From Nucleons and Mesons to Quarks and Gluons

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JLab Scientific "Campaigns"

The Structure of the Nuclear Building Blocks

- How are the nucleons made from quarks and gluons?
- How does QCD work in the 'strong' (confinement) regime?
- How does the NN Force arise from the underlying quark and gluon structure of hadronic matter?

The Structure of Nuclei

- What is the structure of nuclear matter?
- At what distance and energy scale does the underlying quark and gluon structure of nuclear matter become evident?

Symmetry Tests in Nuclear Physics

- Is the "Standard Model" complete? What are the values of its free parameters?

From Nucleons and Mesons to Quarks and Gluons

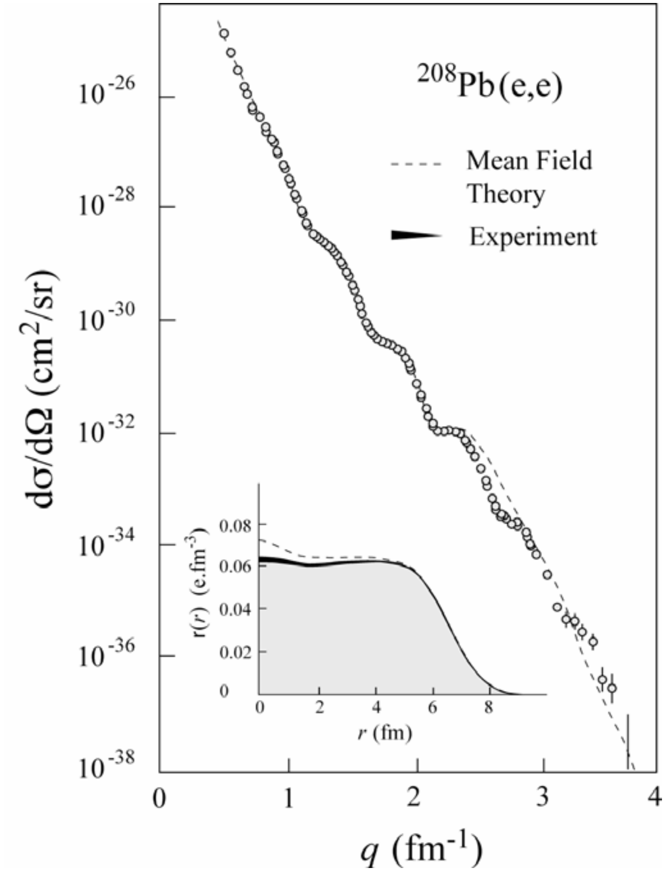
- Introduction
- The Nucleon-Nucleon Interaction
  - Proton Knock-out
  - Nucleon-Nucleon Correlations
    - Two-Nucleon Knock-out
    - Inclusive Scattering at Large x
- Transition to the Quark-Gluon Description
  - The Deuteron
    - Elastic Scattering
    - Photo-disintegration
- The Lambda-Nucleon Interaction
- The Nuclear Medium as Laboratory
  - Medium Modifications of Nucleon Form Factors
  - Color Transparency
- Summary

The Nucleus as Composed of Nucleons and Mesons

Describe basic properties of nuclear system in terms of a realistic N-N interaction

- Single-Particle Description
    - Mean-Field (Hartree-Fock) Approximation
    - Electrons Interact with Single Nucleon Current
- Multi-Baryon Description
    - "Exact" Bound-State Wave Function or
      Mean-Field Wave Function + Nucleon-Nucleon Correlations
    - Two-Body Currents
        - Meson-Exchange Currents (MEC)
        - Isobar Configurations (IC)

History - Charge Distributions



Correlations??

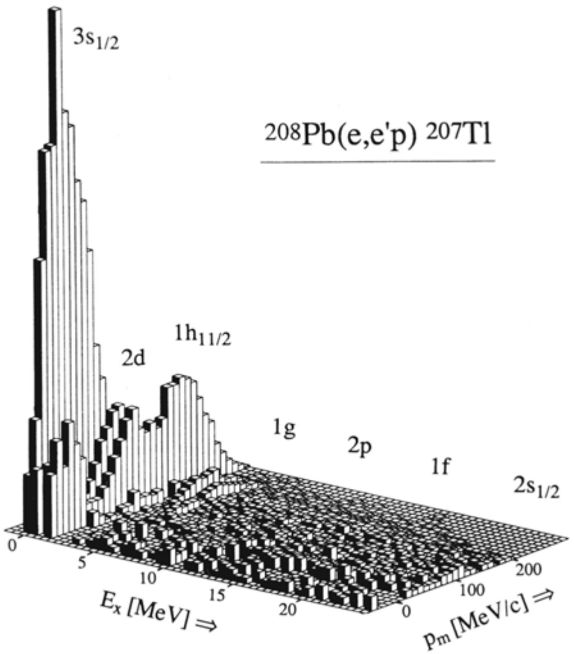
In '70s large data set was acquired on elastic electron scattering (mainly from Saclay) over large Q^2-range and for variety of nuclei

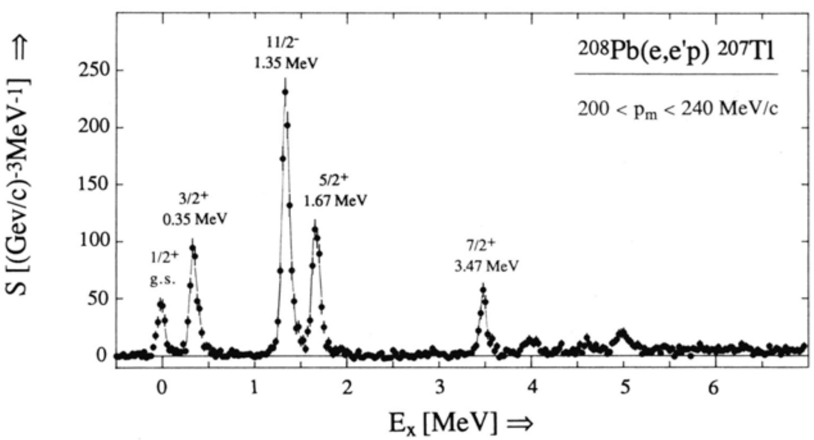
"Model independent" analysis provided accurate results on charge distribution well described by mean-field Density-Dependent Hartree-Fock calculations

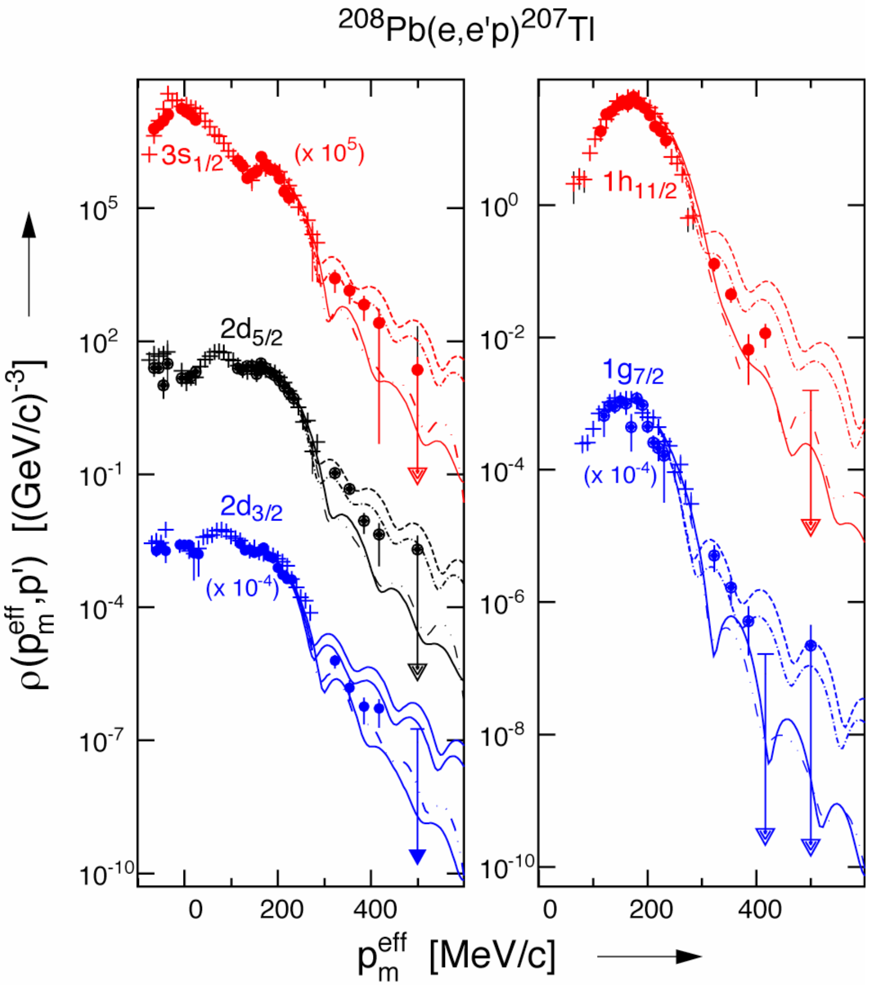
History - Proton Knock-out (NIKHEF)

$$p_m = E_e - E_{e'} - p = q - p$$

$$E_m = \omega - T_p - T_{A-1} = E_{sep} + E_{exc}$$







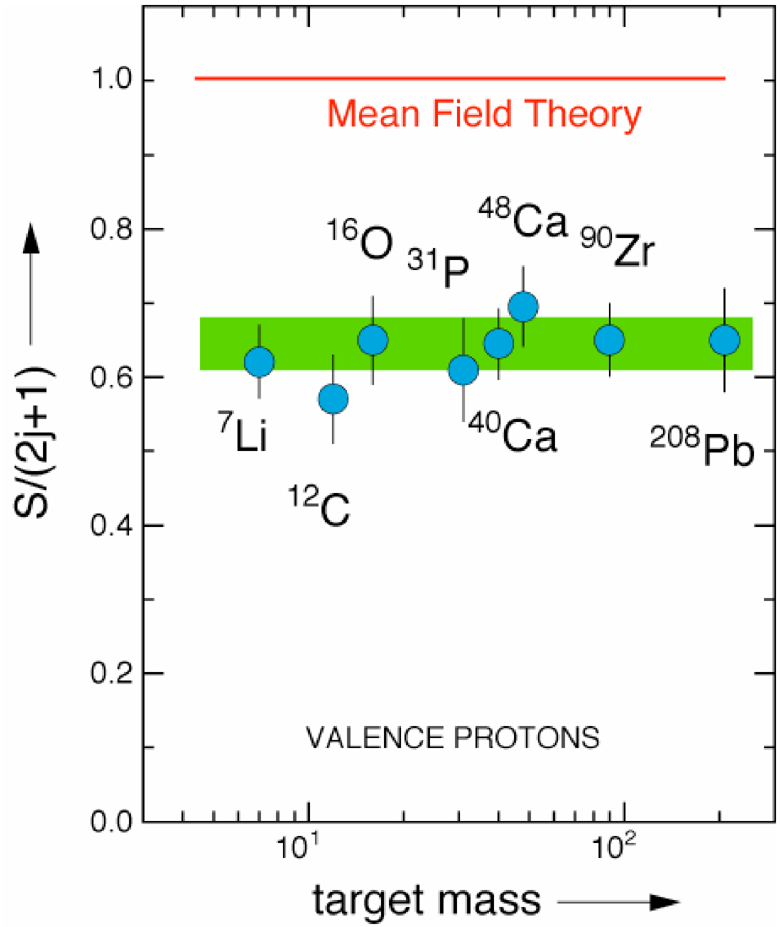
History - Proton Knock-out (cont.)

Electron-induced proton knock-out has been studied systematically since high duty-factor electron beams became available, first at Saclay, then at NIKHEF with ~100 keV energy resolution.
For complex (A>4) nuclei the spectroscopic strength S for valence protons was found to be 60-65% of the IPSM value

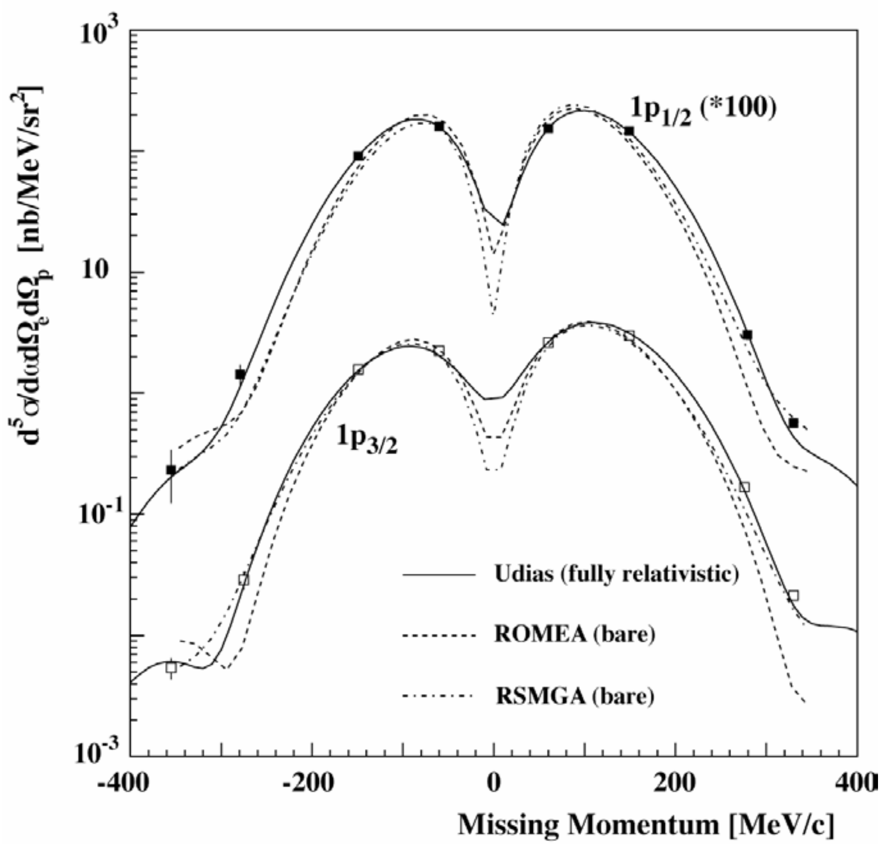
$$S_\alpha = 4\pi \int S(E_m, p_m) p_m^2 dp_m \delta(E_m - E_\alpha)$$

