Lattice-based Studies of QCD.

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Jefferson Laboratory

QCD and Hadron Physics Town Meeting, Temple, Sept. 13-15, 2014

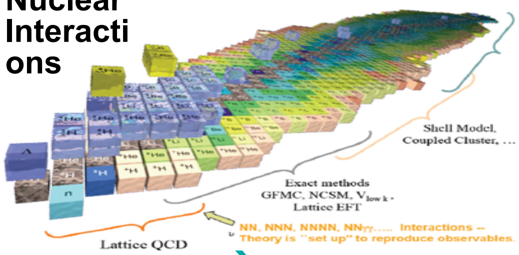
Thanks: R. Briceno, W. Detmold, M. Engelhardt, K-F Liu, S. Meinel, M. Savage + JLab colleagues

Outline

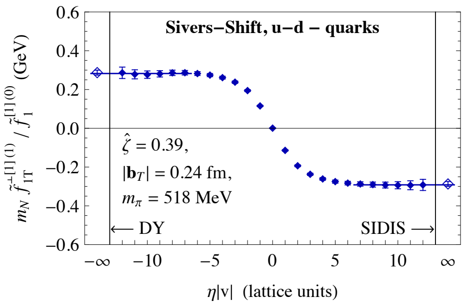
- Lattice : Theory and Computation
- Achievements and Opportunities
  - Spectrum of QCD
  - The structure of hadrons
  - The NN Interaction
  - (Polarizabilities)
  - (Isospin breaking)
  - (Fundamental Symmetries)
  - …….
- Initiatives and Resources

Science ⟷ Infrastructure

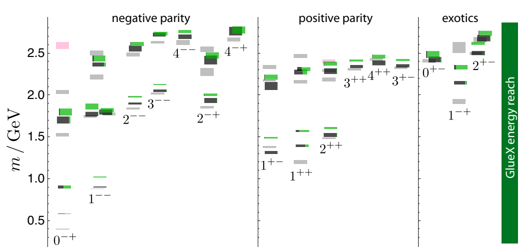
Nuclear Interactions

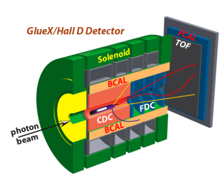


Hadron Structure



Spectroscopy





Lattice QCD

Software

Scidac

USQCD

INCITE

Facilities

Leadership-class

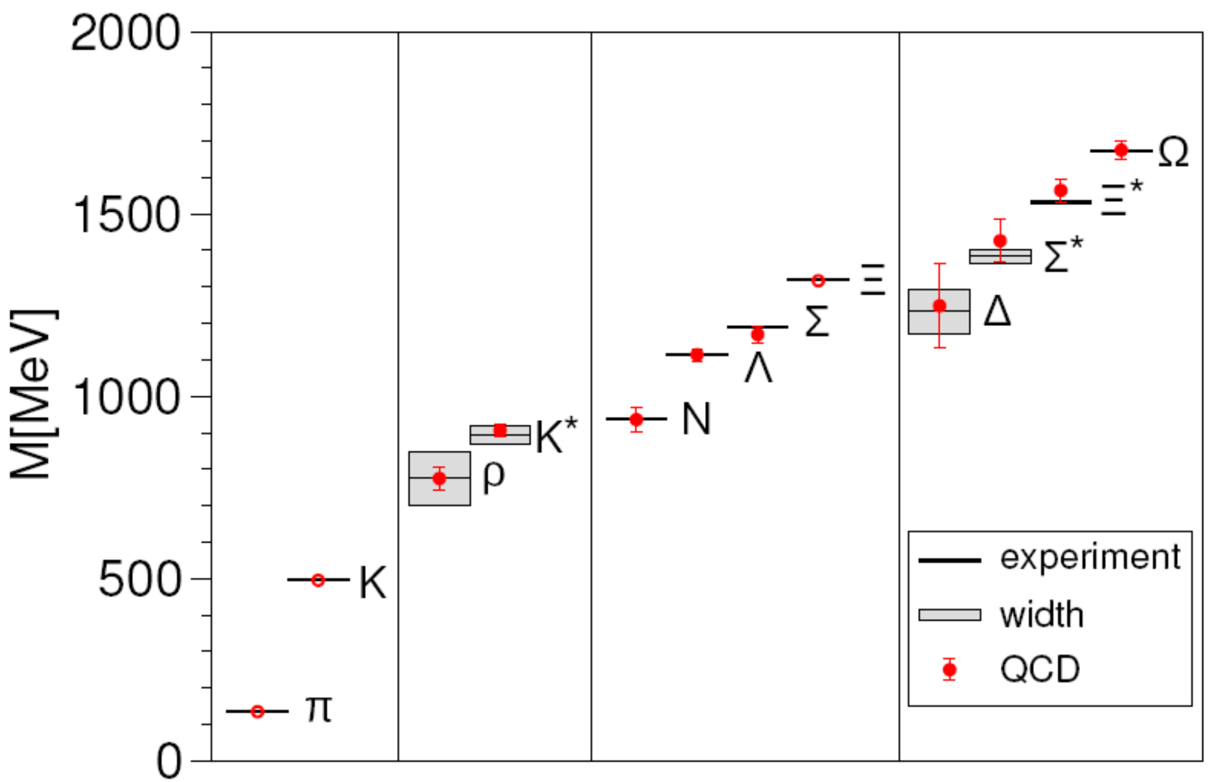
Clusters + GPUS + BG/Q

The Spectrum of QCD

Low-lying Hadron Spectrum

Benchmark of LQCD

$$C(t) = \sum_{\vec{x}} \langle 0 \mid N(\vec{x},t)\bar{N}(0) \mid 0 \rangle = \sum_{n,\vec{x}} \langle 0 \mid e^{ip\cdot x} N(0) e^{-ip\cdot x} \mid n \rangle \langle n \mid \bar{N}(0) \mid 0 \rangle$$
$$= \mid \langle n \mid N(0) \mid 0 \rangle \mid^2 e^{-E_n t} = \sum_n A_n e^{-E_n t}$$



Durr et al., BMW Collaboration

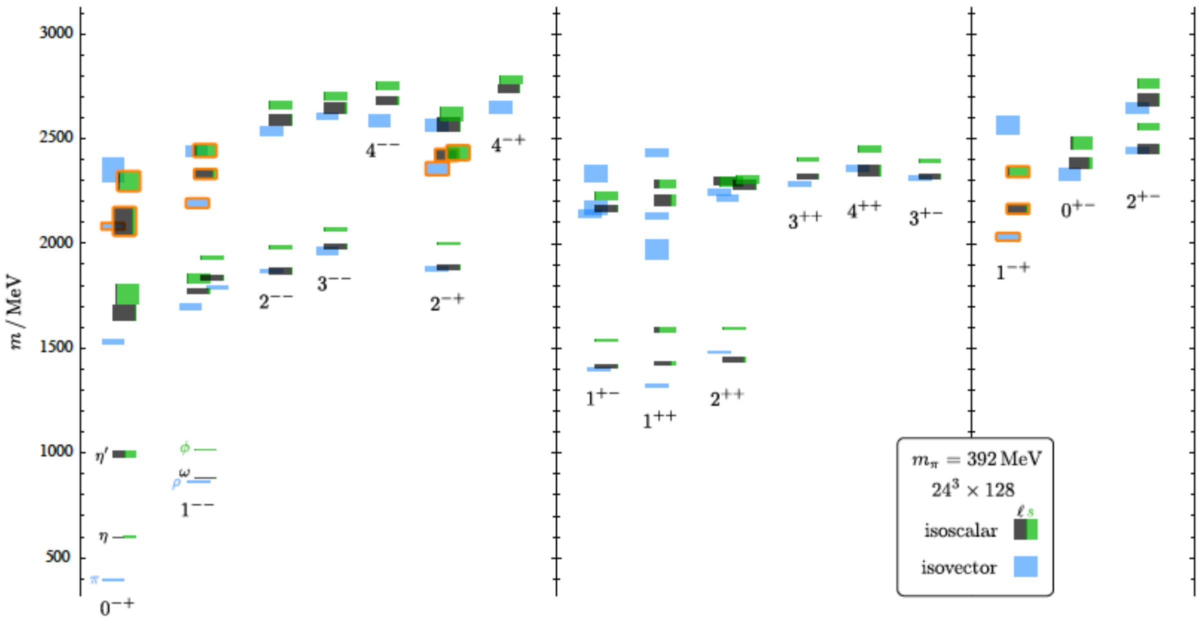
Science 2008

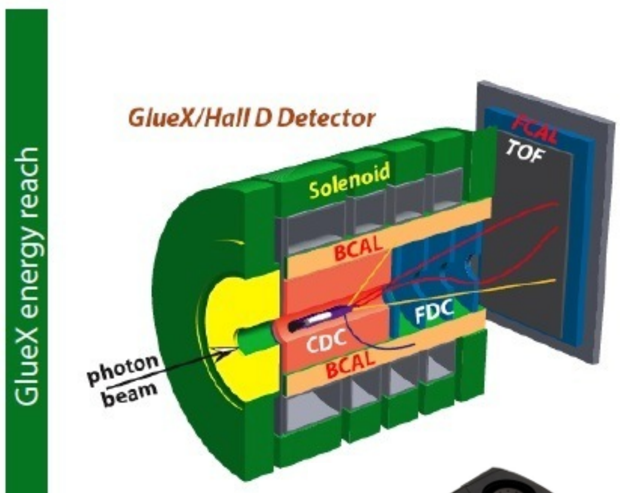
Control over:

- ***Quark-mass dependence***
- ***Continuum extrapolation***
- ***finite-volume effects (pions, resonances)***

Spectroscopy: Isoscalar Meson Spectrum

Dudek et al. arXiv:1309.2608, arXiv:0909.0200



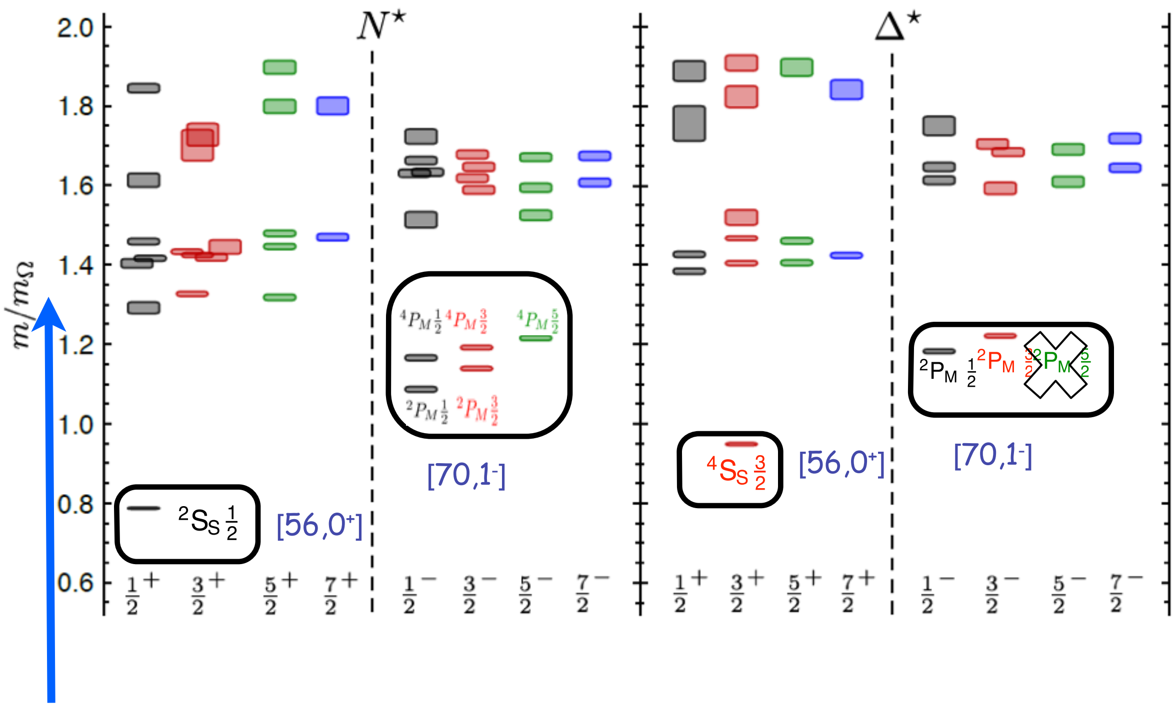


Report to NSAC: *Implementing the 2007 LRP*

"A key part of the 12-GeV physics program at Jefferson Lab is the ability to produce these exotic hybrid mesons using photon beams, which is expected to generate unprecedented numbers of these particles. The GlueX experiment in the new Hall-D is poised to carry out this program using a detector designed to tackle just this problem. *The GlueX experimental program is coupled with both detailed lattice QCD predictions and the strong support of the Jefferson Lab theory center in analyzing and interpreting the expected new data. This puts the U.S. in a unique position to explore this important new science made possible by the 12 GeV CEBAF Upgrade.... "*

J. Dudek *et al.*, PRD73, 11502

Excited Baryon Spectrum



Broad features of SU(6)xO(3) symmetry.

