3D structure of the nucleon gluons field and its implications for associated hadron production in events with dijets and new particles and for hard diffraction.

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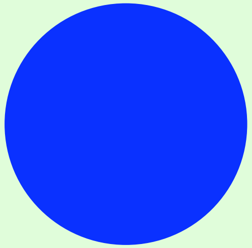
HERA-LHC workshop, October 12, 2004

Outline

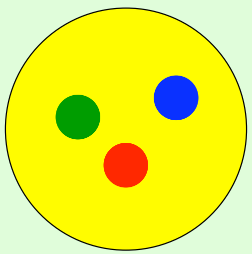
- Introduction: three dimensional structure of high energy nucleon and QCD at LHC
- Impact parameter distributions in inelastic events with dijet trigger vs minimal bias events.
- Up to what p_T pp - interactions are black at small impact parameters at LHC
- ☺ Predictions for LHC

- Lessons/questions from HERA studies
- HERA + "CDF Multi-jet production" - implications for parton correlations in nucleons
- ☺ Input from HERA to gap survival in pp

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



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



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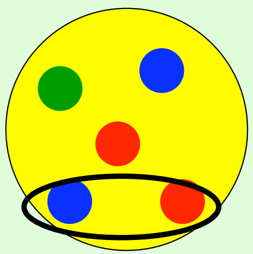


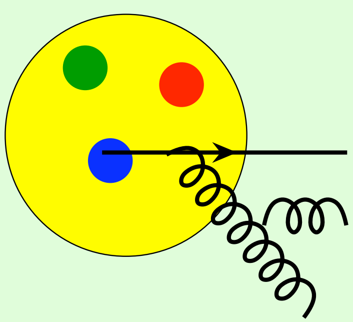
+ ...

$q\bar{q}$ *pair in* □

resolution 1/3 fm

1000 > q > 300 MeV/c

Constituent quarks, pions (picture inspired by chiral QCD)



q > 1000 MeV/c

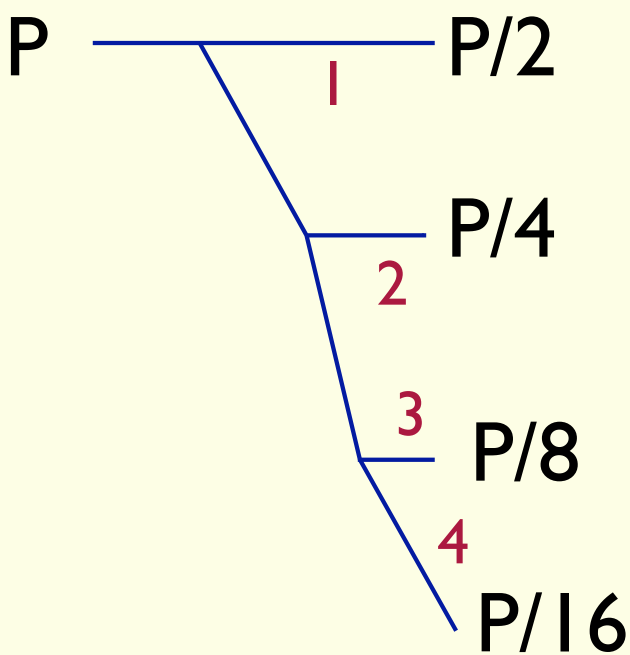
pQCD evolution

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

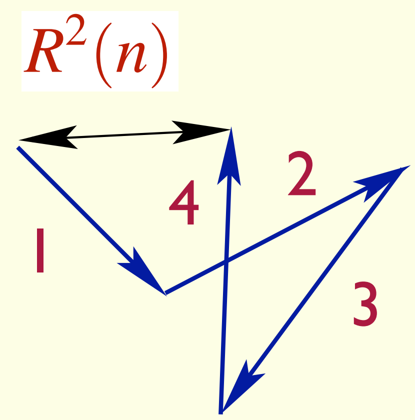
Energy dependence of the transverse size of soft partons.

Decay of a fast parton

Longitudinal momentum



Transverse plane coordinate.



$R^2(n) \approx \frac{n}{k_{t0}^2}$ Random walk in b-space (Gribov 70). *(Drunken sailor walk)*

Length of the walk rapidity, y. The transverse size of the soft wee parton cloud should logarithmically grow with energy.

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

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

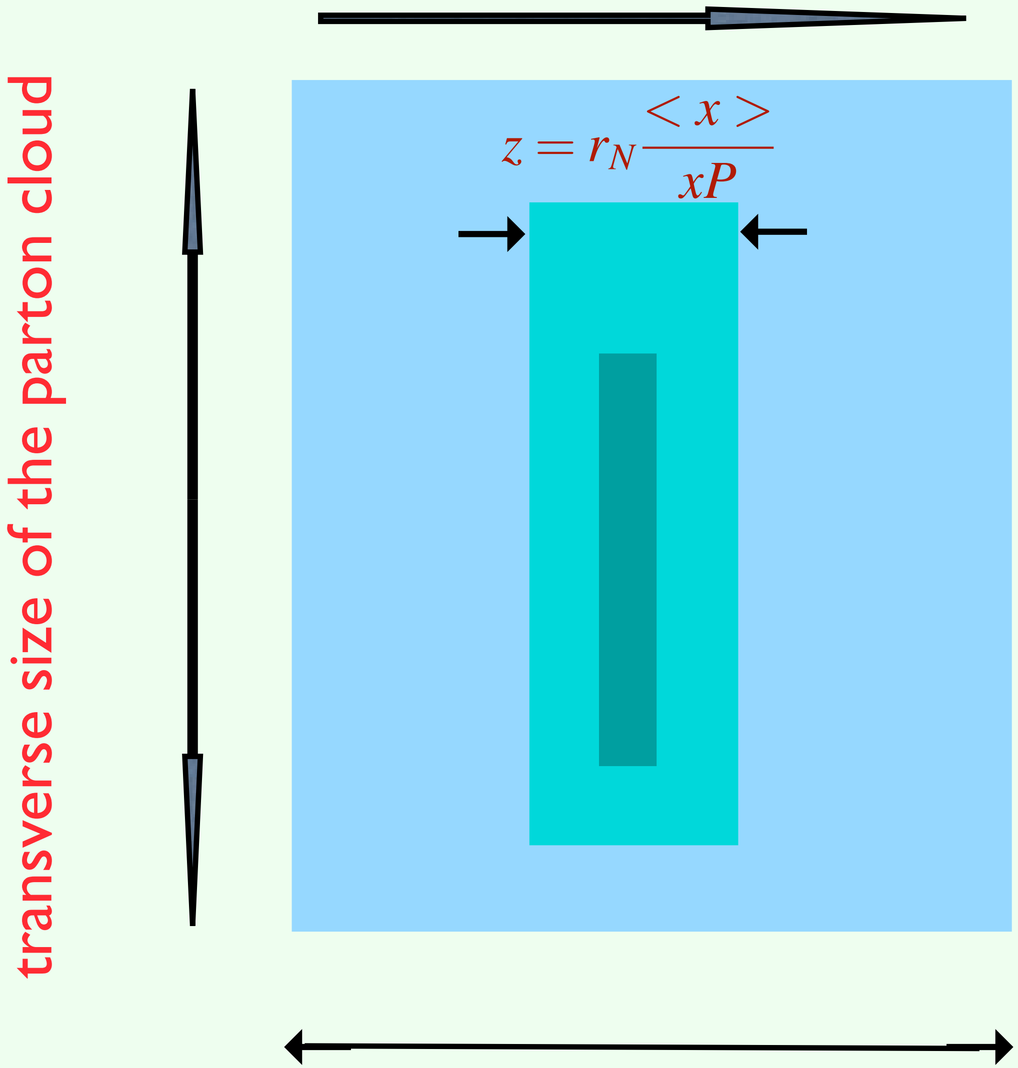
$$f(t) \quad \exp(Bt/2), \;\; B(s) = B_0 + 2\Box' \ln(s/s_0)$$

