Small x physics: from HERA to LHC

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Outline

- Imaging a fast nucleon.
- Onset of black regime of interaction for small dipoles
- Centrality trigger for pp collisions.

Role of High energy QCD:

- ☛ *Understanding the dynamics of strong gluon fields at small x: interesting by itself ; important for effective searches for new particles*
- ☛ *New unique probes of the nucleon structure*
- ☛ *Forward QCD dynamics is crucial for interpretation of the cosmic ray interactions near GZK cutoff*

So far major successes of QCD in describing high energy hadron hadron collisions were for **hard inclusive processes** - collision of two partons. *Sufficient to know only longitudinal single parton densities.*

Knowledge of

- ☛ *the transverse spread of partons*
- ☛ *longitudinal and transverse correlations of partons*

which **depend on flavor, x polarization of the parton,** is necessary for

- ◈ building a realistic description of the global structure of the final states in pp collisions
- ◈ understanding microscopic structure of nucleon bound state.

Progress in the recent years was due to the study of hard diffraction at HERA and related studies at Tevatron.

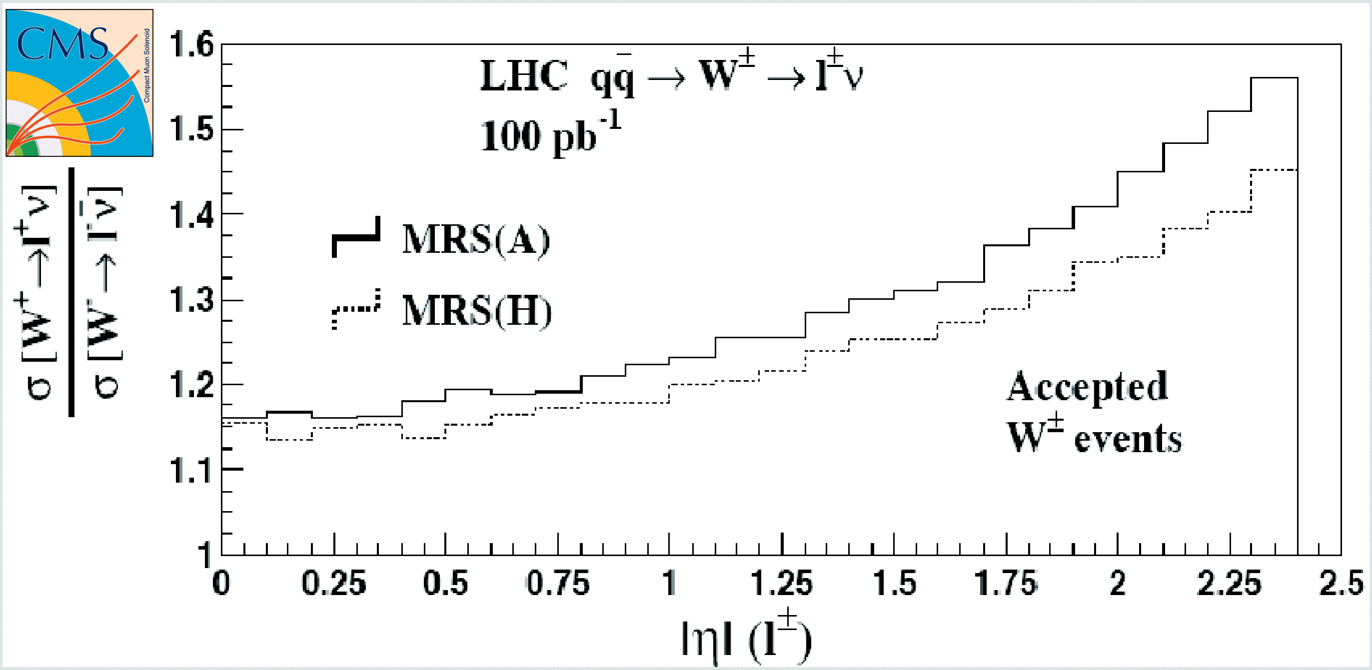
Three years from now LHC will dramatically change the field of QCD studies - parton densities, final states, etc

PDF from W/Z production

- p_T and rapidity distributions are very sensitive to pdf
  - particularly sensitive variable:

ratio of W^+/W^- cross section measures u(x)/d(x)

Example: study for 0.1 fb^{-1}, i.e. $2{\cdot}10^6$ $W\to\mu\nu$ produced



Study of final states in this reaction will allow also to compare transverse sizes of configurations in the nucleon with leading u-quark and leading d-quark. MS

J.Mnich: SM physics at LHC

Want to be able to take CT scans of nucleon

in 3 D in quark and gluon light at different momentum resolutions

instead of one dimensional scans - parton densities - which should continue especially at very small x.

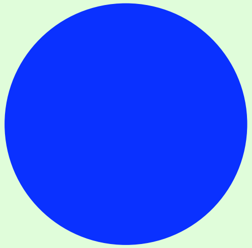
Learn how nucleon responds to various stimuli:

Correlations between partons

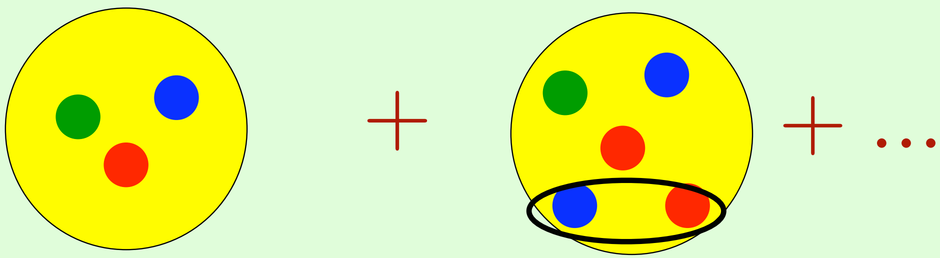
Correlations between longitudinal momenta of partons and transverse size of the nucleon.

Implications for propagation of partons through nuclei and for leading twist nuclear shadowing

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



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

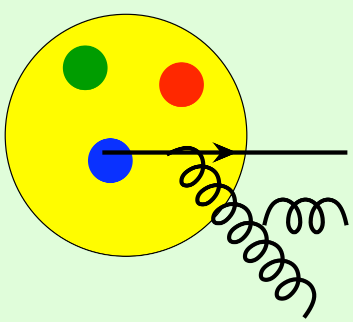


$q\bar{q}$ pair in π

resolution 1/3 fm

1000 > q > 300 MeV/c

Constituent quarks, pions (picture inspired by chiral QCD)



