Nuclear Transparency in Exclusive ρ^0 Production at HERMES

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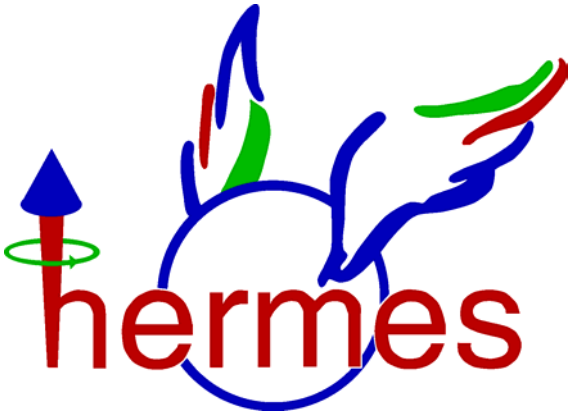
hermes Collaboration

- Introduction
  - Diffractive ρ^0 production
- Nuclear Effects
  - $b_N(Q^2)$ variation (γ shrinkage)
  - coherent/incoherent cross section ratios
  - l_c-dependence
  - Q^2-dependence (Color Transparency)
- Summary

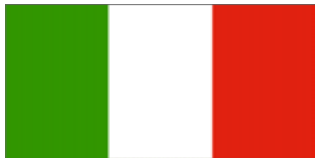
HERMES Experiment at HERA (2003)



29 Institutions


Canada


Germany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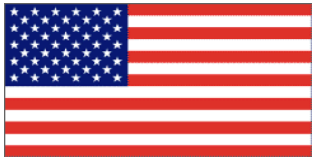
Russia


United Kingdom


USA


Armenia


Belgium

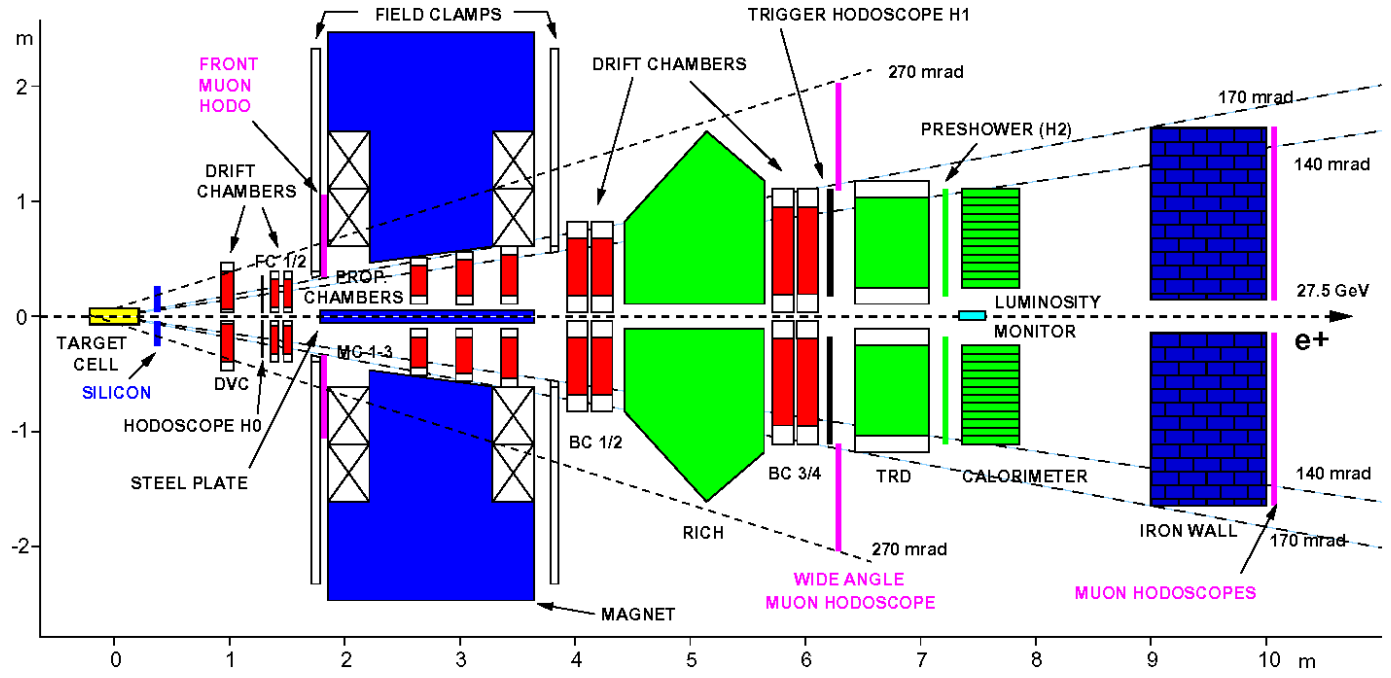

Japan


Netherlands


Poland


China

The HERMES Detector



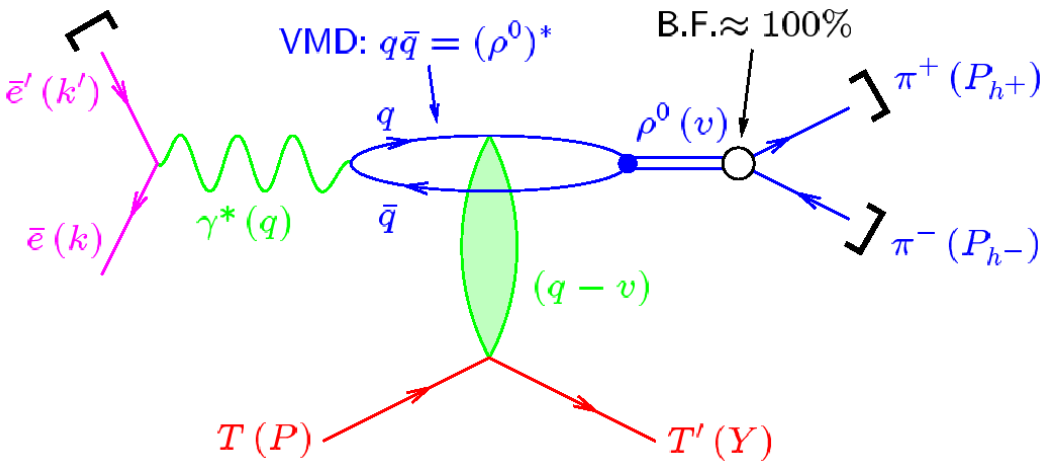
- Forward Spectrometer: $40 < \theta < 220$ mrad, $\delta P/P$ (0.7-1.3)%, $\delta\theta < 0.6$ mrad
- Electron Identification: efficiency $\geq$ 98% with hadron contamination $\leq$ 1%
- Calorimeter: $\delta E/E = 5\%/\sqrt{E[GeV]}$
- RICH (1998): π^{+-}, K^{+-}, p separation overfull kinematic range

