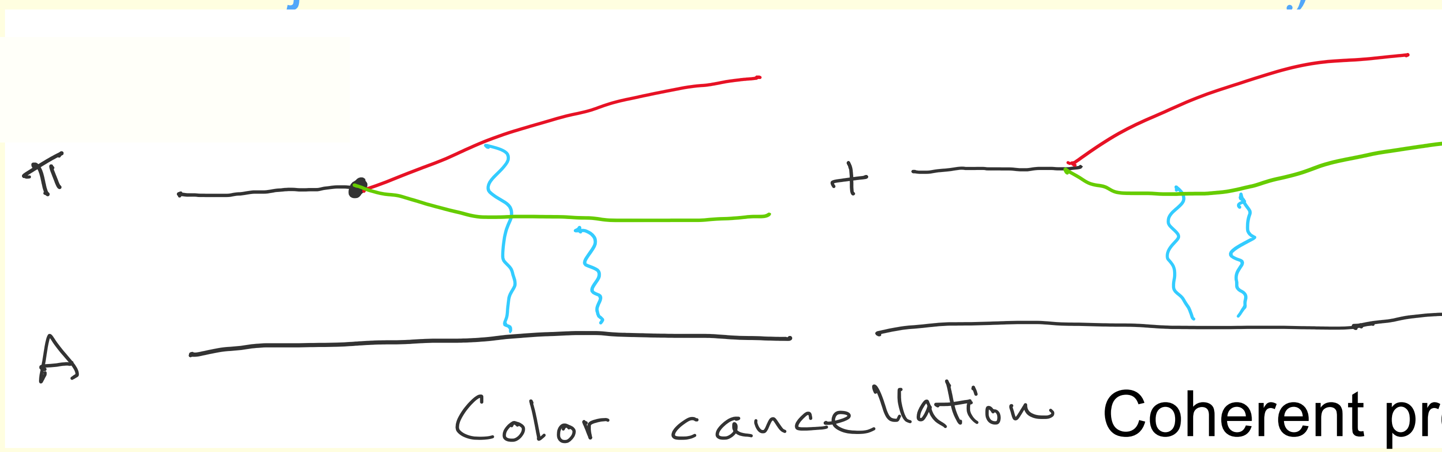
Color Transparency Past, Present and Future

G. A. Miller, UW, Seattle

Color transparency- reduced initial/final state interactions in coherent reactions

1. high-momentum transfer reactions make point-like color singlet states PLC

2. Small objects have small cross sections $Im\, f \propto b^2$



Diffractive Dissociation

Coherent process

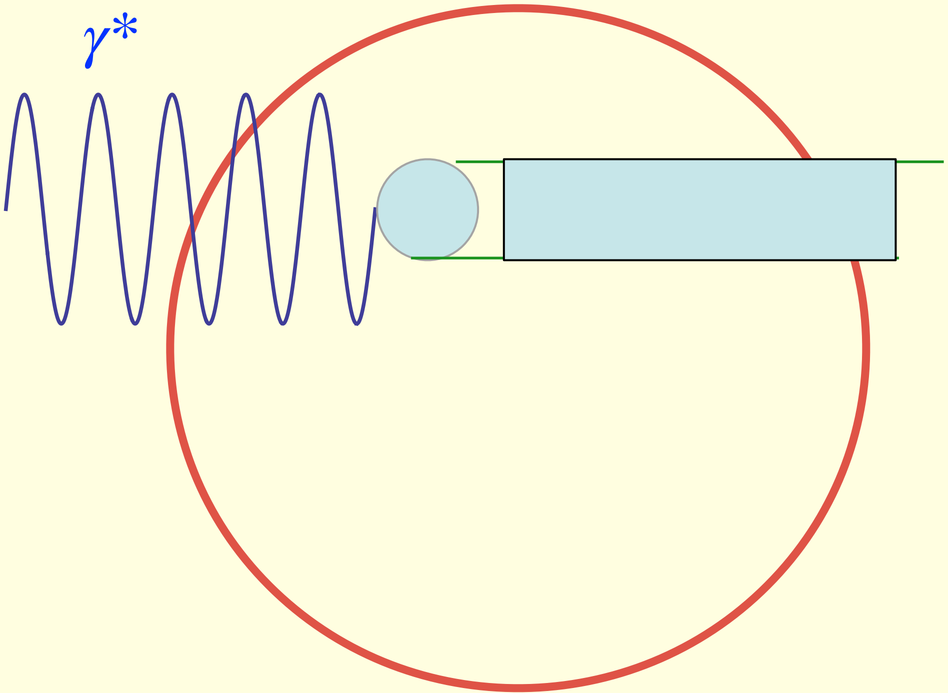
3. PLC are not eigenstates-expand as they move

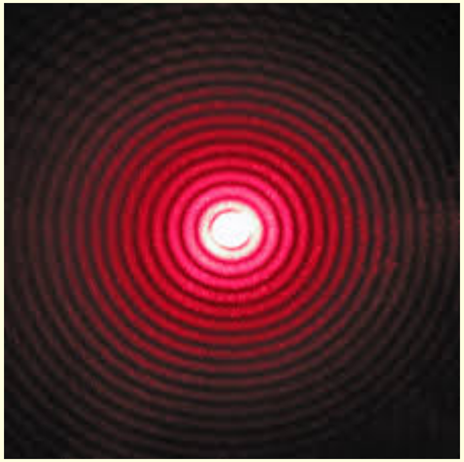
Frankfurt& Strikman, Jennings & Miller

2,3 must be true, 1 is interesting

Old/standard Idea of (e,e'p)

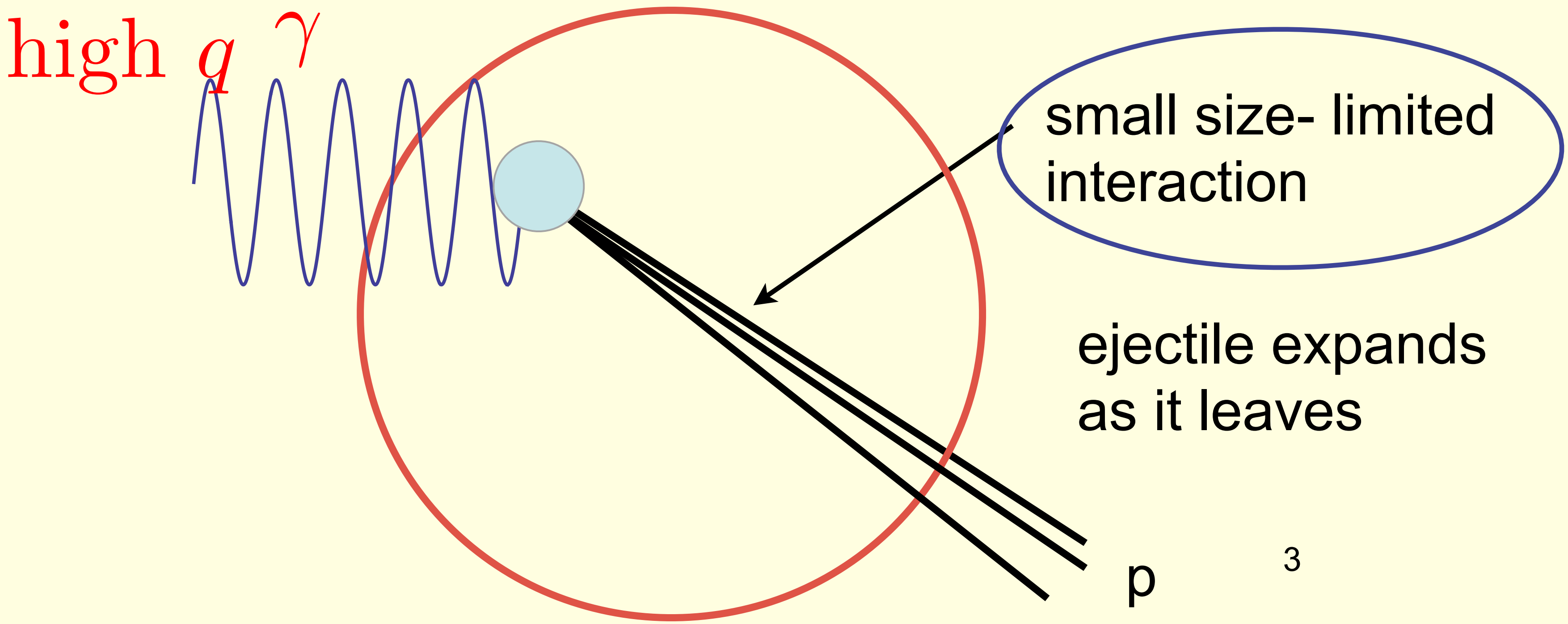
- **Proton in nucleus hit by γ^***
- **proton goes out**
- **absorbed by nuclei, nucleus is absorbing disk, nuclei cast shadow**
- **Diffraction pattern**





