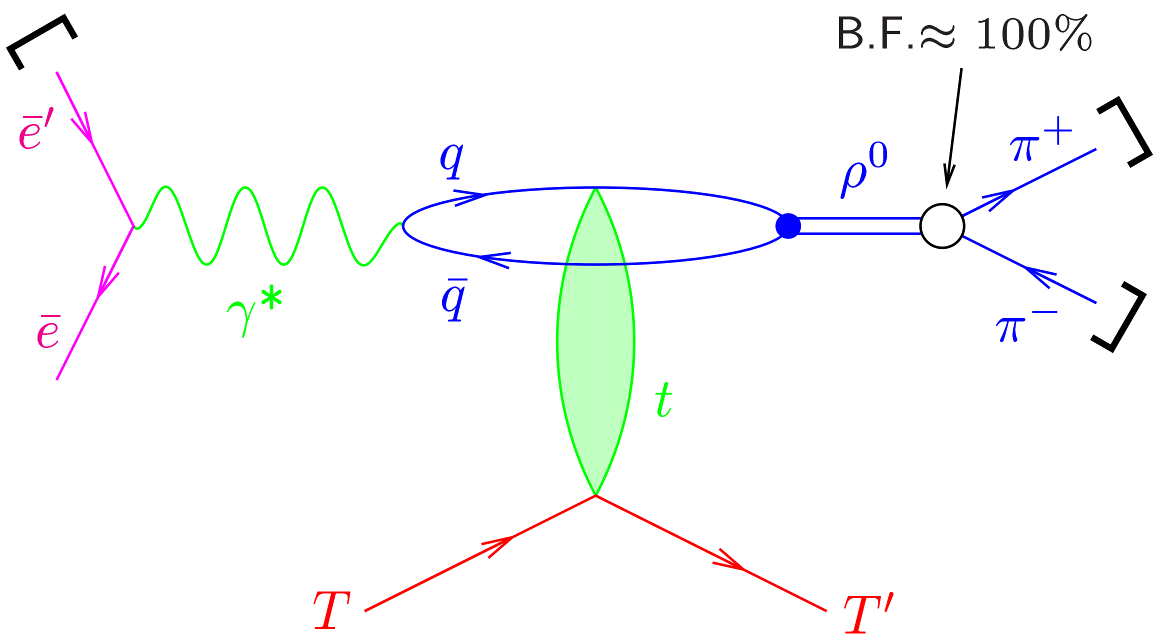
# Nuclear Transparency to $\rho^0$ Electroproduction

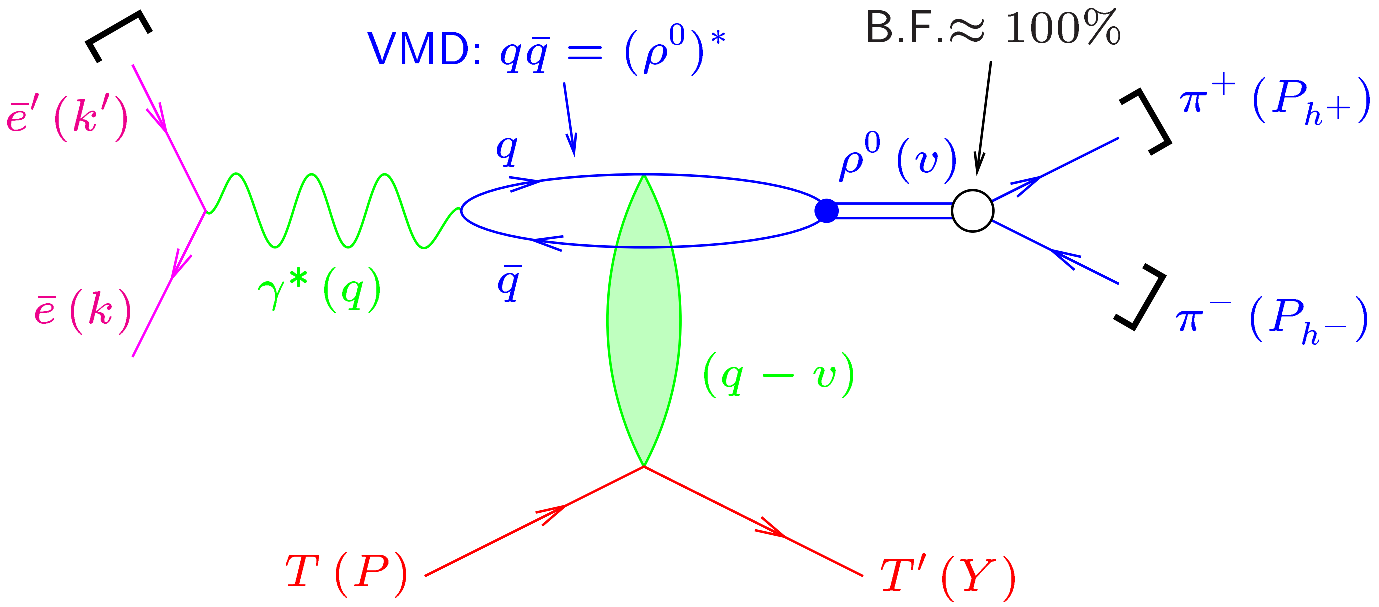
T. O'Neill, ANL (for HERMES collaboration)

Apparent dominant diagram (lab):




1. Exclusive, diffractive $\rho^0$ electroproduction
2. Coherence length effect: initial state interactions (ISI) of $q\bar{q}$ increase with lifetime $l_c$
3. HERMES $\rho^0$ production signal
4. Nuclear transparency $T_A$ for incoherent $\rho^0$ production: $\gamma^*$, $\rho^0$ transmission probability
5. HERMES measurement of $T_{^2\mathrm{H}}$, $T_{^3\mathrm{He}}$, and $T_{^{14}\mathrm{N}}$

# Exclusive, Diffractive $\rho^0$ Electroproduction




| 4-momentum | Mass$^2$ | Description |
|---|---|---|
| $q = k - k'$ | $-Q^2$ | $\gamma^*$ |
| $v = P_{h+} + P_{h-}$ | $M^2_{\pi\pi}$ | $\rho^0$ candidate |
| $P$ | $M^2$ ($^1$H target) | struck nucleon ($T$) |
| $P_Y = P + q - v$ | $M_Y^2$ | undetected final state $Y$ |
| $(q - v) = (Y - P)$ | $t$ $(< 0)$ | momentum transfer to target |

$$\nu = q \cdot P/M$$

$$\Delta E \equiv (M_Y^2 - M_T^2)/2M_T = \nu - E_{\pi\pi} + t/2M_T$$

$$t_0 \equiv \max t|_{(Q^2,\nu,M_Y,M_{\pi\pi})\ \mathrm{fixed}} = t(\theta^{CM}_{\gamma\rho} = 0)$$

$$t' \equiv t - t_0 \sim -v_t^2$$

- Exclusive: $M_{T'} = M_T$
- Diffractive: $d\sigma/dt \sim e^{bt}$ (note $t < 0$)
  - Incoherent: $\gamma^* N \to \rho^0 N$, $b_N \approx 7\ \mathrm{GeV}^{-2}$ (for $A > 1$, this is nuclear inelastic)
  - For $A > 1$, coherent: $\gamma^* A \to \rho^0 A$, $b_{^{14}\mathrm{N}} \approx 55\ \mathrm{GeV}^{-2}$
- HERMES acceptance: $Q^2 > 0.4\ \mathrm{GeV}^2$, $9 < \nu < 20$ GeV
  $0.015 < x_{\mathrm{Bj}} \lesssim 0.2$ ($x_{\mathrm{Bj}} \equiv Q^2/2M\nu$)

# Evolution of Virtual Quantum States

- Virtual state such as $\gamma^{(*)} \rightarrow q\bar{q}$ in $\gamma^{(*)}$-induced reaction
- Finite propagation distance (lifetime) $l_c$; for $q\bar{q}$,

$$l_c = \frac{2\nu}{M_{q\bar{q}}^2 + Q^2}$$

- Measure interactions with perturbing medium at different $l_c$
- $\Rightarrow$ study space-time evolution of VQS

Examples:

- Thought to contribute to shadowing in
  - inclusive DIS lepton-scattering at low-$x_{\mathrm{Bj}}$ ($x_{\mathrm{Bj}} \approx 1/Ml_c$)
  - Elastic (Compton) and inclusive $\gamma A$ at large $E_\gamma$
  - But: $M_{q\bar{q}}$, $l_c$ model-dependent
- Exclusive $\rho^0$ production
  - $M_\rho$ dominates $M_{q\bar{q}}$ and $l_c$
  - $\Rightarrow$ can measure explicit $l_c$ dependence
- LPM suppression of low-energy bremsstrahlung from high-energy $e^-$
  - L.D. Landau and I.J. Pomeranchuk, Dokl. Akad. Nauk SSSR **92**, 535 (1953); **92**, 735 (1953); A. B. Migdal, Phys. Rev. **103**, 1811 (1956)
  - destructive interference of $\gamma$'s from nearby nuclei
  - Recently seen at SLAC [P.L. Anthony *et al.*, PRD **56**, 1373 (1997)]