Counting of states consistent with NR quark model.

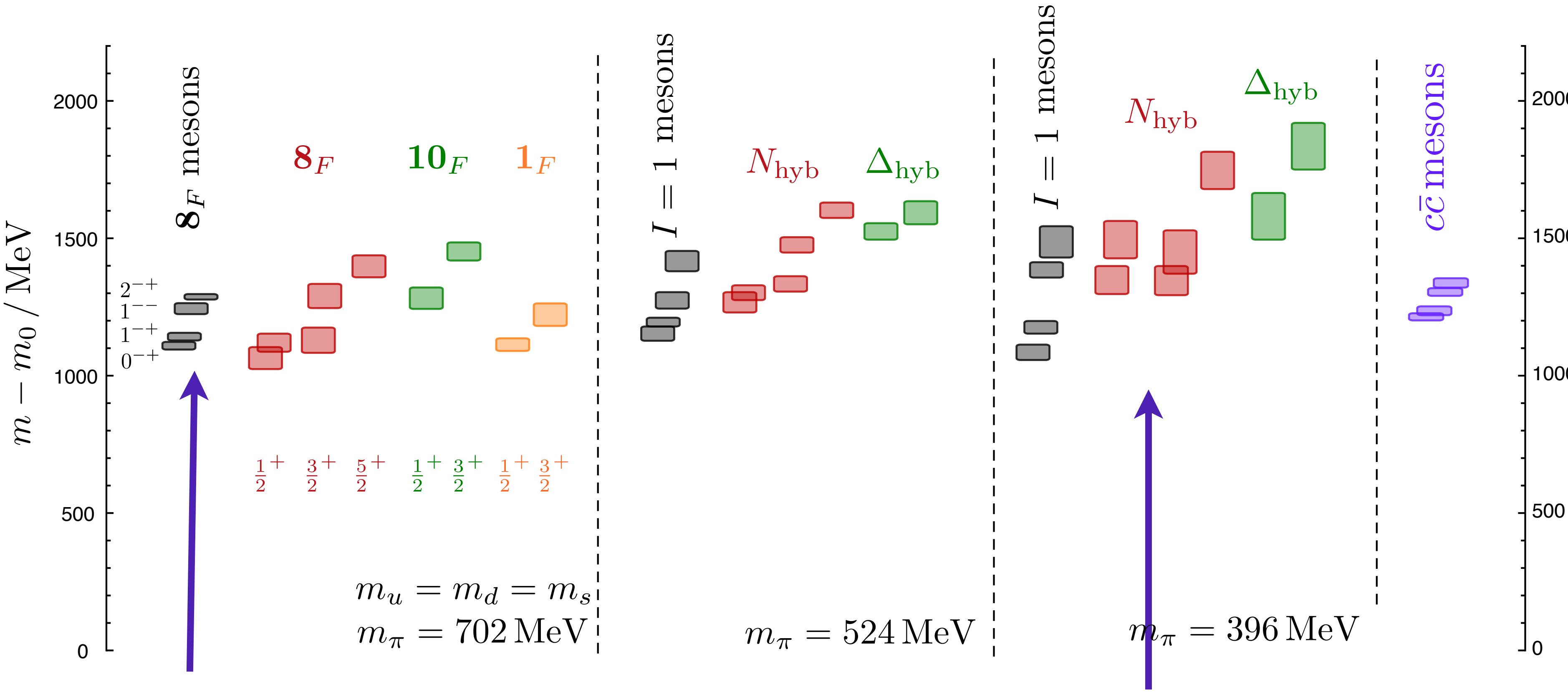
Inconsistent with quark-diquark picture or parity doubling.

$$[70,0^+],[56,2^+],[70,2^+],[20,1^+]$$

N $^{1/2+}$ sector: need for complete basis to faithfully extract states

What we have learned…..

Common mechanism in meson and baryon hybrids: chromomagnetic field with *$E_g \sim$ 1.2 - 1.3 GeV*



Subtract ρ

Subtract N

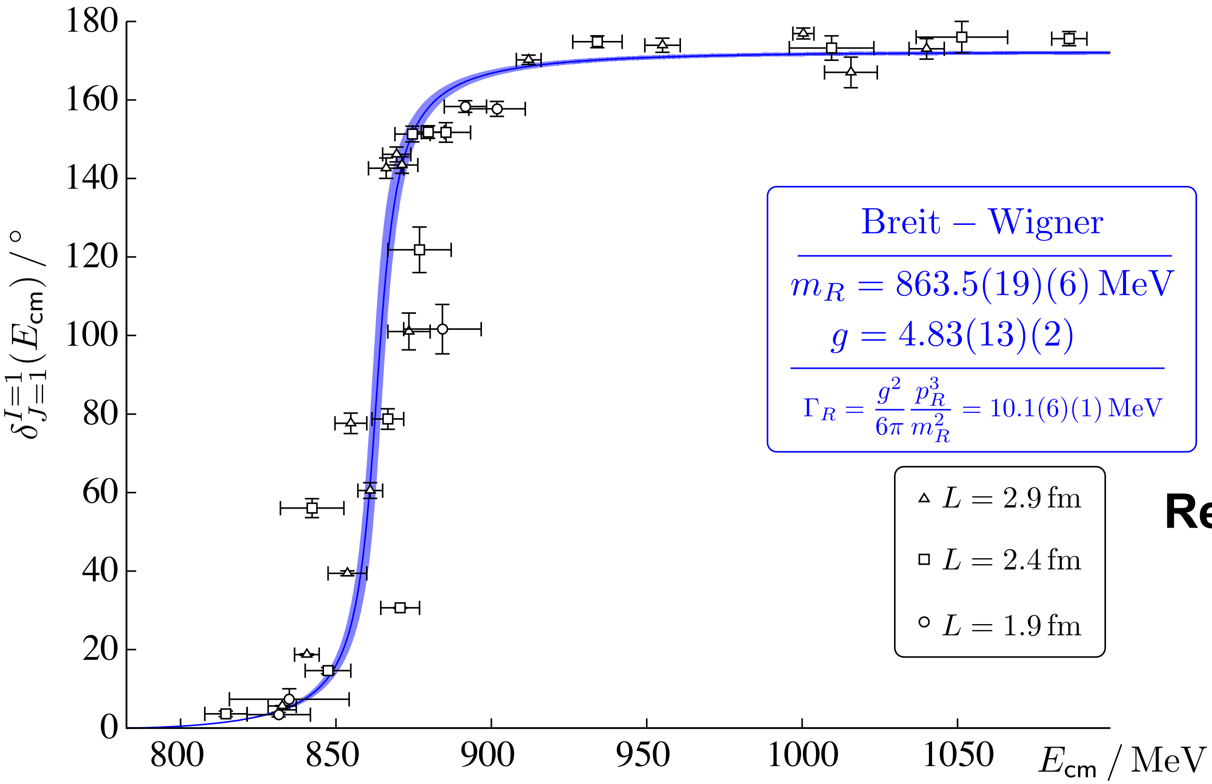
Future Opportunities - I

Luescher: energy levels at finite volume ↔ phase shift at corresponding *k*

$$\det\left[e^{2i\boldsymbol{\delta}(k)} - \mathbf{U}_\Gamma\left(k\frac{L}{2\pi}\right)\right] = 0$$

Matrix in l

lattice irrep

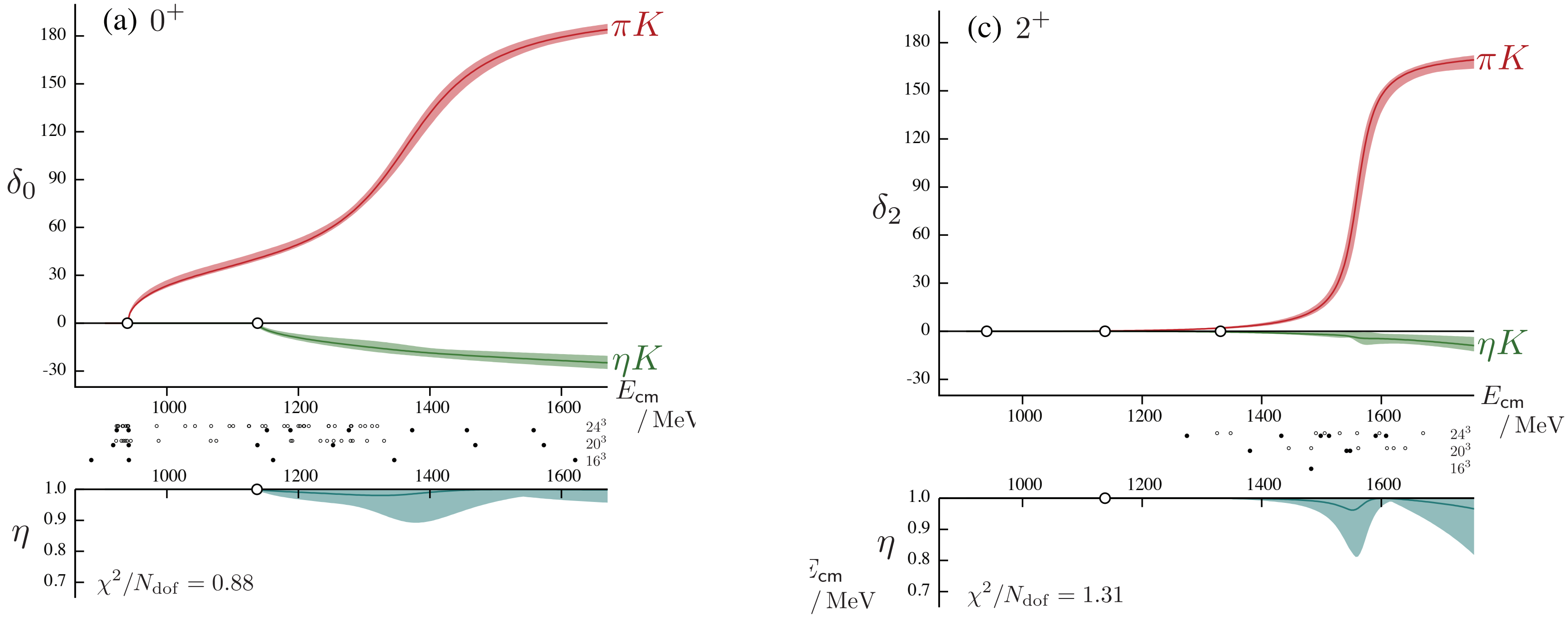


Feng, Renner, Jansen, PRD83, 094505
PACS-CS, PRD84, 094505
Alexandru et al
Lang et al., PRD84, 054503

Resonant I = 1 ππ Phase Shift

Dudek, Edwards, Thomas, Phys. Rev. D 87, 034505 (2013)

