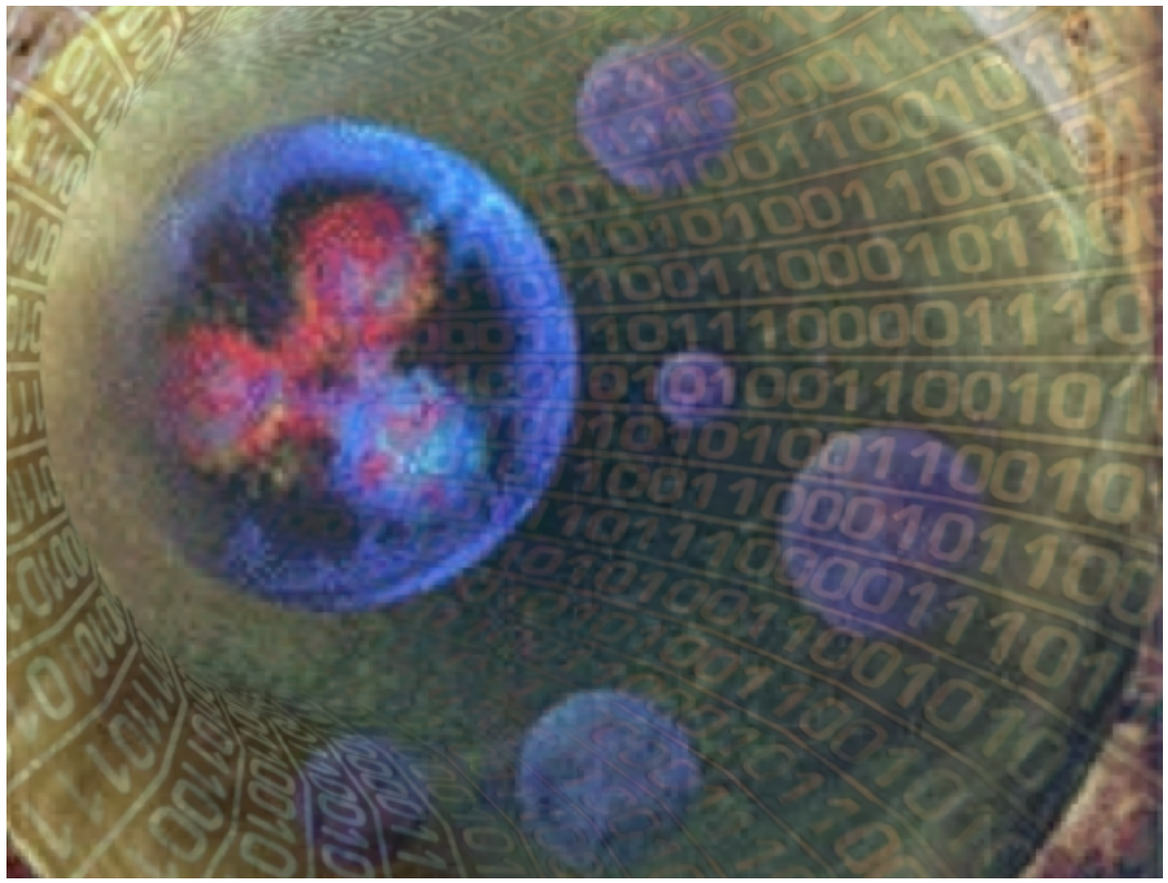


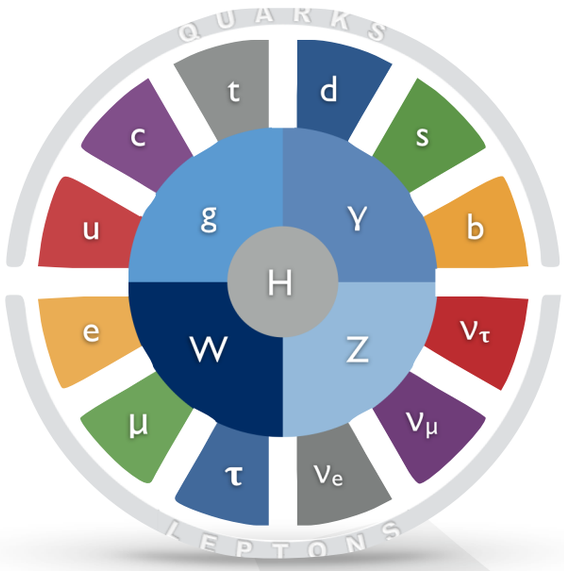
USQCD

USQCD Cold Nuclear Physics Science Program

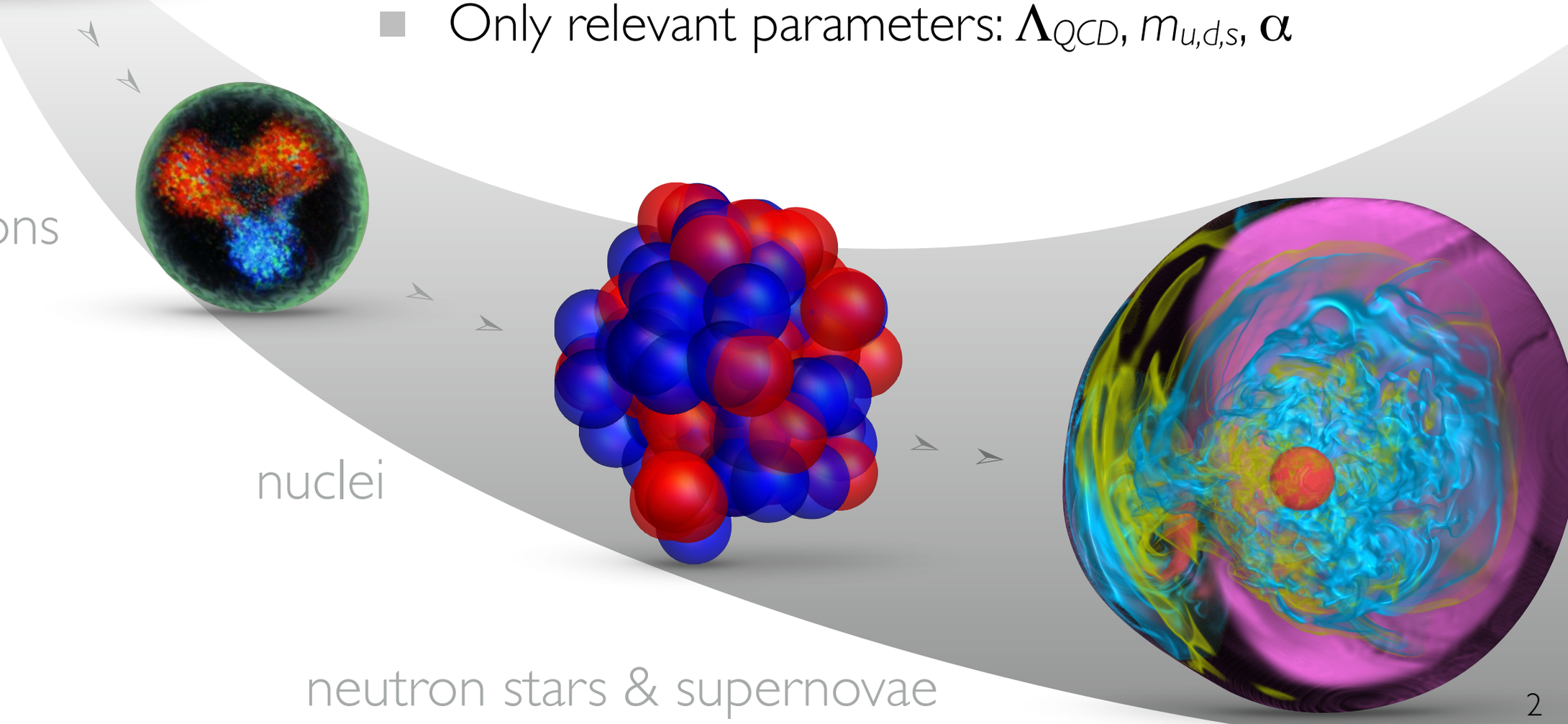
William Detmold, MIT

LQCD-ext II Project Review, BNL, May 21st 2015

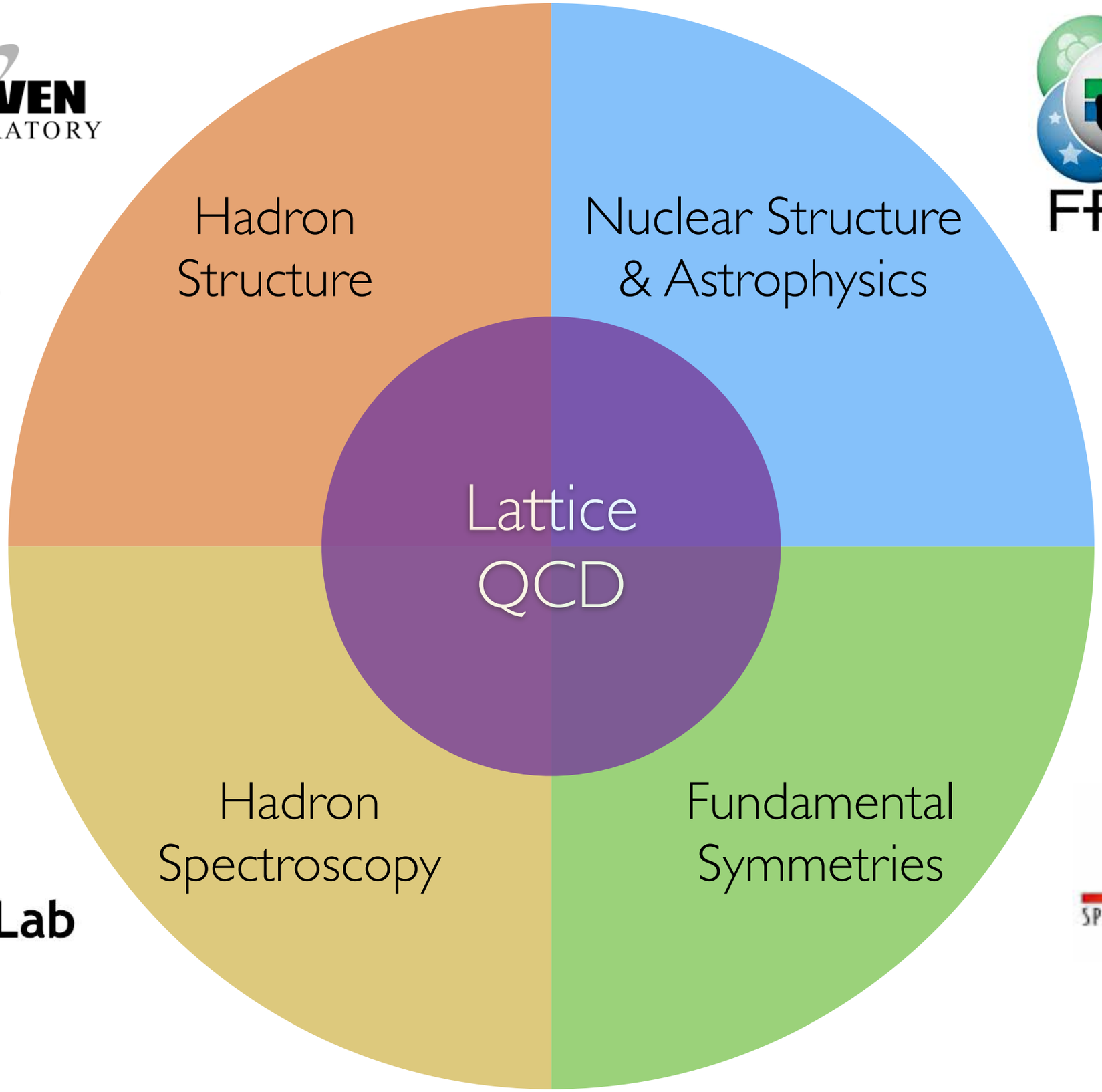
From Quarks to the Cosmos



- Complexity of nuclear physics emerges from the Standard Model
  - Same underlying physics at vastly different scales
  - EM, weak and strong (QCD) interactions
  - Only relevant parameters: Λ_{QCD}, $m_{u,d,s}$, α



Cold Nuclear Physics



Align with NP goals

- LQCD program supports NSAC milestones

2014 HP9	Perform lattice calculations in full QCD of nucleon form factors, low moments of nucleon structure functions and low moments of generalized parton distributions including flavor and spin dependence.	No	Expect to Exceed
2014 HP10	Carry out ab initio microscopic studies of the structure and dynamics of light nuclei based on two-nucleon and many-nucleon forces and lattice QCD calculations of hadron interaction mechanisms relevant to the origin of the nucleon-nucleon interaction.	No	Expect to Achieve
2018	HP15 (new)	The first results on the search for exotic mesons using photon beams will be completed.	
2020	FI15 (new)	Obtain initial results from an experiment to extend the limit on the electric dipole moment of the neutron by two orders of magnitude	

Structure

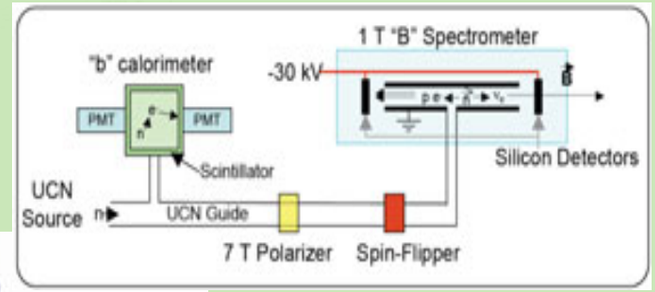
Nuclear

Spectrum

Fund. Symm.

