Challenges of small x hard QCD .

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Introduction

Observation at FNAL, CERN, DESY, SLAC of approximate Bj scaling for cross sections of hard processes :

$$Q^2\sigma = F(x, \alpha_s \ln(Q^2/\lambda^2_{QCD}))$$

was great success of asymptotic freedom in QCD, of decrease of running coupling constant with virtuality :

$$\alpha_s(Q^2) = 4\pi/b \ln(Q^2/\lambda^2_{QCD})$$

Concept of universal parton densities within a hadron modified by calculable NLO pQCD evolution has been effective so far to describe numerous hard phenomena. Hard QCD phenomena form the basis for the search of new particles at LHC.

However leading twist approximation and NLO pQCD calculations produce large parton densities which at sufficiently small x and/or large atomic number A violate probability conservation . pQCD calculations of amplitudes for spatially small dipole scattering off hadron target scattering as well as phenomenological analysis based on diffractive gluon densities of a proton measured at HERA found that for gluon driven processes troubles become serious for $x(pp) \leq 10^{-5}$

and in proton-nucleus collisions at significantly larger x:

$$x(A) \approx Ax(pp)$$

Simplicity of formulae is the result of interplay between unrelated phenomena-dependence of cross section on A due to nuclear shadowing phenomenon and power of increase of amplitude with energy.

Thus behavior of amplitudes of hard processes should radically change, at these x characteristic for the part of kinematics of RHIC and LHC. Bj scaling will disappear completely in spite of asymptotic freedom (V.Gribov 1970): cross section become independent on Q at large Q and small x i.e. concept of parton distributions and conformal invariance of QCD disappear in this kinematics. Concept of structure functions will be still valid.

Thus new QCD regime arises: small running coupling constant but strong interaction with large parton densities. Properties of new QCD regime are actively discussed in the literature : Color Glass Condensate (CGC), Black Disk regime(BDR)etc. I will focus my talk on the universal and model independent properties of hard processes within new QCD regime which are calculable as the consequence of complete absorption of projectile in this regime .

In this talk I will restrict myself by the discussion of some model independent properties of new qCD regime.

Conventional small x pQCD .

1. At interesting for the identification of new QCD regime and achievable experimentally small x analytic pQCD calculations of hard high energy processes are in principle manageable although rather tedious. This is because the number of gluons radiated in multiRegge kinematics (where large interval in rapidity between adjacent gluon radiations) is rather slowly increasing with energy as the consequence of energy-momentum conservation law: 1-2 gluons at HERA and 6-7 at LHC. As a result predictions of popular approximations to hard processes -NLO DGLAP and NLO BFKL pQCD approximations are rather close for $x > 10^{-5}$

2. Parton distributions evaluated within pQCD are fastly increasing with energy at small x :

$$xG_T(x,Q^2) \propto x^{-\lambda(Q^2)}$$

This is numerical fit to actual pQCD calculations with $\lambda \approx 0.25$.
The increase of parton distributions within proton have been observed by CDF, DO(FNAL) ; by H1 and ZEUS at HERA(DESY) .

3.The generalization of QCD factorization theorem to hard exclusive processes (L.F&G.Miller&M.Strikman 91;S.Brodsky,J.Gunion,L.F,A.Mueller,M.Strikman 94; J.Collins ,L.F. and M.Strikman. 97)

$$\sigma_L = c[xG_T(x,Q^2)]^2/Q^6$$

with calculable but depended on the process c. This theorem helped to calculate new variety of hard processes in terms of generalized parton distributions of the hadron(nucleus) target.

One of new QCD phenomena was discovery at FNAL of the transparency of nuclear matter for the propagation of a spatially small wave package of quarks and gluons in the process:

$$\sigma(\pi + A \rightarrow 2jet + A) \propto A^{1.54}$$

and close dependence on A for coherent photoproduction of J/ψ instead of $\propto A^{2/3}$.

4. New variety of hard processes calculable in QCD has been measured at

HERA-mostly diffractive photoproduction $\gamma + p \to J/\psi + p$

diffractive electroproduction of vector mesons: ρ, ϕ, J/Ψ

Besides prove of applicability of pQCD for the description of new variety of hard processes the dependence of generalized gluon distribution on momentum transfer has been measured at HERA in photoproduction

and in electroproduction of ρ, ϕ, J/Ψ

5. At fixed target mode of FNAL, at HERA and lesser energies hard diffractive processes probe gluon core of a proton- the contribution of pion tail of a nucleon carrying small fraction of nucleon energy is dynamically suppressed for the processes rapidly increasing with energy. Radius of gluon core as determined from t dependence of hard diffractive processes is significantly smaller than electromagnetic radius of a nucleon. Important for establishing kinematics of applicability of LT approximation, for the evaluation of moderate x hard processes including production of supersymmetric particles. This suppression of the contribution of pion tail will disappear with increase of energy.

