Central pp collisions at collider energies: triggers, final states

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Physics at LHC 7/16/04

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.

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

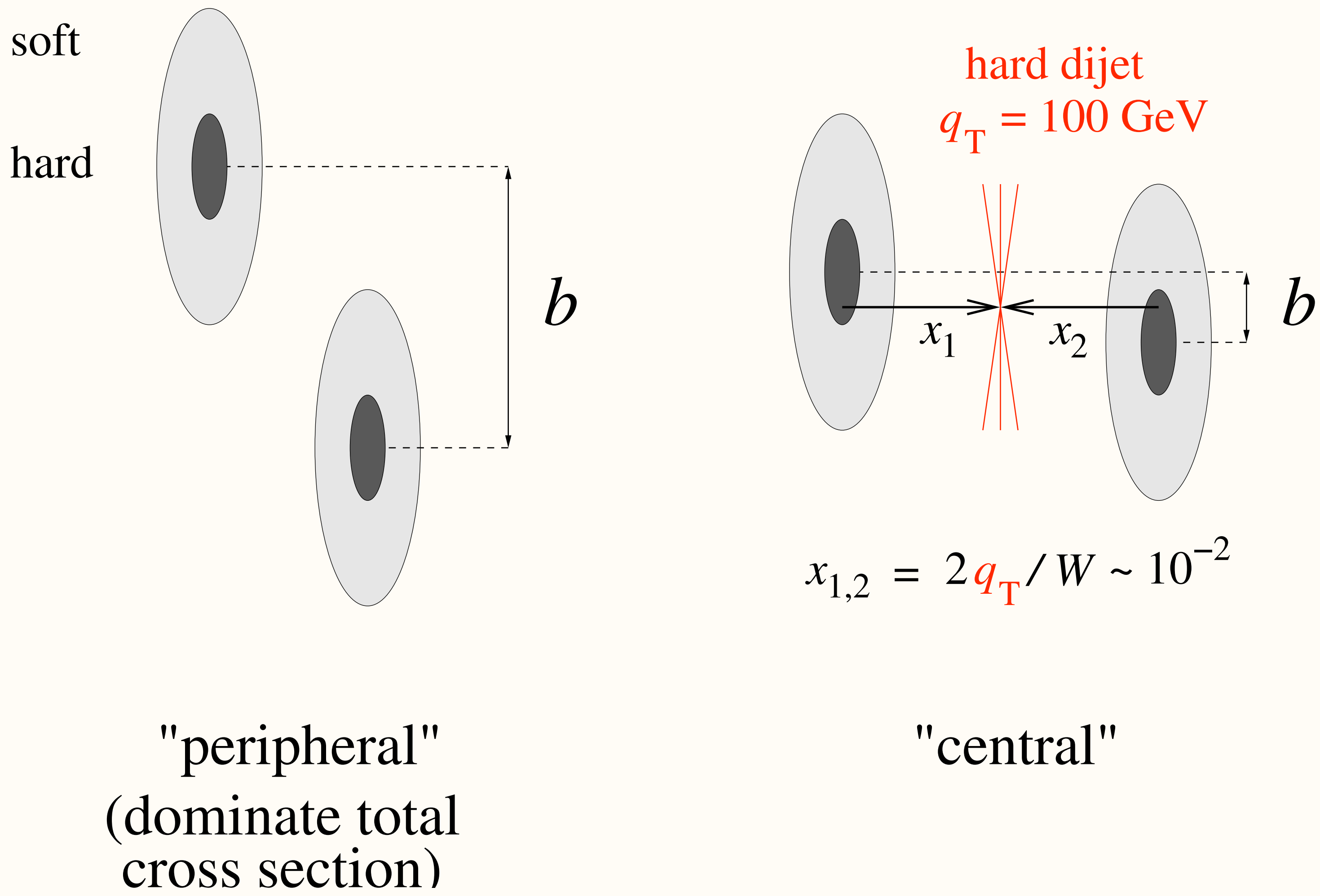
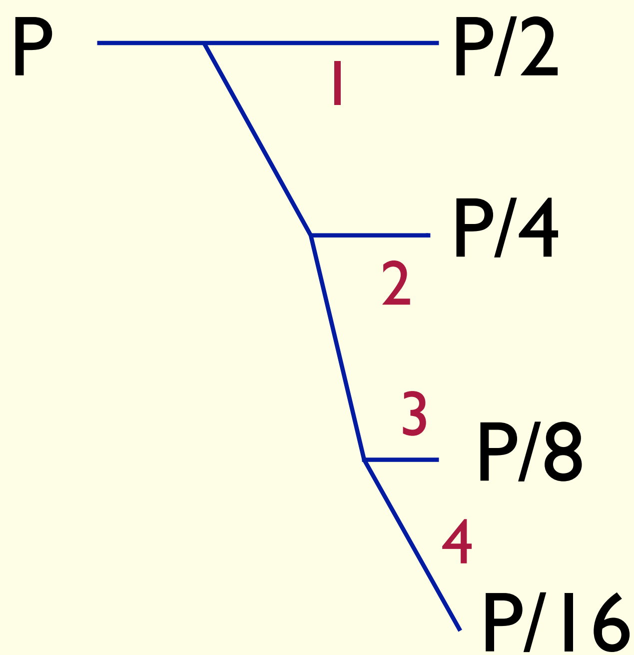


Image of nucleon at different resolutions, q. Fast frame.

