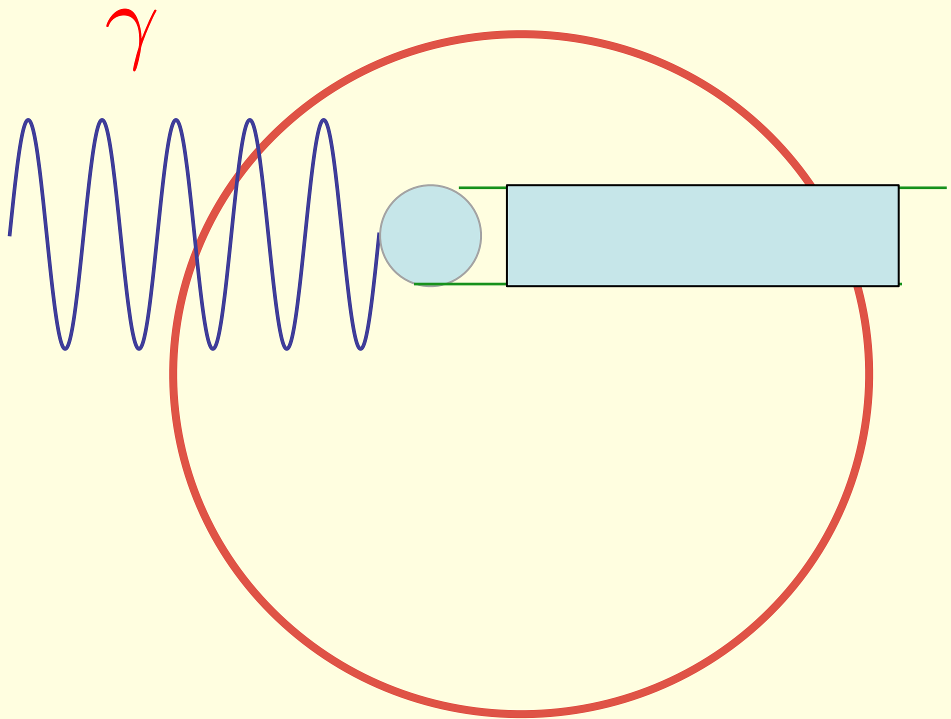
Color Transparency with protons

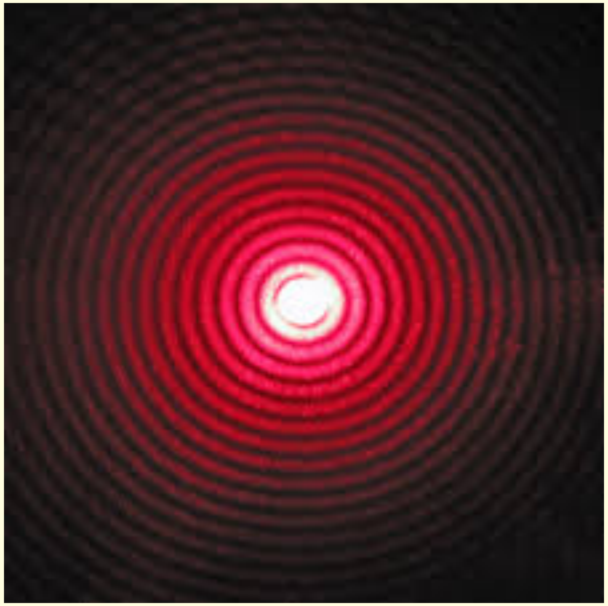
G. A. Miller, UW, Seattle

- What is Color Transparency
- Why important
- Color transparency in (p,pp) and (e,e'p)

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

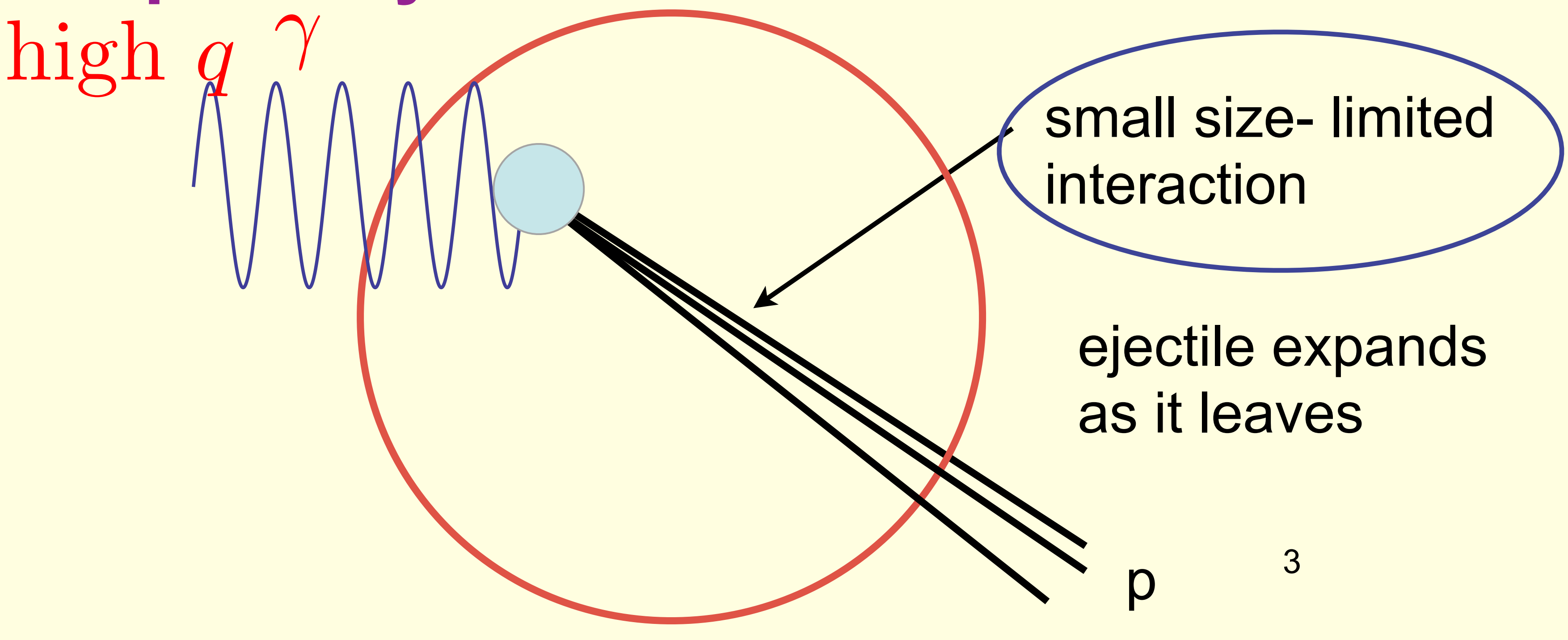
- **Proton in nucleus hit by photon**
- **proton goes out, interacting**
- **absorbed by nuclei, nucleus is black disk, nuclei cast shadow**
- **Diffraction pattern**



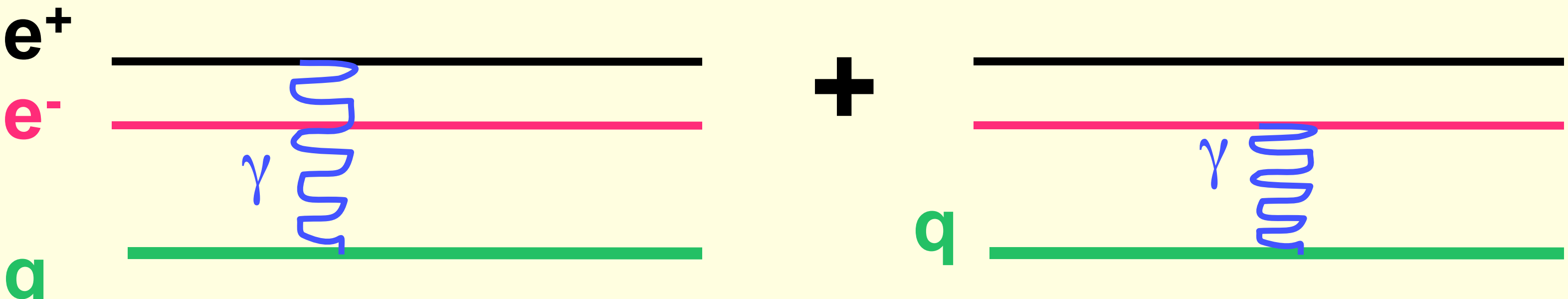


Newer/non-standard Idea

- **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**



QED Charge neutrality and coherence



Same final state, exclusive charge cancellation :

$$V = e\,q/r_+ - e\,q/r_- = e\,q\,(r_- - r_+)\,/\,(r_+ r_-)$$ **dipole**

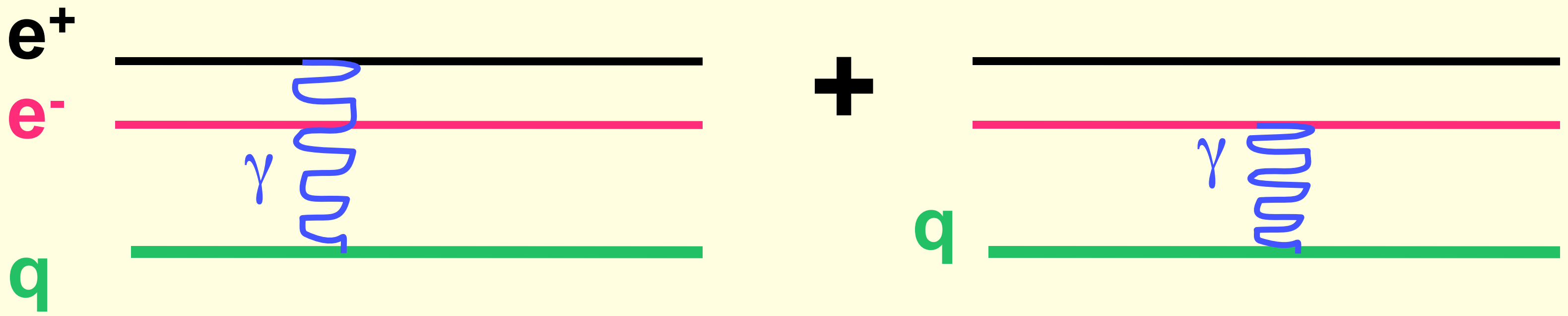
COHERENCE –does your experiment maintain coherence? Inclusive:

square amplitudes first then add,NO cancellation

Must have exclusive reaction

Strong interaction version of charge cancellation used in factorization proofs

QED Charge neutrality and coherence



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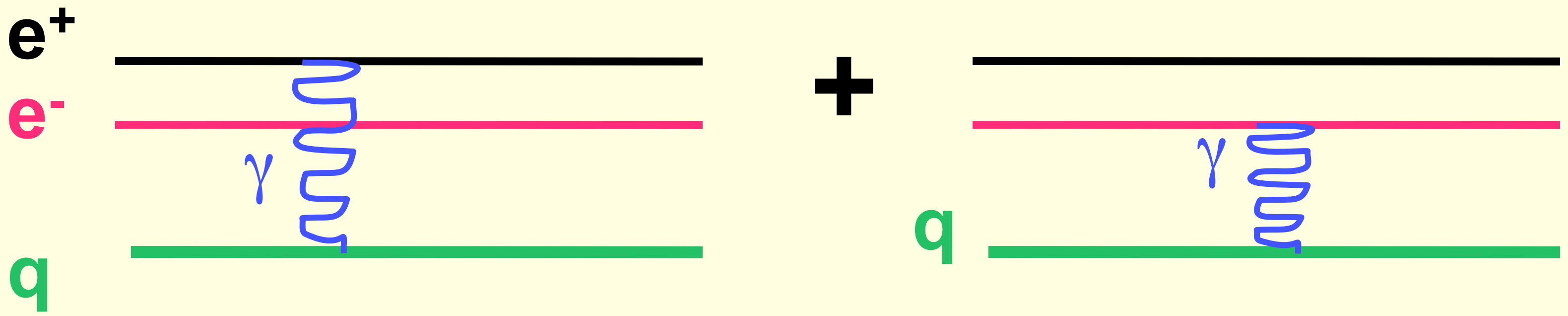


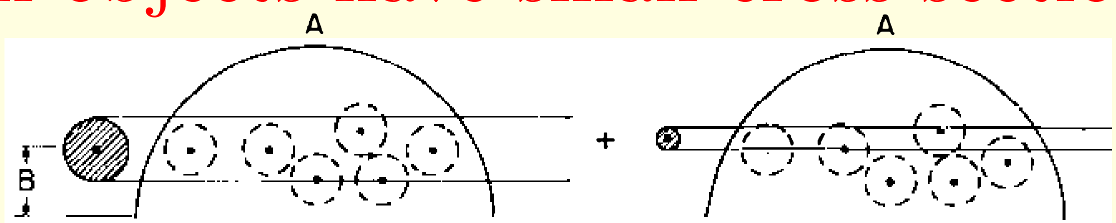
Strong int'n- two gluon exchange- dipole^2

QCD facts

1. Hadrons are made of configurations of very different sizes:

$|3q\rangle,\ |4q\bar{q}\rangle,\ |3q,g\rangle\cdots$

2. Small objects have small cross sections



small b

Two gluon exchange $\sigma(b^2)\sim b^2$ from color neutrality

3. Small objects produced in high Q^2exclusive processes (PQCD) Brodsky, Mueller

Also non-perturbative

Color Transparency- high Q^2 makes small objects that do not interact

Small object is point-like configuration- PLC

Color Transparency Idea

- **make PLC at high Q^2**
- **exclusive process to use coherence -cancel**
- **no or reduced interactions**

Why interesting?

