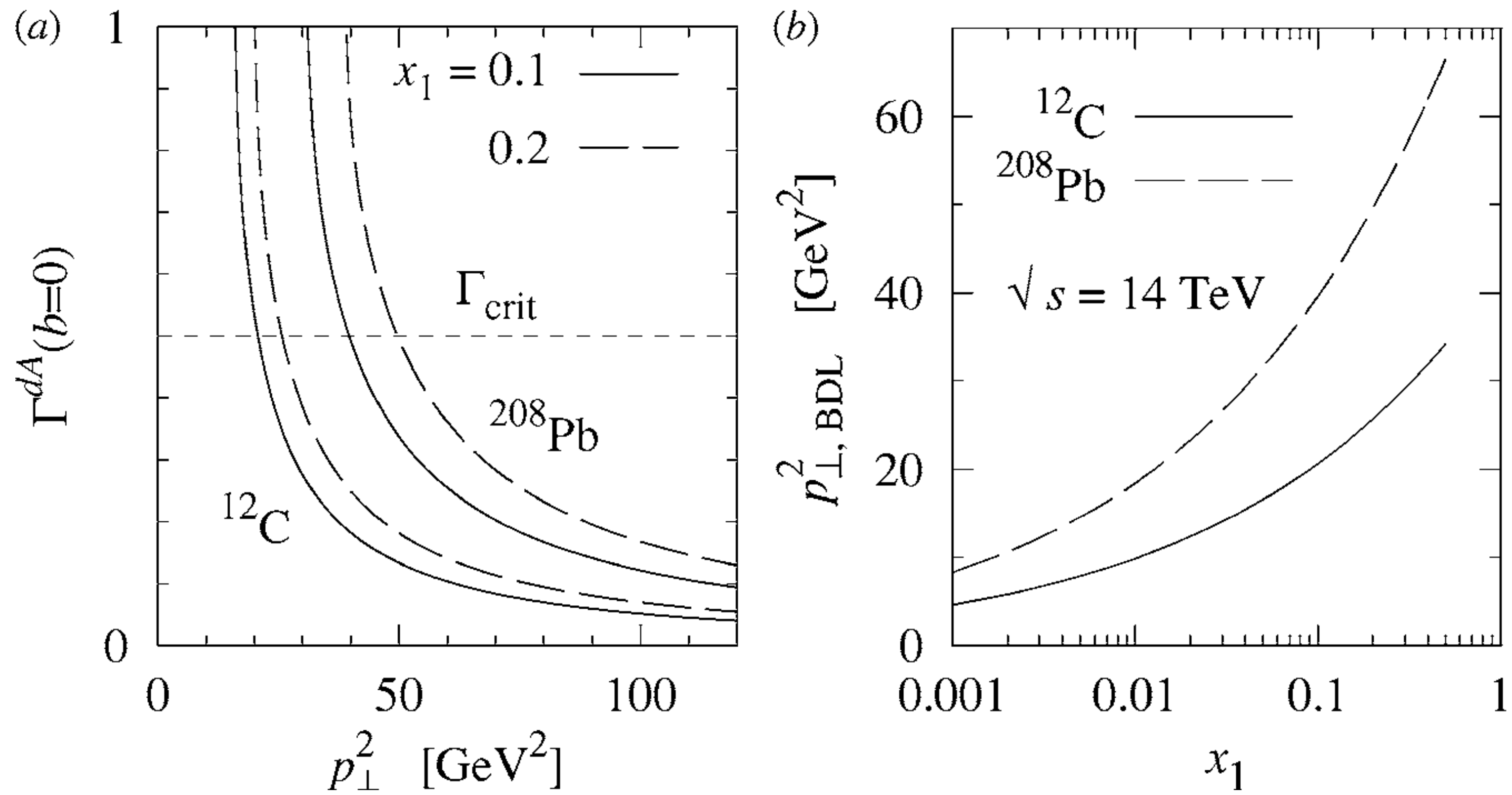
$$d \approx 3/2p_\perp$$

Criterion of proximity to BDL:

