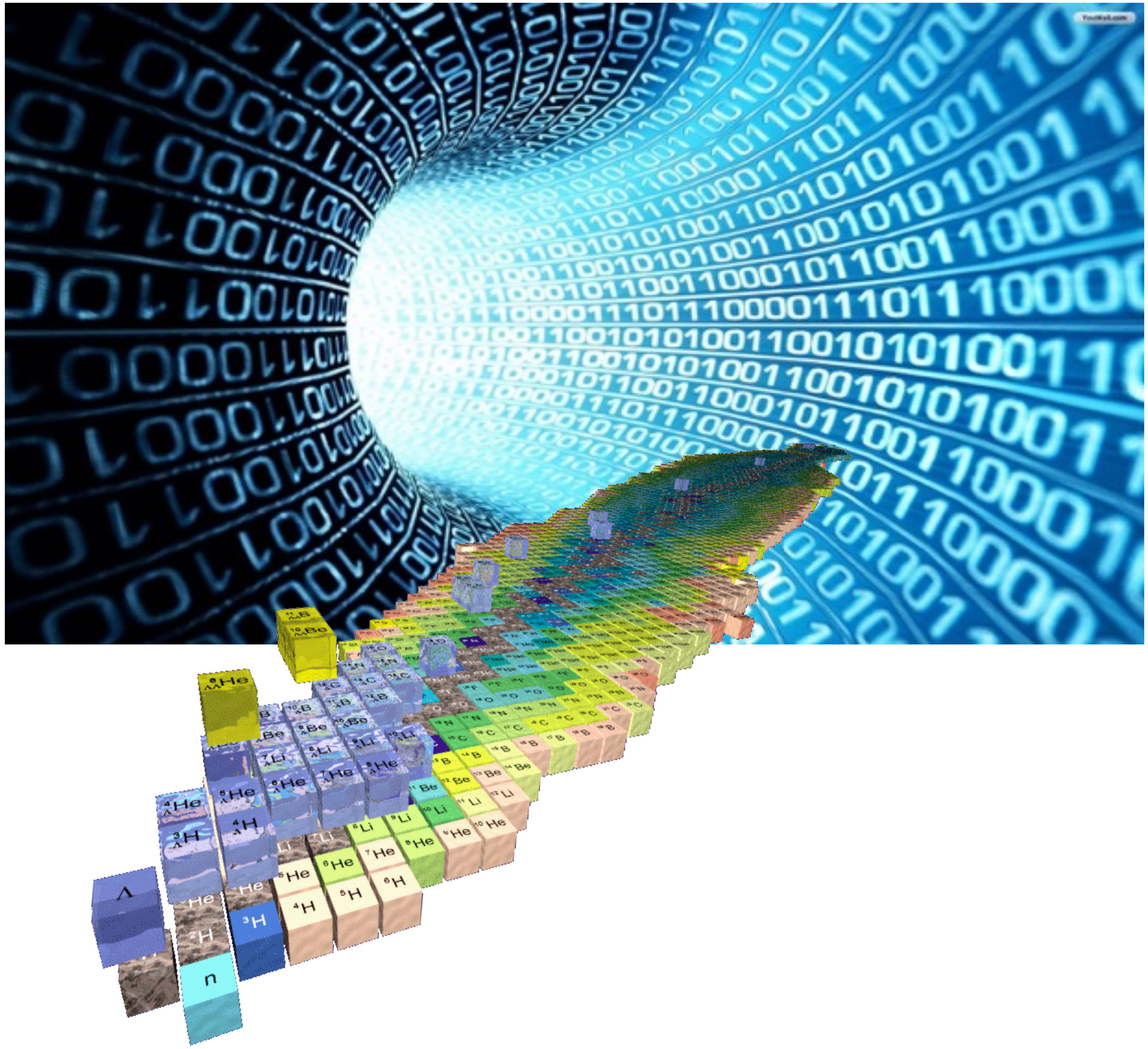
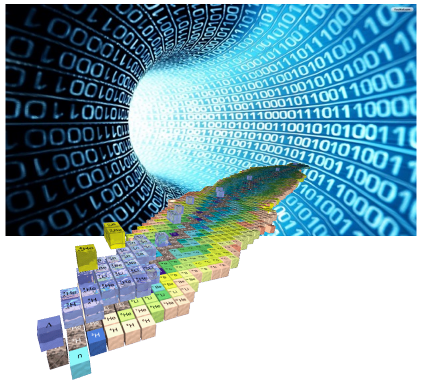


