Dijet trigger for centrality in pp scattering

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based on Frankfurt, Strikman, Weiss, hep-ph/0311231

Outline

1. Introduction: How one can trigger on central collisions in pp scattering -general idea and why it is interesting/important
2. Information from HERA/exclusive processes necessary for quantitative estimates
3. How close are interactions at HERA to the black body limit/saturation regime.
4. Calculation of the distribution over impact parameters for inelastic collisions with dijet trigger and comparison with minimal bias events.
5. Four–jet production: Study of multiparton correlations in nucleons and nuclei, evidence for transverse space correlations.
6. Up to what $p_\perp$ pp - interactions are black at small impact parameters at LHC/Tevatron
7. Long range correlations in rapidity in pp collisions with a dijet trigger and new particle production

Motivations

In proton-ion, ion-ion collisions collisions at small impact parameters are *strongly different* from the minimal bias events.

Is it also true for pp collisions? How to trigger on central pp ?

Qualitative idea - hard processes correspond to collisions where nucleons overlap stronger more partons hit each other - use hard collision trigger gr FELIX 97. How to quantify? Need information about transverse distribution of partons in nucleon. $\Longrightarrow$ Use analyses of the HERA data.

Why this is interesting/ important?

• Amplification of the small x effects: $x = 4p_\perp^2/x_T s$. At LHC for $x_T = 0.01, p_\perp = 2GeV/c$, $x \sim 10^{-5}$.

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

Lessons from HERA

The key problem of the small x physics is related to the fast increase of the gluon densities at small x, and related accumulation of higher twist effects and possible divergence of the perturbative series.

Difficult to notice within the infinite momentum frame (DGLAP) approach. Easier to perform the analysis in the rest frame of the target where space-time geometry is more transparent.

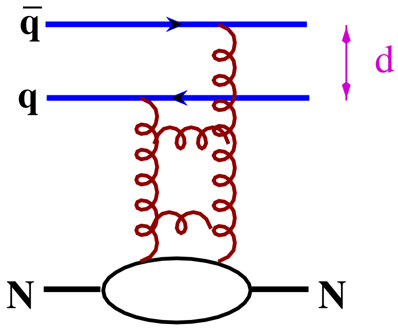
Starting point: at sufficiently small x space-time picture of virtual photon - target interaction in the target rest frame is a three step process:

(1) transition $\gamma^* \to h$ where h are various $q\bar{q}, q\bar{q}g...$ 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. (2) interaction of the evolved configurations with the target, (3) formation of the final state.

Applicable both for inclusive DIS and for production of vector mesons ($J/\psi, \Upsilon$, longitudinally polarized light vector mesons)

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 q and $\bar{q}$ and the off-shellness (virtuality) of the probe which produced the $q\bar{q}$ pair. In some of the models this is ignored. OK - in the leading $\ln x$ approximation.



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

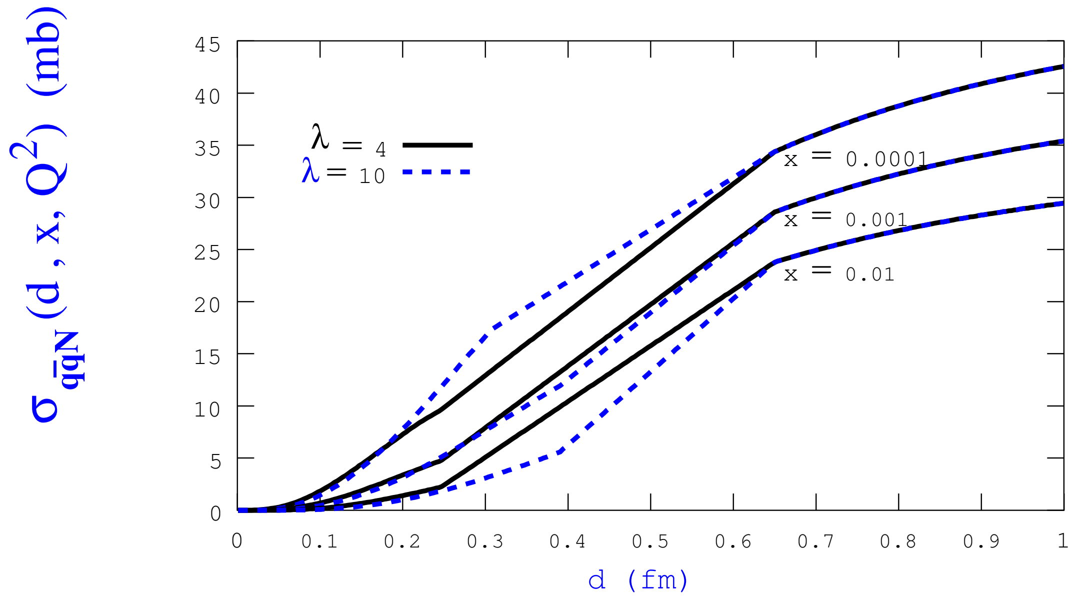
$$\sigma^{inel}_{q\bar{q}N}(d,E_{inc}) = \frac{\pi^2}{3} d^2 \alpha_s\left(\frac{\lambda}{d^2}\right) \text{ x } G_N\left(x, \frac{\lambda}{d^2}\right)$$

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:

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

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

Cross section of the octet dipole-nucleon interaction is 9/4 larger than for the $q\bar{q}$



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

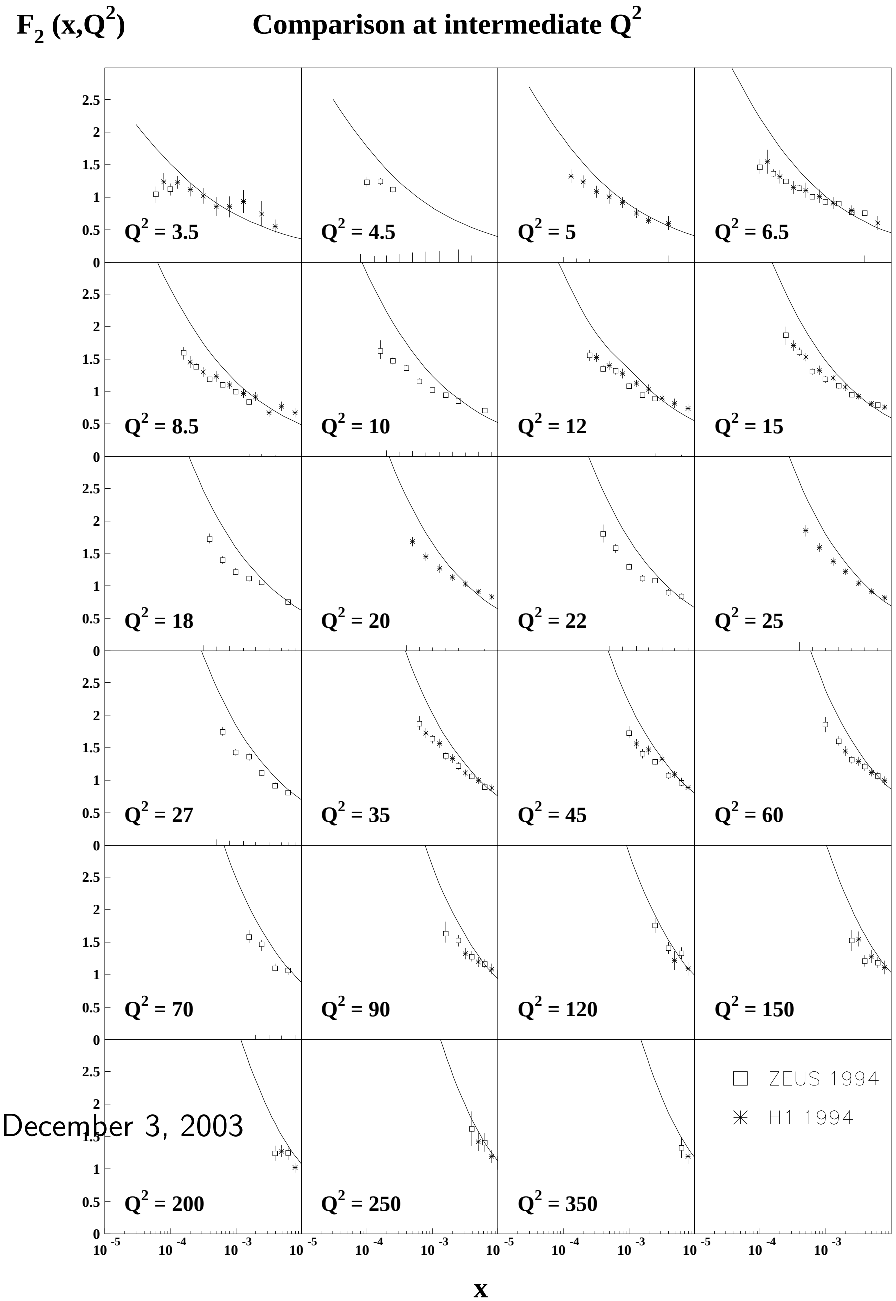
• Calculation of the total cross section of $\gamma^* N$ interaction. $\sigma_T(x,Q^2), \sigma_L(x,Q^2)$ may be written in the leading log approximation in terms of the dipole cross section convoluted with the light-cone wave function of the virtual photon squared:

$$\sigma_L(x,Q^2) = 2\int_0^{1/2} dz \int d^2b\,\hat{\sigma}(b^2)\,|\psi_{\gamma,L}(z,b)|^2\,,$$

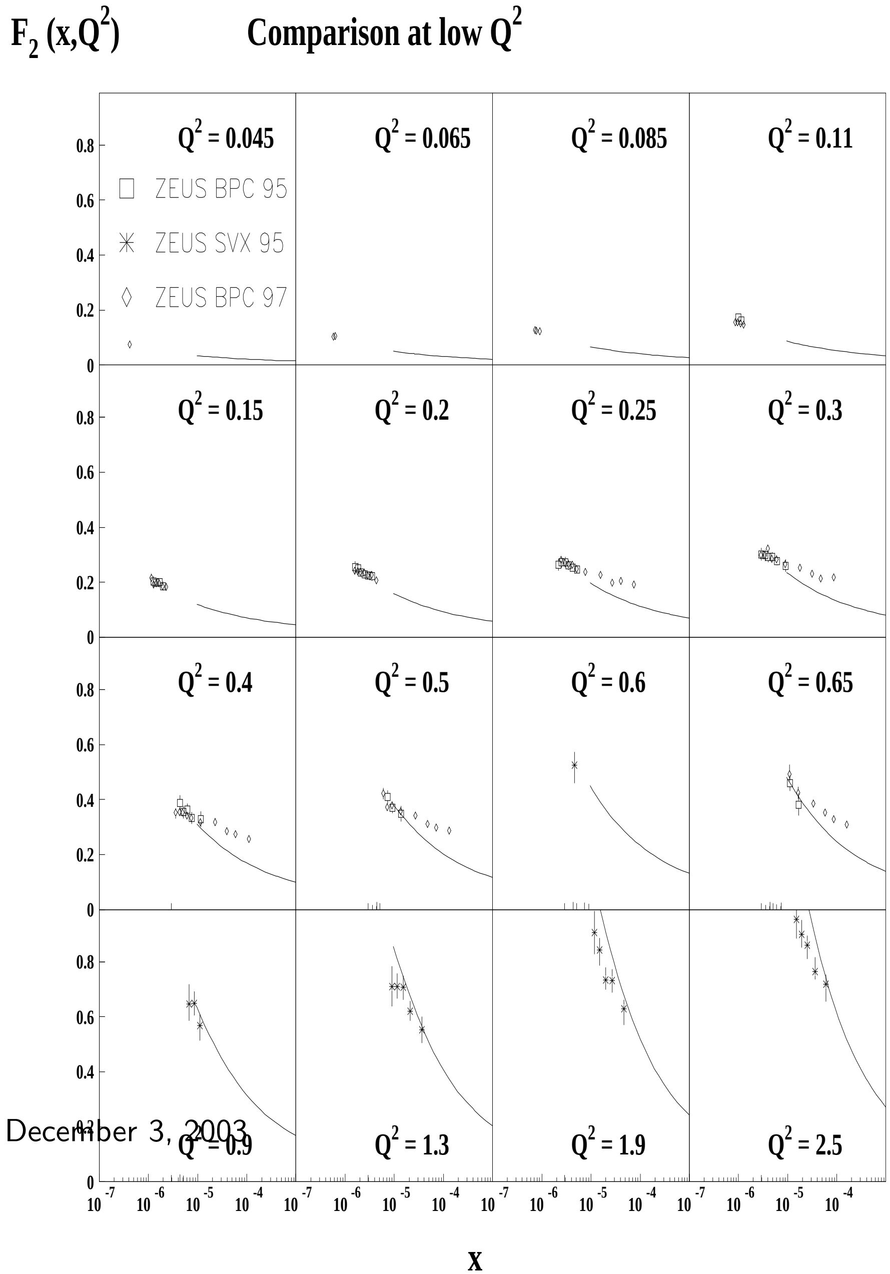
$$|\psi_L(z,b)|^2 = \frac{6}{\pi^2}\alpha_{e.m.}\sum_{q=1}^{n_f} e_q^2 Q^2 z^2 (1-z)^2 K_0^2(\epsilon b)\,,$$

$$|\psi_T(z,b)|^2 = \frac{3}{2\pi^2}\alpha_{e.m.}\sum_{q=1}^{n_f} e_q^2\left[(z^2+(1-z)^2)\epsilon^2 K_1^2(\epsilon b) + m_q^2 K_0^2(\epsilon b)\right]\,,$$