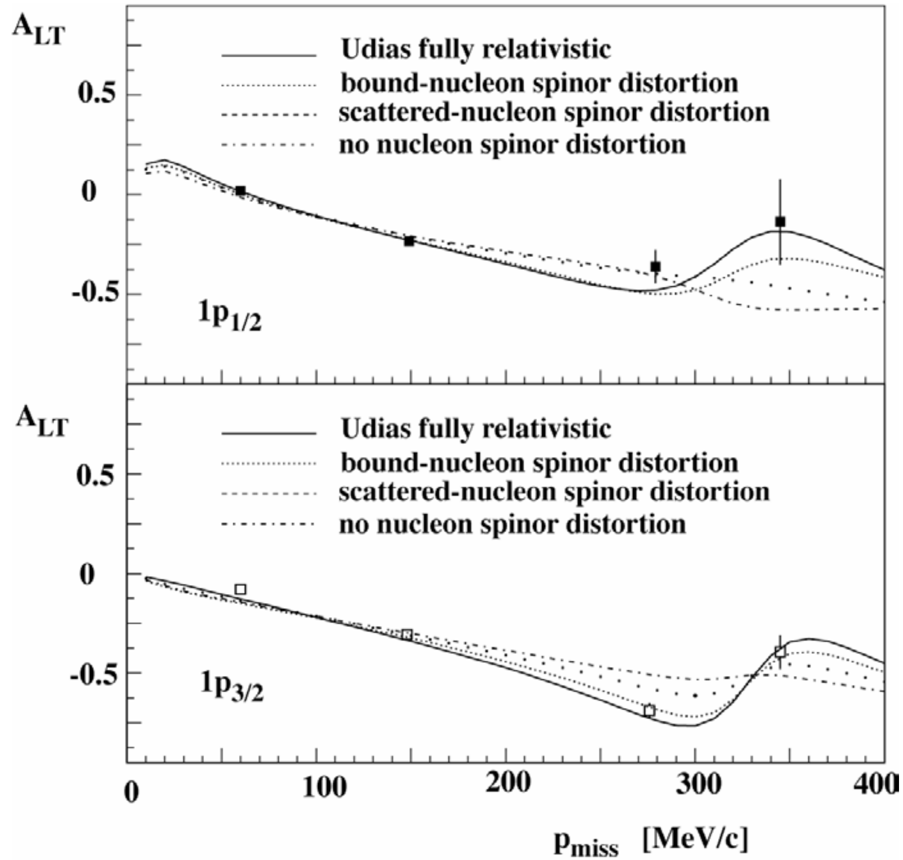
Long-range correlations account for about 10%, but the rest was ascribed to short-range N-N correlations, by which strength was distributed at energies well above the Fermi edge

These kinematics were not accessible at the accelerators of that era, but are at CEBAF



E89-003 $^{16}O(e,e'p)$



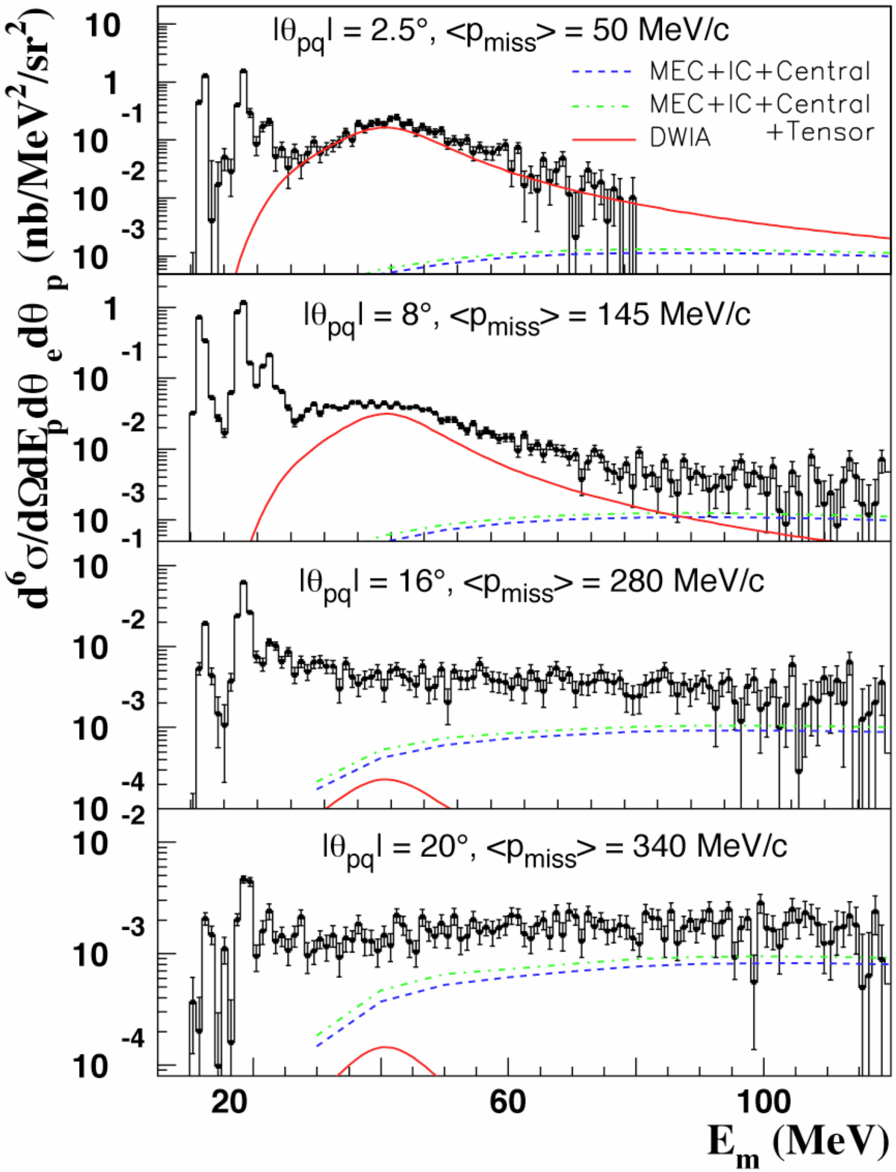


- First high-resolution (~0.8 MeV) (e,e'p) experiment at JLab
- Forward-backward asymmetry A_{LT} at $p_m \approx 300$ MeV/c show need for fully relativistic calculations
- Constant (q,ω) kinematics to minimize variations in reaction kinematics

$$A_{LT} = \frac{\sigma(\varphi = 180°) - \sigma(\varphi = -180°)}{\sigma(\varphi = 180°) + \sigma(\varphi = -180°)}$$

E89-003 ^{16}O(e,e'p) (cont.)

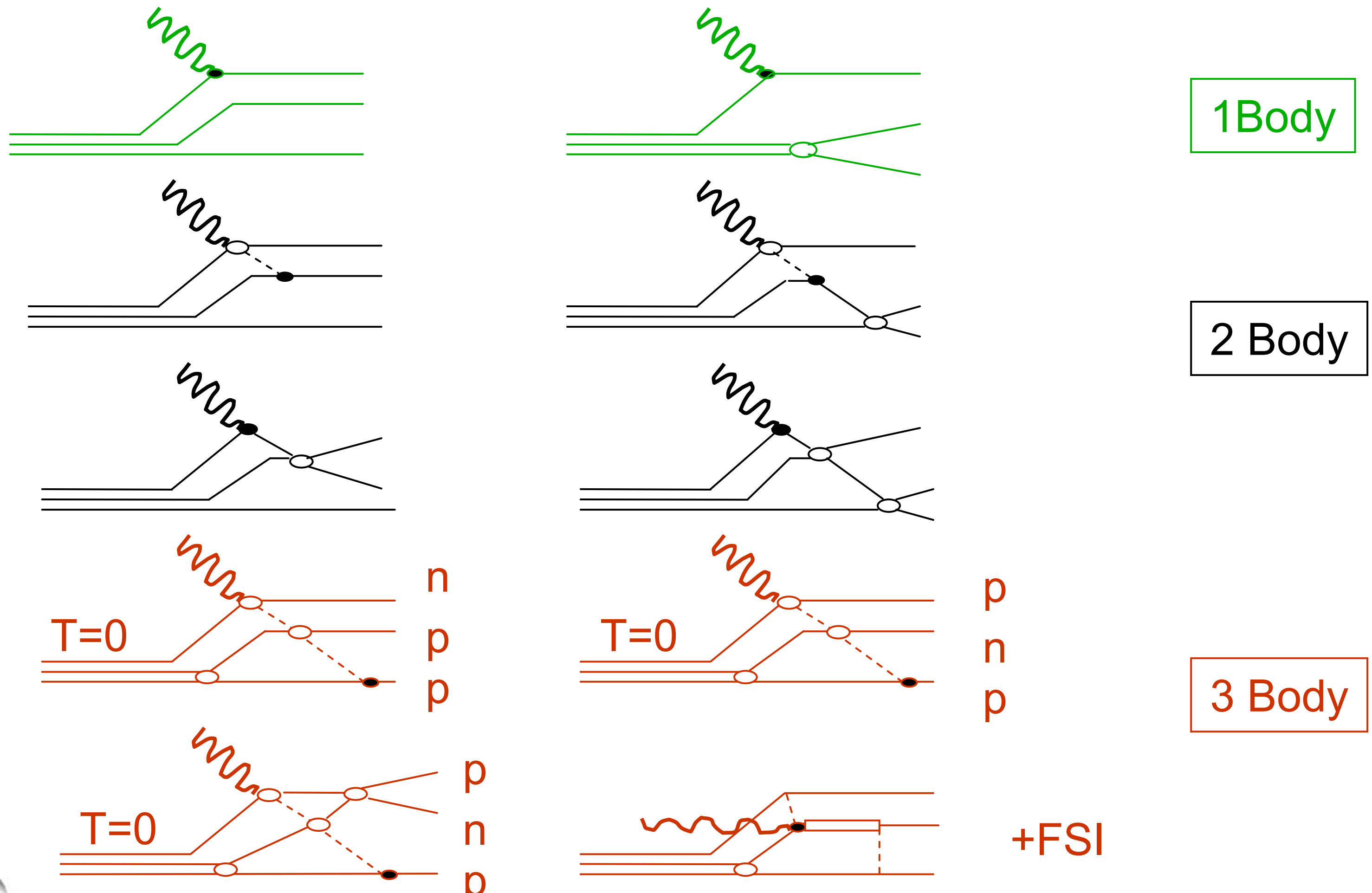
- Cross-section data at E_m up to 120 MeV over range of p_m up to 340 MeV/c
- Broad peak at $E_m \approx 40$ MeV due to knock-out of $1s_{1/2}$-state protons
- Assuming a similar p_m-behaviour as of the valence states, a large cross-section excess is observed at larger p_m-values
- Calculations by Ryckebusch of (e,e'pp) and (e,e'pn) contributions are in reasonable agreement with the data



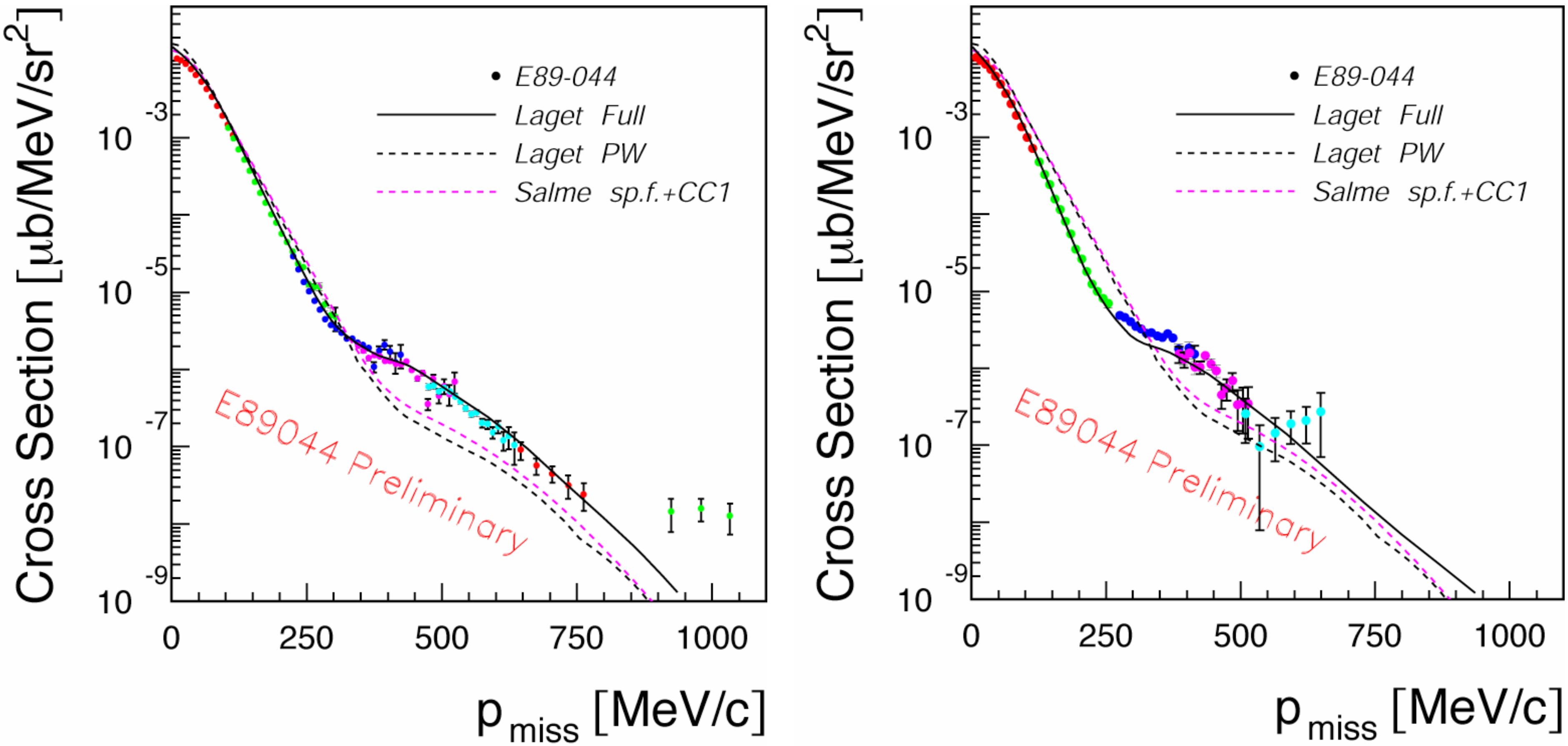
Laget's Calculations

^{3}He Three-Body Disintegration

Ground-State Faddeev WF (Paris potential)



E89-044 $^3He(e,e'p)d$



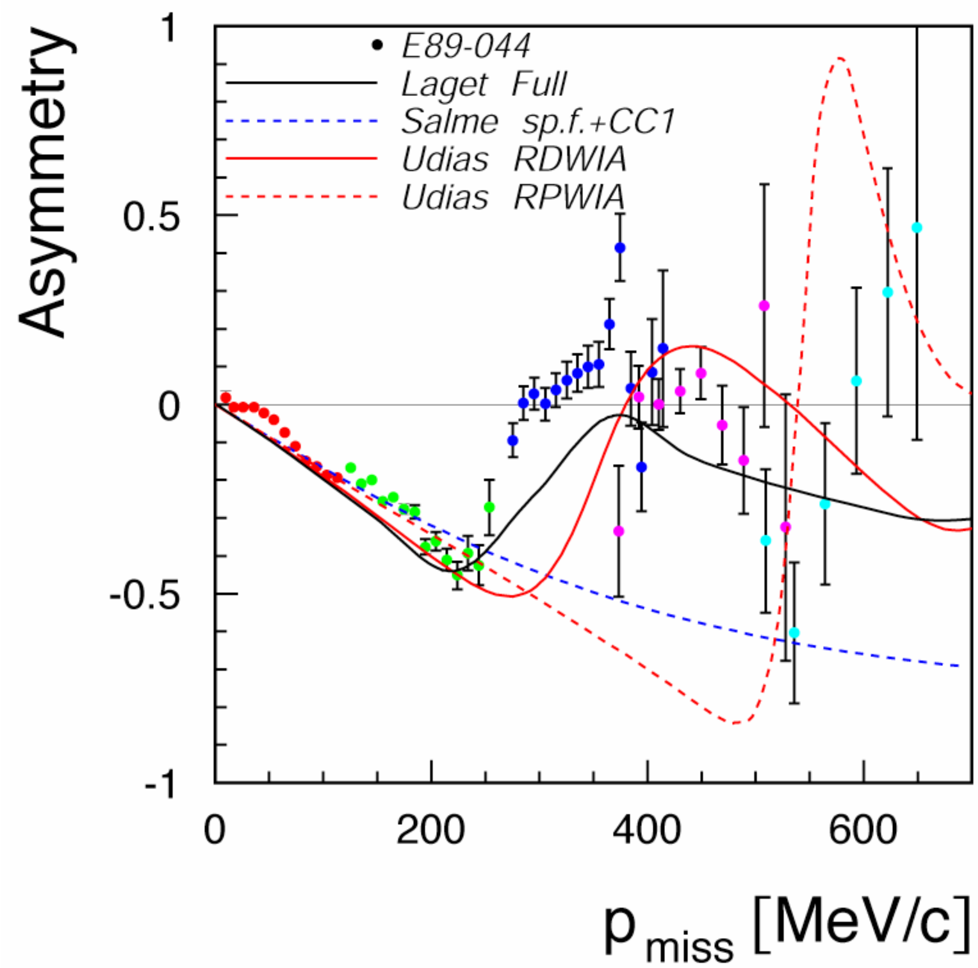
Cross-section data both forward and backward of q up to over 0.6 and 1 GeV/c, resp.
Well described by diagrammatical calculations by Laget (including correlations)

color coding indicates different kinematics

E89-044 $^3He(e,e'p)d$ (cont.)

