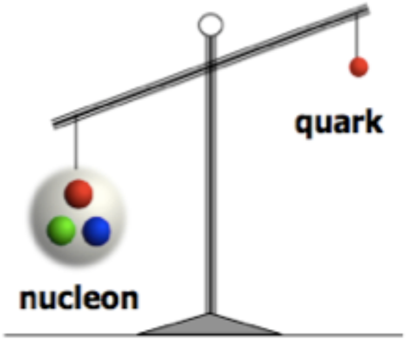
Summary of the Proton Mass Workshop

Jianwei Qiu
Brookhaven National Laboratory

The Proton Mass Workshop at Temple University (March 28-29, 2016):
https://phys.cst.temple.edu/~meziani/proton-mass-workshop-2016/

Proton Mass

- Nucleon mass – dominates the mass of visible world:



$m_q \sim$ few MeV — Current quark mass

$m_N \sim 1000$ MeV — $\sim 1\%$ proton's mass!

Higgs mechanism is not enough!!!

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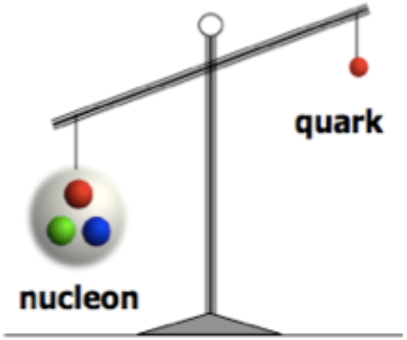

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- How does QCD generate the nucleon mass?

"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"

REACHING FOR THE HORIZON
The 2015 Long Range Plan for Nuclear Science

Proton Mass

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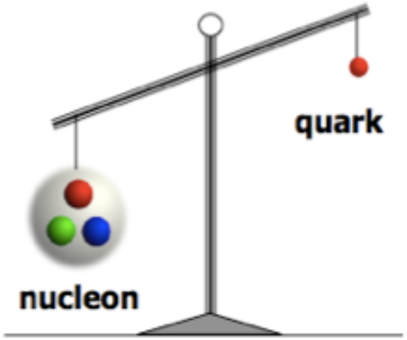

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REACHING FOR THE HORIZON
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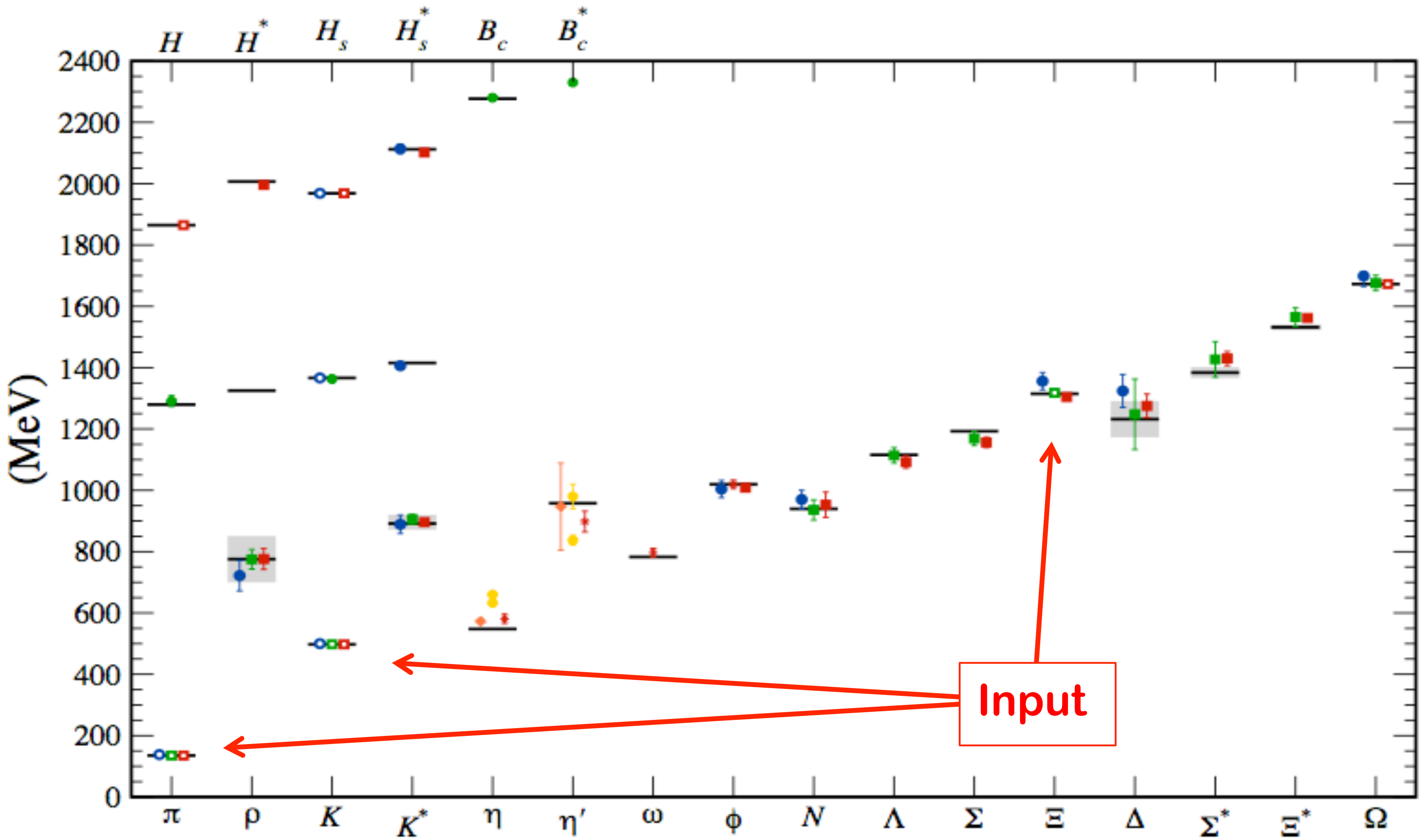
How to quantify and verify this, theoretically and experimentally?

Hadron Mass from Lattice QCD

❑ Hadron mass from Lattice QCD calculation:



A major success of QCD – is the right theory for the Strong Interaction!

How does QCD generate this? The role of quarks vs that of gluons?

Mass vs. Spin

- **Mass – intrinsic to a particle:**

  = Energy of the particle when it is at the rest

  - **QCD energy-momentum tensor in terms of quarks and gluons**

$$T^{\mu\nu} = \frac{1}{2}\,\overline{\psi}\, i\overleftrightarrow{D}^{(\mu}\gamma^{\nu)}\psi + \frac{1}{4}\,g^{\mu\nu}F^2 - F^{\mu\alpha}F^{\nu}{}_{\alpha}$$

  - **Proton mass:**

$$m = \frac{\langle p|\int d^3x\, T^{00}\,|p\rangle}{\langle p|p\rangle} \sim \mathrm{GeV}$$

X. Ji, PRL (1995)

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$$m = \frac{\langle p|\int d^3x\, T^{00}\,|p\rangle}{\langle p|p\rangle} \sim \text{GeV}$$

X. Ji, PRL (1995)

❑ Spin – intrinsic to a particle:

= Angular momentum of the particle when it is at the rest

✧ QCD angular momentum density in terms of energy-momentum tensor

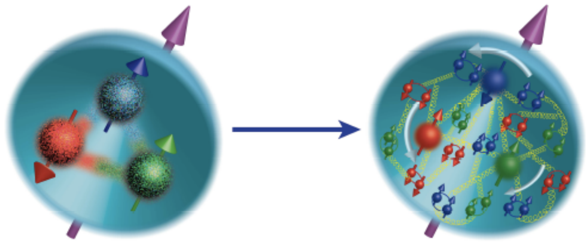
$$M^{\alpha\mu\nu} = T^{\alpha\nu}x^{\mu} - T^{\alpha\mu}x^{\nu} \qquad J^i = \frac{1}{2}\epsilon^{ijk}\int d^3x M^{0jk}$$

