Theoretical Physics at Jefferson Lab

Anthony W Thomas

Outline

- Staff: focus on changes
- Expertise & Recent Achievements
- New Initiatives:

  - Expanded visitor program (focus for hadron physics)
  - Expanded initiative in lattice QCD
  - Excited Baryon Analysis Center (& PWA Hall D)

Role of Theory at Jefferson Lab

- Contribute to Intellectual Leadership of Lab

- Phenomenological Support of Experimental Program

  - development/analysis of proposals

  - provision of essential support in interpretation of data

- Projects of scope/duration appropriate to a national laboratory

JLab Theory Group: Senior Staff

- 4.5 full-time staff (4.5 FTE)

  Robert Edwards *(lattice gauge theory)*
  Franz Gross (0.5 time)
  Wally Melnitchouk (from Feb 04)
  David Richards *(lattice gauge theory)*
  Christian Weiss (from Aug 04)

  Distinguished Visiting Fellow: Stan Brodsky (SLAC), Jan 03-Jun 03
  Barry Holstein (UMass), Jan 04-Jun 04

  Chief Scientist / Group Leader: Anthony Thomas (from April 04)

- 7 staff with joint appointments (3.5 FTE)

  Ian Balitsky (ODU)
  Jose Goity (Hampton)
  Anatoly Radyushkin (ODU)
  Winston Roberts (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, UK) – from Oct 04
  George Fleming (Ph.D. 00, Columbia) – Oct 02 to Sep 05
  Renato Higa (Ph.D. 03, São Paulo, Brazil) - from Oct 03
  Mark Paris (Ph.D. 01, UIUC) – from Nov 03
  Ross Young (PhD 04, Adelaide, Australia) – from Oct 04

- Isgur Distinguished Postdoctoral Fellow (funded by SURA and JLab)
  Evgeny Epelbaum (Ph.D. 00, Bochum) – from Oct 03

JLab Theory Group: Associate Staff

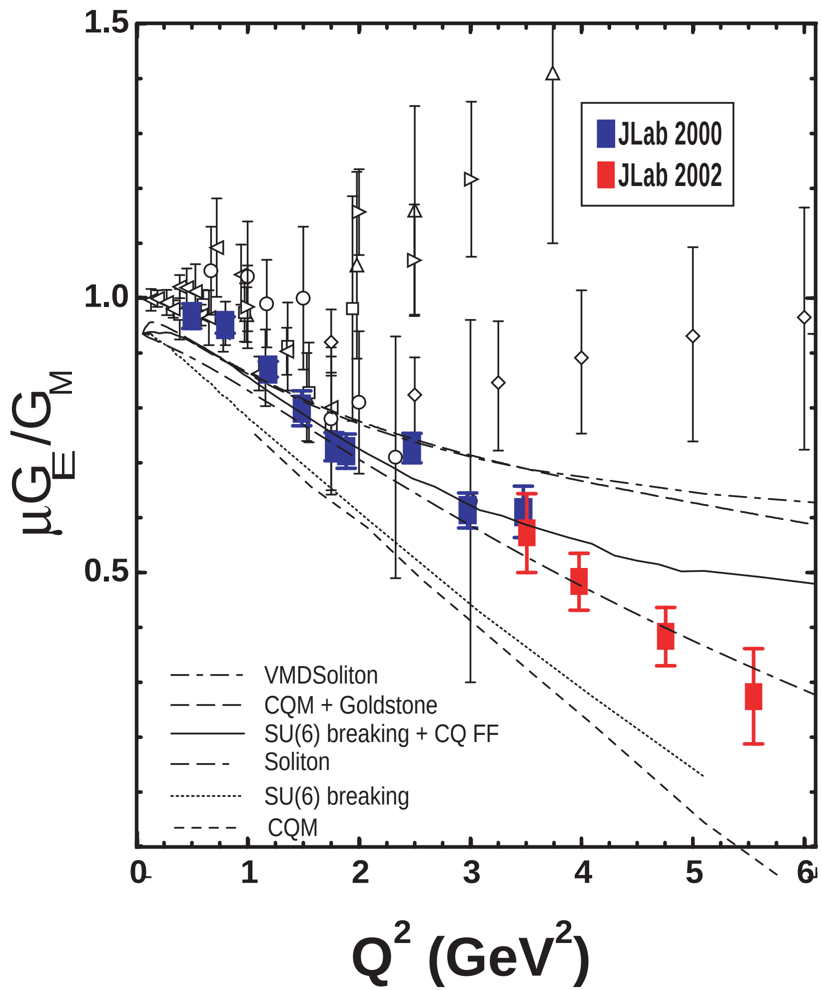
- 4 senior staff (100% university support)
  Carl Carlson (W&M)
  Chris Carone (W&M)
  Marc Sher (W&M)
  Peter Agbakpe (NSU)

- Numerous sabbatical visitors (supported by JLab)
  D. Diakanov (Nordita) - from Apr 04 (9 months)
  J. Tjon (Utrecht) - from Aug 03 (6 months)
  J. Laget (Saclay) – from May 04 (4months)
  D. Leinweber (CSSM) – from Aug 04 (2 months)

- 1 postdoctoral fellow (external funding)
  Vladimir Pascalutsa (W&M, Gross DOE) - from Oct 03

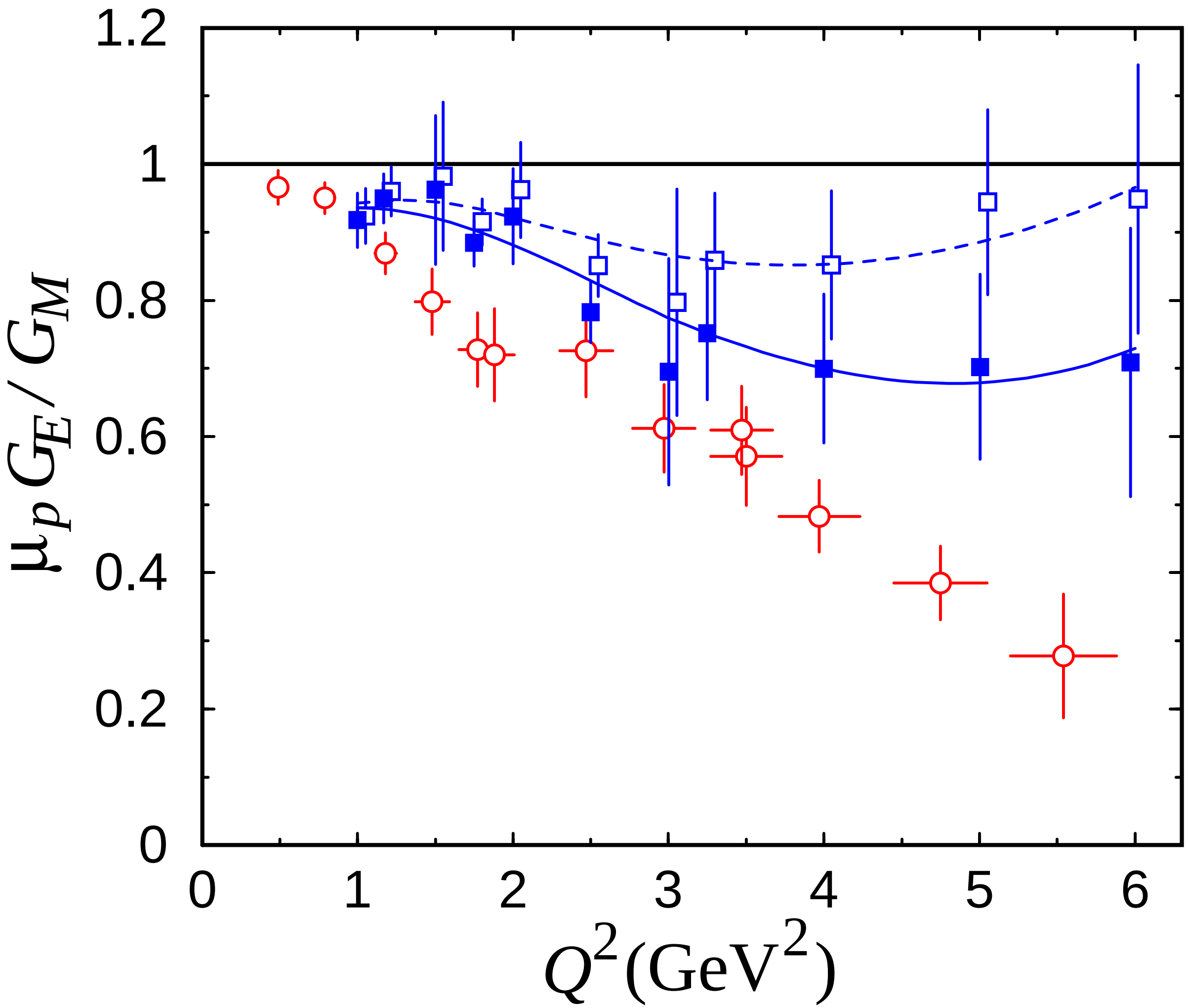
- 8 graduate students:
  3 supported by JLab + 2 LSU (one LSU support, one SURA Fellowship)
  + 3 Adelaide University (with AWT)