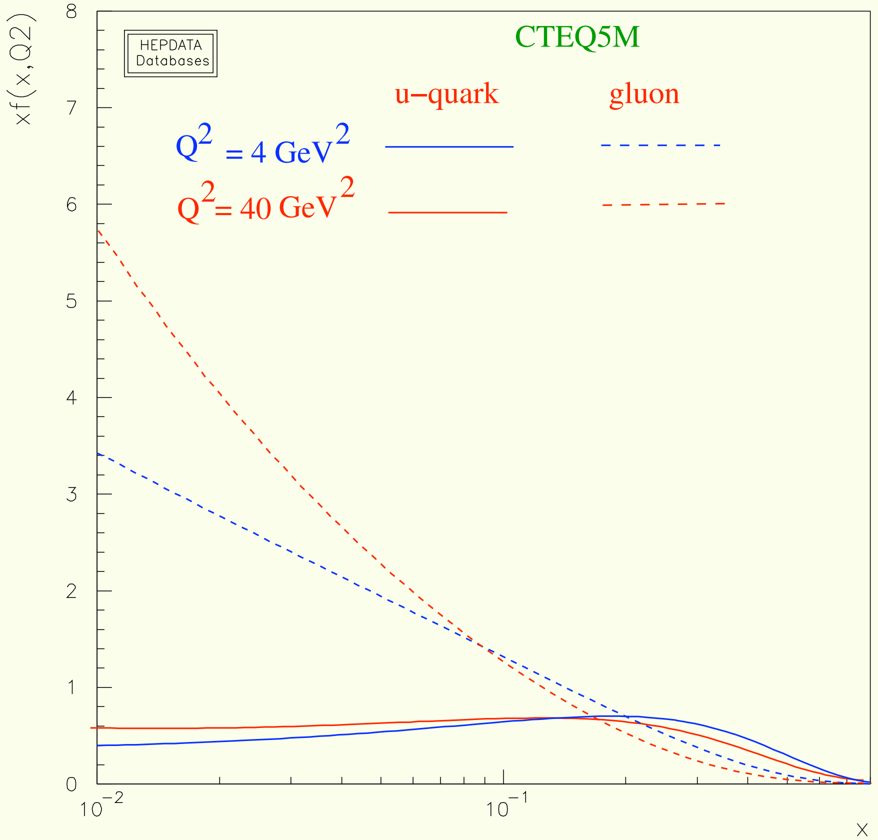
$q >$ 1000 MeV/c

pQCD evolution

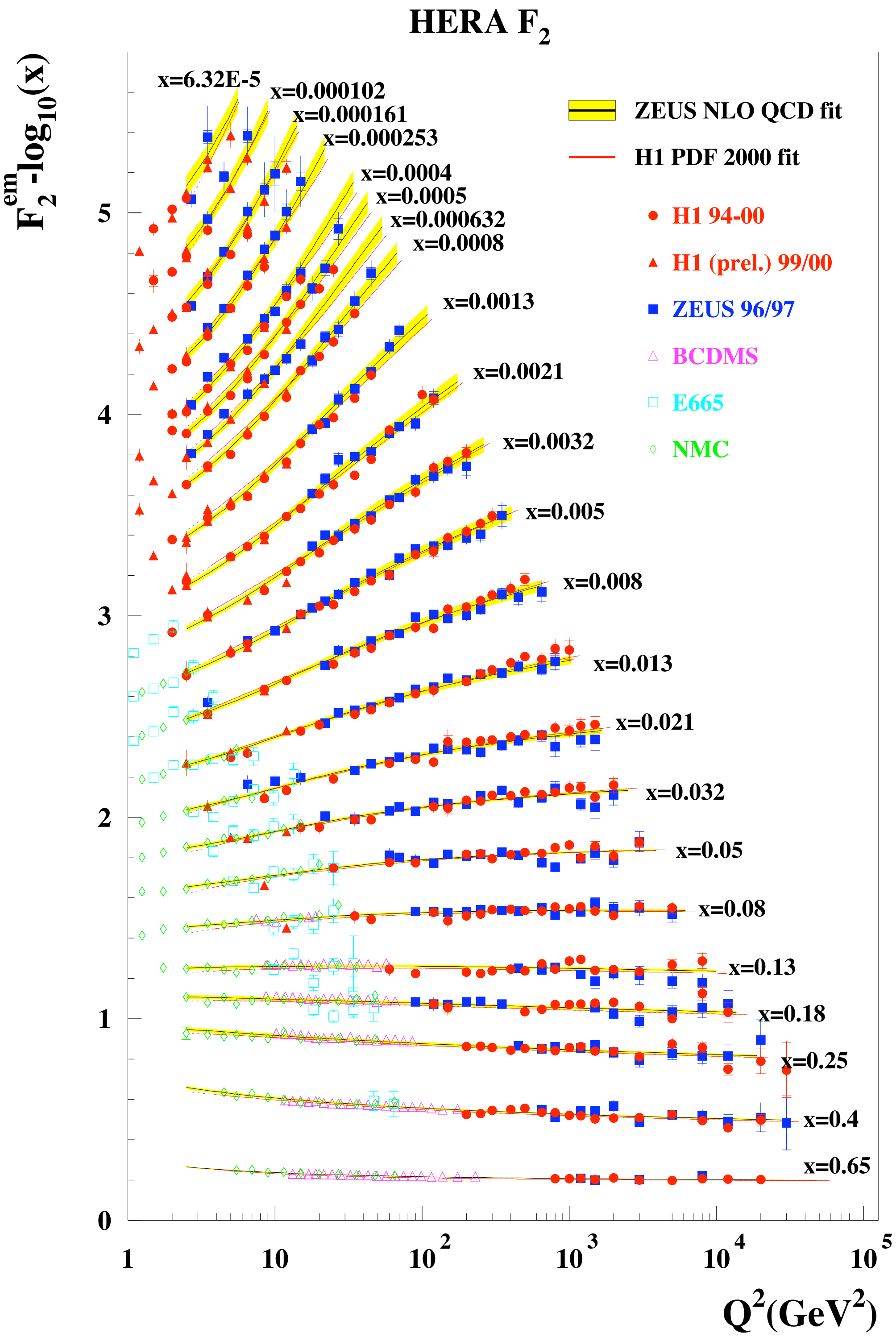
Key features of high energy QCD:

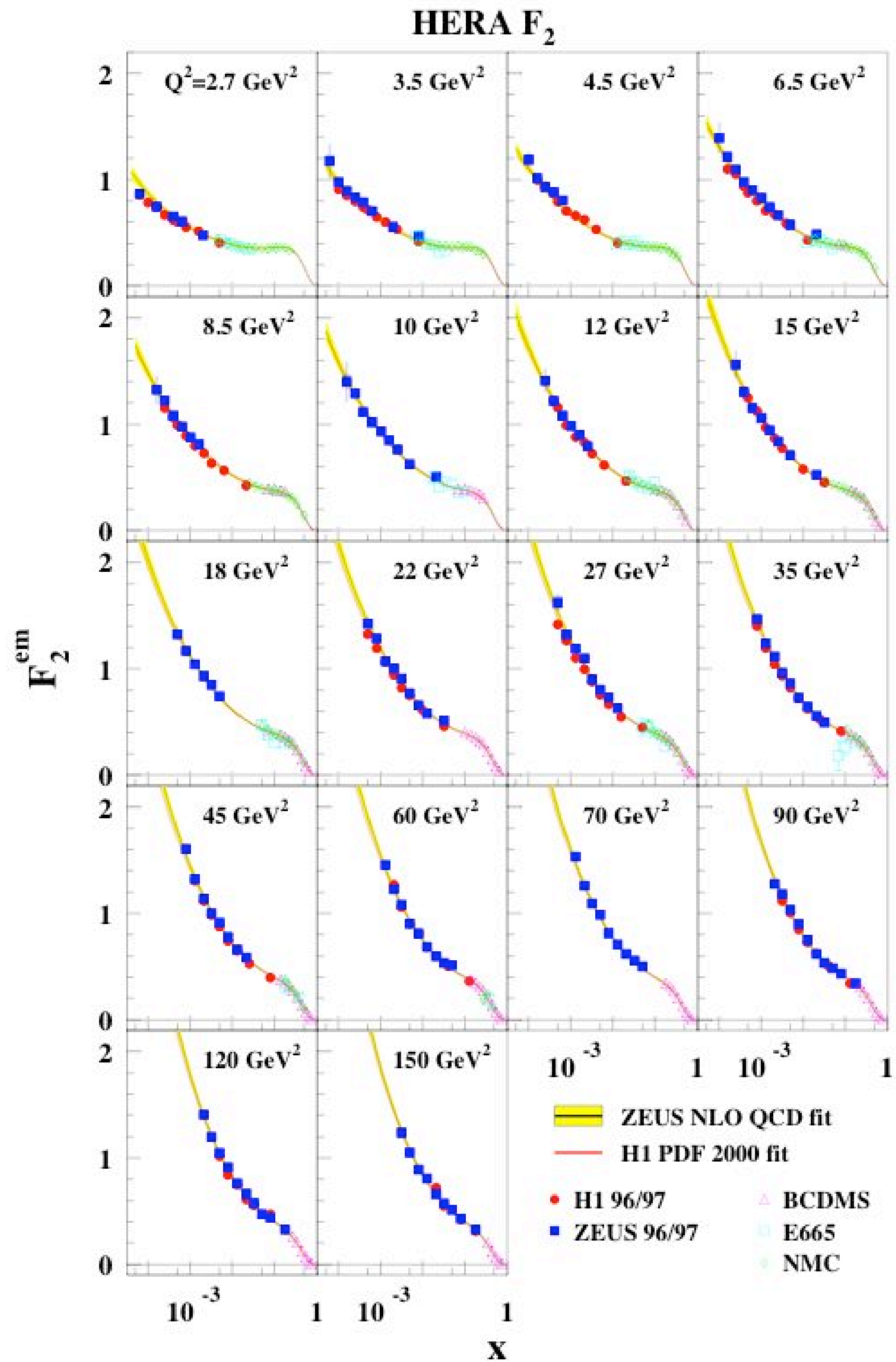
- Slow space-time evolution of the fast component of the high energy wave functions of colliding hadrons (Lorentz slow down)

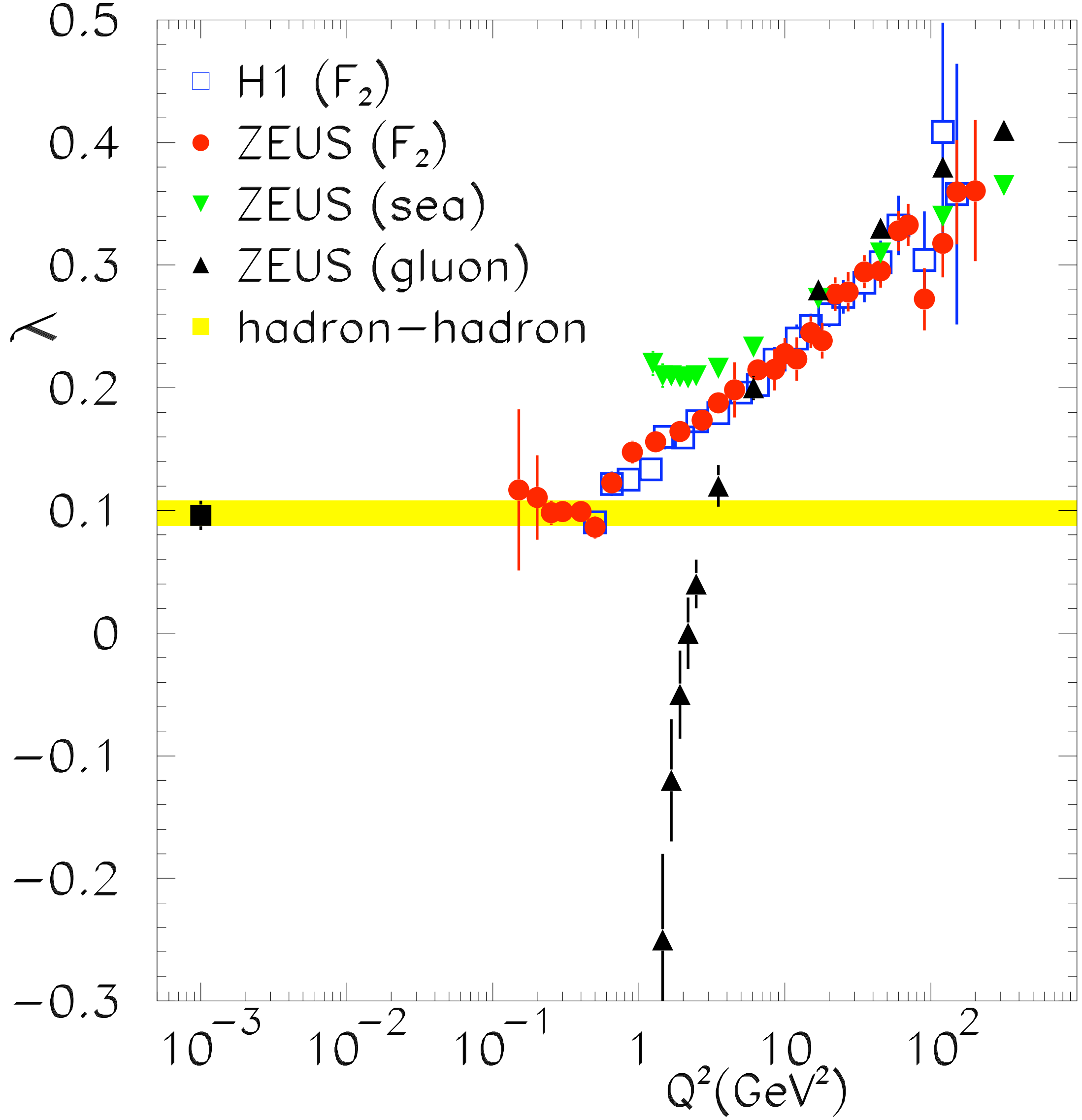
- Already at a rather modest resolution of the probe, Q~ 2 GeV, nucleon consists of not simply three quarks and few gluons but of tens of constituents and the number of constituents rapidly grows with energy.



