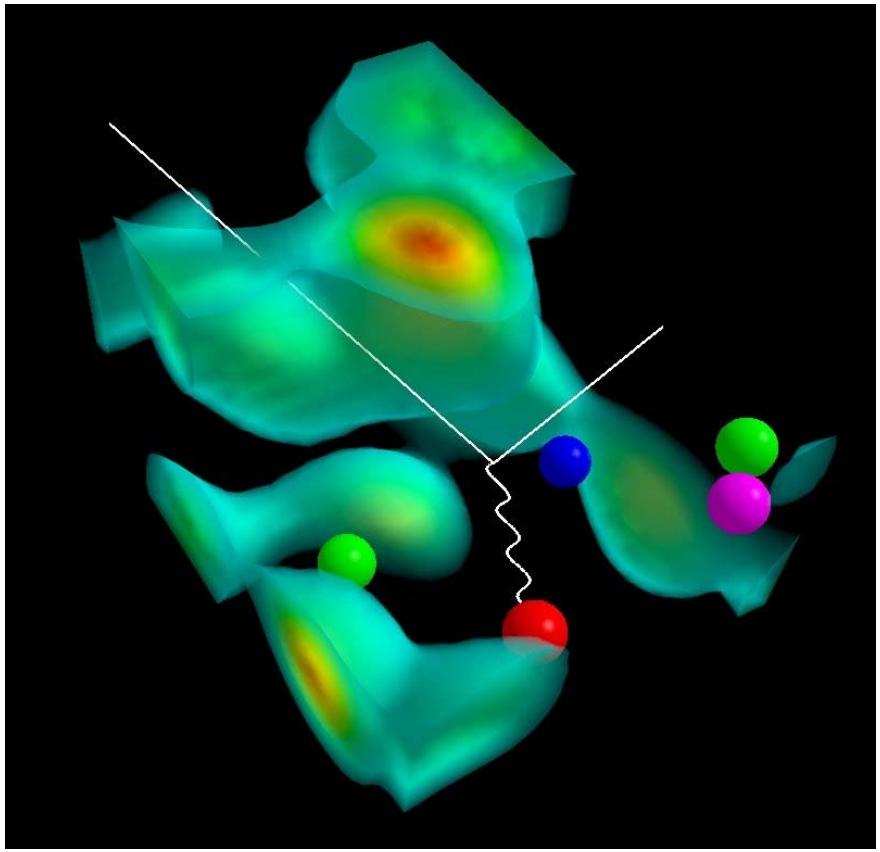
Theoretical Physics at Jefferson Lab



David Richards

DOE JLab Science and Technology Review
July, 2006

Outline

- Why a Theory Center at Jefferson Lab?
- Who are the members?
- What they do – overview
- Highlights
- Focus
  - EBAC – *Tony Thomas*
  - Lattice QCD – *Breakout session*
  - GlueX – *Jo Dudek*

Physics Program for 6 GeV and the 12GeV Upgrade

Key Roles of Theory at Jefferson Lab

- **Contribute to Intellectual Leadership of Lab**
- **Phenomenological Support of Experimental Program**
  - **development/analysis of proposals**
  - **essential support in interpretation of data**
- **Projects of scope/duration appropriate to a national laboratory: *EBAC, Lattice QCD***
- **Education and Development of graduate students and postdoctoral fellows –**
  - **HUGS *(Hampton University Graduate School).***
  - ***Theory-Group mini-lectures (Erlich, Epelbaum)***

JLab Theory Center: Senior Staff

- **5 Laboratory staff (4.5 FTE)**

  Robert Edwards — lattice gauge theory
  Franz Gross — (0.5 time)
  Wally Melnitchouk — phenomenology
  David Richards — Deputy Director (lattice gauge theory)
  Christian Weiss — phenomenology

  Distinguished Visitors: S. Brodsky, W. Bentz, D. Diakonov, V. Flambaum, P. Guichon, B. Holstein, T-S Lee, D. Leinweber, G. Miller, A. Sibirtsev, J. Tjon….

  Chief Scientist / Director: Anthony Thomas

- **8 staff with joint appointments (4.0 FTE ⇒ 50 % Lab support)**

  Ian Balitsky (ODU)
  Jose Goity (Hampton)
  Kostas Orginos (W&M)
  Anatoly Radyushkin (ODU)
  Jozef Dudek (ODU)
  Rocco Schiavilla (ODU)
  Marc Vanderhaeghen (W&M)
  Wally van Orden (ODU)

JLab Theory Group: Junior Staff

- **5 JLab postdoctoral fellows (5 FTE)**

  Jozef Dudek (PhD 04, Oxford) – from Oct 04 to Aug 06
  Renato Higa (Ph.D. 03, São Paulo) - from Oct 03
  Nilmani Mathur (Ph.D. 00, RPI) - from July 05
  Mark Paris (Ph.D. 01, UIUC) – from Nov 03
  Ross Young (PhD 04, Adelaide) – from Oct 04

- **Isgur Distinguished Postdoctoral Fellow**

  Evgeny Epelbaum (Ph.D. 00, Bochum) – Oct 03 to Mar 06
  Joint position between Juelich and University of Bonn.

JLab Theory Group: Associate Staff

- 4 senior staff (100% university support)
  - Carl Carlson (W&M)
  - Chris Carone (W&M)
  - Marc Sher (W&M)
  - Peter Agbakpe (NSU)
- 1 postdoctoral fellow (external funding)
  - Vladimir Pascalutsa (W&M, Vanderhaeghen DOE)
    - from Oct 03
- 12 graduate students:
  8 supported by JLab (includes 2 LSU)
- Bridge Positions:
  T. Mehen, R. Narayanan, new bridge position with UVA

