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From soft to hard QCD and back

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From soft Pomeron to hard QCD and back

Leonid Frankfurt , TAU

Workshop in memory of V.Gribov
Triest, May 27, 2010

The concept of Pomeron has been suggested to solve puzzle with t channel S matrix unitarity. (V.Gribov 1961)

The amplitude of two body collisions due to exchange by Pomeron has the form :

$$A(s,t)_{a+b\Rightarrow c+d}=r_{ac}(t)r_{bd}(t)(s/so)^{\alpha_P(t)}[i-ctg(\pi\alpha_P(t)/2)]$$

where

$$\alpha_P(t)=\alpha_o+\alpha'_P\, t$$

and $r_{ij}(t)$ are residues of Regge pole

Observed in the elastic pp collisions at IHEP, CERN, FNAL as the shrinking of diffractive peak with increase of collision energy with $\alpha_o=1.08-1.1$ and $\alpha'_P=0.25.GeV^{-2}$ Smaller value of α'_P has been observed in the diffractive photoproduction of ρ meson at HERA.

Peripheral collisions dominate in the amplitude due to Pomeron exchange.

The amplitude describing scattering at impact parameter b: $f(b,s)$ has the form:
$f(b,s) \sim (s/s_o)^{\alpha_o} \exp(-b^2/4\alpha' \log(s/s_o))$ Thus essential b^2 are increasing with energy
$b^2 \sim \log(s/s_o)$ and peripheral collisions give dominant contribution at given energy .

Regge pole factorization(independence of residues on instant parton configurations in colliding hadrons) follows from t channel unitarity of S matrix. As the consequence of Regge pole factorization scattering should be the same for any configurations of constituents within colliding hadron-no color transparency phenomenon.

Since $\alpha_o > 1$ multiple Pomeron exchanges become dominant for the hadron collisions at small impact parameters. Modelling found blackening of interaction and appearance of new degrees of freedom . FNAL data on elastic pp collisions found blackening of interaction but at small impact parameters only . Leads to faster increase with energy of essential impact parameters $b^2 \sim \log^2(s/s_o)$ and to the rapid increase of cross section with energy $\sigma \sim \log^2(s/s_o)$ (Froissart 1961).

Competition with hard QCD

- QCD evolution equation describes existing data on structure functions.

- Amplitudes of hard processes in pQCD contain large double logarithmic terms

$\xi=(N_c/2\pi)\int d^2k\,(\alpha_s(k^2)/k^2)\,\log(x_o/x)$ which are absent in the formulae for the Pomeron exchange.
Dominance of double logarithmic terms leads to the specific property of small x processes :

"smaller transverse size of colorless quark-gluon wave package smaller its interaction with a hadron target and faster increase of its interaction with collision energy".

Proved for the interaction of spatially small dipole with a hadron(nucleus) target.

Direct experimental confirmations:

- Color Transparency phenomenon FNAL(2001).

- $xG_p(x,Q^2) \sim \exp[b(Q^2)\log(x_o/x)]$; $b(Q^2 \sim 5\,GeV^2) \approx 0.2$, increases with Q^2. FNAL, HERA

- d\sigma($\gamma+p \to J/\psi$+rap gap +X)/dt $\sim (x_o/x)^{b(t)}$ where b is increasing with t ZEUS(2009).

Color Transparency (CT)- nonPomeron phenomenon

J/ψ discovery -1974 ☀ small σ (γ+N → J/ψ N)

Hot discussions

J/ψ is a small object (?) and hence(?) interacts weakly or hadron cross sections are approximately the same for all hadrons

CT won first round

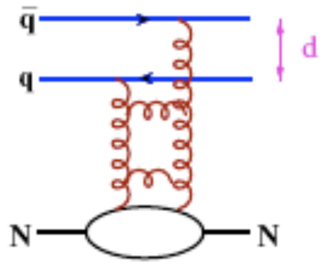
☀ Weak absorption of J/ψ: σ (γ+A → J/ψ +X) ≈Aσ (γ+N → J/ψ N+X) (1975)

☀ dσ/dt(Υ+A →X+rap gap +A)=A^2 [dσ/dt(Υ+p →X+rap gap +p)] (FNAL 1980th)