- 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.


HERA F2
F2em-log10(x)
x=6.32E-5
x=0.000102
x=0.000161
x=0.000253
x=0.0004
x=0.0005
x=0.000632
x=0.0008
x=0.0013
x=0.0021
x=0.0032
x=0.005
x=0.008
x=0.013
x=0.021
x=0.032
x=0.05
x=0.08
x=0.13
x=0.18
x=0.25
x=0.4
x=0.65
ZEUS NLO QCD fit
H1 PDF 2000 fit
H1 94-00
H1 (prel.) 99/00
ZEUS 96/97
BCDMS
E665
NMC
Q2(GeV2)


HERA F2
F2em
Q2=2.7 GeV2
3.5 GeV2
4.5 GeV2
6.5 GeV2
8.5 GeV2
10 GeV2
12 GeV2
15 GeV2
18 GeV2
22 GeV2
27 GeV2
35 GeV2
45 GeV2
60 GeV2
70 GeV2
90 GeV2
120 GeV2
150 GeV2
ZEUS NLO QCD fit
H1 PDF 2000 fit
H1 96/97
ZEUS 96/97
BCDMS
E665
NMC
x

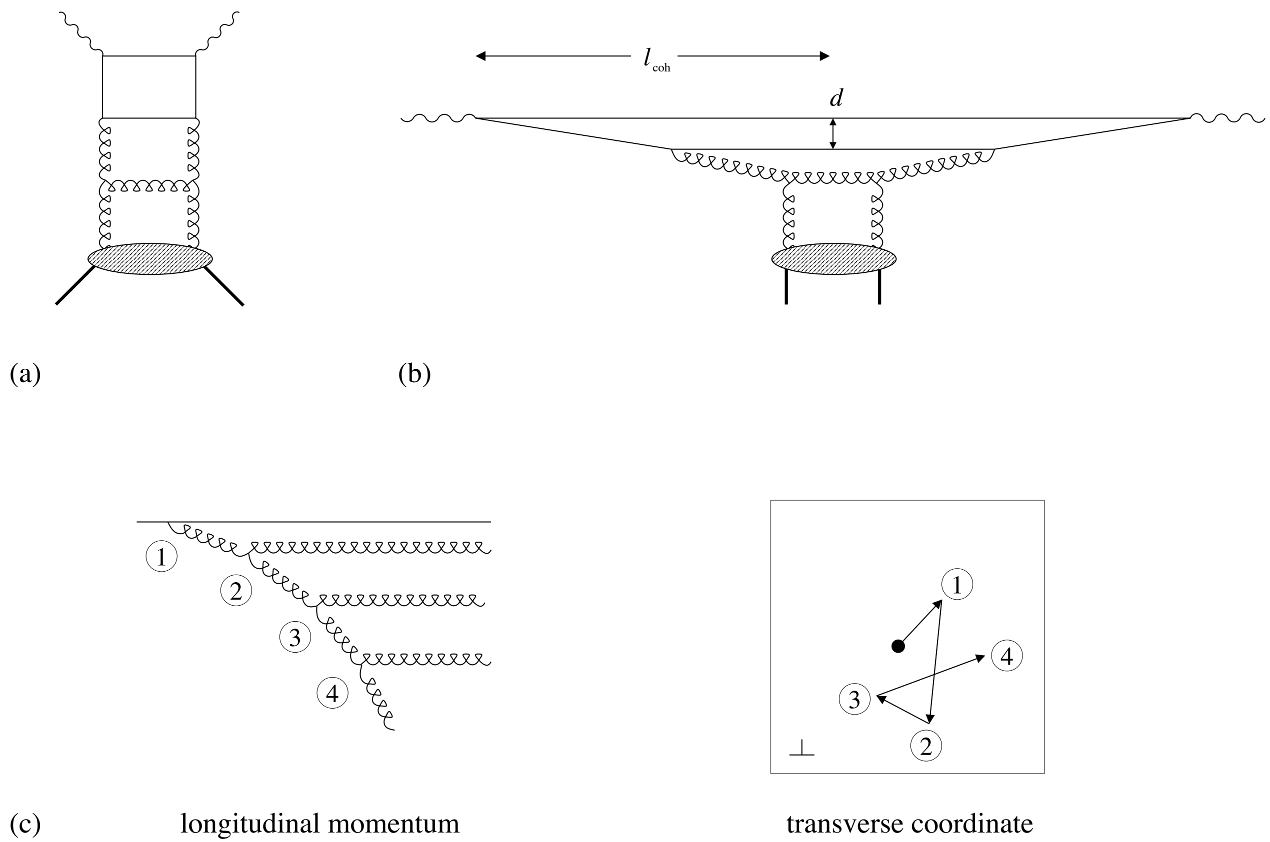


Fits: $F_{2p}(x,Q^2) \propto x^{-\lambda}$ $x\bar{q}(x,Q^2) \propto x^{-\lambda}$

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

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

Energy dependence of the transverse size of small x partons.



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

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

Length of the walk $\propto$ rapidity, 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 with energy.

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

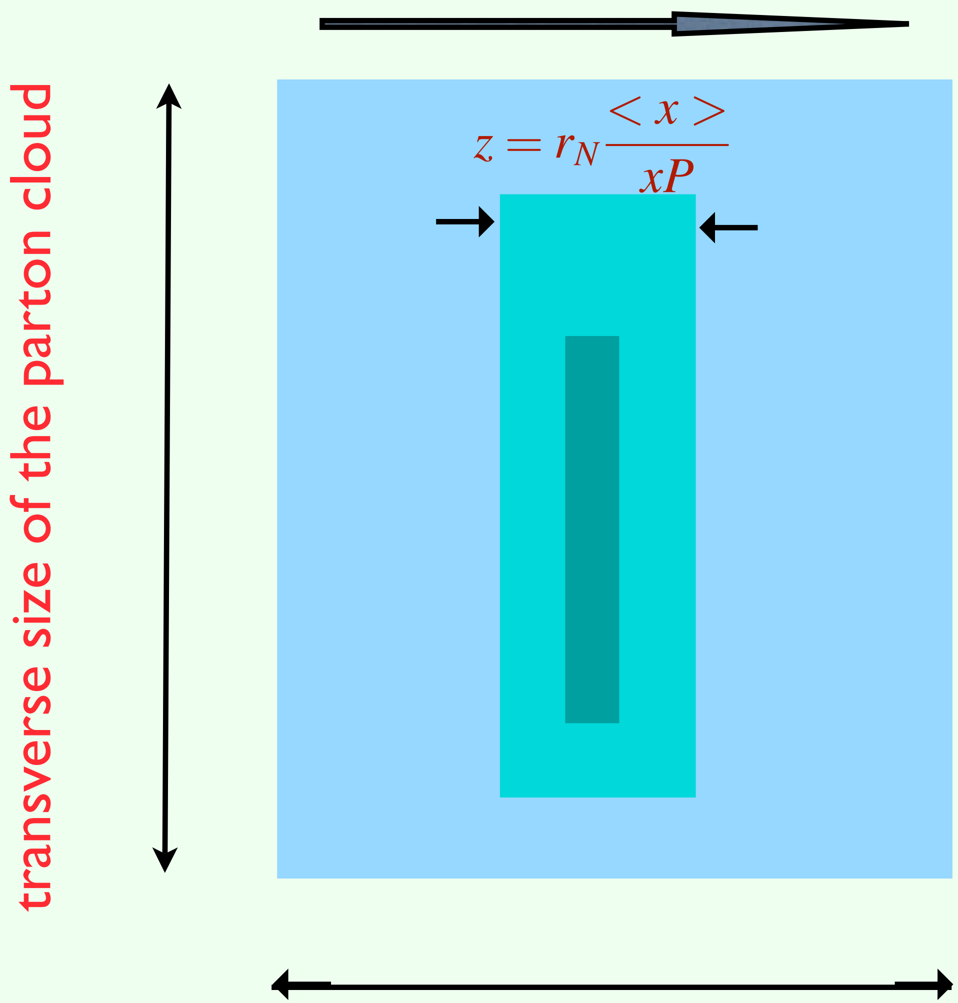
$$f(t) \propto \exp(Bt/2), \;\; B(s) = B_0 + 2\alpha' \ln(s/s_0)$$

