
On the field of color fluctuations=coherent phenomena in high energy hadron(photon) - nucleus collisions
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The aim of my talk is to explain basic theoretical ideas and related phenomena relevant for the diffractive processes in the collisions of sufficiently energetic composite particles .

$$h(photon) + T \to X + T$$

Convenient for a theoretical description is the target rest frame where directions of particles momenta of the system X and of the target fragmentation are different. On the contrary in the IMF only one direction so difficult to visualize diffractive processes.

Coherence of high energy processes:

$$h(\gamma) + T \to X$$

Wave function of a projectile in the target rest frame is prepared long before hitting a target and interacts with all matter of the target at given impact parameter at the same time. Quantum mechanical picture of consequent collisions -Glauber description of scattering process of projectile is invalid in the kinematics where inelastic processes dominate in the cross section.

This has been understood by several generations of scientists who developed framework for the calculation of diffractive processes and experimentalists who observed variety of new striking phenomena.

Coherence of high energy processes follows from 3 well understood fundamental properties of QCD.

1. As the consequence of uncertainty principle and Lorentz slowing down of interaction high energy projectile stays in a frozen configuration of constituents at the distances: $L_{coh} = c\Delta t$

$$L_{con} \approx 1/\Delta E \approx 2E/(m^2_{int} - m^2_h)$$

At LHC for $(m^2_{int} - m^2_h) = 1 GeV^2$ $L_{coh} \sim 10^7$ fm>> $2R_A$>> $2r_N$

For DIS $L = 1/2m_N x$

L has been derived for DIS using structure function of a nucleon evaluated within the parton model or by analyzing DIS data (Ioffe 1970}

Large L explored in the theoretical analysis of elastic photoproduction of vector mesons off nuclei. (Yennie,Bauer.....1970)

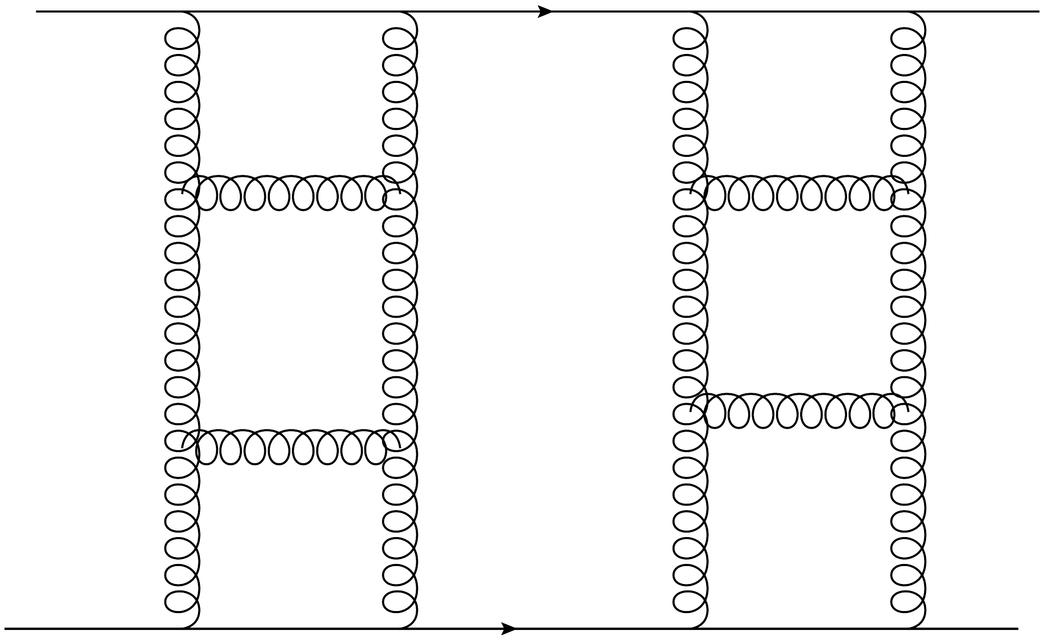
Implications of large L.

