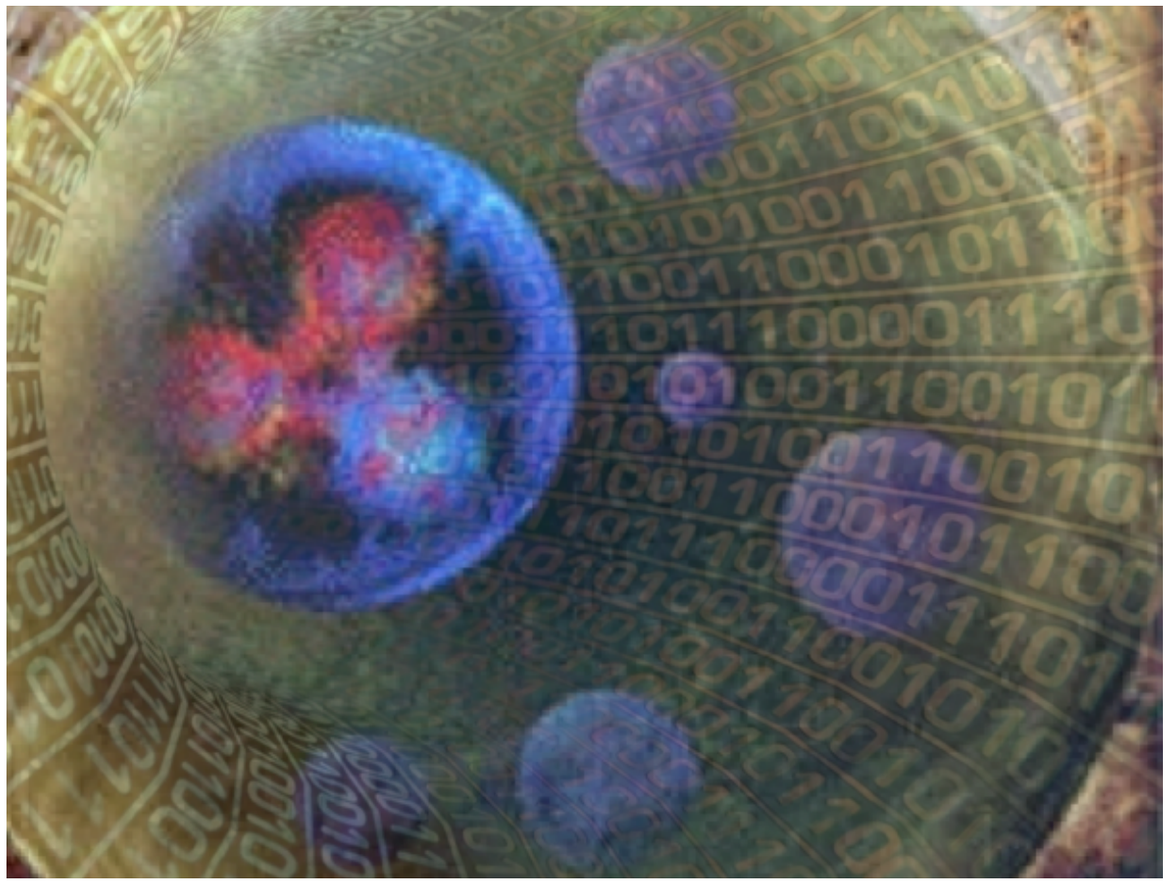


USQCD

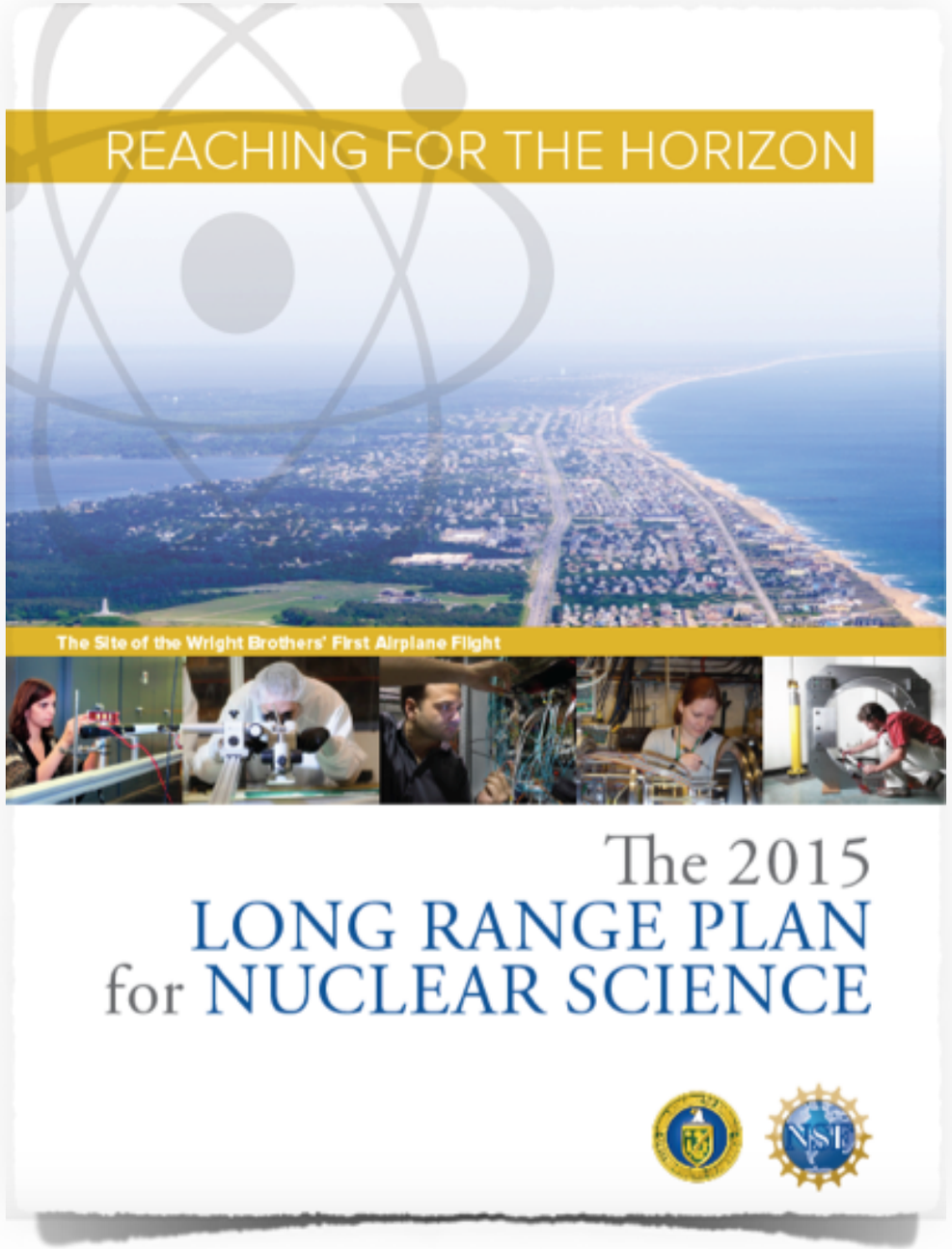
USQCD Cold Nuclear Physics Science Program

William Detmold, MIT

LQCD-ext II Project Review, JLab, June 28th 2016

Science Drivers

- Goals for field set out in 2015 NSAC Long Range Plan
  - JLab 12GeV: hadron spectroscopy and quark structure
  - FRIB: nuclear interactions, matrix elts
  - $\beta\beta$ decay: potential for LQCD input
  - EIC: gluonic structure of nucleons and nuclei
- Central to USQCD planning
- Experiment recognises importance of LQCD: computational NP initiative



http://science.energy.gov/~/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf

Science Drivers

- Goals for field set out in 2015 NSAC Long Range Plan

REACHING FOR THE HORIZON

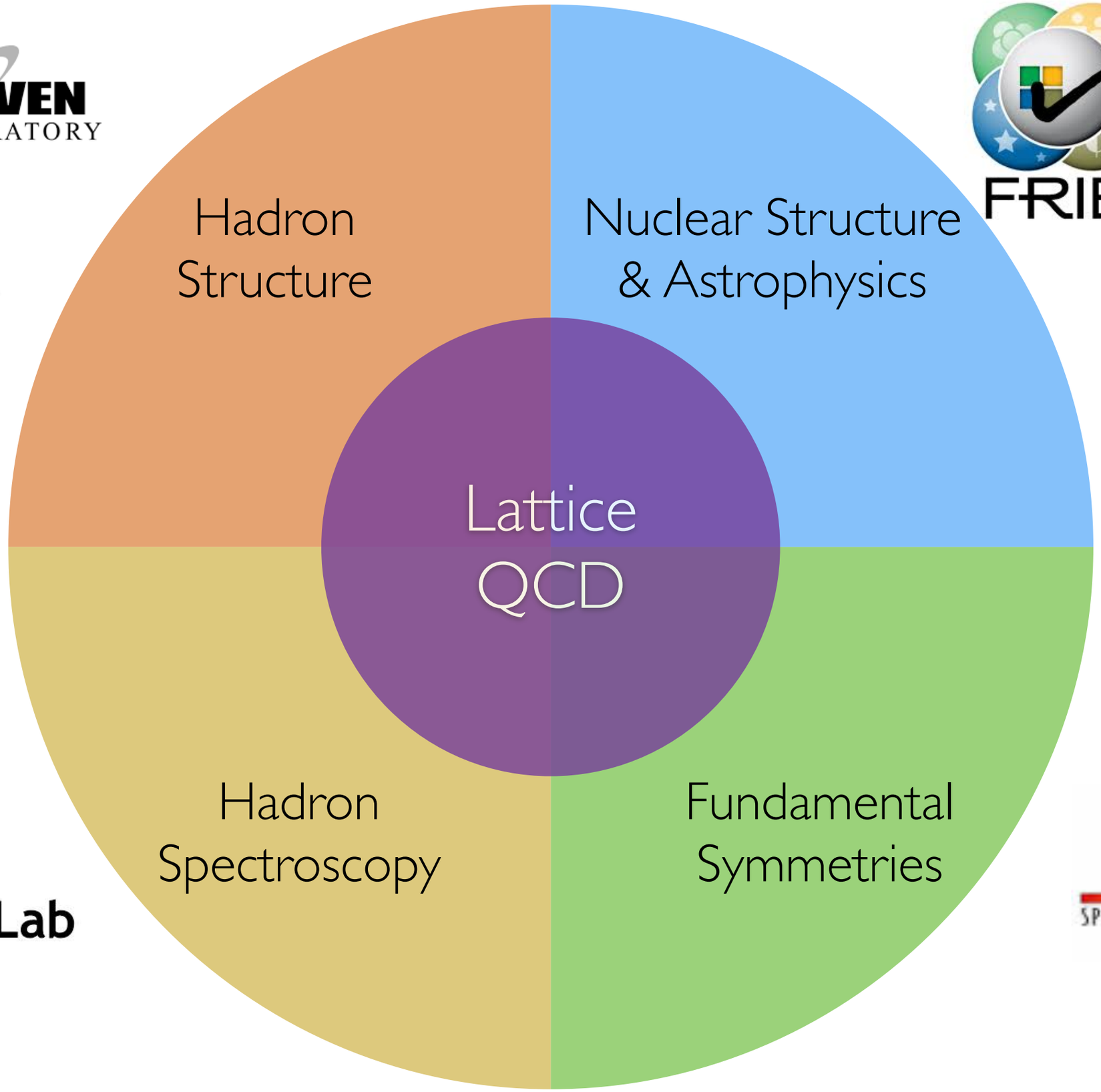
We recommend new investments in computational nuclear theory that exploit the U.S. leadership in high-performance computing. These investments include a timely enhancement of the nuclear physics contribution to the Scientific Discovery through Advanced Computing program and complementary efforts as well as the deployment of the necessary capacity computing.

— 2015 Nuclear Physics Long Range Plan

- Experiment recognises importance of LQCD: computational NP initiative

http://science.energy.gov/~/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf

Cold Nuclear Physics



Impacts Diverse Experimental Program

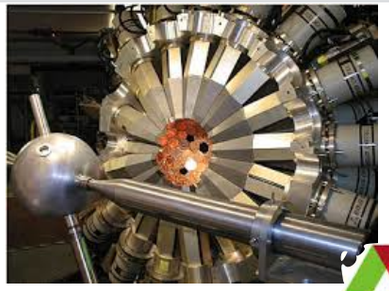
PHENIX

STAR

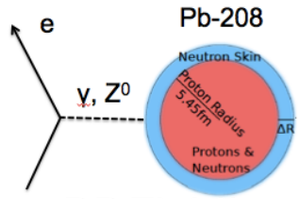
SeaQuest E906

FAIR Facility for Antiproton and Ion Research in Europe GmbH

DUNE



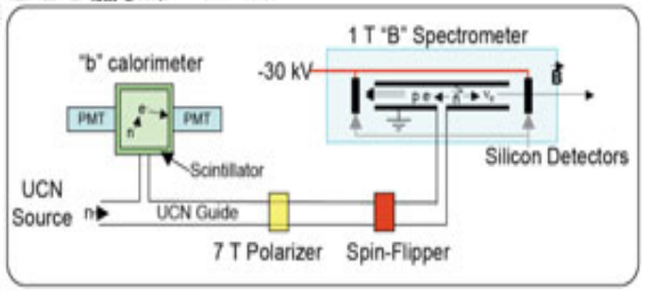
Argonne NATIONAL LABORATORY



PREX II

FRIB

Jefferson Lab



GlueX

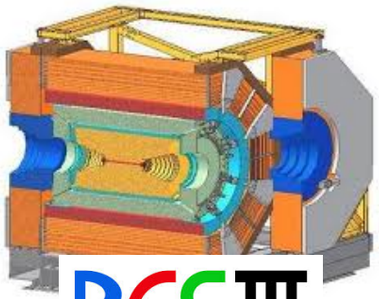
Los Alamos NATIONAL LABORATORY

Enriched Xenon Observatory EXO for double beta decay

PAUL SCHERRER INSTITUT PSI

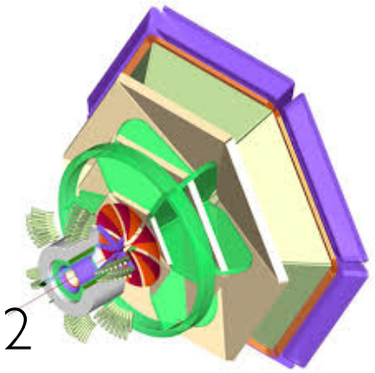
MuSUN

Belle II

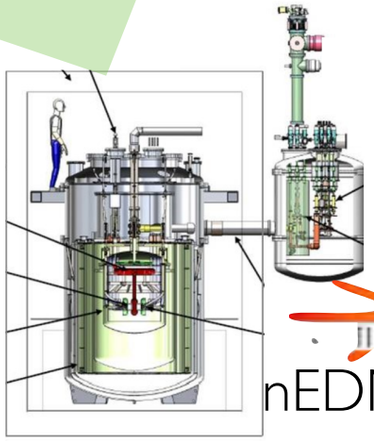


BESIII

LHCb



CLAS12

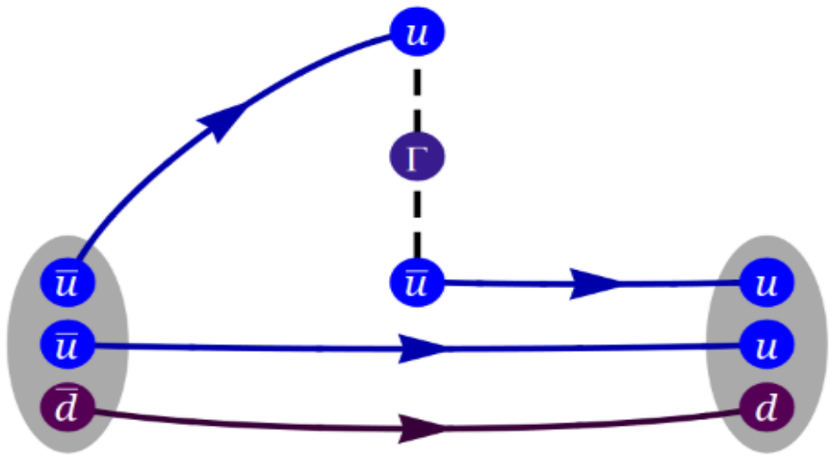


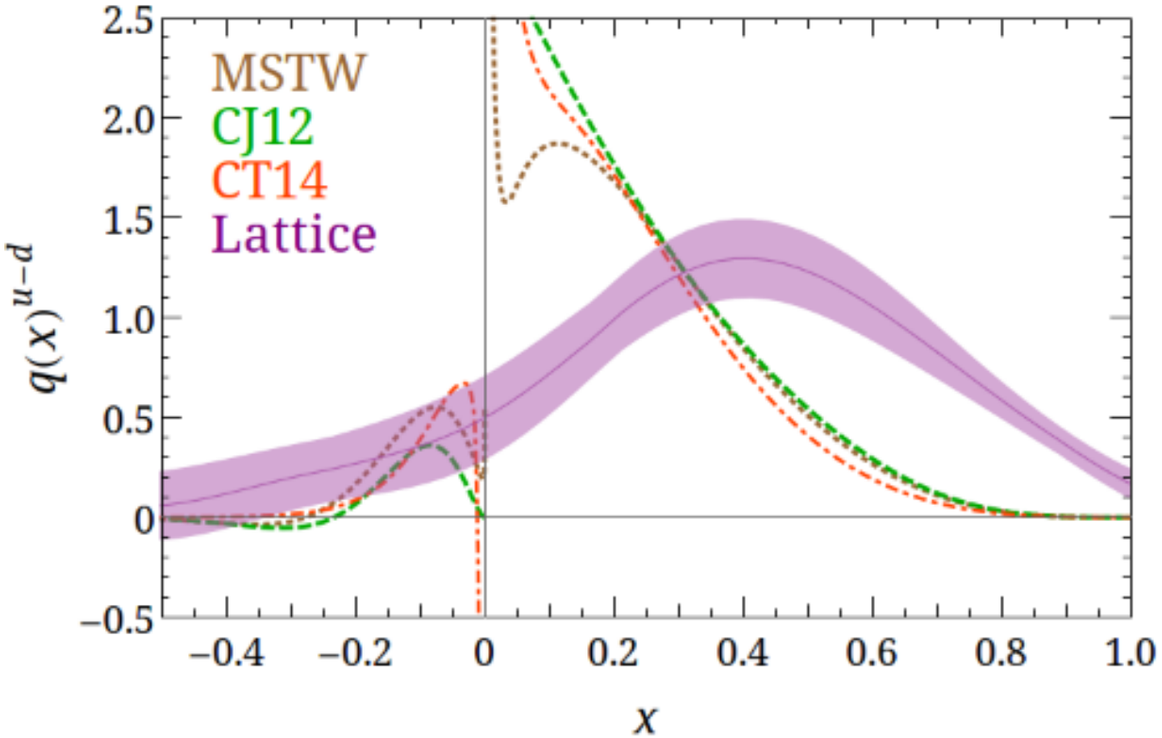
nEDM

SNS SPALLATION NEUTRON SOURCE

npdγ

- Hadron structure probed at JLab, RHIC-spin, …, future EIC
- Parton distributions, q(x), a key aspect bilocal light-cone operators
- LQCD calculations of low moments for many years
- New approach [X Ji]: determine PDFs from boosted Euclidean matrix elements of spacelike operators
- First numerical study - H W Lin et al.
  - Exploratory but very promising





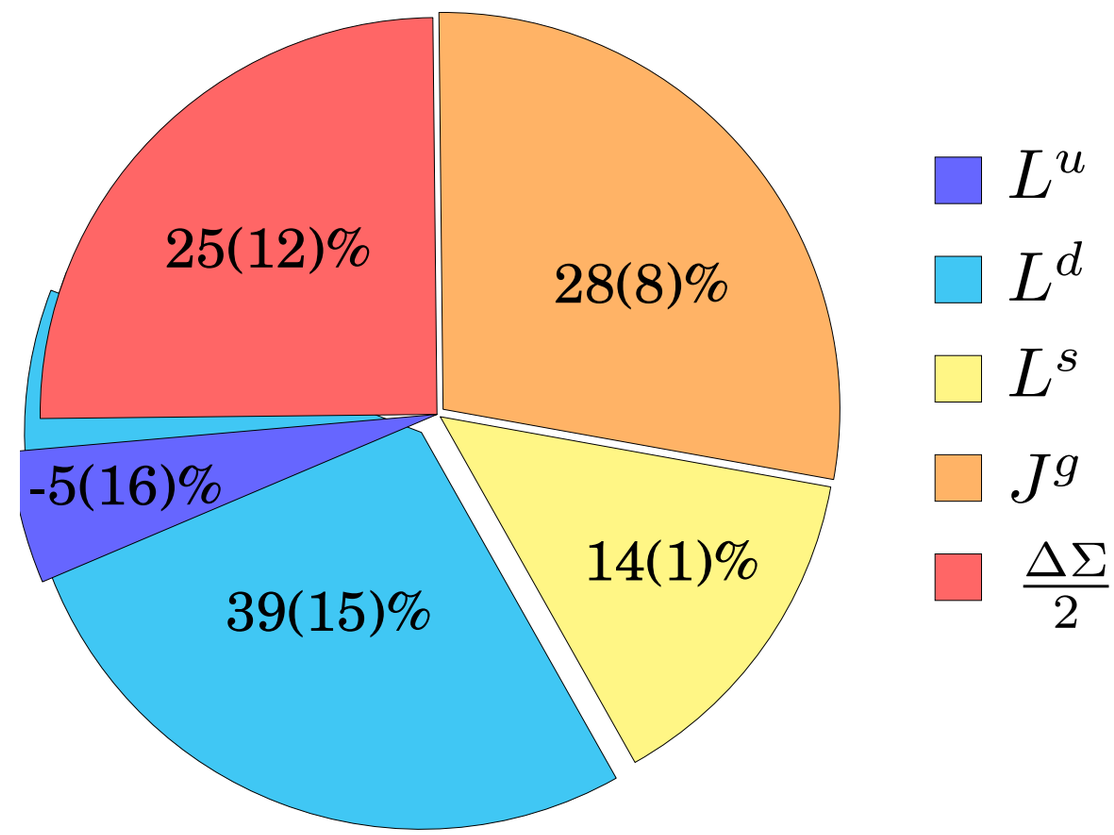
Phys.Rev. D91 (2015) 054510 , arXiv:1603.06664

- Full decomposition of proton spin

$$\vec{J}_{\rm QCD} = \vec{J}_q + \vec{J}_g = \frac{1}{2}\vec{\Sigma}_q + \vec{L}_q + \vec{J}_g,$$

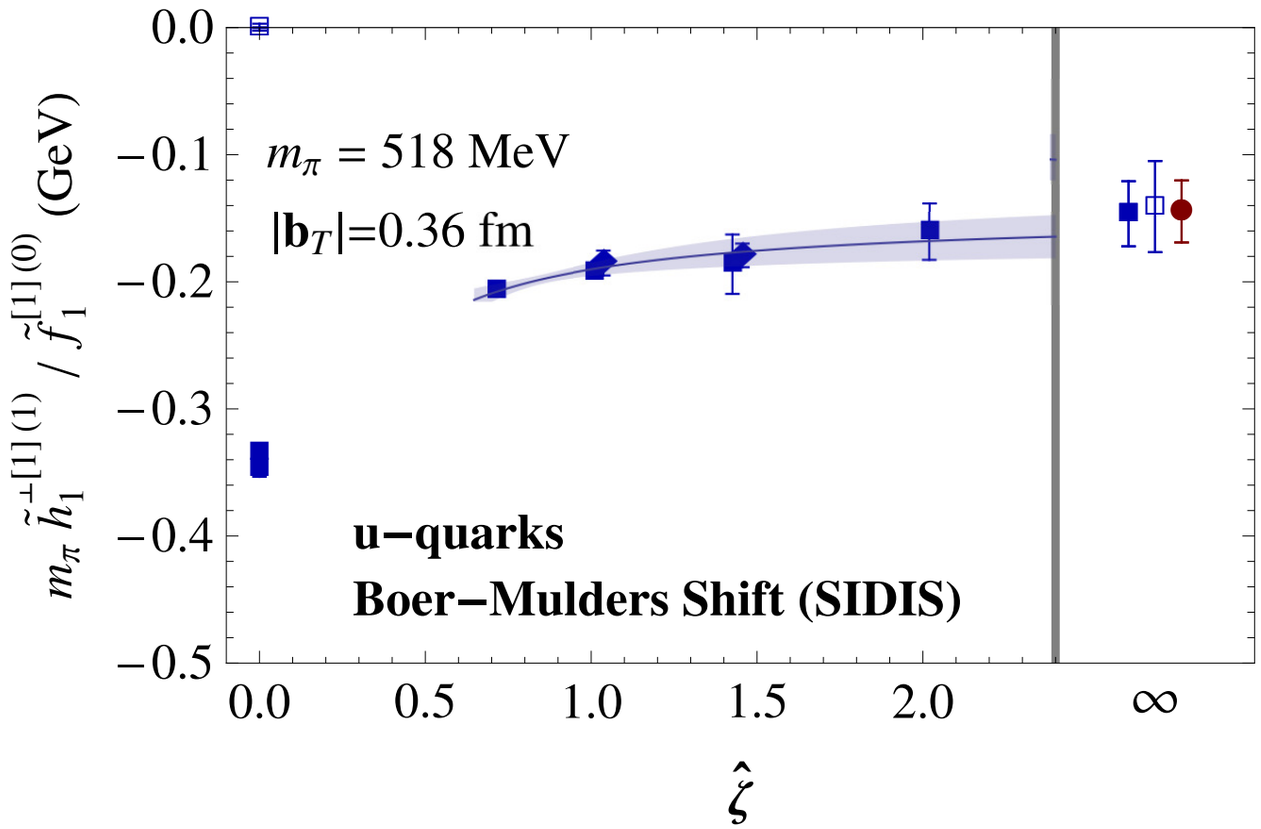
- χQCD collaboration
  - Initial quenched study
  - Repeating with dynamical quarks
  - Eg: gluon spin contribution in a particular frame in Coulomb gauge

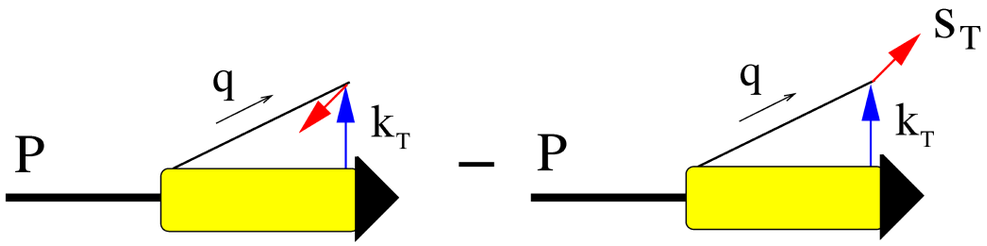
$$S_G = \int d^3x \, \mathrm{Tr}(\vec{E}^C \times \vec{A}^C)$$



Eur.Phys.J. A52 (2016) no.6, 160 ; 1603.05256

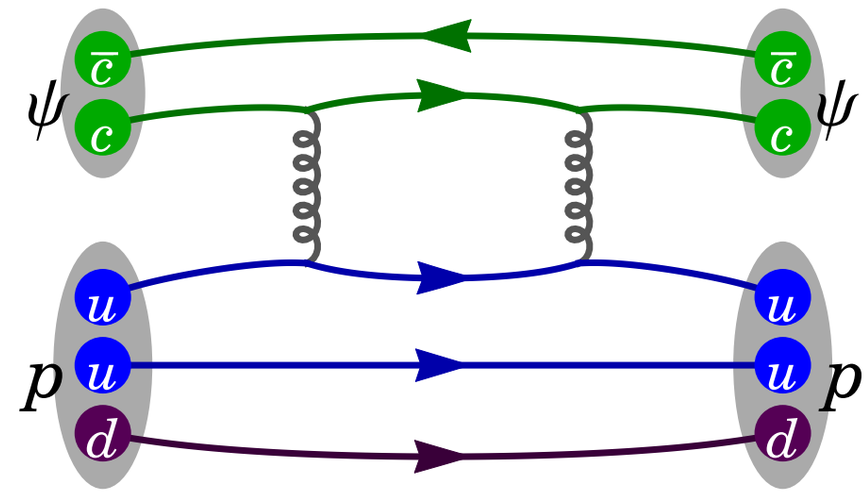
- Transverse momentum dependent parton distributions (TMDs)
- Focus of DOE Nuclear Theory Topical Collaboration
- LHP collab. (Engelhardt)
  - Measure non-local operator matrix elements to determine $q(x,k_T)$
  - First study of pion TMDs
  - Access Boer-Mulders function, which counts transversely polarised quarks in an unpolarised hadron