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

Projection of the fast nucleon in transverse coordinate/ longitudinal momentum - low resolution scale

$$z = r_N \frac{<x>}{xP}$$

Momentum P in z direction



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

wee parton are spread over 1 fm even at high energies

Longitudinal momentum/transverse Image at High resolution

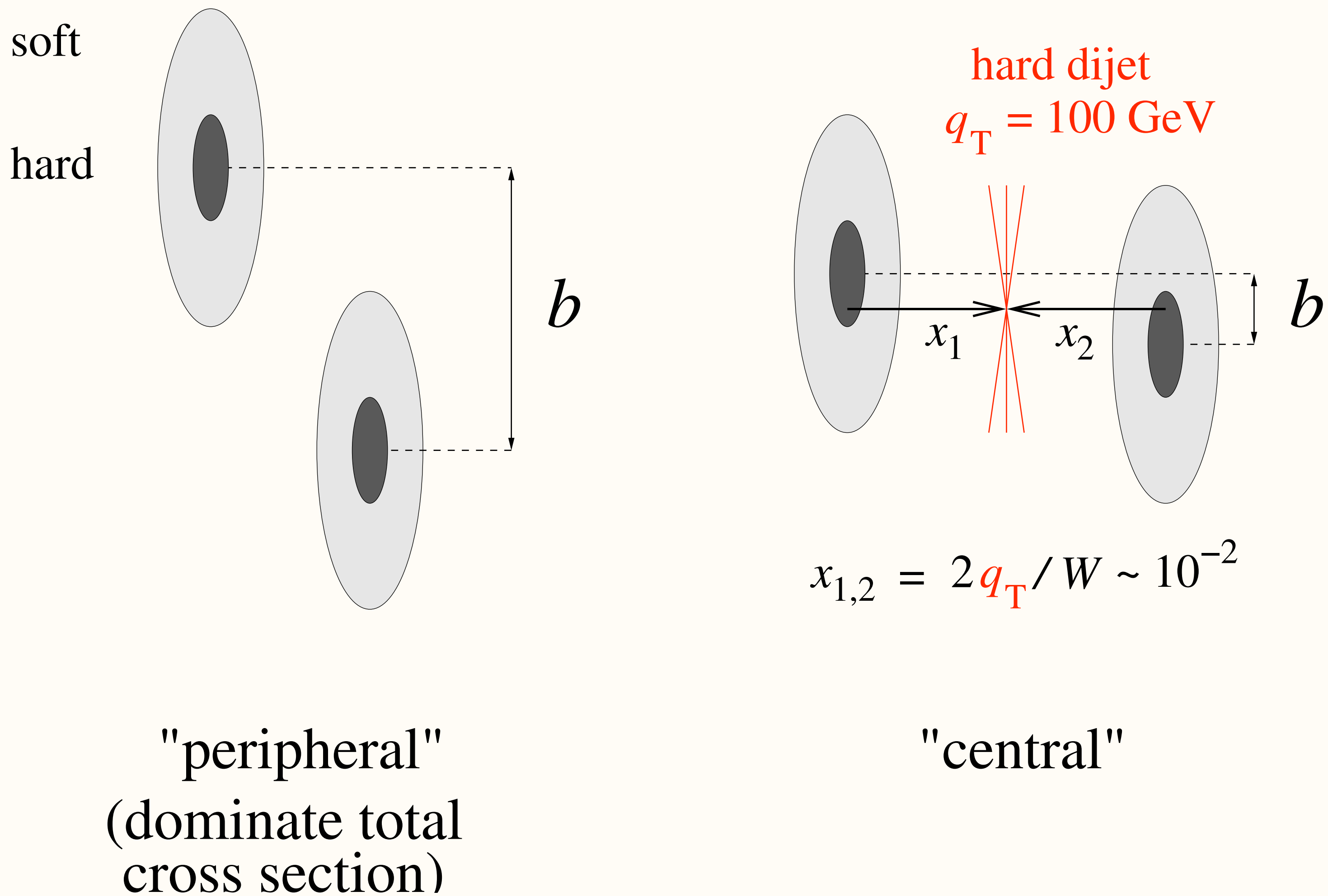
Implications: (b) Gribov diffusion is much weaker as the transverse momenta in most of the decay ladder are much larger than the soft scale. Transverse size shrinks with increase of resolution scale!!! *No analogous effect in classical mechanics (brain images).*

Evidence: α' for the process $\gamma + p \to J/\psi + p$ 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.



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.

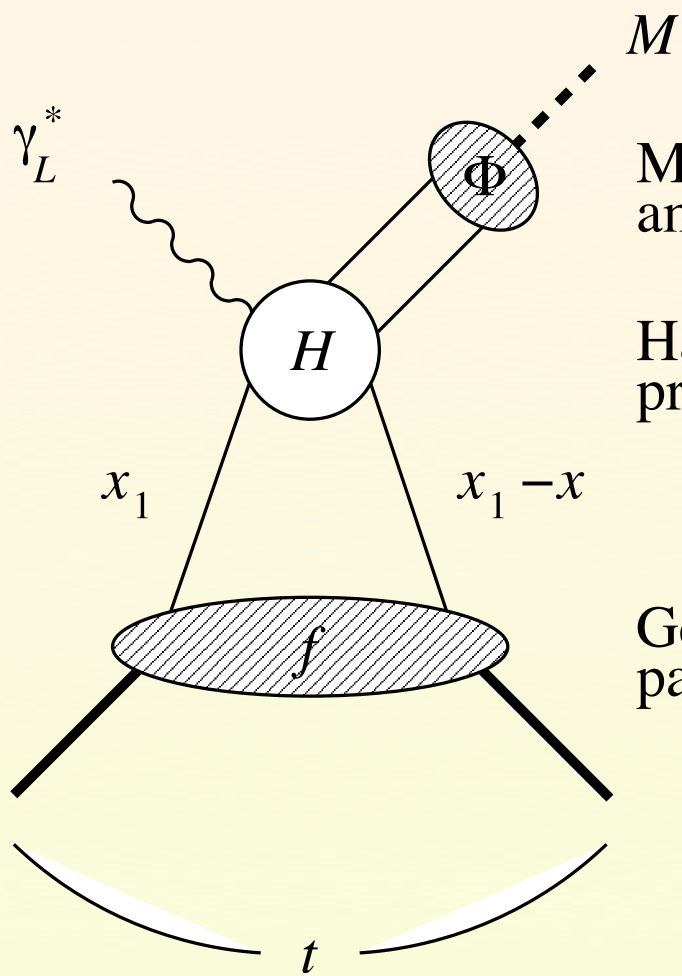
To quantify the difference of the impact parameters and the role of small x gluon field we can use theoretical analyses of the hard phenomena studied at HERA:

- Determination of the transverse distribution of gluons.

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

QCD factrorization theorem for DIS exclusive processes

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



Meson distribution amplitude

Hard scattering process

Generalized parton distribution

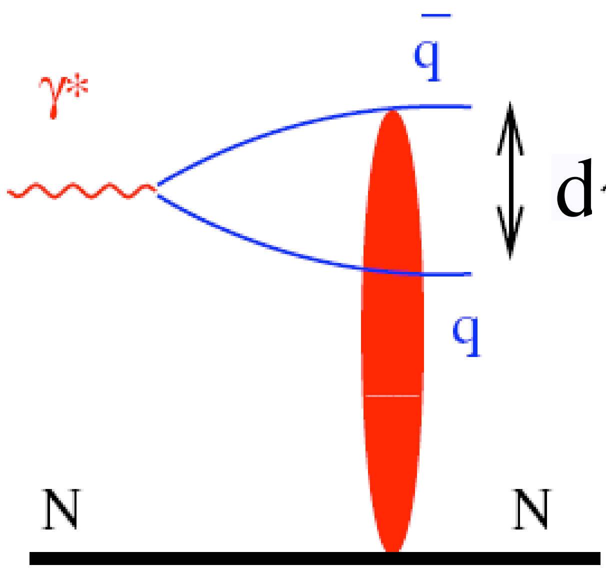
Extensive data on VM production from HERA support dominance of the pQCD dynamics. Numerical calculations including finite transverse size effects explain key elements of high Q^2 *data. The most important ones are:*

