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Hadron Fragmentation at Ultra High Energies Effects of High Gluon Densities

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HADRON FRAGMENTATION AT ULTRA HIGH ENERGIES
- EFFECTS OF HIGH GLUON DENSITIES

Mark Strikman, PSU

QCD at Cosmic energies IV, Trieste, May 2009

Motivation

Cosmic rays of ultrahigh energies: $s \leq 10^{11}\ GeV^2 = 1000\ s_{LHC}$

Interpretation is very sensitive to the forward physics - number of leading particles,...

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

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

For kinematics relevant for the proton fragmentation $s=10^{11}$ GeV^2, $x_1=0.3$, $p_t=1$ GeV/c, $x>x_2=10^{-10}$ are resolved!!!

Outline

- *Increase of gluon densities at small x & onset of black disk regime (BDR)*

  aka taming /saturation of gluon density

- *Propagation of partons through nuclear media in the BDR -*

  p_t broadening and fractional energy losses

- *≈Limiting curve for leading hadron production in BDR*

- *Experimental evidence:*

  fixed target, RHIC dA data (BRAHMS effect)

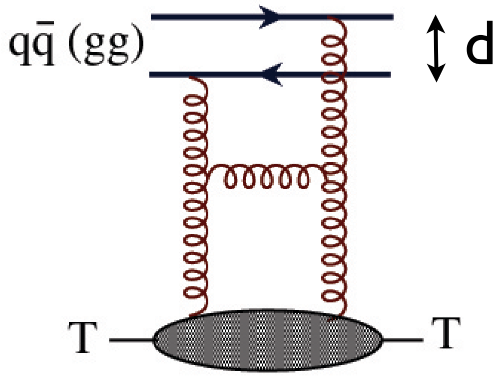
- *Implications for GZK energy range*

- *What is missed in the current MCs for LHC*

- *Matching BDR at GZK with collider data - further studies of dA at RHIC, central pp collisions at LHC, pA at LHC*

Interaction of fast particles in QCD is expected to differ qualitatively from soft dynamics

Consider first "small dipole - hadron" cross section



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

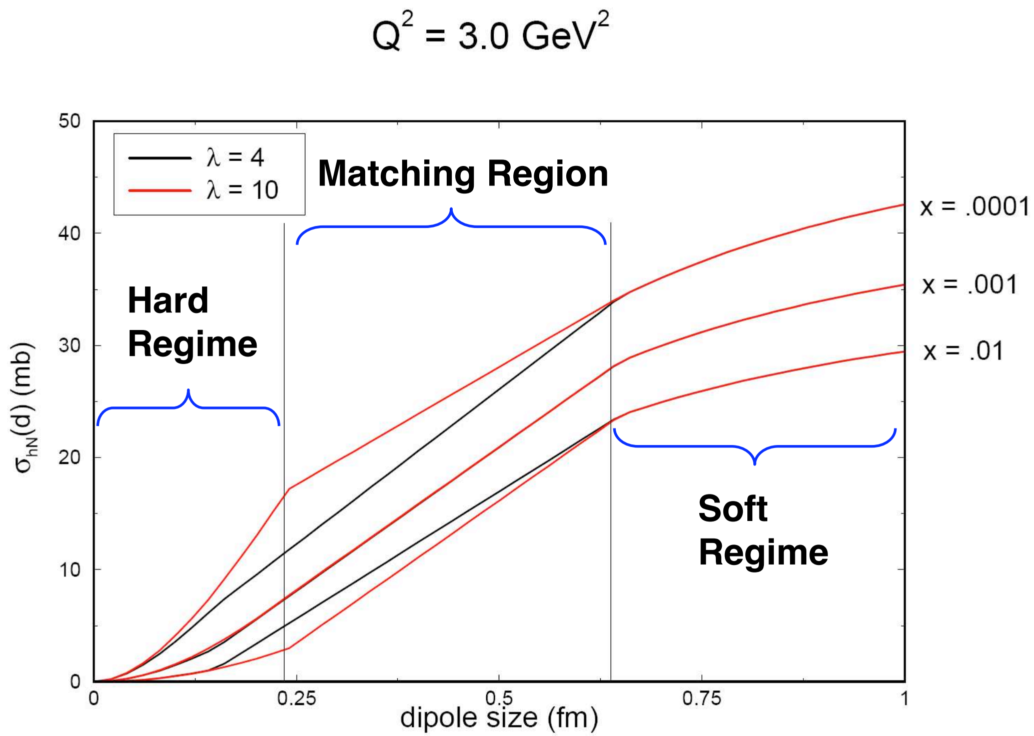
F^2 Casimir operator of color SU(3)

Baym, Blattel, F&S 93

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

Comment: This simple picture is valid only in LO. NLO would require introducing mixing of different components. Also, in more accurate expression there is an integral over x, and an extra term due to quark exchanges. However the general pattern is now tested and works.

HERA data confirm a fast increase of the cross sections of interaction small dipoles with energy predicted by pQCD due to $xG_N \propto x^{-\omega(Q)}$, $\omega \in 0.2 \div 0.4$

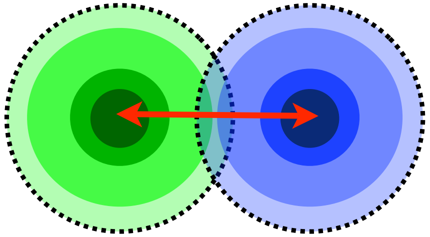


The interaction cross-section, $\hat{\sigma}$ for CTEQ4L, $x = 0.01, 0.001, 0.0001$, $\lambda = 4, 10$. Based on pQCD expression for $\hat{\sigma}$ at small d_t, soft dynamics at large b, and smooth interpolation. Provides a good description of F_{2p} at HERA and J/ψ photoproduction. Provided a reasonable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

Frankfurt, Guzey, McDermott, MS 2000-2001

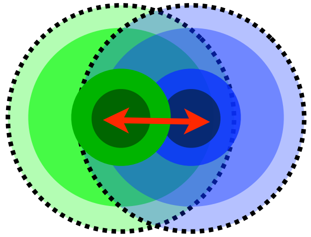
Important variable for describing dynamics is impact parameter:

b



Peripheral pp collisions

b



Central pp collisions

Proton momenta are perpendicular to the plane

L - angular momentum is conserved - $L=bp_{inc}$

b is conserved in the collision

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:

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

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

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

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

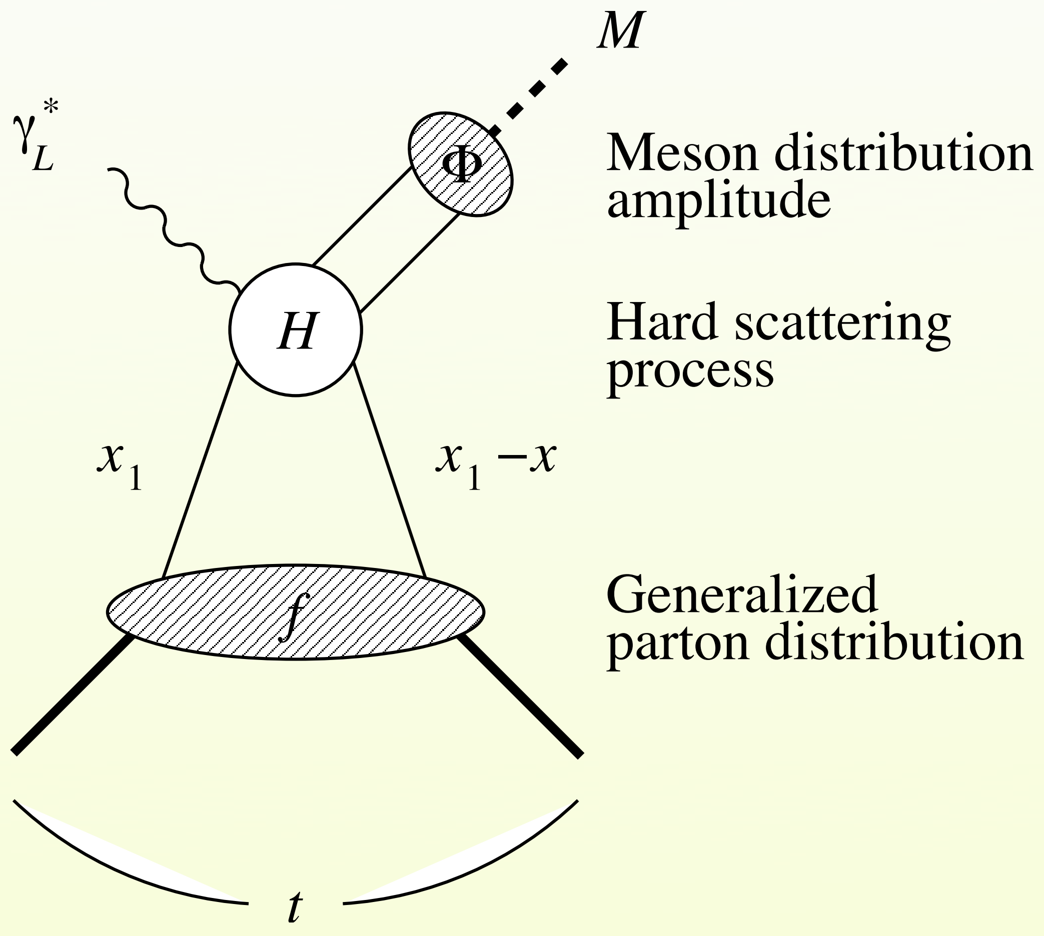
$$\boxed{\Gamma(b) = 1 \;\equiv\; \sigma_{inel} = \sigma_{el}}$$

- black disk regime -BDR

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

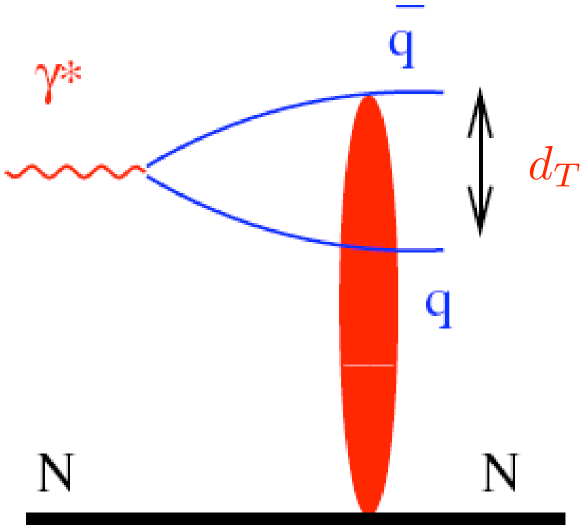
QCD factorization theorem for DIS exclusive processes

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

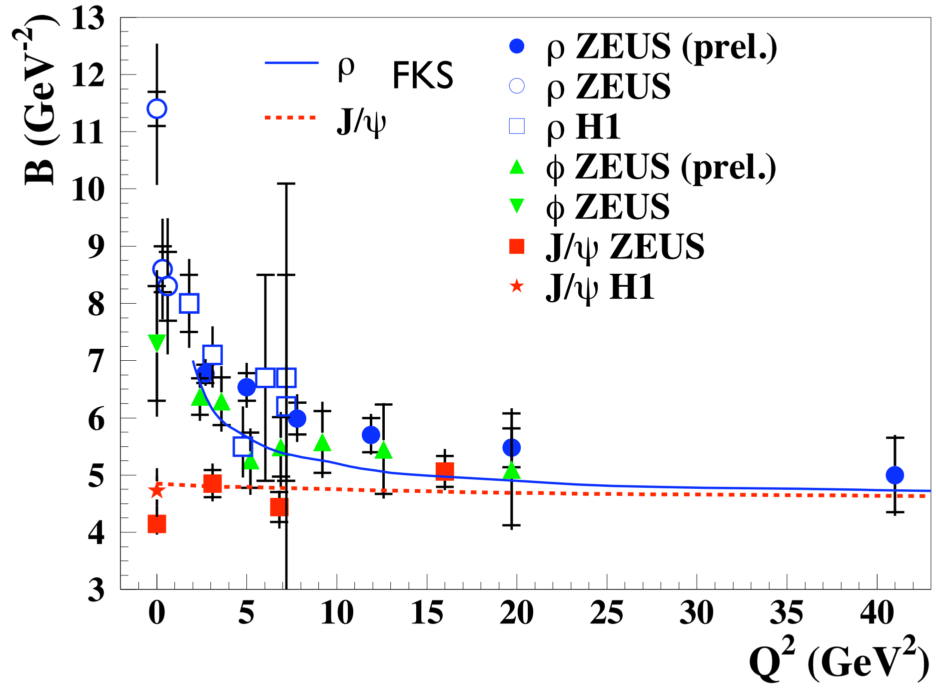


- Universal t-slope: process is dominated by the scattering of quark-antiquark pair in a small size configuration - t-dependence is predominantly due to the transverse spread of the gluons in the nucleon - two gluon nucleon form factor, $F_g(x,t)$. $d\sigma/dt \propto F_g^2(x,t)$.