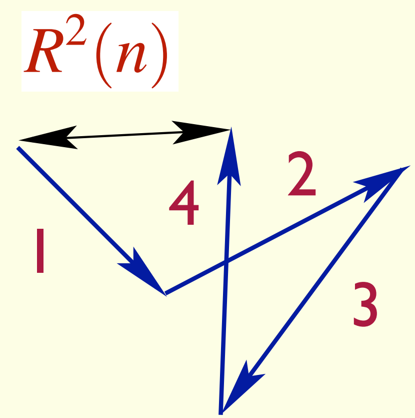
Energy dependence of the transverse size of soft partons.

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:

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

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

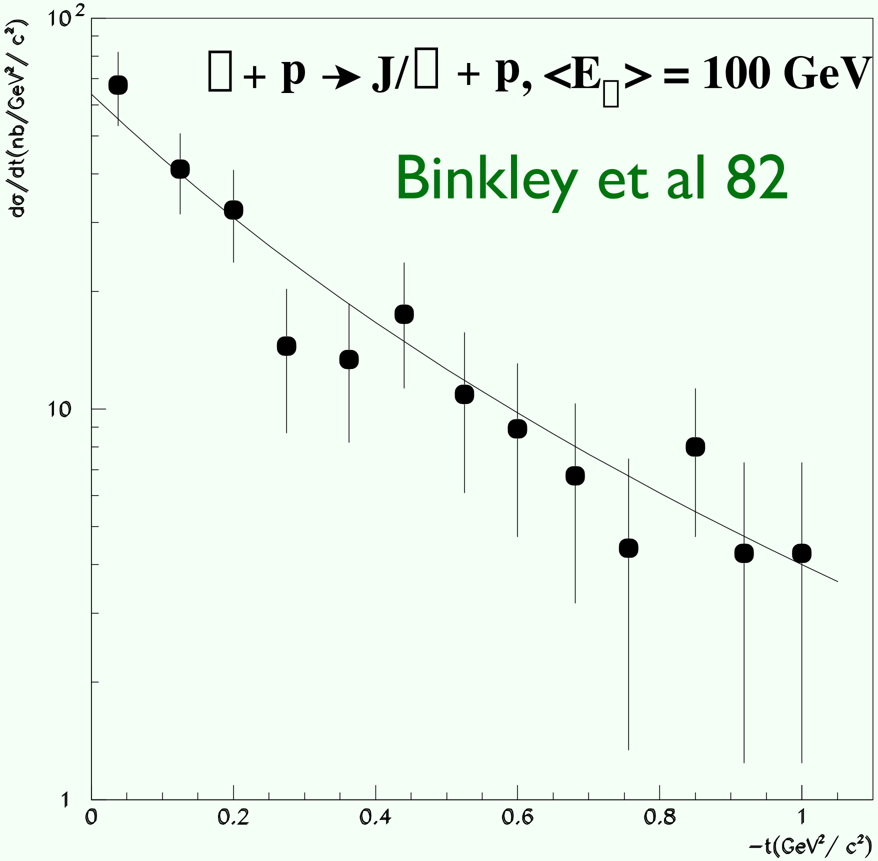
Gribov diffusion is much weaker as the transverse momenta in most of the decay ladder are much larger than the soft scale. Transverse size shrinks with increase of resolution scale!!!

Evidence: $\prod'$ for the process $\Box + p \rightarrow J/\Box + p$

is smaller than for soft processes by a factor of two.

Confirms our prediction of 94 - BFGMS

Important additional 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.



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

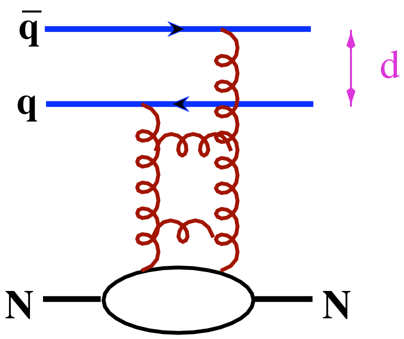
$$m_{e.m.}^2 = 0.7\ GeV^2. \quad \text{(FS02)}$$

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 $x_{parton} > 0.01$.

