CT as the QCD factorization theorems vs Feynman mechanism

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Disappearance of the final state interaction for the spatially small wave package of quarks and gluons traversing nuclear medium is the property of gauge theories: QED and QCD.This phenomenon is absent within the non-relativistic nuclear theory, within the EFT, within the preQCD field theories of meson-nucleon interactions. It is. relevant for the disappearance in QCD of the nullification of hadron-hadron interaction characteristic for the preQCD field theories. CT has been observed in the several experiments.

We formulate CT in the form of the QCD factorization theorems to visualize that CT for the special group of the hard processes is legitimately calculable in QCD. CT can be transformed into the method of investigation of another group of hard processes dominated by the competition between mean field and quark- gluon src within a hadron wf.

CT is the combination of several well understood phenomena:

1. Wf of a hadron contains pQCD core.

Exact valence quark and momentum sum rules present the evidence that within QCD a hadron contains significant pQCD core:

$$\int dx[V_A^m(x,Q^2,t)] = F_A^V(t)$$

$$\int xdx[S_A(x,Q^2,t) + G_A(x,Q^2,t) + V_A(x,Q^2,t)] = T_A(t)$$

Here $(F_A)^V(t)$ is the isotopic (SU(3)) vector form factor of a nucleon calculable in terms of the combination of e.m. form factors of a proton and neutron.