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

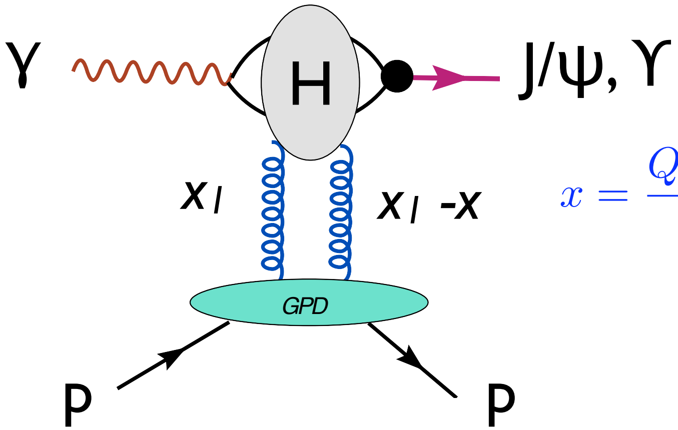


$$d_T \propto \frac{1}{Q}\left(\frac{1}{m_c}\right) \ll r_N$$



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

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



$$x = \frac{Q^2 + m_V^2}{W^2}$$

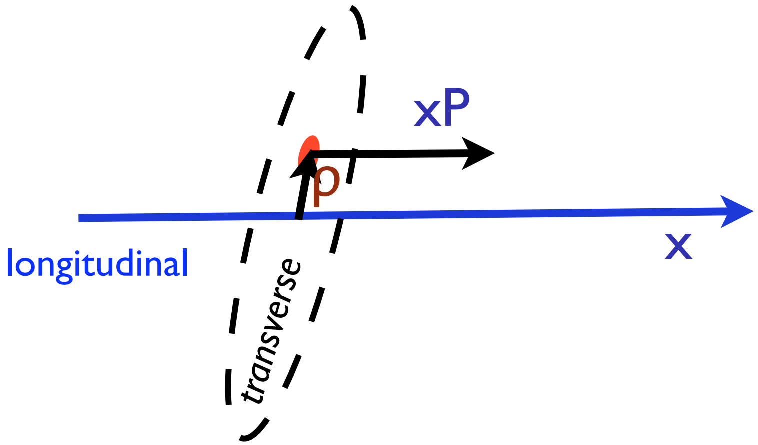
In LT limit x_l -x << x_l

however due to DGLAP evolution skewed GPD kinematics for large Q probes diagonal GPD at Q_0 scale

$$A(\gamma^* + p \to \text{"}Onium\text{"} + p) \propto G(x_1, x1 - x, t)$$

$$G(x,x,t) \equiv G(x,t) = \int d^2\rho e^{-i\vec{\Delta}_\perp \rho} \boxed{G(x,\rho)}$$

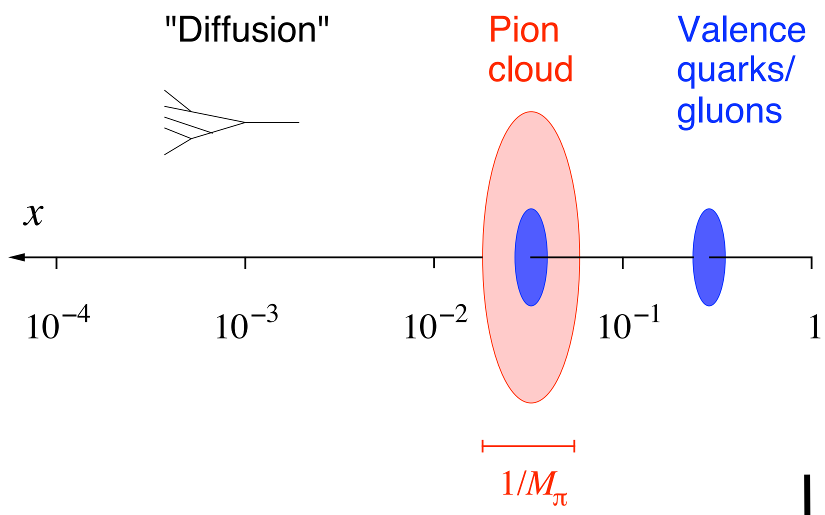
transverse spatial distribution of gluons

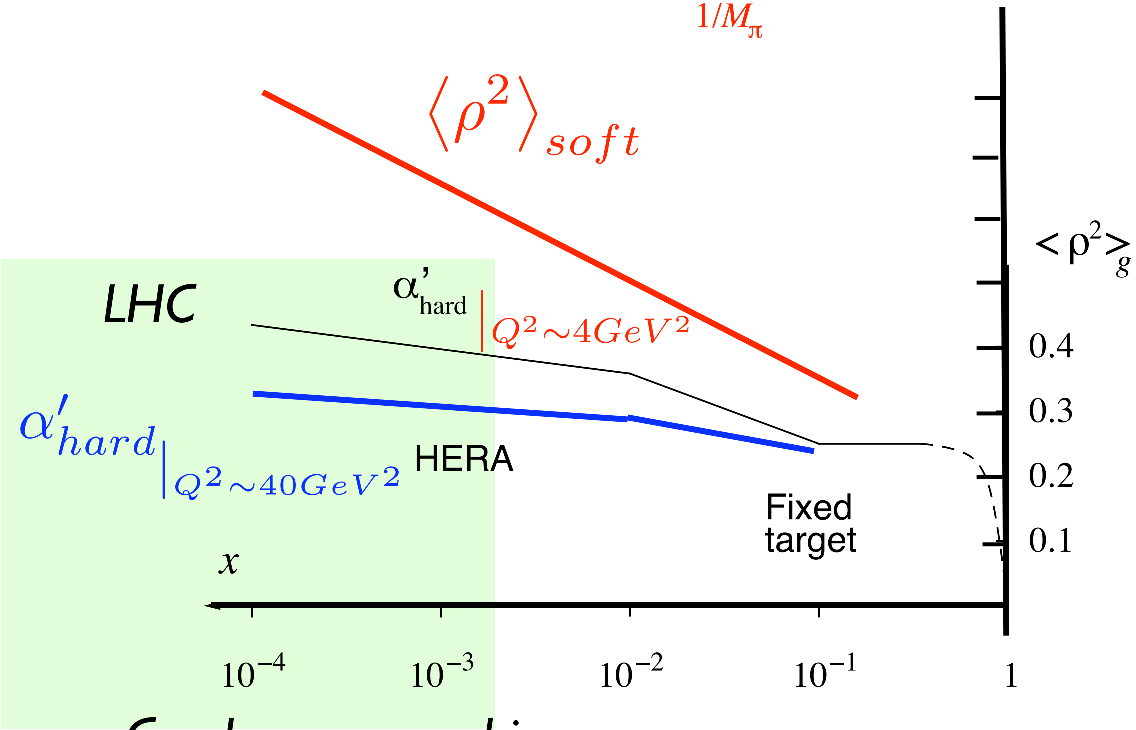


$$\int d^2\rho G(x,\rho) = G(x)$$

total gluon density

- Gluonic transverse size - x dependence





Can be measured in ultraperipheral collisions at LHC

Gluon transverse size decreases with increase of x

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

Transverse size of large x partons is much smaller than the transverse range of soft strong interactions

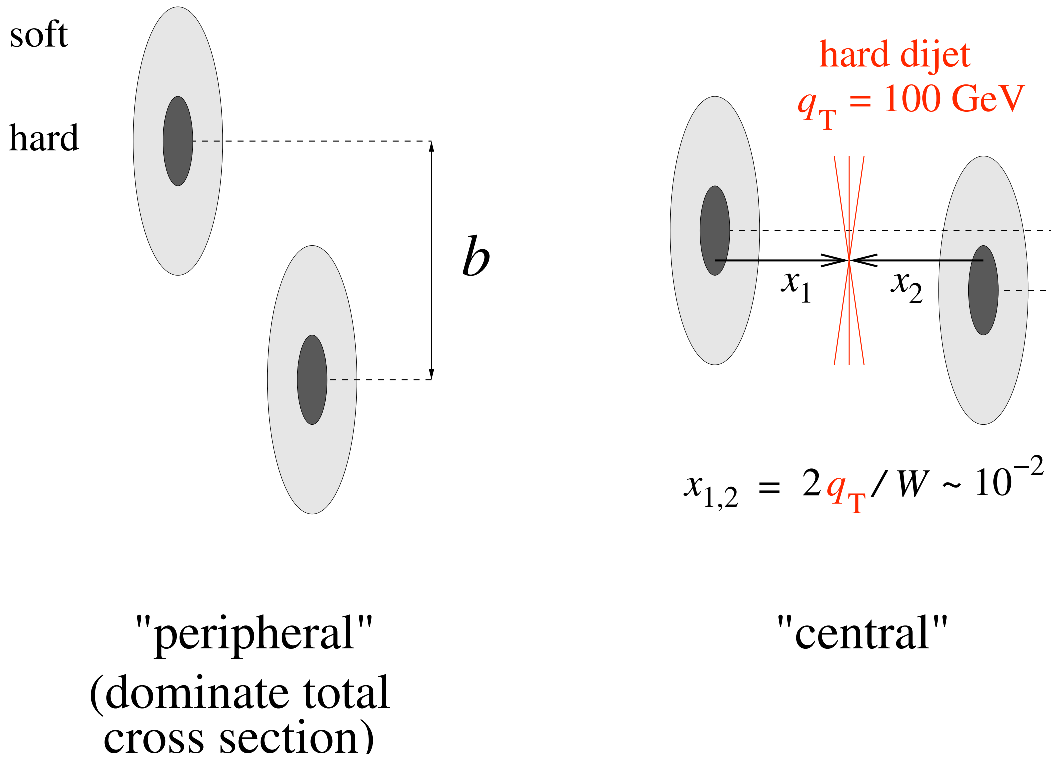
$$\langle\rho^2\rangle_g = \frac{\partial}{\partial t}\frac{G(x.t)}{G(x,0)}$$

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

$$\Downarrow$$

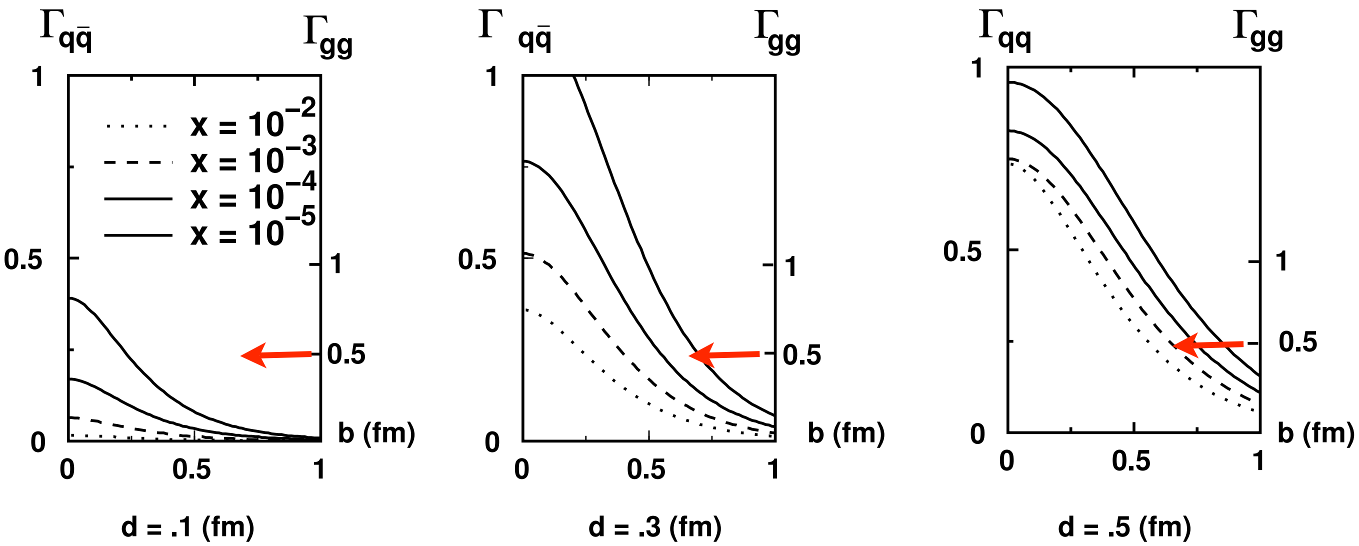
Two scale picture

Interplay of hard and soft interactions in pp collisions, rate of multiple hard collisions is determined by the value of $<\rho^2_g>$ as compared to much larger radius of soft interactions. Note PYTHIA assumes $<\rho^2_g> = <\rho^2_q>$ which is a factor ~ 2 smaller than given by analysis of GPDs from J/ψ production. They also assume it to be x-independent. Note also that from analysis DVCS there is evidence that $<\rho^2_g>$ somewhat smaller than $<\rho^2_q>$



Using information on the exclusive hard processes we can also estimate t-dependence of the elastic dipole-nucleon scattering and hence estimate $\Gamma_{q\bar{q}}\ from\, \sigma(q\bar{q}N).$

For small dipole - nucleon interaction b=ρ.

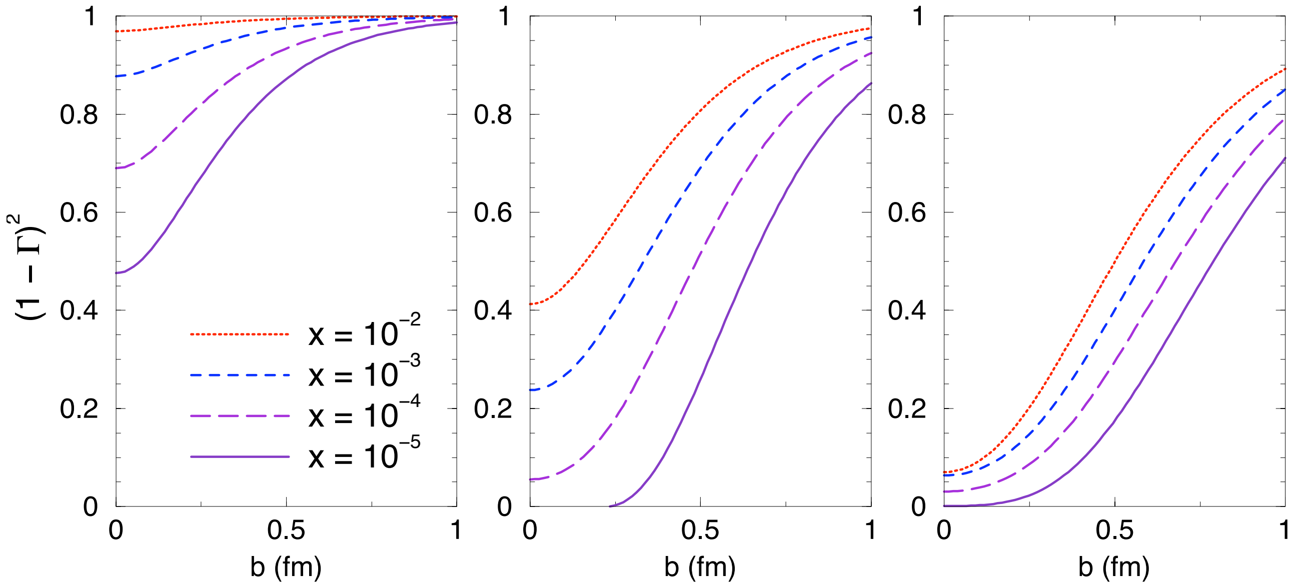


r$_0$ = 0.1 fm r$_0$ = 0.3 fm r$_0$ = 0.5 fm

T.Rogers et al

In the case gg-N scattering we assume pQCD relation

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

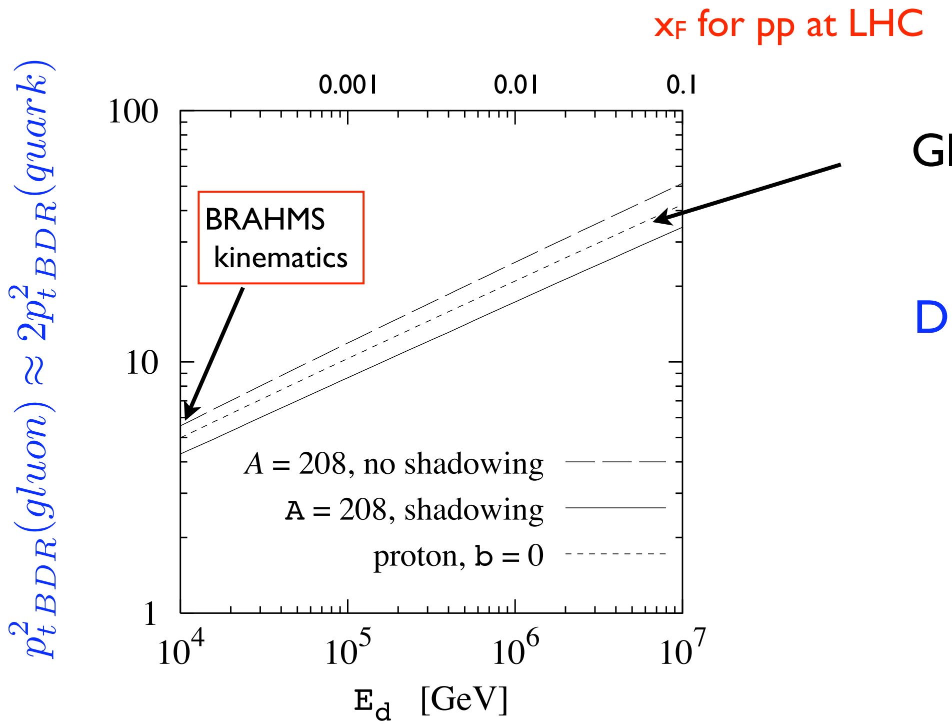


$|1-\Gamma(b)|^2$ - probability for $q\bar{q}$ not to interact with N at given b

In BDR interaction reached maximal strength allowed by unitarity - impact factor $\Gamma(b)$ approaches one