Future Opportunities - II



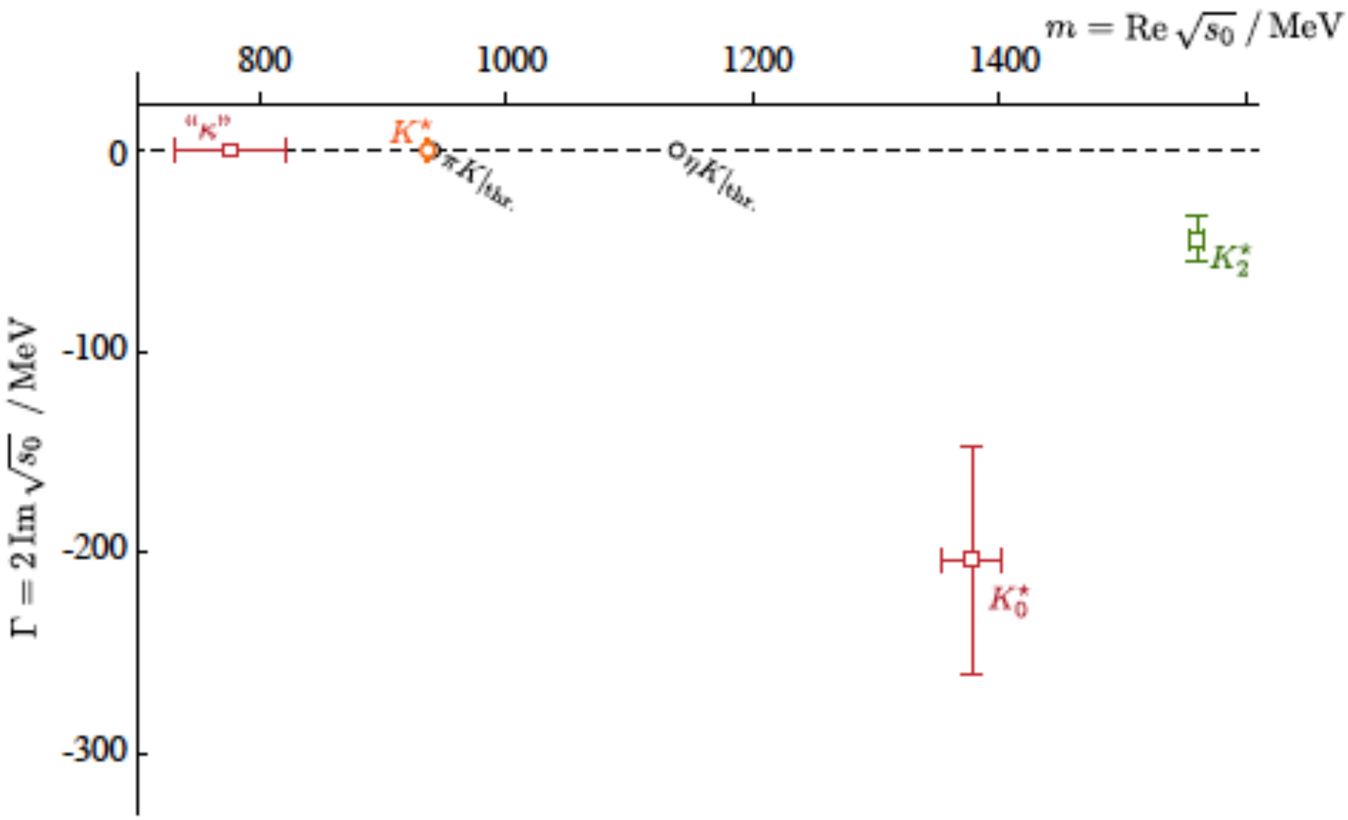
Dudek, Edwards, Thomas, Wilson, PRL (in press)

Extend to inelastic channels: Guo et al, Briceno et al.,

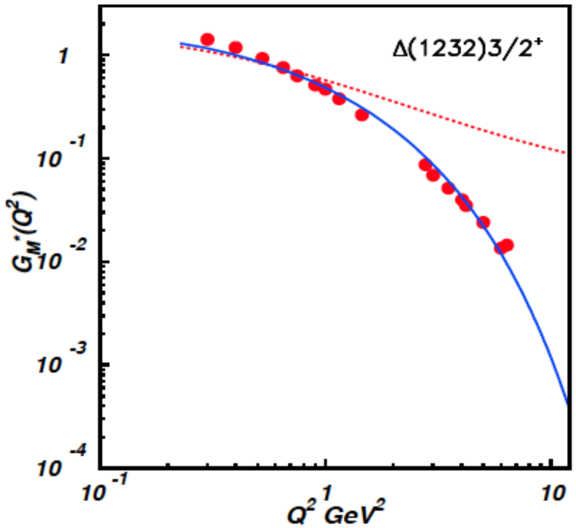
First lattice calculations of inelastic channels

Lattice QCD will predict results before or during GlueX

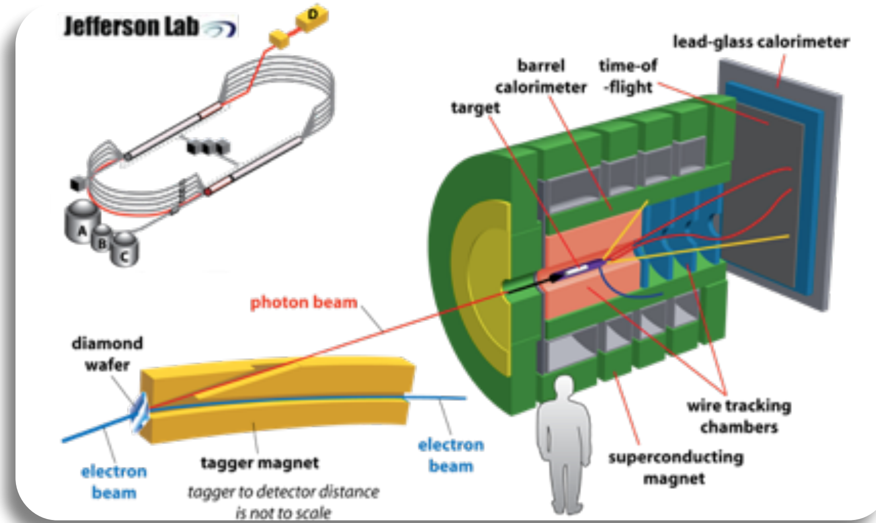
Singularities complex plane…



Meson photoproduction

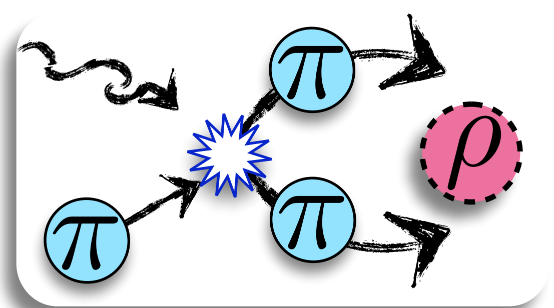


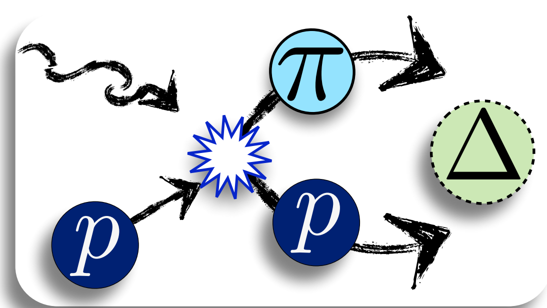
R. Gothe

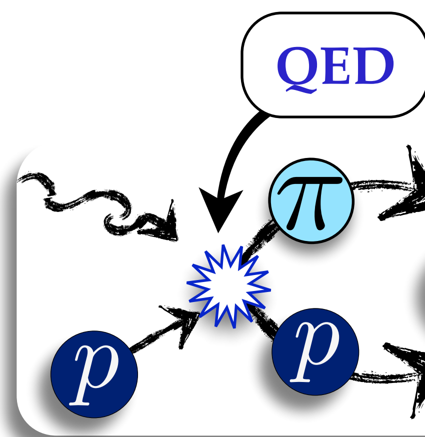


Recent developments to make lattice QCD calculation possible:

- Briceño **[JLab]**, Hansen & Walker-Loud **[JLab/W&M]** (2014)
- Agadjanov,Bernard, Meißner & Rusetsky (2014)