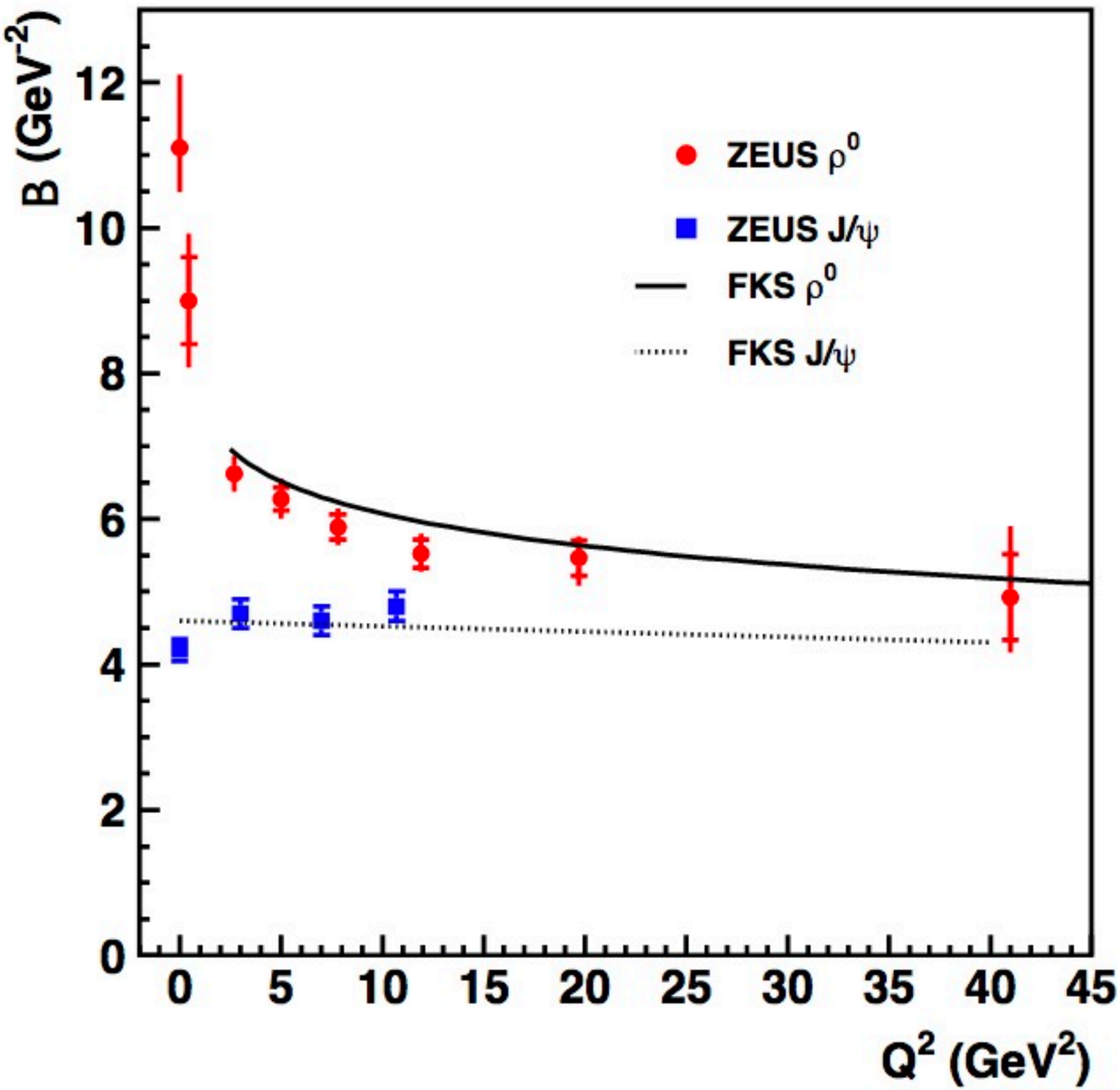
$$< r_V^2 >^{1/2} = 0.65 Fm$$

Valence quark sum rules being valid at any Q proves the duality between hadron and quark-gluon degrees of freedom. So at small Q the radius of the region occupied by pQCD physics within a hadron is smaller ~0.5 Fm. Follows from the upgrade of the method of the dispersion sum rules.

2. Feasibility to select the spatially small configuration of constituents (plc) in the produced hadron.

- Two body processes initiated by the longitudinally polarized photon are calculable in a model independent way within the frame of the QCD factorization theorem. formulated for the processes: investigated at HERA gamma^*+A\to M+A where M=gamma, rho, J/\psi, and in the investigated at FNAL process: pion+A\to 2jet +A ..... The dependence on energy and momentum transfer, on atomic number agrees with the prediction based on the factorization theorem.

For the two body processes initiated by the transversely polarized virtual photon the contribution of plc competes with the contribution of the configurations of constituents more close to the average size configurations.