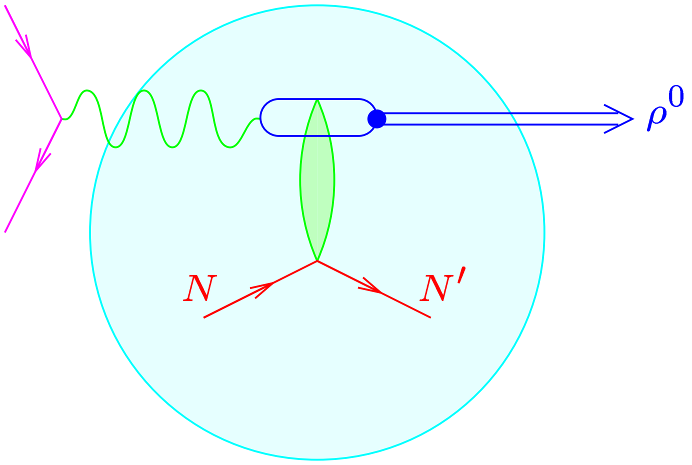
# Coherence Length Dependence of ISI

- Heisenberg $\Rightarrow$ lifetime of $q\bar{q}$ pair ($\hbar = 1$):

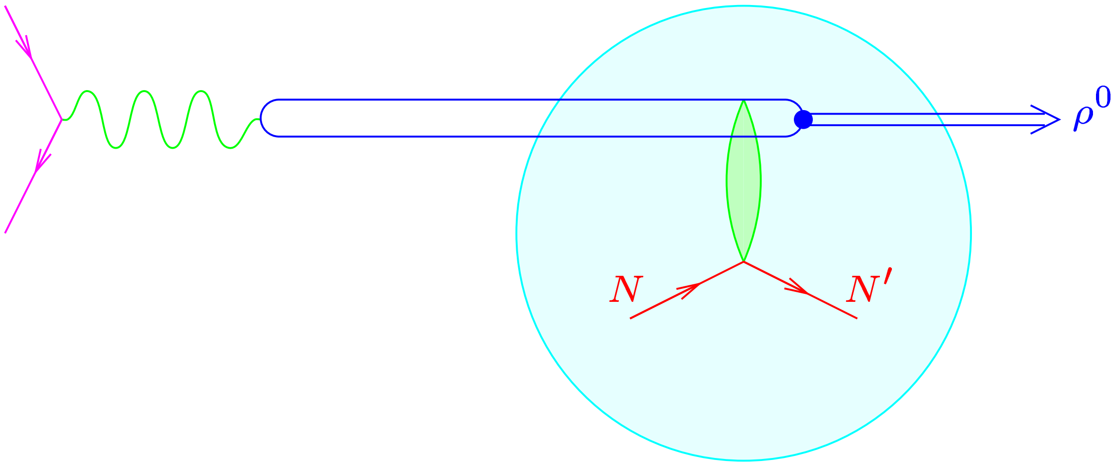
$$\begin{aligned}\Delta E_{q\bar{q}} &= E_{q\bar{q}} - \nu = \sqrt{M_{q\bar{q}}^2 + (Q^2 + \nu^2)} - \nu \\ &\underset{\nu \gg Q, M_{q\bar{q}}}{\approx} \frac{M_{q\bar{q}}^2 + Q^2}{2\nu}\end{aligned}$$

$$l_c \equiv \frac{2\nu}{M_{q\bar{q}}^2 + Q^2} \quad \left(\approx \frac{1}{\Delta E_{q\bar{q}}}\right)$$

- Strength of the ISI depend on $l_c$ [K. Gottfried and D.R. Yennie, Phys. Rev. **182**, 1595 (1969)].
  - $l_c \ll R_A \Rightarrow$ weak electromagnetic ISI (naive expectation):




  - $l_c \gg R_A \Rightarrow$ hadronic Initial State Interactions (ISI):




  - Phase for $\rho^0$ production at longitudinal position $z$ is $e^{iz/l_c}$

# HERa MEasurement of Spin (HERMES)

U. Alberta
Caltech
DESY, Hamburg
U. Erlangen-Nürnberg
Florida International U.
Gent
JINR, Dubna
U. Kentucky
U. Marburg
U. Michigan
MPI, Heidelberg
New Mexico State U.
Oregon State U.
INFN, Rome
Simon Fraser U.
TRIUMF
Vrije U., Amsterdam

Argonne National Lab
U. Colorado, Boulder
DESY-IfH, Zeuthen
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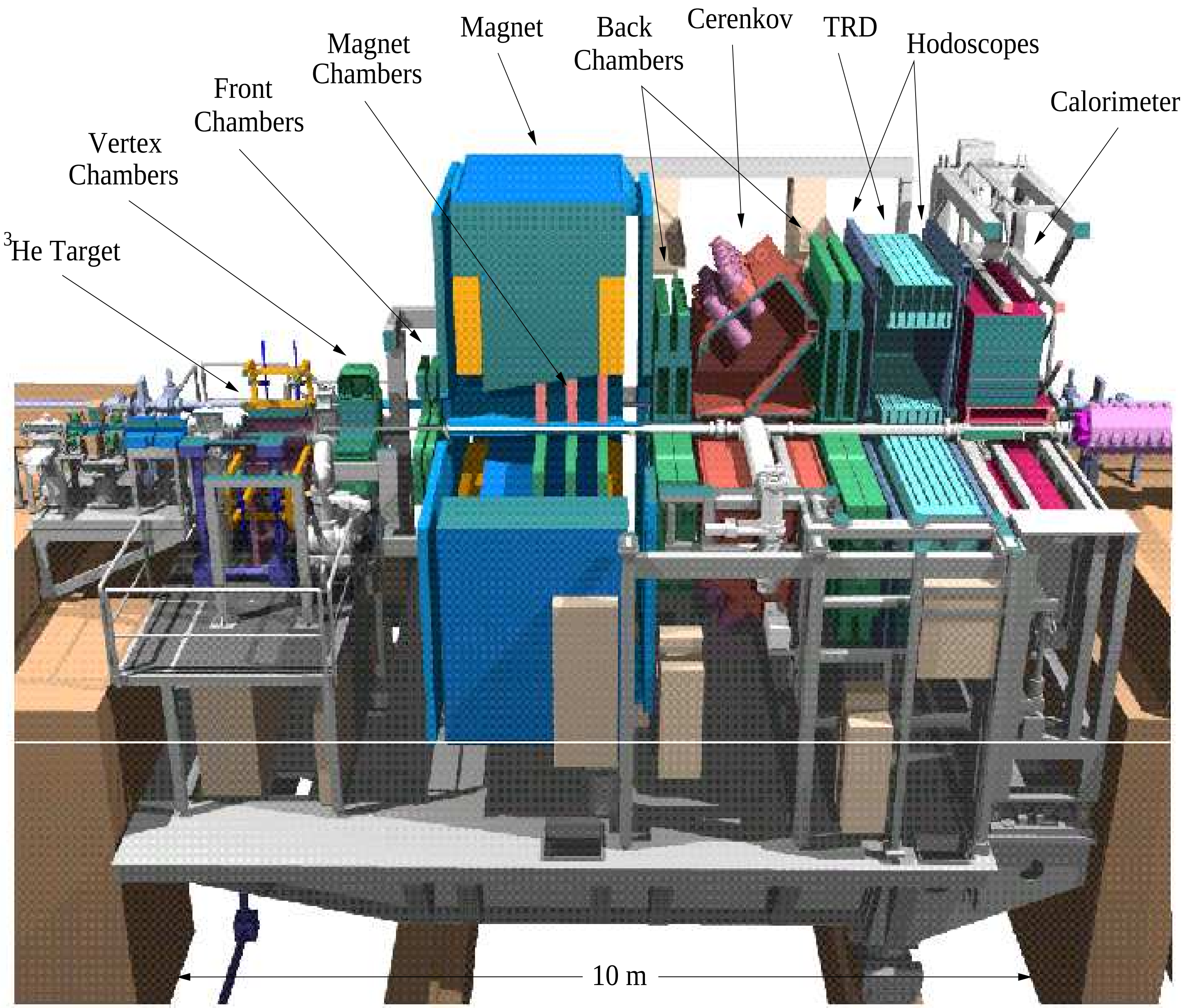
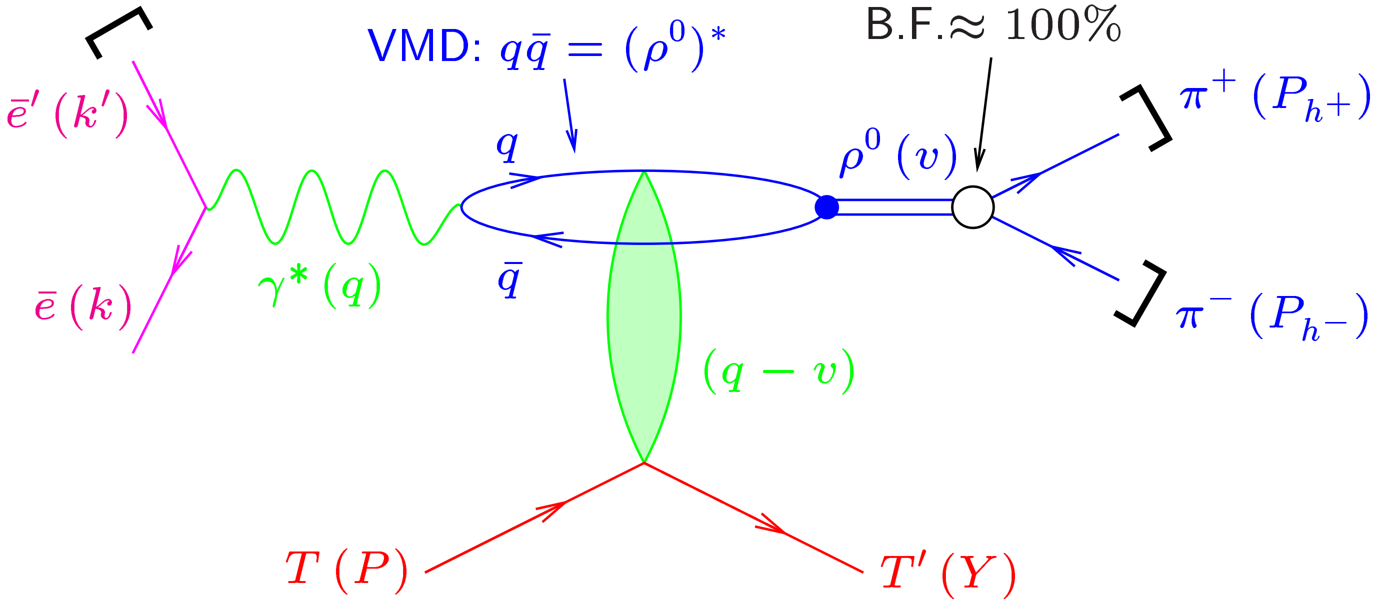
St. Petersburg NPI
Tokyo Inst. Tech.
U. Wisconsin, Madison
Yerevan Physics Inst.

