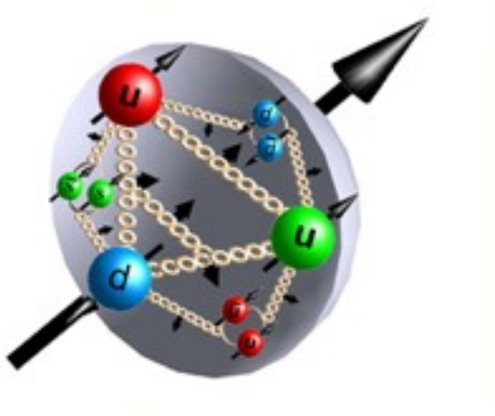
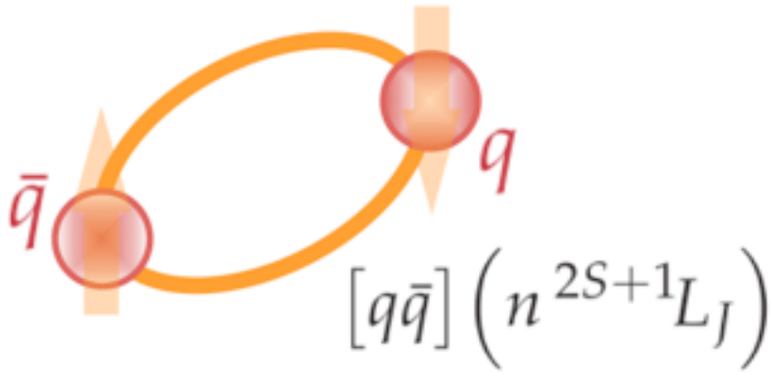




Hadronic Spectroscopy, Structure and Interactions

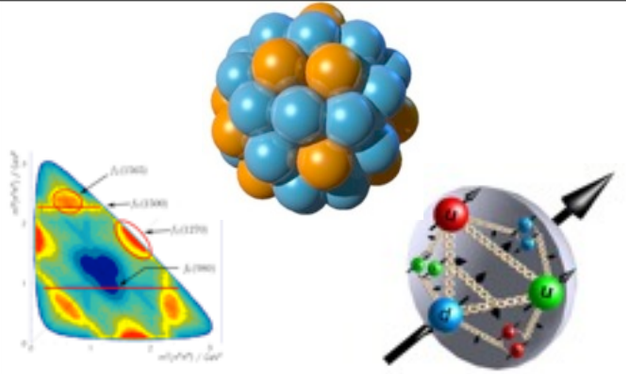
USQCD

DOE Annual Progress Review of the LQCD-Ext Project

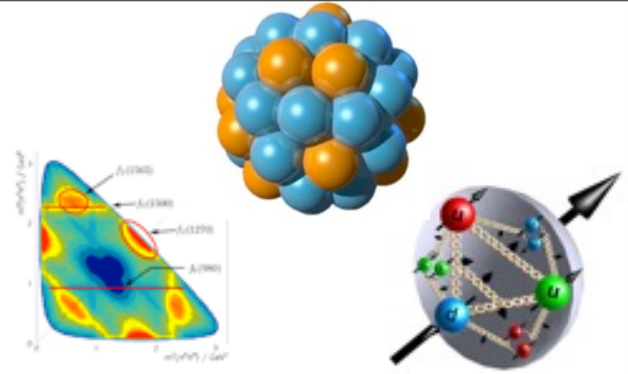
FermiLab

May 15,16, 2014

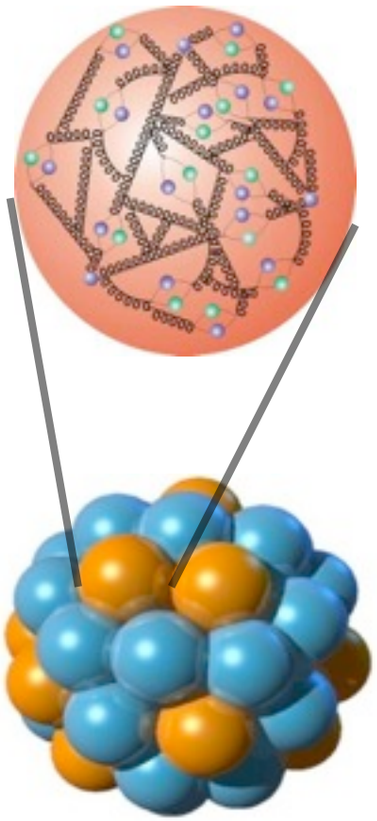
Martin J. Savage



Matter from Quantum Chromodynamics



Proton



Nucleus

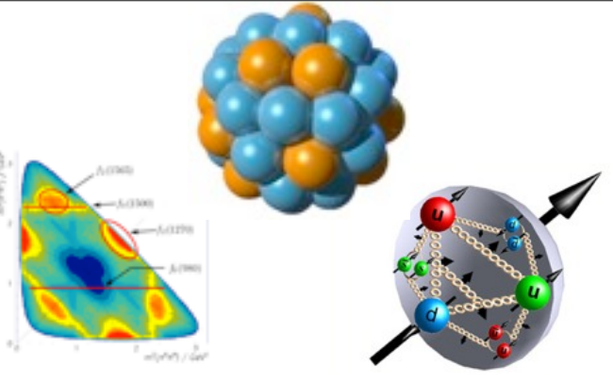
$$\Lambda_{\mathrm{QCD}}$$

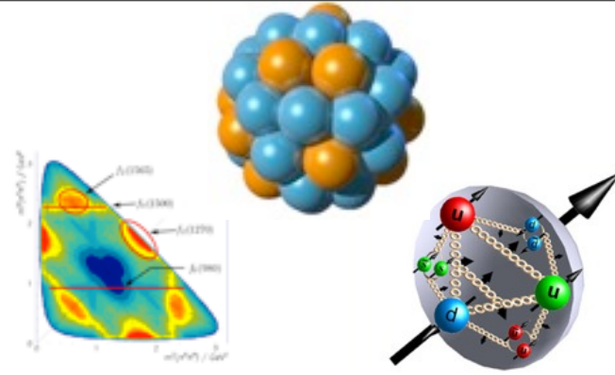
$$\frac{m_u}{\Lambda_{\mathrm{QCD}}} \quad \frac{m_d}{\Lambda_{\mathrm{QCD}}} \quad \frac{m_s}{\Lambda_{\mathrm{QCD}}}$$

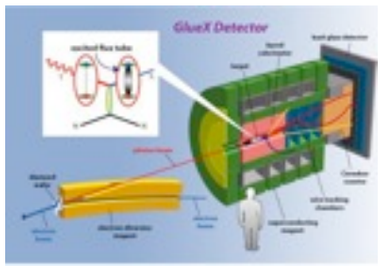
$$\alpha_e$$

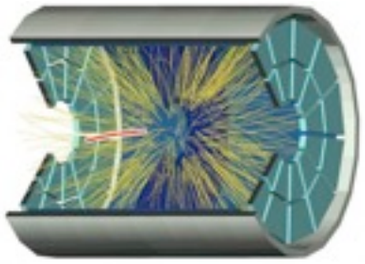
Small number of input parameters responsible for all of strongly interacting matter

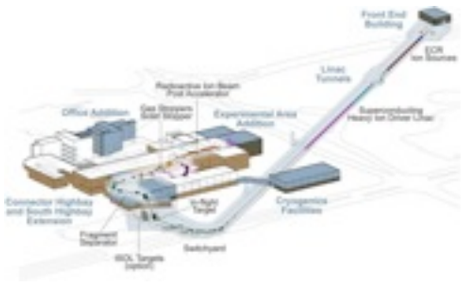
From QCD to Nuclei

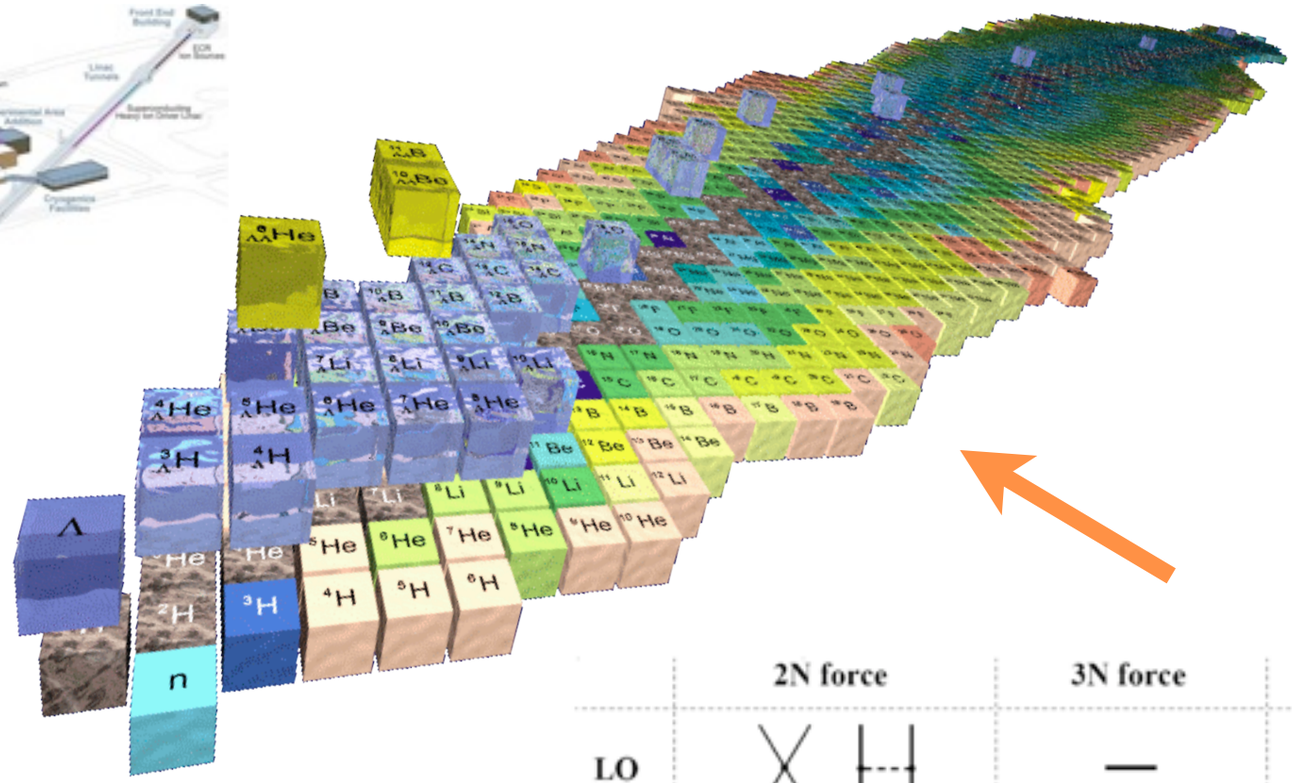


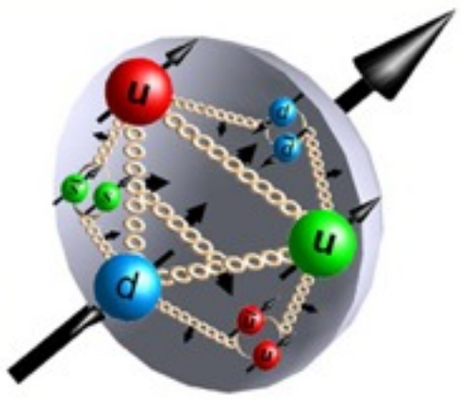








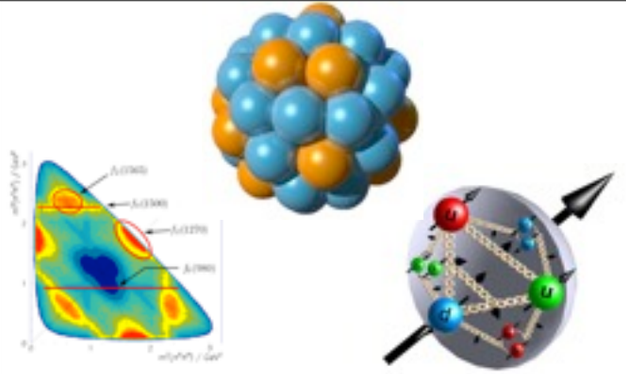




Solve QCD

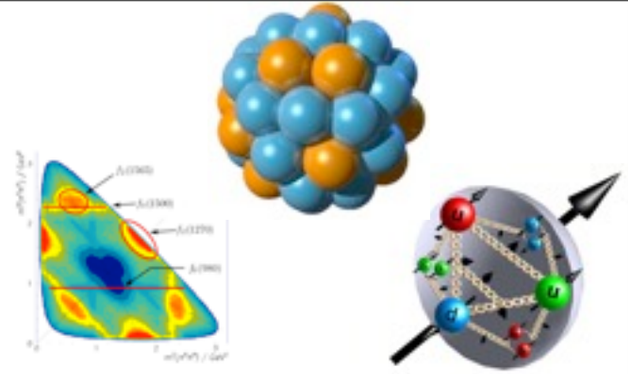
Lattice QCD

	2N force	3N force	4N force
LO		—	—
NLO		—	—
N^2LO			—
N^3LO	...	...	...