Onset of BDR for interaction of a small dipole - break down of LT pQCD approximation - natural definition of boundary: $\Gamma_{dip}(b) = 1/2$ - corresponds the probability for dipole to pass through the target at given b without interaction:

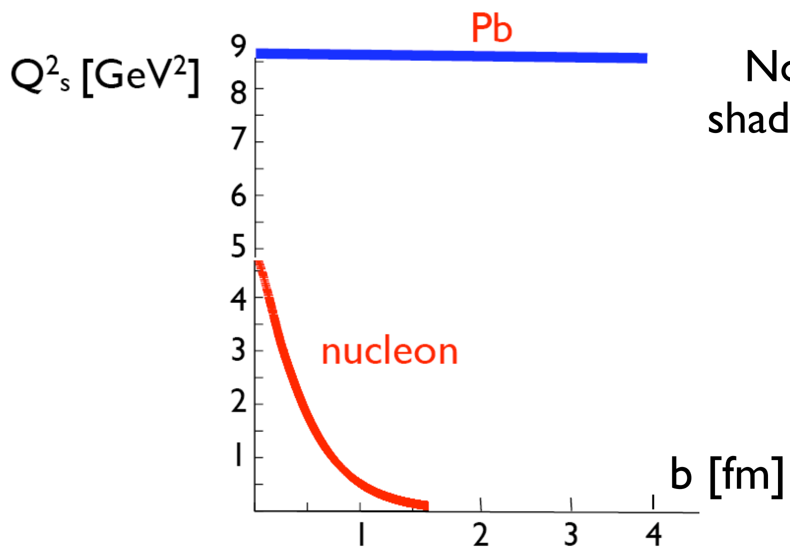
$$|1-\Gamma_{dip}(b)|^2 < 1/4 \quad \Rightarrow \quad p_{t\,BDR} \sim \frac{\pi}{2d_{BDR}}$$



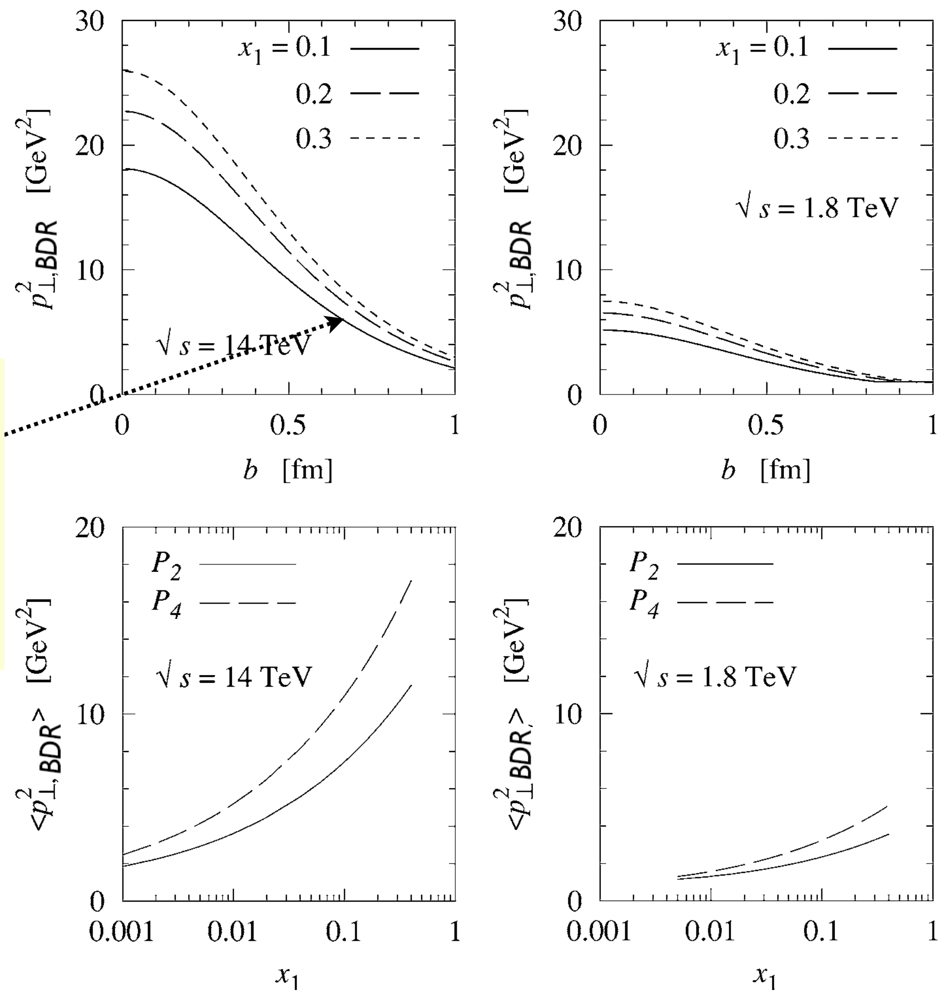
warning - estimate assumes $x^{-\omega}$ regime for all x- may overestimate $p_{t\,BDR}$ - see Anna Stasto talk

Gluon densities in nuclei and proton at b=0 are very similar!!!!

Difference is in a very different spread in b



We find large p_t(BDR) leads to strong suppression of pp→ppH at LHC



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

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

Also, a spectator parton in the BDR regime loses a significant fraction of its energy *similar to electron energy loss in backscattering of laser off a fast electron beam. Very different from eikonal type picture (scattering off the classical field)*

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

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

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

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

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

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

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

$\Gamma(b \sim 0) = 1$!!!

FS & Zhalov - 07

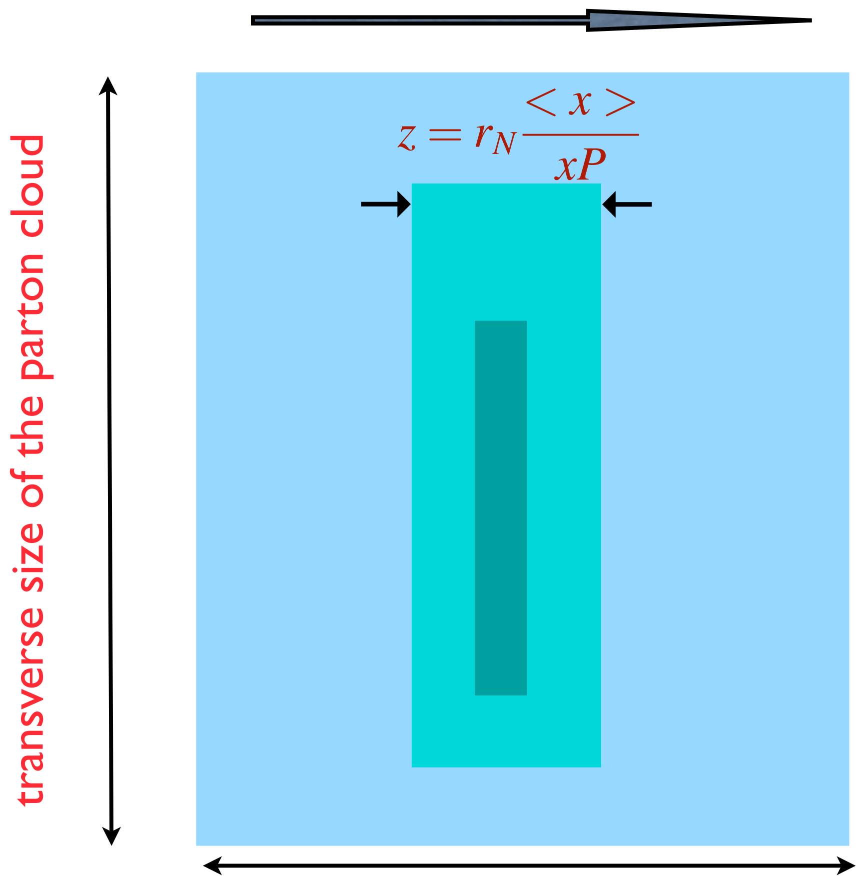
Explains the elastic pp data for small b, predicts an increase of b range, $b<b_F$ where $\Gamma=0$, $b_F=c \ln s$ - Froissart -like regime but $c \ll 1/m_\pi$.

In the BDR soft interaction (soft Pomeron disappear) - minimal scale is $p_{t\,BDR}$ / Q_s . Space structure of the fast nucleon/nucleus is very different from the classical Gribov space - time picture

3 D IMAGE OF FAST NUCLEON - z-x cut

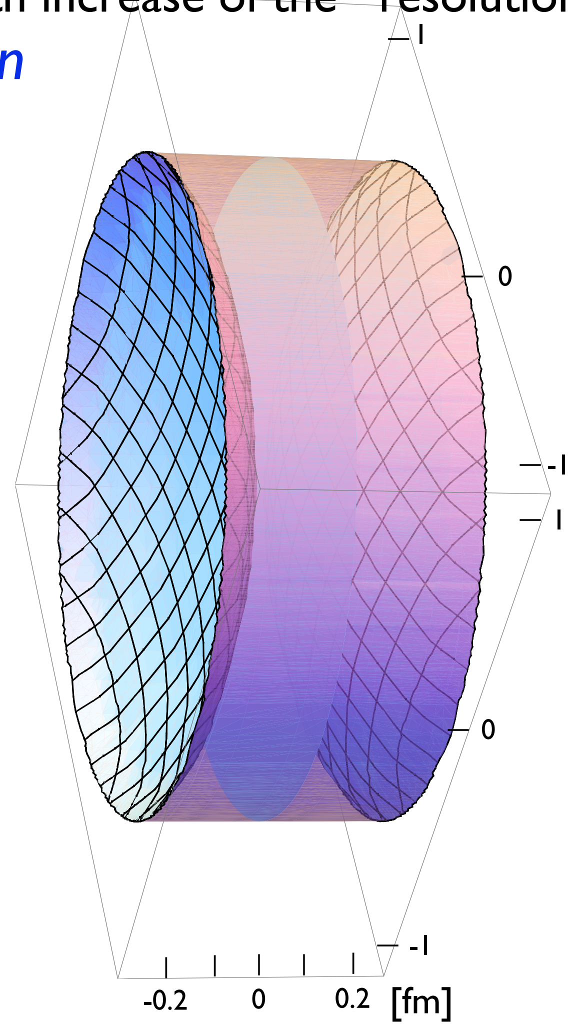
the rate of increase of transverse size with x decreases with increase of the resolution scale

Momentum P in z direction



wee parton are spread over 1 fm even at high energies

Soft physics logic - Gribov 70



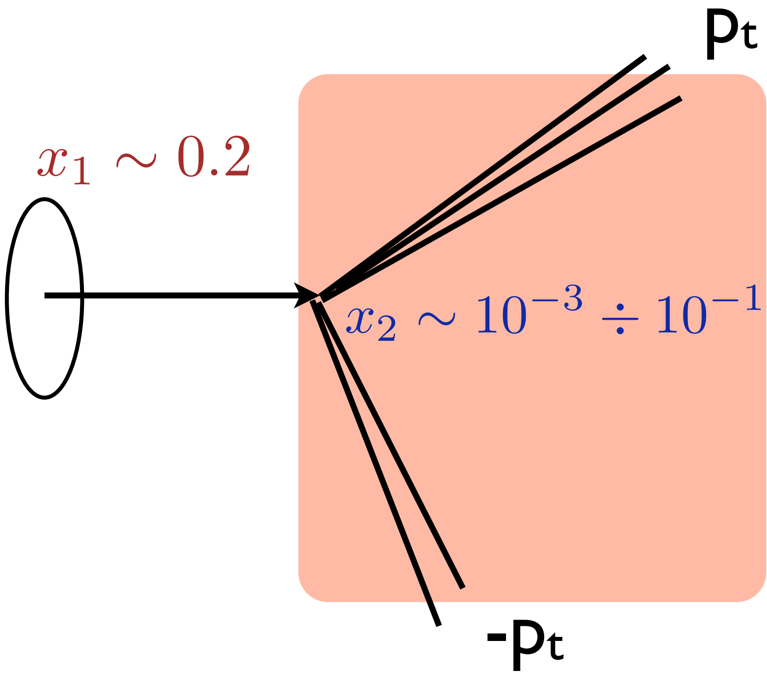
The shape of the fast nucleon in QCD at s=10^7 GeV^2 and the resolution scale $Q^2 \leq 40$ GeV^2

B.Blok, LF, MS 09

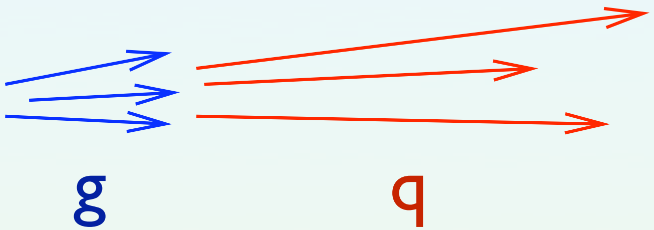
BDR - gross violation of Bj scaling $F_{2p} \sim Q^2 \ln^3(1/x)$, and suppression of the forward hadron spectrum. Both effects are a gross violation of the QCD factorization theorems for LT interactions