☀ dσ/dt(π+A →2jets+rap gap +A)=A^2 [dσ/dt(π+p →2jet+rap gap +p)] (FNAL 2000th)

no shadowing effects

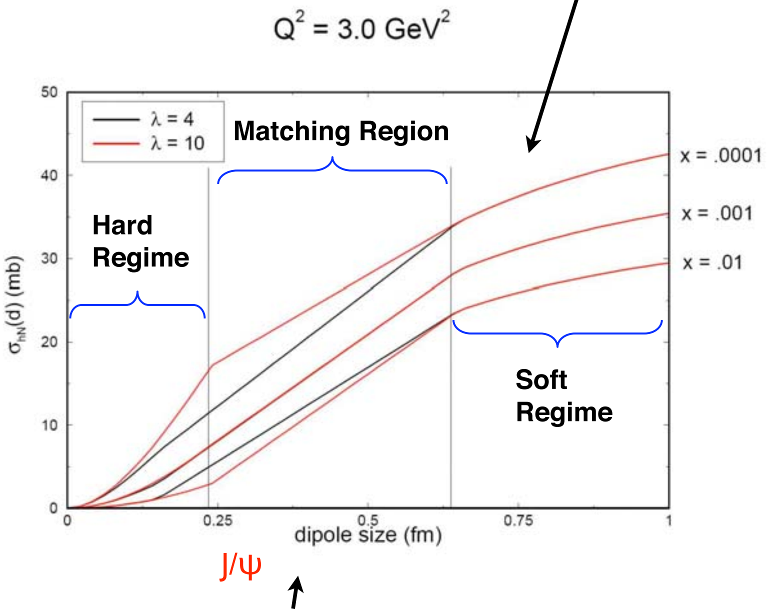
CT is routinely used for the quantitative explanation of DIS phenomena at HERA. *HERA data confirm predicted by pQCD rapid increase with energy of the structure functions of hadrons, i.e. cross sections of small dipoles xG ~exp [c√ξlog(x/x₀)]*



$$\sigma(d,x) = \frac{\pi^2}{3}\alpha_s(Q^2_{eff})d^2\left[xG_N(x,Q^2_{eff}) + \frac{2}{3}xS_N(x,Q^2_{eff})\right]$$

$$Q^2_{eff} = \lambda/d^2, \lambda = 4 \div 10$$

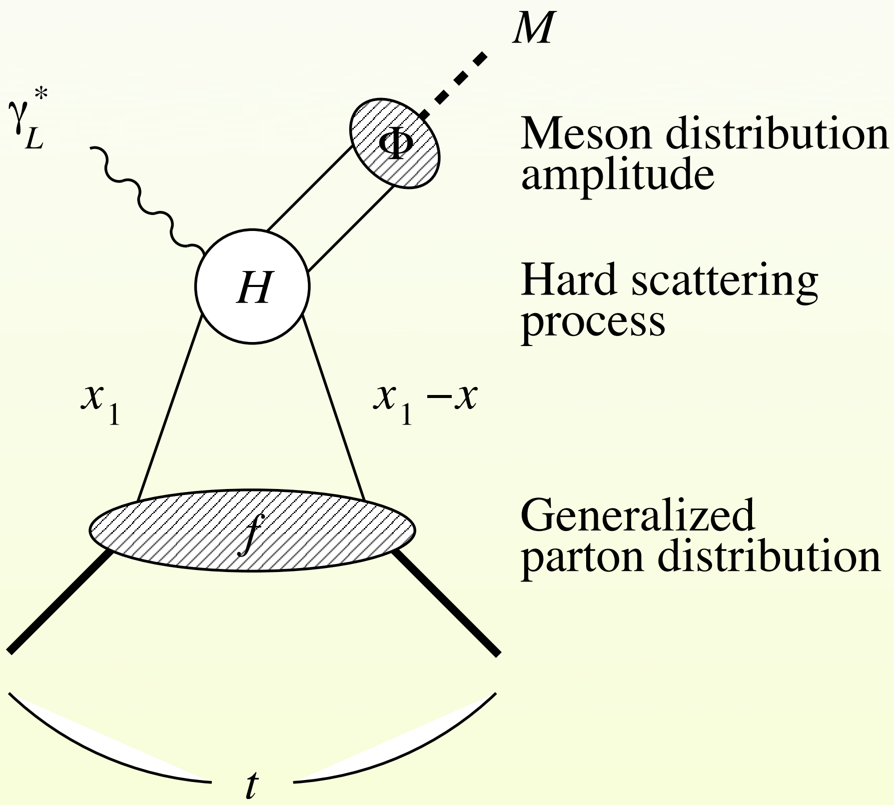
G.Baym, B.Blattel, L.F, M.S, 93, L.F, G.Miller, M.S. 93