Instability of the gluon vacuum

QCD factorization theorem



pQCD in the leading log d approximation (Baym, Blattel,FS, 93)

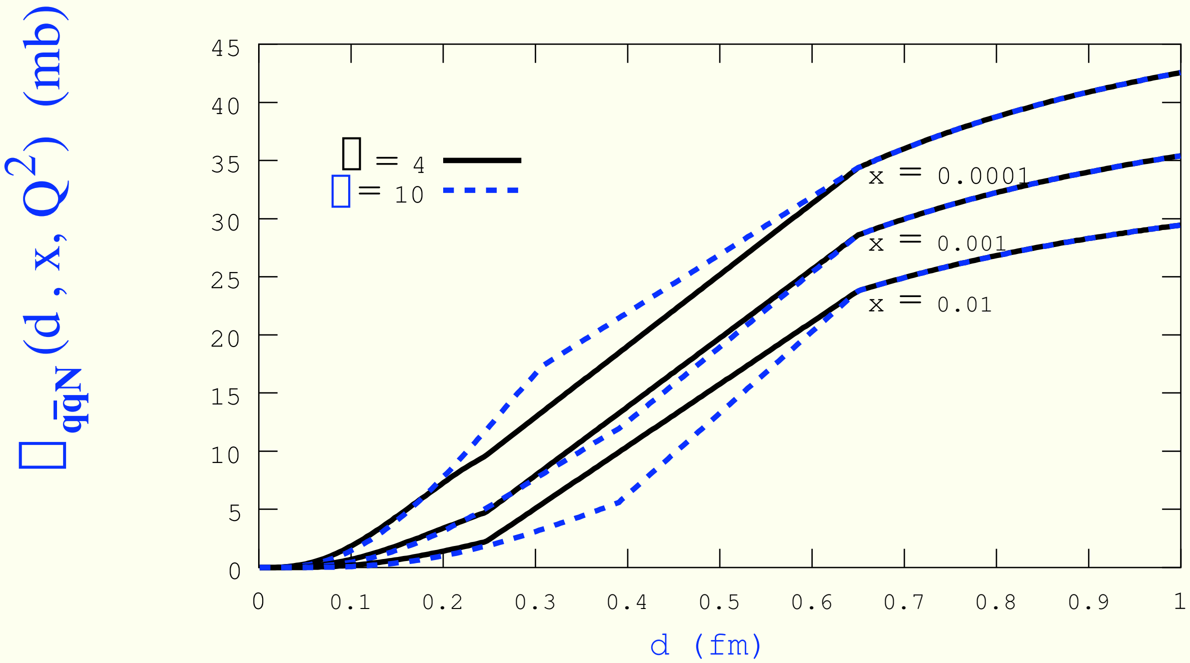
$$\sigma^{inel}_{q\bar{q}N}(d,E_{inc}) = \frac{\pi^2}{3} d^2 \alpha_s\left(\frac{\lambda}{d^2}\right) \text{ x } G_N\left(x, \frac{\lambda}{d^2}\right)$$

where $\lambda(x = 10^{-3}, Q^2 = 10\ GeV^2 \approx 9$. Qualitative difference from QED: cross section rapidly increases with energy - a fingerprint of small size dipole interaction in a wide energy range:).

$$\sigma_{tot}(soft) \propto s^{0.1}, \sigma_{tot}^{dipole-N}(d = .3fm) \propto s^{0.2},$$

