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Lecture Notes

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Suppression of hard processes due to energy losses in the vicinity of black disc regime .

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Introduction

pQCD calculations , FNAL, HERA data found rapid increase with energy of parton densities within proton . Even more rapid increase with energy of cross sections of hard exclusive processes -($xG)^2$ follows from another QCD factorization theorem of (S.Brodsky, JGunion, L.F., A.Mueller and M.Strikman 94) and of (J.Collins, L.F., M.Strikman 96). This increase has been observed in the exclusive photo and electro-production of vector mesons at HERA. Both predictions contradict to each other at sufficiently large energies and to the conservation of probability which forbids increase with energy of amplitudes of hard processes at fixed impact parameter(M.McDermott, L.F, M. Strikman 00). Discovery at RHIC of suppression of jet production in AA collisions as compared to LT calculations indicates the violation of QCD factorization theorem at sufficiently large energies and/or large atomic number. These discoveries may have far going impact for the hunting for new heavy particles at LHC.

Thus both pQCD calculations and experimental data produce evidence for the onset of new QCD regime . In this regime Bjorken scaling disappears completely:

$$F_2(x, Q^2) \propto Q^2$$

but structure functions increase with energy forever. The concept of parton densities within a hadron becomes undefined in the new QCD regime . Becides pQCD series where each term is rapidly increasing with energy being divergent at high energies can not be unambigously summed . It seems now that useful tool to these problems is Black Disc Regime-BDR . Evident advantage of this regime is in the feasibility to perform calculations based on general principles i.e. to avoid model assumptions and to visualize the origin of new phenomena . Becides comparison with formulae of BDR may help to fix parameters in the model dependent approaches. The disadvantage is in the feasibility to evaluate restricted range of phenomena and in the certain kinematics.

Loss of the fraction of the energy carried by a leading parton in a hadron(nucleus) -nucleus collisions is one of distinctive signals of new QCD regime.

The aim of the talk is to quantify generic property of hard high energy processes in QCD in the vicinity of BDR : suppression of leading particles production and suppression of hard processes at moderate x. Sufficiently energetic parton propagating through a medium looses finite fraction of its energy. (M.McDermott. L.F. M. Strikman. 00,L.F. M.Strikman. 06) Production of new particles (Higgs,supersymmetric particles..) at LHC should be suppressed as compared to the calculations based on the R.Feynman,Drell-Yan formulae which express cross section as the convolution of parton densities. The foundations of convolution formulae are more shaky as compared to QCD factorization theorem.

Understood features of small x physics are : rapid increase with energy of inelastic interactions of energetic parton and decrease with energy of amplitude with color octet quantum numbers in the crossed channel due to reggezation of gluon. These effects + probability conservation lead to the increase with energy of the average scale for hadronic interactions (A.Mueller ,L.McLerran, L.F., M.Strikman). Fast increase of inelastic interaction with energy leads to complete absorption of energetic partons = to black disc regime -BDR. In this regime Landau-Pomeranchuk (LP) coherence completely disappears and a parton looses finite fraction of its initial energy in incoherent processes. Crucial properties for treating this dynamics are causality and energy-momentum conservation.

In contrast a parton produced in the moderate x processes looses finite energy in f.s.i. because of dominance of elastic rescatterings of this parton and related LP coherence in the accompanying gluon bremstrahlung. (R.Baer.Y.Dokshitzer.A.Mueller, D. Schiff.)

Ambiguities of pQCD series at high energies.

Fast increase with energy of pQCD amplitudes transforms asymptotic pQCD series into divergent ones. Such series did not define function unambiguously .Therefore one need additional general principles to extract amplitudes of physical processes from pQCD series. Account of conservation of probability=BDR is of help.

To visualize challenges let us consider theoretical example:

$$F=\mathrm{Sum}_n (-1)^n c_n y^n = 1/1+y$$

for $c_n = 1$. However for $c_n = 1+(-1)^n (\epsilon)^n$

$$F=1/(1+y) + \exp(\epsilon y)$$

Even for small ϵ but large y these functions are vastly different.

This instability of asymptotic series raises questions on the possible presence of bifurcation, and/or new (as compared to low energy QCD) degeneracy of vacuum ➽ new zero mode.