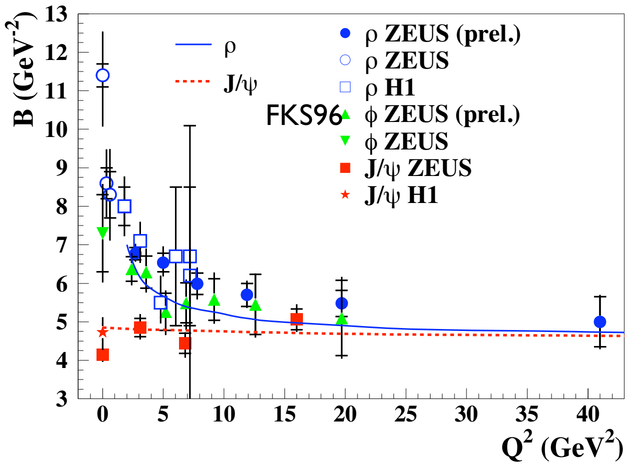
Dipole approximation for DIS and vector meson production describes HERA data. Affirmative answer to the question why J/ψ has cannot interact strongly -it can but if energy is high enough. Thus account of energy-momentum conservation plays crucial role .

Generalized parton distributions have been measured in the hard diffractive processes at high energies. QCD factorization theorem for DIS exclusive processes

Proofs heavily used the CT property of QCD.



Gluon distribution in impact parameter space =mapping form factor of a nucleon Gp(t) as measured at HERA.

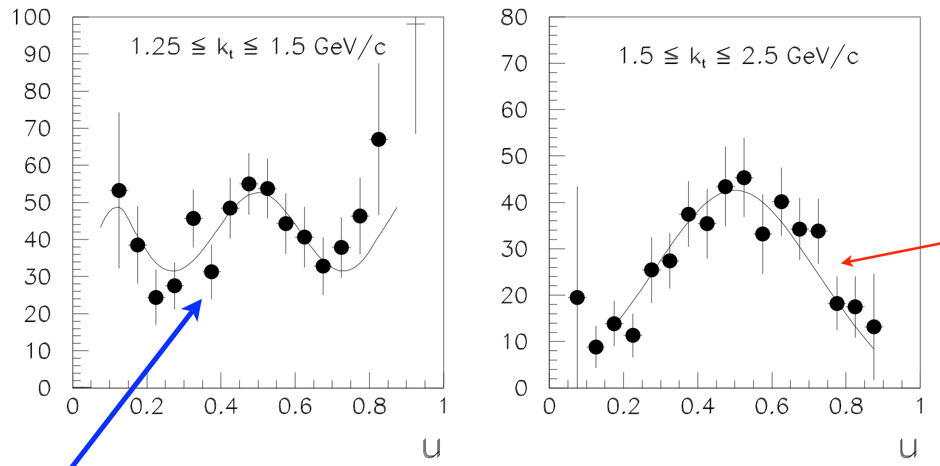


Convergence of t-slope, B of ρ-meson electroproduction to the slope of J/ψ photo(electro)production.

Gp(t) more narrow than the distribution of the electric charge - due to suppression of pion field effects

Observation of CT at FNAL (Ashery 2000): π +A →"jet"+"jet" +rap gap +A.

Confirmed predictions of pQCD (Frankfurt ,Miller, MS93) for *A-dependence[8 times stronger than for soft processes Pb vs C], for the distribution over energy fraction, u carried by one jet, dependence on p_t(jet), etc all agree with QCD factorization.*



prediction

Pion distribution before QCD evolution.

Asymptotic pion distribution z(1-z)

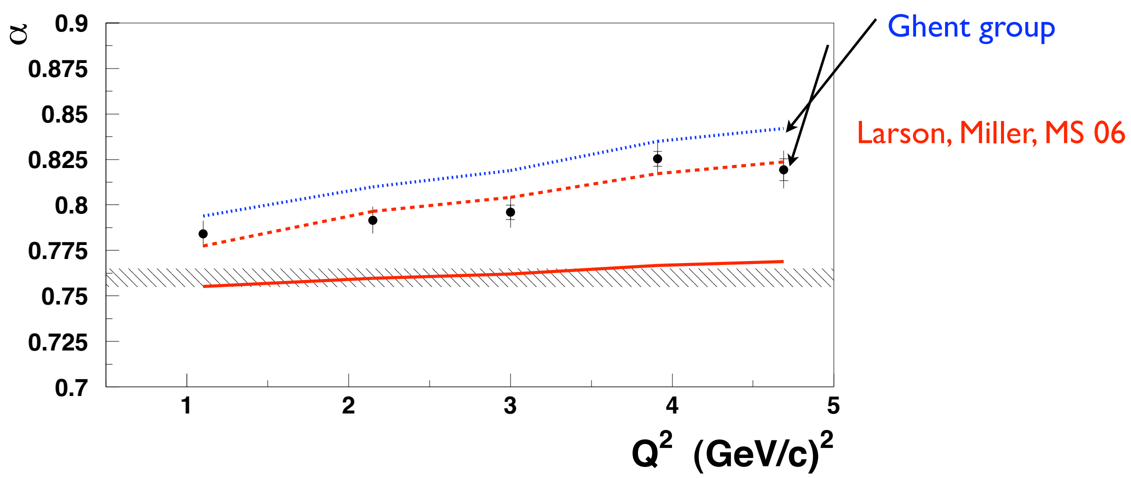
$$Q^2(\pi\ f.f.) \sim 4k_t^2(jet)$$

$$\Downarrow$$

strong squeezing in π form factor for Q^2=6 GeV^2

☀ $\gamma^* + A \to \pi A^*$ Jlab evidence for increase of transparency with Q (Dutta et al 07)

