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Challenges in High Energy QCD

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Challenges of in high energy QCD

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Outline of challenges

pQCD 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, L.Frankfurt, JGunion, 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 QCD factorization theorems contradict to each other at sufficiently large energies : $\sigma(tot) \propto xG \quad \geq \sigma(el) \propto (xG)^2$

Conservation of probability forbids increase with energy of amplitudes of hard processes at fixed impact parameter(M.McDermott, L.Frankfurt, M. Strikman 00). Total xG (integrated over impact parameters) increases with energy forever.

Extrapolation of pQCD methods to LHC domain and higher energies leads to variety of puzzles.

Bjorken scaling (approximate conformal invariance) disappears completely at sufficiently high energies as a result of hard QCD:

$$xD_i(x,Q^2)=c_i(Q^2/Q_0^2)\ln^2(s/s_0)$$

(Soft QCD produces parametrically lesser contribution.) Structure functions but not parton densities are well defined in the new QCD regime where Wilson operator expansion becomes inapplicable..

pQCD series become ambigous at high energies when nonlinear effects are included into effective Lagrangean because of appearance of several extremums. (B.Blok,L.Frankfurt) So practical questions:how to evaluate kinematical region where pQCD approach become misleading, appropriate theoretical tools, novel QCD phenomena? In the specific kinematical conditions calculations based on general principles are feasible =regime of complete absorption =Black Disc Regime-BDR . Becides comparison with the formulae of BDR helps to fix parameters in the model dependent approaches.

QCD amplitudes of high energy processes have important property which is relevant for the energy dependence of QCD environment : harder process faster its increase with energy. This property leads to the variety of novel QCD effects.

Rapid dependence of interaction on energy implies the dependence on energy of QCD environment for new particles production, , to the difference between peripheral and central collisions, to the increase with energy of leading parton transverse momenta , to the significant probability of multiparton collisions. QCD prefers different representations of chiral symmetry for central and peripheral collisions , to two phase picture for pp collisions

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 + probability conservation lead to the increase with energy of the average scale for hadronic interactions (A.Mueller ,L.McLerran, L.Frankfurt, M.Strikman). Fast increase of inelastic interaction with energy leads to disappearance of leading 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 central collisions as a result of preselection -wave function of rapid hadron is build before collision. (L.Frankfurt and M.Strikman)

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.)

Outline

The interplay of central and peripheral pp collisions

Challenges of hard QCD physics in small x domain

Novel QCD phenomena. Two phases environment for new particles production

Preselection and energy "losses".

Peripheral and central soft and hard pp collisions

Conservation of probability is simplified in the impact parameter space where :

$$T_{el}(s,t=-\Delta_t^2) = (is/4\pi)\int d^2b e^{-i(\Delta_t b)}\ \Gamma(s,b)$$

Soft QCD -Pomeron exchange :

$$T \propto s^{\alpha_P(t)}$$

and

$$\alpha_P = 1 + \epsilon + \alpha'_P t$$

$$\epsilon = 0.08 - 0.1$$

$$\Gamma \propto (s/s_o)^{\epsilon} e^{-b^2/2B}$$

Here

$$B = B_o + 2\alpha'_P \ln(s/s_o)$$

V.Gribov

is the slope of t dependence of elastic cross section. Observed at FNAL

Thus Pomeron exchange dominate at increasing with energy impact parameters $b^2 \approx B$ -dominance of peripheral collisions.

Since intercept of Pomeron is larger than 1 Pomeron rescatterings lead to blackening of interaction at central impact parameters .