$$\Box' \quad 1/k_{t0}^2$$

Sagittal (in zx plane) cut of the fast nucleon - low resolution scale

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

Momentum P in z direction



wee parton are spread over 1 fm even at high energies

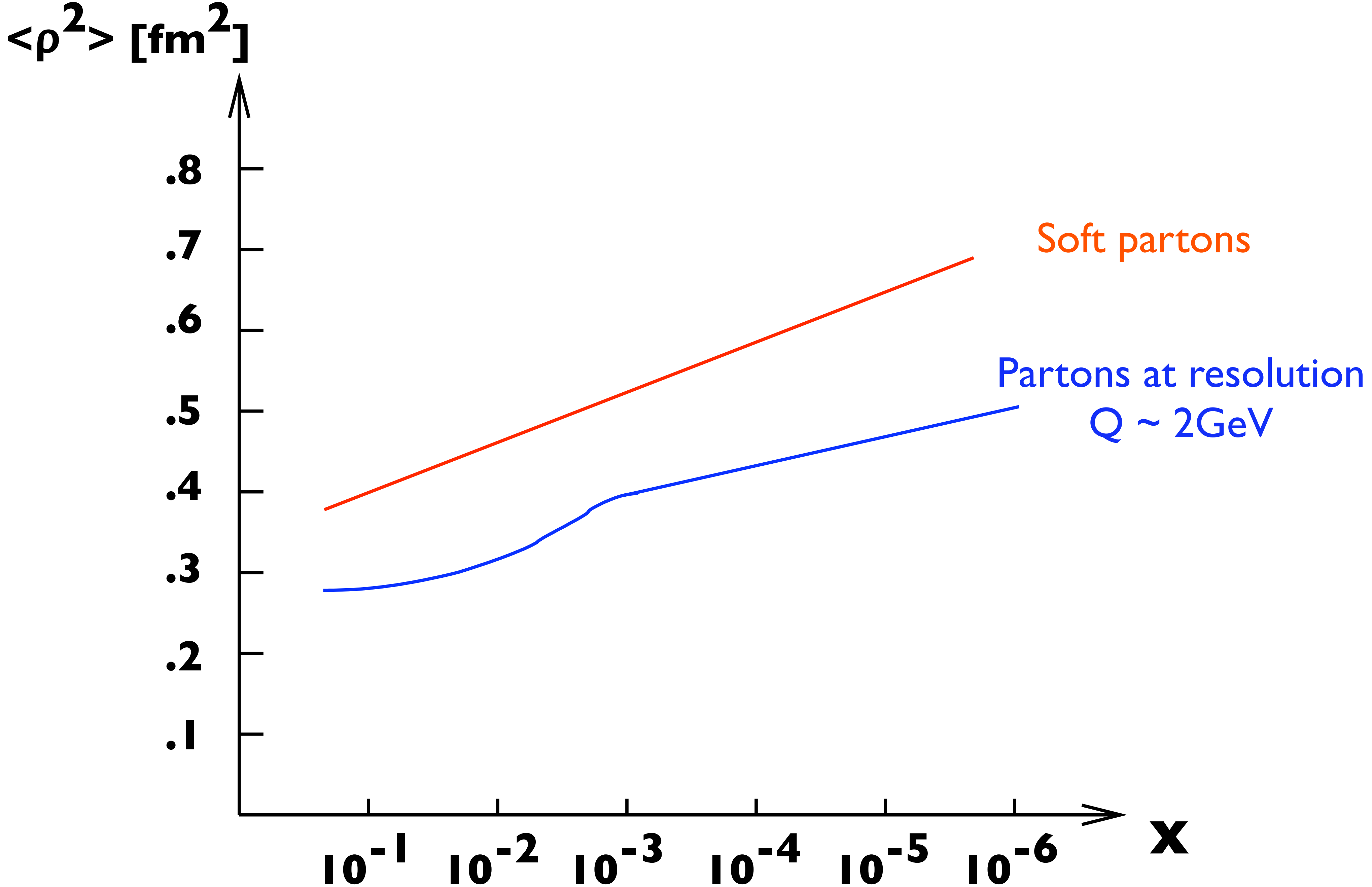
Saggital Image at High resolution

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!!!

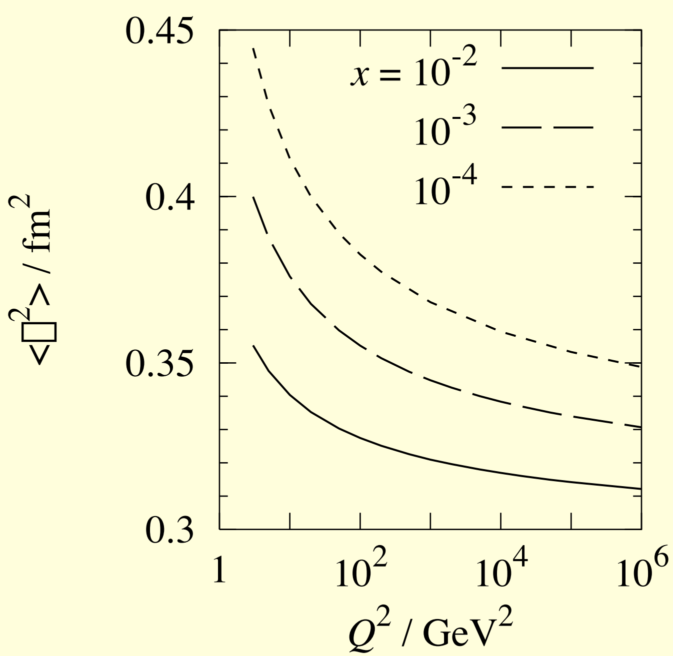
Evidence: $\prod'$ for the process $\square + p \to J/\square + p$
is smaller than for soft processes by a factor of two.

Confirms our prediction of 94 - BFGMS

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



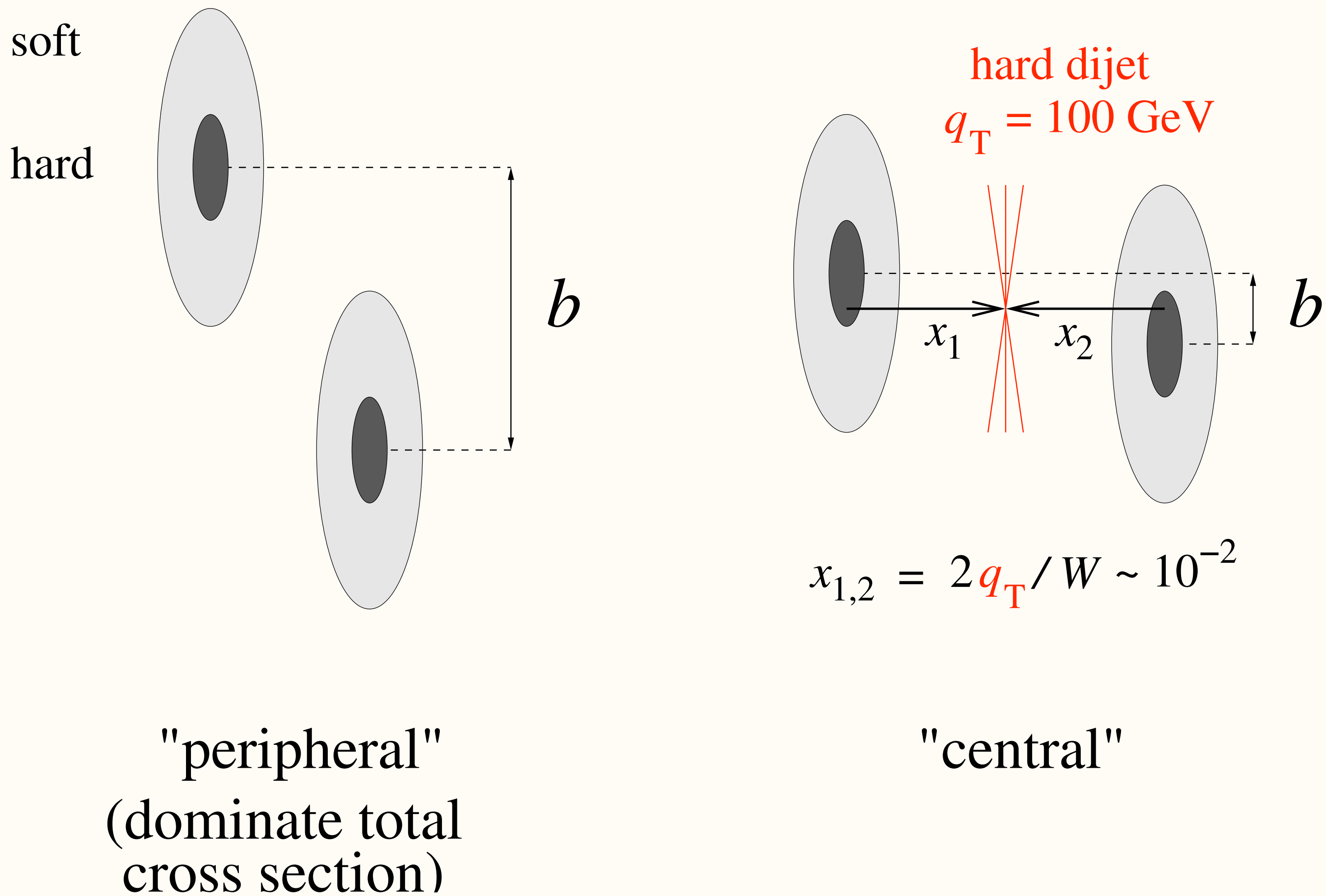
Sketch of the squared radius of the parton distribution for soft and hard regimes as a function of x.



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}.

$$< \rho^2(x = 10^{-3}, Q^2 = 100 GeV^2) > \approx < \rho^2(x = 10^{-2}, Q^2 = 2 \div 3 GeV^2) >$$

Implication - hard processes correspond to collisions where nucleons overlap stronger & more partons hit each other - use hard collision trigger to study central collisions.



Frankfurt, Strikman, Weiss, Phys.Rev. 69, 114010 (2004) [arXiv:hep-ph/0311231].

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 investigated at HERA:

- Determination of the transverse distribution of gluons.

- Strength of of "small dipole"-nucleon interactions at high energies

Will discuss in the second part of the talk

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.

Implications for LHC - impact parameters for collisions with new particle production are much smaller than for generic inelastic collisions.

Using HERA data and fits to elastic pp data we can quantify this.