Exclusive Diffractive ρ^0 Electroproduction

ρ^0, $\rho^\pm$ have $I(J^{PC}) = 1(1^{--})$ [N.B.: γ has $0,1(1^{--})$]

- M_ρ = 770 MeV, Γ_ρ=150 MeV ($c\tau$=1.3 fm)
- ρ^0 content is $(u\bar{u} + d\bar{d})/\sqrt{2}$

Dominant time-ordered diagram (lab frame):



- Exclusive: $M_{T'} = M_T$
- Diffractive: $d\sigma/dt \sim e^{bt}$ (note $t<0$)
  - Incoherent: $\gamma^* N \rightarrow \rho^0 N$, $b_N \approx 7$ GeV^{-2} (for $A>1$, this is nuclear inelastic)
  - For $A>1$, coherent: $\gamma^* A \rightarrow \rho^0 A$, $b_{^{14}N} \approx 57$ GeV^{-2}

Evolution of Virtual Quantum States

- Virtual state such as $\gamma^* \rightarrow q\bar{q}$ in γ^*-induced reaction
- transverse size of $q\bar{q}$ wave packet: $r_{q\bar{q}} \sim 1/\langle Q^2 \rangle \simeq 0.4$ fm

- coherence length l_c: finite propagation distance (lifetime) for $q\bar{q}$

$$l_c = \frac{2 \cdot \nu}{Q^2 + M^2_{q\bar{q}}} = 0.6 \div 8 \text{ fm}, \quad \langle l_c \rangle = 2.7 \text{ fm}$$

  - measure interactions with perturbing medium at different l_c
  - study space-time evolution of VQS
  - for exclusive ρ^0 production: M_ρ dominates $M_{q\bar{q}}$ and l_c
    $\Rightarrow$ can measure explicit l_c-dependence

- formation length l_f: distance needed to evolve to normal-size ρ^0

$$l_f = \frac{2 \cdot \nu}{M^2_{V'} - M^2_V} = 1.3 \div 6.3 \text{ fm}, \quad \langle l_f \rangle = 3.5 \text{ fm}$$

  - governing scale for Color Transparency

Color Transparency

- Vanishing of h – N interaction cross section for h produced in high Q^2 exclusive process
- Requirements: Quantum Mechanics, Relativity, Nature of Strong Interaction
- $h = q\bar{q}$ QED analogy in e^+e^- (Chudakov-Perkins effect)

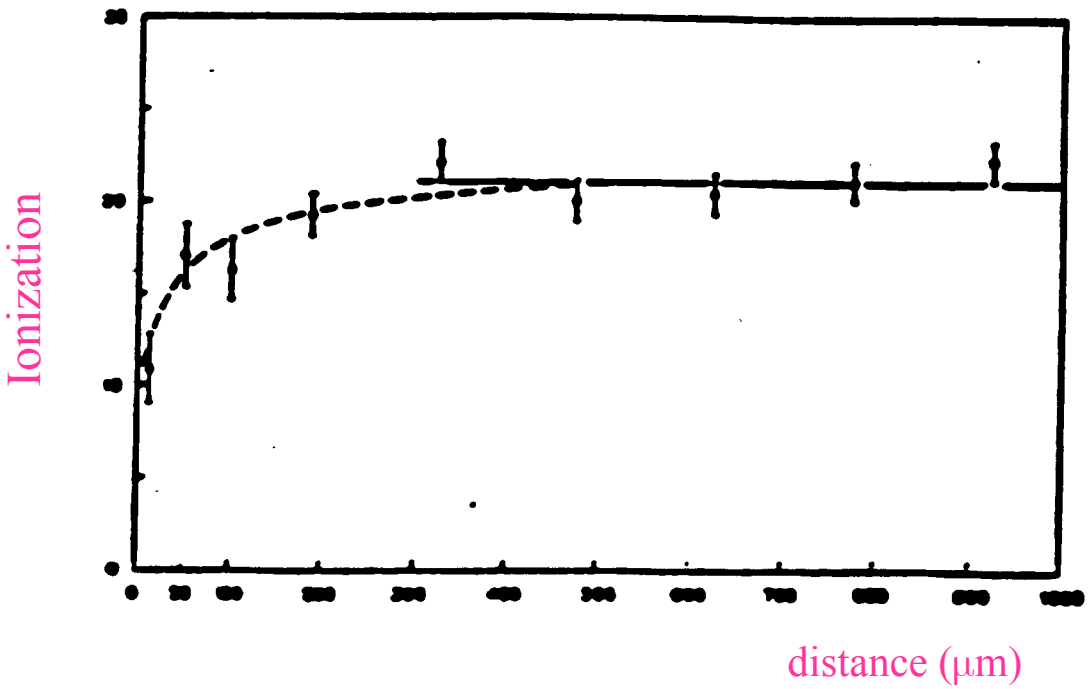
  $h = qqq$ unique to QCD !

"Charge Screening"

Perkins (1955)
[$\pi_0 \rightarrow e^+e^-\gamma$]

e^+e^- pairs (~ 200 GeV) make tracks in photographic emulsions

Measure ionization density
vs. distance from production



Color Transparency

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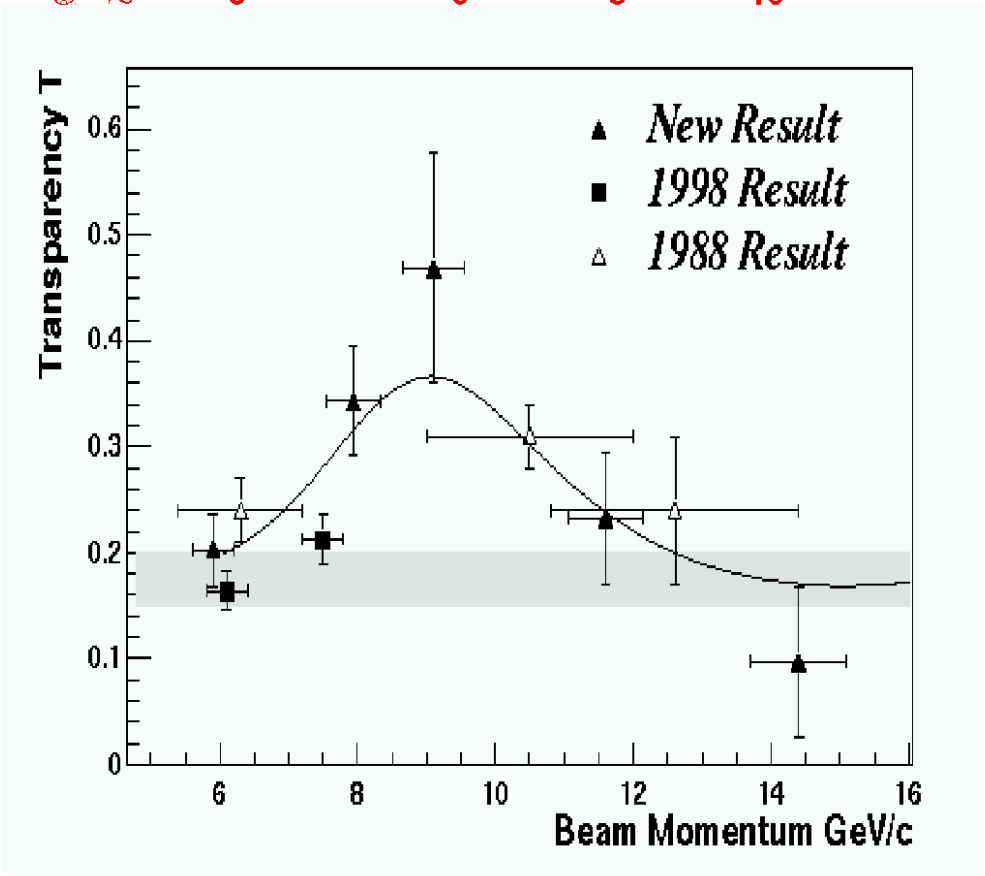
  $h = qqq$ unique to QCD !
- No unambiguous signature found for the onset of CT yet !

