Science Overview and the Experimental Program

L. Cardman

The Structure of the Science Presentations

- Overview of the Experimental Program – Scientific Motivation and Progress (LSC)
- Detailed Talks on Three of the Major Efforts in the “Campaign” to understand Structure:
  - Hadron Form Factors (Rolf Ent)
  - The N* program (Bernhard Mecking)
  - Nucleon Spin Structure (Kees de Jager)
- Details on the Hall Research Programs and Technical Developments (Dennis Skopik)
- Theory (Rocco Schiavilla)
- Nuclear Physics Research Program at 12 GeV (LSC)

JLab's Scientific Mission

- Understand how hadrons are constructed from the quarks and
- Understand the QCD basis for the nucleon-nucleon force
- Explore the limits of our understanding of nuclear structure
  - high precision
  - short distances
  - the transition from the nucleon-meson to the QCD description

To make progress in these areas we must address critical issues in "strong QCD":

- What is the mechanism of confinement?
- Where does the dynamics of the q-q interaction make a transition from the strong (confinement) to the perturbative (QED-like) QCD regime?
- How does Chiral symmetry breaking occur?

Nuclear Physics: The Core of Matter, The Fuel of Stars

(NAS/NRC Report, 1999)

Science Chapter Headings:

The Structure of the Nuclear Building Blocks

The Structure of Nuclei

Matter at Extreme Densities

The Nuclear Physics of the Universe

Symmetry Tests in Nuclear Physics

JLab Scientific "Campaigns"

The Structure of the Nuclear Building Blocks

1. How are the Nucleons Made from Quarks and Gluons?
2. Testing the Origin of Quark Confinement
3. Understanding the Origin of the NN Force

The Structure of Nuclei

4. Testing the Limits of Nuclear Many-Body Physics
5. Probing the Limits of the "Standard Model" of Nuclear Physics

and Gluons?

Vhy are nucleons interacting via V_{NN} such a good approximation o nature?

low do we understand QCD in the confinement regime?

. The distribution of u, d, and s quarks in the hadrons

- G_E^p/G_M^p , w/ Super-Rosenbluth coming
- G_E^n (2 expts in Hall C) G_M^n (Hall A; Hall B to high Q^2)
- HAPPEX, w/ G0 & HAPPEX II coming
- F_π , w/ Higher Q^2 extension coming (6, then 12 GeV)

Rolf's Talk

. The excited state structure of the hadrons

- $N \rightarrow \Delta$ (All three halls)
- Higher resonances (CLAS e1: η, π^0, $\pi^\pm$ production)
- Missing resonance search (CLAS e1 and g1: ρ, ω production
- VCS in the resonance region (Hall A)

Bernhard's Talk

. The spin structure of the hadrons

- Q^2 evolution of GDH integral and integrand for:
  - proton (CLAS) and neutron (Hall A) (w/ low Q^2 extension coming for neutron)
- A_1^n, g_2^n w/ 12 GeV follow-on (Hall A)
- A_1^p (Hall C, CLAS)

. Other hadron properties

- VCS (Hall A)
- DVCS (Hall B, Hall A & B coming)
- Compton Scattering (Hall A)

Kees' Talk

2. Testing the Origin of Quark Confinement

Understanding Quark Confinement is the Key to understanding the QCD basis of nuclear physics

- Lattice QCD Calculations favor the flux tube model
- Meson spectra provide the essential experimental data:
  - use the “two body” system to measure V(r), spin dependence
  - experimental identification of exotics tests the basic mechanism

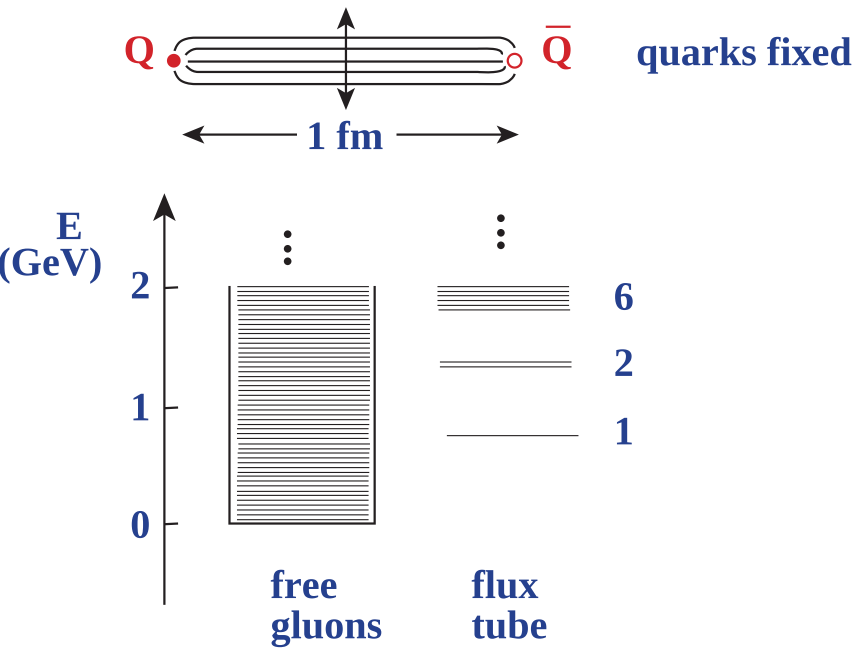
Some experiments in progress with CLAS, but 12 GeV and Hall D are essential to this program

- Also investigate the transition from strong to perturbative QCD by measurements of the pion form factor

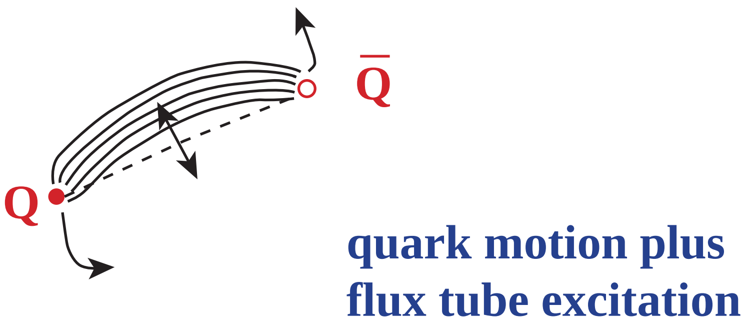
F_π (4 GeV so far; 6 GeV planned, then 11 GeV w/ upgrade) (Rolf’s talk)