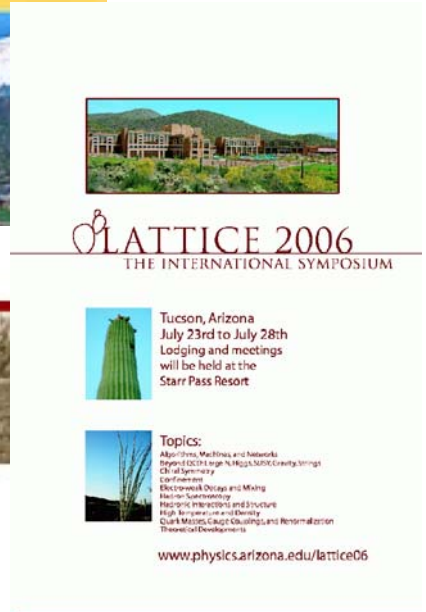
Distinguished Staff

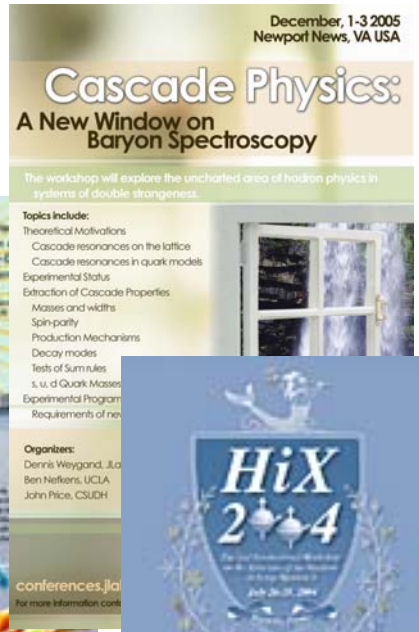
- 7 Fellows of the American Physical Society;
  1 Fellow Australian Academy of Science and IoP

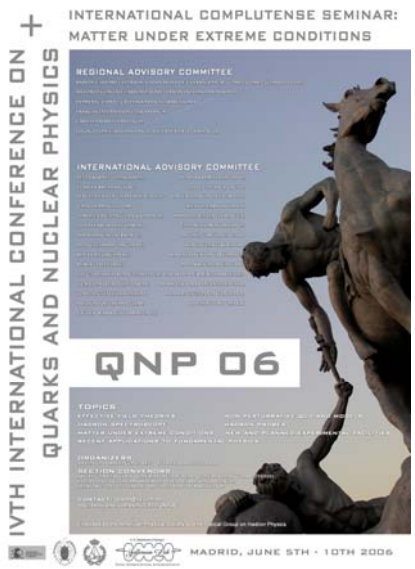
•Continuing impressive publication rate - so far in CY 2006:
  - 6 PRL and PL (9 to appear)
  - 12 other in refereed journals (24 to appear)
- Serve on IAC of every major conference/workshop in related fields
- Organization and planning of major workshops

Marciana Marina, Isola d'Elba, Italy.

Electron-Nucleus Scattering IX Workshop, June 19-23, 2006







Theory Group Research Activity - I

How quarks and gluons form hadrons and nuclei:

- **Solving QCD in the nonperturbative regime:**
  - **Lattice Gauge Theory (Dudek, Edwards, Mathur, Melnitchouk, Orginos, Richards, Thomas, Young)**

- **Solving QCD at the boundary between perturbative and nonperturbative regimes:**
  - **Sum rule techniques (Balitsky, Radyushkin)**
  - **Hadronic form factors, parton distribution functions, and duality (Balitsky, Brodsky, Carlson, Edwards, Mathur, Melnitchouk, Radyushkin, Richards, Vanderhaeghen, Weiss, Young)**
  - **QCD at high densities (Balitsky)**

- **Understanding/modeling the confinement and structure of hadrons and nuclei :**
  - **Heavy-quark effective theory (Goity)**
  - **Chiral dynamics and large N_c QCD (Carone, Epelbaum, Goity, Gross, Thomas, Young)**
  - **Relativistic and nonrelativistic quark models (Dudek, Goity, Gross, Paris, Van Orden, Thomas)**

Theory Group Research Activity - II

- **How nucleons bind together to form nuclei**
  - **– Constructing nuclear interactions and currents:**
    - **One-boson-exchange phenomenology and similar (Gross, Schiavilla, Van Orden)**
    - **Effective field theory approach (Epelbaum, Higa, Thomas, Young)**
    - **Hadronic interactions in Lattice QCD (Orginos)**
  - **– Structure and reactions of nuclei:**
    - **Relativistic approaches to nuclear dynamics (Gross, Schiavilla, Thomas, Van Orden)**
    - **Form factors and weak transitions in few-nucleon systems (Gross, Schiavilla, Thomas, Van Orden)**
    - **EFT studies of the structure of few-nucleon systems (Epelbaum, Gross, Higa, Schiavilla)**
    - **Nuclear reactions of astrophysical interest (Schiavilla)**

Theory Group Research Activity - III

- **The Standard Model and beyond**
  (Carlson, Carone, Sher, Thomas, Young)
  - Constraints on lepton-flavor mixing from experiments
  - TeV-scale physics in low-energy parity violating observables
  - CP Violation
  - Time dependent coupling "constants" as tests of extra dimensions
  - NuTeV "anomaly" : charge symmetry violation of PDFs
  - Theory support for Qweak