Frankfurt,Guzey, McDermott,MS 91

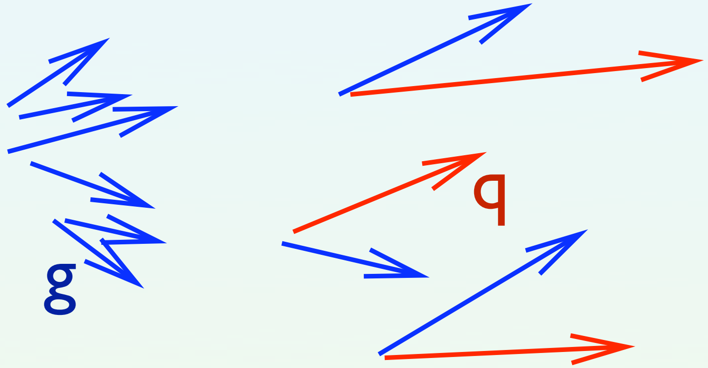
BDR in central pA collisions: Leading partons in the proton, x_1, interact with a dense medium of small x_2 – gluons in the nucleus (shaded area), loosing fraction of its momentum and acquiring a large transverse momentum, $\geq p_{t\,BDR}$



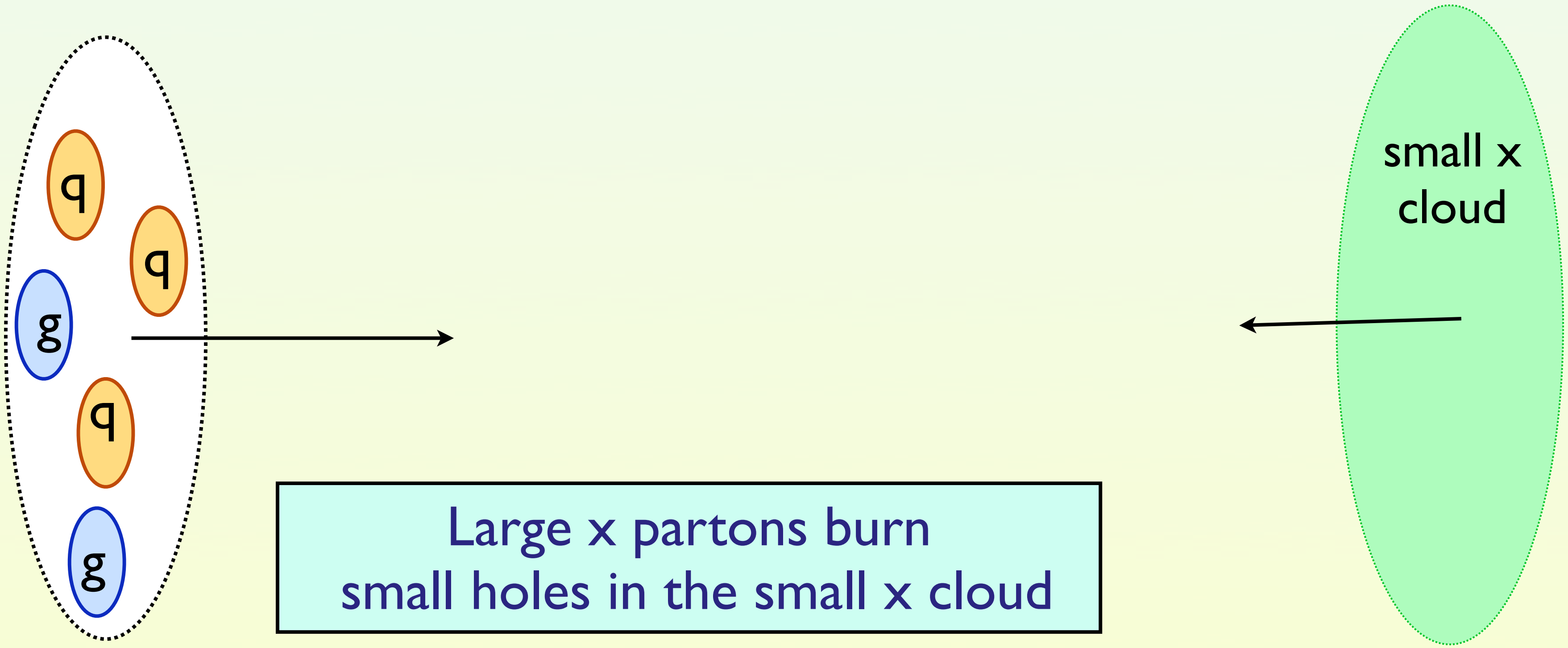
Characteristics of the final state in the central pA(pp) collisions



fast partons in a nucleon before collisions



fast partons in a nucleon after central collisions

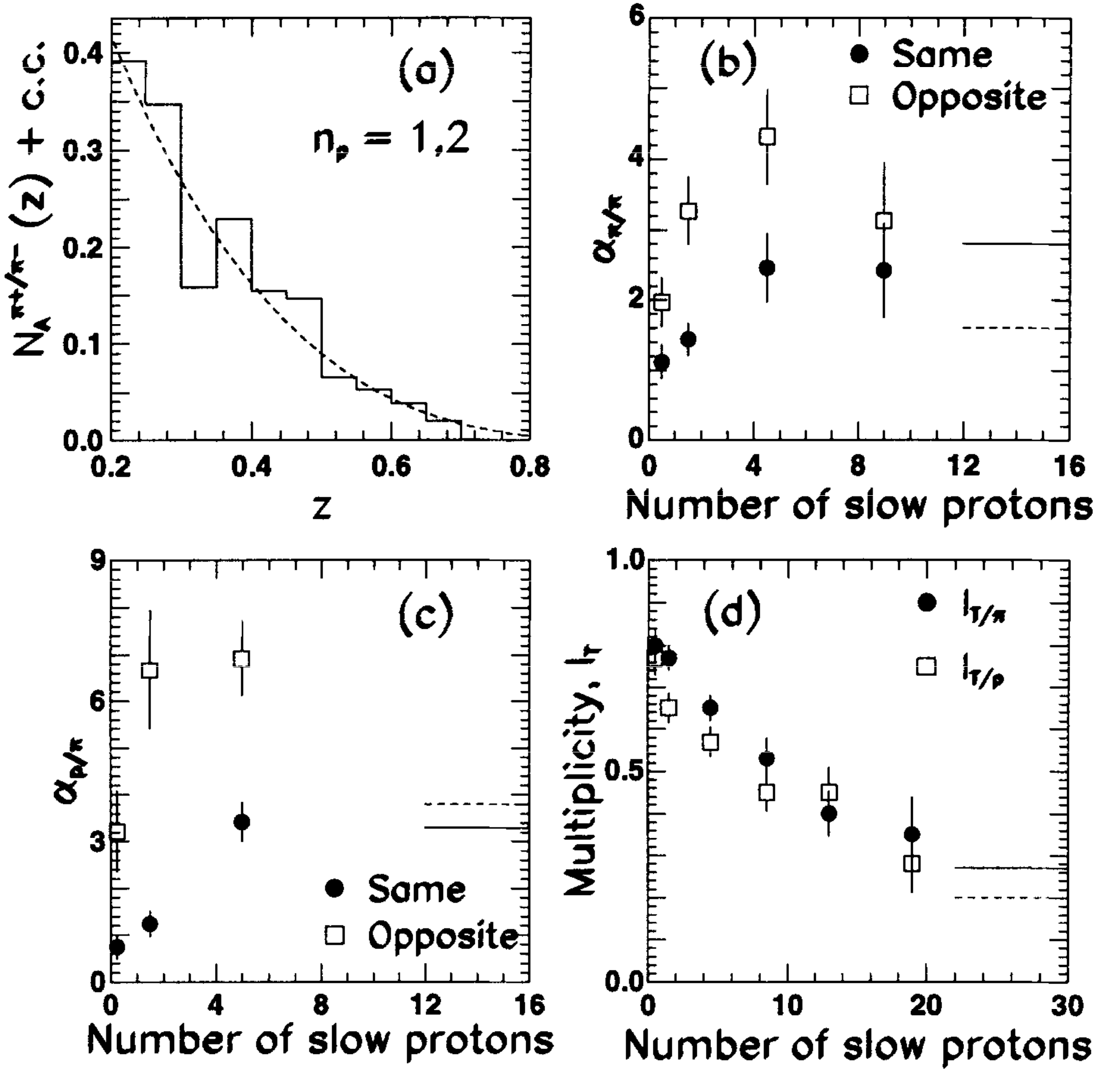


Large x partons burn
small holes in the small x cloud

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

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

Berera, MS, Tothacher, Walker, Whitmore 97



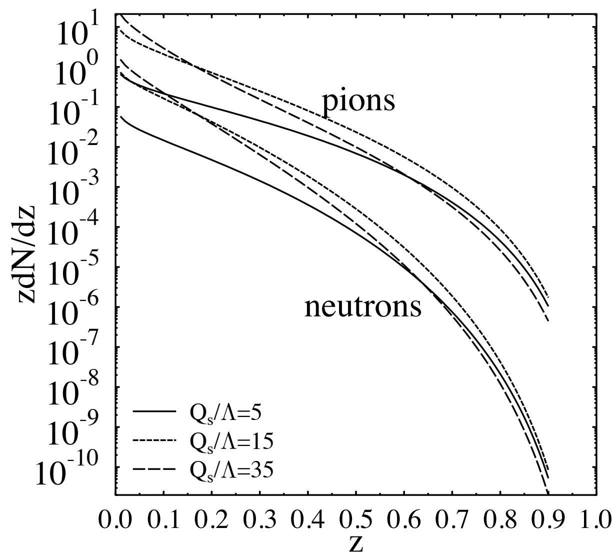
$$\frac{dN}{dz} \propto (1-z)^{\alpha}$$

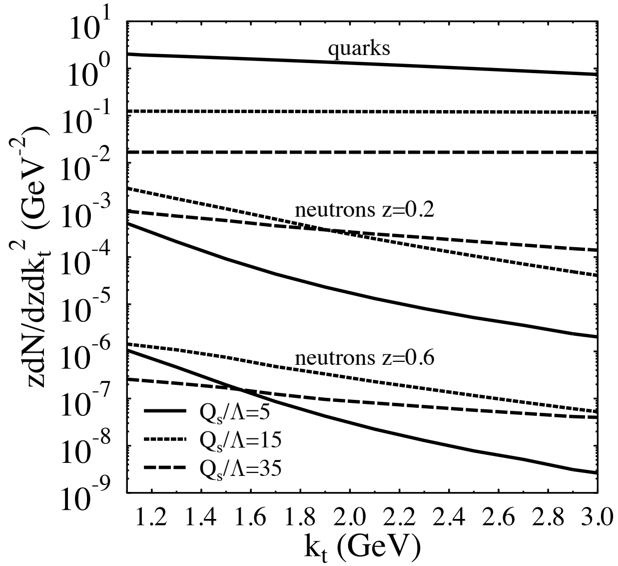
Fig. 2. Experimental results for h–A collisions at 100 GeV$/c$: (a) Differential multiplicity for $\pi^- A \to \pi^+$ combined with $\pi^+ A \to \pi^-$ for events with $n_p = 1,2$ (n_p is the number of slow protons). The dashed curve is a fit to the form $(1-z)^{\alpha}$; (b) Leading exponent α for $\pi A \to \pi$, solid circles (open boxes) when the produced π has the same (opposite) charge to that of the beam projectile; the horizontal lines on the right are the theoretical limits from QGSM fragmentation functions to the same (dashed) and opposite (solid) charge leading particle; (c) Leading exponent α for $\pi A \to p(\bar{p})$, the horizontal lines on the right are the theoretical results from EMC fragmentation functions to like (dashed) and opposite (solid) charge leading particle; (d) The integrated multiplicity of hadrons with $z_m > 0.2$ for $\pi^{\pm}$ (solid circles) and proton (open boxes) beam projectiles as a function of n_p. The horizontal lines on the right of the figure are the theoretical asymptotic limits for π (dashed) and proton (solid) projectiles.

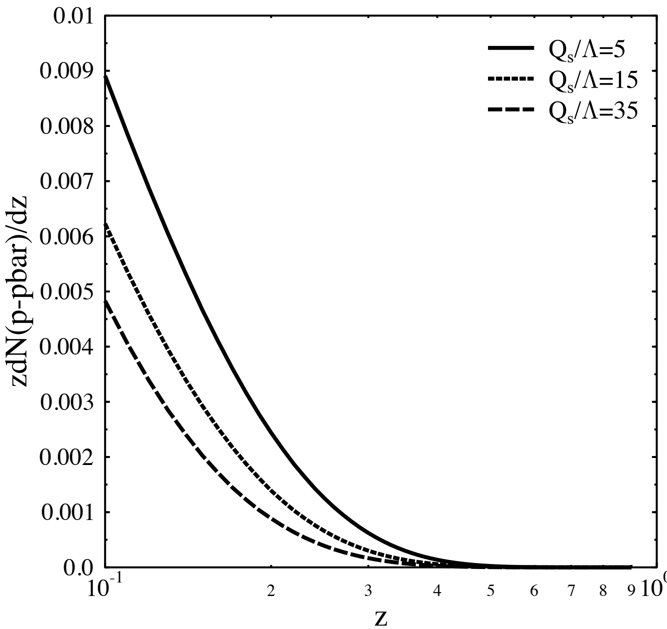
Simple model of p_t broadening - eikonal rescattering model with saturation (Boer, Dumitru 2003)

$$C(k_t) \sim \frac{1}{Q_s^2 \log \frac{Q_s}{\Lambda_{QCD}}} \exp\left(-\frac{\pi k_t^2}{Q_s^2 \log \frac{Q_s}{\Lambda_{QCD}}}\right).$$

Quark gets a transverse momentum of the order Q_s but does not loose significant energy. Use of the convolution formula for fixed transverse momentum of the produced hadron using $C(k_t)$ - Dumitru, Gerland, MS -PRL03







Longitudinal (integrated over p_t) and transverse distributions in Color Glass Condensate (CGC) model for central pA collisions. Spectra for central pp - the same trends.

Longitudinal distribution of net protons

Warning: for moderate Q_s coalescence becomes important for moderate z enhancing the proton yields for these z's.

We expect a new pattern of parton interaction with the media in the BDR - *fractional energy losses*. Parton cannot go through media in the BDR without inelastic interaction and getting a large transverse momenta. Qualitatively different pattern than at finite x - finite energy losses since in the initial moment no accompanying gluon field. In the nucleus rest frame one can speak about preselection of configurations in the partons of the projectile with large transverse momenta.

Denote as $G_{cr}(x,Q^2,b)$ value of gluon density at impact parameter b (generalized gluon density) for which probability of inelastic interaction is $P_{inel}(b,x,Q^2)=1$.