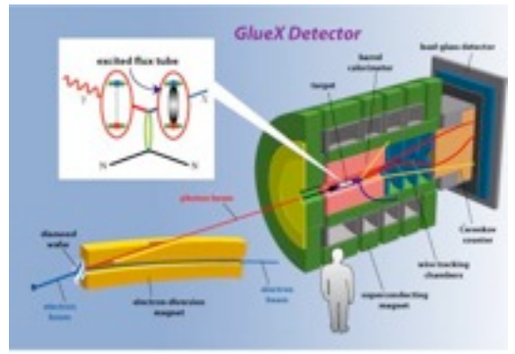


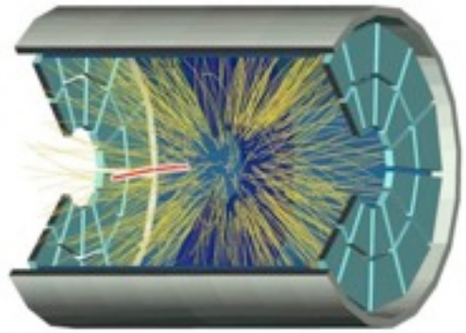
USQCD Program in

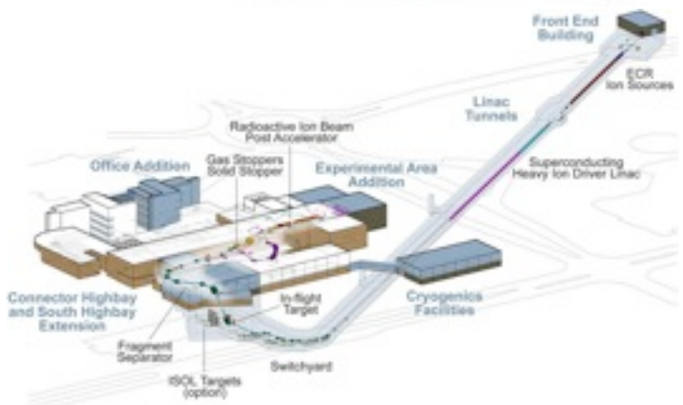
Structure, Spectrum and Interactions of Hadrons



- Closely aligned with NP experimental projects
  - JLab and RHIC - Spectrum and Structure
  - FRIB (under construction) - Interactions







- Closely tied to NSAC Milestones
  - HP 3, 9,10,15
  - FI 15

http://science.energy.gov/~/media/np/nsac/pdf/docs/perfmeasevalfinal.pdf

- Anticipate ~5 Pflop-yrs integrated resources 2013-2018

Relevant NSAC Milestones and their Status as of 2008/2009

Table 4: Milestone Progress in Hadronic Physics

Year	Milestone	Complete?	Status Assessment
2009 HP3	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.	No	Expect to Not Achieve Fully
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	

(2008)

Spectrum

Structure

Interactions

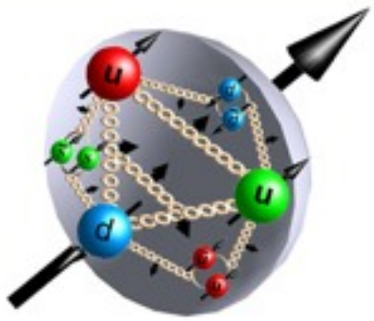
Spectrum

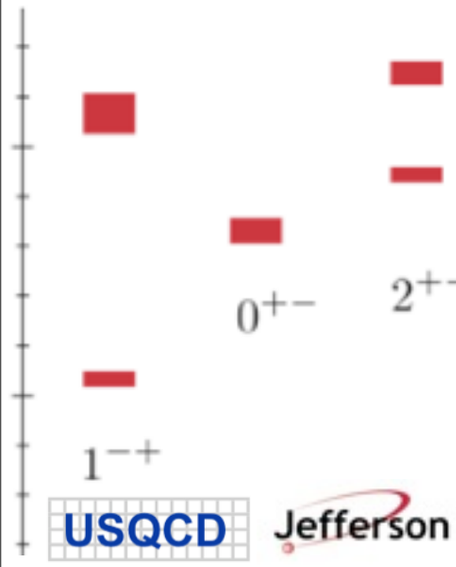
Fundamental Symmetries

http://science.energy.gov/~/media/np/nsac/pdf/docs/perfmeasevalfinal.pdf

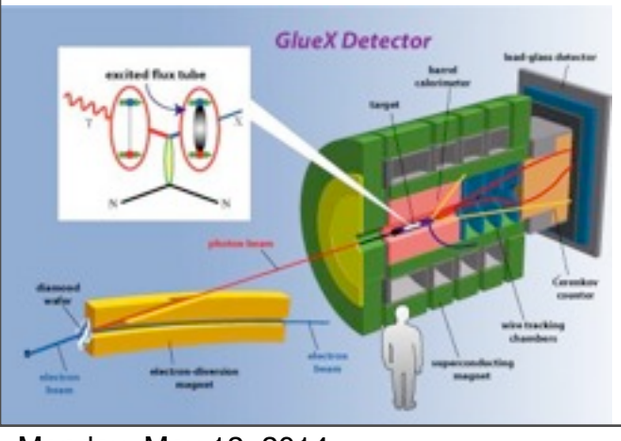
Cold Nuclear Physics

capacity resources

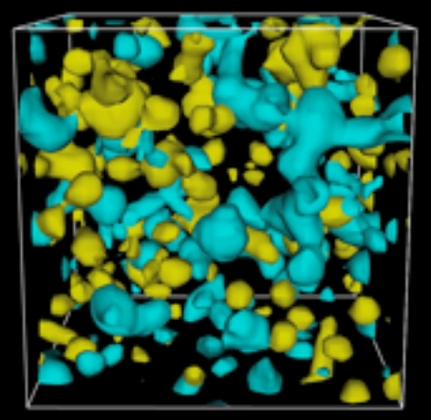




USQCD Jefferson Lab



The Quantum Vacuum



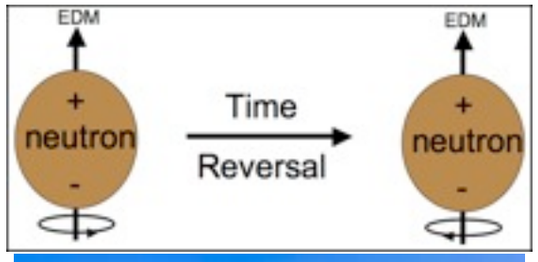
Topological Charge Density

(Massimo DiPierro)

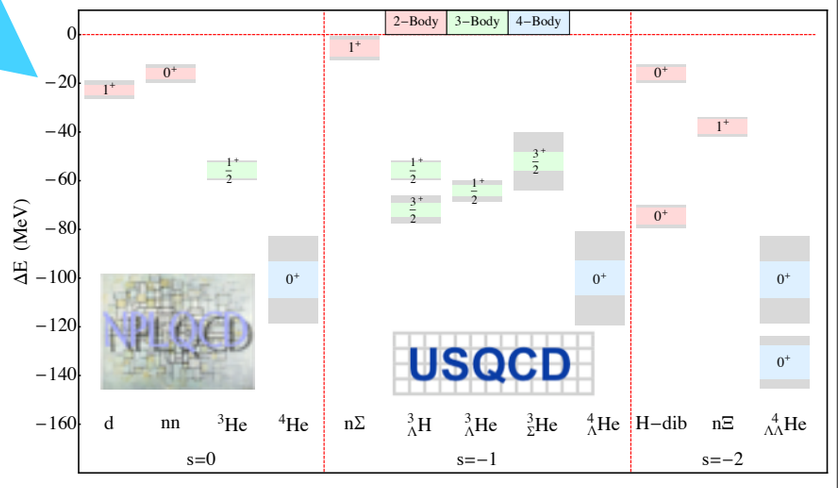
capability resources

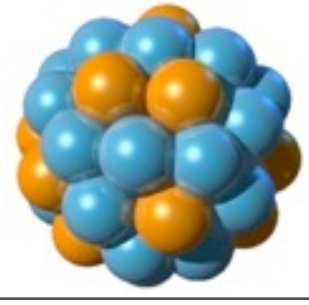
$L \sim 4$ fm

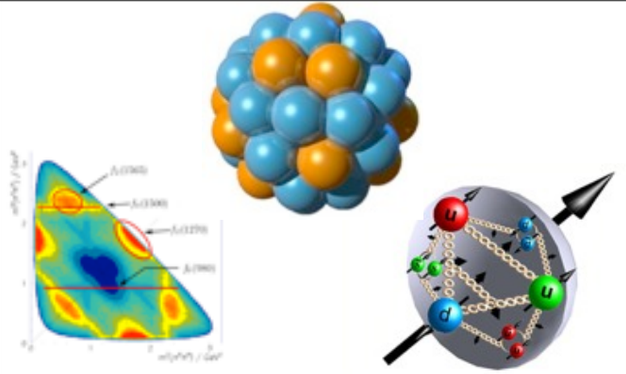
$\Delta t \sim 6 \times 10^{-24}$ s



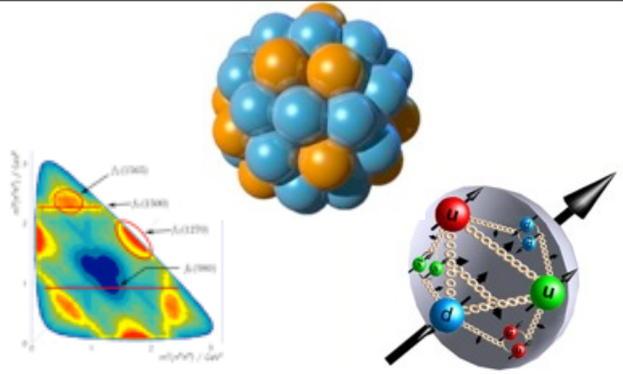
capacity resources

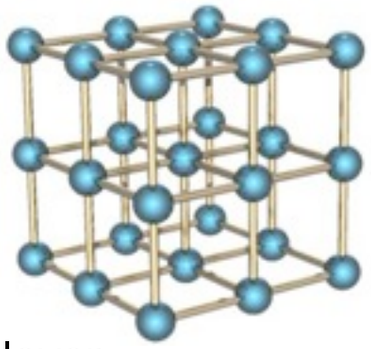




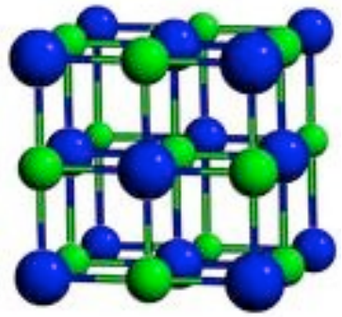


Present Cold Nuclear Physics Program

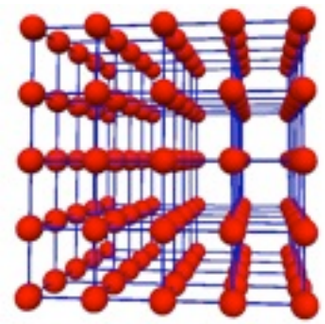




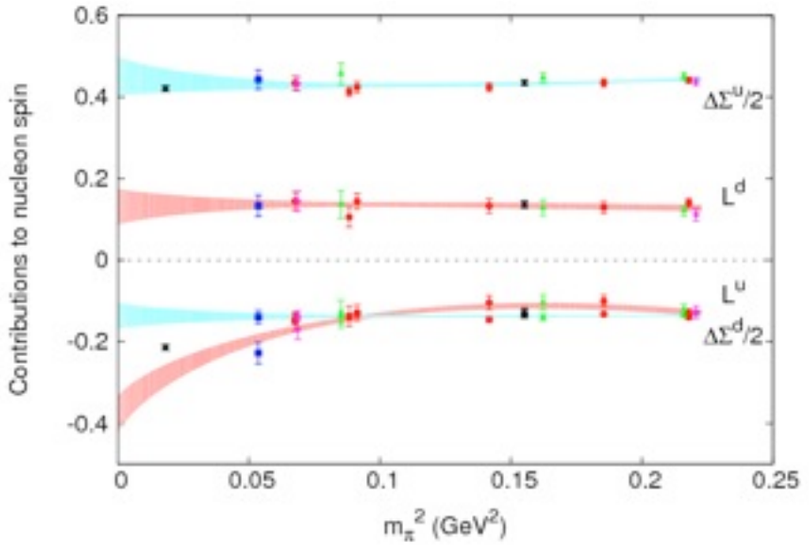
Isotropic clover, domain-wall, overlap, Staggered