G_E^p/G_M^p as Measured by ($\vec{e}$, e' $\vec{p}$): Critical Data for Understanding Proton Structure



The combination of high intensity e beams and proton polarimetry has dramatically improved our knowledge of this fundamental system and raised important theoretical challenges

Estimate of 2- photon Exchange Effects



Blunden, Melnitchouk, Tjon, PRL (2003)

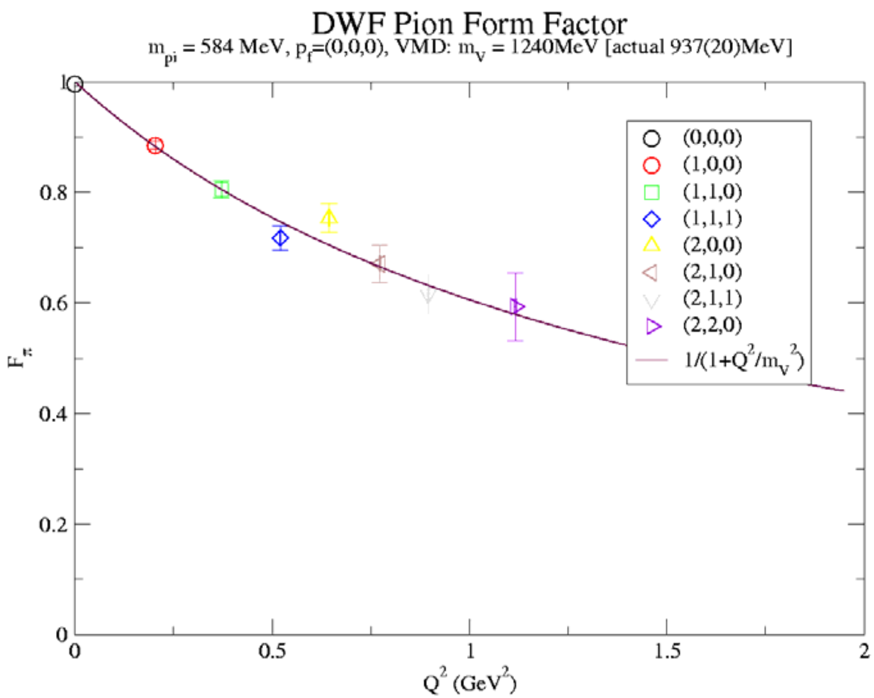
N only… so far

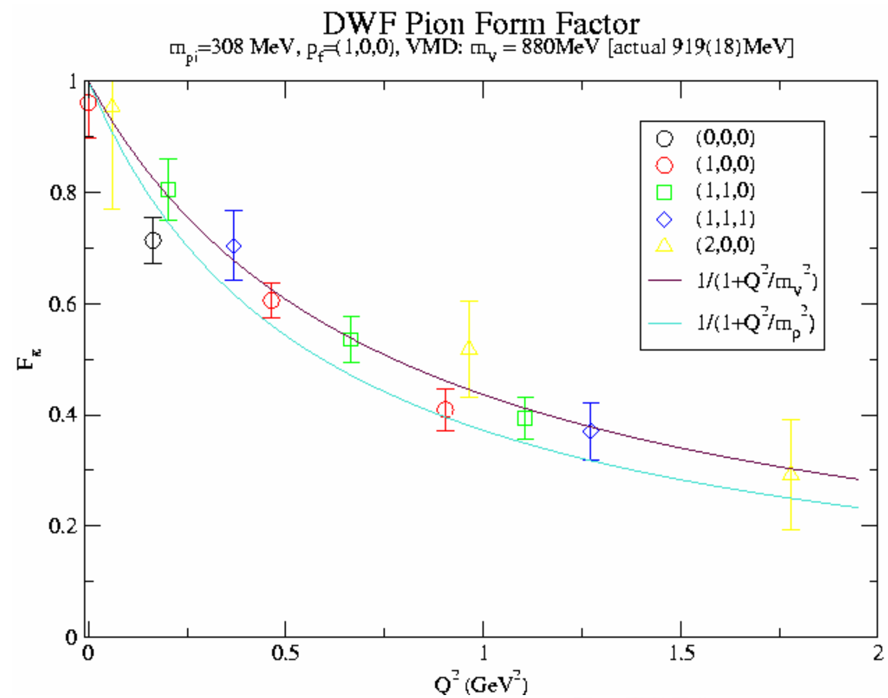
Partially Quenched DWF Form Factor

- DWF $F_\pi(Q^2,t)$: LHPC (Edwards, Richards ….)
  - — Smaller mass close to experimental VMD.

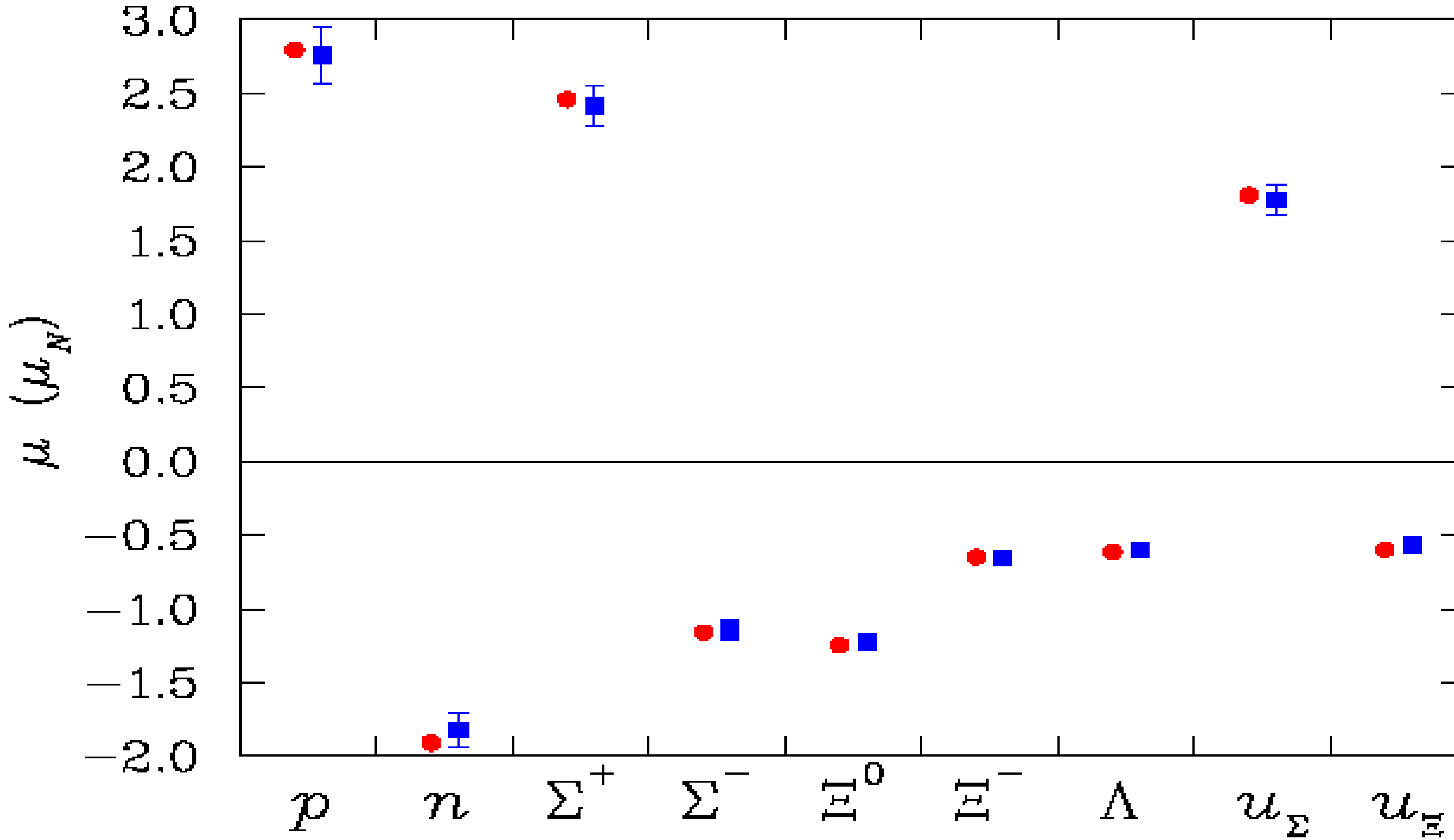
$$\left.\frac{\partial F(Q^2)}{\partial Q^2}\right|_{Q^2=0} = \frac{1}{6}\langle r^2\rangle \quad \to \langle r^2\rangle = \frac{6}{m_V^2}$$