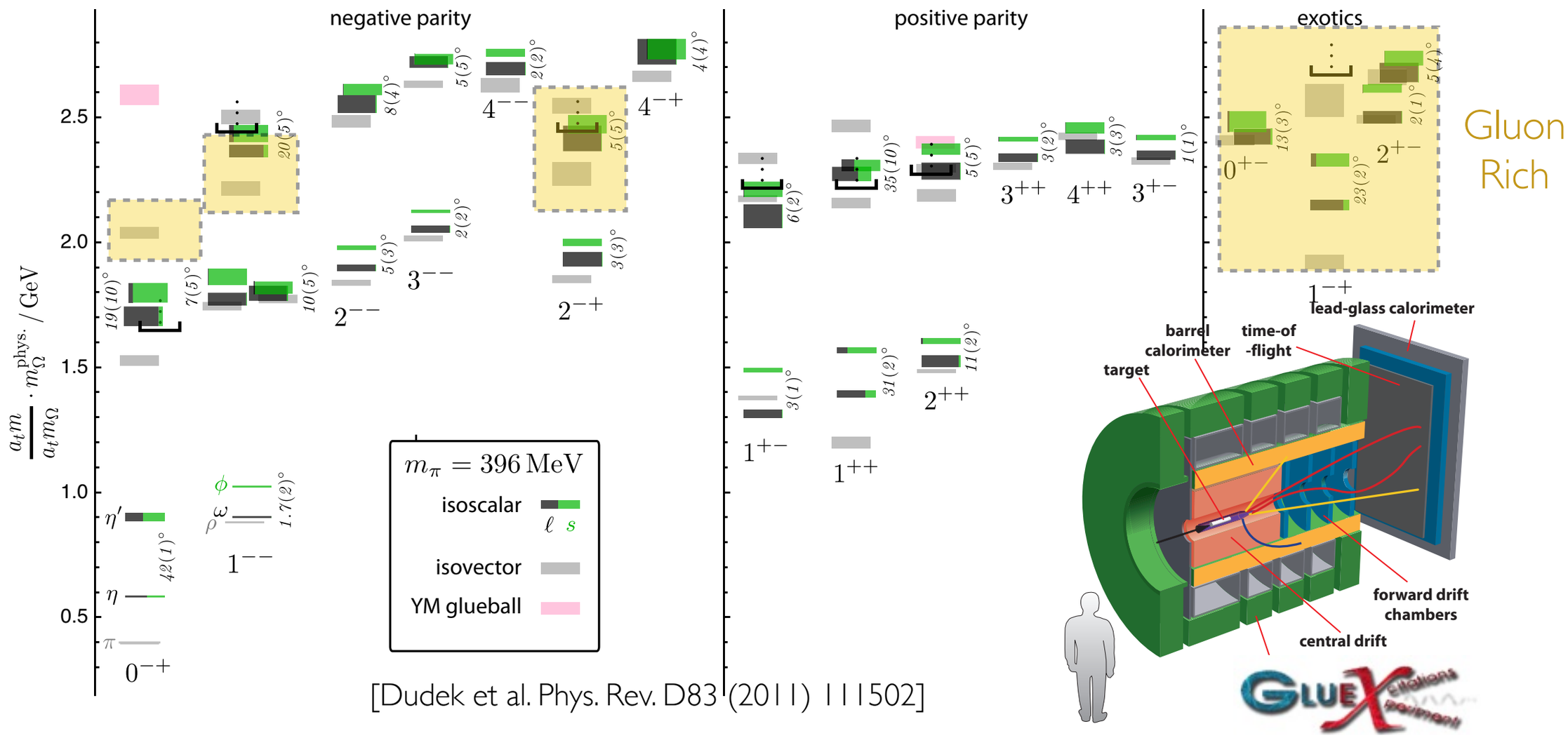
- Strong support for LQCD in cold NP community
  - NRC decadal review of nuclear physics:
    "A plan should be developed within the theoretical community and enabled by the appropriate sponsors that permits forefront computing resources to be deployed by nuclear science researchers and establishes the infrastructure and collaborations needed to take advantage of exascale capabilities as they become available."
  - Comp. Nuclear Theory Initiative (LQCD + …): need for <u>capacity computing</u> and <u>workforce</u> enhancement strongly endorsed by LRP Town Hall Meetings

Impacts Diverse Experimental Program



Impact on experiment: GlueX

- LQCD 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]

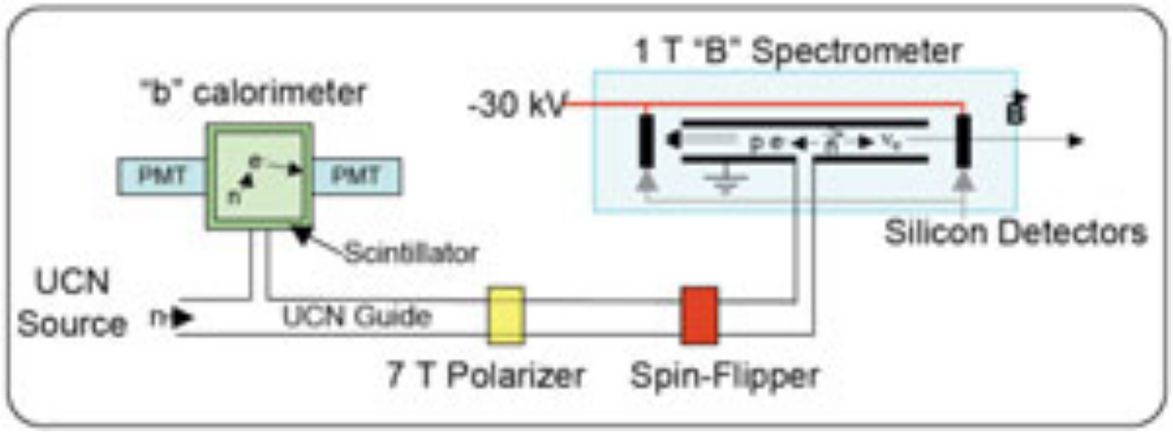
- Important in analysis and interpretation of forthcoming data

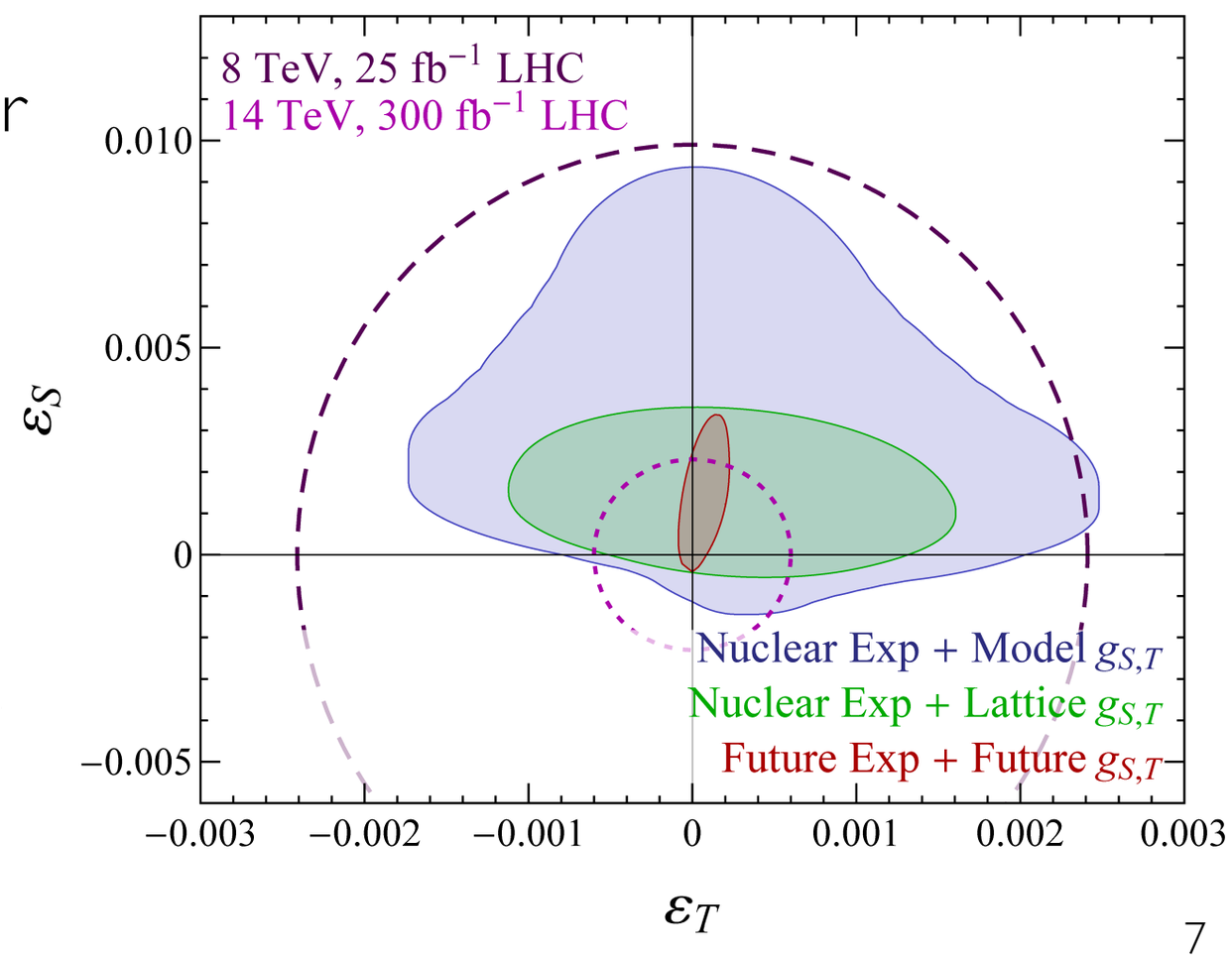
Impact on experiment; LANL UCN

- Ultracold 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*
- Use to constrain BSM given scalar and tensor charges (g_S and g_T)
  - Goal: measure to 10^{-3}
  - Constraint requires precise g_S, g_T