# HERMES




- 27.5 GeV HERA $e^+$ ring ($p$'s not used)
- 10 hour fills with $40\ \mathrm{mA} \to 10\ \mathrm{mA}$
- Internal $^1\overrightarrow{\mathrm{H}}$, $^1$H$_2$, $^2$H$_2$, $\overrightarrow{^3\mathrm{He}}$, $^{14}$N$_2$ targets
- Forward spectrometer $40 < \theta < 220$ mrad
- 1.3 T-m dipole magnet $\Rightarrow$ momentum
- Tracking: $\mu$strip gas counter, drift chambers, proportional chambers
- Particle ID: Čerenkov, TRD, Preshower, and Calorimeter

# HERMES $\rho^0$ Electroproduction Signal




| 4-momentum | Mass$^2$ | Description |
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| $P_Y = P + q - v$ | $M_Y^2$ | undetected final state $Y$ |
| $(q-v) = (Y-P)$ | $t\ (< 0)$ | momentum transfer to target |

$$\nu = q \cdot P/M$$

$$\Delta E \equiv (M_Y^2 - M_T^2)/2M_T = \nu - E_{\pi\pi} + t/2M_T$$

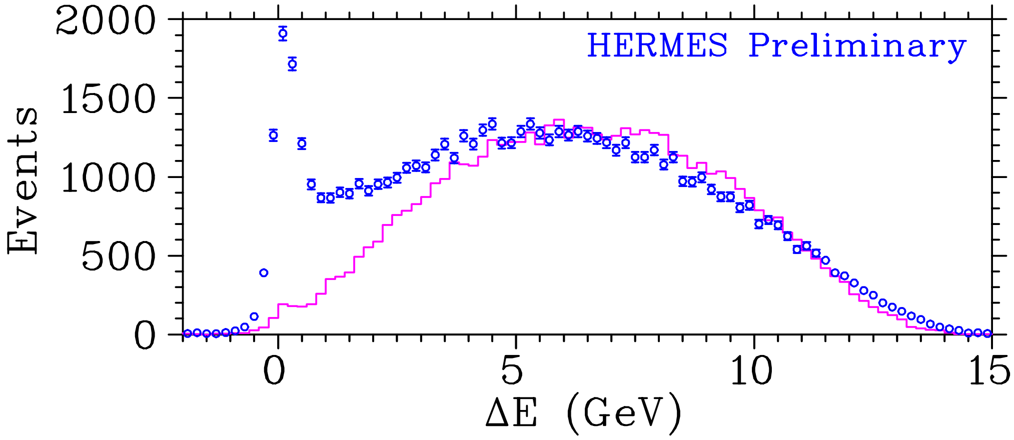
$$t_0 \equiv \max t|_{(Q^2,\nu,M_Y,M_{\pi\pi})\ \mathrm{fixed}} = t(\theta^{CM}_{\gamma\rho} = 0)$$

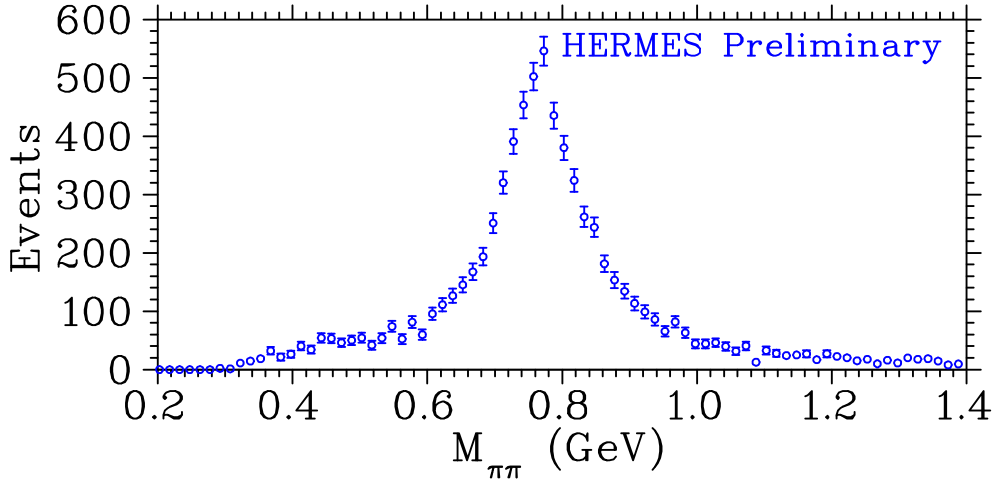
$$t' \equiv t - t_0 \sim -v_t^2$$

| Cut | Description |
|---|---|
| only $e'$, $h^+$, $h^-$ tracks | Exclusive |
| $-2 < \Delta E < 0.6\,\mathrm{GeV}$ | Exclusive ($Y = T'$, like $z \sim 1$) |
| $l'_t < -t' < 0.4\,\mathrm{GeV}^2$ | Incoherent, diffractive |
| $0.6 < M_{\pi\pi} < 1\,\mathrm{GeV}$ | $h^+$, $h^-$ reconstruct to $\rho^0$ mass |
| $9 < \nu < 20\,\mathrm{GeV}$ | Good exclusive separation, trigger efficiency |

# Selecting Exclusive $eN \rightarrow e\rho^0 N$

Events at $0.1 < -t' < 0.4\ \mathrm{GeV}^2$ after cuts (no acceptance corrections):




Excluding $M_{KK} < 1.04$ GeV eliminates $\phi$ production background at $M_{\pi\pi} < 0.5$ GeV