THE BOUNDARY ON THE OFF- SHELL AMPLITUDES

To obtain nonlinear relationship between Green functions in the compact form let us consider scattering of color neutral spatially small dipole of the size (1/Q) off a target T at impact parameter b . Tendency to the regime of complete absorption leads to the inequality:

$$\sigma(el) < 1/2\ \sigma(tot)$$

$$\sigma(el) = \int I A(s,t,Q^2)/s I^2 d\tau \qquad \sigma(tot) = \mathrm{Im}A(s,t=0,Q^2)/s$$

$$\mathrm{Im}f(s,b^2,Q^2) = 1/2 I f(s,b^2,Q^2) + \quad \text{positive terms}$$

Since A is predominantly imaginary Im $f(b,s,Q^2)$ can not exceed 1 .

Within the kinematics of HERA and at larger energies this boundary seems to be achieved in the interaction of colorless gluon (but not quark) dipole with a proton target . Thus problem with probability conservation starts from the kinematics where 1-2 gluons are radiated in multiRegge kinematics. The same conclusion follows from exploring HERA data on gluon diffractive densities within proton . (F.S. 97)

For the theoretical evaluation of f(b,s,Q^2) one need the slope of t dependence of cross section measured in the hard exclusive processes at FNAL, HERA and the cross section for the scattering of dipole (L.F., J.Miller, M.Strikman B.Blattel, G.Baum 93)

$$\sigma = \pi F^2 \alpha_s d^2 x G(x, Q^2 = 1/d^2)$$

Here d is transverse size of dipole and $(F)^2$ is Casimir operator of color group.

The evaluation of partial waves based on this formulae shows that onset on new QCD regime of strong interaction with small coupling constant should occur in the kinematics of leading particle production at RHIC and at wider kinematical region at LHC. This onset of new QCD regime results from two fundamental properties of pQCD-large value for the non perturbative input for gluon distribution within proton and fast increase with energy of pQCD amplitudes of hard processes.

Discussed above boundary for $f(b,s,Q^2)$ helps to evaluate kinematical region where onset of complete absorption=black body regime occurs. For the scattering of colorless gluon dipole both pQCD calculation as well as the analysis using diffractive gluon densities of a proton measured by H1 and ZEUS give for Q^2 approximately 4-10 GeV^2 (L.F.,M.Strikman 97)

$x_{critical(N)}$ approximately 10^{-4}

$x_{critical(A)}/x_{critical(N)}$ approximately A^n

Here n\approximately 0.2/λ and λ \approximately 0.2

$xG \propto x^{-\lambda}$ and we accounted for nuclear shadowing.

In the case of nuclear target new regime should occur at larger x because HT effects are enhanced by the factor approximate $A^{(1/3)}$.

Black body regime.

L.F. M.Strikman. M.Zhalov 04

Fast increase of interaction with energy leads to complete absorption of a projectile for the scattering at central impact parameter i.e. the scattering amplitude at central impact parameter becomes equal one. This QCD regime expands with increase of energy from soft QCD to larger transverse momenta of partons. Observed

✦ directly in the elastic pp collisions at FNAL,

✦✦ indirectly in the significant value of gluon distribution in the proton and its dominance in the diffractive structure function of the proton. The scattering of colorless gluon (but not quark) dipole off a proton target seems to be close to BDR in DIS at HERA.

✦✦✦ directly in the correlation measurements in dA collisions at RHIC-hard QCD .

Increase with energy of structure functions at given impact parameter is stopped but essential impact parameters are increasing with energy:

$$c(x_o/x)\lambda \exp(-\mu b) \text{approx } 1$$

So μb approximately $\lambda \ln(x_o/x)$. Structure function of a hadron rapidly increases with energy forever:

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

(M.McDermott,L.F.,M.Strikman 00) The factor Q^2 means complete disappearance of Bjorken scaling.

The ratio of structure functions of hadrons, nuclei tends with decrease of x to one i.e. coefficient "c" should be the same for hadrons and nuclei at extremely small x. Universality follows from the complete absorption: Im f(b,s,Q^2)=1, from the increase with energy of essential impact parameters and dominance of universal pion tail in the structure functions at large impact parameters.

Froissart formulae should be valid for the total cross sections of hadron-hadron, hadron-nucleus collisions

$$\sigma = c\ln^2(s/s_o)$$

"c" should be the same for any hadron-hadron and hadron-nucleus collisions. Cross section of photo-nucleon collisions should increase with energy even faster: $\sigma = c \ln^3 (s/s_o)$ because of divergency of hadronic renormalization of electric charge.

Universality of "c" follows from:

(a) complete absorption for the scattering at central impact parameters resulting from the fast increase of amplitudes with energy. Partial amplitudes at fixed impact parameter $\to 1$.