F&S 07

$$N(b, x, Q^2) = G_A(x,Q^2,b)/G_{cr}(x,Q^2,b)$$

For $N>1$ we find $\frac{\Delta E}{E} \sim cN, \; c \sim 0.1$

We predict that in the kinematics when BDR is achieved in pA but not in pN scattering, the hadron inclusive cross section should be given by the sum of two terms - scattering from the nucleus edge which has the same momentum dependence as the elementary cross section and scattering off the opaque media which occurs with large energy losses:

$$\frac{d\sigma(d+A\rightarrow h+X)/dx_h d^2p_t}{d\sigma(d+p\rightarrow h+X)/dx_h d^2p_t} = \underbrace{c_1 A^{1/3}}_{\text{edge}} + \underbrace{c_2(A)A^{2/3}}_{\text{area}}$$

gg -N interaction seems close to BDR for $Q^2 \sim 4$ GeV^2, $x \sim 10^{-4}$

for $Q^2 \sim 4$ GeV^2, $x \sim 10^{-3}$ gg - Pb interaction at b=0 is deep in BDR
qq - Pb interaction in BDR (forward RHIC kinematics)

$\Rightarrow$ Large probability of diffraction in gluon channel

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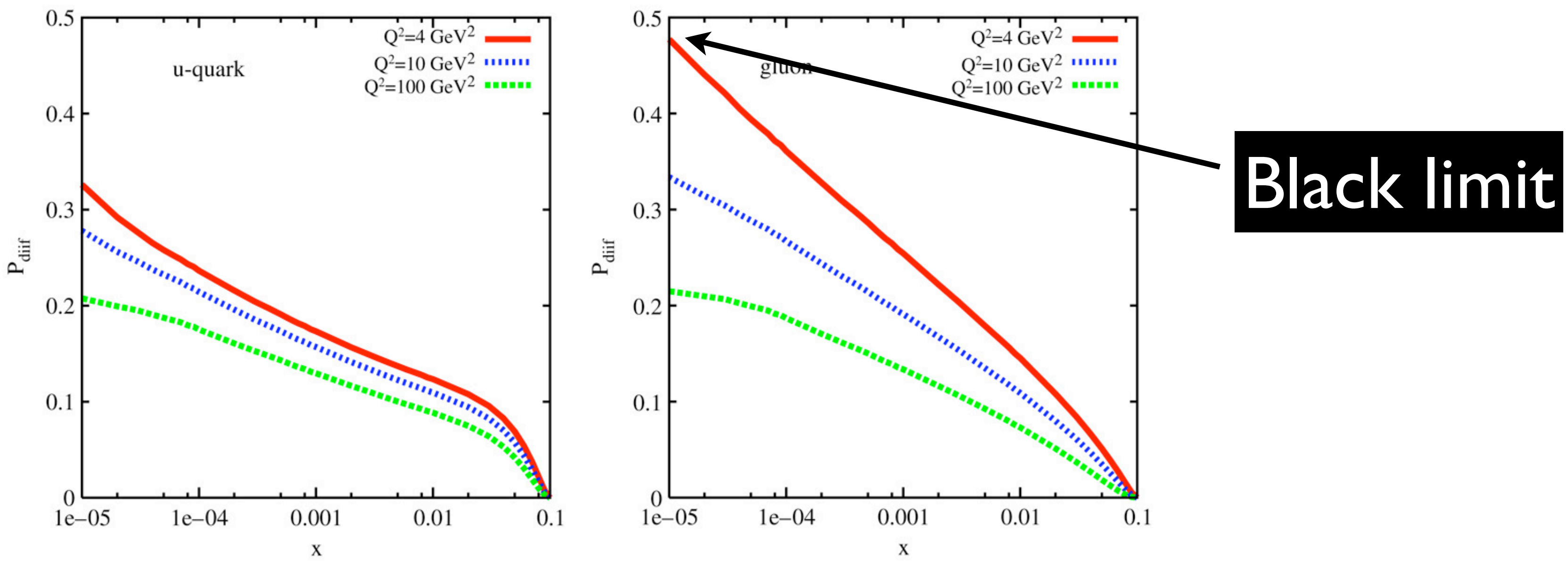


The probability of hard diffraction on the nucleon, $P_{j\ diff}$ as a function of x and Q^2 for u quarks (left) and gluons (right).

Forward partons with p_t less than BDR scale should loose energy and p_t distribution should broaden

for these x nuclear gluon shadowing effect is rather small

Suppression of the leading hadron production in pA scattering at large p_t comparable to the scale of Black disk regime at given energy (FS 01-06)

$\Rightarrow$

Natural explanation of the BRAHMS forward pion result at RHIC, and the forward - central STAR correlations data

Gluon densities at small x in heavy nuclei at b=0 and in the proton at b=0 are similar

$\Rightarrow$

In high energy pp (p-air) collisions at small b no partons with p_t < few GeV can survive

RHIC: Inclusive forward pion production in DAu collisions

- For pp - pQCD works both for inclusive pion spectra and for correlations (STAR)

- Suppression of the pion spectrum for fixed p_t increases increase of η_N. Dynamical suppression effect for η=3.2 is even larger than the BRHAMS ratio (by a factor of 1.5) due isospin effect.

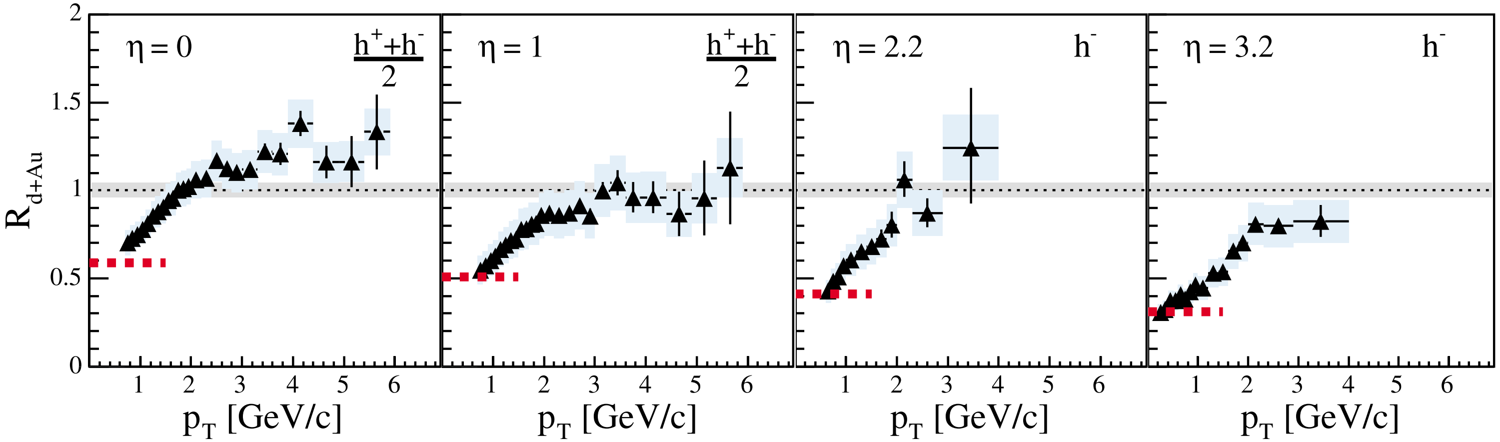


FIG. 2 (color online). Nuclear modification factor for charged hadrons at pseudorapidities $\eta = 0$, 1.0, 2.2, 3.2. On deviation statistical errors are shown with error bars. Systematic errors are shown with shaded boxes with widths set sizes. The shaded band around unity indicates the estimated error on the normalization to $\langle N_{coll}\rangle$. Dashed lines at $p_T <$ show the normalized charged-particle density ratio $\frac{1}{\langle N_{coll}\rangle}\frac{dN/d\eta(\mathrm{Au})}{dN/d\eta(pp)}$.

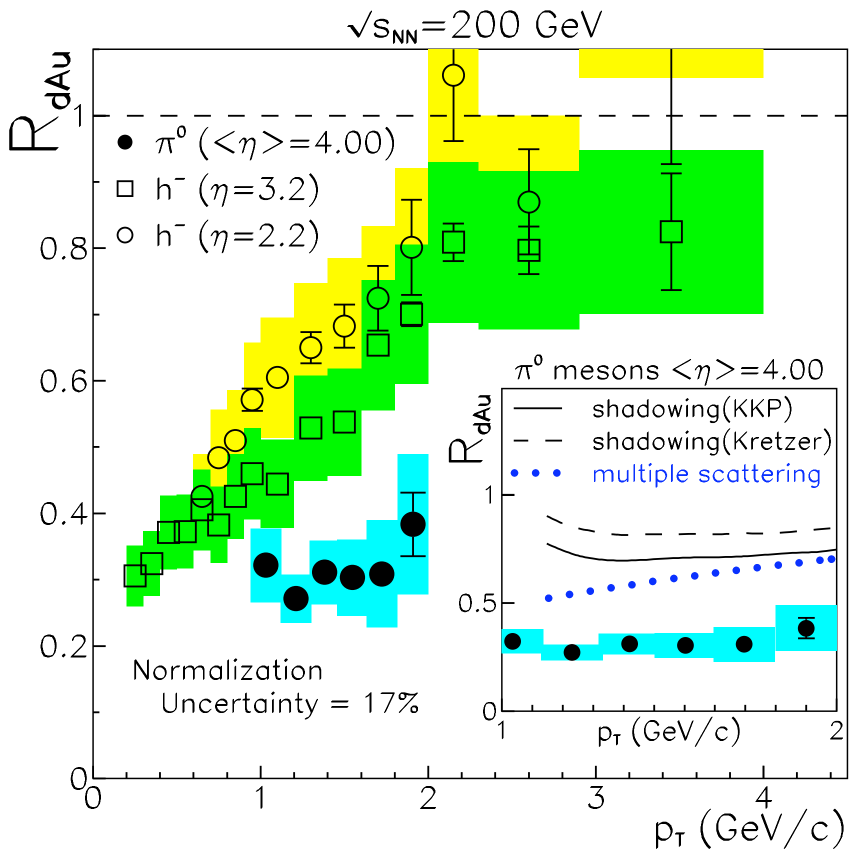


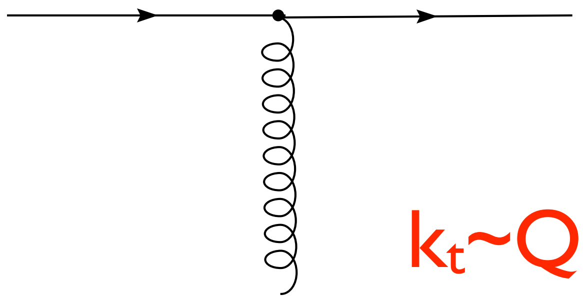
FIG. 3: Nuclear modification factor (R_{dAu}) for minimum-bias d+Au collisions versus transverse momentum (p_T). The solid circles are for π^0 mesons. The open circles and boxes are for negative hadrons (h^-) at smaller η [10]. The error bars are statistical, while the shaded boxes are point-to-point systematic errors. (Inset) R_{dAu} for π^0 mesons at $\langle\eta\rangle = 4.00$ compared to the ratio of calculations shown in Figs. 2 and 1.

BRAHMS and STAR are consistent when an isospin effect in the BRAHMS data is corrected for

Two possible explanations both based on presence of high gluon field effects

Color Glass Condensate model

Assumes that the process is dominated both for a nucleus and nucleon target by the scattering of partons with minimal x allowed by the kinematics: $x \sim 10^{-4}$ in a $2 \rightarrow 1$ process.



$k_t \sim Q_s$

Two effects - (i) density is smaller than for the incoherent sum of participant nucleons by a factor N_{part}, (ii) enhancement due to increase of k_t of the small x parton: $k_t \sim Q_s$. ➔ Overall dependence on N_{part} is $(N_{part})^{0.5}$, collisions with high p_t trigger are more central than the minimal bias events, no recoil jets in the kinematics expected in pQCD.

$\Rightarrow$ dominant yield from central impact parameters

Energy losses in BDR regime - usually only finite energy losses discussed (BDMPS) - hence a rather small effect for partons with energies 10^4 GeV in the second nucleus rest frame. Not true in BDR

$\Rightarrow$ dominant yield from peripheral impact parameters

Challenge - in pQCD main contribution to forward pion production comes from quark scattering off gluons with <x> > 0.01 which are not screened

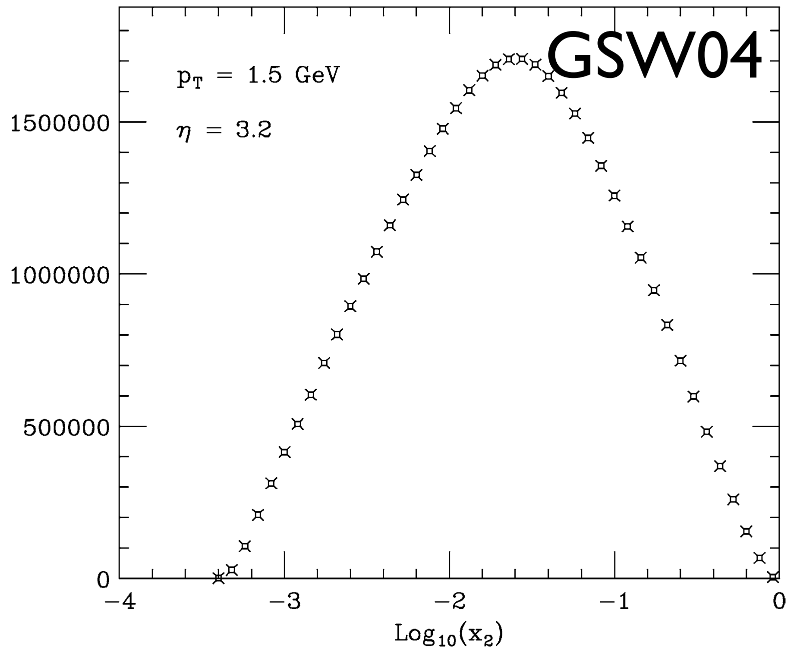


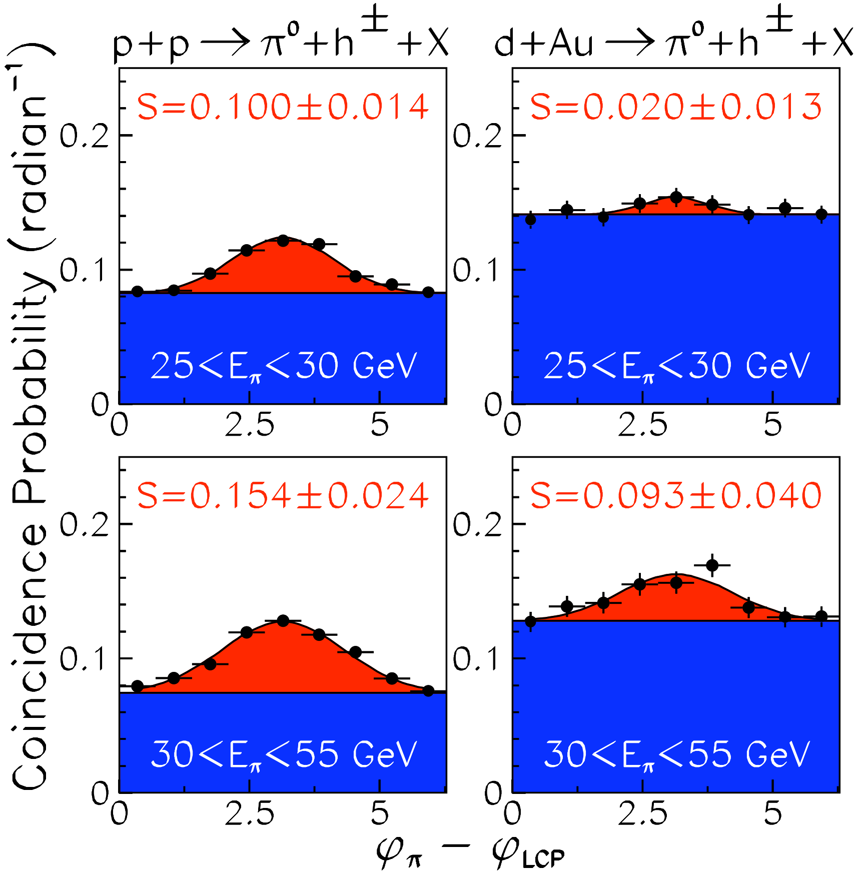
Fig. 1. Distribution in $\log_{10}(x_2)$ of the NLO invariant cross section $E\, d^3\sigma/dp^3$ at $\sqrt{s} = 200$ GeV, $p_T = 1.5$ GeV and $\eta = 3.2$.