- **PAC involvement: (ALL members – including post-docs)**

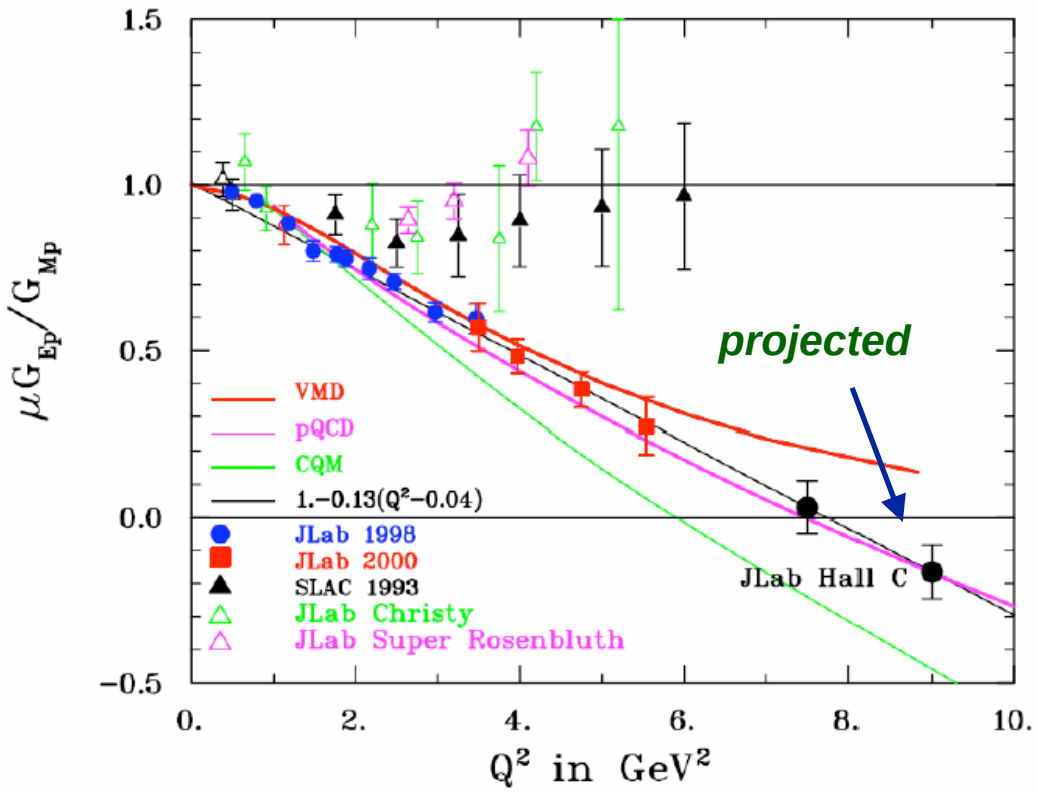
  Deliver written reports to PAC on every new proposed experiment – viewed as extremely valuable by PAC members.

- **Physics Program for the 12GeV Upgrade**

Highlights

- Form factors
- Strange-quark contributions to EM Form Factors
- Generalized Parton Distributions
- Excited baryon spectroscopy
- Charge-symmetry breaking
- EFT in few nucleon systems
- GlueX *Dudek*

Revolutionize Our Knowledge of Distribution of Charge and Current in the Nucleon



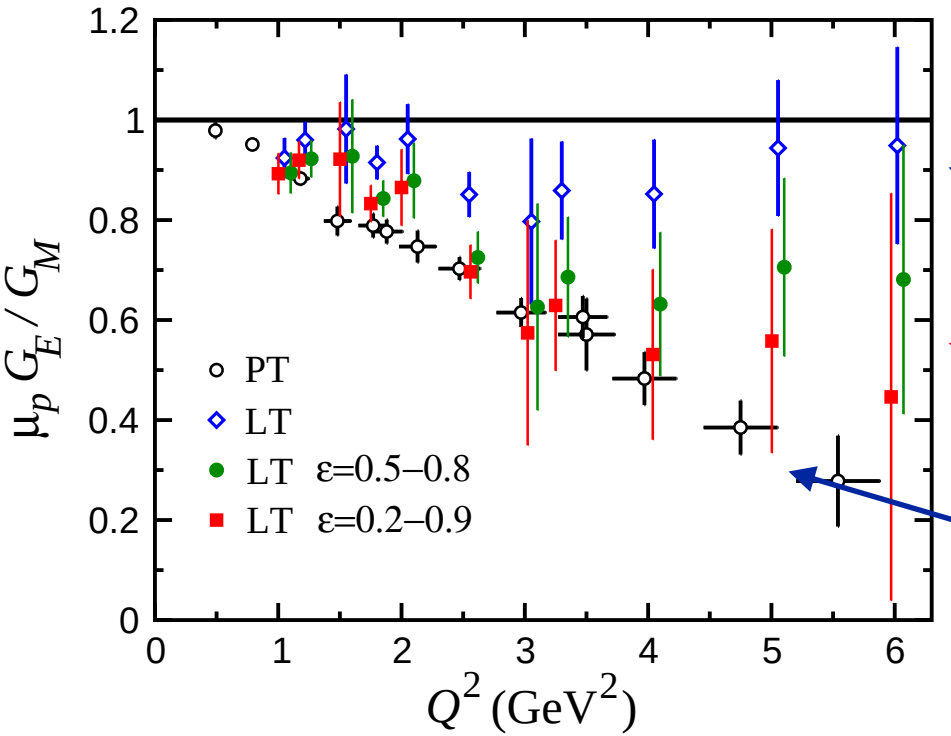
C. Perdrisat (W&M) , JLab Users Group Meeting, June 2005

HP 2010

Precise experimental measurement to confront lattice data

Need to resolve polarization-transfer and LT-separation measurements

Two-photon exchange calculation.



Kondratyuk, Blunden, Melnitchouk, Tjon: **PRL95 (2005) 172503**

Blunden, Melnitchouk, Tjon: **PRC72 (2005) 034612**

LT measurements

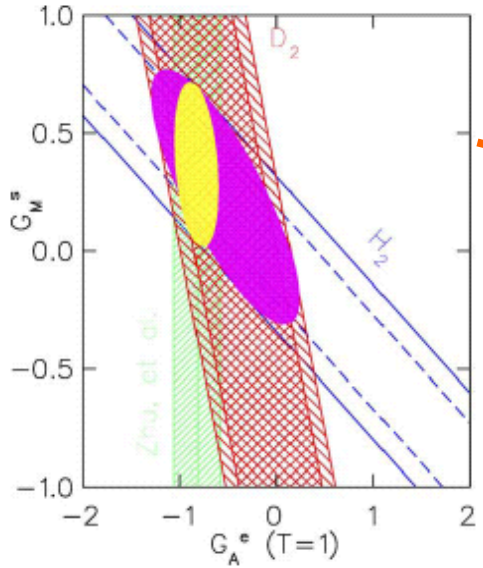
2γ-corrected LT measurements

Polarization transfer, little contaminated by 2γ contributions

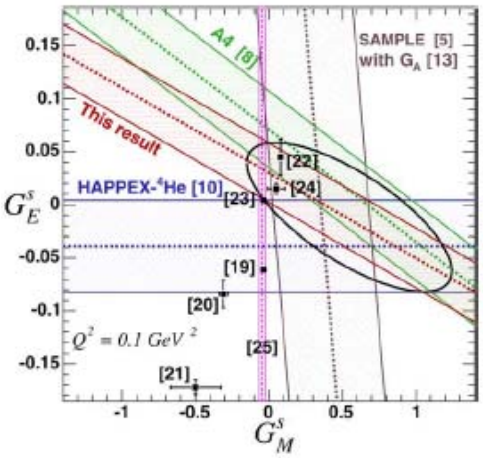
Ongoing work by Melnitchouk and Arrington to analyze global *ep* data → most accurate determination of G_E and G_M