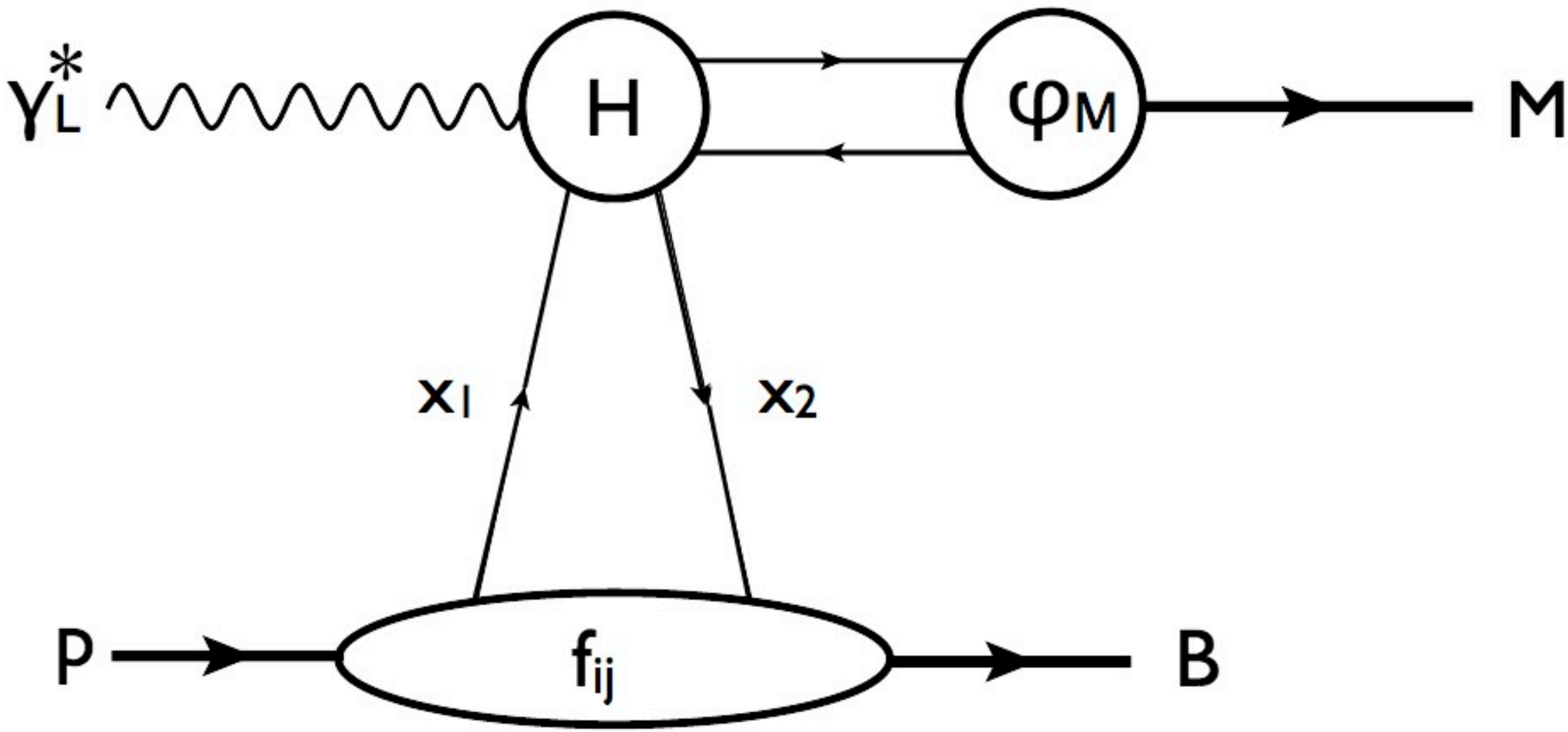


B (GeV^{-2})
12
10
8
6
4
2
0
0
5
10
15
20
25
30
35
40
45
Q^2 (GeV^2)
ZEUS ρ^0
ZEUS J/ψ
FKS ρ^0
FKS J/ψ

The starting point for the analysis is the factorization theorem for the process

γ_L^* (q) + p → "Meson"(q + Δ) + "Baryon"(p − Δ) at large Q^2, with t and x = $Q^2/(2p \cdot q)$ fixed.

It asserts (CFS) that the amplitude



Formation =coherence length-L.

Produced wave package is not the eigen state of QCD Hamiltonian. So it collapses into hadron state. However for the rapid wave package Lorentz dilation of time leads to the increase of its life time. Qualitatively the formula for L follows from the uncertainty principle . Quantitative derivation was made in the analysis of DIS:

- $L=E/(M^2-m_N^2)$ close to the Ioffe time.
- Here M is the mass of wave package,or its virtuality
- The necessary condition to be able to observe CT is L>l where l is the distance which wave package should travel without expansion.

The leading twist expression is

dσ(γ^*N→VN/dt_{t=0} =12πΓ(V→e+e)M_{V}α_s^2(Q)η_{V}^2[1+i\pi /2\pi dlnx] xGT(x,Q)/
α(EM) Q^6Nc^2

- Here, $\Gamma_{V \to e^+e^-}$ is the decay width of $V \to e^+e^-$
- is close to the asymptotic value at $Q^2 \sim$ a few GeV^2.

Note here that in this expression, the difference between the light-cone fractions x_1 and x_2 was neglected. For large Q^2, the non-diagonal GPD is calculable [100, 101] through the diagonal one since the DGLAP evolution for GPDs conserves $x = x_1 - x_2$, while the light-cone fractions essential at the starting point of the evolution grow with an increase of Q^2.

Heavy mass of c and b quarks ensures dominance of plc

J/ψ and Υ have significantly smaller radii than the pion in the quarkonium models which describes properties of hadrons containing heavy quarks:
$r_\pi = 0.5\,\mathrm{fm}$, $r_{J/\psi} \approx 0.2\,\mathrm{fm}$, $r_\Upsilon \approx 0.1\,\mathrm{fm}$.

As a consequence of color screening heavy quarkonia relatively weakly interact with hadrons made of light quarks. Thus CT should reveal itself in the photoproduction of heavy quarkonium. Beginning of CT - discovery of narrow J/ψ - November 74 and observation of small cross section for its photoproduction. Within VDM σ_{tot} (J/psi +N)= 1 mb . This number actually underestimates genuine J/ψ-N cross section due to production of J/ψ in a small size configurations ~1/mc FS85 So σ_{tot}(J\psi+N)= 4 mb

Photo(electro)-production of heavy quarkonia.