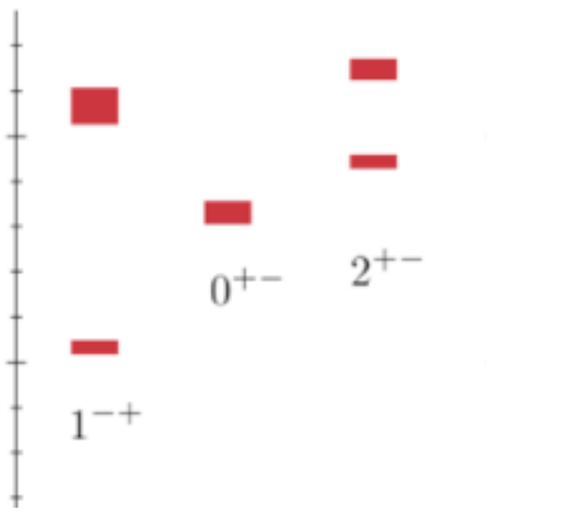


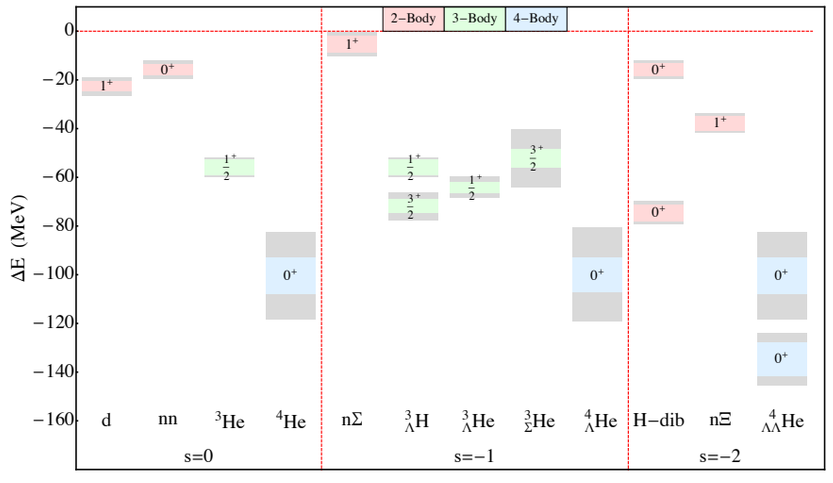
Anisotropic clover

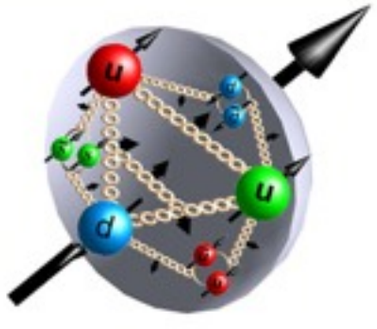


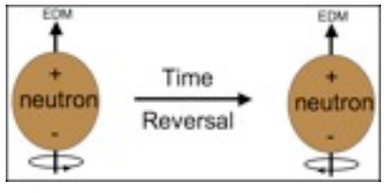
Isotropic clover

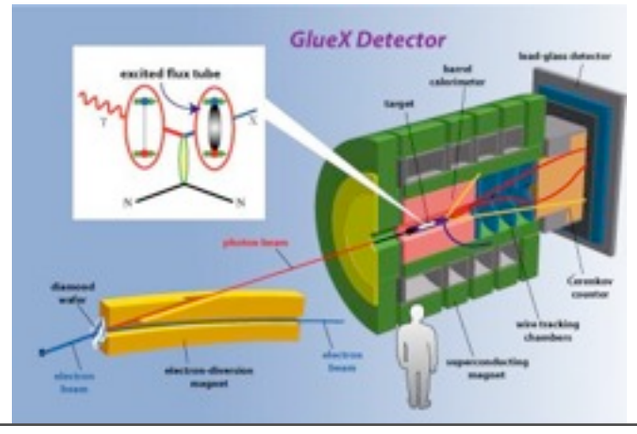


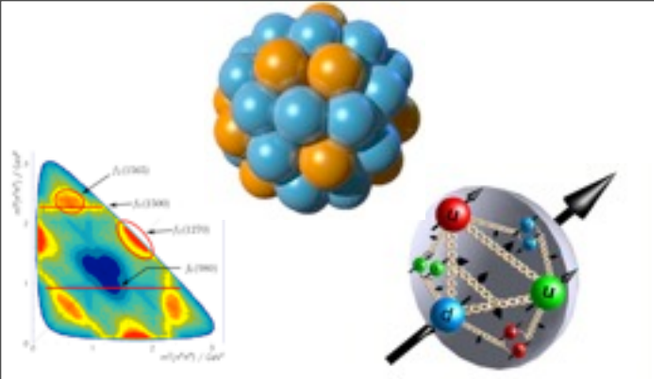




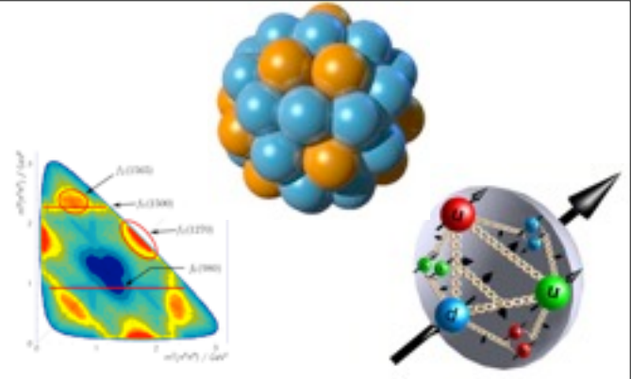








Structure

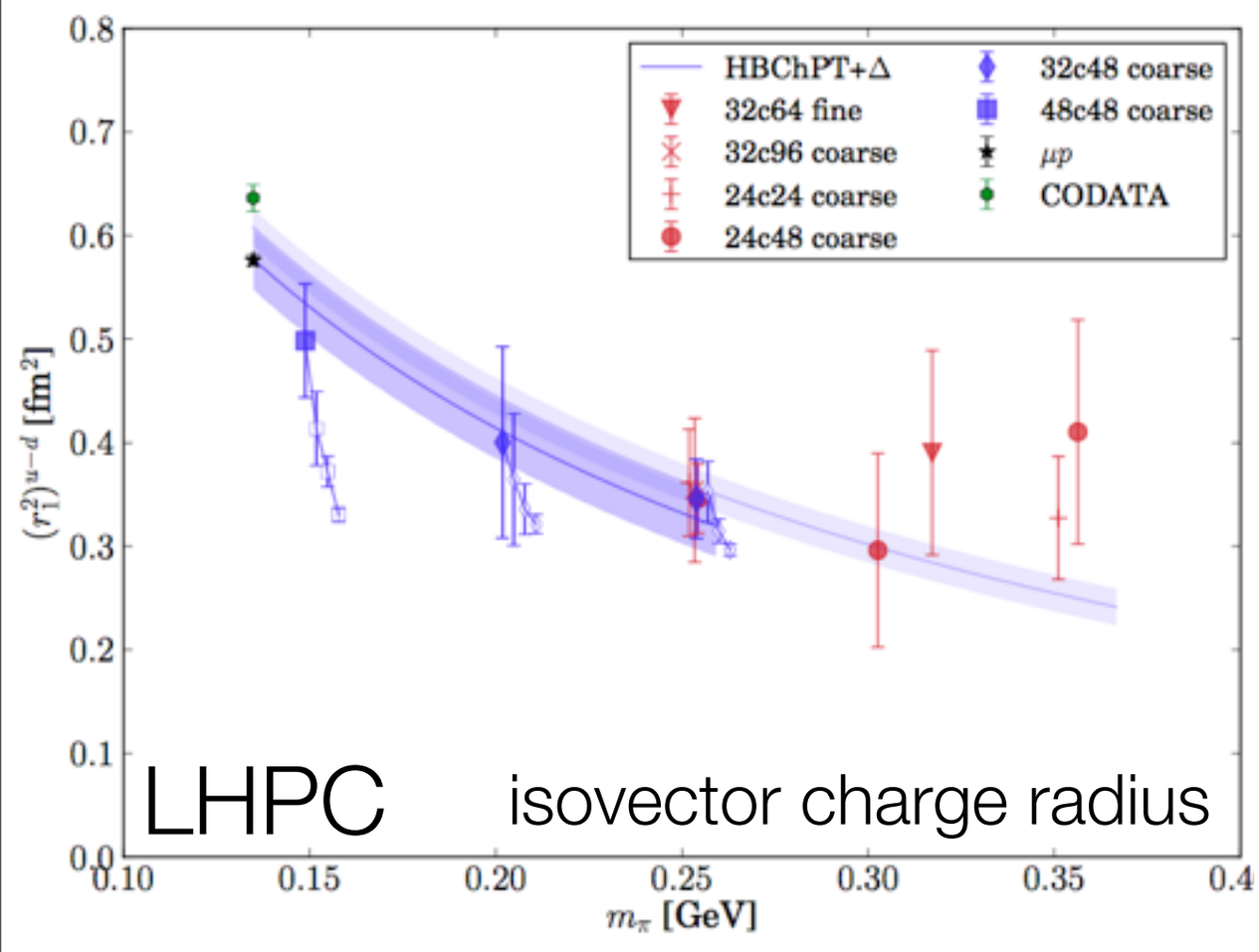


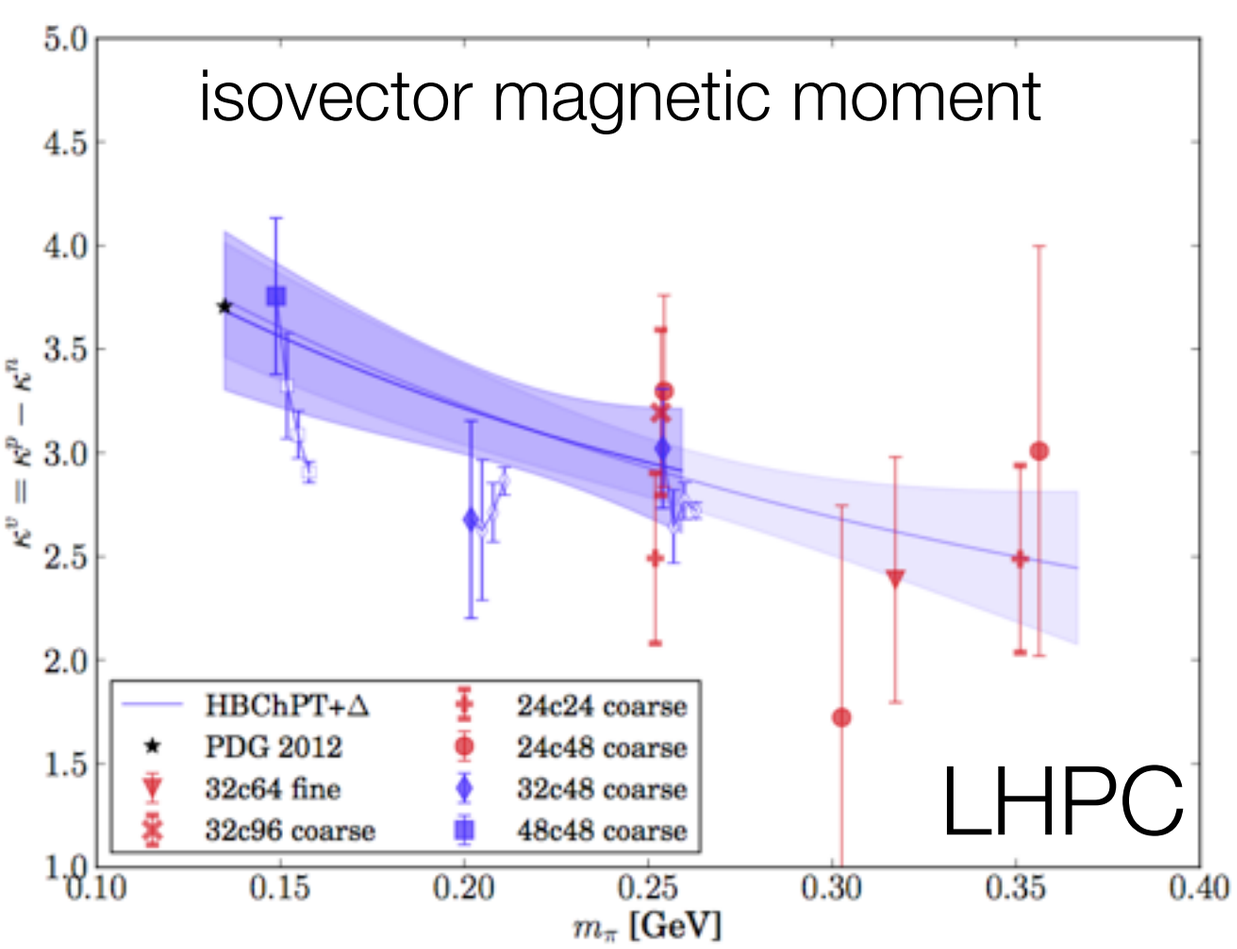
- g_A and other $q^2=0$ matrix elements
- $\langle x^n \rangle$
- charge and magnetic radii, etc