Inelastic diffraction in DIS

Virtual photon produces quark-gluon configurations which have different size when hitting target. Selecting large Q is insufficient to suppress nonperturbative QCD. Observation at HERA of significant cross section of inelastic diffraction in the process:

$$\gamma^* + p \to "diffractivestate" + p$$

whose cross section depends on energy similarly to soft QCD processes (H1) demonstrates presence of nonperturbative QCD contribution- QCD Aligned Jet Model.

Restrictions from probability conservation.

To demonstrate origin of inequality let us evaluate within LT approximation the ratio :

$$\sigma(\gamma^* + T \to V + T)/\sigma(\gamma^* + T \to X) \sim (c(xG_T)^2/Q^4)/(xG_T/Q^2)$$

This ratio becomes larger than 1 at sufficiently small x-probability is violated within LT approximation.

To formalize theoretical restriction let us consider scattering of any wave package (for certainty colorless dipole) off target T. If the interaction is rapidly increasing with energy projectile will be absorbed by target. Thus diagonal matrix element of S matrix(U matrix) should be 0. This is condition of complete absorption. This is generalization to hard processes restrictions from unitarity of S matrix. This condition is important to define unambigous result of summing pQCD series. Remember that pQCD series are asymptotic and therefore dont define sum unambigously.

This inequality can be rewritten in the familiar from soft QCD form that partial wave at given impact parameter should be less than 1. Having formulae for cross section and exploring dependence of gluon distribution on impact parameter b we may evaluate region where complete absorption occur.

The tail of the dependence of gluon distribution within proton on the impact parameter b is dictated by nonperturbative input to QCD evolution -i.e. by phenomenon of spontaneously broken chiral symmetry in QCD which is relevant for the average characteristics of a nucleon. At large distances dominates two pion exchange. So at large b:

$$xG_T(x, Q^2, b^2) \propto exp - (2m_\pi b)$$

Play with numbers shows that complete absorption occur for the scattering of gluon dipole at $Q^2 = 10 GeV^2$ for $x \leq 10^{-5}$

This kinematics is close to leading jet production at RHIC and in a wider region at LHC. At HERA difficult to identify since this physics can be hidden in the initial condition for QCD evolution. The interaction of quark dipole requires smaller x to achieve BDR. The same calculations show that for heavy nuclei onset of BDR should occur at significantly larger x.

Experimental indications for onset of BDR

1. Large value of diffractive gluon density in the proton.

2. Peripheral production of leading jets in deutron-nucleus collisions

Distinctive features of new QCD regime.

1. Structure functions of a nucleon will continue to increase fastly forever.

$$F_2, xG = cQ^2(\ln(x_o/x))^3$$

Additional ln x as compared to Froisart limit for cross sections is because of ultraviolet divergency of renormalization of electric charge. Coefficient c is calculable. Bj scaling disappears. Such behavior is impossible in soft QCD and presence of Q^2 justifies applicability of methods of hard QCD.

2. Structure functions of nuclei are almost energy independent at achievable energies.

$$F_{2A}, xG_A = c2\pi r_N^2 Q^2 \ln(x_o/x)$$

At very large energies unachievable in lab structure functions of nucleon and nuclei will coincide.

3. Cross section of photoproduction should faster increase with energy than total cross section for pp collisions by additional power of log x.

4. Cross section of hard diffractive processes suppressed in LT approximation by power of Q form significant part of cross section:

$$\sigma(\gamma^* + T \to 2jet + T) = 1/2\sigma_{tot}(\gamma^* + T \to X)$$

Cross section of vector meson production becomes much weaker function of Q

$$d\sigma(\gamma_L^* + T \to V + T)/dt = c\frac{(2\pi r_N^2)^2}{16\pi Q^2}$$

c is calculable within BDR .

5. Characteristic p_t of hadrons should rapidly increase with energy.

6.Eikonal diagrams are exactly cancelled in QCD.

7.QCD factorization theorem differs from dipole model.

Dipole model is convenient tool to evaluate amplitudes of processes initiated by virtual photon. However this model use concepts which are in variance with established properties of QCD.

1.Amplitudes of hard diffractive processes are expressed in terms of skewed gluon distributions which are unsuitable for soft QCD processes.

2.Projectile photon produces quark-gluon configurations having different space-time distribution of color. So their interaction with target is different. This property is established both theoretically and experimentally.

Thus fitting parameter of dipole model-cross section has no direct relation to cross sections familiar from hadron collisions.