The Structure of Hadrons

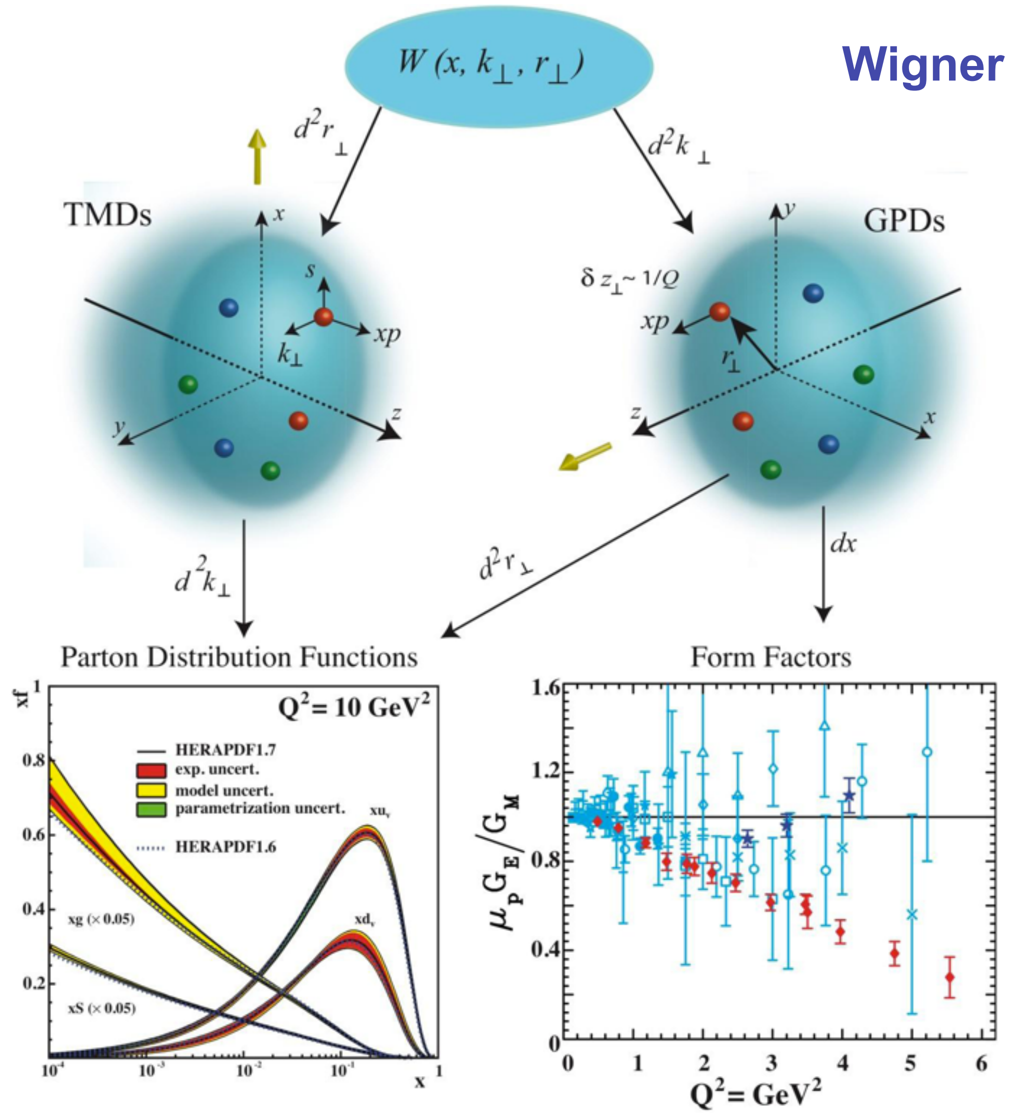
Three-Dimensional Imaging

5D

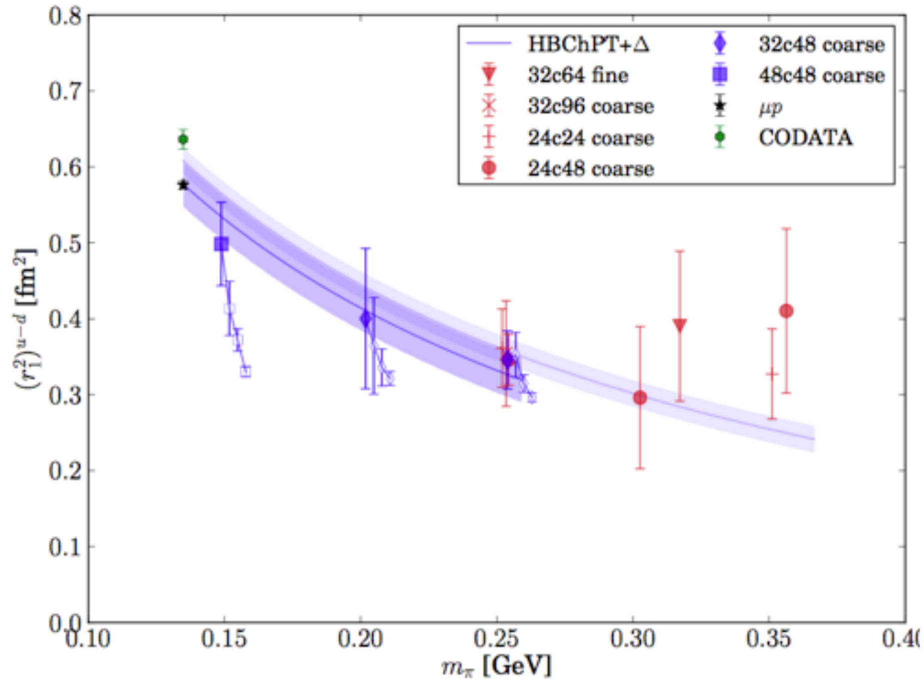
3D

1D

Wigner distributions

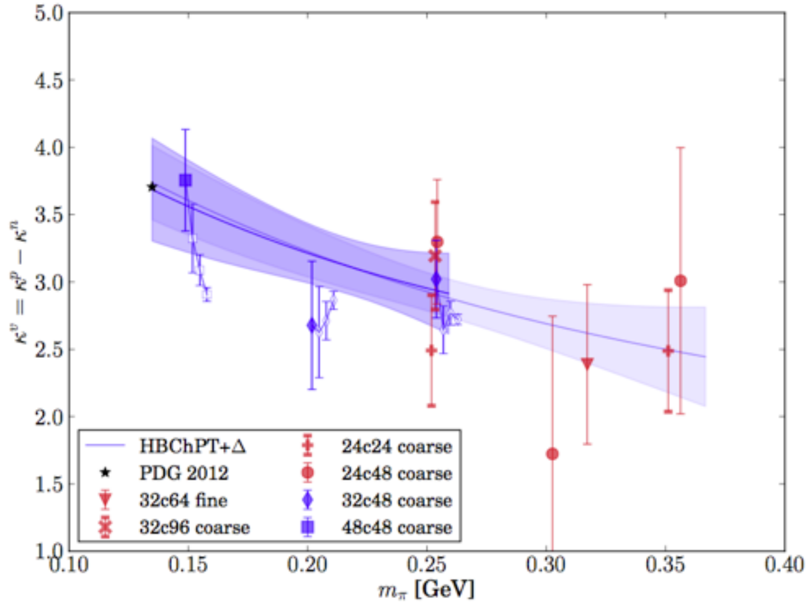


Isovector Charge Radius

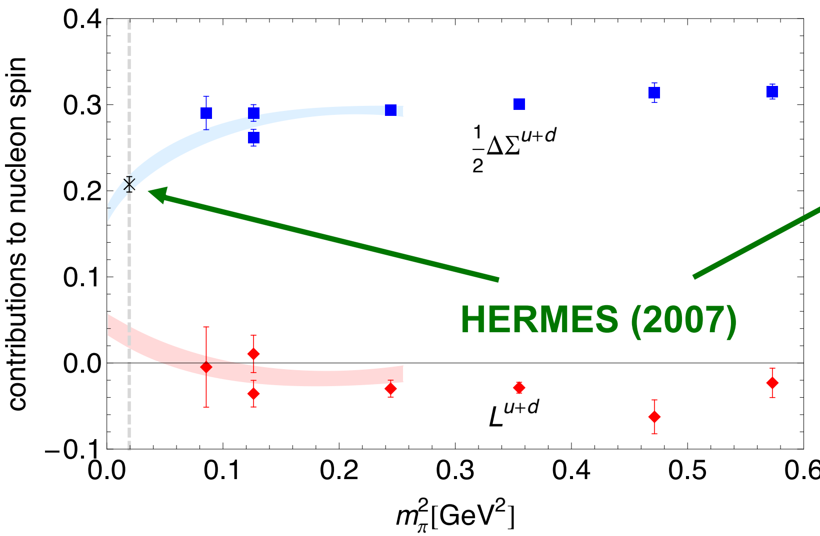


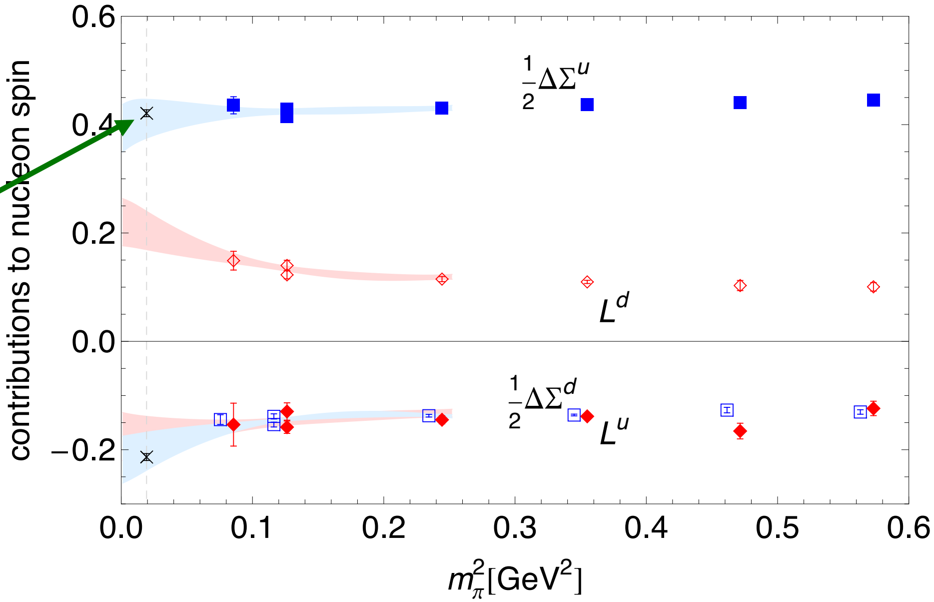
Green et al, arXiv:1404.40

Precision Calculations of the Fundamental Quantities in Nuclear Physics - **at physical quark masses**



Origin of Nucleon Spin



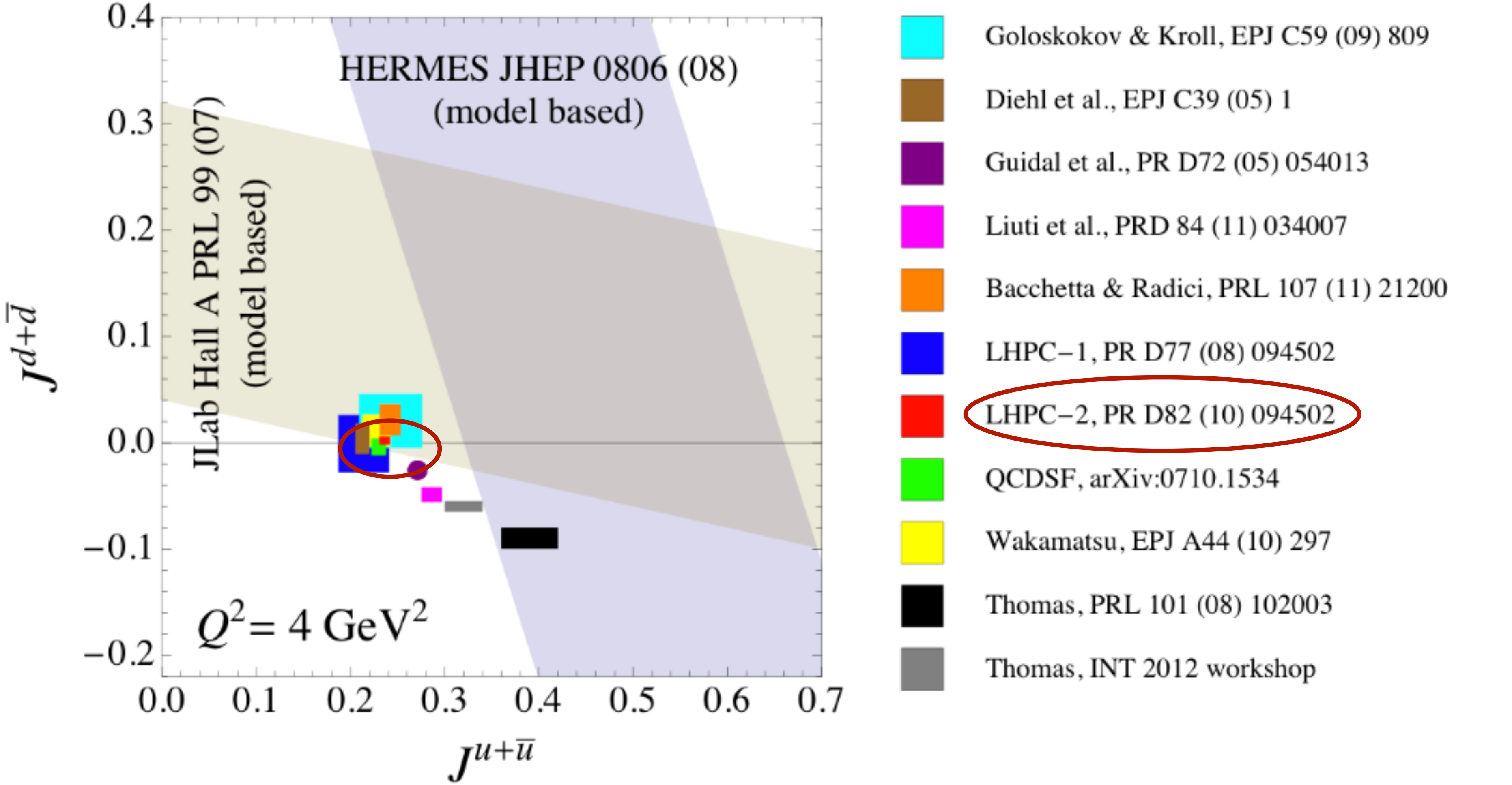


$$
\begin{aligned}
J^q &= 1/2\left(A_{20}^q(t=0)+B_{20}^q(t-0)\right)\\
\Delta\Sigma^q/2 &= \tilde{A}_{10}^q(t=0)/2\\
\frac{1}{2} &= \frac{1}{2}\Delta\Sigma^{u+d}+L^{u+d}+J^g
\end{aligned}
$$

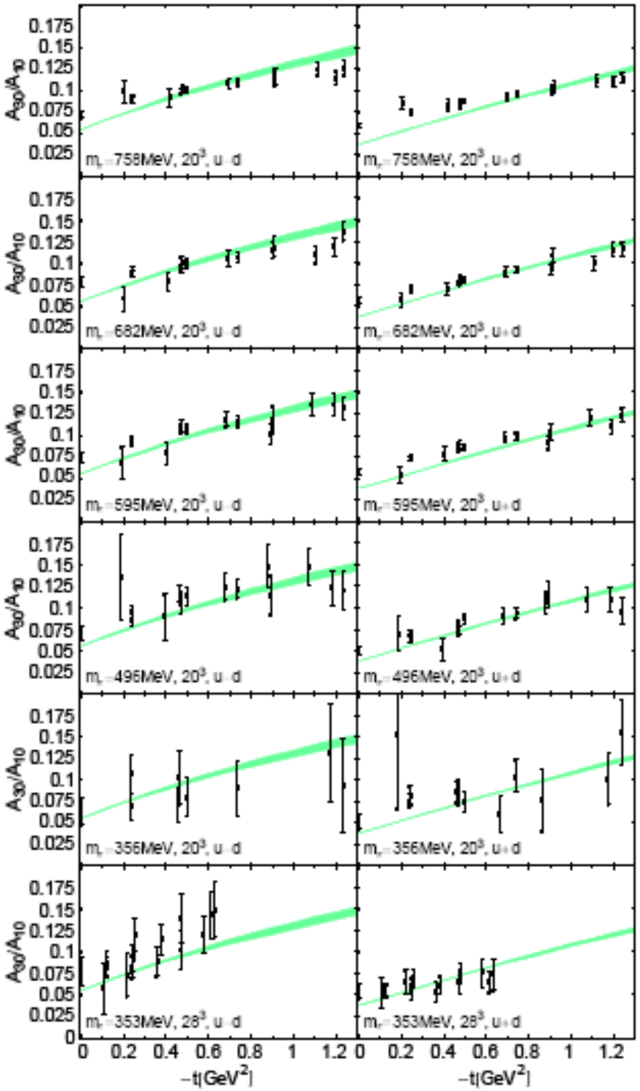
LHPC, Haegler et al., Phys. Rev. D 77, 094502 (2008); D82, 094502 (2010)

- **Total orbital angular momentum carried by quarks small**
- **Orbital angular momentum carried by individual quark flavors substantial.**