E_e = 4.8 GeV
q = 1.5 GeV/c; ω = 840 MeV

- The left-right asymmetry A_{LT} was also extracted from the data
- Udias' calculations did not use a correct ^3He wavefunction, so that his results for the cross section can not be compared to the data
- Both Laget's and Udias' relativistic calculations for A_{LT} are in qualitative agreement with the data

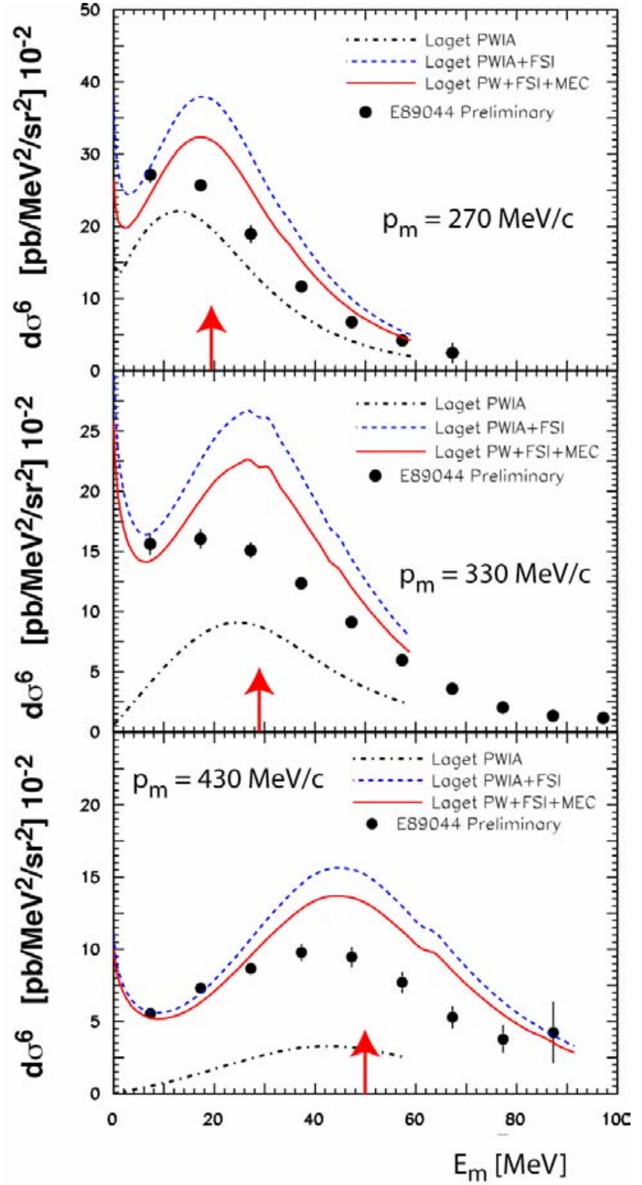


E89-044 $^3He(e,e'p)pn$ (cont.)

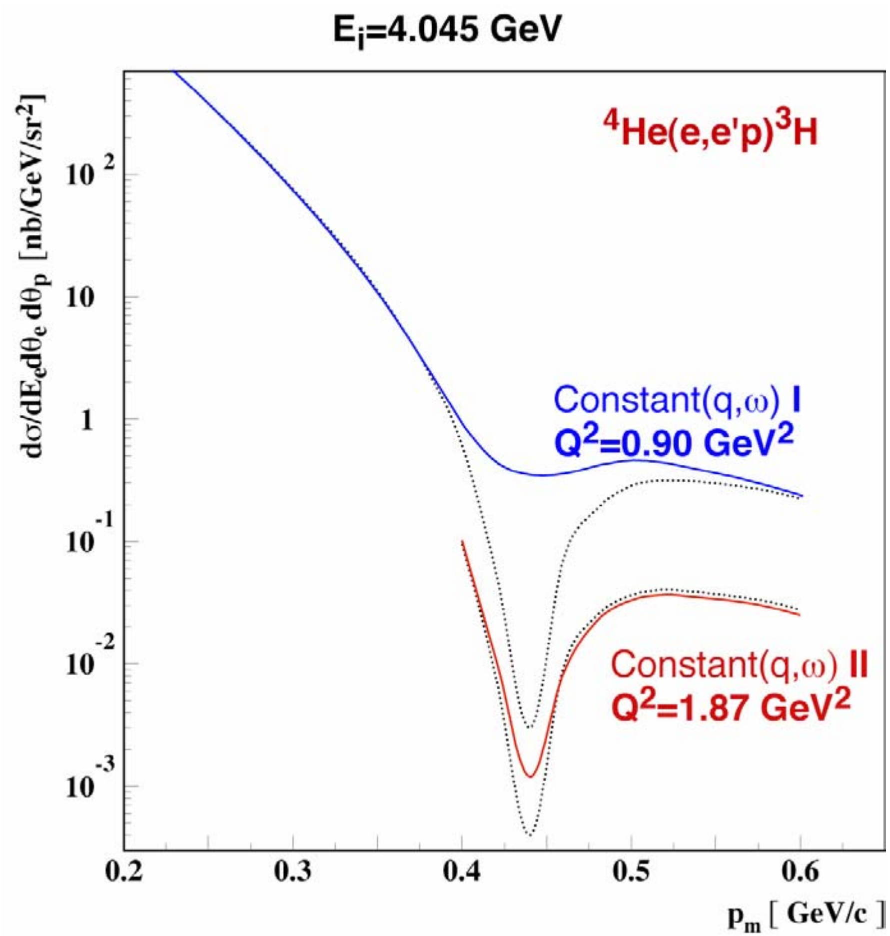
- Earlier Saclay measurements of three-body break-up (PRL 60, 1703 (1988)) showed a bump in the cross section at E_m-values increasing with p_m, interpreted as indications of correlations

$$E_m = E_{thr} + \left(\frac{A-2}{A-1}\right)\frac{p_m^2}{2M_p}$$

- However, the Saclay kinematics were in the dip region, increasing MEC contributions
- E89-044 repeated the Saclay measurements, but in x=1 kinematics
- A similar bump was observed, at smaller E_m-values than predicted by Laget's calculations
- In addition, FSI effects are shown to dominate in x=1 kinematics



E97-111 ^{4}He(e,e'p)



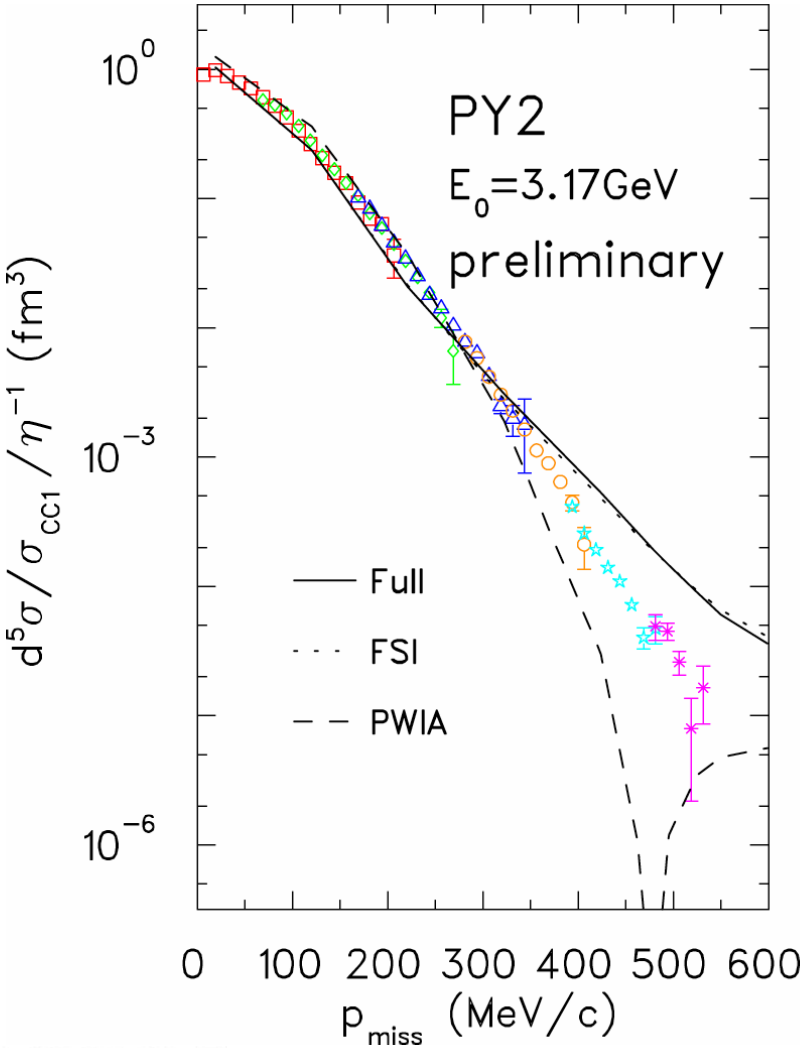
- ^{4}He(e,e'p) cross section in PWIA shows sharp minimum at ~450 MeV/c due to s-wave Short-Range Correlations
- How to Suppress FSI in (e,e'p)?

  higher momentum transfer
  - momentum of outgoing proton increases
  - FSI (elastic rescattering) decreases

  parallel kinematics
  - always selects minimum p_{miss}
  - in perpendicular kinematics: rescattered low p_{miss} nucleons can contribute at larger p_{miss}
  - Generalized Eikonal Approximation predicts minimal sensitivity to FSI for parallel kinematics

E97-111 ^{4}He(e,e'p) (cont.)

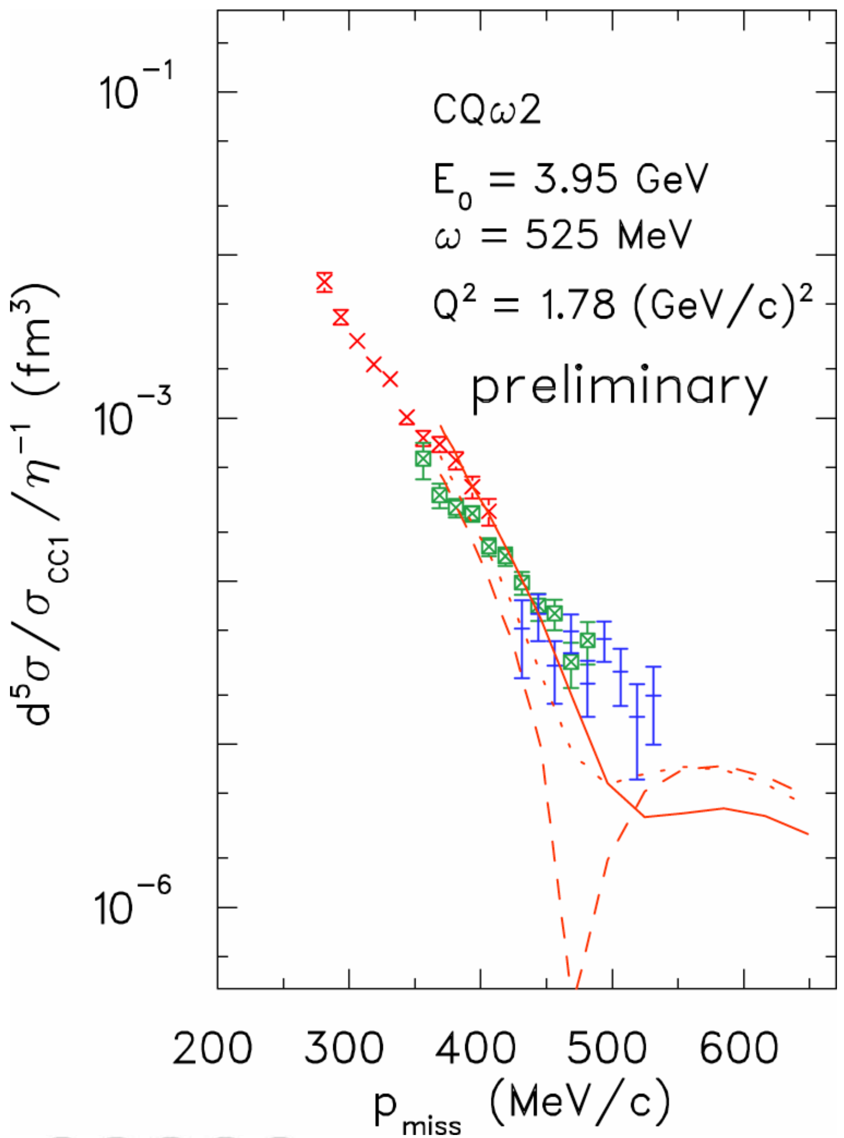
Parallel Kinematics $Q^2 = 0.85\ (GeV/c)^2$



- theory works at low missing momentum
- PWIA predicts minimum
- including FSI the minimum vanishes
- MEC and IC give only minor contributions
- no minimum in experimental data

calculations by J.-M. Laget

E97-111 ^{4}He(e,e'p) (cont.)