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

corresponding to probability of inelastic collision of

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



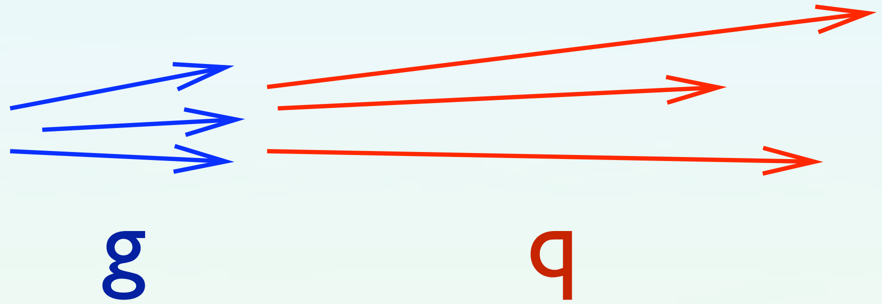
Black–disk limit in central collisions:

(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,

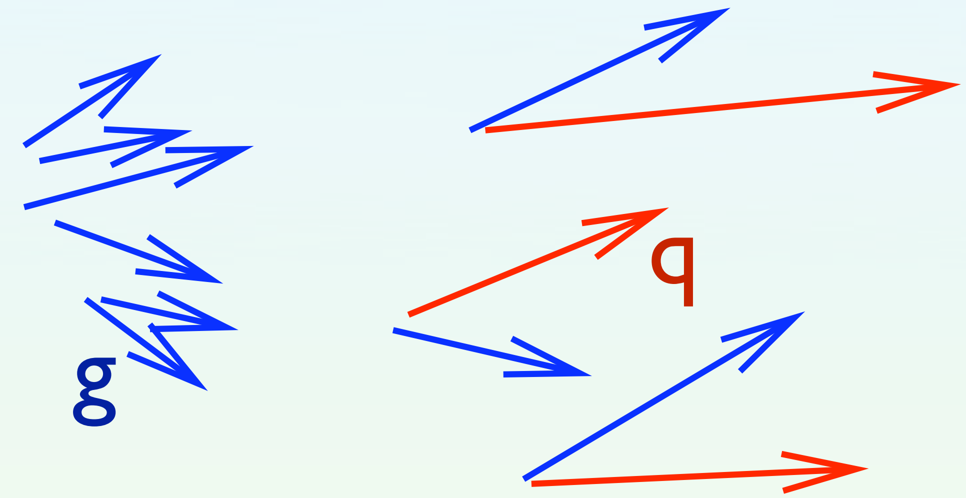
(b) The maximum transverse momentum squared, BDL, for which the interaction of the leading gluon is "black" (for quarks it is a factor of two smaller).

$p^2_{\perp,BDL}$ strongly depends on x, while cutoff in the MC's depends only on s!!!

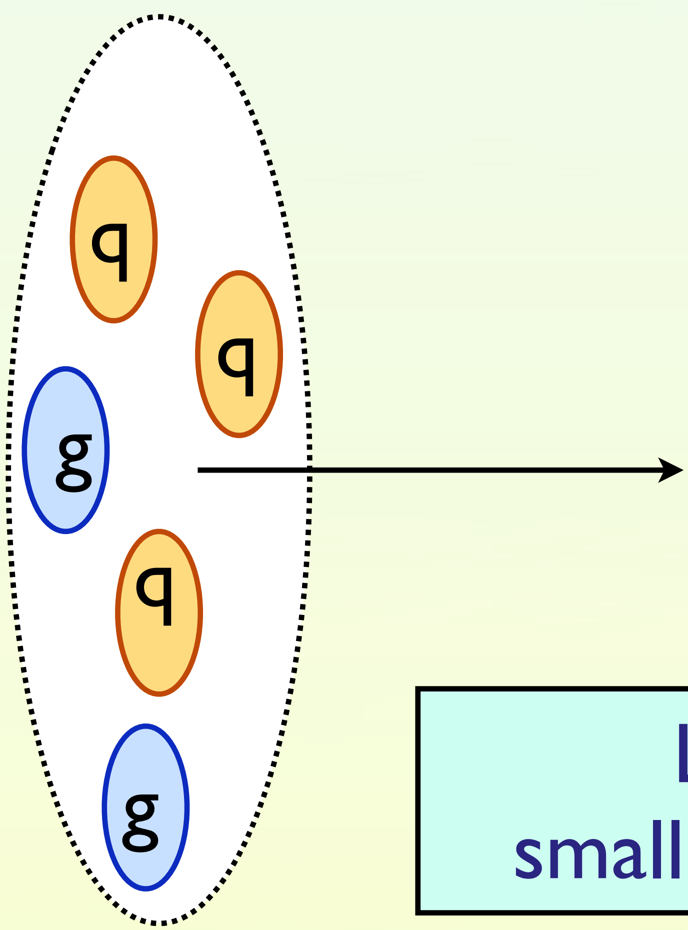
Characteristics of the final state in the central pA(pp) collisions