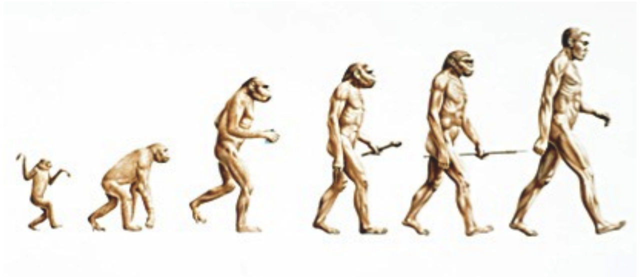
✧ Proton spin:

$$S(\mu) = \sum_f \langle P,S|\hat{J}^z_f(\mu)|P,S\rangle = \frac{1}{2}$$

Hadron Spin

- ❑ **Proton's spin:**





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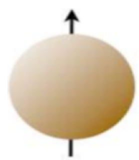

Proton Spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g)$$

Hadron Spin

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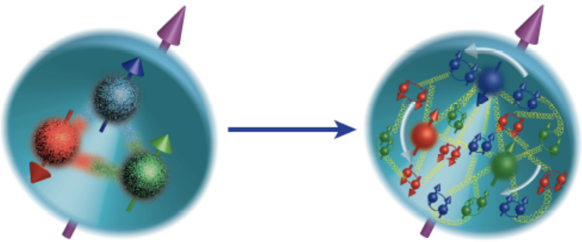

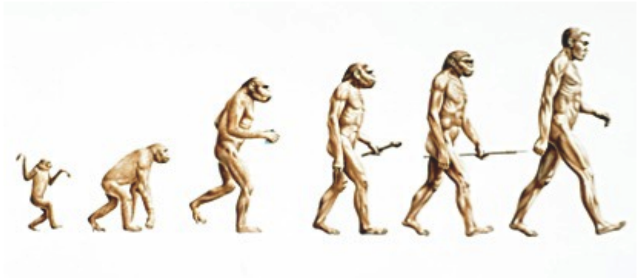

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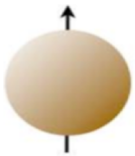

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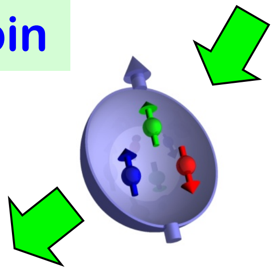


Quark helicity
Best known

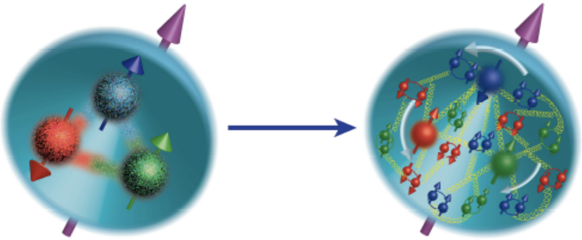
$$\frac{1}{2}\int dx \left(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right)$$

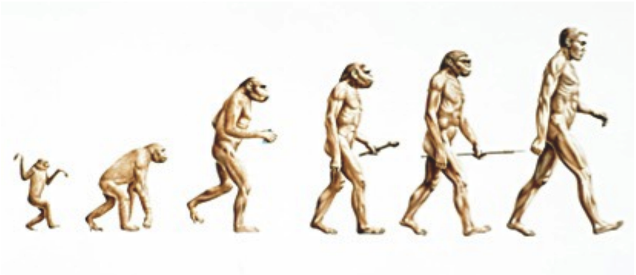
$$\sim 30\%$$

Spin "puzzle"

Hadron Spin

- Proton's spin:





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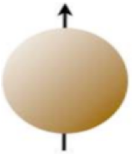

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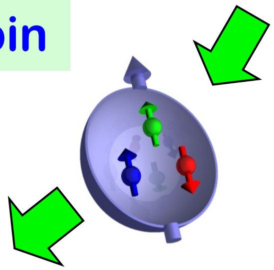

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Hadron Spin

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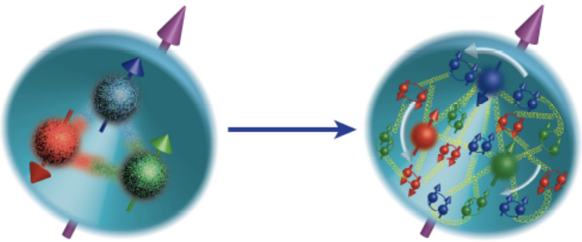

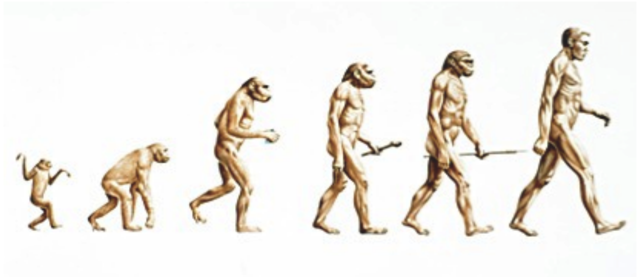

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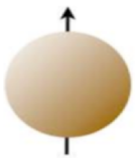

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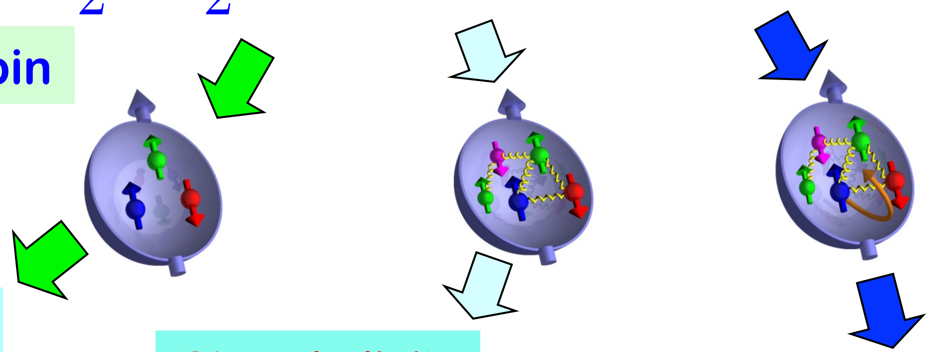

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Hadron Spin

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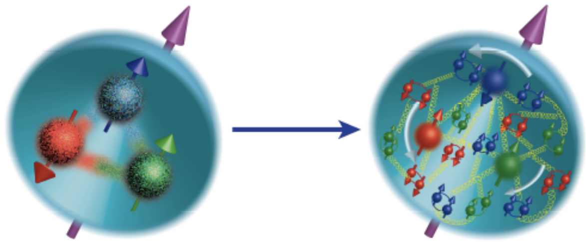

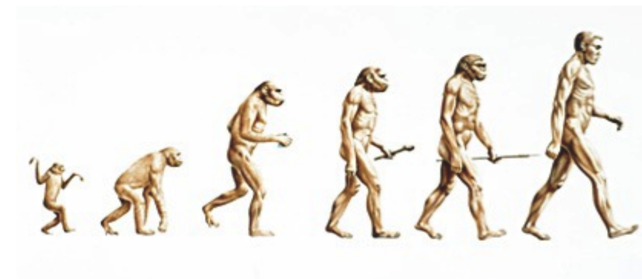

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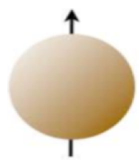

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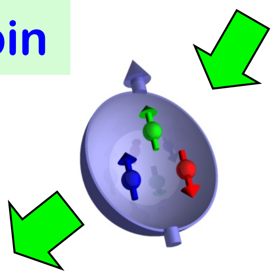

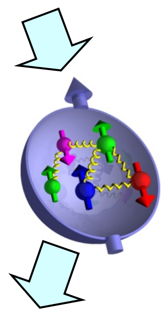

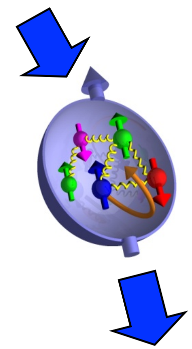

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Orbital Angular Momentum of quarks and gluons
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If we do not understand proton spin, we do not understand QCD

Hadron Mass

- **Three-pronged approach to explore the origin of hadron mass**
  - **Lattice QCD**
  - **Mass decomposition – roles of the constituents**
  - **Model calculation – approximated analytical approach**

https://phys.cst.temple.edu/meziani/proton-mass-workshop-2016/

Hadron Mass

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Speakers

Stan Brodsky (SLAC)
Xiandong Ji (Maryland)
Dima Kharzeev (Stony Brook & BNL)
Keh-Fei Liu (University of Kentucky)
David Richards (JLab)
Craig Roberts (ANL)
Martin Savage (University of Washington)
Stepan Stepanyan (JLab)
George Sterman (Stony Brook)

Moderator

Alfred Mueller (Columbia)