- associated form factors

First LQCD calculations at physical pion mass during 2012

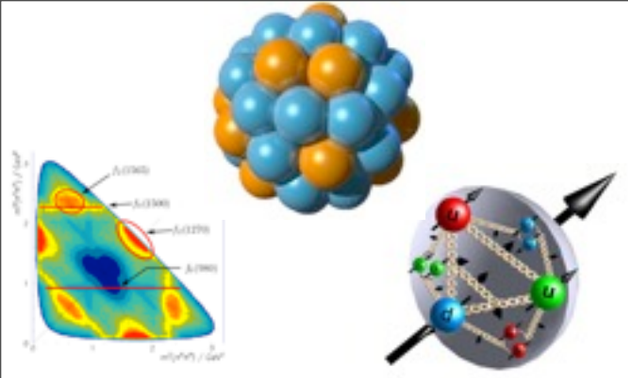
Precision is needed

(complete uncertainty quantification)

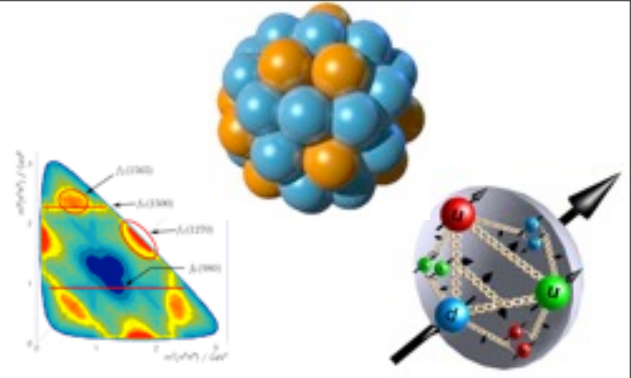




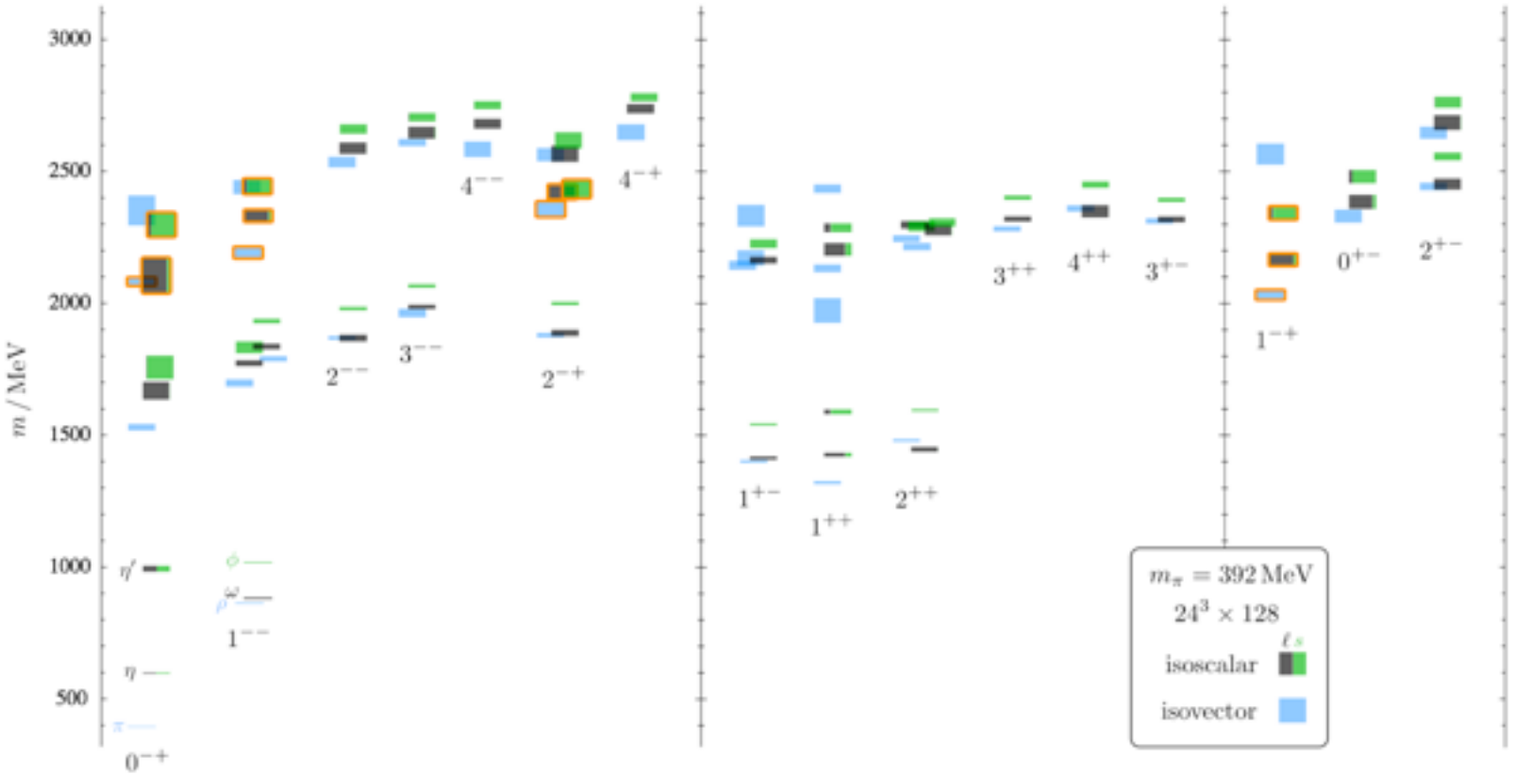
Green *et al*, arXiv:1404.4029



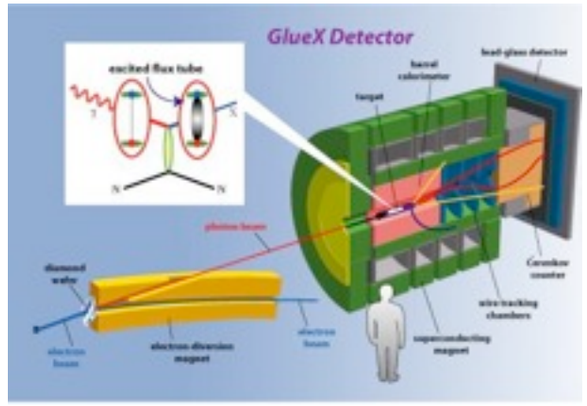
Spectrum



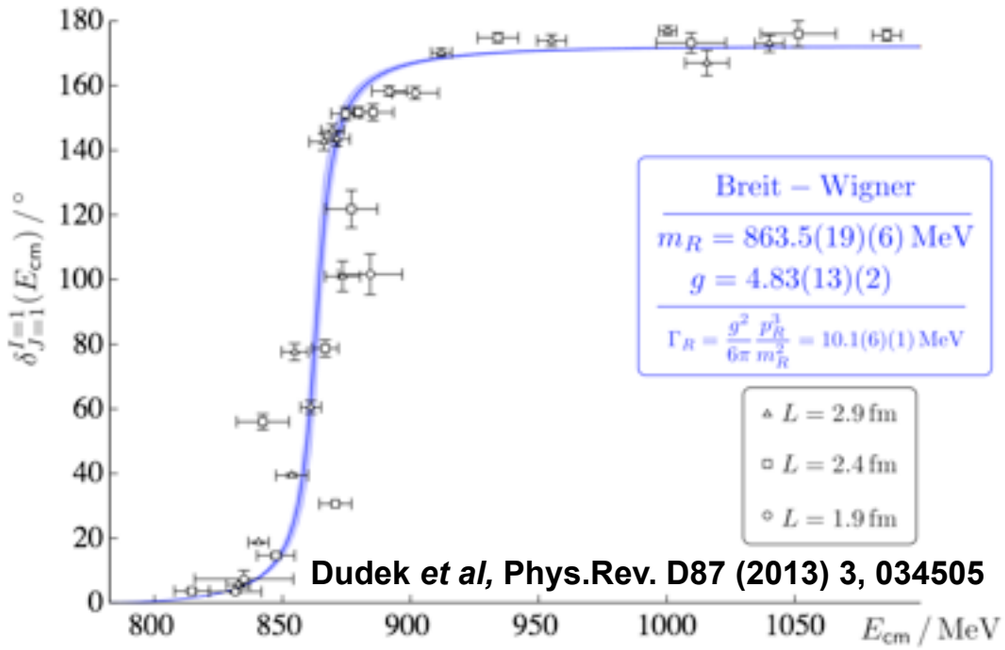
- Spectrum of mesons and baryons
  - exotics, molecules
  - coupled channels, etc
  - provided motivation for 12 GeV upgrade