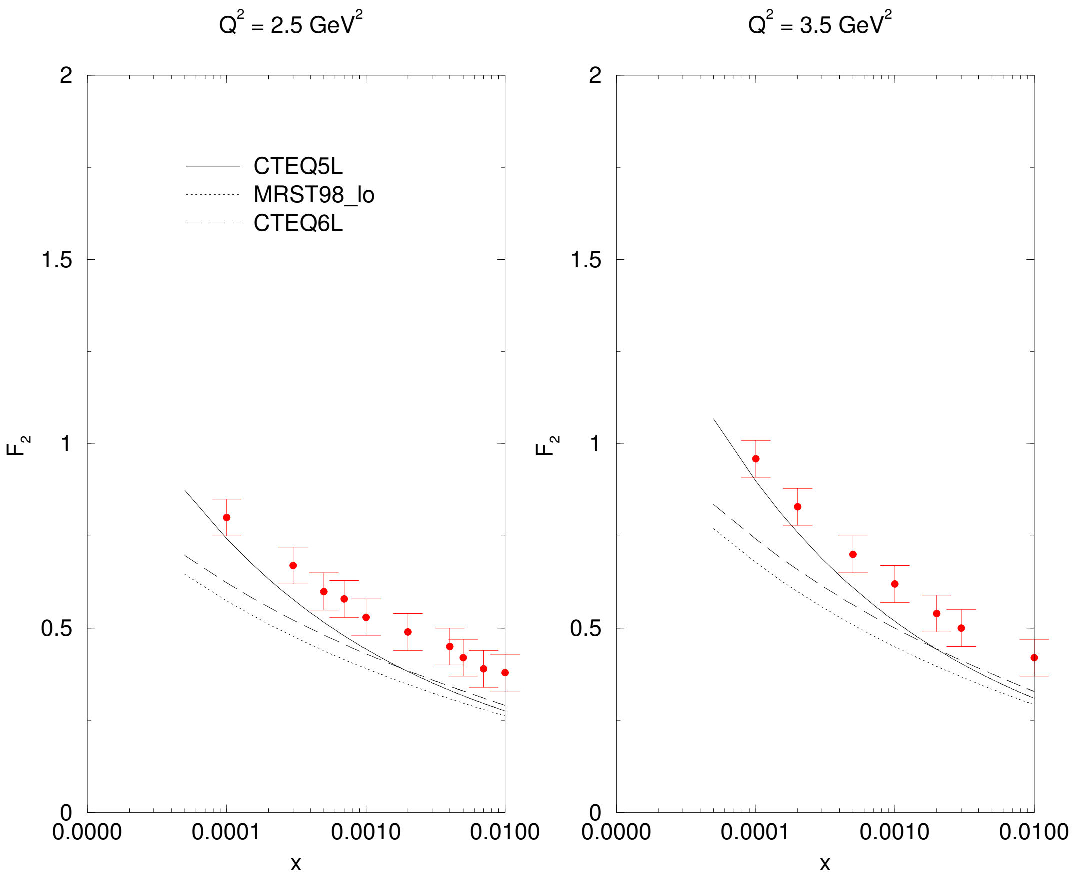
where $\epsilon^2 = Q^2(z(1-z)) + m_q^2$. The requirement of matching with soft physics and radius of the real photon -nucleon interaction requires setting the light quark mass, $m_q \sim$ 300 MeV.



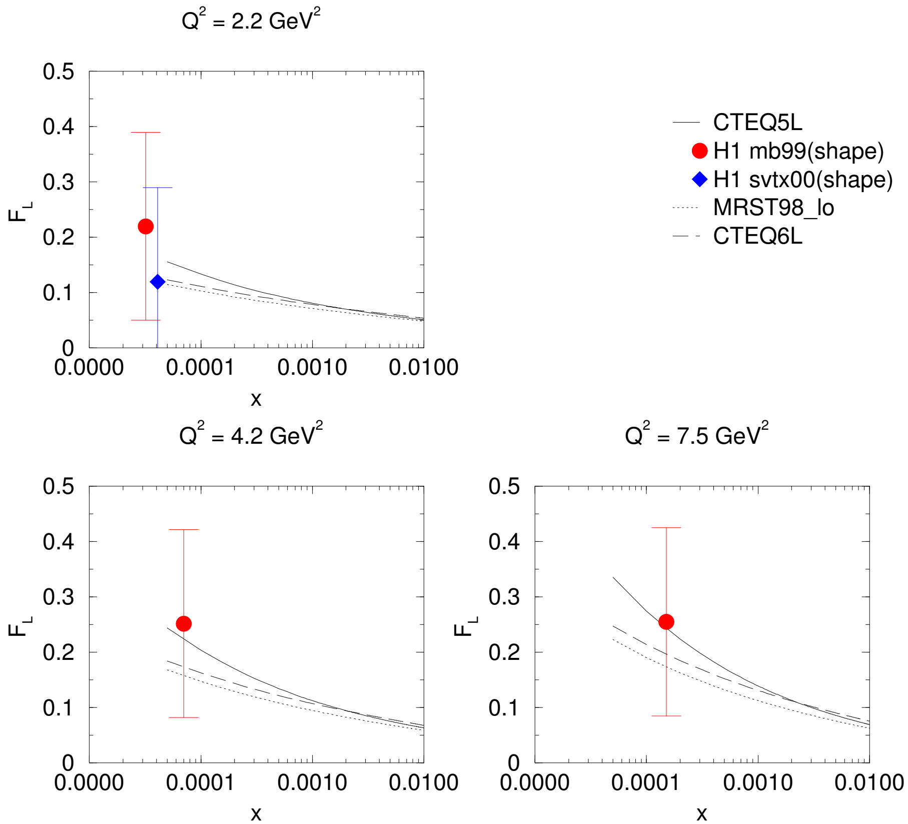
A comparison of the results with the 1994 ZEUS and H1 data, without any fitting procedures.



A comparison of the results with the ZEUS data at low Q^2, without any fitting procedures.



Q^2 = 2.5 GeV^2
Q^2 = 3.5 GeV^2
CTEQ5L
MRST98_lo
CTEQ6L
F2
x
2
1.5
1
0.5
0
0.0000
0.0001
0.0010
0.0100



Q² = 2.2 GeV²
Q² = 4.2 GeV²
Q² = 7.5 GeV²
F_L
x
0.0000
0.0001
0.0010
0.0100
0
0.1
0.2
0.3
0.4
0.5
CTEQ5L
H1 mb99(shape)
H1 svtx00(shape)
MRST98_lo
CTEQ6L

To understand how close the dipole cross section to the maximal strength (unitarity limit)it is necessary to know *the t-dependence of the dipole-nucleon scattering.* Such information can be extracted from the study of the exclusive vector meson production at high energies at large Q^2 (onium production).

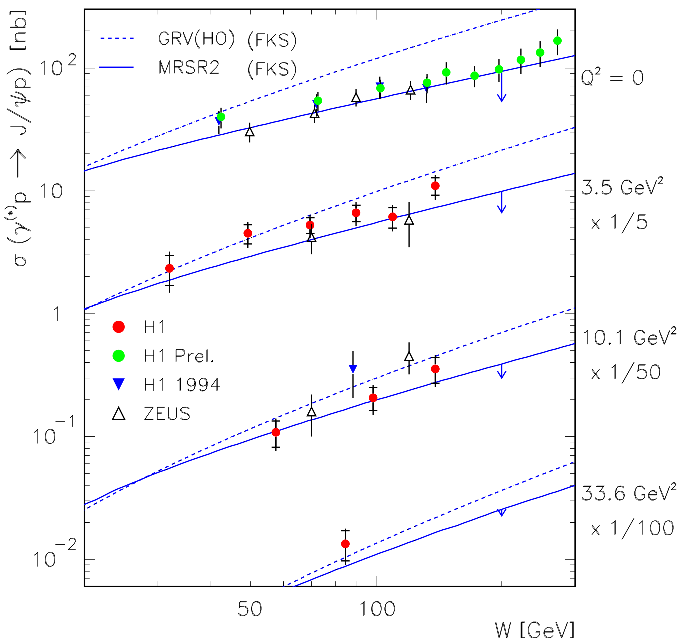
$A(\gamma_L^* + p \to V + p)$ at $p_t = 0$ is a convolution of the light-cone wave function of the photon $\Psi_{\gamma^* \to |q\bar{q}\rangle}$, the amplitude of elastic $q\bar{q}$ - target scattering, $A(q\bar{q}T)$, and the wave function of vector meson, ψ_V: $A = \int d^2 d\psi^L_{\gamma*}(z,d)\sigma(d,s)\psi_V^{q\bar{q}}(z,d)$.