Perpendicular Kinematics

- PWIA (dashed): minimum at 470 MeV/c
- including FSI (dotted): minimum mostly filled in
- full calculation (solid): includes FSI + MEC + IC minimum mostly filled
- experiment: no sign of minimum at all

calculations by J.-M. Laget

Proton Knock-out at JLab

E94-004	^2H	completed	cross section for x=1 up to $p_m \approx 1$ GeV/c
E91-013	^{12}C,Fe,Au	completed	R_L/R_T for T_p 0.4,1.0 GeV, σ for T_p 0.7,2.0 GeV
E94-139	^{12}C	completed	color transparency up to $Q^2 \approx 8$ (GeV/c)^2
E97-006	C,Al,Fe,Au	analysis	$S(p_m,E_m)$ for (p_m,E_m) up to (750 MeV/c, 75 MeV)
E01-020	^2H	analysis	R_{LT} at $Q^2 \approx 0.9$-3.3 GeV^2 and $p_m \approx 0$-400 MeV/c σ in $\perp$/ // kins for x -0.5-1.5 and $p_m \approx 0$-400 MeV/c
E00-102	^{16}O	analysis	R_{LT} at constant (q,ω) p_m to 0.5 GeV/c,E_m to 150 MeV
E01-108	^4He	approved	R_{LT} at constant (q,ω) p_m to 0.5 GeV/c σ for p_m to 1.2 GeV/c R_L/R_T for $Q^2 \approx 0.8$-4.1 GeV^2

Direct Observation of Short-Range Correlations

- Inclusive scattering at large |y|
- Multi-nucleon knock-out

Inclusive scattering at large x

E91-009

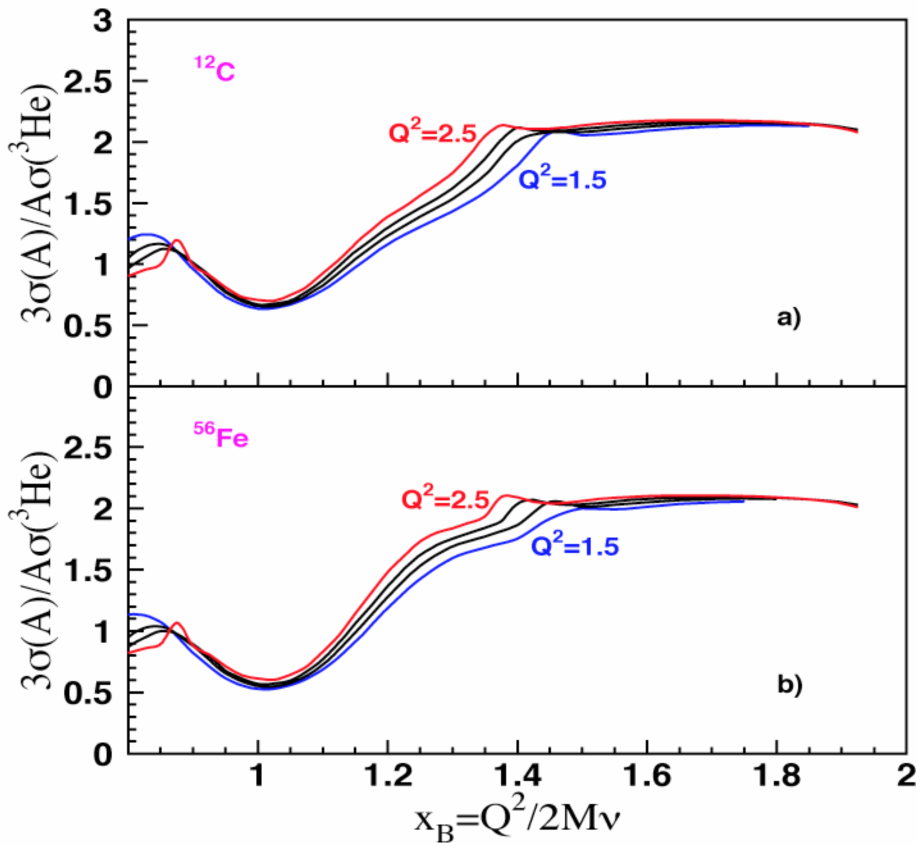
Define y as the x_B-value at which the minimum p_{miss} exceeds p_{Fermi}

SRC model predicts:

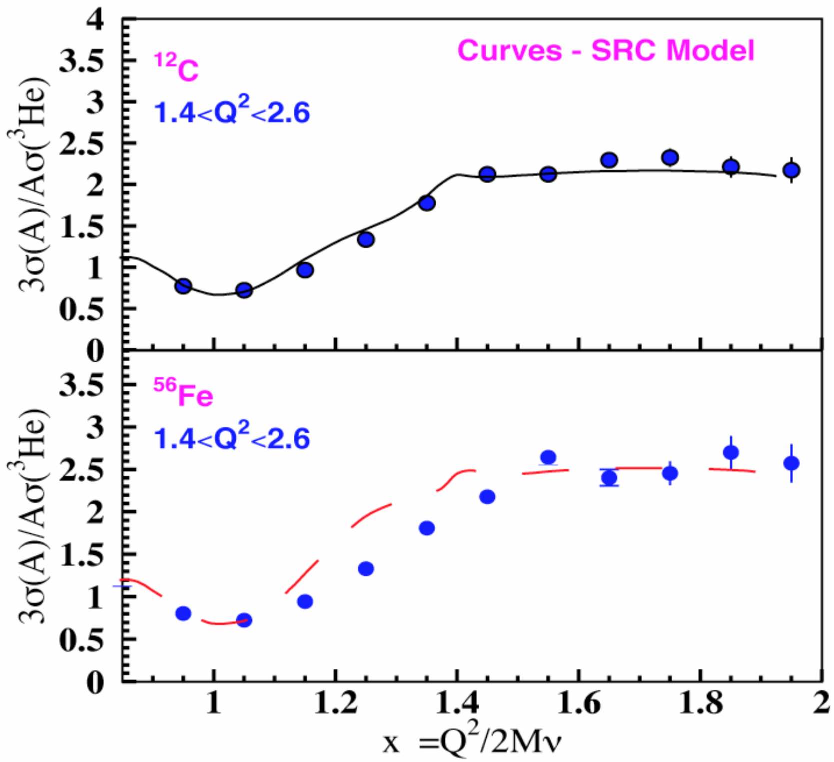
- Scaling for $x_B > y$ and $Q^2 > 1.5$ GeV^2
- No scaling for $Q^2 < 1$ GeV^2
- In scaling regime ratio Q^2-independent and only weakly A-dependent

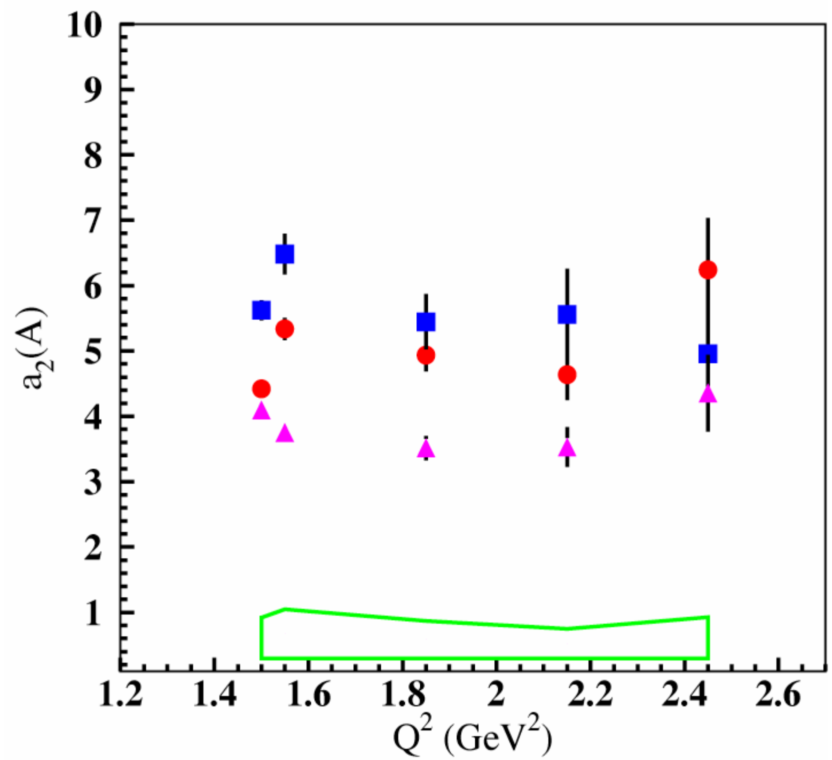
Glauber Approximation predicts:

- No scaling for $x_B < 2$ and $Q^2 > 1$ GeV^2
- Nuclear ratios should vary with A and Q^2



Inclusive scattering at large x





Cross-section ratios closely follow predictions of SRC-model
Analogous results from E89-008 in Hall C

$$a_2(A) = \frac{\sigma(A)}{Z\sigma_p + N\sigma_n}$$

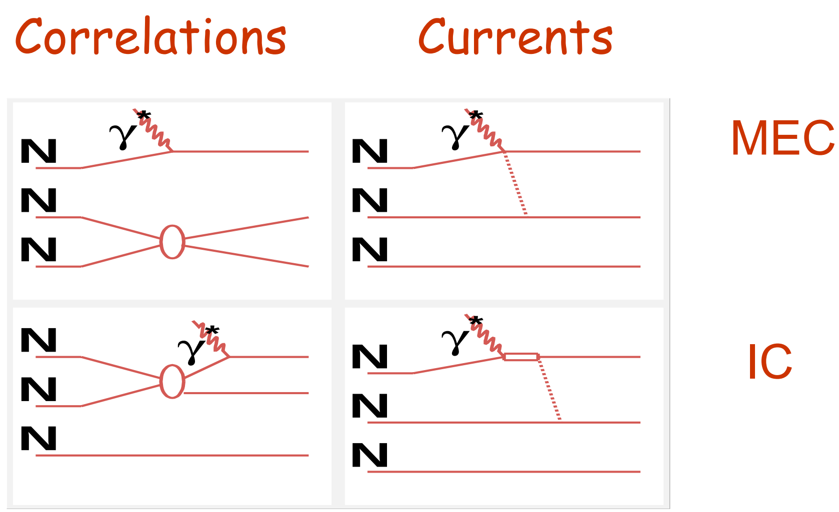
a_2 is Q^2-independent and increases from ~4 (^{4}He) to ~6 (^{56}Fe)

What Are Correlations?

Observable: an NN-pair with

- large relative momentum
- small total momentum

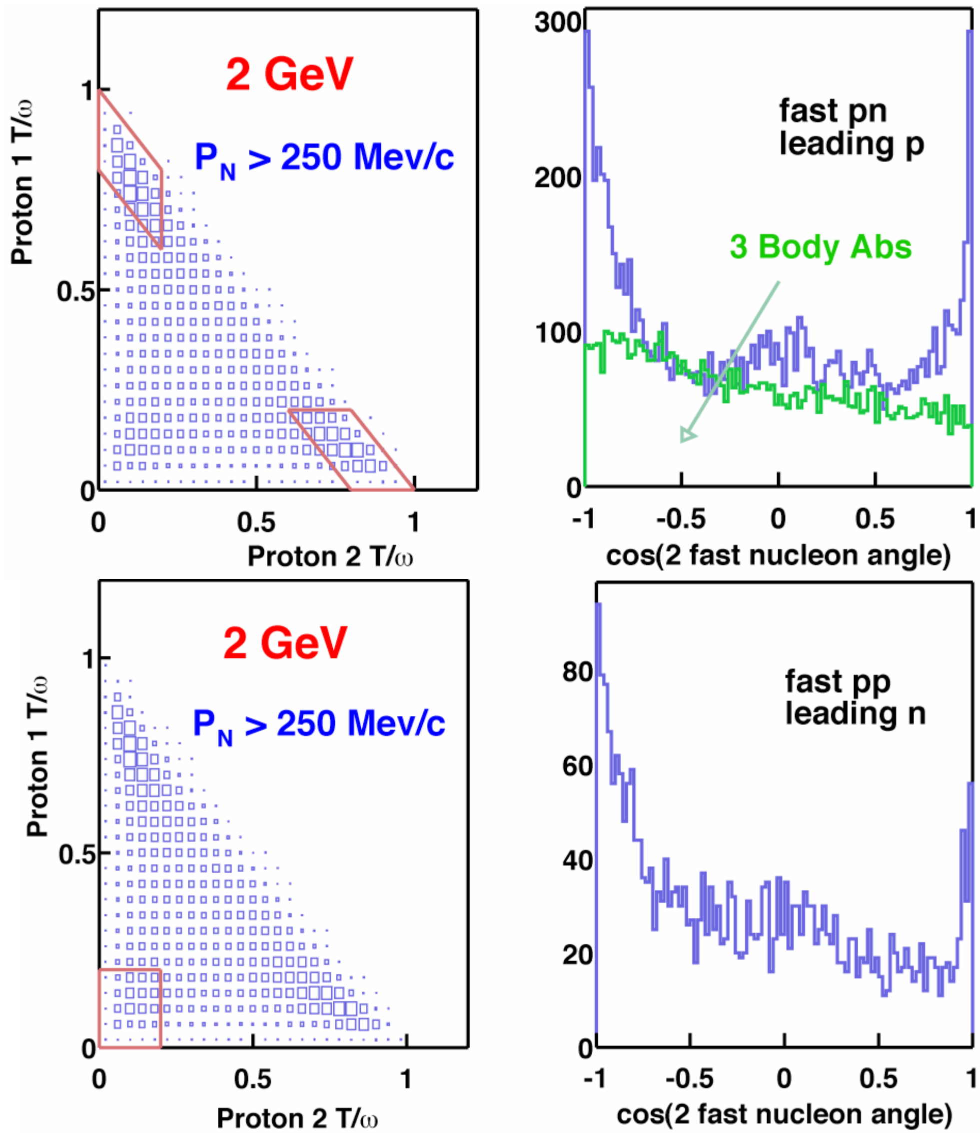
→ Distinguish between Correlations and Currents



Two-Body Currents (MEC + IC)

- Not a Correlation
- Strongly enhance effect of correlation

Select proton/neutron with large ω

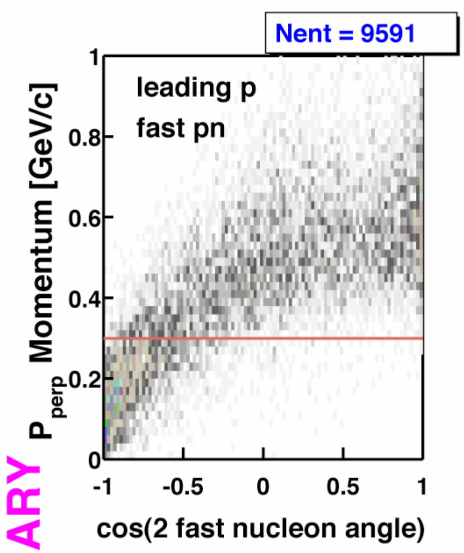


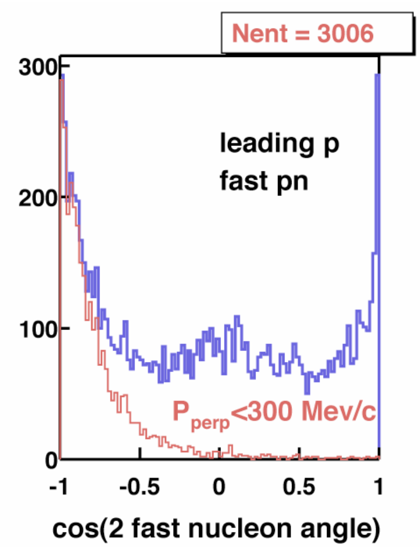
CLAS E89-027
Preliminary results

Two protons detected with $p > 250$ MeV/c $> p_{Fermi}$ reconstruct neutron

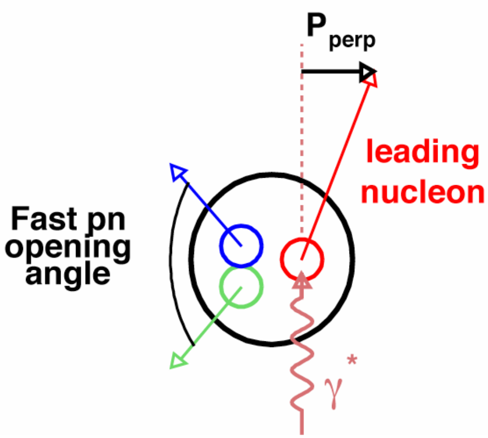
Select proton/neutron with almost all transferred energy ($T_N/\omega \approx 1$)
Clear evidence of back-to-back excess over three-body absorption followed by phase-space decay simulation