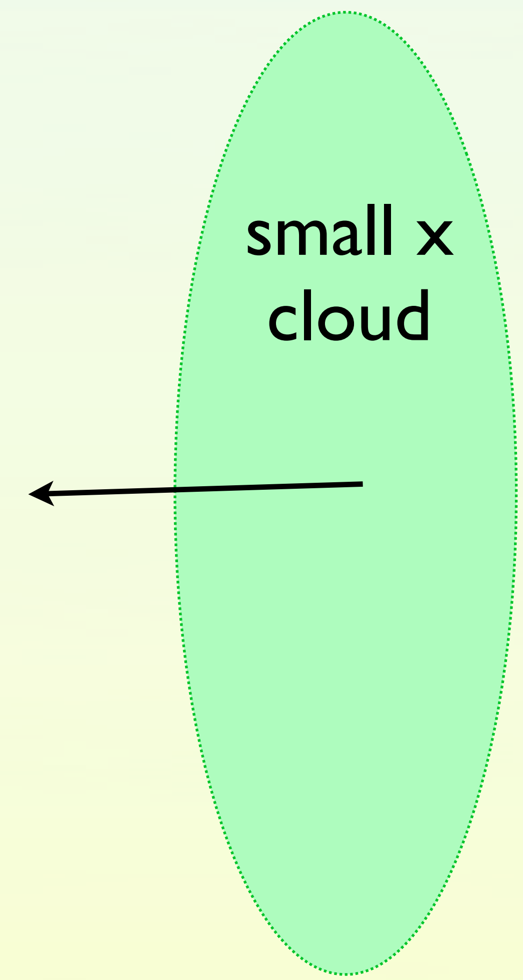


fast partons in a nucleon before collisions



fast partons in a nucleon after central collisions





Large x partons burn
small holes in the small x cloud

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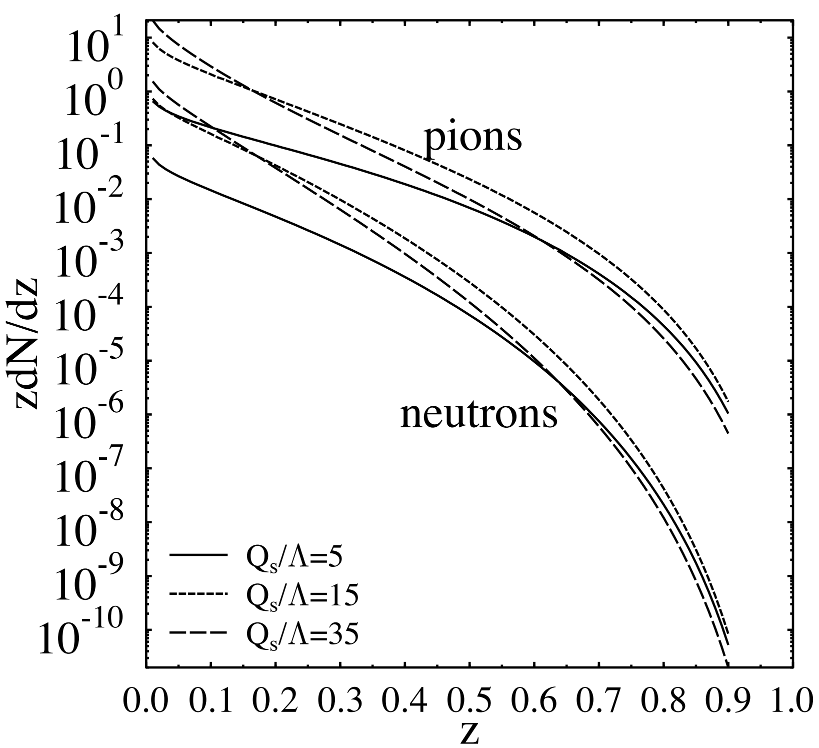
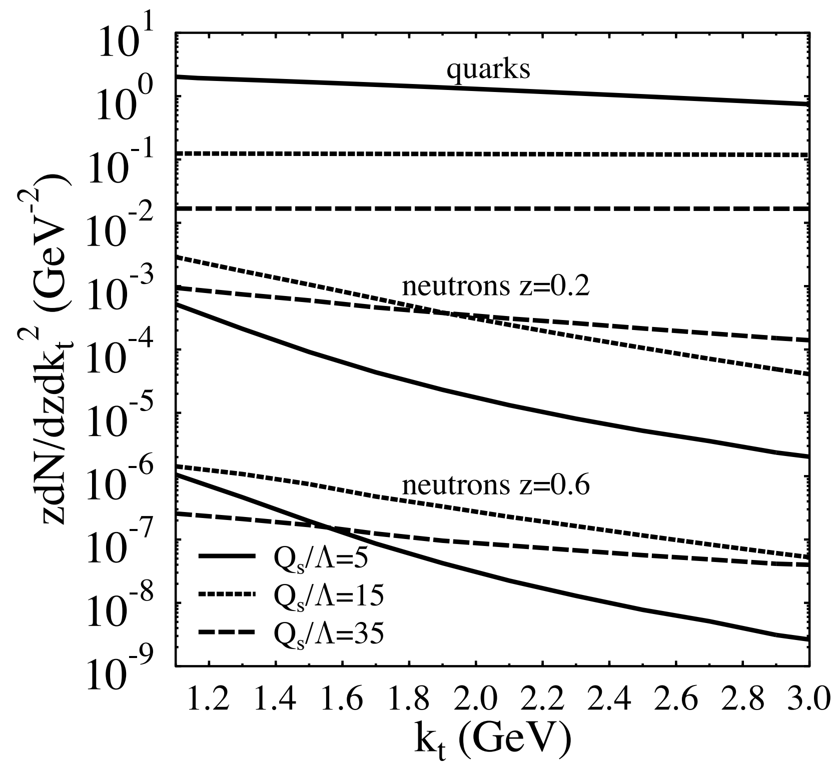
The leading particle spectrum will be strongly suppressed compared to minimal bias events since each parton fragments independently and splits into a couple of partons with comparable energies. The especially pronounced suppression for nucleons: for $z \geq 0.1$ the differential multiplicity of pions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