(b) increase with energy of essential impact parameters due to Gribov diffusion within ladder in soft QCD and due to discussed above increase with energy of scattering amplitude in hard QCD.

(c) dominance of soft QCD, of Pomeron exchange at large impact parameters. This reasoning explains also observed small coefficient in the Froissart formulae for the total cross section of pp collisions.

Equality of all cross sections of hadron-hadron(hadron-nucleus) collisions has been suggested by V. Gribov within the Pomeron Calculus to ensure energy independence of cross sections at high energies. In the case of cross sections increasing with energy this universality is the straightforward consequence of QCD .

Disappearance of L.Landau-I.Pomeranchuk coherence

The evaluation of energy losses heavily uses concept of coherence of gluon radiation and related linear increase with energy of longitudinal distances in the target rest frame:

$$L_c = 1/2m_N x$$

Follows from the analysis of cross section of DIS as the Furier transform of the commutator of electromagnetic currents in coordinate space (V.Gribov,B.Ioffe,I.Pomeranchuk 1970). Within BDR the interaction is predominantly absorptive but cross section of DIS becomes independent on $(Q)^2$. So repeating the same analysis we conclude that in the BDR for hard processes:

$$L_c = const$$

This claim can be checked directly by evaluating diffractive processes within BDR. Thus it is impossible to have in QCD dipole build of bare partons at arbitrary large distances. Becides in the small x regime existing theory of energy losses which is based on LP efects should be reconsidered.

Energy losses in DIS .

In Breit reference frame virtual photon can not produce quark-antiquark pairs and the interaction of leading parton with rest of the target is HT effect :

$F(x,Q^2)=f(x,Q^2)(1\text{-}P)$

Here f is LT structure function of the target. P is HT interaction of leading parton with a target: $P=c(\alpha_s\, xG_T(x,Q^2)/Q^2)$ rapidly increasing with energy but it forms a small correction to moderate x processes. P has been evaluated for nuclear target within the leading $\ln(x_o/x)$ approximation by A.Mueller and J.Qiu 81 . Such type approximation ignores energy-momentum conservation which is accounted for by the series NLO approximations where resulting distribution of leading partons differs from that within the LT approximation. This is one of theoretical examples of fractional energy losses in the case of leading partons in the initial and final states.

Energy losses in the f.s.i.

Leading parton carries in LT DIS fraction $x - \epsilon$ of target momentum. ϵ is lost due to bremstrahlung. Additional fraction $\epsilon(f)$ is lost in the inelastic interaction in the final state which is HT effect. $\epsilon(f)$ is approximately the same as leading parton looses in LT approximation due to radiation. (L.F. and M.Strikman 06) Thus leading parton looses energy:

$$\epsilon(f)P$$

because of the f.s.i. Therefore leading jet carries fraction:

$$x-\epsilon - \epsilon(f)P$$

of target momentum instead of

$$x-\epsilon$$

within LT approximation. Within BDR where P is close to 1 (DIS off heavy nuclei or kinematics of LHC) leading parton will loose significantly larger fraction of its energy because in average it experiences more than one inelastic collisions.

Energy losses within black disc regime.(F.S.06)

1. Calculation of energy losses when a parton experiences one inelastic collision gives:

$$e_N = \langle e \rangle = (1/4)\lambda/(1-\lambda)$$

$\lambda \approx 0.2$ is the intercept of energy dependence of vacuum amplitude. Thus $e_N \approx 0.06$

Valid within DGLAP and NLO BFKL. This effect is absent in LO BFKL

2. Single parton may experience only one inelastic collision so it radiates before collisions at least N(b) gluons which experience N(b) inelastic collisions. Follows from causality -from generalization to pQCD of S.Mandelstam(1963) cancellation of eikonal diagrams , and from the implementation of energy-momentum conservation law- (B.Blok,L.F.06). So

$$e_A(b) = N(b)e_N$$

This formulae is valid when BDR is achieved for nuclear but not for nucleon target. Thus at LHC leading (forward) parton should loose approximately 1TeV while moderate x parton approximately 10 GeV.

HT modifications of structure functions of virtual photon and target.

Account of HT effects lead to several serious changes of structure functions of photon and target. Becides diminishing of the probability of hard collision HT effects are relevant for the depletion of parton distribution because a parton looses energy before hard collision.