Select Quasi-Free Knock-out-> Isotropic Angular Distribution

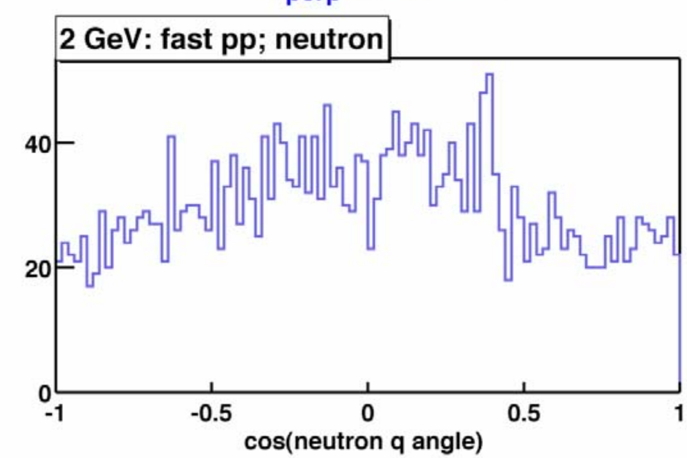




Cut on leading nucleon P_{perp} < 300 MeV/c to select quasifree knockout (reduce FSI)

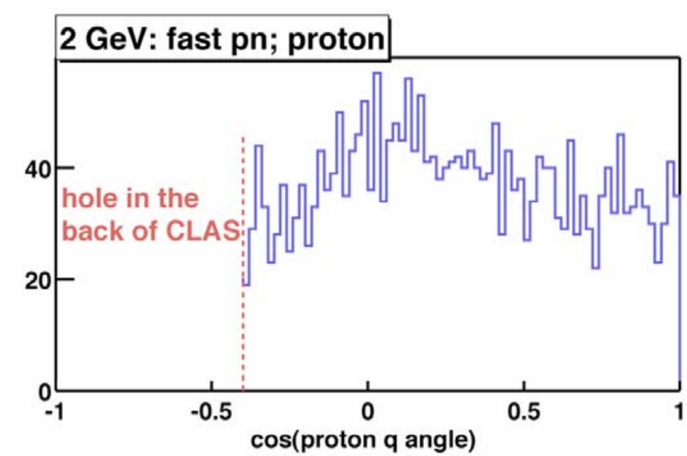


P_{perp}<300 MeV/c



Isotropic Fast Pairs

-> Pair not involved in REACTION!



Summary of E89-027

Select Quasifree Leading Nucleon in $^{3}He(e,e'pp)n$

Fast NN Pair is:

- **Back to Back**
- **Isotropic with respect to q**
- **Small Momentum along q**

➔ **Fast NN Pair Not Involved in the Reaction**

Similar Total and Relative Momentum Distributions for:

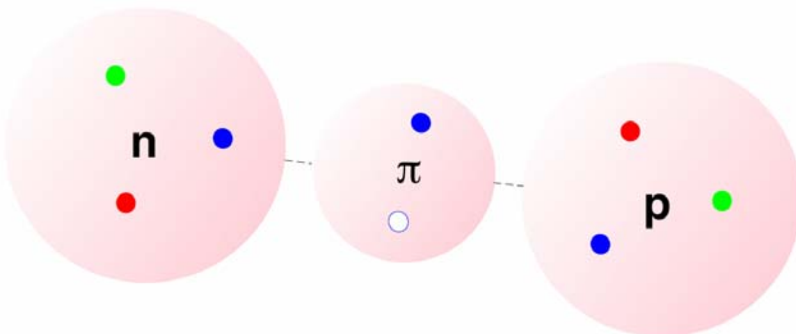
- **pp and pn pairs**
- **$0.5 < Q^2 < 1$ and $1 < Q^2 < 2$ $(GeV/c)^2$**

WE ARE OBSERVING BOUND-STATE CORRELATIONS!

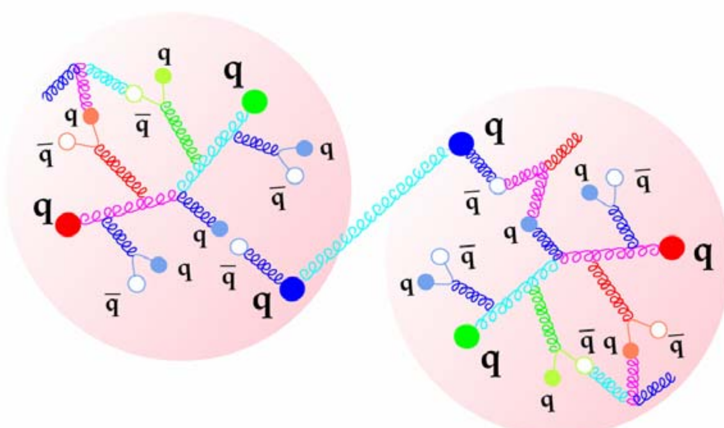
Transition from Nucleon-Meson to Quark-Gluon Description

- Deuteron
  - ➔ Elastic Scattering
  - ➔ Photo-Disintegration
  - ➔ Polarization transfer

Two Views of Deuteron Structure

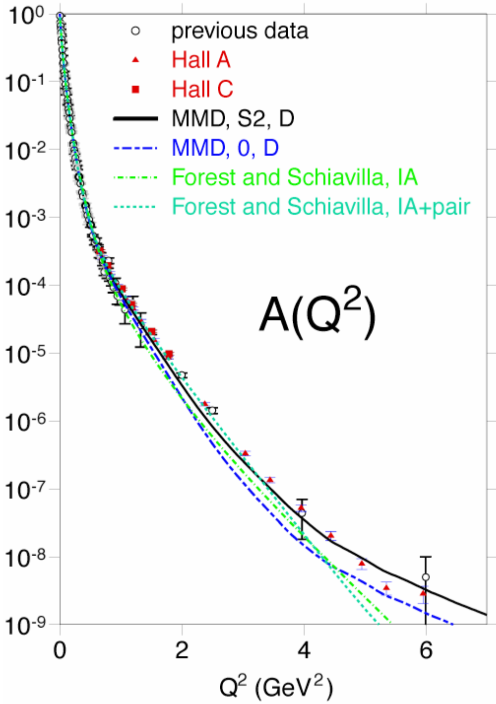


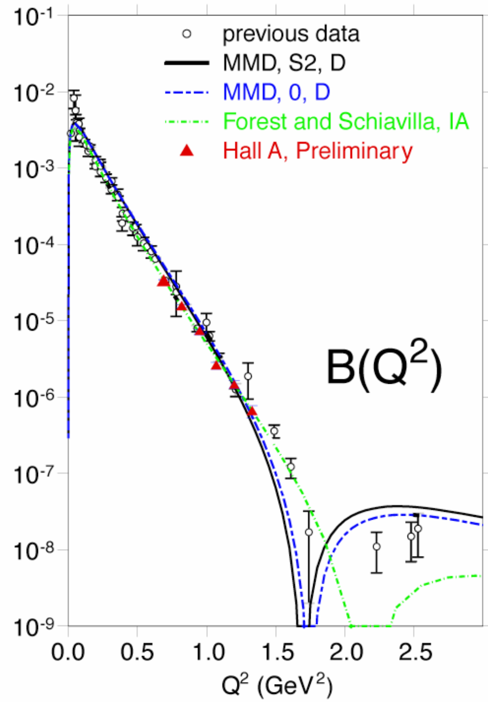
Two nucleons interacting via the (pion-mediated) NN force



Two multi-quark systems interacting via the residue of the (gluon-mediated) QCD color force

JLab Data Reveal Deuteron's Size and Shape





For elastic e-d scattering:

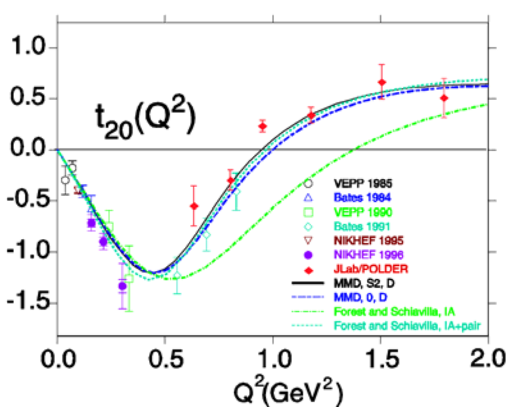
$$\frac{d\sigma}{d\Omega} = \sigma_M \left[A + B \tan^2 \frac{\theta}{2}\right]$$

$$A(Q^2) = G_C^2 + \tfrac{8}{9}\tau^2 G_Q^2 + \tfrac{2}{3}\tau G_M^2$$

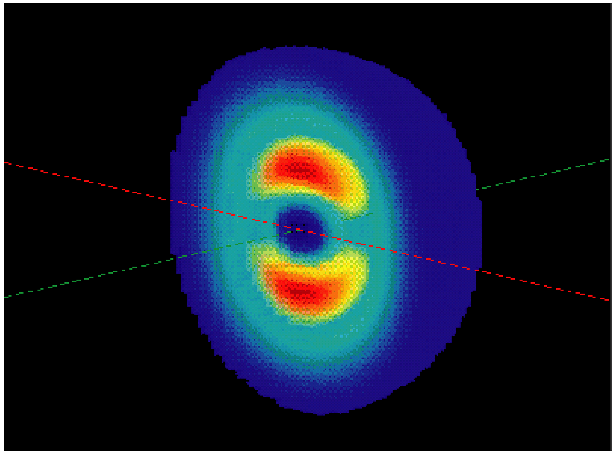
$$B(Q^2) = \tfrac{4}{3}\tau(1+\tau)G_M^2$$