prediction of quantum diffusion model



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A- dependence checks not only squeezing but **small scale of** l_{coh} = 0.6 fm (E /GeV) as well- should be one of basic elements in the theoretical approaches to heavy ion collisions.

The same parameters give a good description of the preliminary $\gamma^* + A \to \rho^0 A^*$ Jlab data

⇒ CT for meson production at Jlab difficult to interpret as two effects - small l_{coh} and moderate Q^2 interwine

First conclusions .

Double logarithmic(DL) approximation to pQCD predicted and described well variety of phenomena which can not be explained within the Pomeron construction-QCD evolution of structure functions of hadrons, Color Transparency phenomena, Color Fluctuations phenomena in hadronic collisions etc. Regge cuts may help in the last case .

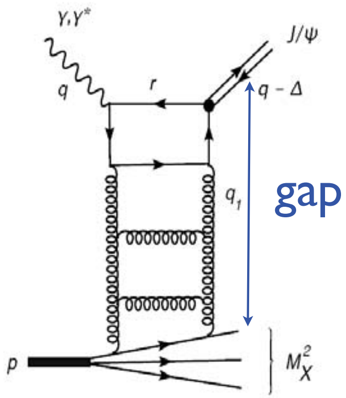
DL amplitudes are proportional to target volume. Thus geometrically they are dominated by the scattering at small impact parameters -confirmed by numerics . So in the kinematics where DL amplitudes become large they compete in pp collisions with Pomeron cuts which are also concentrated at small impact parameters. Only one of options may survive .

New effect - DGLAP at large t

CFS factorization theorem derived in the limit $-t << Q^2$

For $-t \sim Q^2$, in the double log approximation essentially no energy dependence of the ladder - hence α_{IP} is close to one - effectively looks as presence of α' of the order of 0.07 GeV^{-2}- but effect does not reflect increase of the transverse distribution of partons !!! (Blok, FS, 10)

Consider process for $-t \leq Q^2 + M_V^2$



Elementary reaction - scattering of a hadron (γ, γ*) off a parton of the target at large $t=(p_\gamma-p_V)^2$

$$x_J = \frac{-t}{-t + M_X^2 - m_N^2}$$

FS 89 (large t pp→p +gap + jet), FS95
Mueller & Tung 91
Forshaw & Ryskin 95

Larger cross section than exclusive which has the same s - dependence

$$\frac{d\sigma_{\gamma+p\to V+X}}{dt dx_J} = \frac{d\sigma_{\gamma+quark\to V+quark}}{dt}\left[\frac{81}{16} g_p(x_J,t) + \sum_i (q_p^i(x_J,t) + \bar{q}_p^i(x_J,t))\right]$$

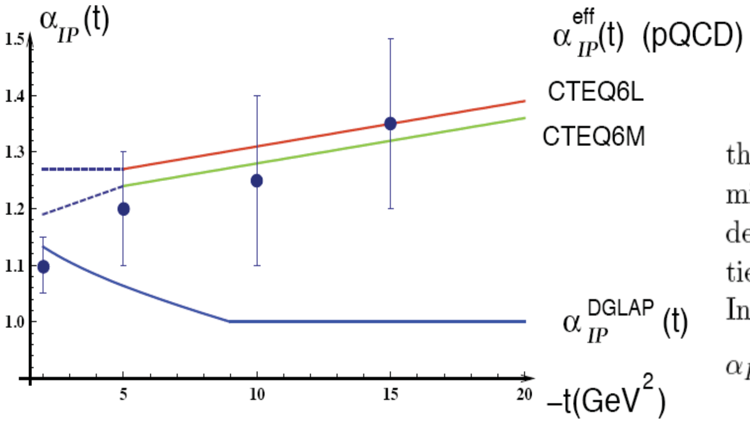
For $-t \leq Q^2 + M_V^2$

$$\frac{d\sigma}{dt dx_J} = \Phi(t, Q^2, M_V^2)^2 \frac{(4N_c^2 I_1(u))^2}{\pi u^2} G(x_J, t).$$