Origin of Nucleon Spin - II



Parametrizations of GPDs

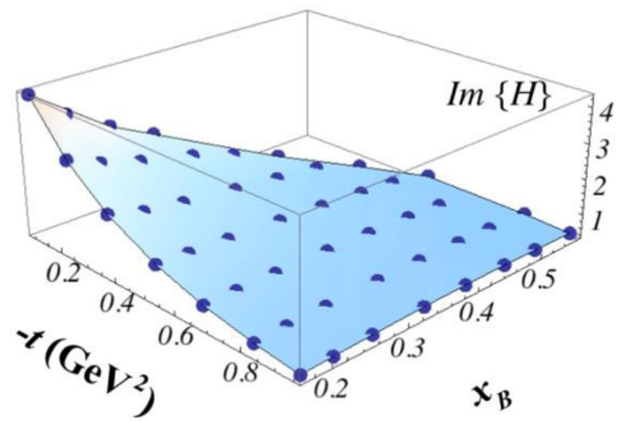


Provide phenomenological guidance for GPD's

- ***CTEQ, Nucleon Form Factors, Regge***

Comparison with *Diehl et al*, hep-ph/0408173

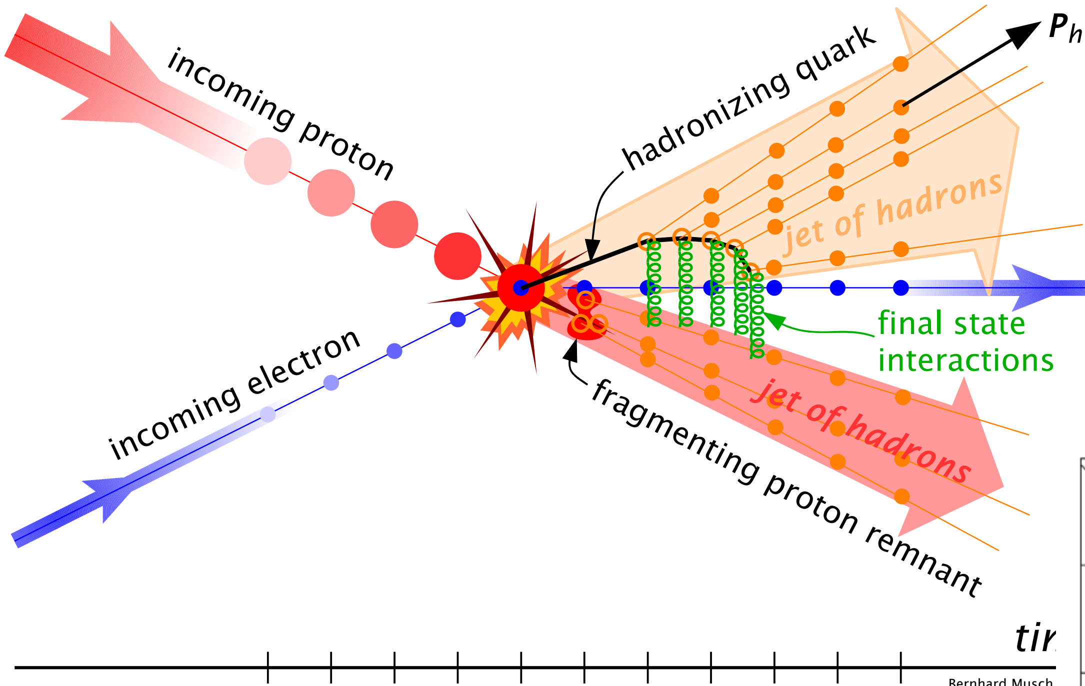
Important Role for LQCD



Transverse momentum distributions (TMDs)

from experiment, e.g., SIDIS (semi-inclusive deep inelastic scattering) + DY

HERMES, COMPASS, JLab 12 GeV , RHIC-spin, EIC, DY



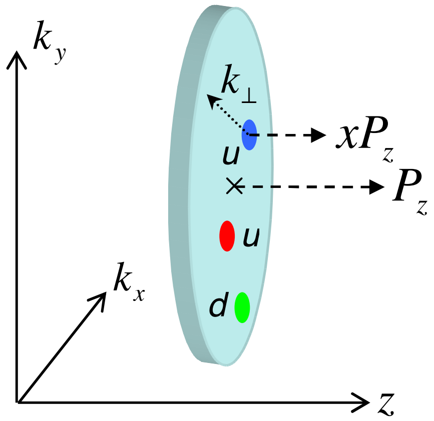
$N \backslash q$	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Boer-Mulders

Sivers ← time-reversal odd

final state interactions!
explain large asymmetries otherwise forbidden!
signature of QCD!

TMDs in Lattice QCD



B. Musch, PhD Thesis; Haegler, Musch, Negele, Schafer arXiv:0908.1283

Introduce Momentum-space correlators

$$\Phi_\Gamma = \int d(n\cdot k)\int \frac{d^4 l}{2(2\pi)^4} e^{-ik\cdot l}\tilde{\Phi}_\Gamma(l;P,S)$$

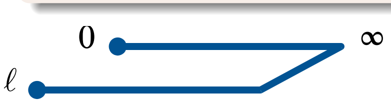
$$= \int d(n\cdot k)\int \frac{d^4 l}{2(2\pi)^4} e^{-ik\cdot l}\langle P,S \mid \bar{q}(l)\Gamma\mathcal{U}q(0) \mid P,S\rangle$$

continuum

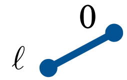
$$\mathcal{U} \equiv \mathcal{P}\exp\left(-ig\int_0^\ell d\xi^\mu A_\mu(\xi)\right)$$