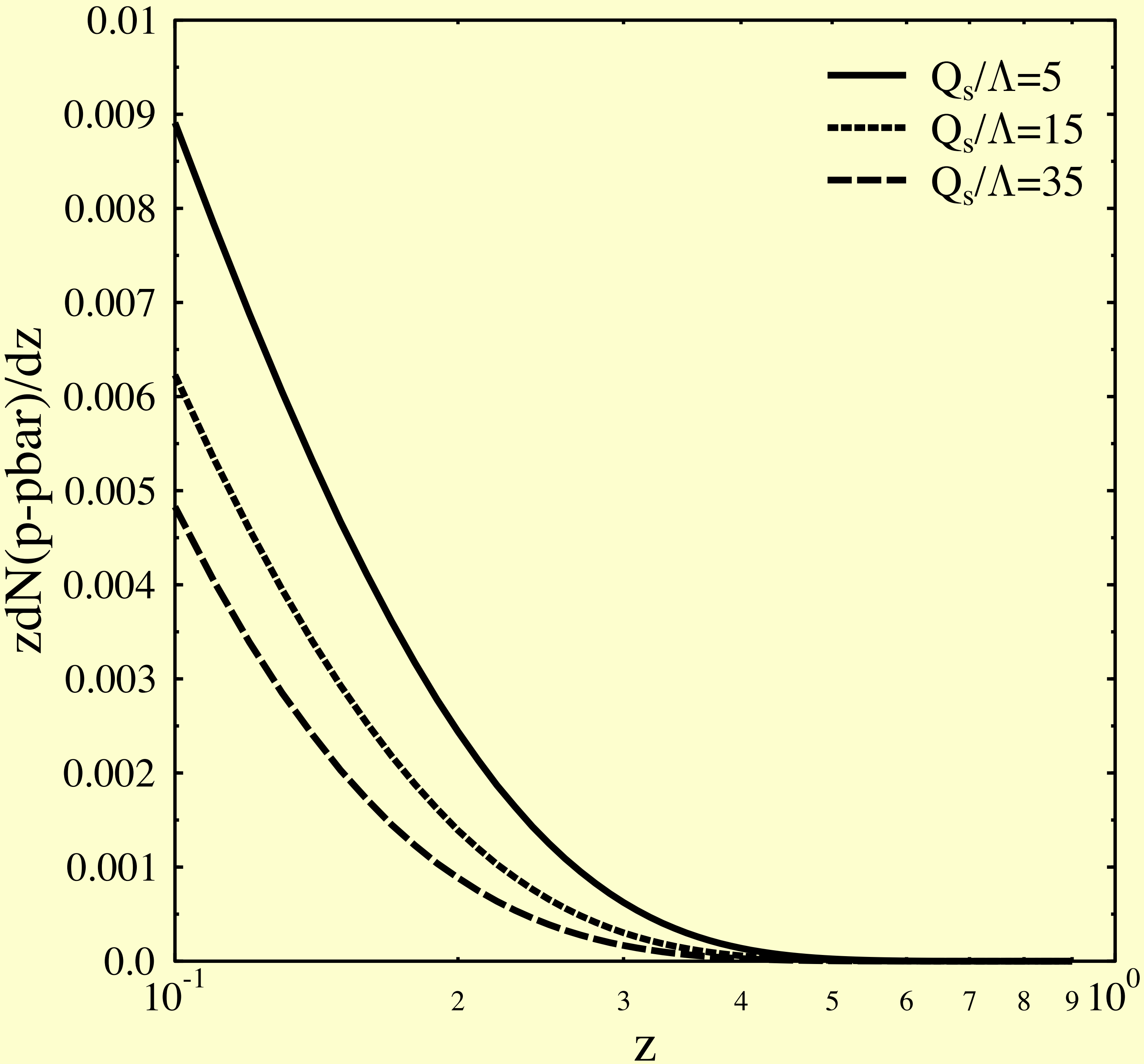
$$\frac{1}{N}\left(\frac{dN}{dz}\right)^{pA\rightarrow h+X} = \sum_{a=q,g}\int dx\, x f_a(x,Q^2_{eff}) D_{h/a}(z/x,Q^2_{eff})$$