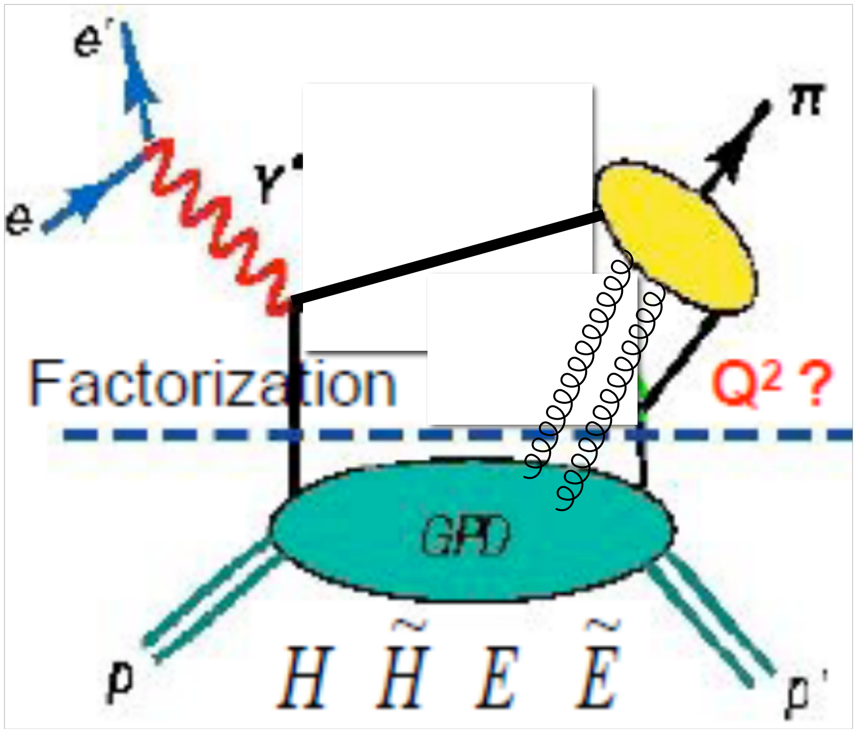
•new dynamical phenomena- turn off strong interactions

•are PLCs made? -high Q^2-exclusives

•color neutrality needed in QCD factorization proofs- cut off integral over large perp momenta, short perp distances, cancel soft gluons

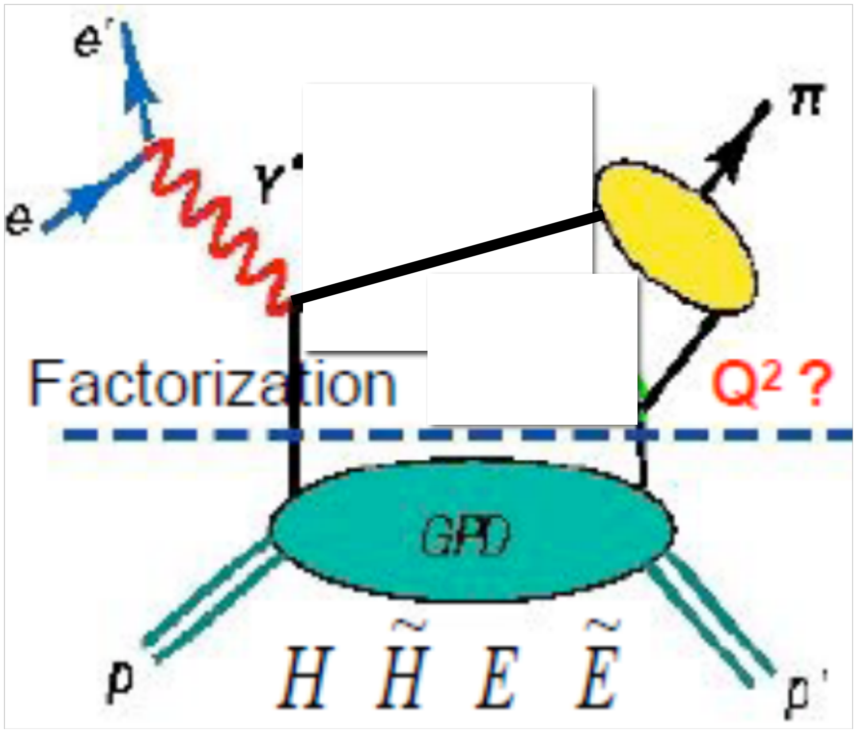
•nuclear physics implications of PLC- nucleon modified- EMC effect

Factorization in Exclusive Cross Sections needed for GPDs



Color neutrality causes cancellations at high momentum transfer so that soft gluon exchanges disappear

Factorization in Exclusive Cross Sections needed for GPDs



- Connection of GPDs to exclusive cross sections enable rigorous mapping of complete nucleon wave functions

- GPD framework assumes dominance of the handbag model

- Outgoing meson maintains small transverse size, suppressing soft interactions ➞ factorization

- Factorizes into a hard interaction with single quark and soft part (GPDs)

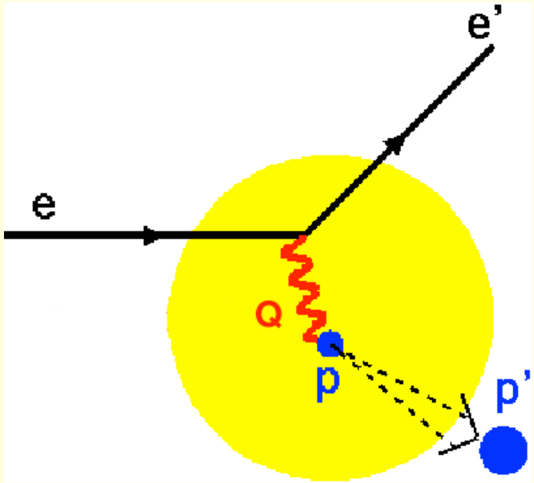
Problem PLC Expansion

- $|PLC\rangle$ 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
- $|PLC\rangle_t = \Sigma_n C_n \, \mathrm{Exp}(-i\, E_n\, t)|n\rangle$ $E_n(P) = \sqrt{P^2 + M_n^2} \approx P + M_n^2/(2P)$
- relative phases change with time, size increases
- $t_{Exp} \sim R_A << 1/(E_n - E_{proton}) << 1$ no expansion
- High P (momentum of PLC)
- $t_{Exp} = 1/(M_n - M_p)(2P/(M_n+M_p))$ = natural rest frame time times dilation factor
- What is M_n ?
- At high enough P we have freezing $t_{Exp} >>> R\_A$

Problem at JLAB6 for sure, Is 12 enough?

Why PLC at high momentum transfer?

Example: e-p scattering



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

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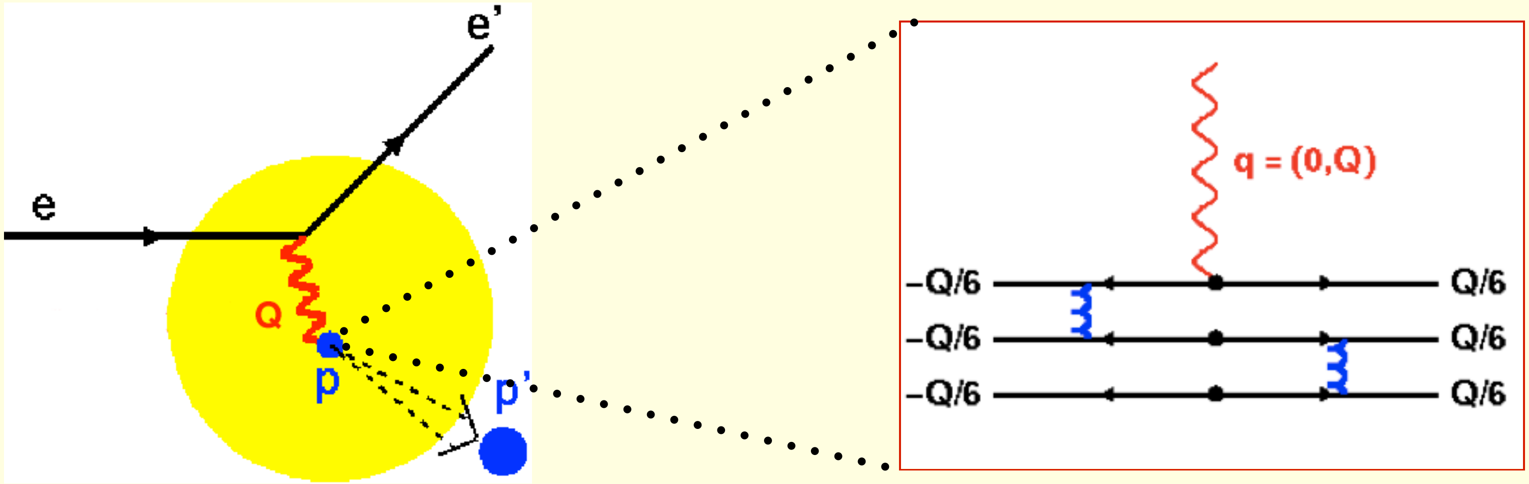

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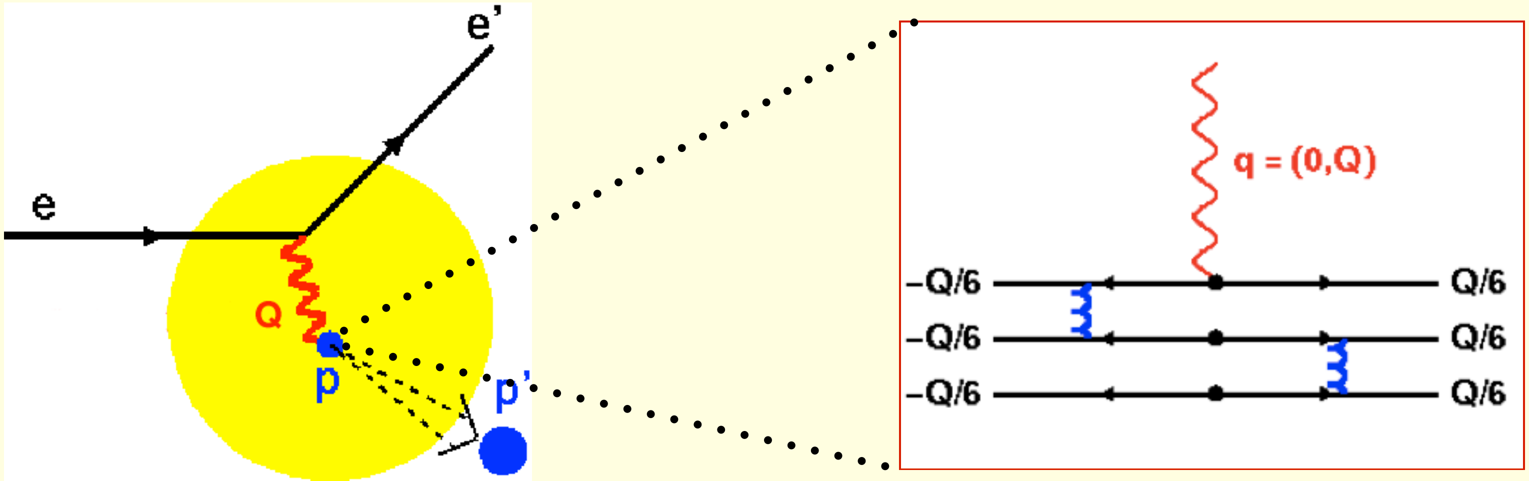
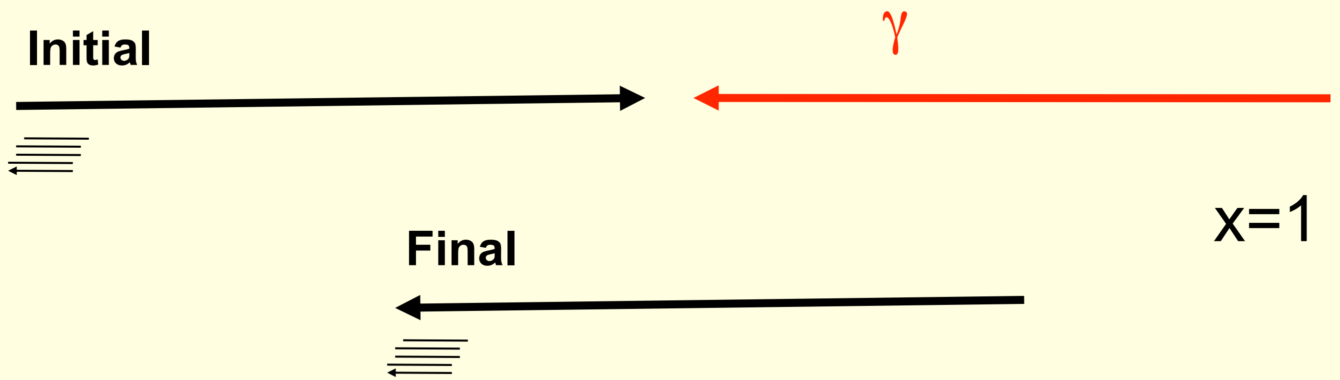


Momentum of exchanged gluon ~Q, separation ~1/Q

- 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

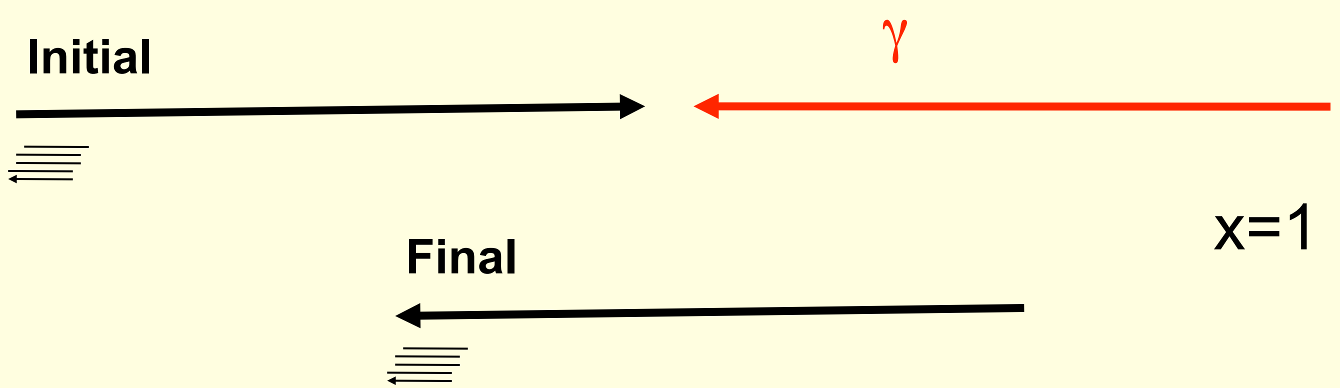
Why not PLC ?

e-p scattering **Feynman mechanism**



Why not PLC ?

e-p scattering **Feynman mechanism**



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

Color transparency with mesons

$T = \sigma/\sigma_B$

- (π, JJ)**Prediction Frankfurt et al. Phys.Lett. B304 (1993) 1. Experiment D Ashery et al PRL 86(2001) 4773 Seen large** T
- $(e, e'\pi)$ **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

Outline of remainder

- Early searches (p,pp) data
- (p,pp) Calculations
- New (e,e’,p) results from Jefferson Lab
- Implications of new data-Experiment
- Implications of new data-Theory

VOLUME 61, 1698

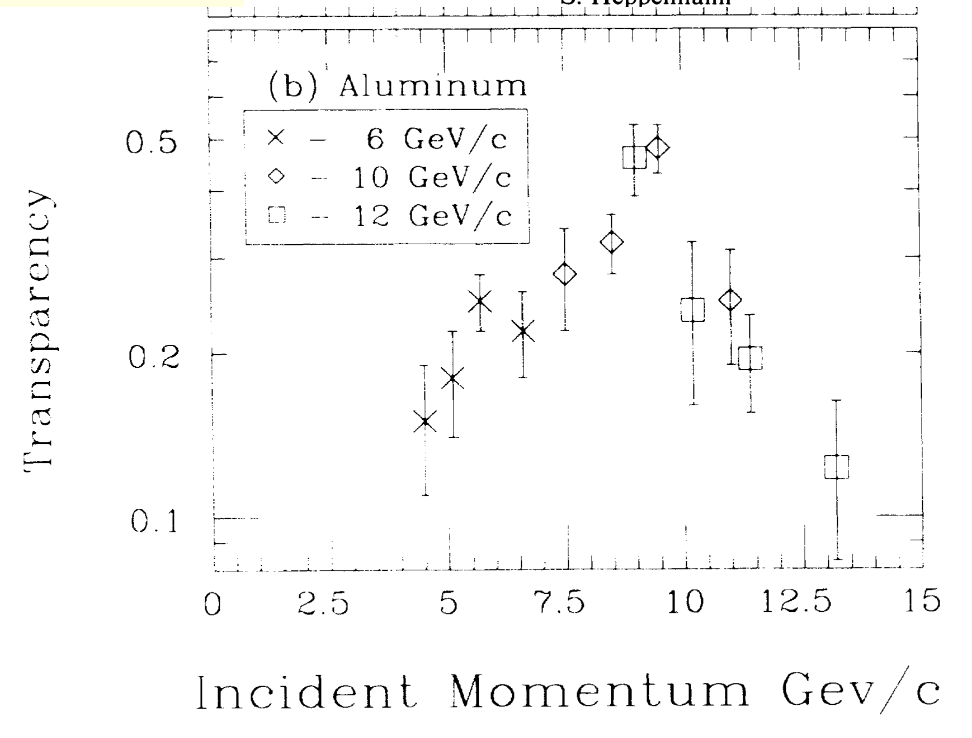
PHYSICAL REVIEW LETTERS

Nuclear Transparency to Large-Angle ***pp*** **Elastic Scattering**

A. S. Carroll, D. S. Barton, G. Bunce, S. Gushue, and Y. I. Makdisi
Brookhaven National Laboratory, Upton, New York 11973