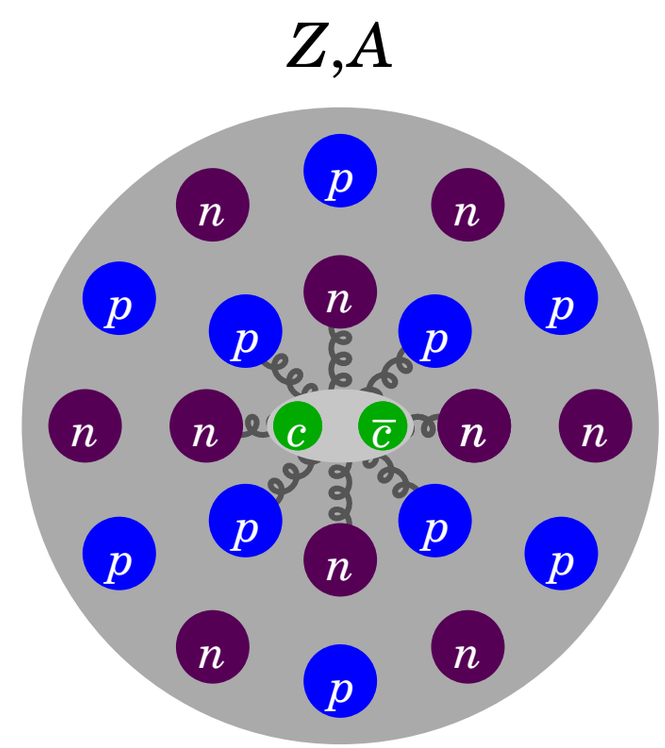




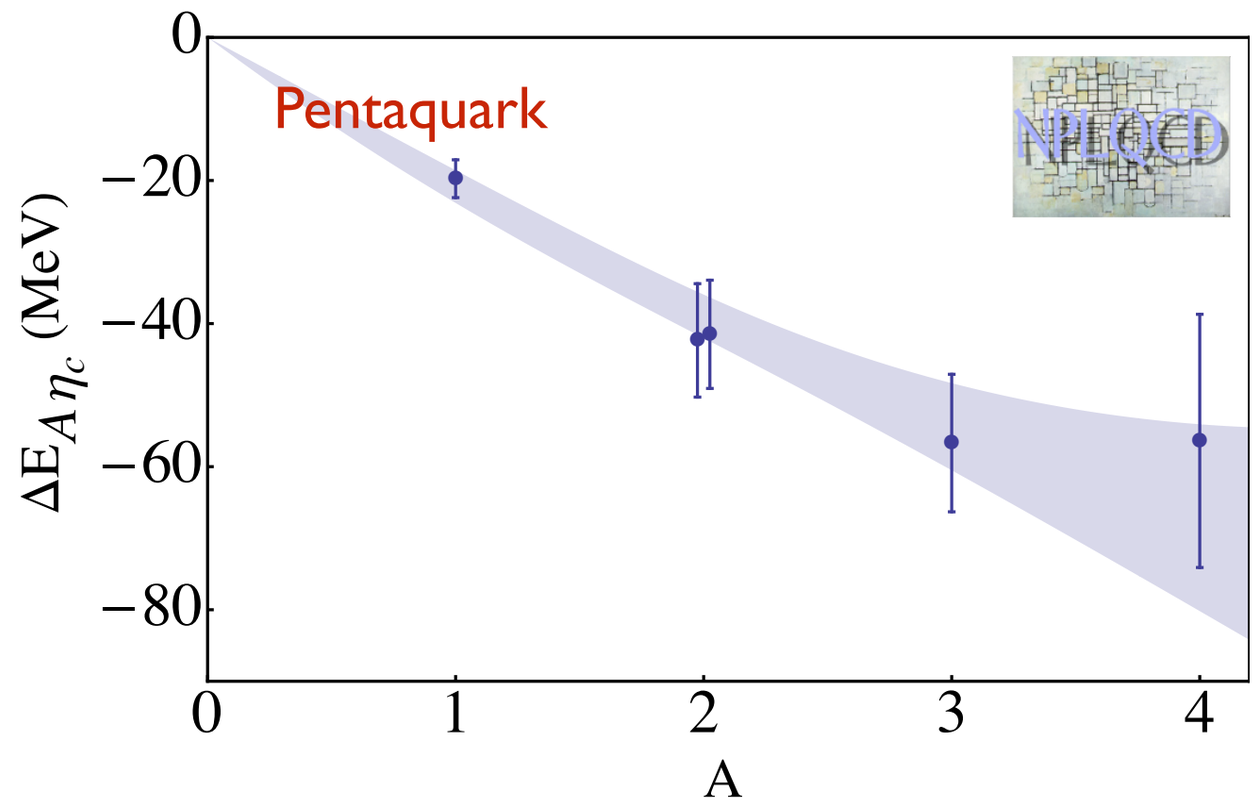
Phys.Rev. D93 (2016) no.5, 054501

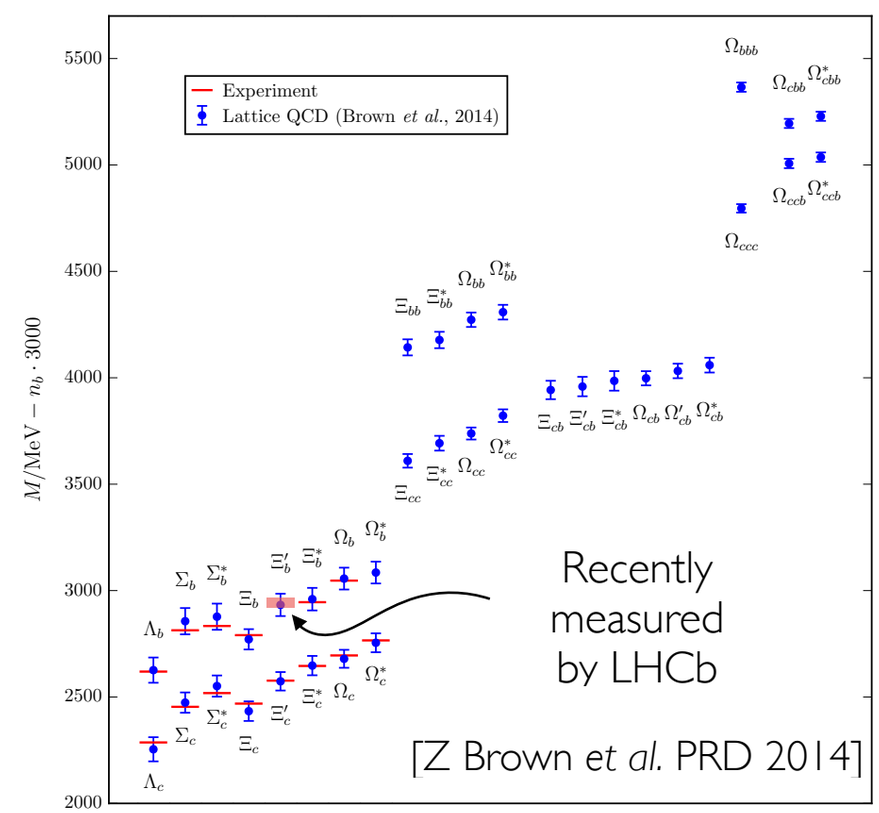
- Quarkonium interactions with light quark systems via colour van der Waals
- Colour stark effect: quarkonium induces dipoles in nucleons that attract
  - Brodsky et al. [PRL64,1011 (1990)] suggested large binding: ^{9}Be–η_c ~ 400 MeV
  - Nuclei not point-like: gluons screened J/Ψ–A ~ 10 MeV
- ATHENNA experiment at JLab12GeV will look for charmonium nuclei





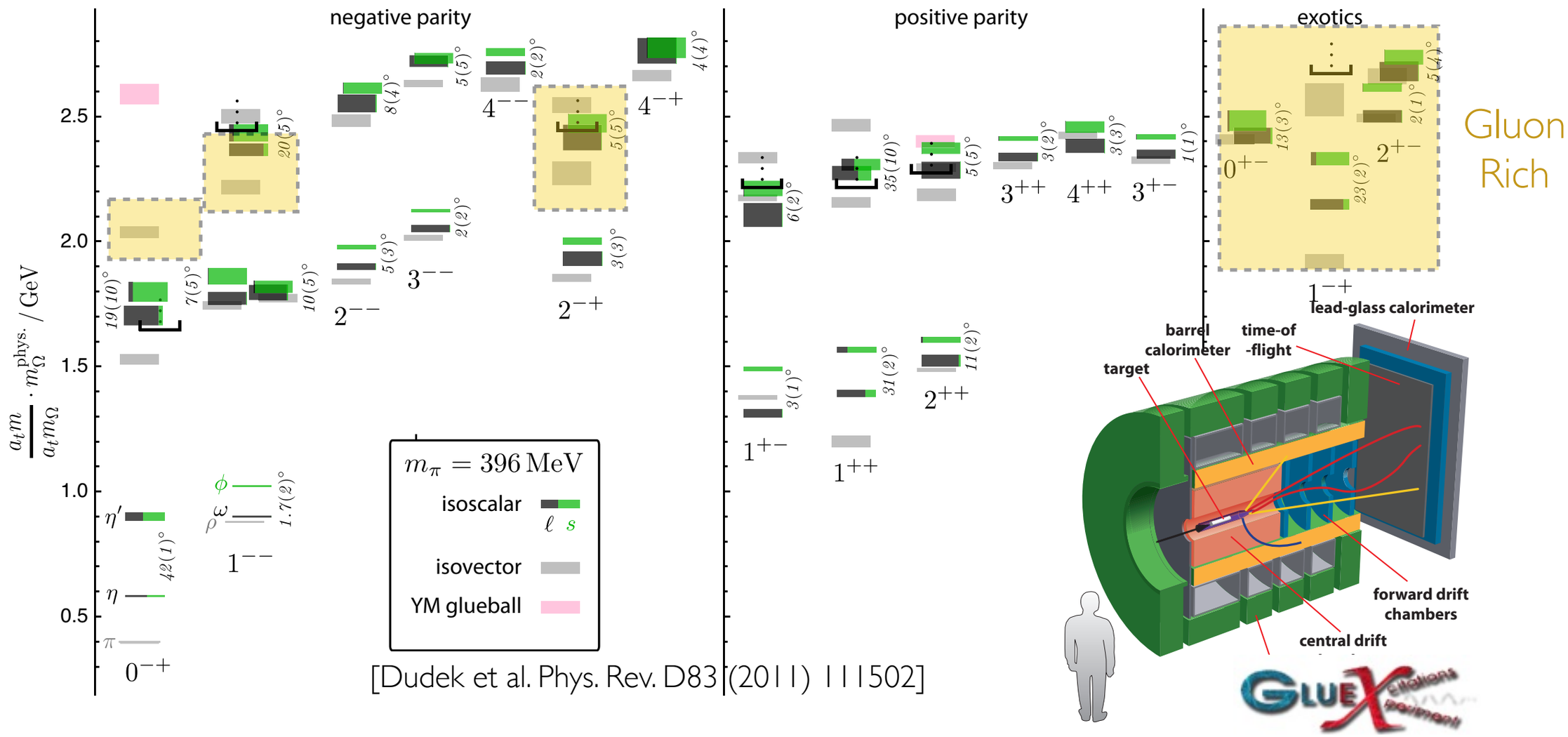
- Study at m_π~800 MeV using strangonium and charmonium
- Energy shift from $M_\eta + M_A$ (also for J/Ψ) in multiple volumes to extract infinite volume binding energy
- Binding energy vs A: very strong
- LHCb pentaquarks (J=3/2, 5/2)!
- Recent LQCD work
  - b baryons
  - X(3872),Y(4140),…





[NPLQCD, 1410.7069 = Phys.Rev. D91 (2015), 114503]

- LQCD spectroscopy important for motivation of flagship GlueX experiment
  - Gluon-rich states in the 1.8-2.7 GeV energy range



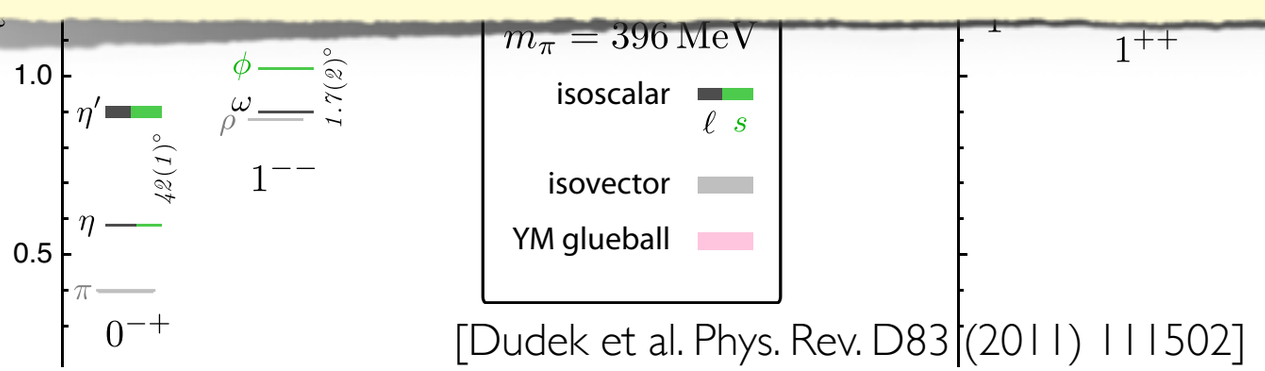
[Dudek et al. Phys. Rev. D83 (2011) 111502]

USQCD Science Highlights: Spectroscopy

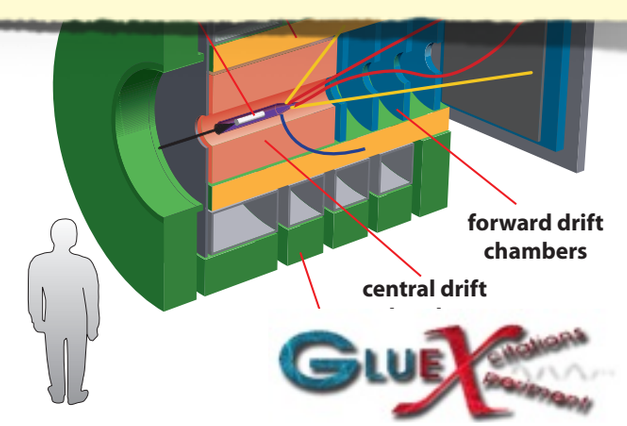
- LQCD spectroscopy important for motivation of flagship GlueX experiment
  - Gluon-rich states in the 1.8-2.7 GeV energy range

Initial LQCD calculations motivated the experiment and guided its design. Recent LQCD results confirm the mass range of the predicted particles. And in the future, LQCD calculations of hadron dynamics will play a critical role in the analysis of the data.

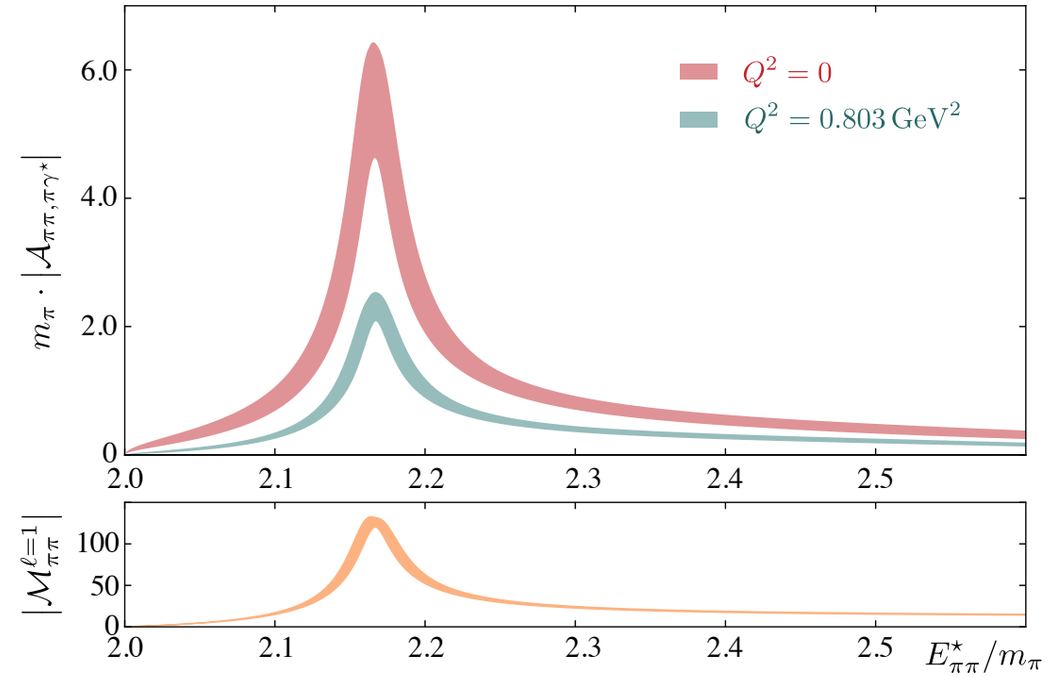
— 2015 Nuclear Physics Long Range Plan

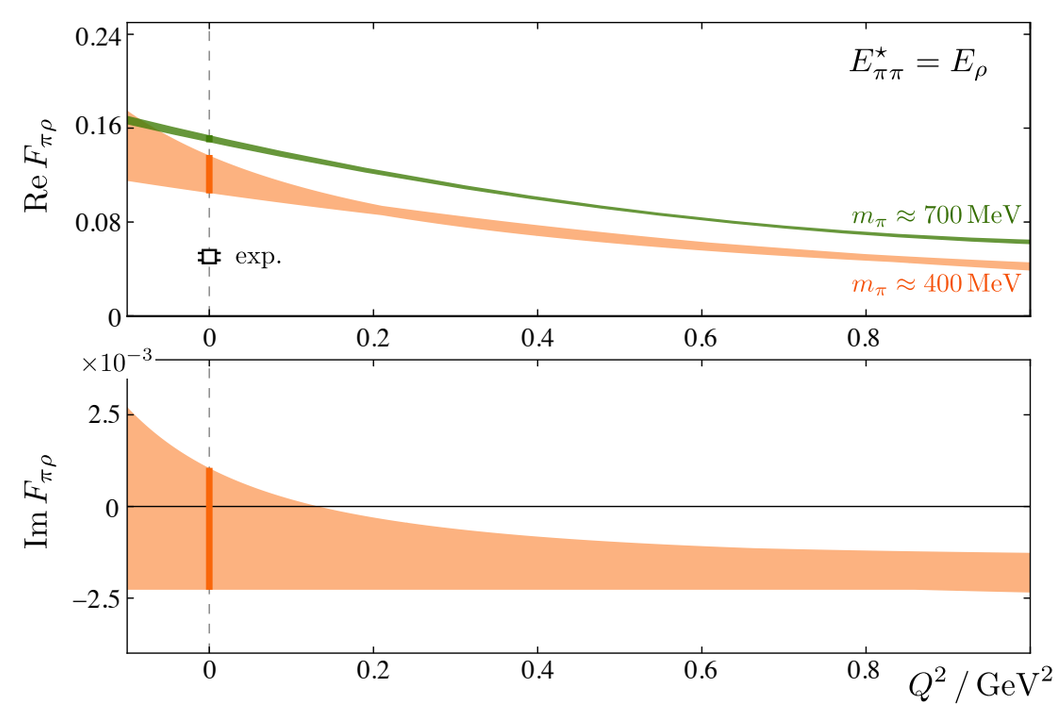


[Dudek et al. Phys. Rev. D83 (2011) 111502]