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 coalecence becomes important for moderate z enhancing the proton yields for these z's.

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,...

A parton with a given x_1 is and resolution pt is sensitive to the partons in the target with $x \geq x_2 = 4p_t^2/s_{NN}x_1$

For $s=10^{11}$ GeV^2, $x_1=0.1$, $p_t=5$ GeV/c, $x>x_2=10^{-8}$ are resolved!!!

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

We 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.

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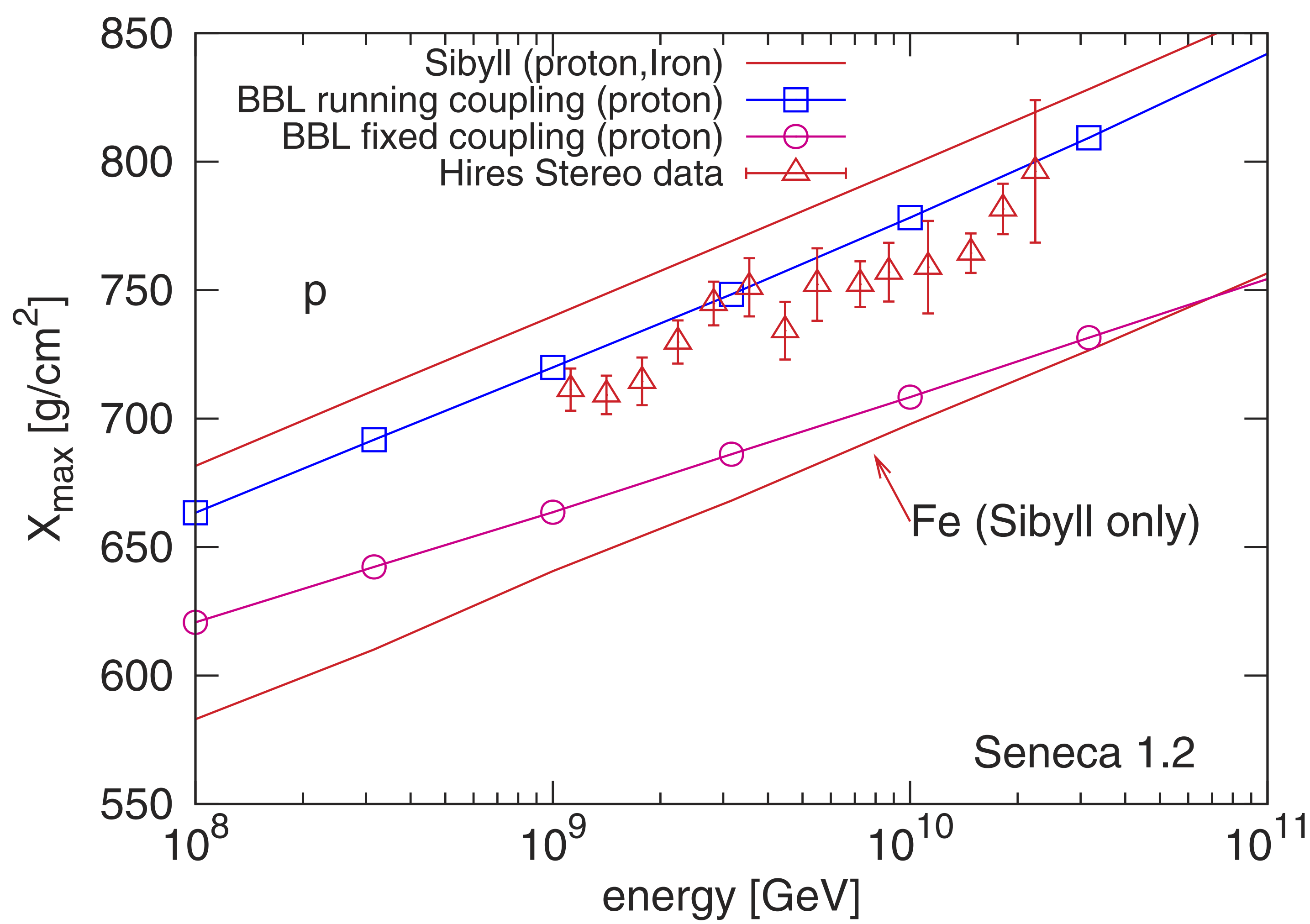