Here

$$u = \sqrt{16 N_c \log(x/x_J)\chi'}, \ \chi' = \frac{1}{b}\log\left(\frac{\log((Q^2+M_V^2)/\Lambda^2)}{\log(-t+Q_0^2)/\Lambda^2}\right),$$

$$x_J = -t/(M_X^2 - m_p^2 - t), x \sim 3(Q^2 + M_V^2)/(2s), \ b = 11 - 2/3 N_f, N_c = 3, s = W_{\gamma p}^2$$



The comparison between the experimental data and theoretical prediction for the HID cross section at HERA for the "effective Pomeron" $\alpha_P^{\rm eff}(t)$, i.e. (1/2) logarithmic derivative of the cross section $d\sigma/dt$, obtained after integrating between the energy dependent cuts, as given in the text. The dashed curve means large theoretical uncertainties in the corresponding kinematic region. The values are given at for $W_{\gamma p} = 150$ GeV. In the same figure we depict also "true (DGLAP) "Pomeron", i.e. logarithmic derivative $\alpha_P(t)^{\rm DGLAP} = 0.5 \frac{d(d\sigma/)dtdx_J))}{dlog(x/x_J)}$ at this energy. $\Lambda_{\rm QCD} = 300$ MeV.

Note that in this calculation the scale governing the J/ψ production was taken to be M_V^2. More realistic estimate (at least for exclusive photoproduction is 3 GeV^2)

Return of Pomeron

Kinematical region dominated by DL includes HERA and above . The conclusion follows from the analysis of the restrictions due to energy-momentum conservation and/or from the analysis of resummation models and/or from the analysis of data on hard diffractive processes with proton dissociation. However the number of radiations in DL approximation is controlled by minimum of $[\log(x/x_o)$, $\log(Q^2/Q^2_o)]$. So at extremely small x (LHC or above) single logarithmic terms $\log^n(x/x_o)$ unaccompanied by $\log(Q^2/Q^2_o)$ may become dominant . Transition to this regime in the resummed models is tunelling transition. In this kinematics DL terms would describe residue of Pomeron.

Blackening of pQCD interactions with energy moves CT to smaller and smaller configurations and ends up to restore universality of hadron interactions suggested by V.Gribov even to equality of all cross sections but at infinite energies.

Is asymptotic freedom sufficient to guarantee that pQCD series are asymptotic one but not divergent ? Answer: no. Model description suggests appearance of additional collective degrees of freedom in the domain where confinement should not be important.

Growth of the cross section of small dipole interaction with a nucleon / nucleus (off mass shell amplitude) should be tamed at very high energies for the scattering at a given impact parameter "b" by the probability conservation= nonlinear relations between Green functions-unrelated to confinement phenomenon.

Knowledge of gluon form factor allows to determine gluon distribution in impact parameter space b for dipole≡h- proton interaction:

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

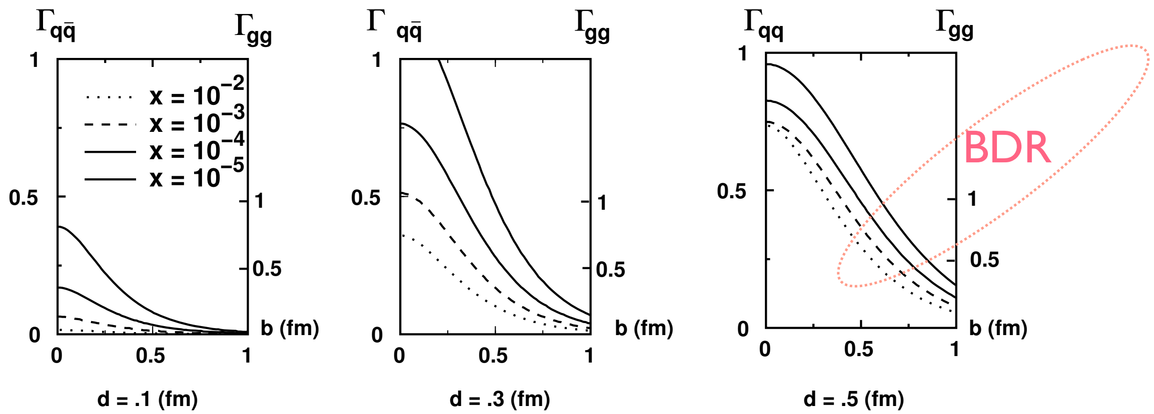
$$\sigma_{tot} = 2\int d^2b \mathrm{Re}\Gamma(s,b)$$

