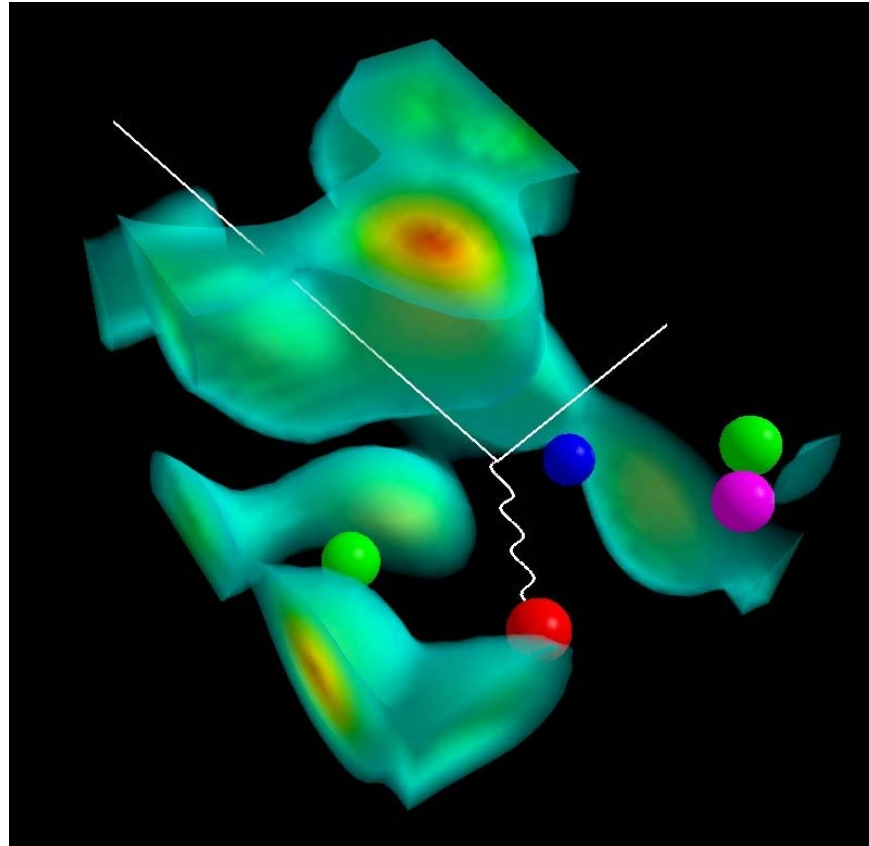


Theoretical Physics at Jefferson Lab



David Richards

**DOE JLab Science and Technology Review
July, 2006**



Thomas Jefferson National Accelerator Facility



U.S. DEPARTMENT OF ENERGY
S and T 2006: Theory

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 \Rightarrow 50 % Lab support)**

Ian Balitsky (ODU)	<i>Jozef Dudek (ODU)</i>
Jose Goity (Hampton)	Rocco Schiavilla (ODU)
Kostas Orginos (W&M)	Marc Vanderhaeghen (W&M)
Anatoly Radyushkin (ODU)	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)

Marc Sher (W&M)

Chris Carone (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

Topics
 The structure of nuclei
 Nuclear structure through experiments
 Nuclear structure through theory
 Nuclear structure through experiments
 Nuclear structure through theory
 Nuclear structure through experiments
 Nuclear structure through theory

March 24-27, 2004
 Laboratoire de Physique Subatomique et de Cosmologie
 Université de Grenoble - FRANCE
 2004 Meeting, March 23

Organizing Committee
 ...

Advisory Committee
 ...



CONFERENCE REPORT

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CONFERENCE REPORT

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December, 1-3 2005
 Newport News, VA USA

Cascade Physics: A New Window on Baryon Spectroscopy

The workshop will explore the uncharted area of hadron physics in systems of double strangeness.

Topics include:
 Theoretical Motivations
 Cascade resonances on the lattice
 Cascade resonances in quark models
 Experimental Status
 Extraction of Cascade Properties
 Masses and widths
 Spin parity
 Production Mechanisms
 Decay modes
 Tests of Sum rules
 s, u, d Quark Masses
 Experimental Program
 Requirements of new experiments

Organizers:
 Dennis Weisand, JLab
 Ben Nefkens, UCLA
 John Price, CSUDH

conferences.jlab.org
 for more information contact

GDH 2004
 June 2-5, 2004
 The 2nd International Symposium on Gerasimovich-Drell-Hearn Sum Rule

Topics:
 ...
 ...
 ...

www.physics.arizona.edu/GDH04

HiX 2004
 High Energy X-ray Scattering
 July 26-31, 2004

TOPICS:
 ...
 ...
 ...