Nuclear physics from QCD: new questions and future directions

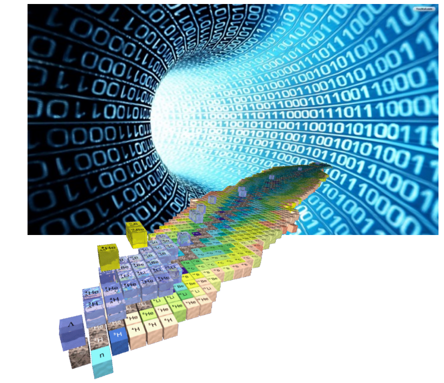
Martin J Savage

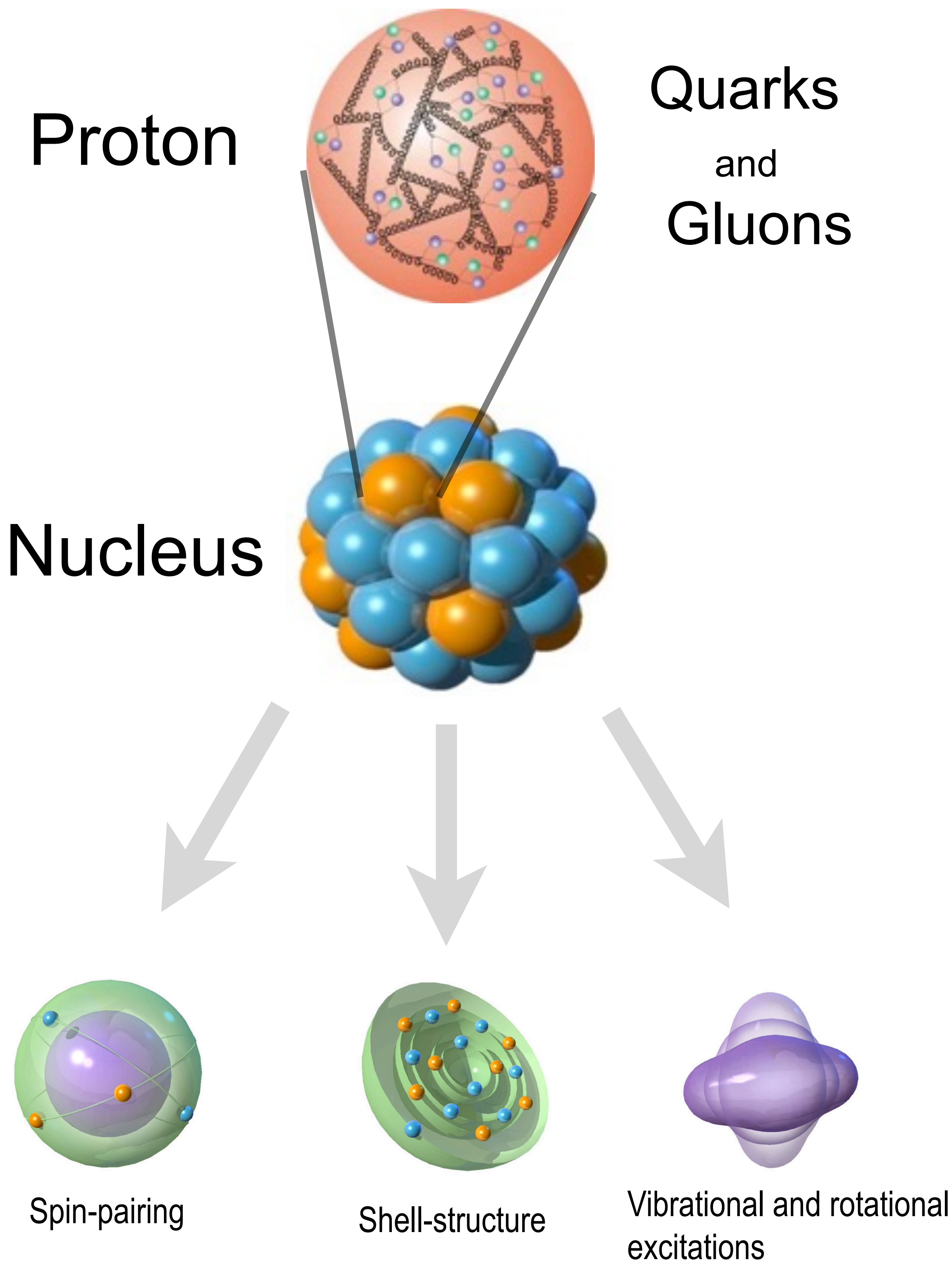
INSTITUTE for NUCLEAR THEORY

INT program : Nuclear Physics from Lattice QCD, May 13, 2016



The Structure and Interactions of Matter from Quantum Chromodynamics



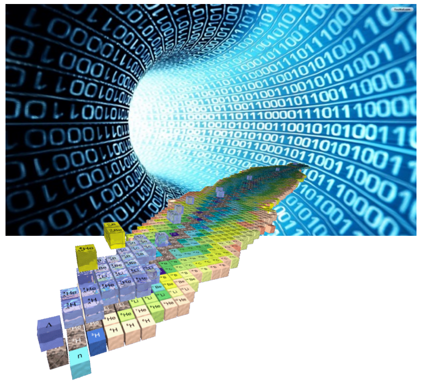


$$\Lambda_{\mathrm{QCD}}$$

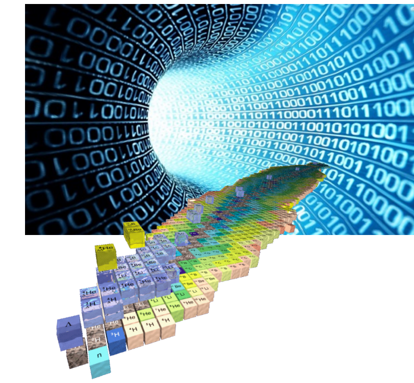
$$\frac{m_u}{\Lambda_{\mathrm{QCD}}} \quad \frac{m_d}{\Lambda_{\mathrm{QCD}}} \quad \frac{m_s}{\Lambda_{\mathrm{QCD}}}$$