Newer Testable Idea

- **At high momentum transfer hadron is in a color neutral Point Like Configuration- PLC**
- **These do not interact, not absorbed by nuclei, cast no shadow**
- **Quantum mechanical invisibility=color transparency**



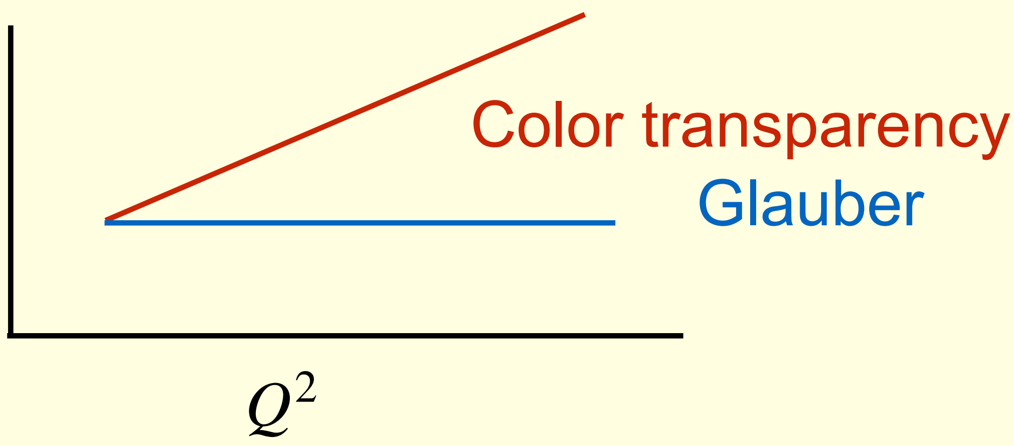
Color Transparency Idea

Why interesting?

- new dynamical phenomena- turn off strong interactions
- are PLCs made? -high Q^2-exclusives
- nuclear physics implications of PLC- nucleon modified- EMC effect

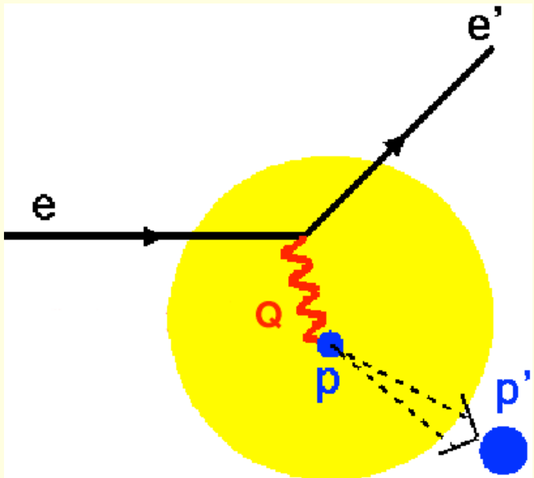
Electroproduction signature

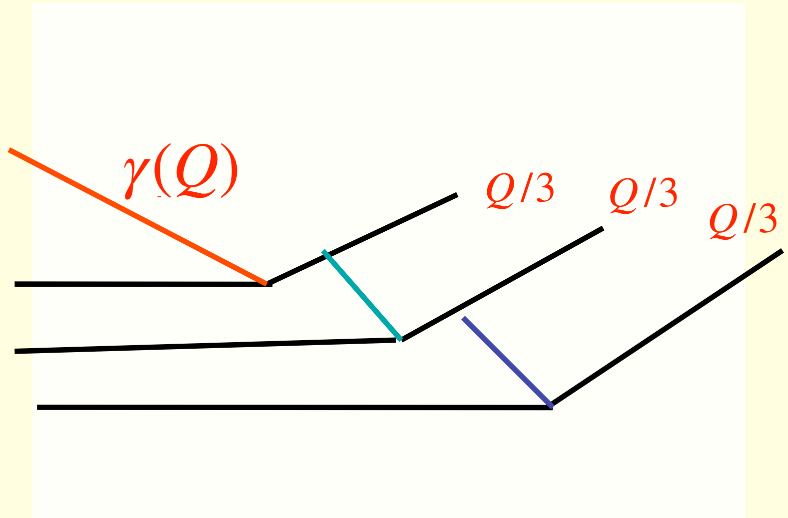
$$T = \frac{\sigma}{\sigma_{PWA}}$$



Why PLC at high momentum transfer?

Example: e-p scattering





Form factor enters

Momentum of exchanged gluon ~Q, separation ~1/Q

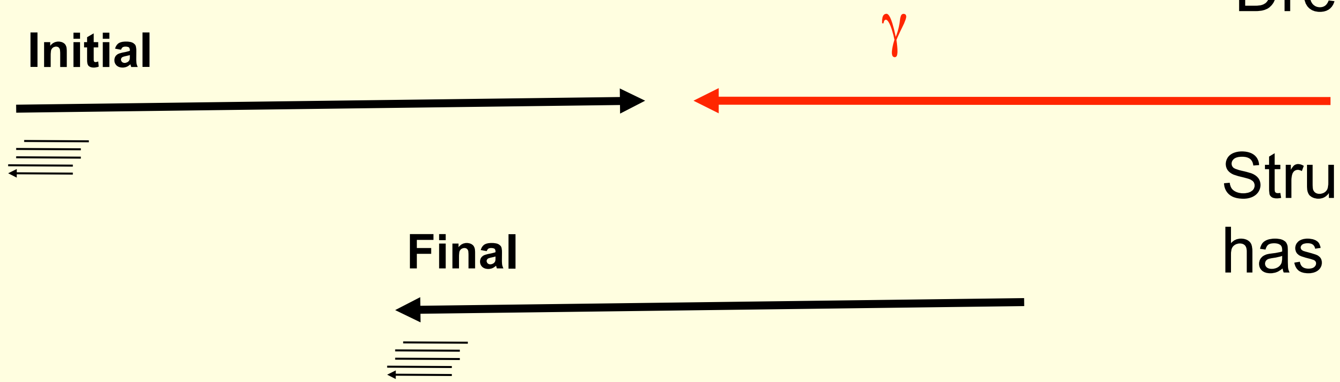
- At high enough Q an exclusive interaction occurs if the transverse size of the hadron is smaller than the equilibrium size.
- Perturbative reasoning-also non-perturbative Nucl.Phys. A555 (1993) 752-764

Why not PLC ?

e-p scattering **Feynman mechanism**

R. P. Feynman, *Photon-Hadron Interactions* (W. A. Benjamin, Inc.l, Reading, MA, 1972).

Drell & Yan



Struck quark has high x

Transverse size not affected -no PLC

Interesting dynamical question about QCD -do PLC exist and participate?

