From Color Transparency to Color Opacity

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FNAL, September 2003

FMS 93, BFGMS 94

Definition of generalized Color Transparency

$$\sigma(\text{dipole} + T \to X) = \frac{\pi^2}{3} d^2 \alpha_s\left(\frac{\lambda}{d^2}\right) \times G_T\left(x, \frac{\lambda}{d^2}\right)$$

d is transverse distance between q and $\bar{q}$.

$Q^2 = \frac{\lambda}{d^2}$; $x = \frac{Q^2}{\nu}$

This formulae is equivalent to DGLAP

$$\frac{\sigma(\text{dipole} + A \to X)}{\sigma(\text{dipole} + N \to X)} \Rightarrow A \quad \text{up to nuclear shadowing}$$

x is fixed, $d^2 \to 0$

This generalized Color Transparency should be valid for any phenomena where small size wave package (SSC) dominates in the wave function of projectile.

Why CT is important.

1. First time cross section of some exclusive processes is calculable in QCD.

2. New method of investigation, of measuring generalized parton distributions

3. Unambigous demonstration that with increase of collision energy new quark-gluon configurations give significant contribution.

4.

For some hard processes dominance of SSC in the projectile wf can be proved in QCD.

1. $\gamma^*_L + T \to V + T$

in the limit of fixed x but $Q^2 \to \infty$

BFGMS 94
CFS 96

2. $h + T \to$ minimal number of jets $+ T$

FMS 93,
FMS 03.

Prove requires accurate account of

i). Ward identities in QCD

ii) Energy-momentum conservation

iii). Rotational invariance in transverse plane.

iv). Properties of trigger for minimal number of jets

Direct observation of generalized Color Transparency

i) $\sigma(\gamma^* + A \to X)$ — SLAC, CERN, FNAL

ii) $\sigma(\gamma + A \to \psi + A)$ — FNAL (1988)

iii) $\sigma(\pi + A \to 2\,jet + A)$ — FNAL (2000)

iv) $\sigma(\gamma^*_L + p \to V + p)$ — H1; ZEUS

$V = \rho^0, \omega, \phi, \psi, \psi', \Upsilon$

(ii) Absolute cross section of ρ production at $Q^2 \sim 20-30\ GeV^2$ and its energy dependence at $Q^2 \sim 20\ GeV^2$. Explanation of the data at lower Q^2 is more sensitive to the higher twist effects, and uncertainties of the low Q^2 gluon densities.