along path from 0 to ℓ

Choice of path - retain gauge invariance



SIDIS: path runs to infinity

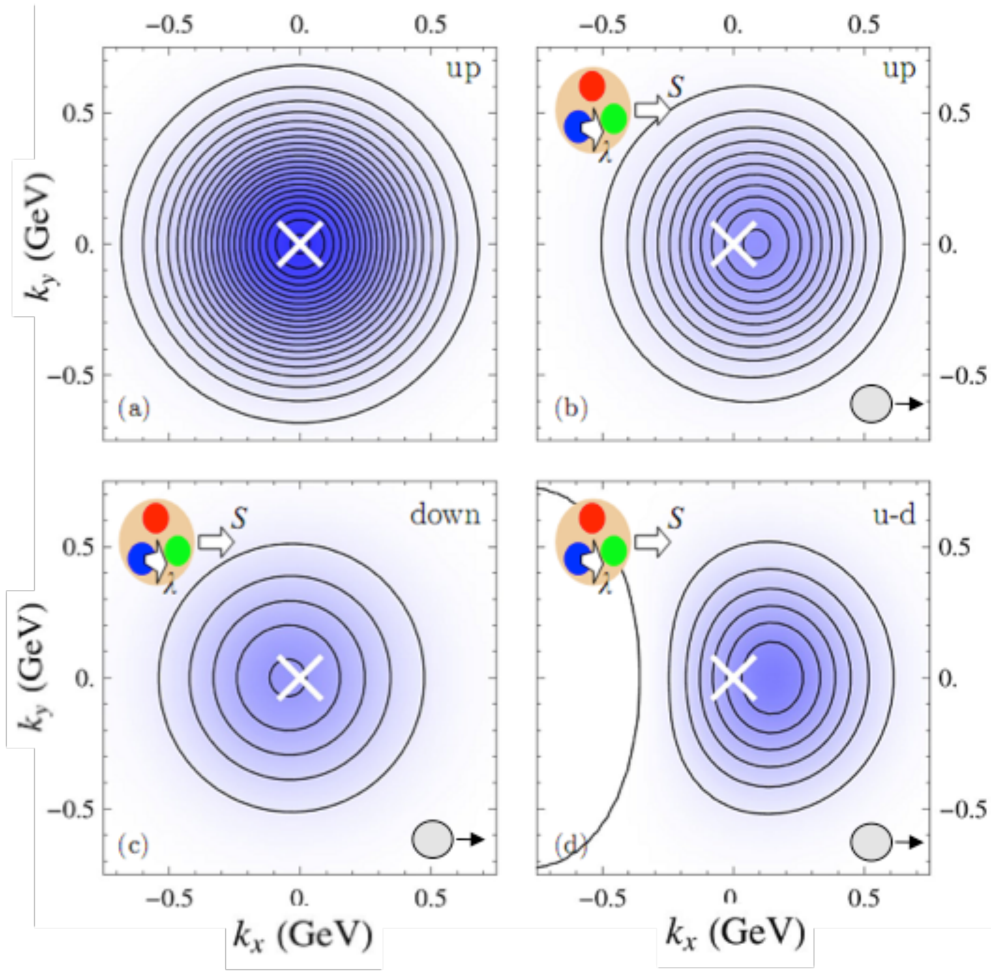


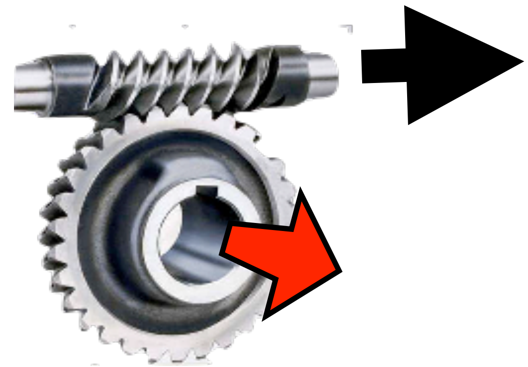
Lattice: equal time slice

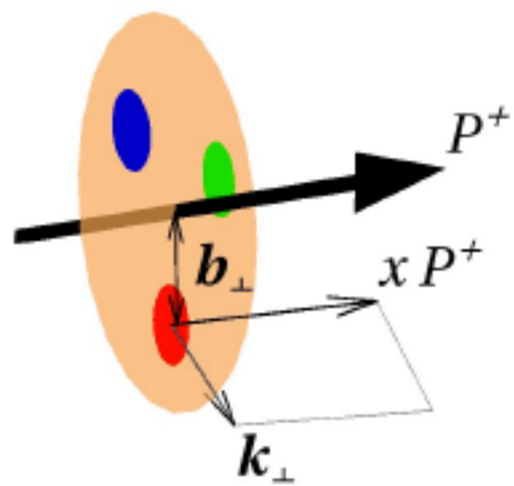
Slide: A. Bacchetta

Worm gears on the lattice

P. Hägler, B. U. Musch, J. W. Negele, and A. Schäfer, Europhys. Lett. 88 (2009) 61001

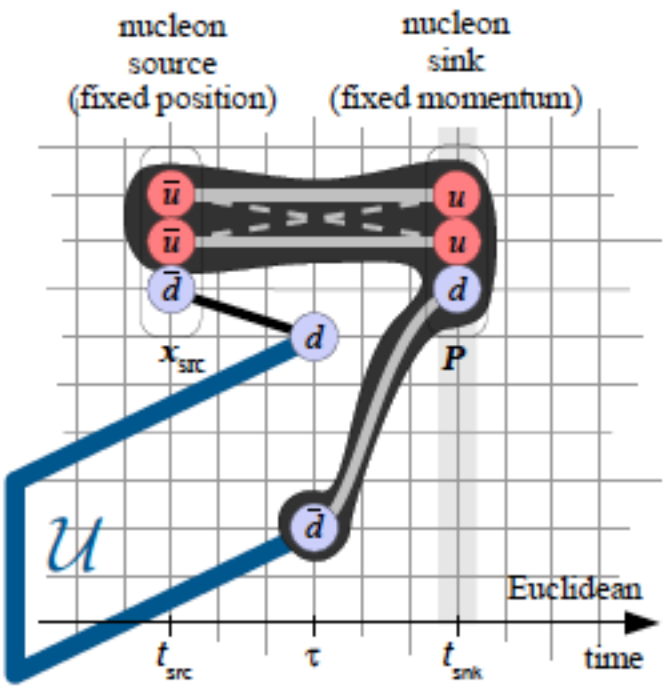




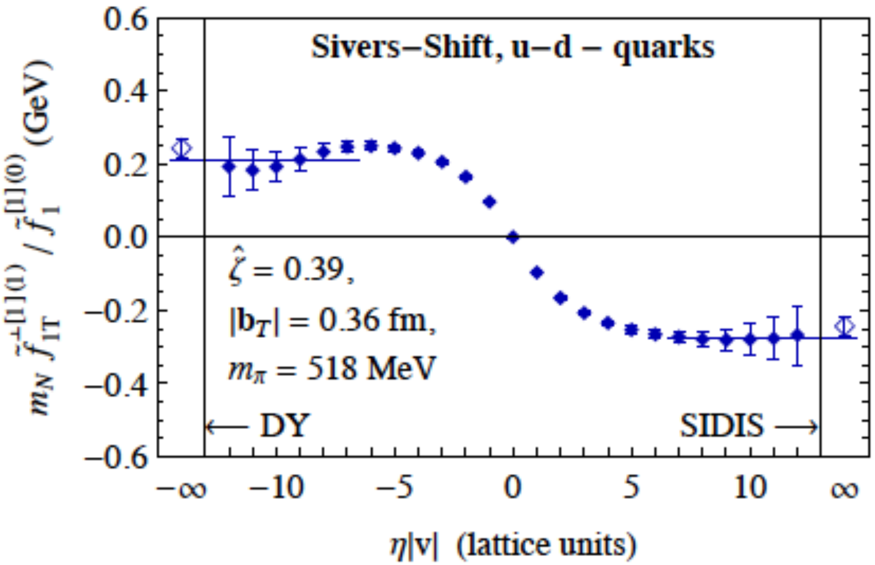


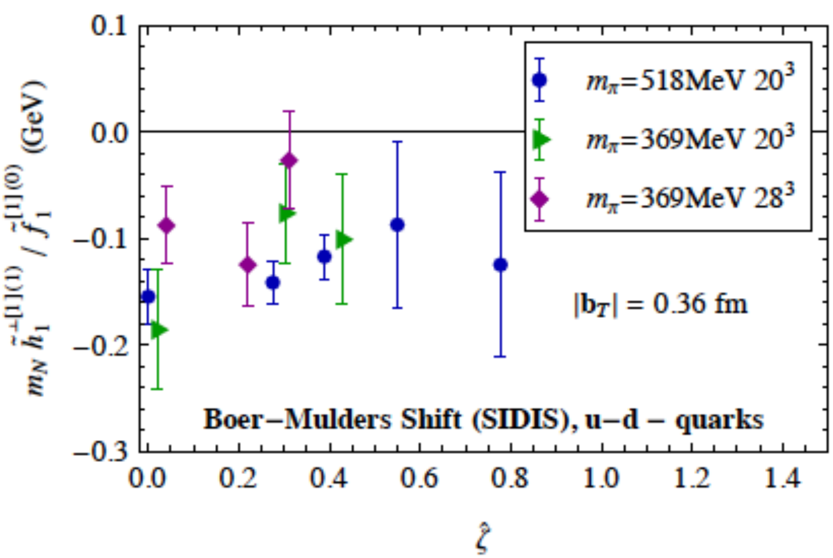
Transverse momentum distributions (TMDs)

Lattice QCD



B. Musch et al., Phys.Rev. D85 (2012) 094510;
M. Engelhardt, Lattice 2014

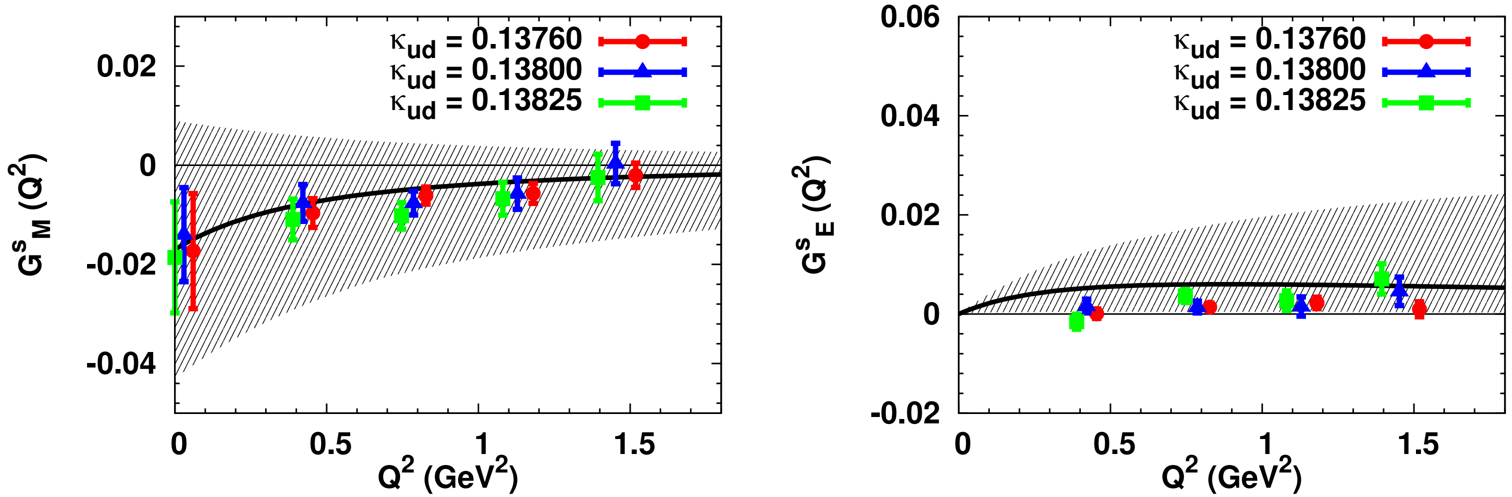




Flavour-separated Hadron Physics

Doi et al. (ChQCD Collaboration), arXiv:0910.2687, PRD79:094502,2009

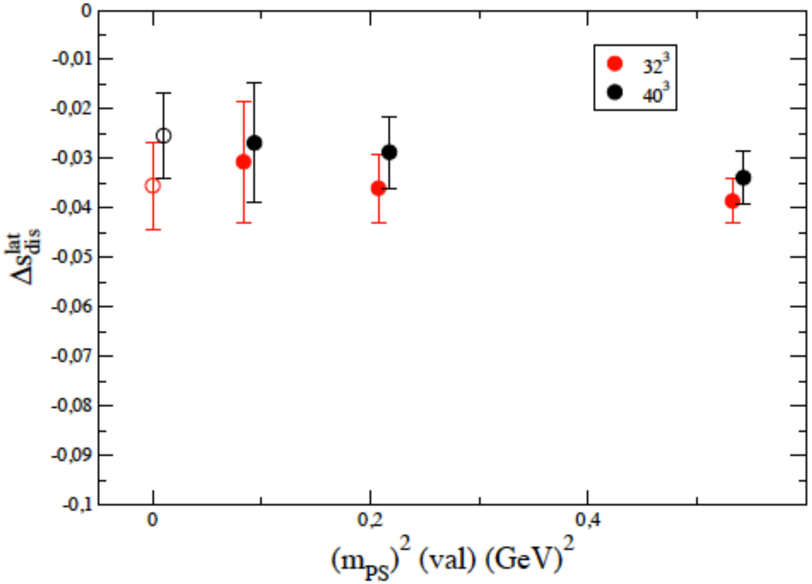
Strangeness contribution to electric and magnetic form factors.



Uncertainties: statistical, Q^2 dependence, chiral extrapolation

$$G^s_M(0) = -0.017(25)(07)$$

Strange-quark contribution to hadron spin



QCDSF, arXiv:1112.3354

$$\Delta s^{\overline{MS}}(\sqrt{7.4}\ \mathrm{GeV}) = -0.020(10)(4)$$

Small, negative contribution

In general, Quark and gluons mix under renormalization

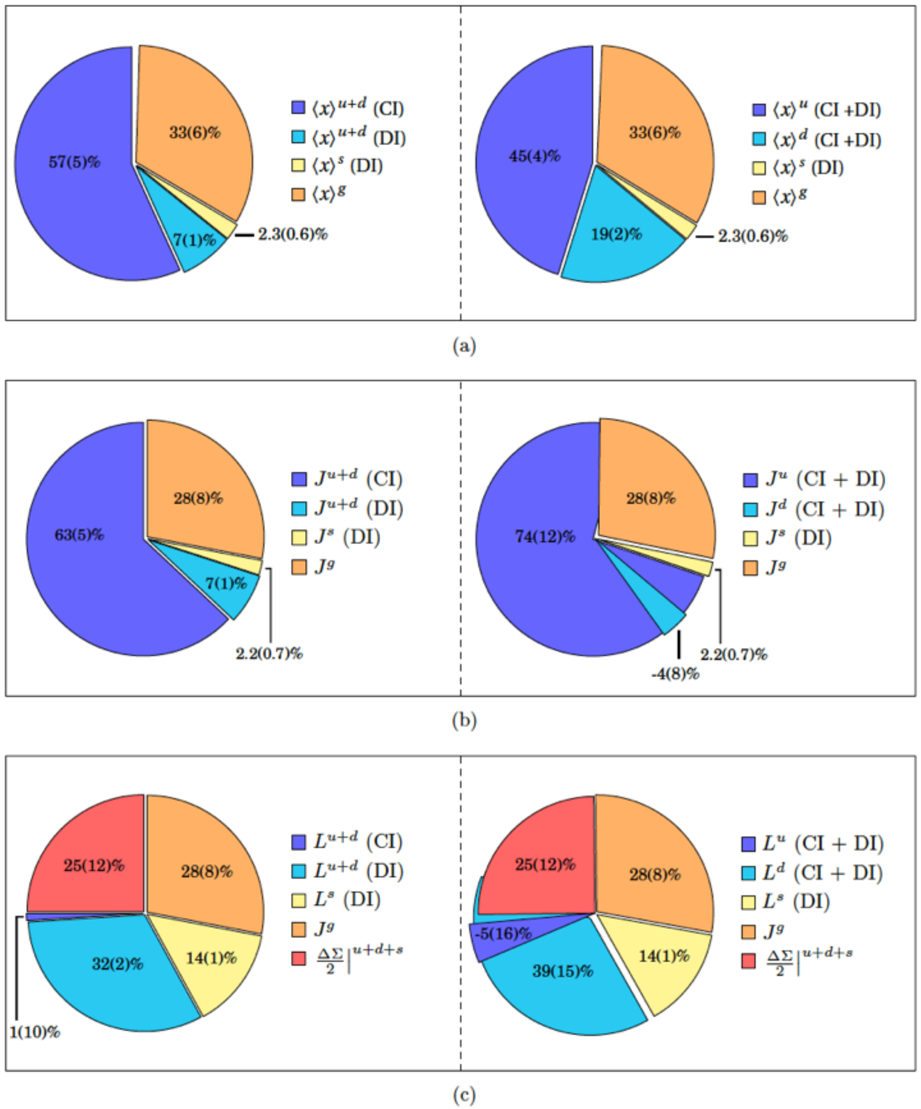
$$\frac{\partial}{\partial \ln \mu^2}\begin{pmatrix} q^S \\ g \end{pmatrix} = \frac{\alpha_s(\mu^2)}{2\pi}\begin{pmatrix} P_{qq} & 2n_f P_{qg} \\ P_{gq} & P_{gg} \end{pmatrix} \otimes \begin{pmatrix} q^S \\ g \end{pmatrix}$$

The local operators mix as follows:

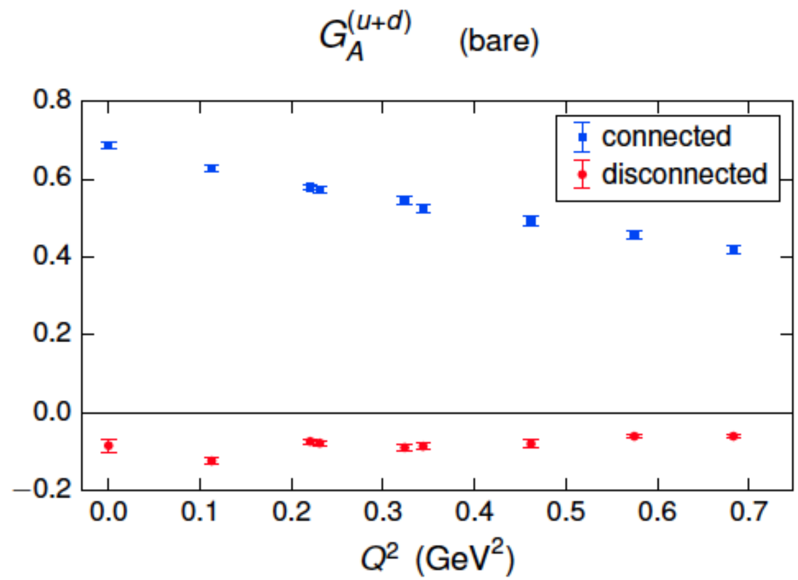
$$O^{qS}_{\mu_1\cdots\mu_N} = \frac{1}{2^N}\overline{\psi}\,\gamma_{[\mu_1}\overleftrightarrow{D}_{\mu_2}\cdots\overleftrightarrow{D}_{\mu_N]}\,(1\pm\gamma_5)\psi$$

$$O^{gS}_{\mu_1\cdots\mu_N} = \sum_\rho \mathrm{Tr}\left[F_{[\mu_1\rho}\overleftrightarrow{D}_{\mu_2}\cdots\overleftrightarrow{D}_{\mu_{N-1}}F_{\rho\mu_N]}\right]$$