Color Transparency in A(p,2p) – BNL Results

$Q^2 \approx$ 3 6 8 10



E-0850, Leksanov et al. PRL 87, 212301 (2001)

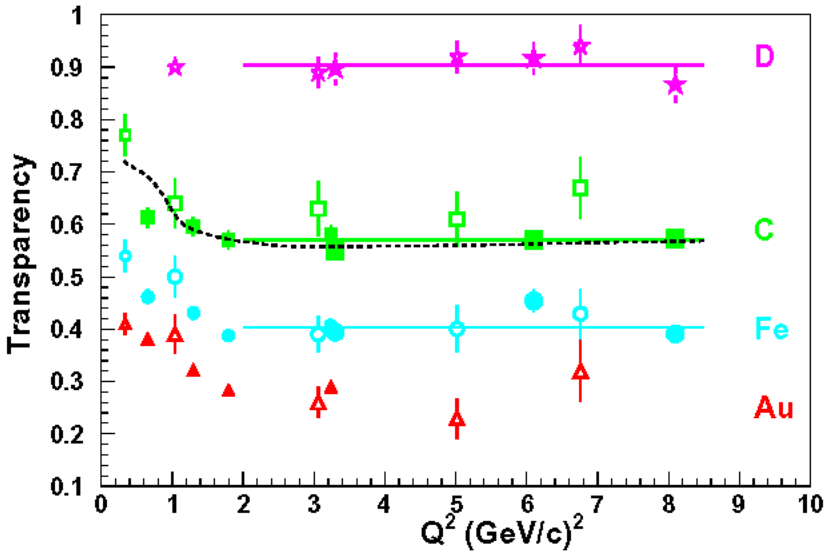
Shaded are is Glauber calculation

solid line is 1/oscillation in p-p scattering

A(p,2p) may remove long-distance component in p-p scattering

(Nuclear Filtering)

Color Transparency in A(e,e'p) – SLAC/JLab Results



E94-139, Garrow et al. PR C66, 044613 (2002)

Constant Value fits for $Q^2 > 2$ GeV^2

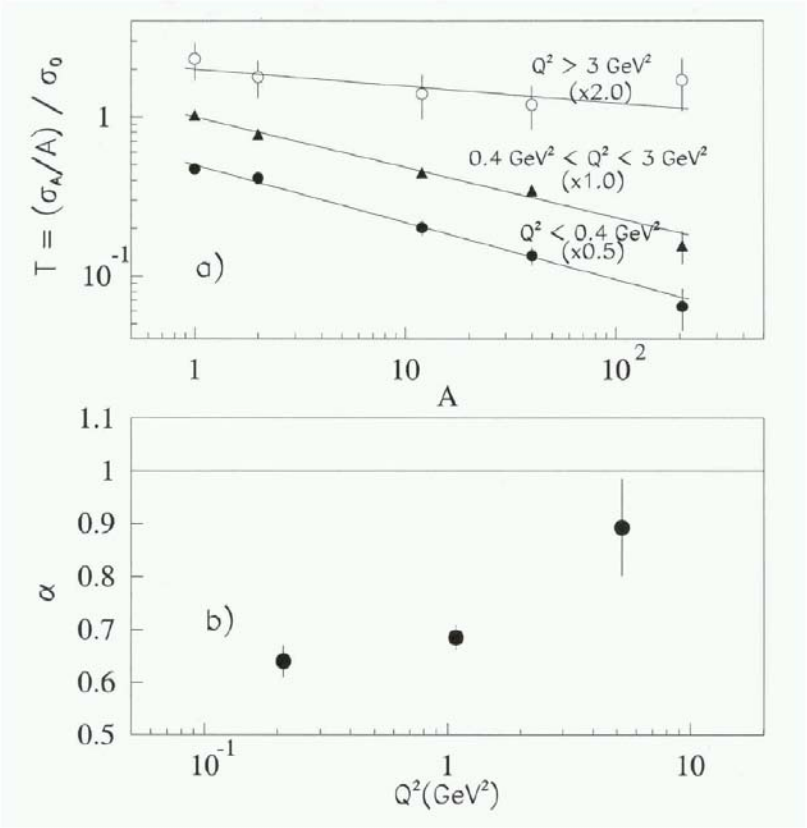
$\rightarrow \chi^2/df \approx 1$

Dashed line is correlated Glauber calculation (Panharipande at al)