(iii) Convergence of the t slopes

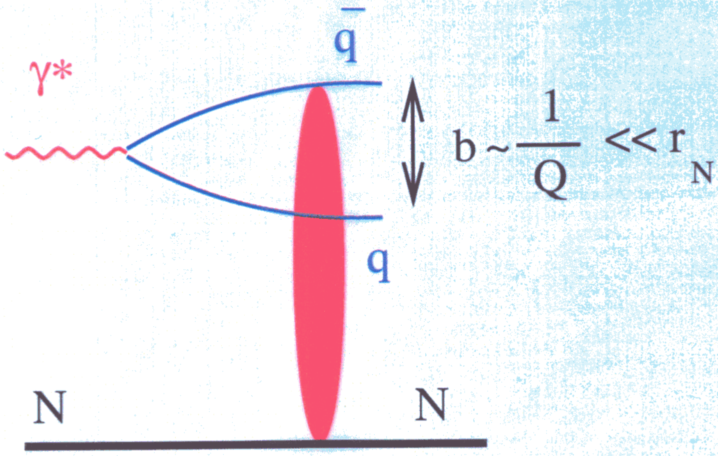
B (σ= Aexp(Bt)) of

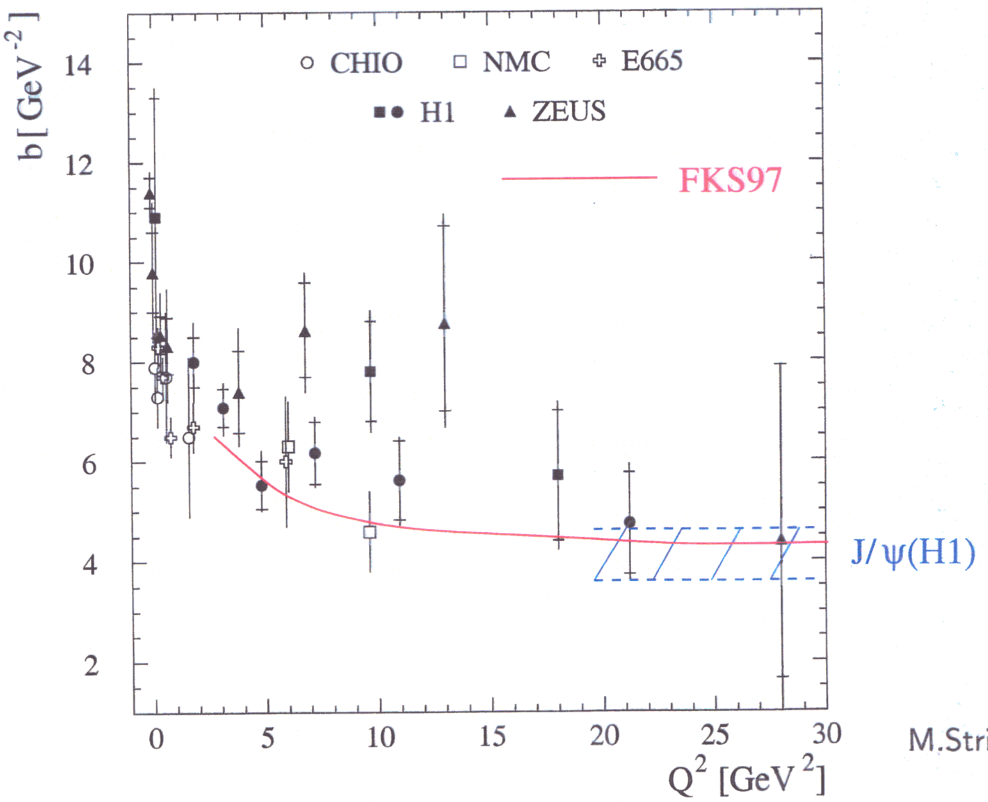
ρ– meson production

at large Q^2 and

J/ψ production

(Brodsky et al 94)





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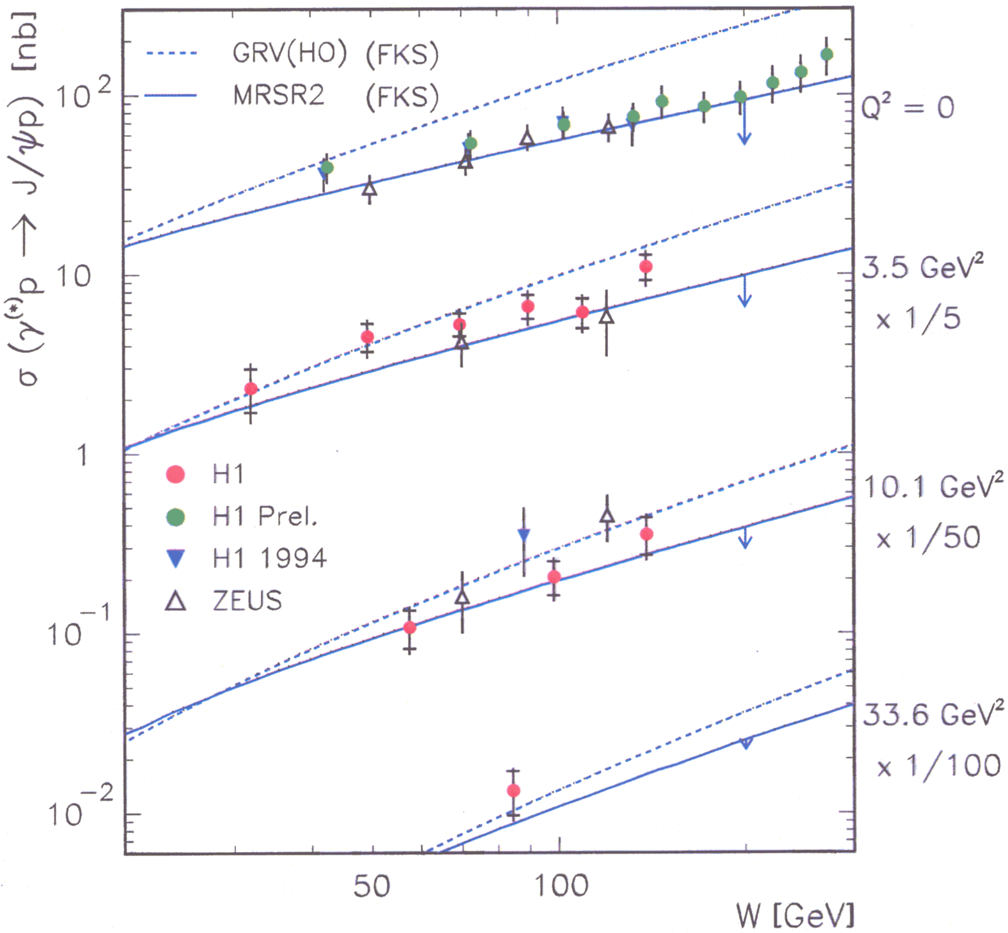
Extensive data on VM production from HERA support *dominance of the pQCD dynamics.* Numerical calculations including finite b effects in $\psi_V(b)$ explain key elements of high Q^2 data. The most important ones are:

(i) Energy dependence of J/ψ production; absolute cross section of $J/\psi, \Upsilon$ production.



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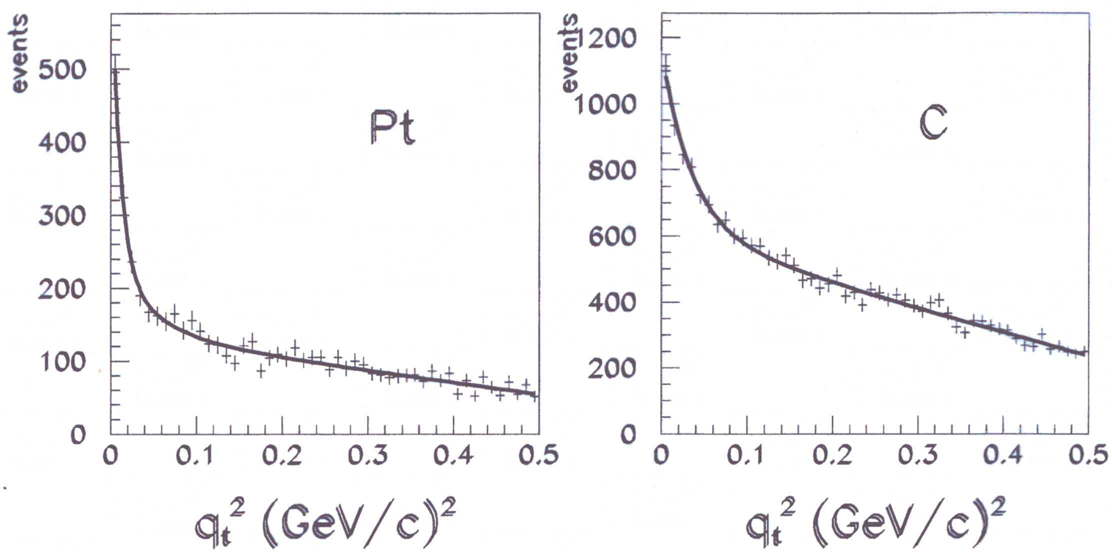
8.

The E-791 (FNAL) data $E^{\pi}_{inc} = 500 GeV$ are recently submitted to PRL (D.Ashery 1998-2000) $\pi + A \to 2jet + A$

♡ Coherent peak is well resolved:



Number of events as a function of q_t^2, where $q_t = \Sigma_i p_t^i$ for the cut $\Sigma p_z \geq 0.9 p_\pi$.

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♡♡ Observed A-dependence $A^{1.61\pm0.08}$ $[C \to Pt]$