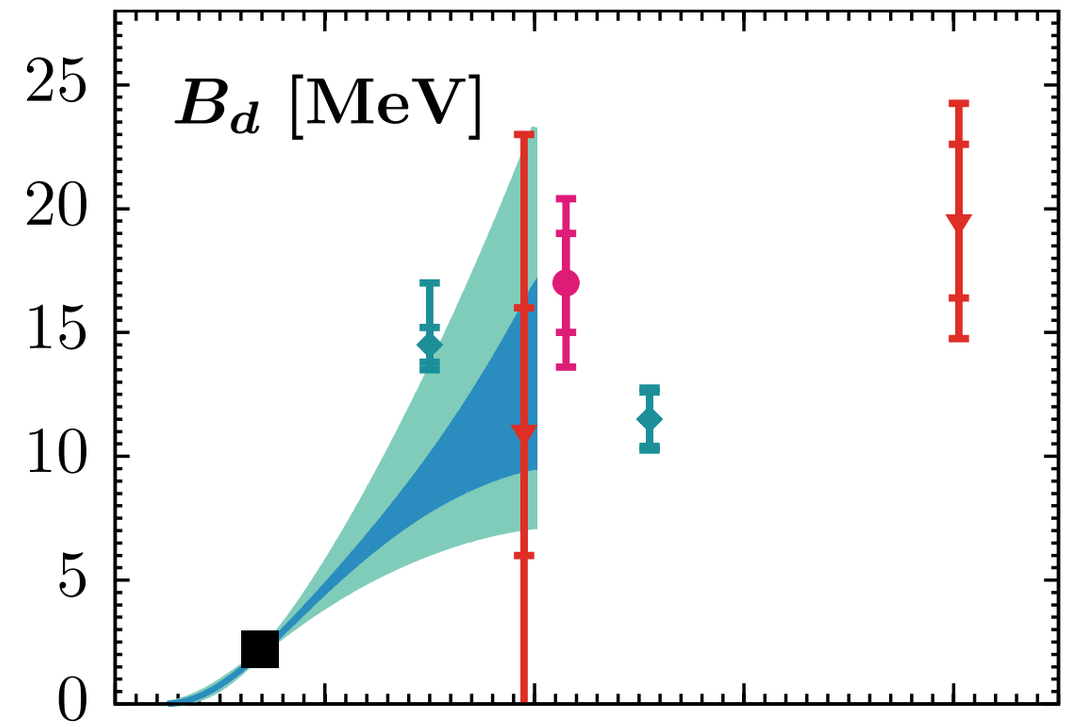




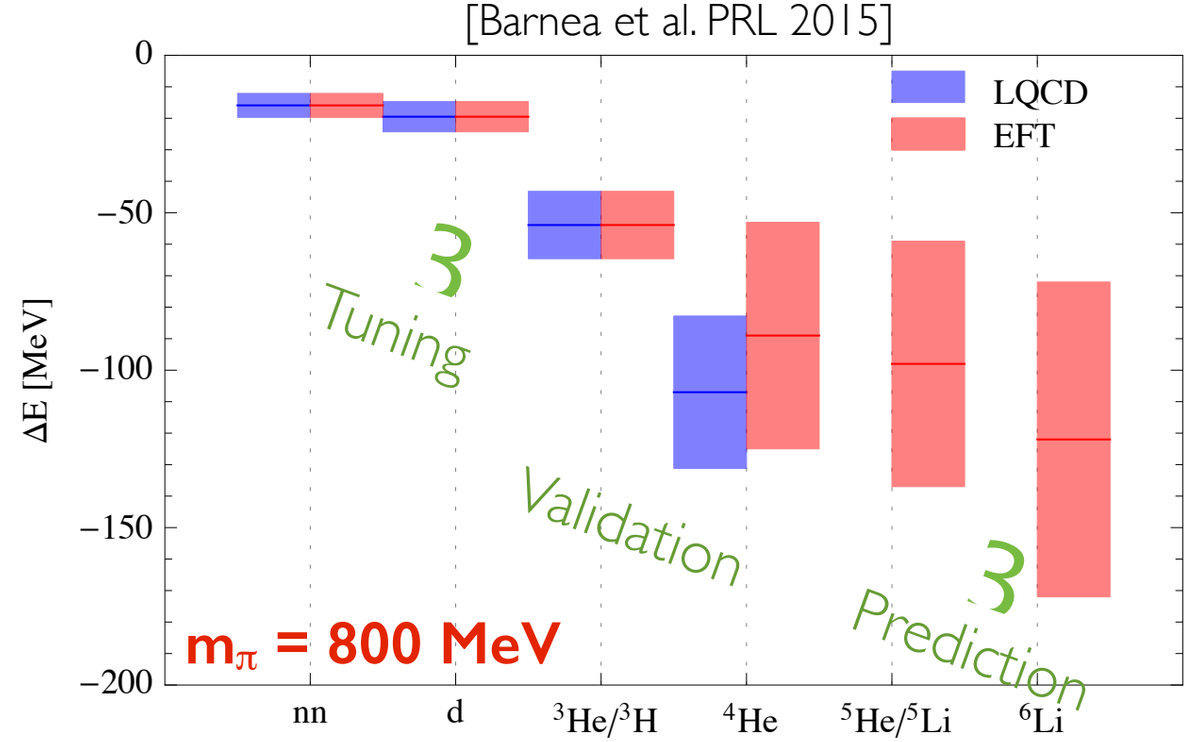
Impact on nuclear theory; EFT

- 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

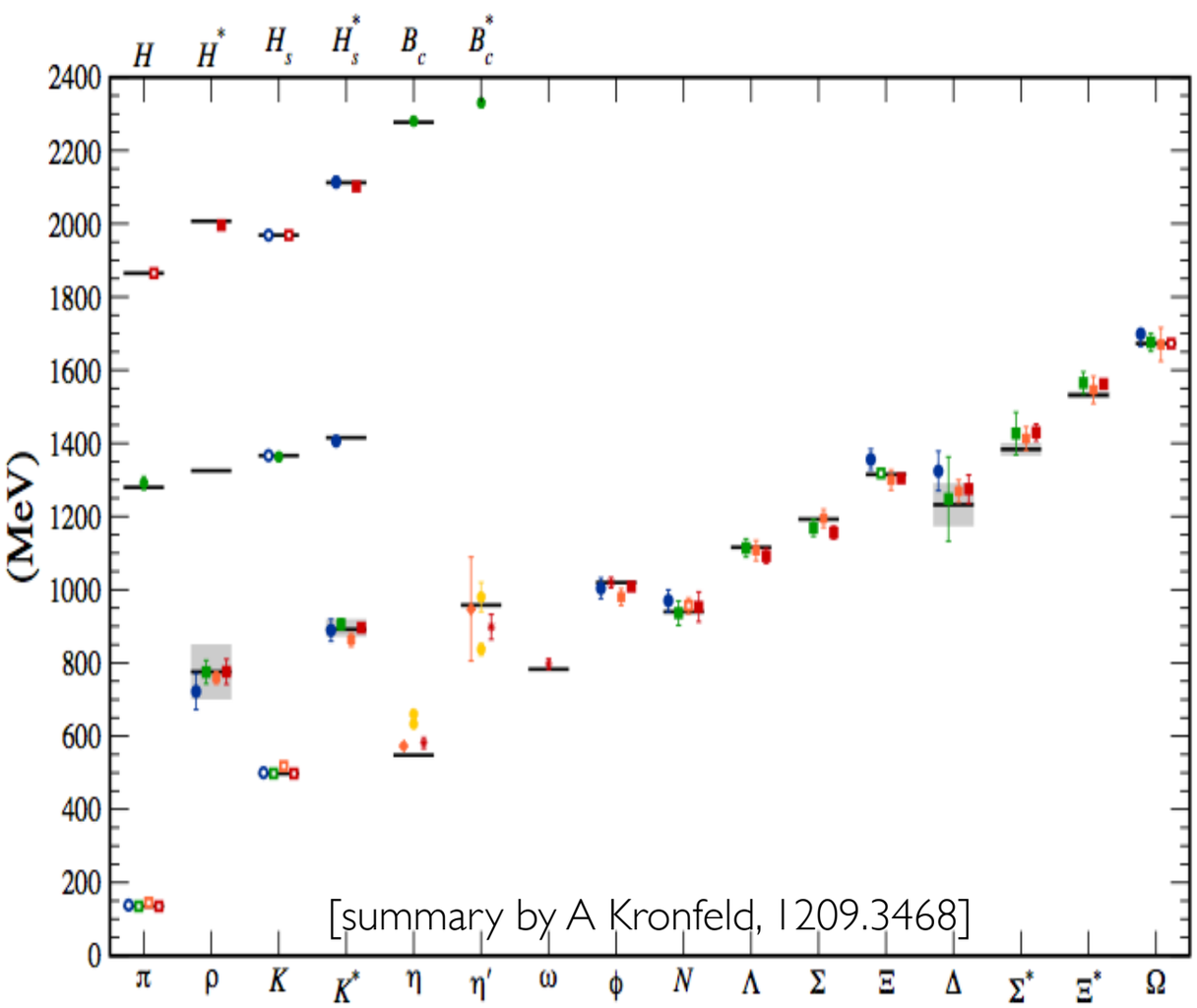


[Barnea et al. PRL 2015]