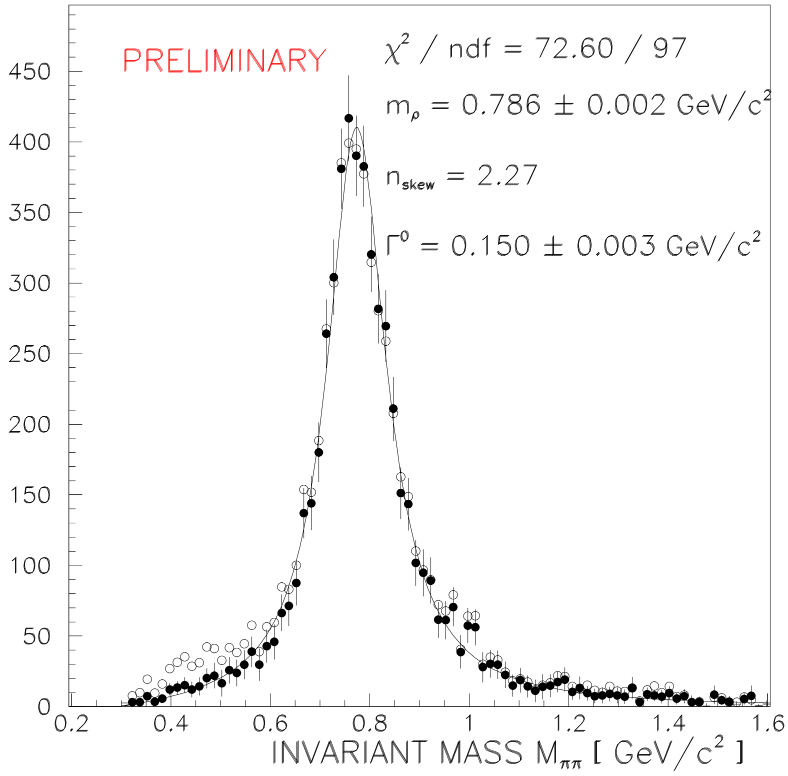
$$\Delta E \equiv (M_Y^2 - M^2)/2M = \nu - E_{\pi\pi} + t/2M$$

$$M_{\pi\pi}^2 \equiv v^2 = (P_{h+} + P_{h-})^2$$

- Cuts: $-2 < \Delta E < 0.6$ GeV, $0.6 < M_{\pi\pi} < 1$ GeV
- $\Delta E > m_\pi(1 + m_\pi/2M)$
  - $\Rightarrow$ non-exclusive $eN \rightarrow eh^+h^-Y$ $(Y \neq N)$
  - Additional (undetected) particles in the final state
- Magenta curve is (mainly) DIS non-exclusive contribution
  - Inferred from distribution at $0.7 < -t' < 5\,\mathrm{GeV}^2$
  - Subtracted separately for each target and $M_{\pi\pi}$, $t'$, $l_c$ bin
  - $\Delta E \sim 2$ GeV: diffr. $\rho^0$ plus brem photon or $N$ dissociation
- $M_{\pi\pi}$: Resonant $\rho^0(770)$ production dominates (plus $\pi^+\pi^-$, $\omega$)

# Selecting Exclusive $\rho^0$ Production

After background subtraction (○) and acceptance correction (●):




- Here $\phi$ production eliminated by requiring $M_{2K} > 1.02\,\mathrm{GeV}$
- fit gives $\rho^0$ contribution as relativistic p-wave Breit Wigner resonance $F(M_{\pi\pi})$
- interference with exclusive, non-resonant $\pi^+\pi^-$ production treated by phenomenological Ross-Stodolsky mass-skewing $n_{\mathrm{skew}}$:

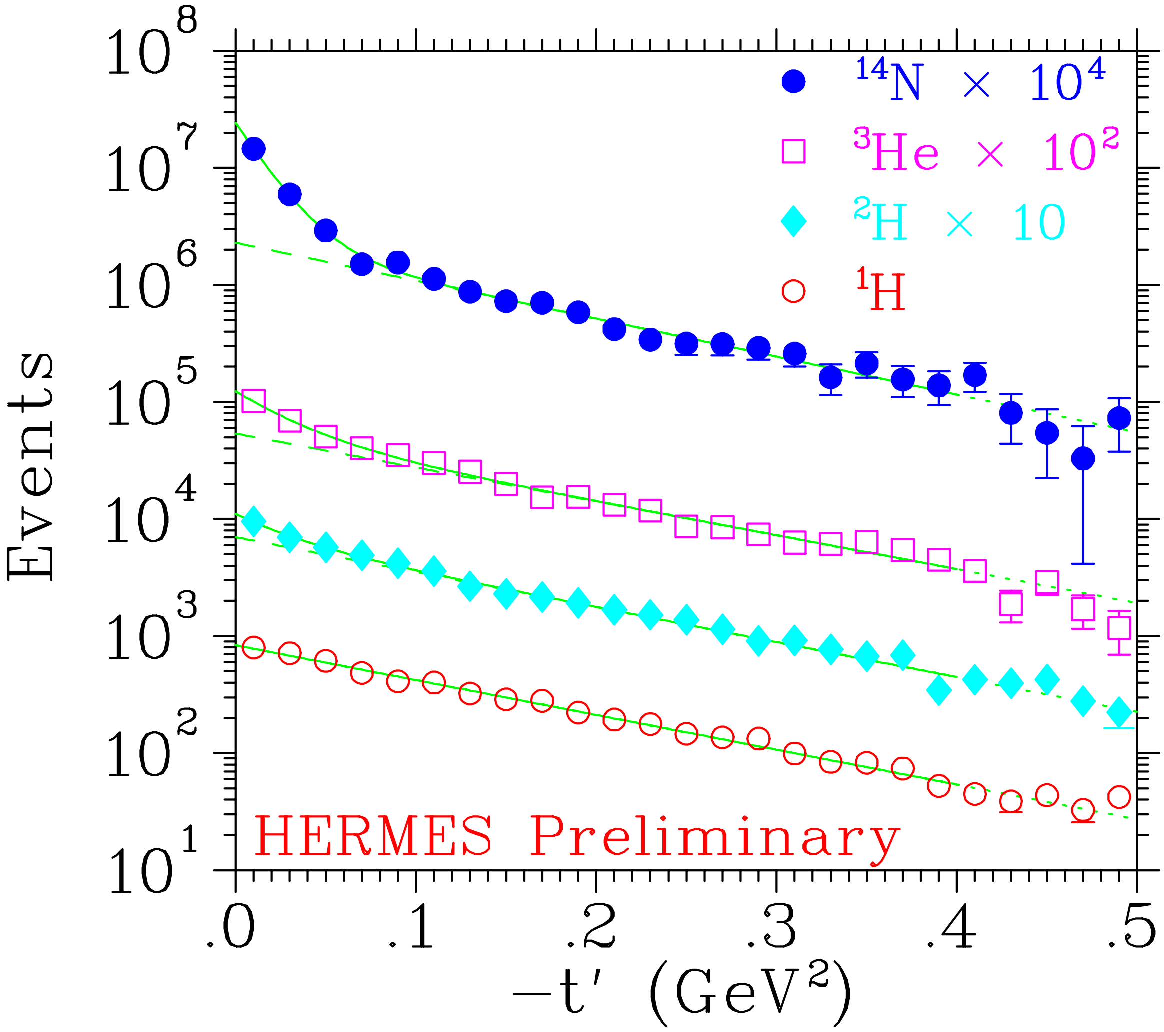
$$\frac{d\sigma}{dM_{\pi\pi}} = F(M_{\pi\pi}) \left(\frac{M_\rho}{M_{\pi\pi}}\right)^{n_{\mathrm{skew}}}$$

- interference from $\omega \to \pi^+\pi^-$ production
  - biases fit to higher $M_\rho$ (PDB: $0.7685 \pm 0.0006\,\mathrm{GeV}$)
  - easily seen in finer binnings
- No other channels apparent
- Cut reduces contributions from other channels (interference terms average out): $0.6 < M_{\pi\pi} < 1\,\mathrm{GeV}$.