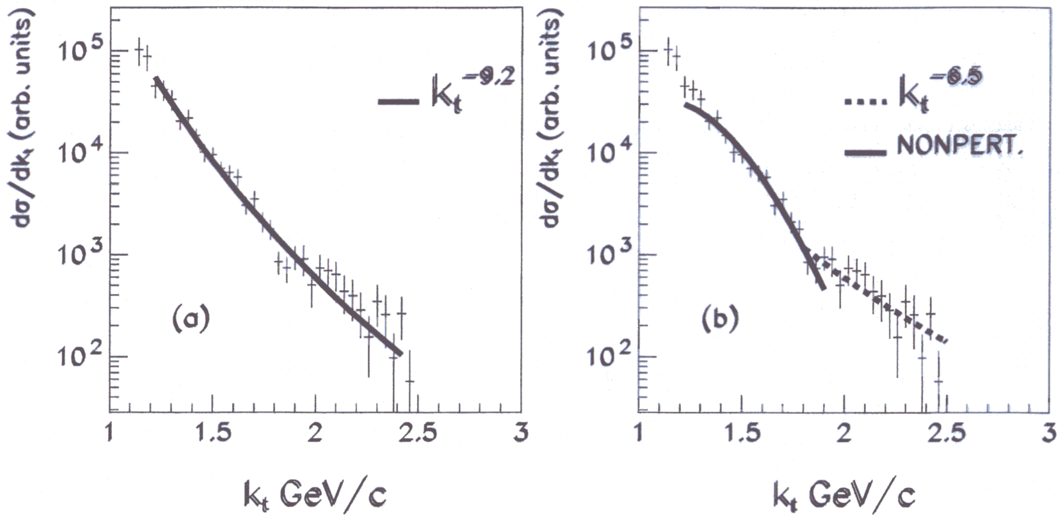
FMS prediction $A^{1.54}$ $[C \to Pt]$ for large k_t
& extra small enhancement for intermediate k_t.

For soft diffraction the Pt/C ratio is $\sim$ 7 times smaller!!

(An early prediction Bertsch, Brodsky, Goldhaber, Gunion 81

$\sigma(A) \propto A^{1/3}$)

♡♡♡♡ k_t^{-n} dependence of $d\sigma/dk_t^2 \propto 1/k_t^{7.5}$ for $k_t \geq 1.7 GeV/c$ close to the QCD prediction - $n \sim 8.0$ for the kinematics of E971



⟹ • High-energy color transparency is **directly** observed.