S. Heppelmann

σ/σ_B



The bound proton has momentum component parallel to the beam p_z

p_z is missing momentum

$P_{\text{eff}} = P_{\text{Beam}}(1 - p_z/M)$

3 beam energies 4 sets of p_z $\neq$ doing experiments with 12 beam energies

Rules of color transparency calculations

- Include the effects of expansion
- Calculate what the experiments measure
- Clearly explain what is calculated

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Clearly explain what you measure

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These rules were violated many times

Rule of color transparency experiments
Clearly explain what you measure

This rule was violated only a few times because only a few experiments exist

Modeling expansion I

Strikman and Frankfurt –diffusion b^2 ~ t=z

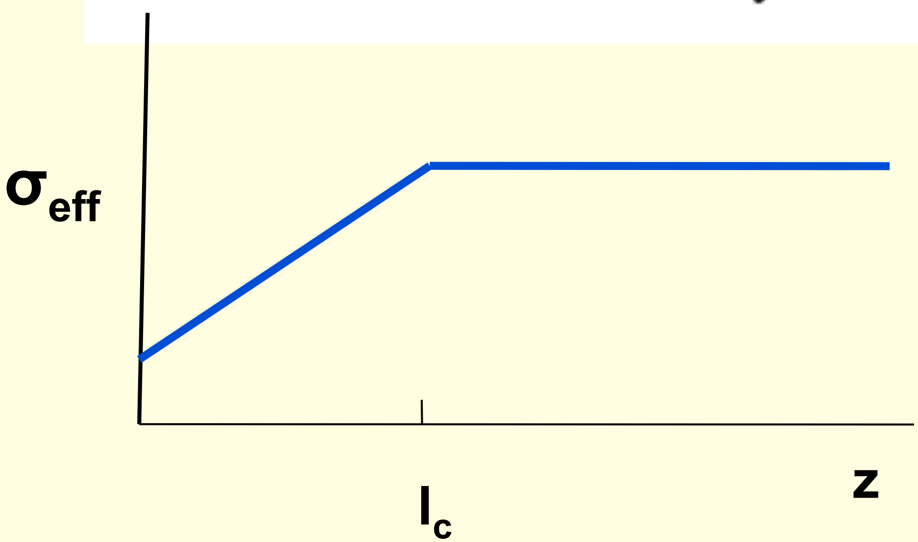
$$\sigma_{eff}(z,p_\pi) = \sigma_{\pi N}(p_\pi)\left[\left(\frac{n^2\langle k_t^2\rangle}{Q^2}(1-\frac{z}{l_c})+\frac{z}{l_c}\right)\theta(l_c-z)+\theta(z-l_c)\right]$$

$$\sigma_{PLC} \equiv \sigma_{\pi N}(p_\pi)\frac{n^2\langle k_t^2\rangle}{Q^2}$$

$$l_c = 2\,p/\Delta M^2$$

$$\Delta M^2 = 0.7\ \mathrm{GeV}^2.$$

$$l_c = 0.6\ \mathrm{fm}\ (\mathrm{p/GeV})$$



Similar formula derived by Jennings & Miller, l_c= expansion time

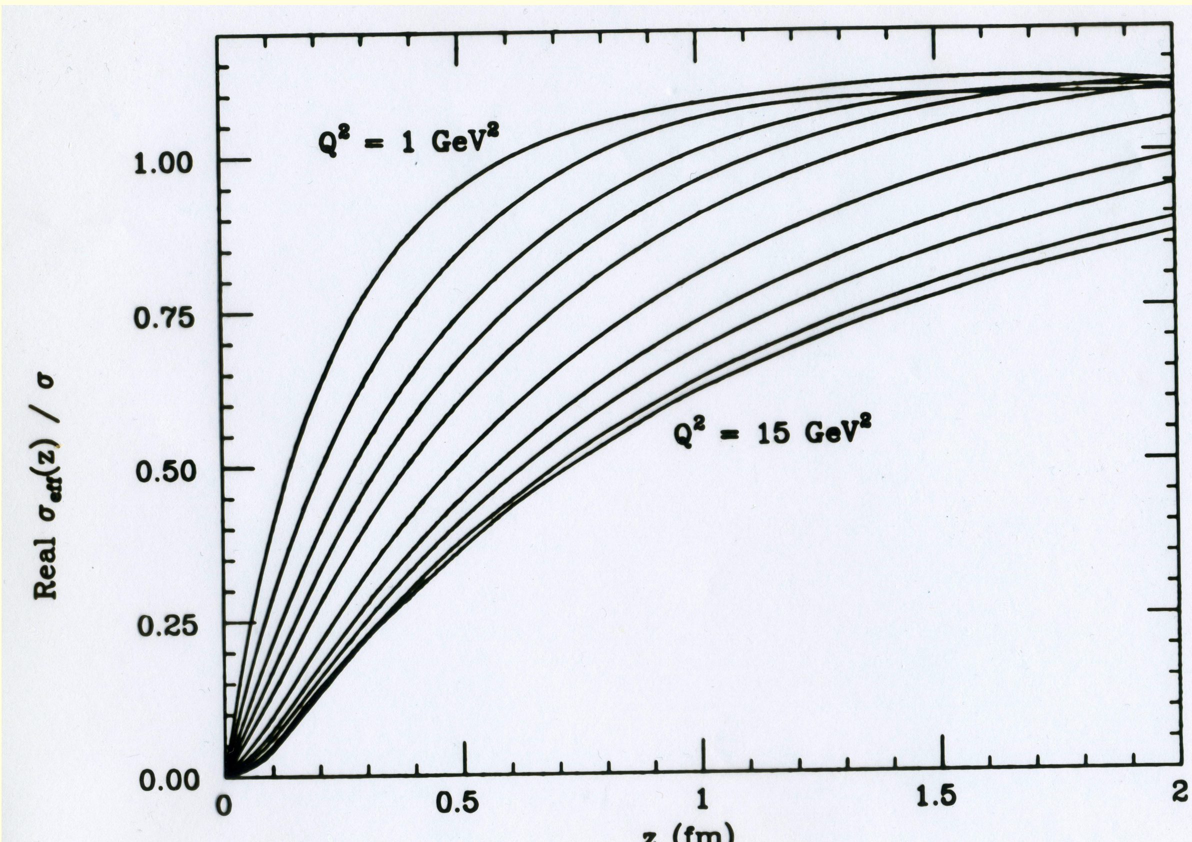
Modeling expansion II

VOLUME 69, NUMBER 25 3620 PHYSICAL REVIEW LETTERS 21 DECEMBER 1992

Realistic Hadronic Matrix Element Approach to Color Transparency

B. K. Jennings G. A. Miller

Used measured electromagnet cross sections and strong diffractive production cross sections



Proton expands as it moves interacts more strongly

kinematics of (e,e'p)

Calculate what is measured-importance of p_z=k_z

Physics Letters B 318 (1993) 7–13

Color transparency in (p, pp) reactions

B.K. Jennings G.A. Miller

New calculations including a variety of necessary kinematic and dynamic effects show that the results of BNL $(p, 2p)$ measurements are consistent with the expectations of color transparency.

BNL date

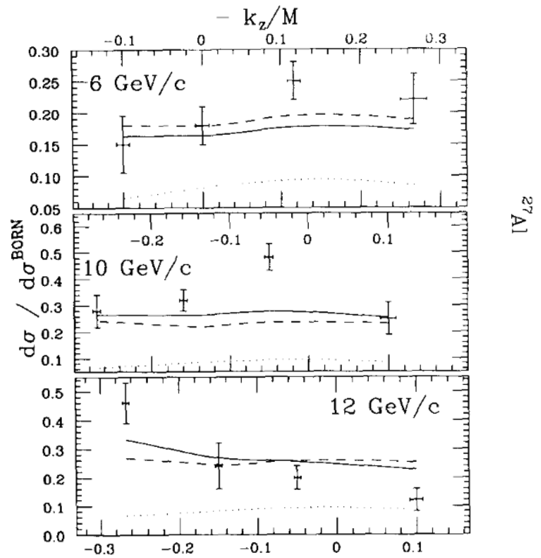


Fig. 2. Full Al data. Solid – full calculation. Dashed – without the Ralston–Pire effect. Dotted – Glauber.

Glauber is dotted low by at least 2

2 Color T calculations

- Different plotting of data is instructive
- Theory fits all data points within 2 st. dev. or less
- "BNL experiments calibrate size of color transparency effects"
- "higher energy experiment which estimates k_z dependence **should observe measurable effects**"

Calculate what is measured-importance of $p_z=k_z$

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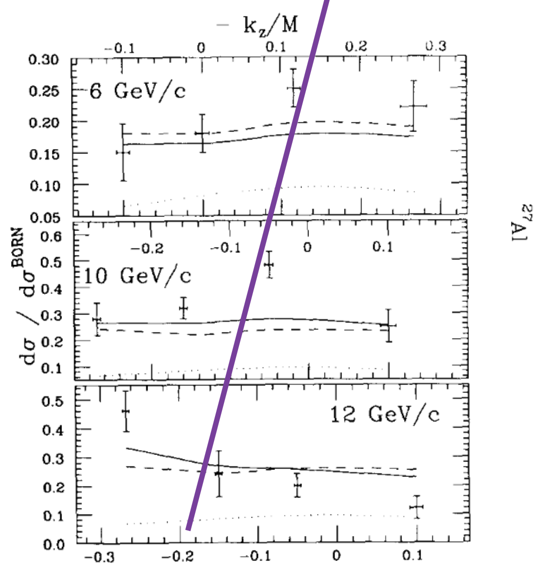


Fig. 2. Full Al data. Solid – full calculation. Dashed – without the Ralston–Pire effect. Dotted – Glauber.

Glauber is dotted low by at least 2

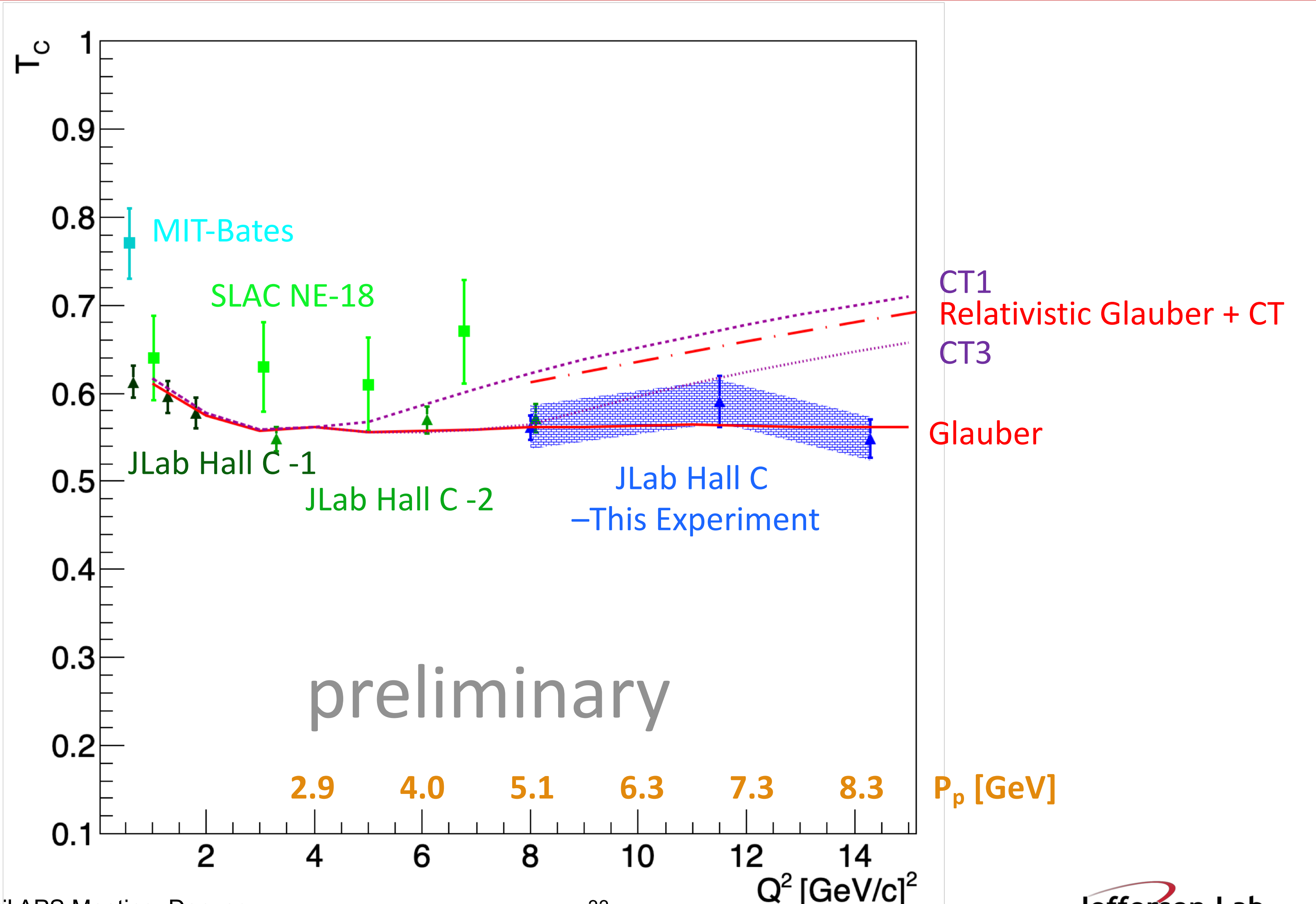
2 Color T calculations

Later experiments measured along the line

- Different plotting of data is instructive
- Theory fits all data points within 2 st. dev. or less
- "BNL experiments calibrate size of color transparency effects"
- "higher energy experiment which estimates k_z dependence **should observe measurable effects**"

Transparencies-preliminary

Holly Szumilla-Vance



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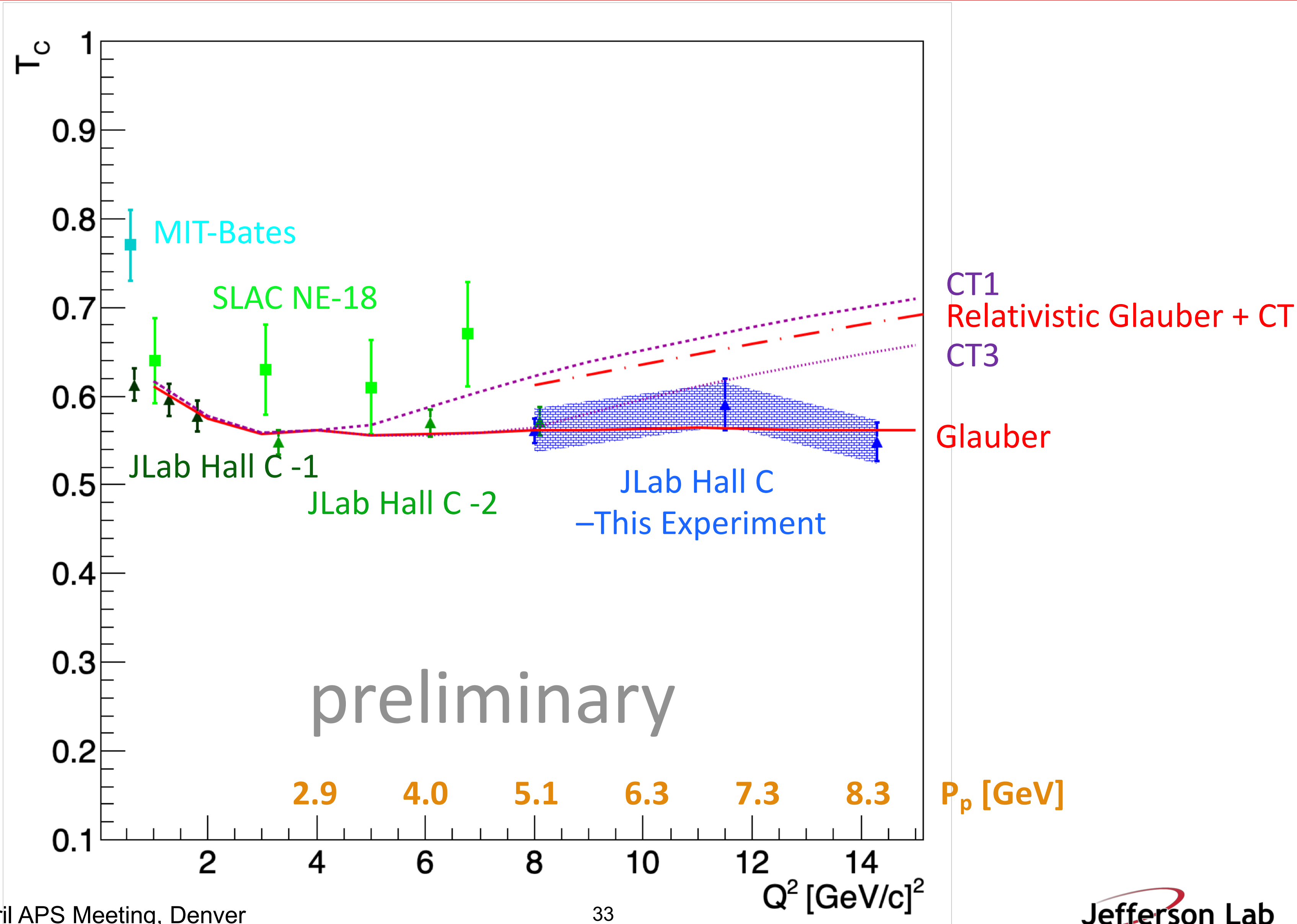