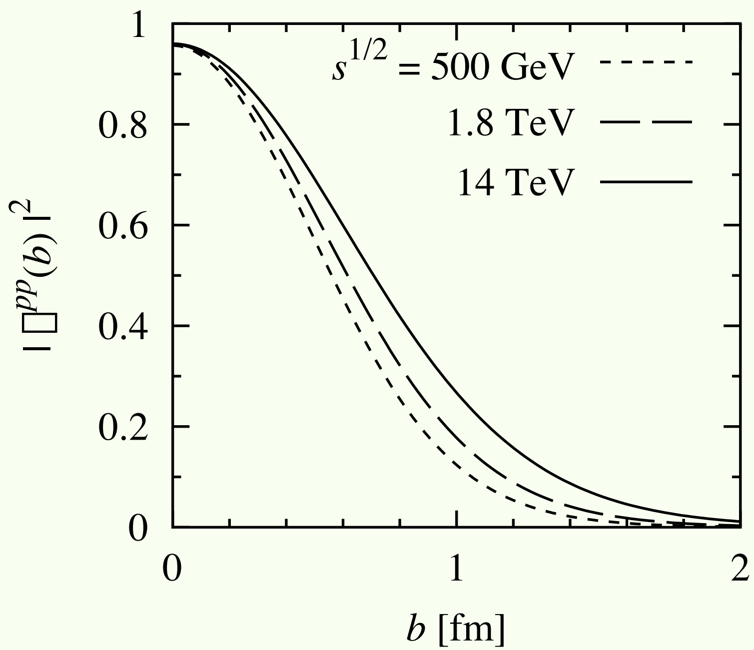
(i) Impact parameter distribution in pp interaction

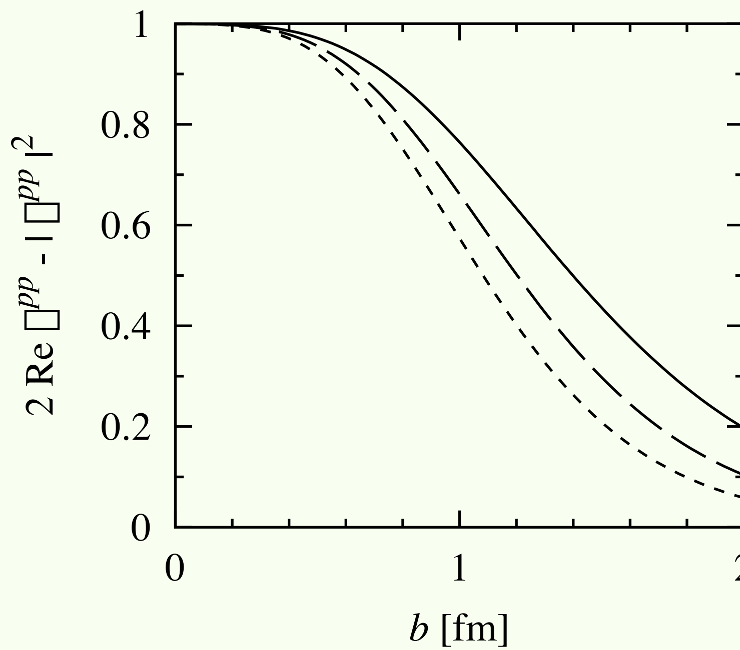
Study of the elastic scattering allows to determine how the strength of the interaction depends on the impact parameter, b:

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

$\square(b) = 1 \;\equiv\; \square_{inel} = \square_{el}$

- black body limit.





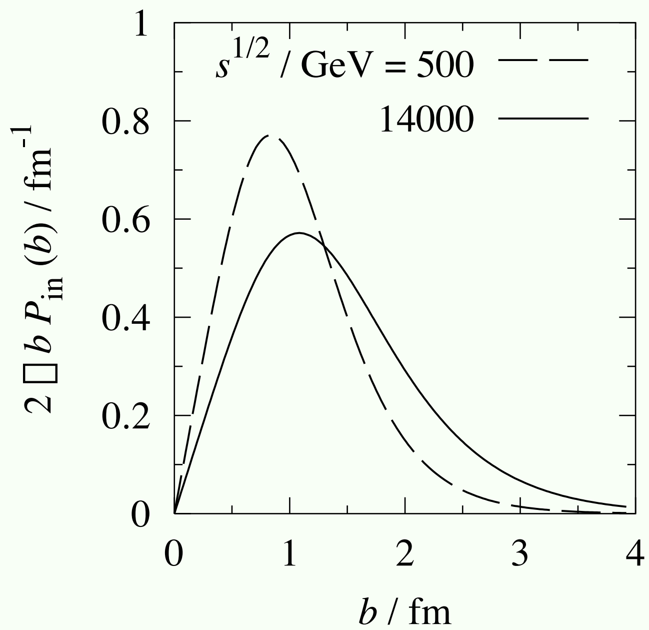
Calculation uses model of Islam et al; use of the model of Khoze et al leads to similar results.

Probability of inel. interaction:

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

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

b-range where P(b)> 0.5 increases with s faster than <ρ^2>.



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

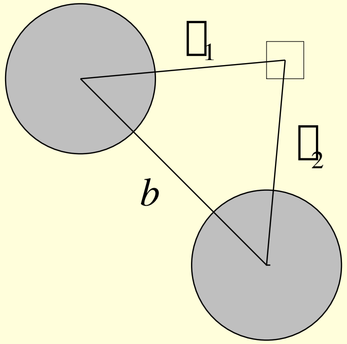
The normalized impact parameter distribution for generic inelastic collisions, $P_{in}(s,b)$, obtained with the parameterization of the elastic pp amplitude of Islam *et al.* ("diffractive" part only). The plot shows the "radial" distribution in the impact parameter plane, $2\pi b\, P_{in}(s,b)$. The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

M.Strikman

Impact parameter distribution for 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

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

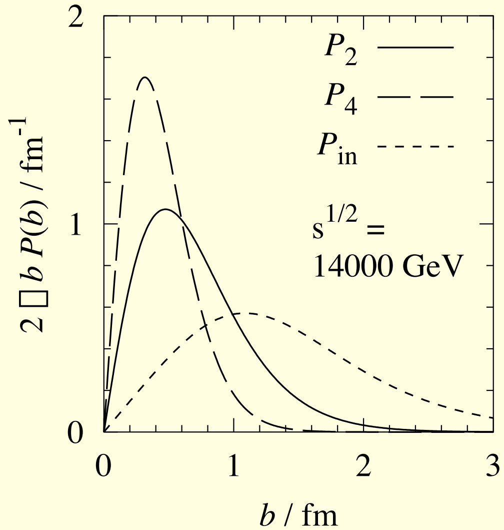
where $x_1 = 2q_\perp/\sqrt{s}$. Obviously $P_2(b)$ is automatically normalized to 1.

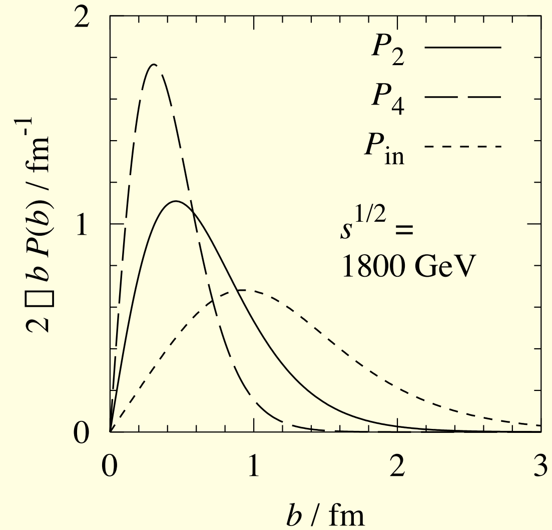
For a dipole parameterization:

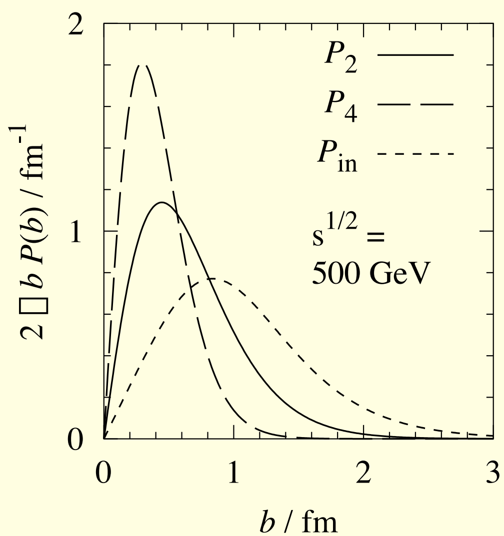
$$P_2(b) \;=\; \frac{m_g^2}{12\pi}\left(\frac{m_g b}{2}\right)^3 K_3(m_g b)$$

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

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







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.

Approaching the black body limit for "spectator" parton interactions in the central pp collisions. Spectator parton interact with gluon densities similar to those in central p- heavy ion collisions!!!

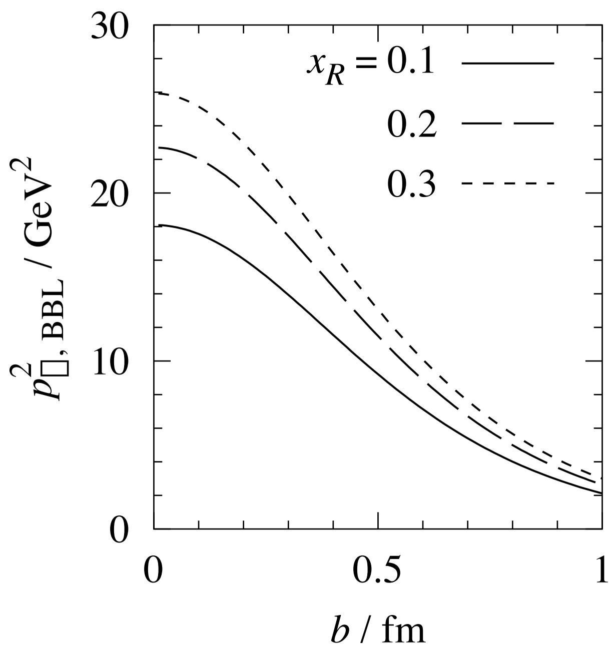
To simplify the discussion, we consider instead of a parton in the "projectile", the scattering of a small color-singlet dipole off the "target" nucleon. This is in the spirit of the dipole picture of high-energy scattering of Mueller 94 in BFKL model. The measure of proximity to the black body limit (BBL) Γ is obviously the value of Γ as a function of the impact parameter.