8. Structure functions of nuclei are practically uninvestigated at $x \leq 10^{-2}$. New QCD phenomena are expected :

i). at $x \leq 10^{-2}$ LT nuclear shadowing. (Calculable within the approximation which assumes that radius of a nucleon is significantly less than internucleon distances in nuclei. (L.F. V.Guzey and M.Strikman. 98-00) . Competing parametrizations were suggested(K.Escola 00))

ii. at $x \leq 10^{-3}$ the violation of LT approximation and related new phenomena. Onset of new QCD regime of strong interaction with small coupling constant .

Intermediate conclusions

Small x physics is seemingly in a good shape -the number of calculable processes is increasing. Some of them are observed and appeared in a reasonable agreement with NLO DGLAP calculations. New phenomena like color transparency were discovered .

However let us consider theoretical toy-scattering of colorless sufficiently small size dipole consisting of gluons or quarks off target T. The application of pQCD factorization theorem produces cross section for the scattering of colorless gluon dipole of transverse size d off a target T (F.S.93) :

$$\sigma(dipole + T \to X) = 2\pi d^2 \alpha_s(1/d^2) x G_T(x, Q^2 = 1/d^2)$$

Simple numerics shows that in the kinematics of HERA gluon dipole interacts with cross section around 20 mb. Quark dipole interacts with factor 2 smaller cross section due to smaller value of Casimir operator for fundamental representation of color group. Thus practical question arises on the role of HT effects, of possible nonperturbative phenomena. Problem exists in the kinematics where pQCD calculations of LT term looks reliable.

Energy losses of energetic partons in the small x processes.

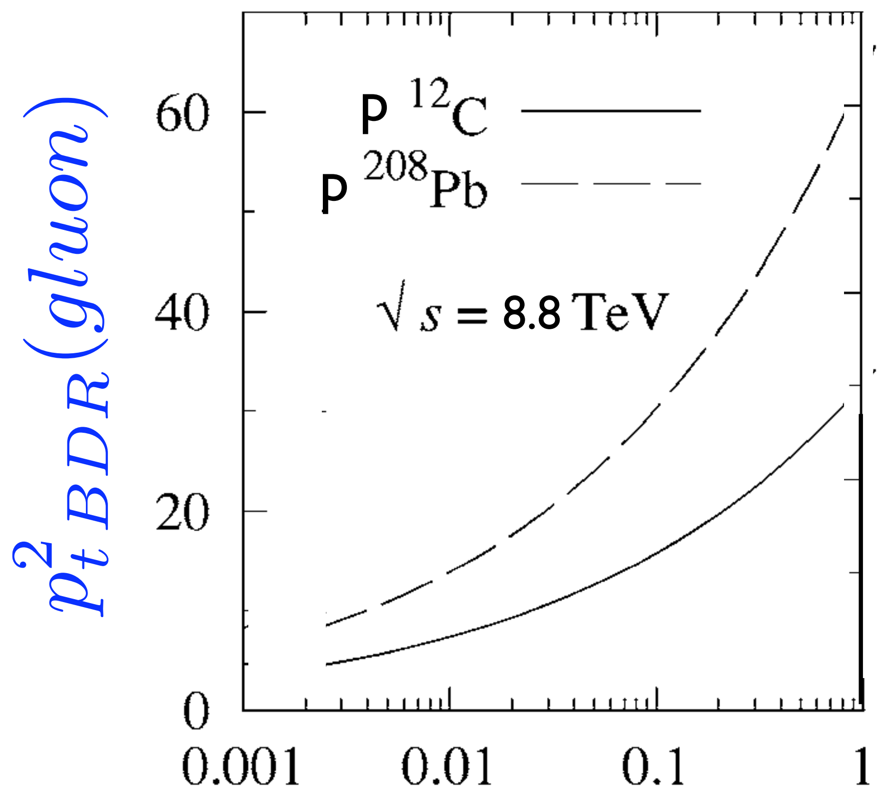
(L.F. ,M.Strikman 06)

When energetic particle crosses dense medium it looses energy. Thus unambigous signal for the formation of large parton density is opacity- increase of absorption, of energy losses. Theoretical calculations shows that in small x processes Landau-Pomeranchuk coherence is lost and leading parton should loose finite fraction of its energy ~ 10% in pp collision and significantly larger in nuclear processes. On the contrary at moderate x a parton looses finite energy: 4 GeV for L=10 fm (Bayer, Y.Dokshitzer, A.Mueller, D.Schiff) Thus in the kinematics of RHIC in the target rest frame leading parton should loose ~1 TeV if large parton densities occur.