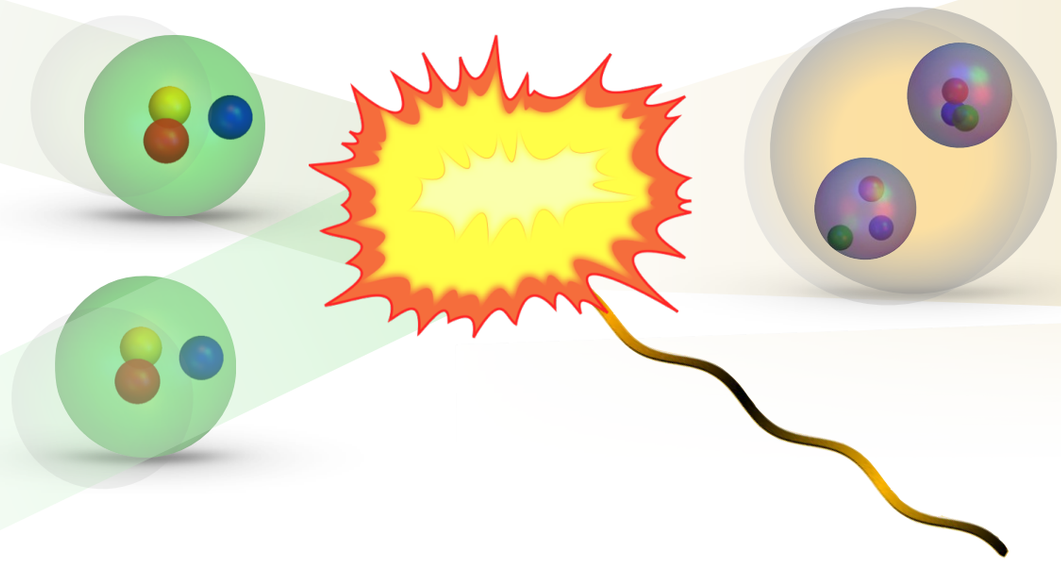


- Program to extract resonances from finite volume Euclidean lattice QCD calculations
- New formalism to deal with matrix elements in scattering states
- First study of $\pi\gamma^* \to \pi\pi$
- Extracts form factor at ρ pole (properties of unstable particles)
- Exciting progress towards radiative decays for GlueX





Phys.Rev. D93 (2016) no.11, 114508 , Phys.Rev.Lett. 115 (2015) 242001

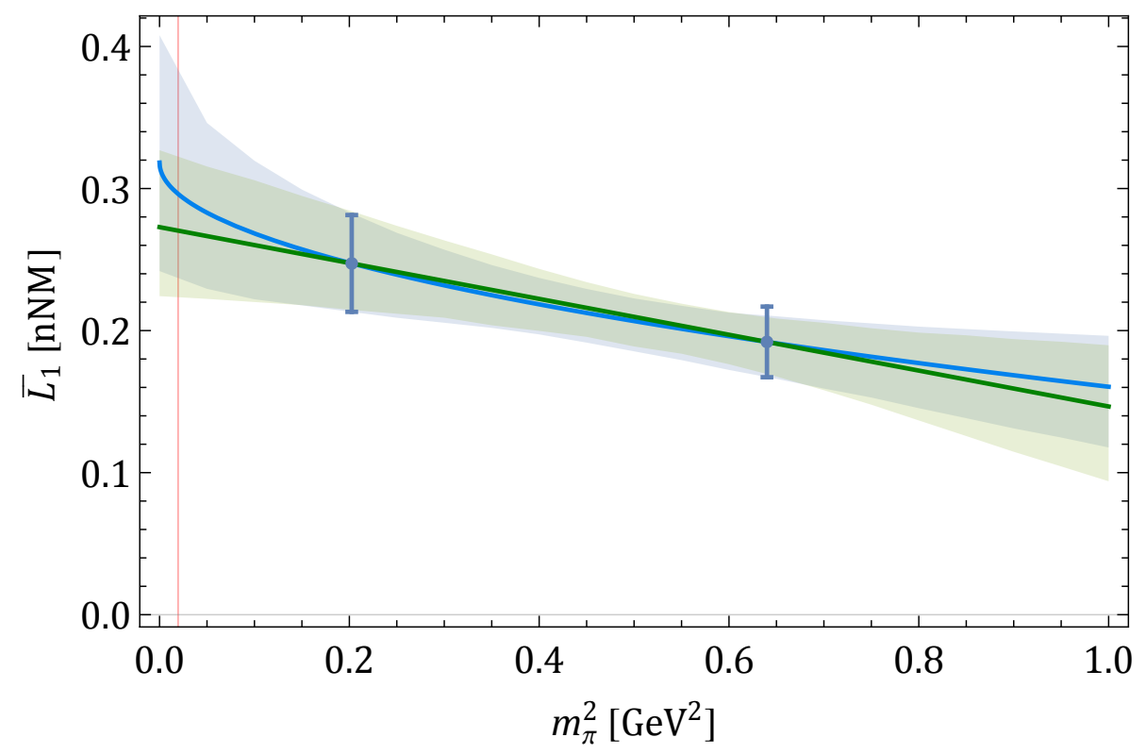


- Thermal neutron capture process $np \rightarrow d\gamma$ crucial in BBN
- Magnetic field mixes $J=0, J=1$ states, mixing proportional to amplitude
- LQCD spectroscopy in B field: two-body EM coupling L_1 (meson-exchange current) ~ 10% effect
- Extrapolation to physical mass

$$\sigma^{\rm lqcd}(np \rightarrow d\gamma) = 332.4(\,^{+5.4}_{-4.7}\,)\ {\rm mb}$$

c.f.

$$\sigma^{\rm expt}(np \rightarrow d\gamma) = 334.2(0.5)\ {\rm mb}$$

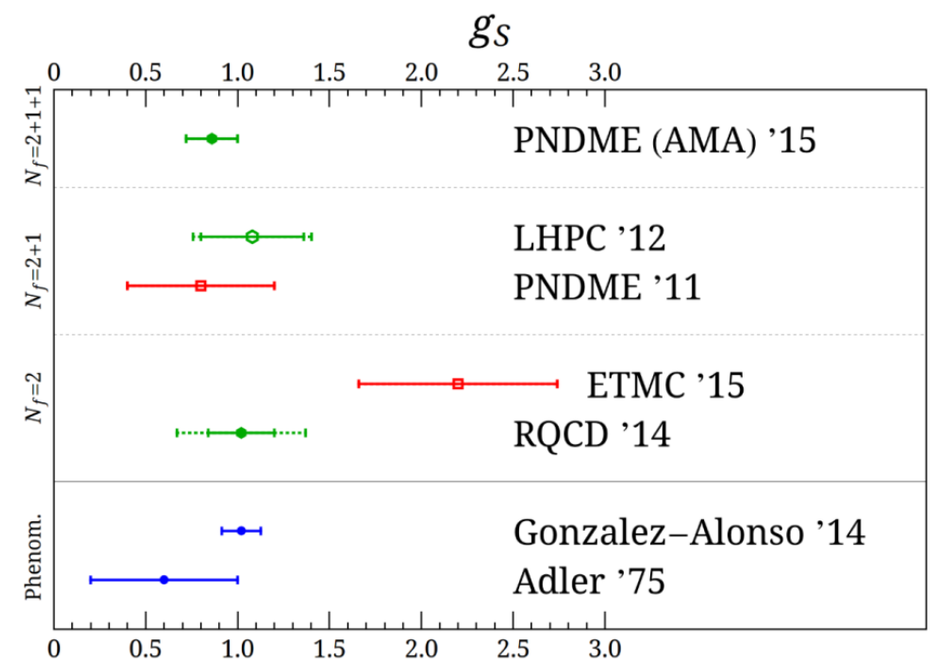


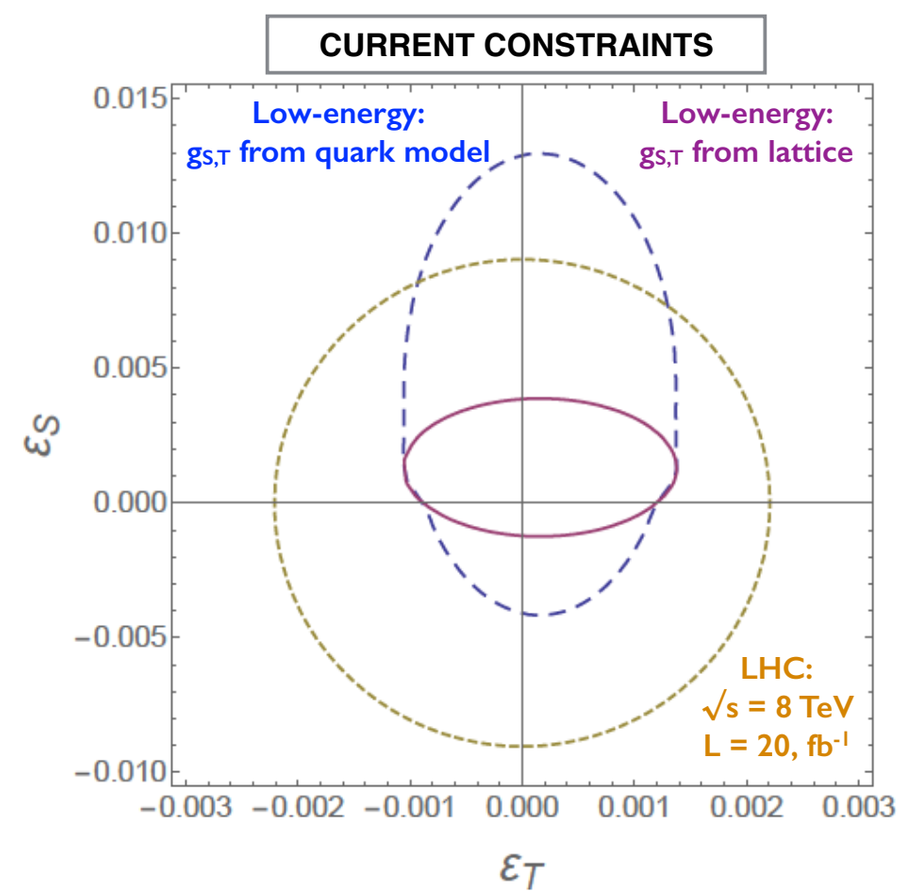
Phys.Rev.Lett. 115 (2015) no.13, 132001

- Ultra-cold neutron beta decay experiments (UCNB/b) at LANL
- Decay rate

$$d\Gamma \propto F(E_e)\left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + B\frac{\vec{\sigma}_n \cdot \vec{p}_\nu}{E_\nu} + A\frac{\vec{\sigma}_n \cdot \vec{p}_e}{E_e} + \ldots\right]$$

- Presence of non-SM scalar or tensor couplings modifies *b, B*
- Constraint on BSM requires precise scalar and tensor couplings g_S, g_T
- PNDME collaboration: most precise calculations to date



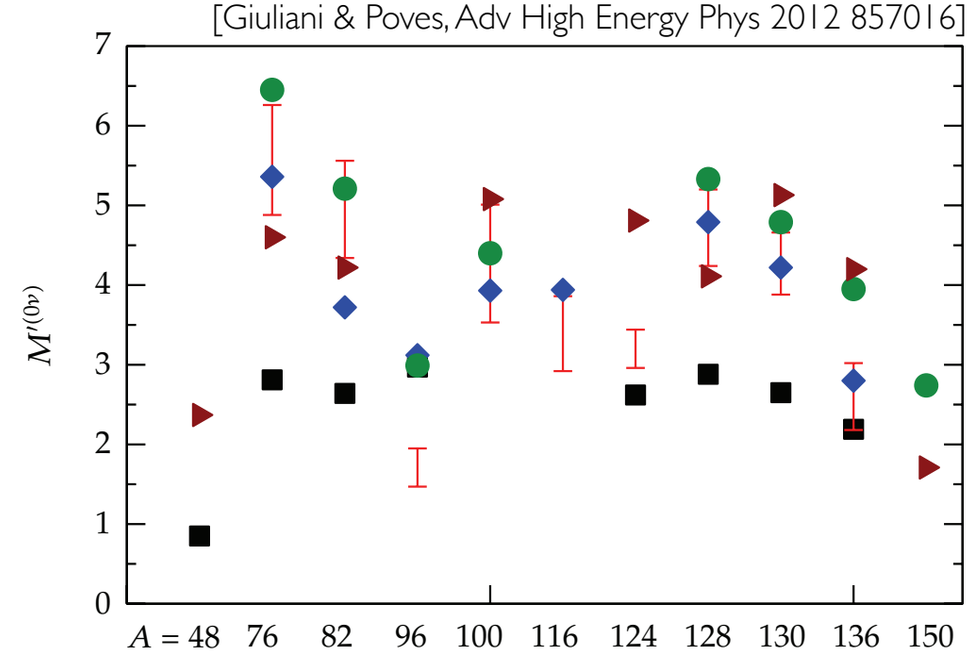


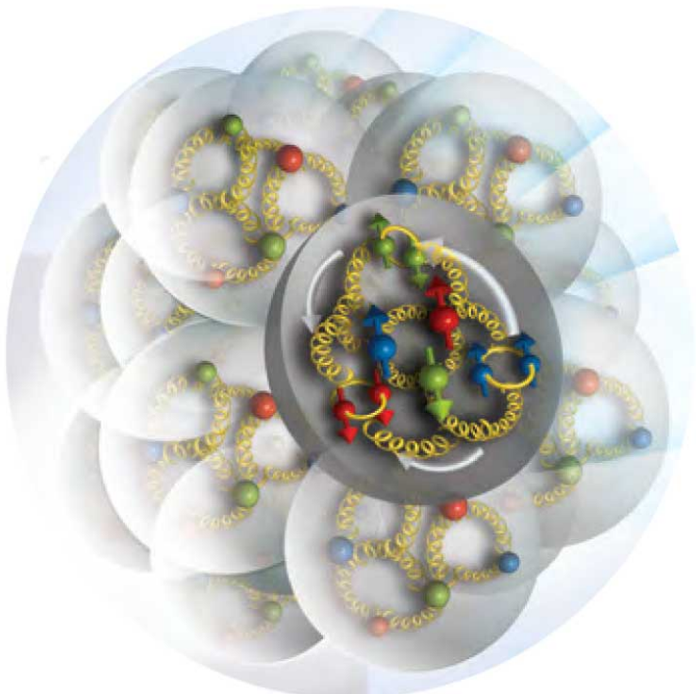
Phys.Rev. D92 (2015) 094511, Phys.Rev.Lett. 115 (2015) 212002 ;1606.07049

USQCD Science Program: new directions

- 2015 Long Range Plan highlighted two new experimental thrusts
  - Ton scale ββ decay experiment
  - Electron-Ion Collider
- Already initial proposals for relevant LQCD calculations
  - ΔI=2 transitions (pp→nn) to constrain nuclear many-body matrix element calculations
  - Gluonic structure calculations

[Giuliani & Poves, Adv High Energy Phys 2012 857016]





Precision Goals and Progress

- Precision goals in NP are more diverse than in flavour physics or g-2

1. Well understood quantities with precision goals
   - g_A, <x>, $\pi\ \pi$ scattering, …

Cold NP Precision Goals

- Quantities with currently quantifiable uncertainties and goals

Quantity	Current uncertainty	Uncertainty Goal	Impact/Target
g_A	5%	3%→1%	Benchmark of LQCD; Neutrino-nucleus X-secs V_{ud} given high enough precision
L_u, L_d	~20%	5%	Understanding the spin of the proton
g_S, g_T	20%, 7%	10%, 3%	Ultracold neutron experimental searches for BSM interactions in neutron decay
$a_{\pi\pi}^{(I=2)}$	1%	✓	More precise than experiment/phenomenology
$\langle N\|\bar{s}s\|N\rangle$	25%	10%	Input for dark matter direct detection experiments; mu2e conversion
$\langle x\rangle$	~15%	5%	Aim for ab initio input to PDFs (USQCD goal)
$\langle r^2\rangle_p$	~10%	2%	Impact proton radius puzzle
L_1, L_{1A}	20%	5%	pp fusion; next generation neutrino detectors

- Most goals achievable achievable in 2021 timeframe

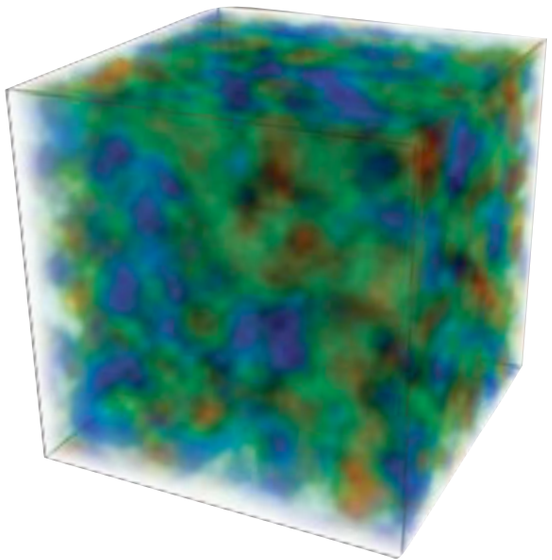
Precision Goals and Progress

- Precision goals in NP are more diverse than in flavour physics or g-2

1. Well understood quantities with precision goals
   - g_A, <x>, $\pi\ \pi$ scattering, …
2. More qualitative quantities
   - Interested in understanding QCD for QCD's sake
   - Excited state spectrum: currently features more important than numbers but this may change in future
3. More exploratory quantities
   - Light nuclear matrix elements, phase shifts above inelastic thresholds, quark chromo-EDM, hadronic parity violation….