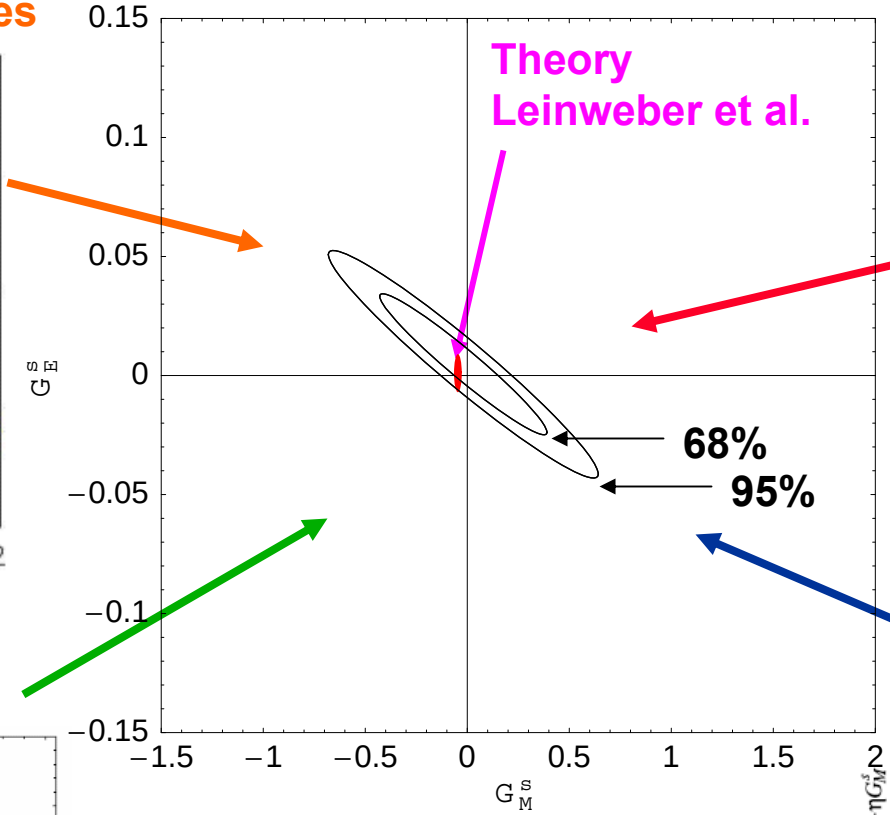
Strange Form Factors: Global Analysis of Parity-Violation Experiments

SAMPLE – MIT Bates

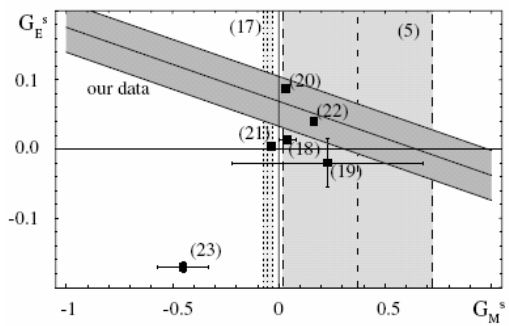


HAPPEX – JLab

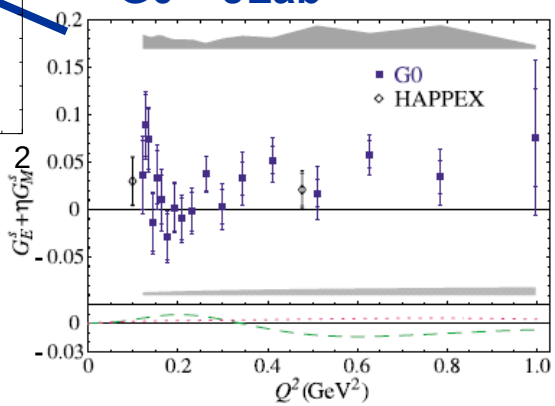




PVA4 – Mainz

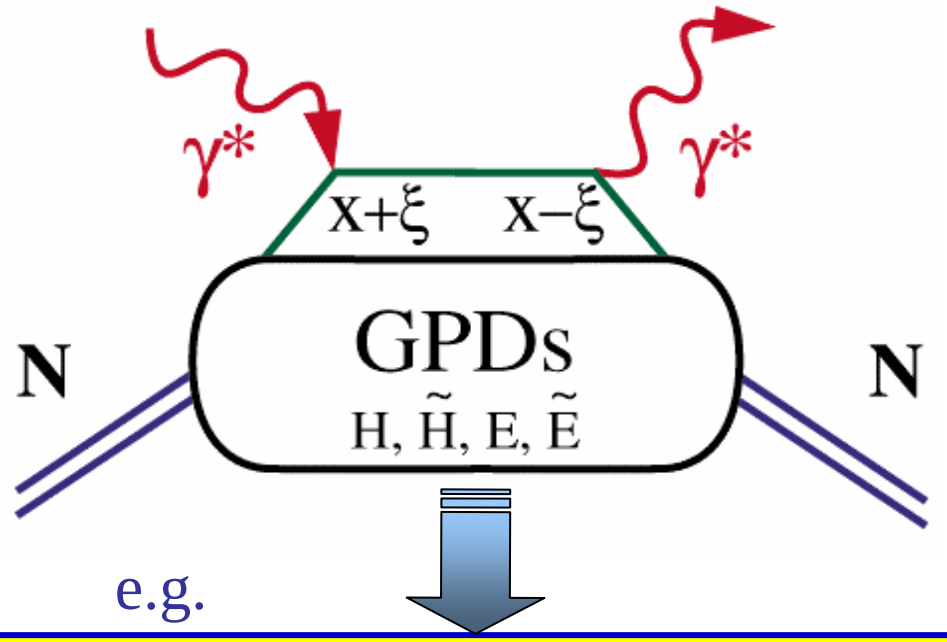


G0 – JLab



Young et al., nucl-ex/0604010
+ NEW HAPPEx (Apr 2006)

Generalized Parton Distributions (GPDs): New Insight into Hadron Structure



HP 2008

X. Ji &
A. Radyushkin
(1996)

e.g.