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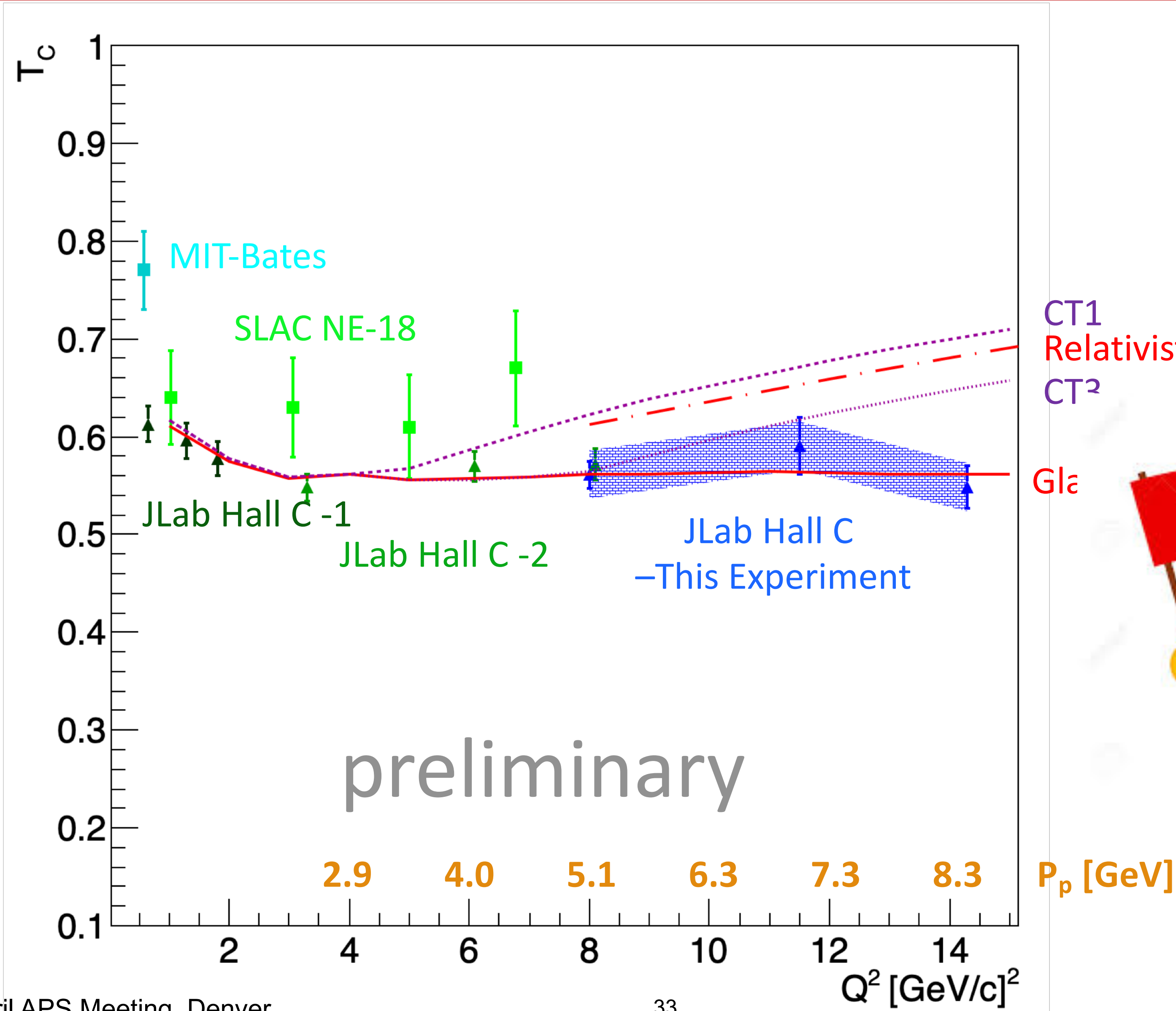

Jefferson Lab

(e,e'p) sees no Color T when (p,pp) does

Some ways to avoid contradiction:

- (p,pp) measurement not exclusive so calibration wrong
- Hidden signal in k_z dependence (e,e'p)?
- Expansion is faster than expected
- high momentum transfer reactions do not make PLC
- still more Q^2 needed, not gonna happen

Is there a problem with factorization in GPDs?

- Both Color T and Factorization in GPDs require color neutrality that cancels if relevant separations are small
- Factorization in GPDs requires cancellations over distances less than size of nucleon
- Color Transparency requires cancellations over distances less than size of nucleus

Is there a problem with factorization in GPDs?

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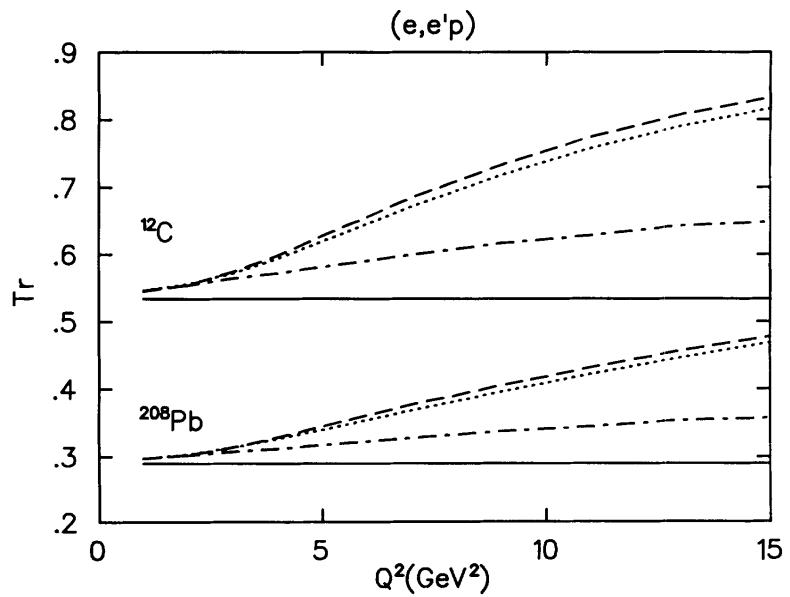
No

VOLUME 69, NUMBER 25 3620 PHYSICAL REVIEW LETTERS 21 DECEMBER 1992

Realistic Hadronic Matrix Element Approach to Color Transparency

B. K. Jennings G. A. Miller



Suppression of PLC in reactions – Color Transparency

Reduced initial, final state interactions in high Q^2 quasielastic nuclear reactions (p,pp),(e,e'p), (e,e',π), (e,e' ρ), (π +A →jet +jet +A, FermiLab)

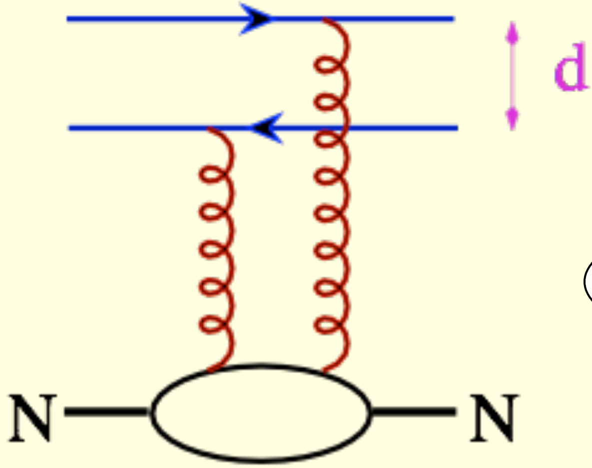
WHY?

1. high Q^2 hadronic exclusive reactions proceed by PLC formation - Brodsky, Mueller '82
2. PLC have small scattering amplitudes-gluon emission amplitudes cancel- coherent
3. Problem-PLC expands as it moves

Strikman, Frankfurt '88, Jennings & Miller '90,'91- Need high energies

Gluonic strong interaction

expectation: small objects interact weakly, like small dipoles in QED.

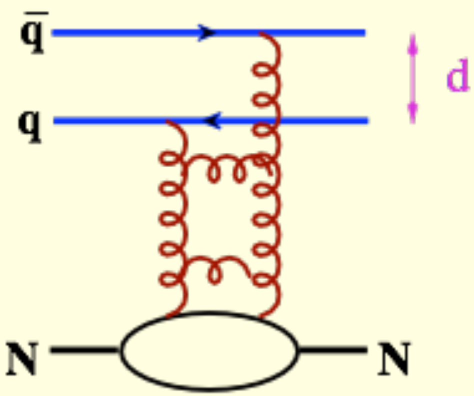


Two gluon exchange model

F.Low & S.Nussinov 75

$\sigma = C\, d^2$ (F.Low 75)

C does not depent on E_{inc}



pQCD in the leading log d approximation (Baym, Blattel,FS, 93)

$$\sigma^{inel}_{q\bar{q}N}(d,E_{inc}) = \frac{\pi^2}{3} d^2 \alpha_s\left(\frac{\lambda}{d^2}\right) x\, G_N\left(x, \frac{\lambda}{d^2}\right)$$

Gluon distribution -x, d dependence - can go from transparent to opaque

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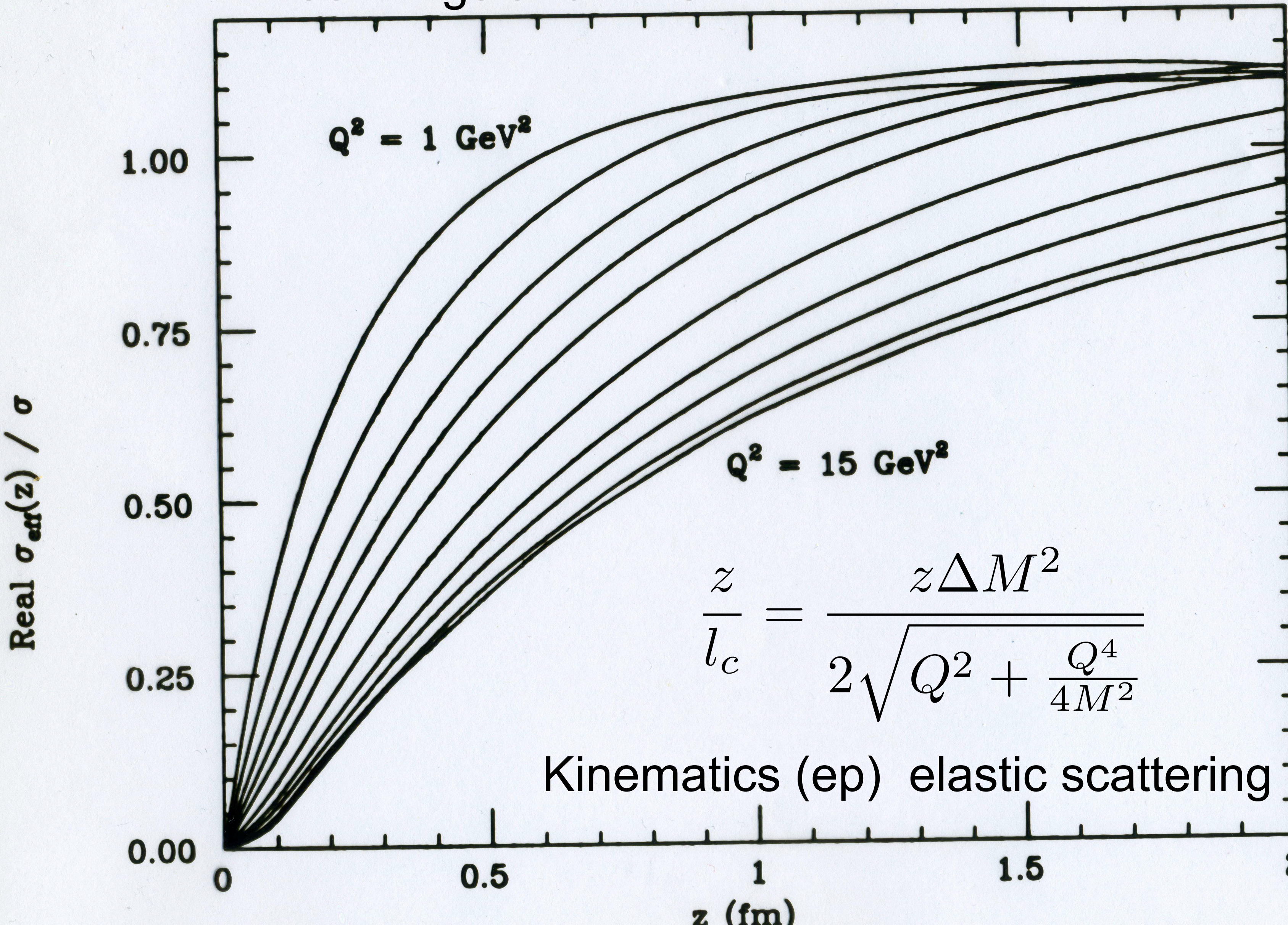
Realistic Hadronic Matrix Element Approach to Color Transparency

Jennings and Miller



$$\frac{z}{l_c} = \frac{z\Delta M^2}{2\sqrt{Q^2 + \frac{Q^4}{4M^2}}}$$

Kinematics (ep) elastic scattering

Ratio of cross-sections for exclusive processes from **nuclei** to nucleons is called **Transparency**

Exclusive Processes

Nucleon

$A + B \rightarrow C + D$

Nucleus

$A + B' \rightarrow C + D + X$

$$T_A = \frac{\sigma(A)}{A\sigma_0}$$

$\sigma(A)$ parameterized as = $\sigma_0 A^{\alpha}$

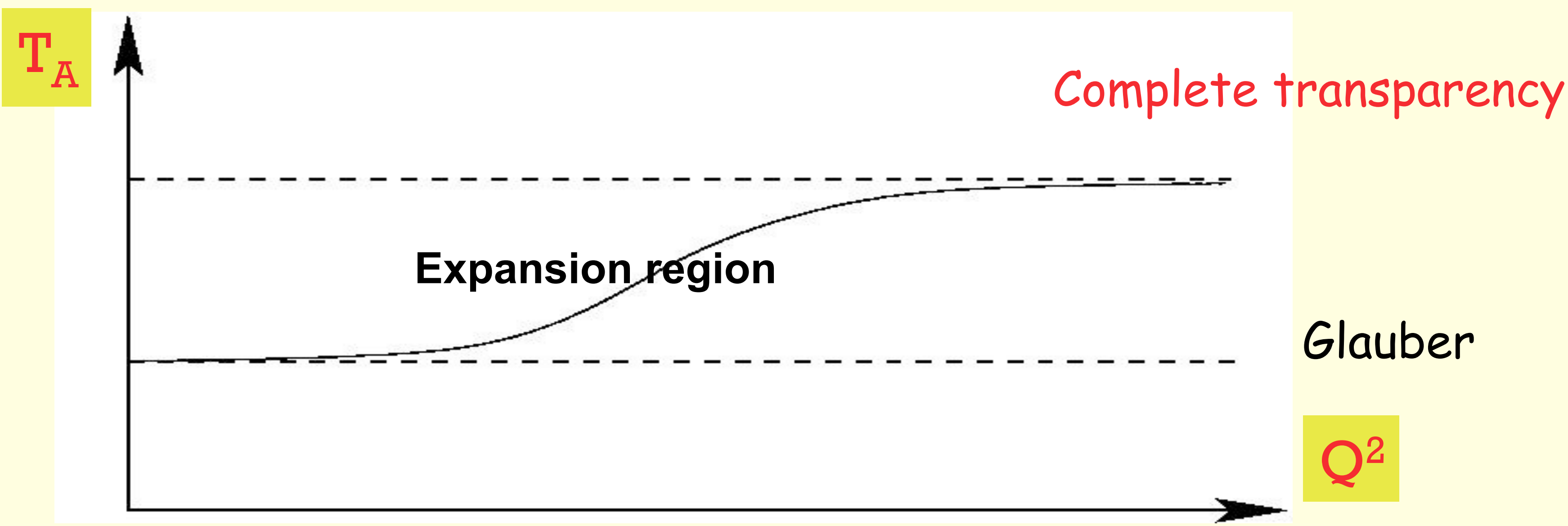
σ_0 = free (nucleon) cross-section

Traditional nuclear physics calculations (Glauber calculations) predict transparency to be **energy independent** .