Dudek *et al*, Phys.Rev. D88 (2013) 094505



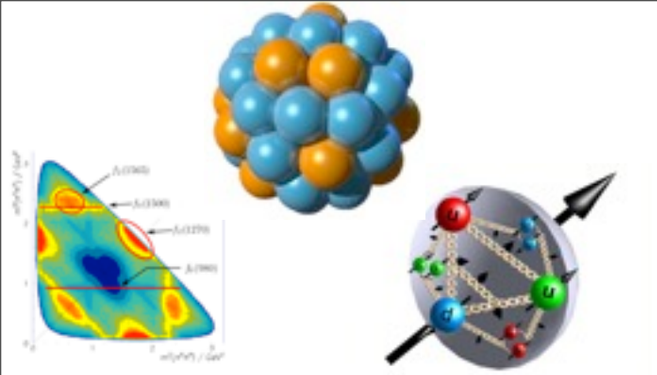
ρ- resonance successfully determined



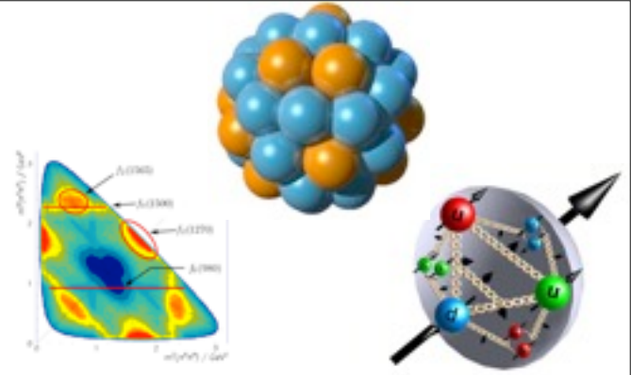
Dudek *et al*, Phys.Rev. D87 (2013) 3, 034505

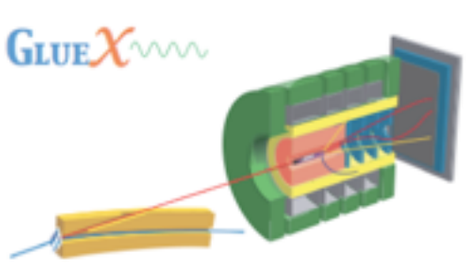
Lattice QCD will predict the exotic spectrum before or during the GlueX experiment

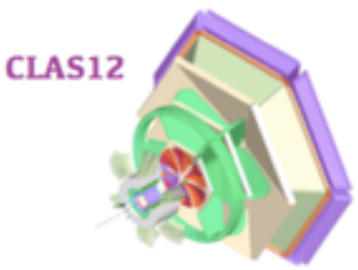
(with sufficient compute resources)

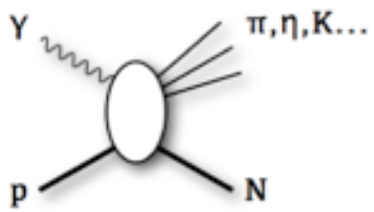


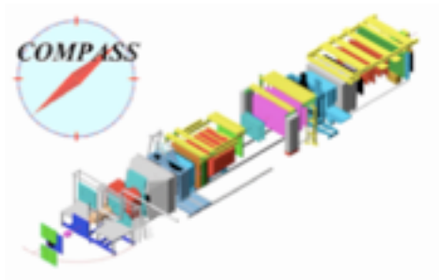
Spectrum

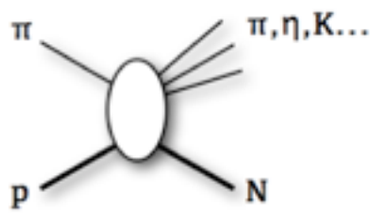


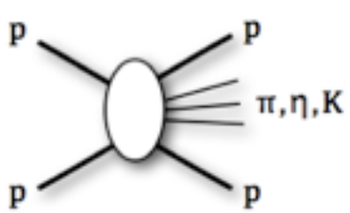


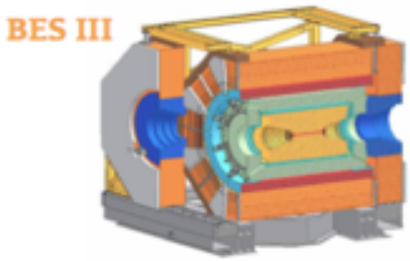


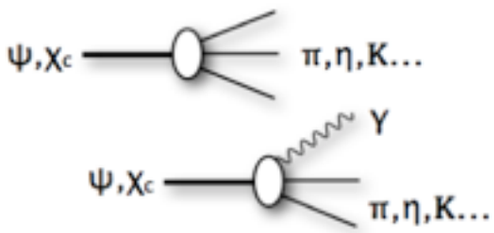






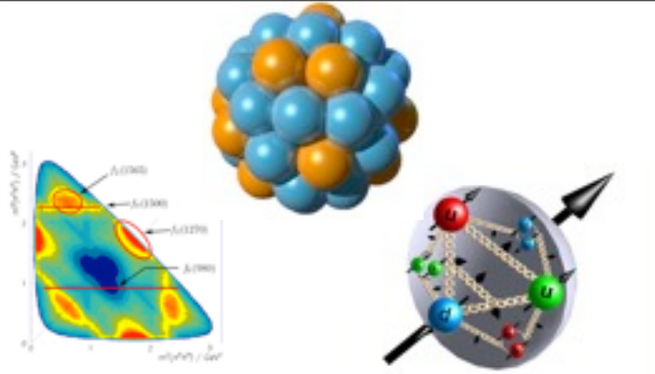




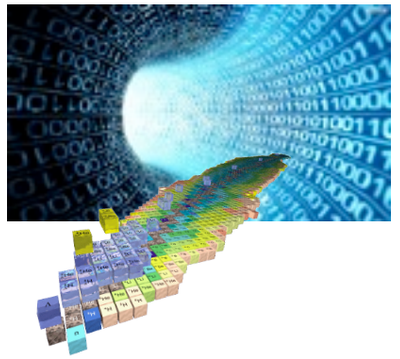


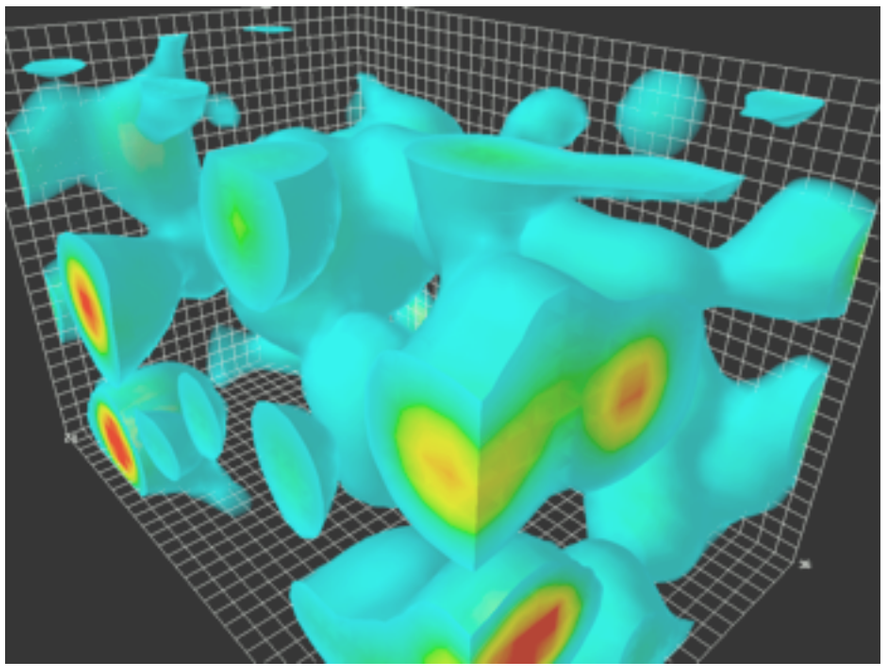
- Coupled channels increase for lighter pion mass
- Sources for multi-hadron appear crucial
- S-matrix elements ? - In progress
- Widths of states
- Number of measurements - USQCD hardware
- Contraction automation

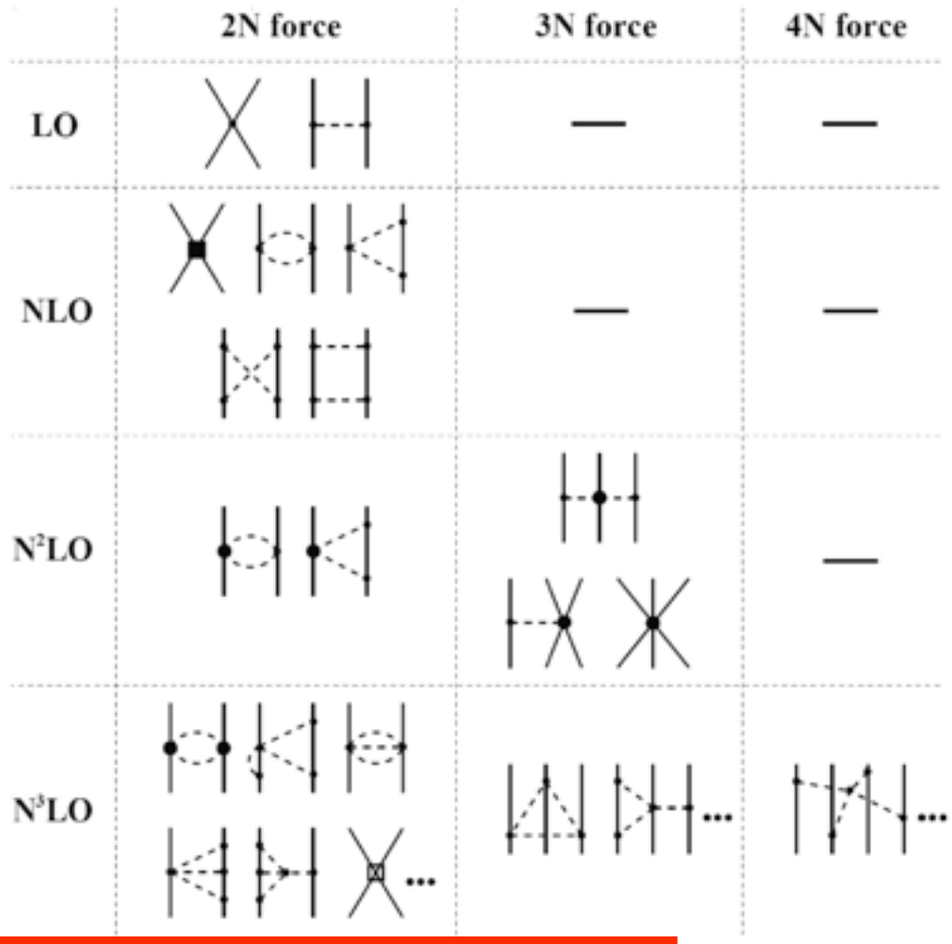
Briceno, Phys.Rev. D89 (2014) 074507,
Phys.Rev. D88 (2013) 114507
Phys.Rev. D87 (2013) 9, 094507
Hansen and Sharpe, arXiv:1311.4848
Phys.Rev. D86 (2012) 016007



Refining Nuclear Forces and Multi-Nucleon Interactions: Enhanced Predictive Capabilities







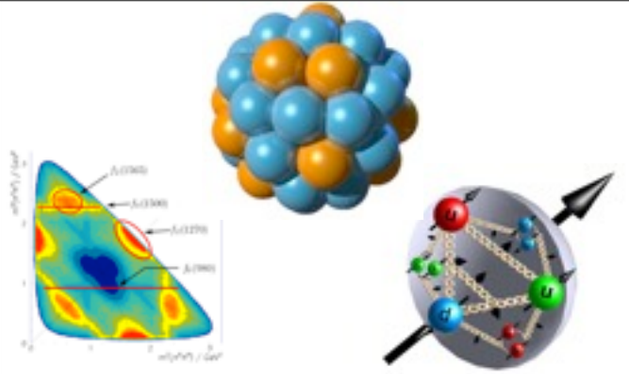
QCD to constrain coefficients

i) Verification and/or better experiment (?)