Local Organizers

Zein-Eddine Meziani (Temple U.)
Jianwei Qiu (Brookhaven National Lab)

Participants

Name	Email	Affiliation
Stanley J. Brodsky	sjbth@slac.stanford.edu	SLAC National Accelera
Leonard Gamberg	lpg10@psu.edu	Penn State University Be
Xiangdong Ji	xji@umd.edu	University of Maryland
Sylvester Joosten	sylvester.joosten@temple.edu	Temple University
Dmitri Kharzeev	dmitri.kharzeev@stonybrook.edu	Stony Brook University
Keh-Fei Liu	liu@pa.uky.edu	University of Kentucky
Andreas Metz	metza@temple.edu	Department of Physics, '
Zein-Eddine Meziani	meziani@temple.edu	Temple University
Alfred Mueller	amh@phys.columbia.edu	Columbia University
Berndt Mueller	mueller@bnl.gov	BNL
Jim Napolitano	tuf43817@temple.edu	Temple University
Jianwei Qiu	jqiu@bnl.gov	Brookhaven National La
David Richards	dgr@jlab.org	Jefferson Lab
Craig Roberts	cdroberts@anl.gov	Argonne National Labor
Martin Savage	mjs5@uw.edu	Institute for Nuclear The
Nikos Sparveris	sparveri@temple.edu	Temple University
Stepan Stepanyan	stepanyan@jlab.org	Jefferson Lab
George Sterman	george.sterman@stonybrook.edu	Stony Brook University
Bernd Surrow	surrow@temple.edu	Temple University
Yi-Bo Yang	ybyang@pa.uky.edu	University of Kentucky

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Hadron Mass

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  - ✧ Lattice QCD
  - ✧ Mass decomposition – roles of the constituents
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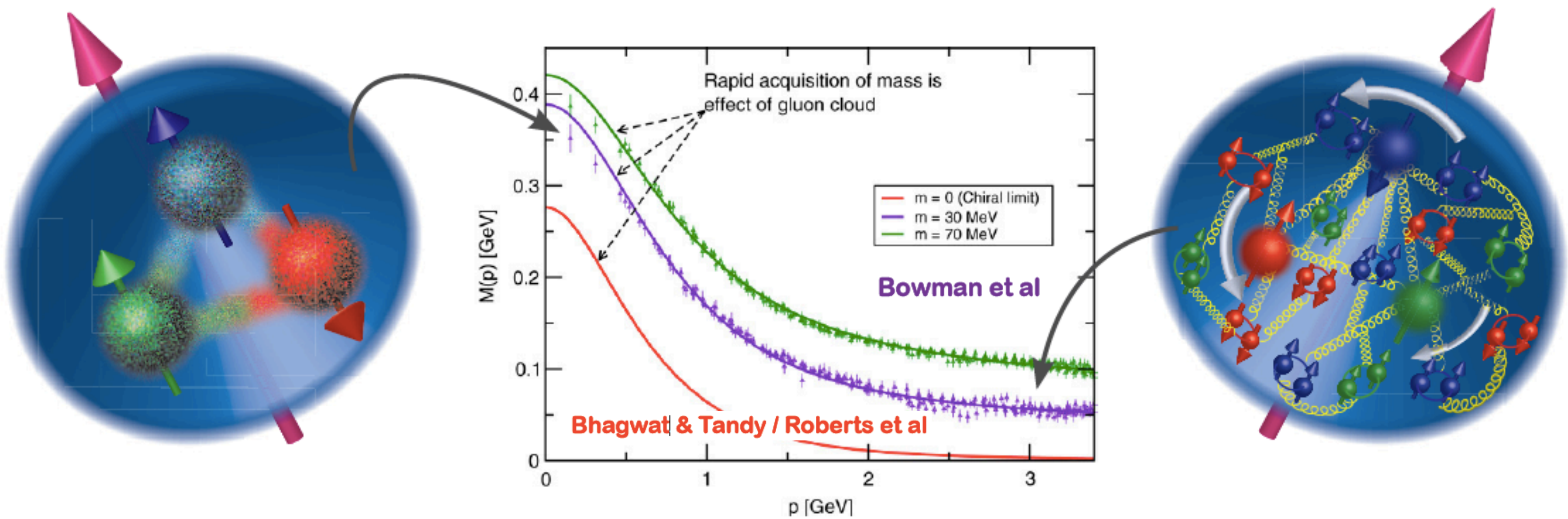


$$M_p = 2m_u^{\text{eff}} + m_d^{\text{eff}}$$

$$H_{\text{QCD}} = H_q + H_m + H_g + H_a$$

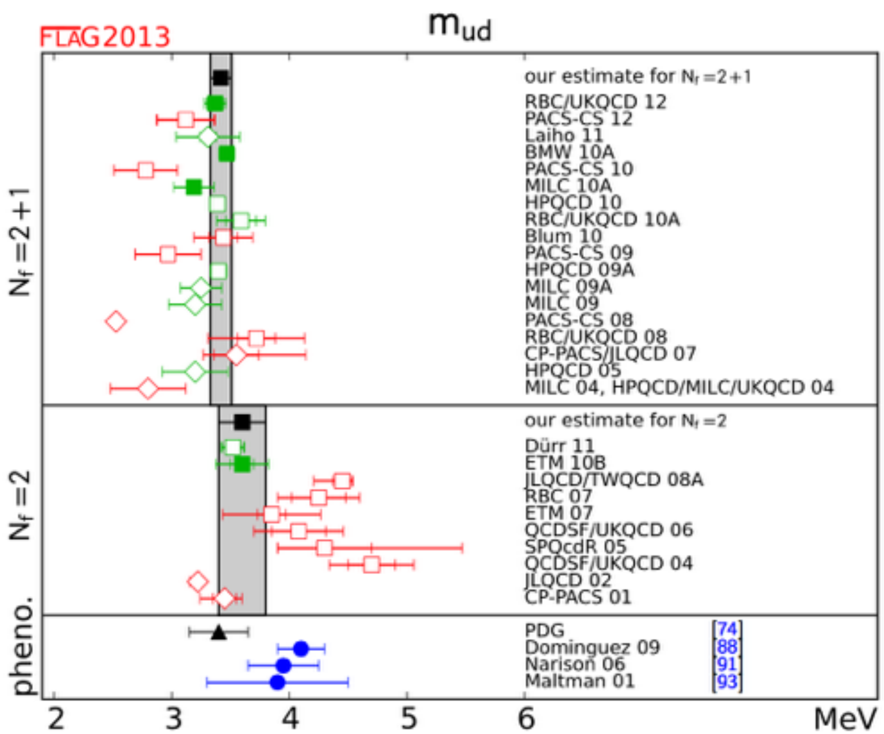
https://phys.cst.temple.edu/meziani/proton-mass-workshop-2016/

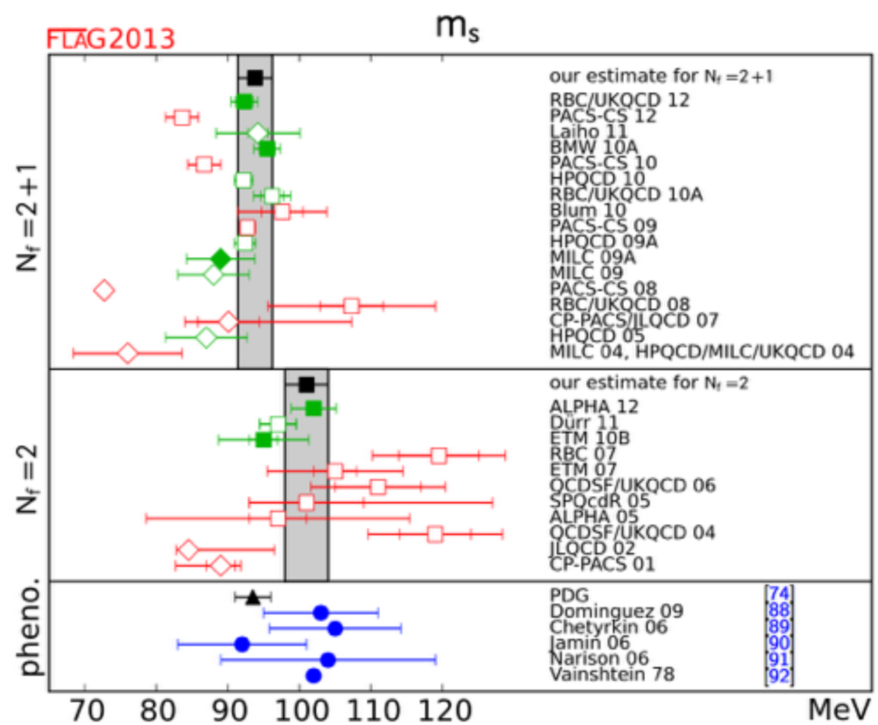
Lattice QCD calculation

Martin Savage (U of Washington)