LATTICE 2006
 THE INTERNATIONAL SYMPOSIUM

Tucson, Arizona
 July 23rd to July 28th
 Lodging and meetings will be held at the Starr Pass Resort

Topics:
 Algorithms, Methods, and Networks
 Beyond QCD: Topology, Higgs, Supersymmetry
 Chiral Symmetry
 Confinement
 Electroweak Design and Mixing
 Hadron Spectroscopy
 Hadronic Interactions and Structure
 High Temperature and Density
 Quark Masses, Gauge Couplings, and Renormalization
 Theoretical Developments

www.physics.arizona.edu/lattice06

INTERNATIONAL COMPLETENSE SEMINAR: MATTER UNDER EXTREME CONDITIONS

REGIONAL ADVISORY COMMITTEE
 ...
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INTERNATIONAL ADVISORY COMMITTEE
 ...
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TOPICS:
 ...
 ...
 ...

QNP 06

14TH INTERNATIONAL CONFERENCE ON QUARKS AND NUCLEAR PHYSICS

MADRID, JUNE 5TH - 10TH 2006

3rd Topical Workshop Lattice Hadron Physics

July 31 - August 3, 2006
 Jefferson Lab, Newport News, Virginia

TOPICS:
 • Hadronic structure from lattice QCD
 • Hadron spectroscopy
 • Interplay of lattice QCD and experiment
 • Chiral fermions
 • Chiral extrapolations
 • Dynamical fermions
 • Algorithms