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

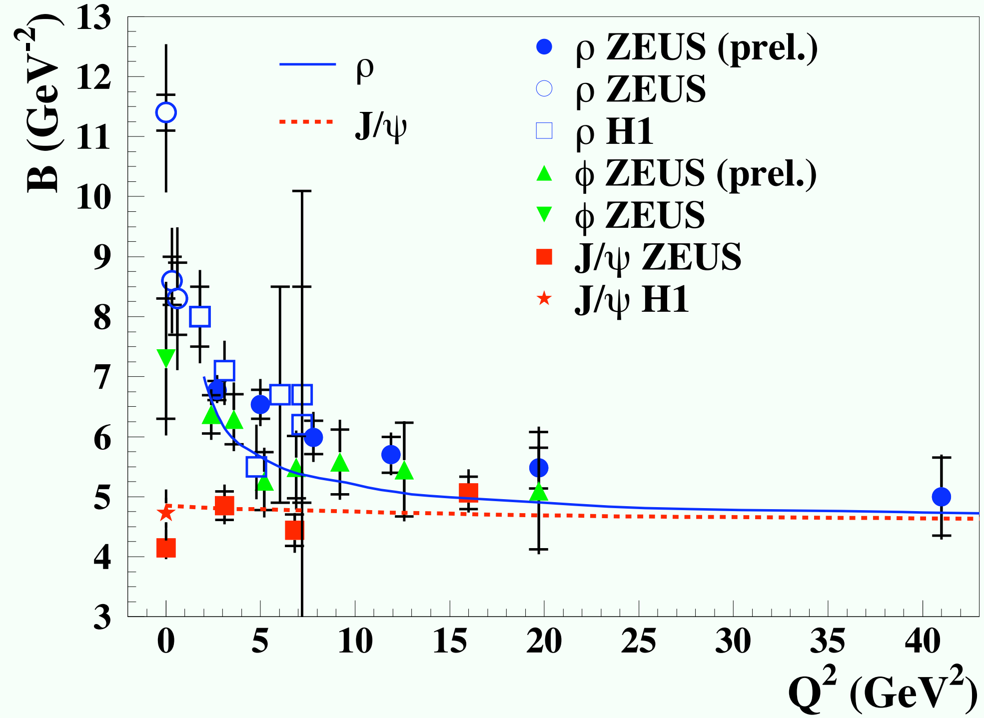
- Absolute cross section and energy dependence of ρ−meson production at $Q^2 \geq 20\ GeV^2$. Explanation of the data at lower Q^2 is more sensitive to the higher twist effects, and uncertainties of the low Q^2 gluon densities.

- 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,

  Onset of universal regime FKS[Fra $F_g(x,t)$. $d\sigma/dt \propto F_g^2(x,t)$.

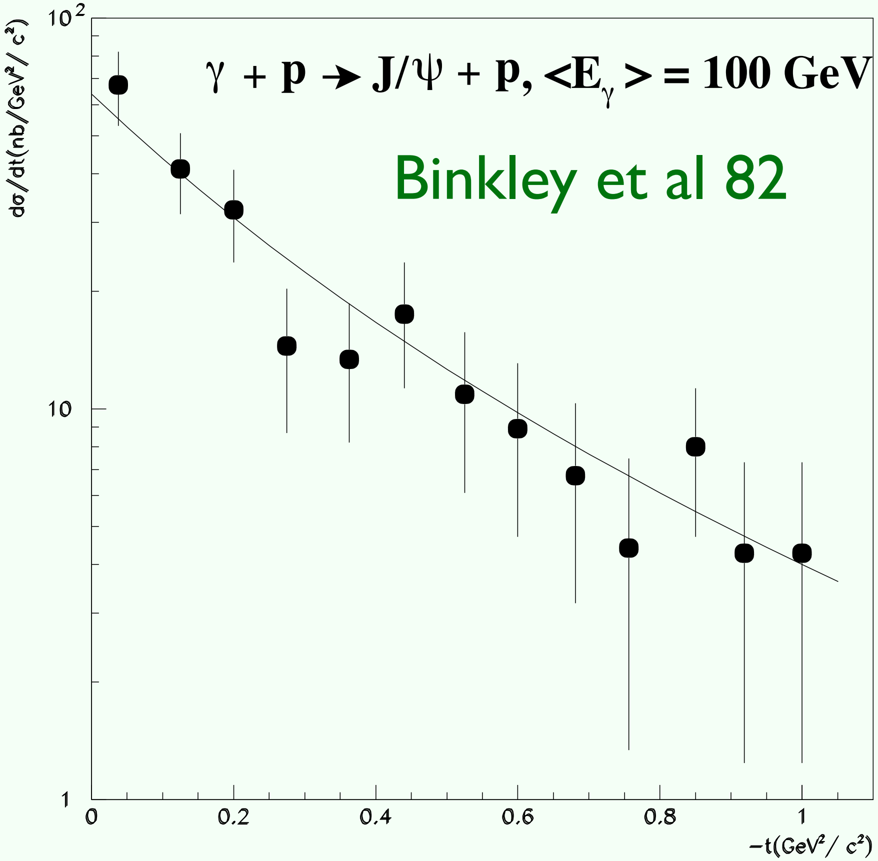


d~ $r_T \propto \frac{1}{Q}(\frac{1}{m_c}) \ll r_N$



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

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



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

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

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 $x_{parton} > 0.01$.

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.

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:

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

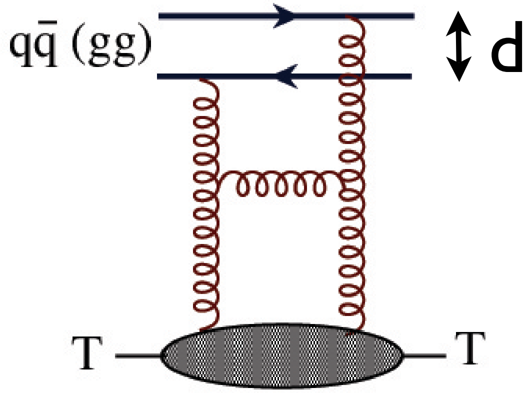
  Slow evolution of this wave package.

- 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.

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.



Consider first "small dipole - hadron" cross section

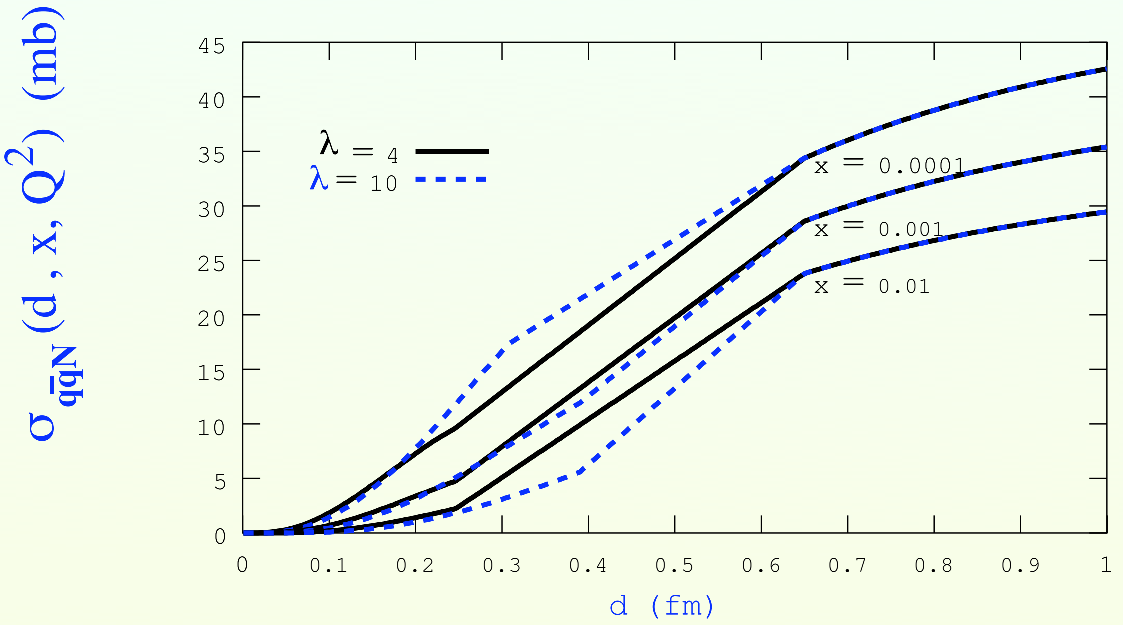
$$\sigma_{inel} = \frac{\pi^2}{3} F^2 d^2 \alpha_s(\lambda/d^2) x G_T(x.\lambda/d^2)$$

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.

Frankfurt, Guzey, McDermott, MS 2000-2001

Provided a reasonable prediction for σ_L

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 body limit.

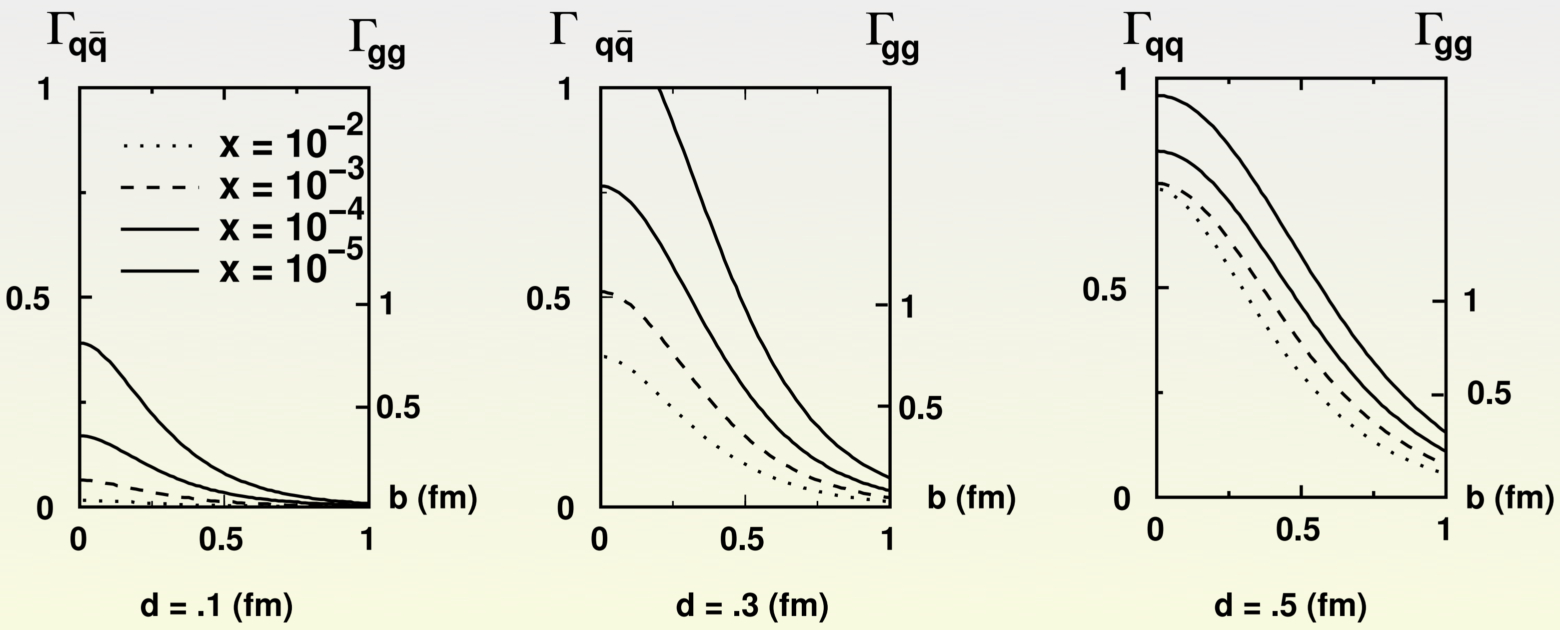
Note that elastic unitarity: $\frac{1}{2}ImA = |A|^2 + \ldots$ allows $\Gamma(b) \leq 2$