David Richards (Jlab)

- **Quark masses:**





N_f	m_u	m_d	m_u/m_d
2+1	2.16(9)(7)	4.68(14)(7)	0.46(2)(2)
2	2.40(23)	4.80(23)	0.50(4)

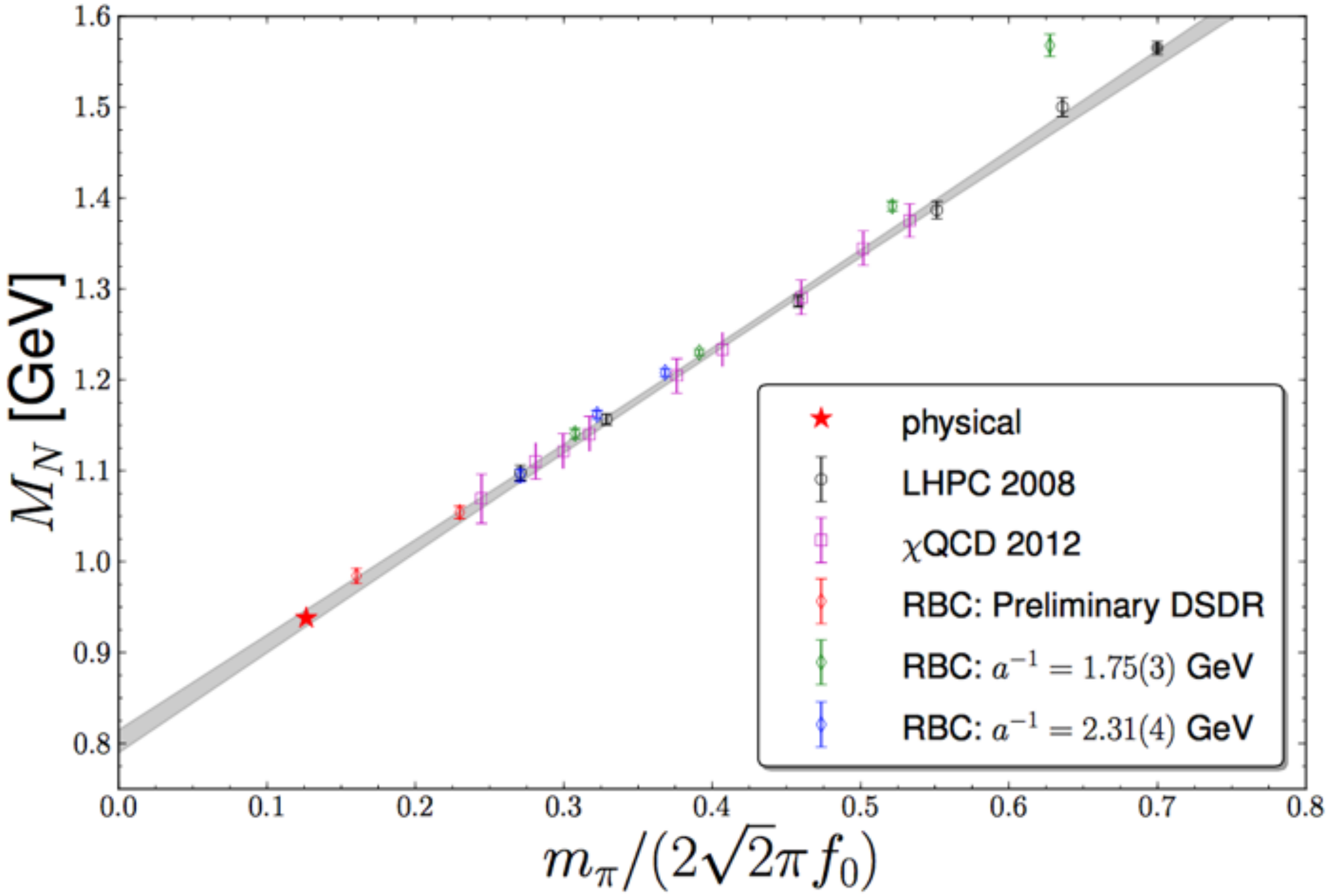
$$\overline{\mathrm{MS}}\ ,\ \mu = 2\ \mathrm{GeV}$$

Lattice QCD calculation

❑ **Nucleon mass:**

Martin Savage (U of Washington)

David Richards (Jlab)



$$M_N = 800 \text{ MeV} + m_\pi$$

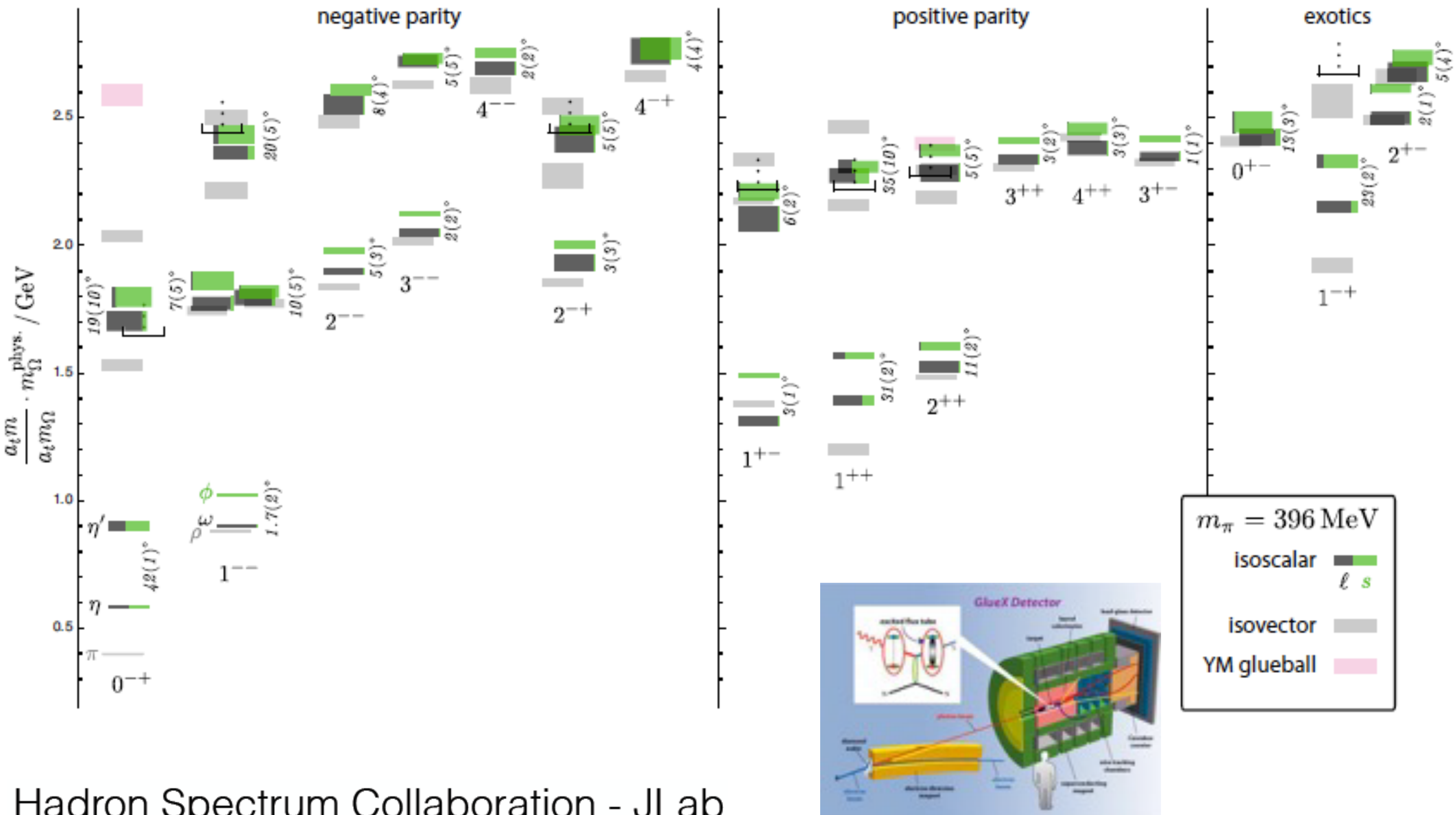
Unexpected behavior !!