Our analysis included the following steps.
FOR FIXED b

- Fixing spectator parton(x_R) resolved by collision with partons in other proton
- Determining what minimal x are resolved in the second proton for given virtuality $x = \frac{4p_\perp^2}{x_R s}, Q^2 = 4p_\perp^2$ $small\ x \leftrightarrow\ large\ x_R$
- for given ρ – distance of the parton from the center of another nucleon – determining maximum virtuality - minimal size of the dipole- d, for which $\Gamma = 0.5$.
- 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_R

- taking into account distribution over ρ for given b



$$P_{black} > P_{crit} \sim 0.5$$

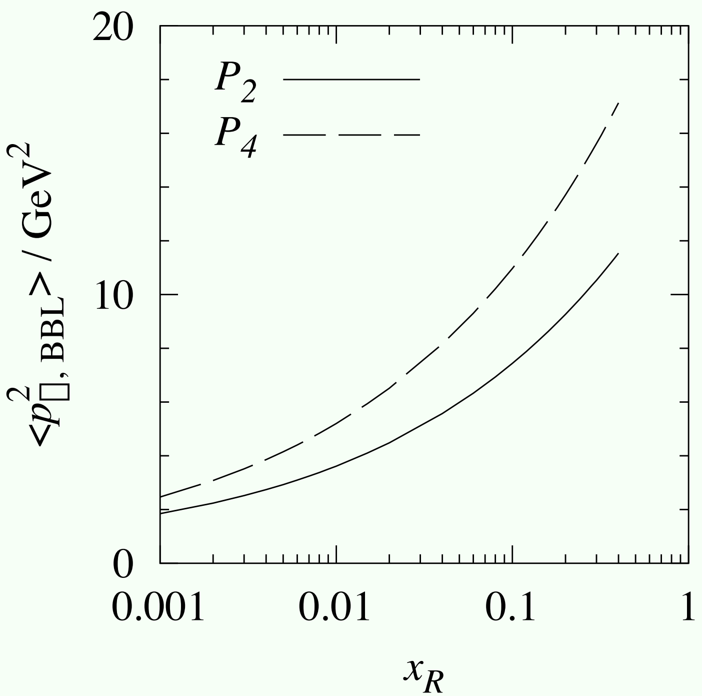
Also, a spectator parton in the BBL regime loses a significant fraction of its energy *similar to electron energy loss in backscattering of laser off a fast electron beam.*

For different triggers we now can take into account distribution over b.

For events with hard dijet at zero rapidity

$$\langle p^2_{\perp,\mathrm{BBL}} \rangle \equiv \int d^2b \; p^2_{\perp,\mathrm{BBL}}(b) P_2(b)$$

average with b-distribution enforced by dijet trigger



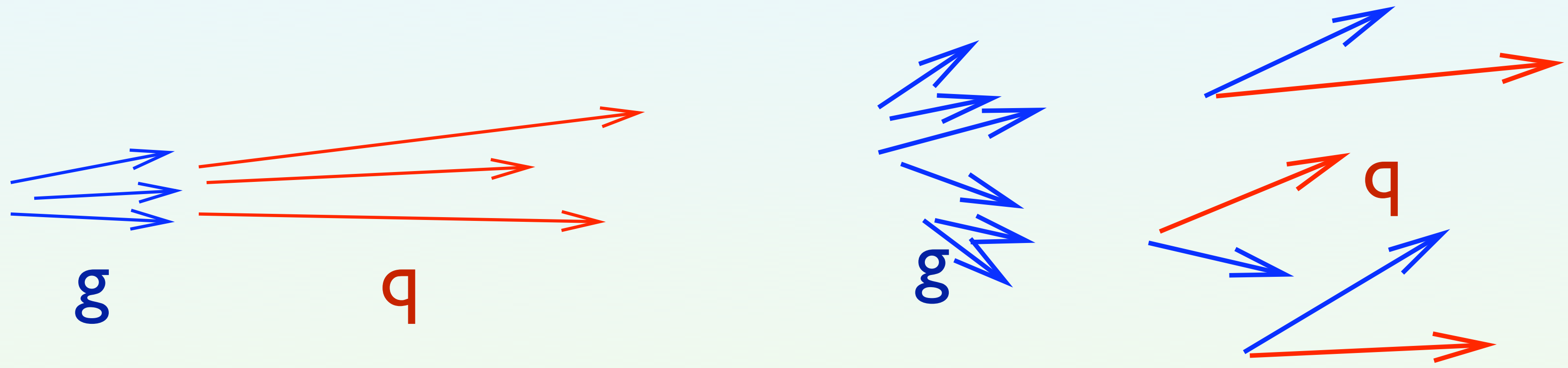
Dijet trigger allows to maximize effects of ``black interactions" of small-- x partons

$p^2_\perp \gg \Box^2_{QCD}$ $\rightarrow$ self consistent picture

Effective gluon densities ~ to central pA collisions

Warning: x>0.01 corresponds to scattering off gluons with x <10^{-5}. Our extrapolation to these x does not include possible slowdown of the increase of gluon density at these x suggested by the recent studies (Altarelli et al , Ciafaloni et al 03). In line with cosmic ray data near GZK.

Characteristics of the final state in the central pp collisions



fast partons in a nucleon before collisions

fast partons in a nucleon after central collisions

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 suppression for nucleons is especially pronounced: 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.

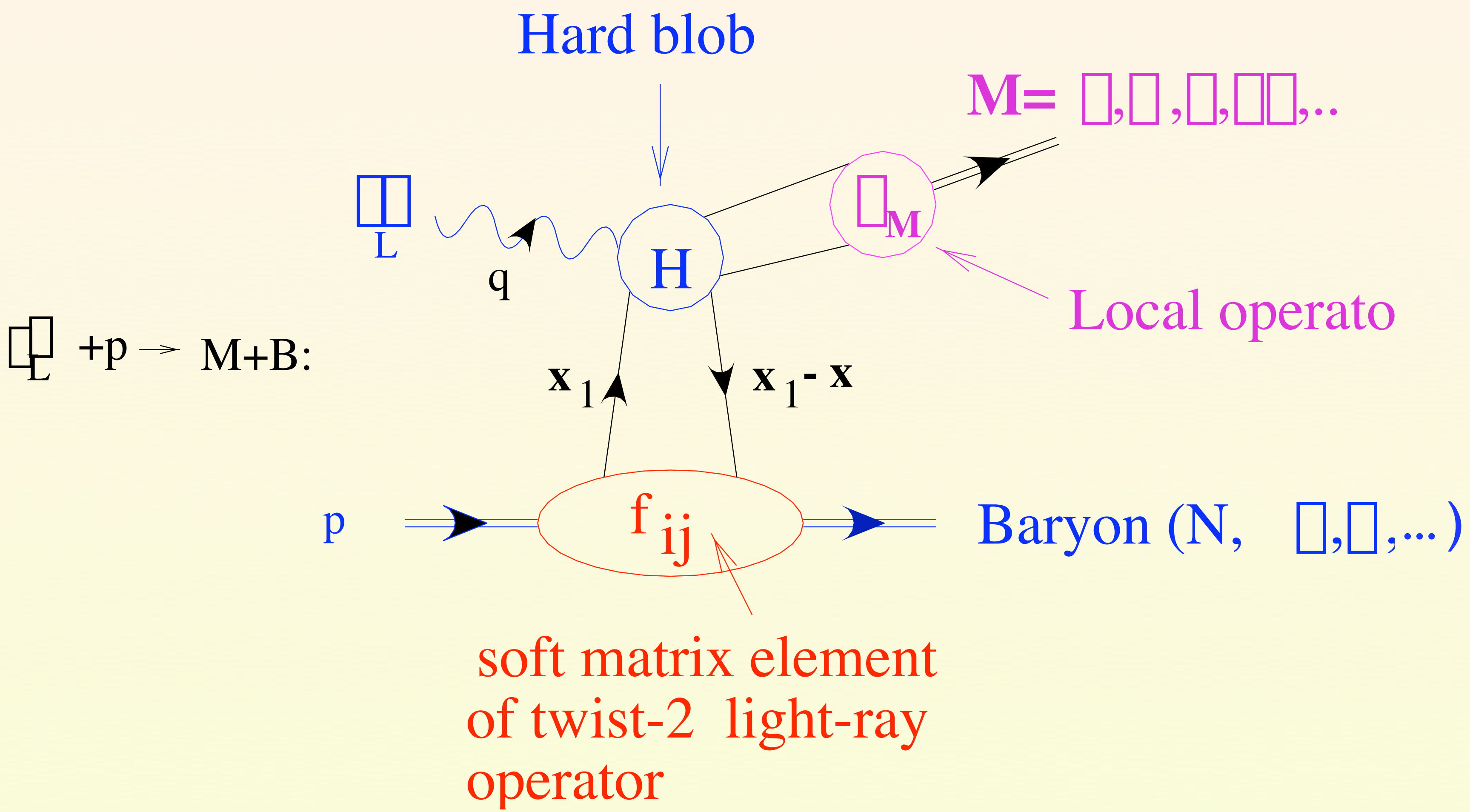
$\Longrightarrow$ Difficult to identify jets, isolated leptons,... unless $p_\perp\,(jet) \gg p_{\perp,BBL}$

$\Longrightarrow$ 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.