Guzey, Strikman, Vogelsang 04

CGC calculations which reproduce absolute yield due to scattering off $x=10^{-4}$ parton via coherent mechanism (Dumitru et al) - assume that there exists a unknown mechanism which kills the x >0.005 contribution

The STAR analysis: leading charge particle (LCP) analysis picks a midrapidity track with $|\eta_h| \leq 0.75$ with the highest $p_T \geq 0.5$ GeV/c and computes the azimuthal angle difference $\Delta\varphi = \varphi_{\pi o} - \varphi_{LCP}$ for each event. This provides a coincidence probability $f(\Delta\varphi)$. It is fitted as a sum of two terms - a background term, $B/2\pi$, which is independent of $\Delta\varphi$ and the correlation term $\Delta\varphi$ which is peaked at $\Delta\varphi = \pi$. By construction,

$$\int_0^{2\pi} f(\Delta\phi) d\Delta\phi = B + \int_0^{2\pi} S(\Delta\phi) d\Delta\phi \equiv B + S \leq 1$$



Coincidence probability versus azimuthal angle difference between the forward π^0 and a leading charged particle at midrapidity with $p_T > 0.5$ GeV/c. The left (right column in p+p (d+Au) data with statistical errors. The π^0 energy increases from top to bottom. The curves are described fits. S is red area.

Obvious problem for central impact parameter scenario of π^0 production is rather small difference between low p_T production in the $\eta=0$ region (blue), in pp and in dAu - (while for b=0, N_{coll} ~13). Presence of recoil jets corresponding to scattering off x ~0.02 partons.

To use information about central rapidities in a detailed way we used the relevant information from dAu BRAHMS analysis. Results are not sensitive to details.

We confirm that pion production is strongly dominated by peripheral collisions, and that there is no significant suppression of dijet mechanism.

For central impact parameters suppression is by a factor > 5, which requires energy losses of >10%

Since the second jet has much smaller longitudinal momentum than the jet leading to the forward pion production it propagates in a much more pQCD like regime with much smaller energy losses, and hence does not affect the rate of correlation. If the energy losses were fractional but energy independent this would not be the case.

Test of our interpretation- ratio, R, of soft pion multiplicity at $y \sim 0$ with π^0 trigger and in minimal bias events.

In CGC scenario R ~ 1.3

In BDR energy loss scenario we calculated R ~ 0.5

STAR - R ~0.5 Gregory Rakness - priv. comm

Further confirmation - the STAR and PHENIX data reported at QM 09

$$G_{air}(x_{min}(GZK), Q^2, b) >> G_{Pb}(x_{min}(RHIC), Q^2, b)$$

$$\Downarrow$$

Even stronger suppression of the forward spectrum than in the convolution approximation

Implications of RHIC data on the forward spectrum don't depend on details of interpretation - just on general pattern of dependence of the suppression on presence of the high gluon density at relevant impact parameters

Widely shared expectation:

Interaction of the fast partons with nuclear media is determined by gluon thickness of media along the parton path for smallest x which the parton can resolve.

Compare central deuteron -gold collision at RHIC and p-air at b < 2 fm at GZK

$$\frac{\text{gluon density GZK p- air}}{\text{gluon density RHIC d Au}} = \left(\frac{14}{200}\right)^{1/3} \underbrace{\left(\frac{x_{min}(dAu)}{x_{min}(p-air)}\right)}_{10^5}{}^{\omega}$$

=**4** (using a conservative value of ω=0.2)

⇒ **Stronger suppression of forward production at GZK than observed at RHIC**

gluon density GZK p-air ~ gluon density LHC p Pb

Why this effect is not observed in MC's?

Main focus of MC's is central rapidities. A large increase of the cross section of dijet production (will discuss later) → too high multiplicities of hadrons for central rapidities → cutoff on p_{tmin} of jets increasing with energy. Fit to current energy range & extrapolation to LHC, GZK - $p_{t\,min}$ (LHC) ~ 5 GeV/c, $p_{t\,min}$ (GZK) ~ 10 GeV/c

Such cutoff leaves fragmentation essentially energy independent.

Does suppression of the forward spectrum matters for GZK energies?

Stronger energy losses of primary and highest energy particles, smaller X_{max}.

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

High-Density QCD and Cosmic-Ray Air Showers

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

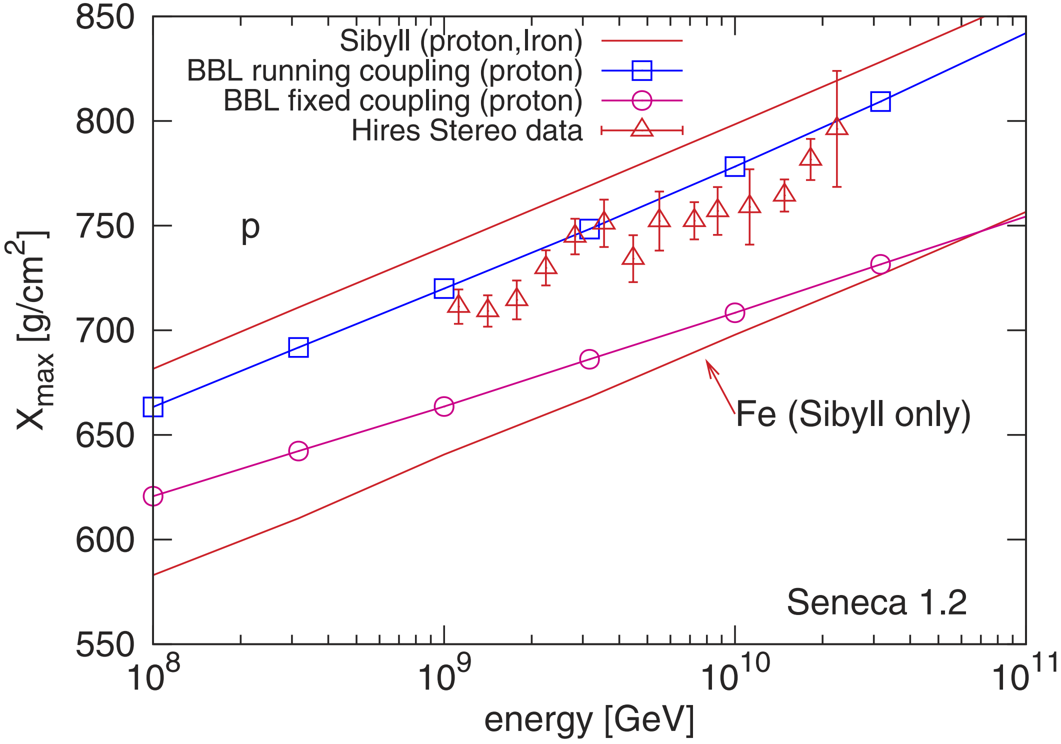
modified cosmic ray code Sybill to include the discussed effects for central impact parameters:

Two versions:

(a) power law increase of the gluon densities to the BBR.

Specific implementation using Sybill contradicts to the data: too large reduction of X_{max}.

(b) Slower increase at very small x as suggested in Altarelli et al, Ciafaloni et al estimates. - Leads to modest reduction of X_{max} - does not contradict the data.



Mean X_{max} as a function of primary energy for the pQCD model Sibyll (proton and iron primaries), the saturation model of BDR (proton primaries fixed and running - coupling evolution of Q_s corresponding to BDR) and the HiRes stereo data.

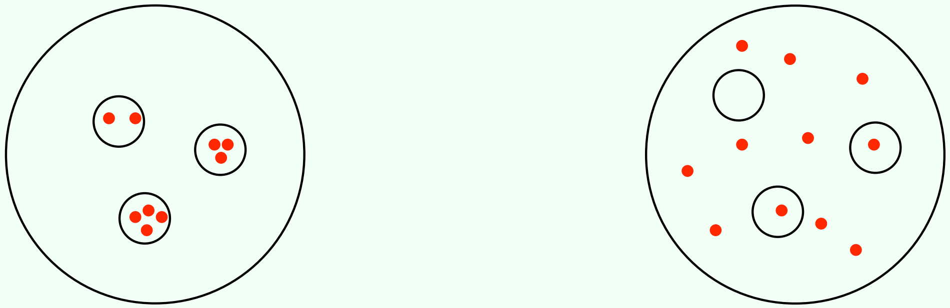
What else is missing in the current MC models?

- ☞ *Transverse correlations between partons*

- ☞ *Fluctuations of the strength of soft interactions*

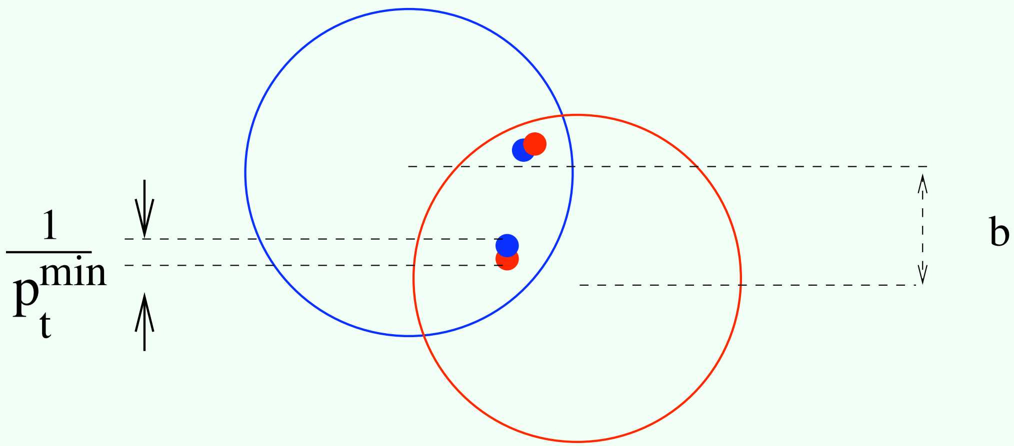
- ☞ *Fluctuations of the strength of soft interactions*

Multi-jet production - probe of parton correlations in nucleons



a) b)

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



A view of double scattering in the transverse plane.

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

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

Experimentally one measures the ratio

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

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 $\sigma_{eff}=14.5\pm 1.7^{+\,1.7}_{-\,2.3}\,mb$ rather small - a naive expectation is σ_{eff} ~ 60 mb indicating high degree of correlations between partons in the nucleon in the transverse plane. No dependence of σ_{eff} on x_i was observed.

Recently new Tevatron data appeared. They agree with these early data

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

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

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

If most of gluons at low Q~ 1GeV scale are in constituent quarks of radius r_q/r_N ~1/3 found in the instanton liquid based chiral mean field 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 for x>0.1. (F&S&W)

<u>small x</u>

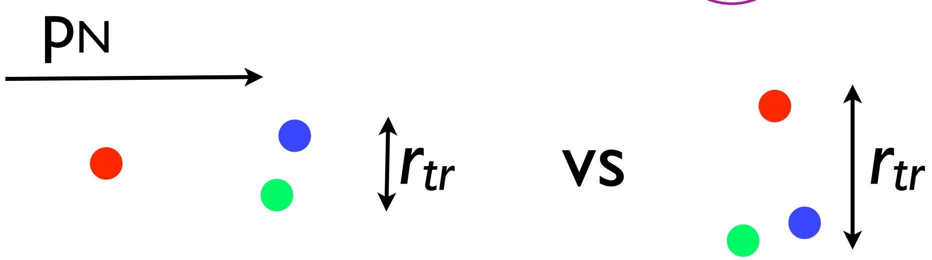
☺ Fluctuations of the transverse size of nucleons (Treliani, &F&S & W) - works in right direction but too small.

☺ QCD evolution leads to "Hot spots" in transverse plane (A.Mueller). One observes that such hot spots do enhance multijet production as well. However this effect is likely not to be relevant in the CDF kinematics as x's of colliding partons are relatively large (>0.01).

