Overview of Theory Program

David Richards

Science and Technology Review

14th July, 2009

Vadim Guzey → Breakout Session

Outline

- **Members**
- **Role of Theory Center**
- **Highlights – *outstanding new results in***
  - ***Spectrum of QCD***
  - ***Hadron Structure***
  - ***Physics of Nuclei***
  - ***Physics beyond the Standard Model***
- **Theory Campaigns:**
  - **EBAC**
  - **Lattice QCD**
  - **EIC**
- **Summary**

JLab Theory Center: Senior Staff

- **Chief Scientist / Theory Director:** Anthony Thomas

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

Robert Edwards	lattice gauge theory
Franz Gross (1/2 time)	
Wally Melnitchouk	phenomenology
David Richards	Deputy Director (lattice gauge theory)
Christian Weiss	phenomenology

Distinguished Visitors: W. Bentz, M. Burkardt, F. Close, R. Crewther, V. Flambaum, Harald Fritzsch, P. Guichon, J-M Laget, D. Leinweber, G. Miller, M. Peardon, T. Pena, S. Ryan, A. Sibirtsev, A. Stadler,…

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

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

JLab Theory Center: Staff (contd)

- **Associate Senior Staff:** Carl Carlson (W&M)
- **Bridge Positions**
  - University of Virginia (Chris Dawson)
  - Hampton University (Andrei Afanasev)
  - University of Connecticut (Peter Schweitzer)
- **5 JLab postdoctoral fellows (5 FTE)**

  HueyWen Lin – since Fall 06 → 5-year at Univ. Washington
  Marc Schlegel - since Fall 06 → PDF at Tübingen
  Ping Wang - since Fall 07 → faculty at IHEP, Beijing
  Vadim Guzey – since Fall 07
  Chris Thomas – since Fall 08

  B Musch, A Prokudin (Fall 2009)
- **Isgur Distinguished Postdoctoral Fellow**

  Alessandro Bacchetta – since Mar 08 → faculty at Pavia
- **Joint post-doctoral position in phenomenology with Hampton Univ.**

  Alberto Accardi
- **Joint post-doctoral position in LQCD with Adelaide**

  Andre Sternberg

Key Roles of Theory at JLab

- Contribute to Intellectual Leadership of Lab
  - *Success of 12 GeV; Preparing for EIC*
- Support of Experimental Program @ 6 GeV
  - development/analysis of proposals; interpretation of data
- Projects of large scope/duration: *EBAC, Lattice QCD*
- Education
  - 9 graduate students (6 supported by Jlab)
    - Giovanni Chirilli: *JSA/Jefferson Lab Graduate Fellowship 2008-9*
    - Ian Cloet: shared 2008 *SURA Thesis Prize*
  - HUGS *(Hampton University Graduate School).*
  - *Virginia Physics Consortium* – Graduate-level course in Hadronic Physics (Wally Melnitchouk)
  - *Theory-Center mini-lectures (Bacchetta)*
  - *High-school Mentorships*
  - *Science Undergraduate Laboratory Internship (SULI)*
    - *2008: Tim Hobbs and Yoni Kahn (Wally Melnitchouk)*
    - *2009: Hannes Schimmelpfennig*
  - *RIFU*
    - *2008: Ermal Rrapaj (Jo Dudek)*

Joint Positions Vital

Hobbs: First prize in *Users Group* poster competition

Distinguished Members

- 8 Fellows of the American Physical Society;

- 1 Fellow Australian Academy of Science and Institute of Physics

- Serve on IAC of all major conferences and workshops in related fields
- Organization and planning of major workshops
  - DNP 2007, Lattice 2008, 4th EIC Workshop (HU), Photon-Hadron Physics with GlueX Detector, DIS 2008, MENU 2010
- Tony Thomas chairs IUPAP Working Group (WG.9) on International Cooperation in Nuclear Physics

Will Detmold - 2009 OJI - "Multi-Meson Systems in Lattice QCD"

Excited Baryon Analysis Center

- **Analyse wealth of experimental data on baryon resonance production at Jlab and elsewhere**
- **Goal: ensure that the OMB Milestones in Hadronic Physics are satisfied:**
  - **HP2009**: ***Complete the combined analysis of available data on single π, η, and K photo-production of nucleon resonances and incorporate the analysis of two-pion final states into the coupled-channel analysis of resonances.***
  - **HP2012**: ***Measure the electromagnetic excitations of low-lying baryon states (<2 GeV) and their transition form factors over the range Q^2 = 0.1 – 7 GeV^2 and measure the electro- and photo-production of final states with one and two pseudoscalar mesons.***
- **Led by Harry Lee (ANL/Jlab)**
- **Three Post-doctoral Fellows**
  - **Mark Paris** → **GWU**
  - **Hiroyuki Kamano (since Fall 2007)**
  - **Kazuo Tsushima (since Fall 2007)**
  - ***Satoshi Nakamura (from Fall 2009)***

Continuing high productivity

Theory & Comp Physics Status Calendar Year 6/09

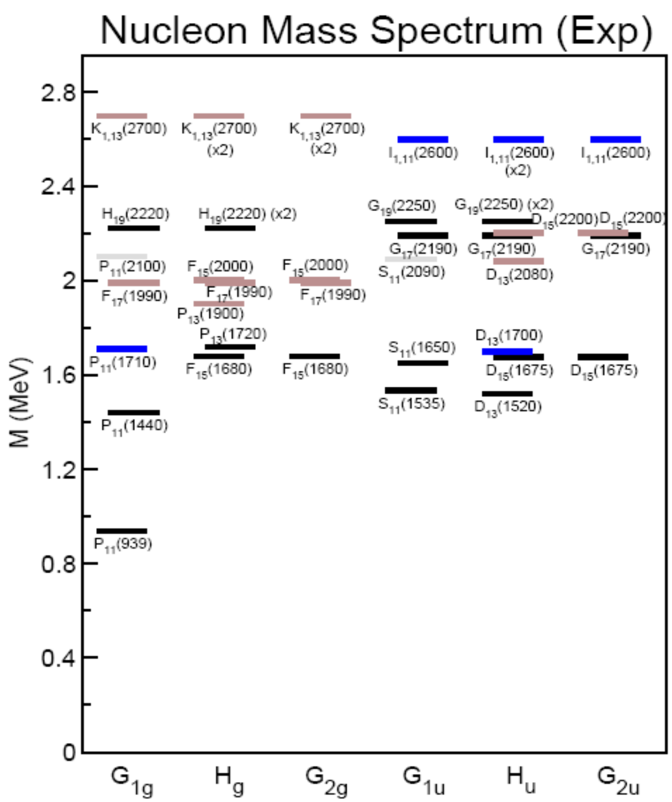
Types of Publications	2005	2006	2007	2008	*2009*	*To Appear*
	Calendar Year					
Phys Rev Lett and Phys Lett	13	16	11	13	3	2
Other Refereed Journals	84	41	47	56	31	18
Invited Talks in Conf. Proc Published	14	10	15	15	1	0
Invited Talks in Conf. Proc. Not Published	28	60	69	109	17	18
Instrumentation Papers	0	1	0	0	0	0
Contributed Papers	15	13	24	11	1	6

Highlights

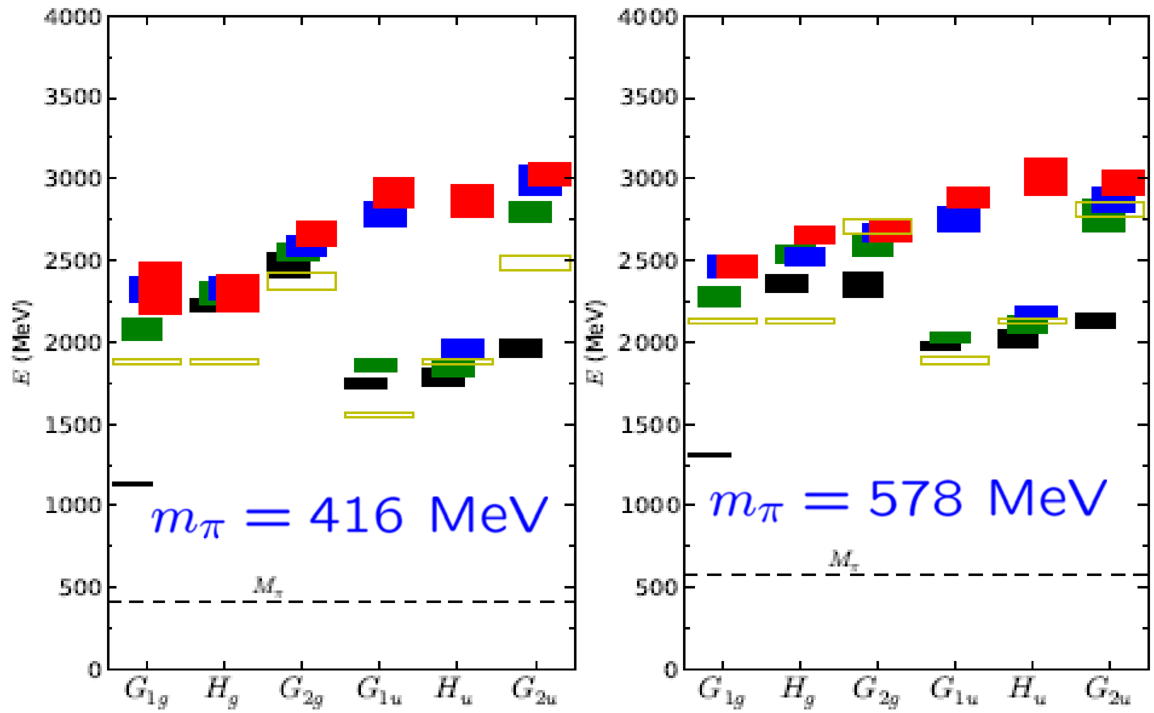
- Themes
  - The Spectrum of QCD
  - The Structure of Hadrons in QCD
  - The Physics of Nuclei
  - The Standard Model and Beyond

The Spectrum of QCD

Lattice QCD and Baryon Spectrum



Hadron Spectrum Collaboration, arXiv:0901.0027



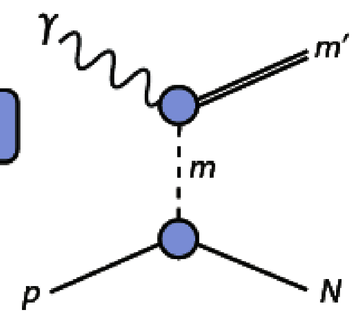
Lattices generated at ORNL under INCITE

Emergence of pattern seen in experiment!