http://conferences.jlab.org/LHP



Thomas Jefferson National Accelerator Facility



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**



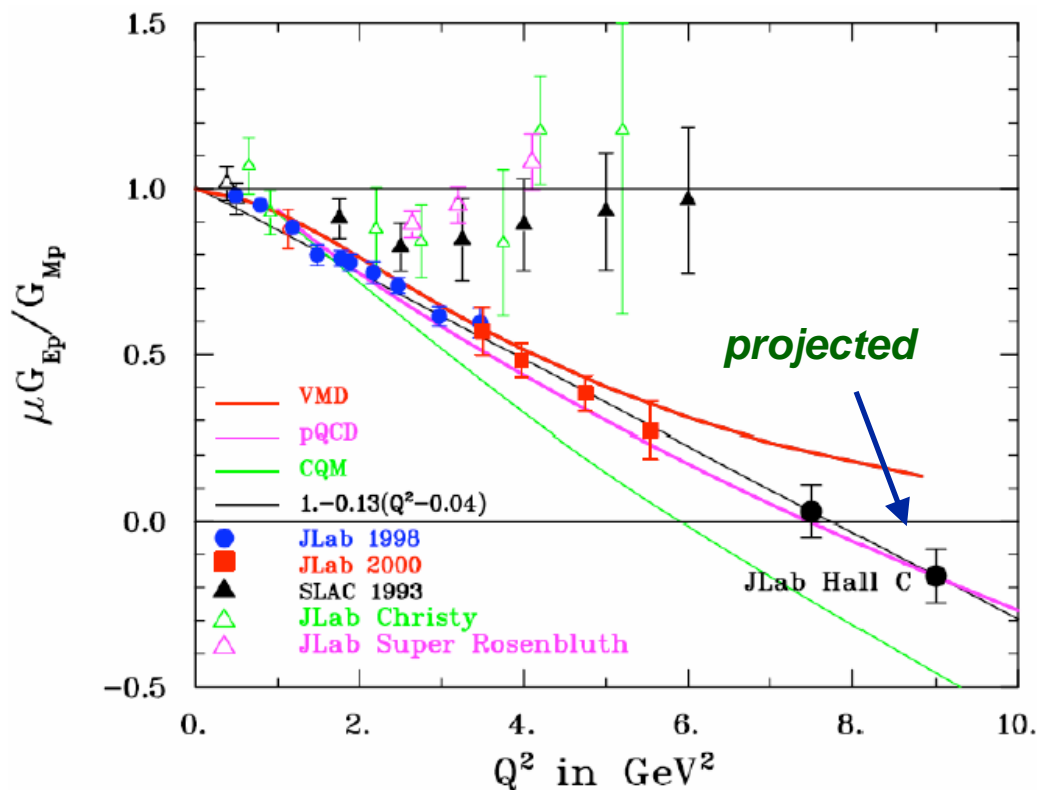
Highlights

- **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***

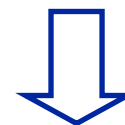


Revolutionize Our Knowledge of Distribution of Charge and Current in the Nucleon

HP 2010



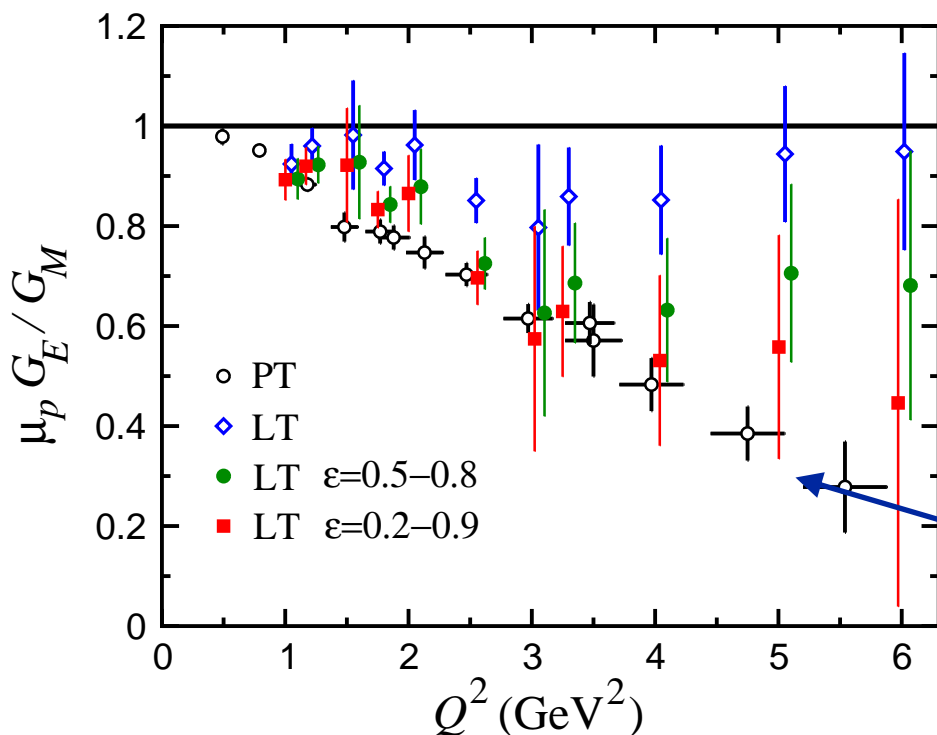