Understanding Confinement

The Ideal Experiment

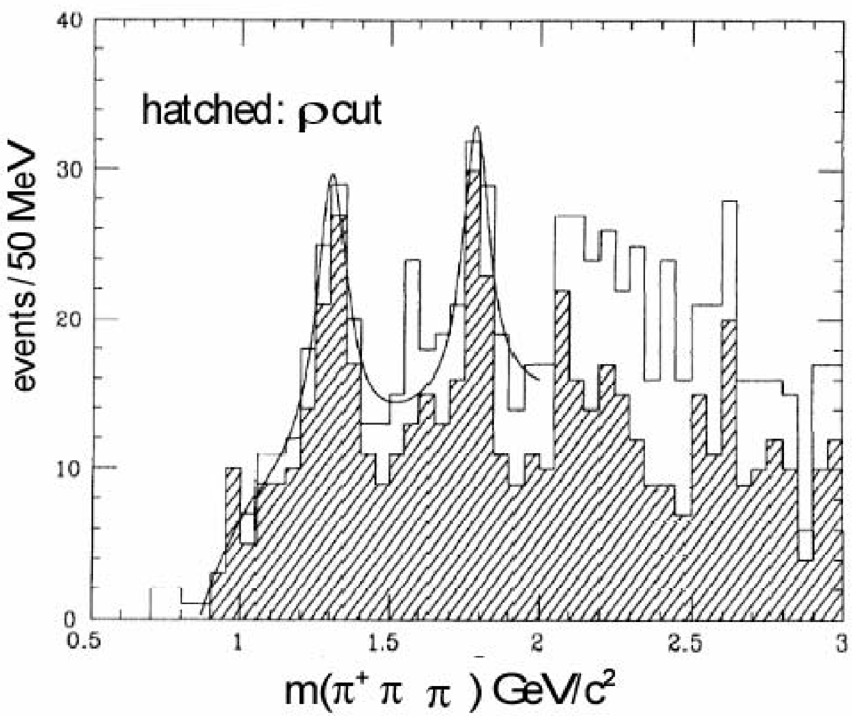


The Real Experiment



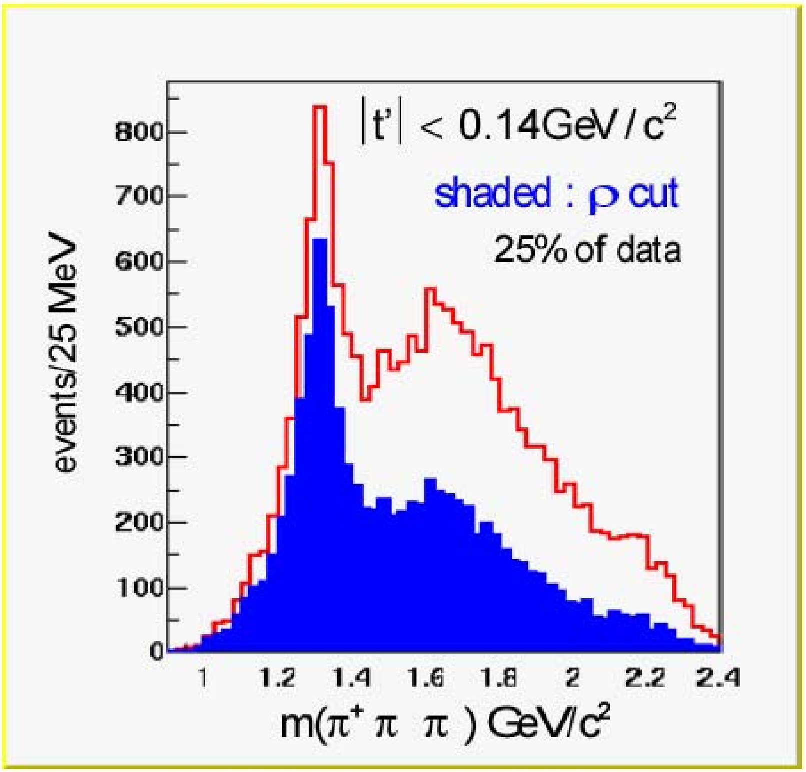
CLAS Data Demonstrates the Promise of Meson Photoproduction

SLAC Hybrid Facility Photon Collaboration



Phys. Rev. D 43, #9 2787 (1991)

g_{6c} CLAS Collaboration



3. Understanding the Origin of the NN Force

The long-range part of the force is well described by pion exchange

The remainder involves the quark-gluon structure of the nucleon:

- Quark exchange
- Color polarization
- Glue-glue interaction

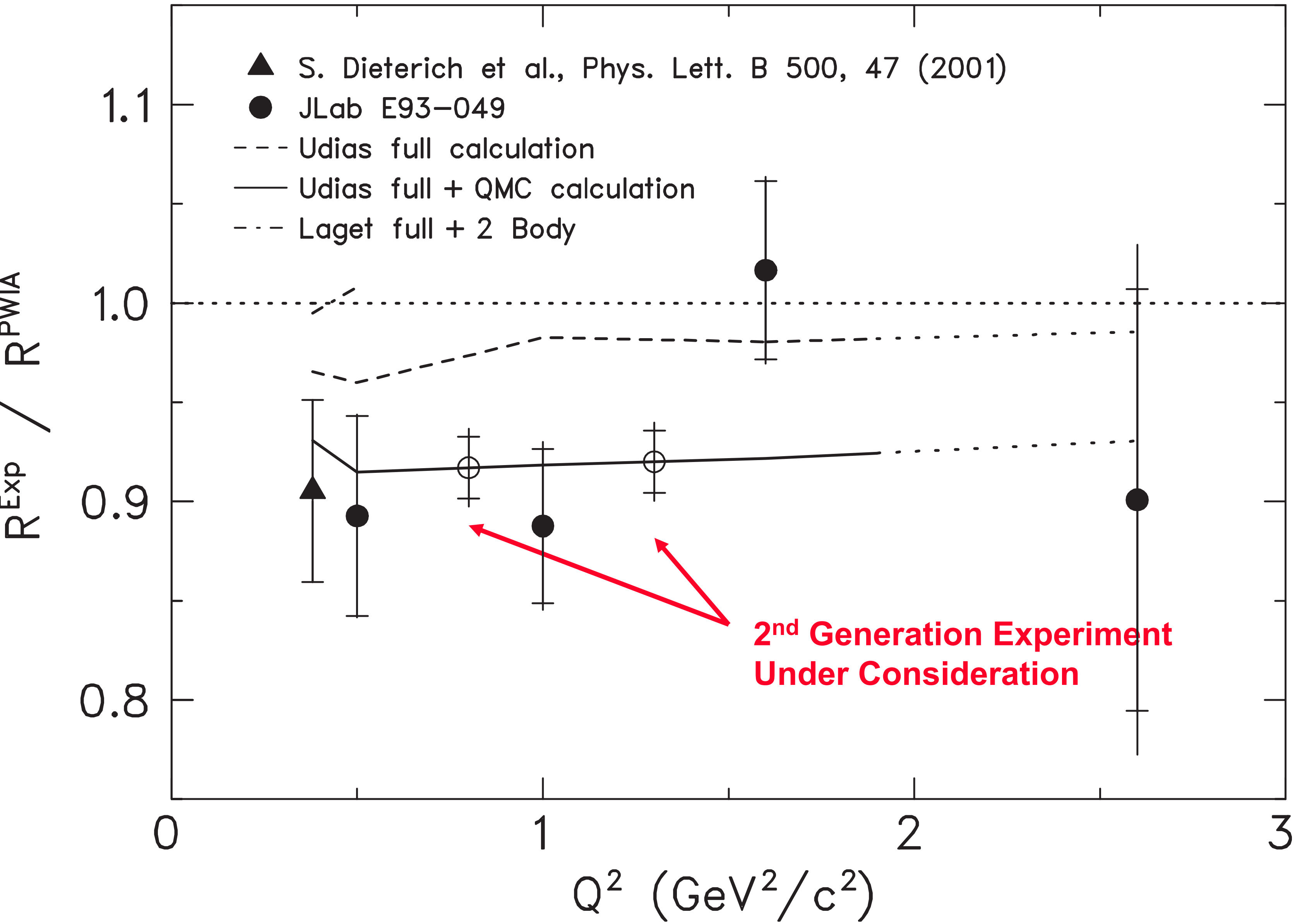
Important experimental information will come from experiments on:

A. Measurement of few body form factors
   - deuteron A, B, t_{20}
   - d(e,e'p)n

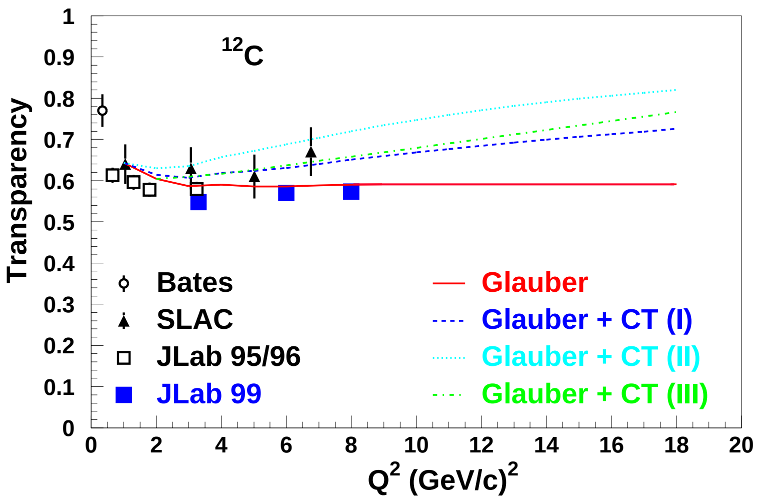
A. Color transparency
   - Geesaman (e,e'p)
   - Milner (e,e'p) to higher Q^2

C. Medium modification of the nucleon properties
   - G_E^p in ^{16}O and ^4He
   - $\gamma n \rightarrow \pi^- p$ in ^2H, ^4He

D. Nucleon-meson form factors
   - CLAS (g1: $\gamma p \rightarrow K^+\Lambda(\Sigma^0)$, under analysis)
   - CLAS (e1: ep$\rightarrow$ e'pρ, under analysis)

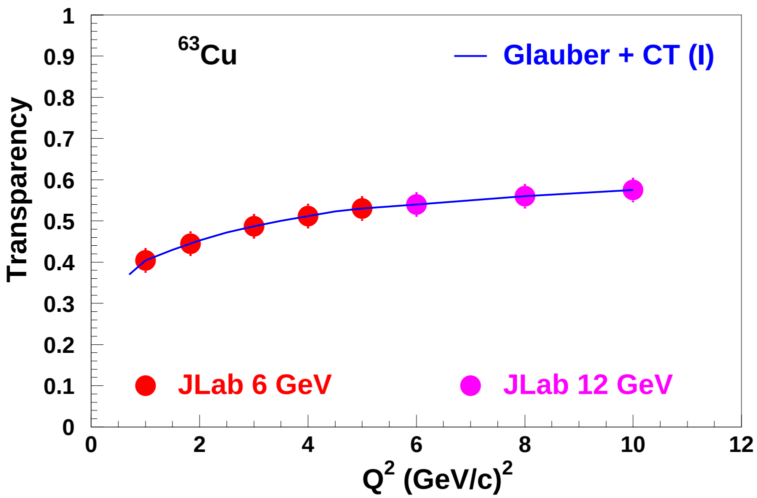

S. Dieterich et al., Phys. Lett. B 500, 47 (2001)
JLab E93–049
Udias full calculation
Udias full + QMC calculation
Laget full + 2 Body
2nd Generation Experiment
Under Consideration
1.1
1.0
0.9
0.8
0
1
2
3
R^{Exp} / R^{PWIA}
Q^2 (GeV^2/c^2)

Color Transparency – Now and at 12 GeV



Hall C (e,e'p) experiments at 4 and 5.5 GeV show no evidence for color transparency

Extending these data to 12 GeV will either reveal color transparency or force us to rethink our understanding of quark-based models of the nucleus



12 GeV will also permit similar measurements using the (e,e'π) reaction, which is expected to show color transparency at lower Q^2

Testing the Limits of Nuclear Many-Body Physics

A broad program of experiments taking advantage of the precision, spatial resolution, and interpretability of experiments performed using electromagnetic probes to address long-standing issues in classical nuclear physics.

A. Measure single particle wavefunctions using the (e,e'p) reaction

- **^{16}O(e,e'p)**
- **^{3,4}He(e,e'p) and ^{4}He($\vec{e}$,e'$\vec{p}$)**
- **d($\vec{e}$,e'$\vec{p}$), and d(e,e'p)**

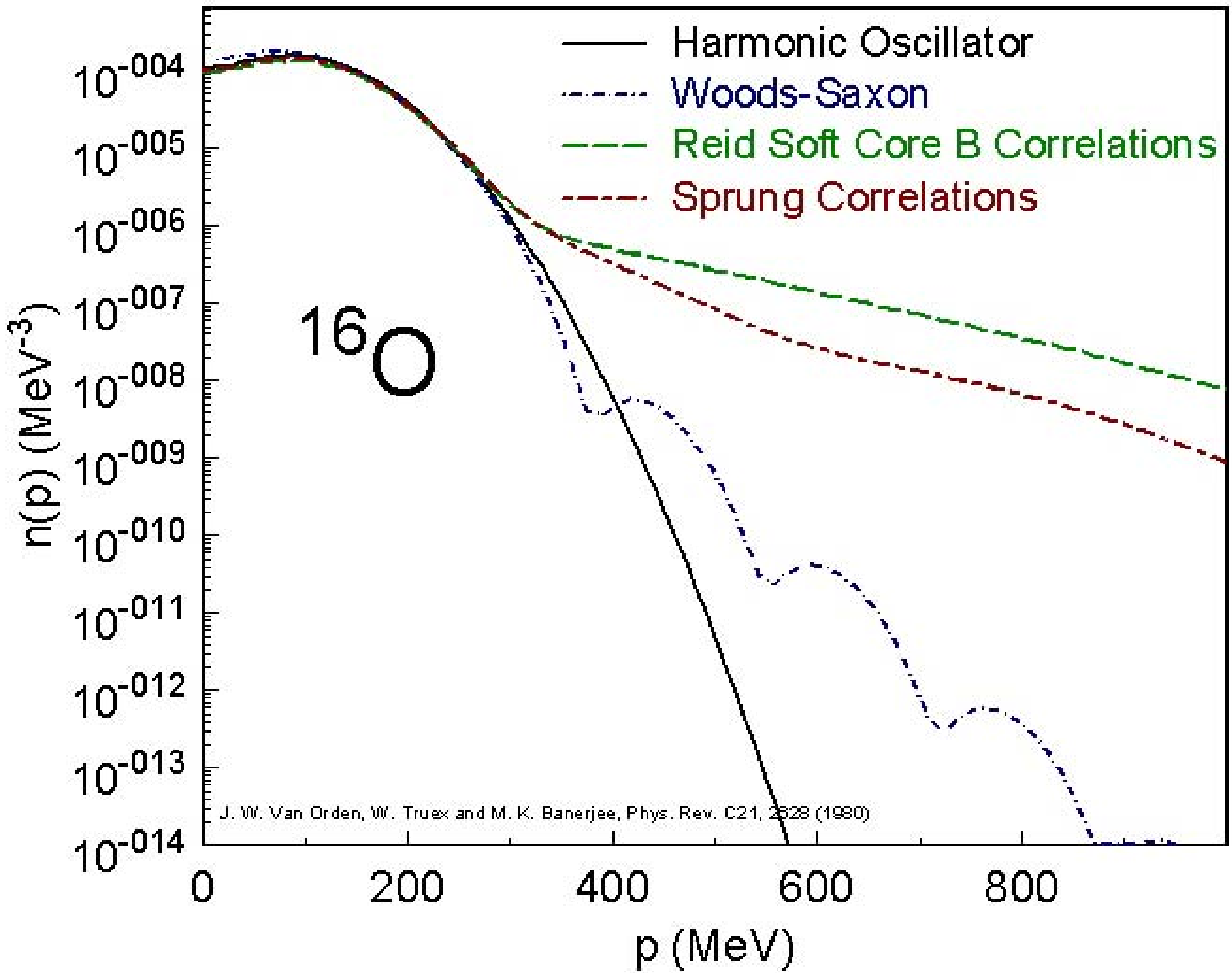
B. Study short range correlations using (e,e'p), (e,e'pp), (e,e'pn), ….Coulomb Sum Rule