Projected Computational Costs

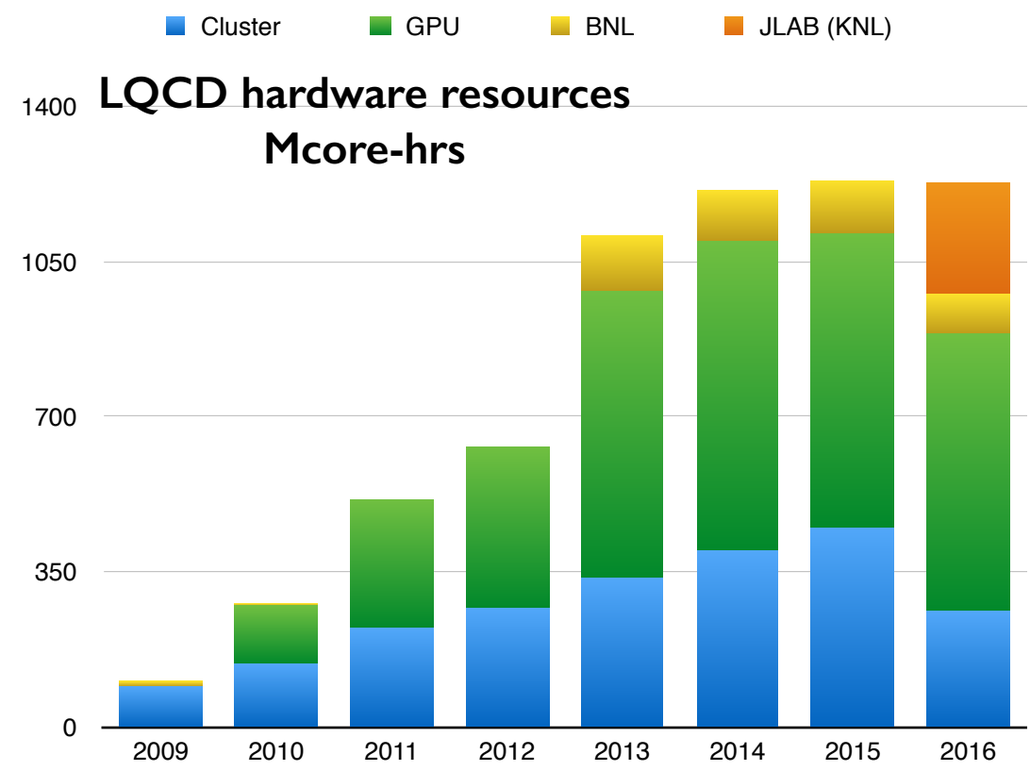
- Costs of different project aspects (structure, spectroscopy, interactions) set out in project proposals and whitepapers
- Production/measurement plans out until 2025 in recent NP/ASCR exascale readiness meeting*
- Science enabled by gauge configuration generation projects Cold NP uses
  - Isotropic clover fermions: structure, interactions, spectroscopy
  - Anisotropic clover fermions: spectroscopy
  - HISQ staggered fermions: structure
  - DW fermions: structure
- Measurement costs larger than gauge generation: make use of USQCD capacity hardware

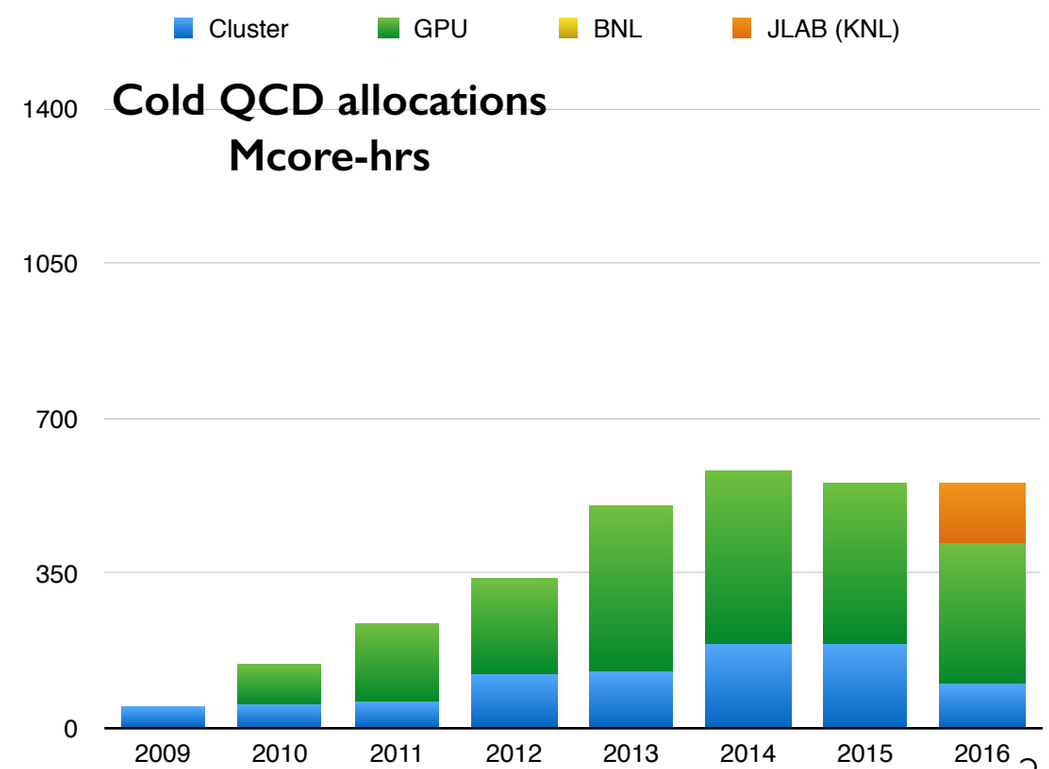


* http://www.orau.gov/npexascale2016/

Cold QCD Resources

- Projections assumed Moore's law (x2 in 1.5yrs) growth (flat funding)
- 2016: USQCD resources have stayed flat (6x deficit since 2012)
- Many excellent projects are only partly supported
  - Reduced efforts on axial couplings to nuclei
  - Reduced efforts on GlueX spectroscopy
  - Reduced efforts on proton form factors/charge radius





USQCD Cold NP

- 4 USQCD cold NP PRLs and ~20 cold NP USQCD journal articles
  `f d after 2015 and a XY`
- 5 US faculty positions in cold NP LQCD in 2015/6 !
  - Lin (MSU)
  - Shindler (MSU)
  - Syritsyn (Stony Brook)
  - Constantinou (Temple)
  - Dudek (William & Mary)

PRL **116,** 112301 (2016) PHYSICAL REVIEW LETTERS week ending 18 MARCH 2016

Unitary Limit of Two-Nucleon Interactions in Strong Magnetic Fields

William Detmold,[1] Kostas Orginos,[2,3] Assumpta Parreño,[4] Martin J. Savage,[5] Brian C. Tiburzi,[6,7,8] Silas R. Beane,[9] and Emmanuel Chang[5]

PRL **115,** 242001 (2015) PHYSICAL REVIEW LETTERS week ending 11 DECEMBER 2015

Resonant $\pi^+\gamma \to \pi^+\pi^0$ Amplitude from Quantum Chromodynamics

Raúl A. Briceño,[1,*] Jozef J. Dudek,[1,2] Robert G. Edwards,[1] Christian J. Shultz,[2] Christopher E. Thomas,[3] and David J. Wilson[2]

PRL **115,** 212002 (2015) PHYSICAL REVIEW LETTERS week ending 20 NOVEMBER 2015

Neutron Electric Dipole Moment and Tensor Charges from Lattice QCD

Tanmoy Bhattacharya,[1,*] Vincenzo Cirigliano,[1,†] Rajan Gupta,[1,‡] Huey-Wen Lin,[2,§] and Boram Yoon[1,‖]

PRL **115,** 132001 (2015) PHYSICAL REVIEW LETTERS week ending 25 SEPTEMBER 2015

***Ab initio* Calculation of the $np \to d\gamma$ Radiative Capture Process**

Silas R. Beane,[1] Emmanuel Chang,[2] William Detmold,[3] Kostas Orginos,[4,5] Assumpta Parreño,[6] Martin J. Savage,[2] and Brian C. Tiburzi[7,8,9]

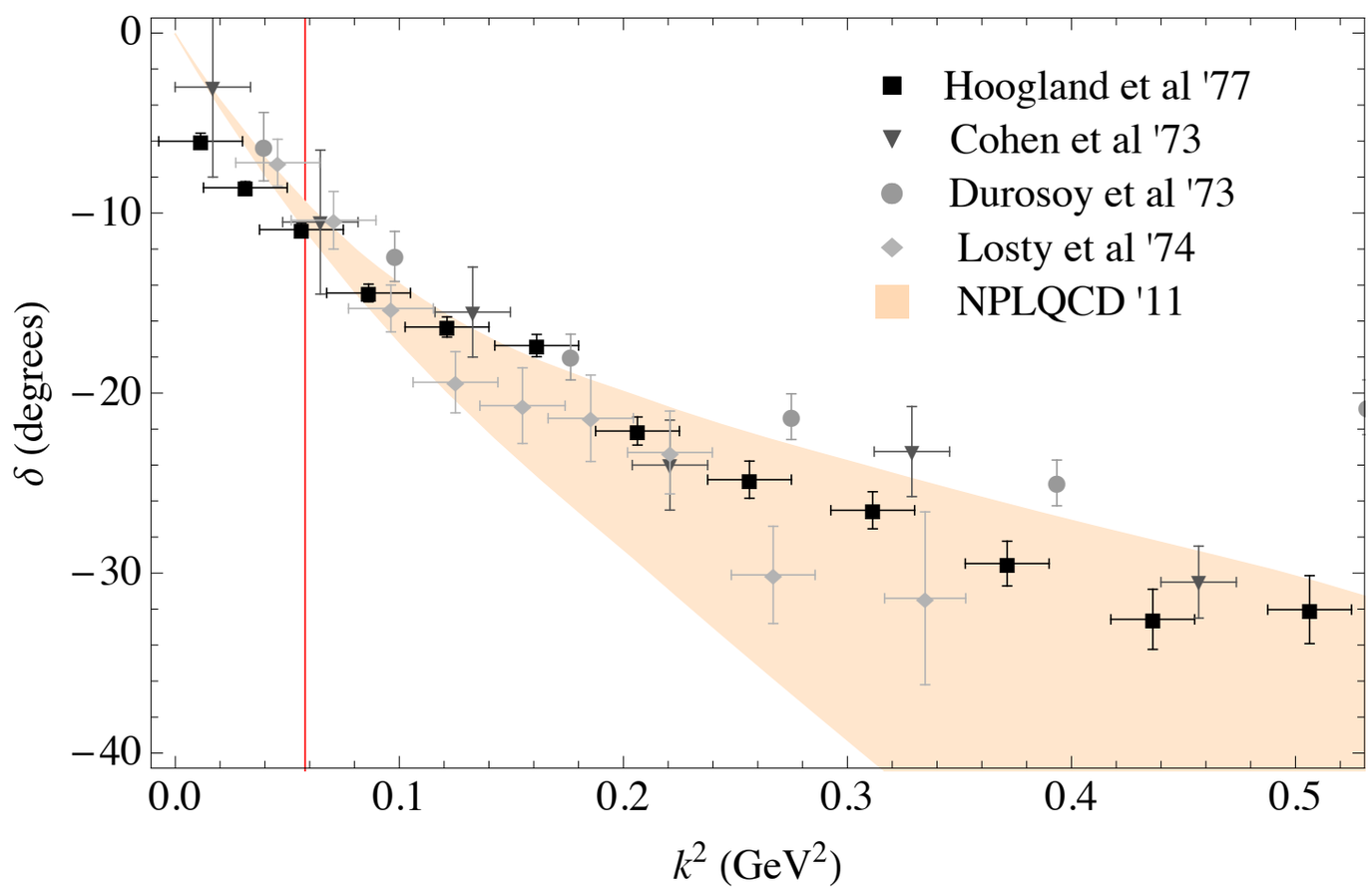
Summary

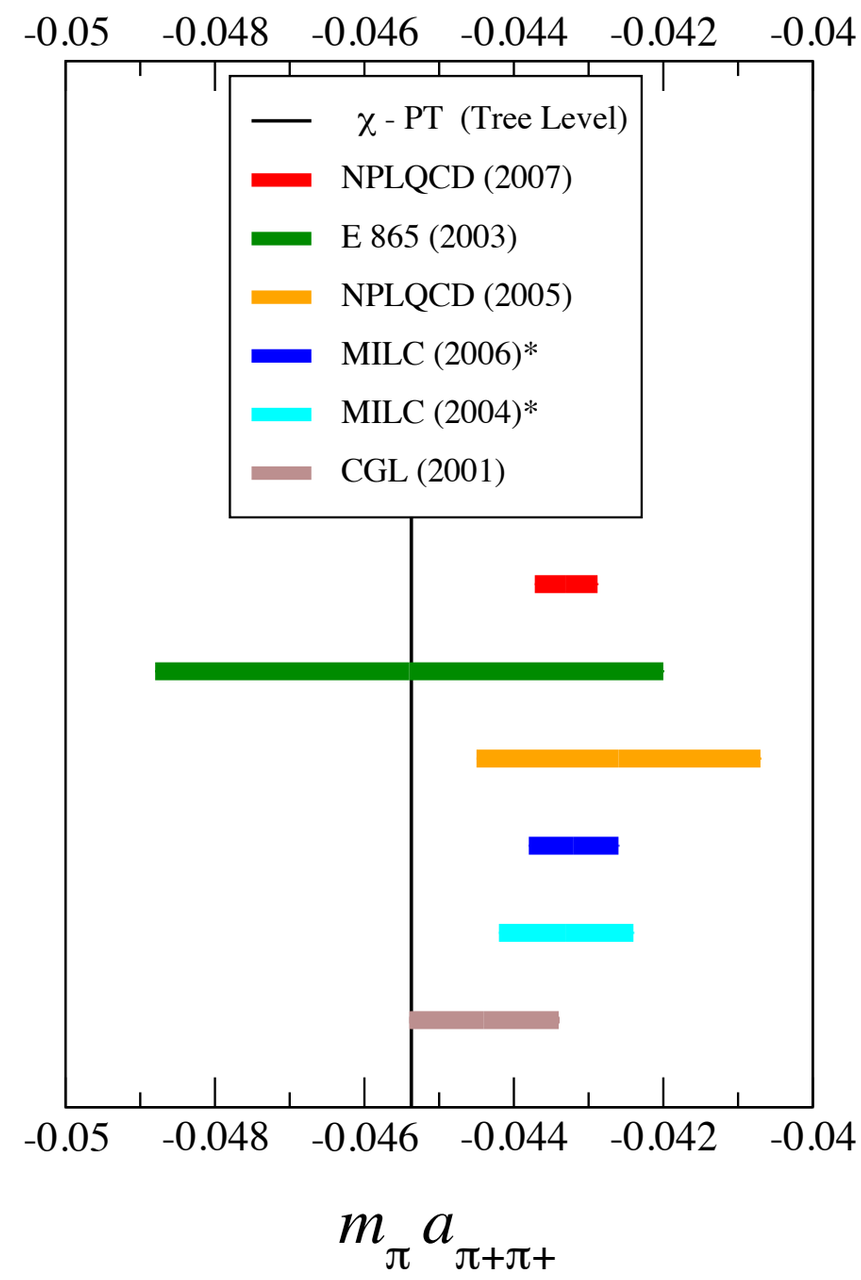
- Cold NP is a vibrant field: important achievements this year
  - Precision hadron structure
  - Coupled-channel scattering phase shifts
  - Nuclear properties
- Closely aligned with NP (HEP) experimental program and long term goals of DoE NP
- Transformative period for the field
  - Peta/exa-scale resources open the door to precision and new possibilities
  - Decreased funding is materially impacting progress