Meson-photon Physics

GlueX intends to photoproduce meson resonances

GlueX



$\langle m\gamma|m'\rangle$

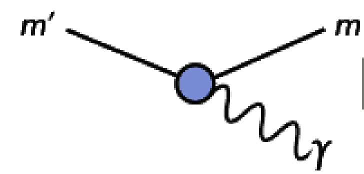
major motivator is the search for mesons with exotic J^{PC} quantum numbers - believed these can arise from excitation of the gluonic field (***hybrids***)

model calculations suggest that exotic photocouplings can be large - can lattice QCD weigh in on this?

& 'non-resonant' effects for EBAC (Q^2 dependence)
& meson exchange currents in nuclear models (Q^2 dependence)

similar physics in radiative transitions (at ***CLEO-c***, ***BES***, ***PANDA*** ...)
charmonium (heavy quarks) is a simple test-bed for the calculations

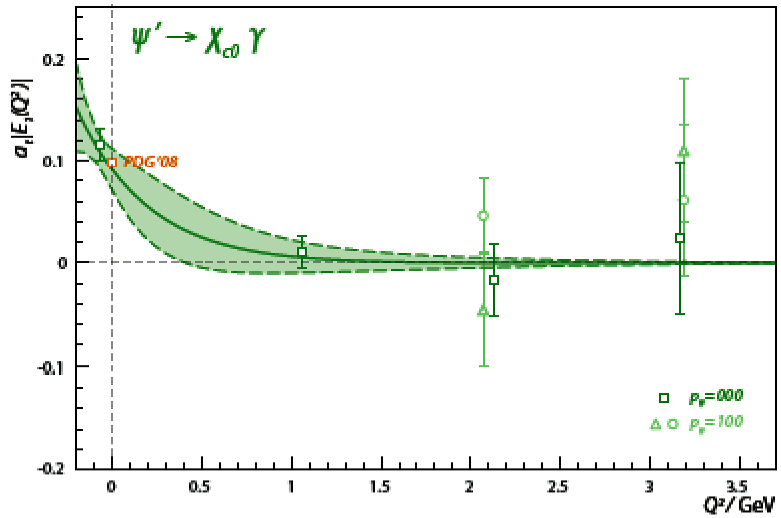
CLEO-c



$\langle m\gamma|m'\rangle$

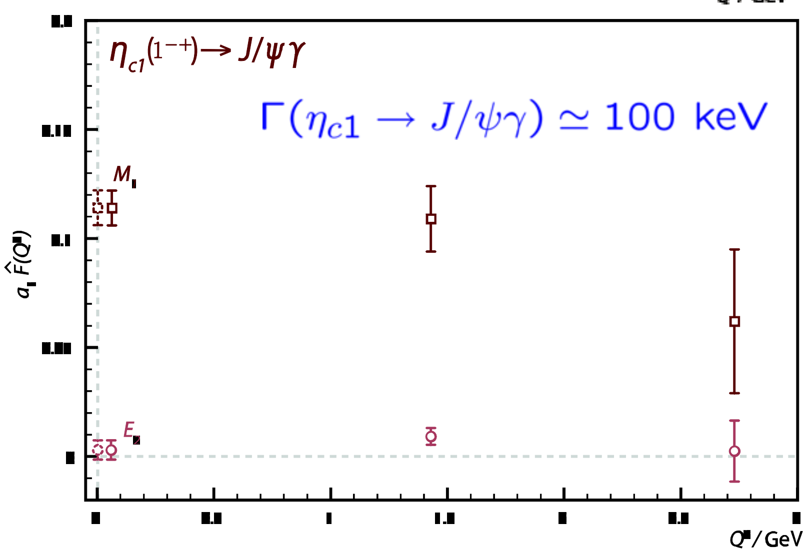
in charmonium there are relatively successful non-relativistic potential models - can verify these and go beyond making statements about the excited glue without model assumptions

Preparing for GlueX: Radiative Transitions



J Dudek, R Edwards, C Thomas, arXiv:0902.2241, PRD in press

Use of variational method, and the optimized meson operators, to compute radiative transitions between excited states and exotics.

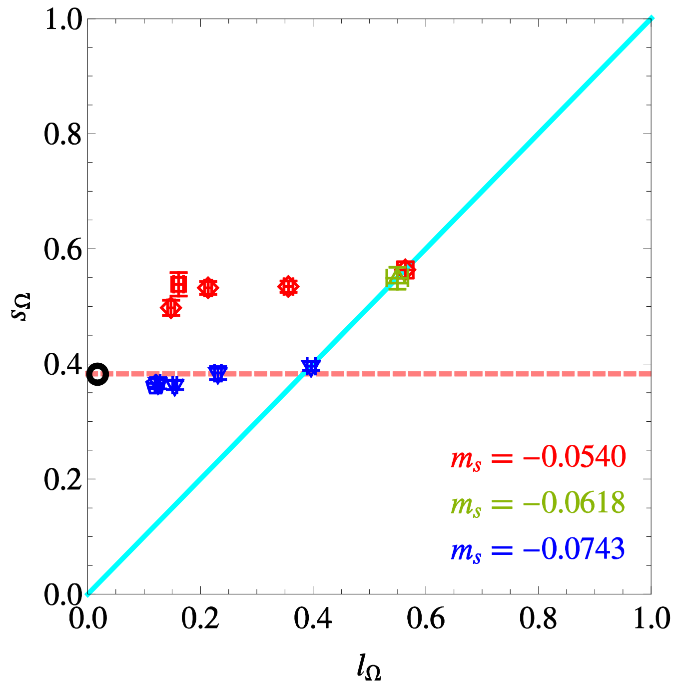


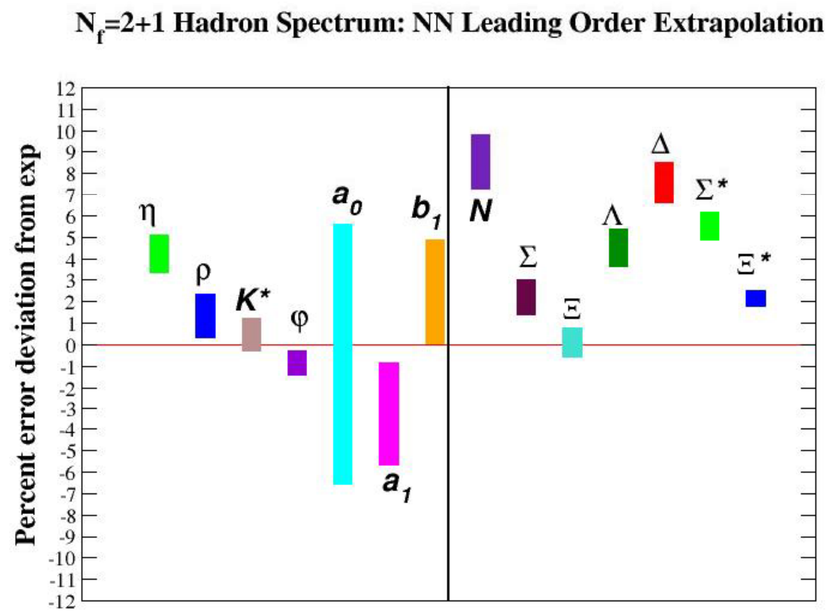
considerable phenomenology developed from the results - supports non-relativistic models and limits possibilities for form of excited glue

Radiative width of hybrid comparable to conventional meson – important for GlueX

Anisotropic Clover Lattice Generation

- "Clover" Anisotropic lattices $a_t < a_s$: *major gauge generation program under INCITE and discretionary time at ORNL designed for spectroscopy*





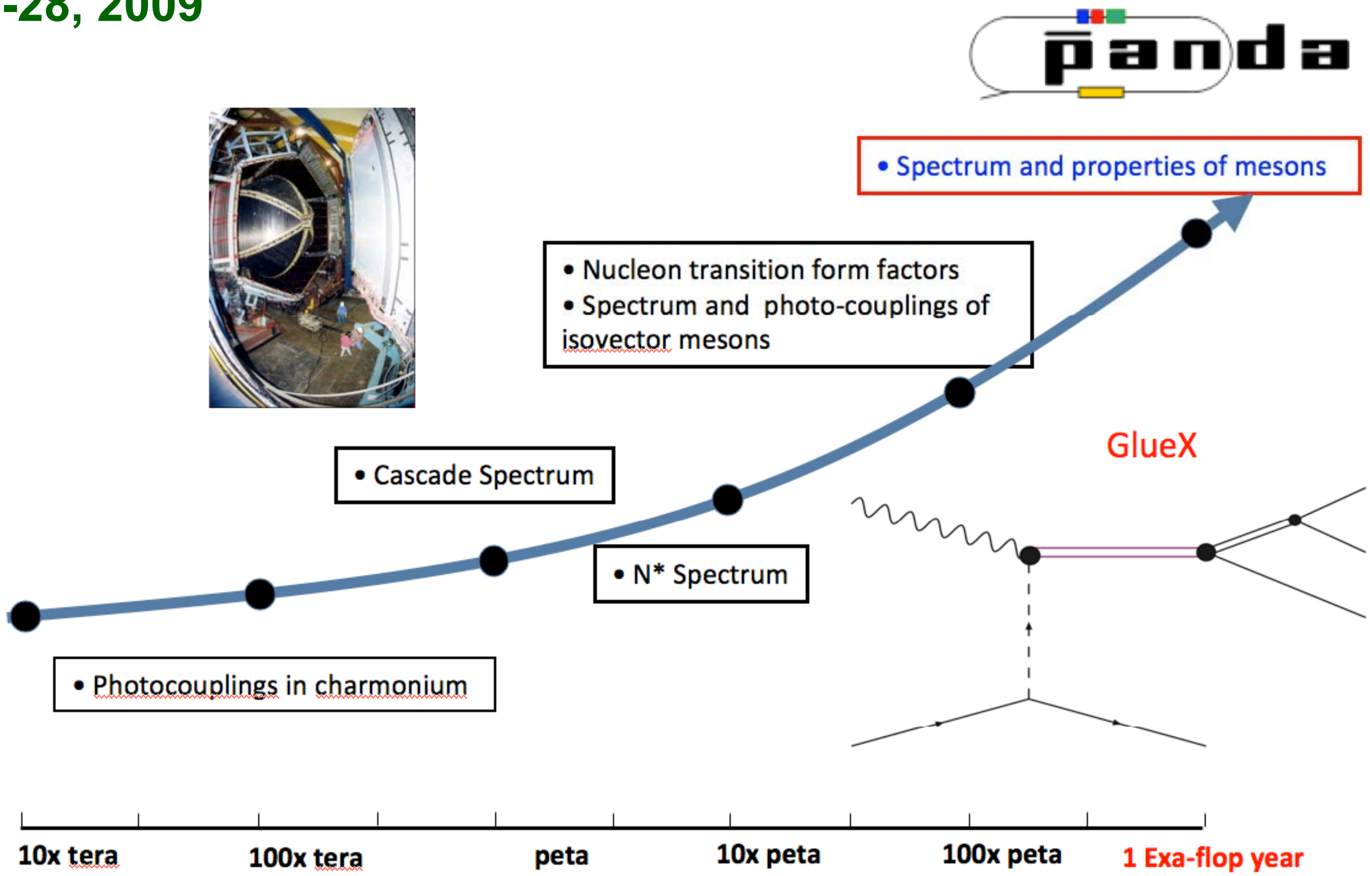
Novel way of specifying quark masses and scale