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

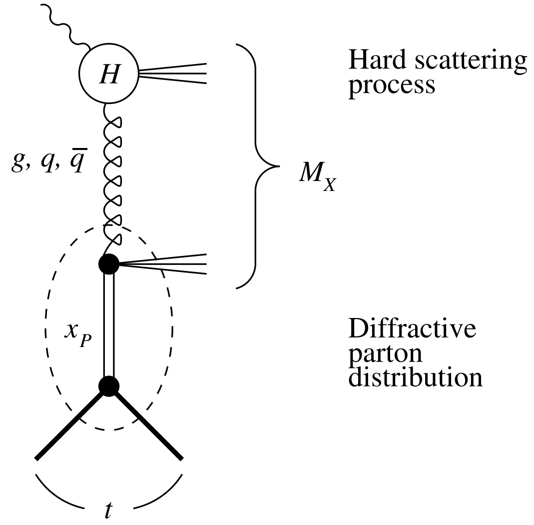
$$\Gamma_{q\bar{q}} \ from \ \sigma(q\bar{q}N).$$

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 BBL



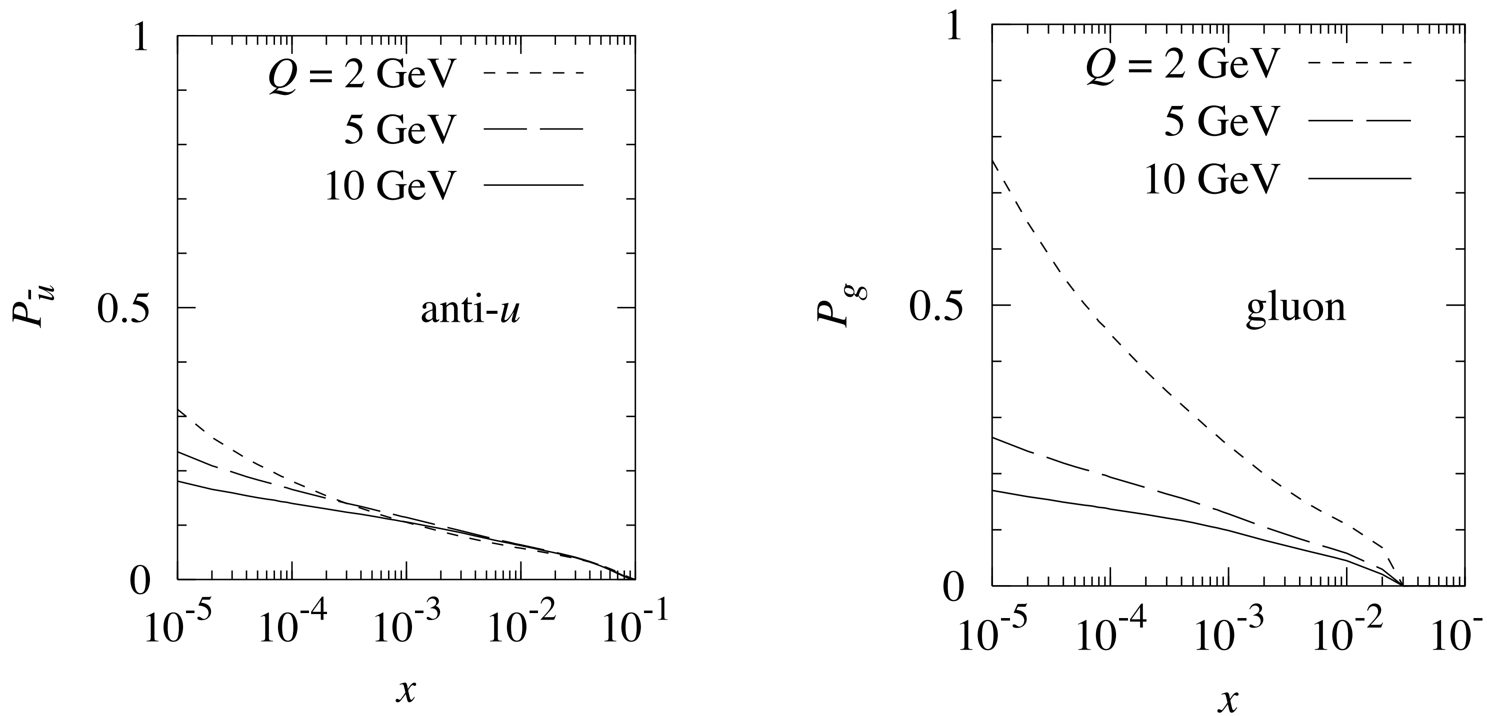
QCD factorization theorem for diffractive processes consistent with the data to define **universal** diffractive parton densities:

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

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



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

FS98

Conclusion

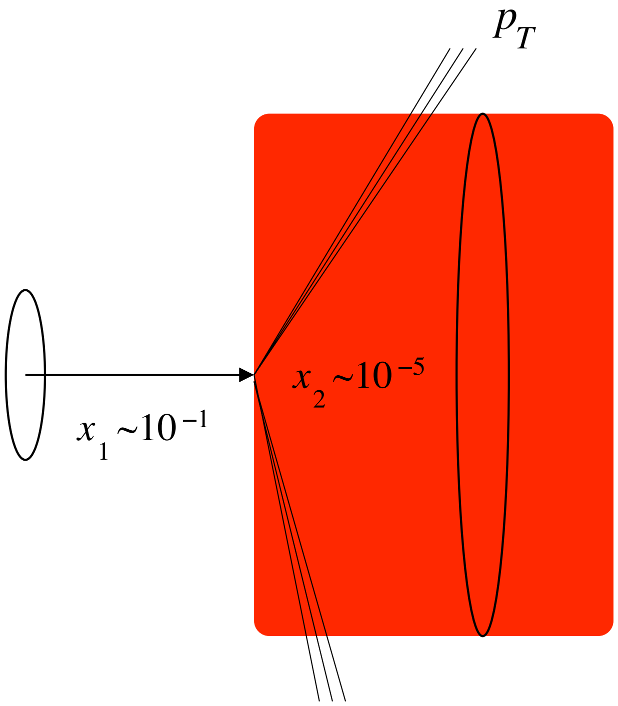
Incident partons which have large enough energies to resolve $x \sim 10^{-4} \div 10^{-5}$ in the target nucleon and which pass close enough $b \leq 0.5 fm$ from the nucleon, interact with the nucleon in a regime which is likely to be close to the black body regime.

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

Hard dynamics governs the BLACK BODY (BB) regime in hadron-hadron collisions at small impact parameters (FSZ 04)

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:

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

F^2 Casimir operator of color SU(3)