# Selecting Exclusive, Diffractive $\rho^0$ Production

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

$$t' \equiv t - t_0 \sim v_t^2$$

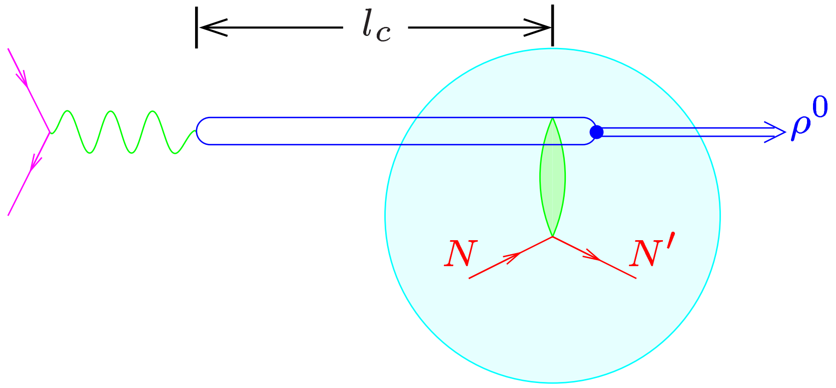



| Approx. $b_A$ $(\mathrm{GeV})^{-2}$ | $R_A$ (fm) |
|---|---|
| 55 | 2.5 |
| 30 | 1.9 |
| 40 | 2.1 |
| 7 | 0.8 |

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

- Incoherent: $b_N \approx 7\ \mathrm{GeV}^{-2}$
- $b \approx \frac{1}{3}\left[\langle R^2_{\mathrm{targ}}\rangle + \langle R^2_\rho\rangle\right]$ ($e^{bt}$ represents elastic F.F., squared)
- Cut: $t'_l(l_c) < -t' < 0.4\,\mathrm{GeV}^2$
  - $t'_l(l_c)$ chosen so $f_{\mathrm{coh}}(l_c) < 1.05$, $\Delta f_{\mathrm{coh}}(l_c) < 0.04$
  - $t'_l(l_c)$: $0.03$–$0.05\ \mathrm{GeV}^2$ ($^2$H), $0.03$–$0.14\ \mathrm{GeV}^2$ ($^3$He), $0.05$–$0.09\ \mathrm{GeV}^2$ ($^{14}$N)

# Incoherent Nuclear Transparency $T_A$



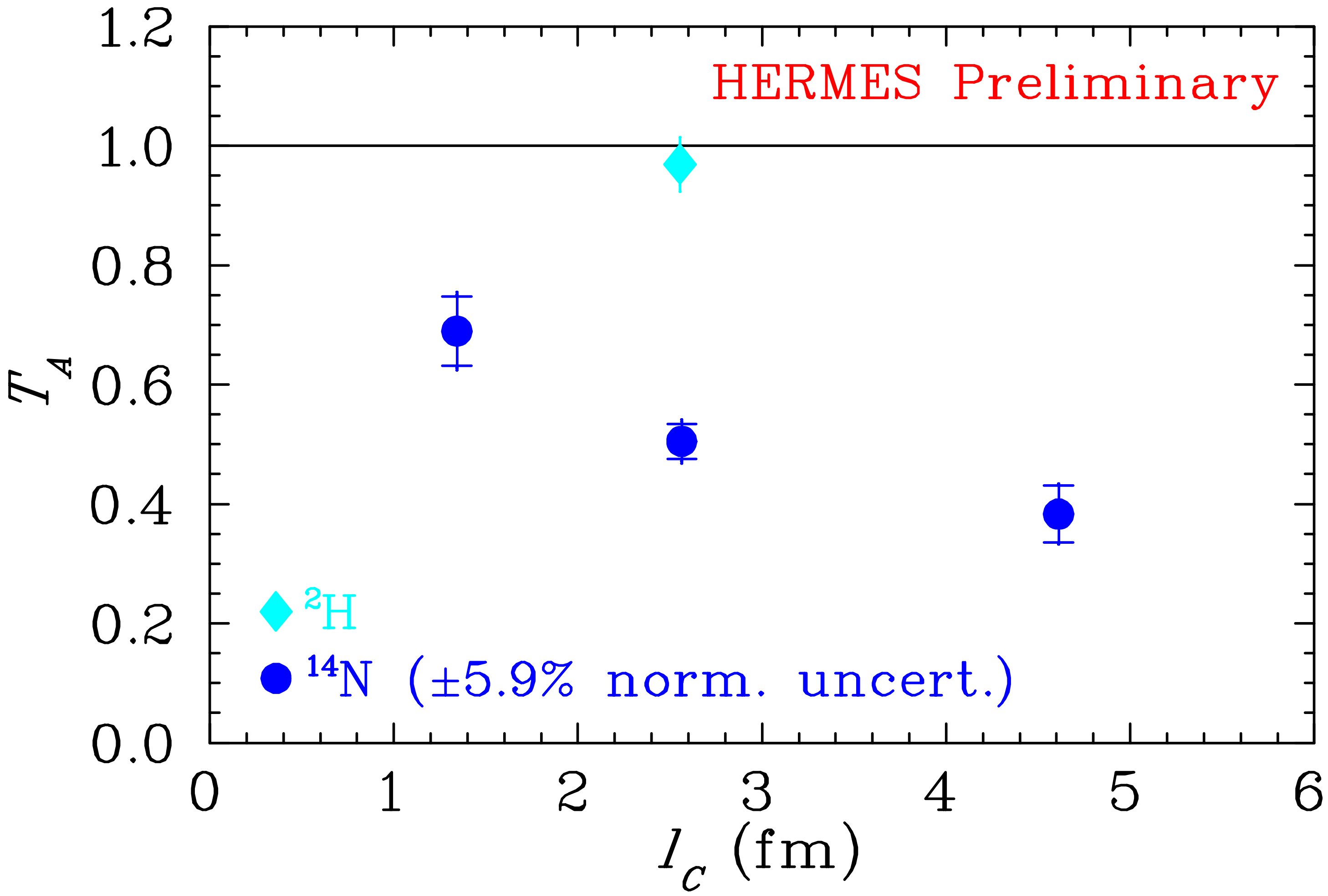

Incoherent nuclear transparency: effect of ISI and FSI on $\sigma_A$

- $\gamma^*$, $q\bar{q}$, $\rho^0$ ISI and FSI $\Rightarrow T_A \equiv \sigma_A / A\sigma_N < 1$
  - $A\sigma_N$ is incoherent $\sigma_A$ in absence of ISI and FSI
  - Expect $\sigma_n \approx \sigma_H \Rightarrow$ use $\sigma_N = \sigma_H$
- If ISI and FSI factorize from exclusive scattering amplitude, $T_A$ is probability of transmitting $\gamma^*$ ($q\bar{q}$) and $\rho^0$ unscathed
- Expect $T_A$ to decrease with onset of hadronic ISI at $l_c \gtrsim R_A$

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

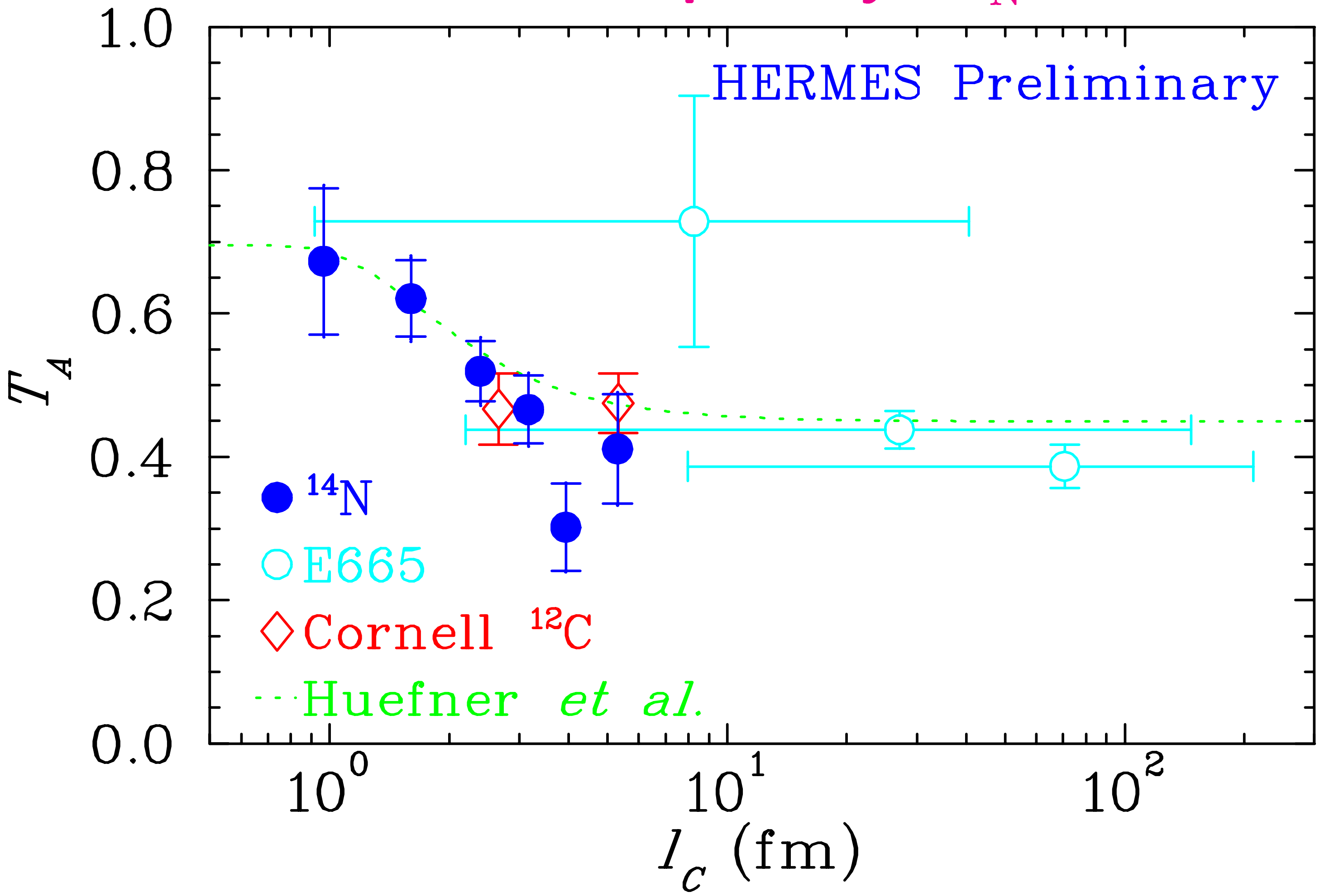
- $L_A$ determined from inclusive DIS $e$ events, corrected for $h^+h^-$ efficiency
- $N_{A,H}$ is number of incoherent events at $t'_l < -t' < 0.4\,\mathrm{GeV}^2$ $(N_A = N_A^{\mathrm{tot}}/f_{\mathrm{coh}})$
- $t'_l$ chosen so that $f_{\mathrm{coh}} < 1.05$, $\Delta f_{\mathrm{coh}} < 0.04$
- Systematic uncertainty from fit uncertainty $\Delta f_{\mathrm{coh}}$ in $f_{\mathrm{coh}}$, background subtraction procedure, time dependences.
- Point-to-point systematic uncertainty added in quadrature