Lattice QCD calculation

❑ Excited Meson Spectrum - Exotics:

Martin Savage (U of Washington)

David Richards (Jlab)



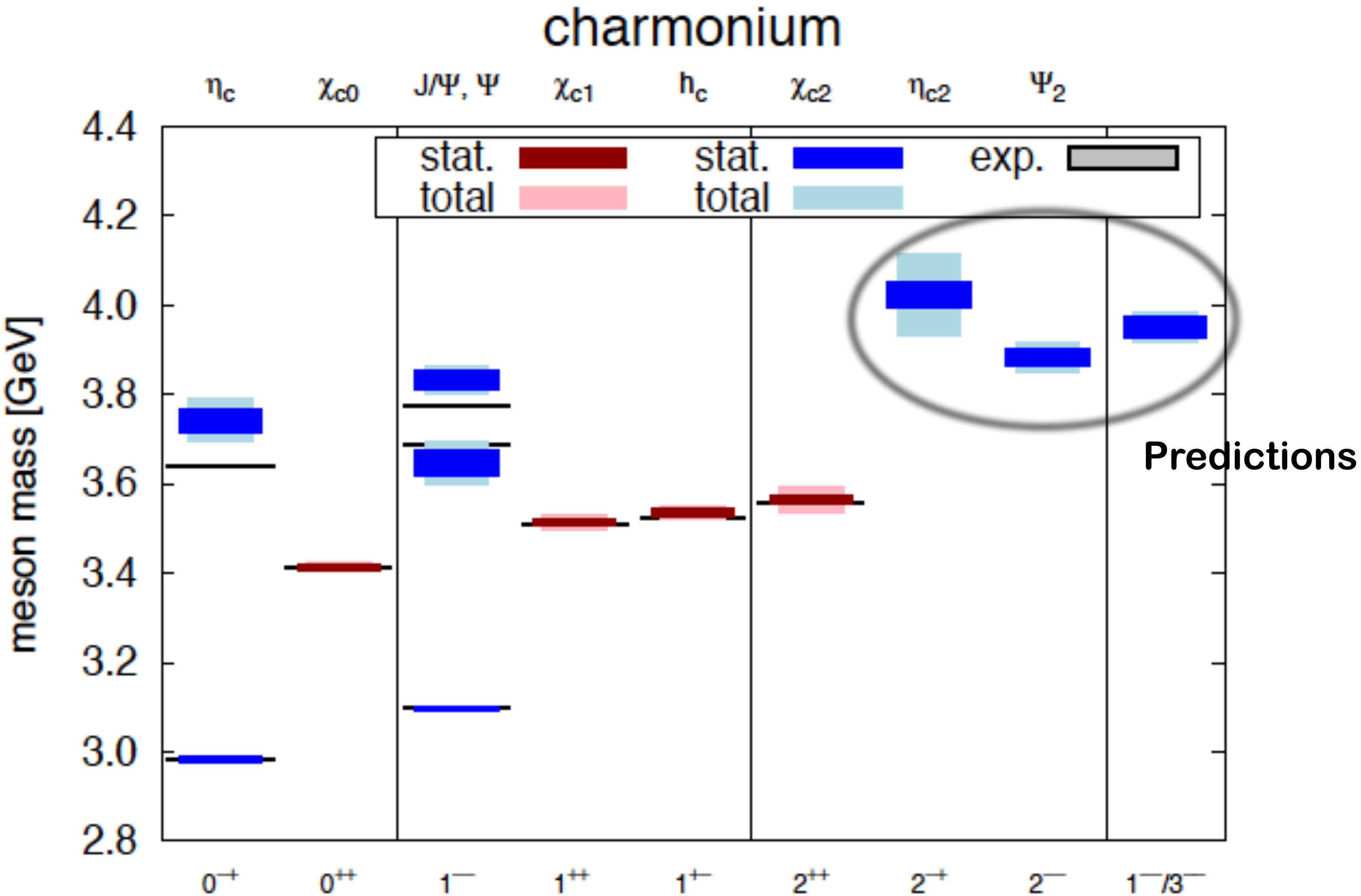
Hadron Spectrum Collaboration - JLab

Lattice QCD calculation

- **Heavy mesons:**

Martin Savage (U of Washington)

David Richards (Jlab)

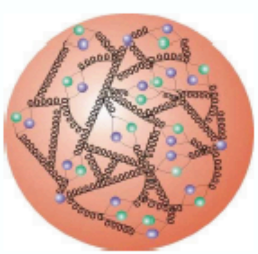
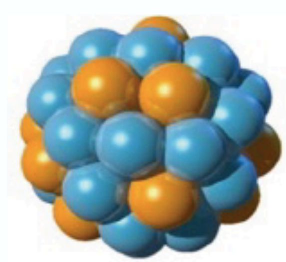
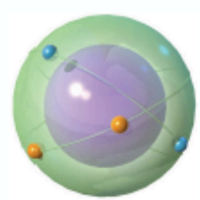
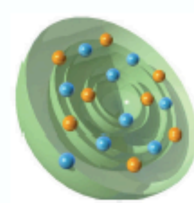


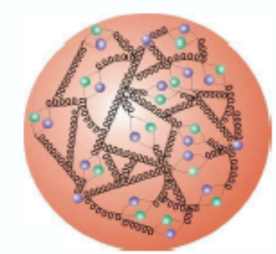
Lattice QCD calculation

❑ Summary:

Martin Savage (U of Washington)
David Richards (Jlab)

- Masses of hadrons and Nuclei are basic to NP and HEP
- Interesting to know numerical values of proton mass as a function of standard model parameters
- Decomposition needs to be carefully considered
- RG scheme-independent statements desired
- Lattice QCD moving toward quark-mass contribution



Decomposition – Sum Rules

- **Roles of quarks and gluons?**

Stan Brodsky (SLAC)
Xiangdong Ji (Maryland)
Dima Kharzeev (Stony Brook)
Keh-Fei Liu (Kentucky)

- **QCD energy-momentum tensor:**

$$T^{\mu\nu} = \overline{T^{\mu\nu}} + \widehat{T^{\mu\nu}}$$

Traceless term: $\overline{T^{\mu\nu}} \equiv T^{\mu\nu} - \frac{1}{4} g^{\mu\nu} T^{\alpha}_{\ \alpha}$

Trace term: $\widehat{T^{\mu\nu}} \equiv \frac{1}{4} g^{\mu\nu} T^{\alpha}_{\ \alpha}$

with $$T^{\alpha}_{\ \alpha} = \frac{\beta(g)}{2g} F^{\mu\nu,a} F^{a}_{\mu\nu} + \sum_{q=u,d,s} m_q (1+\gamma_m) \overline{\psi}_q \psi_q$$

QCD trace anomaly $\quad \beta(g) = -(11 - 2n_f/3)\, g^3/(4\pi)^2 + \ldots$

- **Invariant hadron mass (in any frame):**

$$\langle p | T^{\mu\nu} | p \rangle \propto p^\mu p^\nu \quad \Rightarrow \quad \langle p | T^{\mu\nu} | p \rangle (g_{\mu\nu}) \propto p^\mu p^\nu (g_{\mu\nu}) = m^2$$

$$m^2 \propto \langle p | T^{\alpha}_{\ \alpha} | p \rangle \quad \Rightarrow \quad \frac{\beta(g)}{2g} \langle p | F^2 | p \rangle$$

➡ **At the chiral limit, the entire mass is from gluons!**

Kharzeev @ Temple workshop

Decomposition – Sum Rules

Stan Brodsky (SLAC)
Xiangdong Ji (Maryland)
Dima Kharzeev (Stony Brook)
Keh-Fei Liu (Kentucky)

❑ Sum rule for the mass:

✧ **Hadron state:**

$|P\rangle$ **With the normalization:** $\langle P|P\rangle = (E/M)(2\pi)^3\delta^3(\mathbf{0})$

✧ **Hamiltonian:**

$$\langle P|H|P\rangle = (E^2/M)(2\pi)^3\delta^3(\mathbf{0}) \qquad \text{with} \quad H_{\rm QCD} = \int d^3\vec{x}\, T^{00}(0,\vec{x})$$