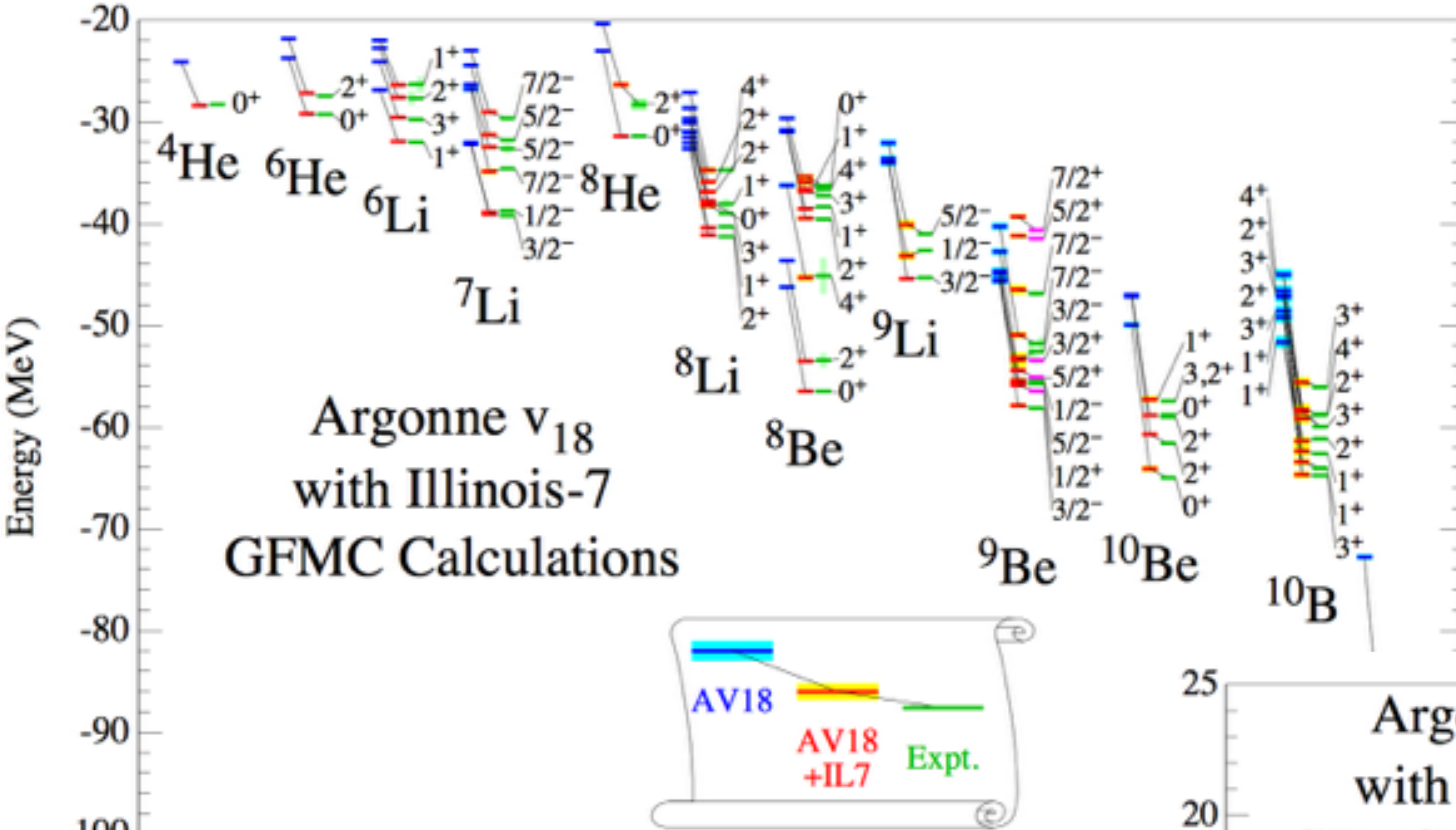
$$\alpha_e$$

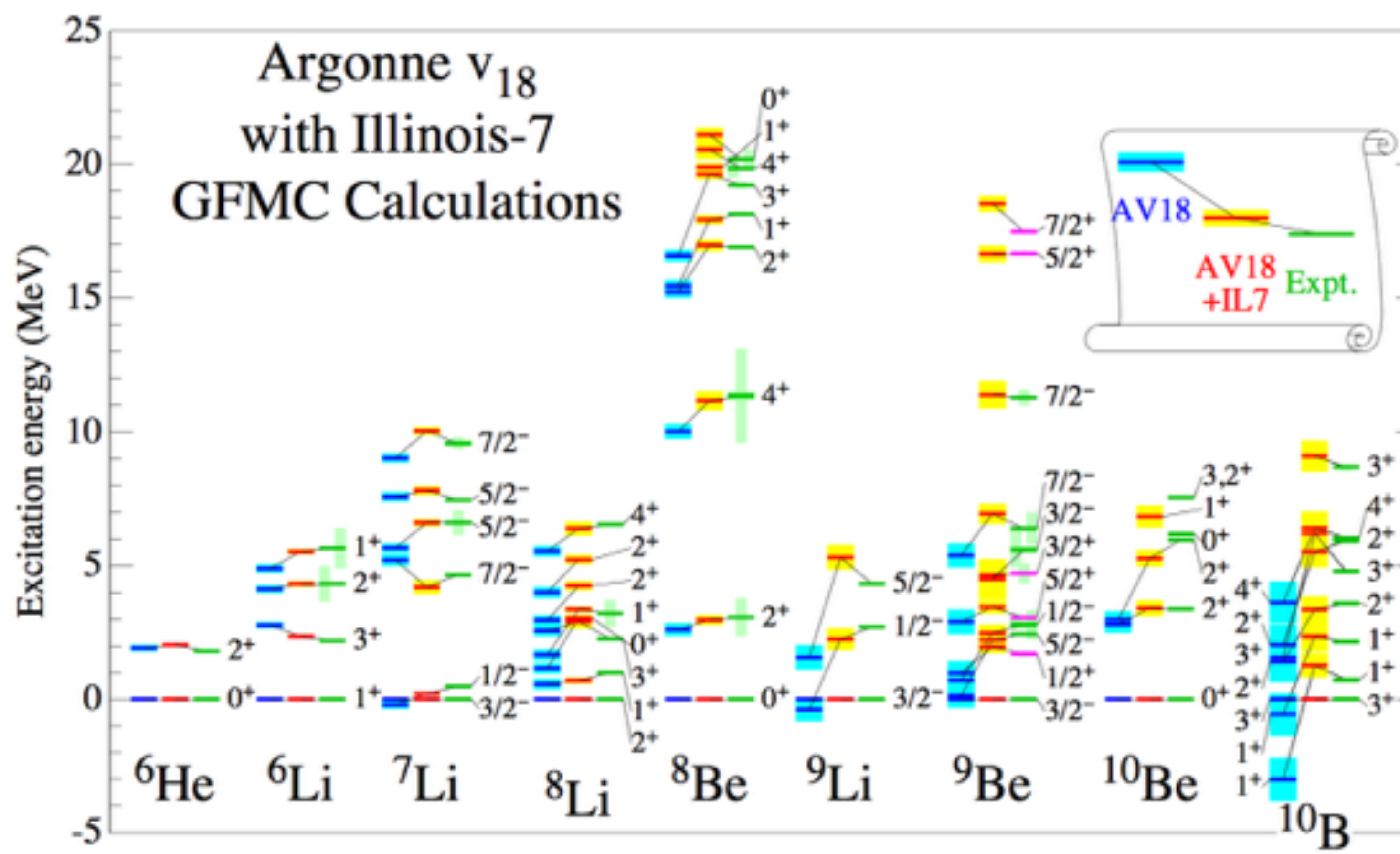
Small number of input parameters responsible for all of strongly interacting matter