Flavor-separated and Gluon Contributions



PRELIMINARY: S. Meinel, Lattice 2014



Complete calculation of flavor-separated and gluonic contributions to nucleon spin

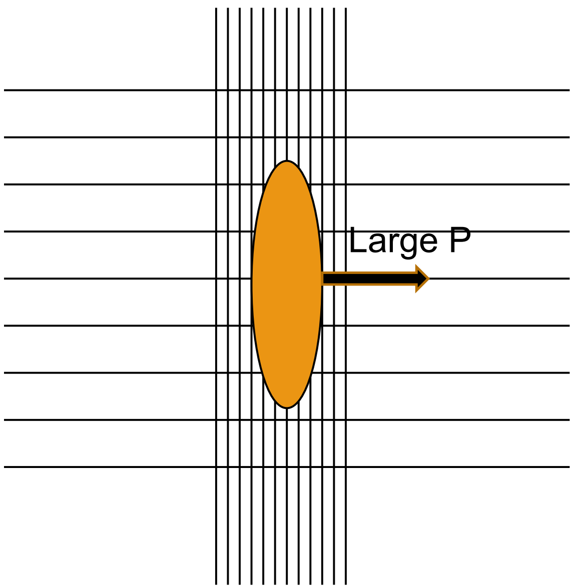
Deka et al, arXiv:1312.4816

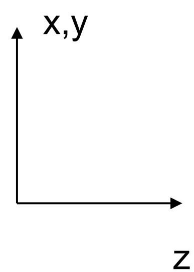
Parton Distributions in LQCD

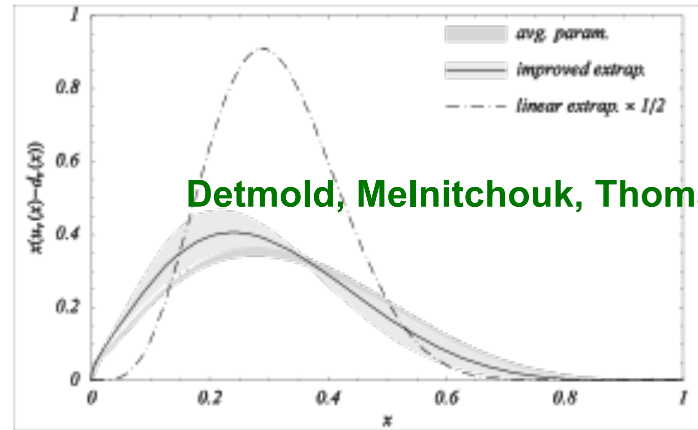
Formulation of LQCD in Euclidean space precludes direct calculation of light-cone correlation functions

→ LQCD computes Moments of parton distributions

New ideas: calculations of QUASI-distributions in *infinite-momentum frame*







Detmold, Melnitchouk, Thomas

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

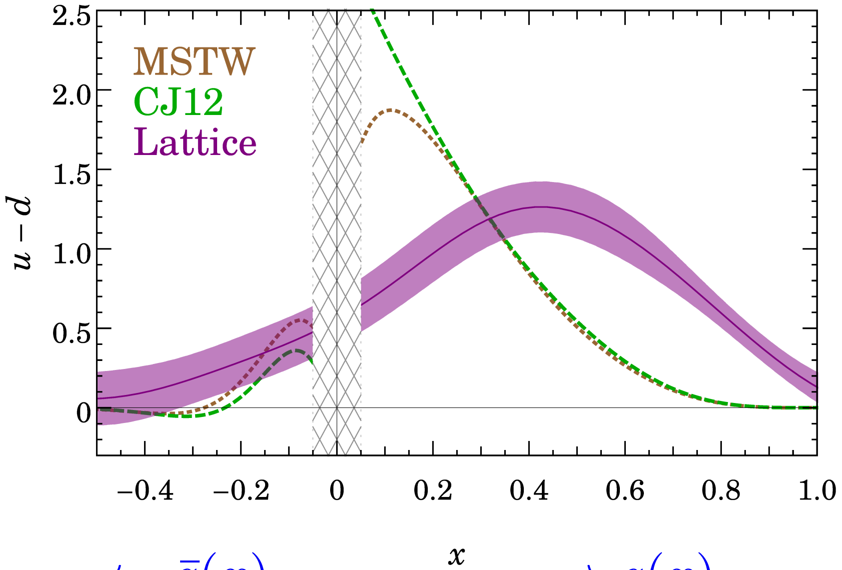
X. Ji, Phys. Rev. Lett. 110, 262002 (2013).
X. Ji, J. Zhang, and Y. Zhao, Phys. Rev. Lett. 111, 112002 (2013).
J. W. Qiu and Y. Q. Ma, arXiv:1404.686.

$$\tilde{q}(x,\mu,P_z) = \int \frac{dz}{4\pi} e^{-izk} \times \left\langle \vec{P} \middle| \bar{\psi}(z)\gamma_z e^{ig\int_0^z A_z(z')dz'}\psi(0) \middle| \vec{P} \right\rangle$$

"Equal time" correlator

...Flavor Structure

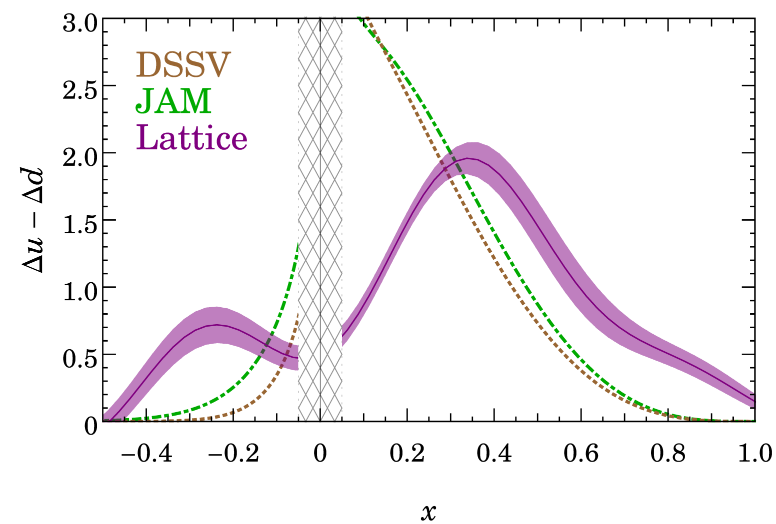
$$\tilde{q}(x,\mu,P_z) = \int \frac{dy}{|y|} Z\left(\frac{x}{y}, \frac{\mu}{P_z}\right) q(y,\mu) + \mathcal{O}\left(\frac{\Lambda^2_{\mathrm{QCD}}}{P_z^2}, \frac{M_N^2}{P_z^2}\right) + \ldots$$



$\leftarrow \bar{q}(x)$ $\rightarrow q(x)$

H.W. Lin et al, arXiv:1402.1462

First lattice calculations of Quasi Distributions

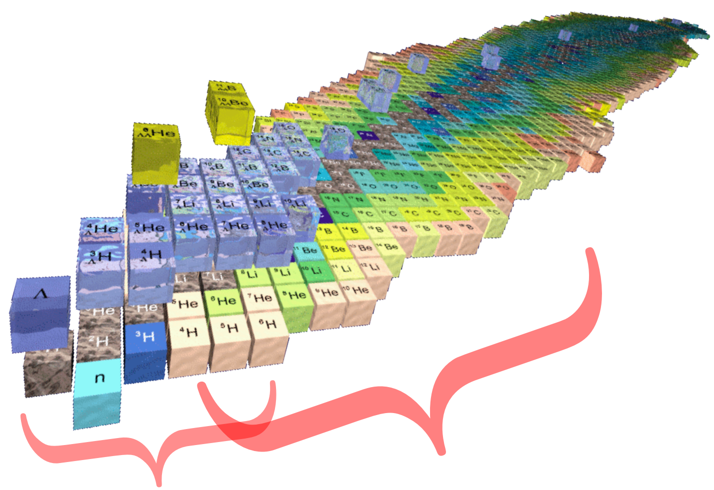


smallest $x \simeq 1/a$

12 GeV; Future EIC

Violation of Gottfried sum rule $\bar{d}(x) > \bar{u}(x)$

NN Interactions and Nuclei



(Lattice) QCD

Many-body methods, EFT, GFMC, NCSM..

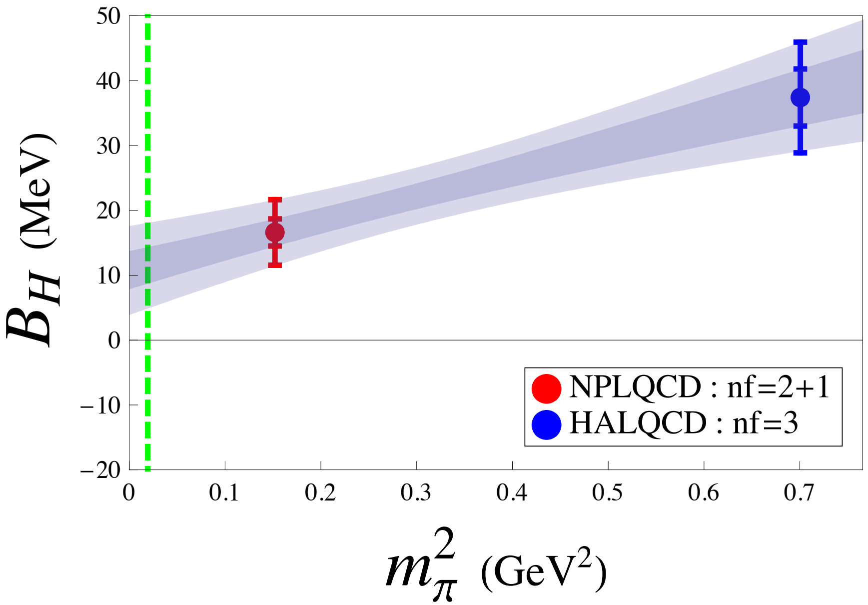
H-Dibaryon

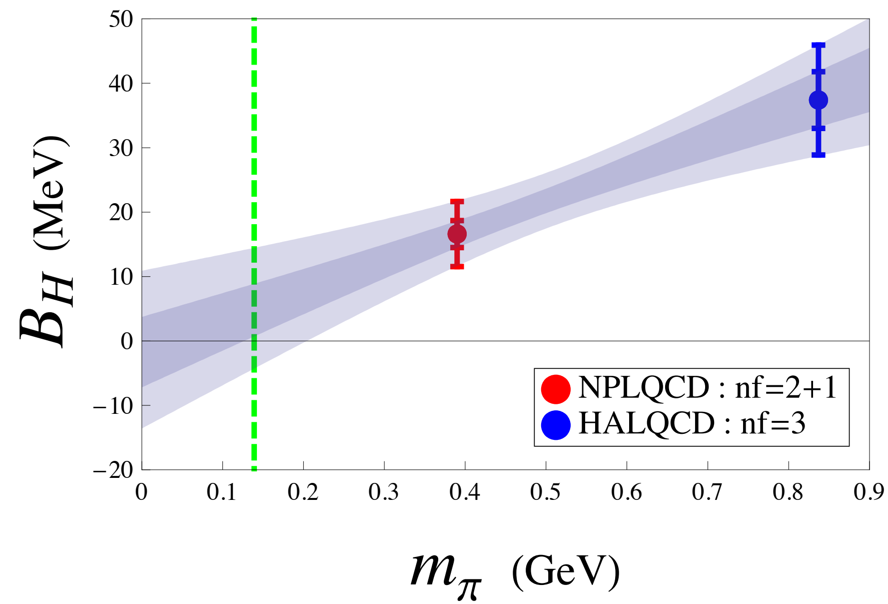
Bound state of two (strange) baryons
uuddss, originally proposed by Jaffe (1977)