In the leading twist the t dependence in given solely by the two gluon form factor of the nucleon.

Note: In the leading twist d=0 in $\psi_V(z,d)$. Finite d effects in the meson wave function is one of the major sources of the higher twist effects. In particular the finite d in the VM wave function result in the Q^2 & quark mass dependence of the slope in the preasymptotic region. (F,Koepf,S97)

$\diamond$ Extensive data on VM production from HERA support *dominance of the pQCD dynamics* and the dipole model approximation. Numerical calculations including finite b effects in $\psi_V(b)$ explain key elements of high Q^2 data. The most important ones are:

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



(ii) Absolute cross section of ρ production at $Q^2 \sim 20 - 30\ GeV^2$ and its energy dependence at $Q^2 \sim 20\ GeV^2$. 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.

(iii) Convergence of the t slopes

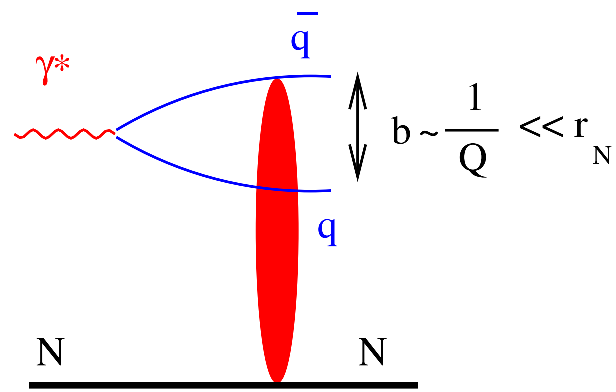
B ($\sigma = A\exp(Bt)$) of

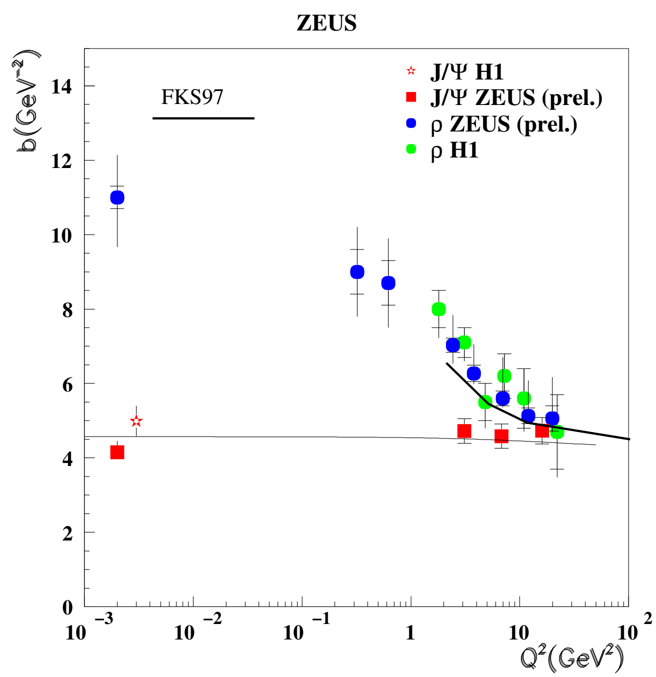
$\rho-$ meson production

at large Q^2 and

J/ψ production

(Brodsky et al 94)





HERA data confirm that slope of the J/ψ photo/electroproduction is due to the two gluon form factor of the nucleon.

The analysis of the data on the exclusive photoproduction of J/ψ at fixed target energies: $100 \geq E_\gamma \geq 10$ GeV - FS02

The two-gluon form factor of the nucleon for $0.2 \leq x \leq 0.03, Q_0^2 \sim 3\ GeV^2$ is

$$F_g(x,t,Q_0^2) = 1/(1-t/M^2)^2, M^2 \sim 1.1GeV^2, |t| \leq 2\ GeV^2.$$

This is much slower than e.m. form factor of the nucleon - finds natural explanation if the presence of the pion degrees of freedom is taken into account

At smaller x the slope of the t-dependence starts to increase - the initial phase of this change appears to be due to the pionic degrees of freedom C.Weiss talk.

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

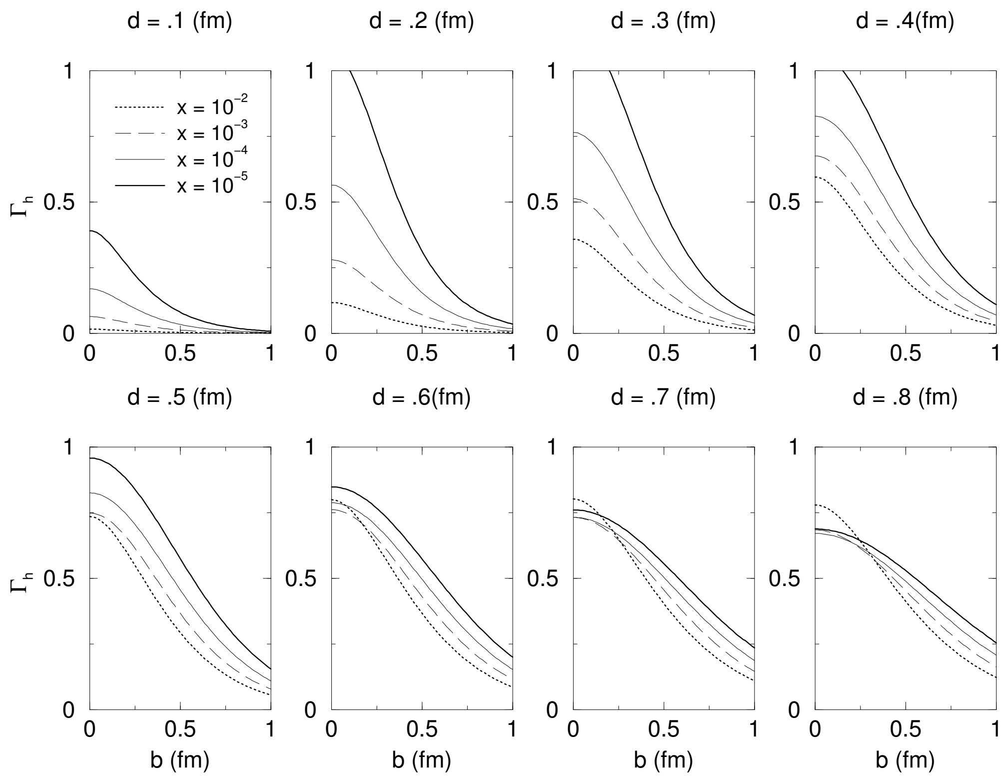
Can the rapid increase of σ continue forever?

Knowing information about the t-dependence of the elastic dipole-nucleon scattering we can test how far are the partial waves of elastic scattering from the S-channel unitarity limit:

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

$\Gamma(b) = 1$ corresponds to the black body limit (BBL) $\sigma_{inel} = \sigma_{el}$.

For small 88 dipole -hadron scattering where pQCD is applicable $\Gamma(b)$ is 9/4 times larger).