Q^2 dependence consistent with standard Glauber

Color Transparency in $A(\mu,\mu'\rho^0)$ – FNAL Results

E_μ = 470 GeV; A = H, D, C, Ca, Pb

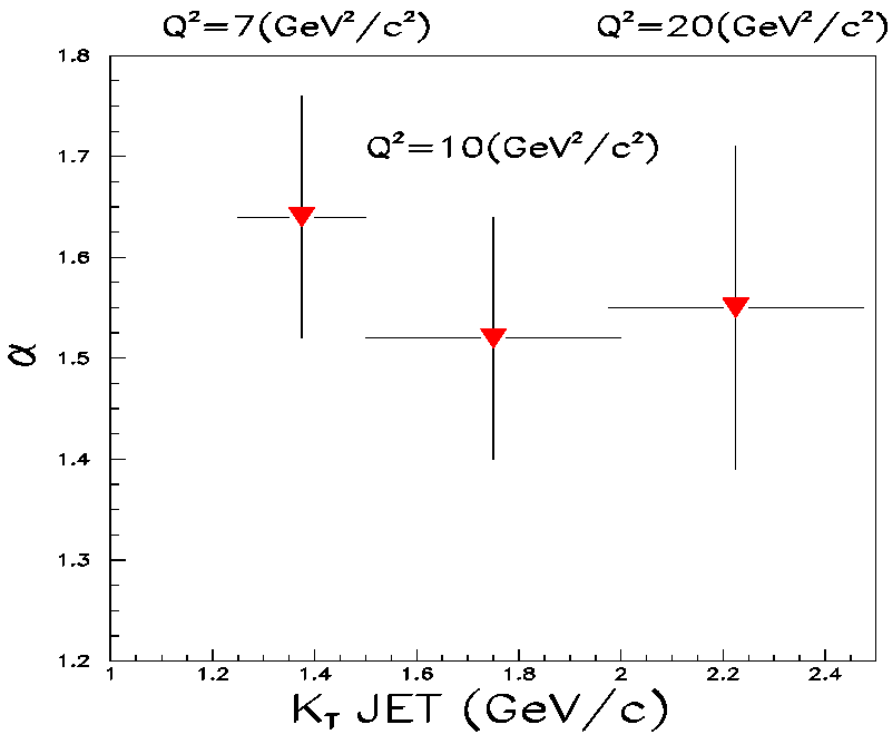


E665, Adams et al. PRL 74, 1525 (1995)

E665 fit: Fit to $\sigma_A(Q^2) = \sigma_N(Q^2)\, A^\alpha$.
"The probability of α being independent of Q^2 is 2.7%."

Skeptical fit: assumes $\alpha \neq f(Q^2)$,
$\chi^2/df = 10.0/11 = 0.91$, with $\alpha = 0.69$

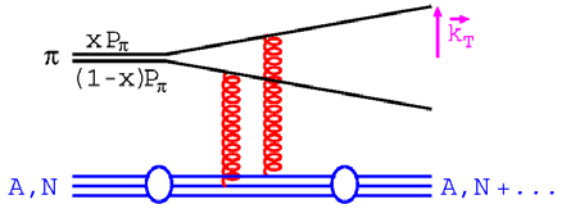
Color Transparency in A(π,di-jet) – FNAL Results



$\alpha > 0.76$ from pion-nucleus total cross sections

E791, Aitala et al. PRL 86, 4773 (2001)

Coherent π^+ diffractive dissociation at T_π=500 GeV/c



Parameterized as $\sigma(A) = \sigma_0 A^\alpha$, using ^{12}C and ^{195}Pt nuclei, with $Q^2 \geq 4k_T^2$

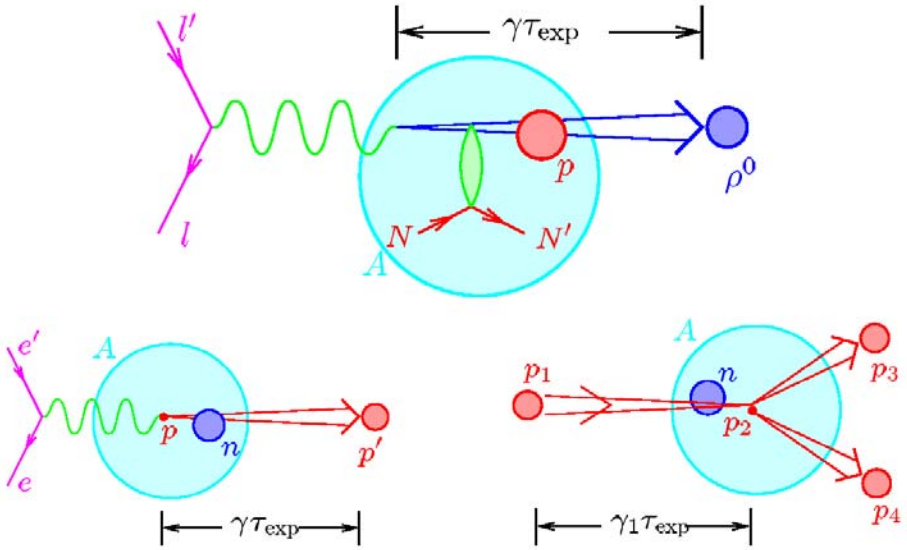
Color Transparency

- Vanishing of h – N interaction cross section for h produced in high Q^2 exclusive process
- Requirements: Quantum Mechanics, Relativity, Nature of Strong Interaction
- $h = q\bar{q}$ QED analogy in e^+e^- (Chudakov-Perkins effect)

  $h = qqq$ unique to QCD !
- No unambiguous signature found for the onset of CT yet !
  - A(p,2p) Oscillation in Transparency data — Leksanov et al. PRL 87, 212301 (2001)
  - A(e,e'p) Consistent with conventional nuclear physics — Garrow et al. PR C66, 044613 (2002)
  - A(l,l' ρ^0) Coherence/Formation length Issues — E665, Adams et al. PRL 74, 1525 (1995)
  - A(π,di-jet) claims full CT at $Q^2 \approx 10$ GeV^2, but only A-dependence — E791, Aitala et al. PRL 86, 4773 (2001)
- There is more at stake:
  - CT required for strict validity of factorization in deep exclusive processes
    $\Rightarrow$ essential for access to General Parton Distributions

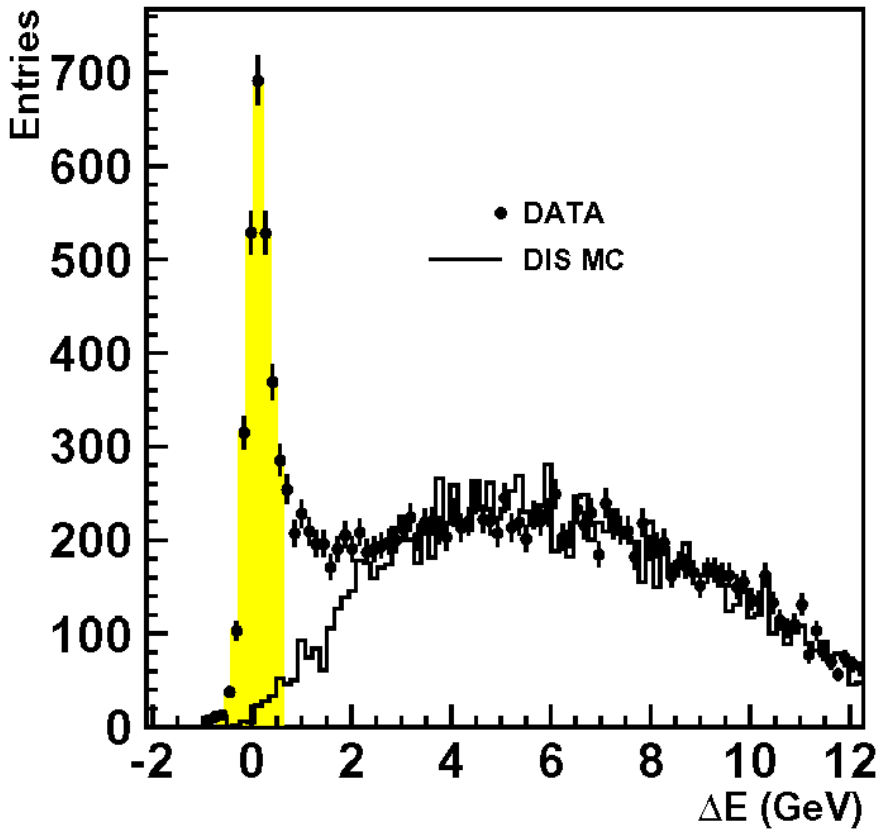
Color Transparency and ρ^0 Leptoproduction