Second part

QCD factrorization theorem for DIS exclusive processes

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



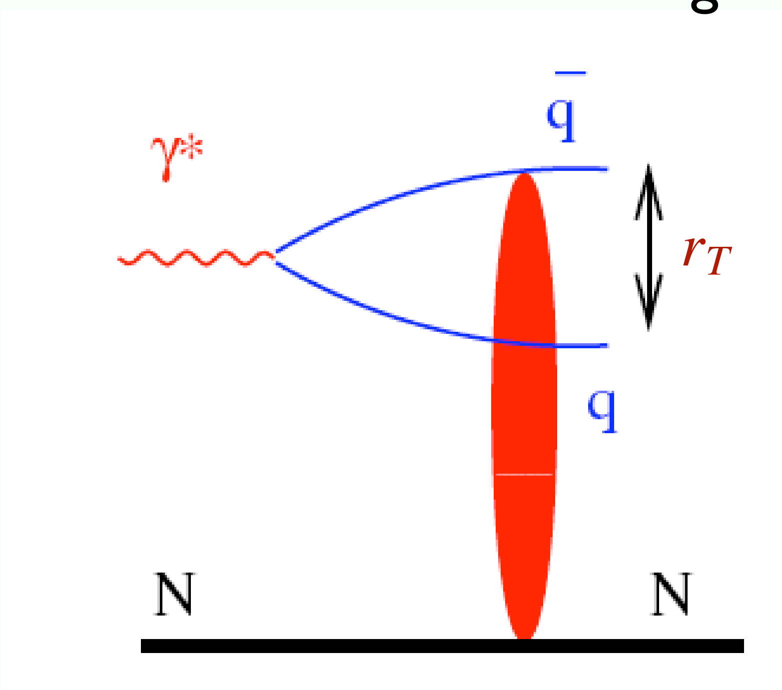
Extensive data on VM production from HERA support dominance of the pQCD dynamics. Numerical calculations including finite transverse size effects explain key elements of high Q^2 data. The most important ones are:

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

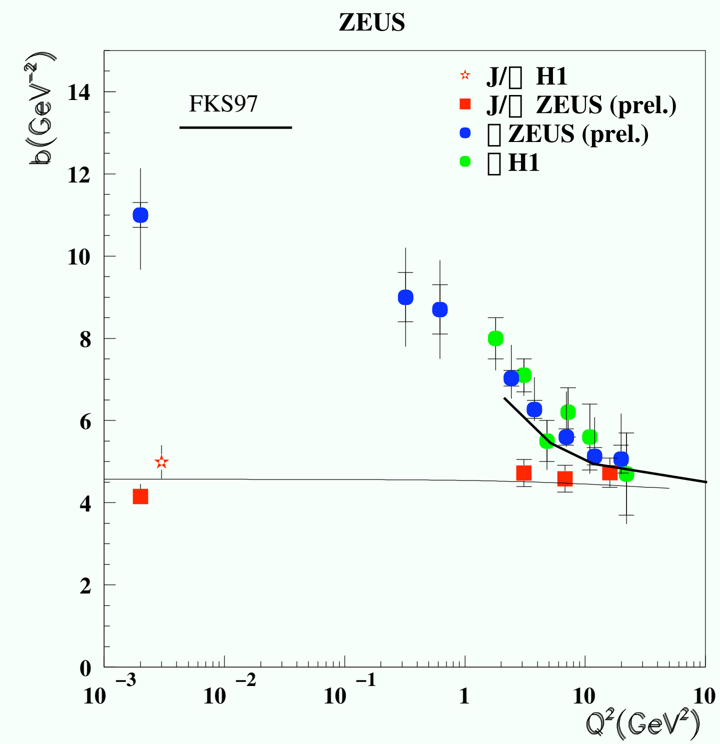
- Absolute cross section and energy dependence of ρ−meson production at $Q^2 \geq 20\ GeV^2$. Explanation of the data at lower Q^2 is more sensitive to the higher twist effects, and uncertainties of the low Q^2 gluon densities.

- 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, $F_g(x,t)$. $d\sigma/dt \quad F_g^2(x,t)$.

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

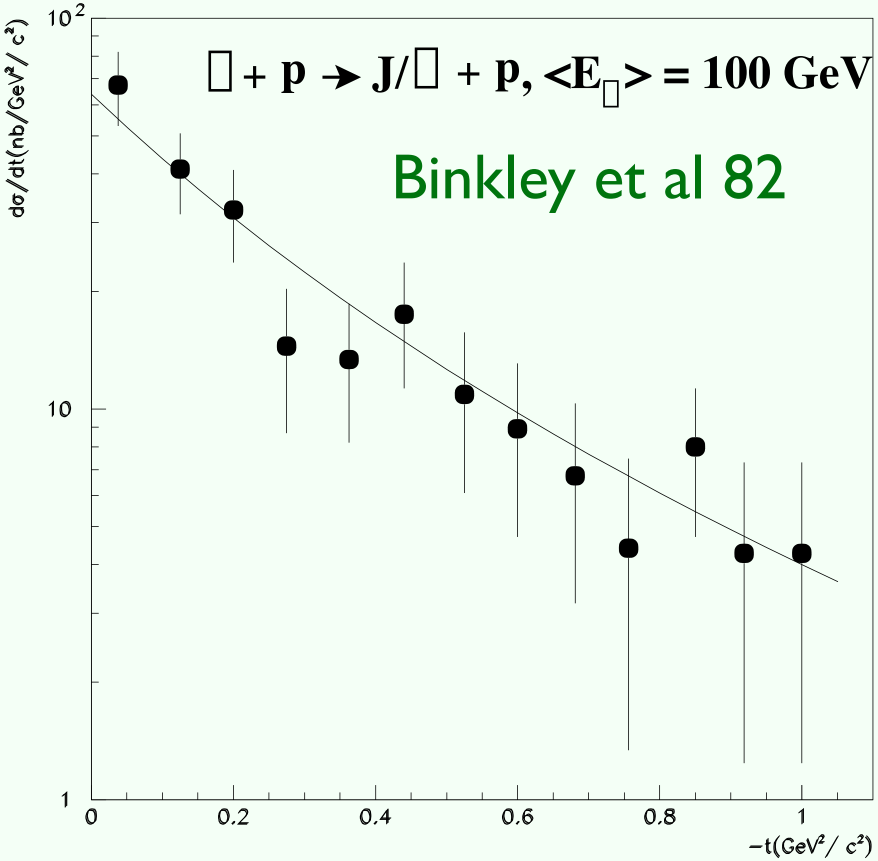


$$\frac{1}{Q}\left(\frac{1}{m_c}\right) \ll r_N$$



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

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



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

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

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

Note: we used FKS analysis to correct for the finite size of J/psi which is a 10% correction for m_g^2 for x>0.03.

Open problems with t-dependence of DIS exclusive processes .

Lack of understanding of the transition from the fixed target region energies to HERA even for the best case of J/psi.

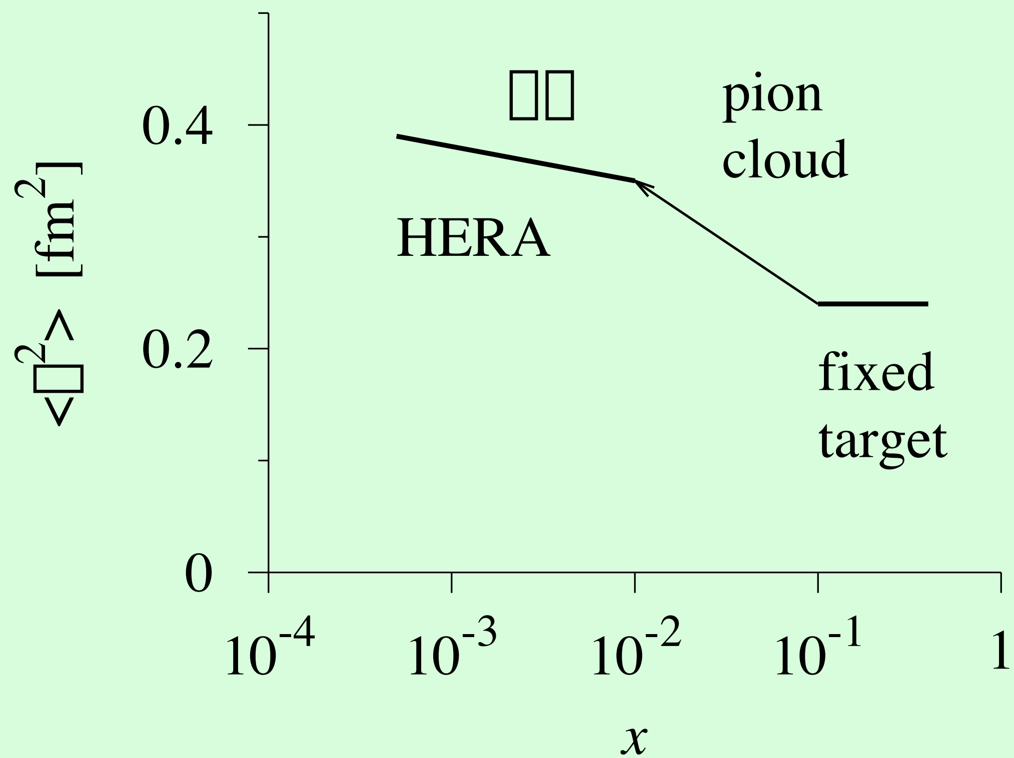
FNAL data:

- t-dependence deviates from exponential behavior
- slopes are ~ 3 GeV^{-2} if one uses exponential fit .