Fluctuations of the strength of soft interactions

Are there global fluctuations of the strength of interaction of a fast nucleon, for example due to fluctuations of the size /orientation

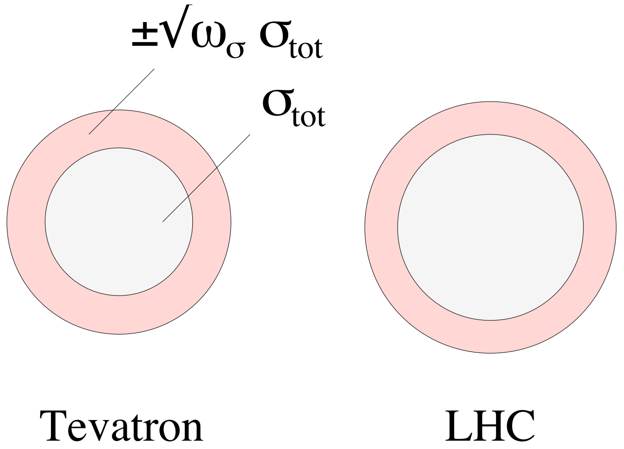
$$|N\rangle = 3q + 3qg + 3q+\pi + \ldots$$

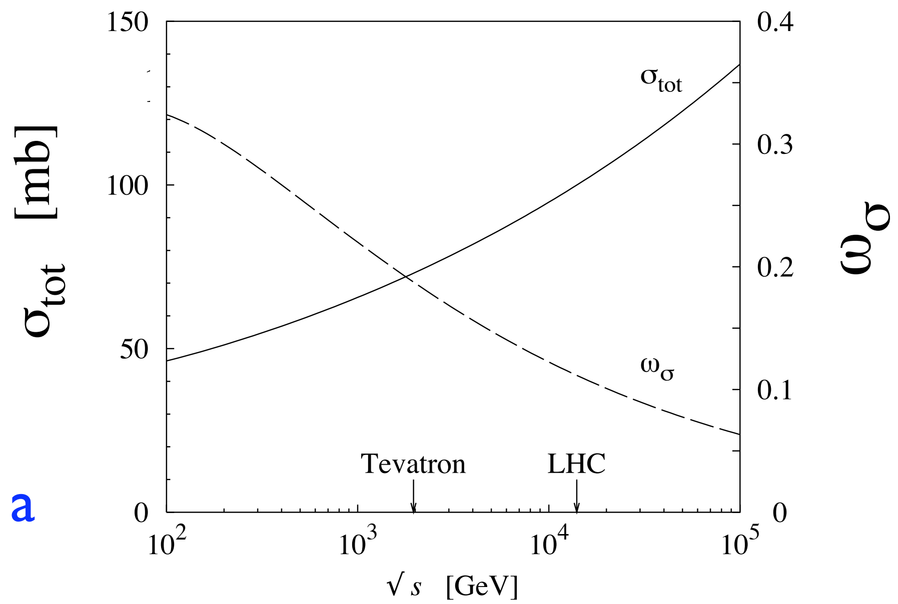


Convenient quantity - $P(\sigma)$ -probability that nucleon interacts with cross section σ

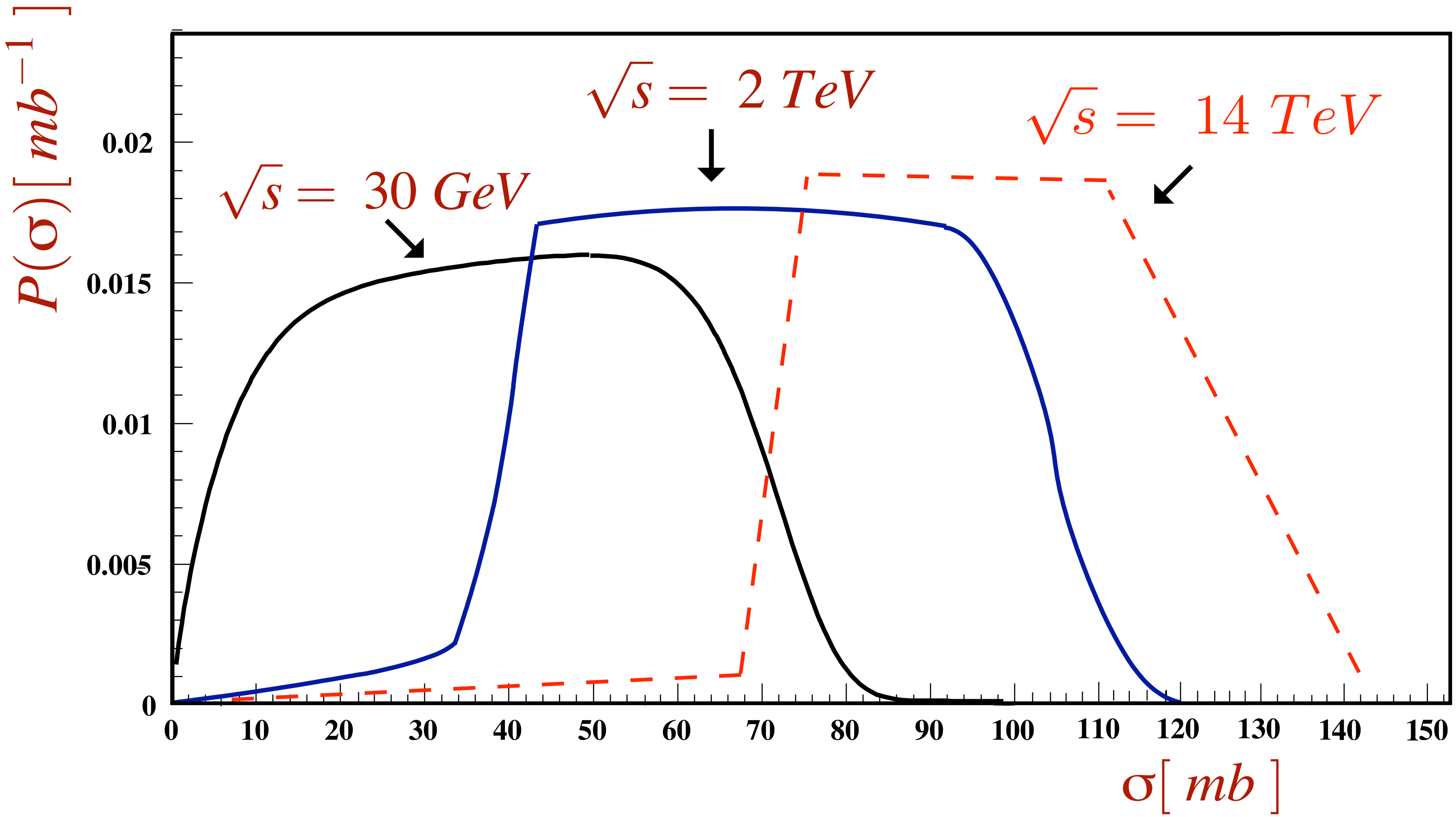
If there were no fluctuations of strength - there will be no inelastic diffraction at t=0:

$$\left.\frac{\frac{d\sigma(pp\to X+p)}{dt}}{\frac{d\sigma(pp\to p+p)}{dt}}\right|_{t=0} = \frac{\int(\sigma-\sigma_{tot})^2 P(\sigma)d\sigma}{\sigma_{tot}^2} \equiv \omega_\sigma \quad \text{variance}$$





Both small and large configurations grow a periphery - still there is a correlation between σ and parton distributions - smaller σ, harder quark distribution



The 30 GeV curve is result of the analysis (Baym et al 93) of the FNAL diffractive pp and pd data which explains FNAL diffractive pA data (Frankfurt, Miller, MS 93-97). The 14 and 2TeV curves are my guess based on matching with fixed target data and collider diffractive data.

Strength of the gluon field should depend on the size of the quark configurations - for small configurations the field is strongly screened - gluon density much smaller than average.

Do we know anything about such fluctuations?

Yes - MS + LF + C.Weiss, D.Treliani PRL 08

Consider $\gamma_L^* + p \to V + X$ for Q^2 > few GeV^2

In this limit the QCD factorization theorem (BFGMS03, CFS07) for these processes is applicable

Expand initial proton state in a set of partonic states characterized by the number of partons and their transverse positions, summarily labeled as $|n\rangle$

$$|p\rangle = \sum_n a_n |n\rangle$$

Each configuration n has a definite gluon density $G(x, Q^2| n)$ given by the expectation value of the twist--2 gluon operator in the state $|n\rangle$

$$G(x, Q^2) \;=\; \sum_n |a_n|^2 G(x, Q^2|n) \;\equiv\; \langle G \rangle$$

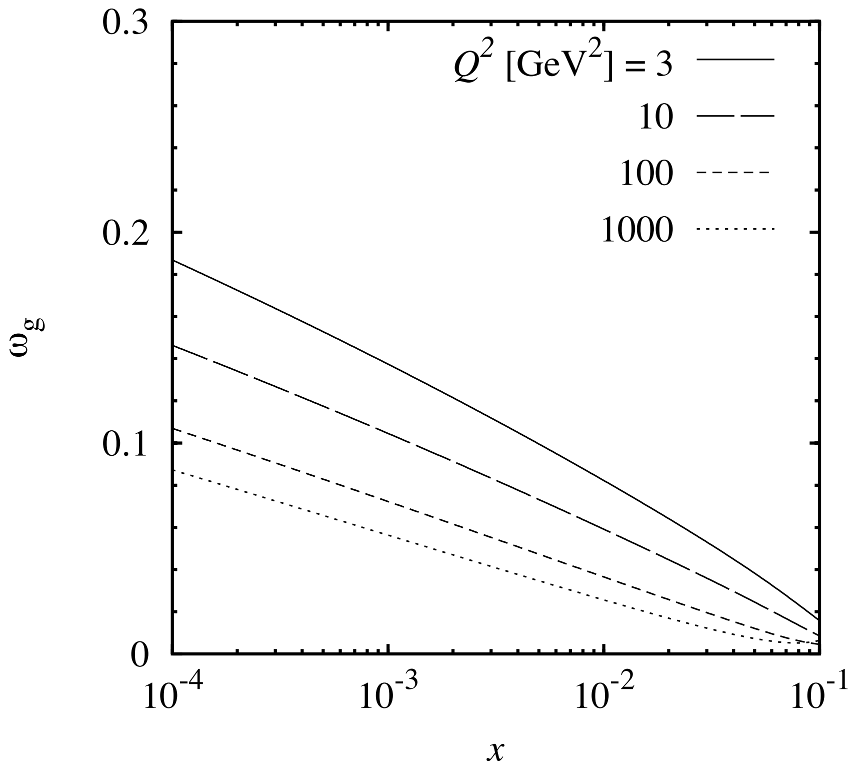
Making use of the completeness of partonic states, we find that the elastic($X = p$) and total diffractive (X arbitrary) cross sections are proportional to

$$(d\sigma_{\mathrm{el}}/dt)_{t=0} \quad \propto \quad \left[\sum\nolimits_n |a_n|^2 G(x, Q^2|n)\right]^2 \equiv \langle G\rangle^2,$$

$$(d\sigma_{\mathrm{diff}}/dt)_{t=0} \quad \propto \quad \sum\nolimits_n |a_n|^2 \left[G(x, Q^2|n)\right]^2 \equiv \langle G^2\rangle.$$

Hence cross section of inelastic diffraction is $\sigma_{\mathrm{inel}} = \sigma_{\mathrm{diff}} - \sigma_{\mathrm{el}}$

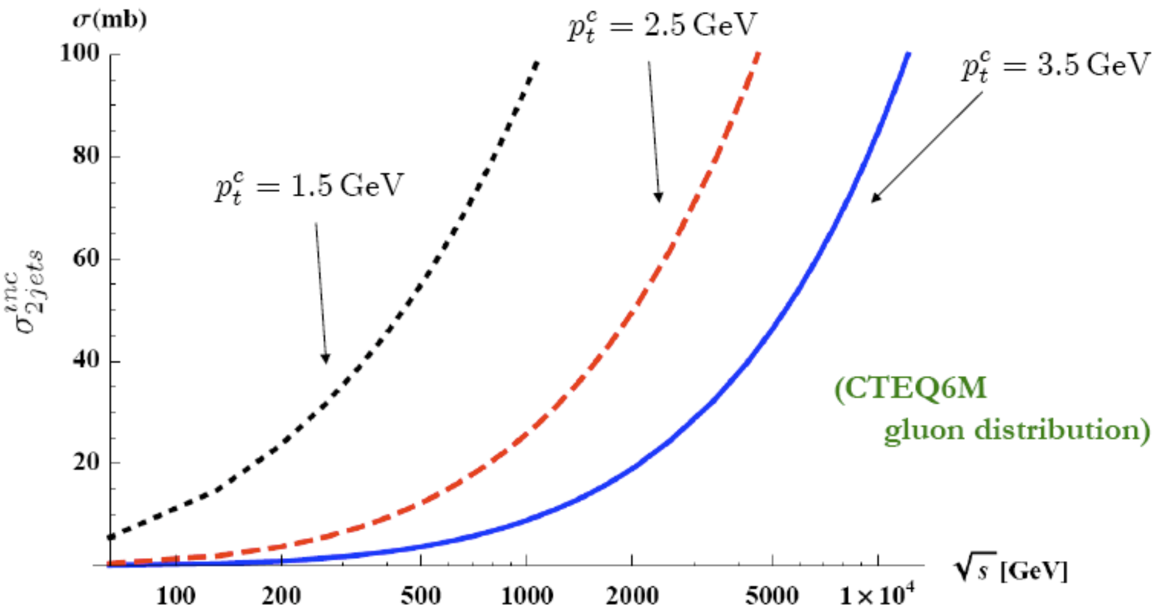
$$\Rightarrow \quad \boxed{\omega_g \equiv \frac{\langle G^2\rangle - \langle G\rangle^2}{\langle G\rangle^2} = \frac{d\sigma_{\gamma^*+p\to VM+X}}{dt} \Big/ \left.\frac{d\sigma_{\gamma^*+p\to VM+p}}{dt}\right|_{t=0}}.$$



The dispersion of fluctuations of the gluon density, ω_g, as a function of x for several values of Q^2, as obtained from the scaling model we developed which connects fluctuations of σ and fluctuations of color. We naturally reproduce the observed magnitude of the ratio measured experimentally at HERA.

Problem with p_t cut.

<u>*Hard Scattering*</u>



Rapid Increase!

jet multiplicity = $\sigma^{inel}_{2jets}/\sigma_{inel}(pp)$

It is this growth which leads to a MC fixes:

$p_{t\,min}$ (Tevatron) ~ 3 GeV/c, $p_{t\,min}$ (LHC) ~ 5 GeV/c, $p_{t\,min}$ (GZK) ~ 10 GeV/c

Is the problem with jet fragmentation algorithm?

One can see that the problem emerges already on the level of S-channel unitarity (T.Rogers, A.Stasto, MS, 2008)

Idea: use information about transverse gluon distribution to calculate probability of inelastic interactions at given b, due to interactions with production of exactly 2 jets, 4 jets,... - $\Gamma^{inel}_{jets}(s,b)$

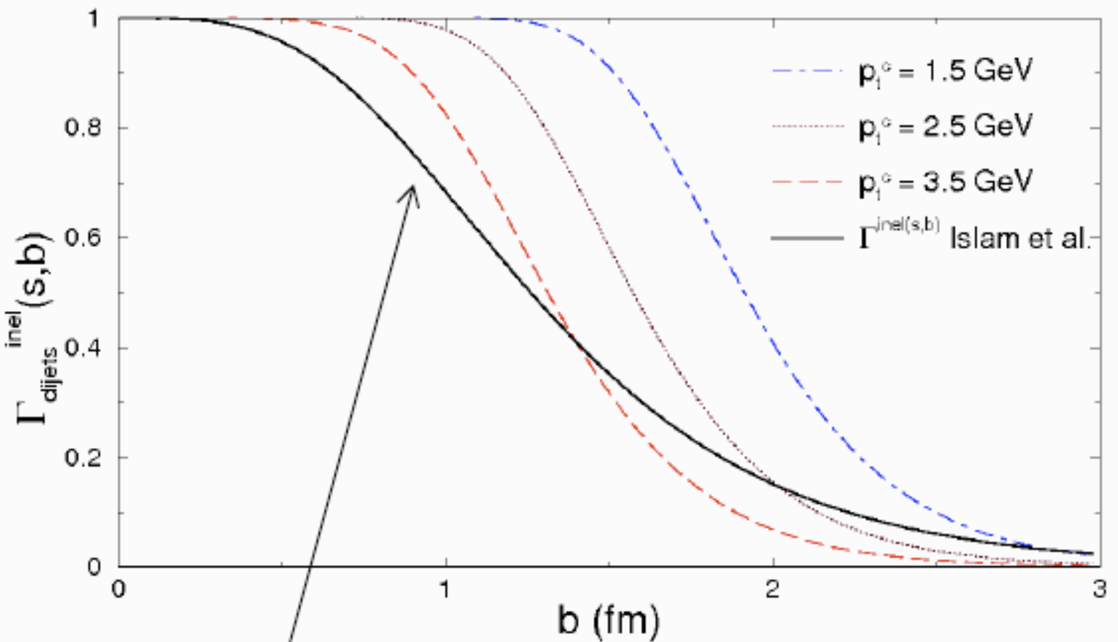
- Consistency requirement:

$$\boxed{\Gamma^{inel}_{ndijets}(s,b) \leq \Gamma^{inel}(x,b)}$$

- Compare with inelastic profile obtained from unitarity relation models/extrapolation of elastic profile:

$$\Gamma^{inel}(s,b) \equiv 2\Gamma(s,b) - |\Gamma(s,b)|^2$$

Compare reconstructed profile with model extrapolation.