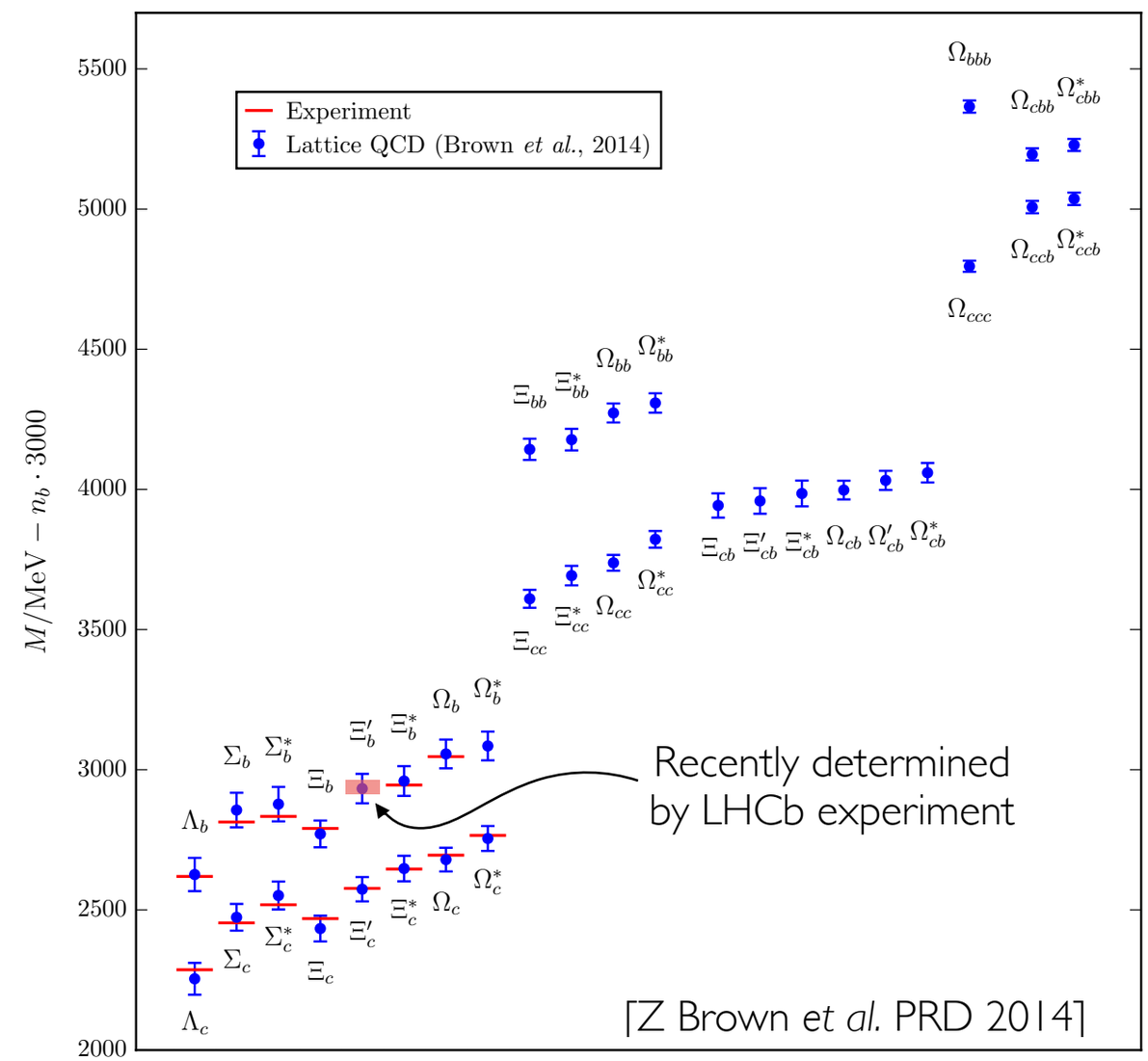


USQCD Science Highlights: Spectroscopy

- Ground state hadron spectrum reproduced

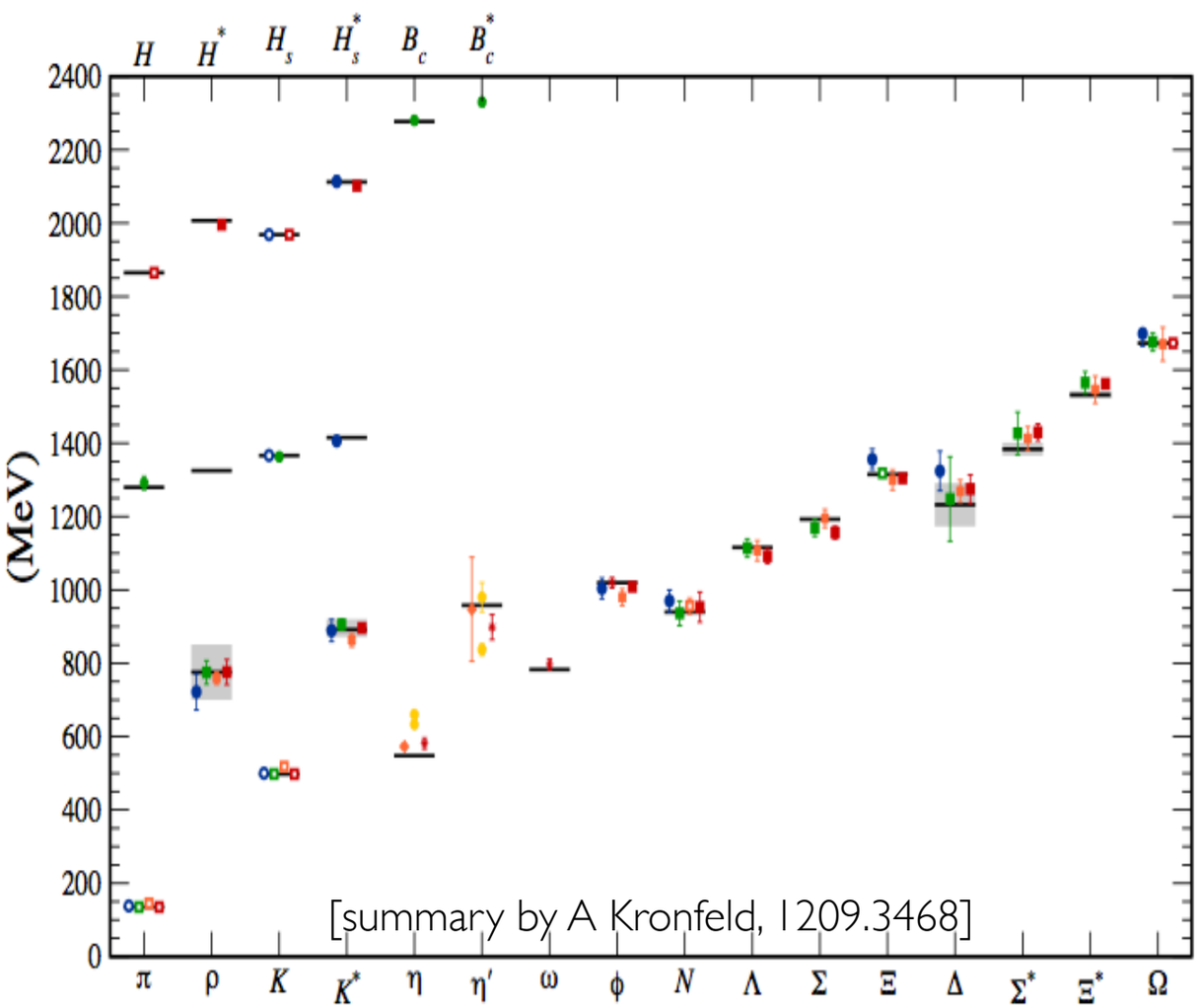


- Predictions for new states with controlled uncertainties



USQCD Science Highlights: Spectroscopy

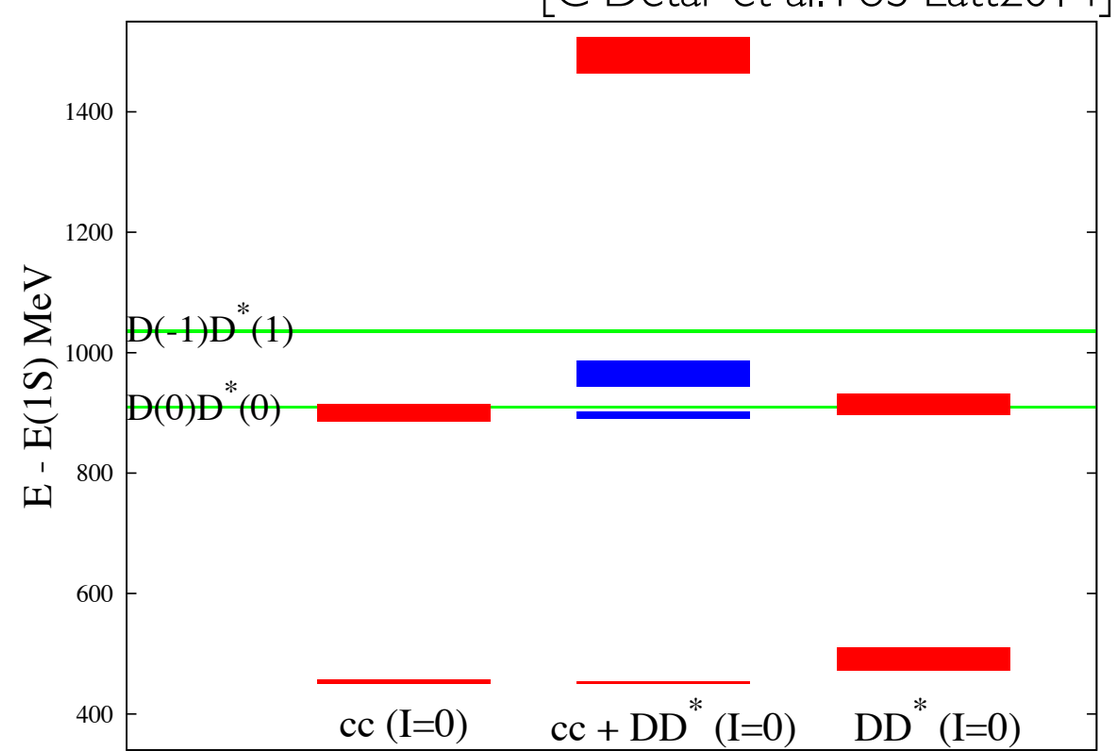
- Ground state hadron spectrum reproduced



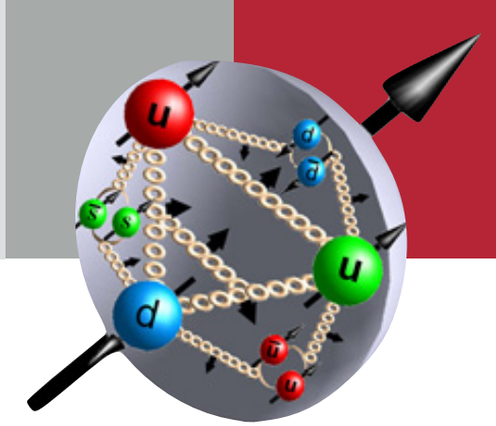
[summary by A Kronfeld, 1209.3468]

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

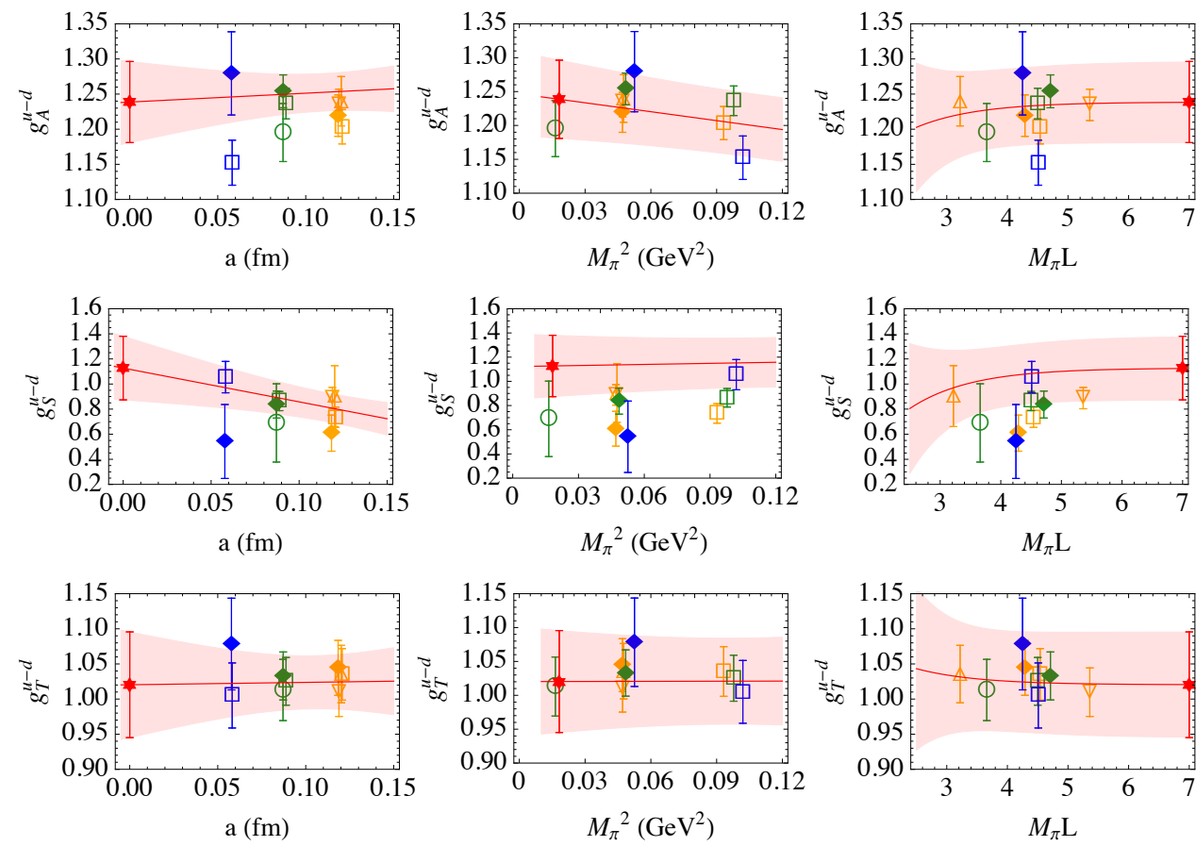
[C Detar et al. PoS Latt2014]

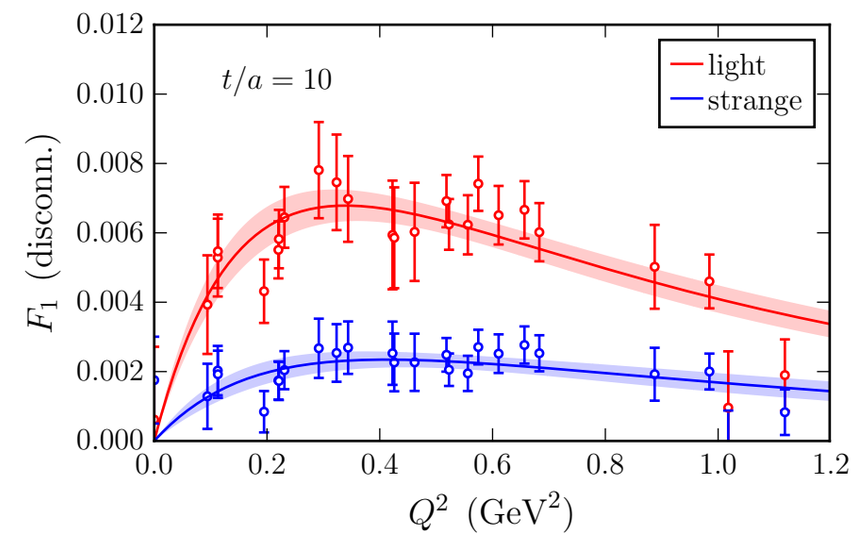


USQCD Science Highlights: Structure



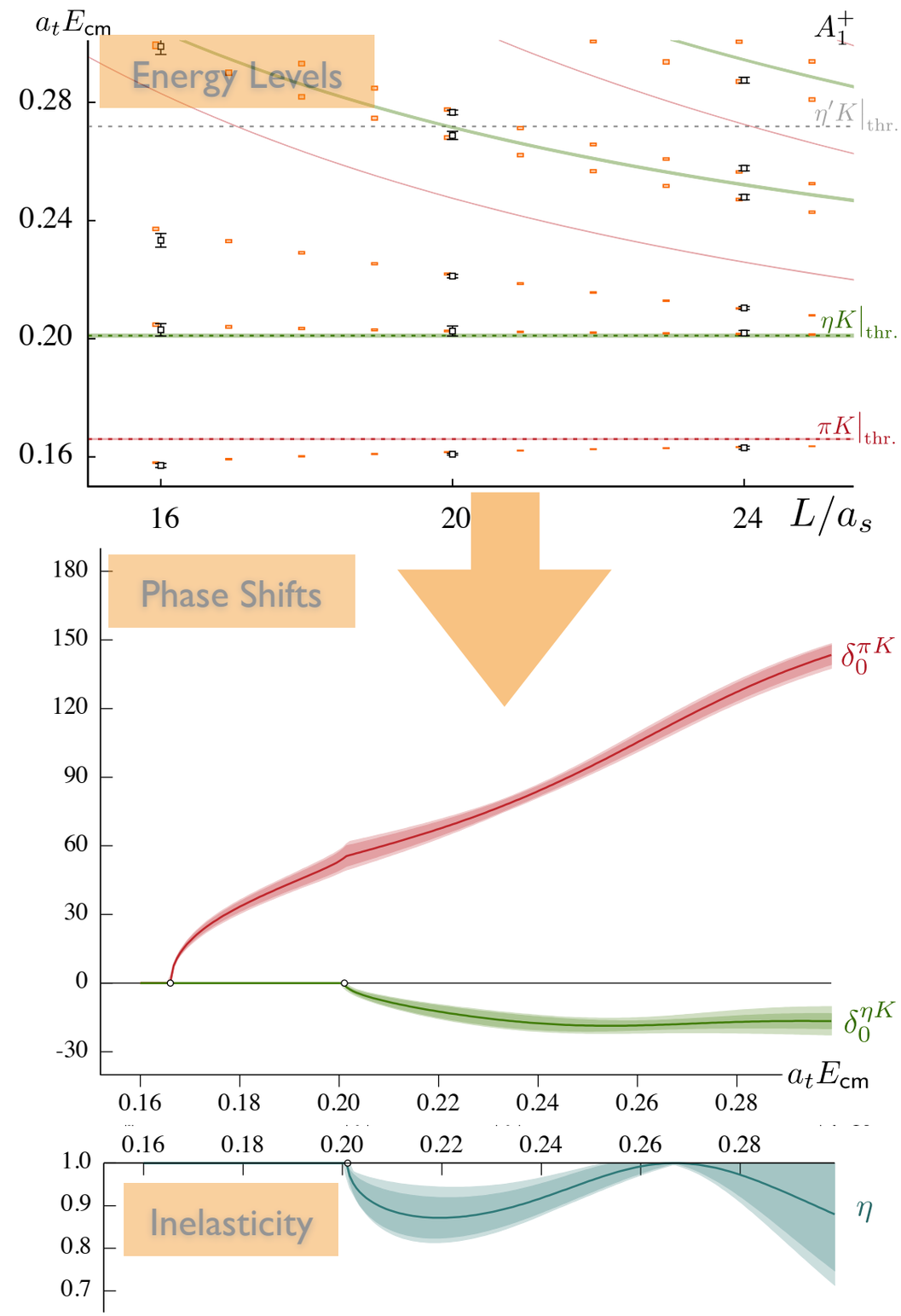
- Hadron structure probed at JLab, RHIC-spin, …, future EIC
- Vector, tensor, axial couplings, form factors, radii
  moments of PDFs, GPDs, TMDs
  - Axial FFs central in HEP neutrino program
  - New: x dependence of PDFs
- Spin decomposition of nucleon
- PNDME: precision axial, scalar, tensor charges ($\Delta g_A/g_A \sim 5\%$)
- LHP: disconnected contributions to EM form factors