## Nuclear Transparency $T_{^2\mathrm{H}}$, $T_{^{14}\mathrm{N}}$



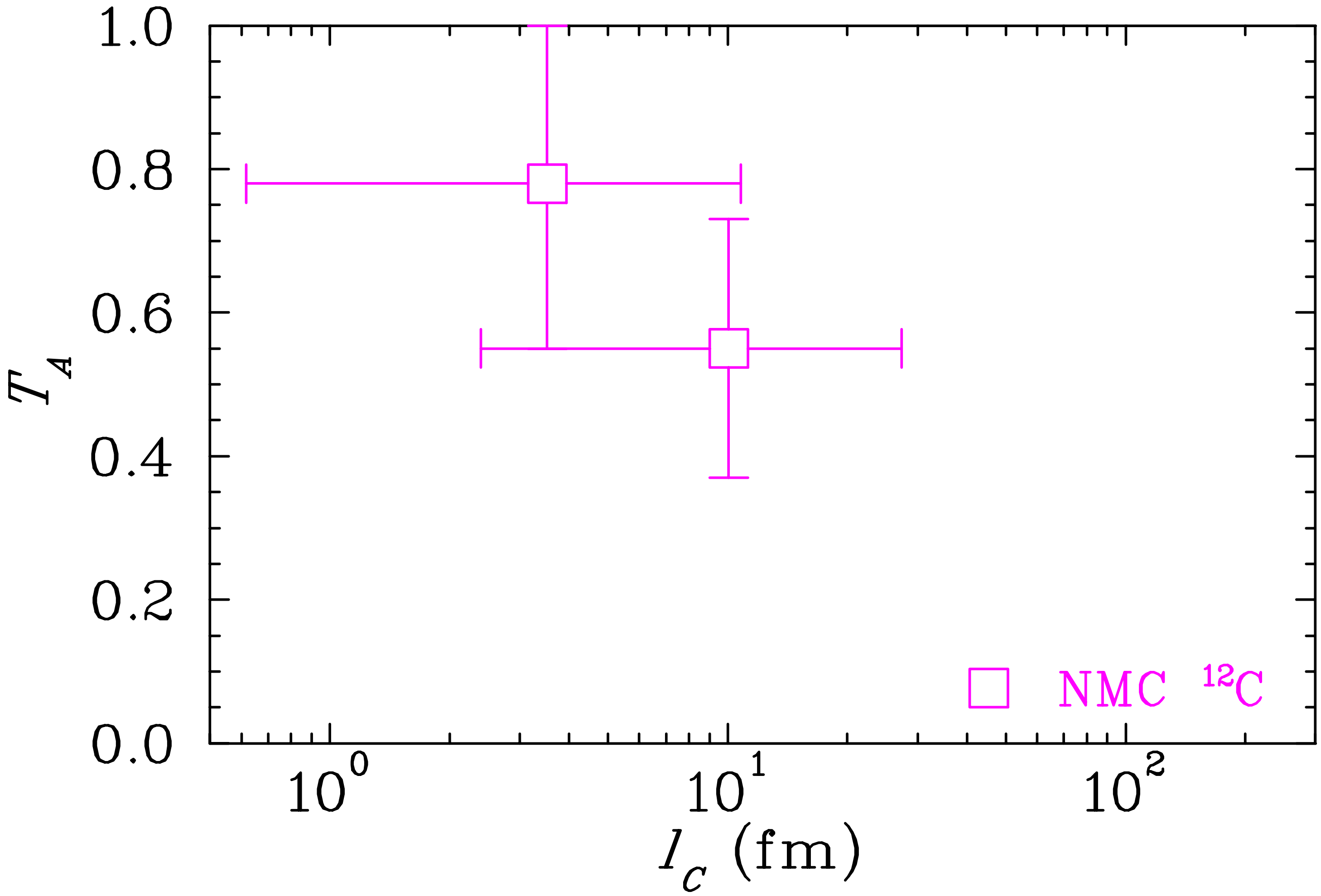

- $T_{^2\mathrm{H}}$ independent of $l_c$
- $T_{^2\mathrm{H}}$ consistent with unity: suggests $\sigma_n \approx \sigma_H$ and small ISI/FSI in $^2$H
- $T_{^{14}\mathrm{N}}$ inconsistent at $> 3\sigma$ level with constant value predicted in absence of coherence length effects

# Nuclear Transparency $T_{^{14}\mathrm{N}}$




- 5.9% uncertainty in HERMES $\langle T_{^{14}\mathrm{N}} \rangle$ not shown
- $T_{^{14}\mathrm{N}}$ decreases with onset of hadronic ISI at $l_c \gtrsim R_{^{14}\mathrm{N}}$
- Consistent with $\rho^0$ production data with 4, 8 GeV $\gamma$ [G.N. McClellan *et al.*, PRL **23** (1969) 554] and 470 GeV $\mu$ beams
- FNAL E665 $\mu$ beam data inferred from $A$-dependence for three $Q^2$ bins [M.R. Adams *et al.* PRL **74** (1994) 1525]
- NMC measurement with 200 GeV $\mu$ beam [M. Arneodo *et al.* Nucl. Phys. B 429 (1994) 503]
- Color transparency may influence:
  - E665 $Q^2 > 3\ \mathrm{GeV}^2 \leftrightarrow \mathrm{l_c} \sim 8$ fm point ($\nu \gtrsim 100$ GeV)
  - All NMC data, taken at $Q^2 > 2\ \mathrm{GeV}^2$ and $40 < \nu < 180$ GeV
- Previous data didn't show $l_c$ dependence
- Consistent with Glauber prediction [J. Hüfner, B. Kopeliovich, J. Nemchik, PLB **383** (1996) 362]

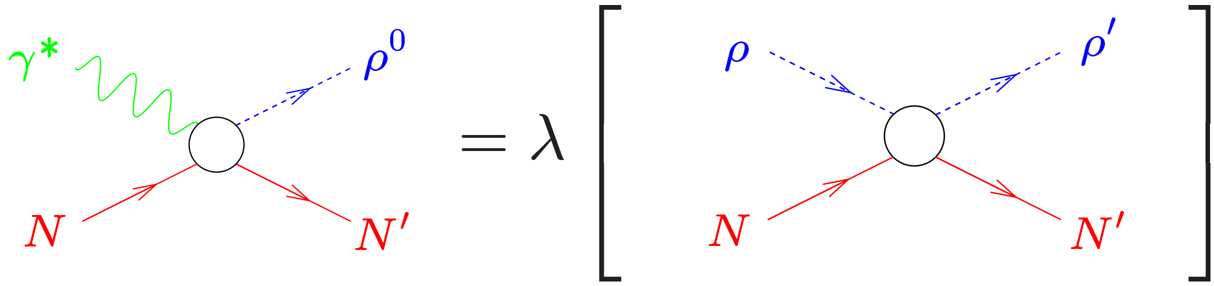
## Nuclear Transparency $T_{^{14}\mathrm{N}}$



# Prediction for Coherence Length Dependence

Recent Glauber prediction [J. Hüfner, B. Kopeliovich, J. Nemchik, PLB **383** (1996) 362]

- $\gamma^* N \to \rho^0 N$ amplitude proportional to elastic $\rho^0 N$ amplitude ($>$ VMD)




- Effective ISI emerge naturally at $l_c \gg R_A$
  - Consistent with $\gamma \to \rho^0$ before entering nucleus
  - Agreement with data at low and high $l_c \Rightarrow \sigma_{q\bar{q},N} \approx \sigma_{\rho N}$