Making PLC is squeezing- and is the interesting part

Feynman:

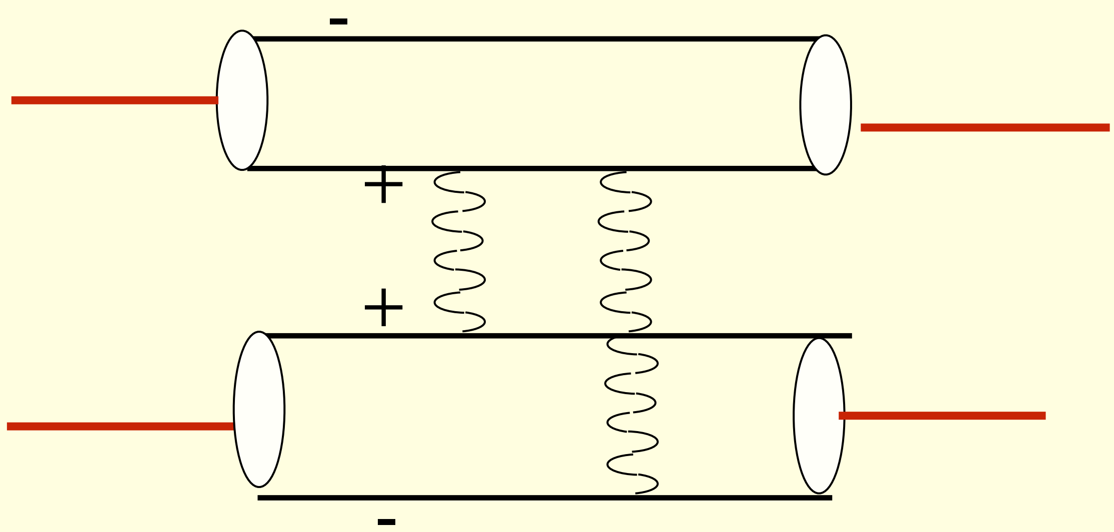
remarked that "if a system is made of 3 particles, the large Q^2 behavior depends not on the singularity when just two come together, but rather when all three are on top of one another". Furthermore, "such pictures are too simple and inadequate".

End point dominance

Relate to high -x behavior of structure functions

- Much interest in high x behavior in structure functions $q(x) \to (1-x)^{2n_s - 1 + f(Q^2)}$
- Original idea of quark counting rules comes from perturbative ideas -form factor dominated by plc
- End-point dominance- gives Drell-Yan & West relations $q(x) \to (1-x)^{\delta}; \; F(Q^2) \to \left(\frac{K^2}{Q^2}\right)^{\delta}$
- Proton $n_s \approx 3, \delta = 2$ same
- Color transparency could resolve

Small objects -small cross sections



Color cancellation
++ & +-

Coherent process
add before square

$$\sigma(pp) > \sigma(\pi p) > \sigma(kp)$$

Color dipole model in high-energy physics

For small transverse separations, b, $\sigma \propto b^2$

Problem PLC Expansion

- $|PLC\rangle$ is **not** an eigenstate = $\Sigma_n C_n |n\rangle$ each physical state n has large size
- coherent sum of buildings can act as if it has size of golf ball –phases
- $|PLC\rangle_t = \Sigma_n C_n \, \mathrm{Exp}(-i E_n t)|n\rangle$ $\quad E_n(P) = \sqrt{P^2 + M_n^2} \approx P + M_n^2/(2P)$
- relative phases change with time, size increases
- High P (momentum of PLC)
- Expansion $t = 1/(M_n - M_p)(2P/(M_n + M_p))$ = natural rest frame time times dilation factor
- What is M_n ?
- At high enough P we have freezing t >>>R_A

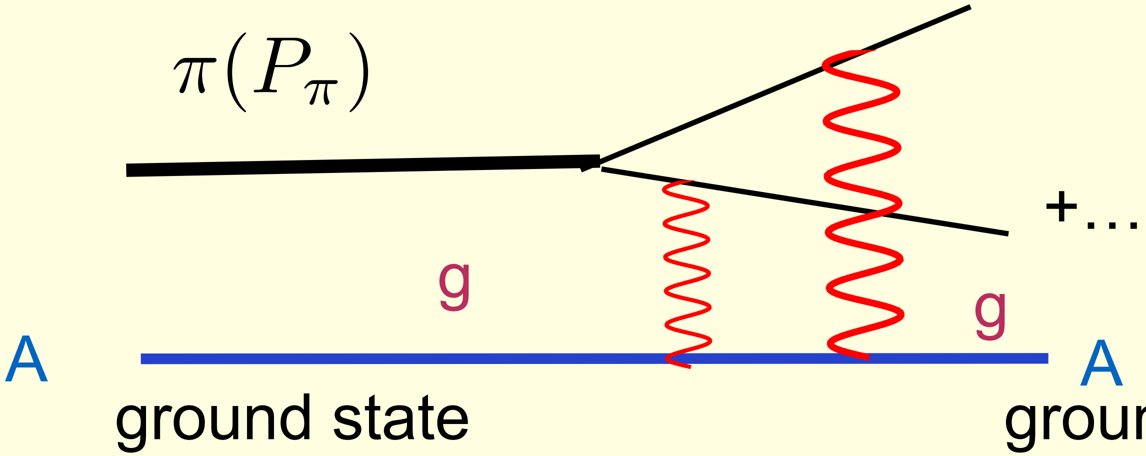
Problem at JLAB6 for sure, is 12 enough?

Color transparency experiments

$T = \sigma/\sigma_B$

- (π, JJ)**Prediction Frankfurt et al. Phys.Lett. B304 (1993) 1. Experiment D Ashery et al PRL 86(2001) 4773** A-dependence
- $(e, e'\pi)$ **B. Clasie** *et al.* **PRL 99(2007)242502-Promising rise in** T
- $(e, e'\rho)$ **L. El Fassi** *al.* **PLB 712 (2012) 326- Promising rise in** T
- Several (e,e'p) experiments, no evidence for CT
- Messy kinematics -Higinbotham
- $\pi + A \rightarrow J + J + A$ is diffractive dissociation
  $(e, e'\pi), (e, e'p)$ reactions depend on form factor
  $(e, e'\rho)$

$\pi + N(A) \rightarrow$ "2 high transverse momentum jets" $+ N(A)$
The one that worked



$p_\pi = 500\,\mathrm{GeV}$

- final state $q\bar{q}$ becomes 2 high rel. momentum jets, small transverse separation, PLC of pion
- $\pi \rightarrow q\bar{q}$ before hit target, no expansion
- one interaction
- Coherent process- enhanced!