- Identical partons,
- CTEQ6M gluon PDF

$\sqrt{s} = 14$ TeV

extrapolated profile function from elastic cross section

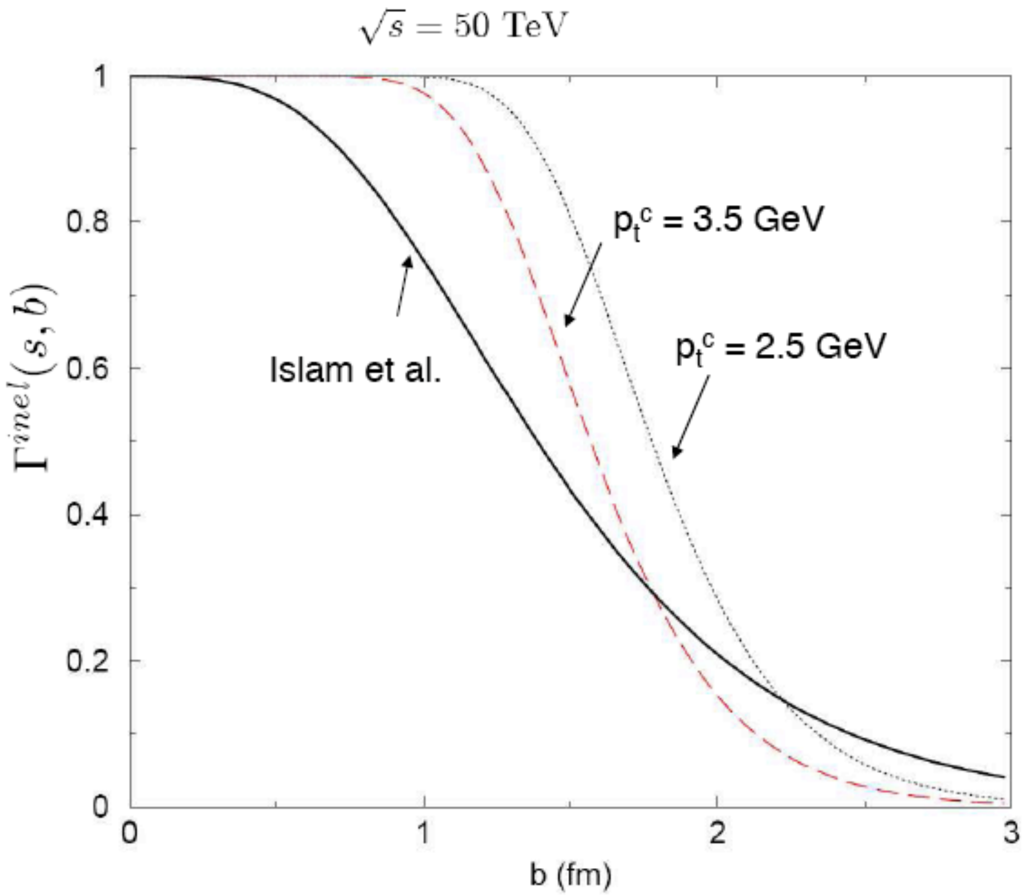
Small effect from correlations ?

❑ **Mismatch in description at large impact parameters where we** naively **expect small effect from correlations.**

Main contribution from moderate x where taming effects are small

Comparison with extrapolation: UHE

(Cosmic ray energies.)



- Identical partons,
- CTEQ6M gluon PDF

Could correlations in the proton be as large at large ρ as for small ρ where they are required by the multijet data? Would reduce the problems with unitarity, and allow distribution over the number of pairs of jets similar to that generated by PYTHIA with correct transverse gluon distribution (T.Rogers & MS)

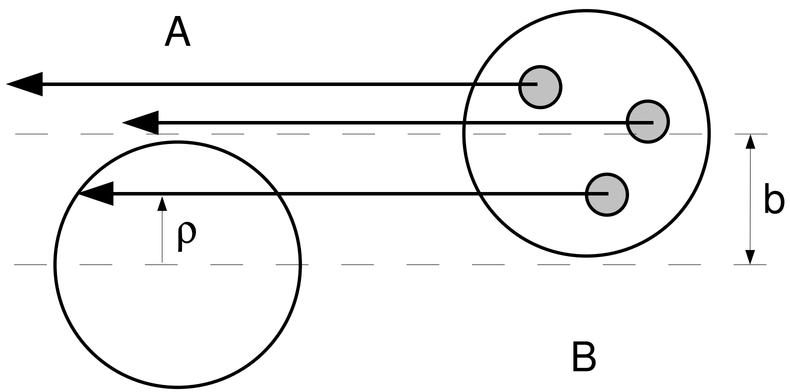
☞ *Use of LHC pp and in a long term pA*

To get information useful for CR at GZK need to develop a effective trigger for central pp collisions at LHC. Also necessary for

- ☛ *more realistic modeling of QCD environment for new particle production*
- ☛ *QCD interactions at gluon densities similar to those for AA collisions at LHC*

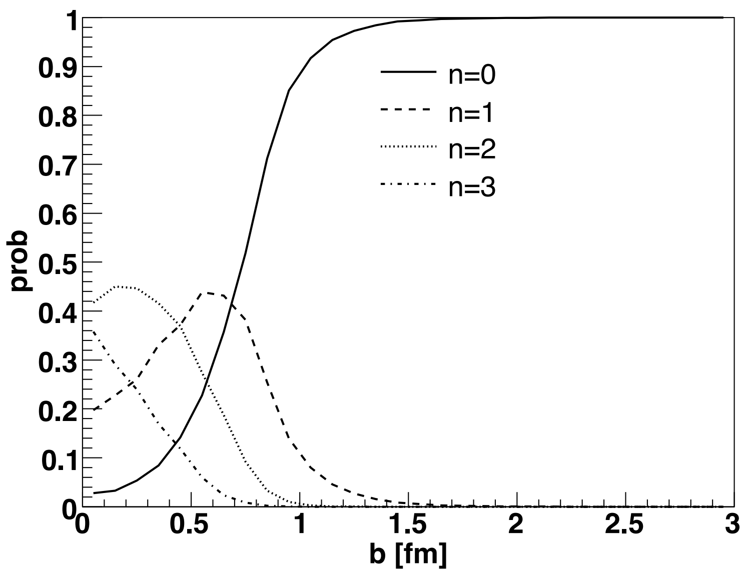
MC code was developed by H.Drescher and MS - <u>focus on forward particles</u>; PRL 08

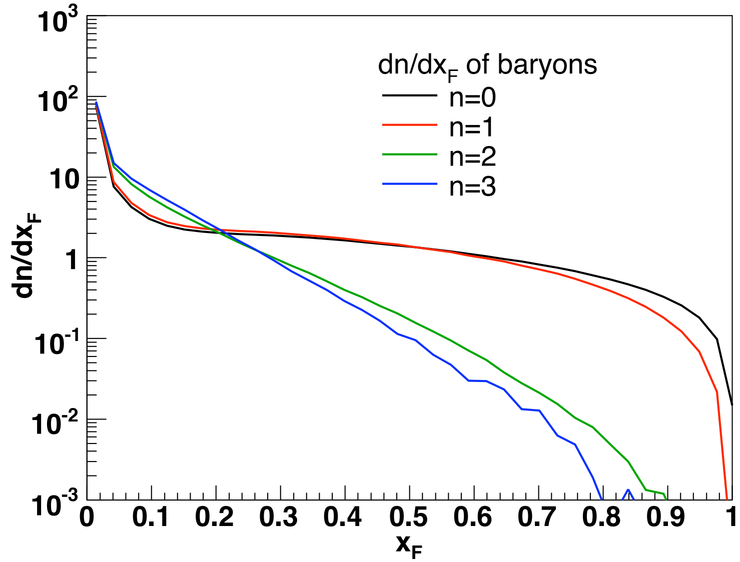
Generates configurations of three valence quarks, traces them through the gluon field of the second nucleon, and generates transverse momentum using the simplest version of color glass condensate model. If generated transverse momentum large enough - independent fragmentation. Otherwise string junction.



Schematic view of the collision geometry

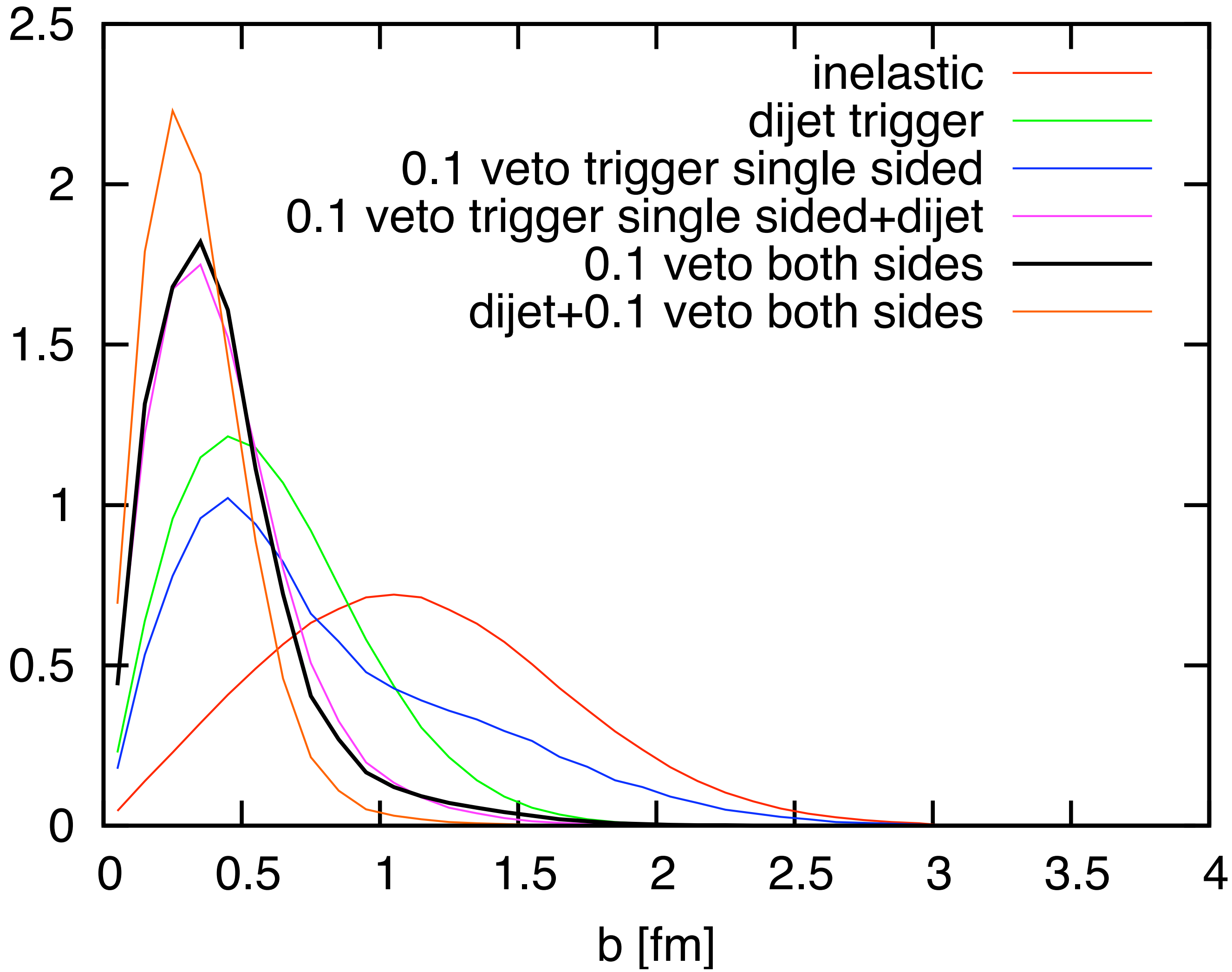
Impact parameter dependence of interaction probabilities and forward spectra





Relative probabilities for the different classes of events with n quarks struck at a given impact parameter b.

strong suppression of large x for n=2,3



0.1 veto single sided = no baryons with x>0.1

0.1 veto single sided ≈ 0.1 veto both sides no neutrons with x>0.1

One can trigger on <b>=0.4 fm - collisions with gluon field at <ρ> ~ 0.6 fm where gluon density 2- 3 times smaller than in AA at LHC but at higher energy where $G_p(x)$ is higher by a factor of two. Encounted densities >> larger densities at RHIC.

However dispersion in strength of interaction is much larger than in AA.

Additional effects - so far neglected - much larger (by 9/4) p_t^2 which gluons get in the process

⇒ independent fragmentation of gluons down to smaller x_F

⇓

suppression of forward particles is underestimated

Generation of color in high representations in the proton fragmentation region for central collisions should lead to increase of multiplicity below x_F where BDR holds over broad range of rapidities.

- Long range correlations in rapidity, how decrease in the forward production propagates to more central rapidities: CMS: T2, T1, CASTOR,...

- Large increase of multiplicities for y ~0

Observed at Tevatron with Z-boson trigger? A factor of two increase. Likely much larger for our triggers and for LHC.

Conclusions

- ★ *Understanding of the complexity of the nucleon structure is gradually emerging*

- ★ *Double hard processes at Tevatron provides evidence for transverse correlations between partons. Maybe due to lumpy structure of nucleon at low scale (constituent quarks) and size fluctuations. Further studies of transverse correlations are necessary at colliders.*

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

- ★ Challenge- understand dynamic mechanism which is modeled in the current MC by introducing ad hoc cutoff on $p_t > p_{min}$ of the jets (> 3GeV for LHC)

Prepare for QCD surprises at LHC --highly desirable to have a sample of minimal bias and central trigger events which would allow among other things to adjust quickly MCs for high lumi runs.