$$\sigma_{tot}^{dipole-N}(d = .1fm) \propto s^{0.4}.$$

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



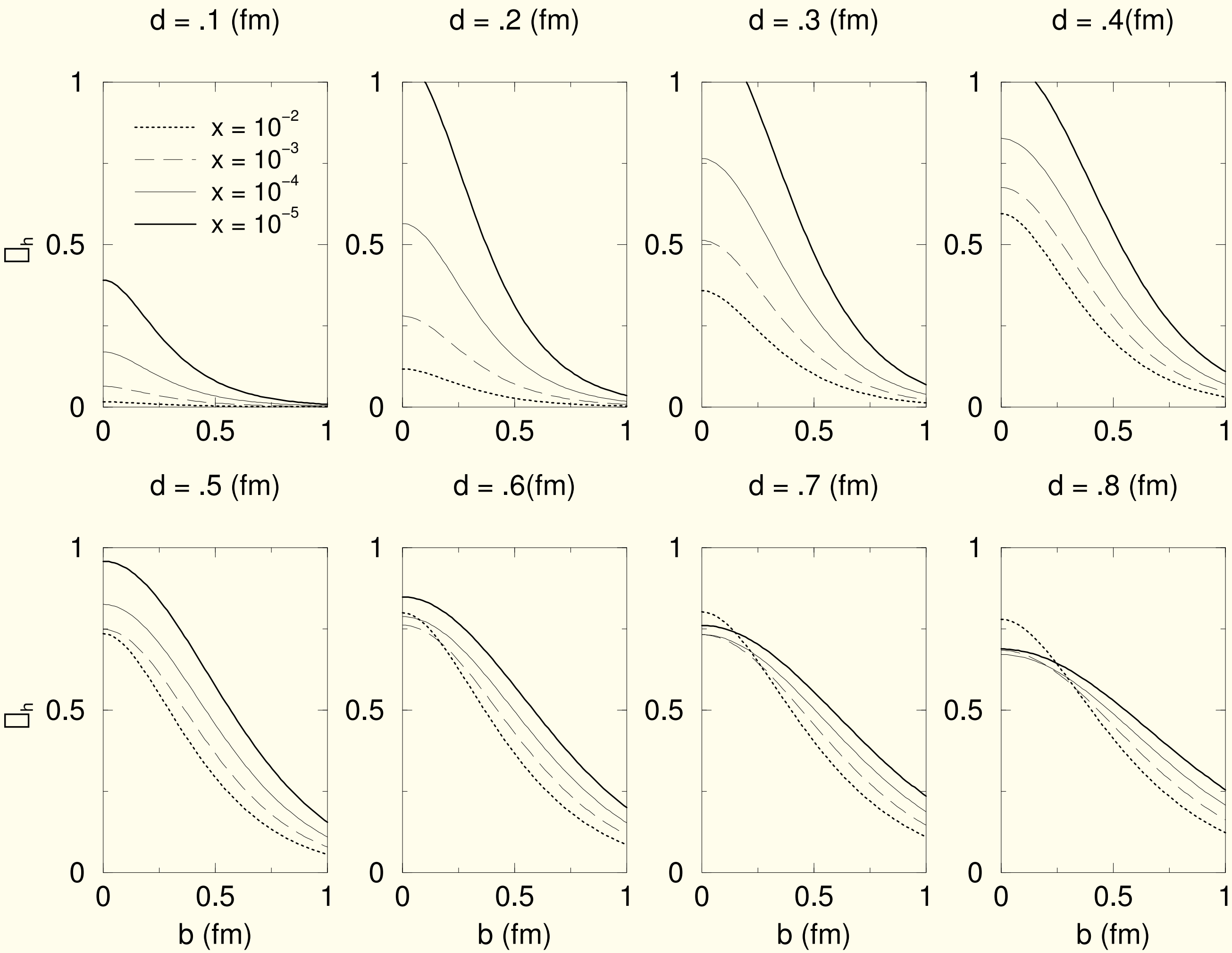
The interaction cross-section, $\hat{\sigma}$ for CTEQ4L, $x = 0.01, 0.001, 0.0001$, $\lambda = 4, 10$. Based on pQCD expression for $\hat{\sigma}$ at small d_t, soft dynamics at large b, and smooth interpolation. Provides a good description of F_{2p} at HERA and J/ψ photoproduction.

Frankfurt, Guzey, McDermott, MS 2000-2001

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

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.

Impact parameter distribution of inelastic pp collisions.

The radius of strong interactions (the average impact parameters) increases with energy. The t–slope of the elastic cross section, B, increases with the collision energy as $B(s) \;=\; B(s_0) + 2\alpha' \, \ln(s/s_0)$, with $\alpha' \approx 0.25 \, GeV^{-2}$. Thus, the radius of strong interactions is expected to be a factor of 1.5 larger at LHC as compared to fixed target energies.

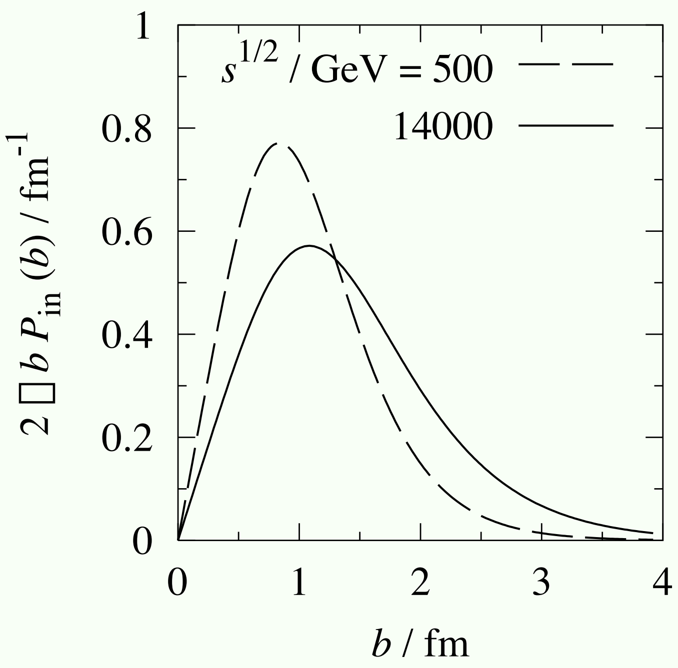
Determining $\Gamma^{pp}(s,b)$ for elastic amplitude using current fits to high-energy data (we used model of Islam et al) we can write:

$\sigma_{in}^{pp}(s) = \int d^2b \, \left[2Re\,\Gamma^{pp}(s,b) - |\Gamma^{pp}(s,b)|^2\right].$ It is convenient to define a normalized b–distribution as

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

.

Distribution in impact parameter for soft QCD interactions



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).

