From Color Transparency
to Color Opacity

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Definition of generalized Color Transparency

\[ \sigma(T \rightarrow p) = \frac{\pi^2}{3} d^2 \ \eta_{5} \left( \frac{A}{d^2} \right) \times \eta_{7} \left( x, \frac{A}{d^2} \right) \]

d is transverse distance between 9 and 7.

\[ Q^2 = \frac{A}{d^2}; \quad x = \frac{Q^2}{V} \]

This formula is equivalent to DECAP

\[ \frac{\sigma(A \rightarrow X)}{\sigma(p \rightarrow X)} \Rightarrow A \] up to nuclear shadowing

\[ x \text{ is fixed, } d^2 > 0 \]

This generalized Color Transparency should be valid for any phenomenon where small size wave package dominates in the wave function of projectile.
Why CT is important:

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


3. Unambiguous demonstration that with increase of collision energy new quark-glueon configurations give significant contribution.
For some hard processes dominance of ssc in the projectile wf can be proved in QCD.

1. $e^+p \rightarrow V + T$

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

2. $b + T \rightarrow \text{minimal number of jets} + T$

Proxe 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) $\sigma(\gamma^* + A \rightarrow X)$

ii) $\sigma(\gamma A \rightarrow \gamma + A)$

iii) $\sigma(\pi A \rightarrow 2\mu A)$

iv) $\sigma(\gamma^* + p \rightarrow N + p)$

$v = p^0, \omega, \phi, \psi, \psi', \rho, \pi,

SLAC, CERN, FNAL

FNAL (1980)

FNAL (2000)

H1, ZEUS
(ii) Absolute cross section of $\rho$ production at $Q^2 \sim 20-30 \text{ GeV}^2$ and its energy dependence at $Q^2 \sim 20 \text{ GeV}^2$. 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 $B (\sigma = A \exp(Bt))$ of $\rho$-meson production at large $Q^2$ and $J/\psi$ production (Brodsky et al 94)
Extensive data on VM production from HERA support dominance of the pQCD dynamics. Numerical calculations including finite b effects in $\psi_N(b)$ explain key elements of high $Q^2$ data. The most important ones are:

(i) Energy dependence of $J/\psi$ production; absolute cross section of $J/\psi, \Upsilon$ production.
The E-791 (FNAL) data $E_{inc}^{\pi} = 500 GeV$ are recently submitted to PRL (D.Ashery 1998-2000) \( \pi + A \rightarrow 2 \text{jet} + A \)

♥ Coherent peak is well resolved:

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

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Observed A-dependence $A^{1.61 \pm 0.08}$ \( [C \rightarrow Pt] \)

FMS prediction $A^{1.54}$ \( [C \rightarrow Pt] \) 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 $k_t \geq 1.7\text{GeV}/c$ 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 $p + A \rightarrow 3\ \text{jets} + A$ (RHIC) & $p + \bar{p} \rightarrow 3\ \text{jets} + p$ (Tevatron collider)

Will measure matrix element relevant for proton decay in GUTs
The $z$ dependence is consistent with dominance of the asymptotic pion wave function $\propto z(1-z)$.

Solid lines - fit: $\sigma(z) \propto \phi^2_{\pi}(z) \propto (1-z)^2 z^2$
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

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The unitarity boundary for the inelastic $q\bar{q}g(gg)$ (color octet)-nucleus cross sections for nuclei with $A=12, 40, 100, \text{ and } 200$. 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

\[ \text{Im } f_\rho = 0 \quad \rho < \rho_0(s) \]

\[ \text{Im } f_\rho = 1 \quad \rho > \rho_0(s) \]

**Advantage:** all amplitudes are unambiguously calculable

**Disadvantage:** unclear whether it follows from QCD - strong QCD interaction may appear nonperturbative?
Properties of unitarity bound (BBL).

1. \( \sigma(\gamma^* + N \rightarrow X) \sim c \ln^2 \frac{\tilde{E}}{\tilde{s}_0} \left( \ln \frac{\tilde{s}}{\tilde{s}_0} \right) \)

Increase with energy is due to increase of impact parameters \( \sim \ln^2 \tilde{s} \), because of width of \( \gamma^* \sim \ln \tilde{s} \).

2. The slope of \( t \) dependence \( \frac{d\sigma}{dt} \) is constant.

3. \( \sigma(\gamma^* + p \rightarrow N + \nu) \sim \frac{1}{\tilde{t}} \)

4. \( \sigma(\gamma^* + A + X) \sim \ln \frac{s}{s_0} \)

Nuclear density is uniform, possible to select central collisions.
Unitarity of $U$ matrix for the amplitude of dipole $+T \rightarrow$ dipole $+T$.

Approximations: $d^2 \ll \lambda^2_{a\omega}$, $d_3 \ll 1$

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

\[ \text{Im} \, f_e (\xi, d^2) = \frac{1}{2} |16e|^2 \cdots \]

Thus $|16e| < 1$ within proper normalization.

QCD formulae cannot be applicable at arbitrary small $x$ but at fixed impact parameters.
5. \[ \frac{\sigma(L^+ + A \rightarrow 2 \text{jet} + A)}{\sigma(r^+ + A + x)} \times \frac{1}{2} \]

DGLAP

\[ \frac{1}{N_c} \]

6. For the central heavy ion collisions at LHC

\[ A + A \rightarrow \{ \text{fragmentation of nucleus} = X \} + x \]

i) Nonperturbative physics will be killed for system \( S \).

ii) Cases of quarks, of gluons are produced in system \( S \).

iii) Case of gluons tends to cool gas of quarks. Impluse. 

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