Precise experimental measurement to confront lattice data



Need to resolve polarization-transfer and LT-separation measurements

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

Two-photon exchange calculation.



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

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

LT measurements

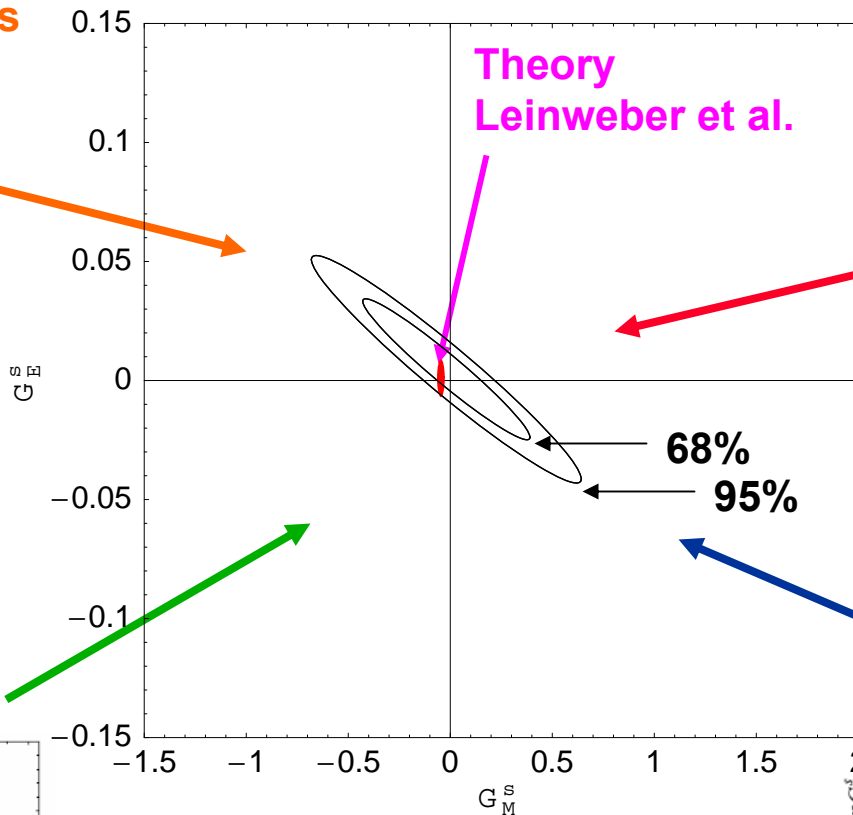
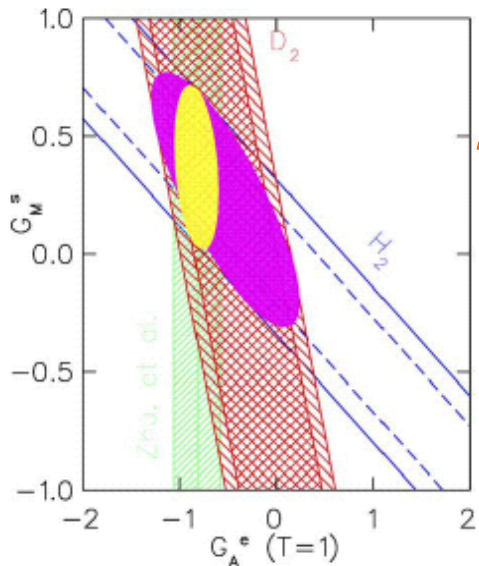
2 γ -corrected LT
measurements