Signature of Color Transparency

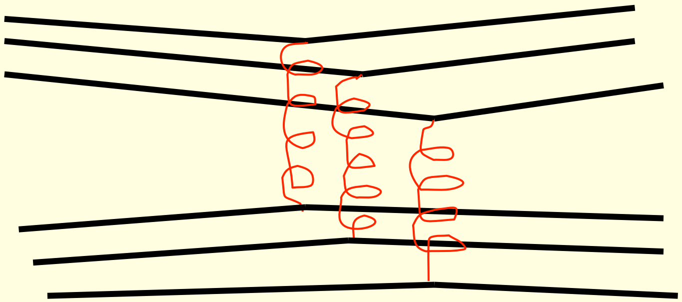
The signature of CT is the rising of the nuclear transparency T_A

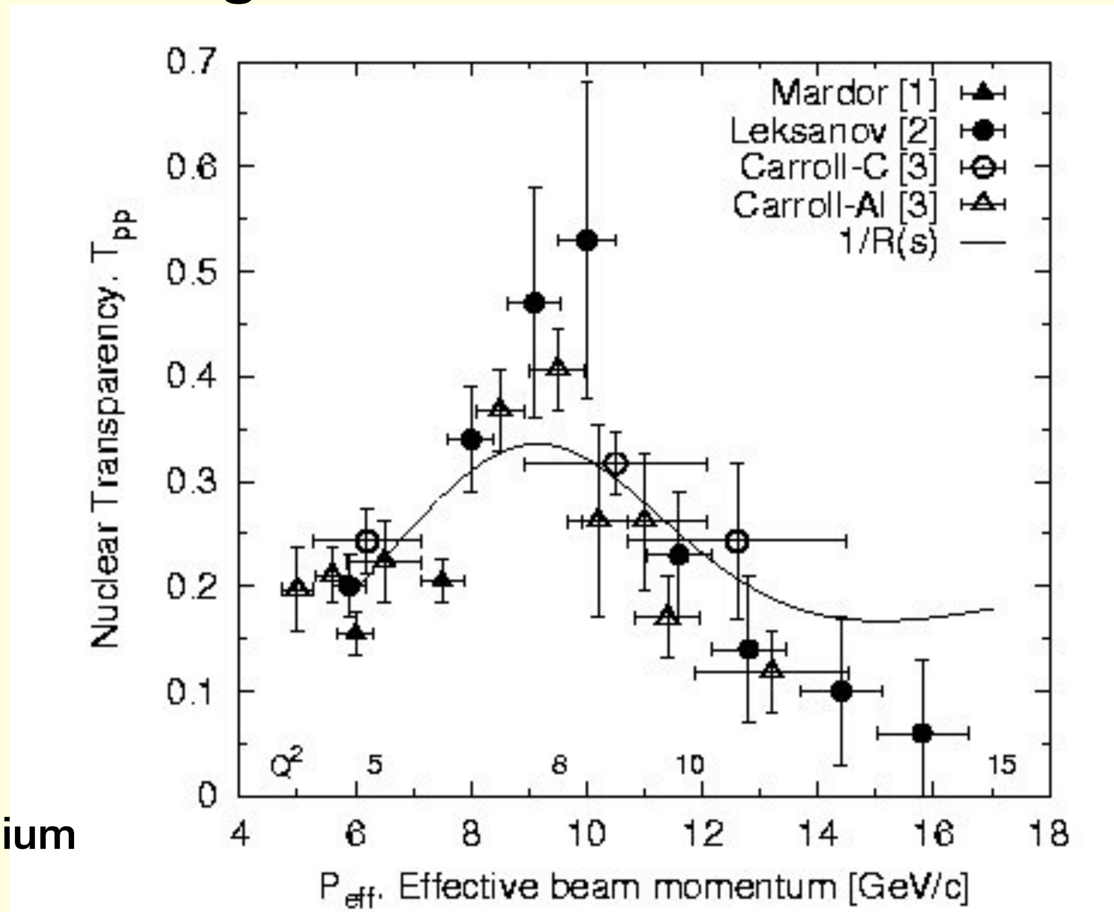
with increasing hardness Q^2 of reaction (Q)



Quasi-elastic A(p,2p) : BNL E834, **E850**

PLC plus Blob like configuration- BLC





Landshoff process in pp

Ralston and Pire :
Interference between short and long distance amplitude in the free pp cross-section where the nuclear medium acts as a filter for the long distance amplitudes

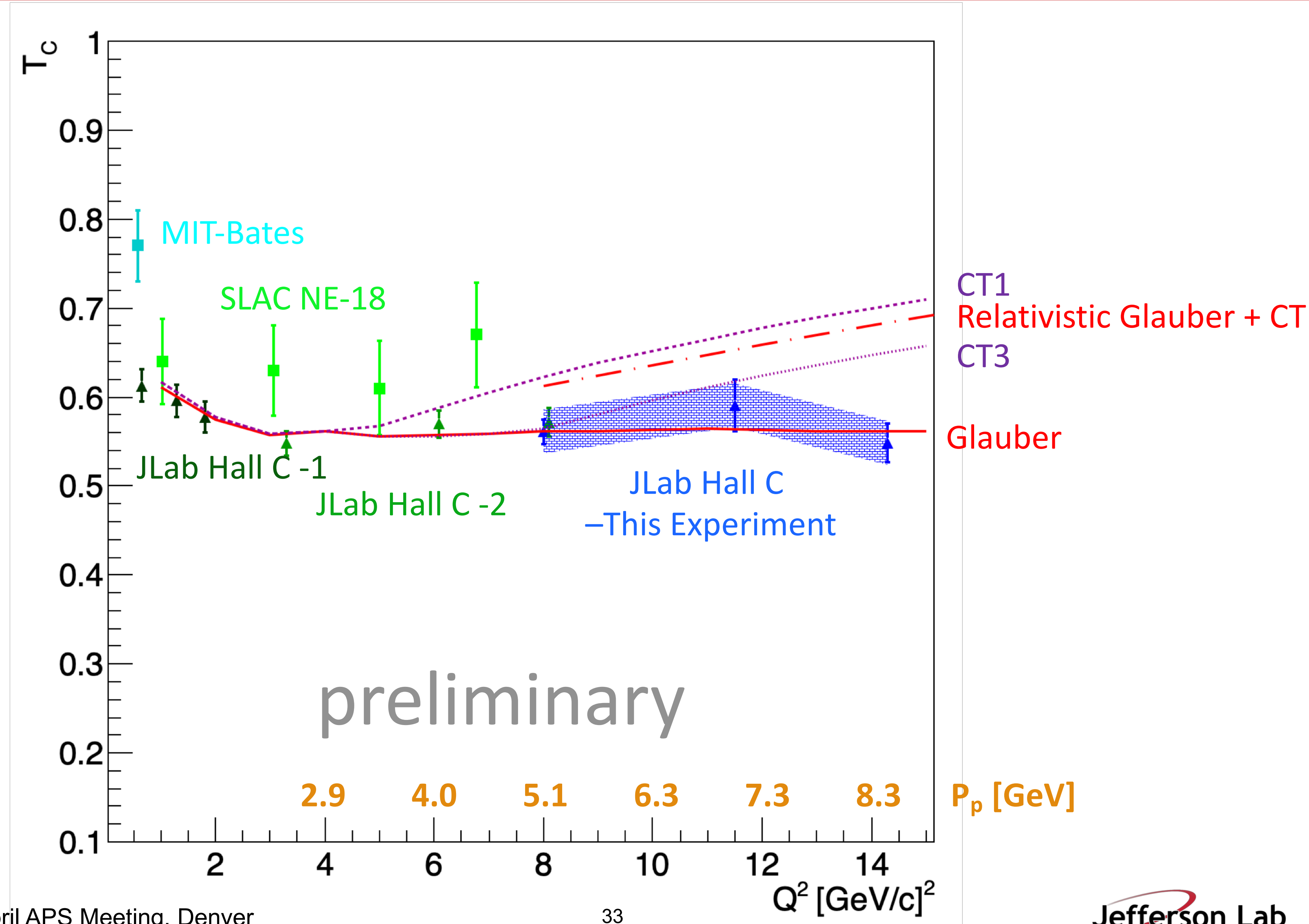
Brodsky and De Teramond : Unexpected decrease could be related to the crossing of the open-charm threshold

Problem- Fermi motion correction, experimental resolution???

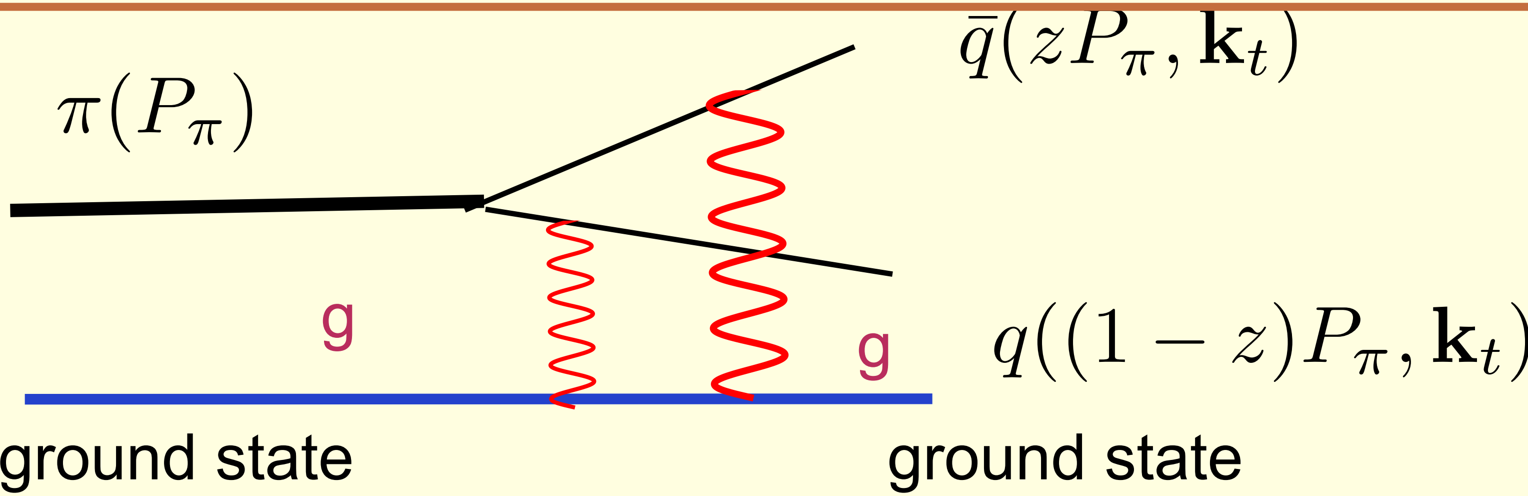
Do better expt!

Transparencies-preliminary

Holly S-V talk



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

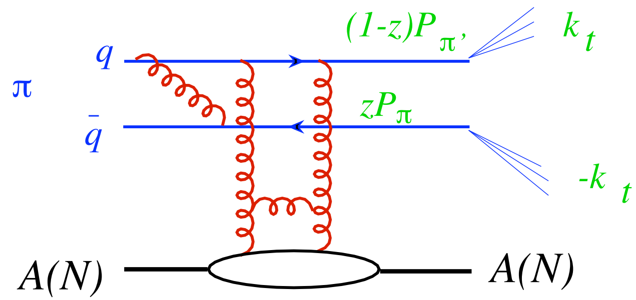


- final state $q\bar{q}$ becomes 2 high rel. moment jets, select PLC component of pion
- $\pi \to q\bar{q}$ before hit target, no expansion
- one interaction $f \sim id^2 \sim i/\mathbf{k}_t^2$
- Coherent process- enhanced! FMS

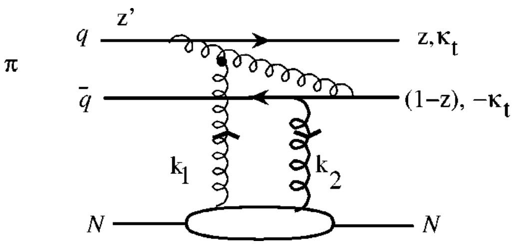
Phys.Lett. B304 (1993) 1

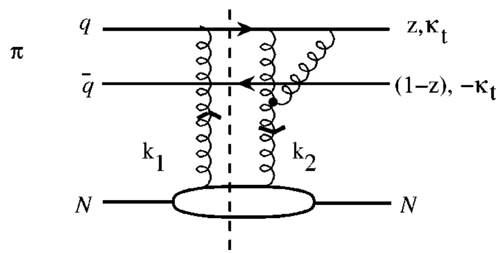
$$\mathcal{M}_A(forward) \propto Af$$

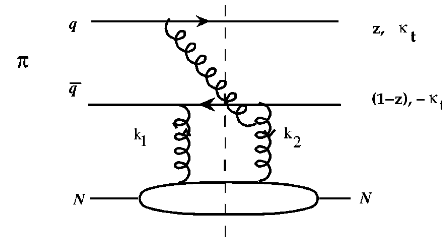
Dominant diagram

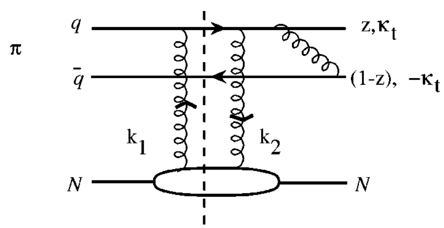


Examples of the Suppressed diagrams









1993 predictions Frankfurt, Miller, Strikman

M(A) =A $e^{t\,R(A)}$ M(N) , σ(A)~$A^{4/3}$ + O(1/k^2) ~$A^{1.55}$

$$\frac{d\sigma(z)}{dz} \propto \phi_\pi^2(z) \approx z^2(1-z)^2 \text{ where } z = E_{jet_1}/E_\pi .$$

k_t dependence: $\frac{d\sigma}{d^2k_t} \propto \frac{1}{k_t^n}, n \approx 8$ for $x \sim 0.02$

k_t>1.5 GeV/c

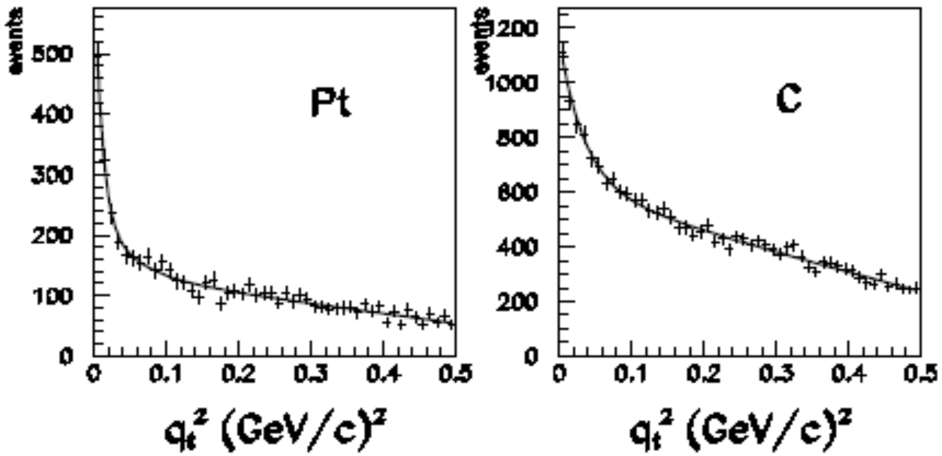
Naive expectation M(A)~ $A^{1/3}$ (nuclear path length), inelastic diffraction FMS93: M(A)~ $A^{.7}$