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

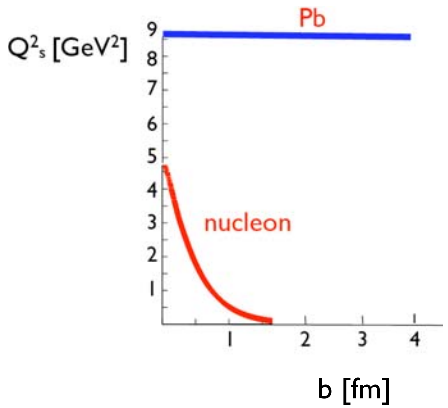
$$\sigma_{inel} = \int d^2b(1-(1-\mathrm{Re}\Gamma(s,b))^2 - [\mathrm{Im}\Gamma(s,b)]^2)$$

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

- black disk regime -BDR



No LT shadowing

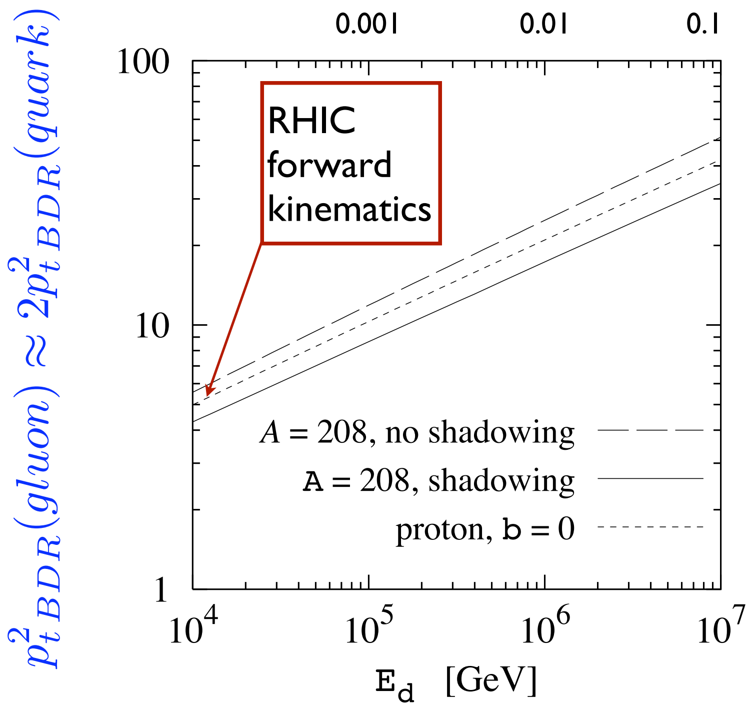


Gluon densities in nuclei and proton at b=0 are rather close !!!!

Advantage of nuclei is the flat shape in b

Proximity to BDR at small b already at relatively large x, where log (x_o/x) effects are still small.
Stronger effect in the gluon channel - supported by larger fraction of diffraction events in the gluon channel

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



x_F for pp at LHC: 7 x 7 TeV

warning - estimate assumes $x^{-\omega(Q2)}$ regime for all x- may overestimate $p_{t\,BDR}$ for parton energies (in nucleus rest frame) $E_d > 10^5$ GeV

Distinctive features of black disc regime(BDR).

•*At small impact parameters "b",* in the kinematical region of large virtualities where confinement is inoperative onset of BDR and disappearance of Bj scaling at x achievable at HERA. Follows from the data (*partial wave for gluon dipole -proton interaction becomes close to 1),* from the pQCD calculations . BDR gives small contribution into structure functions= integral over impact parameters.

•Suppression of the yield of hadrons in the fragmentation region as compared to LT phenomena = preselection phenomena. In $D+A \rightarrow \pi$+rap gap +X - mimics energy losses for the hadrons in the deuteron fragmentation region . Experimental hints at RHIC.

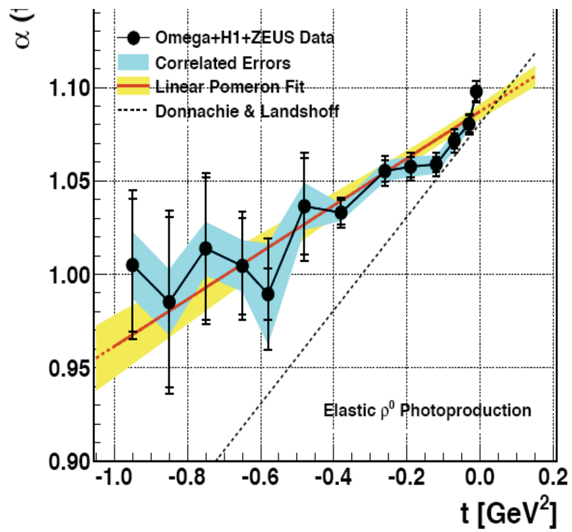
•Structure functions of a nucleon will increase with decrease of x forever : $F_{2p}(x,Q^2) \sim \log^3(x_o/x)$+pQCD contribution at peripheral impact parameters. Structure function of a nucleus at achievable energies $F_{2A}(x,Q^2) \sim \log(x_o/x)$+contribution off nuclear edge .