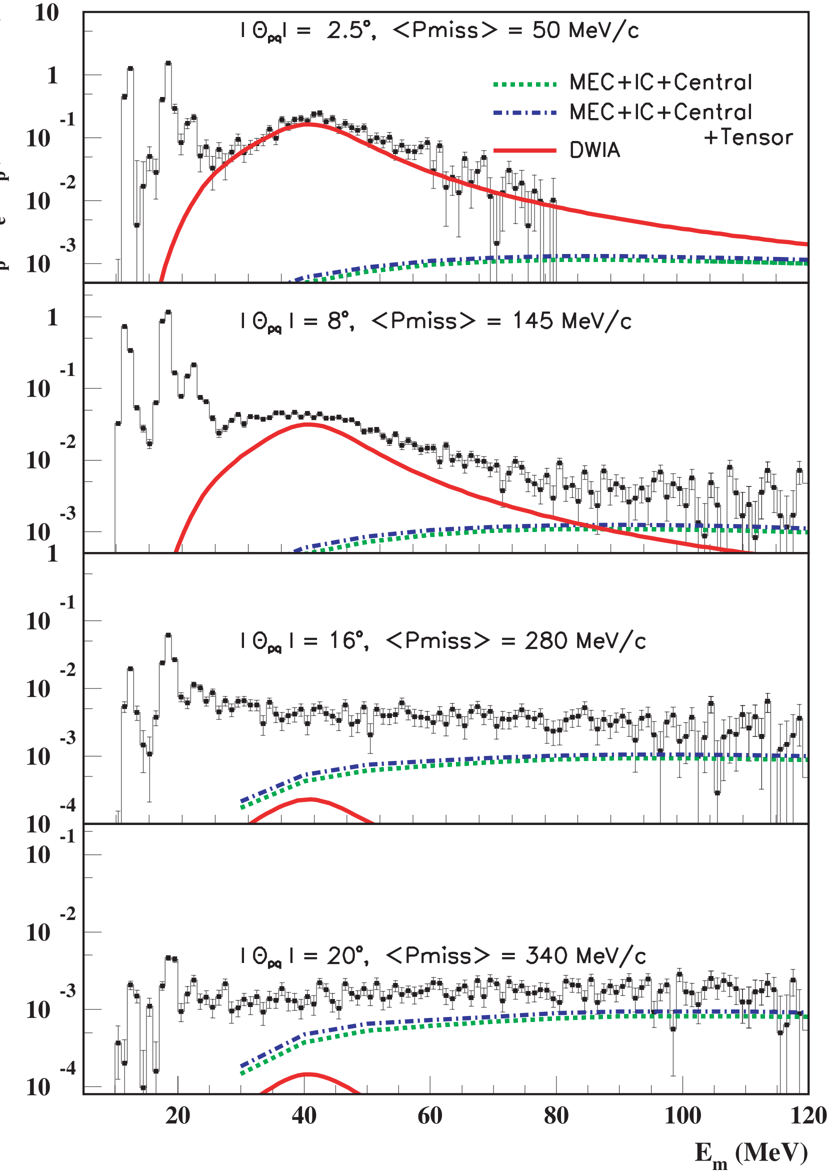
- CLAS e2: ^{12}C(e,e'Np), ^{3}He(e,e'pp)
- ^{4}He(e,e'p) to high Q^2 and E_m
- Sick (e,e'p) study

C. Hypernuclei

- HNSS Experiment
- Upcoming Hall A and Hall C extensions

Correlation Effects in O (Theory)





2445 MeV Electron Beam

23.4° Electron angle

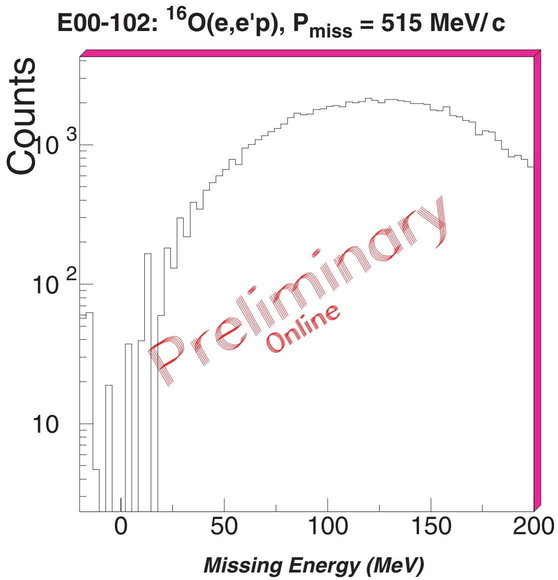
Q^2 = 0.802 $(GeV/c)^2$

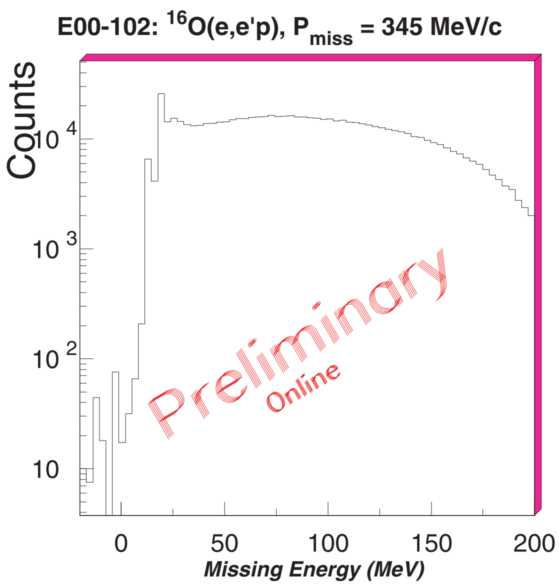
$\Rightarrow$ q = 1 GeV/c and

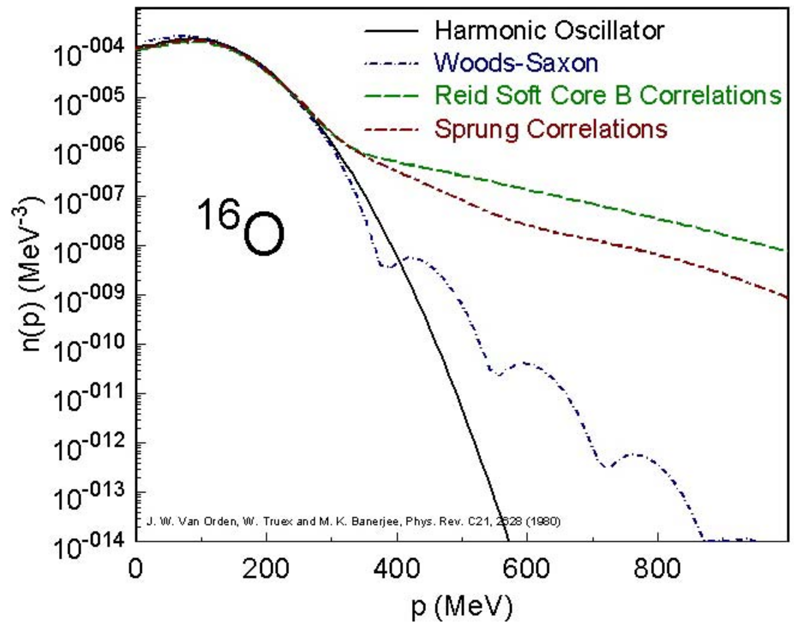
ω = 445 Mev

- Bound State strength consistent with theory, but final-state interactions do not account for strength at high missing energy
  $\Rightarrow$ Correlations