Polarization transfer,
little contaminated by 2 γ
contributions

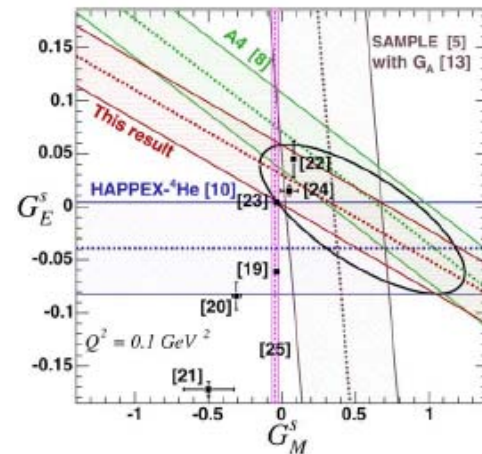
Ongoing work by **Melnitchouk** and **Arrington** to analyze
global ep data \rightarrow **most accurate determination of G_E and G_M**

Strange Form Factors: Global Analysis of Parity-Violation Experiments

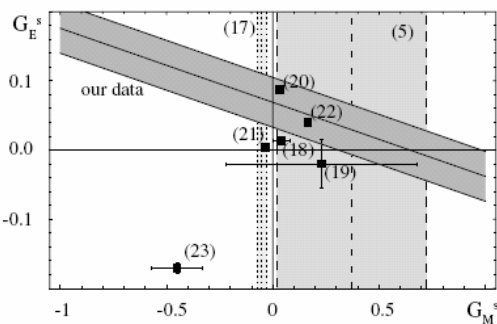
SAMPLE – MIT Bates



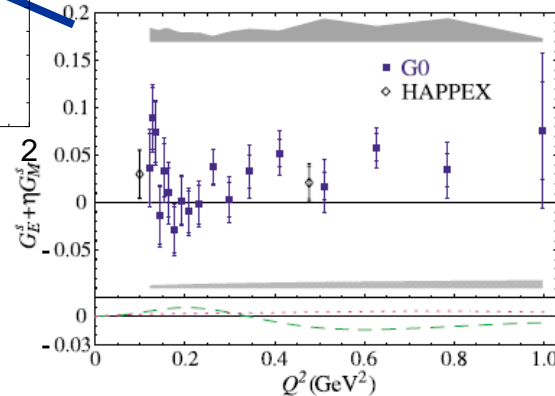
HAPPEX – JLab



PVA4 – Mainz



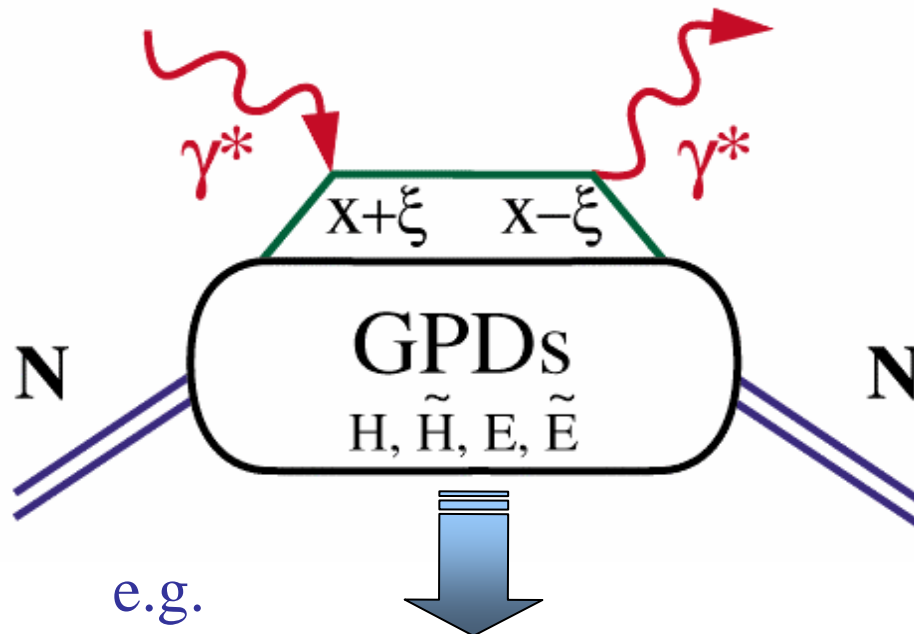
G0 – JLab



**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)

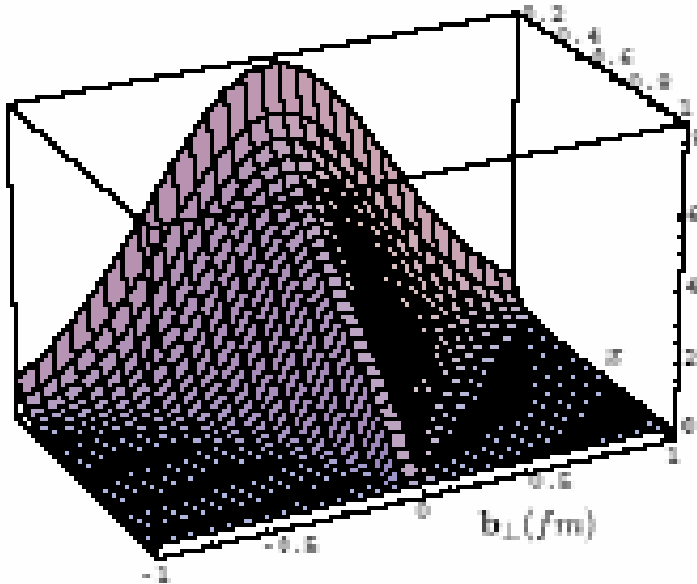
$$J^q = \frac{1}{2} - J^G = \frac{1}{2} \int_{-1}^1 x dx [H^q(x, \xi, 0) + E^q(x, \xi, 0)]$$

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

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

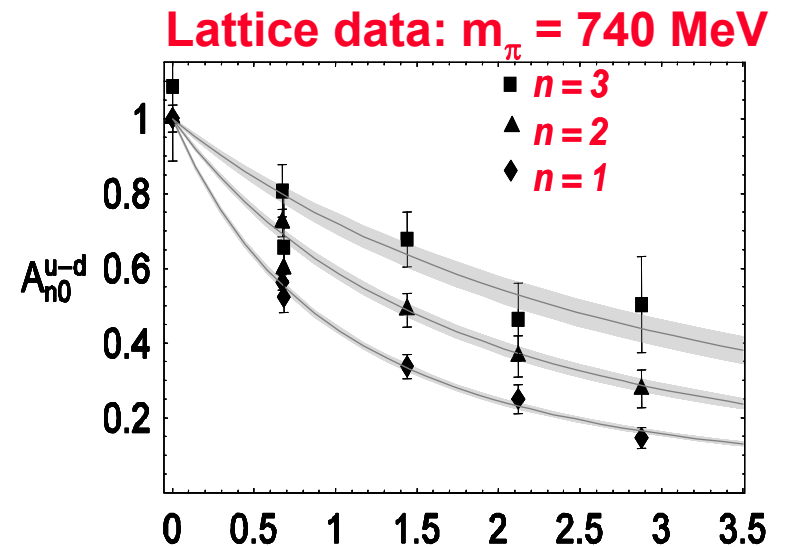
GPDs - II

- 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 $x \rightarrow 1$ -

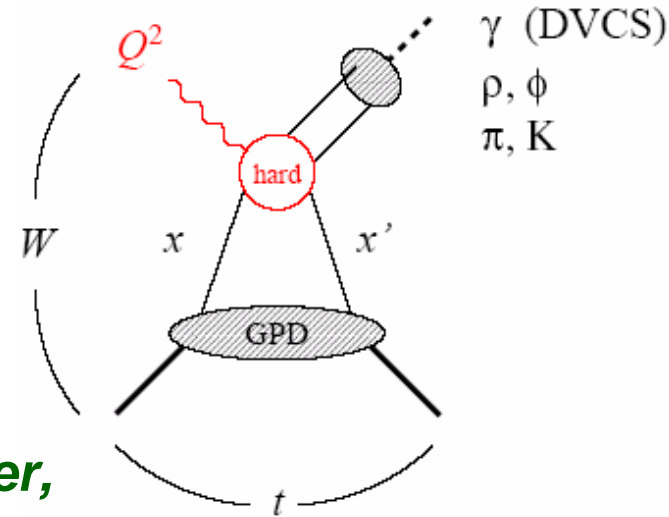
Burkardt



LHPC/SESAM Collab.

GPDs: Phenomenology of hard exclusive processes in eN Scattering

- $Q^2, W \rightarrow \infty$: 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 \leftrightarrow hadronic structure of photon
 - Successful gluon imaging of proton