- Charge radius (crude analysis):
  - — Exp. h r^2i = 0.439(8)fm^2 , VMD ! 0.405fm^2
  - — Statistical: 0.156(5)fm^2, 0.310(6)fm^2 strong mass dependence





Octet Magnetic Moments



Leinweber, AWT, Young, hep-lat/0406003

s_ℓ may be estimated from the Kaon loop integrals

- Regulated by a dipole form factor with $\Lambda = 0.8$ GeV

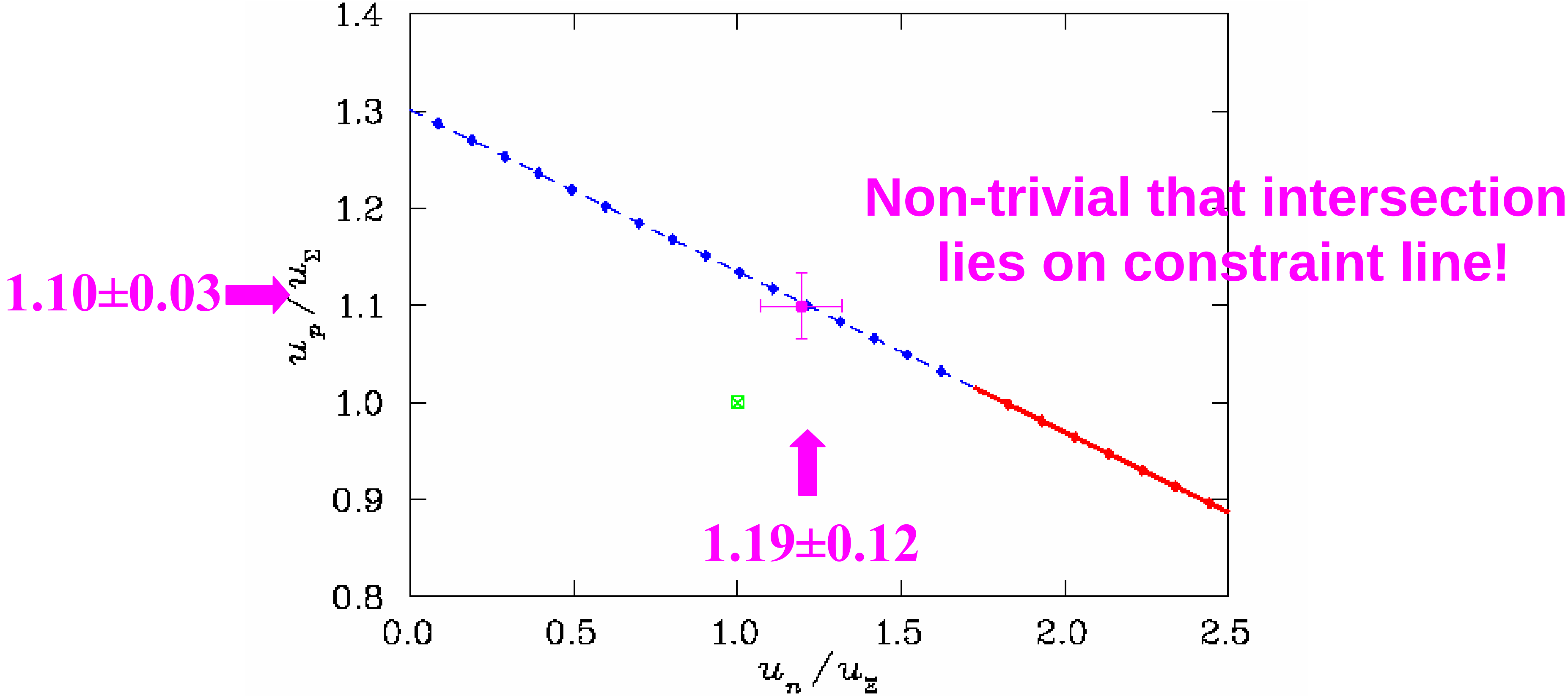
$$^{\ell}R_d^s = \frac{s_\ell}{d_\ell} = \frac{-0.036}{-0.258} = 0.140$$

- Repeating the calculation for $\Lambda = 0.8 \pm 0.2$ GeV provides

$$^{\ell}R_d^s = \frac{s_\ell}{d_\ell} = 0.140 \pm 0.040$$

(dots are steps of 0.01 μ_N)

Hence $G_M{}^s = -0.051 \pm 0.021\ \mu_N$



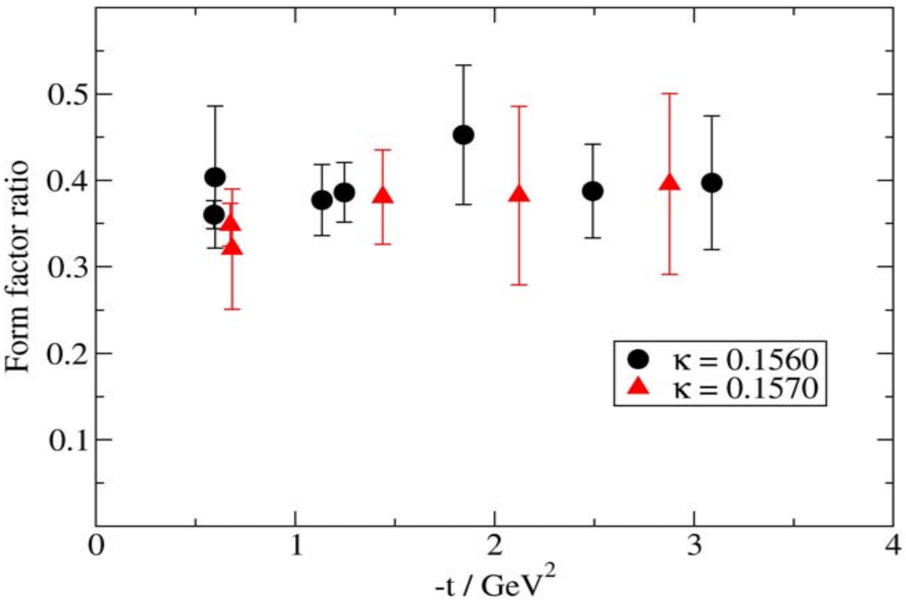
Generalized Parton Distributions

- Off-forward matrix elements related to moments of **H, E**
- Lowest moments give form factors: $A_{10}(t) = F_1(t)$, $B_{10}(t) = F_2(t)$

$$A_{n0} = \int dx\, x^{n-1} H(x,0,t);\ B_{n0} = \int dx\, x^{n-1} E(x,0,t)$$

- Asymptotic behavior of F_2/F_1 (Belitsky, Ji, Yuan)

$$\frac{Q^2 F_2(Q^2)}{\log^2(Q^2/\Lambda^2) F_1(Q^2)} \sim \text{const}$$



LHPC/SESAM, hep-lat/0404009
(Edwards, Fleming, Richards at JLab)

New Theory Initiatives at JLab

- **Make JLab international focus of theoretical work in hadron physics ; expanded visitor & sabbatical program**

- **Expand LQCD effort to world-class computational capability**

- **Strengthen support of the experimental program through the establishment of the Excited Baryon Analysis Center (EBAC) (linked to PWA/Hall D initiative) at JLab**