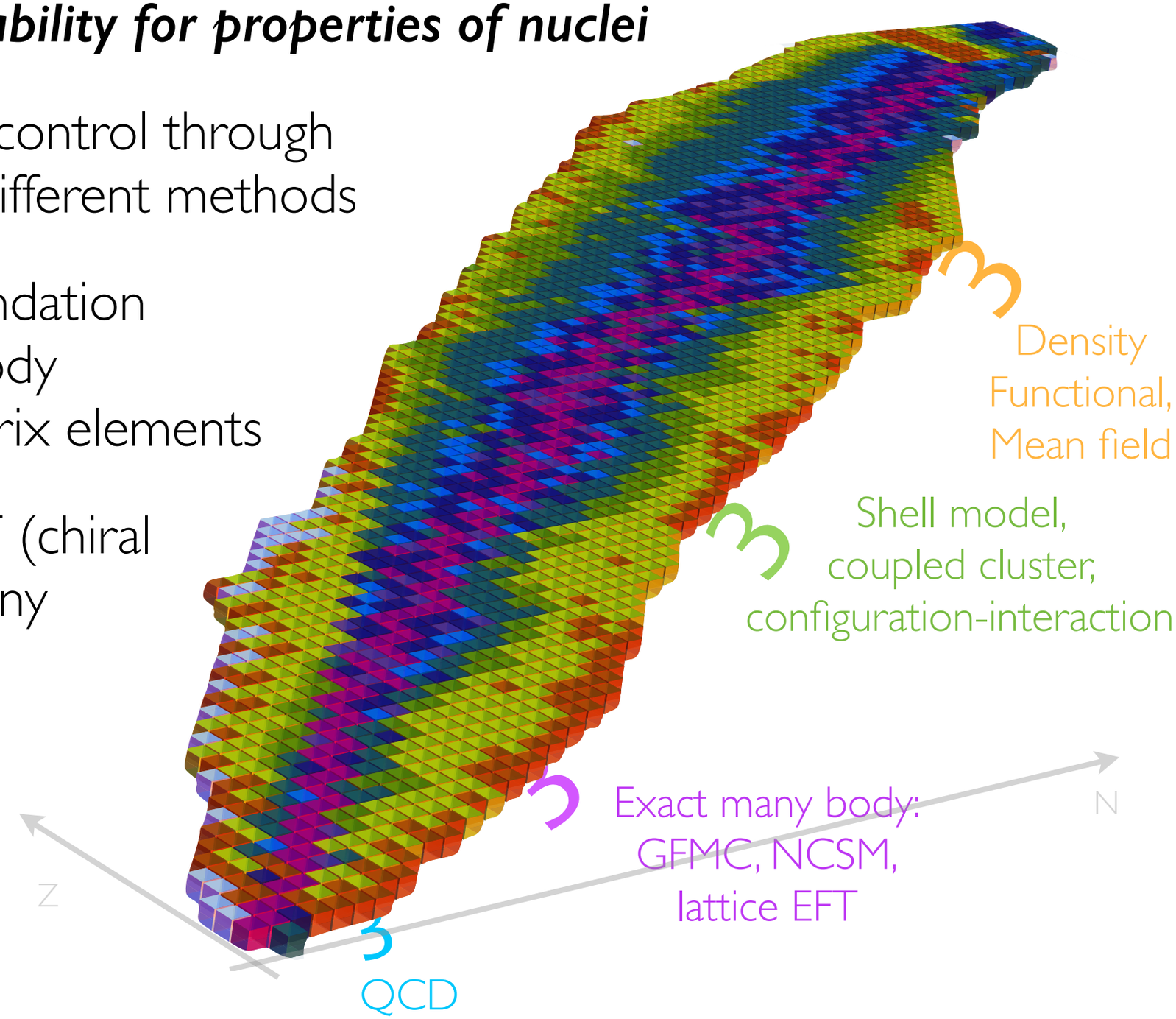
USQCD Science Highlights: Interactions

- HadSpec Collaboration
- Analysis of coupled channel system: πK–ηK
- Energy levels in multiple volumes and with multiple boosts
  - Phases shifts and inelasticities
- S, P, D waves
- Far ahead of other groups
- Progress in understanding three body channels [Hansen & Sharpe,…]

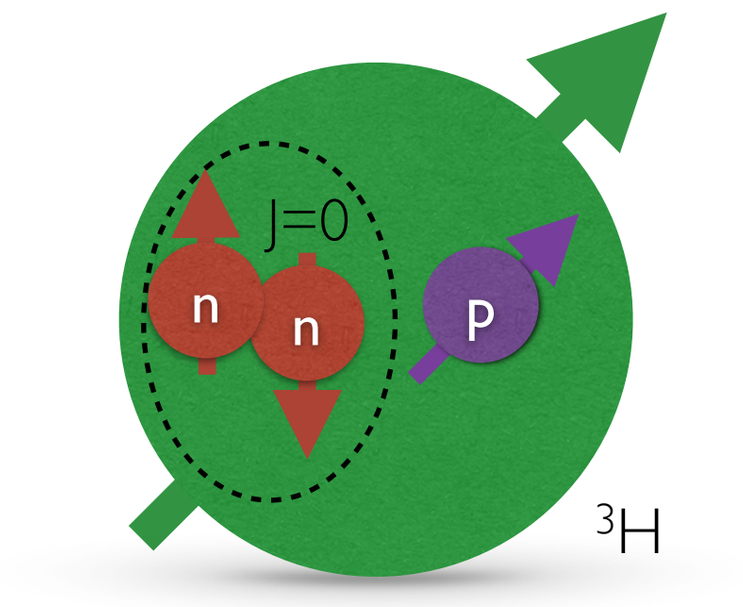


[Wilson et al., 1411.2004]

- ***Goal: Predictive capability for properties of nuclei***
- Establish quantitative control through linkages of QCD to different methods
  - QCD forms a foundation determines few body interactions & matrix elements
  - Match existing EFT (chiral potentials) and many body techniques onto QCD

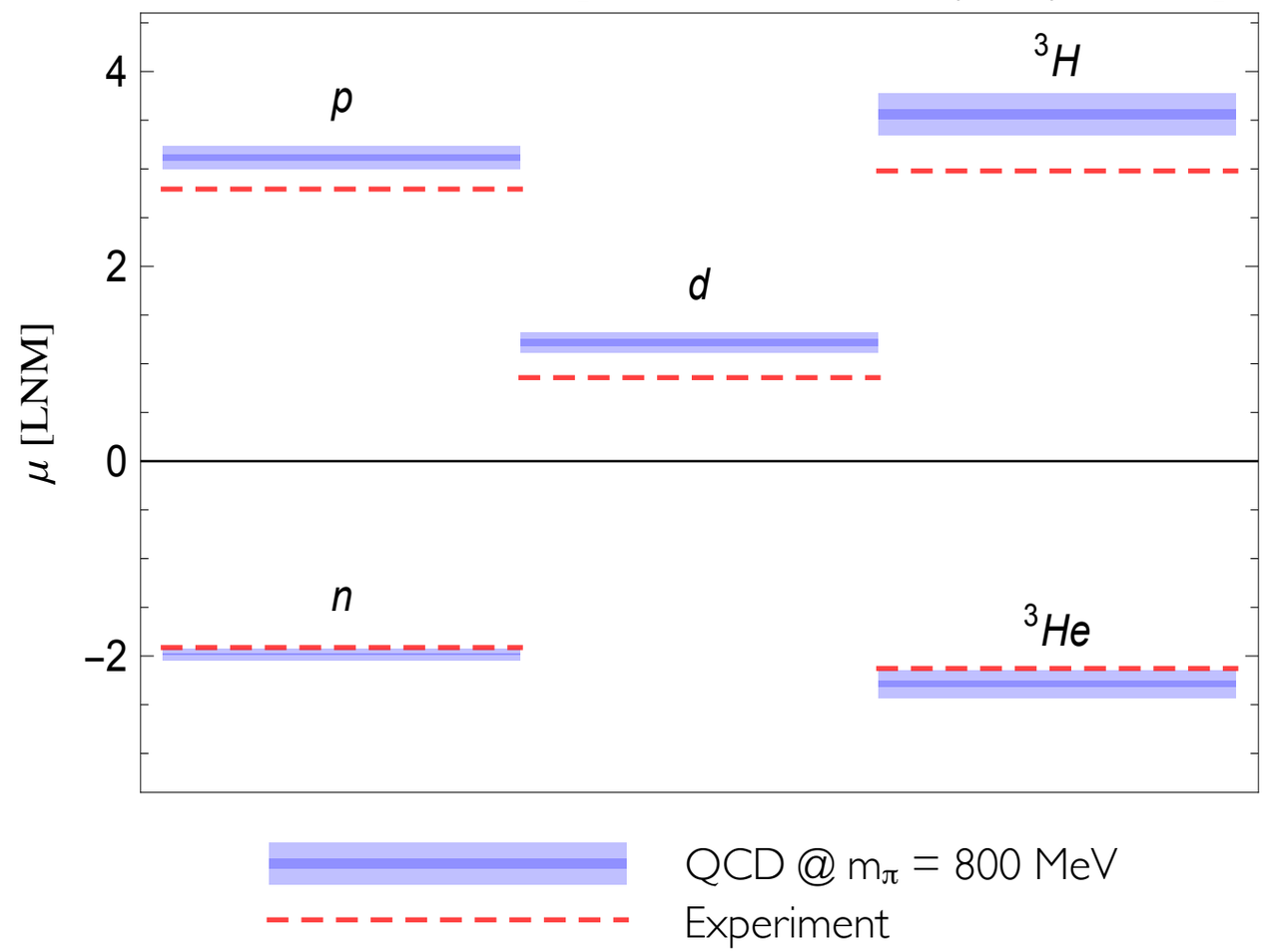


- Magnetic moments of nuclei
- Calculate using QCD in external magnetic field
- Measure induced energy shifts



- Results appear to suggest heavy quark nuclei are shell-model like!