•No limiting regime at high energies -composition of partons in the colliding particles depends on collision energy. Violation of Wilson operator expansion (uncertainty in the formulation of the leading log approximation) is reflected in the increase with energy of quark transverse momenta in the photon wf i.e. in the box diagram $k^2_t \sim s^{0.09}$, in the appearance of additional $\log(x_o/x)$ as compared to Froisart limit.

Rapid increase with energy of hadron, jet transverse momenta in pp collisions at zero impact parameters -future of QCD physics at LHC.

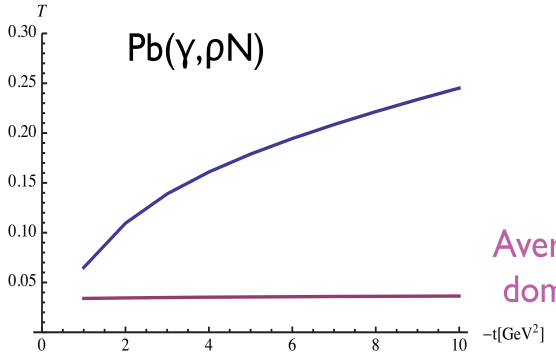
Both small x pQCD physics (including BDR) and heavy particles production are concentrated at small impact parameters LF, MS, C.Weiss 2009. So difficult challenge expects a person who dreams to separate huge fluctuations of QCD background from the signal from new particles production at LHC .

Maybe relevant for the explanation of the pattern observed in photoproduction of ρ-mesons. No diffusion if -t is larger than the soft scale.



Test of squeezing: $\gamma + A \rightarrow \rho + p + (A-1)^*$ $(p_t(\rho) + p_t(N) \leq k_F)$

Transparency ratio: $T = \sigma(\gamma + A \rightarrow \rho + p + (A-1)^*) / Z\sigma(\gamma + p \rightarrow \rho + p) >>$ Glauber value



CT (optimistic)

Average configuration dominance

Early squeezing - graduate shift of <σ> for dominant configurations

Negligible effect from proton squeezing - fast expansion

G.Miller, MS

BDR up to $p_t^{(BDR)}$ ~ few GeV

↓

suppression should be larger than in eikonal rescattering CGC models - *color opacity regime*

Propagation for $p_t \leq p_t^{(BDR)}$ Post-selection - effective fractional energy losses

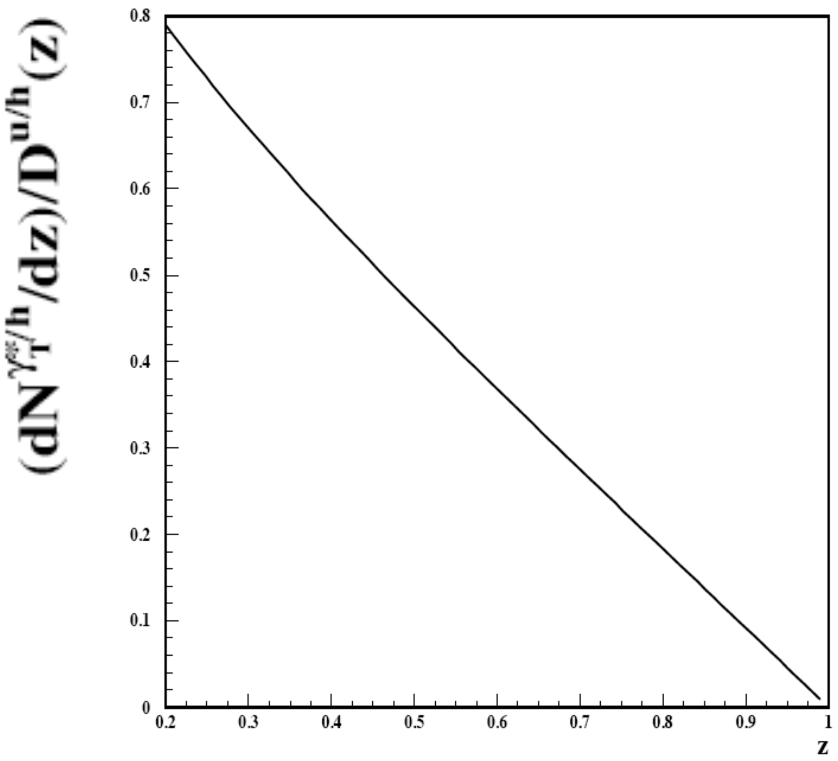
First example: *Inclusive production of leading hadrons in DIS for* $Q < 2p_t^{(BDR)}$

The mechanism of fragmentation in BDR: target selects quark and antiquark in the γ^* wave function with $p_t \propto Q_{BDR}$ and known z-distribution peaked at ~1/2 fragment independently since in this case overlap between showers is small (as long as LC fractions are large).