Lattice QCD Initiative – Software and Hardware

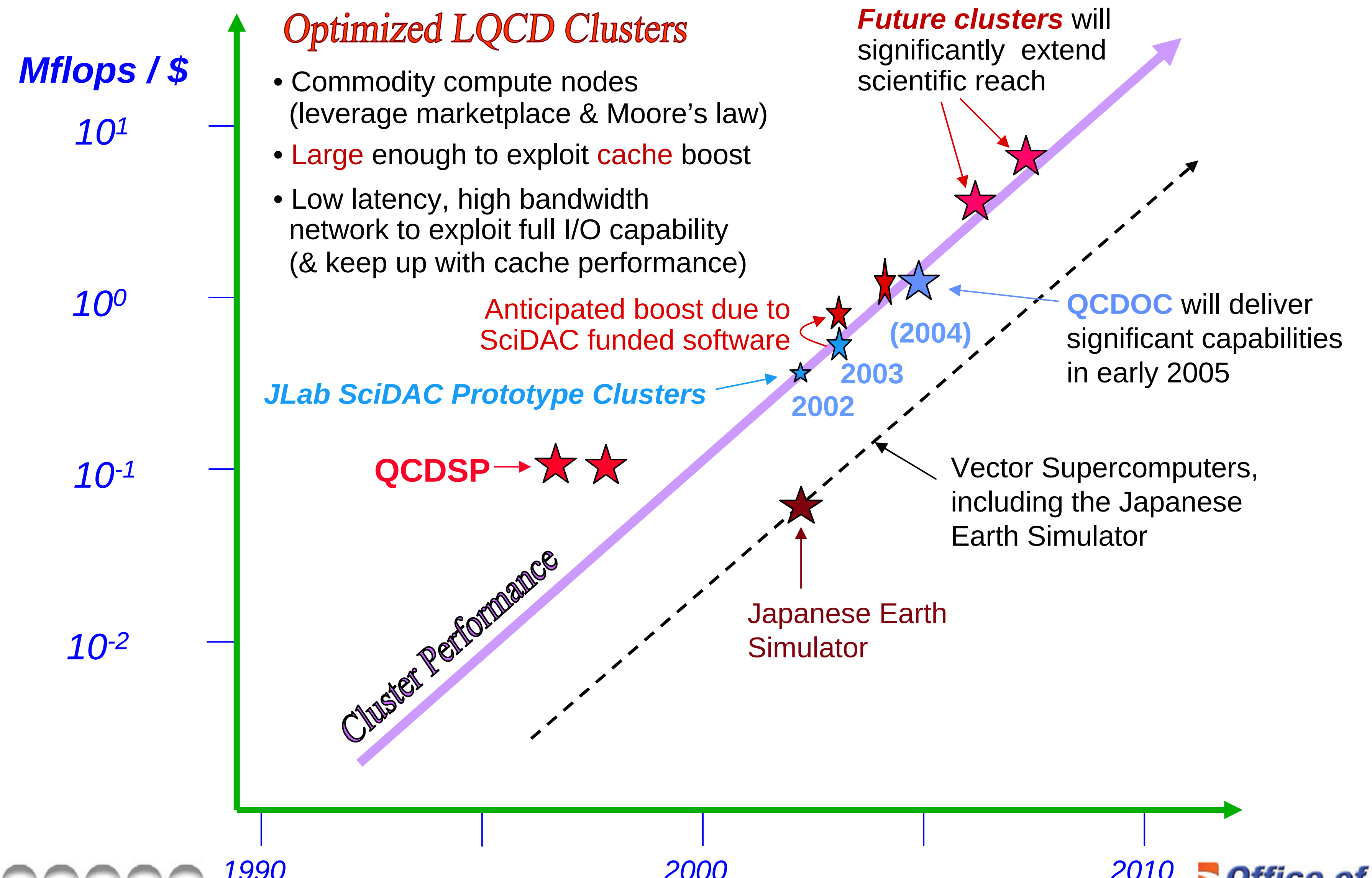
- **Software developments:**
  - **QCD-API: portable programming interface for diverse computational platforms. Development of QDP++, a C++ implementation, led by Edwards**
  - **Implementation of LHPC physics program being performed by Edwards, Fleming and Richards**
- **Hardware developments:**
  - **128-node Pentium IV cluster connected by Myrinet commissioned in Sep 02; tackling key problems including moments of structure functions and GPD's**
  - **256-node Pentium IV grid-based machine connected by GigE; aggregate computational capability of around 400 Gflops**
  - **Prototype machines for envisioned multi-Tflops facility**

Clusters at Jefferson Laboratory - *SciDAC*

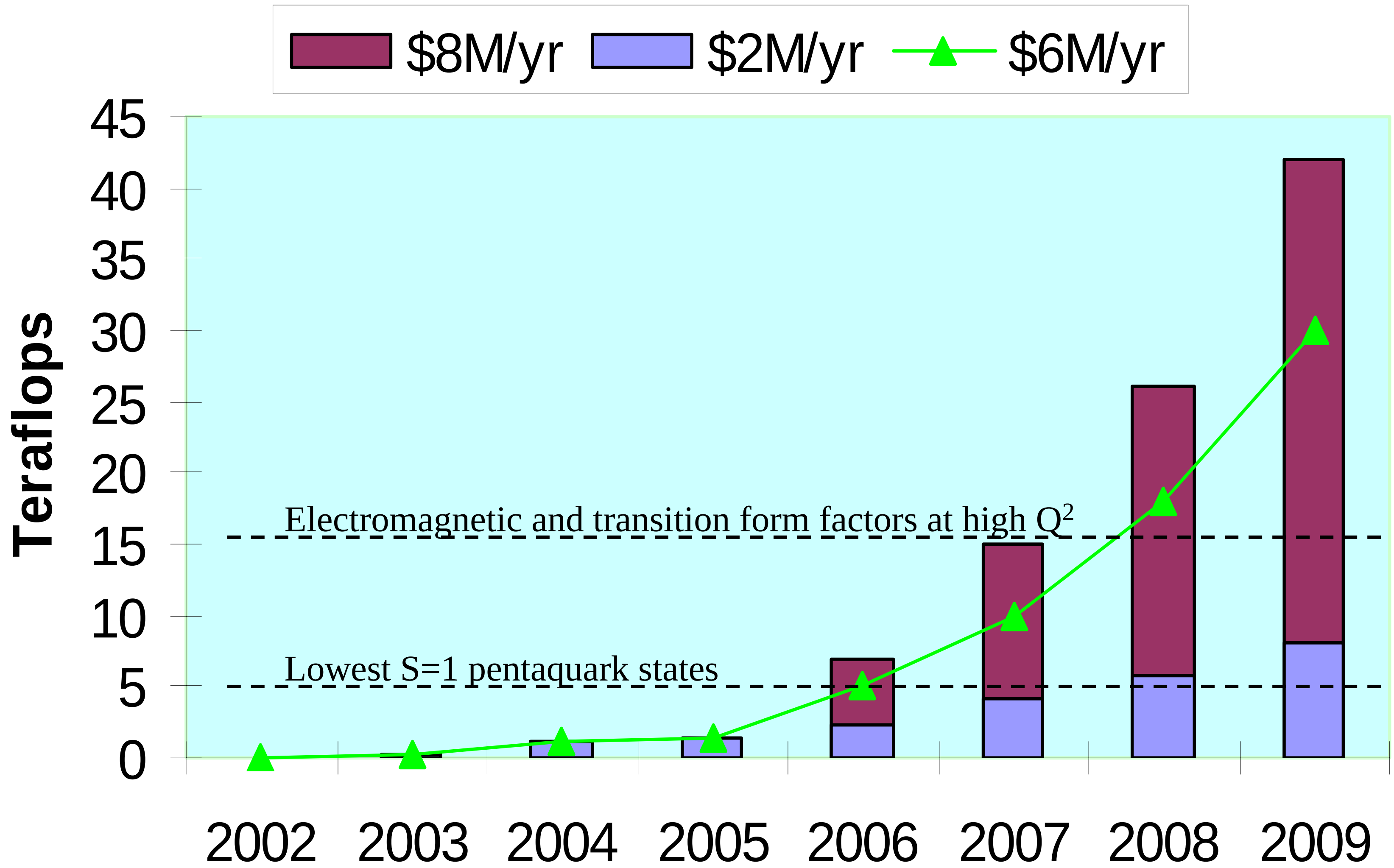
128-node P4 Xeon, with Myrinet

256-node P4 Xeon, with 3d gigE torus

Performance per Dollar for Typical LQCD Applications



Jefferson Lab Teraflops for 3 Funding Scenarios



LQCD Hadron Physics Roadmap

Tflops-yrs	
1-5	QQCD: N^* spectroscopy ; pentaquarks; valence PDFs & GPDs
5-10	Lighter quark (large volume): GPDs; (transition) form factors; spectroscopy
10-50	Flavor singlet distributions; high-Q^2 form factors; gluon structure
50-500	Fully consistent valence & sea computations; decay widths…..
Open problems	Functional form of PDFs & GPDs; light nuclei…