• The pion $q\bar{q}$ wave function is **directly** measured.

Next step: Measuring three quark component of the proton wave function in the process $p + A \to 3\ jets + A$ (RHIC) & $p + \bar{p} \to 3\ jets + p$ (Tevatron collider)

Will measure QCD part of matrix element relevant for proton decay in GUTs

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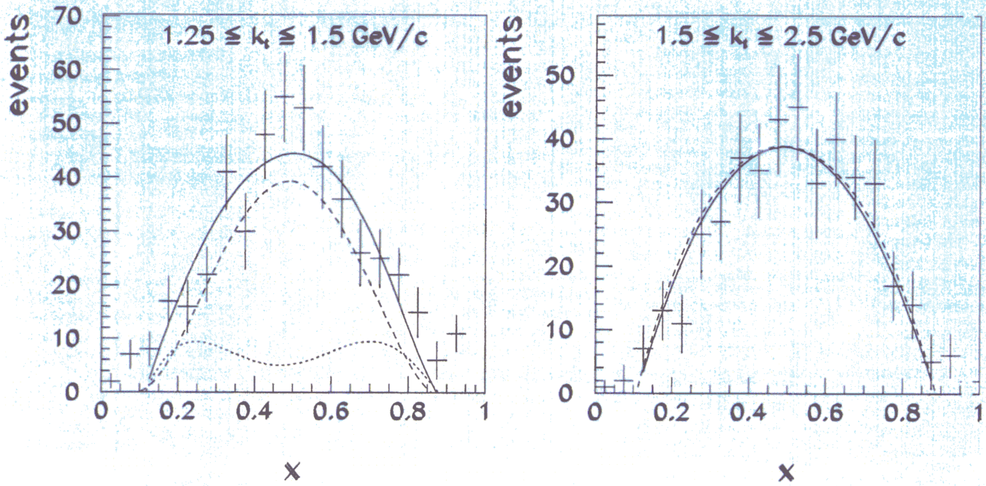
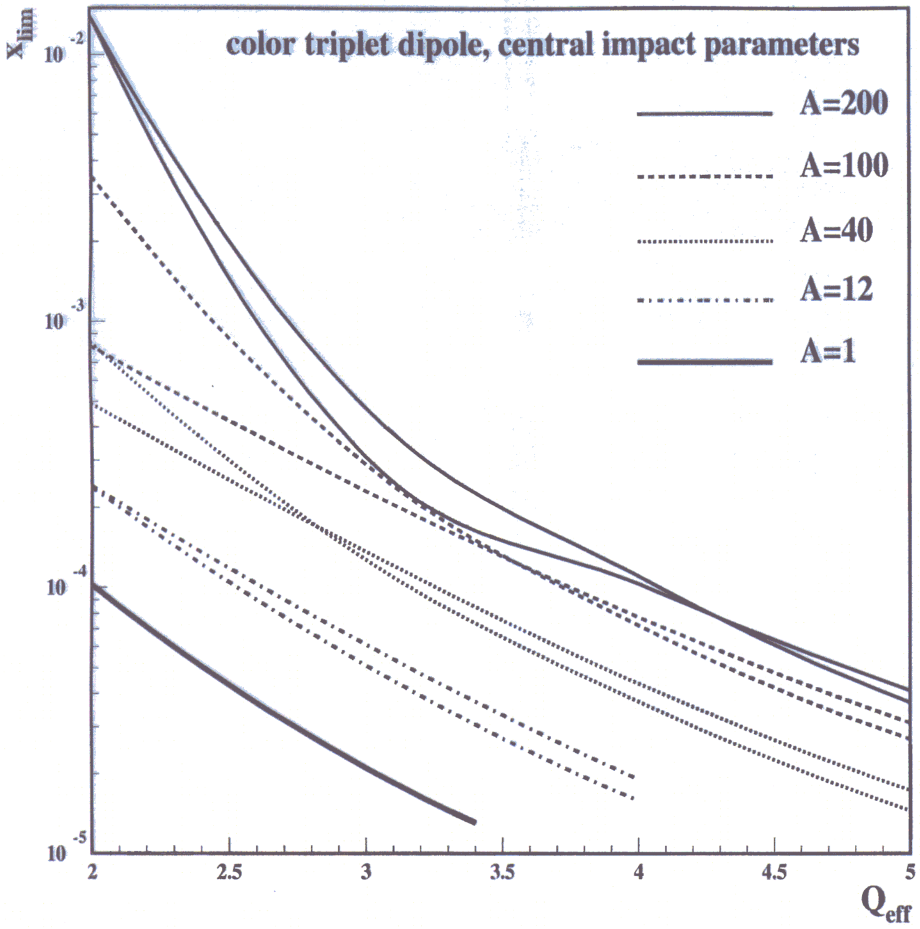
♡♡♡ The z dependence is consistent with dominance of the asymptotic pion wave function $\propto z(1-z)$.