Transverse spatial distribution of hard partons in the nucleon

For gluons it is given by the Fourier transform of the two gluon form factor as

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

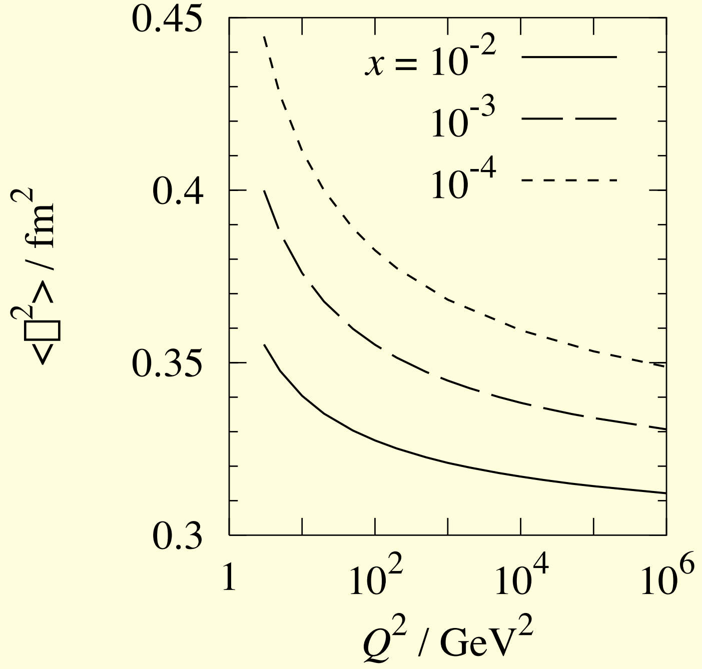
It is normalized to unit integral over the transverse plane: $\int d^2\rho\, F_g(x,\rho;Q^2) \;=\; 1.$

In the analysis we used the dipole fit to the two-gluon form factor:

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

with x-dependent m_g fitted to reproduce the slope of J/ψ photoproduction.

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

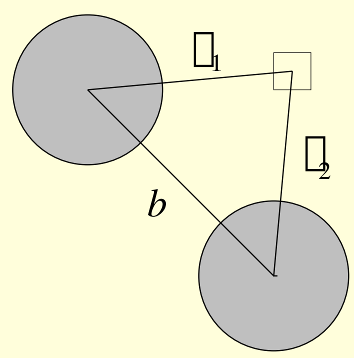


The change of the average transverse gluonic size squared, $\langle\rho^2\rangle$, due to DGLAP evolution, for $x = 10^{-2}, 10^{-3}$ and 10^{-4}.

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

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

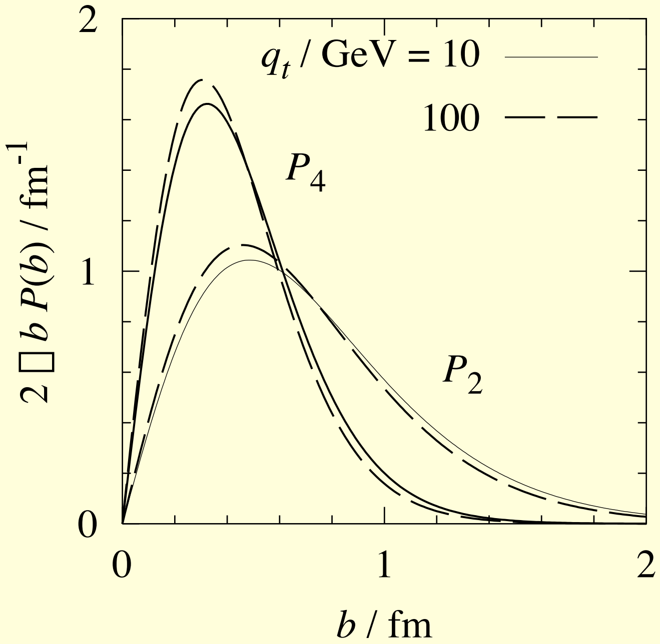
where $x_1 = 2q_\perp/\sqrt{s}$. Obviously $P_2(b)$ is automatically normalized to 1.

For a dipole parameterization:

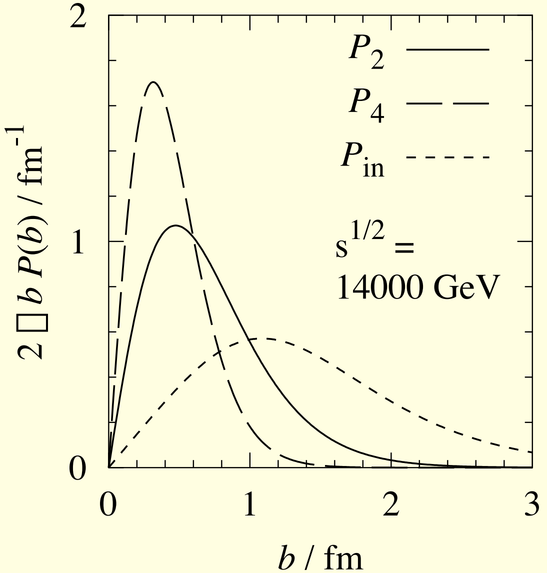
$$P_2(b) \;=\; \frac{m_g^2}{12\pi} \left(\frac{m_g b}{2}\right)^3 K_3(m_g b)$$