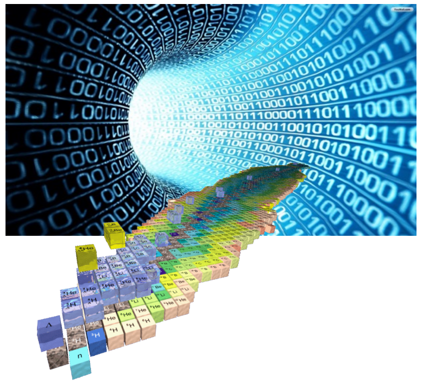
State-of-the-Art Nuclear Many-Body



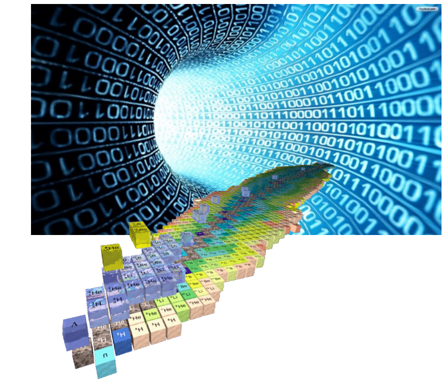


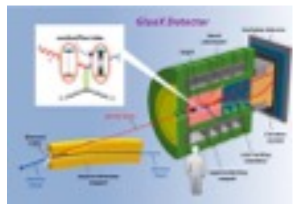


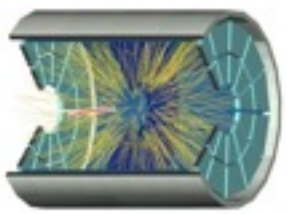
Carlson, Gandolfi, Pederiva, Pieper, Schiavilla, Schmidt and Wiringa (2015)