The hadronic configuration-nucleon profile function for different x values. The large $\Gamma_h(b)$ region ($\Gamma_h \geq 1/2$) is reached for intermediate hadronic sizes. T.Rogers, et al

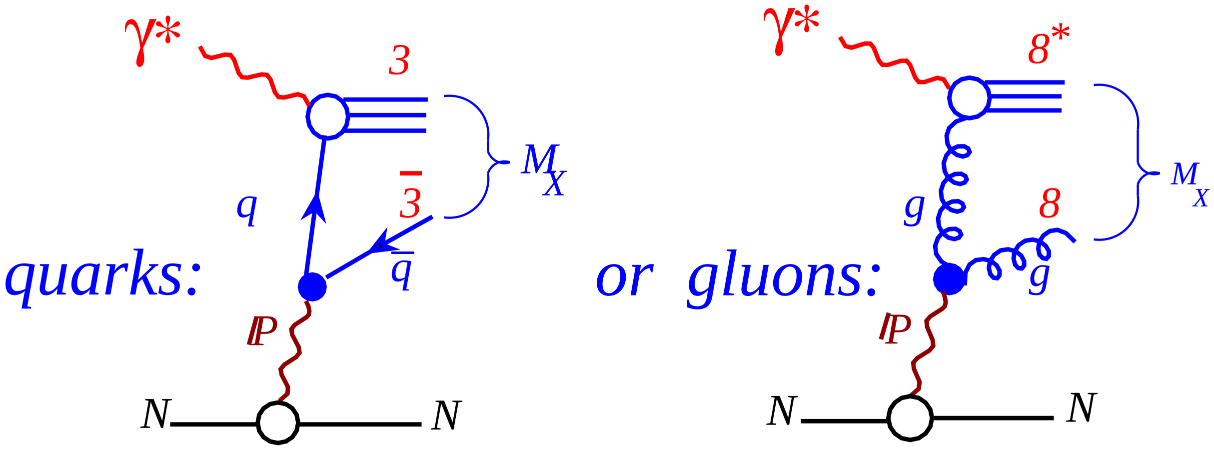
In this estimate inelastic diffraction was neglected which increase the overall probability of diffraction in the quark channel. However not much for medium d - consistent with HERA data on probability of diffraction in DIS: $\sim 10 - 15\%$.

At the same time for the octet dipole for d where pQCD is valid $\Gamma(b)$ is 9/4 larger $\Longrightarrow$

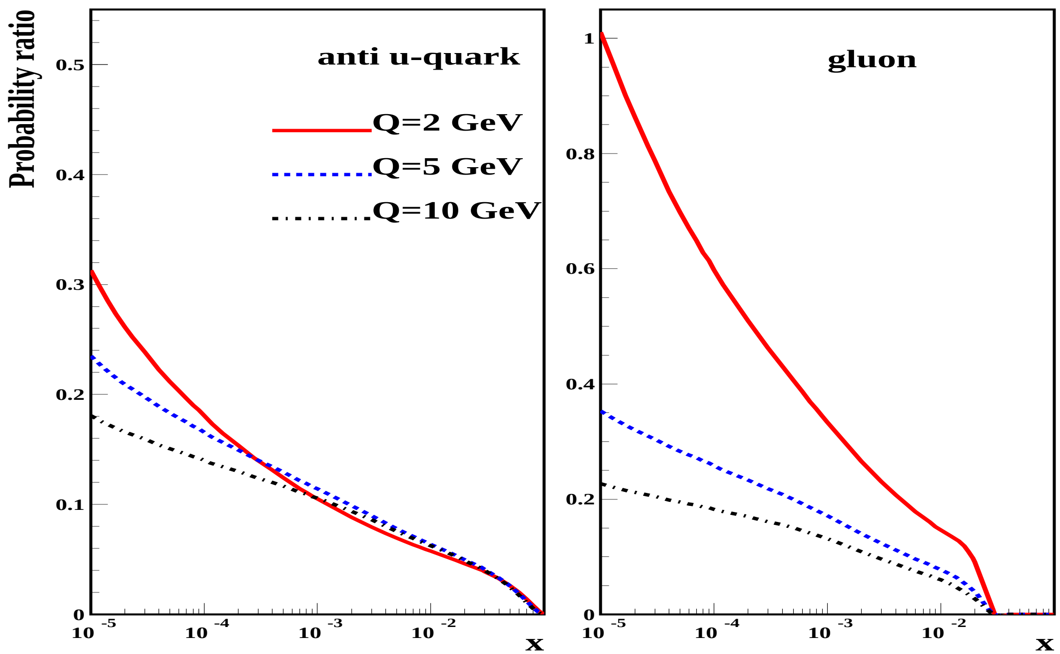
Enhancement of diffraction in the gluon channel is expected - probability of the order 30% at Q_0 scale -close to BBL.

Critical check FS98 - use the Collins factorization theorem for DIS diffraction Collins 97

It allows to define a probability $P_j(x,Q^2) = \int f_j^D(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t)dtdx_{I\!P}/f_j(x,Q^2)$ of diffractive gaps for the hard processes induced by hard scattering off



The HERA data on hard diffraction as analyzed in the NLO support large probability of the gluon induced diffraction:



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.

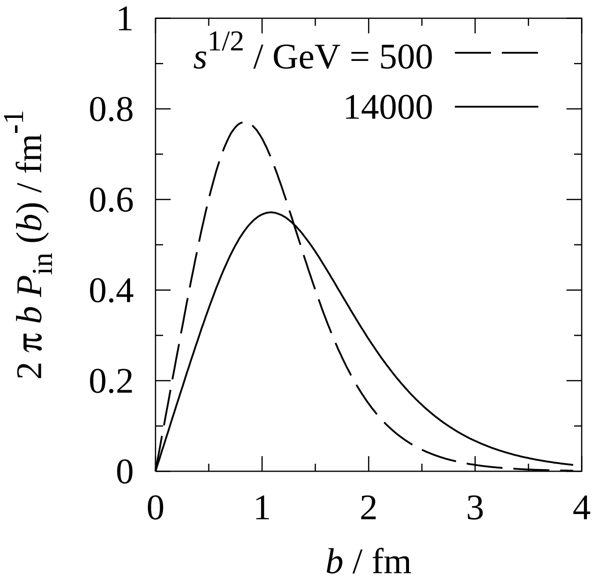
The radius of strong interactions (the average impact parameters) increases with energy. The t–slope of the elastic cross section, B, increases with the collision energy as $B(s) \;=\; B(s_0) + 2\alpha' \, \ln(s/s_0)$, with $\alpha' \approx 0.25\, GeV^{-2}$. Thus, the radius of strong interactions is 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

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

.



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

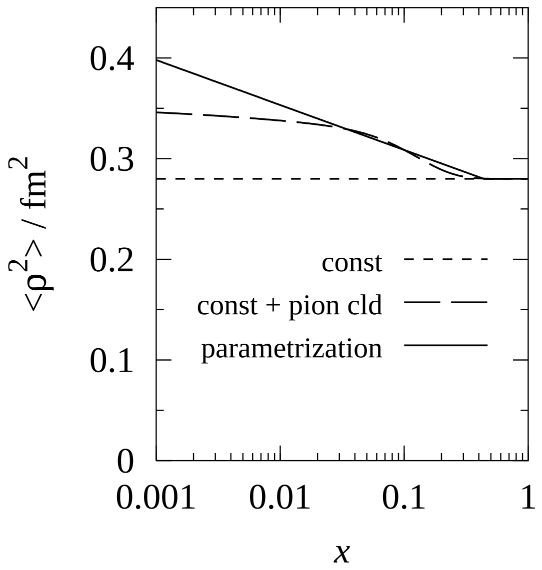
$$F_g(x,\rho;Q^2) \; \equiv \; \int \frac{d^2\Delta_\perp}{(2\pi)^2}\, e^{i(\boldsymbol{\Delta}_\perp \boldsymbol{\rho})}\, F_g(x,t=-\boldsymbol{\Delta}_\perp^2;Q^2)$$