- The contribution of planar diagrams relevant for the formulae of semiclassical approximation within the quantum mechanics is cancelled out completely. PreQCD prove explores the feasibility to move contour of integration in the complex energy plane and analytic properties of amplitude in the energy plane=causality. S.Mandelstam1963,V.Gribov1972

Complimentary reasoning. In the kinematical domain where cross section of hN scattering is dominated by inelastic processes planar eikonal diagrams violate energy-momentum conservation in the case of nuclear shadowing or saturation. A projectile hadron with energy E produces n inelastic processes with the same energy and total energy is n E.

Blok and Frankfurt 2006

Illustration-planar diagram.



$$E_{intermediate} = 2E_{projectile}$$

This result demonstrates the inapplicability of quantum mechanical description of the scattering process , of the eikonal approximation, of the Glauber description of shadowing phenomenon at the energies when inelastic processes dominate in the total cross section . The contribution of consequent rescatterings of projectile -Glauber approximation is completely cancelled out in the regime when inelastic processes dominated in the cross section.

Non planar diagrams give non zero contribution. The contribution of non planar diagrams have no discussed above drawbacks. Use of duality between s and t channels allows to rewrite the contribution of non planar diagrams in the form which includes Gribov inelastic shadowing in addition to the more familiar Glauber shadowing. Thus correct formulae are somewhat different from that in the quantum mechanics but the interpretation is completely different. Formulae for the nuclear shadowing without inelastic shadowing are selfcontradictive and incorrect at high energies.

2. Fluctuations of overall strengths of high energy interaction

IMF=parton model produces:

$$\sigma_{\gamma^* T}(x,Q^2) = c(x)/Q^2$$

Question: what phenomenon is relevant for for such a behaviour in the target rest frame? CONSPIRACY between hard and soft QCD. Bjorken

γ^* transforms into quark-antiquark pair long before the target. Configurations where quarks have large transverse momenta interact as in IMF.

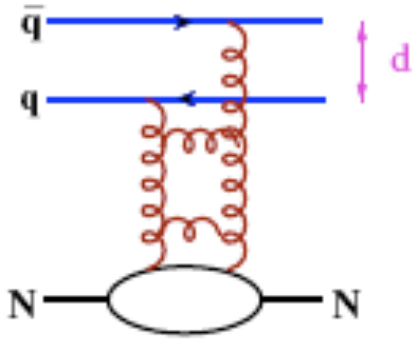
Quarks with small transverse momenta interact as hadrons. But probability of such configurations is small $\approx 1/Q^2$

Thus fluctuations of strengths of interaction is organic property of QCD.

In pQCD strength of interaction of white small system is proportional to the area occupied by color (holds qualitatively in the soft regime as well)

QCD factorization theorem for the interaction of small size color singlet wave package of quarks and gluons.

For quark - antiquark dipole:



$$\sigma(d,x) = \frac{\pi^2}{3}\alpha_s(Q^2_{eff})d^2\left[xG_N(x,Q^2_{eff}) + \frac{2}{3}xS_N(x,Q^2_{eff})\right]$$
$$Q^2_{eff} = \lambda/d^2, \lambda = 4 \div 10$$

Baym, Blättel, Frankfurt, ; Strikman,Miller, 93

compare: $\sigma(d, x) = cd^2$ in QED or two gluon exchange model of Low - Nussinov (1975)

In the soft QCD additional fluctuations of strengths: parton densities in the central and peripheral collisions differ etc.