N* Spectrum

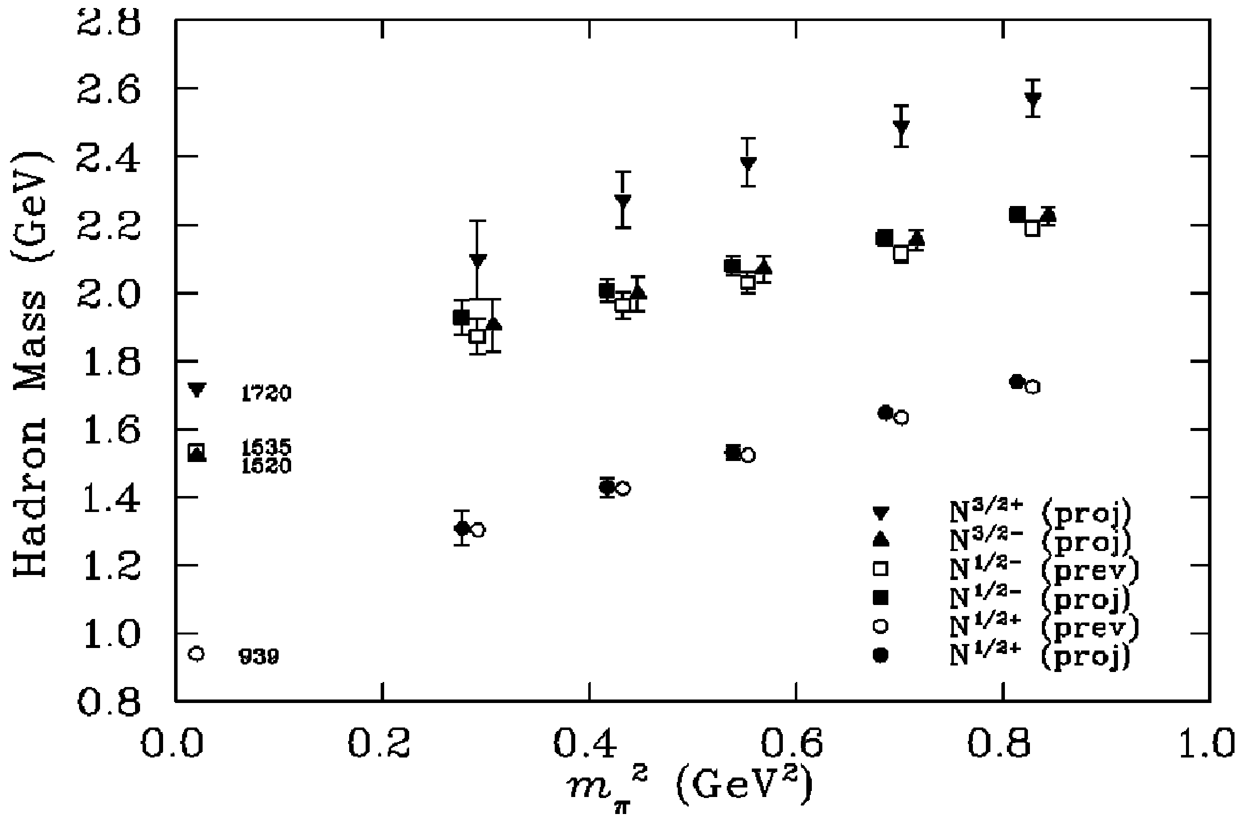
- First generation calculations – largely for quarks masses around that of ***strange quark***

Zanotti et al, PRD68, 054506

•Spectrum in accord with naïve ***oscillator quark model*** at large m_q

$$M_N < M_{N\,1/2-} < M_{N*\,1/2+}$$

•Development of tools to extract radial excitations **LHPC, hep-lat/0312003**



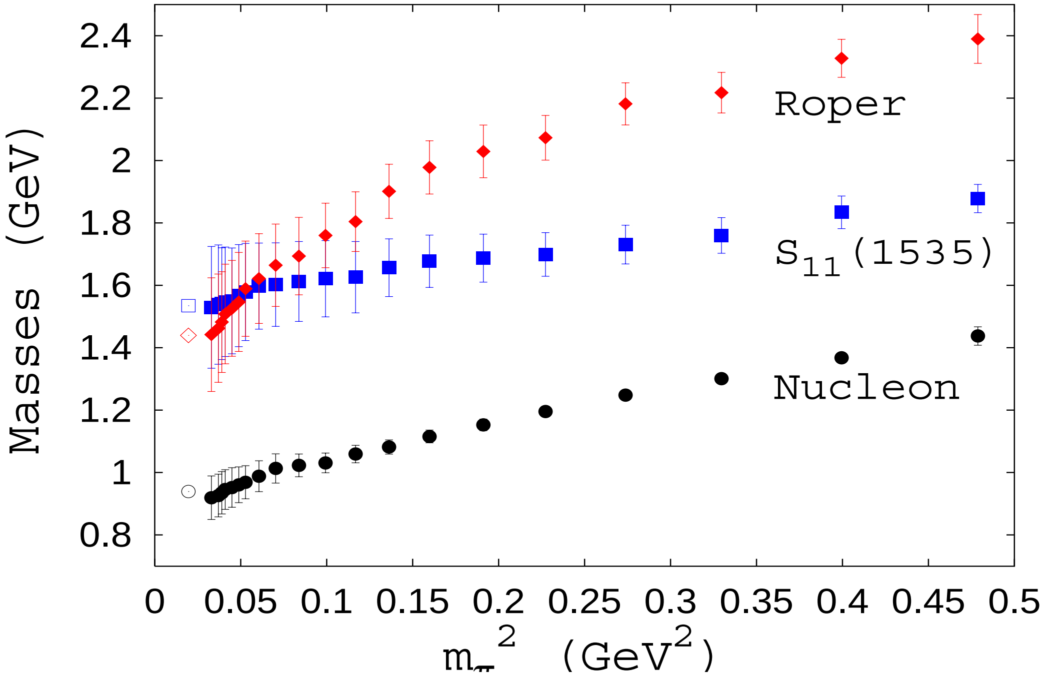
Nature of Roper, Λ(1405),…??

Roper Resonance

- **Roper resonance at light quark masses**
S.J. Dong et al, hep-ph/0306199

- **Bayesian statistics and constrained curve fitting?**

- ***Roper predominantly a three-quark state?***

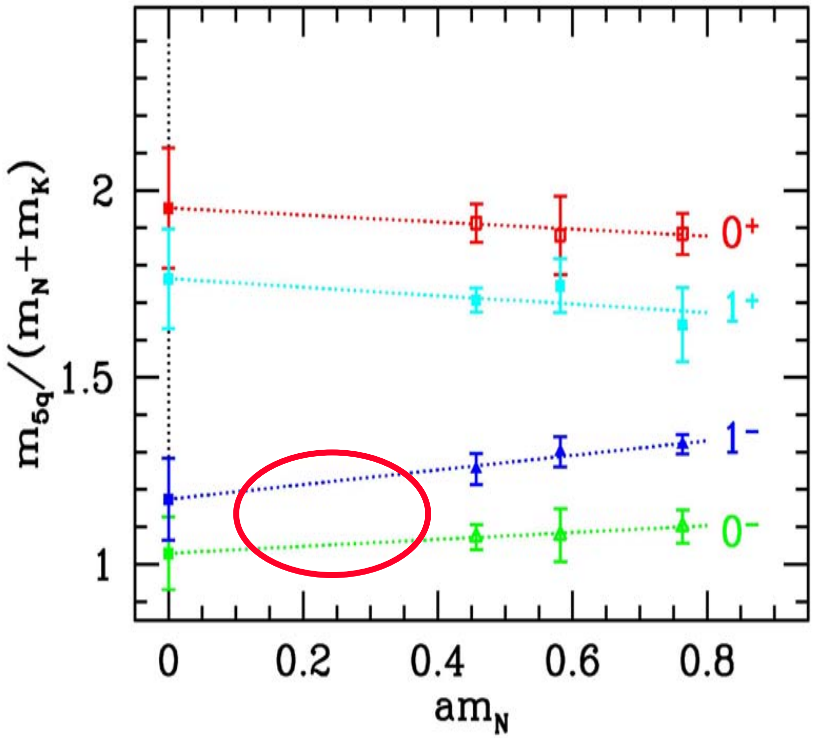


Physics at physical values of the pion mass very different from the heavy-quark regime

Pentaquarks

- First tentative lattice results (Csikor et al, Sasaki), I = 0, spin ½.
- Need to isolate "resonance" from two-body spectrum
- Require study of full spectrum – & various interpolating fields…

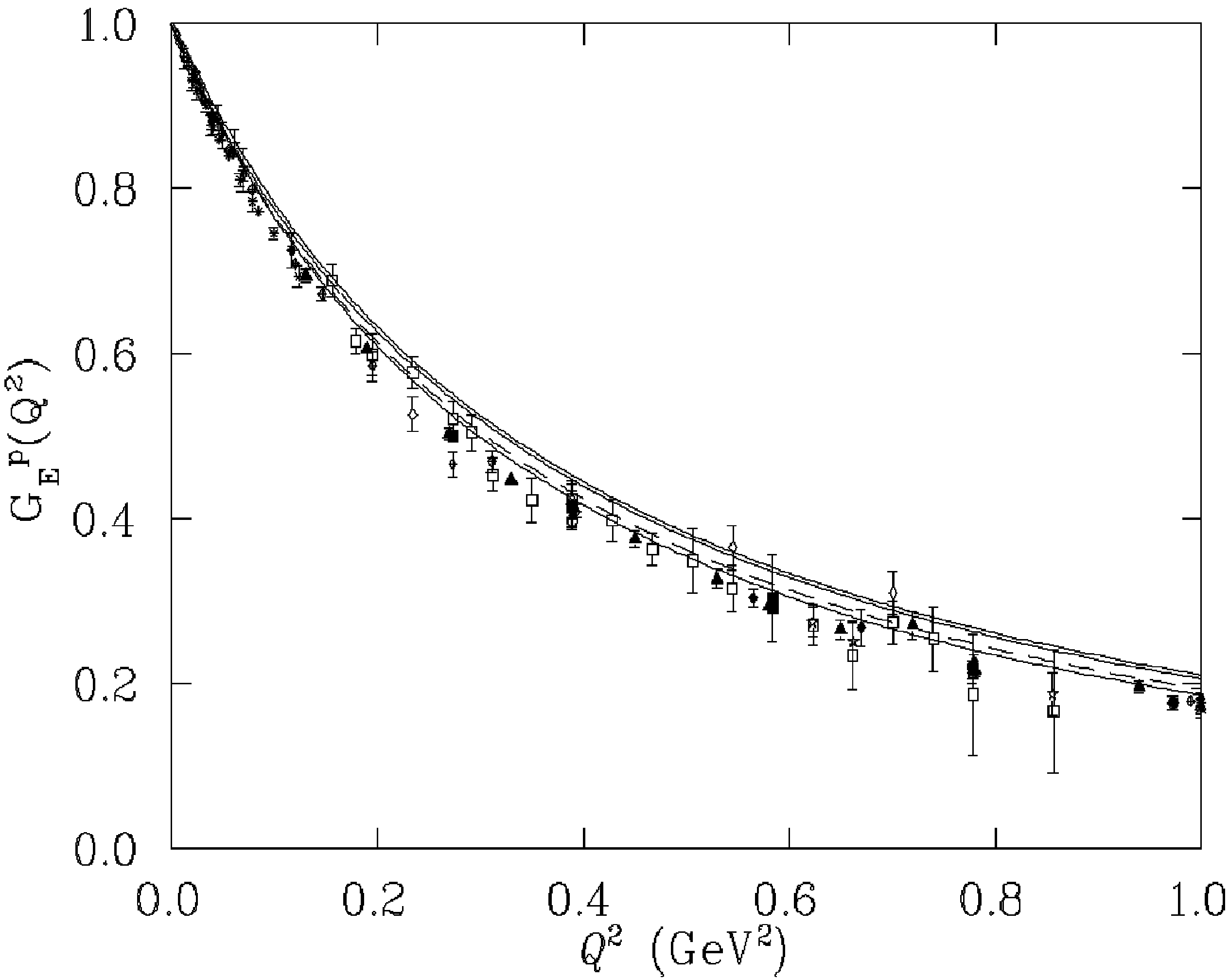
Bottom line dependent on χ'al extrapolation