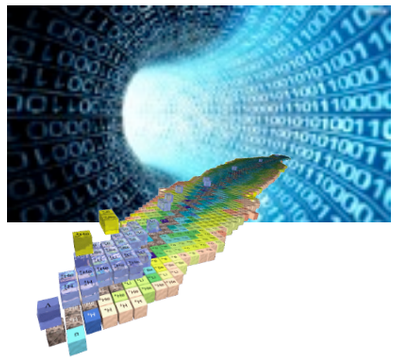
ii) Inaccessible to experiment, e.g. nnn, nnnn

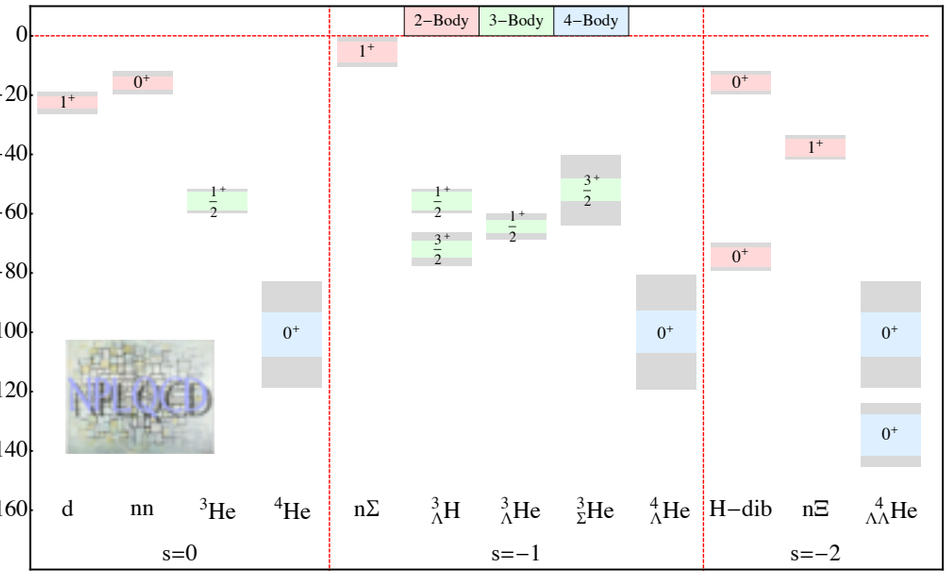
iii) Number of coefficients for required level of precision

iii) and/or direct calculation of desired quantity



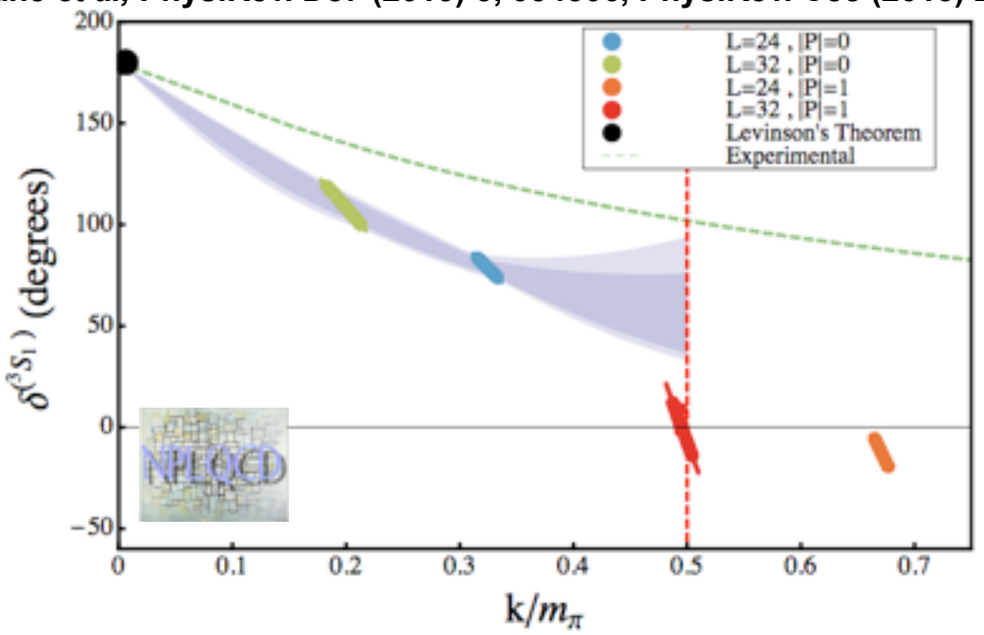
Hadronic Interactions

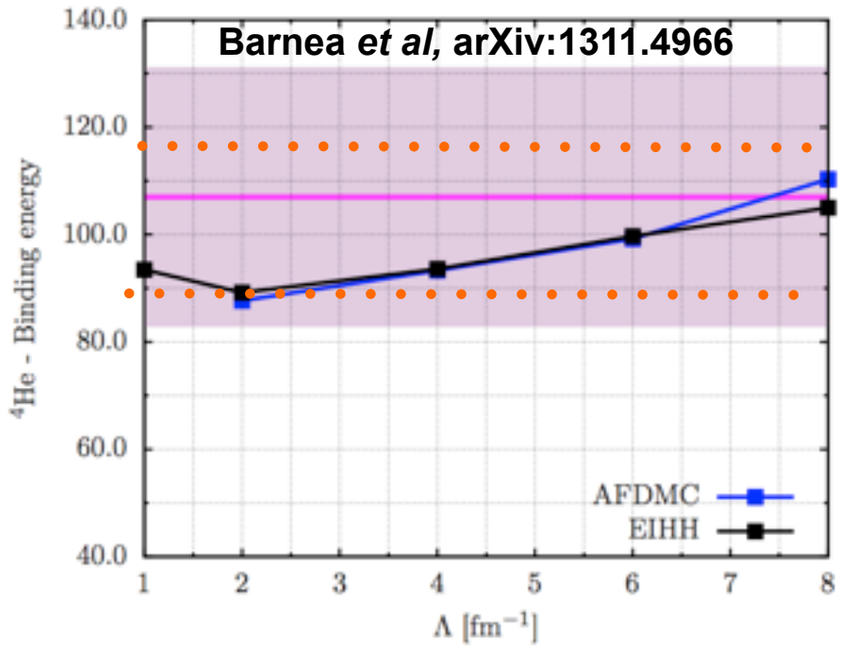


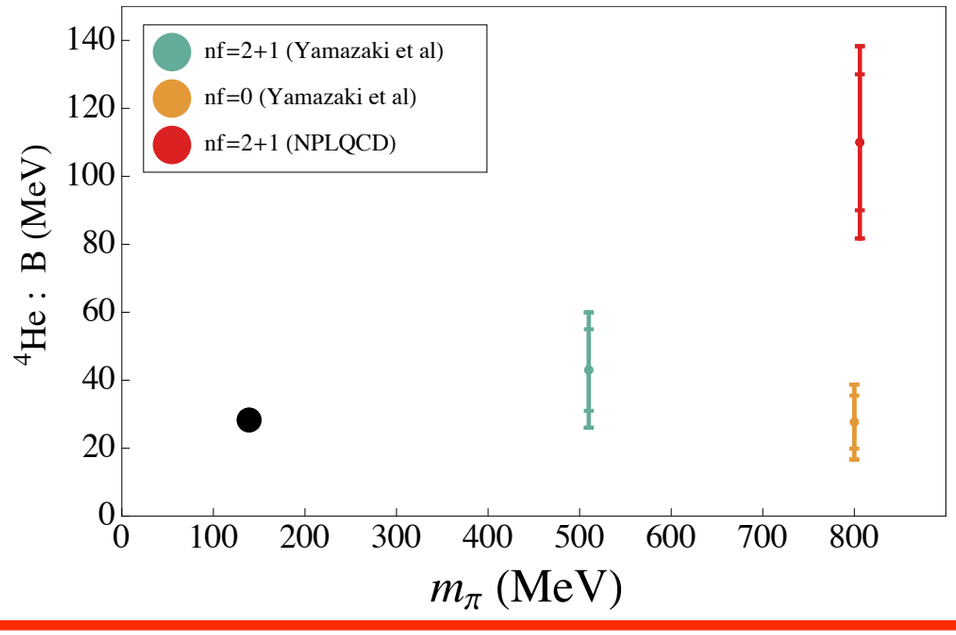


m_π ~ 800 MeV

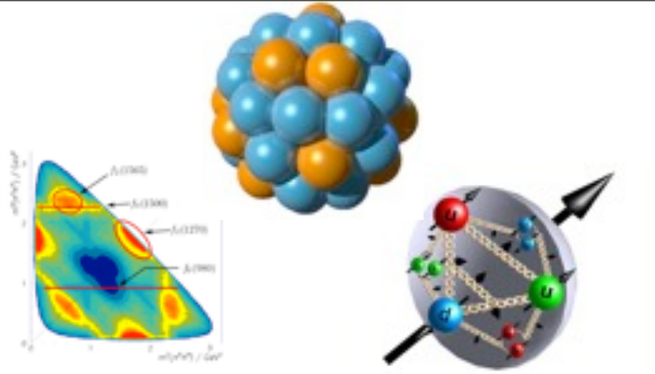
Beane *et al*, Phys.Rev. D87 (2013) 3, 034506, Phys.Rev. C88 (2013) 2, 024003



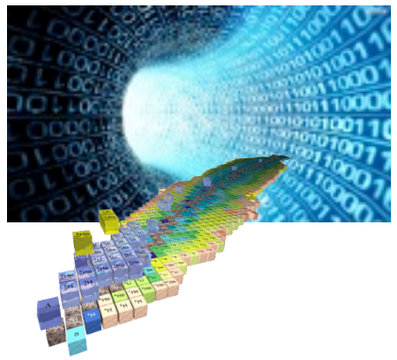


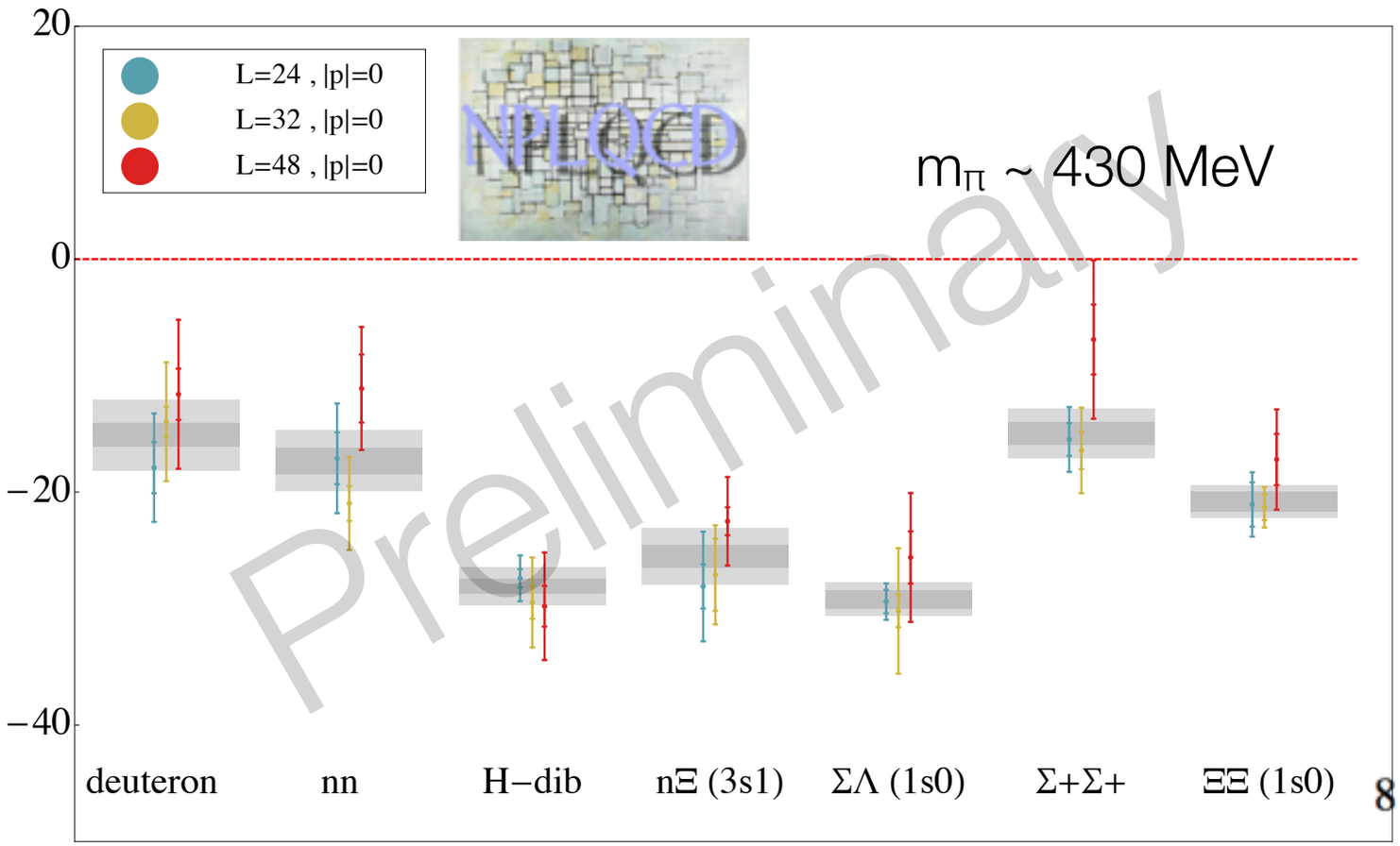


Extensive study of s-shell nuclei and hypernuclei, and baryon-baryon interactions at SU(3) symmetric point