Physical Review Letters
moving physics forward

Evidence for a Bound *H* Dibaryon from Lattice QCD

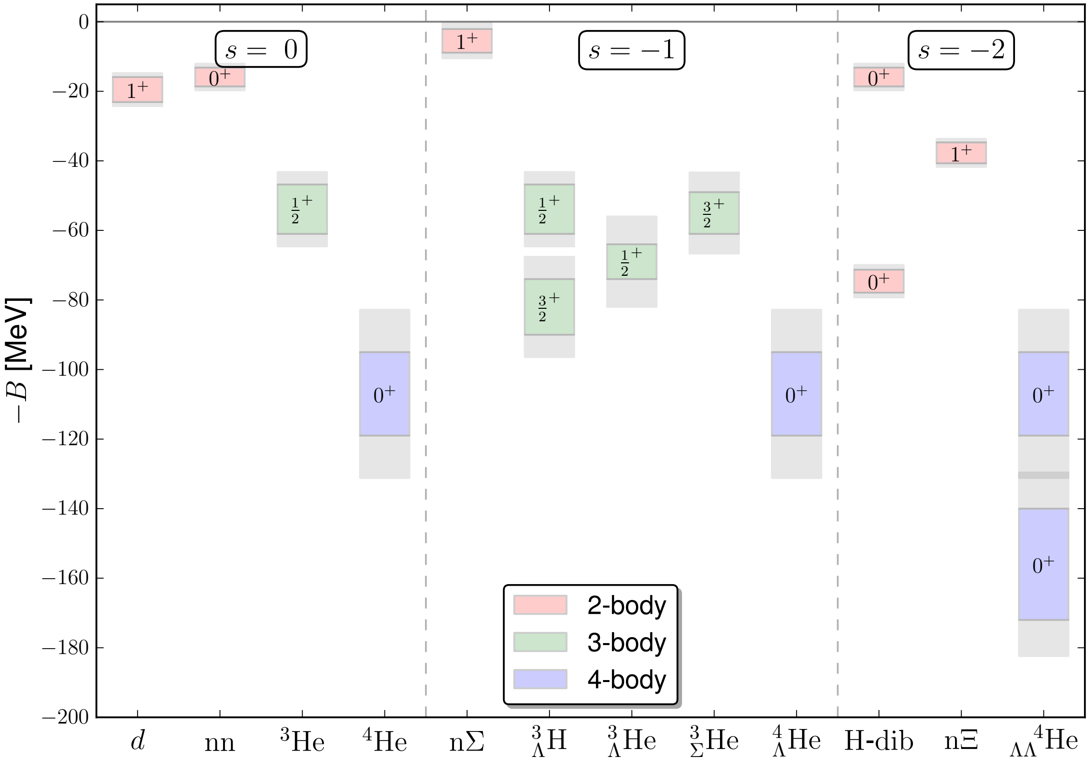
S. R. Beane,[1,2] E. Chang,[3] W. Detmold,[4,5] B. Joo,[5] H. W. Lin,[6] T. C. Luu,[7] K. Orginos,[4,5] A. Parreño,[3] M. J. Savage,[6]
A. Torok,[8] and A. Walker-Loud[9]





Evidence for weakly bound or just unbound dibaryon

Nuclear Physics from QCD is Possible!



Binding energies at physical strange-quark mass

PHYSICAL REVIEW D **87**, 034506 (2013)

Light nuclei and hypernuclei from quantum chromodynamics in the limit of SU(3) flavor symmetry

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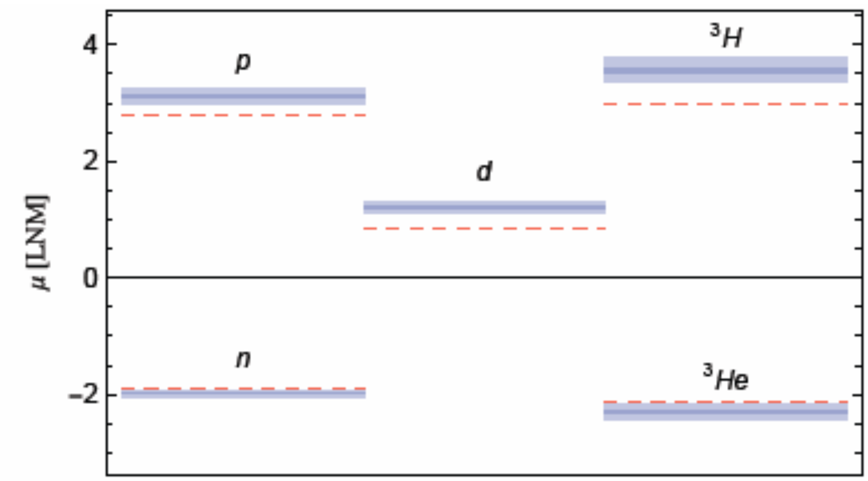
The Structure of Hadrons in Nuclei

- How is the structure of a hadron modified "in medium"?
- Calculation of magnetic moments of lightest nuclei.

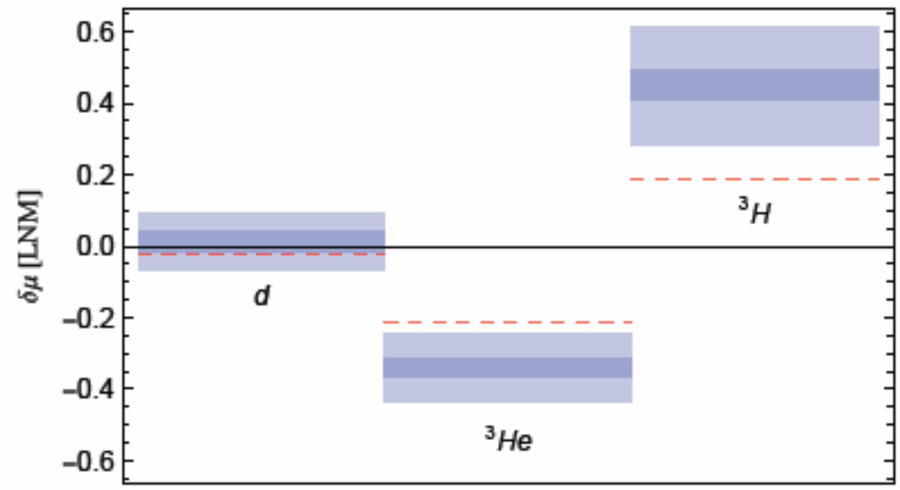


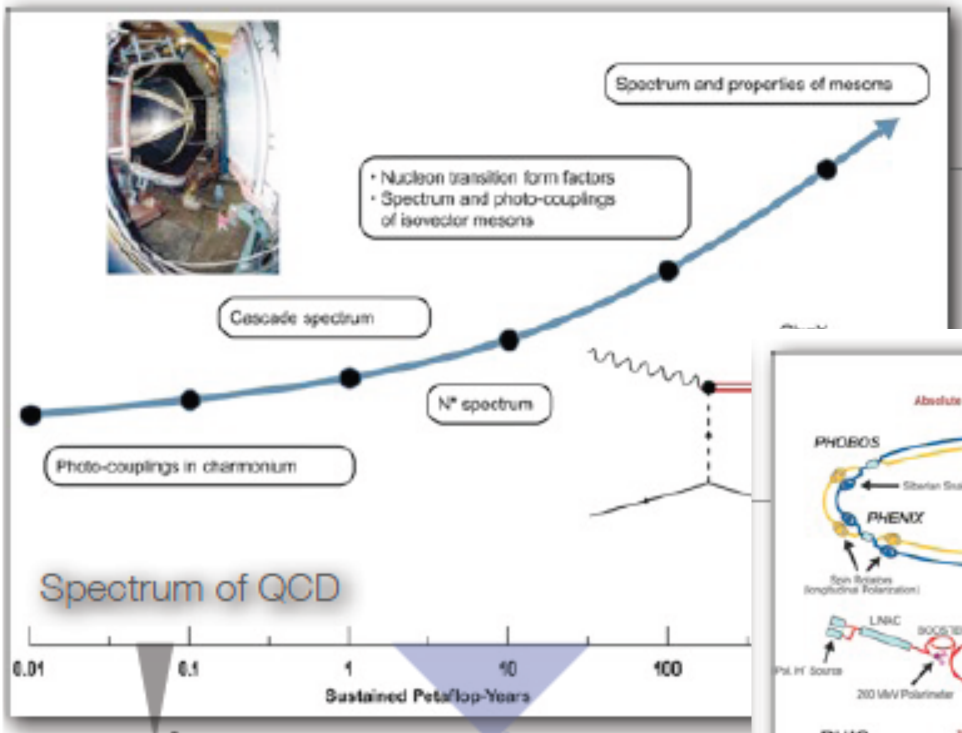
Experimentally measured values

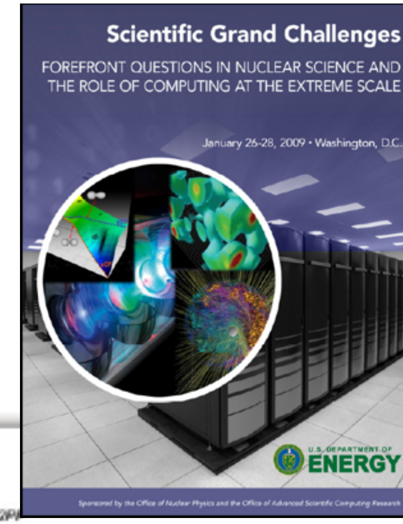
NPLQCD, arXiv:1409.3556

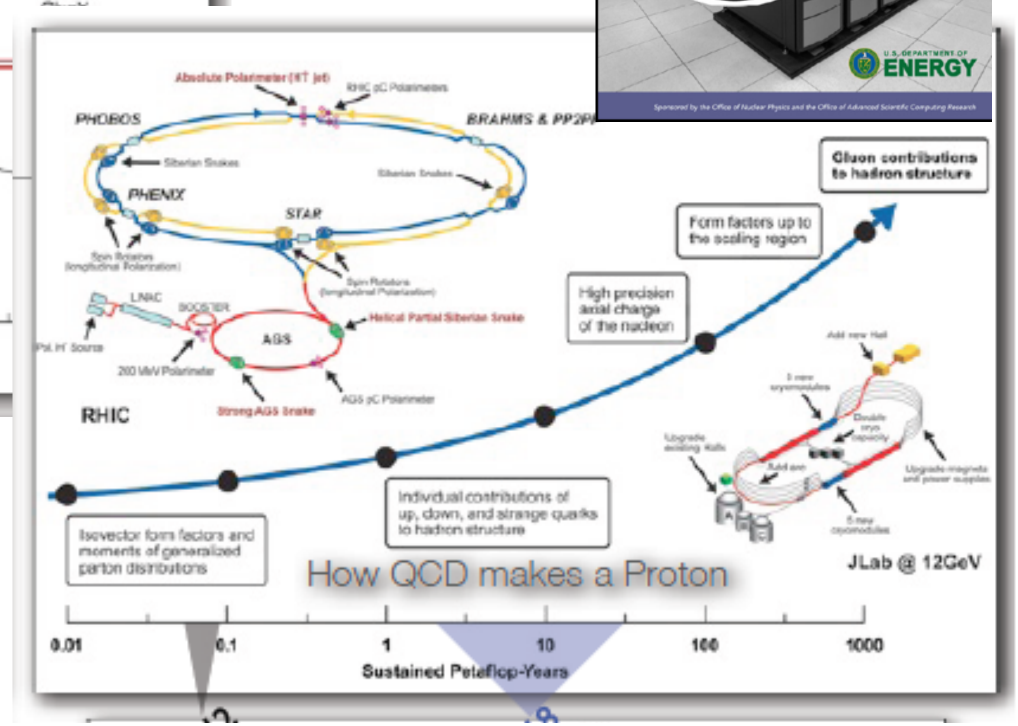
$m_\pi \simeq 800\ \mathrm{MeV}$

Differences from naive shell model









http://www.usqcd.org/documents/13nuclear.pdf

SUMMARY

“Person, Moment, Machine”

Amalgam of new ideas, algorithmic advances, and peta- and exa-scale computers: lattice QCD essential to fulfill NP mission.

- **Spectrocopy**: Calculations of resonances that can confront experimental analysis. Electromagnetic Properties.
- **Structure:** Calculations of the fundamental properties *at the physical quark masses.* GPDs, TMDs, + “Lattice QCD + Expt greater than each alone”.
- An ab initio understanding of the NN interactions - ***properties of hadrons in nuclei***