Extra Slides

I=2 π π Scattering

- I=2 π π scattering is high precision
  - scattering length @ 1%



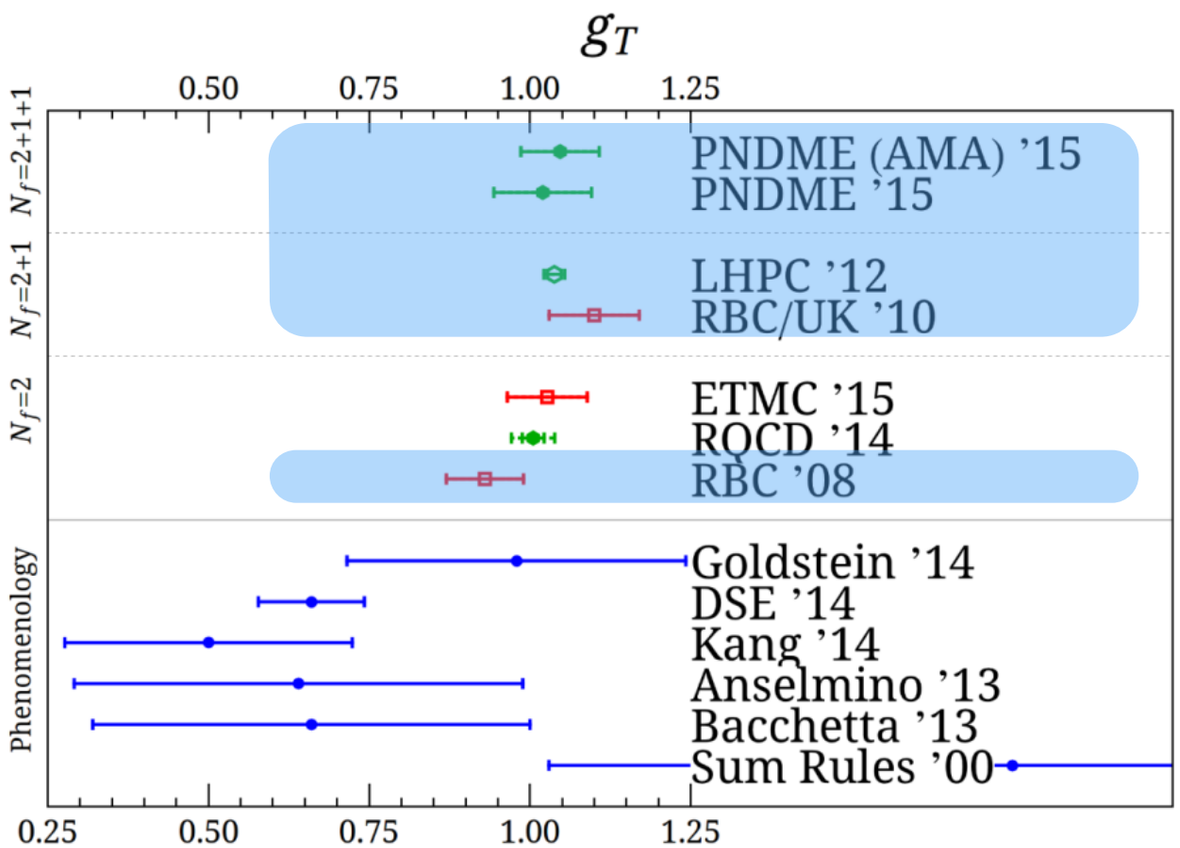


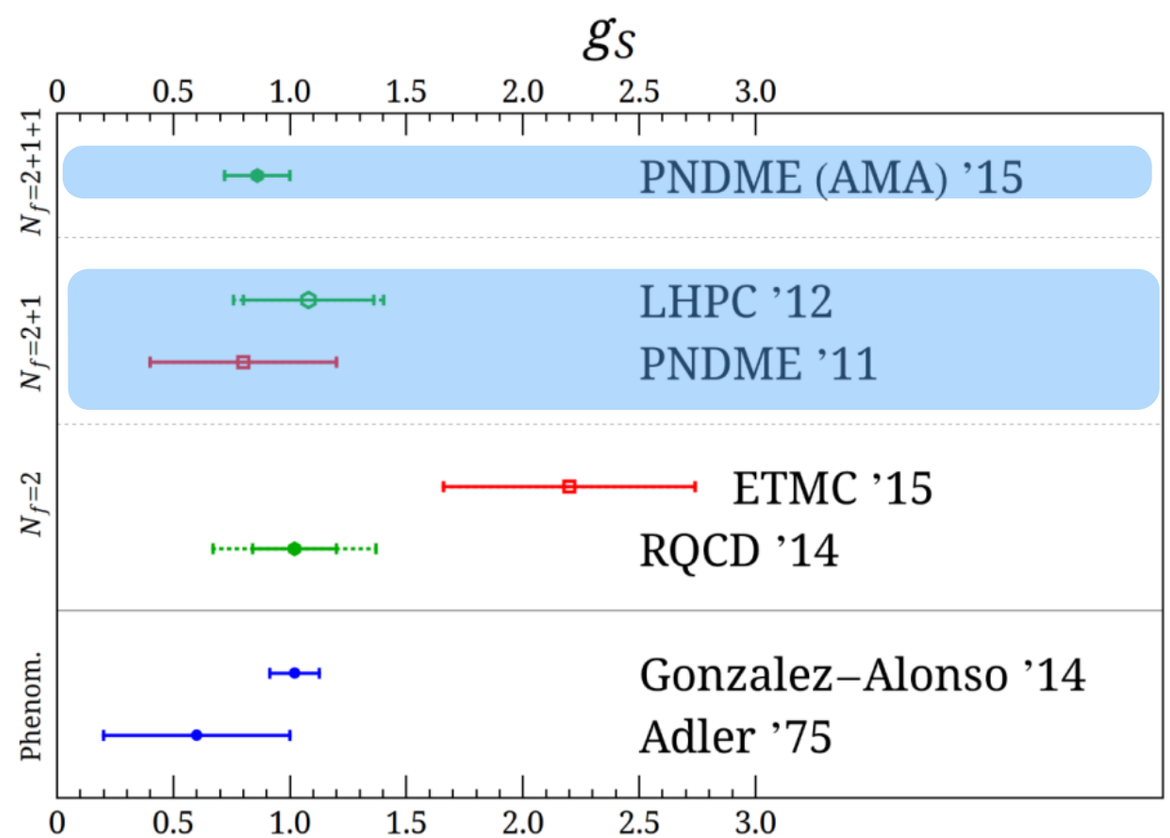
NPLQCD 2007, 2011

Scalar and tensor charges

Thanks to Huey-Wen Lin

- Isovector scalar and tensor charges @ scale 2 GeV



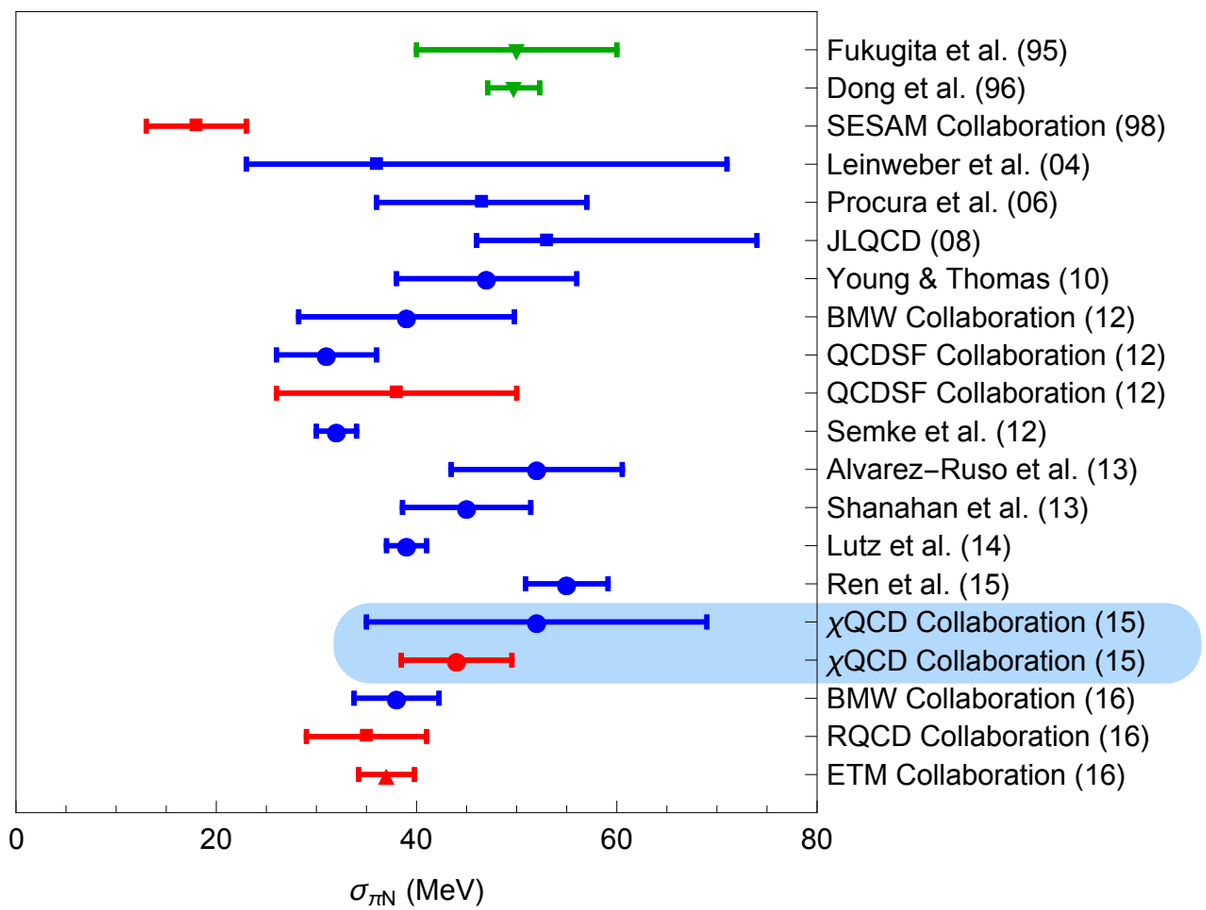


Collaboration	Ref.	publication status	N_f	chiral extrapolation	continuum extrapolation	finite volume	excited state	renormalization	g_T
PNDME'15	This work	P	2+1+1	★	★	★	★	★	1.020(76)[a]
ETMC'13	[30]	C	2+1+1	■	○	○	■	★	1.11(3)[b]
LHPC'12	[28]	A	2+1	★	○	★	○	★	1.037(20)[c]
RBC/UKQCD'10	[29]	A	2+1	○	■	★	★	★	1.10(7) [d]
RQCD'14	[31]	P	2	★	★	★	○	★	1.005(17)(29))[e]
ETMC'13	[30]	C	2	★	■	○	■	○	1.114(46) [f]
RBC'08	[32]	P	2	■	■	★	■	★	0.93(6) [g]

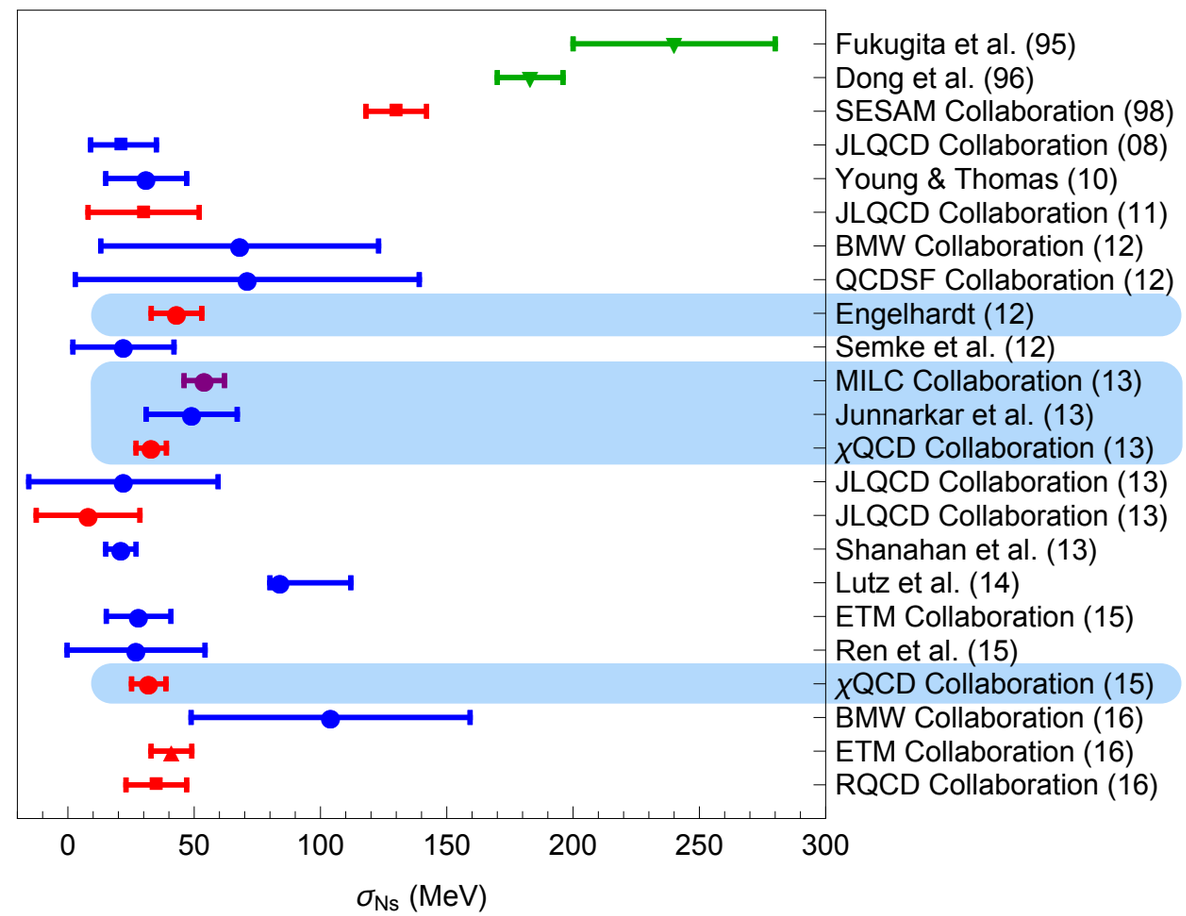
Sigma term and strangeness content

Thanks to Phiala Shanahan

- Nucleon sigma term and strangeness content of nucleon



(a) $\sigma_{\pi N} = \frac{m_u + m_d}{2} \langle N | \overline{u}u + \overline{d}d | N \rangle$