[NPLQCD PRL 113 (2014) 252001]



	n	p	d	^{3}He	^{3}H
μ	-1.98(1)(2)	3.21(3)(6)	1.22(4)(9)	-2.29(3)(12)	3.56(5)(18)

In units of appropriate nuclear magnetons (heavy M_N)

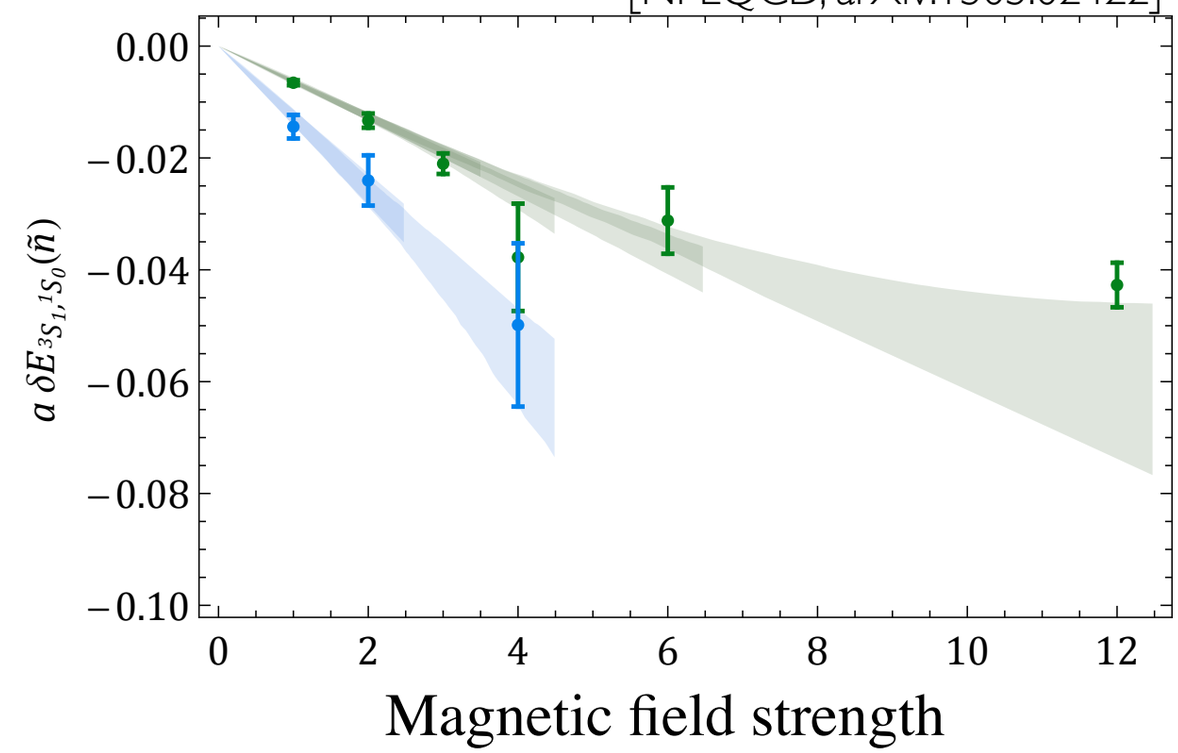
- Recent extension to $I_z=J_z=0$ components of *np* system
- Magnetic field mixes *J=0, J=1* states, mixing proportional to $np \rightarrow d\gamma$ amplitude
- Determine two-body EM coupling L_1 (meson-exchange current) ~ 10% effect
- Extrapolation to physical mass

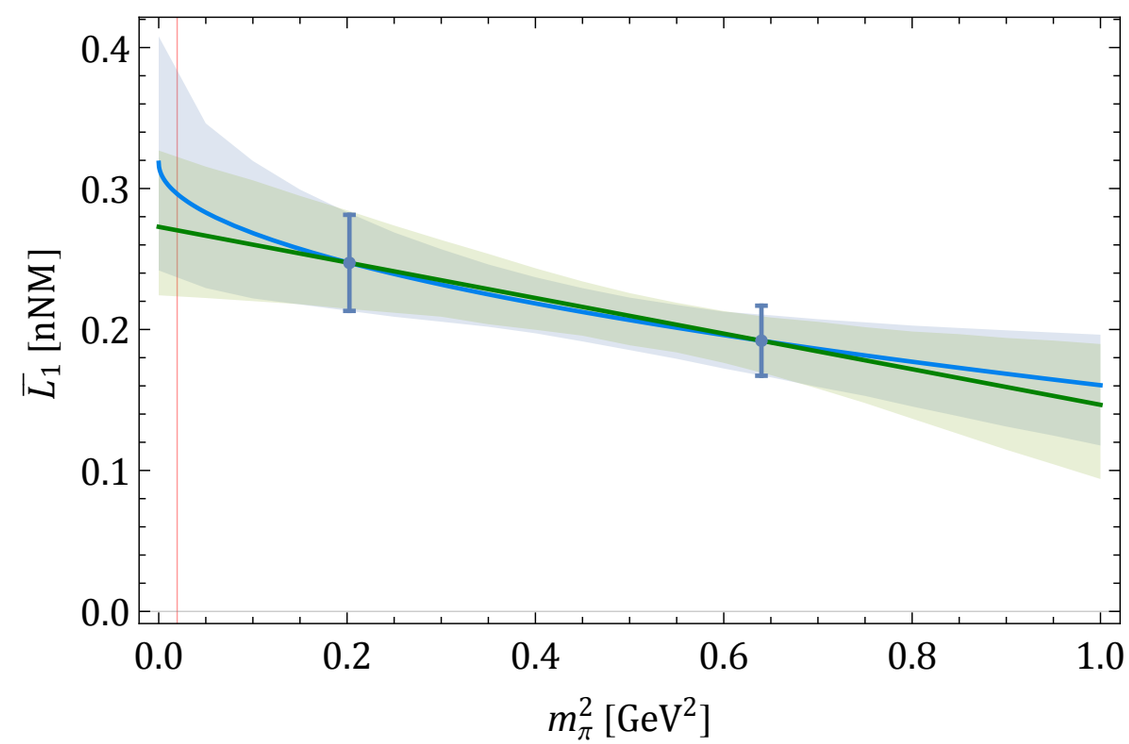
$$\sigma^{\rm lqcd}(np \to d\gamma) = 332.4(\,^{+5.4}_{-4.7}\,)\ {\rm mb}$$

c.f.

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

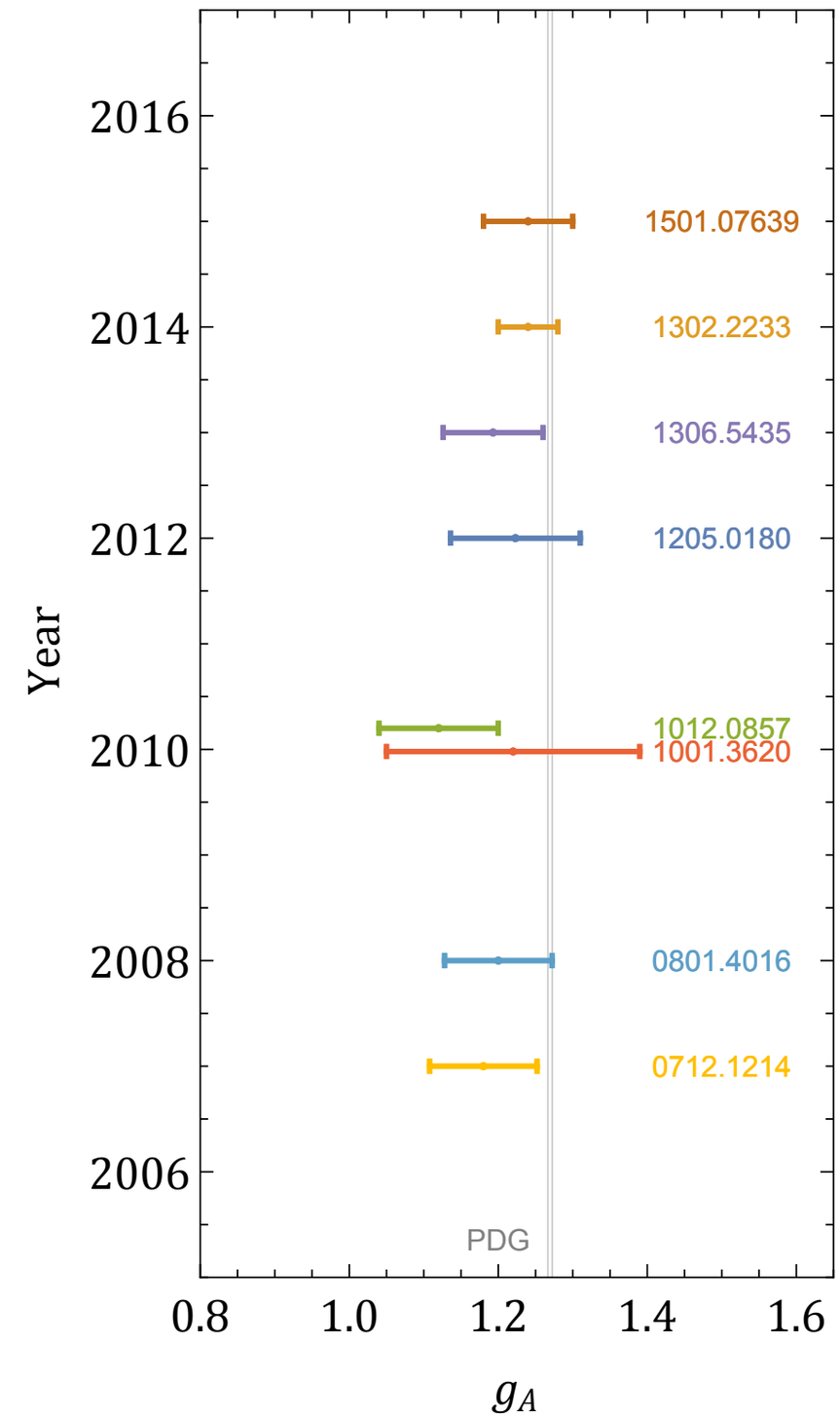
[NPLQCD, arXiv:1505.02422]





Goals and Progress

- USQCD goals articulated in 2013 White Paper (5 year plan)
- Well understood quantities with precision goals
  - g_A, <x>, $\pi\ \pi$ scattering, …
- Other more qualitative quantities
  - Excited state spectrum
- Difficult to project quantities
  - Light nuclear matrix elements, phase shifts above inelastic thresholds, hadronic parity violation….



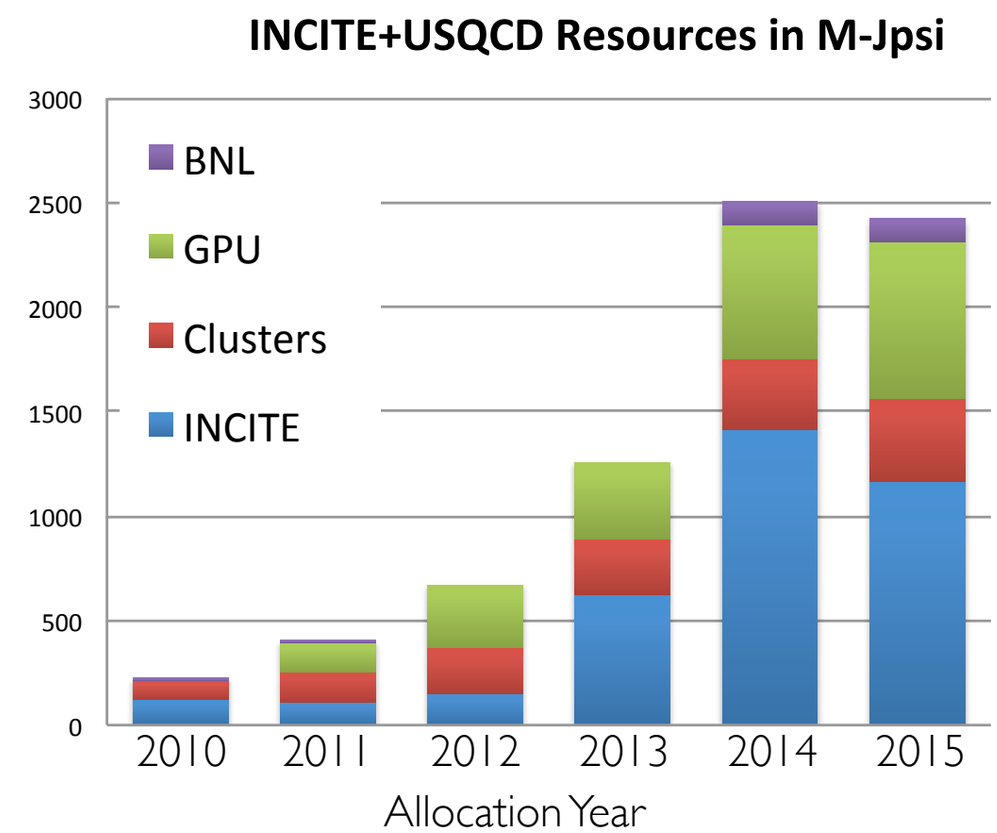
Projected Computational Costs

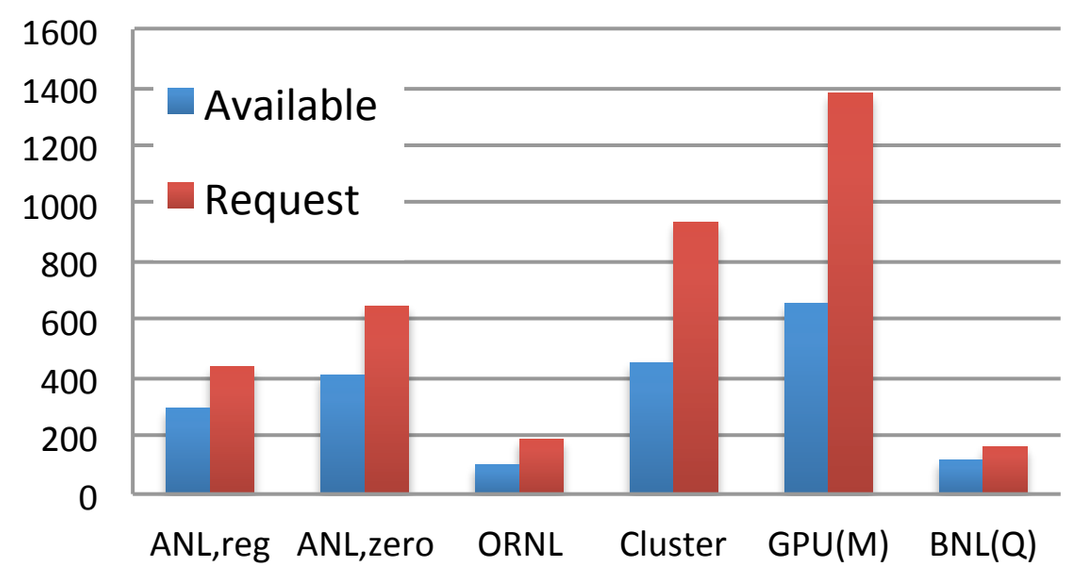
- Costs of different project aspects (structure, spectroscopy, interactions set out in project proposal
- Production/measurement plans out until 2019