Quark angular momentum (Ji's sum rule)

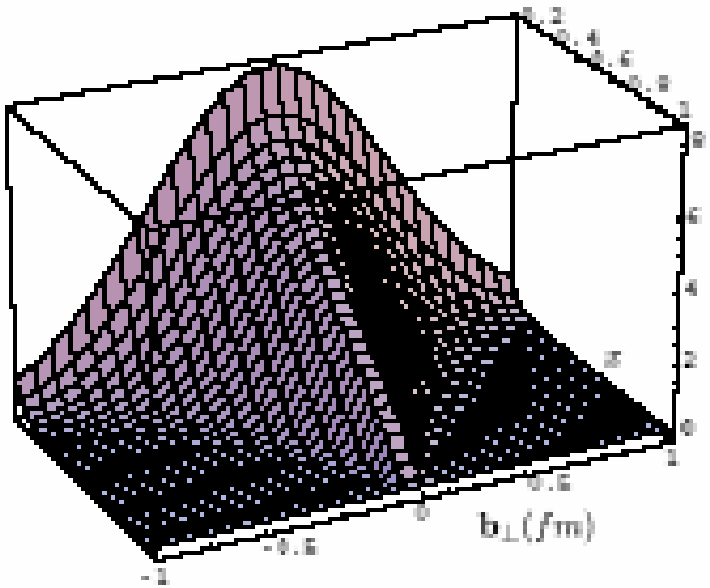
$$J^q = \frac{1}{2} - J^G = \frac{1}{2}\int_{-1}^{1} x\,dx\left[H^q(x,\xi,0) + E^q(x,\xi,0)\right]$$

X. Ji, Phy.Rev.Lett.78,610(1997)

Major review by *Belitsky and Radyushkin*, Phys. Rep. 418 (2005), 1-387

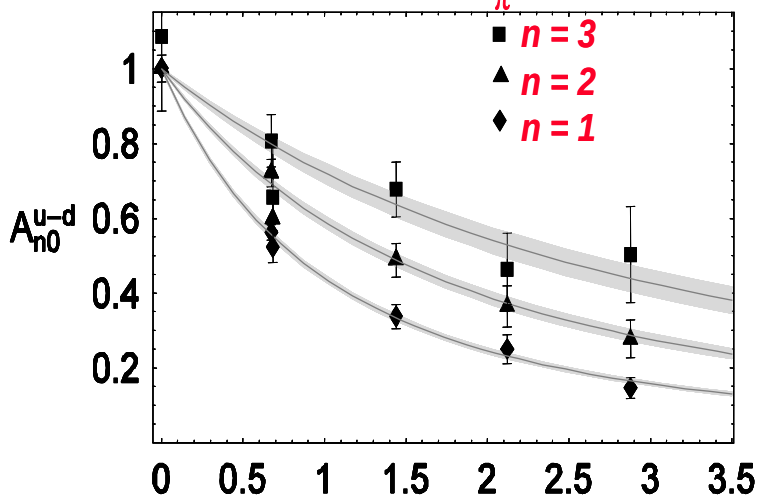
GPDs - II

- QCD computation of hard processes (factorization etc)
- Extracting information about GPDs from data
- Modeling GPDs and *gaining new insight into hadron structure*



Decrease slope : decreasing transverse size as x → 1 -
Burkardt

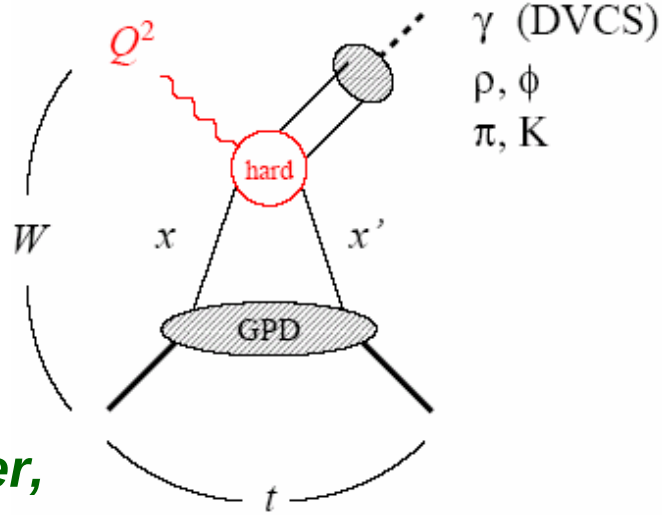
Lattice data: m_π = 740 MeV



LHPC/SESAM Collab.

GPDs: Phenomenology of hard exclusive processes in *eN* Scattering

- $Q^2, W \to \infty$: *QCD factorization*
- **Aim: extract information from data about GPDs at finite Q^2, W.**
- ***This requires significant theory input!***



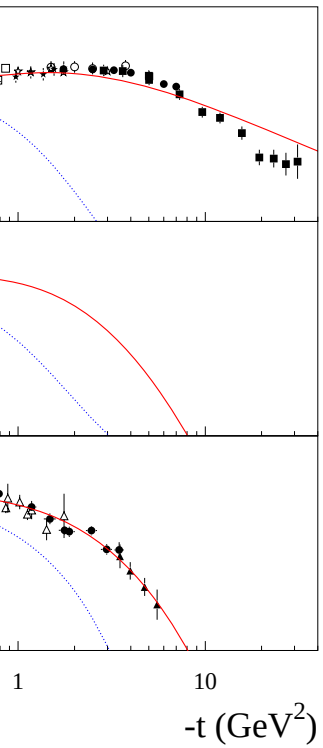
- **Study uncertainties in model predictions for leading-twist amplitudes – *Diehl, Kugler, Schafer, Weiss*, PRD72, 034034 (2005)**
- **Review of high-energy data at HERA**
  - **Higher-twist ↔ hadronic structure of photon**
  - **Successful gluon imaging of proton**