Prediction that in exclusive reactions, ISI and FSI vanish at high Q^2, ν:



	(p,2p)	*(e,e'p)*	*(l,l'ρ^0)*
Small size Config. (high Q^2)	?	?	Yes
Color Screening	Yes	Yes	Yes
$t_{exp} = \gamma\tau_{exp}$ (high ν)	small	small	Large
(E_m, p_m) sensitivity	Yes	Yes	No
$\sigma(\nu, Q^2)$ smooth	No	Yes	Yes
Good QED or QCD model	No	Yes	Yes
l_c ambiguity	No	No	Yes

Exclusive Diffractive ρ^0



Main cuts:

- exclusive: -0.4 GeV $< \Delta E <$ 0.6 GeV
- diffractive: -t' $<$ 0.4 GeV^2
- select mass: 0.6 GeV $< M_{\pi\pi} <$ 1 GeV
- eliminate background: 1.04 GeV$< M_{KK}$

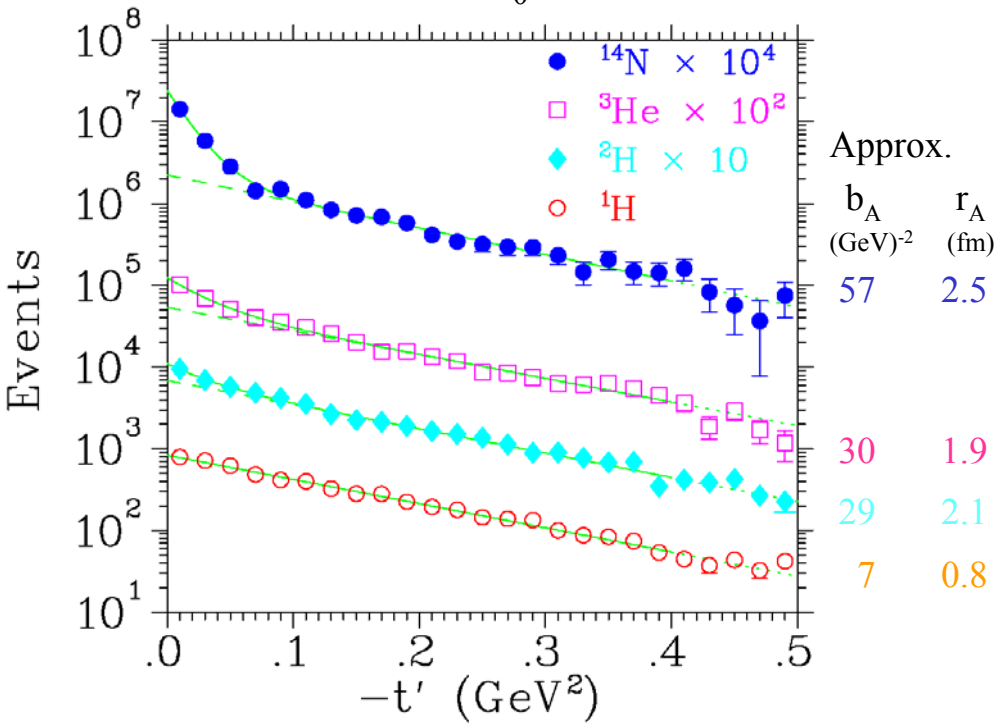
Kinematics:

- Q^2 = 0.6 ÷ 6 GeV^2, $\langle Q^2 \rangle$ = 1.7 GeV^2
- W = 3.0 ÷ 6.5 GeV, $\langle W \rangle$ = 4.9 GeV
- x_{bj} = 0.01 ÷ 0.35, $\langle x_{bj} \rangle$ = 0.07
- ν = 5 ÷ 24 GeV, $\langle \nu \rangle$ = 13.3 GeV

t' Distributions

$$t \equiv (q-v)^2 = (P-Y)^2 < 0; \qquad t_0 \equiv t\left(\theta_{\gamma p}^{CM} = 0\right)\Big|_{(Q^2,\nu,M_Y,M_{\pi\pi})\ \text{fixed}}$$