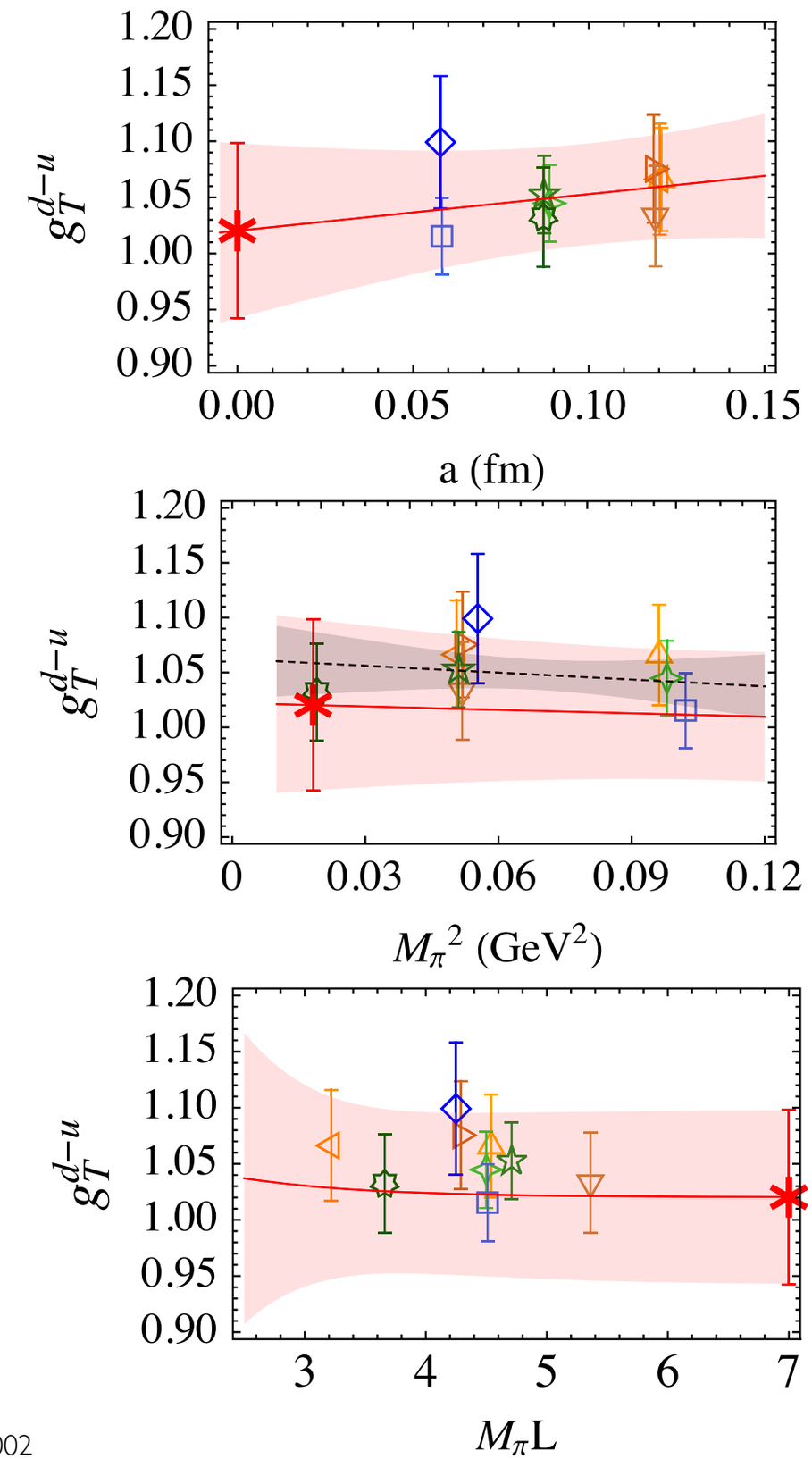


(b) $f_s^N = \frac{\sigma_{sN}}{m_N}$

- Ultra-cold neutron beta decay experiments (UCNB/b) at LANL
- Decay rate

$$d\Gamma \propto F(E_e)\left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + B\frac{\vec{\sigma}_n \cdot \vec{p}_\nu}{E_\nu} + A\frac{\vec{\sigma}_n \cdot \vec{p}_e}{E_e} + \ldots\right]$$

- Presence of non-SM scalar or tensor couplings modifies *b*, *B*
- Constraint on BSM requires precise scalar and tensor couplings g_S, g_T
- PNDME collaboration: most precise calculations to date



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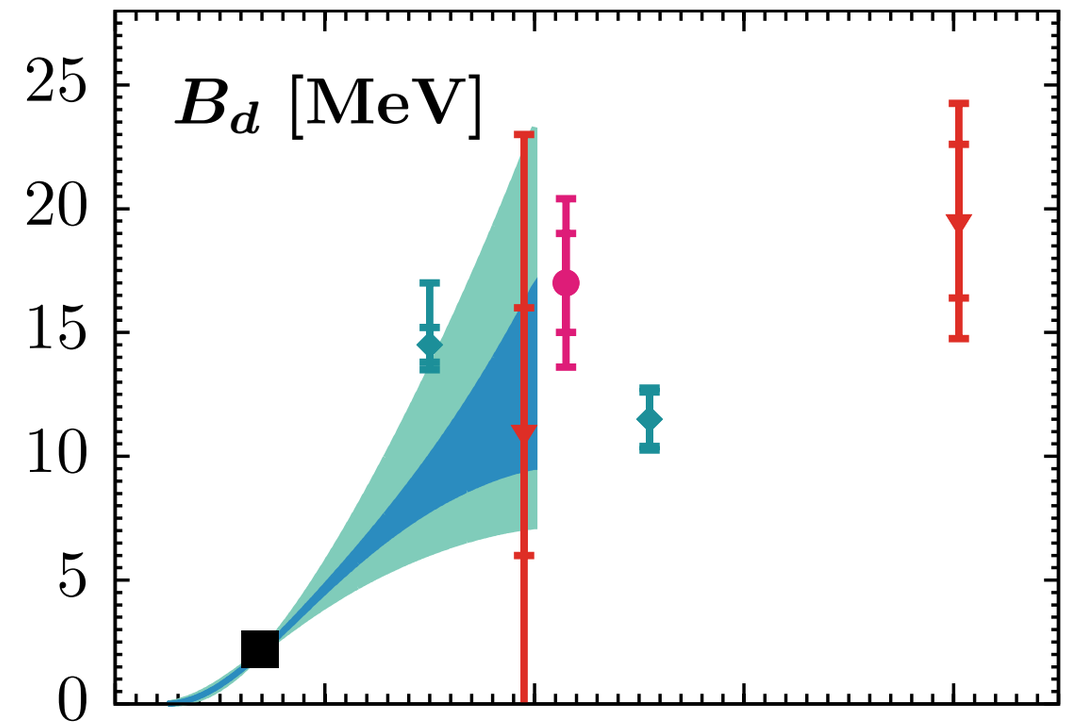
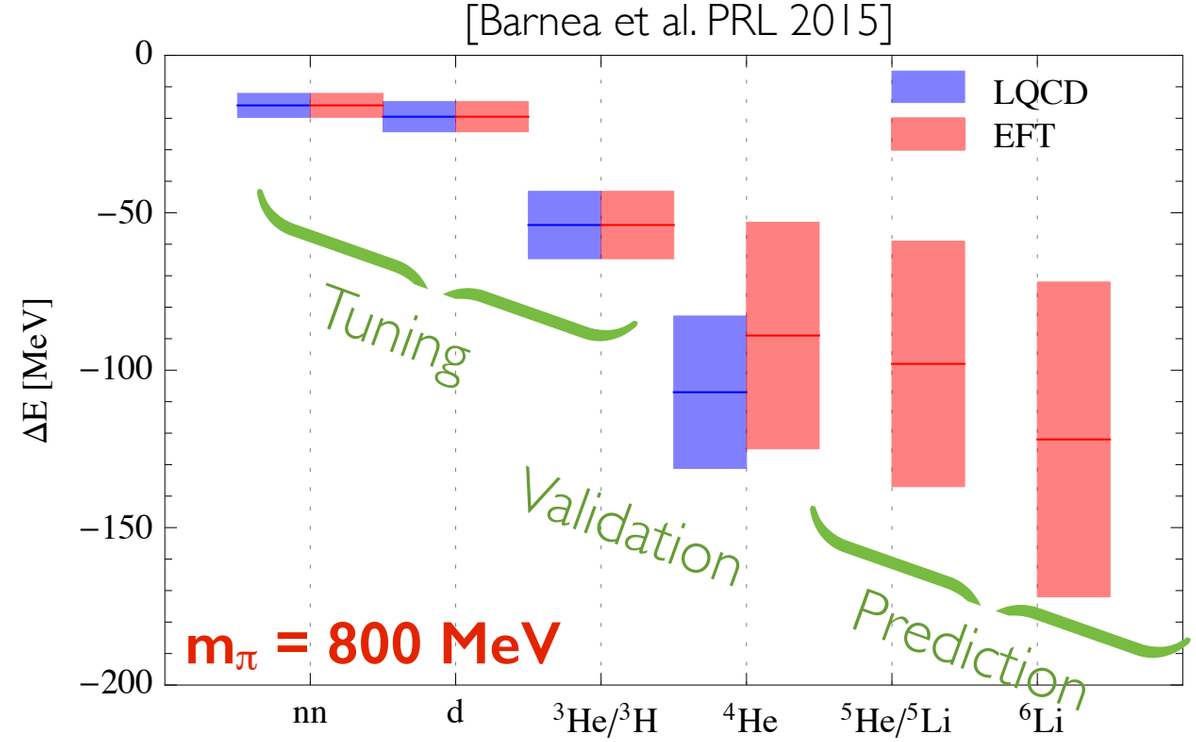
Impact on nuclear theory; EFT

- LQCD nuclear spectroscopy being used to constrain nuclear EFTs
- Baru *et al.*: use low-energy theorems to understand mass dependence
- Barnea *et al.*: match 2-/3-body interactions to LQCD
  - Many-body methods to go to large A

[Baru et al. 1504.07852

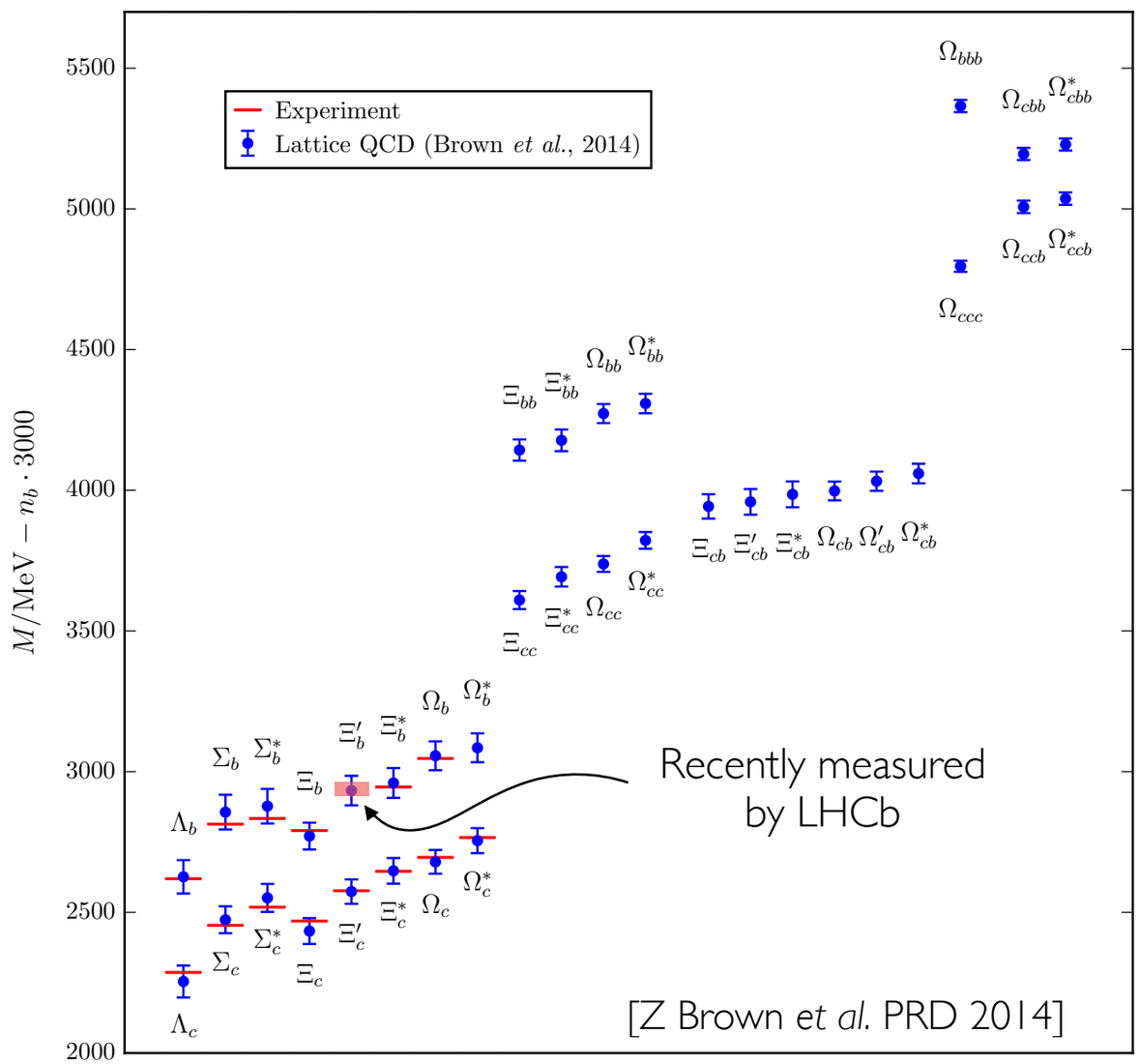


[Barnea et al. PRL 2015]



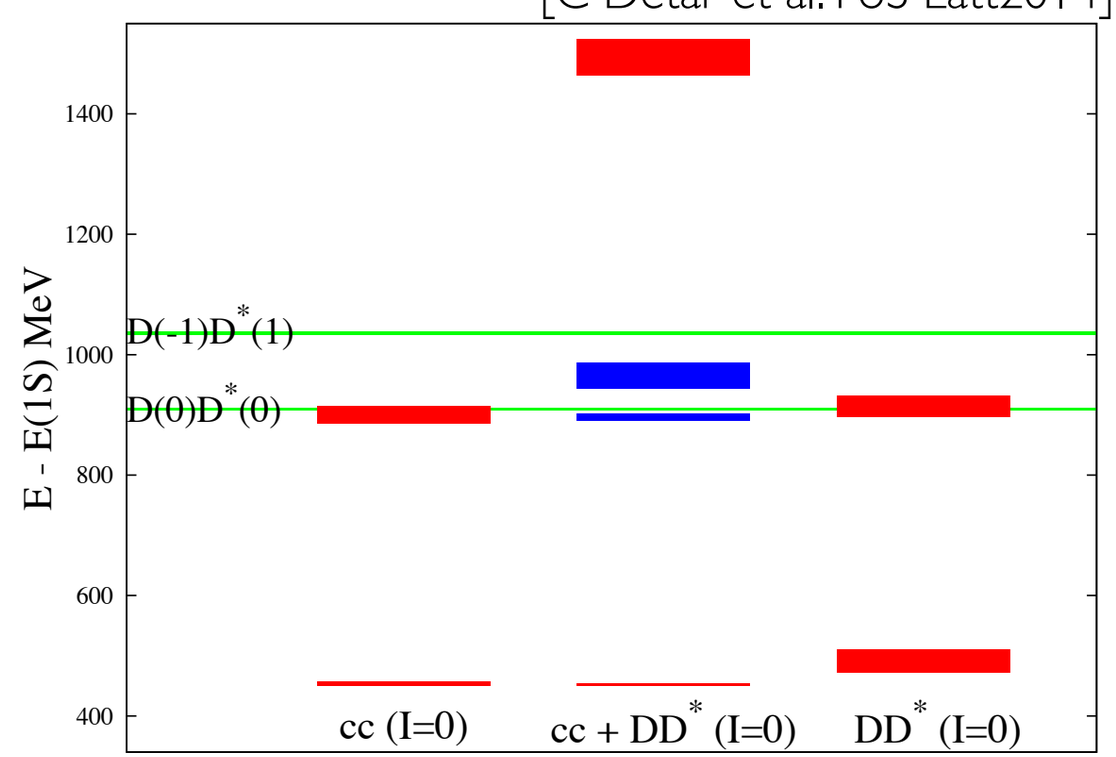
USQCD Science Highlights: Heavy Exotica

- Predictions for new states with controlled uncertainties



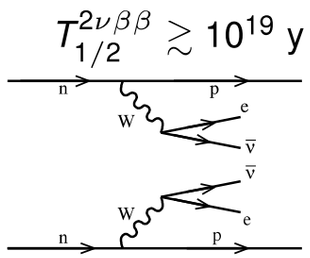
- Exotic States: X(3872)
  - ~13(6) MeV below threshold
  - What is its nature?