- 3rd observable needed to separate G_C and G_Q

→ *tensor polarization t_{20}*

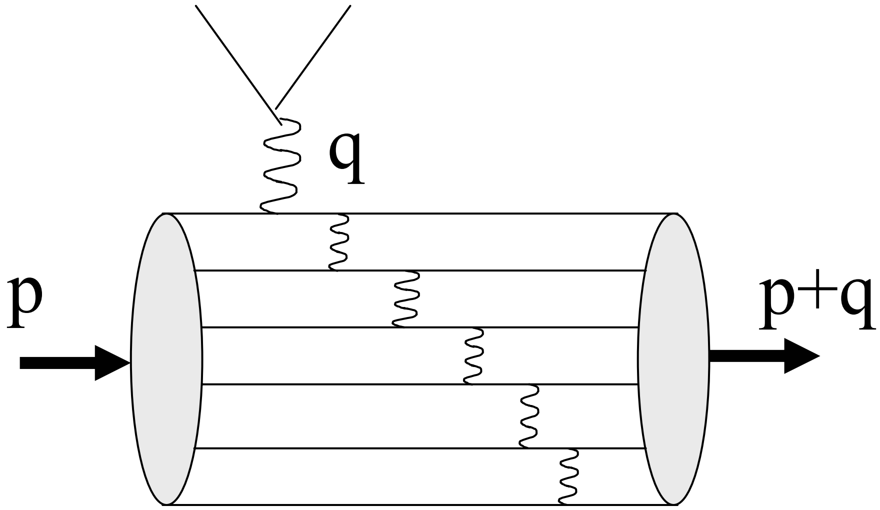


Combined Data ->
Deuteron's Intrinsic Shape



The nucleon-based description works down to < 0.5 fm

pQCD Counting Rules

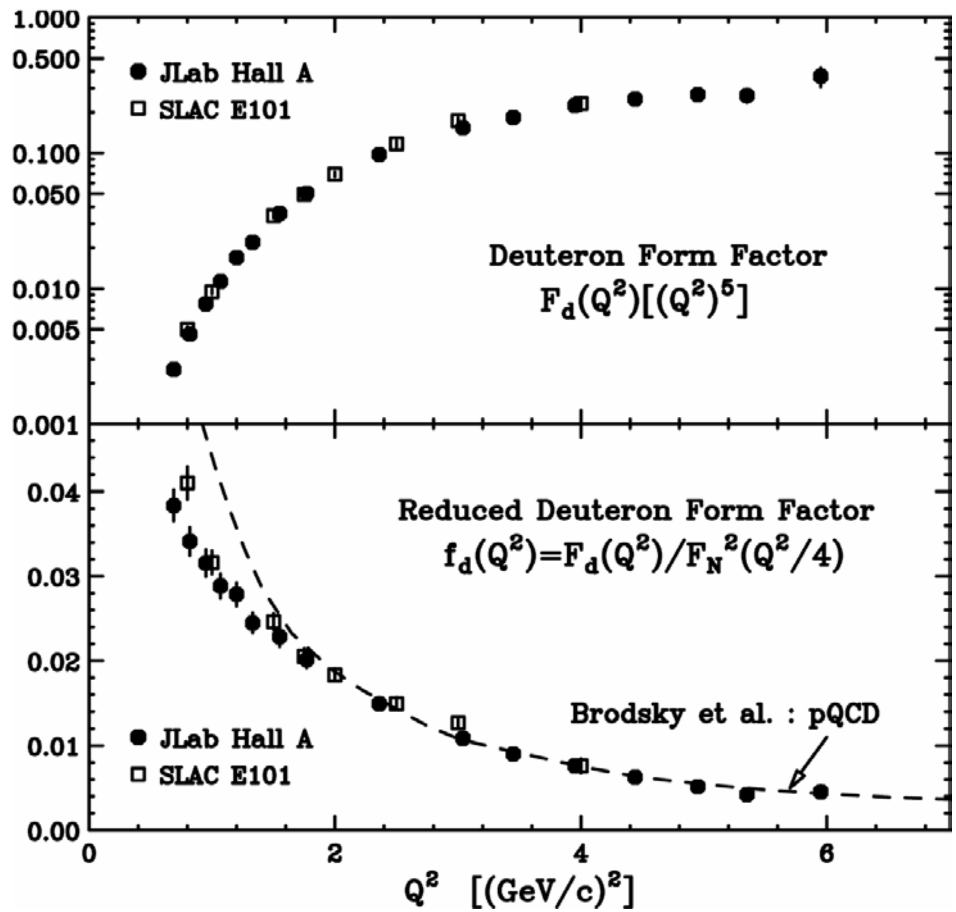


Dimensional Scaling Quark Model

$$\sqrt{A} \sim (Q^2)^{-(n-1)} \qquad n = 6 \quad \text{quarks}$$

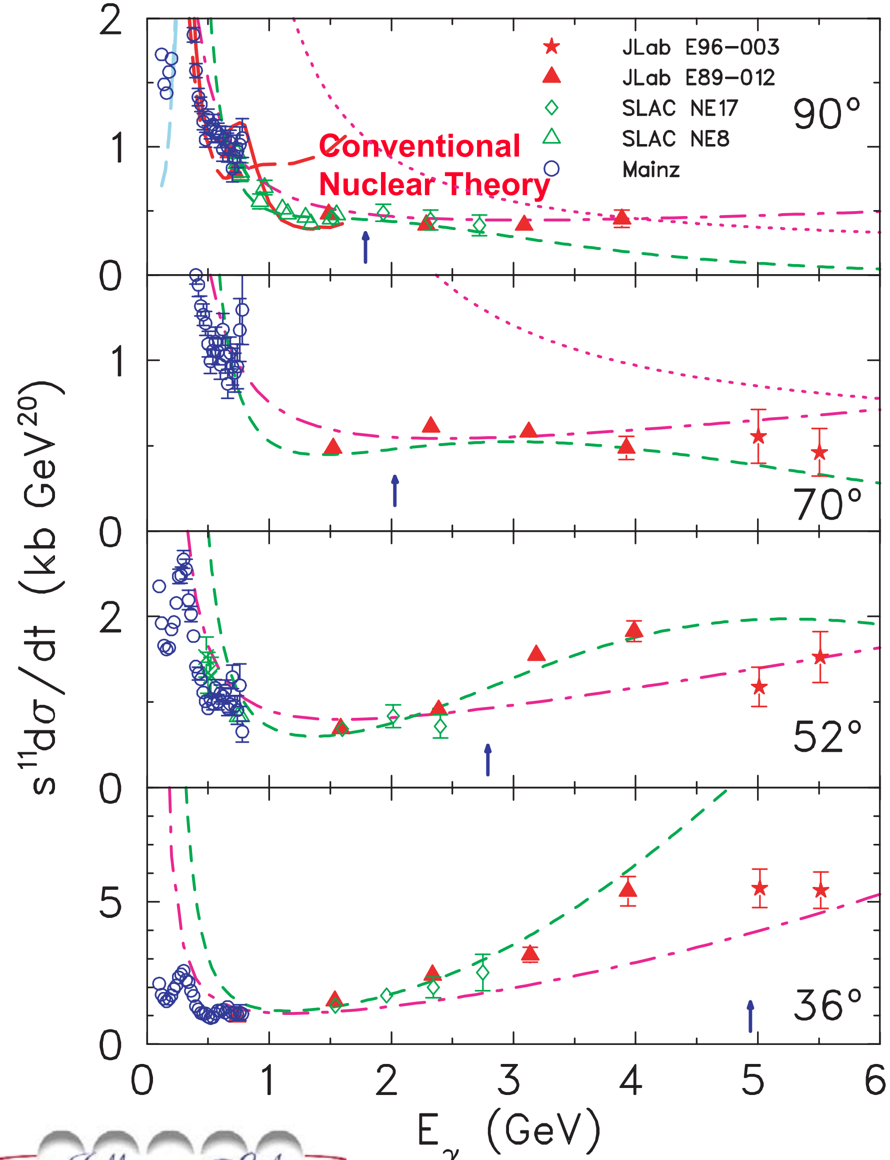
Perturbative QCD

$$\sqrt{A} = \left[\frac{\alpha_s(Q^2)}{Q^2}\right]^5 \sum_{m,n} d_{mn} \left(\ln \frac{Q^2}{\Lambda^2}\right)^{-\gamma_n - \gamma_m}$$



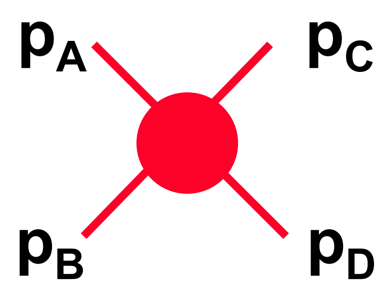
Data indicate that pQCD scaling is fulfilled for $Q^2 > 5$ GeV^2

Transition to the Quark-Gluon Description



- Deuteron photo-disintegration probes momenta well beyond those accessible in (e,e′) (at 90°, E_γ=1 GeV ⇔ Q^2= 4 GeV^2/c^2)
- Conventional nuclear theory unable to reproduce the data above ~1 GeV
- Scaling behavior ($d\sigma/dt \propto s^{-11}$) sets in at a consistent t = – 1.4 $(GeV/c)^2$ (see ↑)

⇒ seeing underlying quark-gluon description for scales below ~0.1 fm



$d\sigma/dt \propto f(\theta_{cm})/s^{n-2}$

where $n = n_A + n_B + n_C + n_D$

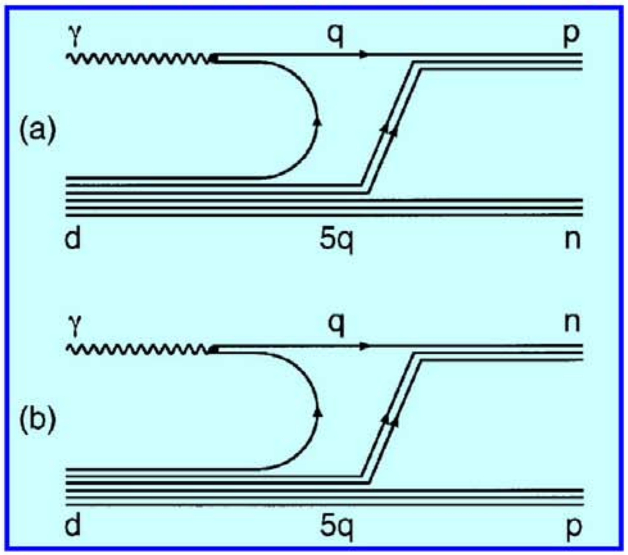
$s = (p_A+p_B)^2$, $t=(p_A-p_C)^2$

$\gamma d \rightarrow pn \Leftrightarrow n=13 \Leftrightarrow d\sigma/dt \propto s^{-11}$

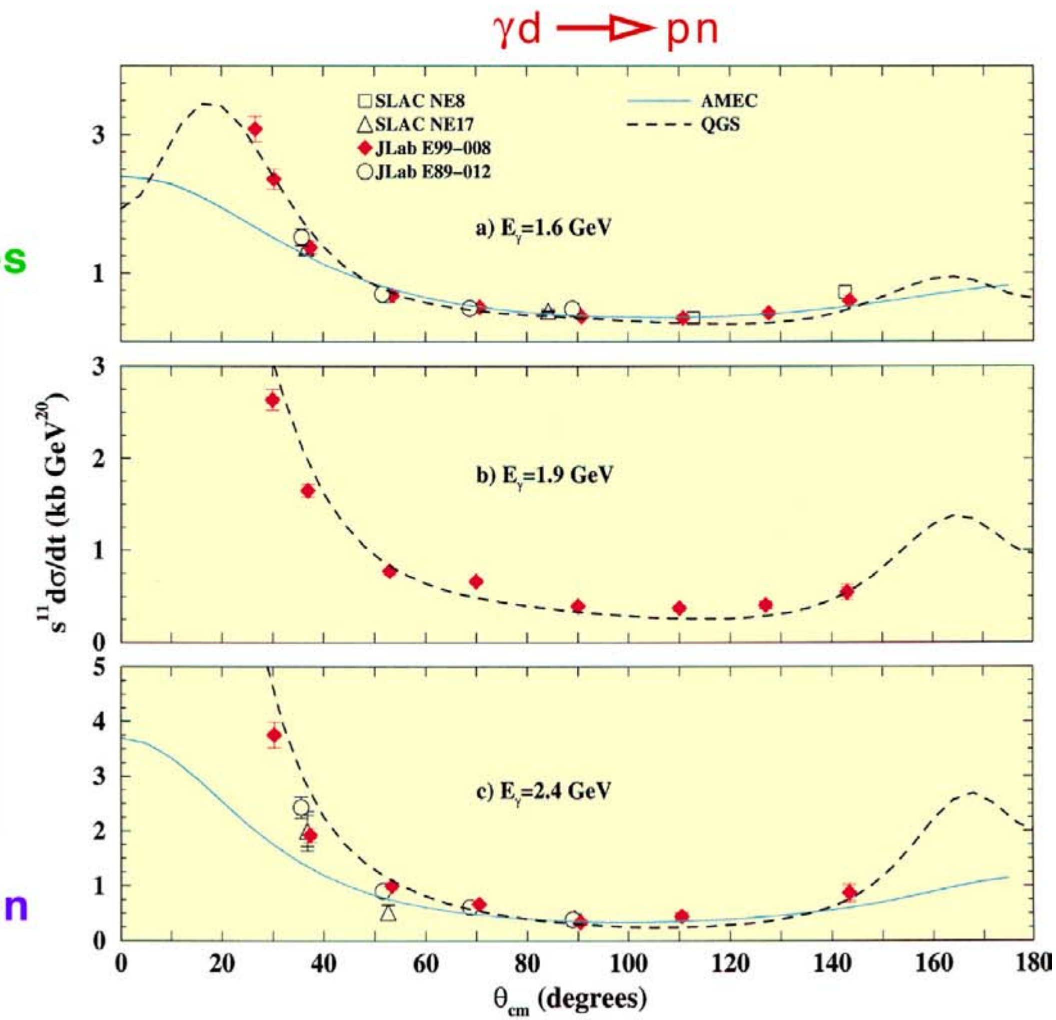
Exploring the Transition Region: E99-008

Do we see the effects of quarks and gluons in a nuclear reaction ?

Three valence quark-exchanges



- **Complete angular distribution measurements.**
- **Quark-exchange model is consistent with the data.**



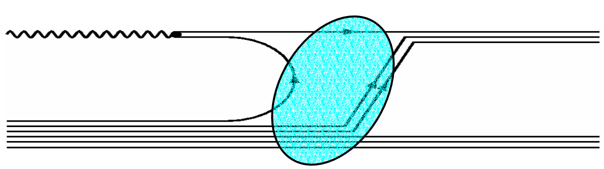
E.C. Schulte et al., PRC R042201 (2002)

Exploring the Transition Region: CLAS g2

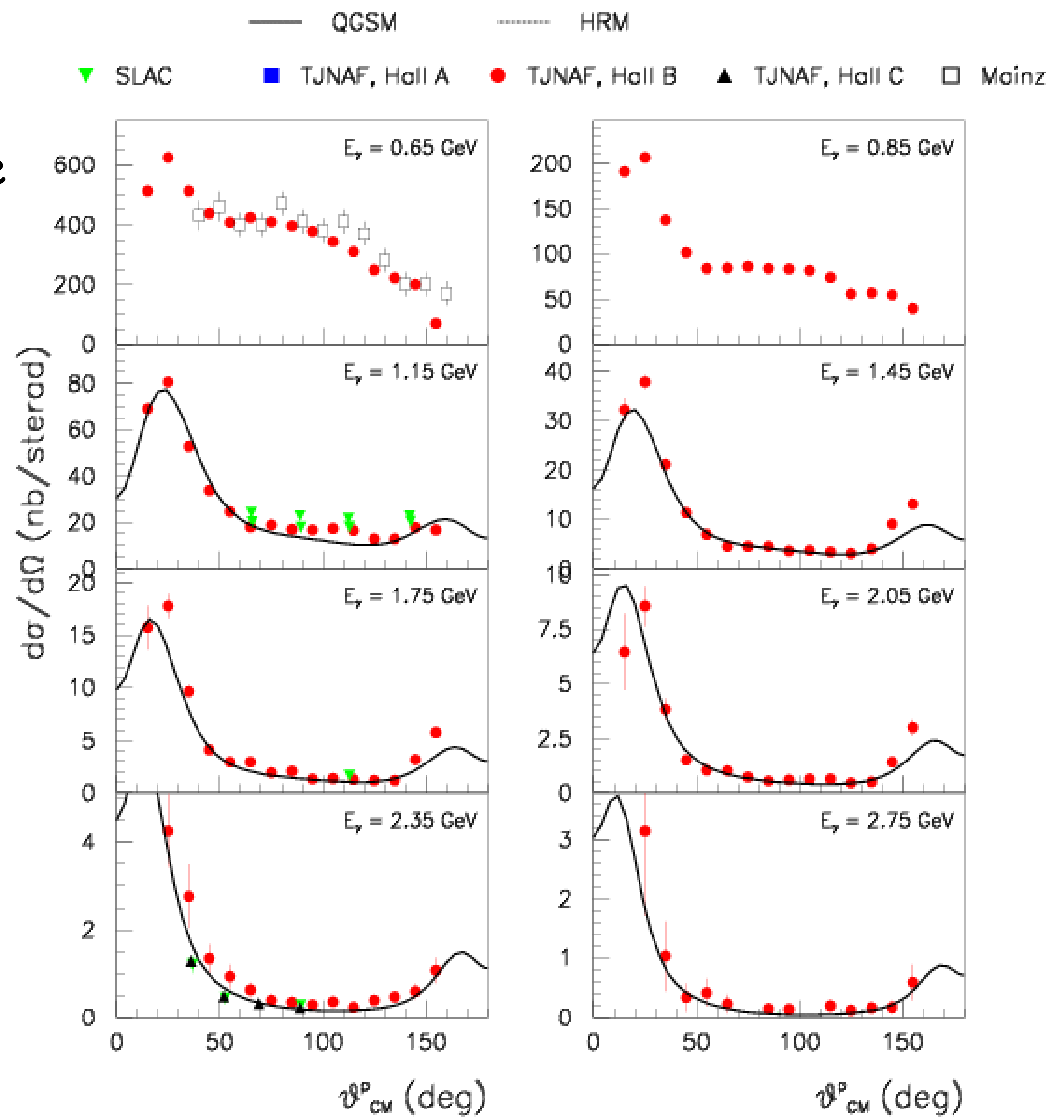
Quark Gluon String Model

- A microscopic theory for the Regge phenomenology.
- Non-perturbative approach
  (V.Grishina et al., EPJ A 10 (2001), 355)