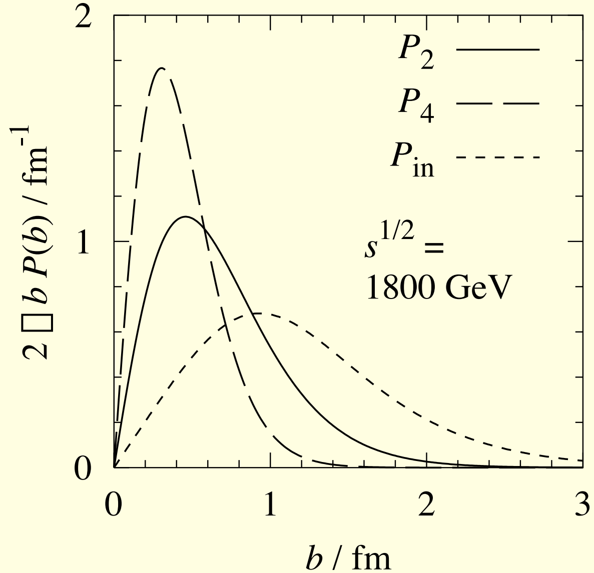
For two binary collisions producing four jets *assuming no correlation between gluons in the transverse plane*:

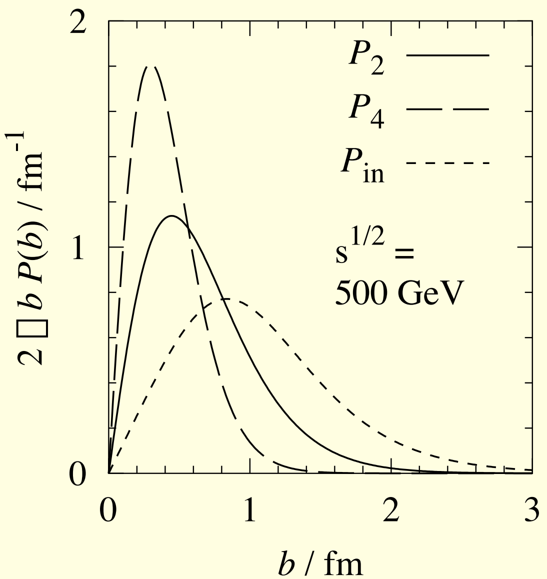
$$P_4(b) \;=\; \frac{P_2^2(b)}{\int d^2b \; P_2^2(b)}; P_4(b) \;=\; \frac{7\, m_g^2}{36\pi} \left(\frac{m_g b}{2}\right)^6 [K_3(m_g b)]^2 .$$



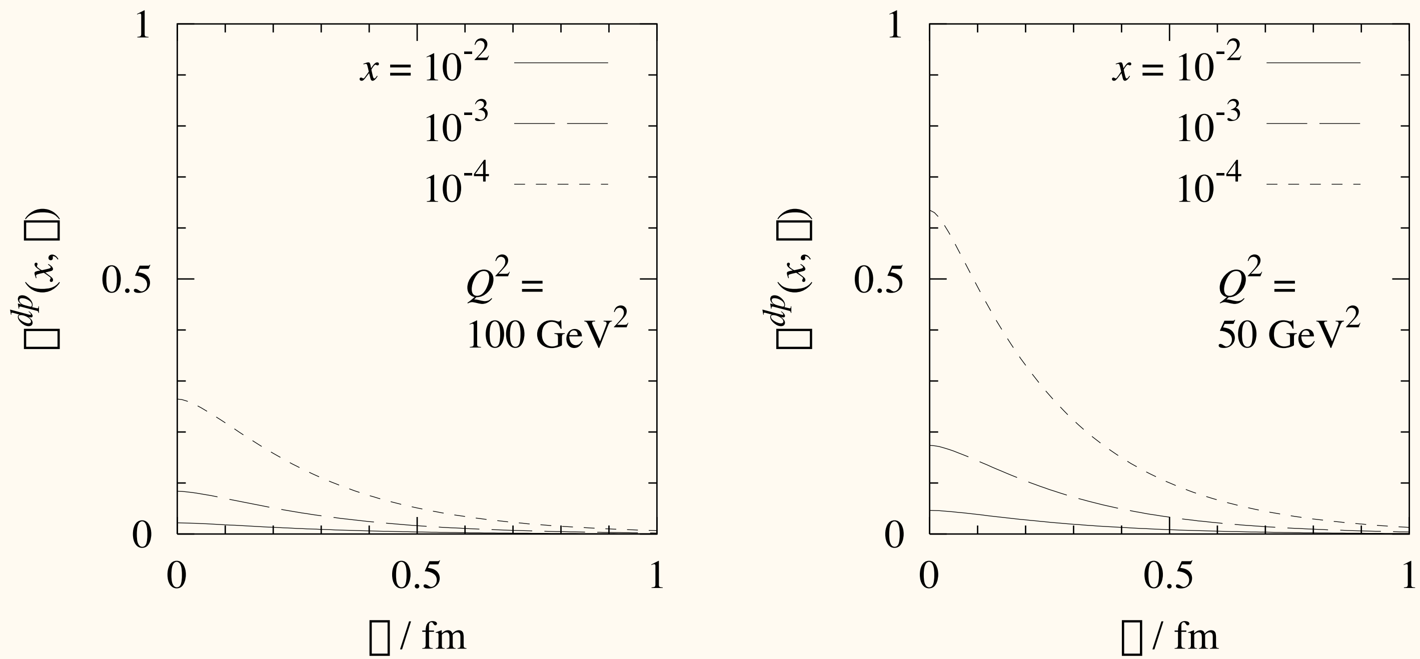
The b–distribution for the trigger on hard dijet production, $P_2(b)$, obtained with the dipole form of the gluon b–profile, for $\sqrt{s} = 14000\,GeV$ and $q_\perp = 10\,GeV$ and $100\,GeV$. The plots show the "radial" distributions in the impact parameter plane, $2\pi b\,P_2(b)$. Also shown is the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