BRAHMS, STAR investigated leading pion production in dA collisions. They found suppression of leading pion. Also ~STAR found little or no suppression of recoil jet, correlation between forward and slow hadrons. All experimental facts are consistent with energy losses, with dominance of peripheral collisions. So probably this is the first direct observation of large parton densities formed in small x processes. Current CGC inspired models which assume production of single jet have problems with data.

$$F_{2A}(x,Q^2) = \sum_q e_q^2/12\pi^2 Q^2 2\pi R_A^2[1/3\ln A + \lambda \ln(x_0/x)]\theta(0.05/A^{1/3} - x),\ \lambda \sim 0.2 \div 0.3$$

$$\frac{d\sigma(p + A \rightarrow \mu^+\mu^- + X)}{dx_A dx_p} = \frac{4\pi\alpha^2}{9}\frac{K(x_A, x_p, M^2)}{M^2} F_{2p}(x_p, Q^2)\cdot\frac{1}{6\pi^2}M^2\cdot 2\pi R_A^2 \ln(x_0/x_A).$$



$x_p = 2.5x_A(\sqrt{s_{AA}} = 5.5TeV)$

Within reach of CMS +TOTEM

$x_A = 10^{-5}$, Q < 5 - 7 GeV

RHIC II?

$p_{t\,BDR}^2(gluon) \approx 2p_{t\,BDR}^2(quark) \approx M^2(DY)/2$

Change of the structure of final states due to BDR:

Suppression of the forward production due to fractional parton energy losses and p_t broadening (RHIC and LHC)

Energy dependence of the dijet cross section at fixed p_t in the x range between 10^{-2} and 10^{-4} (UPC). Signal: taming of the rate if increase of cross section at the smallest x.

Hard diffraction

$$\sigma_{diff}(\gamma^* A \to M + A)/\sigma_{tot}(\gamma^* A) \approx 0.5 \;,$$

$$M \approx 2\, jets, < p_t^2 > \propto M^2$$

$$\frac{d\sigma_{(\gamma+A\to``M''+A)}}{dtdM^2} = \frac{\alpha_{em}}{3\pi}\frac{(2\pi R_A^2)^2}{16\pi}\frac{\rho(M^2)}{M^2}\frac{4\left|J_1(\sqrt{-t}R_A)\right|^2}{-tR_A^2}$$

$$\gamma A \rightarrow jet_1 + jet_2 + X + A$$

for direct photon: $\beta \approx 1$

$$\frac{\sigma(\gamma A \rightarrow jet_1 + jet_2 + X + A)}{\sigma(\gamma A \rightarrow jet_1 + jet_2 + X)} \approx 0.5$$

Doable at LHC for $x > 5*10^{-5}$, $p_t > 5$ GeV

M.Strikman R.Vogt, S.White, 06

$$\gamma + A \rightarrow 2jets + A$$

dominant in BDR , negligible in LT especially for forward direction FGMS 01

Vector meson exclusive and semiexclusive production

- a fine probe of onset of BDR for interaction of small quark dipoles and dynamics of dipole media interaction. In BDR

$$\frac{d\sigma^{\gamma_T^*+A\to V+A}}{dt} = \frac{M_V^2}{Q^2}\,\frac{d\sigma^{\gamma_L^*+A\to V+A}}{dt} = \frac{(2\pi R_A^2)^2}{16\pi}\,\frac{3\Gamma_V M_V^3}{\alpha(M_V^2\;+\;Q^2)^2}\,\frac{4|J_1(\sqrt{-t}\,R_A)|^2}{-tR_A^2}$$

Gross violation of Collins and FS factorization theorem
- enhancement by a factor Q^4

EIC - DIS for light vector meson coherent production

UPC - onium photoproduction in x range exceeding HERA by a factor ~100 at LHC ($W_{\gamma A} \leq$ 1 TeV) + RHICII?

Expectation:

Transition from the CT regime without LT nuclear shadowing at x> 0.01 *(observed at FNAL)*:

$$\sigma_{elastic}(\gamma A \to J/\psi + A) \propto A^{4/3}, \sigma_{quasielastic}(\gamma A \to J/\psi + A') \propto A$$

$\Downarrow$ *LT shadowing*

$\Downarrow$ *BDR*

$$\sigma_{elastic}(\gamma A \to J/\psi + A) \propto A^{2/3}, \sigma_{quasielastic}(\gamma A \to J/\psi + A') \propto A^{1/3}$$

Change of A dependence by a factor ~$A^{2/3}$!!!

➳ New QCD domain

Conclusions

Small x physics open series challenging problems.
Some of them can be solved by existing methods.

Small x phenomena can be investigated in UPC
which is natural expansion of HERA physics
into LHC domain.