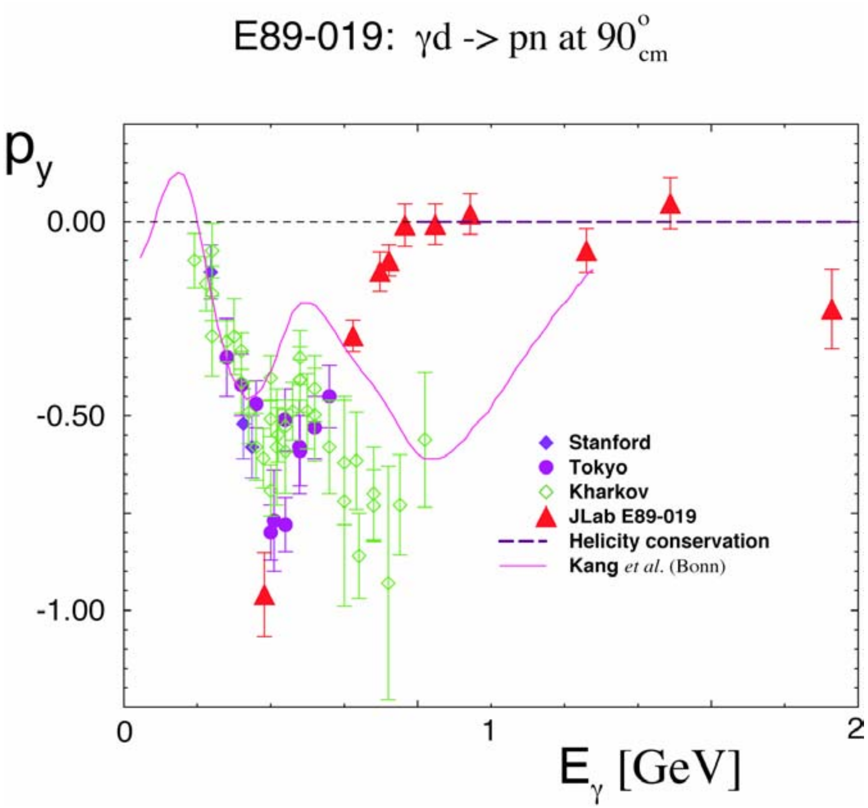
- Production in the intermediate states of a color string leading to factorization of amplitudes

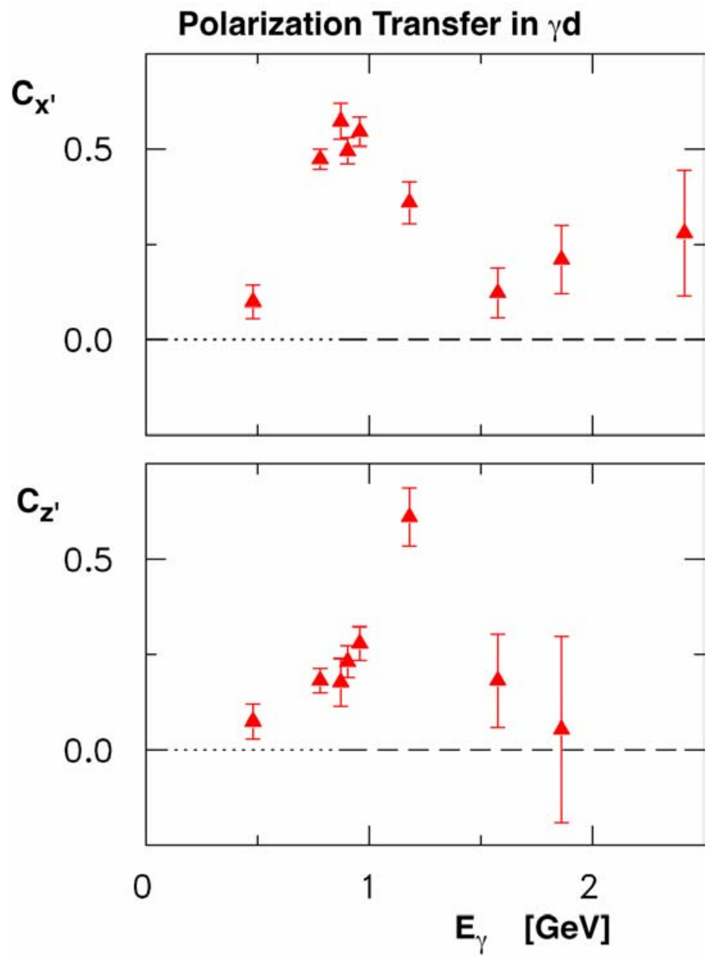


- *t* channel : quark-gluon string
  (3 valence q + g's)



Polarization Transfer in ^2H Photo-disintegration





In pQCD region hadron helicity should be conserved
Appears valid in P_y (induced polarization), not in $C_{x'}$ (polarization transfer) and marginally in $C_{z'}$
Clearly the pQCD region has not been reached

The Lambda-Nucleon Interaction

- Electron-induced Hypernuclear Spectroscopy

Hypernuclear Spectroscopy - Introduction

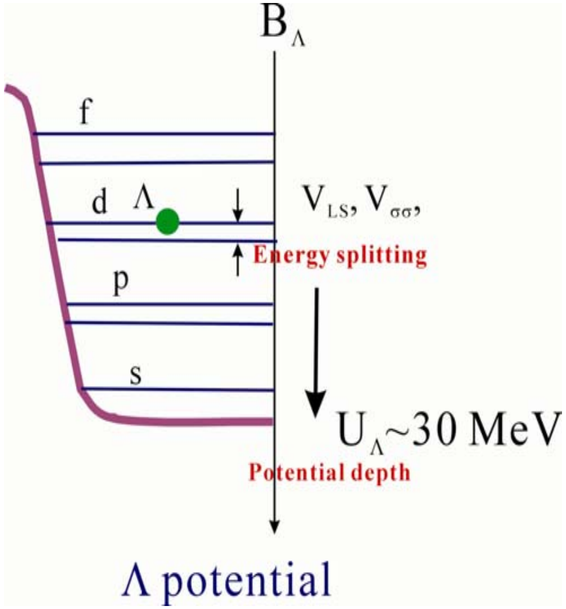
- A hypernucleus $^{A}Z_{\Lambda}$ is a hyperon impurity in the nuclear medium, hence without Pauli blocking
- Hypernuclear spectroscopy aims at a study of the Λ-N interaction
- Practically all data so far obtained with secondary meson beams, significantly limiting the energy resolution (~2 MeV)

$$V_{\Lambda N} = V(r) + V_{\sigma}(r) S_{\Lambda} \cdot S_{N} + V_{\Lambda}(r)(S_{N} + S_{\Lambda}) \cdot L_{N\Lambda} + V_{T}(r) S_{12}$$

central spin-spin spin-orbit tensor

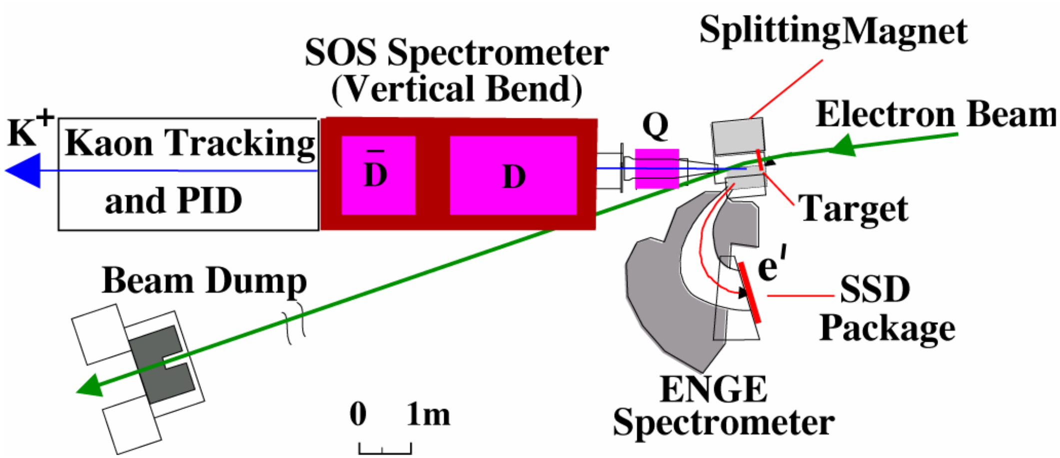
Electroproduction offers the possibility

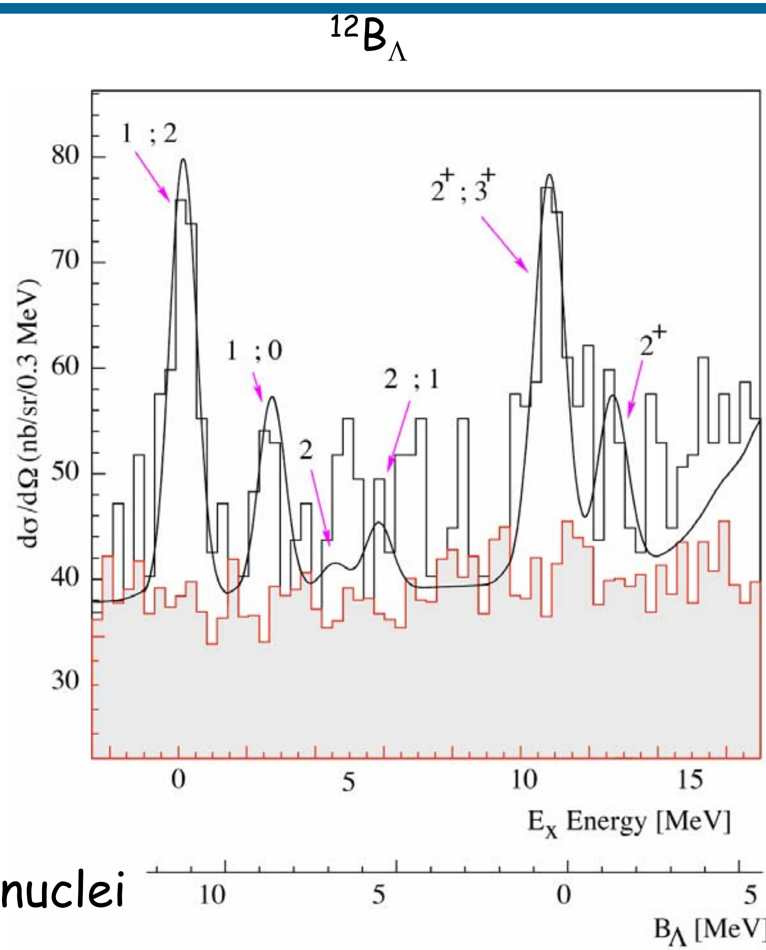
- to improve the energy resolution (~0.3 MeV)
- increase angular momentum transfer
- probe spin-flip amplitude
- to produce Λ throughout nucleus



$$e + {}^{A}Z \rightarrow e' + K^{+} + {}^{A}(Z-1)_{\Lambda}$$

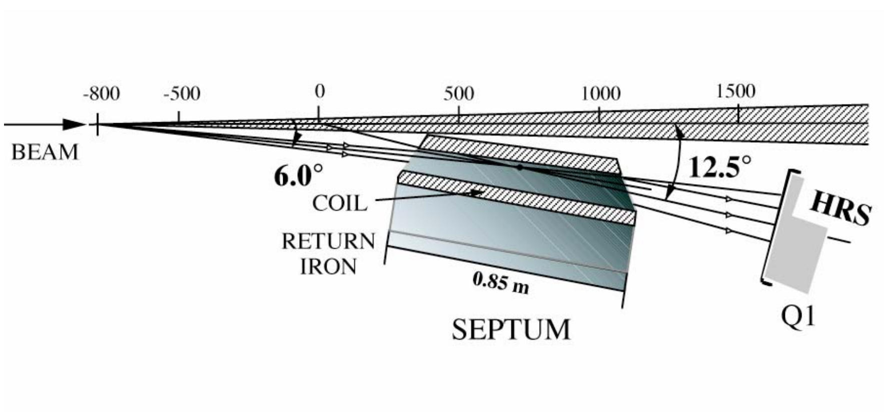
Hypernuclear Spectroscopy - E89-009



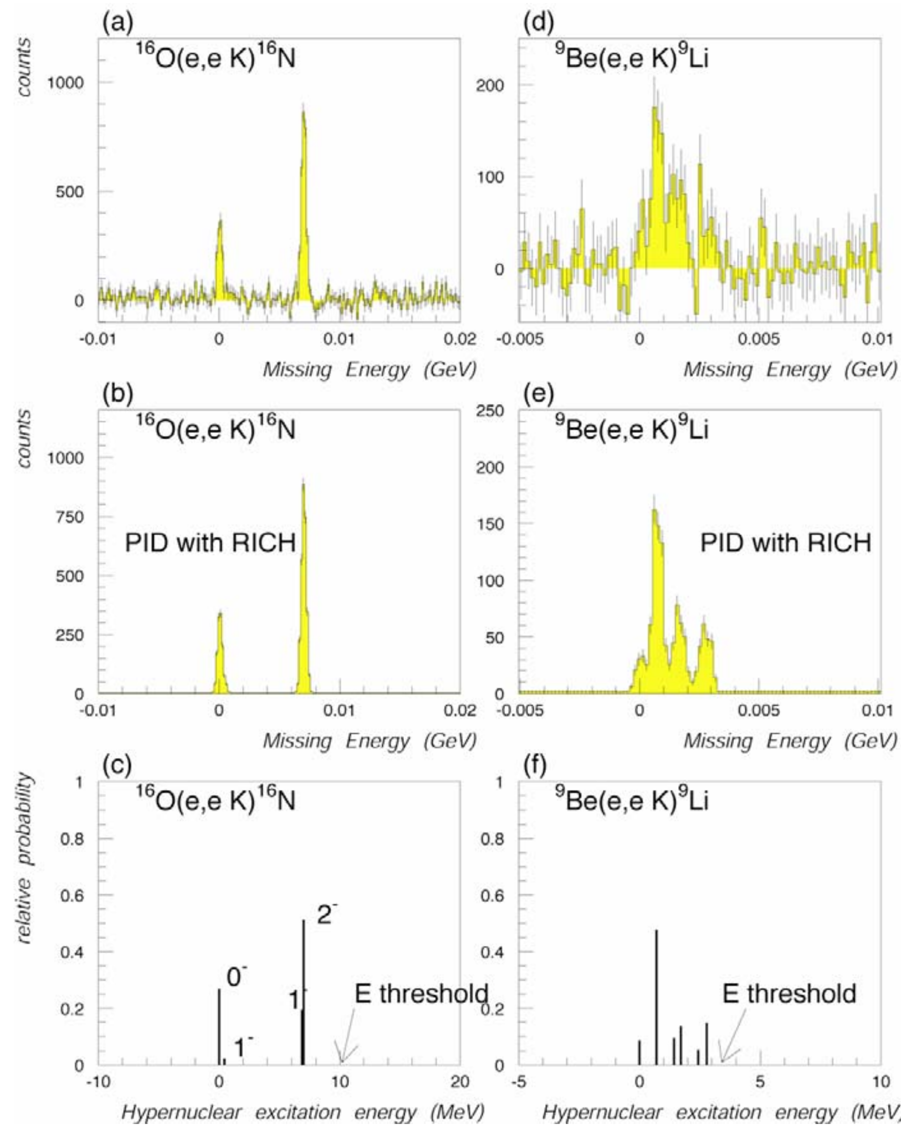


First successful electroproduction of hypernuclei
Using "zero degree" virtual photon tagging
Good energy resolution (< 1 MeV)