✧ **Hadron mass:**

X. Ji, PRL (1995)

$$M = \frac{\langle P|H_{\rm QCD}|P\rangle}{\langle P|P\rangle}\Big|_{\text{rest frame}} = H_q + H_m + H_g + H_a$$

Mass type	H_i	M_i	$m_s \to 0$ (MeV)	$m_s \to \infty$ (MeV)
Quark energy	$\psi^\dagger(-i\mathbf{D}\cdot\boldsymbol{\alpha})\psi$	$3(a-b)/4$	270	300
Quark mass	$\bar{\psi}m\psi$	b	160	110
Gluon energy	$\frac{1}{2}(\mathbf{E}^2+\mathbf{B}^2)$	$3(1-a)/4$	320	320
Trace anomaly	$\frac{9\alpha_s}{16\pi}(\mathbf{E}^2-\mathbf{B}^2)$	$(1-b)/4$	190	210

$$a(\mu^2) = \sum_f \int_0^1 x[q_f(x,\mu^2) + \bar{q}_f(x,\mu^2)]dx$$

$$bM = \langle P|m_u\bar{u}u + m_d\bar{d}d|P\rangle + \langle P|m_s\bar{s}s|P\rangle$$

Decomposition – Sum Rules

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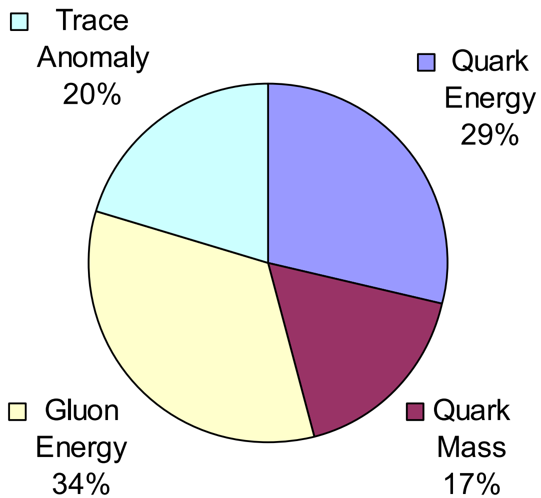
Update on
lattice effort
K.-F. Liu



Approximated Analytical Calculations

Xiangdong Ji (Maryland), …

❑ "Bag" model:

THE MASS OF A BAG, ALONG WITH 3 QUARKS

- A free quark inside of the nucleon has a kinetic energy 1/R, according to the uncertainty principle.
- However, the free space of volume V has energy BV—you must pay for the bag!
- Therefore, the total energy is

$$M = \frac{3}{R} + \frac{4}{3}\pi R^3 B$$

- Minimizing with respect to R, one finds that the second term contributes 1/4 and M=4/R. And since R is about 1 fm, one gets about 900 MeV!

Approximated Analytical Calculations

Craig Roberts (Argonne), …

❑ “Mass without mass”:

✧ **Fermion mass generation:**

$$S_F(p) = \frac{\mathcal{F}(p)}{\not{p} - \mathcal{M}(p)}$$

wavefunction renormalisation

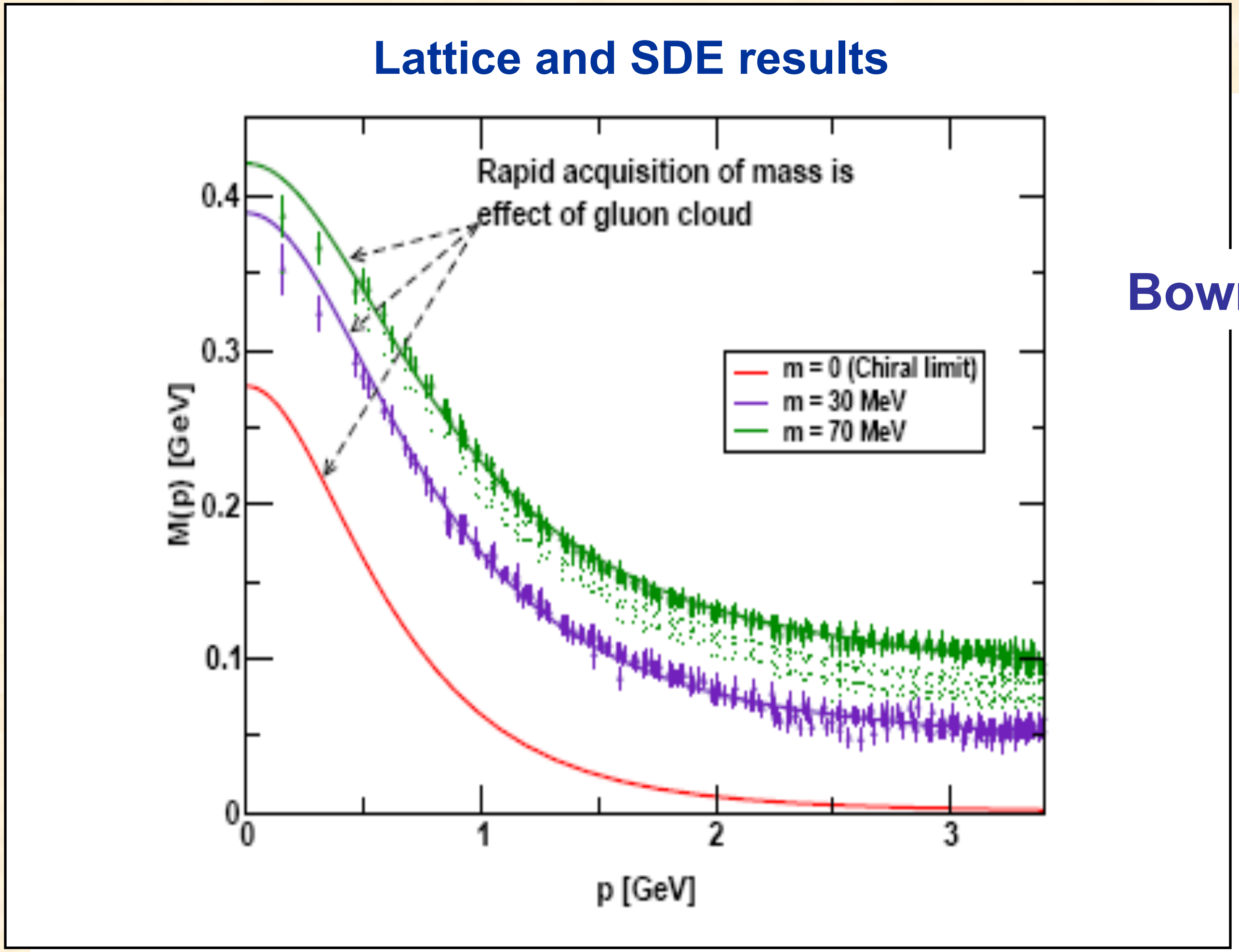
mass function

$$S_F(p)^{-1} = \not{p} - m_0 - \frac{\alpha}{4\pi} \int d^4k \, \gamma_\mu S_F(k) \Gamma_\nu(k,p) \Delta^{\mu\nu}(q)$$

Approximated Analytical Calculations

- "Mass without mass":

Craig Roberts (Argonne), …



Bowman et al

Bhagwat & Tandy / Roberts et al

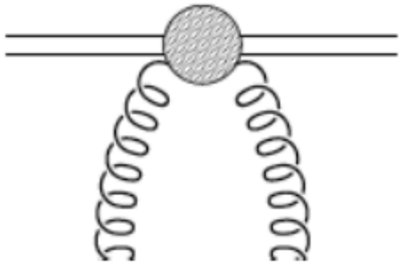
Measurements

Dima Kharzeev (Stony Brook)

- **Theory background:**
  - **Recall:** $m^2 \propto \langle p|T^{\alpha}{}_{\alpha}|p\rangle \Rightarrow \frac{\beta(g)}{2g}\langle p|F^2|p\rangle$

What is the distribution of proton mass?

Need to study the scalar gluon formfactor of the proton – quarkonium scattering



theoretically, we can do onium-onium scattering at low energy

Measurements

Dima Kharzeev (Stony Brook)

❑ Theory background:

- ✧ **Recall:** $m^2 \propto \langle p | T^{\alpha}{}_{\alpha} | p \rangle$ ➡ $\frac{\beta(g)}{2g} \langle p | F^2 | p \rangle$

How do we probe the distribution of mass inside the proton?