FMS Phys.Lett. B304 (1993) 1

Phys. Rev D65,094015

$$\mathscr{M}(\text{forward}) \propto A,\ \sigma_A \propto A^2 * A^{-2/3} = A^{4/3} + \text{positive corrections}$$

The E-791 (FNAL) data $E^{\pi}_{inc} = 500 GeV$ (D.Ashery et al, PRL 2000)

♡ Coherent peak is well resolved:

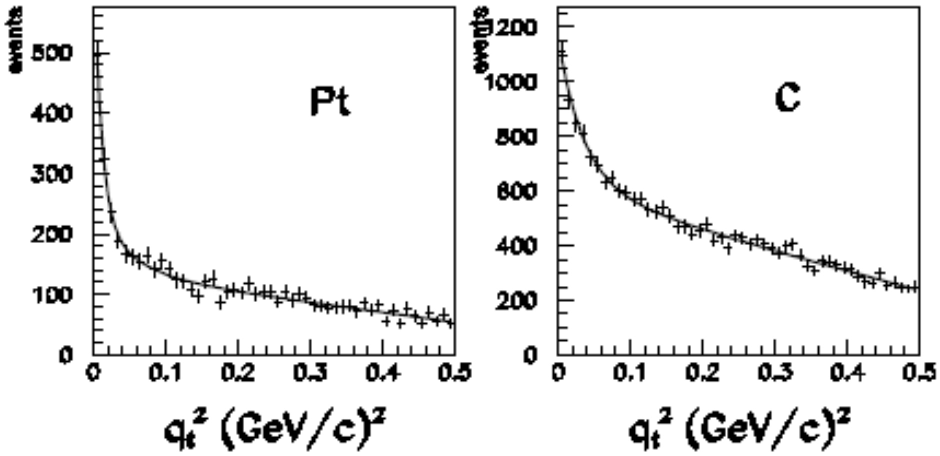


TABLE I. The exponent in $\sigma \propto A^{\alpha}$, experimental results for coherent dissociation and the color-transparency predictions.

k_t bin GeV/c	α	$\Delta\alpha_{stat}$	$\Delta\alpha_{sys}$	$\Delta\alpha$	α (CT)
1.25–1.5	1.64	±0.05	+0.04 −0.11	+0.06 −0.12	1.25
1.5–2.0	1.52	±0.09	±0.08	±0.12	1.45
2.0–2.5	1.55	±0.11	±0.12	±0.16	1.60

PRL 86,4773

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

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

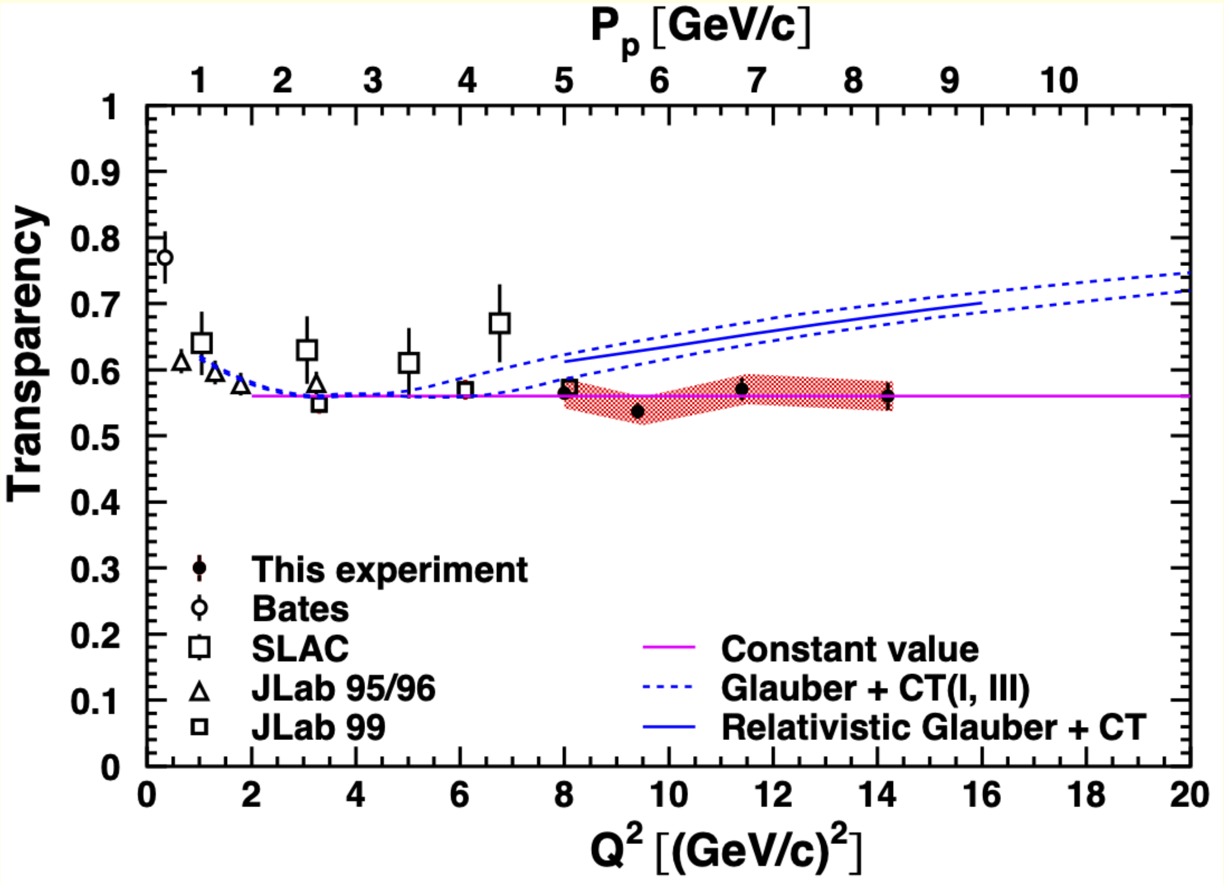
For soft diffraction the Pt/C ratio is ~ 7 times smaller!!

Why it worked

- High momentum -no expansion
- Different than other experiments- not a form factor measurement- final state is not pion
- Transition from Glauber regime not studied