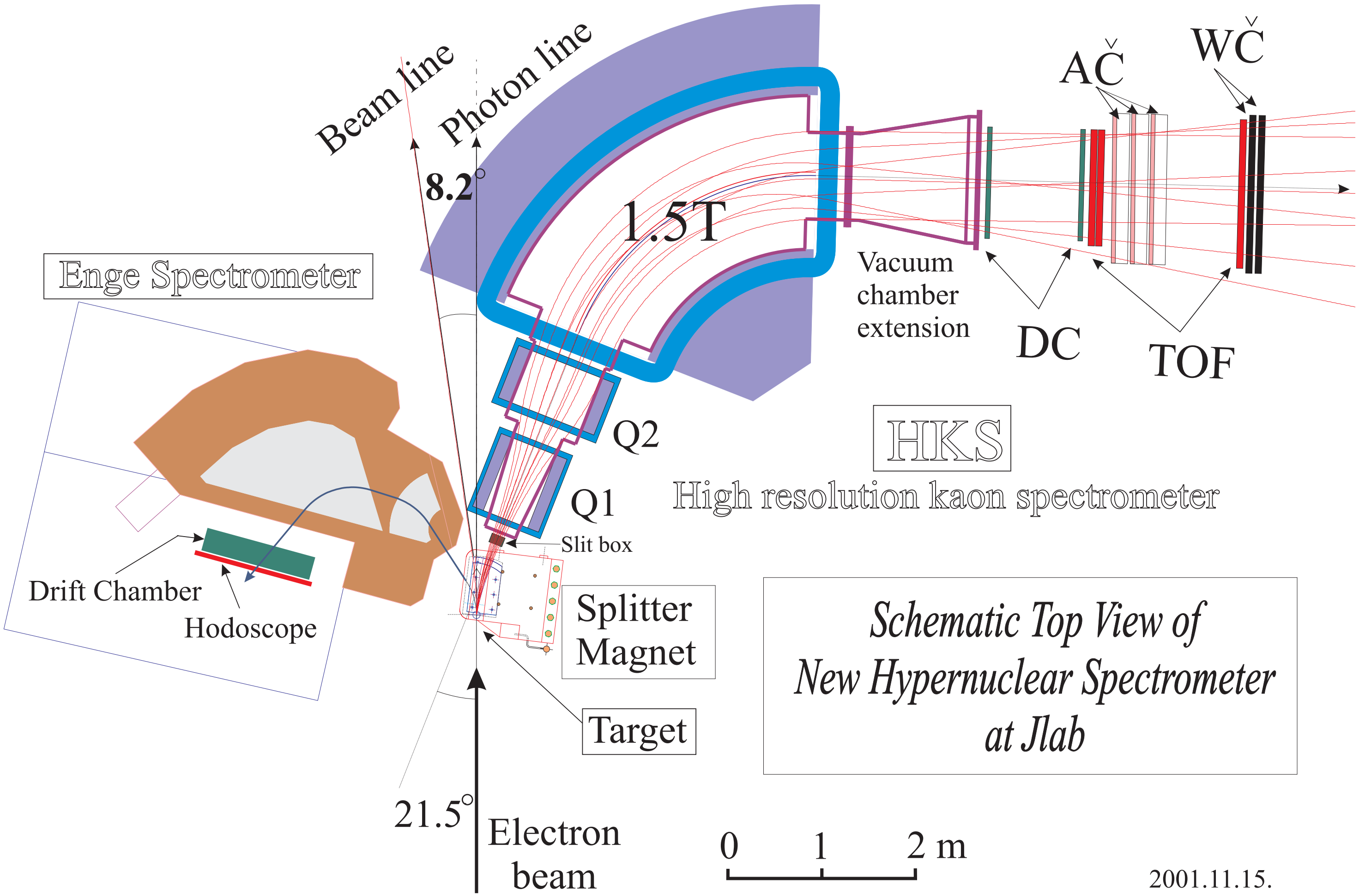
Hypernuclear Spectroscopy - E94-107



Next experiment in Hall A
Symmetric set-up of HRS at 6° with two septum magnets (INFN/Rome)
Energy resolution ~ 350 keV
Improved particle ID with RICH
Targets ^{7}Li, ^{9}Be, ^{12}C, ^{16}O, ^{52}Cr
Scheduled to run December 2003



Hypernuclear Spectroscopy - E01-011



Second-generation experiment in Hall C with specially designed HKS spectrometer (Tohoku University) with greatly improved production rates and energy resolution
Expected to run in 2004

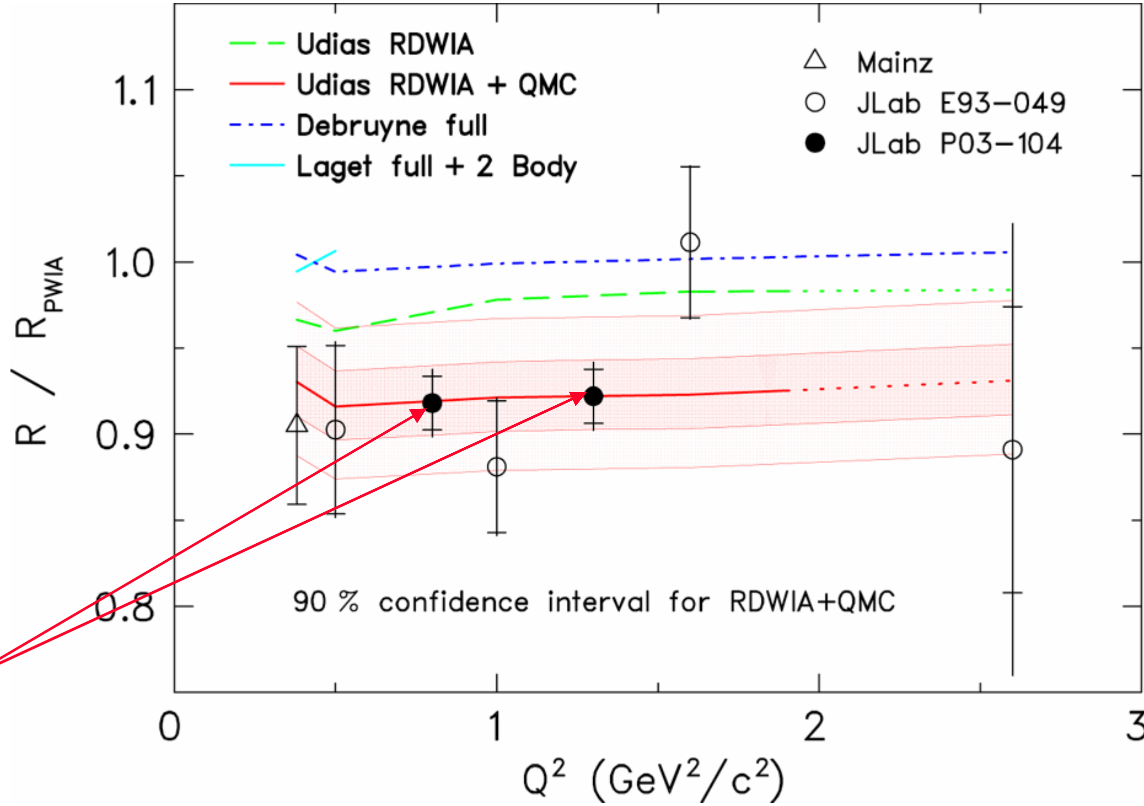
Using the Nucleus as a Laboratory

- Medium Modifications
- Colour Transparency

Polarization transfer in $^4He(\vec{e},e'\vec{p})$

Medium Modifications of Nucleon Form Factor

- E93-049 (Ent, Ulmer)
- Measured $^4He(\vec{e},e'\vec{p})^3H$ in quasi-elastic kinematics for Q^2 = 0.5, 1.0, 1.6 and 2.6 $(GeV/c)^2$ using Focal Plane Polarimeter
- Extracted $R_{exp} = G_E^p/G_M^p$

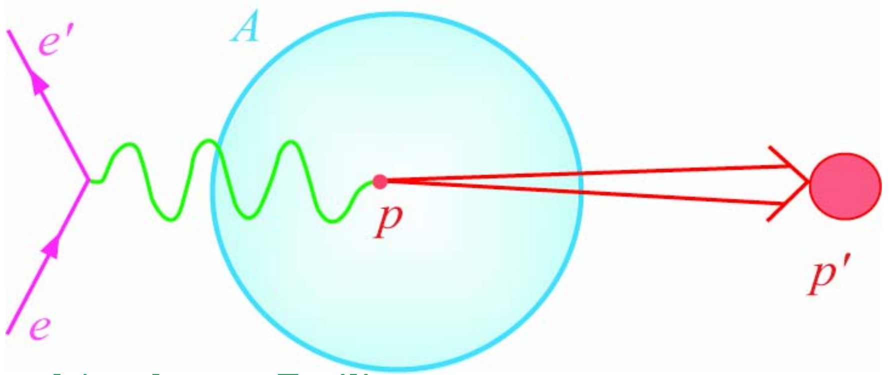


- Compared to calculations by Udias without and with inclusion of medium effects predicted by Thomas *et al.* (Quark Meson Coupling model)
- New proposal approved by PAC24

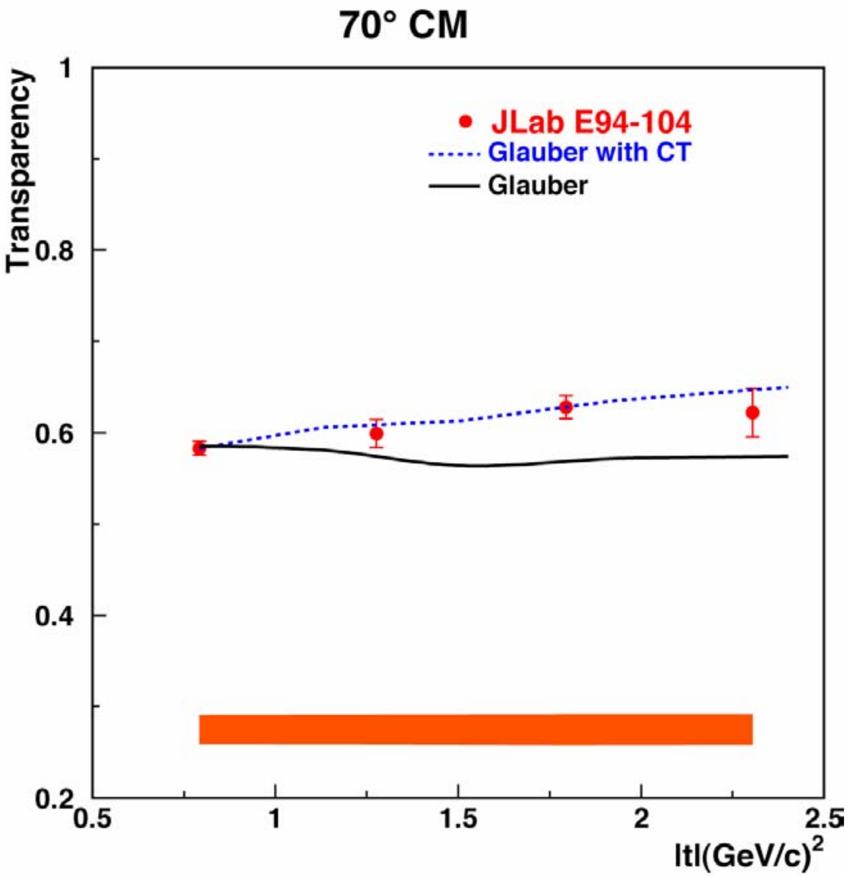
Color Transparency

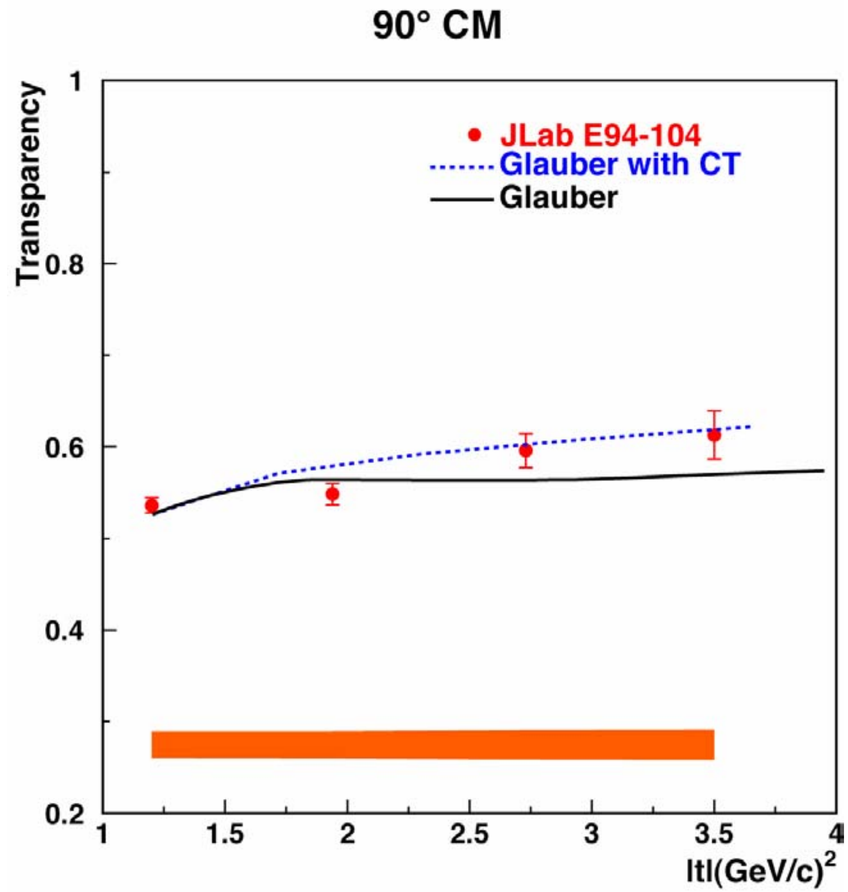
CT refers to the vanishing of the hadron-nucleon interaction for a hadron produced in exclusive processes at high Q^2

- At high Q^2, the hadron involved fluctuates to a small transverse size – called the point-like configuration (PLC)
- The PLC experiences a reduced interaction with the nucleus – it is color screened
- The PLC remains small as it propagates out of the nucleus
- So far, no hint of CT in (e,e′p) reactions



Results from E94-104 (γ n -> π^- p in ^{4}He)





- Calculations use Glauber theory and correlations from Argonne v_{14} and Urbana VIII
- CT estimated from quantum diffusion model, normalization can be chosen arbitrarily
- Data show t-dependence seemingly at variance with traditional nuclear physics
- Clear need for extension to higher t-values

Summary

CEBAF has a broad and vibrant program of nuclear physics in all three halls

- The single-nucleon response is being studied through proton knock-out over a wide range of kinematics (in momentum transfer, missing momentum and missing energy) in few-body and many-body systems
- Nucleon-nucleon correlations have been clearly identified
- A variety of studies has established that the description of nuclei in terms of nucleons and mesons is valid down to a distance scale of less than 0.5 fm
- This description, however, is unable to reproduce photo-disintegration data above ~1 GeV, revealing the underlying quark-gluon description at scales below ~0.1 fm
- A ground-breaking experiment has established the feasibility of electron-induced hypernuclear spectroscopy with potentially excellent energy resolution
- The nucleus is being used as a laboratory to study the effect of the nuclear medium on nucleon properties and to search for the onset of color transparency