First prediction and discovery of high energy CT phenomenon

$$\pi + N(A) \to \text{“}2\ high\ p_t\ jets\text{''} + N(A)$$

Mechanism: Pion approaches the target in a frozen small size $q\bar{q}$ configuration and scatters elastically via interaction with $G_{target}(x, Q^2)$.

- First attempt of the theoretical analysis of πN process - Randa 80 - power law dependence of p_t of the jet (wrong power)
- First attempt of the theoretical analysis of πA process - Brodsky et al 81 - exponential suppression of p_t spectra, weak A dependence ($A^{1/3}$)
- pQCD factorization theorem - Frankfurt, Miller, MS 93; elaborated arguments related to factorization 2003.Experiment confirmed a number of the predicted features of the reaction.: A-dependence (CT), p_t and $z=E_{jet}/E_\pi$ -dependence,.

- Presence of small size qq Fock components in light mesons is unambiguously established
- At transverse separations d ≤ 0.3 fm pQCD reasonably describes "small qq - dipole"- nucleon interaction for $10^{-4} < x < 10^{-2}$
- Color transparency is established for the small dipole interaction with nucleons, nuclei (for x $\sim 10^{-2}$)

CT is easier to probe for mesons than for baryons as only two quarks have to come close

High energy color transparency is well established

At high energies weakness of interaction of point-like configurations with nucleons - is routinely used for explanation

First experimental observation of high energy CT for pion interaction (Ashery 2000):p_π=500 GeV/c

π +A →"jet"+"jet" +A. Confirmed predictions of pQCD (Frankfurt ,Miller, MS93) for A-

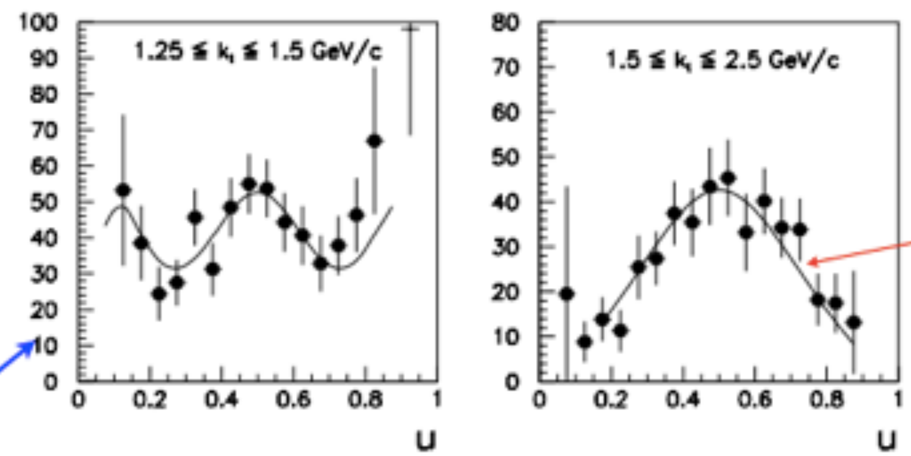
$$A^{4/3}=A^2/R_A^{2/3}$$

A- dependence $A^{4/3}$ (vs Bertch, Brodsky et al $A^{1/3}$)

light cone z distribution $z^2(1-z)^2$

$1/k_t^8$. vs BB ...exp (- a k_t^2)

Thus QCD is different from two gluon exchange model by the factor xG_T, from the mean field approximation by power dependence on kt.



prediction

(π wave funct)^2

Squeezing occurs already before the leading term (1-z)z dominates!!!

$$Q^2(\pi\ f.f.) \sim 4k_t^2(jet)$$
$$\Downarrow$$
strong squeezing in π form facto for Q^2=6 GeV^2

Relativistic bound state, the formation length and the CT.