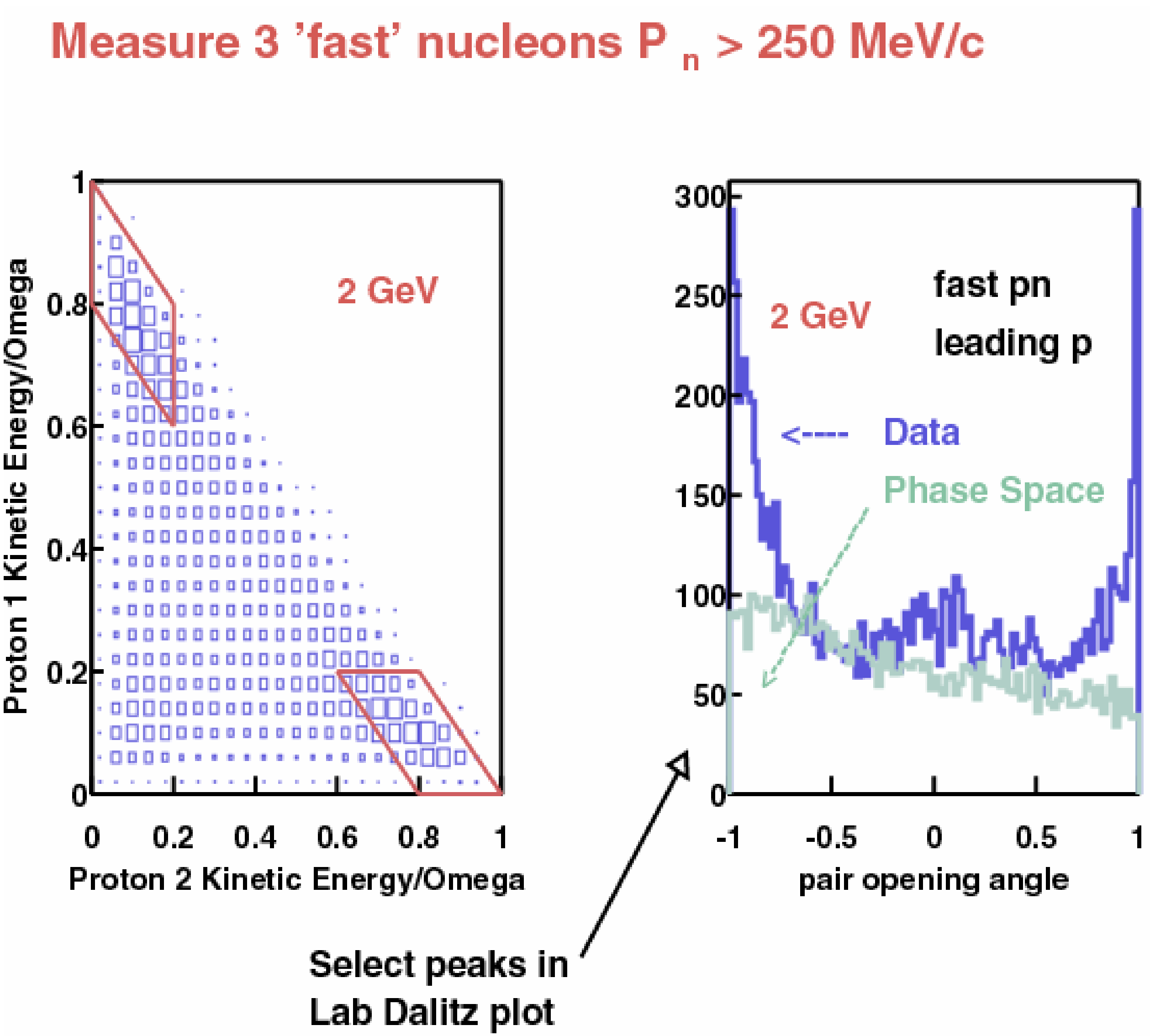
E00-102: Testing the Limits of the Single Particle Model in $^{16}O(e,e'p)$





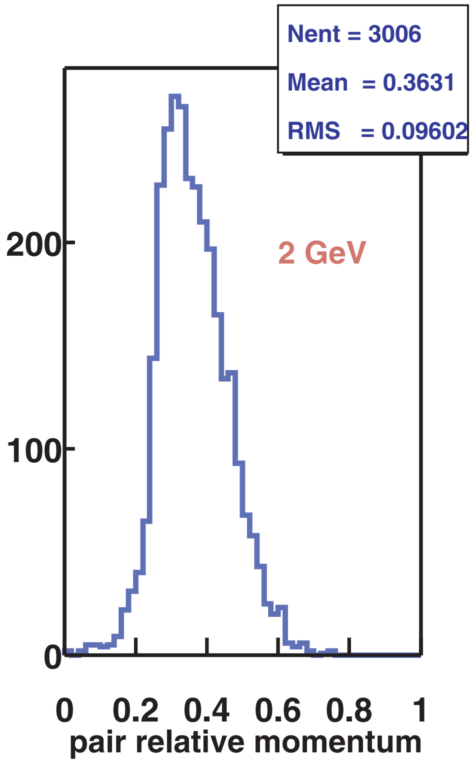


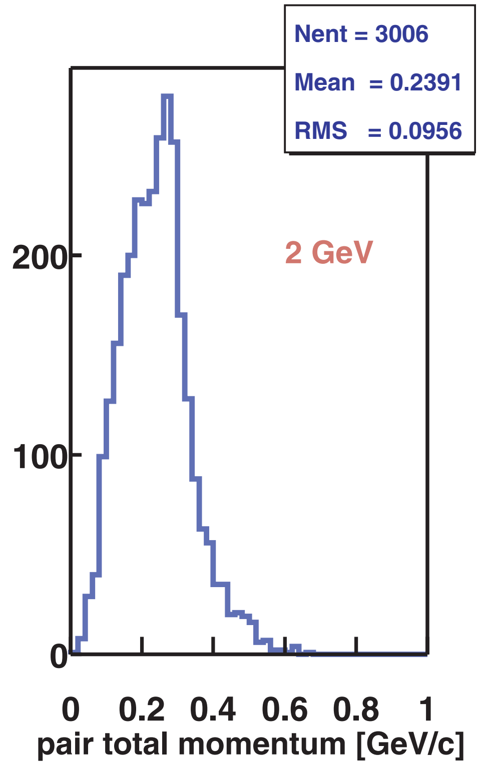
- On-line spectra show the expected disappearance of single-particle strength and growth of strength at high missing energy expected from correlations