Low-lying hadron spectrum

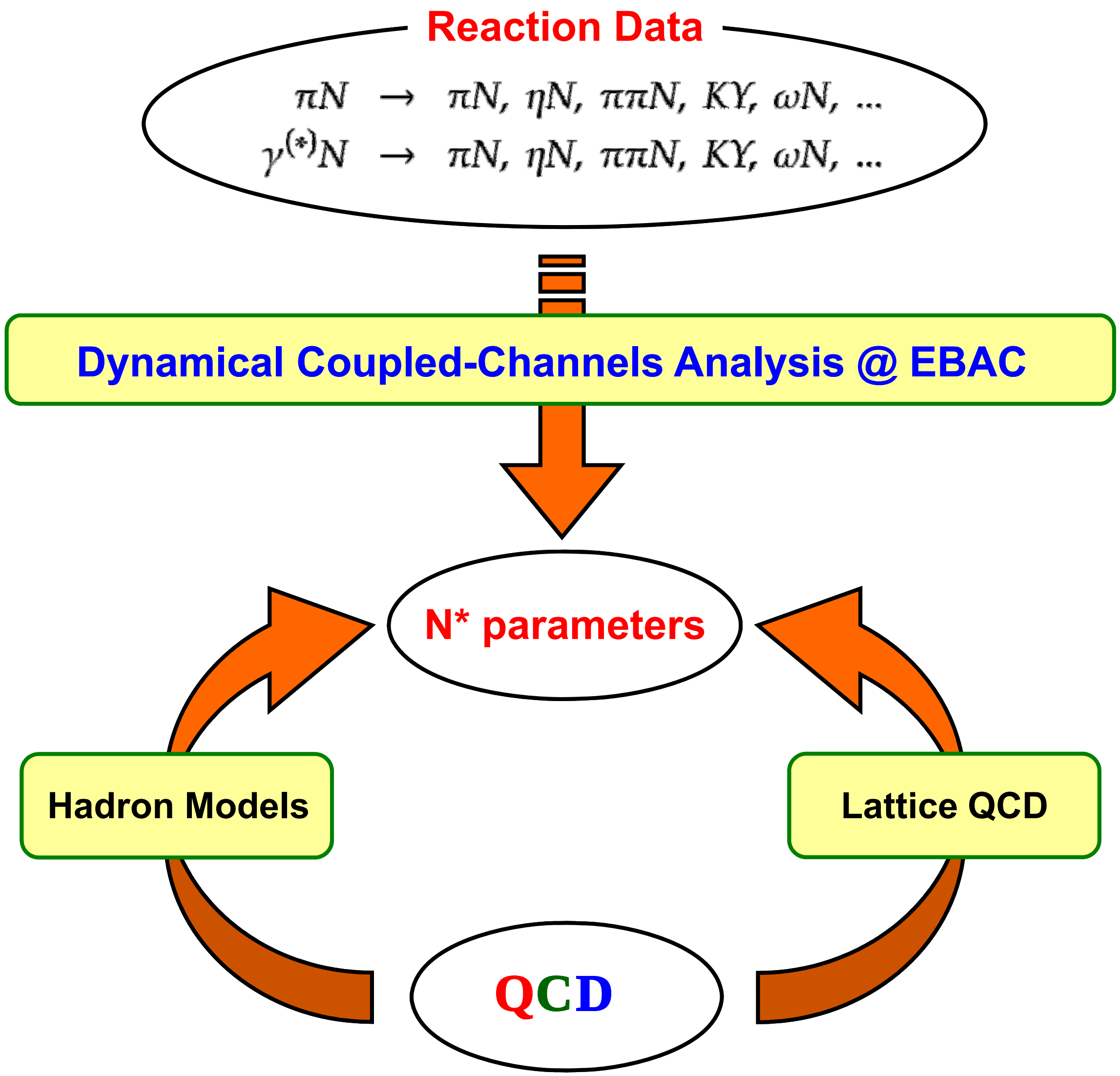
H-W Lin et al (Hadron Spectrum Collaboration), PRD79, 034502 (2009)

Lattice Roadmap for Spectroscopy

"Extreme Scale" Computing Workshop,
Jan 26-28, 2009



EBAC: extract and Interpret N*



EBAC (Contd)

Accomplishments

- Dynamical coupled-channel analysis of $\pi N \rightarrow \pi N$, $\pi\pi N$ reactions.
- Dynamical coupled-channel analysis of electromagnetic π production reactions.
- Extraction of nucleon resonances from dynamical coupled-channel model.

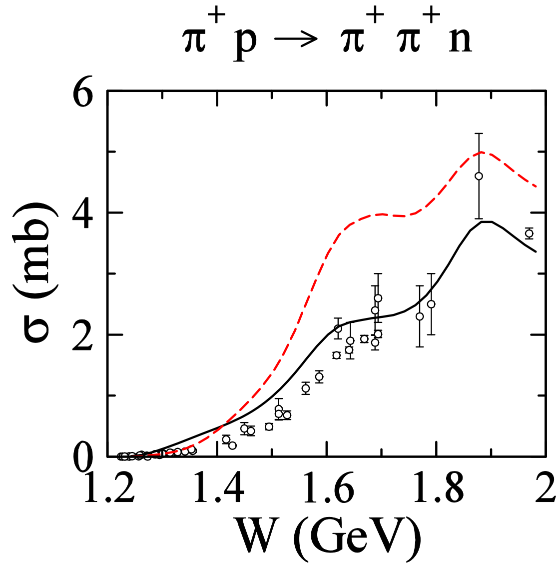
Plans

- Combined coupled-channel analysis
- Amplitude extractions from complete measurements
- Connection with hadron-structure calculations