Later $M(A) = A\, e^{t\,R(A)} M(N) \frac{G_A}{AG_N}$

E791 results

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

♡ Coherent peak is well resolved:



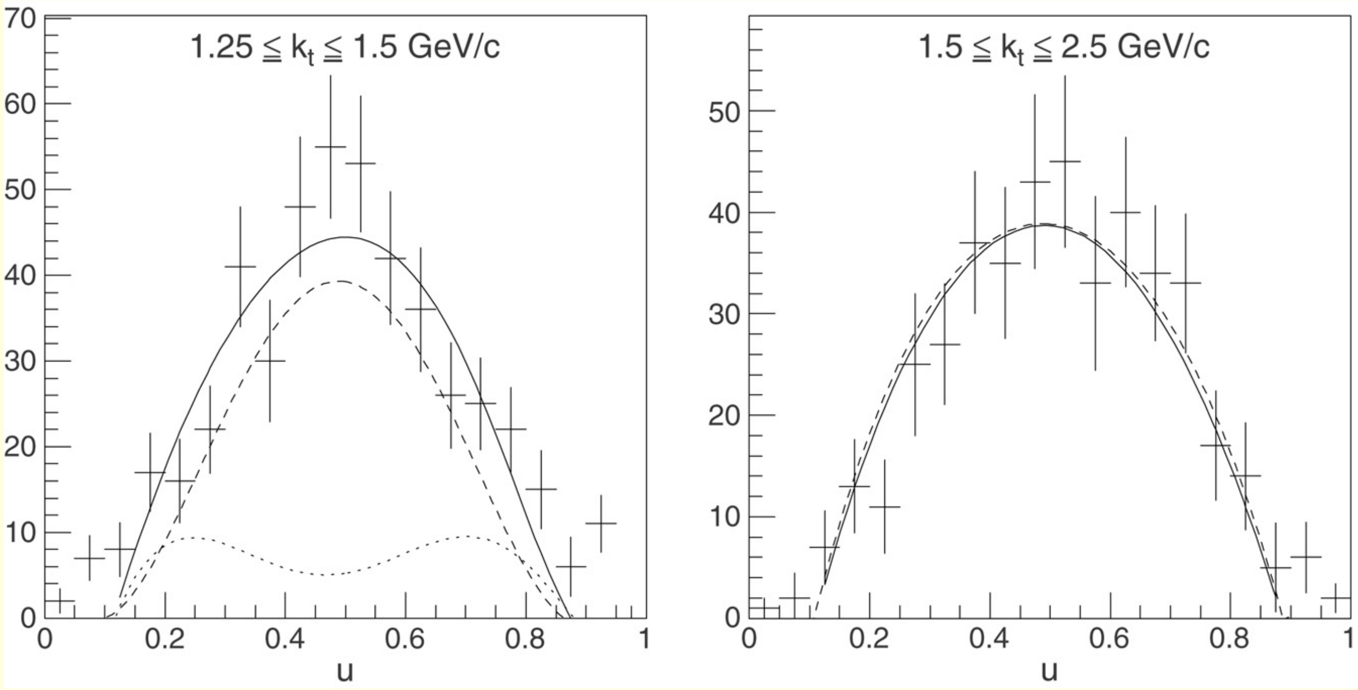
♡♡ Observed A-dependence $A^{1.61\pm0.08}$ $[C \to Pt]$

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!!

z-dependence confirmed, high k_t

D. Ashery / Progress in Particle and Nuclear Physics 56 (2006) 279–339



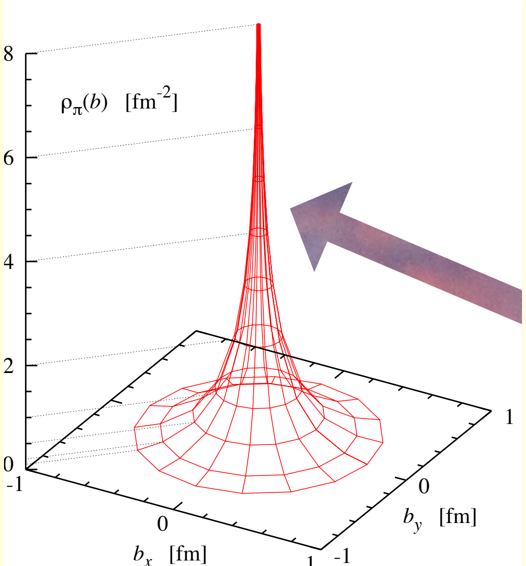
u=z of previous

E791 summary

- Color transparency discovered factor of 7 over Glauber
- seen clearly for k_t=1.8,2.3 GeV/c
- corresponds to Q^2=3.2, 5.3 GeV^2 low values accessible at Jlab
- p_π is large –no expansion
- plc made at Jlab only problem is expansion:small effects at Jlab6 should be strong signals at Jlab12

Color Transparency in meson production

- **(e,e' π) – E01-107**
- **(e,e',ρ^0) –CLAS eg2**
- **should be easier to have q q close together than qqq**
- Pion decays - W emission, must have PLC
- Pion has a PLC-singular central charge density G A Miller, **Phys.Rev.C79:055204,2009**.



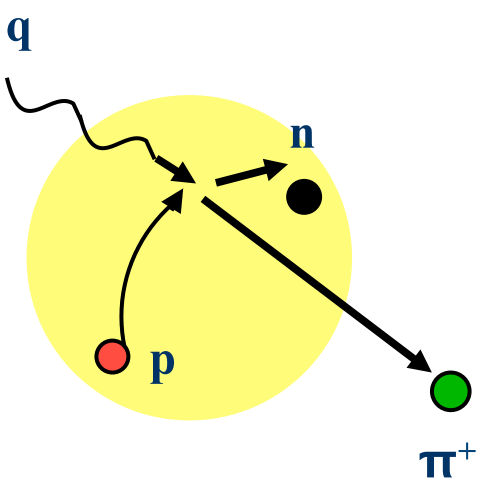
Pion transverse density

MS,2010 Weiss

Phys.Rev. D83 (2011) 013006

A(e,e'π⁺) for CT Search

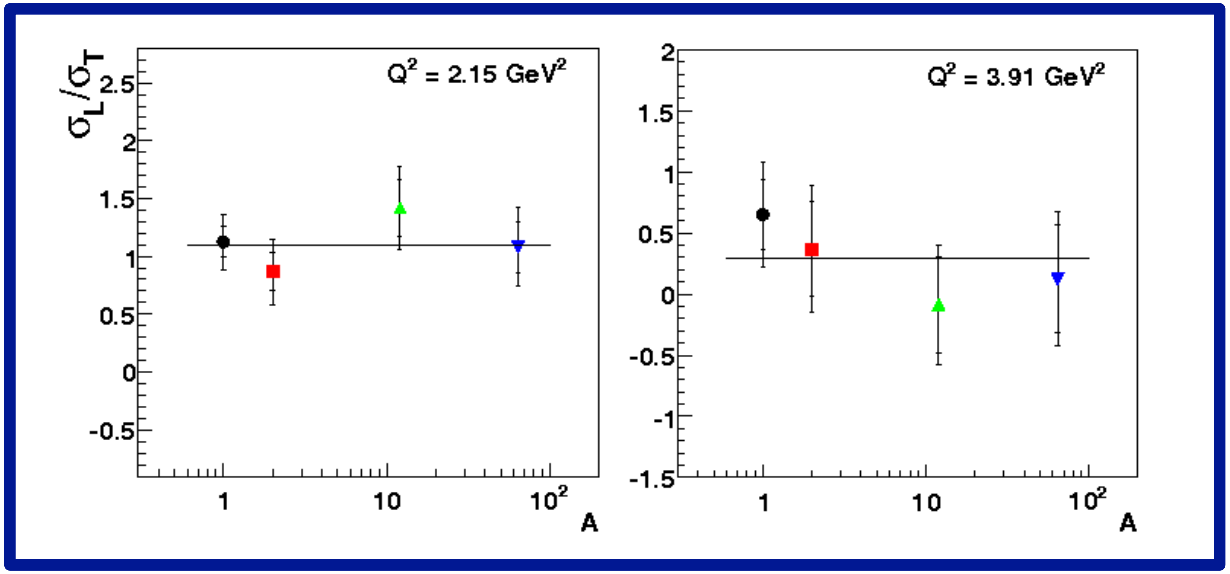
If π^+ electroproduction from a nucleus is similar to that from a proton we can determine nuclear transparency of pions.



$$\sigma_{A(e,e'\pi^+)X} = \sigma_{p(e,e'\pi^+)n} \otimes S(E,p)$$

$S(E,p)$ = Spectral function for proton

X. Qian et al., PRC81:055209 (2010),

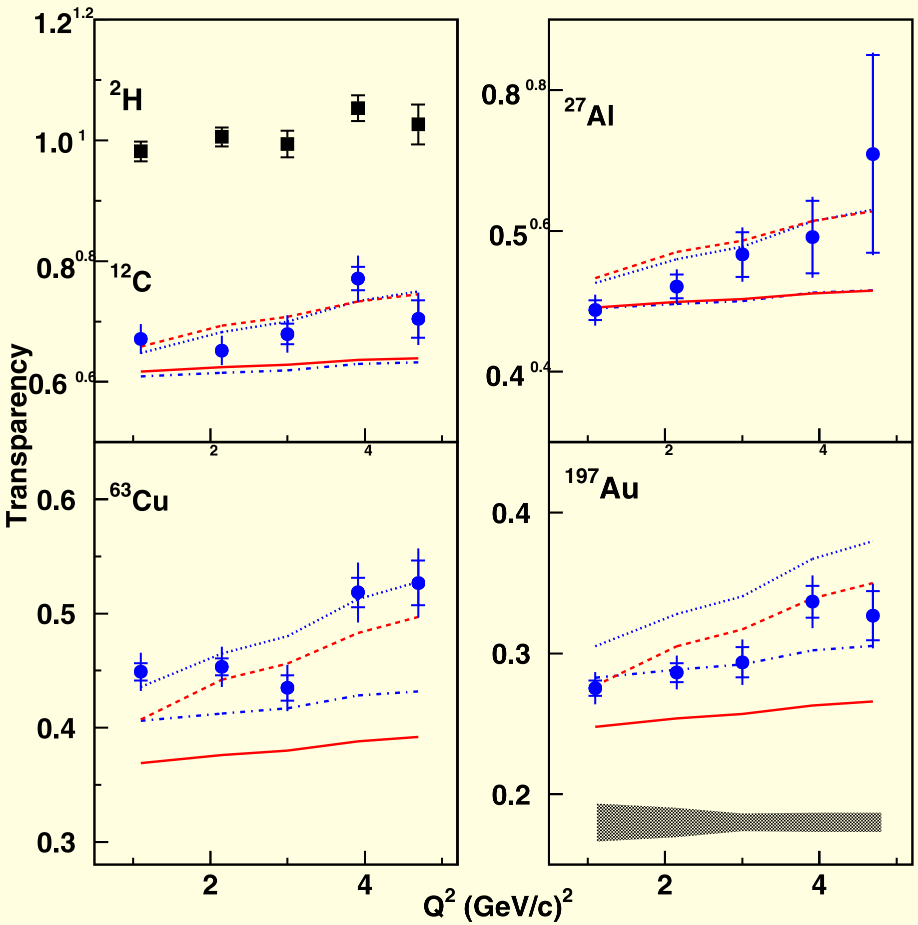


data well described via a MC simulation of a quasifree model including Fermi smearing, FSI and off-shell effects.

The quasi-free assumption was verified by L/T separation

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]



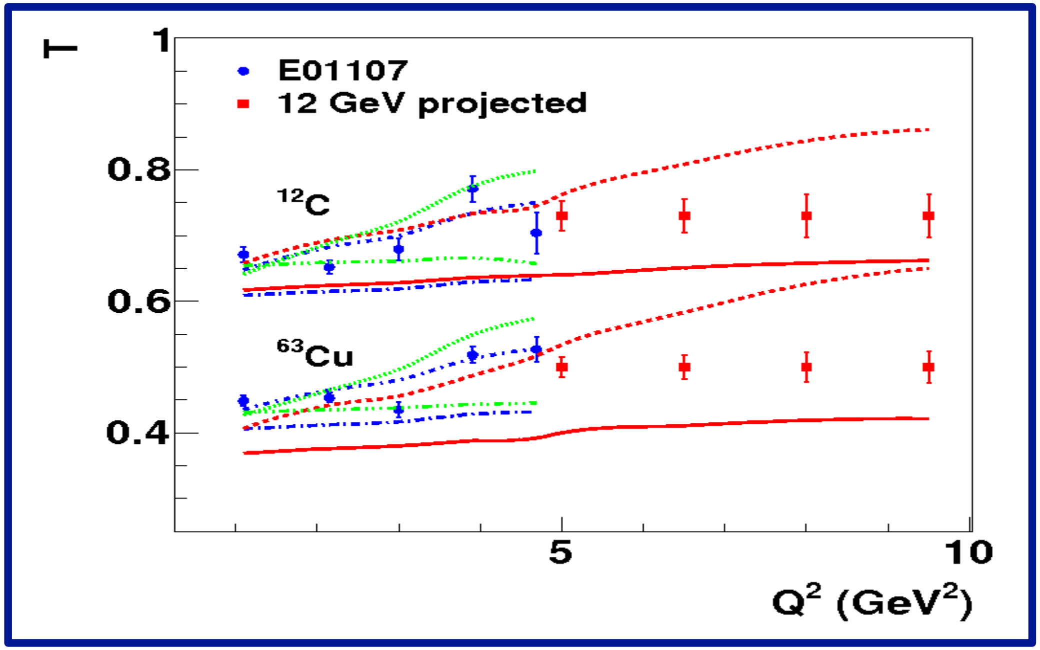
Solid Dashed
Glauber, Glauber
+CT
LMS
prc74,018201

dot-dashed, dotted
CosynPRC74,062201

$\pi - A$ total cross section

Solid-Glauber

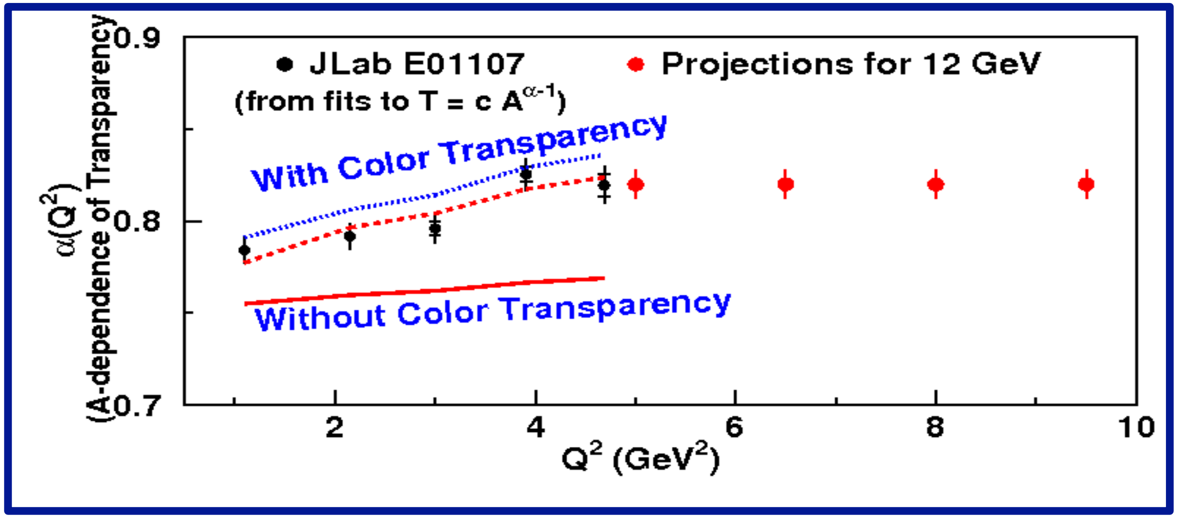
$A(e,e'\pi^+)$ @ 11 GeV



Will help confirm the onset of CT observed at 6 GeV

will verify the strict applicability of factorization theorems for meson electroproduction