Need a dilaton source… closest approximation: the heavy quarkonium

The scattering amplitude

$$F_{\Phi h} = r_0^3 \epsilon_0^2 \sum_{n=2}^{\infty} d_n \langle h | \frac{1}{2} G_{0i}^a (D^0)^{n-2} G_{0i}^a | h \rangle$$

↑ Wilson coefficients

Measurements

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  - **Recall:** $m^2 \propto \langle p | T^{\alpha}{}_{\alpha} | p \rangle$ ➡ $\frac{\beta(g)}{2g} \langle p | F^2 | p \rangle$

The Wilson coefficients

$$d_n^{(1S)} = \left(\frac{32}{N}\right)^2 \sqrt{\pi} \, \frac{\Gamma(n + \frac{5}{2})}{\Gamma(n+5)}$$

M.Peskin '78

$$d_n^{(2S)} = \left(\frac{32}{N}\right)^2 4^n \sqrt{\pi} \, \frac{\Gamma(n + \frac{5}{2})}{\Gamma(n+7)} (16n^2 + 56n + 75)$$

$$d_n^{(2P)} = \left(\frac{15}{N}\right)^2 4^n 2\sqrt{\pi} \, \frac{\Gamma(n + \frac{7}{2})}{\Gamma(n+6)}$$

DK, nucl-th/9601029

Measurements

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❑ Theory background:

✧ **Recall:** $m^2 \propto \langle p | T^{\alpha}{}_{\alpha} | p \rangle \Rightarrow \frac{\beta(g)}{2g} \langle p | F^2 | p \rangle$

Quarkonium-proton interaction

$$F_{\Phi h} = r_0^3 \epsilon_0^2 \sum_{n=2}^{\infty} d_n \langle h | \frac{1}{2} G_{0i}^a (D^0)^{n-2} G_{0i}^a | h \rangle$$

1. Interaction is attractive (VdW force of QCD)

   S.Brodsky, I.Schmidt, G. de Teramond '90

2. For n=2 (low energy) the amplitude is proportional to the trace of the energy-momentum tensor

   M.Luke, A.Manohar, M.Savage '92

Measurements

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❑ Theory background:

✧ **Recall:** $m^2 \propto \langle p|T^{\alpha}{}_{\alpha}|p\rangle \rightarrow \frac{\beta(g)}{2g}\langle p|F^2|p\rangle$

Quarkonium-proton interaction
at low energy probes the distribution
of mass inside the proton

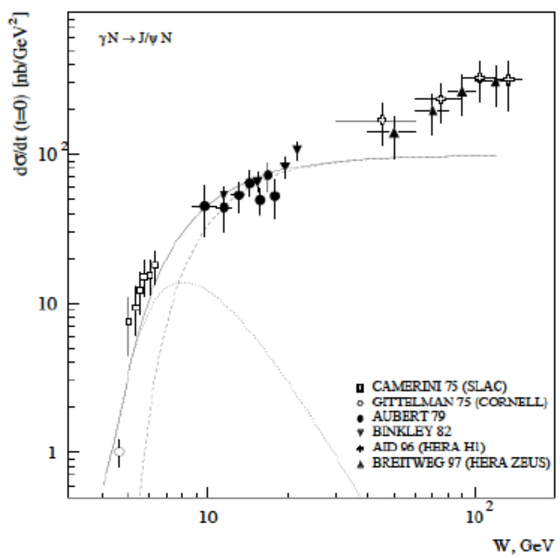

Figure 1: Forward J/ψ photoproduction data compared to our results with (solid line) and without (dashed line) the real part of the amplitude. The curves were obtained using a scaling PDF [4]

The real part of the amplitude is crucially important

DK, Satz, Syamtomov, Zinovjev EPJ '99

Measurements

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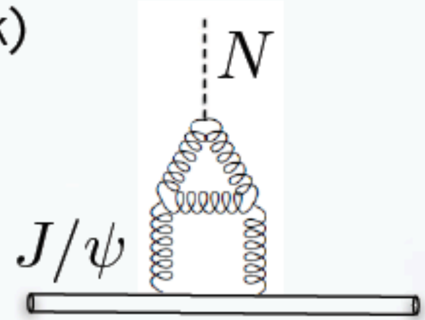
❑ **Theory background:**

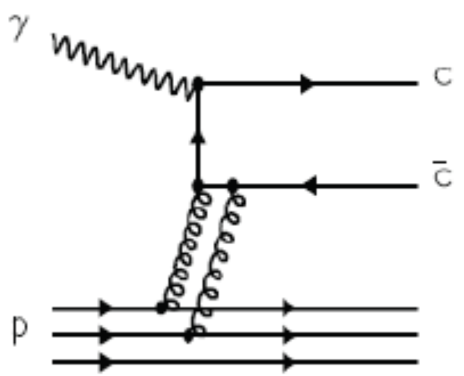
✧ **Recall:** $m^2 \propto \langle p | T^{\alpha}{}_{\alpha} | p \rangle$ ➡ $\frac{\beta(g)}{2g} \langle p | F^2 | p \rangle$

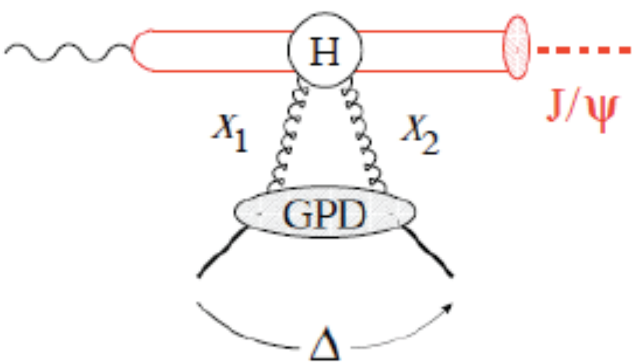
"Low-energy J/psi-N interaction is a probe of the scalar gluon form factor of the nucleon. This quantity is of fundamental importance since it is related to conformal anomaly of QCD and to the origin of the nucleon's mass".

Dima Kharzeev (Stony Brook)



✧ **Lots competitions (reaction mechanisms):**





Measurements

Dima Kharzeev (Stony Brook)

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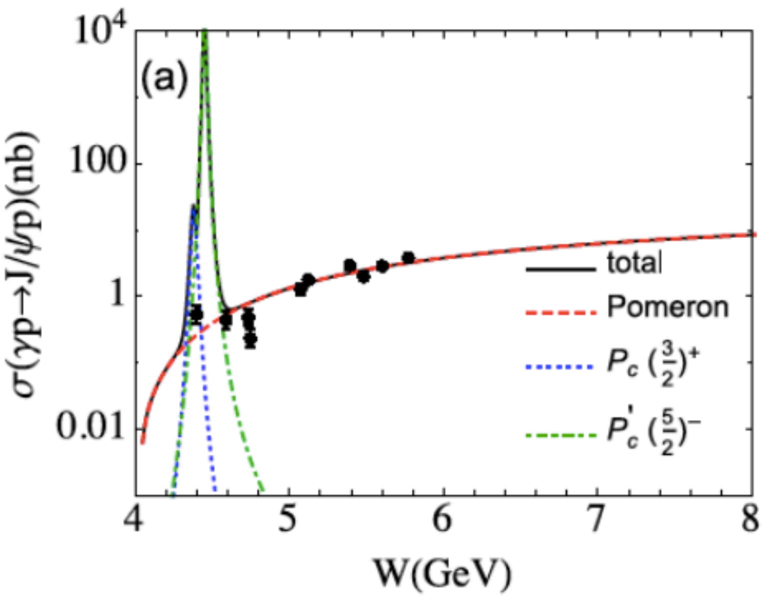
Charmonium photoproduction
close to the threshold