- Non-leading Nucleons are back-to-back
  $\Rightarrow$ Correlations

CLAS e2: ^{3}He(e,e' pp)n Measuring NN Correlations





CLAS Multihadron 6/02

R.Niyazov, L.Weinstein

Data:

- Back-to-back NN pairs
- Small pair momentum along $\vec{q}$
- Small Q^2 dependence of pair momentum
- Similar pp and pn distributions

  $\Rightarrow$pair is a spectator

# of Nuclear Physics

Test via electromagnetic interaction studies of few-body systems where precise, directly interpretable experiments can be compared with exact calculations feasible in the context of the "standard model" of nuclear physics

DEFINE THE "STANDARD MODEL" OF NUCLEAR PHYSICS AS:

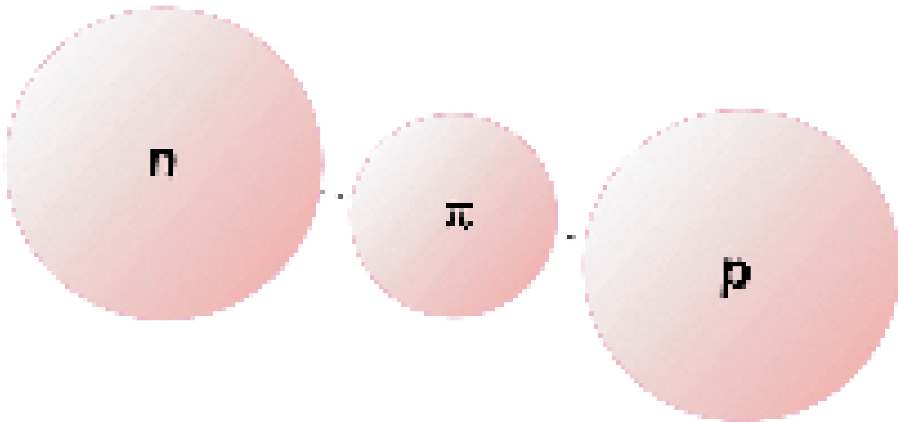
- Nucleus has A nucleons interacting via force described by V_{NN}
- V_{NN} fit to N-N phase shifts
- Exchange currents and leading relativistic corrections in V_{NN} and nucleus

Push precision, λ to identify limits

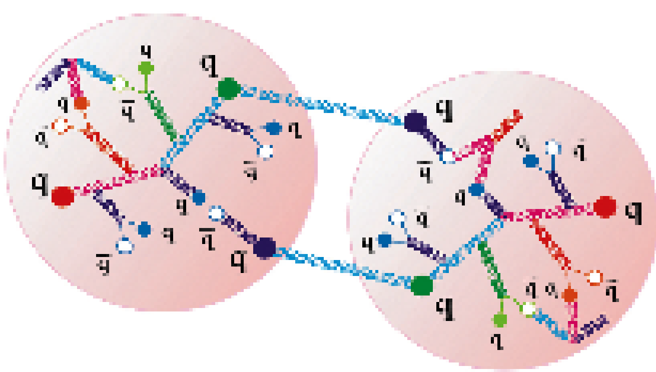
Examples Include:

- **Deuteron:**
  - **A, B, t_{20}**
  - **photodisintegration**
  - **Induced polarization in photodisintegration**
- **^{3}He to high Q^2**

Two Views of Deuteron Structure

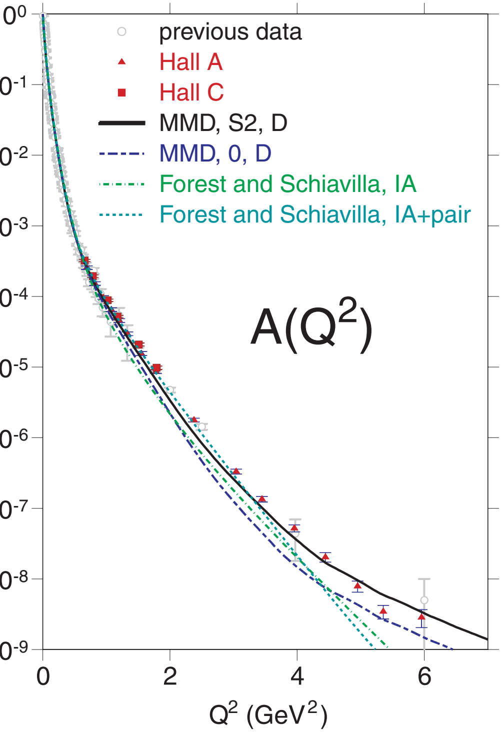


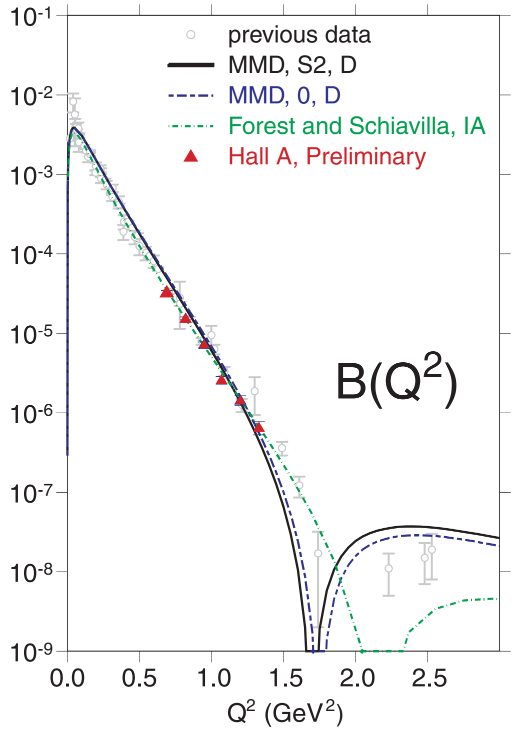
Two Nucleons interacting via the (pion-mediated) NN force



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

The Size and Shape of the Deuteron





For elastic e-d scattering:

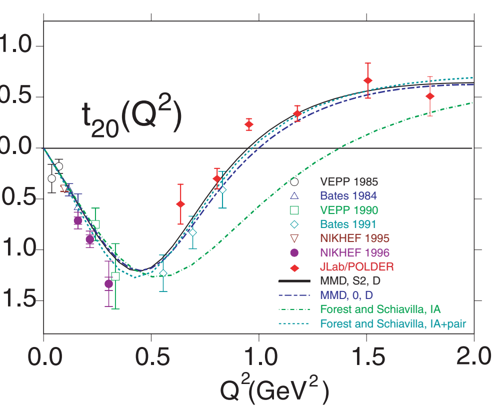
$$\frac{d\sigma}{d\Omega} = \sigma_M \left[A + B \tan^2 \frac{\theta}{2}\right]$$