[C Detar et al. PoS Latt2014]



0νββ decay

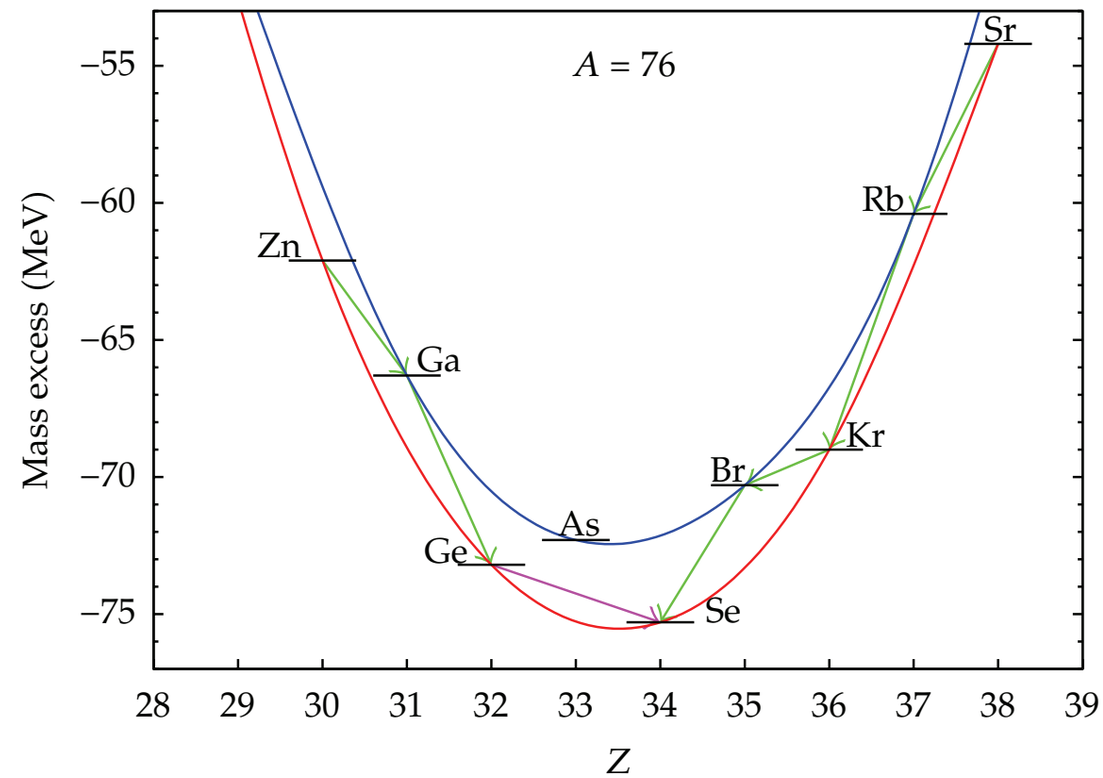
- Certain nuclei allow observable ββ decay

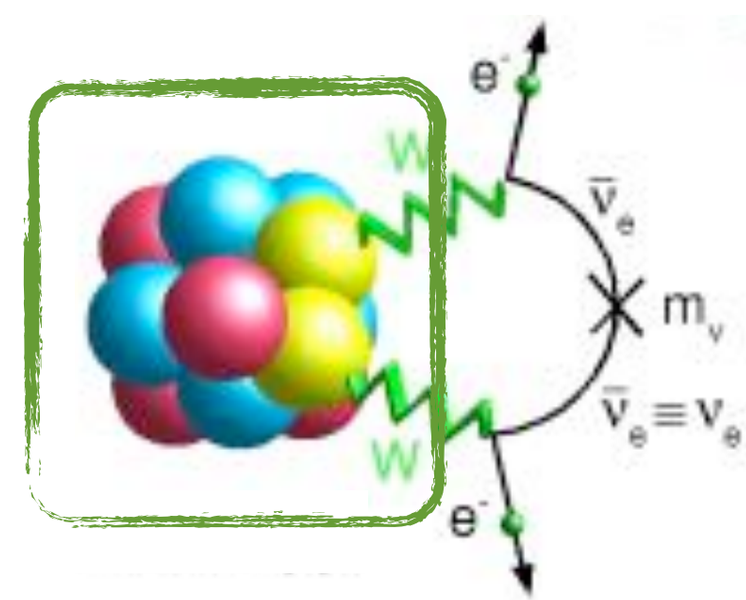


- If neutrinos are massive Majorana fermions 0νββ decay is possible

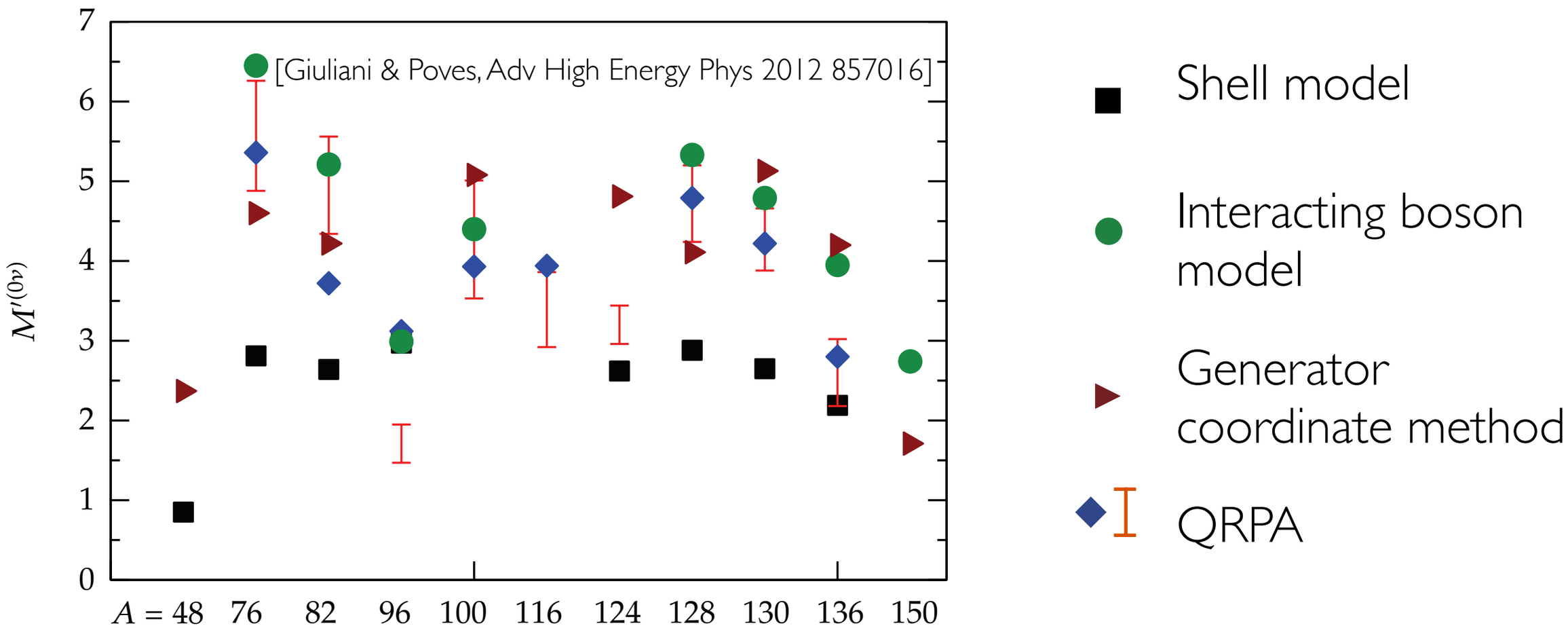
- Half-life depends critically on the nuclear matrix elements of two weak currents

$$\left(T_{1/2}^{0\nu\beta\beta}(0^+ \rightarrow 0^+)\right)^{-1} = G_{01}\left|M^{0\nu\beta\beta}\right|^2\left(\frac{\langle m_\nu \rangle}{m_e}\right)^2$$





0νββ decay nuclear matrix elements



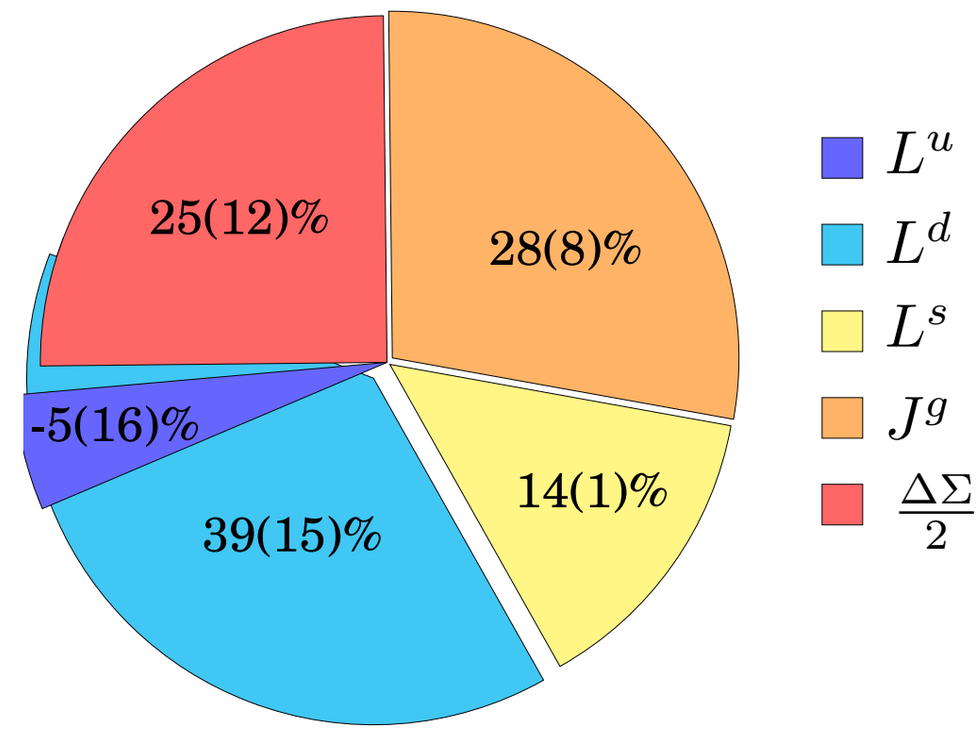
- Is the spread of results representative of the true uncertainty?
- Can LQCD provide constraints for light nuclei

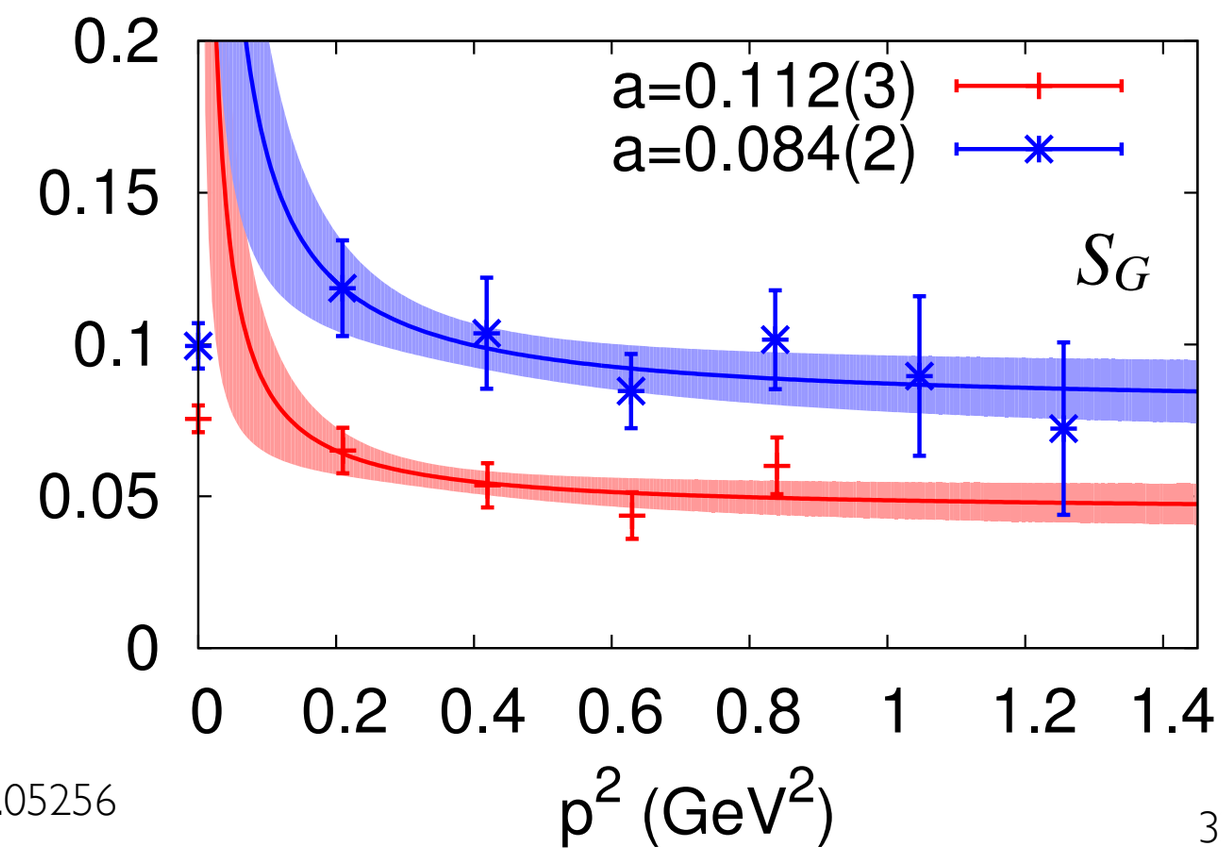
- Full decomposition of proton spin

$$\vec{J}_{\rm QCD} = \vec{J}_q + \vec{J}_g = \frac{1}{2}\vec{\Sigma}_q + \vec{L}_q + \vec{J}_g,$$

- χQCD collaboration
  - Initial quenched study
  - Repeating with dynamical quarks
  - Eg: gluon spin contribution in a particular frame in Coulomb gauge

$$S_G = \int d^3x \, {\rm Tr}(\vec{E}^C \times \vec{A}^C)$$





Eur.Phys.J. A52 (2016) no.6, 160 ; 1603.05256