***Frankfurt, Strikman, Weiss*, Ann. Rev. Nucl. Part. Sci. 55, 403 (2005)**

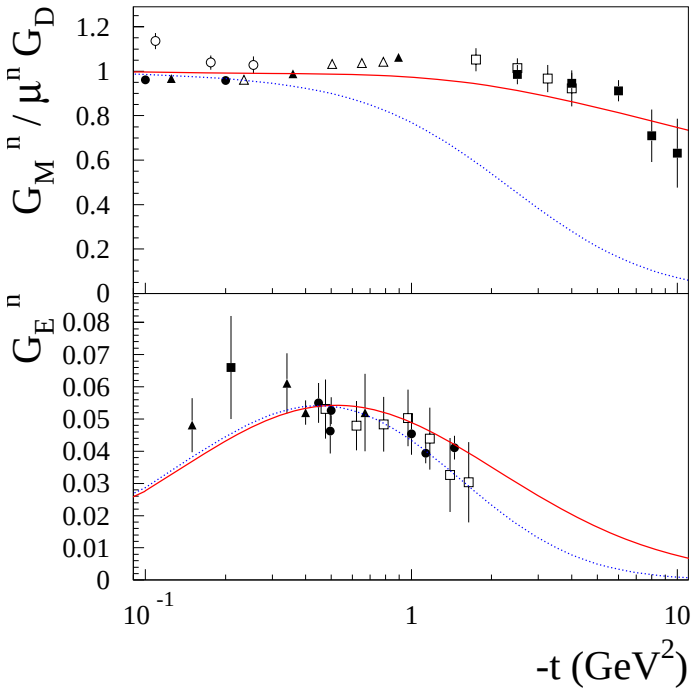
Develop techniques for GPD analysis of exclusive reactions at JLab@12 GeV

Modeling GPD's

Links between GPDs and FFs explored, using Regge param. at small *t*.



Description of the four p and n form factors.

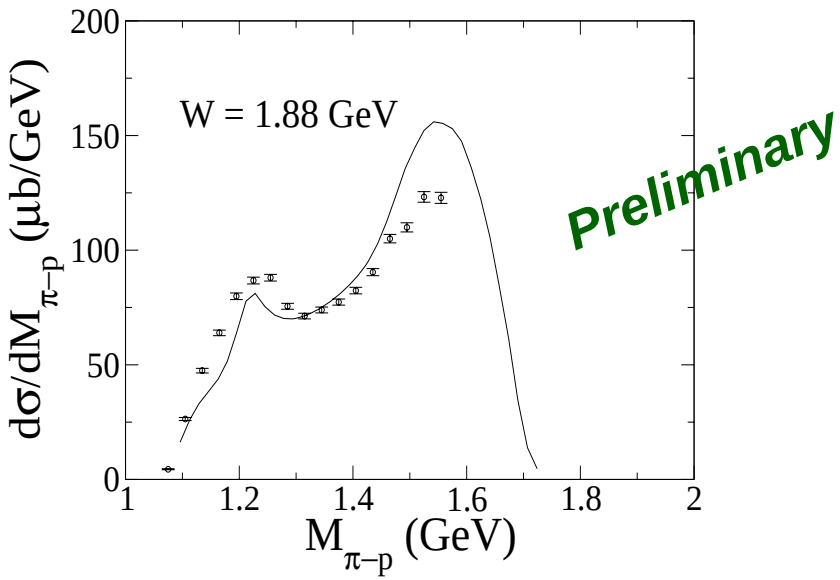


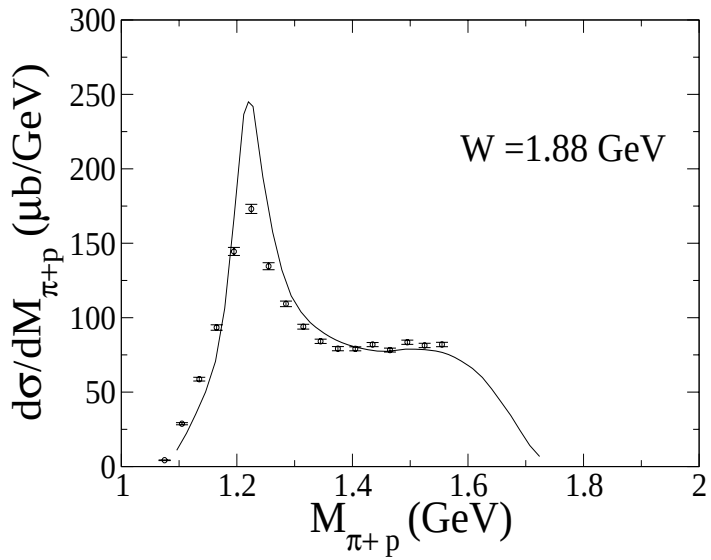
Guidal, Polyakov, Radyushkin, Vanderhaeghen, PRD72 (2005), 054013

Baryon Spectroscopy

- **EBAC founded in January 2006, with lead investigator T-S Harry Lee**
- **Hired Mark Paris as research associate: team formed to analyse π, η and π π production data**