- Higher spin states require construction of operators in IR of cubic symmetry of lattice
- Method developed for fermionic states in hep-lat/0312003 (Richards, Edwards .. at JLab)
- Computations of baryon operators in G_1, G_2 and H IR's in progress

J	$n^J_{G_1}$	$n^J_{G_2}$	n^J_H
1/2	1	0	0
3/2	0	0	1
5/2	0	1	1
7/2	1	1	1
9/2	1	0	2

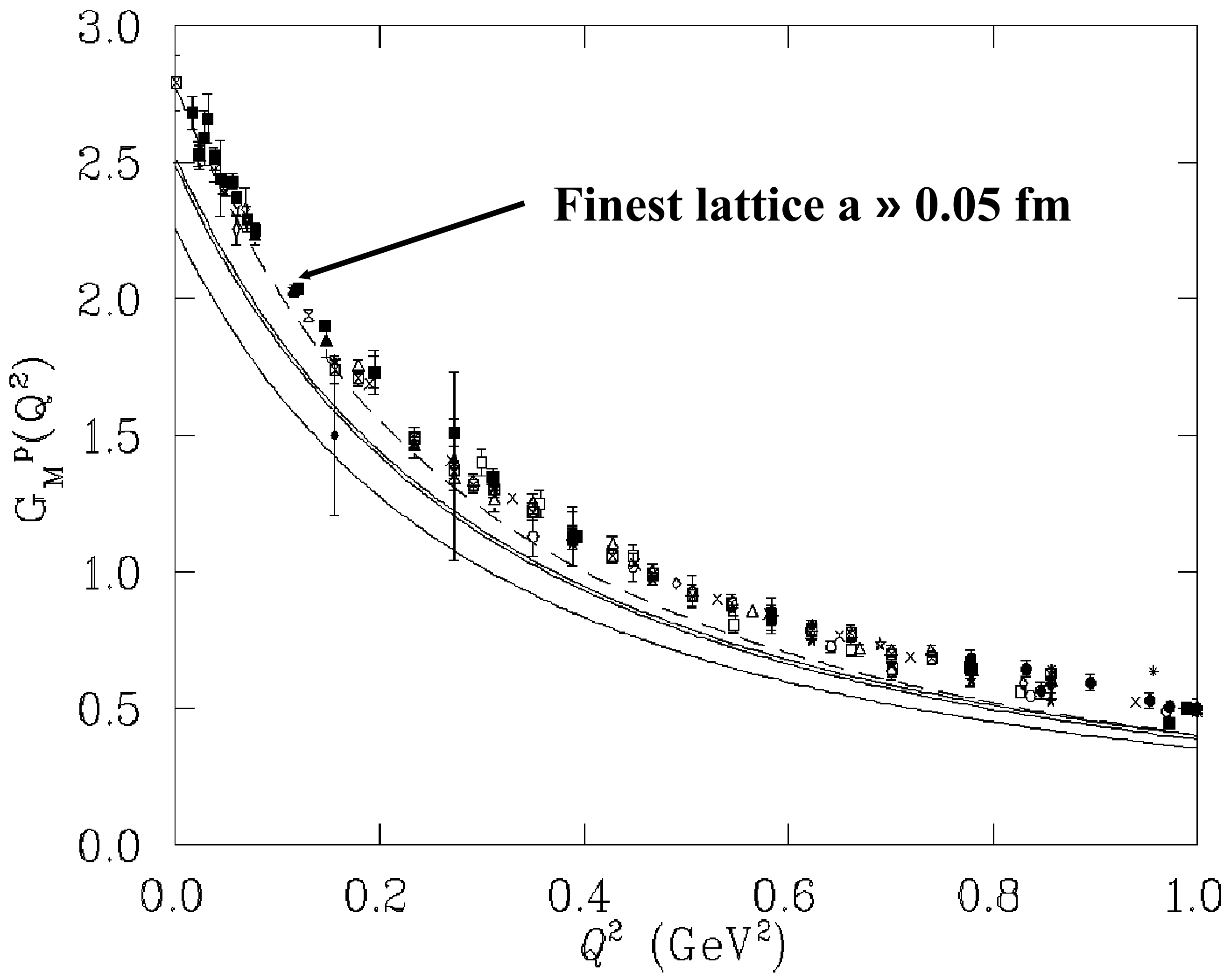
Chiral Extrapolation of G_E^p



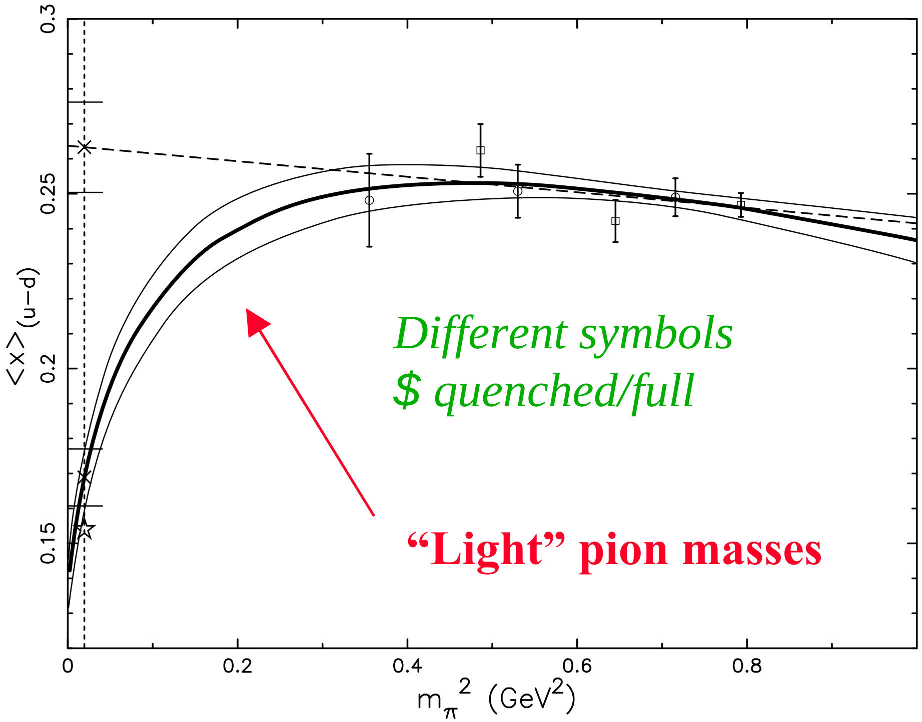
Lattice data:
Göckeler et al. (QCDSF), hep-lat/0303019 – Wilson fermions

Chiral Extrapolation:
Ashley et al. (CSSM), Nucl. Phys. A721 (2003) 915

Chiral Extrapolation of G_M^p



DIS – Chiral Extrapolations



Physics of pion cloud crucial for making contact with experiment.