Mean X_{max} as a function of primary energy for the pQCD model Sibyll (proton and iron primaries), the saturation model BDL (proton primaries, fixed- and running- coupling evolution of Q corresponding to the disk body limit), and the Hires stereo data .

PRL **94,** 231801 (2005) PHYSICAL REVIEW LETTERS week ending 17 JUNE 2005

High-Density QCD and Cosmic-Ray Air Showers

H. J. Drescher,[1] A. Dumitru,[1] and M. Strikman[2]

Let us estimate what average transverse momenta are obtained by a parton in the collision at a fixed b. Estimate involves several steps.

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

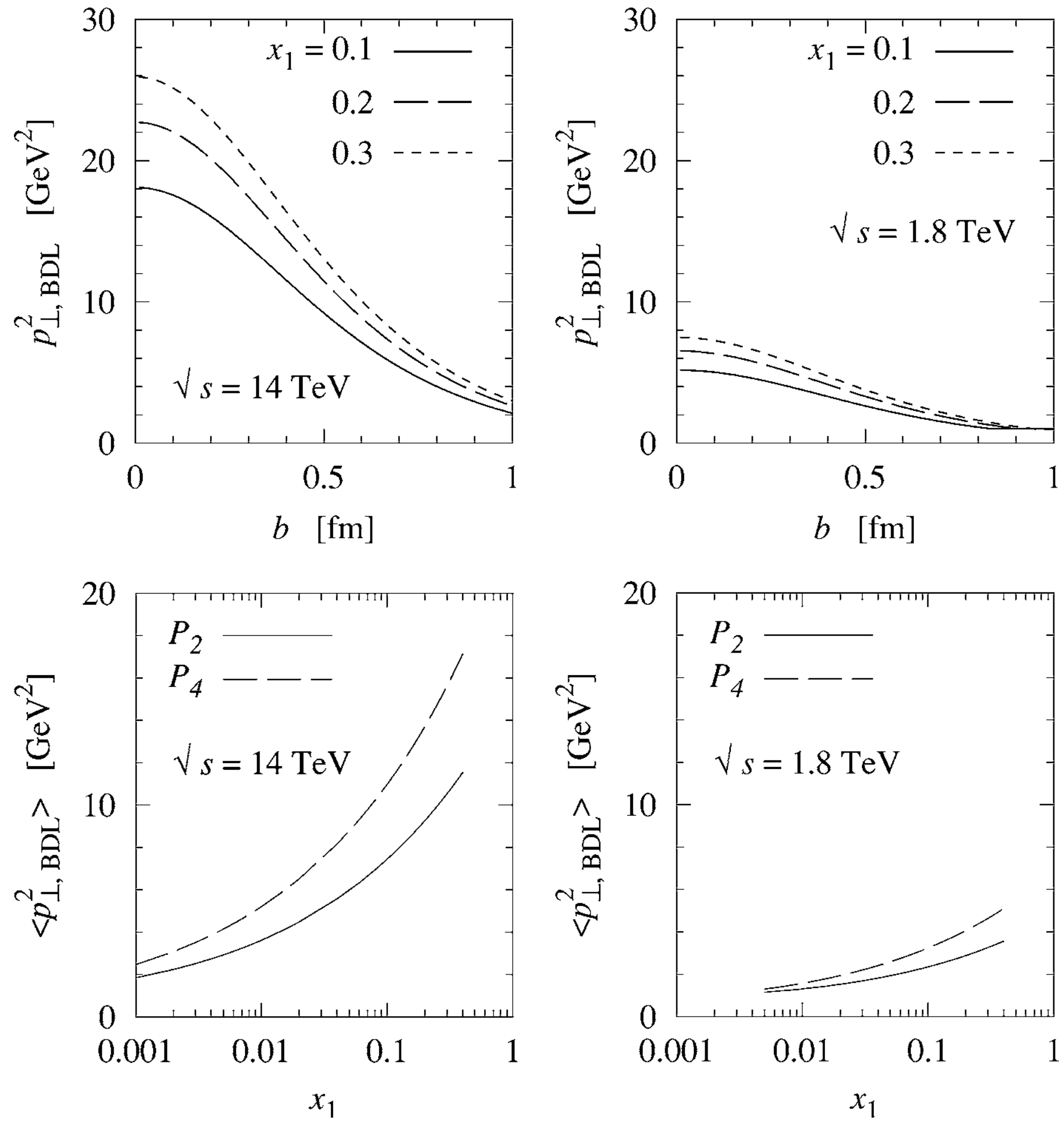
- Determining what minimal x are resolved in the second proton for given virtuality $x = \frac{4p_\perp^2}{x_1 s}, Q^2 = 4p_\perp^2$ $\quad small\, x \leftrightarrow large\, x_1$