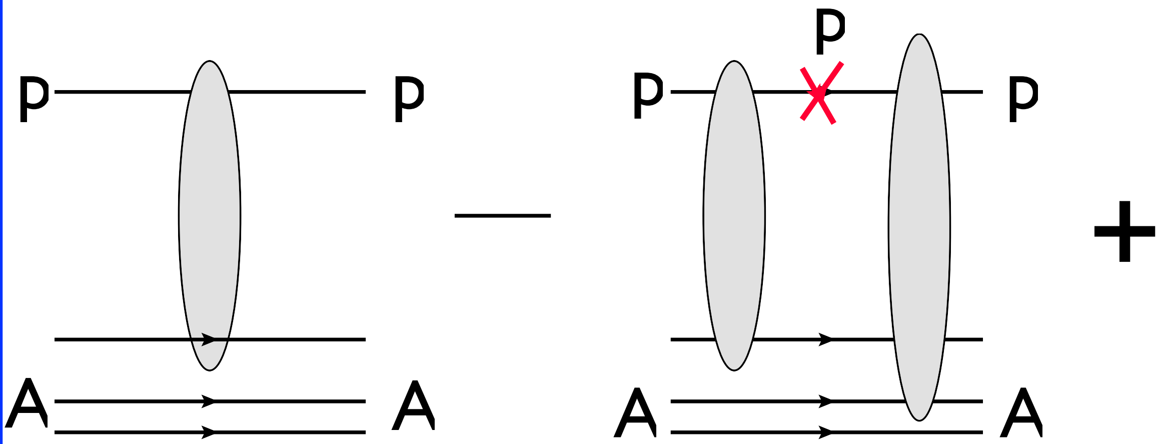
Coherent phenomena follow from the necessity to account for the coherence of interactions of produced diffractive states. Time formation phenomena are a particular case of coherent phenomena. So third condition is the necessity to guarantee legitimacy of exploring closure over diffractively produced states in the calculation of coherent phenomena . This condition is applicable for the forward scattering only. Will be explained later.

First conclusions which follow from the general properties of QCD:

Constituents of projectile are frozen during of collisions.

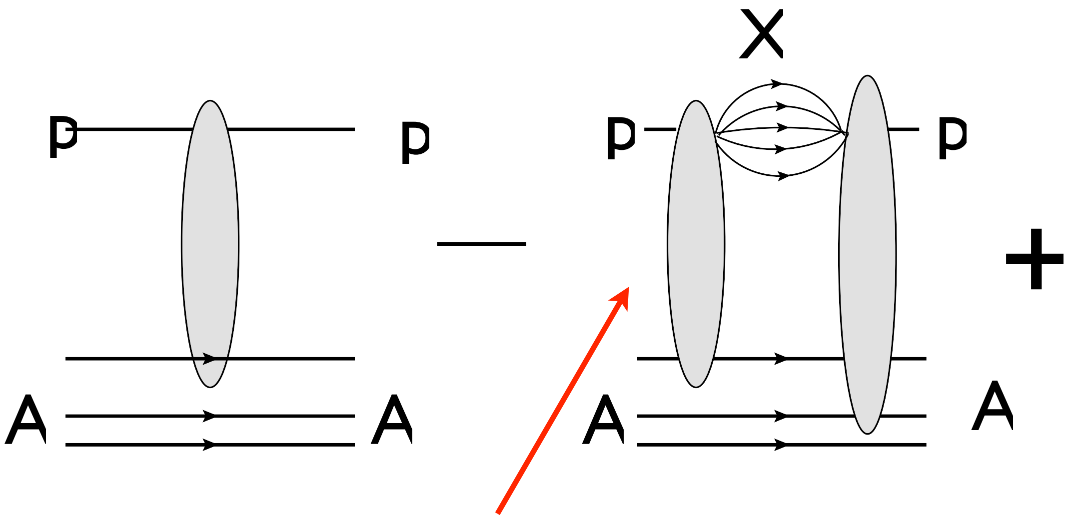
Fluctuations of strengths of interaction is the property of gauge theory QCD and QED (atomic collisions).

Account of large l_{coh} ➟ p A scattering is described by different set of diagrams:



Glauber model

in rescattering diagrams proton propagates in intermediate state - zero at high energy - cancelation of planar diagrams (Mandelstam & Gribov)- no time for a proton to come back between interactions.