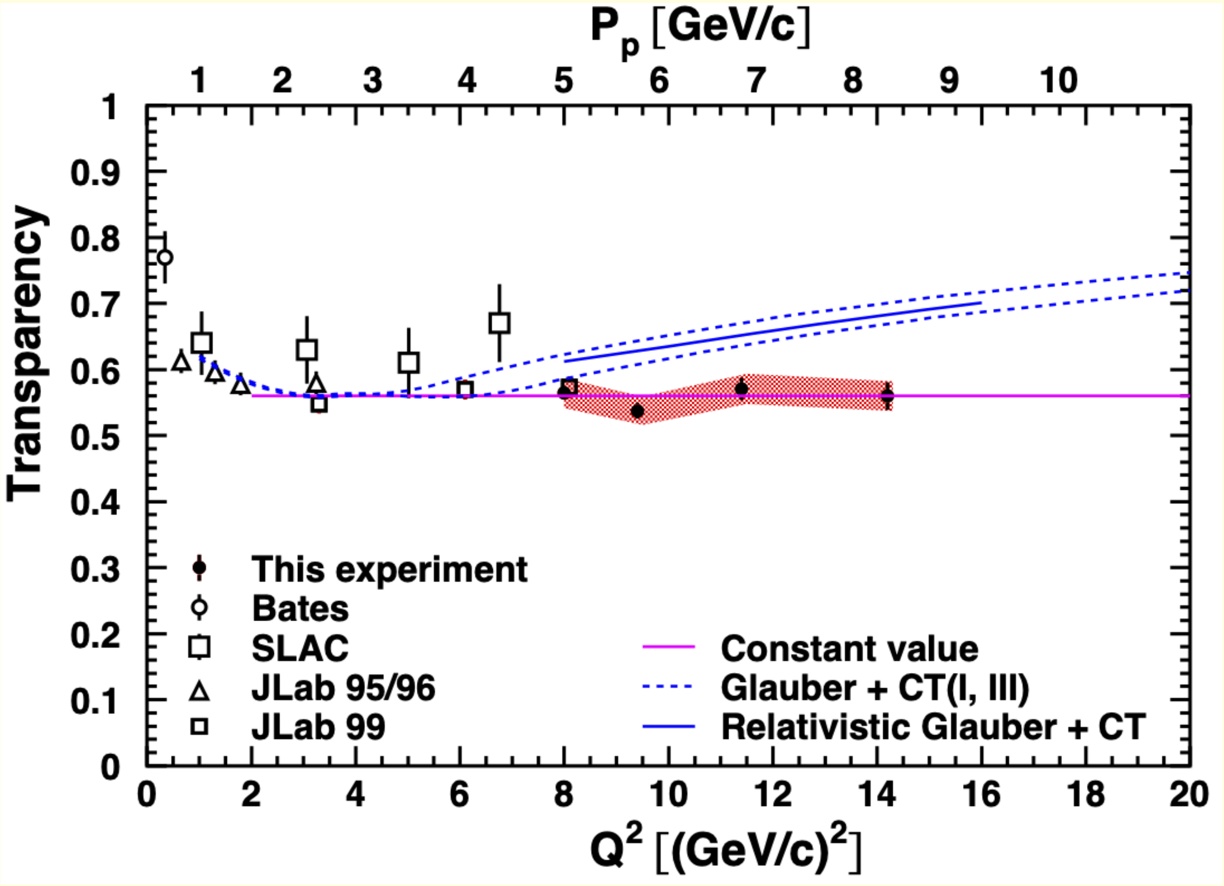
Ruling out color transparency in quasi-elastic $^{12}C(e,e'p)$ up to Q^2 of 14.2 $(GeV/c)^2$

Phys. Rev. Lett. 126, 082301



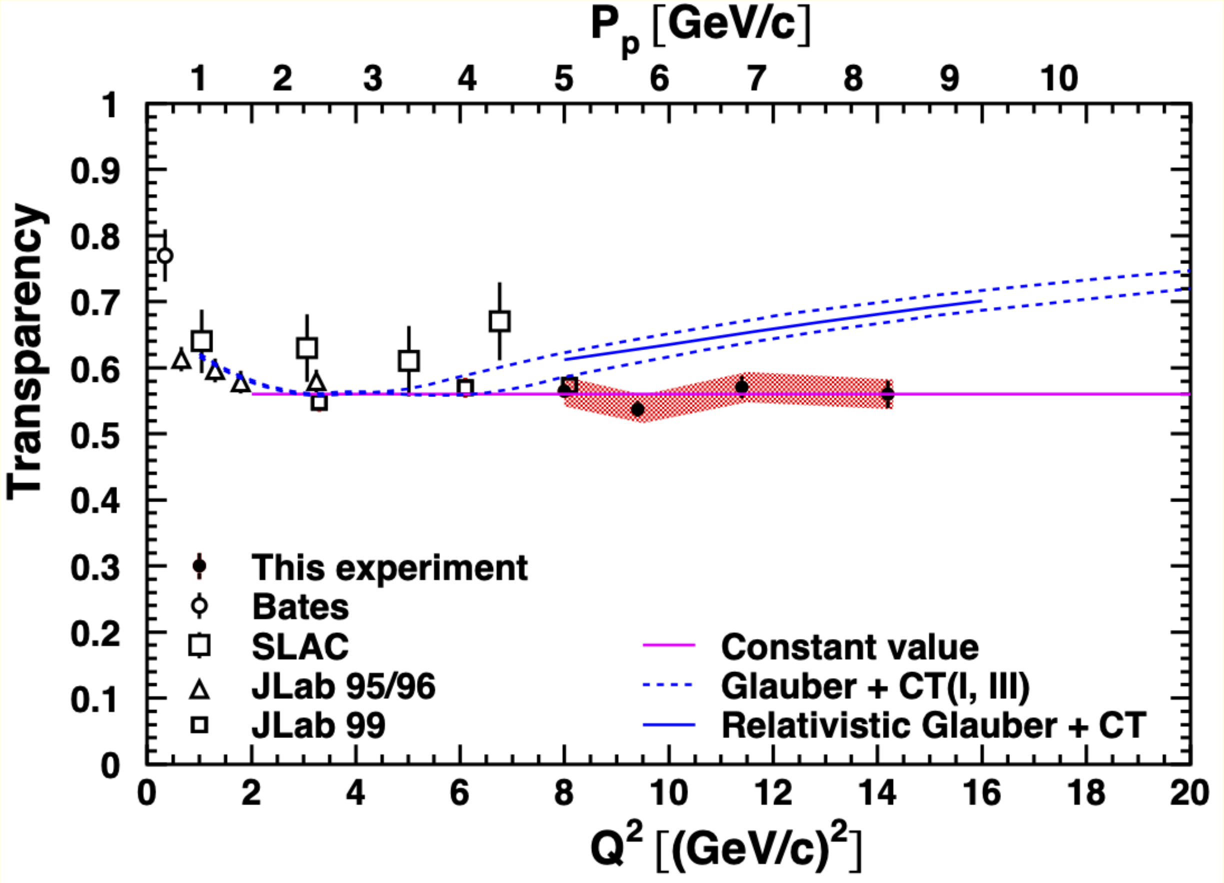
Ruling out color transparency in quasi-elastic $^{12}C(e,e'p)$ up to Q^2 of 14.2 $(GeV/c)^2$

Phys. Rev. Lett. 126, 082301



Ruling out color transparency in quasi-elastic ^{12}C(e,e$'$p) up to Q^2 of 14.2 (GeV/c)^2