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

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

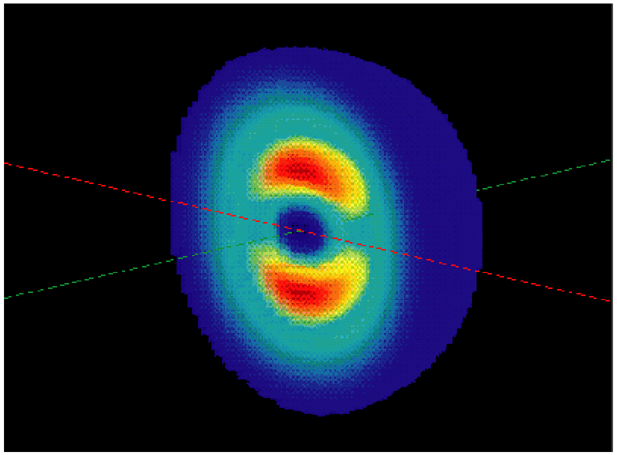
- 3rd observable needed to separate G_C and G_Q

$\rightarrow$ *tensor polarization t_{20}*



Combined Data $\Longrightarrow$

Deuteron's Intrinsic Shape



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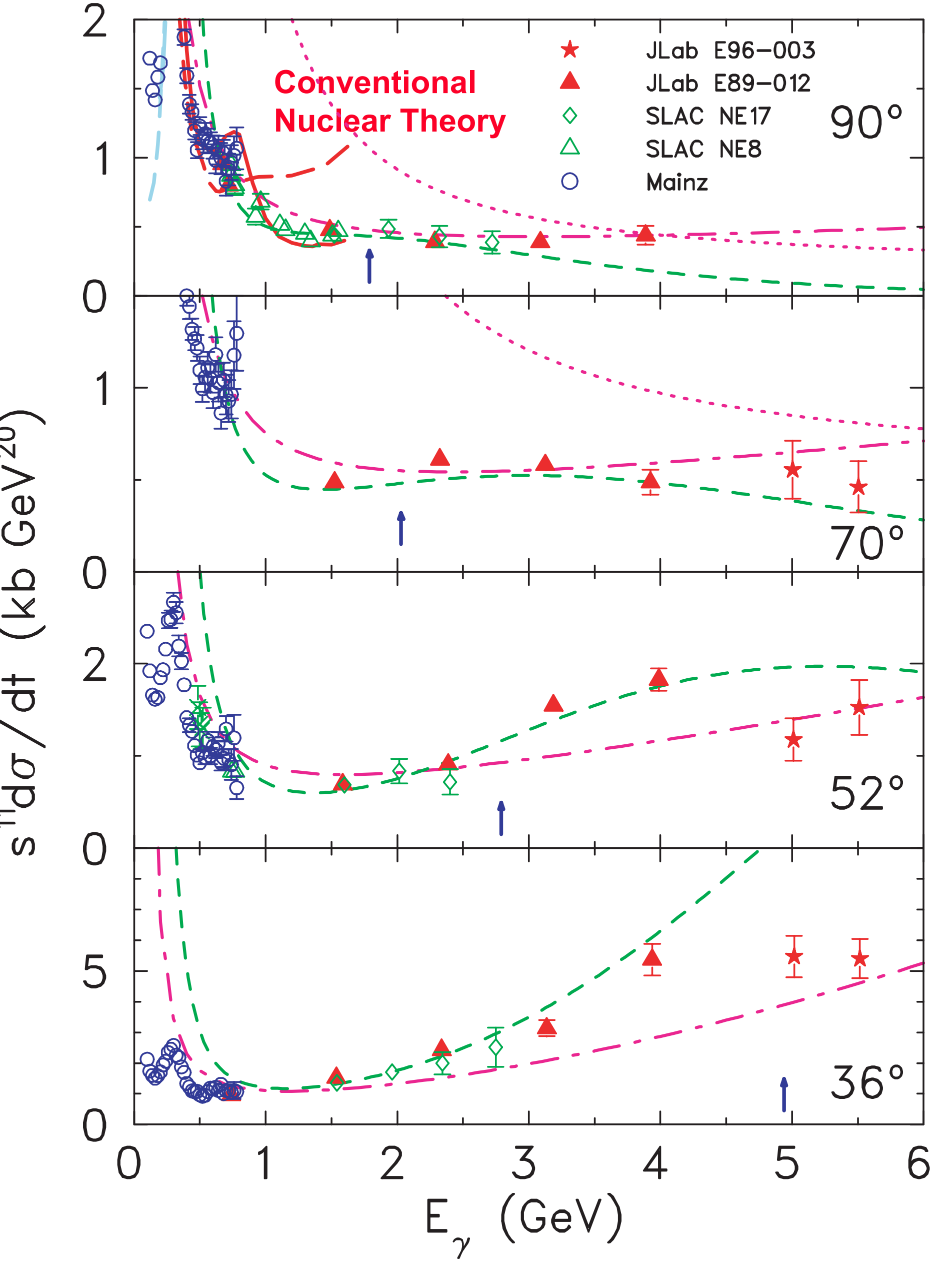
Deuteron Photodisintegration