$N_s^3 \times N_t$	Action	a fm	m_π MeV	$m_\pi L$	$m_\pi T$	Traj.	Configs. (TF-yrs)	Str-A (TF-yrs)	Str-B (TF-yrs)	HSp (TF-yrs)	HI (TF-yrs)
$64^3 \times 128$	W	0.076	250	6.1	12.3	5×10^3	8				
$64^3 \times 128$	W	0.09	200	5.8	11.7	5×10^3	9			167	27
$32^3 \times 512$	AW	0.12	200	3.8	17.6	1×10^4	44			41	
$48^3 \times 512$	AW	0.12	200	5.8	17.6	1×10^4	197			142	
$48^3 \times 192$	W	0.09	140	3.0	12.3	5×10^3	7	40			
$64^3 \times 192$	W	0.09	140	4.1	12.3	5×10^3	21	40			
$96^3 \times 64$	W	0.09	140	6.1	4.1	5×10^3	24	13			
$96^3 \times 96$	W	0.09	140	6.1	6.1	5×10^3	40	20			
$96^3 \times 192$	W	0.076	140	6.1	12.3	5×10^3	96	40	350*	334	288
$128^3 \times 192$	W	0.076	140	6.9	10.4	5×10^3	323	67		792	970
$48^3 \times 96$	DWF	0.110	140	3.9	7.8	5×10^3		28	360†		
$64^3 \times 128$	DWF	0.086	140	3.9	7.8	5×10^3		64	844†		

Resources

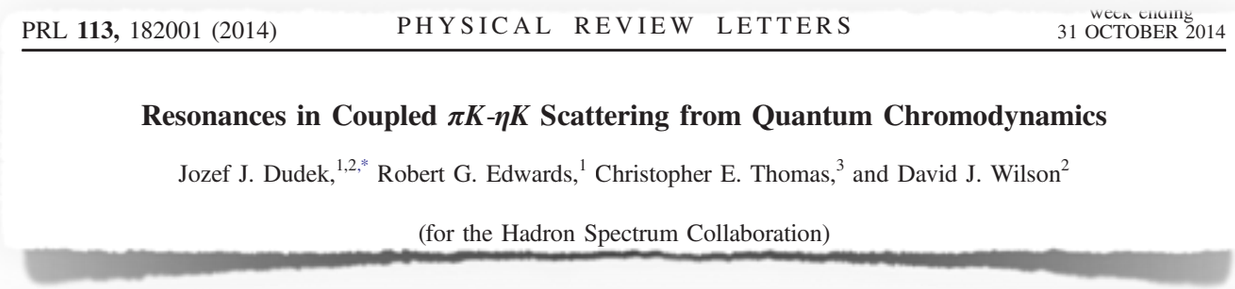
- Projections assumed Moore's law (x2 in 1.5yrs) growth (flat funding)
- 2015: USQCD resources have shrunk for the first time!!
- Many excellent projects are only partly supported
- Other scientifically sound projects not supported





USQCD Cold NP Publications

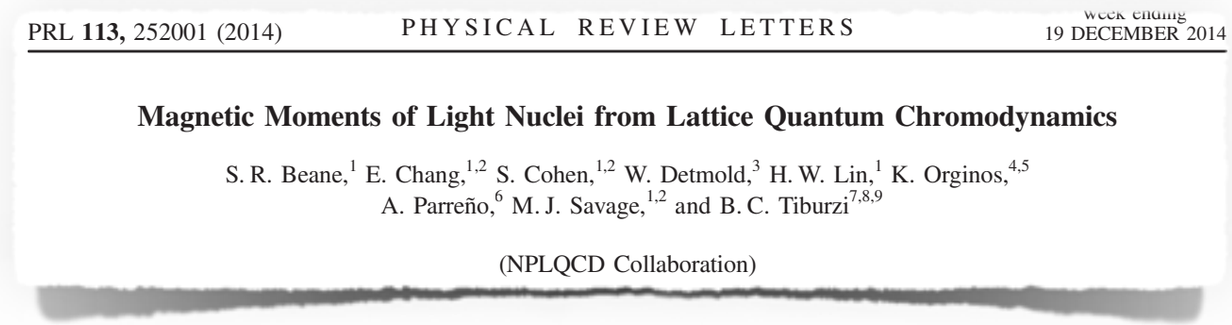
- 2014: 2 USQCD cold NP PRLs
- ~50 cold NP USQCD papers (excluding proceedings)
  `f d after 2013 and a XY`
- Science highlights @ NERSC, OLCF
- Lecture Notes in Physics on *Lattice QCD for Nuclear Physics* (H W Lin, H B Meyer eds.)


PRL **113,** 182001 (2014) PHYSICAL REVIEW LETTERS week ending 31 OCTOBER 2014

Resonances in Coupled πK-ηK Scattering from Quantum Chromodynamics

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

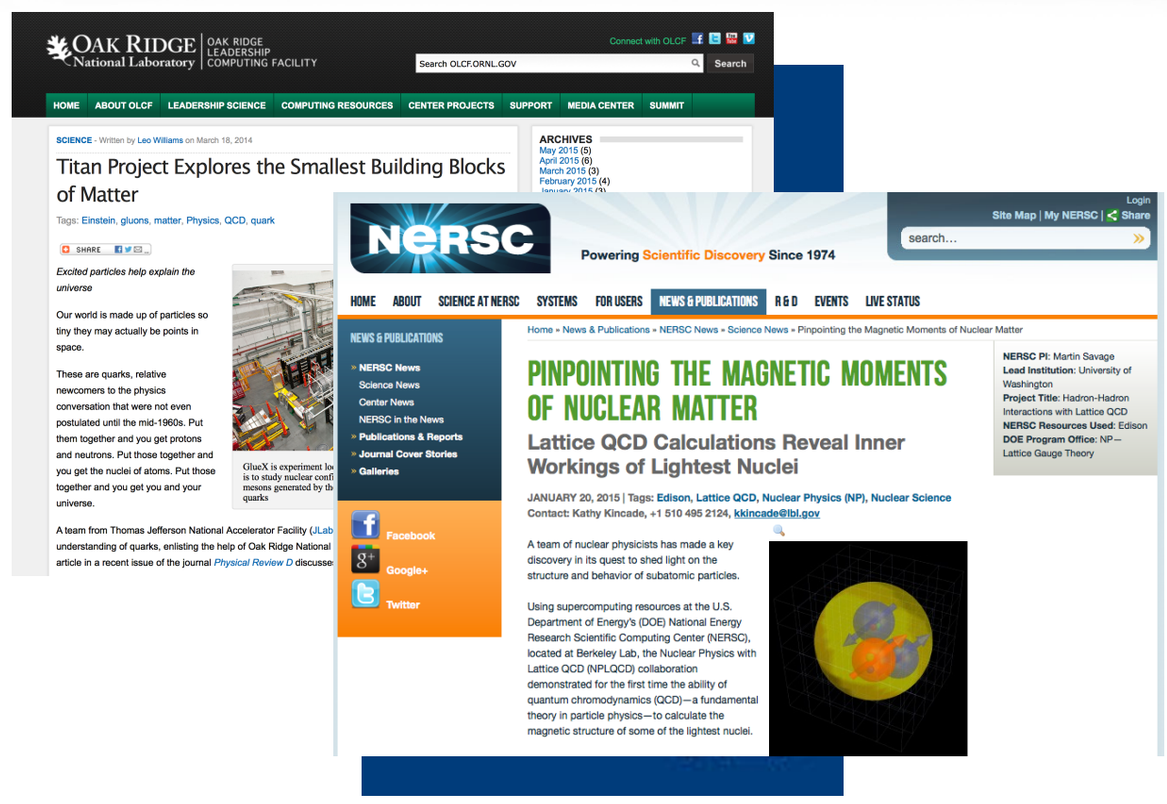
(for the Hadron Spectrum Collaboration)


PRL **113,** 252001 (2014) PHYSICAL REVIEW LETTERS week ending 19 DECEMBER 2014

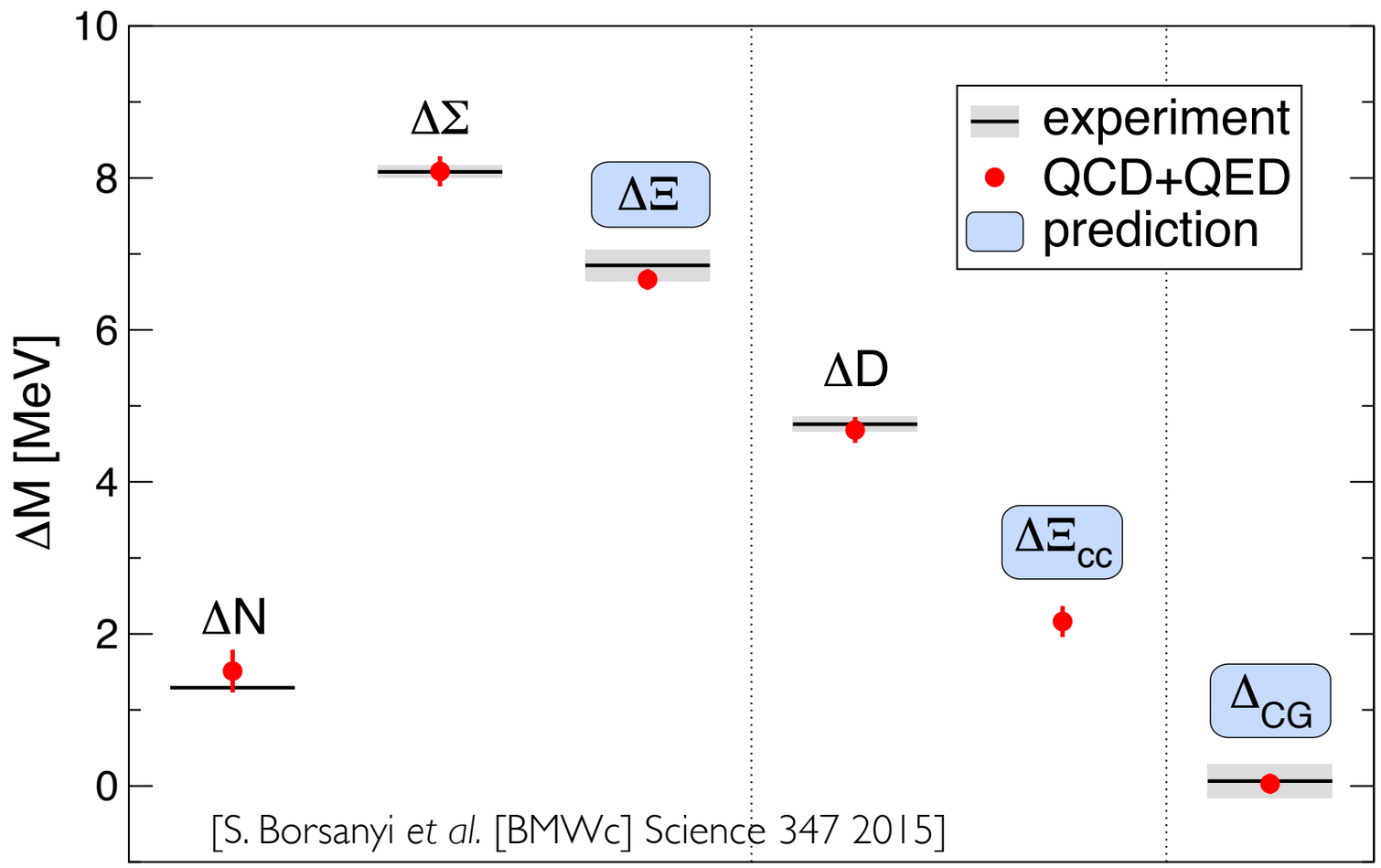
Magnetic Moments of Light Nuclei from Lattice Quantum Chromodynamics