HERA data:

- Cannot distinguish between exponential and dipole fits. However these fits give **$<\rho^2>$** which **differ by 30%.**
- Energy dependence of B is weak (in agreement with BFGMS94) but uncertainties are very large:

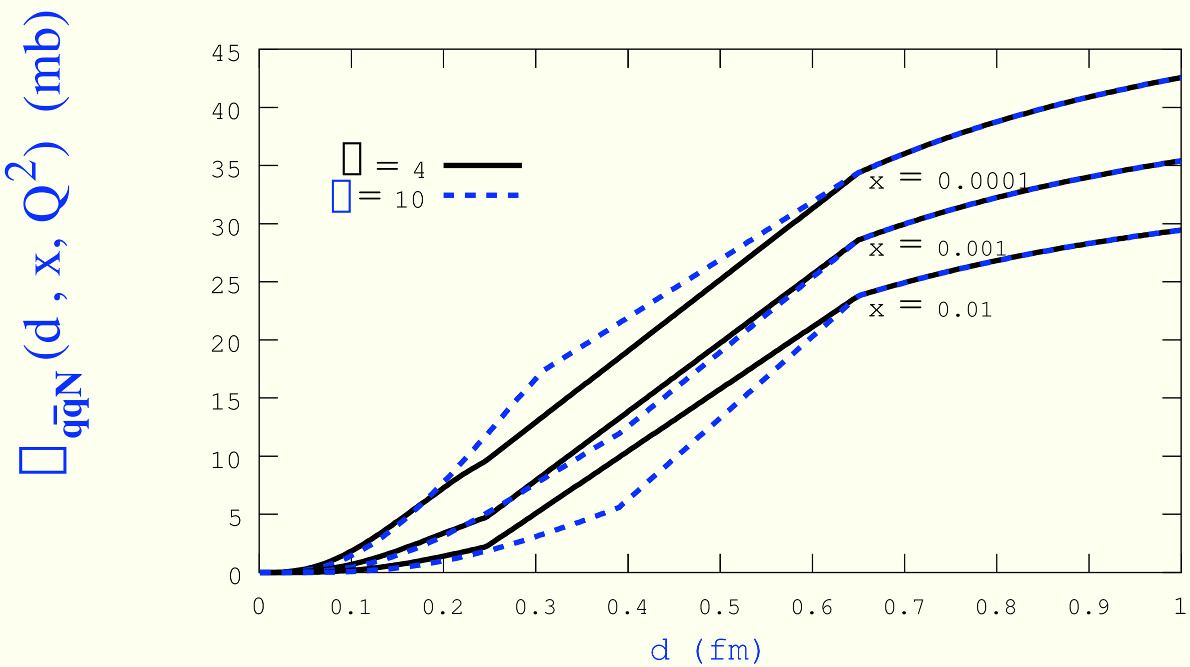
  α' between 0 and 0.12 GeV^{-2} are not excluded !!!



Schematic illustration of the x--dependence of the gluonic transverse size of the nucleon, $\langle\rho^2\rangle$. The increase between $x \sim 10^{-1}$ and $x \sim 10^{-2}$ can be attributed to the contribution of the nucleon's pion cloud to the gluon density.

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

$$\sigma^{inel}_{q\bar{q}N}(d, E_{inc}) = \frac{\pi^2}{3} d^2 \alpha_s(\frac{\lambda}{d^2}) x G_N(x, \frac{\lambda}{d^2})$$



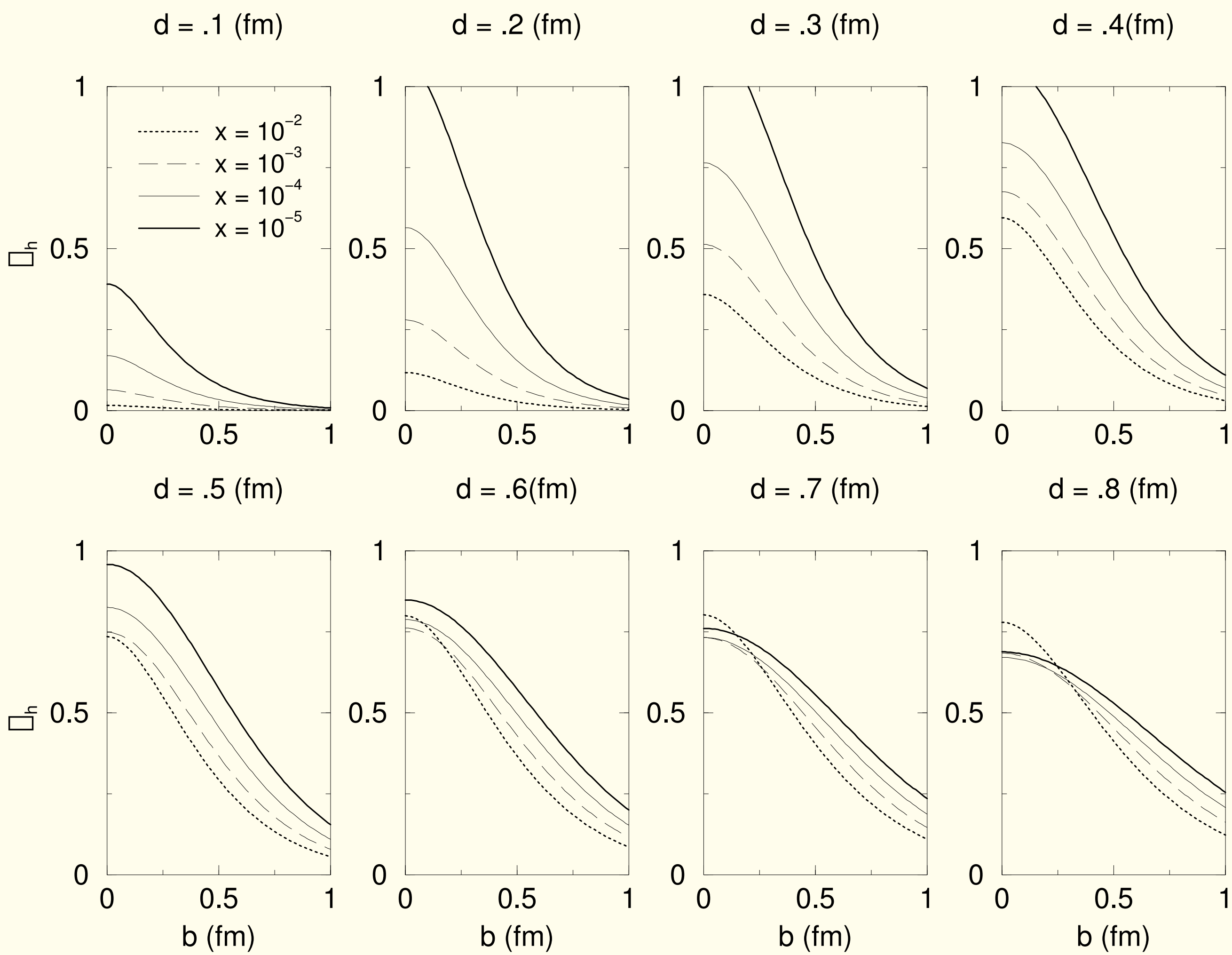
The interaction cross-section, $\hat{\sigma}$ for CTEQ4L, $x = 0.01, 0.001, 0.0001$, $\lambda = 4, 10$. Based on pQCD expression for $\hat{\sigma}$ at small d_t, soft dynamics at large b, and smooth interpolation. Provides a good description of F_{2p} at HERA and J/ψ photoproduction.

Frankfurt, Guzey, McDermott, MS 2000-2001

Using information on the transverse gluon distribution we can consider elastic scattering of small dipoles and check how close are partial waves

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

to the maximal possible strength: $\Gamma = 1$ - black body limit $\sigma_{inel} = \sigma_{el}$



$"q\bar{q}\ dipole" - N$ profile functions

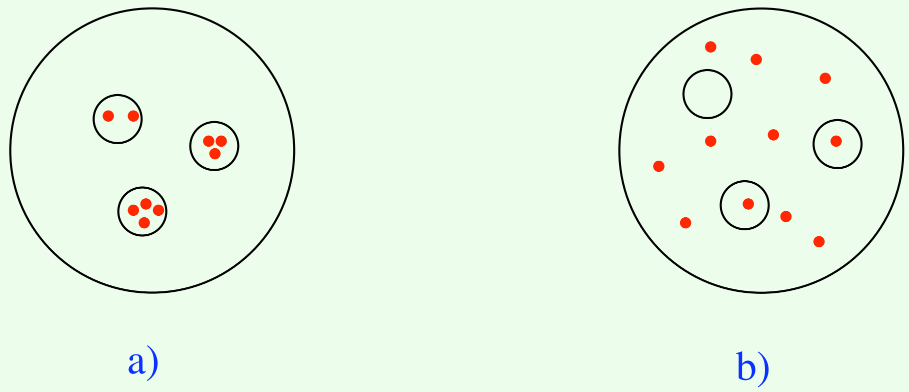
in pQCD domain

$"gg\ dipole" - N$

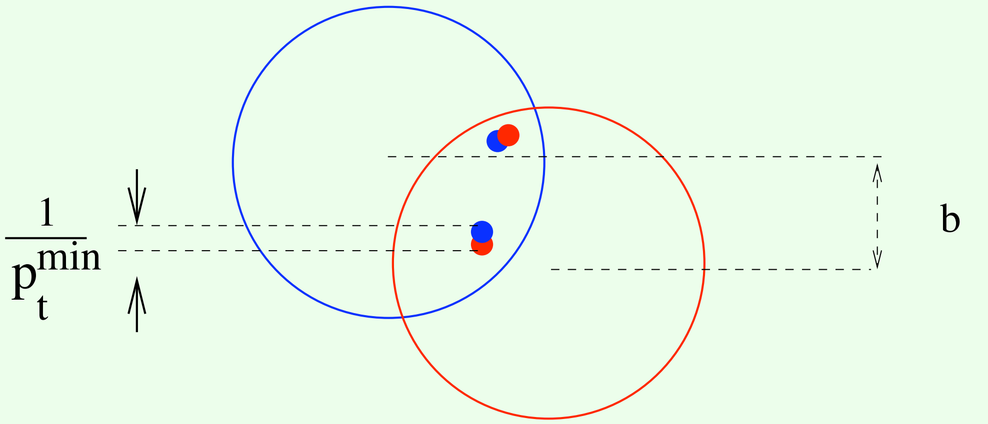
profile functions are 9/4 times larger and hence much closer to 1.