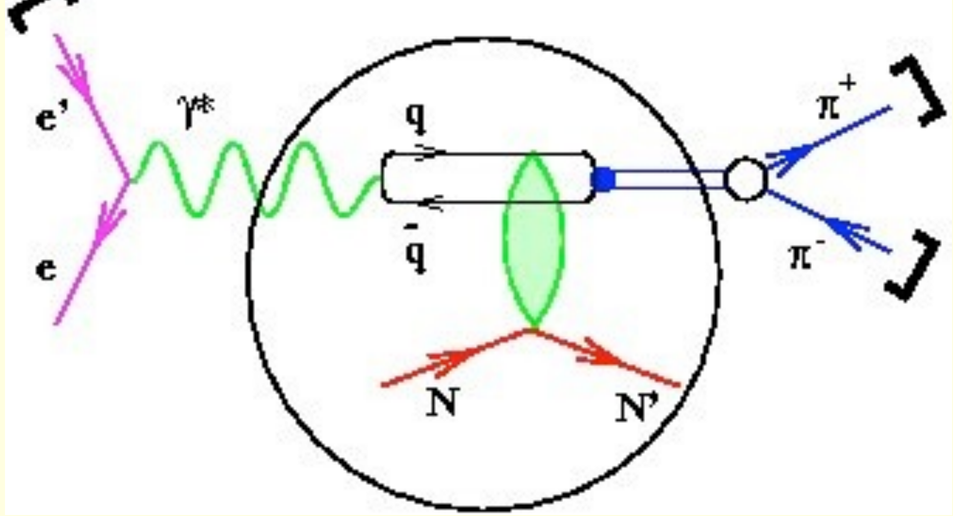
Need both C and Cu targets to extract Q^2 and A dependence and thus disentangle the CT effect



ρ^0 electroproduction on nuclei- CLAS

Detected particles are :
scattered electron and the π^+ and π^- from ρ^0 decay

$e + N \rightarrow e' + N + \rho^0$



Finite propagation distance l_c (lifetime) of the (q,q-bar) virtual state

$$l_c = 2\nu / (M^2 + Q^2)$$

small l_c –pair formed anywhere in nucleus, large l_c pair formed before photon hits nucleus

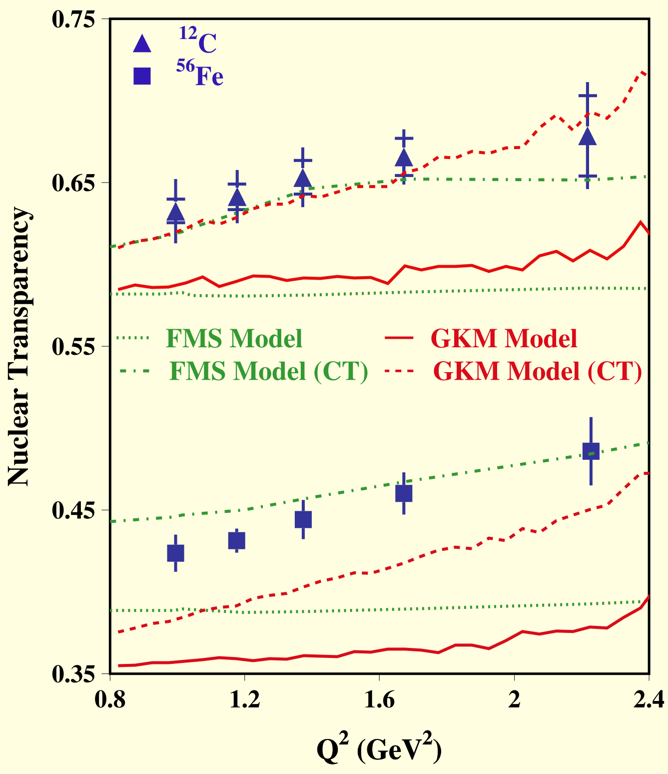
M is the mass of the vector meson

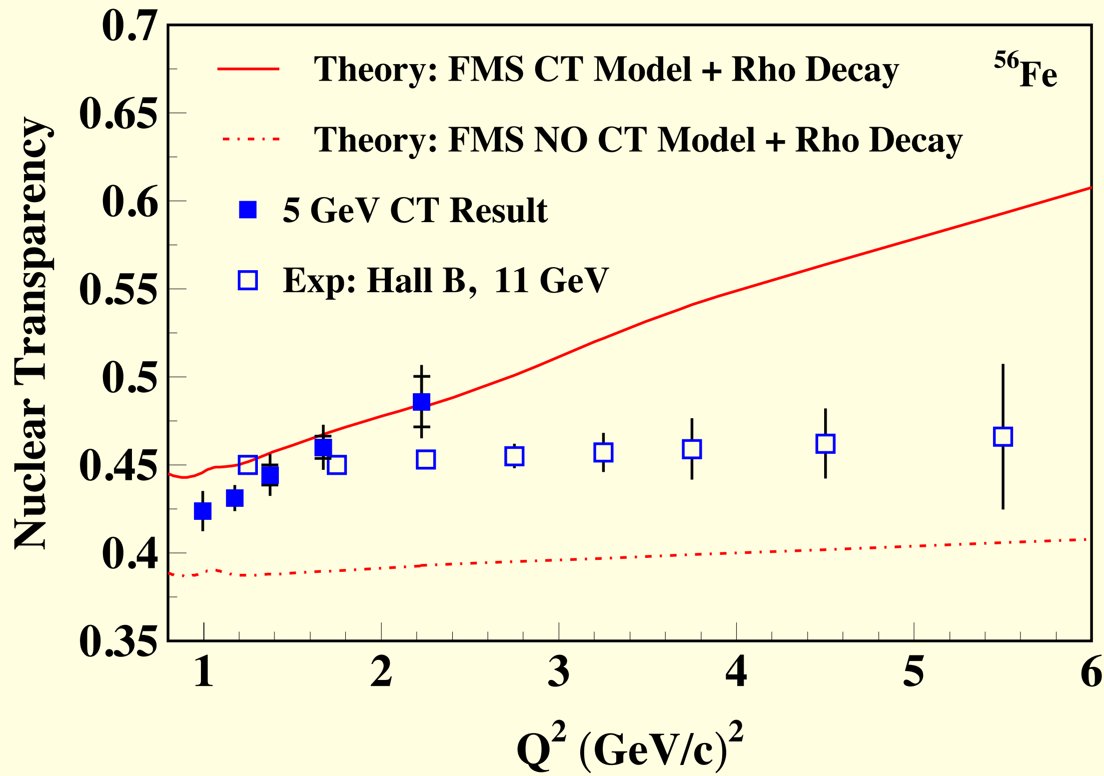
ν is the energy transferred by the electron

Experiment done at fixed coherence length,kinematics appropriate

El Fassi et al, arXive:1201.2735 to be in PLB

11 GeV expt





Further experimental studies

- Higher energies for (e,e'p), pi and rho production
- Kaon production (e,e',k)
- Higher energies, intensities for (p,pp)
- Reactions where final state interactions are required disappear at high Q^2 D(e,e'p)
- Vector meson production: vary x, to go from transparency to opacity, G(A)
- π N quasielastic scattering in nuclei $T(A) \propto A$

Summary

- Color transparency seen in high energy coherent nuclear production of jets by pions
- Hints seen in (p,pp), -need higher energy
- Likely seen in (e,e',π), (e,e',ρ) need higher energy to enhance effect by reducing expansion
- Not seen in (e,e',p)-need higher energy test, proton transparency important does red plus green plus blue cancel?

Extras follow

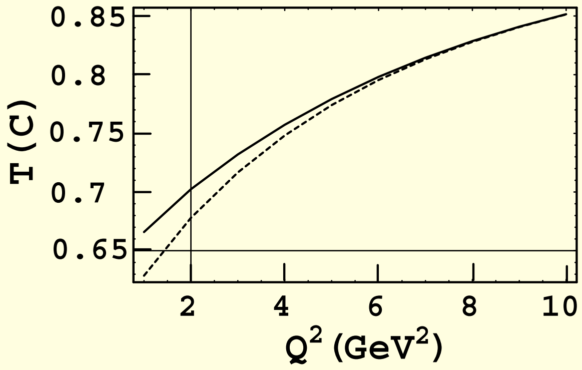
Avoid PLC Expansion

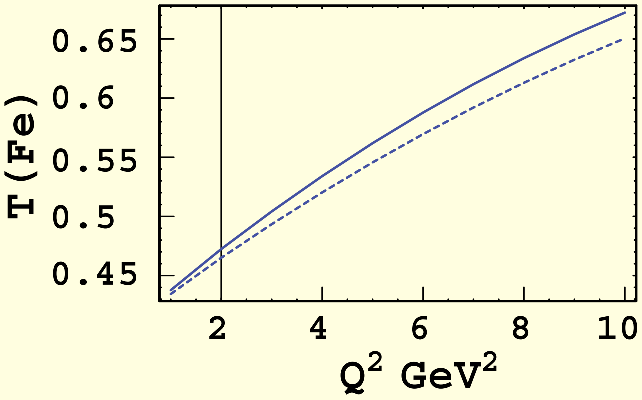
- $t \ll 1/(E_n - E_{proton})$ for no expansion
- t = nuclear transit time ~ R_A
- need $R_A(E_n - E_{proton}) \ll 1$
- P large, $E_n - E_{proton} = (M_n - M_p)\ (M_n + M_p)/2P$
- $t = 1/(M_n - M_p)(2P/(M_n + M_p)) =$ natural rest frame time times ≈ dilation factor
- What is M_n ?
- At high P we have freezing

PHYSICAL REVIEW C **78**, 015208 (2008)

Color transparency in semi-inclusive electroproduction of ρ mesons

L. Frankfurt,[1] G. A. Miller,[2] and M. Strikman[3]





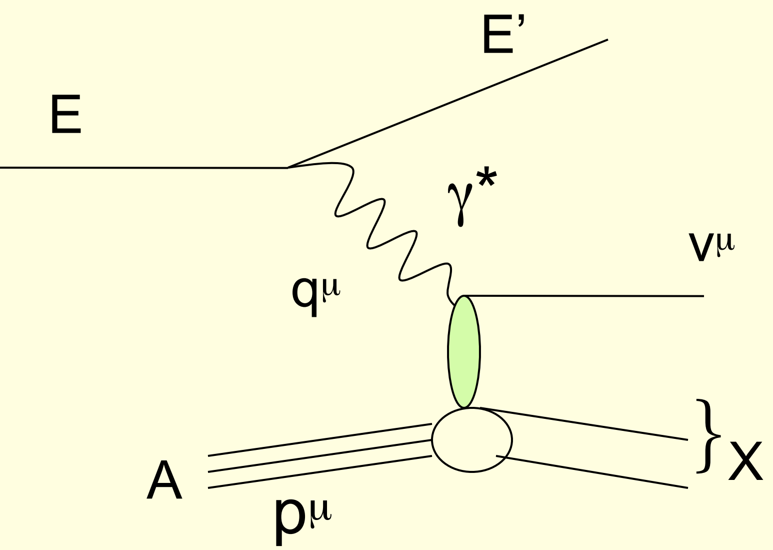
Preliminary CLAS data look like this, but ...

$e + Fe \rightarrow e' + \rho^0 + X$

$\rho^0 \rightarrow \pi^+\pi^-$

$e + D \rightarrow e' + \rho^0 + X$

$\rho^0 \rightarrow \pi^+\pi^-$



$\nu = E - E'$
$Q^2 = -(q^\mu)^2 \cong 4\,E\,E' \sin^2(\theta/2)$
$t = (q^\mu - v^\mu)2$
$W^2 = (p^\mu + q^\mu)^2 = -Q^2 + M_p^2 + 2M_p\nu$