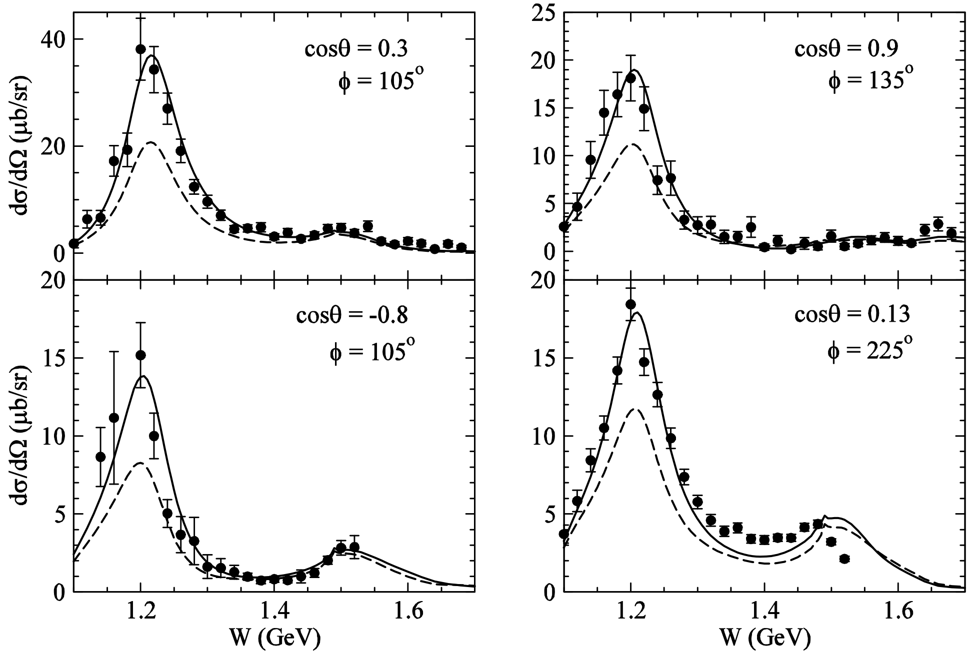
Progress in 2008-2009 - I

- Complete analysis of p(π, 2π)N data

Red: no coupled-channel



- Obtain fits of CLAS p(e, e'π)N data



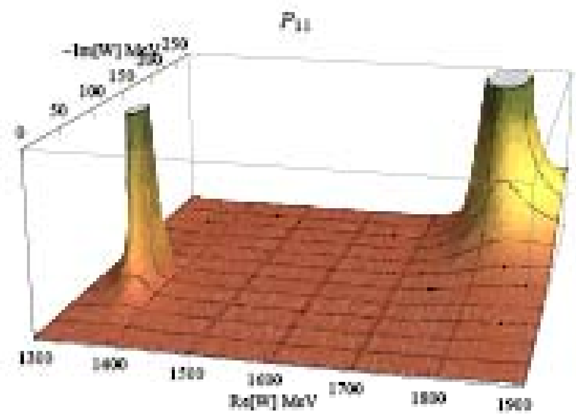
Dashed: no coupled-channel

Clear evidence of coupled-channel effects

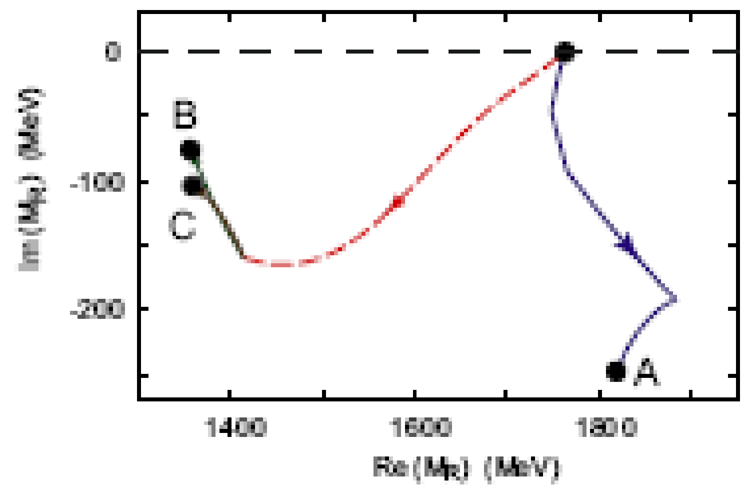
Progress in 2008-2009 - II

Extraction of nucleon resonances from dynamical coupled-channel model

Trajectories of extracted resonance poles



P_{11} resonances, extracted within EBAC-CC model



New information on interpreting Roper

Suzuki et al (Kamano, Lee), submitted to PRL

Hadron Structure

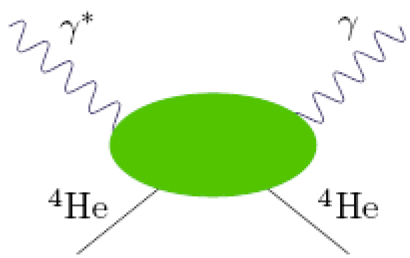
Theory Support for "GPD" Program

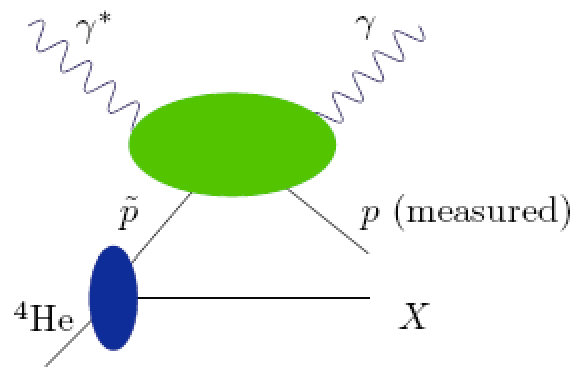
- GPDs and nucleon structure
  - Nucleon imaging and polarization effects [Burkardt]
  - Chiral dynamics at large distances [Weiss]
  - GPD/TMD connection [Schlegel, Bacchetta]
  - Model calculations [Schweitzer]
  - Orbital angular momentum [Thomas]
  - Lattice calculation of GPD moments [--> Lattice]
- Extracting GPDs from DVCS/meson production data
  - DVCS: t-channel based GPD parametrizations [Guzey]
  - DVCS: Nuclear targets [Guzey]
  - Meson production: Reaction mechanism, finite-size effects
  - ("higher twist"), model-indendent comparative studies [Weiss]
  - GPDs in pp scattering [Weiss]
- Communication/representation: Working Group meetings (experiment + theory), topical lectures, strong representation at international conferences, contributions to 2007 NSAC LRP

Medium modifications of bound nucleon GPDs

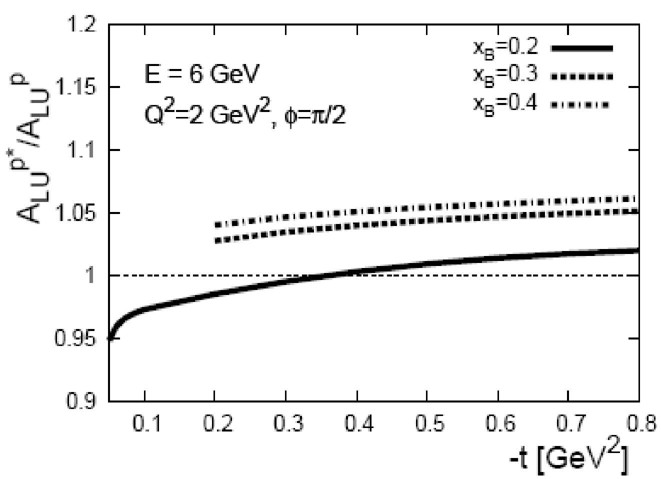
V. Guzey, A.W. Thomas, K. Tsushima, Phys. Lett. B673 (2009) 9
V. Guzey, A.W. Thomas, K. Tsushima, arXiv:0902.0780 [hep-ph]