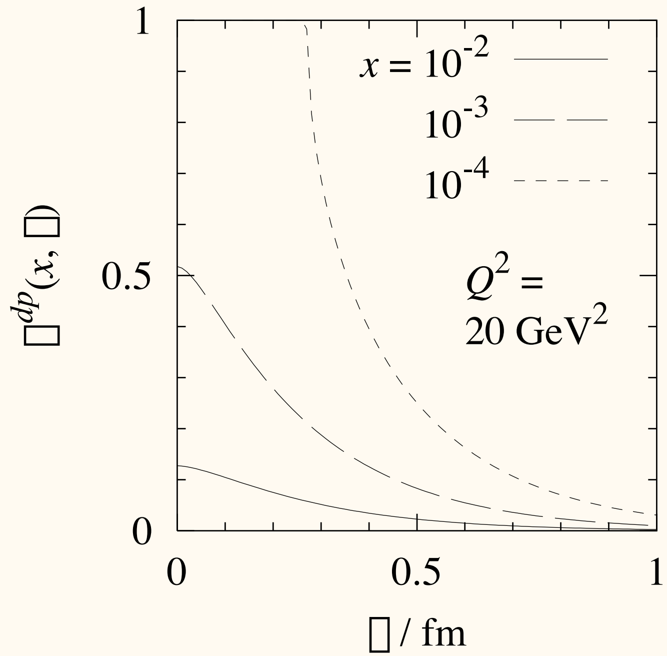






Difference between b-distributions for minimal bias and dijet, four jet events strongly increases with increase of incident energy. *Solid lines:* b–distributions for the dijet trigger, $P_2(b)$, with $q_\perp = 25\,GeV$, as obtained from the dipole–type gluon ρ–profile. *Long–dashed line:* b–distribution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





The profile function for elastic dipole–nucleon scattering, $\Gamma^{dp}(x, \rho)$, with the inelastic cross section given by the leading–twist expression. Shown are the results for an 88 dipole with $Q^2 = 100\, GeV^2$ (upper left panel), $50\, GeV^2$ (upper right panel), and $20\, GeV^2$ (lower left panel), for various values of x.

- Spectator parton resolved by collision with a parton in other proton (x_R)

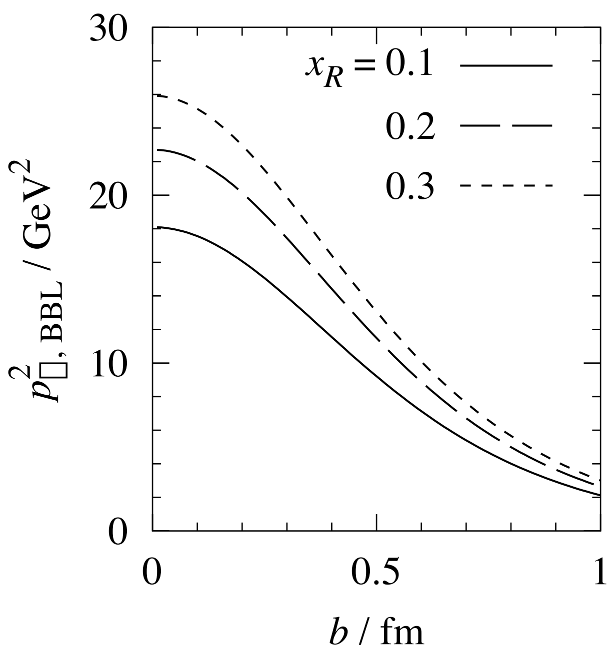
$$x = \frac{4p_\perp^2}{x_R s}, Q^2 = 4p_\perp^2$$