Wang, Liu, Zhang
arxiv:1508.00339

Kubarovsky, Voloshin
arxiv:1508.00888

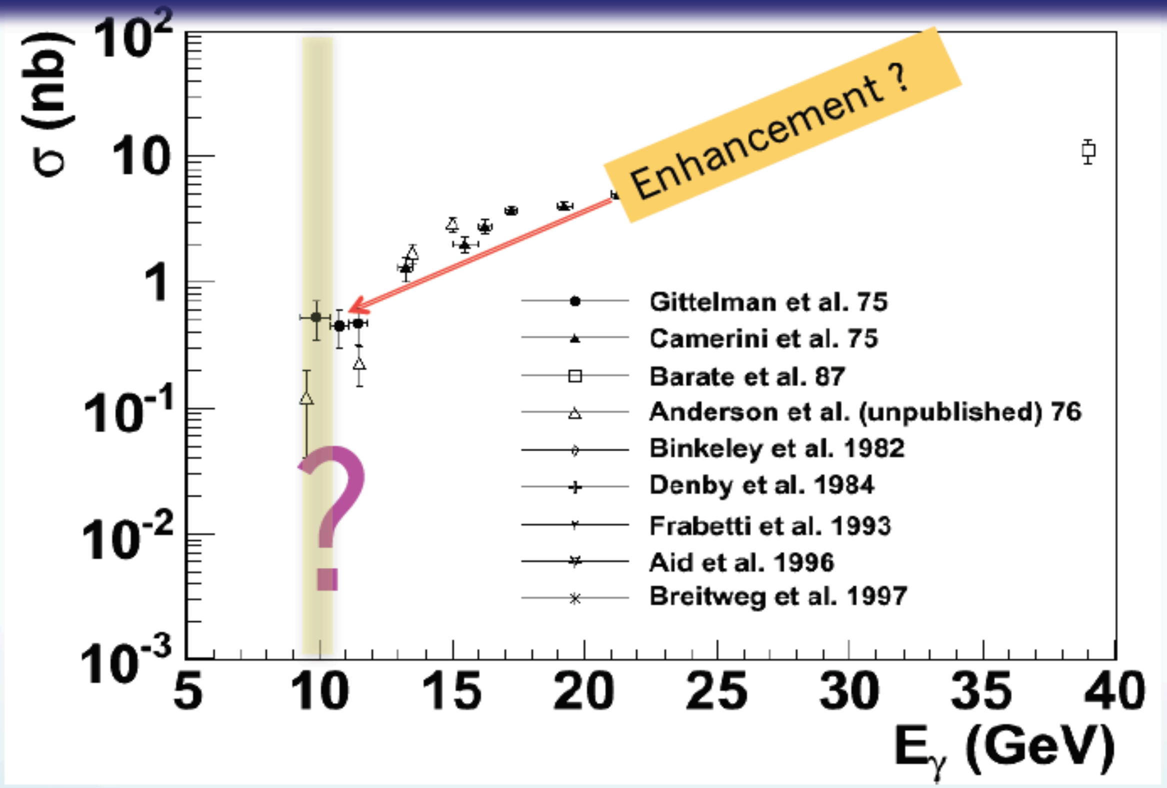
But, the cross section may be much smaller – O(pb)
Gobbi, Boffi, DK '94

Measurements

- Experiments:

Zein-Eddine Meziani (Temple)
S. Stepanyan (JLAB)

Near Threshold $\gamma + N \longrightarrow N + J/\Psi$



Intense experimental effort (SLAC, Cornell …) shortly after the discovery of J/ψ

But near threshold not much since (**36 years till now**)

“Summary”

- The proton mass closely connected to quantum anomalies

  Non-perturbative QCD generates a new scale: $\langle 0|F^2|0\rangle \neq 0$

- Three-pronged approach to explore the origin hadron mass

  lattice QCD
  mass decomposition – roles of the constituents
  approximated analytical approach

- Questions:

  - What can lattice QCD do to explore the role of “individual” constituent in making up the proton mass?
  - What can the mass decomposition teach us?
  - How well can we control the approximation of the analytical or model approaches
  - …

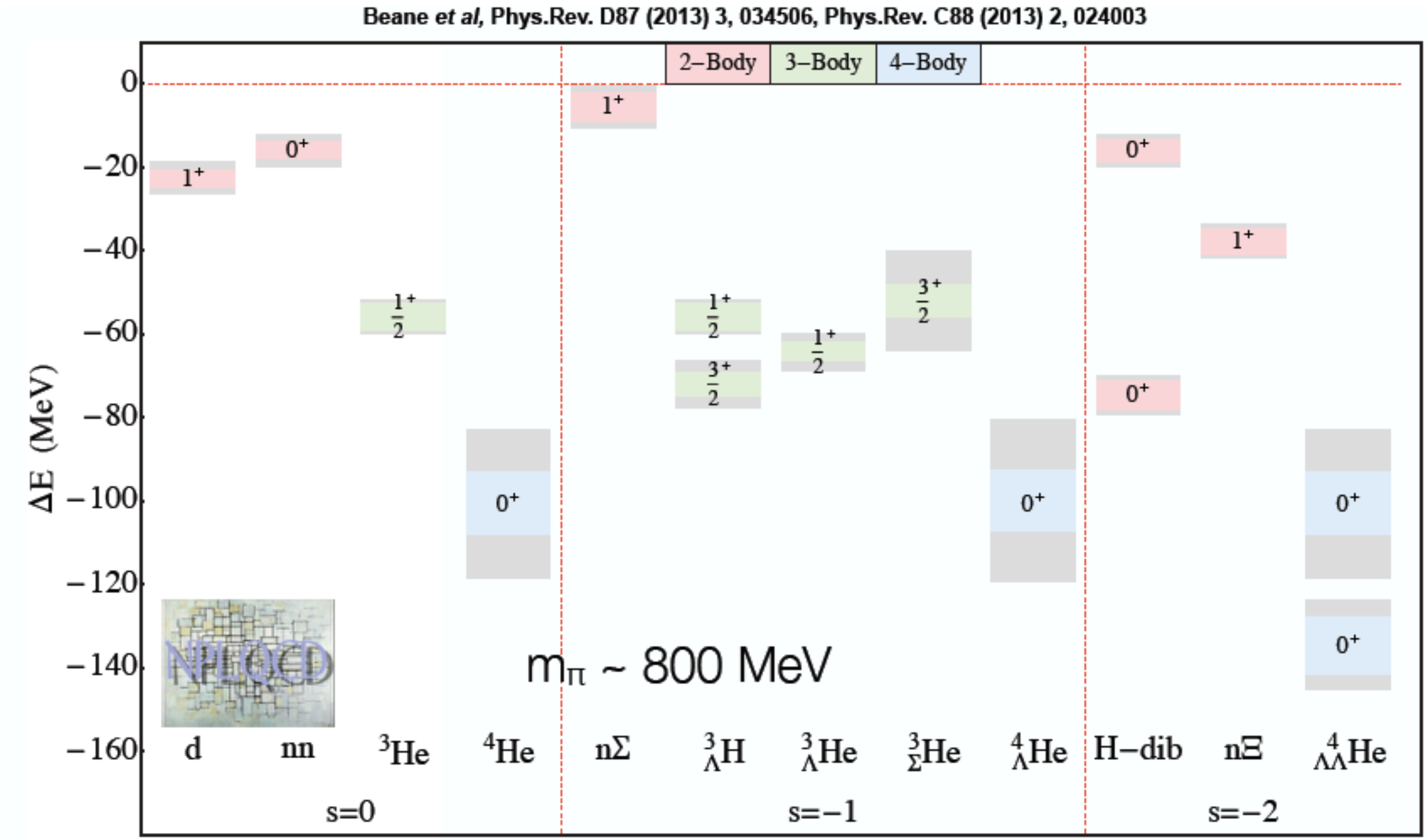
Thank you!

Lattice QCD calculation

- Nuclei from QCD:

Martin Savage (U of Washington)

David Richards (Jlab)



Extensive study of s-shell nuclei and hypernuclei, and baryon-baryon interactions at SU(3) symmetric point

Measurements

Dima Kharzeev (Stony Brook)

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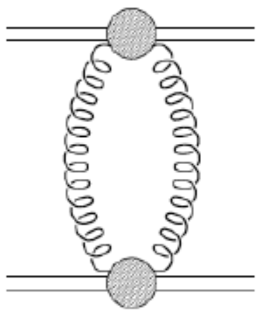
✧ **Recall:** $m^2 \propto \langle p | T^{\alpha}{}_{\alpha} | p \rangle$ ➡ $\frac{\beta(g)}{2g} \langle p | F^2 | p \rangle$

Quarkonium interactions at low energy
and the scale anomaly



Perturbation theory:

at large distances,
the Casimir-Polder
interaction (retardation)

$$V^{\rm pt}(R) = -g^4 \left(\bar{d}_2 \frac{a_0^2}{\epsilon_0} \right)^2 \frac{23}{8\pi^3} \frac{1}{R^7}$$

Bhanot, Peskin '78

Fujii, DK, PRD'99