Jlab expt. DVCS on ^{4}He

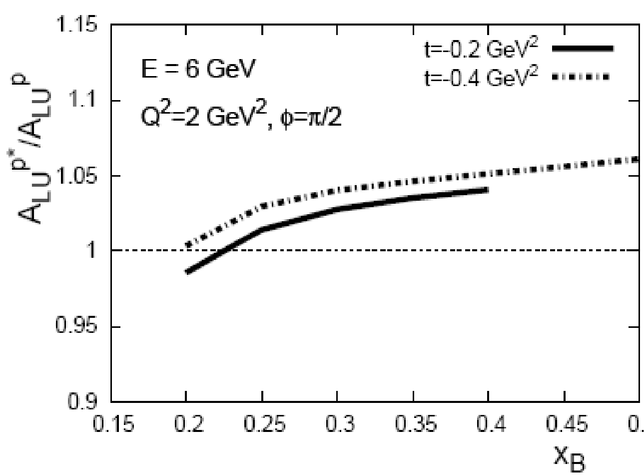




Coherent



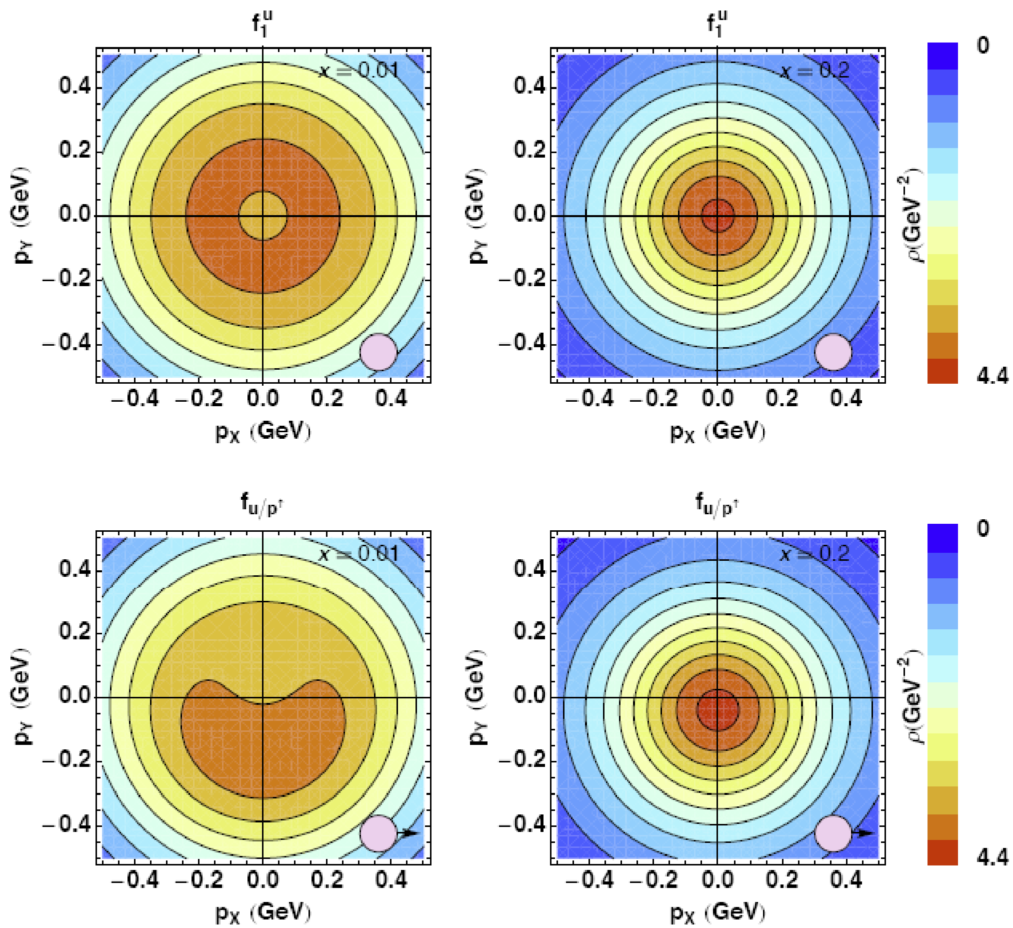
incoherent



Transverse Momentum Distributions

Bacchetta et al

Sivers' Effect



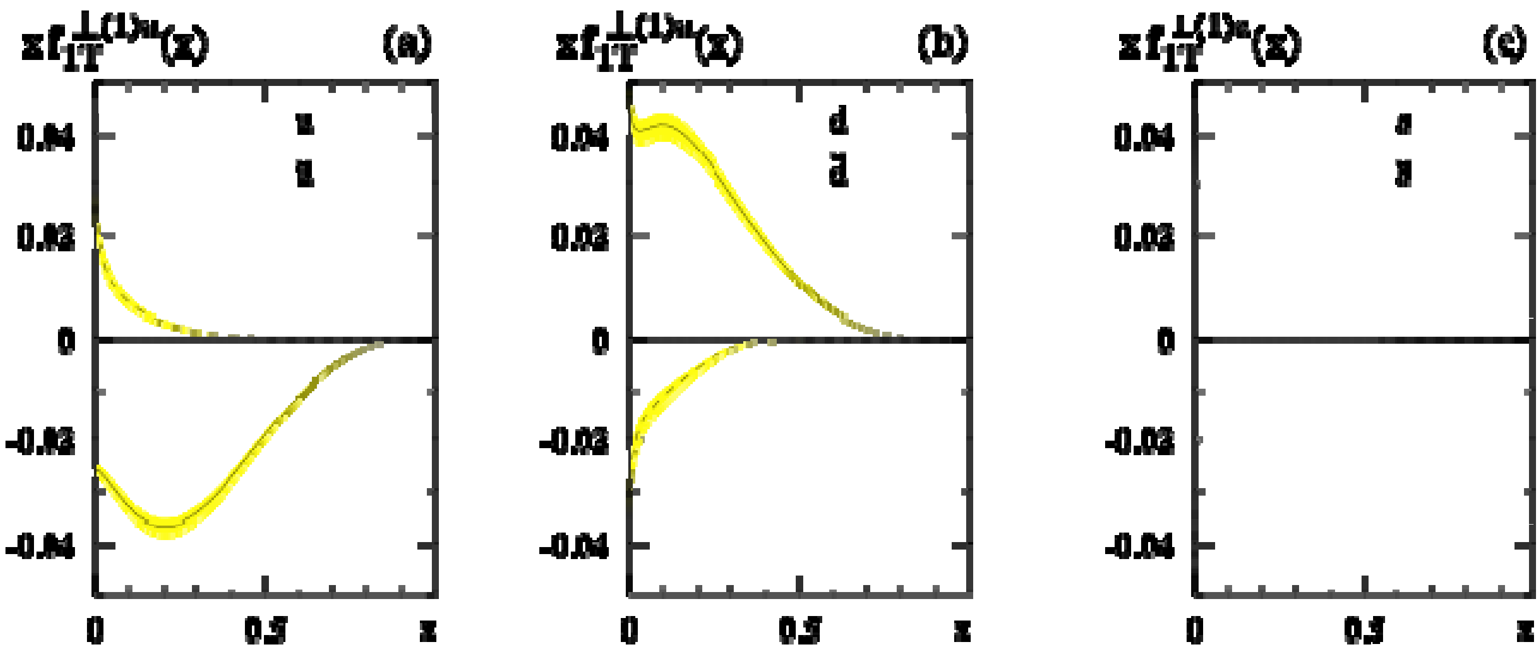
unpolarized

polarized

Tomographic images of nucleon in momentum space

Example of extraction from experiments

Fits based on HERMES and COMPASS single-spin asymmetries in semi-inclusive DIS. Similar measurements are a large component of the future Jlab@12GeV plans



Arnold, Efremov, Goeke, Schlegel, Schweitzer, arXiv:0805.2137

See also work by A. Prokudin, future post-doc at JLab

Connections between TMDs and GPDs

GTMD (Generalized Transverse Momentum Distribution)

"mother distribution"

$$F(x, \xi, \boldsymbol{k}_T^2, \boldsymbol{k}_T \cdot \boldsymbol{\Delta}_T, \boldsymbol{\Delta}_T^2)$$

$$\int d^2 \boldsymbol{k}_T$$

$$\xi = 0, \ \boldsymbol{\Delta}_T = 0$$

$$H(x, \xi, t)$$

Model-dependent connections

$$f(x, \boldsymbol{k}_T^2)$$

GPD

TMD

Meissner, Metz, Schlegel, arXiv:0906.5323

Higher-twist effects from g_2

- Sizeable higher-twist terms ~15-40% can be isolated in g_2:

$$g_2(x) = g_2^{WW}(x) + g_2^{HT}(x)$$

Accardi, Bacchetta, Melnitchouk, Schlegel

$$g_2^{WW} = -g_1 + \int_x^1 \frac{dy}{y} g_1(y)$$

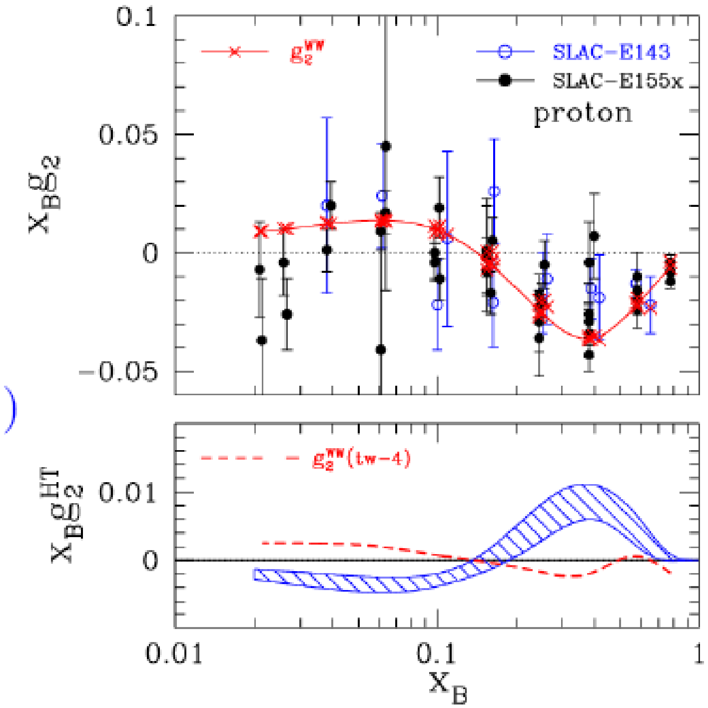
"Wandzura-Wilczek relation"

$$g_2^{HT} = \tilde{g}_T - \int_x^1 \frac{dy}{y} \tilde{g}_T(y) + \int_x^1 \frac{dy}{y} \hat{g}_T(y)$$

- 2 different contributions to g_2^{HT}
  - can be separated by measuring g_{1T} in double LT spin asymmetries

$$\hat{g}_T(x) = g_2(x) - \frac{d}{dx} \int d^2k_T \frac{k_T^2}{2M} g_{1T}(x, \vec{k}_T)$$

  - preliminary data on g_{1T} coming soon from Hall A

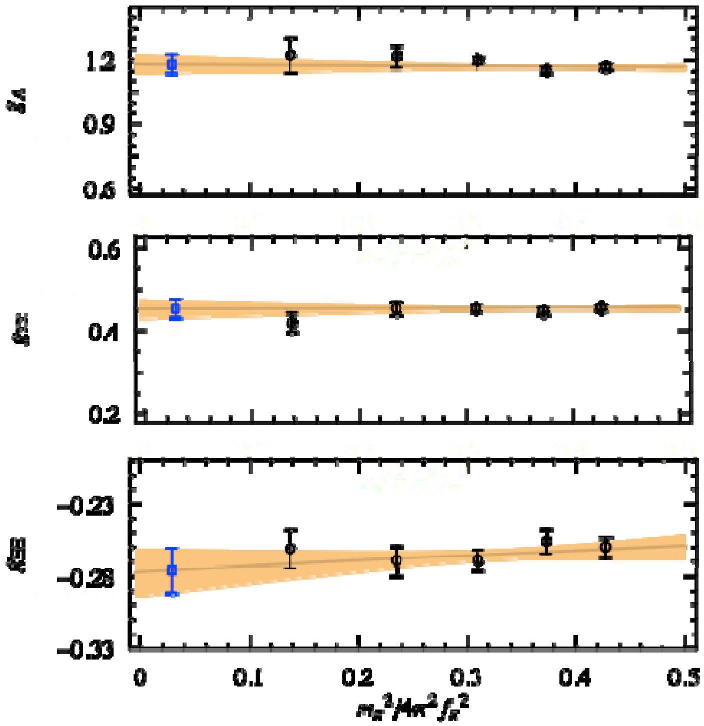


Lattice QCD

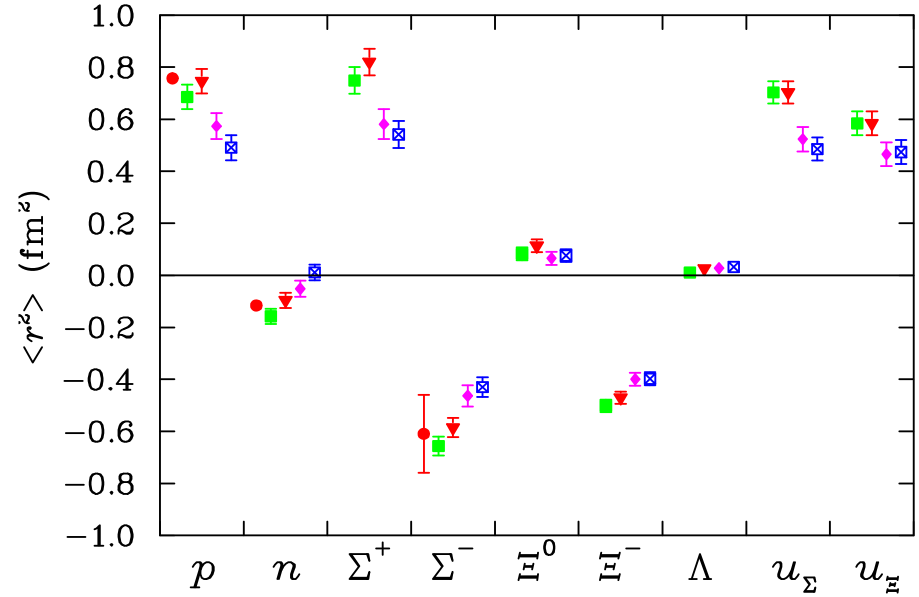
- **Lattice group has major effort in understanding *nucleon* structure:**
Moments of GPDs and structure functions, Form Factors,…
- **Extending to other flavor sectors**