Consistent with analysis of the HERA data on hard inclusive diffraction - gluon diffractive pdfs >> quark diffractive pdfs

HERA + "CDF Multi-jet production" - implications for parton correlations in nucleons



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 multijet events which have distinctive kinematics from the process two partons → four partons.

CDF measured the ratio

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

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 $\sigma_{eff}=14.5\pm1.7^{+\,1.7}_{-\,2.3}\,mb$ 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 $\sqcup_{eff}$ for CDF kinematics of x ~0.1-0.3 include:

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

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

If most of gluons 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* $\frac{8}{9}+\frac{1}{9}\frac{r_N^2}{r_q^2} \sim 2$

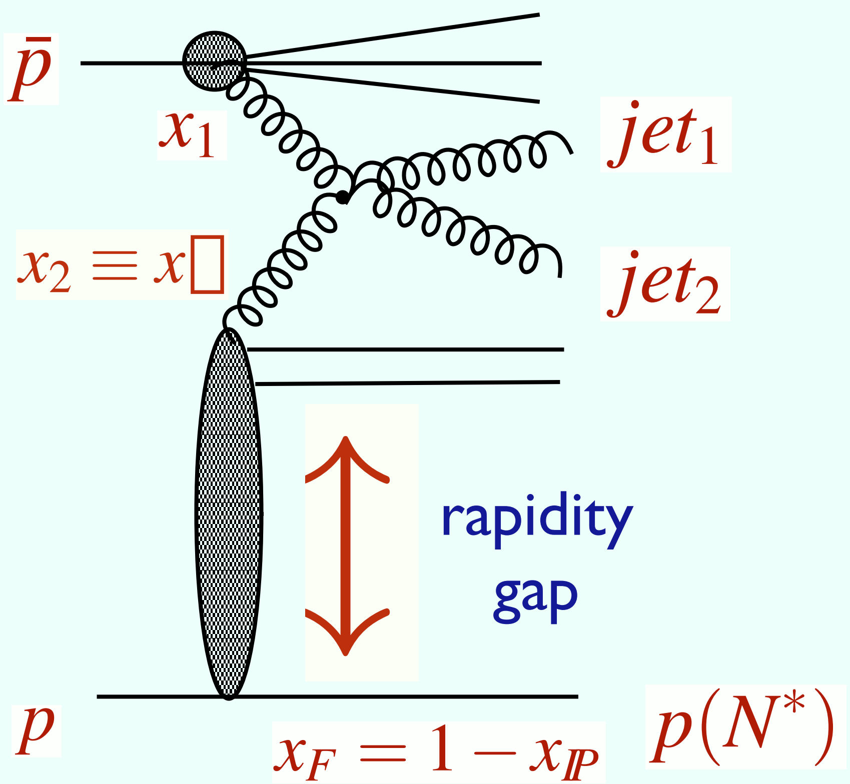
Hence, combined these two effects are sufficient to explain CDF data.

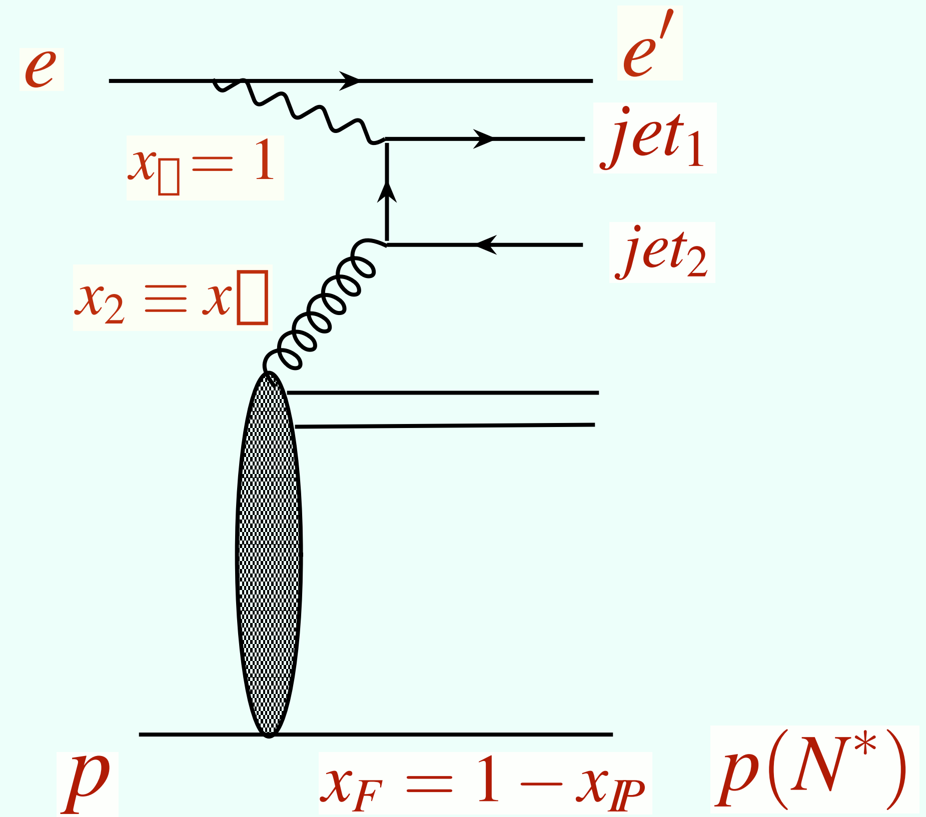
☺ QCD evolution leads to "Hot spots" in transverse plane (A.Mueller). Hot spots do enhance multijet production as well. However this effect is likely not to be relevant in the CDF kinematics as x's are relatively large but will lead to additional enhancement at LHC.

Inclusive hard diffraction - *probing nucleon periphery and color fluctuations.*

$p\bar{p} \to jet_1 + jet_2 + X + p$

$e + p \to e + jet_1 + jet_2 + X + p$



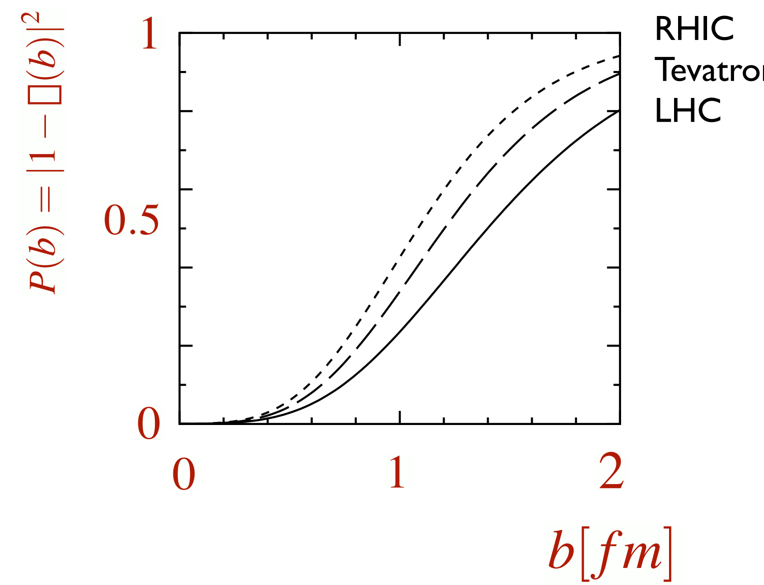


Process was first suggested by Ingelman and Schlein as a way to study dynamics of diffraction. For DIS one can introduce fraction / diffractive structure function which satisfy QCD factorization theorem for fixed $x_{I\!P}, p_N^T$

What is the difference between γ* and p projectiles?

Strong suppression in the proton case is due to the requirement that soft partons do not lead to inelastic interaction:

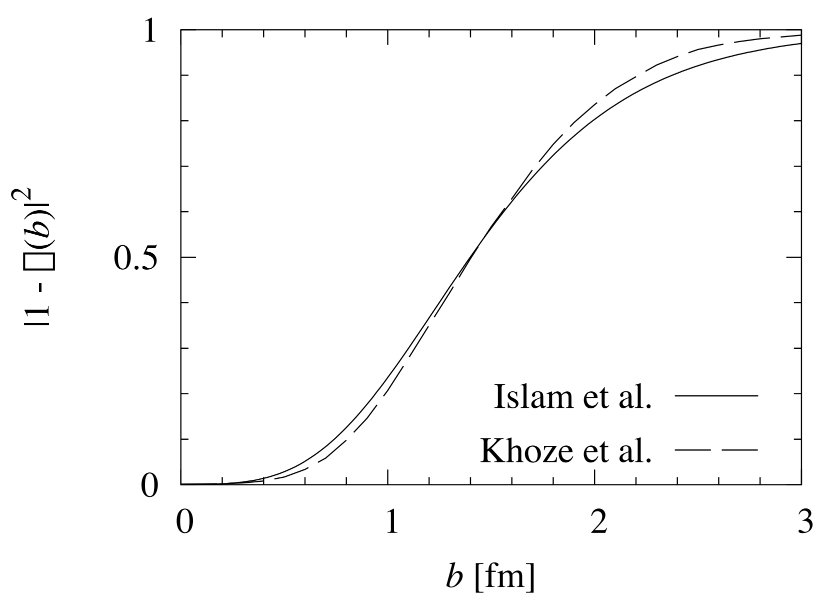
$$P(b) = |1 - \square(b)|^2$$ -- favors large b



find a gluon in antiproton with $x = x_1 \geq 0.05$

at a transverse distance $\square$ given by $F_g(x_1, \square)$

and parton in diffractive pdf at transverse distance $\square' \approx \vec{b} - \square$



-- favors small $\square' \ \& \ \square$ and hence small b.