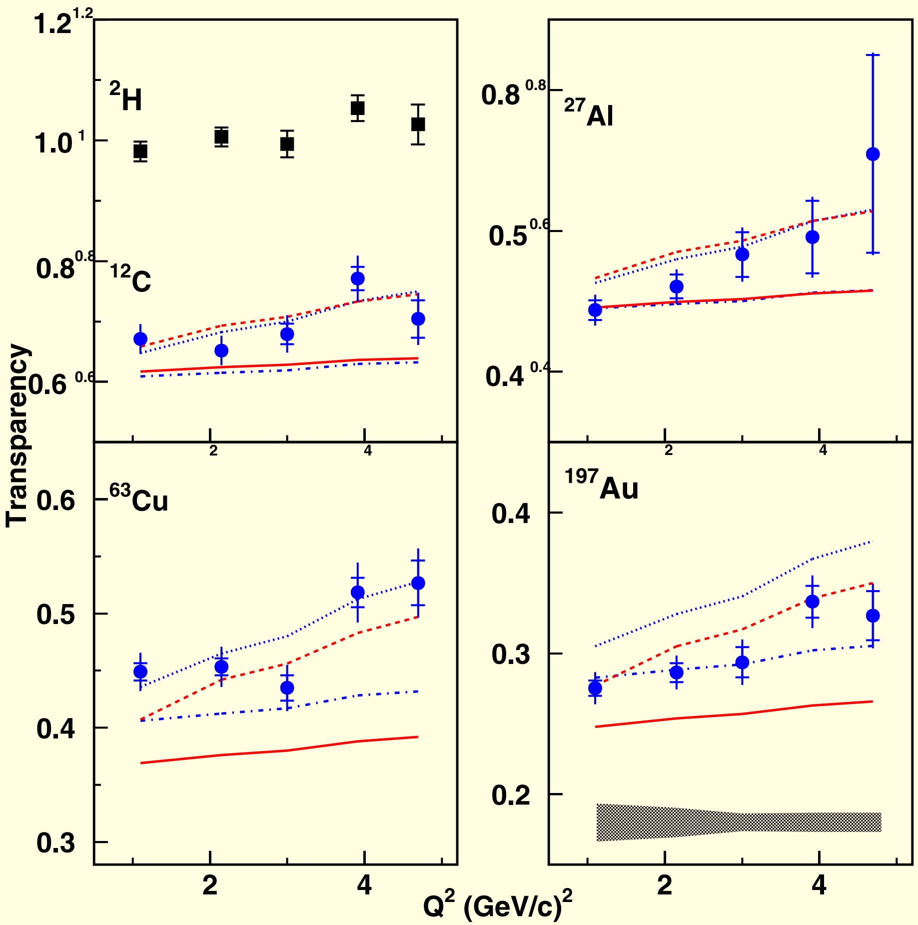
Phys. Rev. Lett. 126, 082301



PRL 99, 242502 (2007) PHYSICAL REVIEW LETTERS week ending 14 DECEMBER 2007

Measurement of Nuclear Transparency for the $A(e, e'\pi^+)$ Reaction

B. Clasie,[1] X. Qian,[2] J. Arrington,[3] R. Asaturyan,[4] F. Benmokhtar,[5] W. Boeglin,[6] P. Bosted,[7] A. Bruell,[7] M. E. Christy,[8] E. Chudakov,[7] W. Cosyn,[9] M. M. Dalton,[10] A. Daniel,[11] D. Day,[12] D. Dutta,[13,2] L. El Fassi,[3] R. Ent,[7] H. C. Fenker,[7] J. Ferrer,[14] N. Fomin,[12] H. Gao,[1,2] K. Garrow,[15] D. Gaskell,[7] C. Gray,[10] T. Horn,[5,7] G. M. Huber,[16] M. K. Jones,[7] N. Kalantarians,[11] C. E. Keppel,[7,8] K. Kramer,[2] A. Larson,[17] Y. Li,[11] Y. Liang,[18] A. F. Lung,[7] S. Malace,[8] P. Markowitz,[6] A. Matsumura,[19] D. G. Meekins,[7] T. Mertens,[20] G. A. Miller,[17] T. Miyoshi,[11] H. Mkrtchyan,[4] R. Monson,[21] T. Navasardyan,[4] G. Niculescu,[14] I. Niculescu,[14] Y. Okayasu,[19] A. K. Opper,[18] C. Perdrisat,[22] V. Punjabi,[23] A. W. Rauf,[24] V. M. Rodriquez,[11] D. Rohe,[20] J. Ryckebusch,[9] J. Seely,[1] E. Segbefia,[8] G. R. Smith,[7] M. Strikman,[25] M. Sumihama,[19] V. Tadevosyan,[4] L. Tang,[7,8] V. Tvaskis,[7,8] A. Villano,[26] W. F. Vulcan,[7] F. R. Wesselmann,[23] S. A. Wood,[7] L. Yuan,[8] and X. C. Zheng[3]



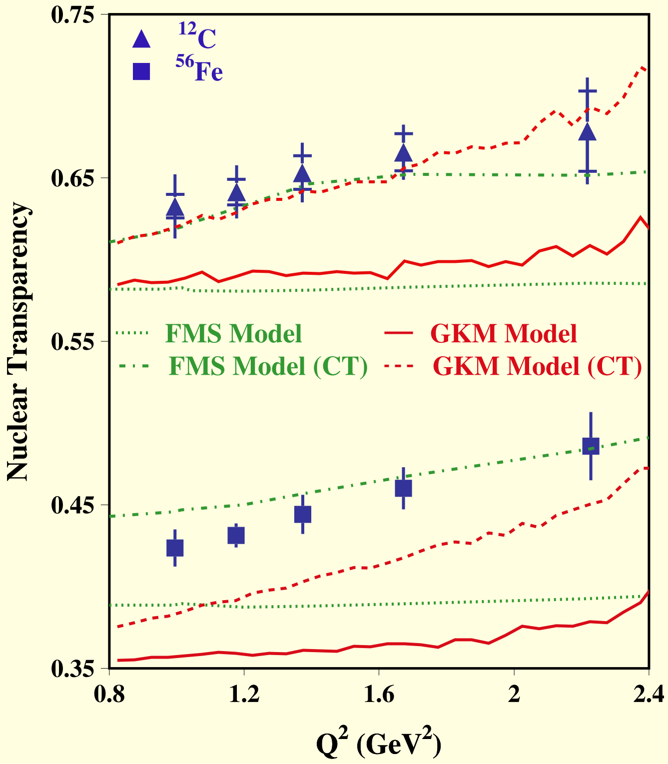
Solid Dashed
Glauber, Glauber
+CT
LMS
prc74,018201

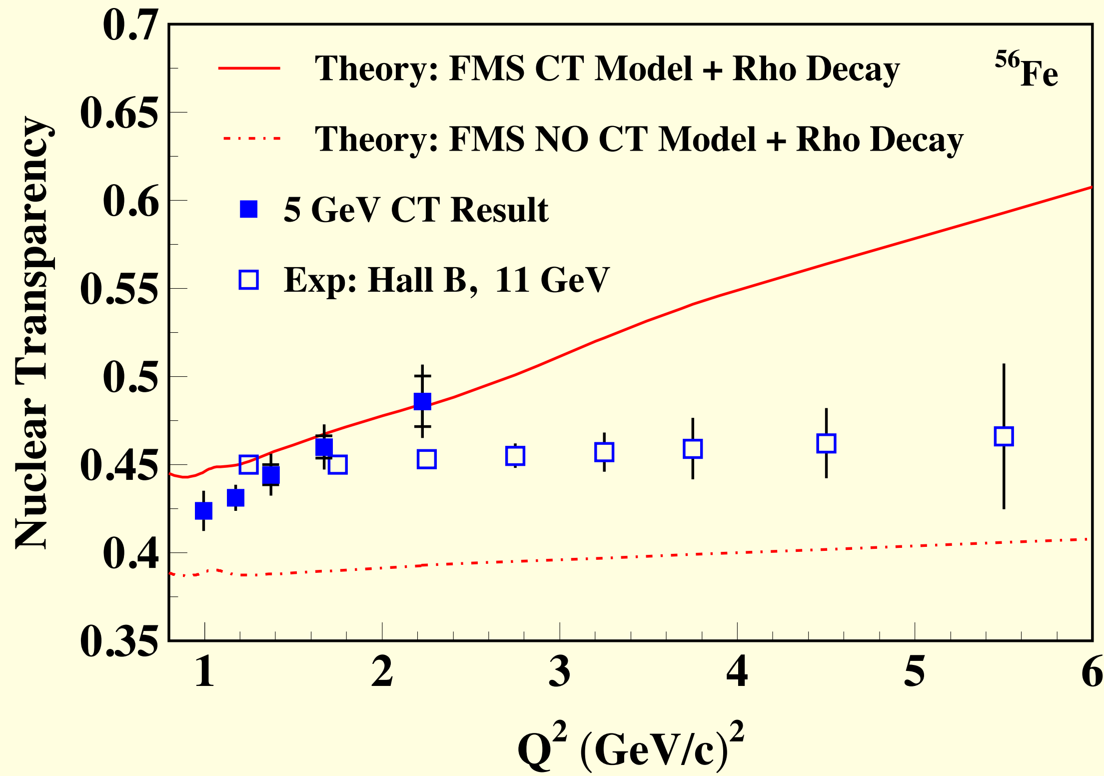
dot-dashed, dotted
CosynPRC74,062201

Solid-Glauber

$(e, e'\rho)$
El Fassi et al. PLB 712(2012)326

11 GeV expt





JLab: expansion is the problem

Goal: evaluate effects of expansion with new approach
Olivia Caplow-Munro, G A Miller 2104.11168, PRC 104(2021) L012201