$$small\ x \leftrightarrow\ large\ x_R$$

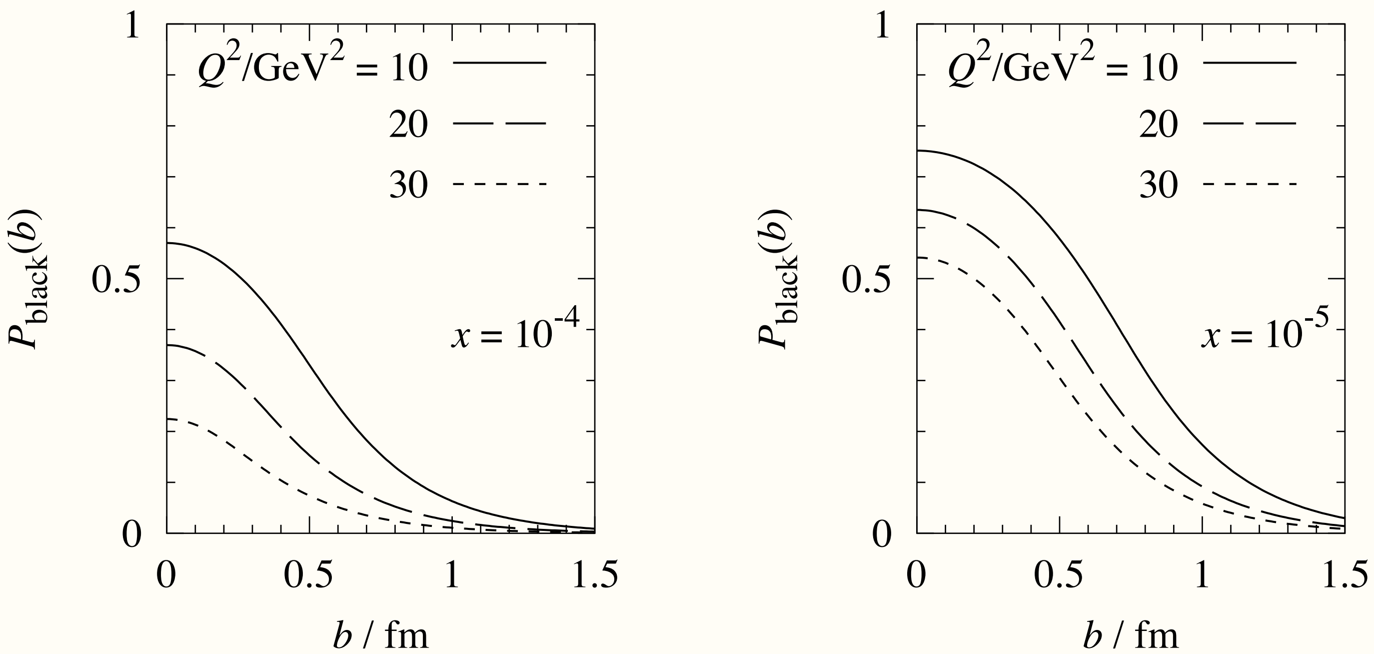
$p_\perp$ acquired by a spectator parton $\approx$ Maximal $p_\perp$ for which interaction remains black for given x_R

Also, parton loses a significant fraction of its energy

like happens with electron in backscattering of laser off a fast electron beam.



$$P_{black} > P_{crit}$$



The probability for partons in the projectile proton with given x and Q^2 to interact with the target proton near the BBL, as a function of the impact parameter of the proton–proton collision, b. Shown are the results for $x = 10^{-4}$ (left panel) and $x = 10^{-5}$ (right panel), for $Q^2 = 10, 20$ and $30\,GeV^2$.

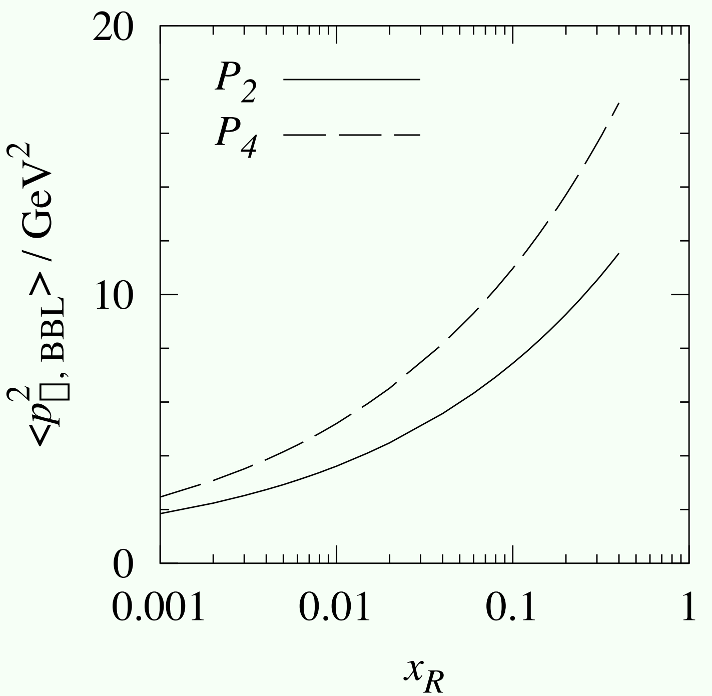
⇒ Probability of "black" interactions rapidly decreases with pp impact parameter

Control b with dijet trigger!!!

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

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

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.

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 compaable 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 $p_\perp \leq p_{\perp,BBL}$ differential cross setions of new particle production.

Conclusions

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

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

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