High energies = Gribov -Glauber model

X= set of frozen intermediate states the same as in pN diffraction

deviations from Glauber are small for E_{inc} < 10 GeV as inelastic diffraction is still small.

$$\sigma_2 \propto \int dt F_A^2(t) \frac{d\sigma(p+p \to p + X(p+ \; inel \; diff))}{dt}$$

practically model independent for scattering off two nucleons (ν=2)

Extend to arbitrary number of interactions ν: introduce quantity - $P(\sigma)$ -probability that a hadron/photon interacts with cross section σ with the target.

$\int P(\sigma) d\sigma = 1$, $\int \sigma P(\sigma) d\sigma = \sigma_{tot}$,

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

variance Pumplin &Miettinen

$\int (\sigma - \sigma_{tot})^3 P(\sigma) d\sigma = 0$, Baym et al from pD diffraction

$$P(\sigma)_{|\sigma\to 0} \propto \sigma^{n_q - 2}$$

Baym et al 1993 - QCD counting rules probability for all constituents to be in a small transverse area

+ additional consideration that *for a many body system fluctuations near average value should be Gaussian*

$$P_N(\sigma_{tot}) = r\frac{\sigma_{tot}}{\sigma_{tot} + \sigma_0} exp\{-\frac{(\sigma_{tot}/\sigma_0 - 1)^2}{\Omega^2}\}$$

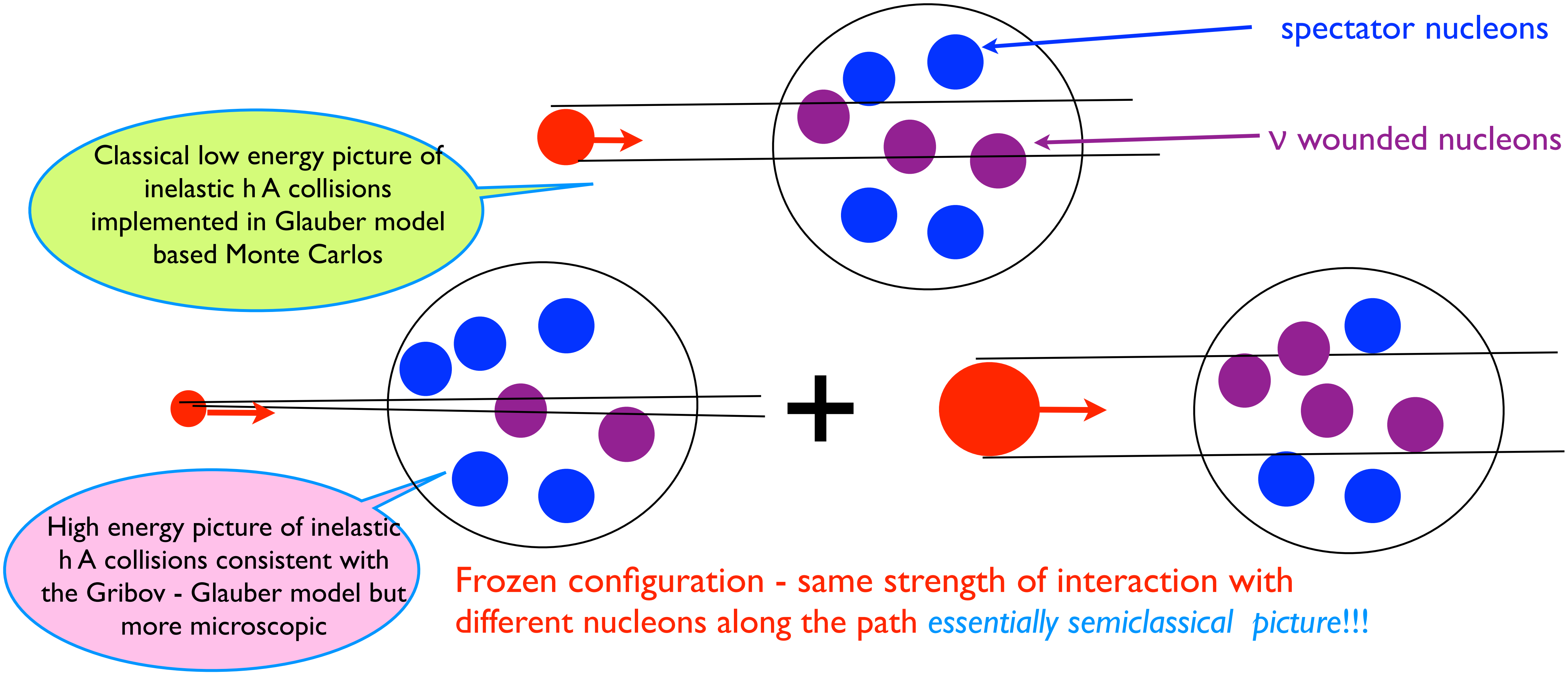
$$P_\gamma(\sigma)_{|\sigma\to 0} \propto \sigma^{-1}$$