Light front (LF) wave functions of Holographic QCD:

- Stanley J. Brodsky, Guy F. de Teramond, Hans Gunter Dosch, and Joshua Erlich, "Light-Front Holographic QCD and Emerging Confinement," Phys. Rept. 584, 1–105 (2015), arXiv:1407.8131 [hep-ph].

First semiclassical approximation: quantum loops & $m_q = 0$
relativistic bound-state equation reduced to effective LF Schroedinger eq.

Invariant mass of free constituents is the dynamical variable $\zeta = \sqrt{b^2 x(1-x)}$,
measures parton separation at equal light-front time (deTeramond:2008ht).

QCD multi-parton problem reduced (first semi-classical approximation) to effective 1-dimensional quantum mechanics

complexities of strong interaction in effective potential U

quark-diquark model

$$\left(-\frac{d^2}{d\zeta^2}-\frac{1-4L^2}{4\zeta^2}+U(\zeta,J)\right)\phi(\zeta)=M^2\phi(\zeta)$$

$$\zeta^2=b^2x(1-x),\ \phi\ \text{prob . amp .}$$

L, J orbital total ang mom .

Depends on Hadron

$$U(\zeta,J)=\kappa^4\zeta^2+\underline{2\kappa^2(J-1)}$$

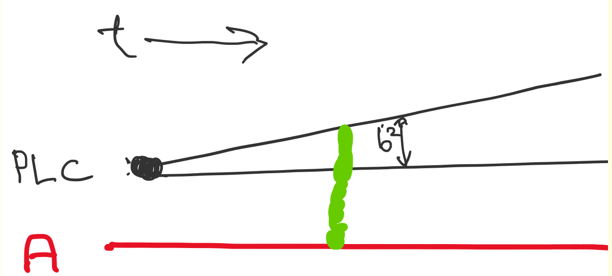
- Excellent baryon & meson spectroscopy, form factors Feynman mechanism PR102.081601,PRD.91.045040,PRD.91.085016
- Gives masses & wave functions

Time dependence

$$2i\frac{\partial}{\partial\tau}\Psi = \frac{1}{P^+}\left(-\frac{1}{x(1-x)}\nabla_b^2 + U(b^2(x(1-x),J)\right)\Psi,$$

$$\tau \equiv x^+, \Psi = \text{PLC wave packet}$$

- Procedure, $H \to L$, Legendre trans. (Momentum to velocity)
- path integral formalism to get τ development operator $K(t)$
- $$b^2(t) \equiv \frac{\langle \Psi_{00} | b^2 K(t) | \text{PLC} \rangle}{\langle \Psi_{00} | \text{PLC} \rangle}$$



- Effective size of PLC moving thru nucleus

For small transverse separations, b, $\sigma \propto b^2$

- First-order in multiple scattering $b(0) = 0$, here

Rate of Expansion Depends on Hadron

$$\frac{b_\pi^2}{2\bar{b}^2} = \sin^2\left(\frac{2\kappa^2}{P+}t\right) \to 4(\kappa/P)^2 t^2$$

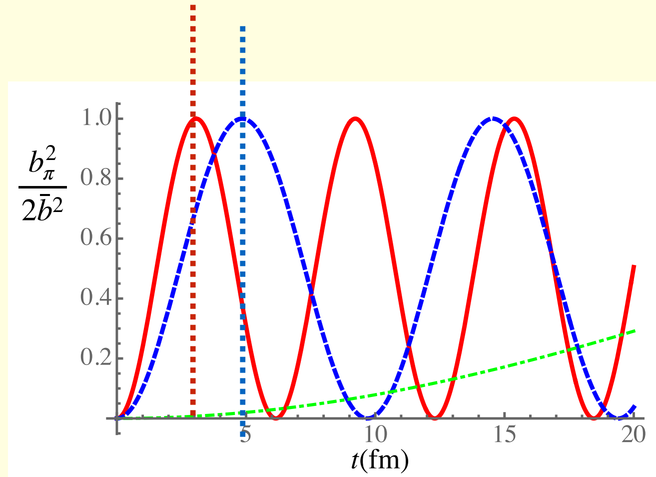
$$\frac{b_\rho^2}{2\bar{b}^2} = \sin\left(\frac{2\kappa^2}{P+}t\right)\sin\left(\frac{4\kappa^2}{P+}t\right) \to 8(\kappa/P)^2 t^2$$

$$\frac{b_N^2}{2\bar{b}^2} = \sin\left(\frac{2\kappa^2}{P+}t\right)\sin\left(\frac{6\kappa^2}{P+}t\right) \to 16(\kappa/P)^2 t^2$$

Difficulty of seeing color transparency $p > \rho > \pi$

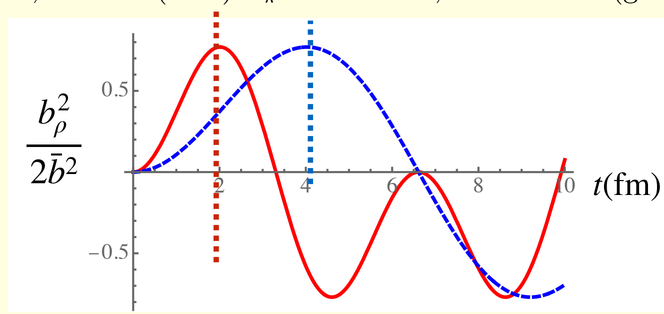
Meson results- expansion time , t_E, : vertical lines

Pion: t_E between 2 and 5 fm in exp. CT seen more Likely



Expansion does not occur for Fermilab Experiment

FIG. 2. $\frac{b_\pi^2}{2\bar{b}^2}$. Solid (red) $P_\pi^+ = 5.5$ GeV, Dashed (blue) $P_\pi^+ = 8.8$ GeV, Dot-dashed (green) $P_\pi^+ = 100$ GeV. t is in units of fm



Rho: t_E about 2 fm for exp. CT less likely Higher energy would see CT

FIG. 3. $\frac{b_\rho^2}{2\bar{b}^2}$. Solid (red) $P_\rho^+ = 6$ GeV, Dashed (blue) $P_\rho^+ = 12$ GeV. t is in units of fm