$$t' \equiv t - t_0$$

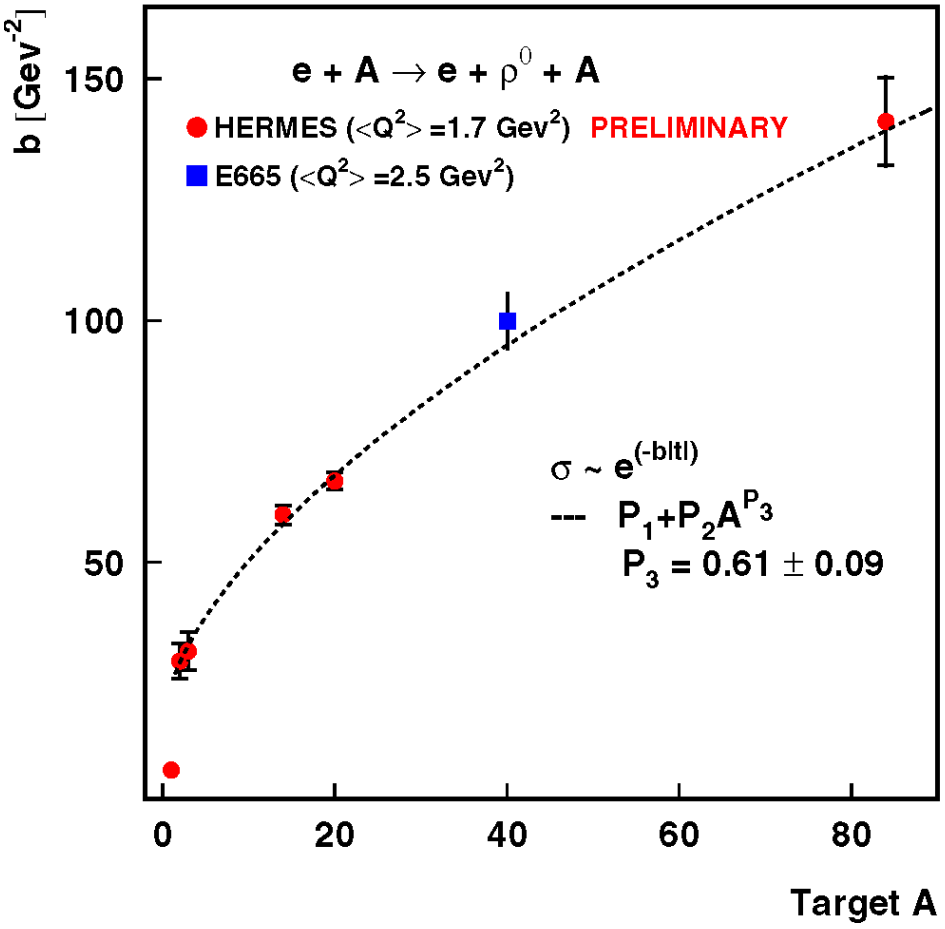


	Approx. b_A $(GeV)^{-2}$	r_A (fm)
^{14}N	57	2.5
^{3}He	30	1.9
^{2}H	29	2.1
^{1}H	7	0.8

$$\frac{dN}{dt'} = a_N\left(b_N e^{b_N t'} + f_A b_A e^{b_A t'}\right)$$

- For ^{14}N:
  - for $-t' \leq 0.045$ GeV² coherent ρ^0 dominates
  - for $-t' \geq 0.09$ GeV² incoherent ρ^0 dominates
- incoherent: $b_N \approx 7$ GeV^{-2}
- $b_A \approx \frac{1}{3}\left(r_A^2 + r_{q\bar{q}}^2\right)$ (e^{bt} represents elastic F.F., squared)
- b_N of various nuclei consistent with hydrogen value

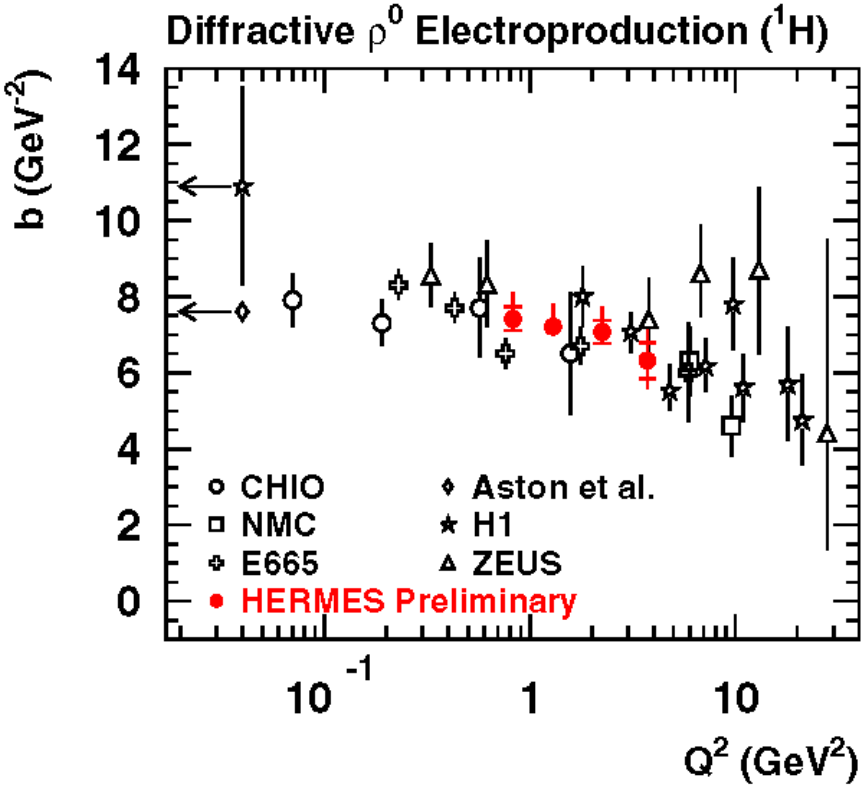
Size of Nuclei



$$b \approx \frac{1}{3}\left(r_A^2 + r_{q\bar{q}}^2\right)$$

- in agreement with world data of nuclear size measurements,
  $r_A^2 \sim A^{2/3}$
  H. Alvensleben at al., PRL 24, 786 (1970)
- r_A dominates

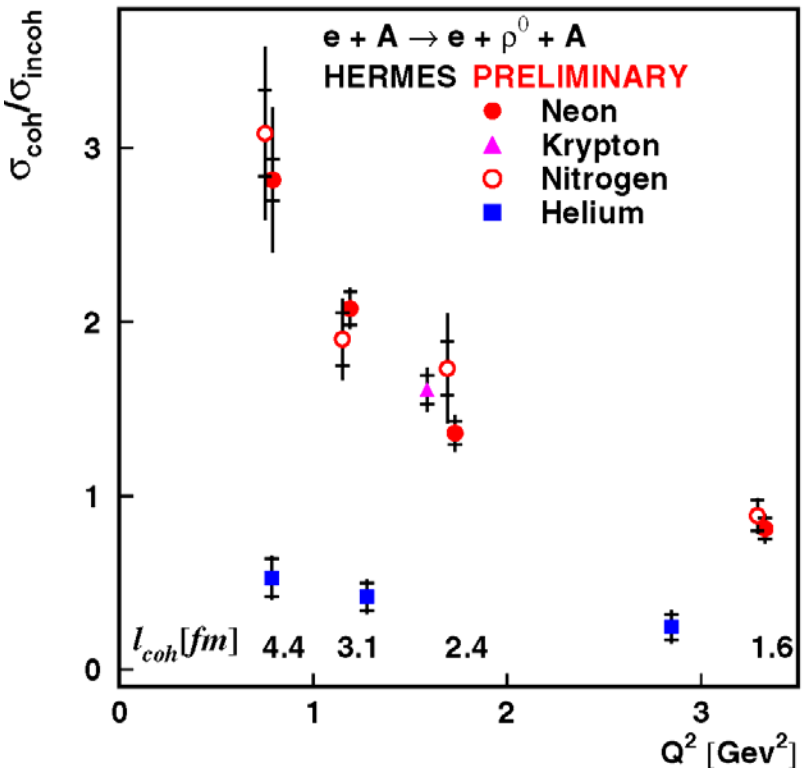
b_N (Q^2) – "Photon Shrinkage"



$b \approx r^2_{q\bar{q}}$

- $d\sigma/dt \sim e^{-bt}$
- size of virtual photon controlled via Q^2
- prerequisite for CT

Q2 dependence of σ_{coh} / σ_{incoh}



Very strong Q^2-dependence of ratio
$\Rightarrow$ have to study coherence length effects