At the energies of LHC $B \approx 2B_o$

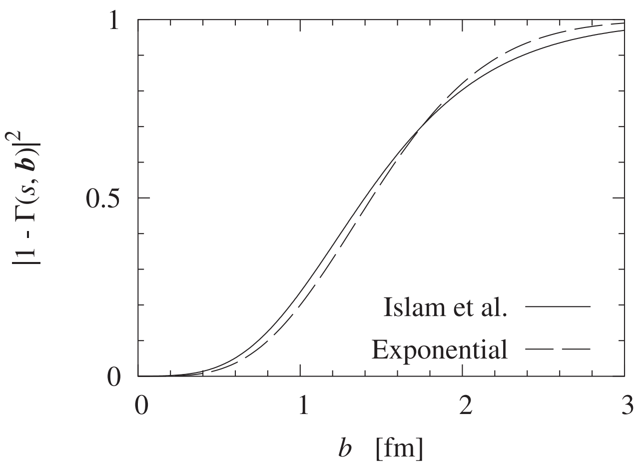
So peripheral collisions ($b^2 \approx B$) can be separated experimentally from the central collisions: $b^2 \approx B_o$ (L.Frankfurt,M.Strikman,C.Weiss)

Restrictions due to probability conservation for central hadron collisions:

$$T_{\rm el}(s, t=-\boldsymbol{\Delta}_{\perp}^2) = \frac{is}{4\pi}\int d^2b e^{-i(\boldsymbol{\Delta}_{\perp}\boldsymbol{b})}\Gamma(s, \boldsymbol{b}),$$

$$\left.\begin{array}{c}\sigma_{\rm el}(s)\\ \sigma_{\rm tot}(s)\\ \sigma_{\rm inel}(s)\end{array}\right\} = \int d^2b \times \left\{\begin{array}{l}|\Gamma(s, \boldsymbol{b})|^2,\\ 2\,{\rm Re}\Gamma(s, \boldsymbol{b}),\\ [1-|1-\Gamma(s, \boldsymbol{b})|^2].\end{array}\right.$$

Thus $\Gamma(s, b) \leq 1$ L.Landau, E.Lifshitz



The probability distribution $|1-\Gamma(s, \boldsymbol{b})|^2$ for no inelastic interaction, as a function of b, at the LHC energy (W=14TeV)as computed with different parametrizations of the pp elastic scattering amplitude. Solid line: parametrization of Islam et al ("diffractive part" only). Dashed line: exponential parametrization, with Γ(b=0) =1 (BLACK DISK LIMIT) and B=21.8 GeV^{-2}.

Amplitudes of hard processes are increasing with energy more rapidly:

$$\epsilon = 0.2$$

and increasing with virtuality. (DGLAP and FNAL, HERA data on hard processes)

For hard Pomeron α'_P should be small. Thus essential

$$b^2 \approx B_o$$

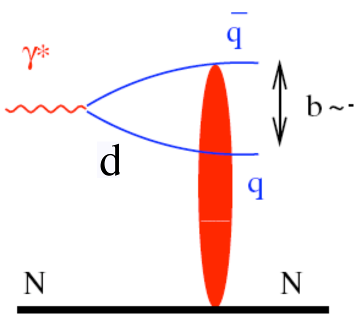
Thus hard processes are concentrated at central impact parameters.

Impact parameter distribution of hard processes follows from two -gluon form factor measured in hard diffractive processes.

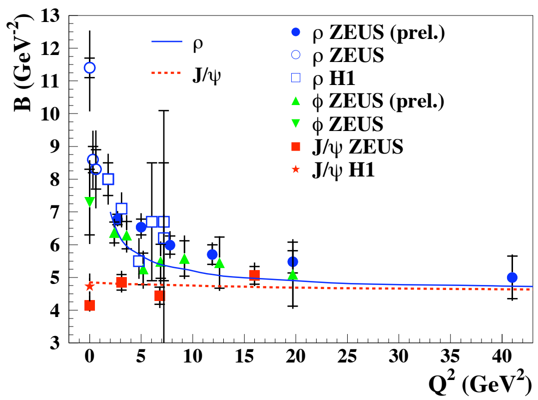
In LT in pQCD t-distribution of exclusive VM production measures transverse distribution of gluons given by the Fourier transform of the two gluon form factor $F_g(x,t)$

$$d\sigma/dt \propto F^2_g(x,t)$$

Onset of universal regime FKS[L.Frankfurt,W.Koepf, M.Strikman] 97.



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



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

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

Fourier transform of two gluon form factor gives impact parameter dependence of hard processes,(new particles production .