- **$W \geq 2$ GeV**

  $\Rightarrow$ avoid resonance region

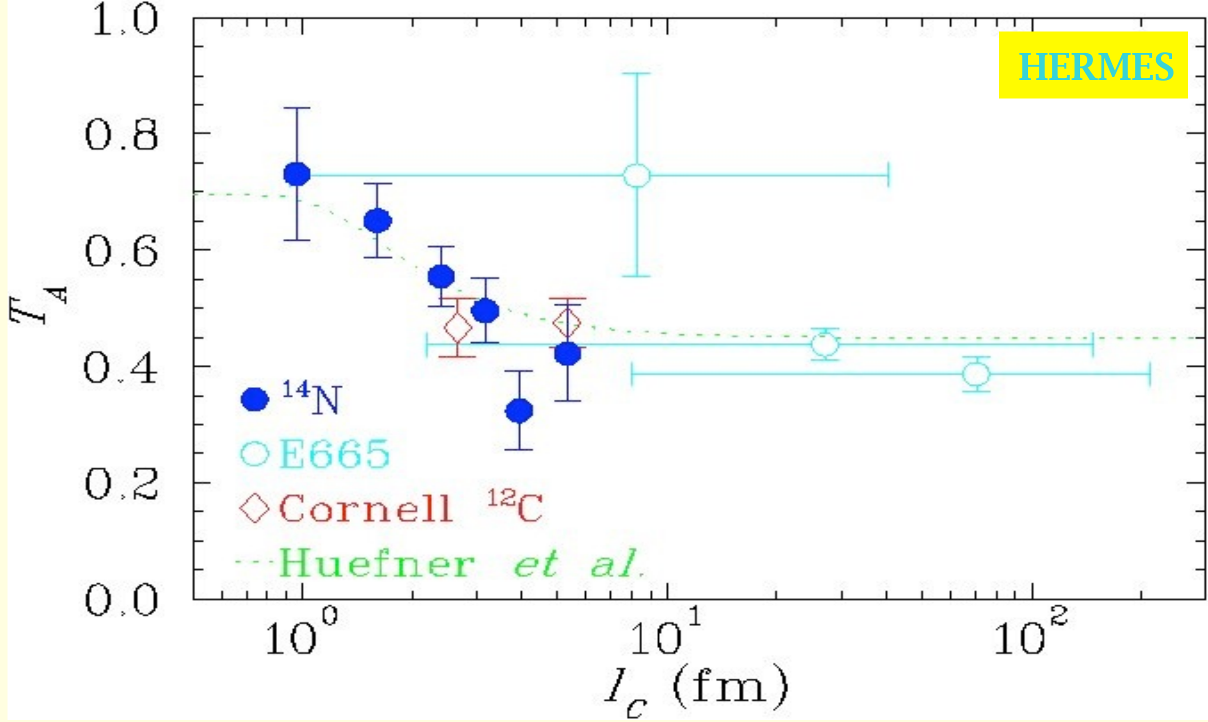
- **$-t \leq 0.45$ GeV^2**

  $\Rightarrow$ select diffractive process

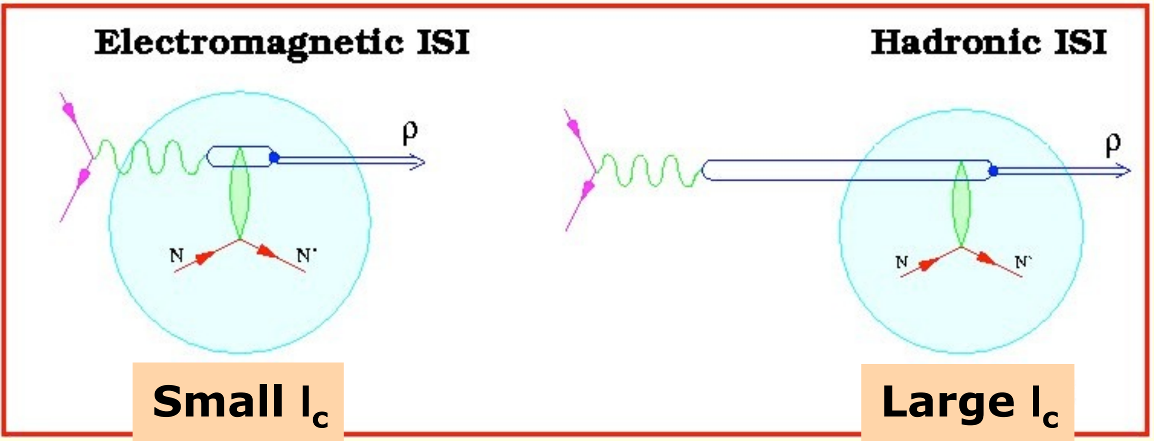
mimic CT signal ?

Coherence Length

$l_c = 2\nu/(M_V^2 + Q^2)$

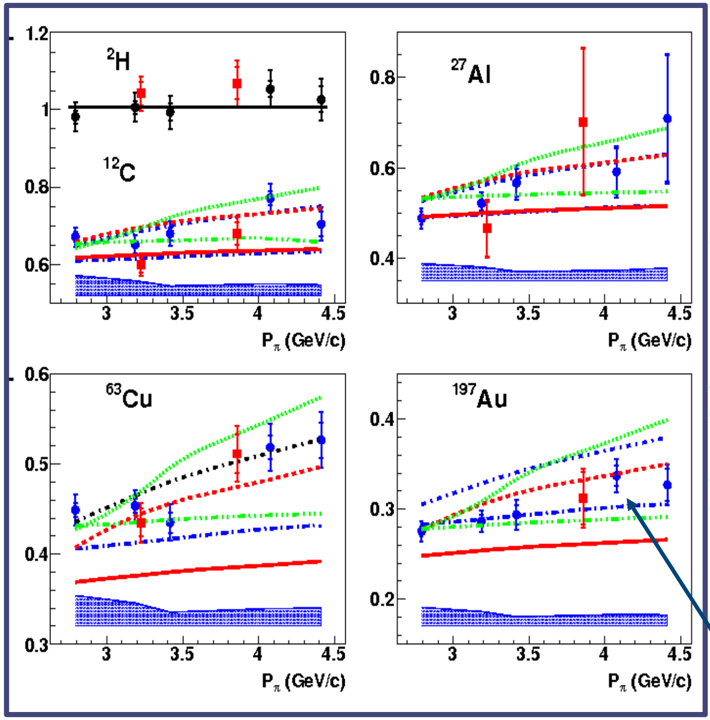


Coherence length effect (CL): Q^2 increases $\Rightarrow T_A$ increases



- Coherence Length effect can mimic CT signal
- To be safe, one should keep l_c fixed and measure the Q^2 dependence of T_A

P_π Dependence of Pion Transparency



(X. Qian et al., PRC81:055209 (2010),
B. Clasie et al, PRL99:242502 (2007))

$$T = \frac{(Data/Simulation)_A}{(Data/Simulation)_p}$$

Red solid : Glauber (semi-classical)
Red dashed : Glauber +CT (quantum diff.)
Larson, Miller & Strikman, PRC 74, 018201 ('06)

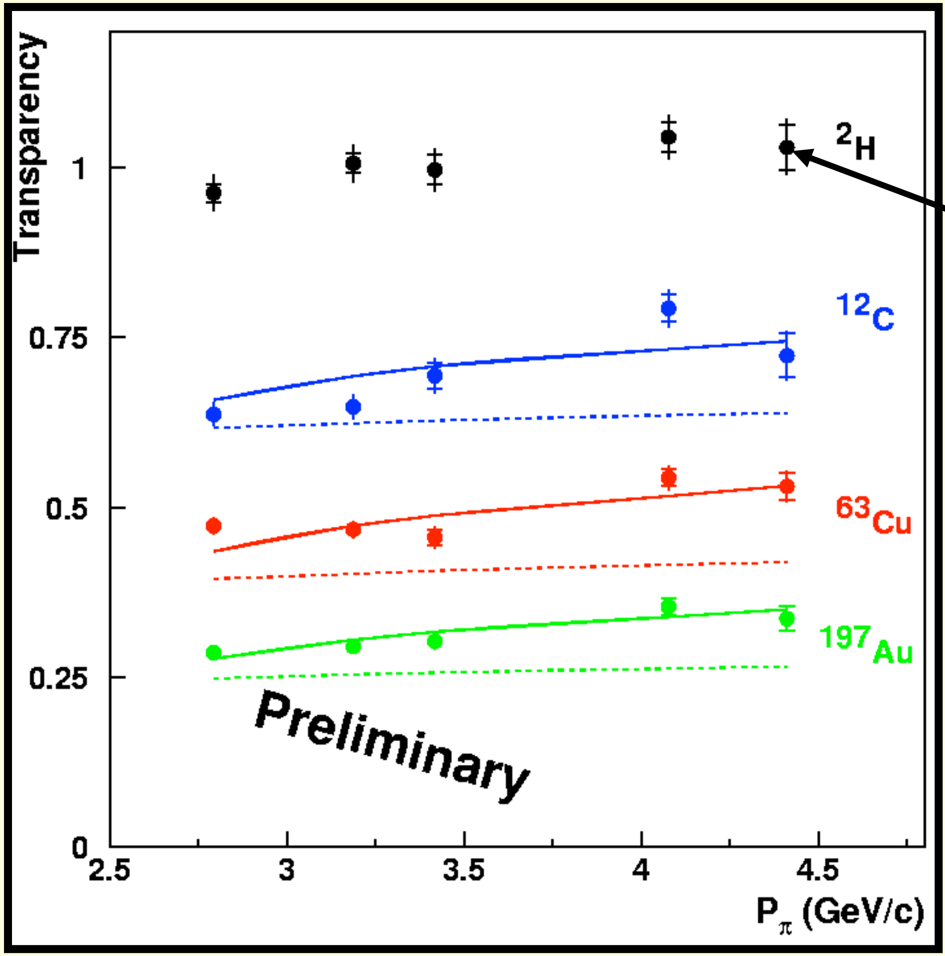
Blue dot-dash : Glauber (Relativistic)
Blue dotted : Glauber +CT (quantum diff.) +SRC
Cosyn, Martinez, Rychebusch & Van Overmeire, PRC 74, 062201R ('06)

Green dot : BUU Transport
Green dot-dot-dash : BUU Transport + CT (quantum diff.)
Kaskulov, Galmiester & Mosel, PRC 79, 015207 ('09)

Inner error bar are statistical uncertainties outer error bar are the quadrature sum of statistical and pt. to pt. systematic uncertainties.

JLab Exp. E01-107

$$T = \frac{(\text{Data/Simulation})_A}{(\text{Data/Simulation})_p}$$



Spokespersons:
D. Dutta, R. Ent & K. Garrow
Thesis Student: Ben Clasie (MIT)

Inner error bar are statistical uncertainties outer error bar are the quadrature sum of statistical and pt. to pt. systematic uncertainties.

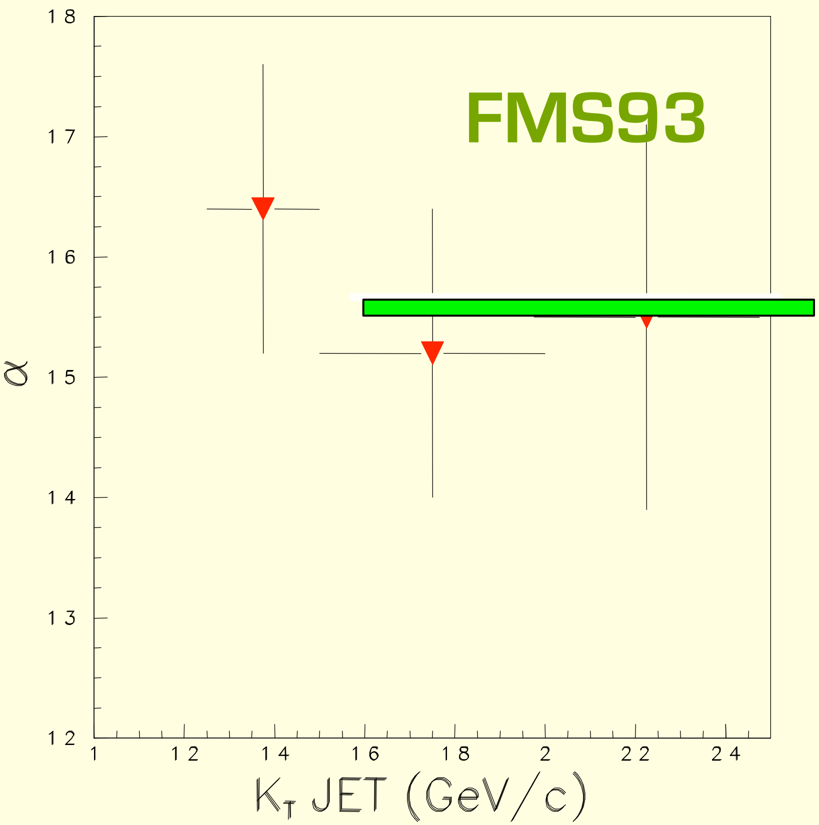
$$\Delta M^2 = 0.7 \text{ GeV}^2.$$

$$l_c = 0.6 \text{ fm (p/GeV)}$$

Solid/Dashed lines are predictions with and without CT
A. Larson, G.A Miller and M. Strikman, nuc-th/0604022

A(π,dijet) data from FNAL

Aitala et al., PRL 86 4773 (2001)



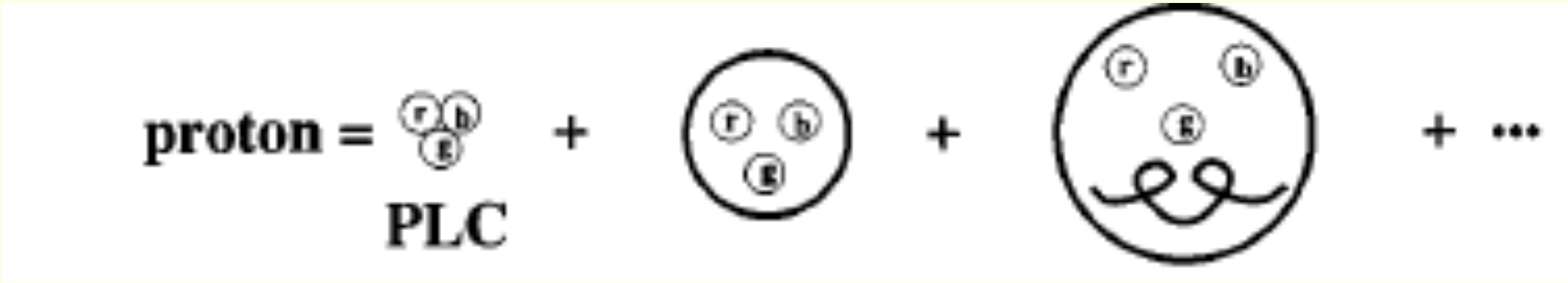
Coherent π^+ diffractive dissociation with 500 GeV/c pions on Pt and C.

Fit to $\sigma = \sigma_0 A^{\alpha}$

α= 0.71 from diffractive pion production-
Pt/C ratio $(179/12)^{1.55}$ instead of $(179/12)^{.71}$ ratio increased by factor of 7

Implications of PLC vs Feynman- EMC Effect Suppression of PLC in medium

free



place in medium:

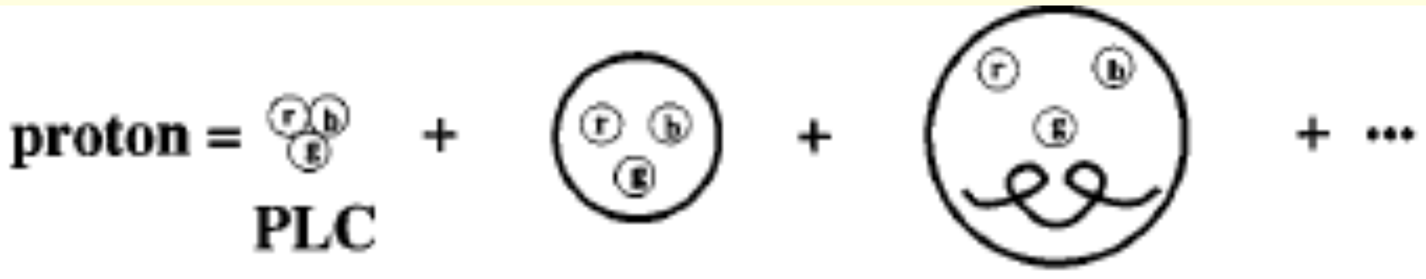
normal size components attracted energy goes down

PLC does not interact- color screening

energy denominator increased, PLC suppressed

quarks lose momentum in medium

Nuclear Physics -Suppression of Point Like Configurations- Frankfurt, Strikman

free 

place in medium:

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energy denominator increased, PLC suppressed

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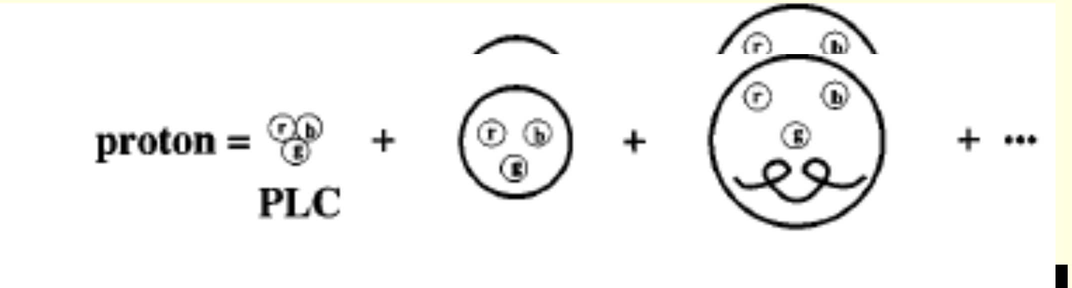
Suppression of Point Like Configurations- Frankfurt,



PLC has NO int.
with medium

energy denominator increased

EMC ratio Frank,Jennings Miller '95