- Color transparency predicted to have little effect (5% increase in $\langle T_{^{14}\mathrm{N}} \rangle$, $< 2\%$ $l_c$ dependence)

- Glauber multiple-scattering theory
- Sum amplitudes from each nucleon
- Amplitudes modified by $\rho^0$ elastic and inelastic rescattering
  - Free FSI amplitudes used
  - $\sigma_{\rho N}^{\mathrm{tot}} = 25\ \mathrm{mb}$
- Neglect nucleon-nucleon correlations $\Rightarrow \rho_A(r)$

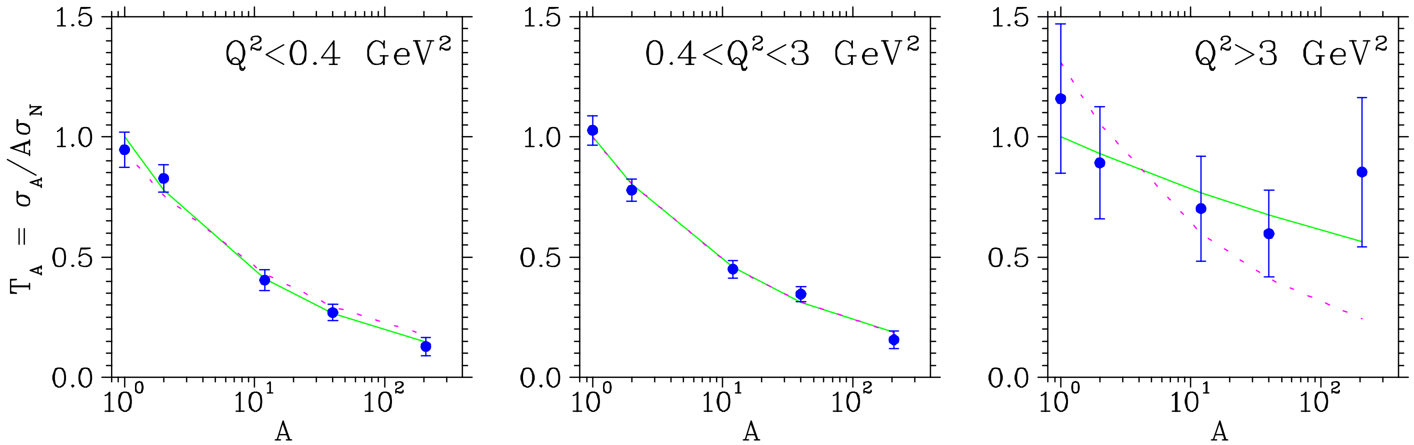
# Extrapolation of FNAL E665 Data

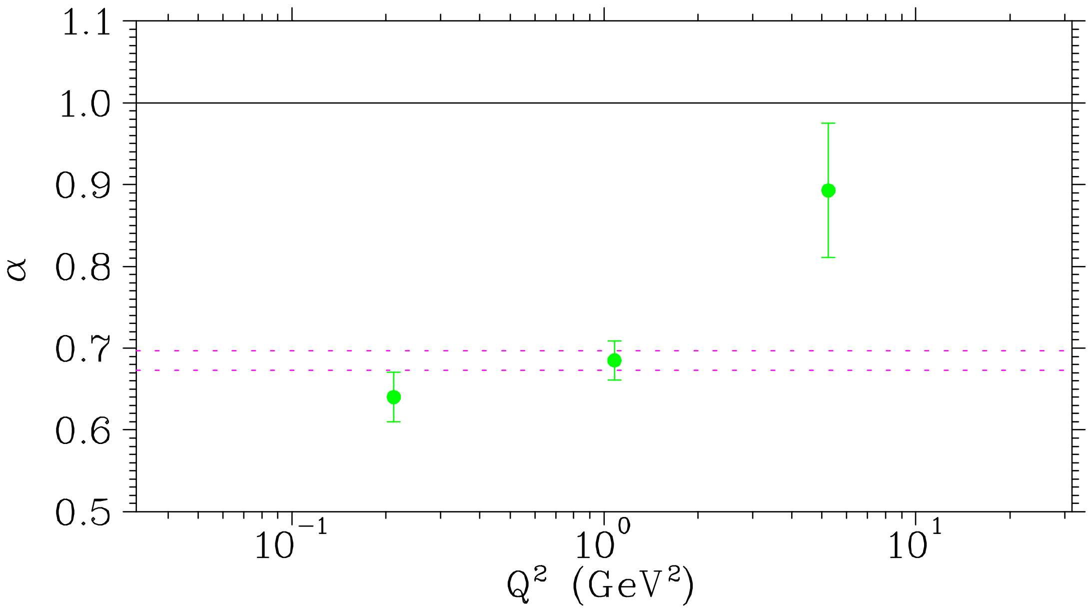
FNAL E665 [M.R. Adams *et al.* PRL **74** (1994) 1525] measured the $(\mu, \mu' \rho^0)$ rate on $^2$H, C, Ca, and Pb targets with a 470 GeV beam and an open geometry spectrometer.

**•:** Nuclear transparency data as function of $A$

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

**skeptical fit:** assumes $\alpha \neq f(Q^2)$, $\chi^2 = 10.0/11 = 0.911$.

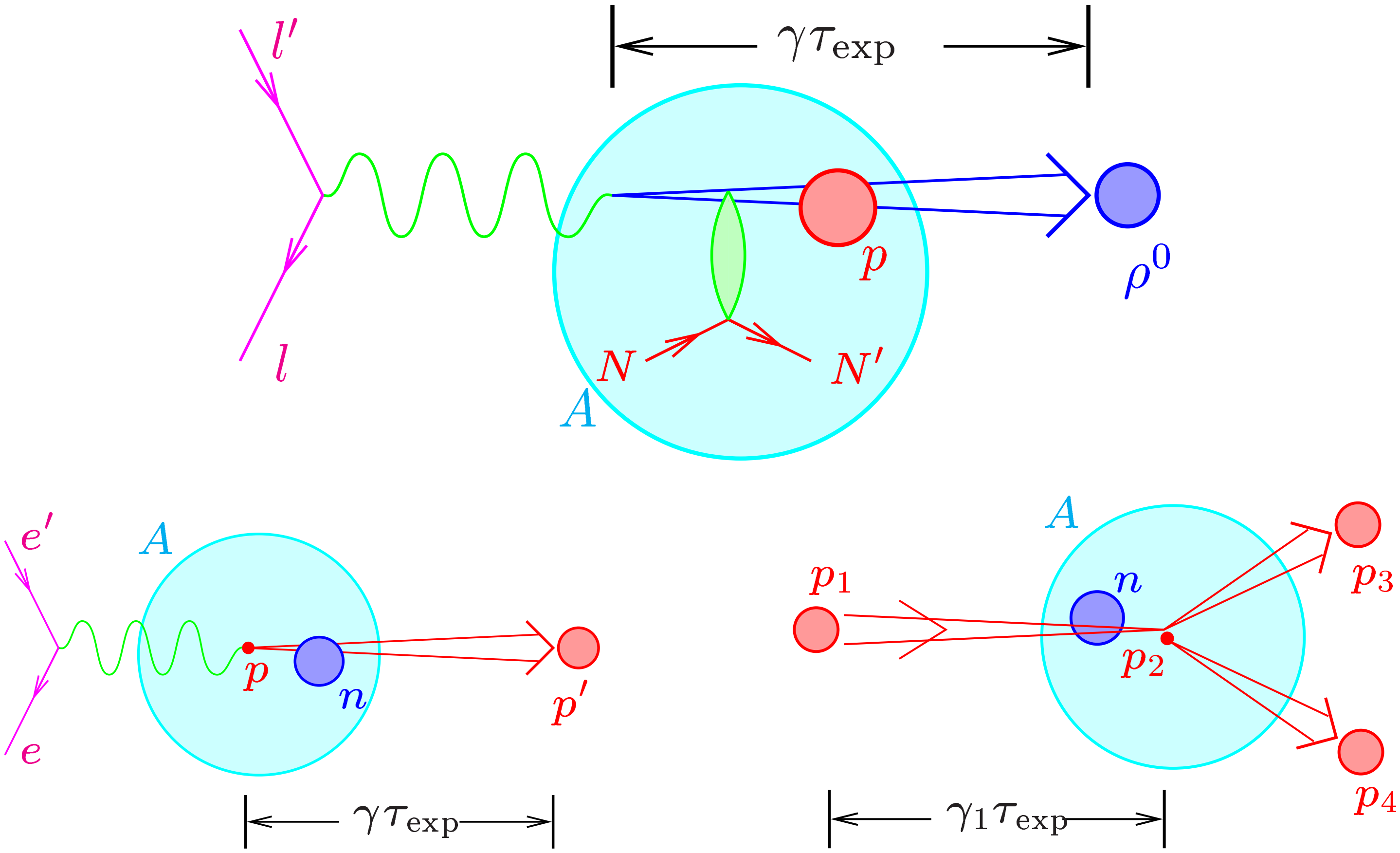



- E665: $50 \lesssim \nu < 330\,\mathrm{GeV}$, HERMES: $9 < \nu < 20\,\mathrm{GeV}$.
  - E665 has much less $l_c$ effect
  - Smaller CT effect at HERMES kinematics.