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

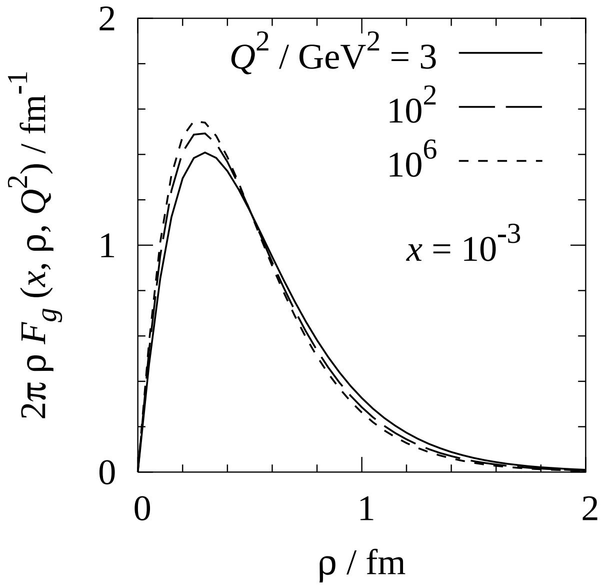
Using the dipole fit to the two-gluon form factor:

$$F_g(x,\rho) = \frac{m_g^2}{2\pi}\; \left(\frac{m_g\rho}{2}\right)\; K_1(m_g\rho), m_g = 1.1 GeV$$

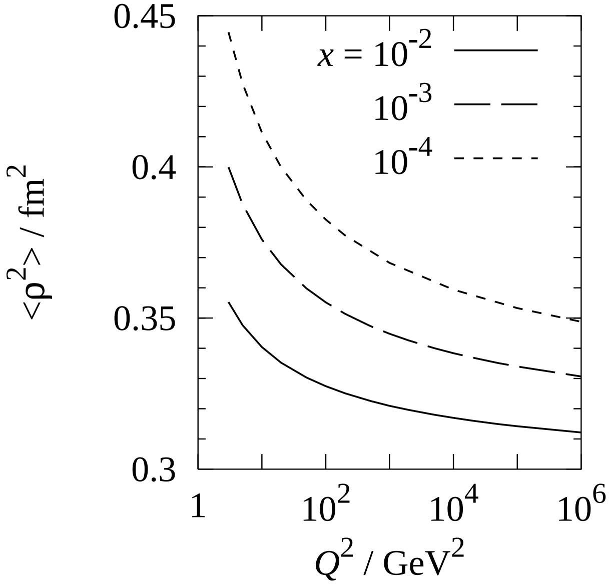
The x dependence of the slope was modeled by fitting $m_g(x)$ to reproduce J/ψ data. The Q^2 dependence was accounted using LO DGLAP evolution at fixed ρ.



Our model for the x–dependence of the average transverse gluonic size squared of the nucleon, $\langle\rho^2\rangle$ at the scale $Q_0^2 = 2 \div 4\, GeV^2$ relevant to J/ψ production. *Short–dashed line:* $\langle\rho^2\rangle = 0.28\, fm^2$, as extracted from the t-slope of the J/ψ production cross section measured in various experiments (F& S 02) *Long–dashed line:* Sum of the constant value $\langle\rho^2\rangle = 0.28\, fm^2$ and the pion cloud contribution calculated in Strikman & Weiss, 2003 *Solid line:* The parameterization based on the experimental value of α'_{hard} as measured at HERA.



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.

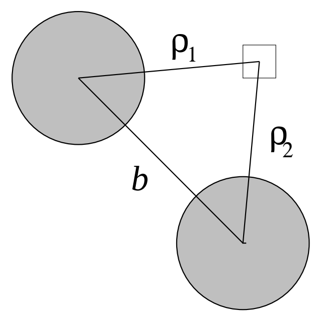


The change of the average transverse gluonic size squared, $\langle\rho^2\rangle$, due to DGLAP evolution, for $x = 10^{-2}, 10^{-3}$ and 10^{-4}.

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

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

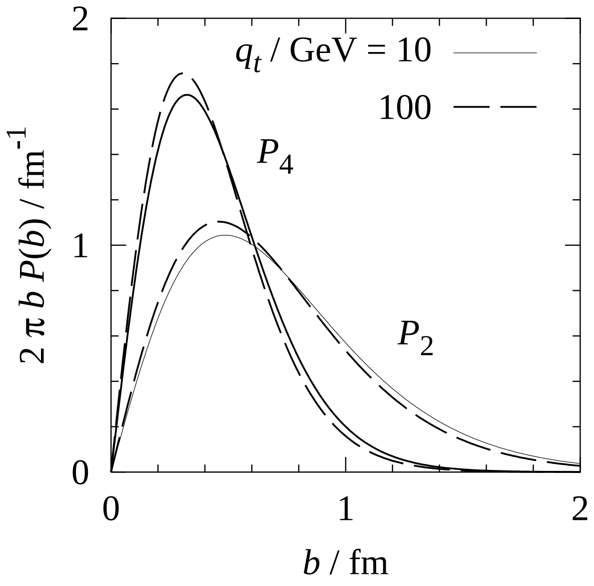
where $x_1 = 2q_\perp/\sqrt{s}$. Obviously $P_2(b)$ is automatically normalized to 1.

For a dipole parameterization:

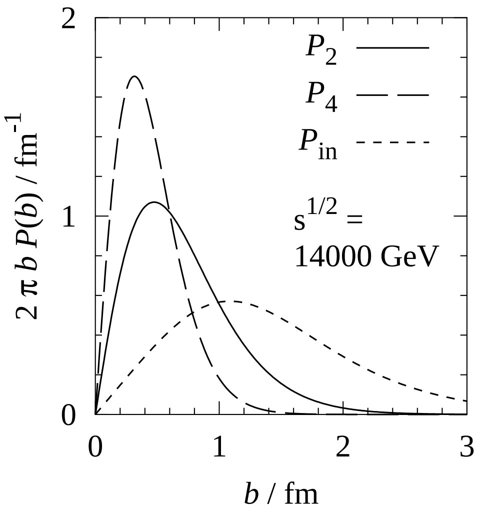
$$P_2(b) \;=\; \frac{m_g^2}{12\pi}\left(\frac{m_g b}{2}\right)^3 K_3(m_g b)$$

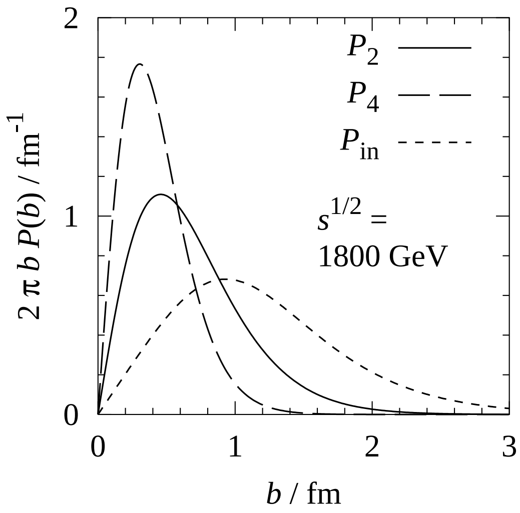
For two binary collisions producing four jets *assuming no correlation between gluons in the transverse plane*:

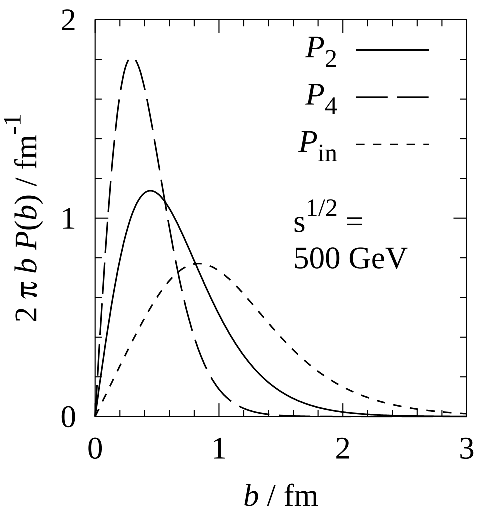
$$P_4(b) \;=\; \frac{P_2^2(b)}{\int d^2b \; P_2^2(b)}; P_4(b) \;=\; \frac{7\,m_g^2}{36\pi}\left(\frac{m_g b}{2}\right)^6 \left[K_3(m_g b)\right]^2.$$



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 ratio of the cross section of double dijet events and the square of the single dijet cross section is proportional to $\sigma_{eff} = \left[\int d^2b\, P_2^2(b)\right]^{-1}$. In our calculation we find $\sigma_{eff} = 34\, mb$, which should be compared with $\sigma_{eff} = 14.5 \pm 1.7^{+1.7}_{-2.3}\, mb$ reported by CDF assuming that there is no correlations in the longitudinal distribution of partons.

$\Longrightarrow$ Evidence for correlations of gluon/quarks in transverse plane. Possible origin:

- Hot spots (QCD evolution) A.Mueller
- Constituent quarks.

$\Longrightarrow$ A more realistic estimate of $P_4(b)$ is

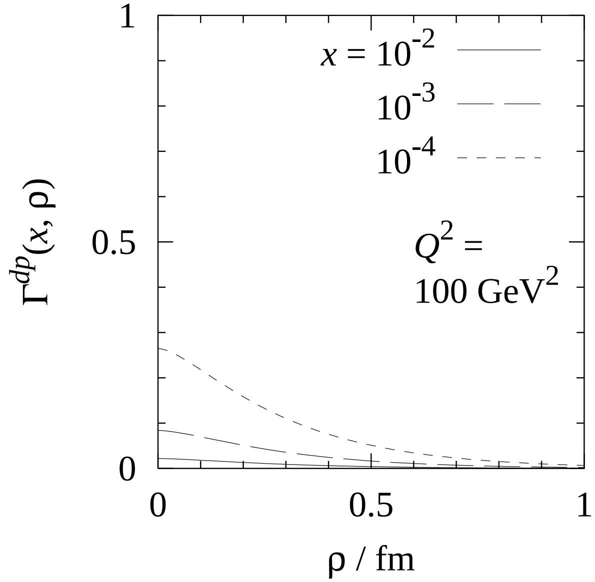
$$P_{4,corr}(b) \approx P_2(b)\, \frac{\sigma_{eff}(model)-\sigma_{eff}(CDF)}{\sigma_{eff}(model)} + P_4(b)\, \frac{\sigma_{eff}(CDF)}{\sigma_{eff}(model)}$$

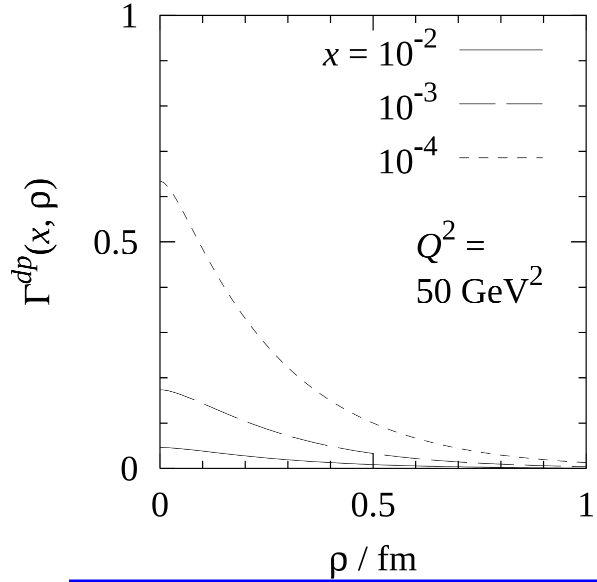
Need measurements using different channels, and at different incident energies. RHIC versus Tevatron.

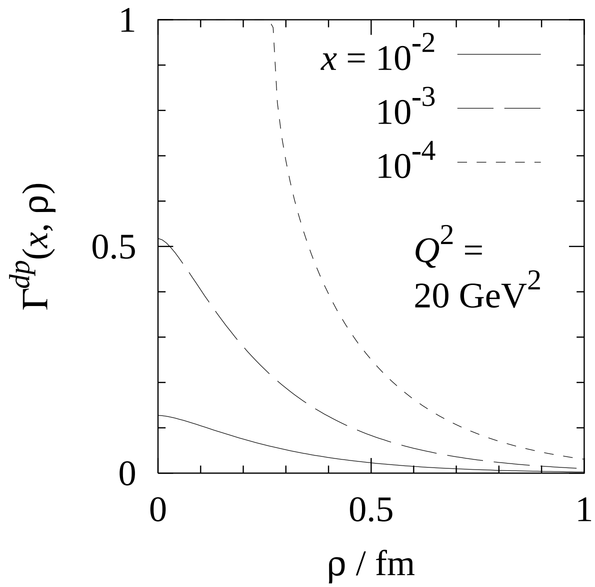
Approaching the black-body limit for "spectator" parton interactions in the central pp collisions

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.

Similar to the case of $q\bar{q}$ dipoles we first look at values of Γ as a function of ρ.

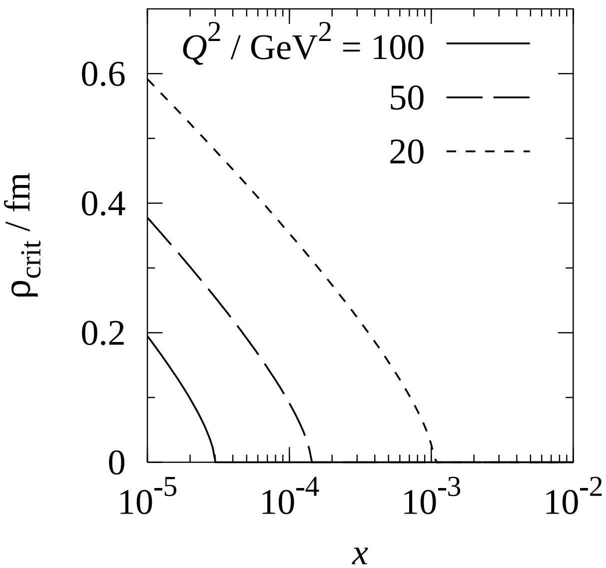






The profile function for elastic dipole–nucleon scattering, $\Gamma^{dp}(x,\rho)$, with the inelastic cross section given by the leading–twist expression. Shown are the results for an 88 dipole with $Q^2 = 100\,GeV^2$ (upper left panel), $50\,GeV^2$ (upper right panel), and $20\,GeV^2$ (lower left panel),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

It is convenient also to consider the critical value of impact parameter, ρ_{crit}, for which the profile function of elastic dipole–nucleon scattering, exceeds the value $\Gamma^{dp}_{crit} = 0.5$. Here ρ_{crit} is shown as a function of x. A value of $\rho_{crit} = 0$ implies that $\Gamma^{dp}(x, \rho) < \Gamma^{dp}_{crit}$ for all values of ρ. Shown are the results for an 88 dipole; the $Q^2 = 100, 50, 20 GeV^2$.