Lowest moment of unpolarized Structure function – *momentum carried by valence quarks in Nucleon*

- **Physics of pion cloud…** ***Detmold et al., hep-lat/0103006***

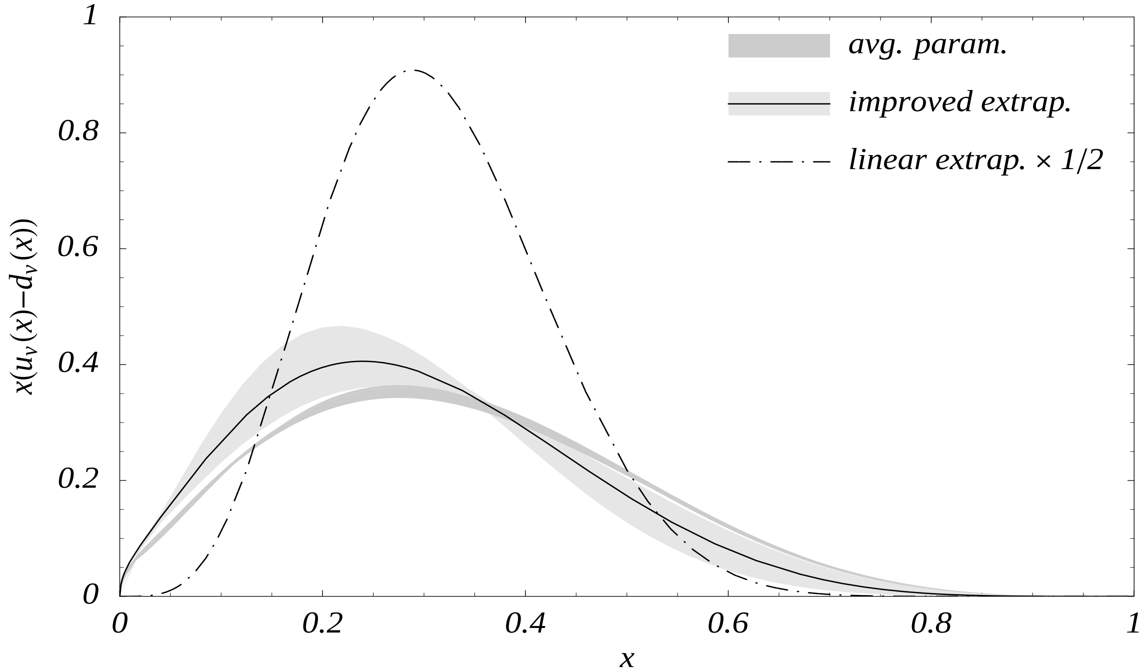
$$\langle x^n \rangle_u - \langle x^n \rangle_d \sim a_n \left[1 - \frac{(3g_A{}^2 + 1) m_\pi^2}{(4\pi f_\pi)^2} \ln\left(\frac{m_\pi^2}{m_\pi^2 + \mu^2} \right) \right] + b_n m_\pi^2$$

Shape…

- Calculations give moments of distributions
- Higher moments harder - hypercubic symmetry…
- **Can we recover shape from knowledge of, say, first three moments?**

Detmold, Melnitchouk, Thomas

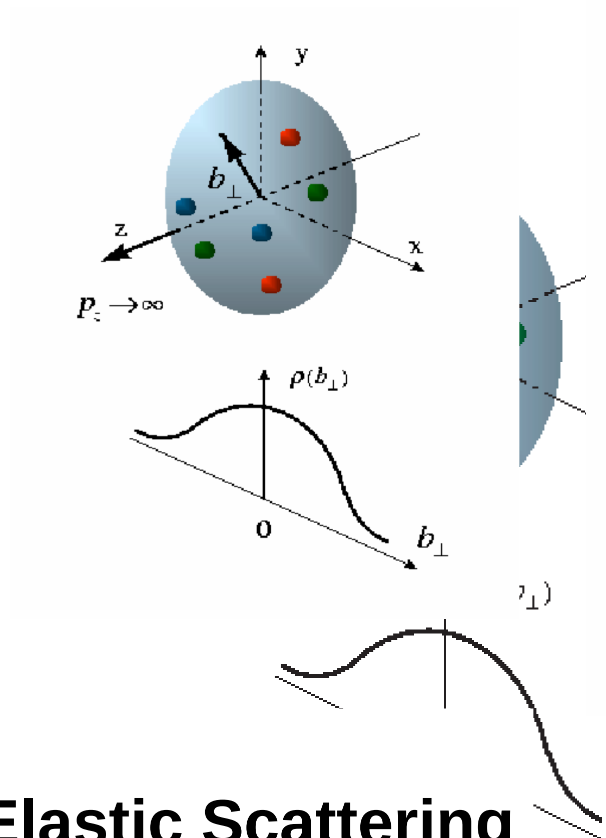
Employs parametrization strongly motivated by experiment

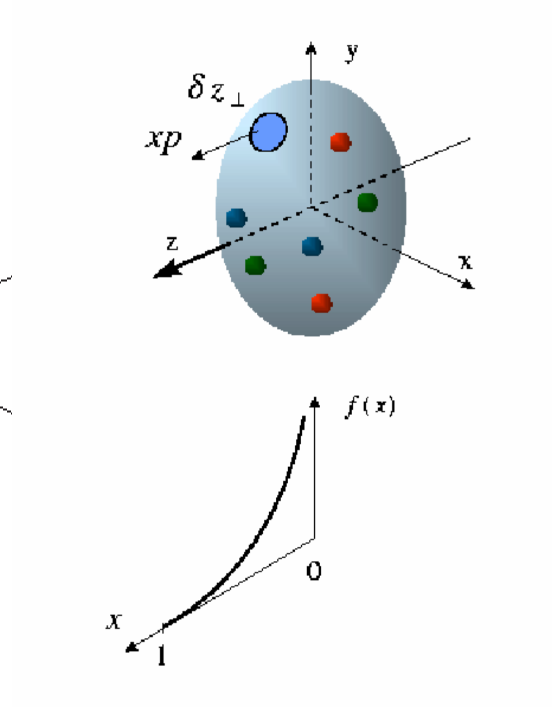


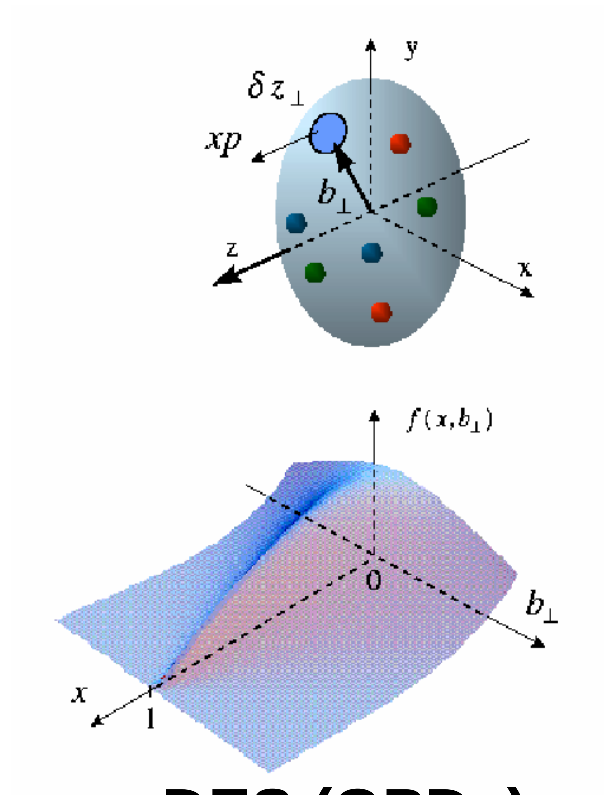
$$x(u_v(x) - d_v(x)) = a\, x^b (1-x)^c (1 + \varepsilon \sqrt{x} + \gamma\, x)$$