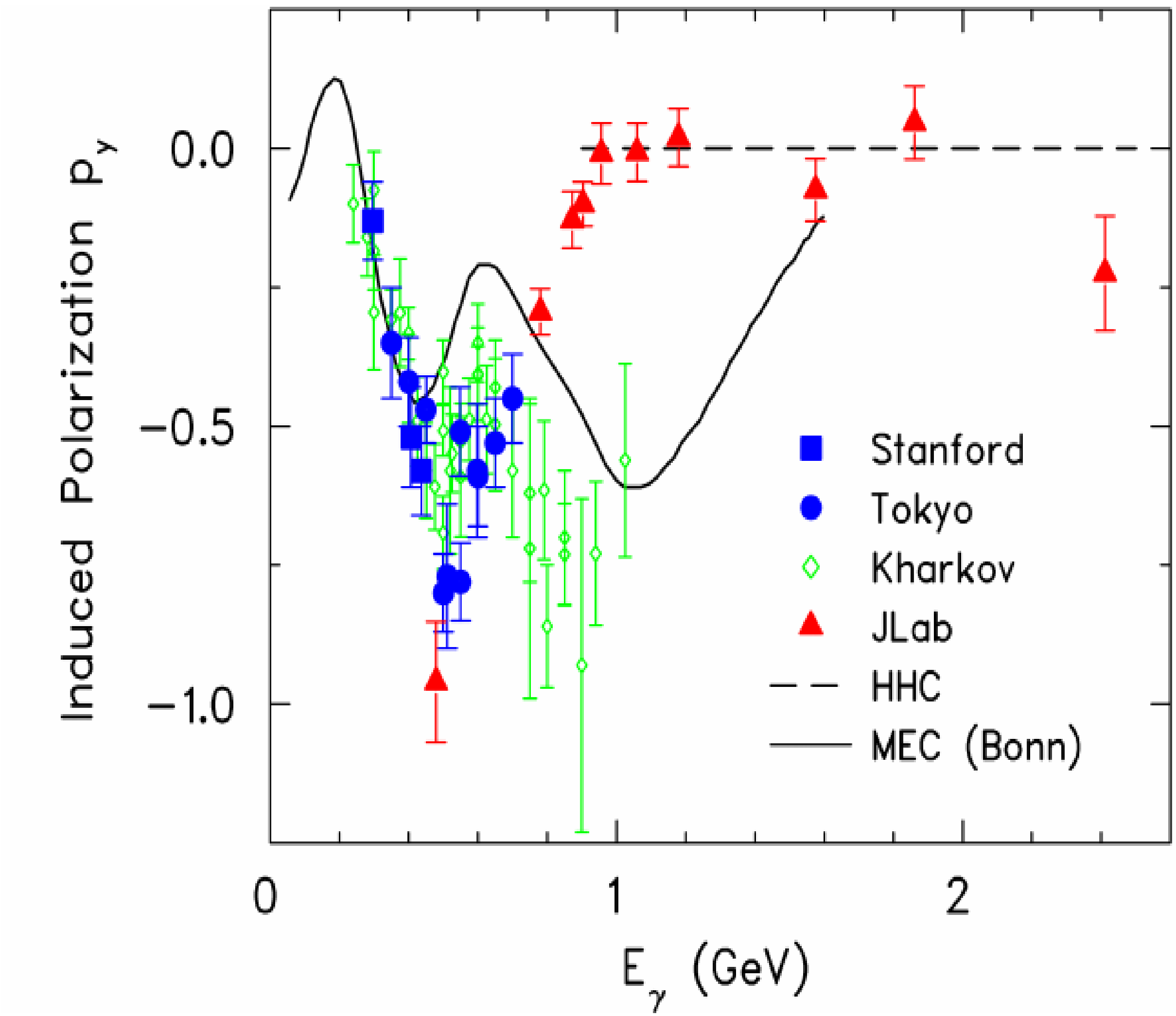


Deuteron Photodisintegration probes momenta well beyond those accessible in (e,e') (at 90^o, E_γ=1 GeV ⇔ Q^2= 4 GeV^2/c^2)

Conventional nuclear theory unable to reproduce the data above ~1 GeV

Scaling behavior ($d\sigma/dt \propto s^{-11}$) consistent with underlying constituent quark description sets in at consistent p_t

Polarization Transfer in Deuteron Photodisintegration (E89-019)



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(NAS/NRC Report, 1999)

Science Chapter Headings:

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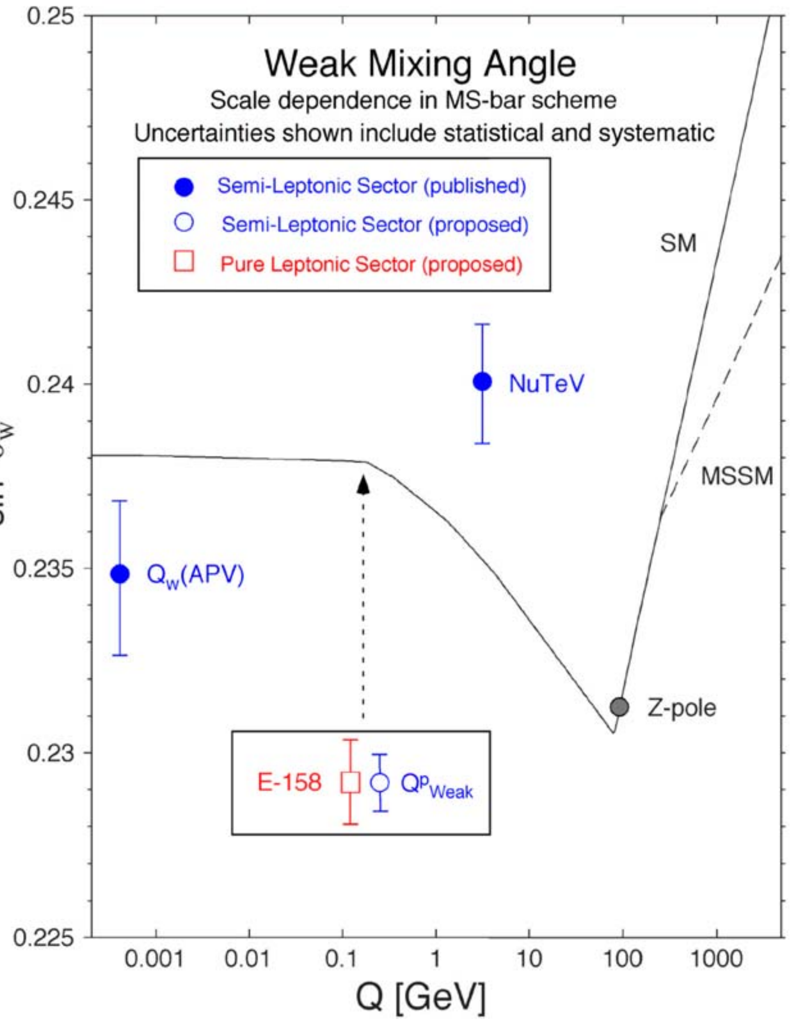
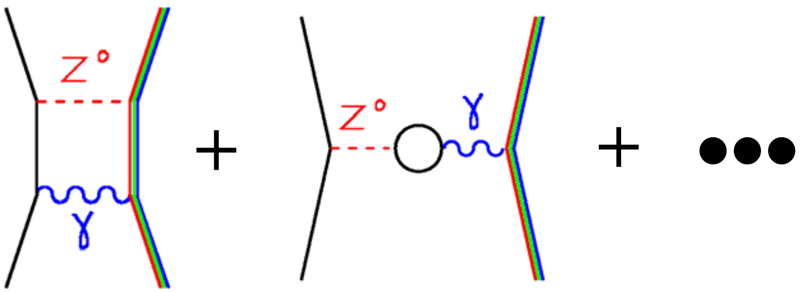
"Running of $\sin^2\theta_W$" in the Electroweak Standard Model



- Electroweak radiative corrections
  $\rightarrow \sin^2\theta_W$ varies with Q



- All "extracted" values of $\sin^2\theta_W$ must agree with the Standard Model prediction or new physics is indicated.

- Q^p_{weak} (semi-leptonic) and E158 (pure leptonic) together make a powerful program to search for and identify new physics.

2001 NSAC Long Range Plan

- **One of three construction recommendations states:**

  "We strongly recommend the upgrade of CEBAF at Jefferson Laboratory to 12 GeV as soon as possible. The 12 GeV upgrade of the unique CEBAF facility is critical for our continued leadership in the experimental study of hadronic matter. The upgrade will provide new insights into the structure of the nucleon, the transition between the hadronic and quark/gluon description of matter, and the nature of confinement."

Major Effort Toward Planning for the 12 GeV Upgrade Continues

- **Development of pCDR for the experimental equipment is well underway**
  - 1st Major draft by 9/1/02
  - Nearly final draft by 11/02 for augmented PAC review early in 2003

- **Key Developments Include:**
  - Many Hall Collaboration and/or Upgrade-focused meetings held this Spring to refine the science case and equipment plans
  - The Summer User's Group Meeting focused on the Upgrade

- **Scientific priority setting for the various Upgrade projects will begin following PAC23 (January/February 2003) with a review of the draft pCDR**

- **CD-0 is key to the next steps:**
  - Work on the CDR can begin in earnest as soon as we have CD-0 authorization to carry out the remaining needed R&D
  - It will permit serious exploration of non-DOE/NP funding sources

Summary and Perspectives

- CEBAF@JLab is fulfilling its scientific mission:
  - To understand how hadrons are constructed from the quarks and gluons of QCD
  - To understand the QCD basis for the nucleon-nucleon force
  - To explore the limits of our understanding of nuclear structure
    - high precision
    - short distances
    - The transition from the nucleon-meson to the QCD description
- The research program going well:
  - Exciting physics emerging in a steady stream (I've shown some, the Hall Leaders will show much more)
  - The data quality is extraordinary (the result of hard work by the entire JLab community, a superb accelerator and a complementary array of experimental equipment)
- We have made real progress toward planning the next steps in the research program leading to refined designs for the 12 GeV upgrade and its experimental equipment