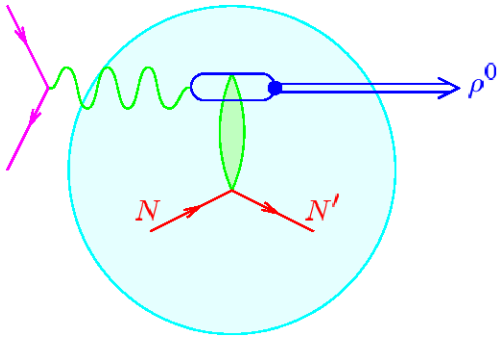
r^{He}=1.9 fm r^{N}=2.5 fm r^{Ne}=2.7 fm r^{Kr}=5.5 fm

Coherence Length Dependence of ISI

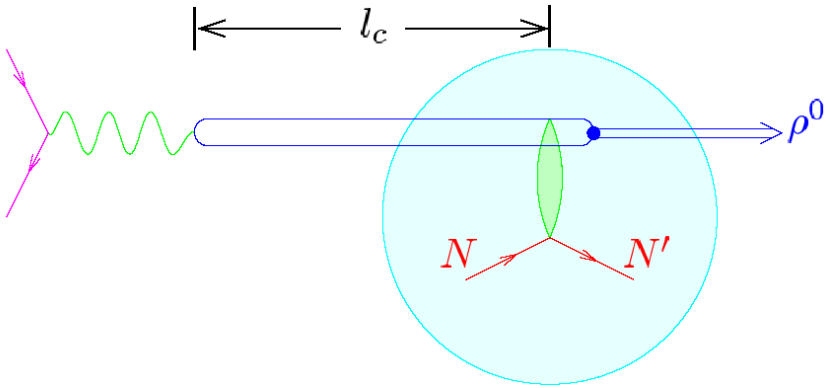
Initial State Interactions (ISI) of photon's hadronic components

Strength of the ISI depend on l_c [K. Gottfried and D.r. Yennie, PR 182, 1595 (1969)]

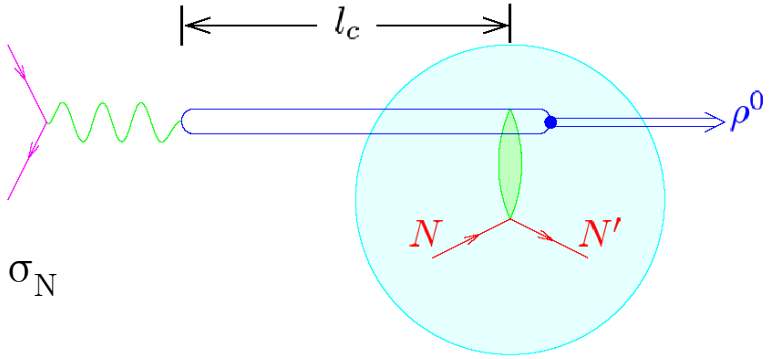
- $l_c \ll r_A \Rightarrow$ weak electromagnetic ISI (naïve expectation):



- $l_c \gg r_A \Rightarrow$ hadronic ISI:



Incoherent Nuclear Transparency T_A



- Nuclear transparency T
  → search for Color Transparency
- Without ISI and FSI, incoherent $\sigma_A = A\,\sigma_N$
- Incoherent nuclear transparency: $T_A \equiv \sigma_A / A\,\sigma_N$
  - effect of ISI of γ^*, $q\bar{q}$ and FSI of ρ^0
  - if ISI and FSI factorize ⇒ T_A = probability of transmitting γ^* ($q\bar{q}$) and ρ^0 unscathed
- ISI increase with lifetime l_c of $q\bar{q}$ fluctuation

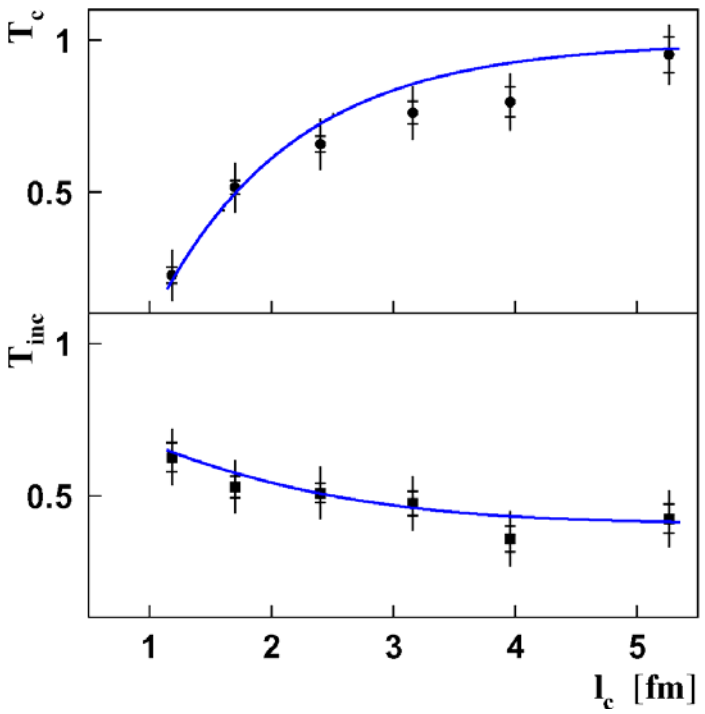
  ⇒ T_A should decrease with onset of hadronic ISI at $l_c \geq 1$ fm

  (note: $\sigma_{\rho N} \approx$ constant for $\nu > 1$ GeV
  expect $\sigma_n \approx \sigma_H \Rightarrow$ use $\sigma_N = \sigma_H$)

$$T_A = \frac{\sigma_A}{A\sigma_H} = \frac{N_A L_H}{A N_H L_A}$$

  - $L_{A,H}$ from inclusive DIS e events, corrected for h^+h^- efficiency
  - $N_{A,H}$ = # of incoherent events
- CT signature is rise in T_A with Q^2
  - l_c effect can mimic Q^2-dependence of T_A predicted by CT for $l_c \leq r_A$