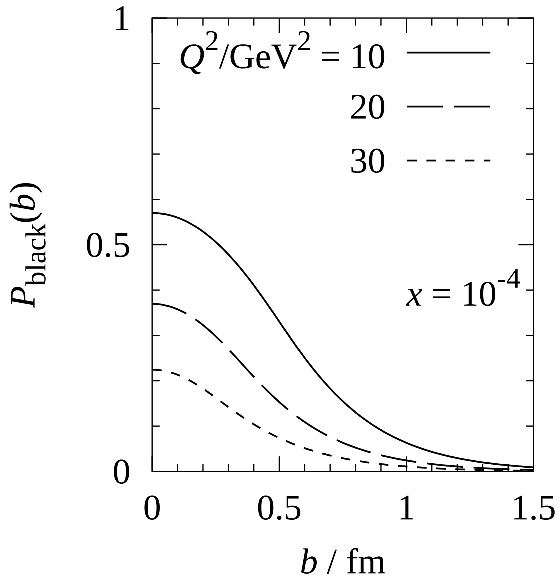


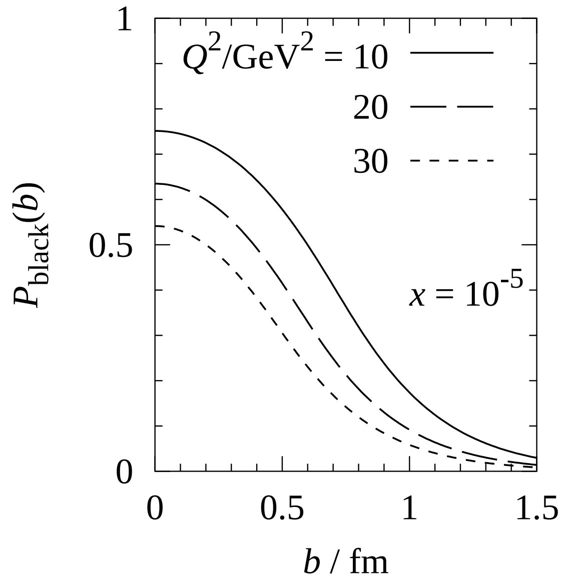
Under which conditions in proton–proton collisions a parton in the "projectile" will interact with the gluon field in the "target" proton near the BBL?

An interesting measure is the total probability for partons in the projectile with given momentum fraction x and virtuality Q^2 (but arbitrary transverse position) to interact near the BBL. It is given by the overlap integral of the normalized transverse spatial distribution of the partons in the projectile proton (shifted by the impact parameter vector, $\boldsymbol{b}$), with the characteristic function of the "black" region in the target proton, $\Theta(\rho_1 < \rho_{crit})$,

$$P_{black}(b) \equiv \int d^2\rho_1 \, \Theta(\rho_1 < \rho_{crit}) \, P_g(x, \rho_2)(\rho_2 \equiv |\boldsymbol{\rho}_1 - \boldsymbol{b}|).$$

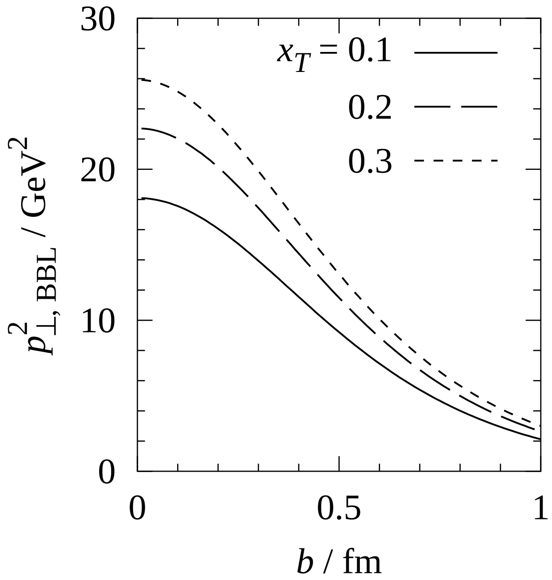
This integral measures the fraction of the partons with given x and $Q^2 = 4p_\perp^2$ which hit the target proton in the "black" central region.





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 $30\,GeV^2$.

An important quantity is the maximum value of $p_\perp$ for given x_T for which the resolved projectile parton sees the target as "black". We can estimate this maximum $p_\perp$ using P_{black}. For given x_T, and given impact parameter b, we ask for the maximum value of $p_\perp^2$ for which $P_{black}(b)$ exceeds a certain critical value: $P_{black}(b) \ > \ P_{crit} \quad for \ \ p_\perp^2 \ < \ p_{\perp,BBL}^2.$



The maximum value of the jet transverse momentum squared, $p^2_{\perp,BBL}$, for which a projectile parton resolved by a target parton with x_T interacts with the target close to the black–body limit (BBL), as a function of the impact parameter of the proton–proton collision, b. The criterion for proximity to the BBL is $P_{black}(b) > 1/2$. Shown are the results for $x_T = 0.1, 0.2$ and 0.3.

For large b, $p^2_{\perp,BBL}$ is small — soft physics dominates.

On the contrary, for dijet trigger $p^2_{\perp,BBL}$ is large. For example we can define:

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

For $x_T = 0.1,\ 0.2,\ 0.3$, respectively

$$p^2_{\perp,BBL}\,(dijet) \;=\; 7.4,\ 9.3,\ 10.5\, GeV^2\ .$$

For double dijet trigger with the same $p_\perp$:

$$p^2_{\perp,BBL}\,(double\ dijet) \;=\; 11.0,\ 13.7,\ 15.6\, GeV^2.$$

Final state properties for central pp collisions

In the central (dijet triggered) pp collisions all leading partons will end up with large (few GeV/c) transverse momenta - similar to central pA collisions at RHIC.

$\longrightarrow$ Many similarities with expectations for spectra of leading hadrons in pA collisions Dumitru,Gerland, MS02.

Qualitative predictions for properties of the final states with dijet trigger

- The leading particle spectrum will be strongly suppressed compared to minimal bias events. The especially pronounced suppression for nucleons: for $z \geq 0.1$ the differential multiplicity of pions should exceed that of nucleons.

- The average transverse momenta of the leading particles $\geq 1\, GeV/c$.

- A large fraction of the 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.

- In the forward production of dimuons or dijets one expects a broadening of the distribution over transverse momenta Gelis,Jalilian-Marian 2002, as well as a weaker dependence of the dimuon production cross section on the dimuon mass for masses $\leq$ few GeV Frankfurt, MS2002.

- The background for heavy particle or high–$p_\perp$ jet production should contain a significant fraction of hadrons with transverse momenta $p_\perp \sim p_{\perp,BBL}$, originating from fragmentation of partons affected by the strong gluon field. The direction of the transverse momenta of these hadrons should be unrelated to the transverse momenta of the jets. This phenomenon will make it difficult to establish the direction of jets unless

$p_\perp\ (jet) \gg p_{\perp,BBL}$.

- Forward cone of the primary proton - air interaction near ZGK cutoff will often resemble iron-air interactions.

Conclusions

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

• Corrections to LT factorization approximation in production of new particles at LHC are likely to be significant - especially for $p_\perp$ distributions.

• Double hard processes provides evidence for transverse correlations between partons. Interesting to study at RHIC for pp scattering (including spin) and for proton-nucleus.