FNAL,HERA data on hard diffractive processes can be described as

$$F_g(t) = 1/(1 - t/\mu_g^2)^2$$

$\mu_g^2(x = 10^{-2}) \approx 1GeV^2$ $\mu_g^2(x = 10^{-4}) \approx 0.7GeV^2$

At sufficiently large energies $\mu_g = 2m_\pi$

Gluon distribution depends on energy as

$$xG(s, Q^2) \propto (x_o/x)^{\lambda(Q^2)}$$

$\lambda(Q^2 = 10GeV^2) = 0.2$ and increasing with Q

So

$$\Gamma(b, x) = (x_o/x)^{\lambda(Q^2)} \mu_g b K_1(\mu_g b)$$

Challenges

1. $\Gamma(b,x)$ is rapidly increasing with energy but it can not exceed 1 -maximal absorption .

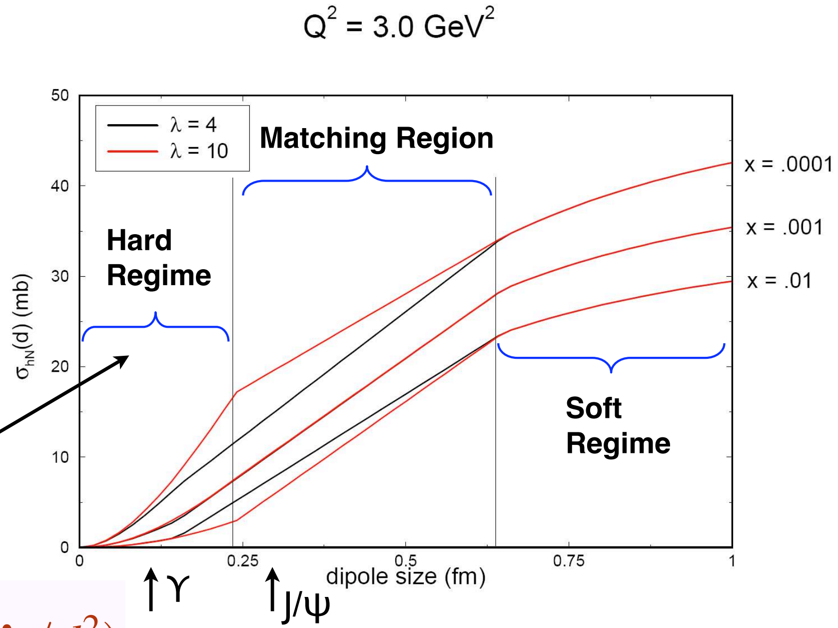
2. The condition that absorption can not exceed 100% allows to quantitatify kinematical boundaries of applicability of methods of pQCD to hard high energy processes and some general properties of novel QCD regime.

3. Specific properties of high energy processes coexistence of different QCD phases for peripheral and central pp collisions - different representations of continious symmetries.

4. QCD environment for new particles production at LHC - electroweak and QCD physics in the overlapping kinematical domains.

New high energy QCD regime: regime of complete absorption for small α_s:
limit - fixed Q & large energies -black disk regime (BDR)

Evidence for proximity to BDL at HERA



studies of the "quark-antiquark dipole"(transverse size d) - nucleon cross section based pQCD and HERA data

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

Frankfurt et al 2000-2001

Baym et al 93

Provided a reasonable prediction for σ_L

F^2 Casimir operator of color SU(3)

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

Analyze strength of interaction of small color dipoles with nucleons:

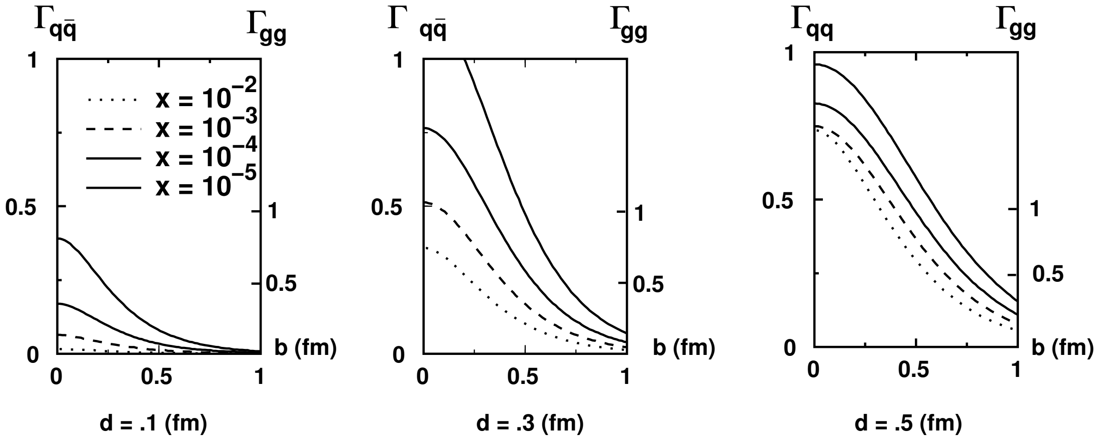
Combine study of dipole nucleon cross section (description of F_{2p} and analysis of exclusive hard processes (t-dependence of the dipole - nucleon scattering)

determine impact factors for elastic $q\bar{q} - N\, scattering$

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

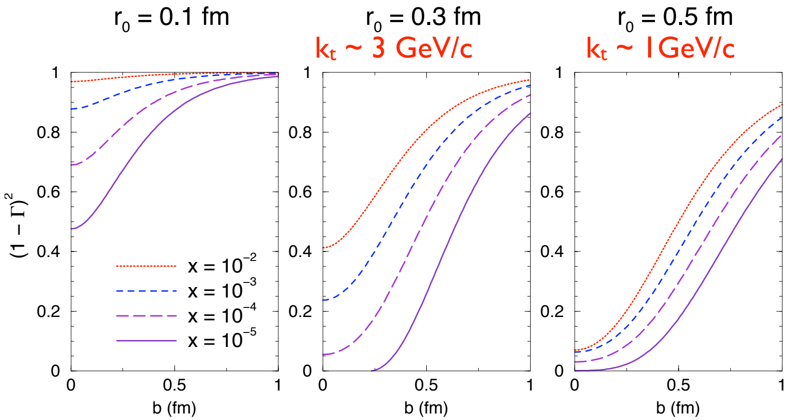
$\Gamma = 1$ *corresponds to regime of complete absorption - BDR*

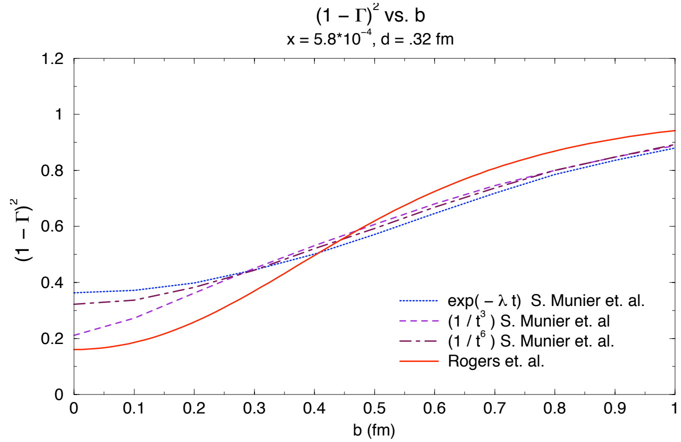
T.Rogers et al



In the case gg-N scattering we assume pQCD relation

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





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

⇒ Large probability of diffraction in gluon channel

↓

for $Q^2 \sim 4$ GeV^2, $x \sim 10^{-3}$ gg - Pb interaction at b=0 is deep in BDL
$q\bar{q}$ - Pb interaction in BDR

for these x nuclear gluon shadowing effect is rather small

↓

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

Test ↓

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

⇒ Natural explanation of the BRAHMS result at RHIC, the only one consistent with the STAR data on correlations

↓

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

⇒ In high energy pp collisions at small b no partons with p_t < few GeV can survive

General properties of QCD black regime

1.Complete disappearance of Bjorken scaling

$$xD_i(x,Q^2) = c_i Q^2 \ln^2(x_0/x)$$

2. Certain universalities in the hadron collisions:

$\Gamma(b,s) = 1$ for $b \leq b_F = (1/\mu_g)\lambda(Q^2)\ln(s/s_o)$

b_F and therefore total cross sections are the same for any hadron collisions for sufficiently large energies (L.Frankfurt.M.Strikman ,M.Zhalov

$\Gamma(b,s) = e^{\mu_g(b_F - b)}$ $for\ b_P \geq b \geq b_F$

$\Gamma = ce^{-b^2/2B}$ for $b \geq b_P$ where

$$e^{\mu_g(b_F - b_P)} = c(s/s_o)^{\alpha_P - 1} e^{-b^2/2B}$$

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.