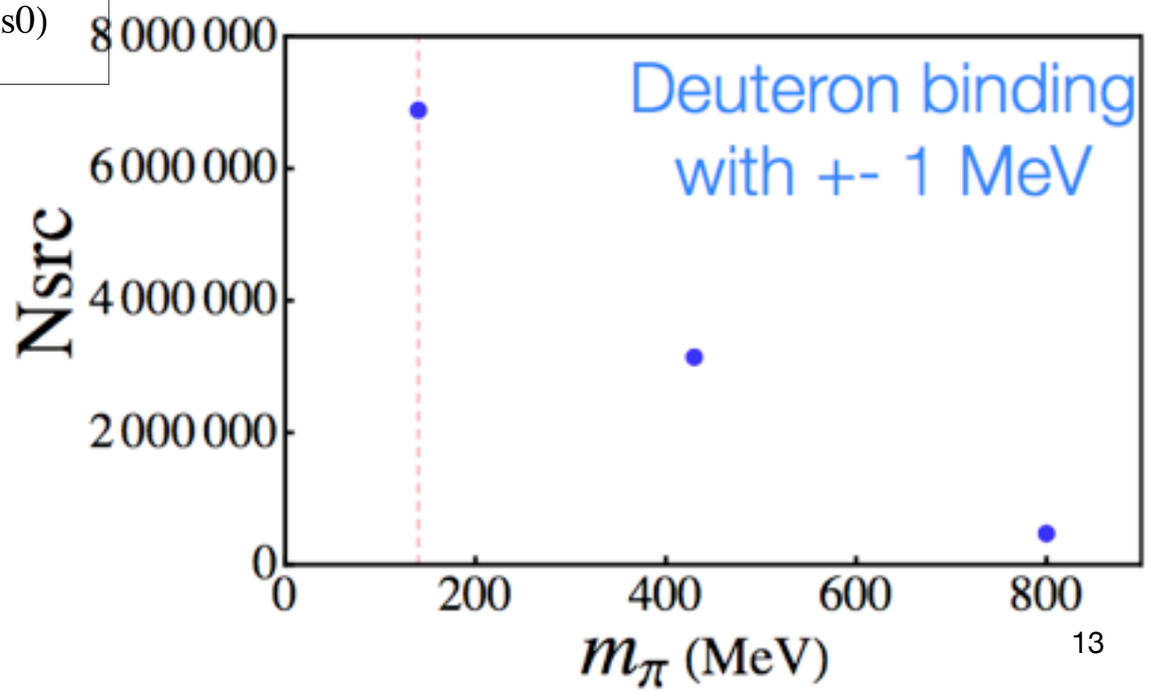


Hadronic Interactions

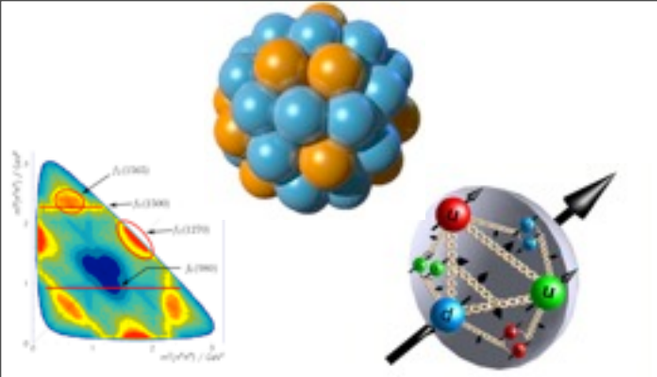


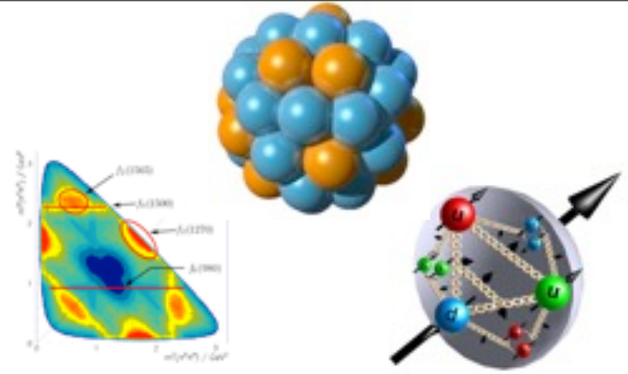


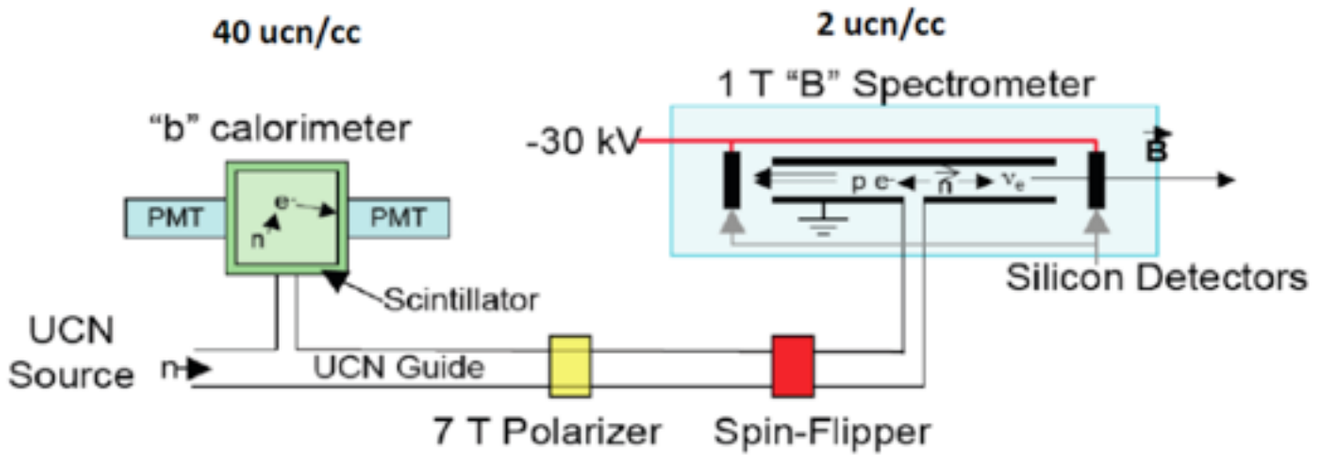
Preliminary



Fundamental Interactions

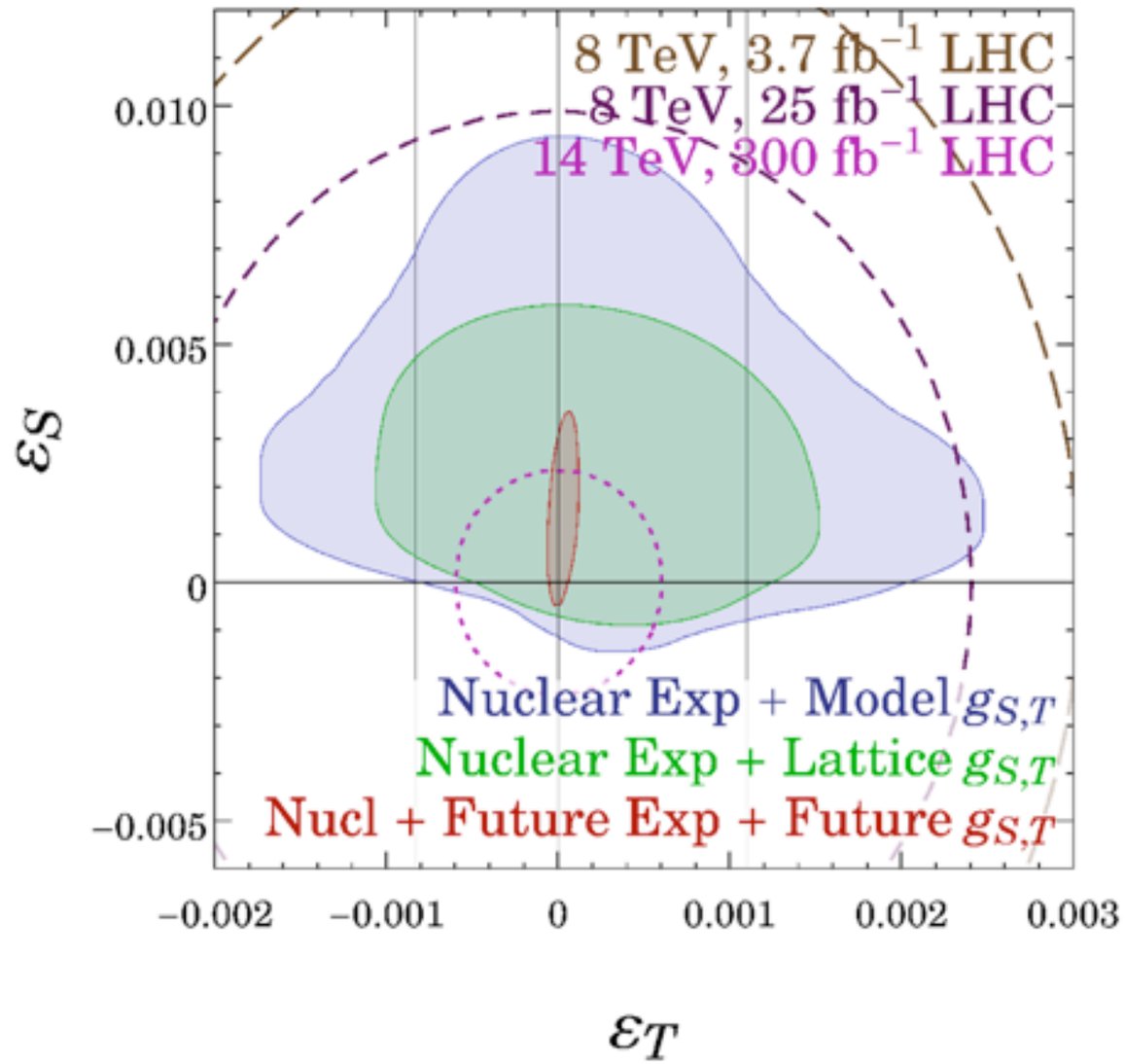






LANL experiment

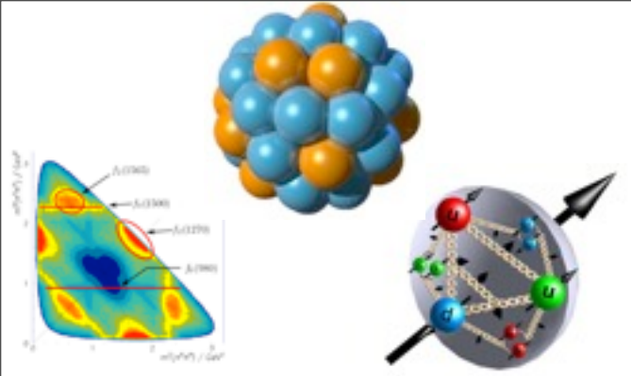
- LQCD calcs at pion mass of 220 MeV
- Looking toward 140 MeV