Flavor “off-forward” GPDs

Octet baryon axial-vector couplings



Octet baryon charge radii

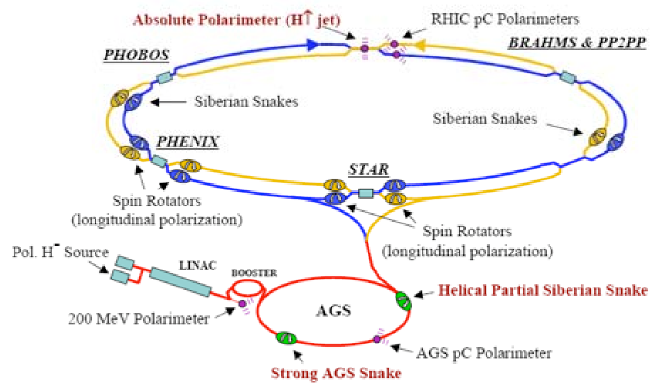


■: **full QCD at physical pion mass**

H-W Lin, K Orginos, PRD79:034507 (2009)

P Wang, A Thomas et al., arXiv:0810.1021

Lattice QCD Roadmap

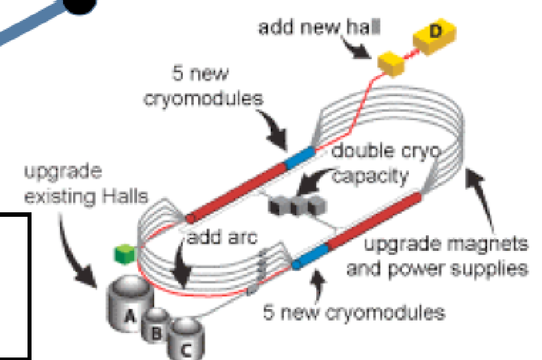


RHIC

- Gluon contributions to hadron structure

- Form factors up to scaling region

- High precision axial charge



Jlab @ 12GeV

- Individual contributions of up, down, and strange quarks to hadron structure

- Isovector form factors and moments of generalized parton distributions

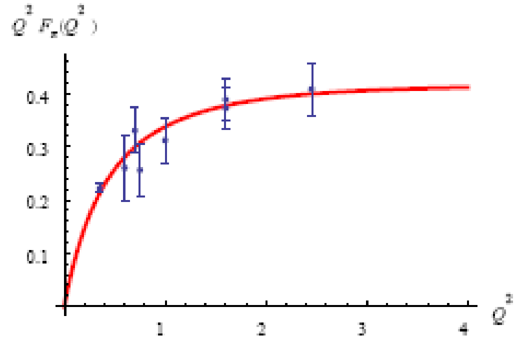
10x tera | **100x tera** | **peta** | **10x peta** | **100x peta** | **1 Exa-flop year**

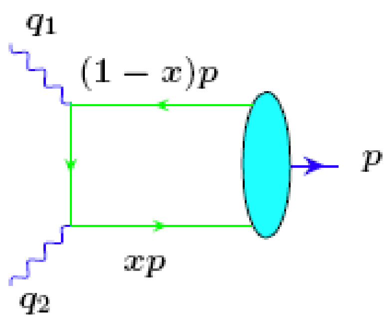
Pion Form Factor – Holographic QCD

- Simple analytic result (z_0 - "confinement" radius)

$$F_\pi(Q^2) = \frac{4}{Q^2 z_0^2}\left[1 - \frac{1}{I_0(Qz_0)}\right]$$

- H.R. Grigoryan, A.V. Radyushkin. Phys.Rev. D78:115008 (2008)
- Pion charge radius $\langle r_\pi^2 \rangle_{\mathrm{AdS/QCD}} = \frac{9}{8} z_0^2 \simeq 0.42\,\mathrm{fm}^2$
- Experiment: $\langle r_\pi^2 \rangle \approx 0.45\ \mathrm{fm}^2$
- Large-Q^2 behavior: $Q^2 F_\pi(Q^2) \longrightarrow \frac{4}{z_0^2} \simeq 0.42\,\mathrm{GeV}^2$





- Anomalous form factor $\pi^0\gamma\gamma^*$ in this model is given by the same expression
- Slope $a_\pi \equiv -m_\pi^2 \left[\frac{dF_{\gamma\gamma^*\pi^0}(Q^2)}{dQ^2}\right]_{Q^2=0}$

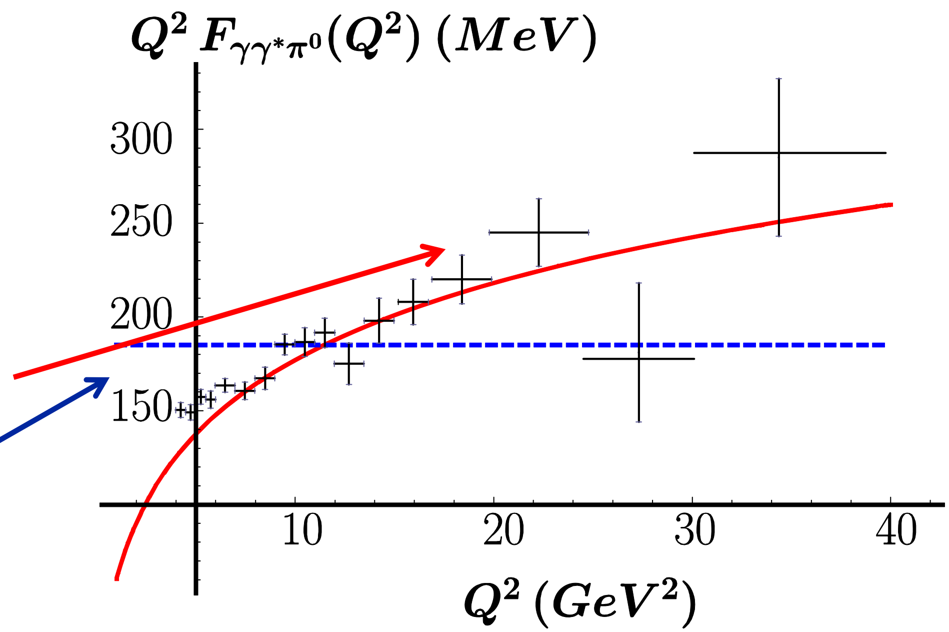
$$= \frac{3}{16} m_\pi^2 z_0^2 \simeq 0.035$$

- Experimentally
$a_\pi = 0.026 \pm 0.024 \pm 0.0048,$
$a_\pi = 0.025 \pm 0.014 \pm 0.026$ (1992)
Interesting to measure in modifications of PRIMEX

Shape of pion distribution amplitude

- **New *BaBar data (May 2009)* indicate no flattening of *γγ*π* form factor**

•Model for light-front pion wave function that is consistent with flat leading-twist pion distribution amplitude
• Such a model can describe BaBar high-Q^2 data.
• asymptotic pQCD calculation.
• Lattice calculation consistent with such a form



***A Radyushkin*, arXiv:0906:0323**

Physics of Nuclei

How nucleons bind together to form nuclei

Variety of approaches:

– **Constructing nuclear interactions and currents:**

- **One-boson-exchange phenomenology and similar**
  (Gross, Schiavilla, Van Orden)
- **Effective field theory approach**
  (A. Thomas)
- **Hadronic interactions in Lattice QCD (Detmold, Orginos)**

– **Structure and reactions of nuclei:**

- **Relativistic approaches to nuclear dynamics**
  (Gross, Schiavilla, A. Thomas, Van Orden)
- **Form factors and weak transitions in few-nucleon systems**
  (Gross, Schiavilla, A. Thomas, Van Orden)
- **EFT studies of the structure of few-nucleon systems**
  (Gross, Schiavilla)
- **Nuclear reactions of astrophysical interest (Schiavilla)**

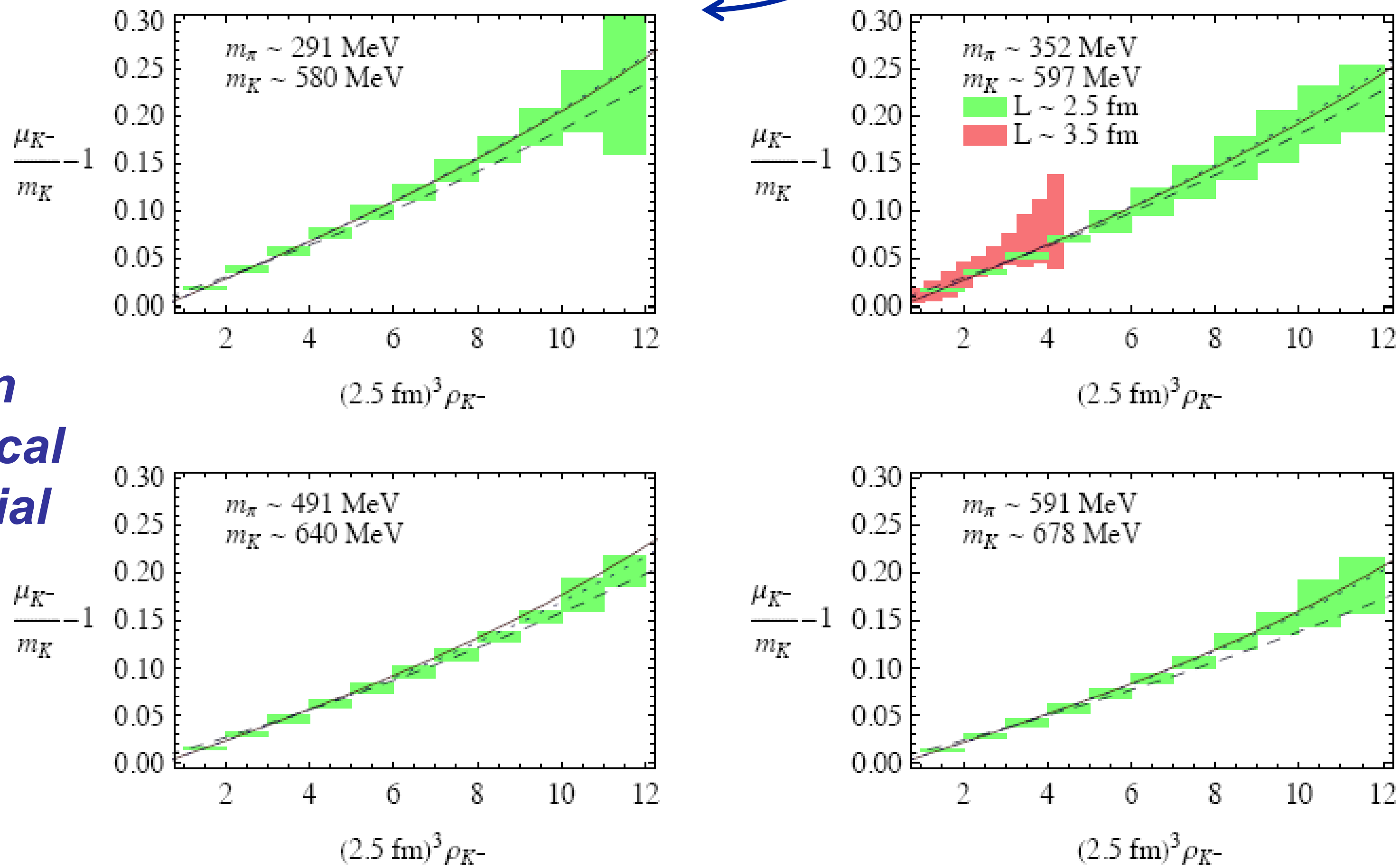
- **Nuclear effects on nucleon properties *V. Guzey***