The fixing special final state allowed us to quarantee the dominance of the single intermediate state in the theoretical description of the special hard processes.This is essence of the QCD factorization theorem. For the large group of the two body processes the intermediate state is dominated by the competition between semi-soft and hard QCD, rapid formation of a hadron in the final state. So onset of CT depends on the interplay of these phenomena, on the formation length, on the role of color in the properties of hadrons. The example of such a process is high Q^2:
e+A-> e'+N+(A-1)

Let us analyze the feasibility to select plc in the interacting nucleon:
1.Non-relativistic theory of bound state. Form factor of two body bound state:

$$F(q^2) = \int d^3k\psi(k)\psi(k+q/2) \approx \int d^3k\psi(k)\psi(q/2)$$

is dominated by the contribution of small distances between constituents.

- For certainty, let us consider two body system where this feature of light- cone mechanics has been first discussed but without Sudakov form factor [Kogut-Suuskind]:

F (q_t^2) = \int $\psi((m^2+k_t^2)/\alpha(1-\alpha))\psi(m^2+(k_t+q_t(1-\alpha))^2/\alpha(1-\alpha)S^2(q_t^2/k_t^2)d\alpha/\alpha(1-\alpha)d^2k_t$

Here $S(Q^2_t/k_t^2)$ is the Sudakov form factor which squeezes the wave function of a nucleon. Thus at $Q^2_t \to \infty$ the two body system is squeezed. At realistic q_t maximal contribution arises from the region where α is close to 1. This is the Feynman mechanism which is mostly mean field approximation -so no strong squeezing. Raduskin observed that at achievable Q Feynman mechanism dominates over hard one. He presented model of pion wave function having no correlations. See also talk of J.Miller.

Sudakov form factor accounts for the fact that we consider the process without radiation.

Probability of gluon radiation off a quark

$$w_q = 2 \cdot C_F \int_{\mu^2}^{Q^2} \frac{dk_\perp^2}{k_\perp^2} \frac{\alpha_s(k_\perp^2)}{2\pi} \int_{k_\perp/Q}^{1} dx \, \frac{1+(1-x)^2}{x}$$