Hence **only peripheral collisions can contribute**.

Net result is *a very strong suppression of hard diffraction as compared to calculations assuming the impulse approximation with the diffractive parton densities measured at HERA -a factor 5 -10. Main uncertainty - what part of t-dependence of diffraction is due to the size - part could be due to the spread in impact parameter - would lead to a larger suppression.*

Consistent with the FNAL data - a more detailed comparison requires better HERA diffractive data including t-dependence and detailed modeling of x_1 range of the FNAL data. *Is the t-dependence for gluon diffractive pdf's is the same as for the quark ones? Due Regge factorization holds?*

This simple model accounts for geometry of high energy collisions and does not have free parameters. It does not explicitly use eikonal approximation. Numerical results are similar in several respects to that obtained in Khoze, Kaidalov, Martin, Ryskin & Gottesman, Levin, Maor papers.

$\Longrightarrow$ Hard diffraction is a good way to scan the nucleon periphery.

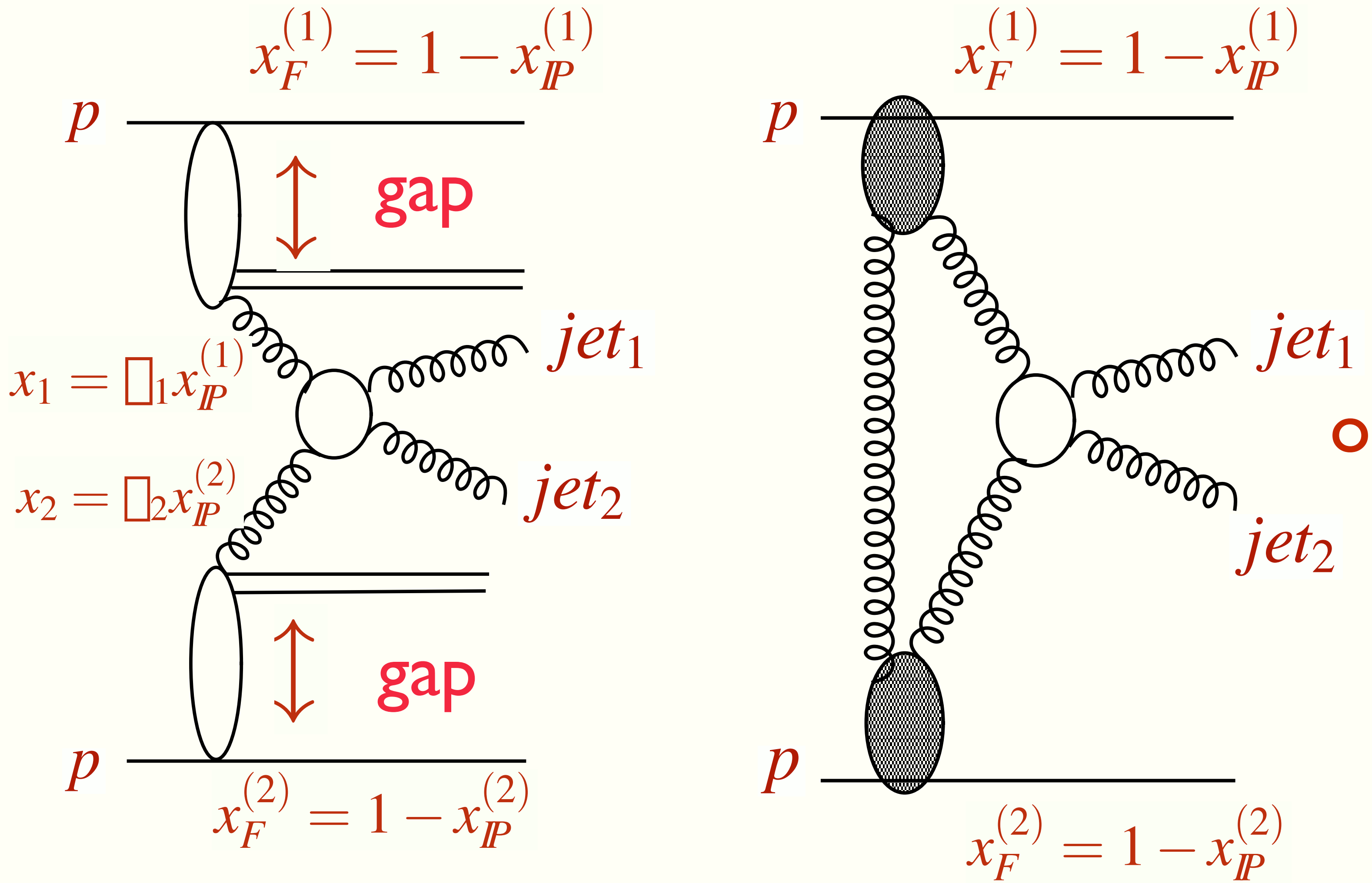
- Sensitivity to the increase of the overall nucleon size with energy -larger suppression of hard diffraction at higher energies Observed at Tevatron.

- Possibility to probe correlation between strength of interaction and x_1 & flavor of the parton in the diffracting nucleon.

  Breakdown of QCD factorization for hard diffraction is not just by an overall renormalization factor as compared to HERA diffractive pdf's.

- Look for breakdown of the Regge factorization that is the same x dependence of diffractive pdf's at different $x_{I\!P}$

Complementary information from hard double diffraction.

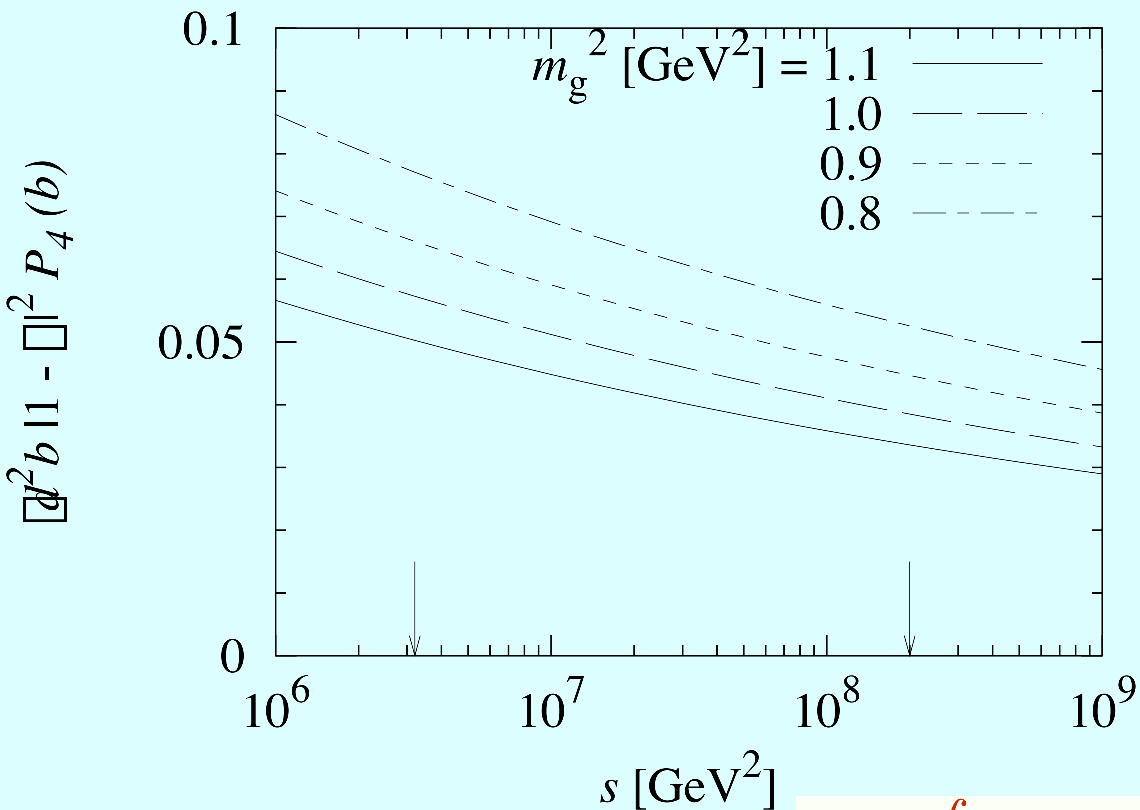


or Higgs, χ_c

several talks

Erarchy of gap survival probabilities, P, (suppression due to soft interactions)

$$P(pp \to p + X + 2\ jets) \sim 0.05 - 0.1 > P(pp \to pp + 2 jets + X) \sim 0.1$$
$$> P(pp \to pp + Higgs) \sim 0.04$$



The rapidity gap survival probability, $S^2 = \int d^2b|1-\Gamma(s,b)|^2 P_4(b))$

Shown is the result as a function of incident energy, s, for various values of the mass parameter in the two--gluon form factor, m_g^2. The Tevatron and LHC energies are marked by arrows.

Necessary to determine $m_g^2(x \sim 0.01, Q^2 = 10^4 GeV^2)$

$\Rightarrow$ accurate measurements of the t-dependence of the exclusive onium photo(electro)production at relatively small W.

Conclusions

★ *QCD factorization for exclusive vector meson production is applicable at HERA and provides 3 D image of the nucleon at high resolution.*

★ *Small x physics is an unavoidable component of the new particle physics production at LHC.*

★ *Minijet activity in events with heavy particles should be much larger than in the minimum bias events or if it is modeled based on a naive extrapolation from Tevatron.*

★ *Double hard processes provides evidence for transverse correlations between partons. Further studies of transverse correlations are necessary both at LHC and at RHIC (including spin) in pp and pA.*

★ *Links between gap survival and HERA: need more accurate information on t-dependence of exclusive and inclusive hard diffraction in a wide W.*