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

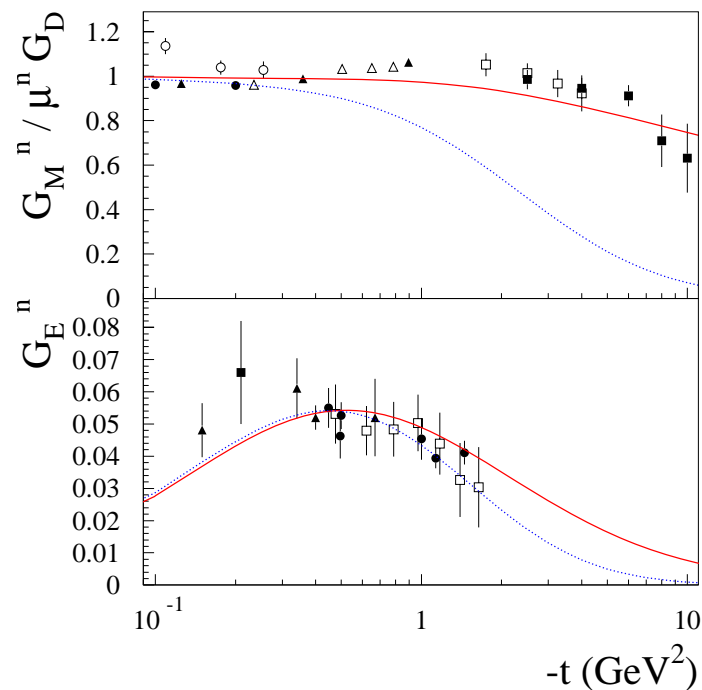
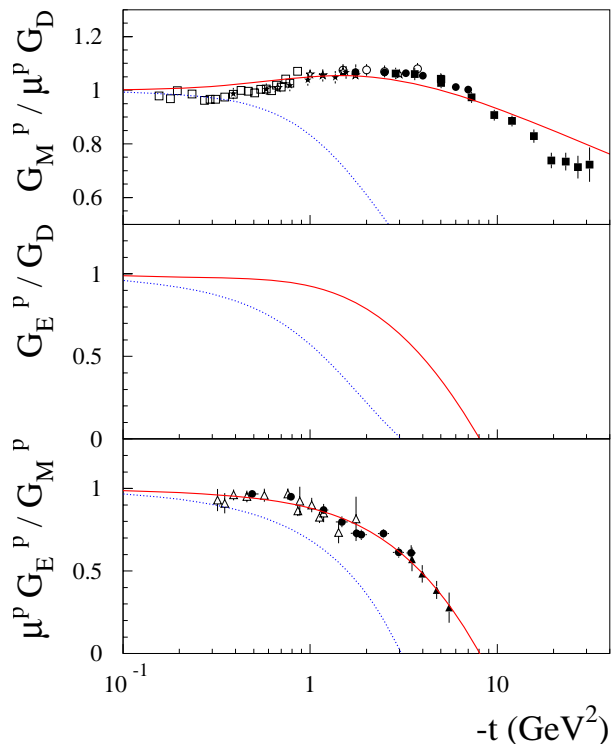
Develop techniques for GPD analysis of exclusive reactions at JLab@12 GeV

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



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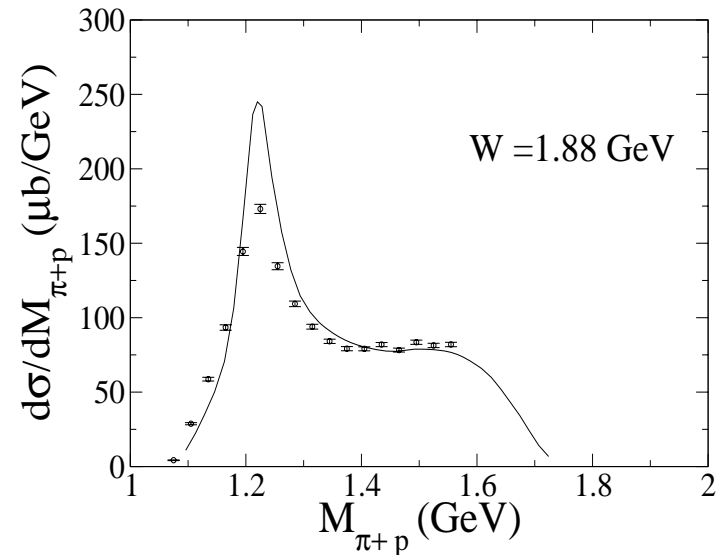
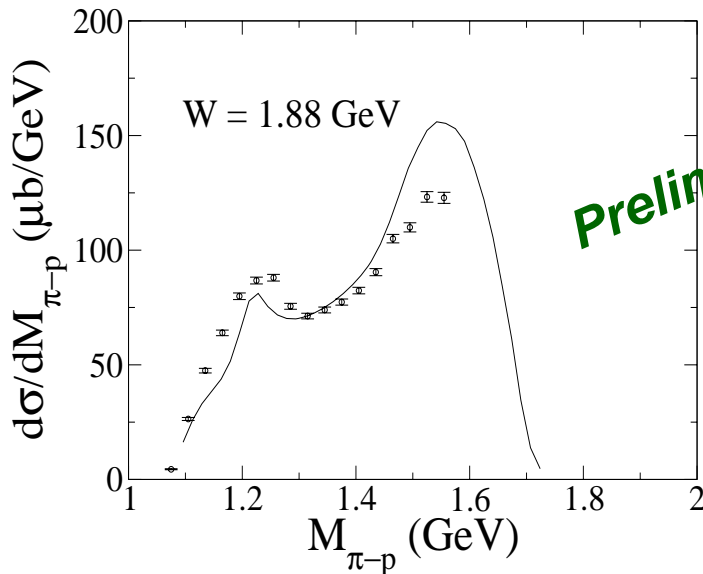