γ =mix of small $q\bar{q}$ and mesonic configurations

Practical test: calculation of coherent diffraction off nuclei: $\pi A \to XA$, $p A \to XA$ through $P_h(\sigma)$ -works

$P_N(\sigma)$ provides constructive way to account for coherence of the high-energy dynamics

Fluctuations of interaction cross section formalism: *Color fluctuation model*

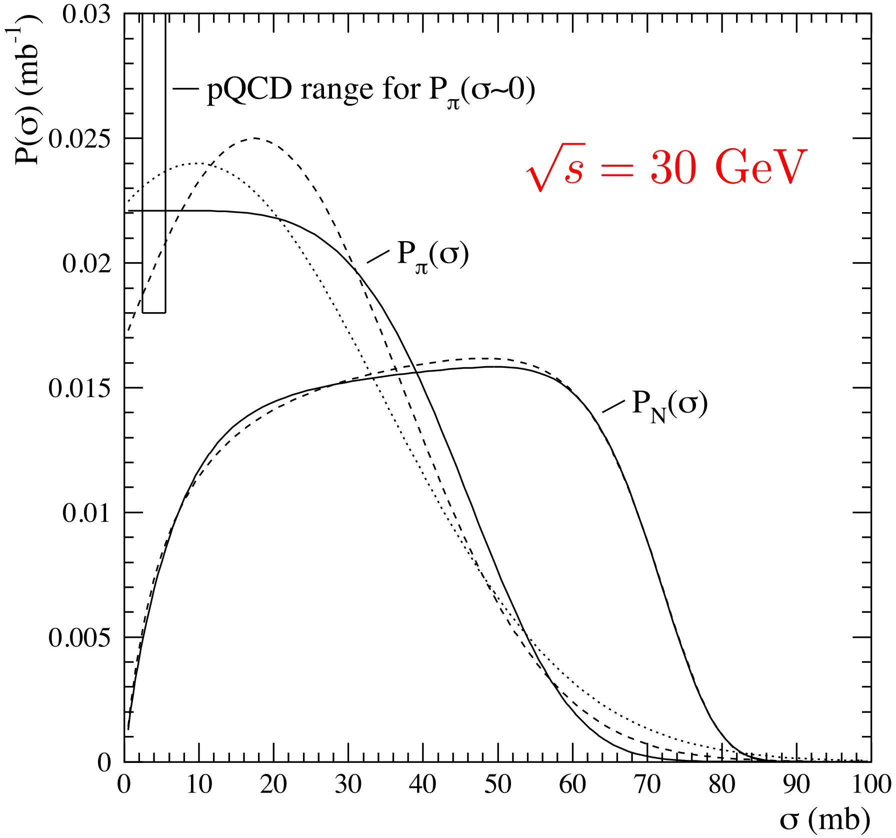