Lattice QCD for Nuclear Physics

Kaon condensation

χPT

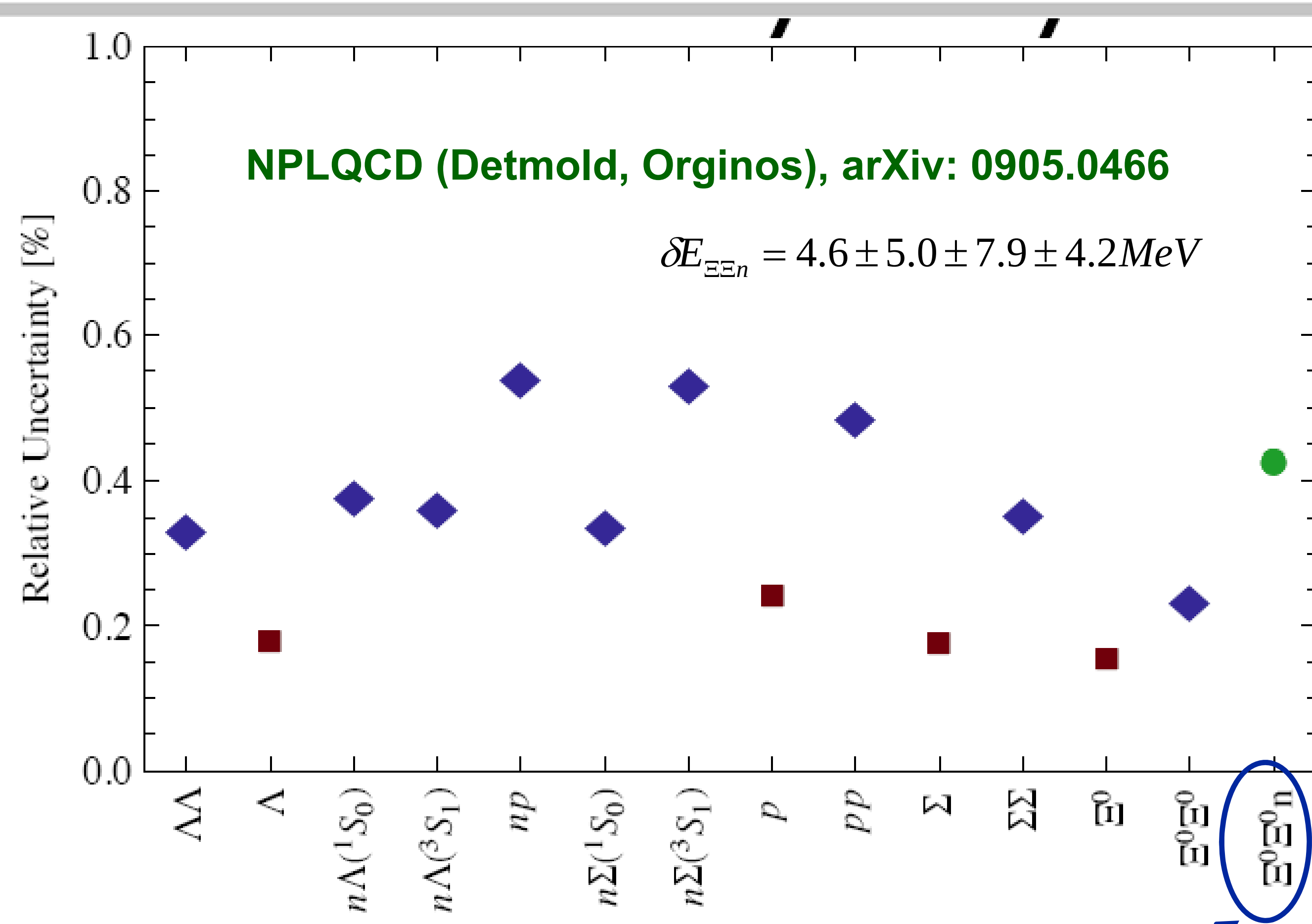
Isospin Chemical potential



NPLQCD (Detmold, Orginos): PRL 100,082004 (2008); PRD 77, 057502 (2008); PRD 78,014507 (2008); PRD 78,054514 (2008)

Three-baryon system

Relative uncertainty in ground-state energy



Feasibility of extracting three-nucleon interaction demonstrated

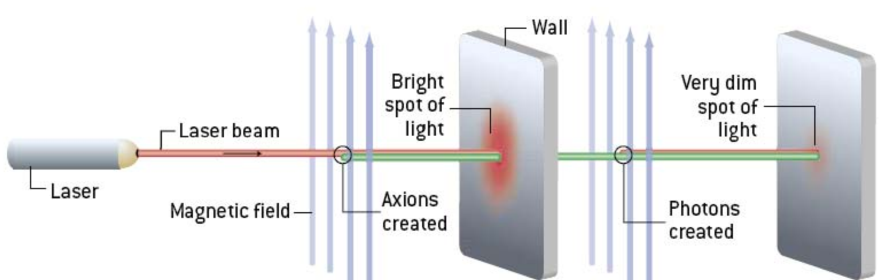
Standard Model and Beyond

Axion Search: LIPSS

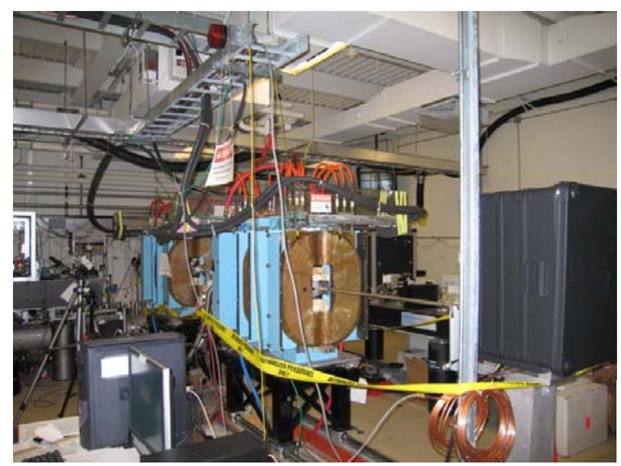
- **`Dark matter puzzle': Cosmology and recent data from space telescopes provide evidence that most of the mass of the observable universe cannot be associated with any of the known Standard-Model elementary particles.**
- **Axions - hypothetical particles proposed to solve a strong CP problem in Quantum Chromodynamics - are dark matter candidates.**

"Light shining through a wall…"

- **Theoretical idea: Sikivie(1983); Ansel'm (1985); Van Bibber et al (1987)**
- **First limits on axion-photon mixing obtained by BFRT Collab, (BNL,1993)**
- **Implemented at JLAB FEL by LIPSS Collaboration (2007-present)**



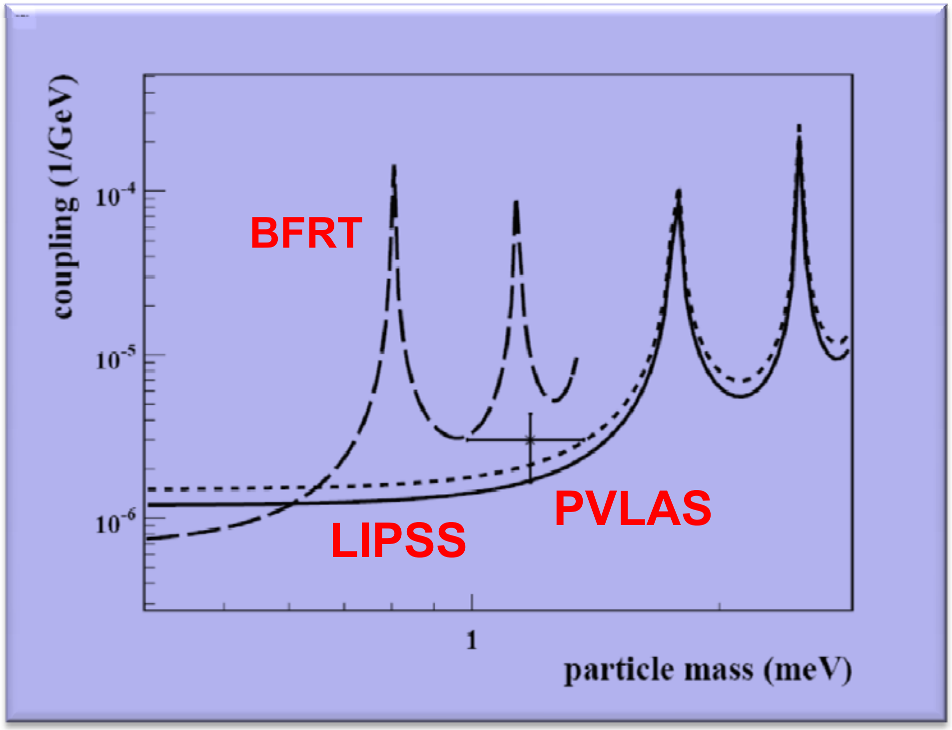
LIGHT BEAM experiment that would confirm the existence of axions passes a laser beam through a strong magnetic field, converting some photons to axions (*green beam*). The axions penetrate a wall before passing through another magnetic field that converts some of the particles back to photons, which form an extremely faint spot on the far wall.