Hence to a first approximation

$$D^{\gamma_T^* \to h}(z) = 2\int_z^1 dy D_q^h(z/y)\frac{3}{4}(1+(2y-1)^2)$$

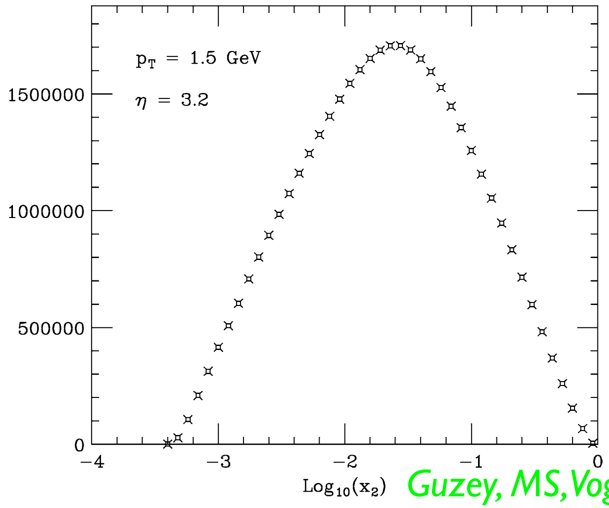
Gross scaling violation in BDR as compared to DGLAP. The leading particle spectrum in BDR is strongly suppressed. The inclusion of the $q\bar{q}g$ states in the virtual photon wave function (due to the QCD evolution) further amplifies the effect.



The total differential multiplicity normalized to the up quark fragmentation function $dN^{\gamma_T^*/h}/dz)/D^{u/h}(z,Q^2)$ as a function of z at Q^2=2 GeV^2.

Post selection and forward pion production in DAu collisions at RHIC

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

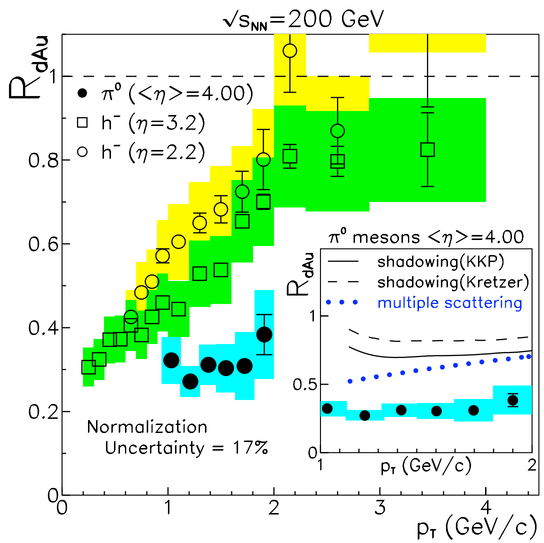


Guzey, MS, Vogelsang 04

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 $\eta = 3.2$.

Tests that main contribution to forward pion production comes from quark scattering off gluons with <x> > 0.01 which are not screened in the case of scattering off nuclei

- 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.

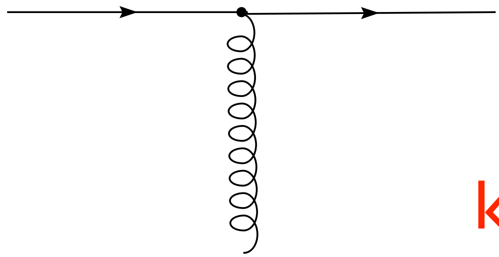


BRAHMS and STAR are consistent when the BRAHMS data are corrected for the isospin effect

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 $2 \to 1$ 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 - post selection - energy splits before the collision - effectively 10- 15 % energy losses.

$\Rightarrow$ dominant yield from peripheral impact parameters

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 concluded that pion production is strongly dominated by peripheral collisions, and that there is no significant suppression of dijet mechanism for forward - central correlation for a forward trigger.

For central impact parameters suppression is by a factor > 5, which requires effective energy losses for quarks of >10%. Consistent with our numerical estimates

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 ~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 - private communication

Further confirmation - forward -central correlation data reported by STAR and PHENIX at QM 09

New forward dipion data qualitatively consistent with increase of the suppression for this kinematics as the second jet is also in BDR. Stronger post selection effect (since second jet is from gluon) - enhanced effective energy losses - *hope experiments will provide more information on centrality dependence, etc.*

Independent of details - strong evidence for breaking pQCD approximation in the kinematics sensitive to strong gluon field in nuclei

- onset of color opacity regime.