- 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

- taking into account distribution over ρ for given b



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 $p^2_{\perp,BDL}$ 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)*

What dynamics governs the BLACK DISK regime in hadron-hadron collisions?

☺ In central pp collision at collider energies leading quarks get transverse momenta > 1 GeV/c

If a leading parton got a transverse momentum $p_\perp$

probability for a nucleon to remain intact is $P_q \sim F_N^2(p_\perp^2)$

If $\langle p_\perp \rangle > 1 GeV/c \Longrightarrow P_q \ll 1/2$

However there are three leading quarks (and also leading gluons) in each nucleon.

$\Rightarrow$ Probability not to interact $\equiv |1-\Gamma(b)|^2 \leq [P_q]^6 \sim 0$

☛ $\Gamma(b \sim 0) = 1$!!!

Explains the elastic pp data for small b, predicts an increase of b range, $b<b_F$ where $\Gamma=0$, $b_F = c \ln s$ - Froissart regime.

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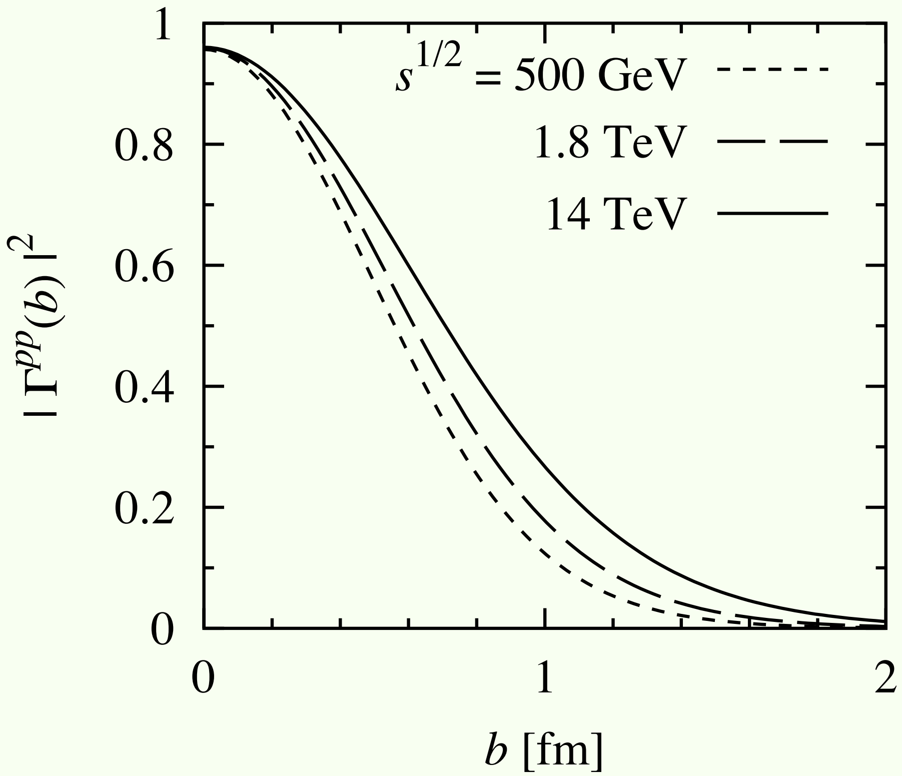
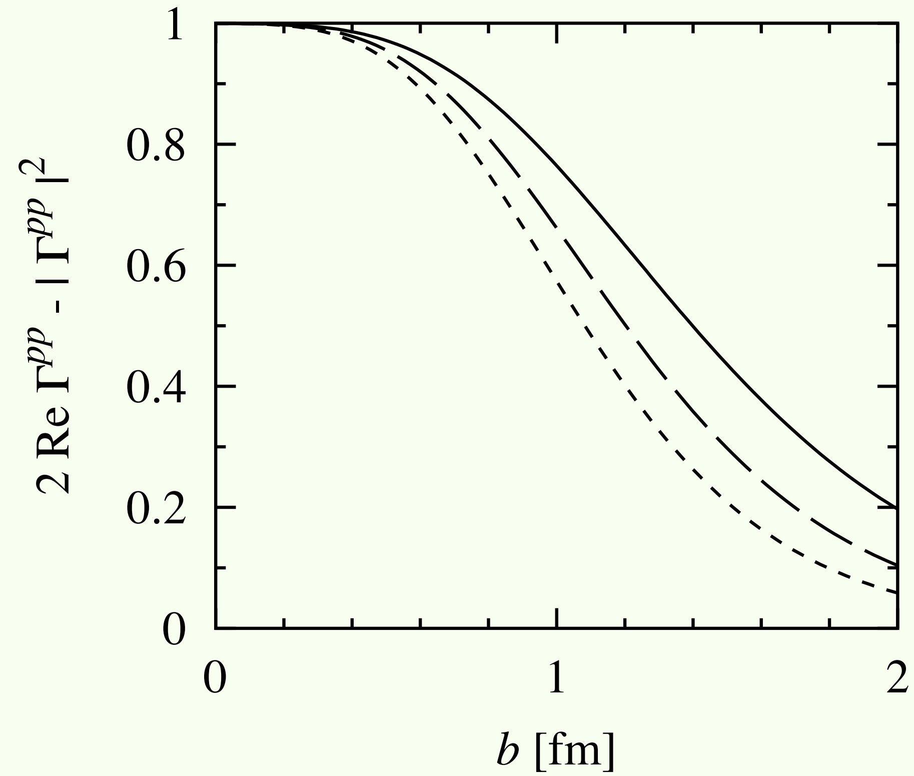
Warning - it is not all hard physics - peripheral collisions are contributing for all realistic energies - rate of jet production in this case is small - crucial to model for GZK dynamics





Calculation uses model of Islam et al; use of the model of Khoze et al leads to similar results.

Probability of inelastic interaction:

$$P(b) = 2\,Re\Gamma(b) - |\Gamma(b)|^2$$

Large b > 1 fm collisions generate ~ 50% of the total inelastic cross section of pp scattering. In such interactions nucleons interact mostly via their periphery - and valence quarks are likely not to be disturbed. Hence for such events - leading particle effect will