JLAB data of γp → π+π- p

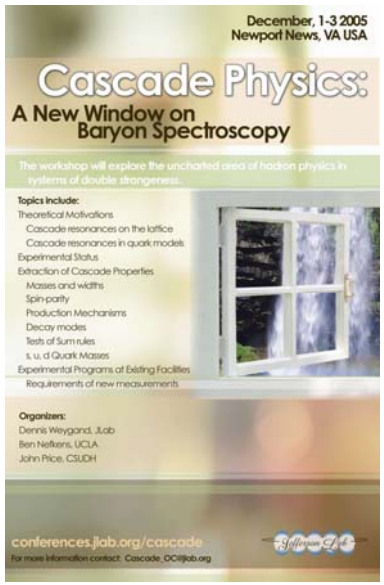


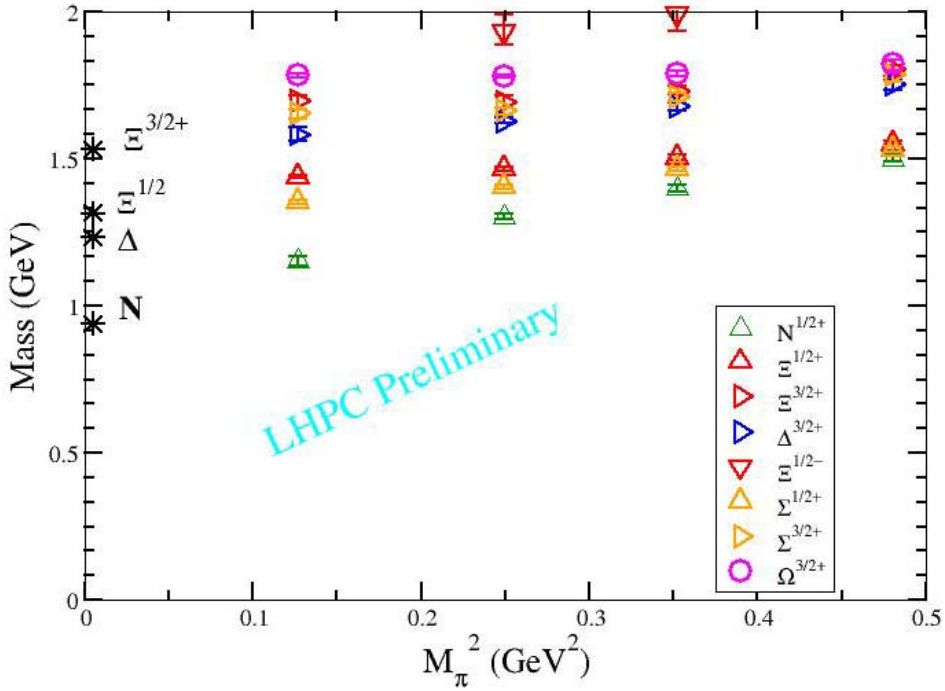


Baryon Spectroscopy - II

- **Major effort at predicting and interpreting spectrum in lattice QCD and QCD-inspired models, e.g. large-N_c (Goity), quark model (Goity, Roberts).**

Workshop on Cascade Physics
December 2005, and whitepaper
Being drafted





Narrow widths, straightforward to measure and calculate

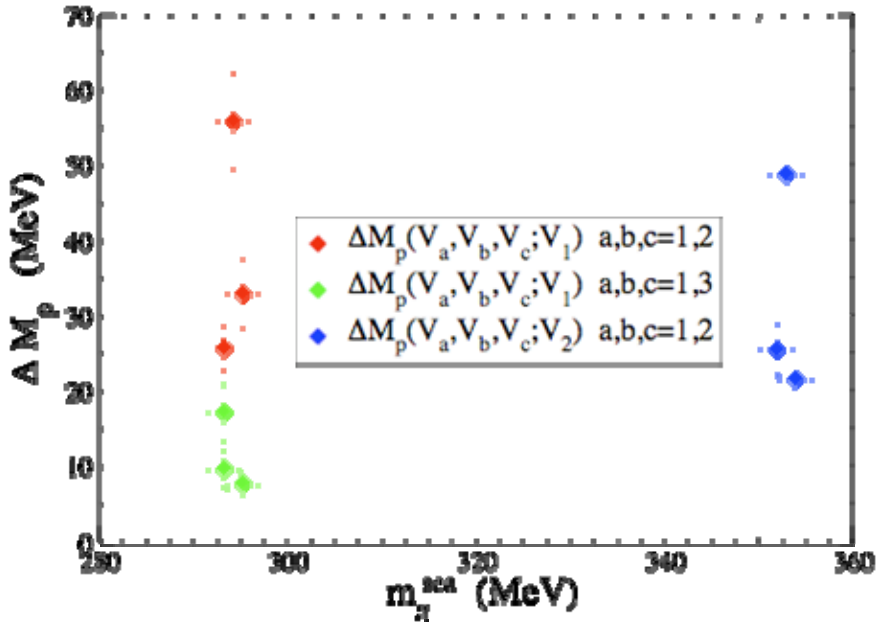
Charge-symmetry Breaking

$$M_n - M_p|^{d-u} = \frac{2}{3}\left(2\overline{\alpha} - \overline{\beta}\right)\left(\frac{1-\eta}{1+\eta}\right) m_\pi^2$$

MILC: $\eta = m_u/m_d = 0.43(1)(8)$

Extraction	$M_n - M_p\|^{d-u}$ (MeV) at $m_\pi^{\text{phys.}}$
LO $\mathcal{O}(m_q)$	$1.96 \pm 0.92 \pm 0.37$
NLO $\mathcal{O}(m_q^{3/2})$	$2.26 \pm 0.57 \pm 0.42$

Beane, Orginos, Savage,
hep-lat/0605015



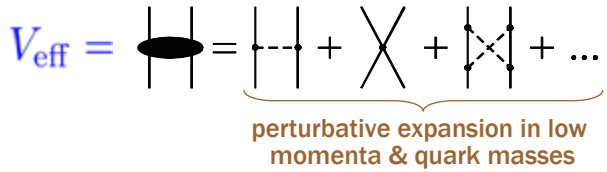
Exp. value: $M_n - M_p = 1.2933317(5)$ MeV —(minus EM part; Gasser Leutwyler '82)→ $M_n - M_p = 2.05(30)$ MeV

Few-nucleon systems: chiral effective field theory

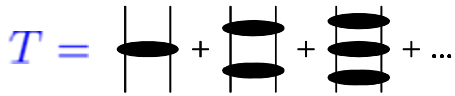
Weinberg 1990:

Epelbaum

Step I: Use effective field theory to derive:
[= kernel of the dynamical equation]



Step II: Solve the corresponding dynamical equation



Key features:

- Linked to QCD.
- Systematic & model independent framework.
- Works at low energy (nucleon momenta ~M_π)
- Errors can be estimated.
- Straightforward to improve.

Applied this framework to study the 2N system up to N^3LO and 3N, 4N, 6N systems up to N^2LO in the chiral expansion.