S. R. Beane,[1] E. Chang,[1,2] S. Cohen,[1,2] W. Detmold,[3] H. W. Lin,[1] K. Orginos,[4,5] A. Parreño,[6] M. J. Savage,[1,2] and B. C. Tiburzi[7,8,9]

(NPLQCD Collaboration)



- Isospin mass splittings in QCD+QED [Budapest-Marseille-Wuppertal]



- Well funded LQCD group: publication in *Science*
- Clarifies role of E&M effects and quark masses in M_n - M_p

Career paths and awards

- Junior faculty positions in cold NP LQCD since 2012
  - Meyer (Mainz), Detmold (MIT), Walker-Loud (W&M), Luu (Jülich), Gong(IHEP), Alexandru (GWU), Meinel (Arizona), Thomas (Cambridge)
- 3 MSU LQCD jobs recently announced!
- DOE/NSF Early Career Awards in cold NP LQCD (since 2011)
  - Dudek, Alexandru, Detmold, Walker-Loud
- Ken Wilson Award: Walker-Loud (2013)
- Feshbach Prize: Negele (2014)

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 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

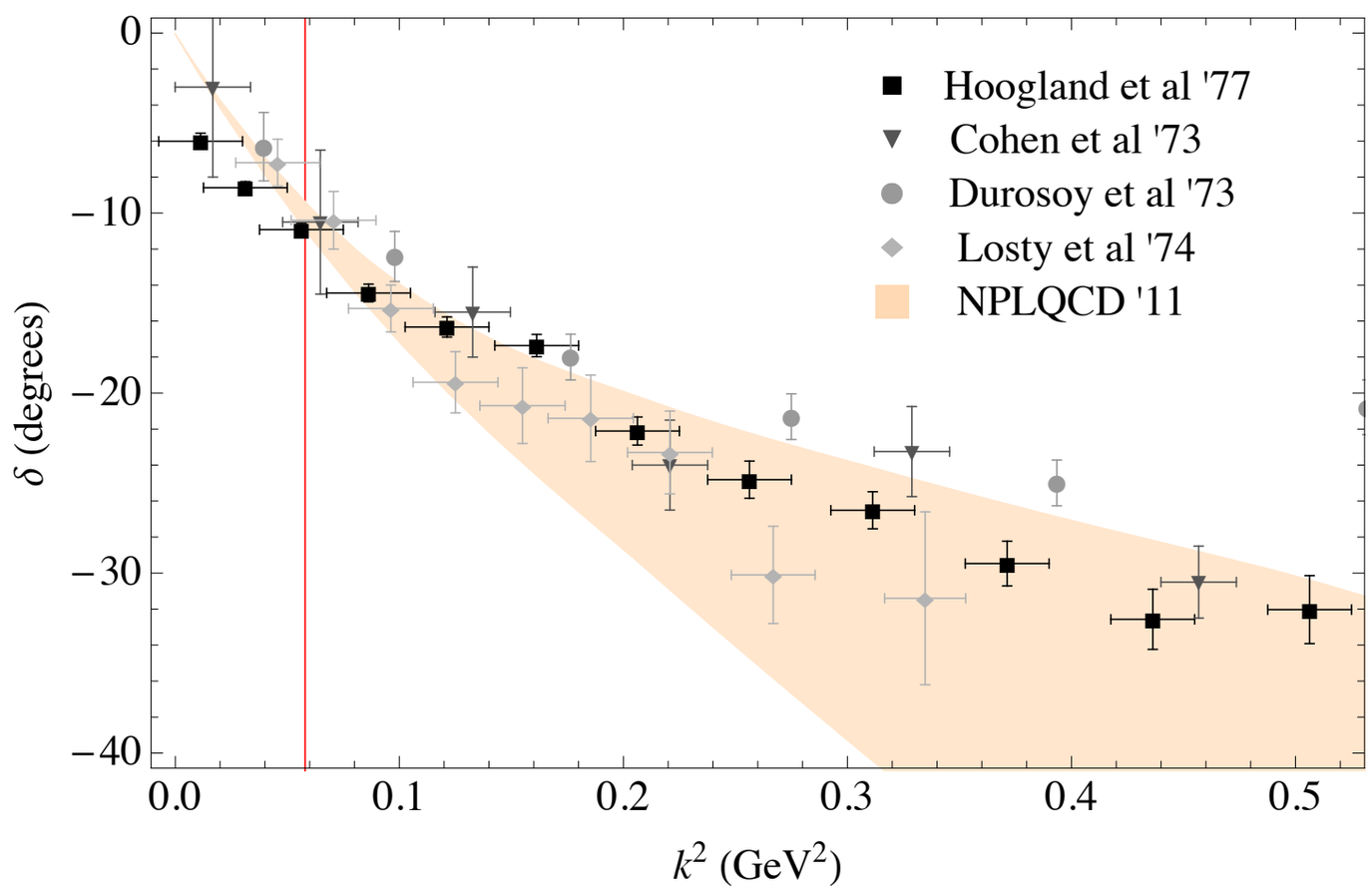
Precision Goals Table

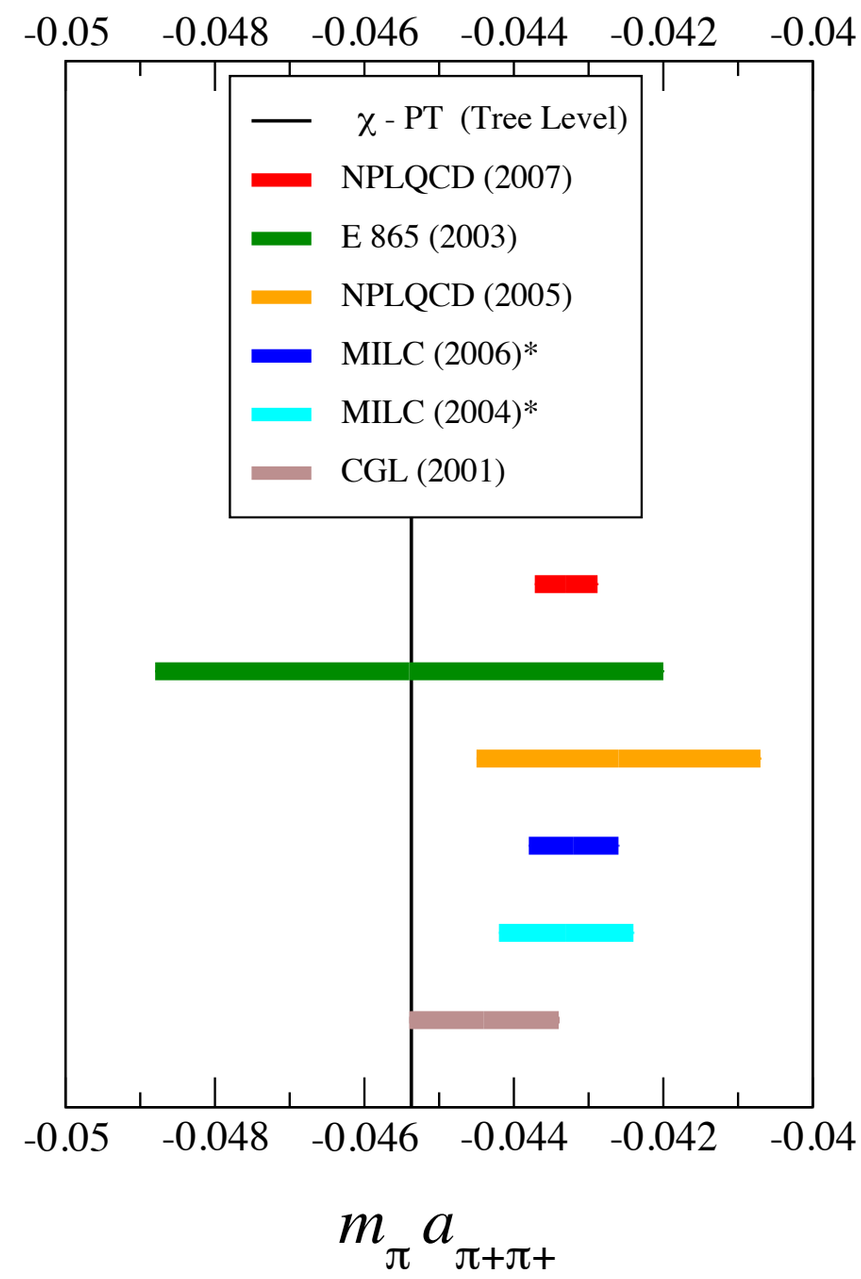
- Quantities with currently quantifiable uncertainties and goals

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	5%,20%	10%	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%	3%	Aim for ab initio input to PDFs (USQCD goal)
$\langle r^2\rangle_p$	~25%	2%	Impact proton radius puzzle

I=2 Pi-Pi Scattering

- I=2 $\pi\,\pi$ scattering is high precision
  - scattering length @ 1%

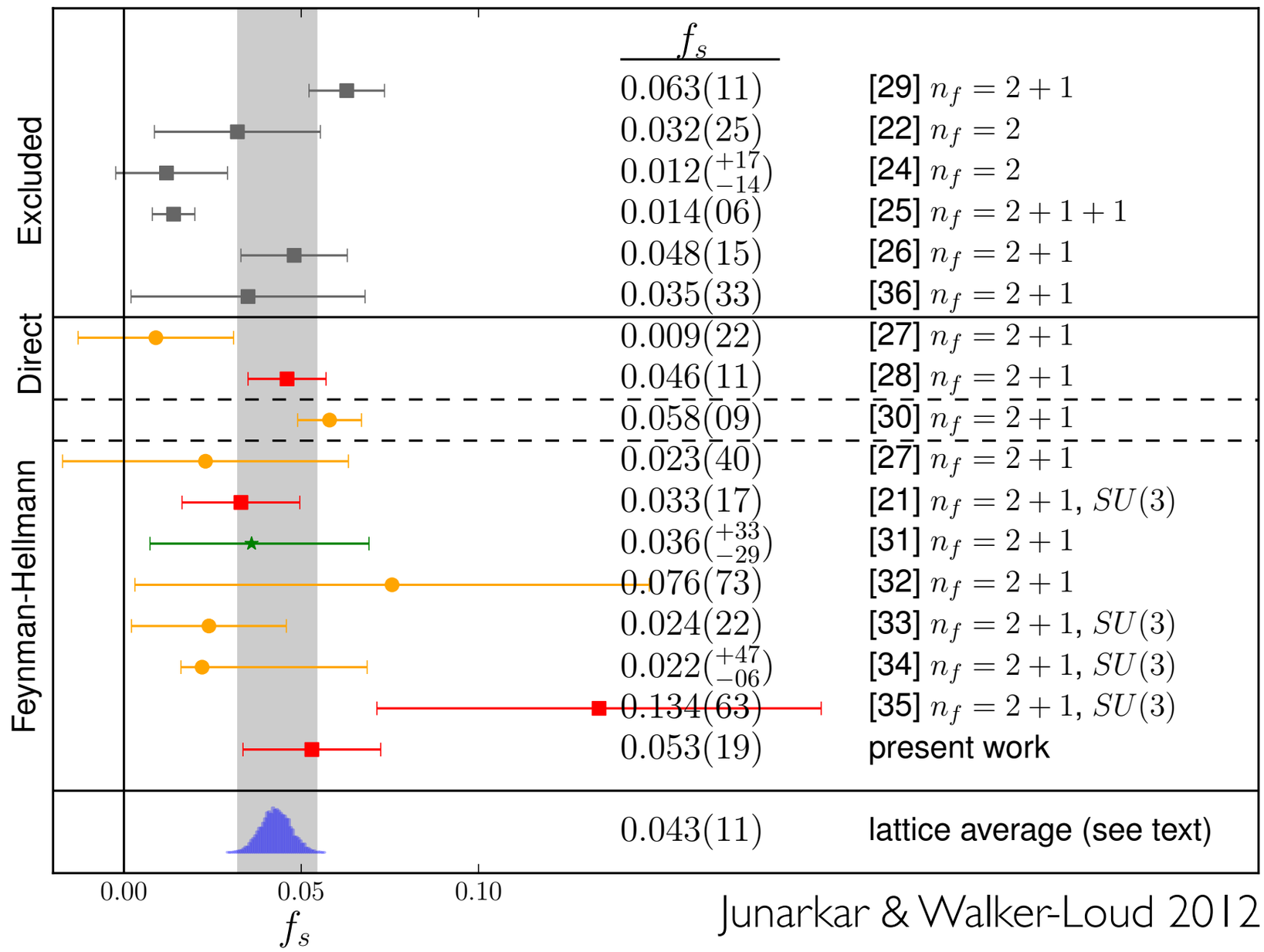




NPLQCD 2007, 2011

Strangeness content

- Strangeness content <N|ss|N> relevant for dark matter



Junarkar & Walker-Loud 2012