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S and T 2006: Theory

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 $\pi\pi$ production data

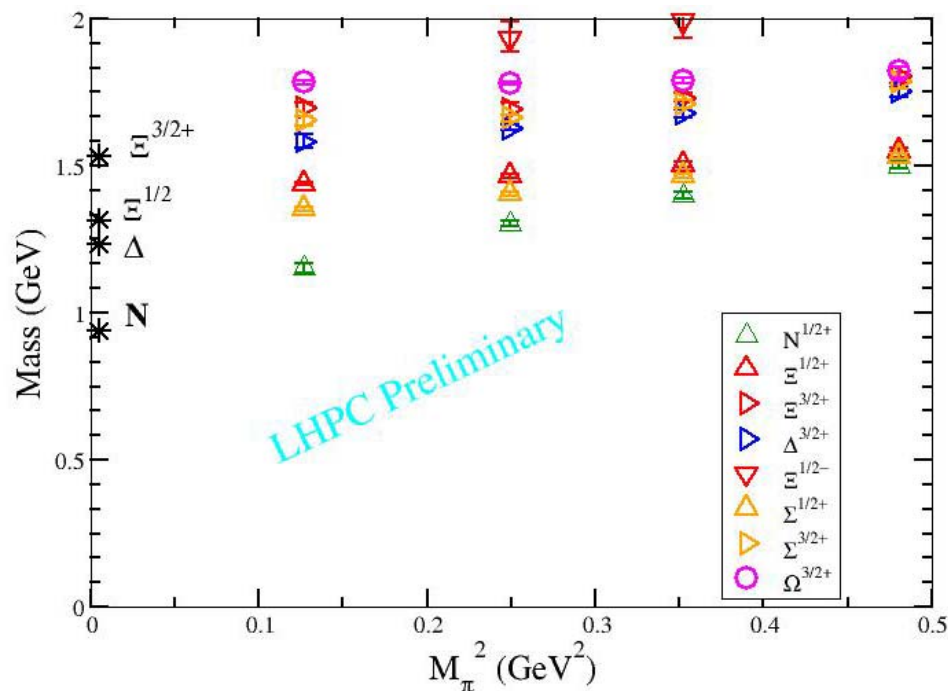
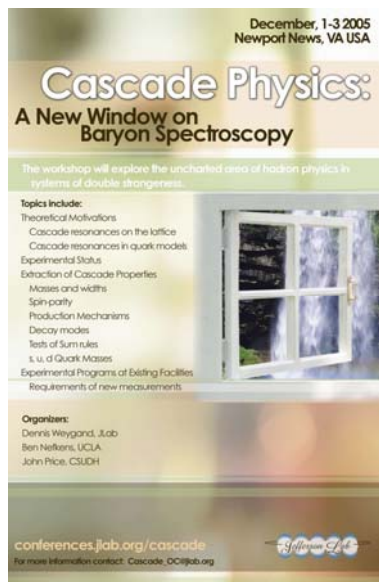
JLAB data of $\gamma p \rightarrow \pi^+\pi^- p$



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**



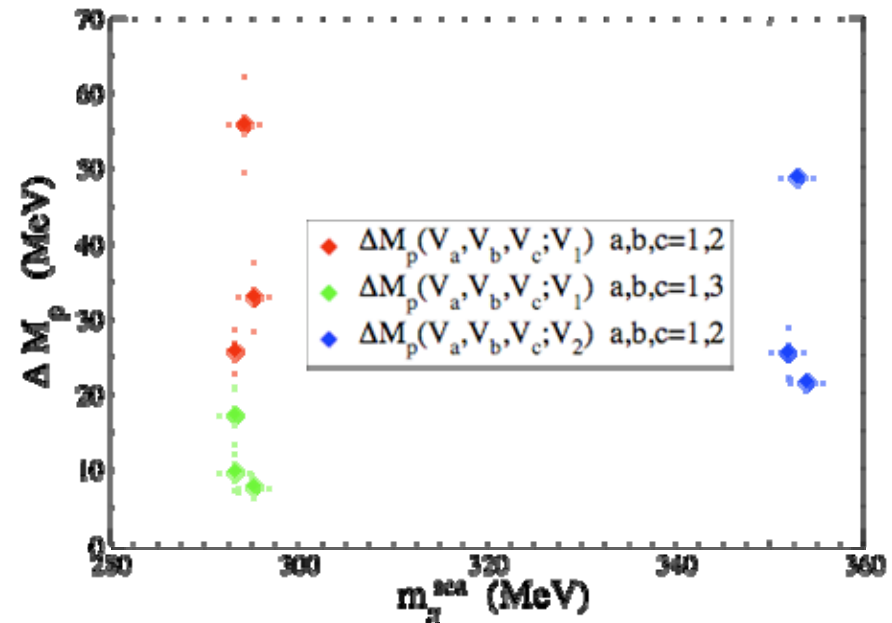
Charge-symmetry Breaking

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

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 $\xrightarrow{\text{minus EM part}}$ $M_n - M_p = 2.05(30)$ MeV
 Gasser Leutwyler '82

Few-nucleon systems: chiral effective field theory

Weinberg 1990:

Epelbaum

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

$$V_{\text{eff}} = \text{[diagram: blob]} = \text{[diagram: two lines with dashed line]} + \text{[diagram: two lines with X]} + \text{[diagram: two lines with dashed X]} + \dots$$

perturbative expansion in low momenta & quark masses

Step II: Solve the corresponding dynamical equation

$$T = \text{[diagram: blob]} + \text{[diagram: two blobs]} + \text{[diagram: three blobs]} + \dots$$

Key features:

- **Linked to QCD.**
- **Systematic & model independent framework.**
- **Works at low energy (nucleon momenta $\sim M_\pi$)**
- **Errors can be estimated.**
- **Straightforward to improve.**

Applied this framework to study the 2N system up to N³LO and 3N, 4N, 6N systems up to N²LO in the chiral expansion.