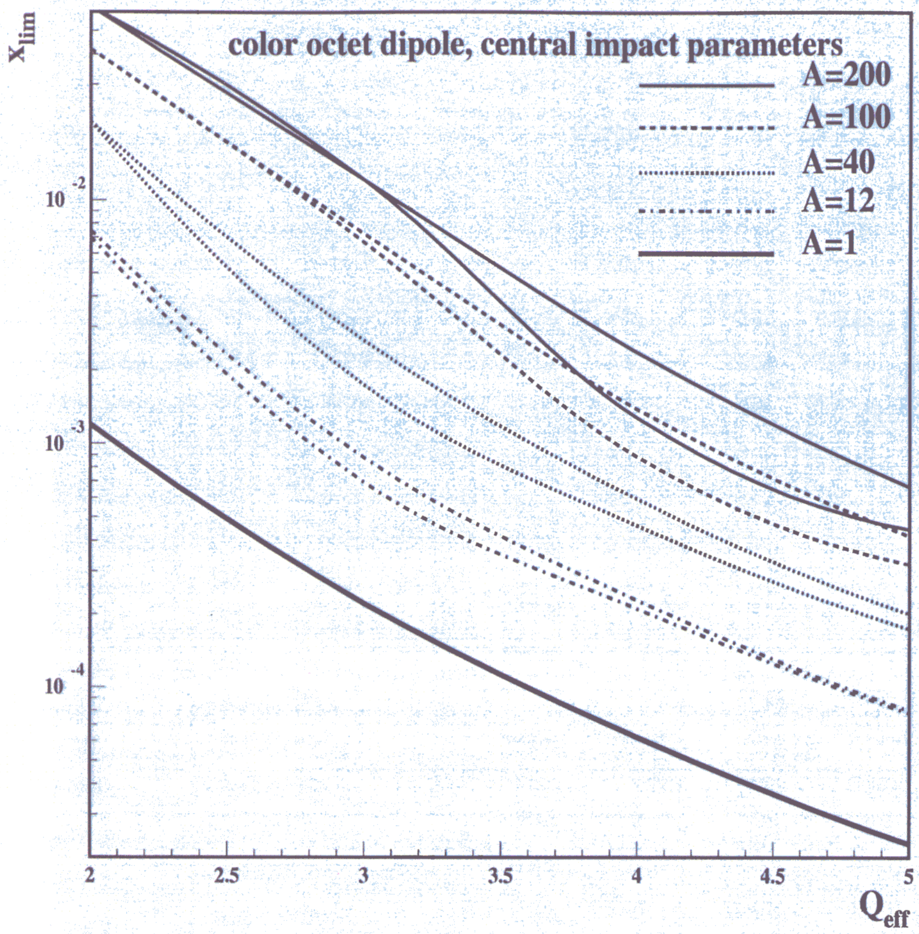


Solid lines - fit: $\sigma(z) \propto \phi_\pi^2(z) \propto (1-z)^2 z^2$



The unitarity boundary for the inelastic $q\bar{q}$-nucleus cross sections for nuclei with A=12, 40, 100, and 200 for the central impact parameters. The unitarity boundary for the inelastic $q\bar{q}$-nucleon cross section is presented as a thick solid line. Guzey & FS 2000 & FGS+McDermott 2001

3.



The unitarity boundary for the inelastic $q\bar{q}g(gg)$ (color octet)-nucleus cross sections for nuclei with A=12, 40, 100, and 200. The unitarity boundary for the inelastic $q\bar{q}g$-nucleon cross section is presented as a thick solid line.

Black body limit = Unitarity Bound

$\text{Im}\, f_\rho = 0 \qquad \rho < \rho_0(s)$

$\text{Im}\, f_\rho = 1 \qquad \rho > \rho_0(s)$

Advantage: all amplitudes are unambigously calculable

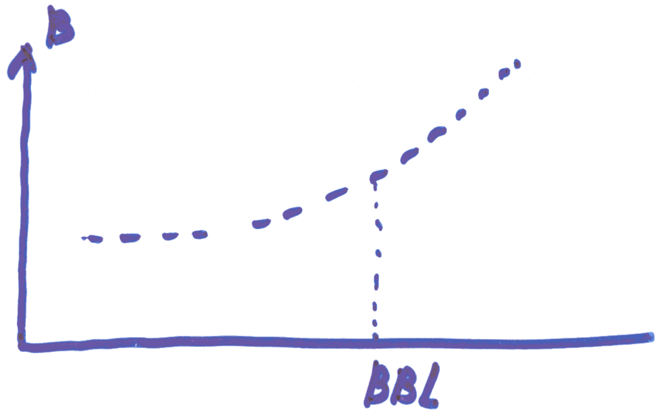
Disadvantage: unclear whether it follows from QCD - strong pQCD interaction may appear nonperturbative?

Properties of unitarity bound. (BBL).

1. $\sigma(\gamma^* + N \to X) \sim c \ln^2 \frac{s}{s_0}$ $\left(\ln \frac{s}{s_0}\right)$

Increase with energy is due to increase of impact parameters $\sim \ln^2 s$, because of wf of γ^* $\sim \ln s$!

2. The slope of t dependence $\frac{d\sigma}{dt} = e^{Bt} \frac{d\sigma}{dt}\Big|_{t=0}$



3. $\sigma(\gamma_L^* + p \to V + p) \sim \frac{1}{Q^4}$ BBL

$\frac{1}{Q^8}$ DGLAP

4. $\sigma(\gamma^* + A \to X) \sim \ln s/s_0$

Nuclear density is uniform. Possible to select central collisions

Unitarity of U matrix for the amplitude of dipole + T → dipole + T:

Approximations: $d^2 \ll \lambda^2_{QCD}$, $\alpha_s \ll 1$

Large contributions are due to x, Q^2 evolution.

$$\mathrm{Im}\, f_e(s, d^2) = \frac{1}{2} |f_e|^2 + \cdots$$

Thus $|f_e| \lesssim 1$ within proper normalization.

PQCD formulae can not be applicable at arbitrary small x but at fixed impact parameters.

5. $\frac{\sigma(\gamma^* + A \to 2\,jet + A)}{\sigma_{tot}(\gamma^* + A + X)} \approx \frac{1}{2}$ BBL

$\frac{1}{K_t^8}$ DGLAP

6. For the central heavy ion collisions at LHC

A + A → {fragmentation of nucleus = Σ} + X

i) Nonperturbative physics will be killed for system Σ.

ii) Gazes of quarks, of gluons are produced in system Σ

iii) Gaz of gluons tends to cool gas of quarks. Implosion.

FS. 2003