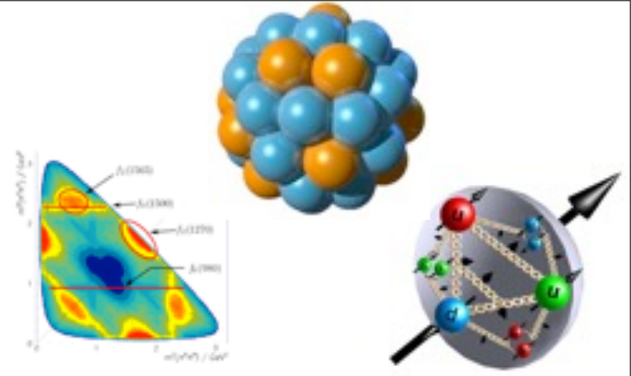


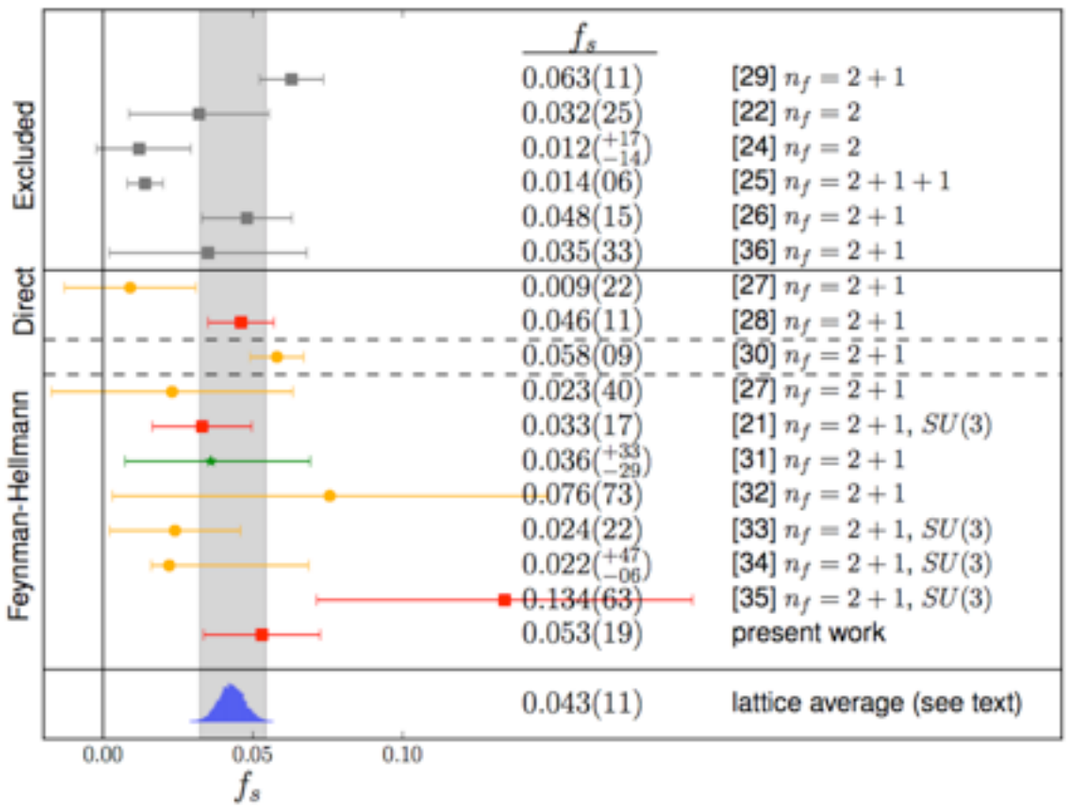
PNDME collab

Bhattacharya et al, Phys.Rev. D89 (2014) 9, Phys.Rev. D85 (2012) 054512

Fundamental Interactions
Dark Matter ?



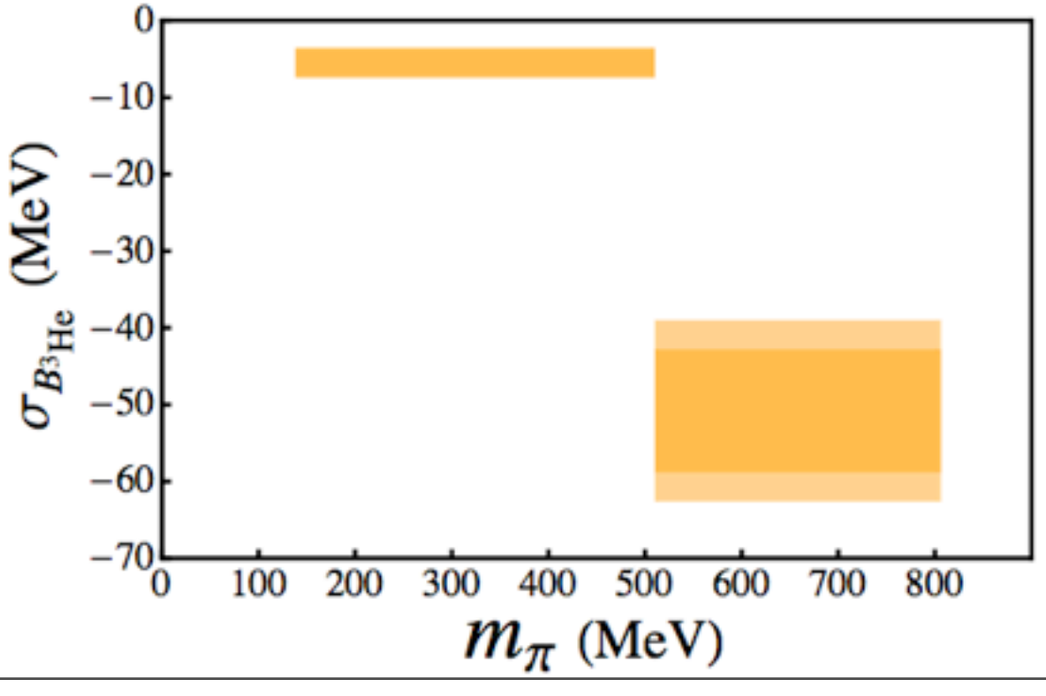


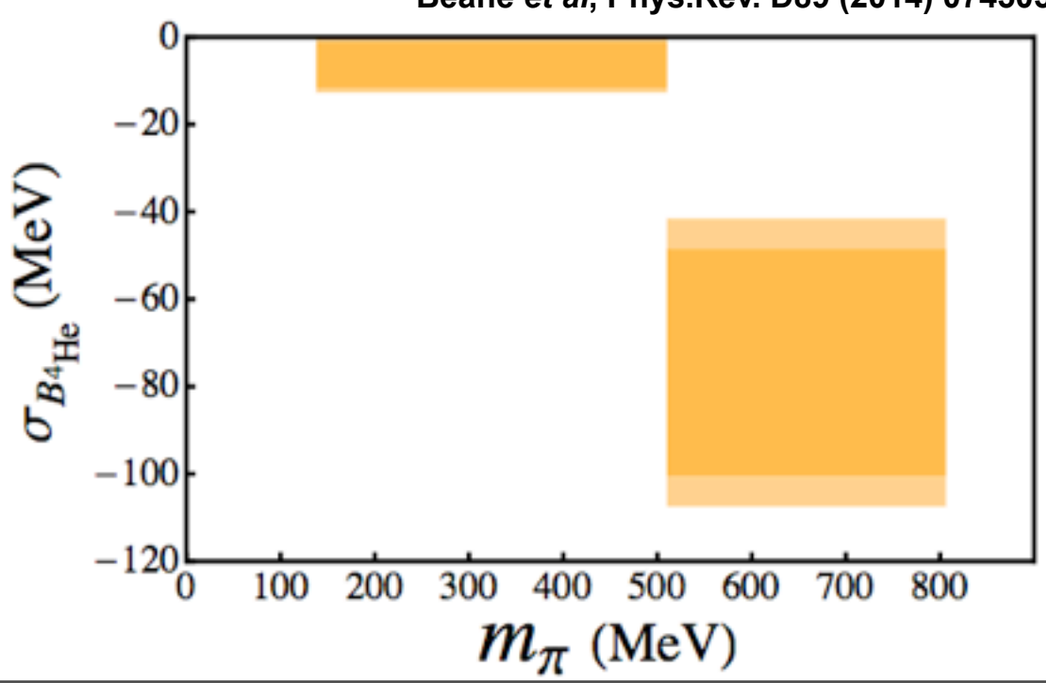


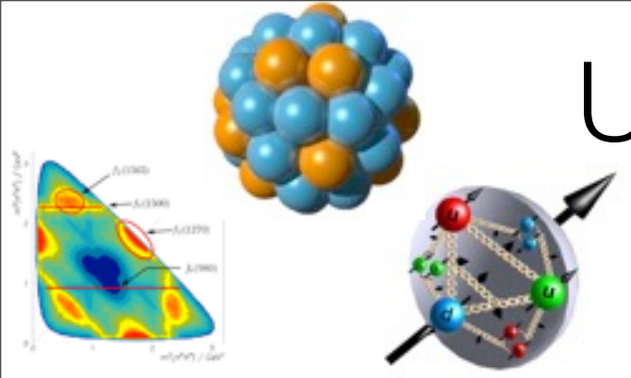
$$m_s\langle N|\bar{s}s|N\rangle = 48 \pm 10 \pm 15 \text{ MeV}\,,$$
$$f_s = 0.051 \pm 0.011 \pm 0.016$$

Junnarkar and Walker-Loud, Phys.Rev. D87 (2013) 11, 114510

Beane *et al*, Phys.Rev. D89 (2014) 074505







USQCD Proposed Production 2014-2019

$N_s^3 \times N_t$	Action	a fm	m_π MeV	$m_\pi L$	$m_\pi T$	Traj.	Configs. (TF-yrs)	Str-A	Str-B (TF-yrs)	HSp	HI
$64^3 \times 128$	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†		

Assumed current funding levels throughout period - NP 50% partner

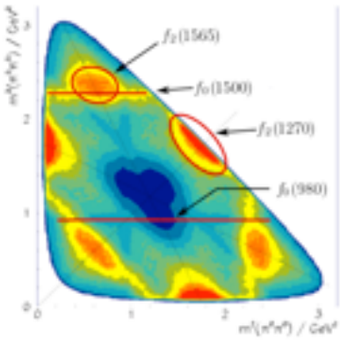
Summary

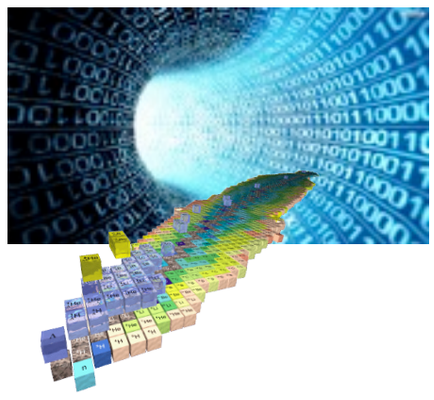
- Good year for USQCD cold NP program
  - Spectrum - refined exotic spectrum at m_π ~400 MeV
  - Structure - $\langle r^2 \rangle$ at m_π ~140 MeV, src-sink separation systematics
  - Interactions - s-shell nuclei and hypernuclei at m_π ~430 MeV
  - Fundamental Symmetries - improved constraints on g_S and g_T

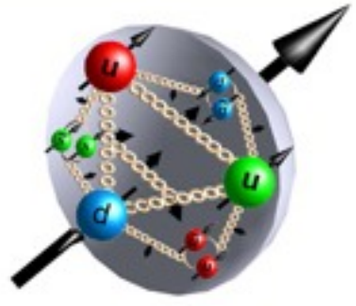
- Next few years will be transformational for the field
  - peta-scale computational resources
  - compute resources less than expected - delaying physics delivery

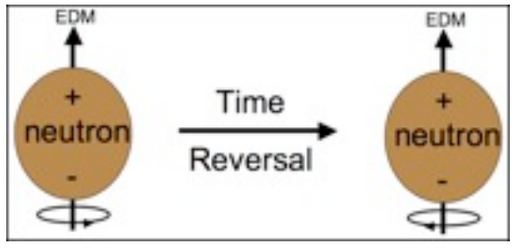
- Physical pion mass - nucleon structure only - exploring systematics

- Anticipated computational resources no longer following Moore's Law = problem.









THE END