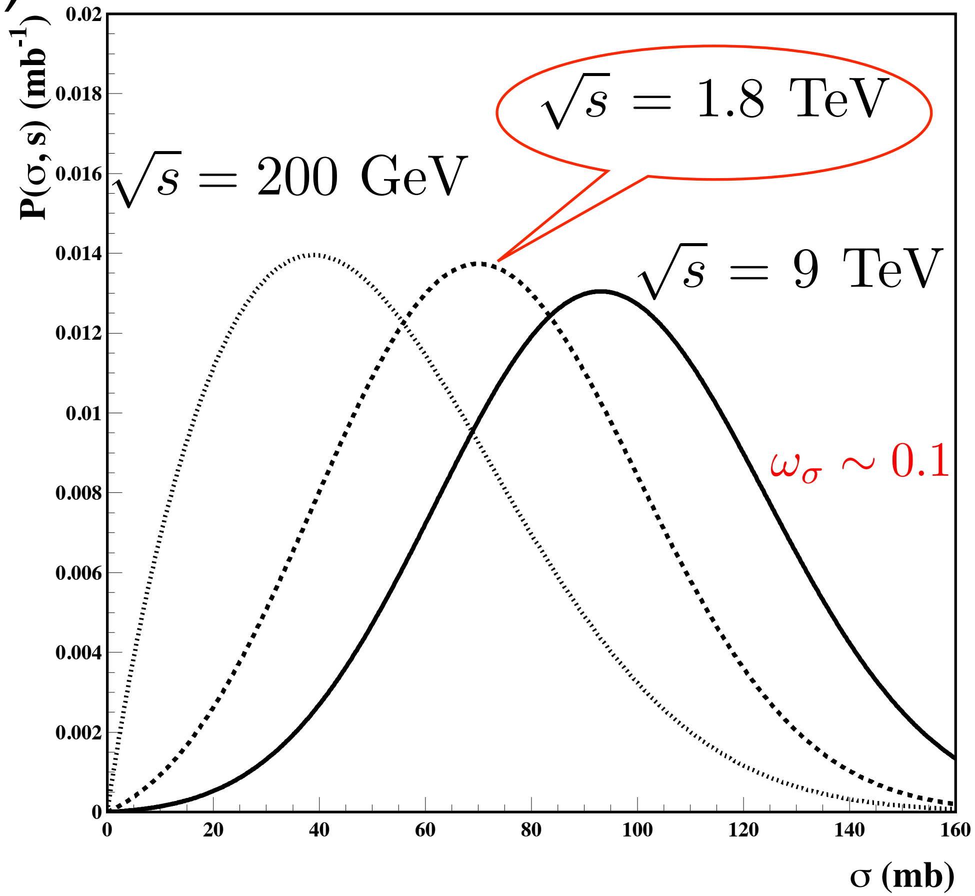
Frozen configuration - same strength of interaction with different nucleons along the path *essentially semiclassical picture*!!!

$$\sigma_\nu = \int d\sigma P_h(\sigma) \cdot \frac{A!}{(A-\nu)!\,\nu!} \cdot \int d\boldsymbol{b}\,(\sigma T(b)/A)^\nu\,[1-\sigma T(b)/A]^{A-\nu}$$

simplified expression (optical limit)