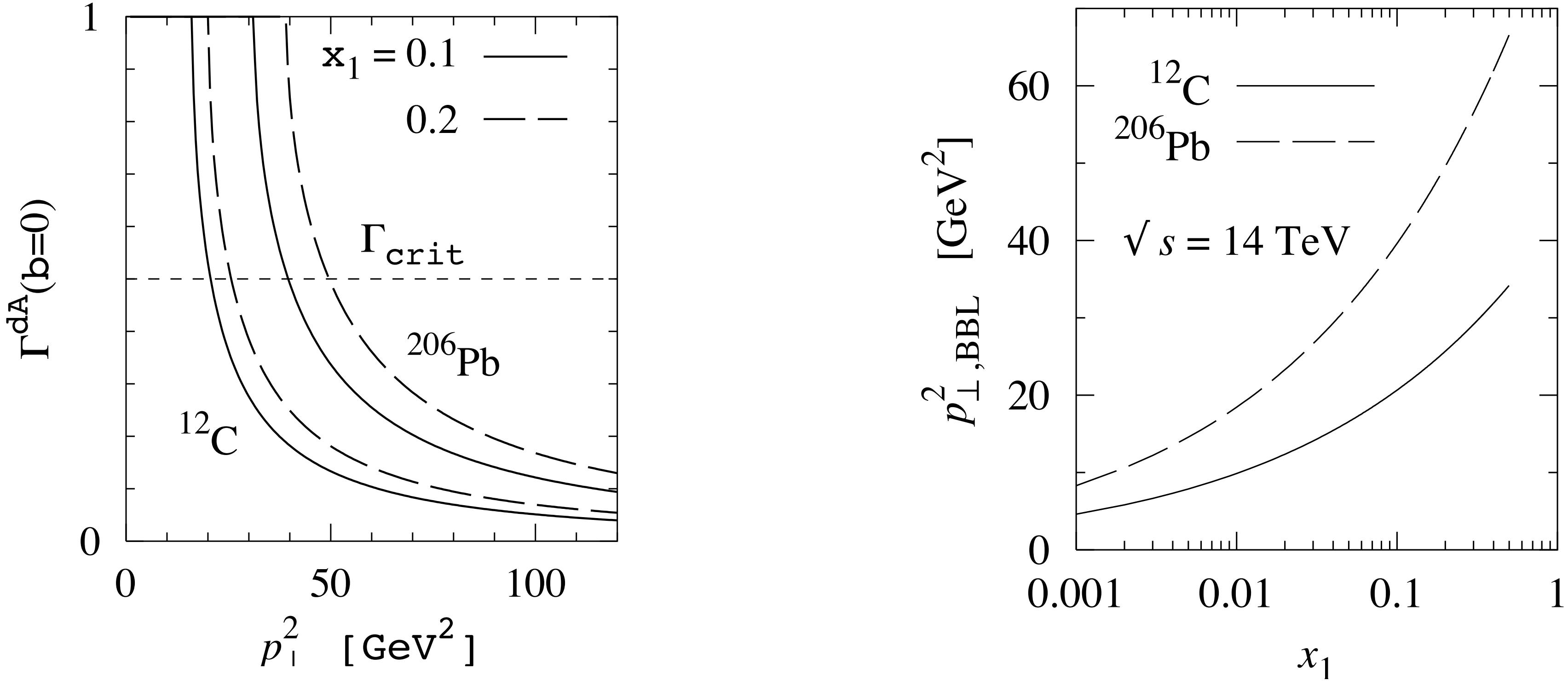
F^2 (quark) =4/3 F^2 (gluon)=3

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 BBL:

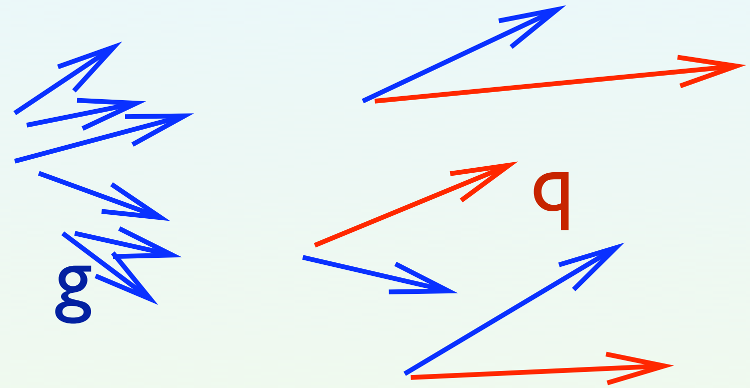
$$\Gamma^{\text{"}dipole\text{"}A}(b=0) \geq \Gamma_{crit} \sim 0.5$$

corresponding to probability of inelastic collision of .75



Black–body 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, BBL, for which the interaction of the leading gluonis“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

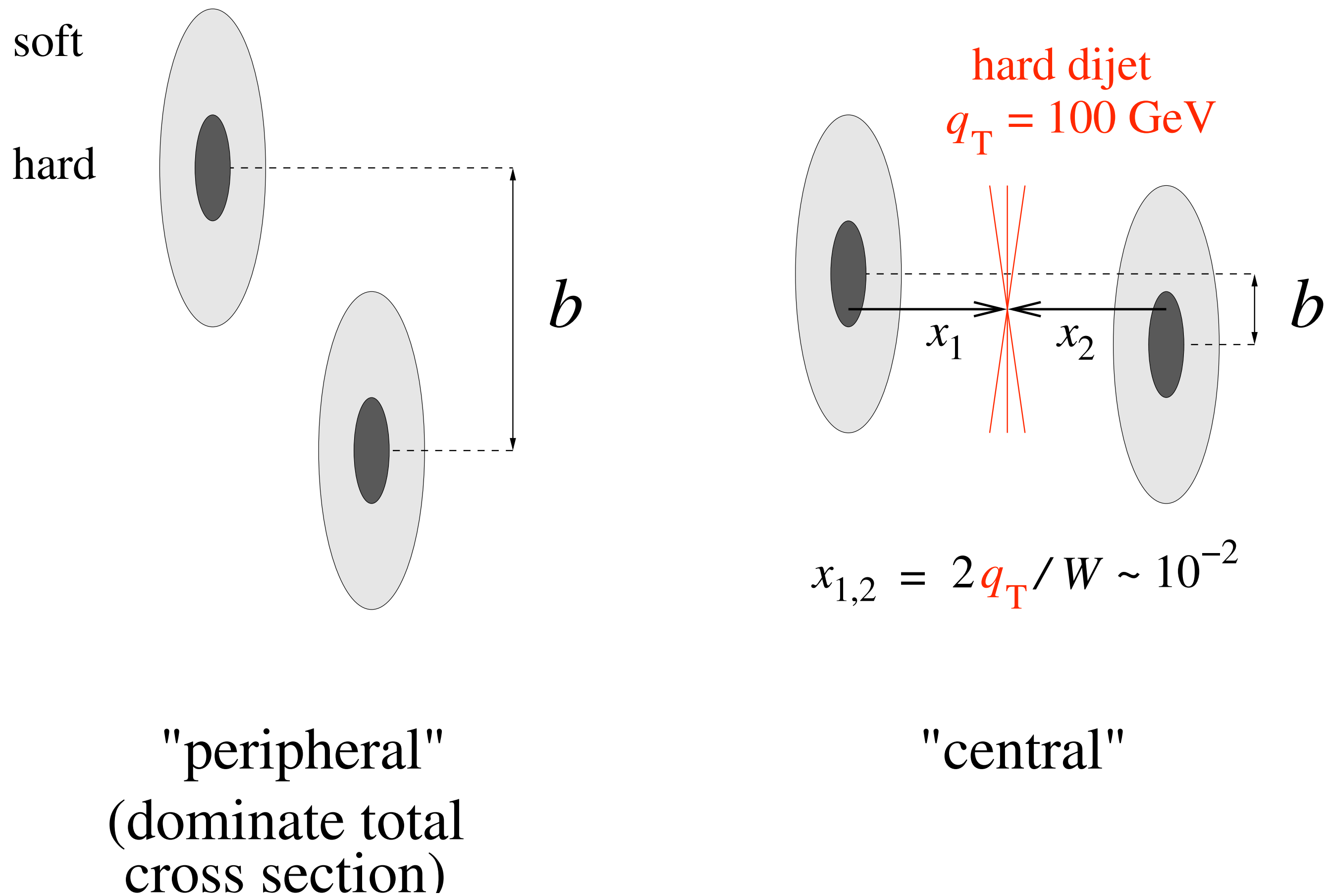
The leading particle spectrum will be strongly suppressed compared to minimal bias events since each parton fragments independently and splits into a couple of partons with comparable energies. The especially pronounced suppression for nucleons: for $z \geq 0.1$ the differential multiplicity of pions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

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

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.***

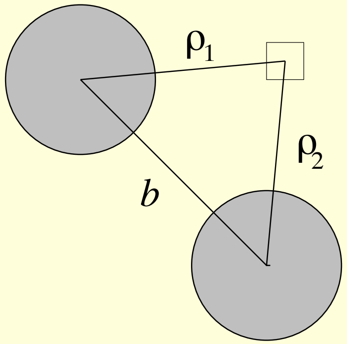
Hence in events with hard interaction spectator partons experience much stronger gluon fields.



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 $q_\perp$.

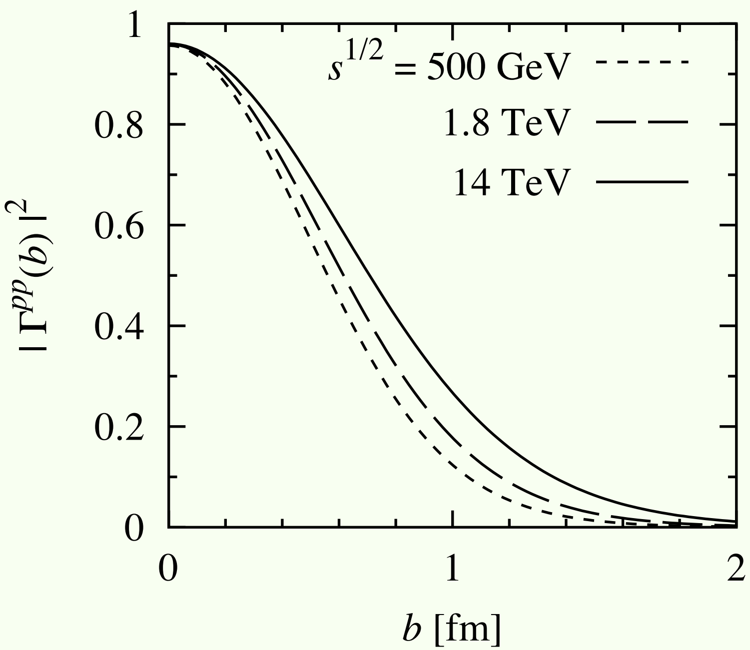
The overlap integral of parton distributions in the transverse plane, defining the b–distribution for binary parton collisions producing a dijet follows from the figure:

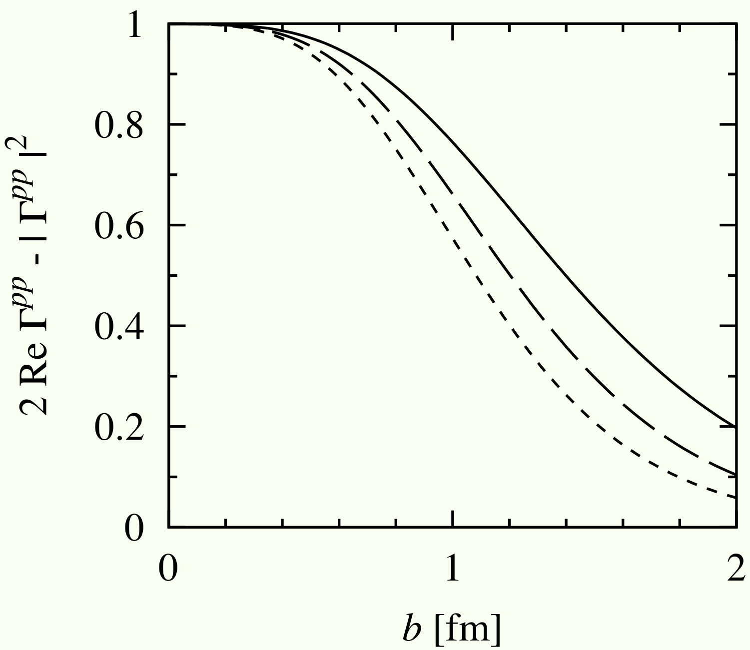


Impact parameter distribution in pp interaction

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

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





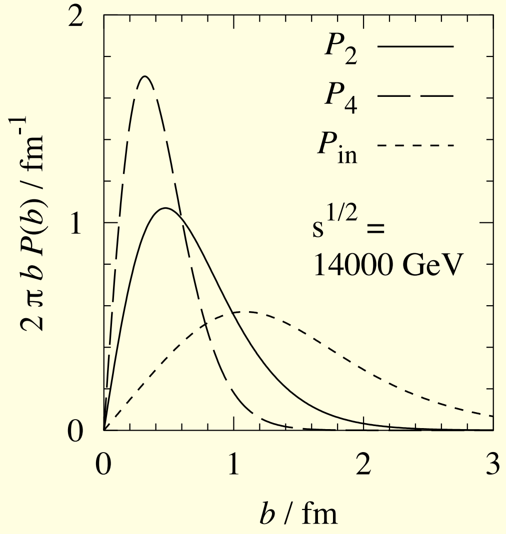
Calculation uses model of Islam et al

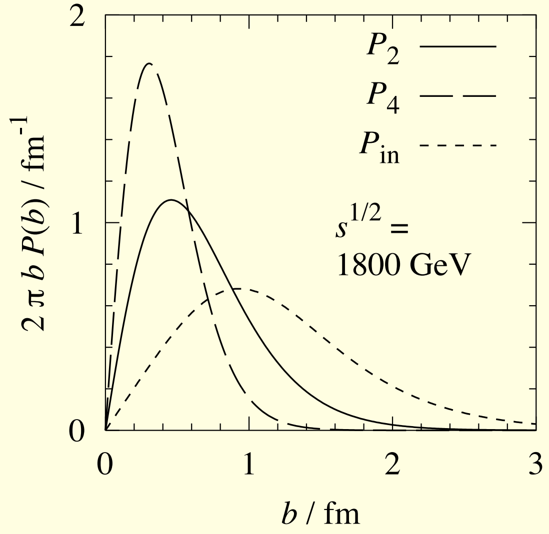
Probability of inel. interaction:

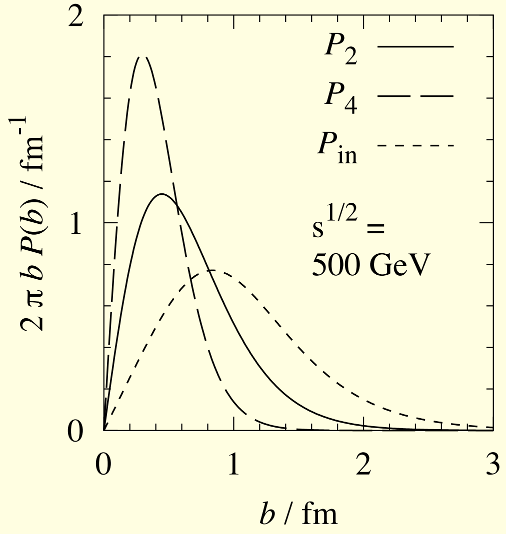
$$P(b) = 2\,Re\Gamma(b) - |\Gamma(b)|^2$$

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

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







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. Estimate involves several steps.

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

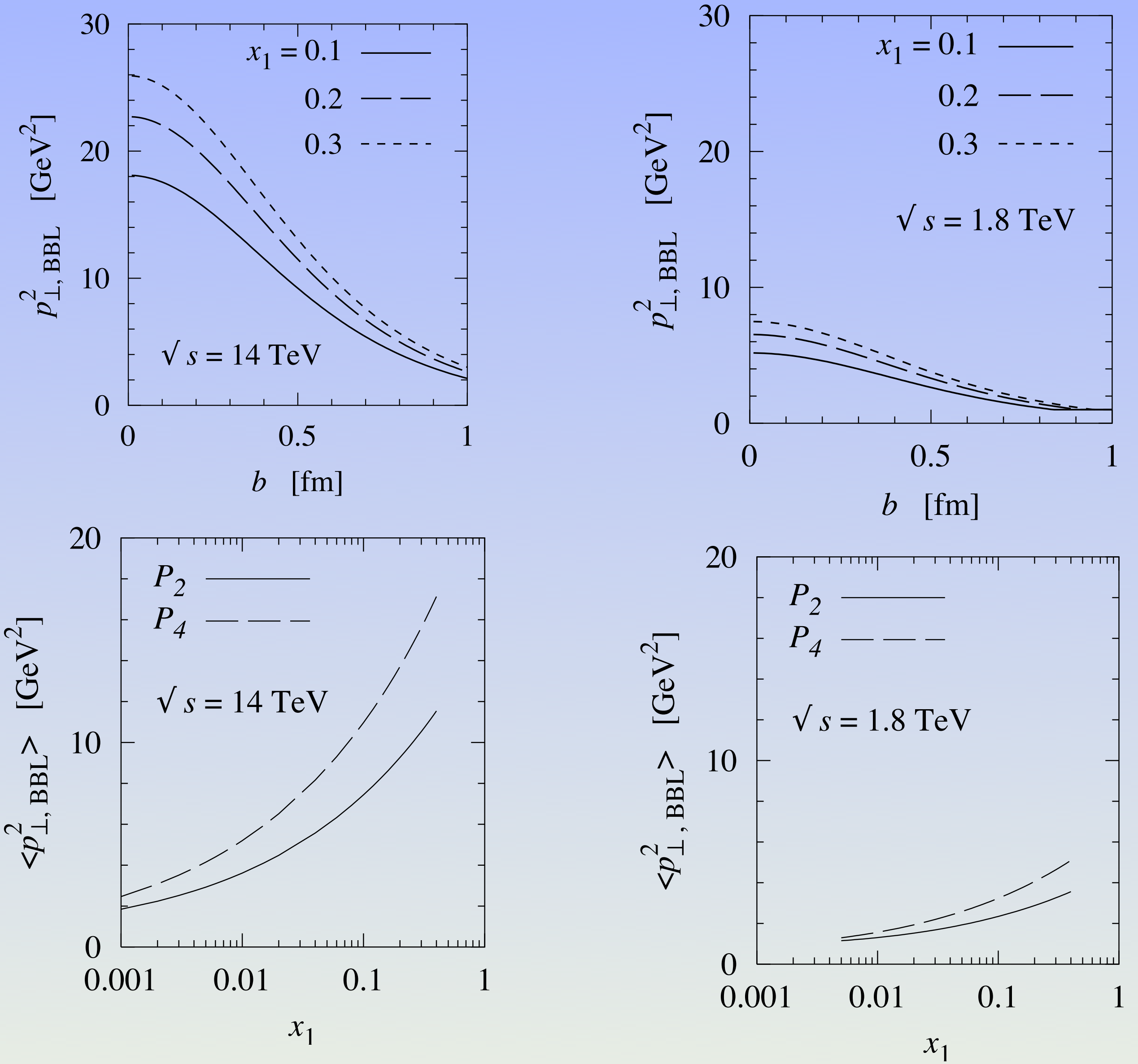
- Determining what minimal x are resolved in the second proton for given virtuality $x = \frac{4p_\perp^2}{x_1 s}, Q^2 = 4p_\perp^2$ $small\, x \leftrightarrow large\, x_1$

- 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 $p^2_{\perp,\mathrm{BBL}}$ are about half of those for gluons.

Also, a spectator parton in the BBL regime loses a significant fraction of its energy *similar to electron energy loss in backscattering of laser off a fast electron beam.*

☺ 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.

⇒ 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.

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 $\Rightarrow$ 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 $p_\perp \le p_{\perp,BBL}$ 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.*

- ★ *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.*

- ★ *Total opacity at small b ($\Gamma = 1$) in pp collisions is due transition from soft to semi hard QCD - consistent with expected changes of the inelastic events for small impact parameters.*

- ★ *Double hard processes at Tevatron provides evidence for transverse correlations between partons. Maybe due to lumpy structure of nucleon at low scale (constituent quarks) [did not have time to discuss]. 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.*