ρ – nucleon cross section, σ not measured

Proton results

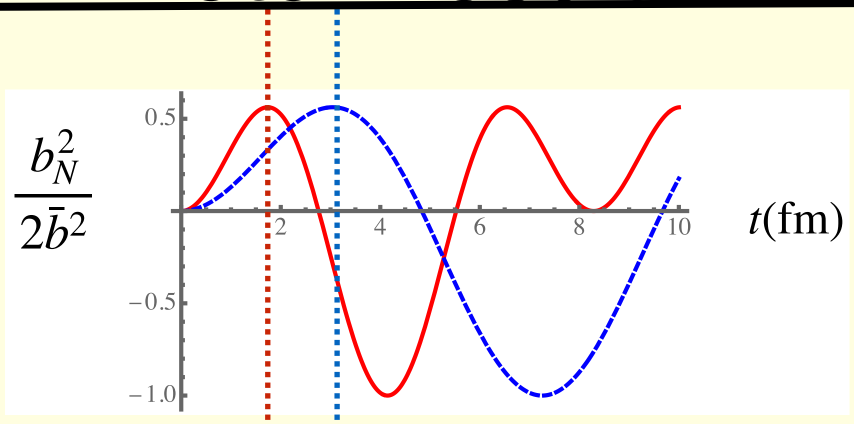


FIG. 4. $\frac{b_N^2}{2\bar{b}^2}$ Solid (red) $P_N^+ = 8$ GeV, Dashed (blue) $P_N+ = 14$ GeV. t is in units of fm.

t_E ranges between 2 and 3fm . For ^{12}C CT should have seen as rise in transparency ratio

Expansion is not excuse for lack of CT

Conclude PLC is not formed

Feynman mechanism is responsible for proton em form factor at high Q^2

Why not correct?

Diffractive dissociation to jets seems more promising only one Bound-state wave function involved. Two gluon exchange

Messy kinematics

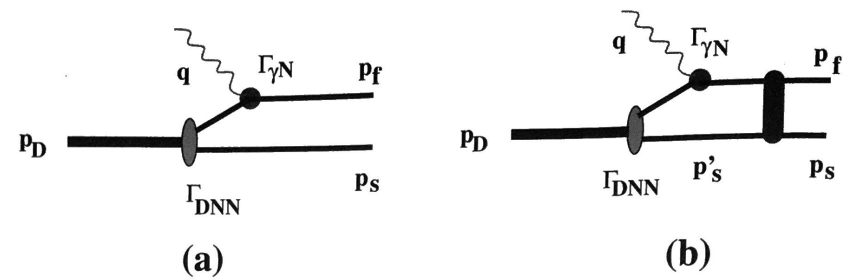


Figure 11.7. (a) Impulse approximation diagram. (b) Rescattering diagram.

Kinematics where
Final state ints
Needed

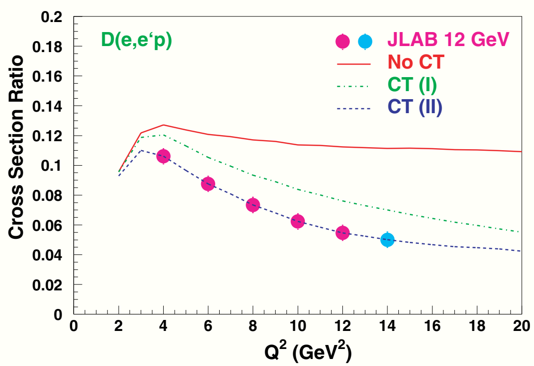


Figure 15. The ratio of the cross section at 400 MeV/c missing momentum to the cross section at 200 MeV/c as a function of Q^2. The solid line corresponds to the GEA prediction. The dashed and dash-dotted lines represent the quantum diffusion model of CT with $\Delta M^2 = 0.7$ and 1.1 GeV^2, respectively. The drop with Q^2 in the colour transparency models comes from a reduction in the rescattering of the struck nucleon, which is the dominant source of events with $p_m > k_F$.

Sargsian et al. JPG 29,R1 (2001)
Egiian et al NPA(1994) 365
Frankfurt et al PLB (1996)201

Color Transparency and Holographic Light Front QCD

$$\text{Form factor } F(Q^2) = \int d^2b\,dx\, \psi^*(x,b) e^{i\mathbf{Q}\cdot\mathbf{b}(1-x)} \psi(x,b)$$

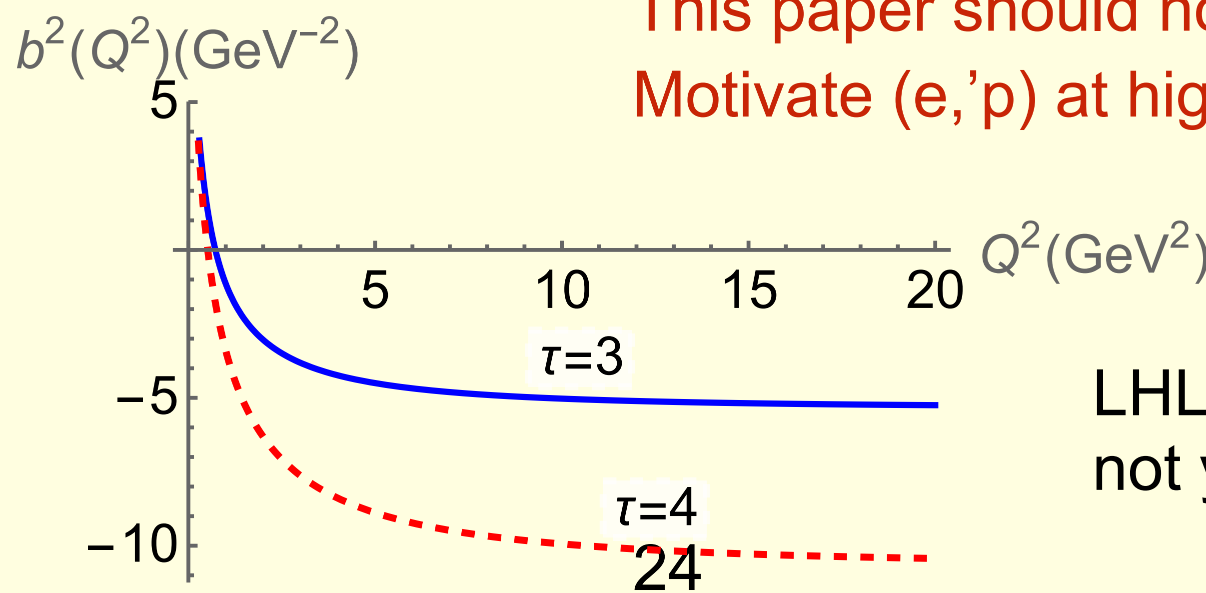
Measure of σ :
$$b^2(Q^2) = \frac{1}{F(Q^2)} \int d^2b\,dx\, \psi^*(x,b)\, b^2\, e^{i\mathbf{Q}\cdot\mathbf{b}(1-x)} \psi(x,b)$$

Tells whether or not PLC exists in model

Brodsky *MDPI Physics* 4 (2022) 2, 633 did not use this

Difference is big because of large x dominance

This paper should not be used to Motivate (e,'p) at higher Q^2



LHLFQCD does not yield PLC

Summary and future

- Color transparency may resolve underlying mechanism of high x behavior of quark structure functions
- Holographic theory results - expansion assumes PLC exists in model. PLC does not exist in proton model. Expansion calculation may still be correct
- Experiments are difficult- high Q^2 in nucleus
- $(e, e'\pi)$ likely best bet -2 quarks
- $(e, e'\rho)$ interesting, but baseline less well known
- $(e, e'pn), (e, e'pp)$ interesting
- $(e, e'p)$ at higher Q^2 not so promising