EFT - II

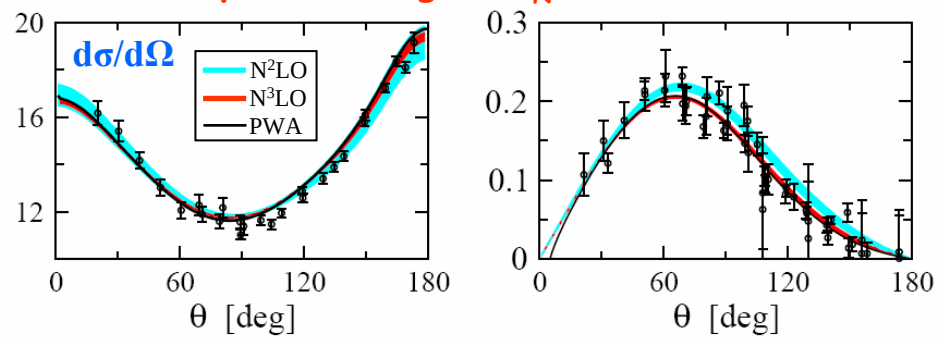
2 nucleons

- analyzed up to N^3LO, see *Epelbaum et al. NPA 747 (05)*
- accurate results up to E_{lab}~200 MeV

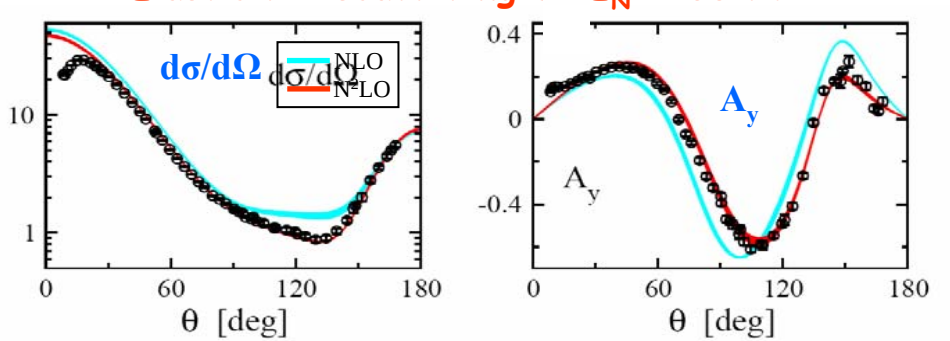
3 nucleons

- parameter-free results at NLO, *Epelbaum et al., PRL 86 (01)*
- complete analysis at N^2LO including chiral 3N force, *Epelbaum et al., PRC 66 (02)*

np scattering at E_N = 65 MeV



Elastic Nd scattering at E_N = 65 MeV



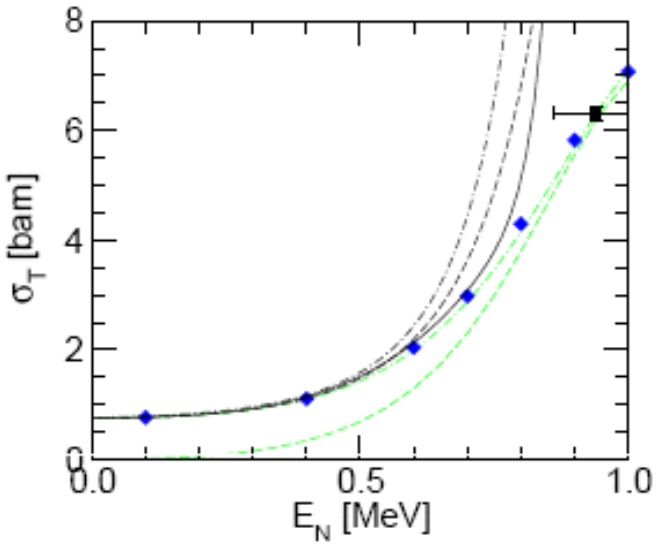
Epelbaum, nucl-th/0511025

First extension to 4N force in EFT

EFT for Halo Nuclei - I

- **Rare isotopes close to neutron drip line: *formation of weakly-bound clusters***
- **Halo nuclei: large radius, low-energy cross sections relevant for nuclear astrophysics, e.g. p + ^{7}Be $\rightarrow$ ^{8}B + γ, RIA,…**
- **EFT power-counting for p-wave resonances developed by Bertulani *et al.*, Bedaque *et al.*.**

Bedaque, Hammer, van Kolck →



EFT for Halo Nuclei - II

Including Coulomb interactions…

e.g. p - α

Coulomb interactions

$$\Rightarrow \frac{Z_1 Z_2 e^2}{k^2} = 4\pi \frac{Z_1 Z_2 \alpha_{em}}{k^2}$$

Insertions of $4\pi \frac{Z_1 Z_2 \alpha_{em}}{k^2} \frac{\mu}{4\pi} \frac{k}{} \sim \frac{Z_1 Z_2 \alpha_{em} \mu}{k} \equiv \eta$

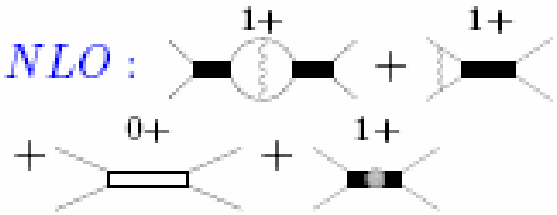
$$\rho \equiv \frac{Z_1 Z_2 \alpha_{em} \mu}{M_{lo}}$$

- power counting:
  - $\rho > 1 \Rightarrow$ Coulomb is non-perturbative and dominant
  - $\rho \sim 1 \Rightarrow$ Coulomb is non-perturbative and comparable to strong
  - $\rho \sim M_{lo}/M_{hi} \Rightarrow$ Coulomb is perturbative for $k \sim M_{lo}$ and comparable to strong (in the resonance region Coulomb is leading), leading and non-pert. for $k < M_{lo}^2/M_{hi}^2$

in the resonance region,

LO :

NLO :



Higa, Bertulani and Van Kolck

- **Bubble double loop can be treated perturbatively**
- ***However*, vertex corrections have to be summed to all orders**

Conclusions

- JLab Theory Center has major impact in inspiring, facilitating, and interpreting the JLab program.
- Recent initiatives coming to fruition – Lattice QCD, EBAC – and new theoretical focus on GlueX
- Impact of Theory Center seen in both publications in high-impact journals, and invited talks at major conferences