where x is the gluon energy fraction $(\omega = x \cdot Q \geq k_\perp)$

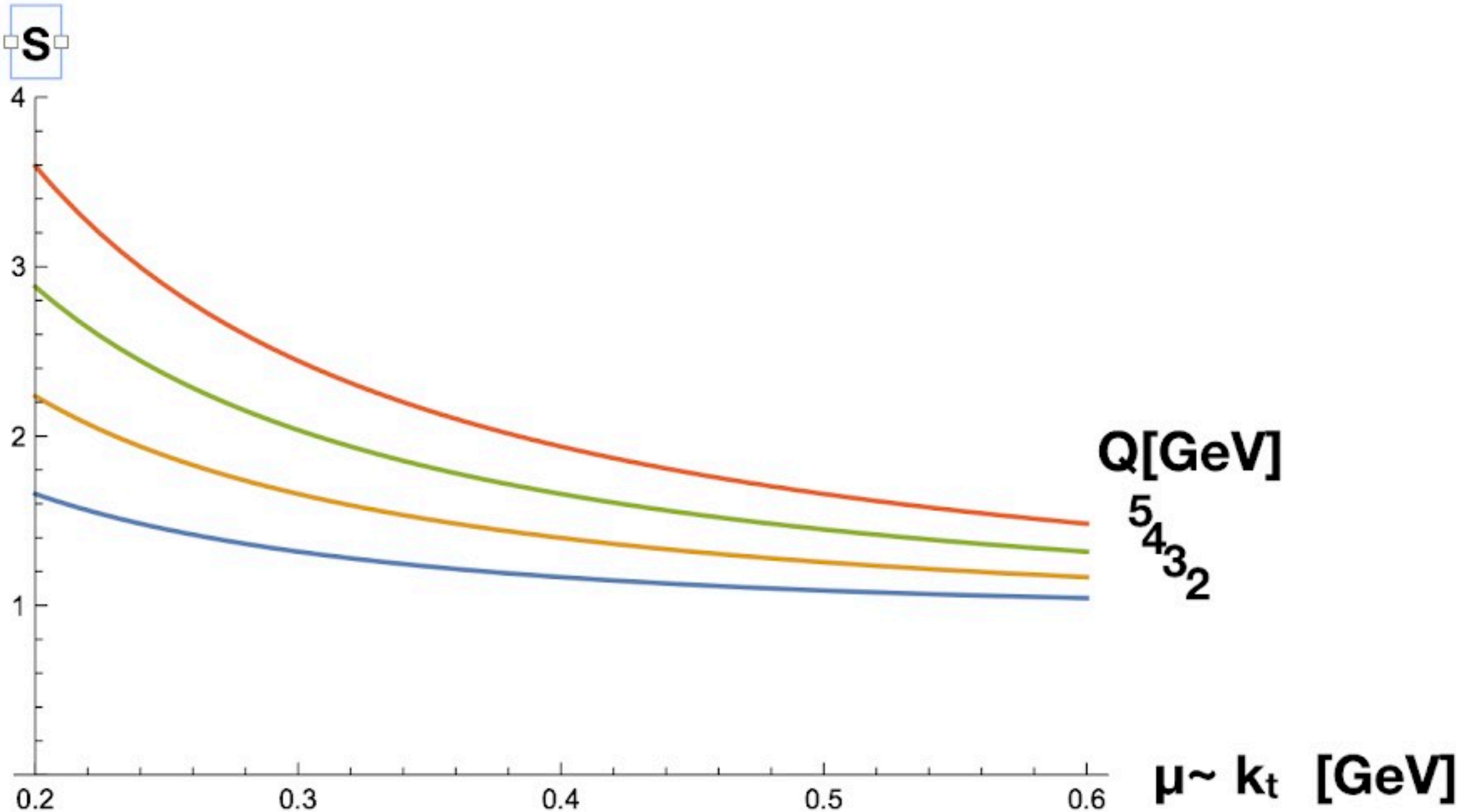
In collinear approximation

$$w_q \simeq 2 \cdot C_F \int_{\mu^2}^{Q^2} \frac{dk_\perp^2}{k_\perp^2} \frac{\alpha_s(k_\perp^2)}{\pi} \left[\ln \frac{Q}{k_\perp} - \frac{3}{4} \right]$$

This expression has to be put into exponent to get the Sudakov form factor squared, that is the probability that the accelerated quark won't emit gluons (either from the initial or final state!):

$$W_0 = S^2(Q^2; \mu^2) = e^{-w_q}.$$

ession factor, S, as a function of Q and resolution scale $\mu \sim k_t$



Formation length

Let us present semiquantitative analysis of e+A → e′ +p+(A−1) process:
$Q^2 = 2q_0m_N$ $L = 2q_0/(M^2 - m^2_N)$ where M is the mass of state corresponding to the Feynman mechanism. To evaluate M for the 3q >system we use usual value for the average transverse momentum of a parton within a nucleon to be $k_t = 0.4GeV$. So M is

$M^2 \approx [q_t^2(1-\alpha)/\alpha + k_t^2/\alpha_i] \approx q_t^2(1-\alpha)/alpha + 4k_t^2/1-\alpha)$ (37) i

In the estimate we ignore running masses of quarks to simplify description. Minimum in α gives $(1 - \alpha)/\alpha = \sqrt{4k_t^2/Q^2}$. Thus produced state should have minimal mass around

$M^2 > 2\sqrt(Q^24k_t^2)$. For $Q^2 = 7GeV^2$ $M^2 \approx 2.1GeV$. Coherent length $L = 7/1.2GeV \approx 1F$ m.
Actual L_c can appear even smaller since we ignored that gluons carry momentum also.Thus produced wave package rapidly returns to the size of a hadron.This is relatively slow transition to the hard regime accompanied by CT phenomenon.

Promizing direction for the search of CT phenomenon is e+d-> p+n as the function of Q. cf. presentation of M.Sargsian
In this process L=1Fm is the natural scale.

Conclusions

- CT is derived within QCD for the special hard processes and observed in the high energy. phenomena

- CT is the tool for the investigation of quark-gluon core of a hadron.

- CT is one of the basic QCD phenomena relevant for the restoration of chiral symmetry with the increase of a nucleon density. (This phenomenon is probably occurs in the inner core of heavy neutron star.)

$$\mathcal{M} = \sum_{i,j} \int_0^1 dz \int dx_1 f_{i/p}(x_1, x_2, t, \mu)\, H_{ij}(x_1/x, Q^2, z, \mu)\, \phi_j(z, \mu)$$
$$+\text{power-suppressed corrections}\,,$$