Effect of energy losses can be accounted for approximately by substituting parton distribution within the projectile virtual photon by:

$$xD\gamma(x,Q^2)(1\text{-}P)+ xD\gamma(x\text{-}\epsilon,Q^2)P$$

Since P is large at small x account of the energy losses leads to the softening of parton distribution similar to nuclear shadowing phenomenon. Moreover as a result of increase with energy of the scale of interaction fractional energy losses and widening of transverse momentum distribution of leading partons becomes increasingly important at larger energies.

Status of convolution formulae for hard processes in hadron collisions is shaky at large energies.

Physics of hard processes in hadron-hadron, (photon-hadron) collisions differs from that in DIS by the absence of Feynman reference frame where separation between initial and final state interactions is unambigous . In hadron -hadron collisions the interaction between projectile and target exists before hard interaction which is probably HT at moderate x if the cross section is integrated over transverse momentum of final state. Proved for moderate x processes by J.Collins, D.Soper,G.Sterman long ago where isi and fsi were accounted for within the eiconal approximation.

In the small x processes the contribution of eiconal diagrams is zero-follows from causality (S.Mandelstam63, L.F and B.Blok 06.L.Lipatov and J.Bartels06) and energy-momentum conservation.(B.Blok,L.F06).Thus problem of energy losses for new particles production at large x should be reinvestigated.

Convolution formulae used to evaluate cross sections of hard processes in the hadron-hadron collisions like large mass lepton pair , Higgs boson etc production are based on the additional fundamental assumption. It is usually assumed that as the consequence of significant difference in the scales of hard and soft QCD processes these processes are independent. This assumption justifies use of closure over soft QCD interactions. In small x processes scale of non-perturbative interactions is increasing with energy which invalidates above reasoning. So it is necessary to generalize the form of QCD factorization theorem by accounting for the specifics of high energies. Conditional parton densities for the system of projectile and target should be used instead of convolition of parton densities within free hadrons. Conditional parton densities include fractional energy losses.

Leading parton production in N(d) A collision.

Yields of leading hadrons produced in NN collisions can be described as

$$\propto (1 - x_F)^n$$

n=4 for pion production. Thus for large x_F evaluated energy losses lead to significant stopping by increasing effective x_F. Fractional energy loss approx 8-10%

reproduces data on leading hadron production in dA collisions obtained by BRAHMS,STAR as well as correlation between forward hadrons and slow hadrons and lack of suppression of recoil jet. (L.F. M.Strikman 06)

Such energy losses lead to dominance of peripheral collisions in the production of leading partons but no suppression of recoiling jet.

At energies of LHC dominance of peripheral collisions moves to larger transverse momenta of jets and smaller x_F

by the factor $$s(LHC)/s(RHIC) \approx 10^3$$

Thus within onset of black disc regime :

$$d\sigma(dA \to h + X)/d\sigma(d + p \to h + X) = c_1 A^{1/3} + c_2 A^{2/3}$$

Coefficient c_1 describes scattering from single nucleon from nucleus edge.

Coefficient c_2 decreases with increase of energy due to increase of energy losses

On the contrary for sufficiently large transverse momentum of jet -far from BDR - volume term should dominate.

CGS motivated models (D.Kharzeev, A.Dumitry..) predict lack of recoil jet and yield of leading hadrons $\propto A^{5/6}$ These models assumed that hadron transverse momenta are significantly larger than that characteristic for BDR.

Analysis of STAR data on leading hadron production in dA collisions with account of interplay of soft and hard QCD phenomena found
i. selection of forward hadron with

$$p_t \approx 1.5 GeV/c$$

leads to suppression of effective number of collisions and

ii.there is no suppression of recoil jet. All features are consistent with onset of BDR.

Suppression of Higgs boson production.

Fractional energy losses of leading partons lead to softening of parton distributions with projectile and target. Expected effect can be estimated roughly as $(1-\epsilon/1-x)^{10}$

For the realistic value of $\epsilon \approx 0.06$ we obtain suppression factor: ≈ 0.5

Conclusions

pQCD and theoretical analysis of FNAL, HERA data on hard processes indicate that QCD regime of complete absorption of leading partons in the strong color fields will dominate at LHC.

Increase with energy of typical scale of the interaction leads to the complete disappearance of Bjorken scaling for the hard processes in a certain part of phase volume , to the disappearance of increase with energy of coherence length familiar from the hard processes at moderate x and in particular to the modifications of conventional factorization theorems for hard processes in hadron (hadron-nucleus) collisions.

Produced in a hard process leading parton looses increasing with energy and atomic number fraction of its initial energy in difference from the loss of finite energy in the large x processes. Energy losses by a parton in the initial state will lead to the certain suppression of hard processes (Higgs...production) .