$P_N(\sigma)$





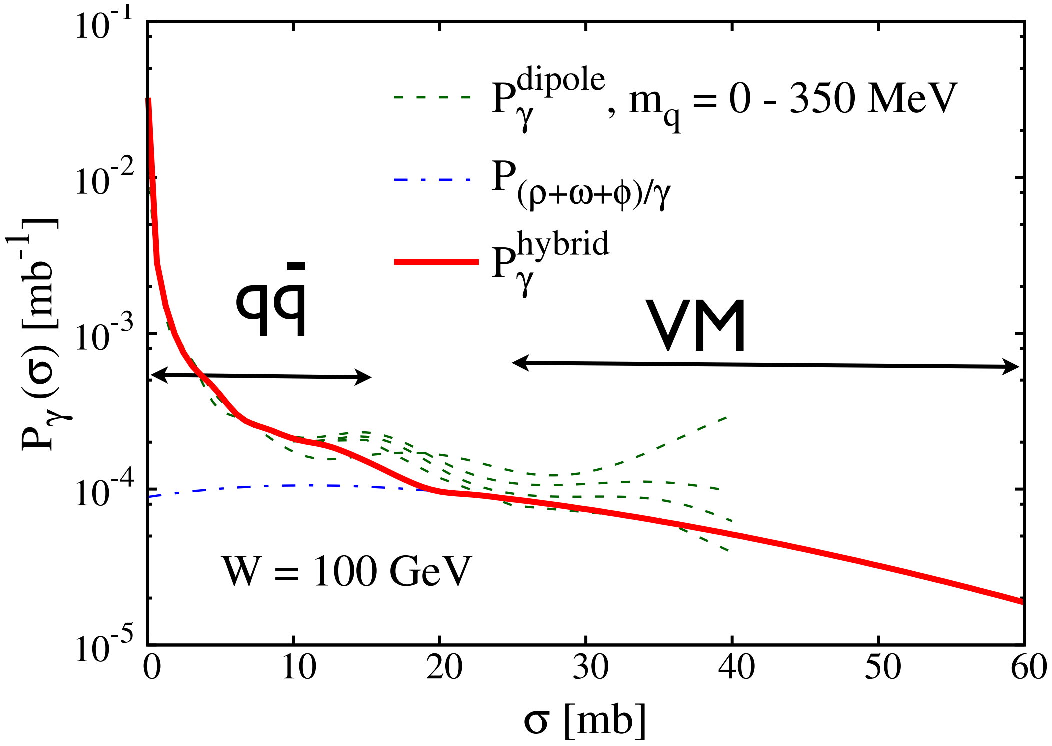
$P_N(\sigma)$ nearly flat in wide range of σ.
Elongated configurations?

Extrapolation of Guzey & MS before the LHC data; consistent with LHC data which are still not too accurate

Color fluctuations in photon - nucleus collisions

Photon is a multiscale state:

$P_\gamma(\sigma) \propto 1/\sigma$ for $\sigma \ll \sigma(\pi N)$ $P_\gamma(\sigma) \propto P_\pi(\sigma)$ for $\sigma > \sigma(\pi N)$



Inelastic diffraction in DIS

The analysis of impact factor of transversely polarized photon shows that distribution of quark-antiquark pair over transverse size is rather wide in transverse plane . Significant fluctuations of strengths of interaction are needed to keep agreement with the parton model. (Bjorken) . It follows from the formulae for dispersion discussed above that QCD predicts significant cross section of diffraction. (Frankfurt,Strikman) In the case of longitudinally polarized virtual photon the ratio of diffraction to the total cross section should be significantly smaller.

Significant cross section of diffraction in DIS has been discovered at HERA.This is rather direct experimental confirmation of the concept of color fluctuations.

Exclusive processes of vector meson production off nuclei at LHC in ultraperipheral collisions allow to test theoretical expectations for small and large σ

(a) ρ-meson production: $\gamma + A \to \rho + A$

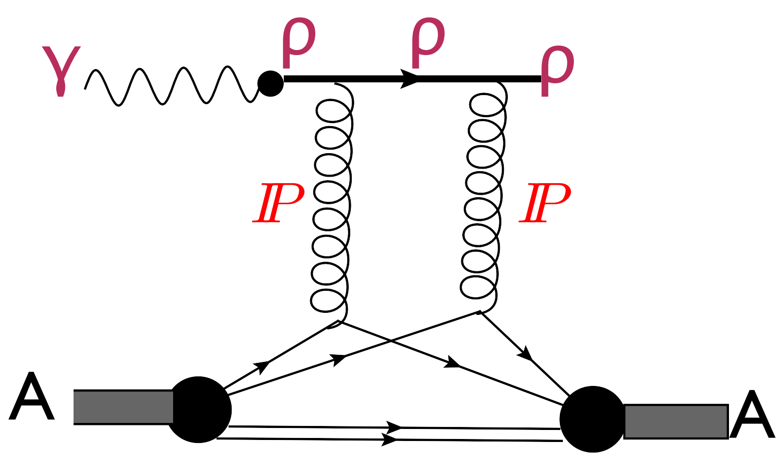
Expectations:

- *vector dominance model for scattering off proton* $\sigma(\rho N) < \sigma(\pi N)$