EFT - II

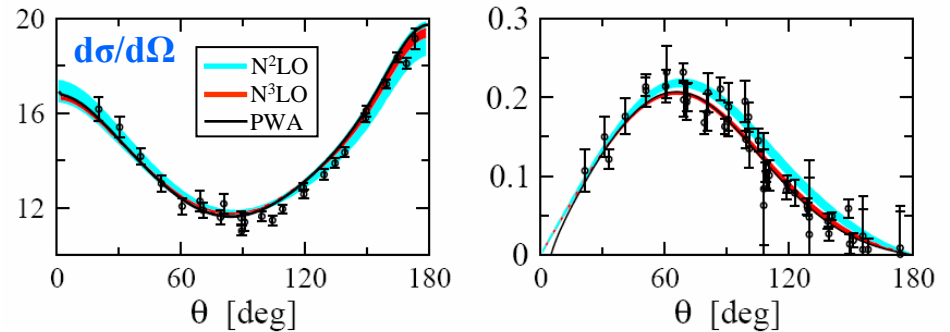
2 nucleons

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

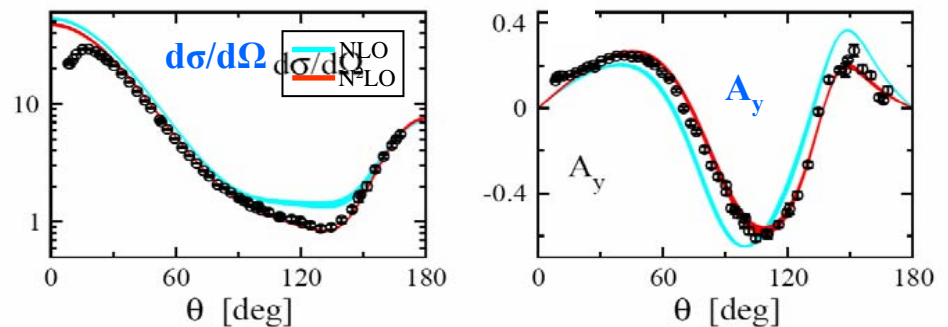
3 nucleons

- parameter-free results at $N\text{LO}$, *Epelbaum et al., PRL 86 (01)*
- complete analysis at $N^2\text{LO}$ 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



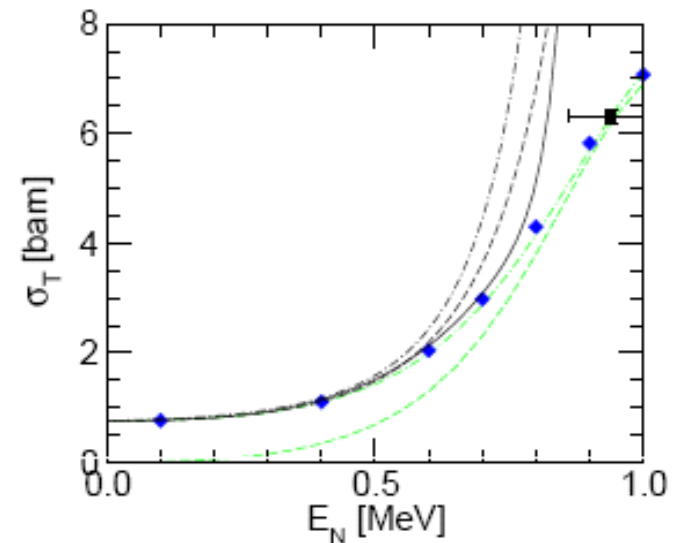
Epelbaum, nucl-th/0511025

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. $p + {}^7\text{Be} \rightarrow {}^8\text{B} + \gamma$, 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

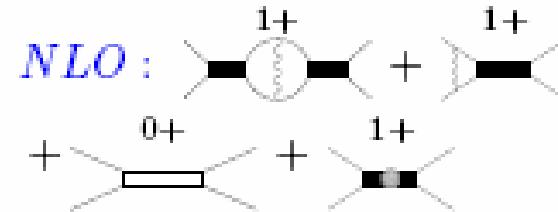
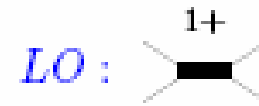
Coulomb interactions

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

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

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

in the resonance region,



• 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 $k < M_{lo}^2/M_{hi}^2$

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