survive. Challenge is to model simultaneously both small and large b collisions. Necessary for determining a fraction of events with leading nucleons. In any case this picture leads to large fluctuations of the global structure of the events in pp and to lesser extent in p-air interactions. At LHC look for anticorrelation between the forward protons/neutrons and activity at central rapidities.

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 $p_\perp \sim p_{\perp,\,BDL}$ 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 $p_\perp(jet) \gg p_{\perp,\,BDL}$

$\Longrightarrow$ Significant corrections to the LT approximation results for total cross sections and small $p_\perp \leq p_{\perp,\,BDL}$ differential cross sections 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.*

- *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.*

- *Significant corrects for the LT predictions especially for moderate transverse momenta.*

- *Double hard processes at Tevatron provides evidence for transverse correlations between partons. Maybe due to lumpy structure of nucleon at low scale (constituent quarks). Further studies of transverse correlations are necessary both at Tevatron and at RHIC in pp and pA scattering to improve modeling of LHC event structure.*

Conclusions II

- ★ *Many of the discussed effects are not implemented or implemented in a very rough way in the current MC's for LHC and cosmic rays*
- ★ *Forward physics for cosmic rays sensitive to small x physics - connection between pPb at LHC and GZK cosmic rays*
- ★ *Total opacity at small b ($\Gamma=1$) is due transition from soft to semi hard QCD - consistent with expected changes of the inelastic events for small impact parameters.*