← Model dependence

Proton Properties Measured in Different Experiments





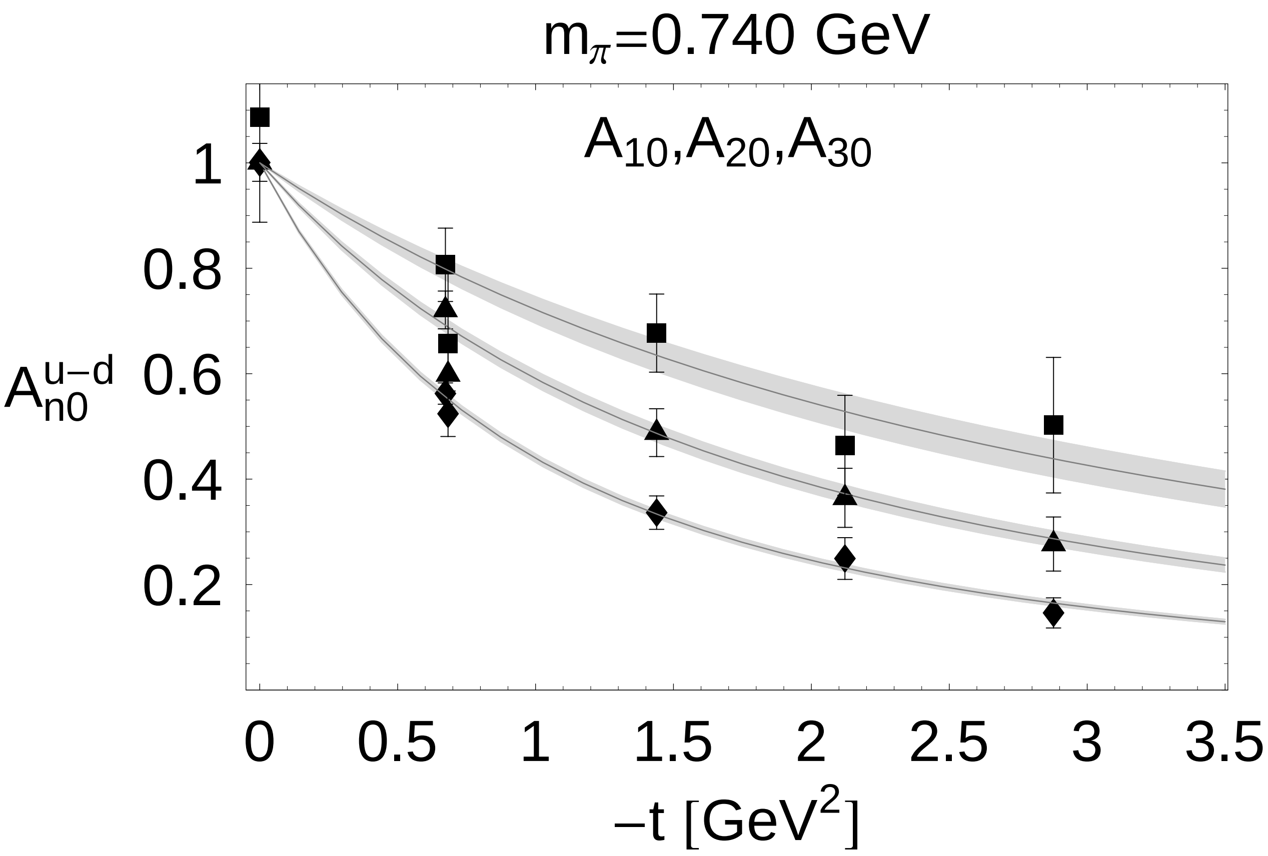


Elastic Scattering
transverse quark distribution in Coordinate space

DIS
longitudinal quark distribution in momentum space

DES (GPDs)
Fully-correlated quark distribution in both coordinate and momentum space

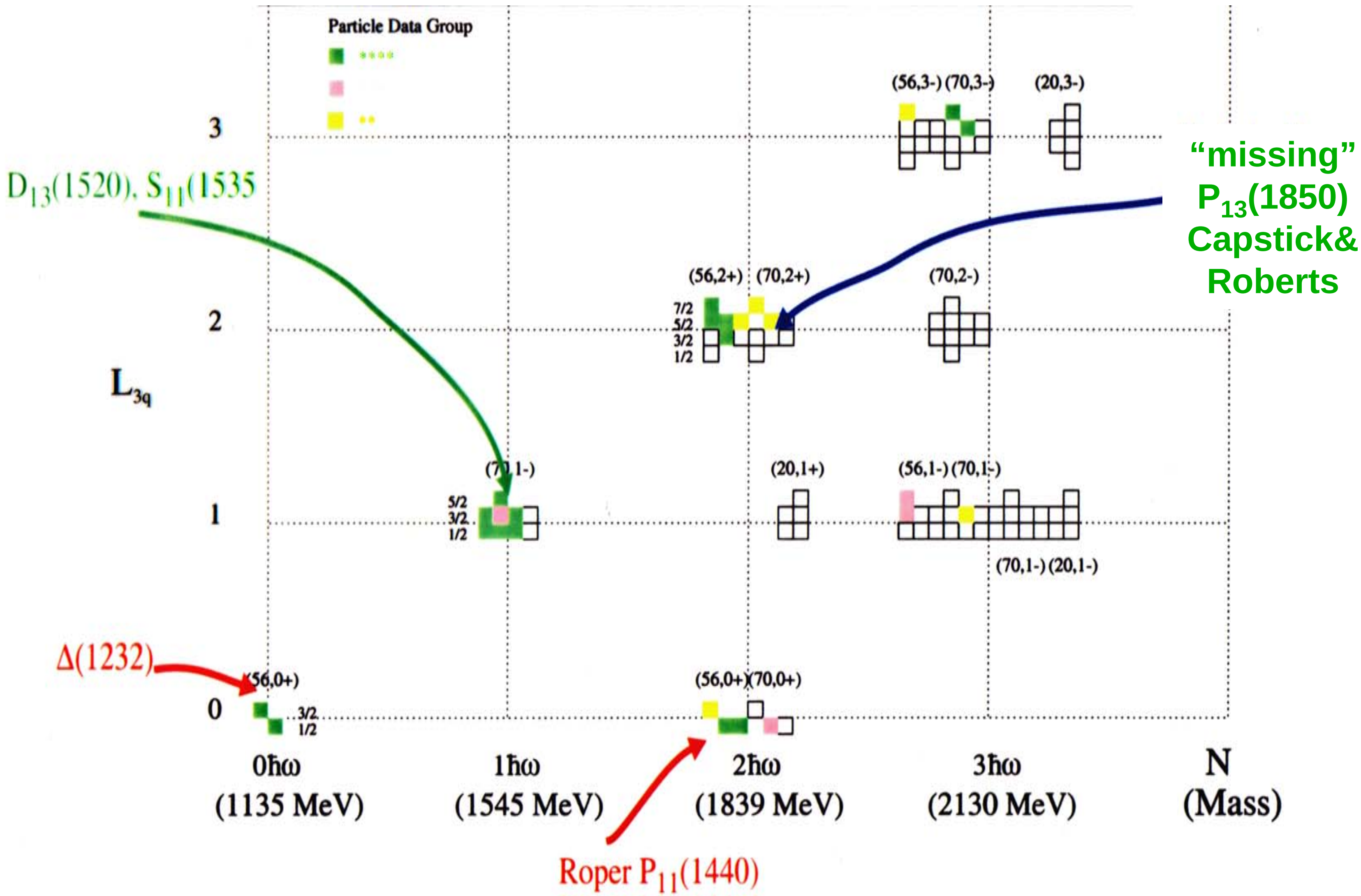
Generalized form factors…



LHPC
(Edwards et al..)

Decrease slope : decreasing transverse size as $x \to 1$
Burkardt

The Search for “Missing States” in the Quark Model Classification of N*



Excited-Baryon Analysis Center

A proposal for the establishment of an excited-baryon analysis center at JLab

- Role: **To develop theoretical tools (e.g. coupled channel; EFT) to analyze existing & future CLAS data**

- Scientific relevance:
  - **i) identify new baryon resonances**
  - **ii) measure couplings & transition form factors**
  - **iii) comparison with LQCD**
  - **iv) deepen understanding of how QCD is realized**

- Critical theoretical issues:
  - **i) background-resonance separation**
  - **ii) incorporation of multi-particle final states**
  - **iii) importance of unitarity, analyticity…**

Proposed Structure of EBAC

- Senior theorist with a broad knowledge of hadronic and electromagnetic interactions, reaction theory, and the methods used in phenomenological analysis
- Mid- and junior-level staff positions and term/visiting positions for theorists and experimentalists to advance the program and to interface with relevant groups. Strong workshop/visitor program.
- Independent, Expert Scientific Advisory Board
- Total budget ~ $ 700k per year (+overhead)

S&T Review 2003: "A critical need in the overall JLab program is to have a systematic effort dedicated to analysis of photo- and electro-production of baryons and mesons. The theory group, in concert with the needs of the experimental collaborations, has begun to formulate a plan to establish an N^* Analysis Center. We applaud this long-needed initiative."

Close Working Link Between Baryon and Meson Analysis

PHYSICAL REVIEW D **68**, 036003 (2003)

Meson model for $f_0(980)$ production in peripheral pion-nucleon reactions

F. P. Sassen, S. Krewald, and J. Speth
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(Received 3 December 2002; published 25 August 2003)

The Jülich model for $\pi\pi$ scattering, based on an effective meson-meson Lagrangian, is applied to the analysis of the S-wave production amplitudes derived from the BNL E852 experiment $\pi^- p \rightarrow \pi^0 \pi^0 n$ for a pion momentum of 18.3 GeV and the GAMS experiments performed at 38 GeV and 100 GeV. The unexpected strong dependence of the S-wave partial wave amplitude on the momentum transfer between the proton and neutron in the vicinity of the $f_0(980)$ resonance is explained in our analysis as an interference effect between the resonance and the nonresonant background.

Conclusion

Further development of Theory at JLab is vital to:

- **Success of present experimental program**
- **Design and implementation of the 12 GeV Upgrade**
- **Development of the case for Hadron Physics Beyond 12 GeV**