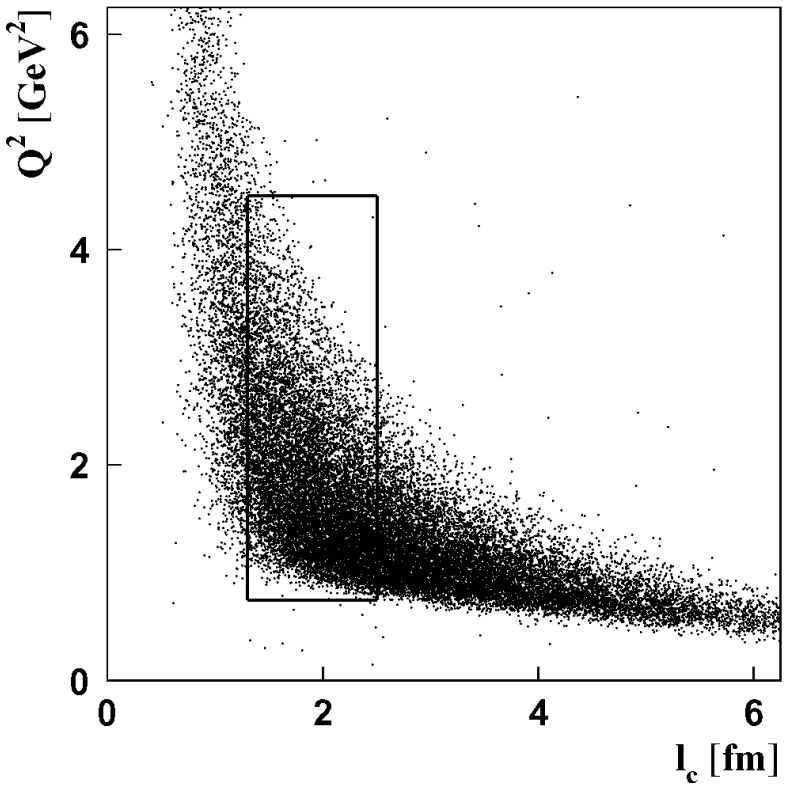
Coherence Length Effects



- coherent nuclear transparency: $T_c \equiv \sigma_A / A\,\sigma_N$
  - opposite l_c dependence
    $\Rightarrow$ cannot mimic Color Transparency
  - T_c can **no longer** be associated directly with probability of escape from nucleus
    $\Rightarrow$ T_c is ratio of σ_A/σ_N: can exceed unity !
- incoherent nuclear transparency: $T_{inc} \equiv \sigma_A / A\,\sigma_N$
  - ISI increase with l_c for $l_c \leq r_A$
    $\Rightarrow$ can mimic Q^2-dependence of T_{inc} predicted by Color Transparency

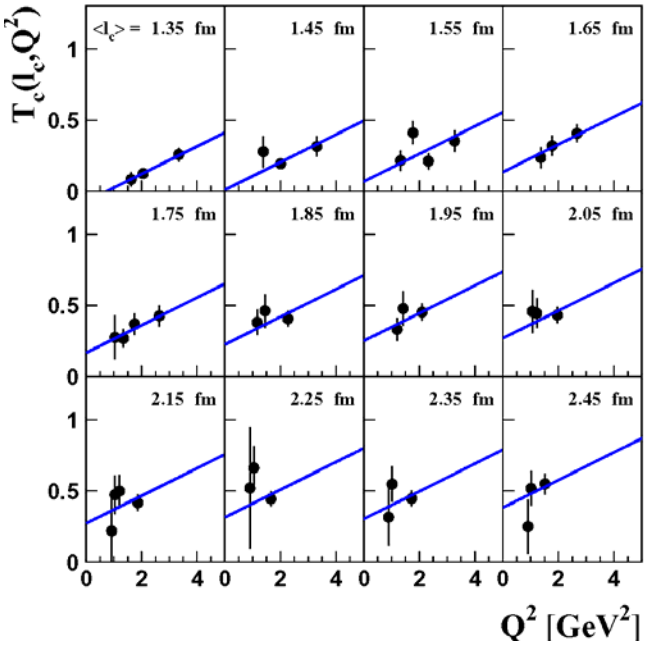
study $T=T(Q^2)$ while keeping l_c fixed $\Rightarrow$ disentangle CL from CT effects

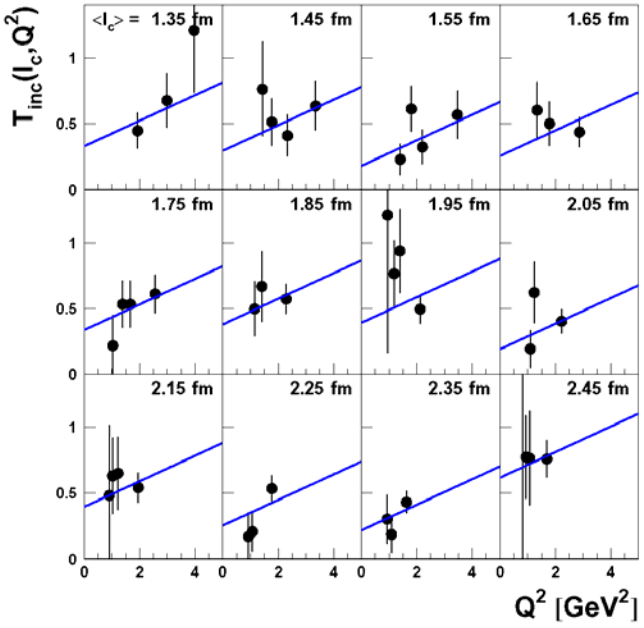
HERMES acceptance in Q^2 vs l_c



- allows 2-dim analysis
- $\langle Q^2 \rangle$ = 1.7 GeV^2; $\langle l_c \rangle$ = 2.7 fm
- same kinematics for coherent and incoherent ρ^0, except:
  - coherent: $|t'| < 0.045$ GeV^2
  - incoherent: $0.09 < |t'| < 0.4$ GeV^2
- limited region used:
  - lower l_c $\rightarrow$ acceptance corrections get large
  - higher l_c $\rightarrow$ Q^2 range gets too small

Color Transparency





- Common fit at fixed l_c yields positive slope of Q^2-dependence of nuclear transparency in nitrogen HERMES collaboration, PRL 90, 052501 (Feb 2003)

  $\Rightarrow$ signature of Color Transparency B.Z. Kopeliovich et al., PR C65, 035201 (2002)

Data sample	Measured Q^2 slope	Prediction
coherent	$0.070 \pm 0.021 \pm 0.012$	0.060
incoherent	$0.089 \pm 0.046 \pm 0.008$	0.048

Summary

- Exclusive ρ^0 production: virtual $\gamma^* \rightarrow q\bar{q}$
  - lifetime given by Heisenberg assuming $M_{q\bar{q}} = M_{\rho^0}$
  - interacts like a ρ^0
- t' slope parameter *b* agrees with $r_A^2 \sim A^{2/3}$
- size of virtual γ^* controlled via Q^2 (photon shrinkage)
- strong coherence length effects in $\sigma^A_{coh} / \sigma^A_{incoh}$
- intricate mixture of coherence and formation length effects
  - different appearance for coherent and incoherent ρ^0 production
  - can mimic CT effects (incoherent)
  - can obscure clean observation of CT effect (coherent)
- for clean observation of CT: study variation of T with Q^2 for fixed l_c
- new evidence (3.4σ) of CT in exclusive ρ^0 production