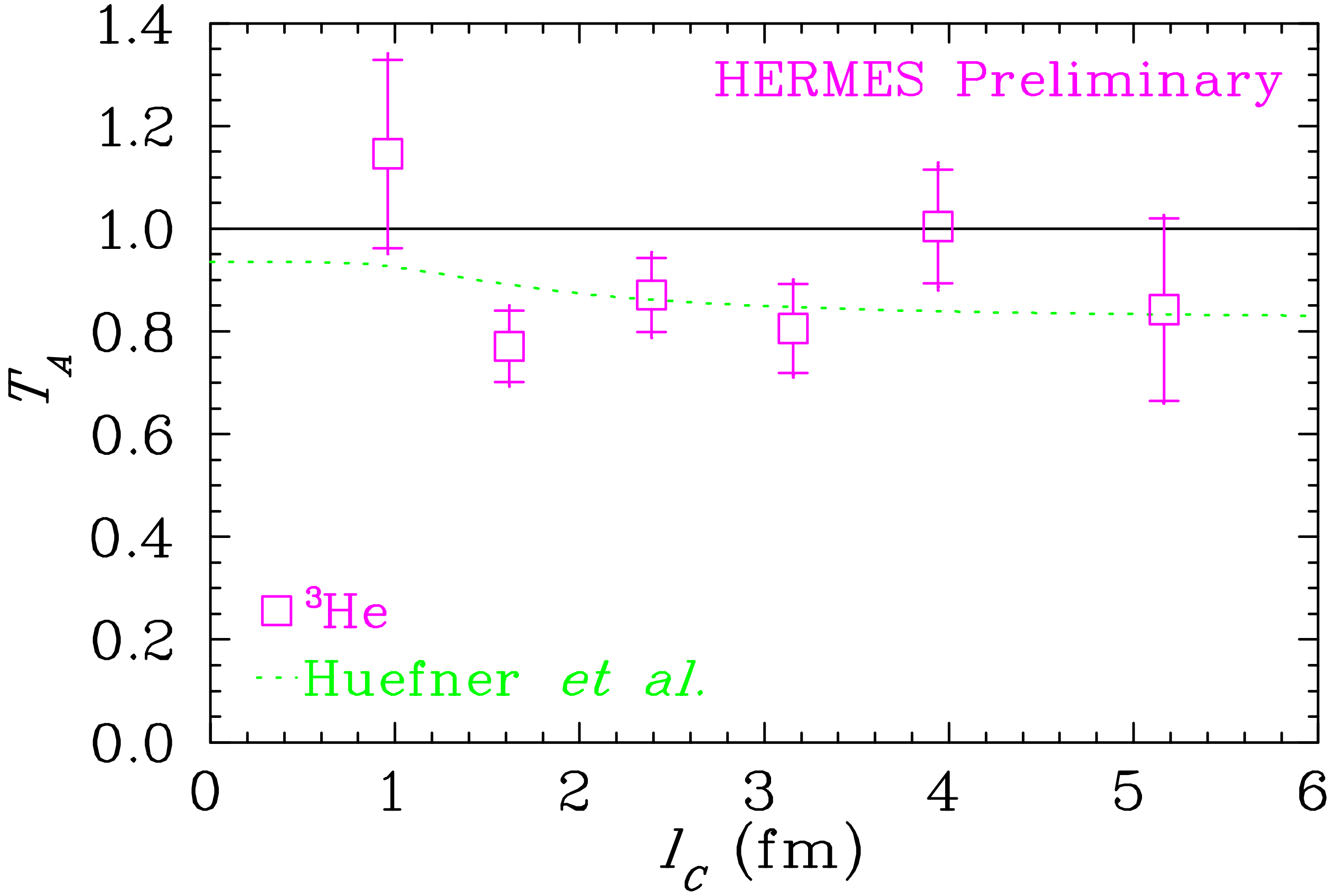
# Color Transparency and $\rho^0$ Leptoproduction

Prediction that in exclusive reactions, Initial and Final State Interactions vanish at high $Q^2$, $\nu$:




| | $(p, 2p)$ | $(e, e'p)$ | $(l, l'\rho^0)$ |
|---|---|---|---|
| Point-Like Config. (high $Q^2$) | ? | ? | Yes |
| Color Screening | Yes | Yes | Yes |
| $t_{\text{exp}} = \gamma\tau_{\text{exp}}$ (high $\nu$) | 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 |
| # ISI/FSI trajectories | 3 | 1 | 1-2 |
| $l_c$ ambiguity | No | No | Yes |

# Nuclear Transparency $T_{^3\mathrm{He}}$




- 5.5% uncertainty in $\langle T_{^3\mathrm{He}} \rangle$ not shown
- Consistent with Glauber prediction
- Insufficient statistics to show $l_c$ dependence

# Other $\rho^0$ Production Topics

- Unpolarized decay angular distributions (J.E. Belz)
  - Test $s$-channel helicity conservation (SCHC), natural parity exchange
  - $r^{04}_{00} \Rightarrow R_{LT}$ (assuming SCHC)
  - Other helicity matrix elements
  - Future: as functions of $Q^2$, $t'$ (coherent/incoherent), $A$,. . .

- $\sigma(Q^2, W)$ at $W \sim 5$ GeV (OFPD, M. Kolstein)

- Nuclear transparency to *coherent* $\rho^0$ production $\Rightarrow$ opposite $l_c$ dependence

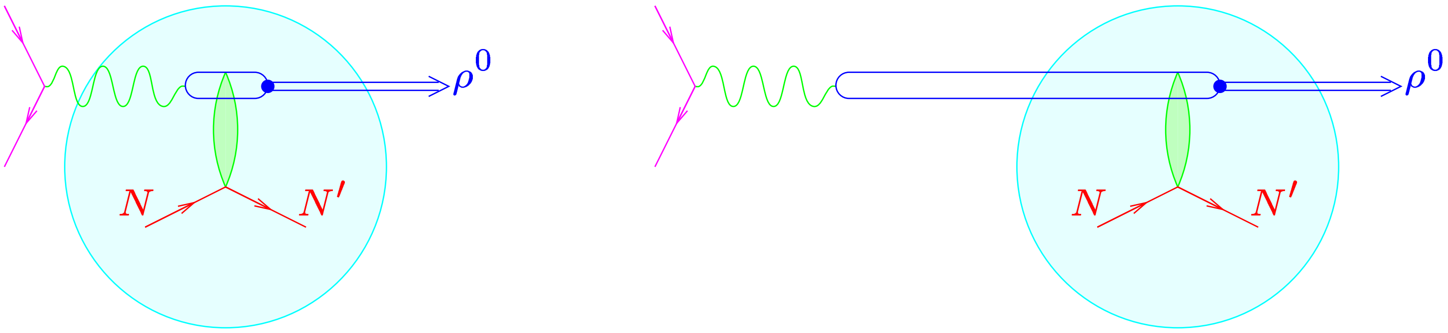
- $b_N(Q^2)$ variation ($\gamma$ shrinkage)

- FIRST TIME: $\rho^0$ production in polarized $\vec{e}\vec{A}$ scattering

# Conclusions

Nuclear transparency $T_A$ for incoherent $\rho^0$ electroproduction:

- Measured at HERMES for $Q^2 > 0.4\ \mathrm{GeV}^2$, $9 < \nu < 20\ \mathrm{GeV}$, $0.6 \lesssim l_c < 8\ \mathrm{fm}$
- $T_{^2\mathrm{H}}$ consistent with isospin symmetry, small ISI/FSI
- $T_{^3\mathrm{He}}$, $T_{^{14}\mathrm{N}}$ agree with standard treatment of ISI, FSI
- $T_{^{14}\mathrm{N}}$ agrees with previous data
- $> 3\sigma$ decrease in $T_{^{14}\mathrm{N}}$ with $l_c$
  - Clear evidence that $\rho^0$ is formed as fluctuation of $\gamma$:
    * ISI increase with lifetime $l_c$ of fluctuation
    * Lifetime $l_c$ consistent with Quantum Mechanics
    * When $l_c \gg R_A$, $q\bar{q}$ ISI as strong as $\rho^0$ FSI
  - Supports contention that $q\bar{q}$ ISI contribute to nuclear shadowing of inclusive $\gamma^{(*)}A$




Small $l_c$ Large $l_c$