To visualize challenges let us consider theoretical example.For small y function F is defined as

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

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.

Increase with energy of parton transverse momenta in the fragmentation region.

B.Blok,L.Frankfurt, M.Strikman

We investigated numerically within LO DGLAP with k_t factorization the dependence on energy of leading parton transverse momenta in the total cross section for the scattering of dipole off a hadron target. We found that transverse momentum of leading parton is increasing with energy as small power of energy

$$k_t^2 \propto s^{0.1}$$

Power is not universal-somewhat different for longitudinal and transverse photons.

This is novel effect. It differs from increase with energy in the center of rapidity obtained within BFKL approximation for the transverse momenta of partons if energy-momentum conservation is ignored.

In the black limit increase of transverse momenta with collision energy is even more rapid

Two phases structure of hadronic states in pp collisions

1. The generalization to pp scattering is trivial. Thus we demonstrated that soft QCD disappears for the scattering at central impact parameters at sufficiently large energies.

2. Another practical conclusion: at central pp collisions hard regime dominates. In the hard regime chiral symmetry is not spontaneously broken.

3. In the peripherical collisons hard physics is a correction, Pomeron exchange dominates.

Thus we come to conclusion that kinetics of pp collisions is dominated by two phases of QCD having different continious symmetry.

QCD environment for new particles production.

Common assumption is that hard and soft QCD interactions are unrelated and initial and fsi are cancelled in the cross section of heavy particles production integrated over its transverse momenta. If so this cross is given in the kinematics of LHC ($x \approx 10^{-2}$) by usual convolution formulae. The foundations of convolution formulae are more shaky as compared to QCD factorization theorem for DIS.

Hard small x processes and heavy particles production occur mostly in the central pp collisions. So background for new particles production depends strongly on collision energy and on impact parameter. It is dominated by the strong QCD interaction with small coupling constant . Thus in one kinematical domain two different phenomena. Practical problem is in the ambiguity in the prescription how to distribute hadrons with "small" transverse momenta between jets.

Preselection and suppression of spectrum of leading partons.

In the hard small x process: $p+A\rightarrow a+X$ where parton "a" carries finite fraction of proton momentum in the vicinity of BBL following new hard phenomena are important: i) hard interaction leads to absorption of leading partons "a" with transverse momenta $\le p_t(BBL)$ ii) at larger transverse momenta energy of parton "a" is preselected by the choice of final state X which dictates essential impact parameter "b". The energy of projectile proton is shared between A(eff, b) partons. Here A(eff, b) is the number of nucleons in target nucleus located at impact parameter "b". Thus the ratio of fraction of proton momentum carried by particle "a" for the scattering off nuclear and nucleon target is 1/A(eff,b). So this process is dominated by peripheral collisions and the fraction of proton momentum carried by parton "a" somewhat decreases with atomic number. In the process $d+A\rightarrow \pi+X$ this effect was probably observed at RHIC.

Conclusions

i. Bjorken scaling should disappear in hard processes at small "x" where the number of radiated gluons is 1-2 - no serious need to sum powers of ln (x_0/x).

ii. Regime of new strong interaction with small coupling constant arises in the central pp,pA and AA collisions at achievable energies

iii.Background for new particles production at LHC is the interplay of two phases of chiral symmetry . It depends strongly on collision energy and on impact parameter.

iv. Novel QCD phenomena like: fractional energy losses for leading partons , strong dependence of interaction on impact parameter, existence of maximal interaction at small impact parameters , two chiral phases are the signals for new QCD regime.