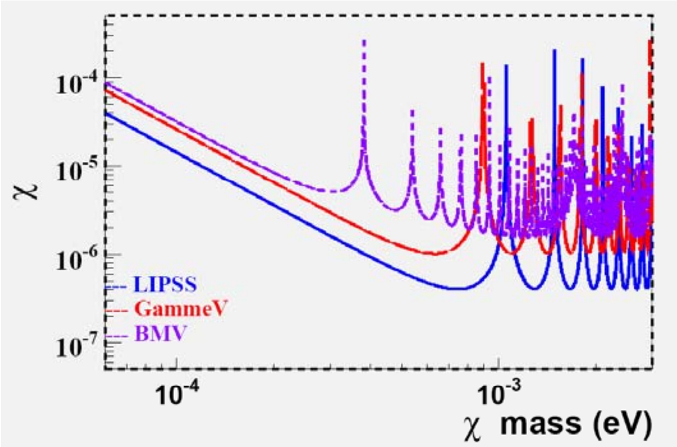


Published LIPSS Result

Afanasev et al, Phys Rev Lett 101, 120401 (2008)

- No signal observed, regions above curves excluded by the experiment
- LIPSS reached the sensitive region for scalar coupling
- In agreement with other measurements: BFRT, GammeV, BMV

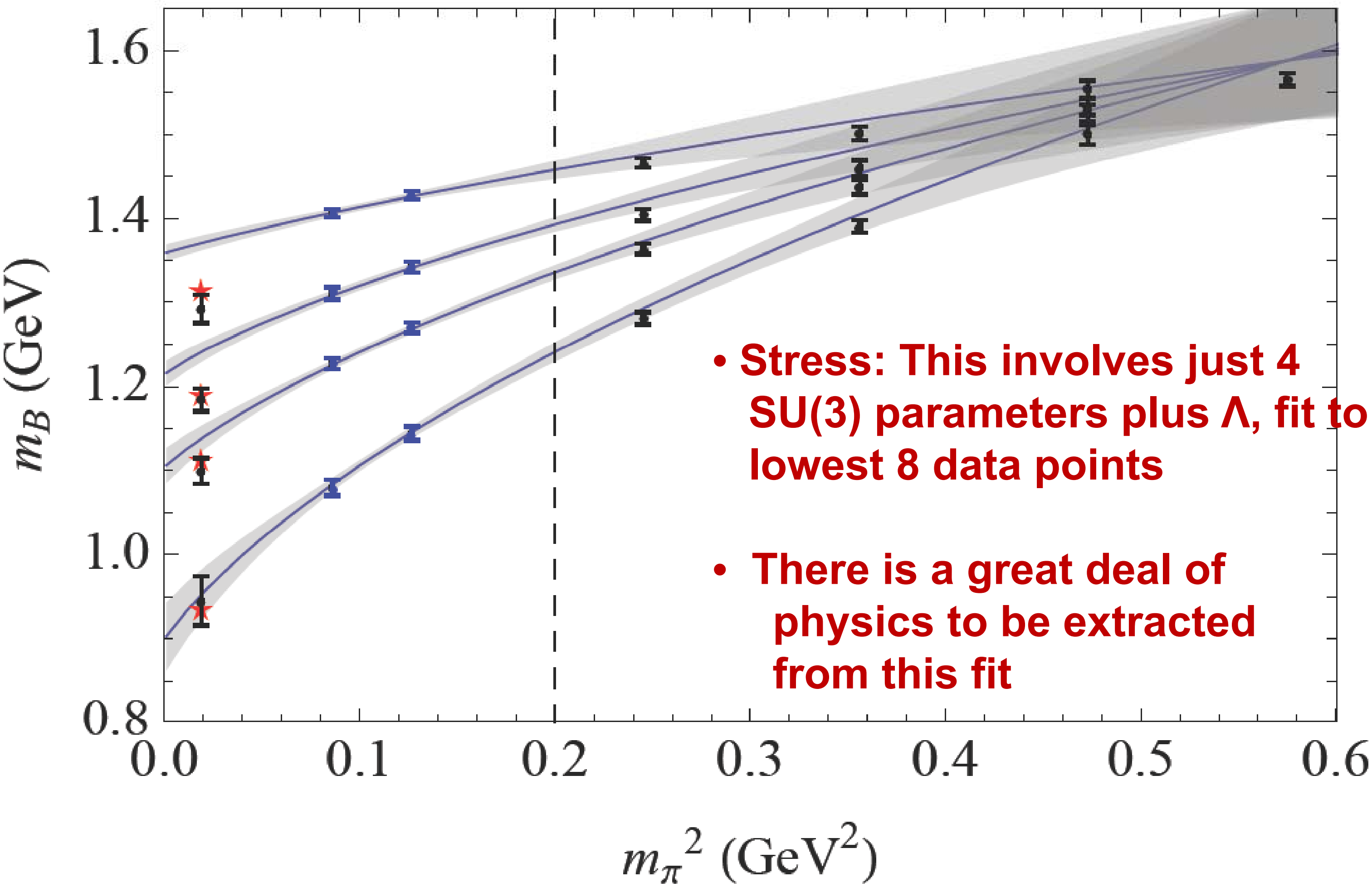




BSM Physics: mixing between photons and paraphotons.

Afanasev et al, arXiv:0810.4189

EFT Fits to Lattice Data



- Stress: This involves just 4 SU(3) parameters plus Λ, fit to lowest 8 data points
- There is a great deal of physics to be extracted from this fit

Young & Thomas, arXiv:0901.3559 [nucl-th]

Summary Fits to LHPC and CP-PACS

B	Mass (GeV)	$\bar{\sigma}_{Bl}$	$\bar{\sigma}_{Bs}$
N	0.939(19)(4)(2)	0.054(7)(2)(2)	0.020(11)(7)(3)
Λ	1.108(11)(10)(1)	0.0296(31)(5)(10)	0.138(11)(2)(2)
Σ	1.185(9)(2)(1)	0.0221(20)(7)(7)	0.176(11)(6)(2)
Ξ	1.321(9)(20)(0)	0.0095(7)(4)(0)	0.236(11)(4)(3)

$$\bar{\sigma}_{Bq} = (m_q/M_B)\partial M_B/\partial m_q$$

Of particular interest:

σ commutator well determined : $\sigma_{\pi N}$= 51 (6) (2) (2) MeV

and strangeness sigma commutator small

$m_s \, \partial M_N / \partial m_s$ = 18 (10) (6) (3) MeV

NOT several 100 MeV !

Profound Consequences for Dark Matter Searches

Hadronic Uncertainties in the Elastic Scattering of Supersymmetric Dark Matter

John Ellis,[1,*] Keith A. Olive,[2,†] and Christopher Savage[2,‡]

CERN-PH-TH/2008-005
UMN–TH–2631/08
FTPI–MINN–08/02

We find that the spin-independent cross section may vary by almost an order of magnitude for 48 MeV $< \Sigma_{\pi N} <$ 80 MeV, the ±2-σ range according to the uncertainties in Table I. This uncertainty is already impacting the interpretations of experimental searches for cold dark matter. Propagating the ±2-σ uncertainties in $\Delta_s^{(p)}$, the next most important parameter, we find a variation by a factor ~ 2 in the spin-dependent cross section. Since the spin-independent cross section may now be on the verge of detectability in certain models, and the uncertainty in the cross section is far greater, *we appeal for a greater, dedicated effort to reduce the experimental uncertainty in the π-nucleon σ term* $\Sigma_{\pi N}$. This quantity is not just an object of curiosity for those interested in the structure of the nucleon and non-perturbative strong-interaction effects: it may also be key to understanding new physics beyond the Standard Model.

$$\mathcal{L} = \alpha_{2i}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}_i\gamma_\mu\gamma^5 q_i + \alpha_{3i}\bar{\chi}\chi\bar{q}_i q_i$$

spin

σ terms

Neutralino (0.3 GeV / cc :WMAP)

Opportunities beyond 12 GeV: EIC

- EIC Collaboration (BNL & JLab, since 2007): Substantial JLab Theory involvement — V. Guzey, C. Weiss
  - ep/eA Physics Working Group Conveners
  - Models for physics simulations; conceptual development
  - EIC Workshops: Stony Brook 07, Hampton 08, Berkeley 08
  - Representation at international conferences: DIS 07/09, Trento 08, INT 09
  - White Paper for 2007 LRP
- New development (2008): Medium–energy ep/eA collider for nuclear physics at JLab — C. Weiss
  - Natural extension of 12 GeV nucleon structure/QCD program
  - Conceptual/technical development in co-operation with CASA group and JLab users
- Future: Expand/intensify collider R&D effort — C. Weiss
  - Exciting opportunities: Sea quarks, gluons, spin, QCD vacuum, nuclei in QCD, . . .
  - Theory input essential for physics program, simulations
  - Depends critically on Lab staff!

Lattice QCD

- **Jefferson Laboratory partner with BNL and FNAL in lattice QCD effort.**

FNAL
Weak matrix elements

BNL
RHIC and HEP

JLAB
Hadronic Physics

Facilities – LQCD-I, LQCDext

SciDAC – R&D Vehicle

Close (two-way) connection with HPC Group

- **Balint Joo, Saul Cohen vital to theory effort**
- **Robert Edwards vital to software effort**

Lattice QCD at JLab has major impact on DOE's Nuclear Physics Program

- **$5M ARRA for LQCD**

Summary

- **JLab Theory Center has major impact in inspiring, facilitating, and interpreting the JLab program at both 6 and 12 GeV and preparing for EIC.**
- **Recent initiatives coming to fruition – Lattice QCD, EBAC; new theoretical focus on large-x structure functions**

Experiment

"Sir, I have found you an ~~argument~~; but I am not obliged to find you an understanding." **– That's where theorists are useful…**

Boswell's Life of Johnson