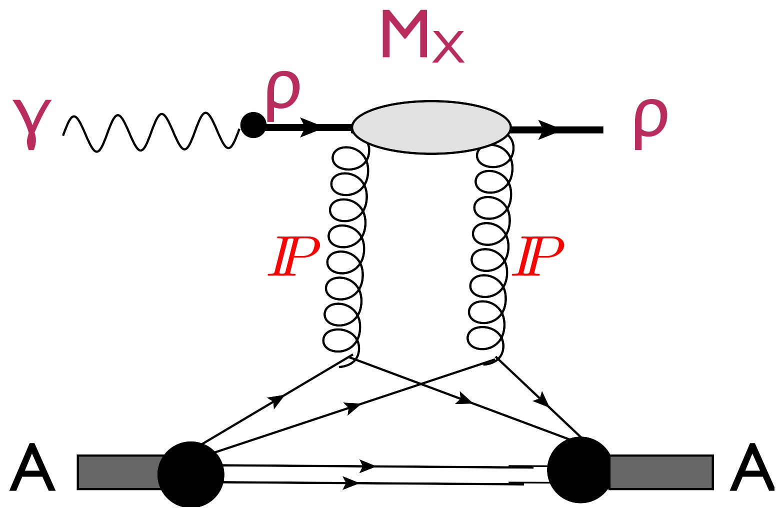
  since overlapping integral between γ and ρ is suppressed as compared to $\rho \to \rho$ case

observed at HERA but ignored before our analysis: $\sigma(\rho N)/\sigma(\pi N) \approx 0.85$

Analysis of Guzey, Frankfurt, MS, Zhalov 2015 (1506.07150)



Glauber double scattering



Gribov inelastic shadowing

❖ Gribov type inelastic shadowing is enhanced in discussed process - fluctuations grow with decrease of projectile - nucleon cross section. We estimate $\omega_{\gamma\to\rho}\sim 0.5$ and model $P_{\gamma\to\rho}(\sigma)$

Next we use $P_{\gamma\to\rho}(\sigma)$ to calculate coherent ρ production. Several effects contribute to suppression a) large fluctuations, b) enhancement of inelastic shadowing is larger for smaller σ_{tot}. for the same ω, c) effect for coherent cross section is square of that for σ_{tot}.

Variety of color coherent phenomena has been observed

Observation of diffraction in DIS confirmed concept of color fluctuations.

Color transparency phenomena were observed at FNAL, TJNAF. Confirmed QCD factorization theorem

Diffractive electroproduction of vector mesons observed at HERA. Confirmed QCD factorization theorem, CFs

Fluctuations of cross section observed at ATLAS are in line with CFs

Violation of coherence for non forward diffractive processes.

Disintegration of deuteron at moderate energies

$$\sum_{pn} \frac{d\sigma(h+d \to h+p+n)/dt_{t=0}}{d\sigma(h+d \to h+d)/dt_{t=0}} = [1 - F_d^2(t)]_{t=0} = 0$$

Calculations were made in the impulse approximation since radius of deuteron is small.

For the forward scattering 0 -no fluctuations of color.For non zero t -inapplicability of logic.

Violation of coherence in the hard processes

For a hard probe "a" usual relation for hard processes:

$$\sum_Z d\sigma(a+T \to Y+Z)/dt/d\sigma(a+T \to Y+T)/dt(t=0) =$$
$$g^2(x_1,x_2) > / < g(x_1,x_2) >^2 -1$$

Abramowitz, LF, MS 1995

Weiss, Treleani, LF, MS 2008

Here

$$< a|g(x_1,x_2)|n >$$

is non diagonal GPD

For large t and keeping leading term in t:

$$\sum_Z d\sigma(a + T \to VM + gap + Z)/dt = c[F^2(8)xG(x_1, x_2) + F^2(3)xS_N(x_1, x_2))]$$

proportional to the parton density-violation of coherence.

Conclusions

Coherence phenomenon is understood theoretically including kinematical region of applicability.

Variety of coherent phenomena were observed .

Time is coming to use coherent phenomena for the analysis of more complicated phenomena.