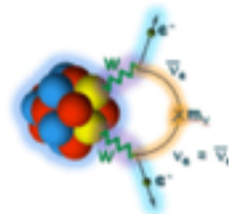
The Emergence of Nuclei from QCD





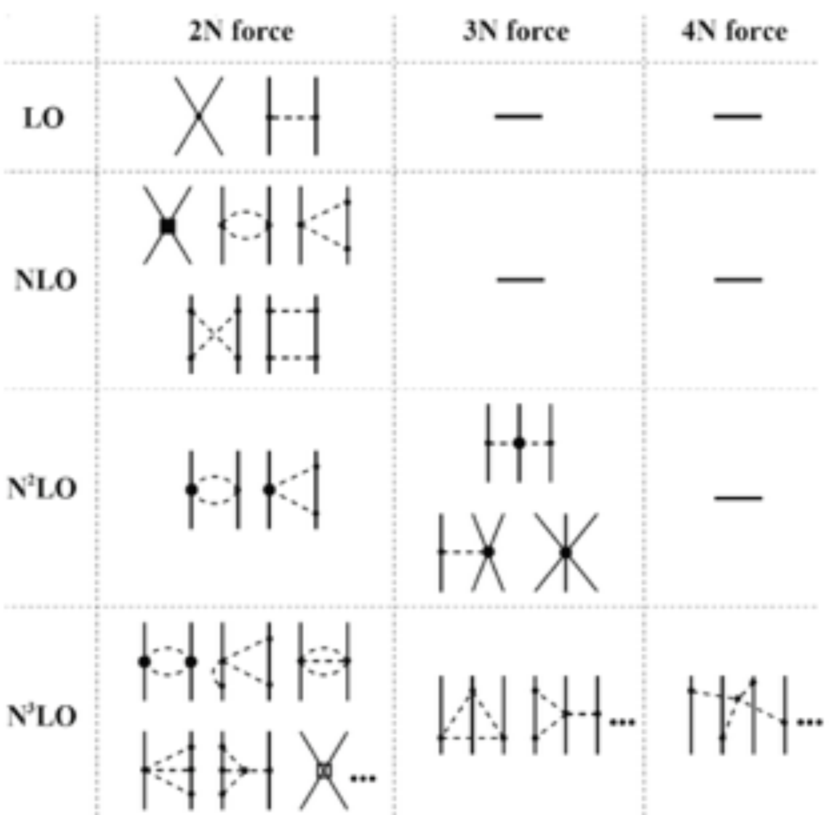


FRIB

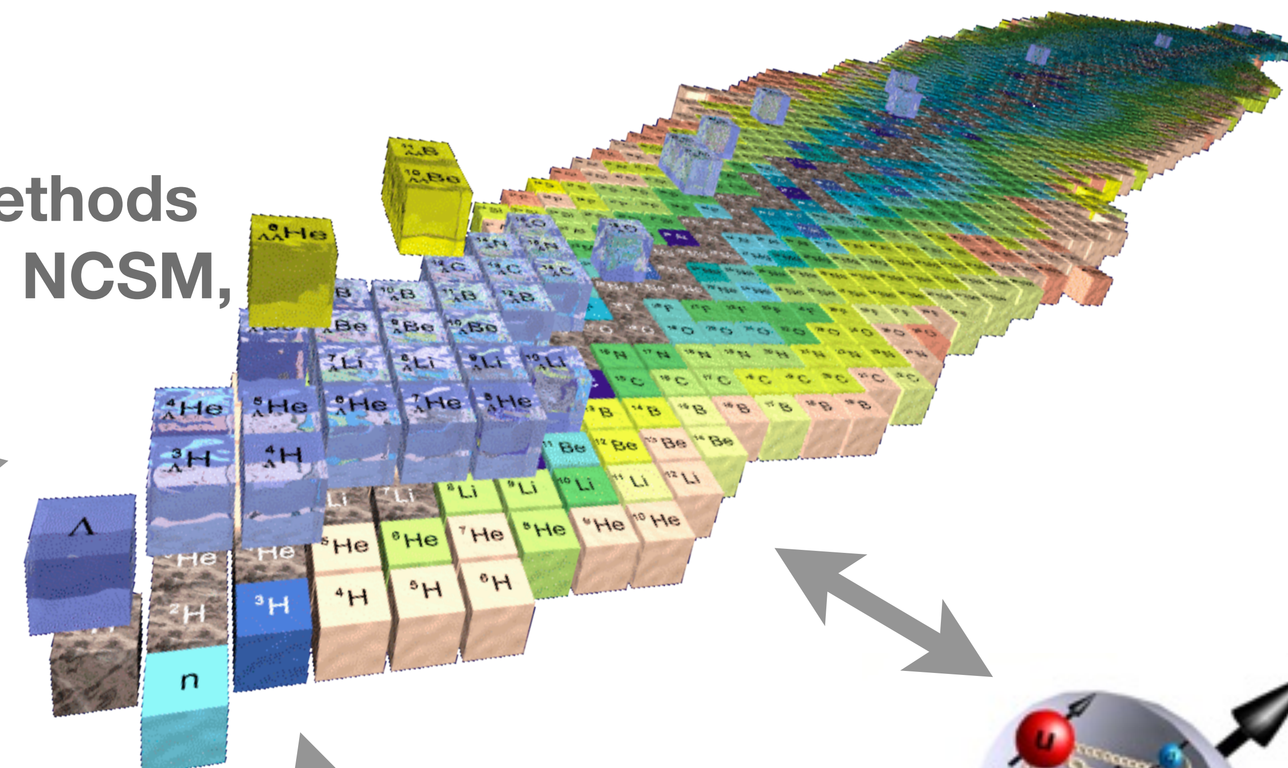


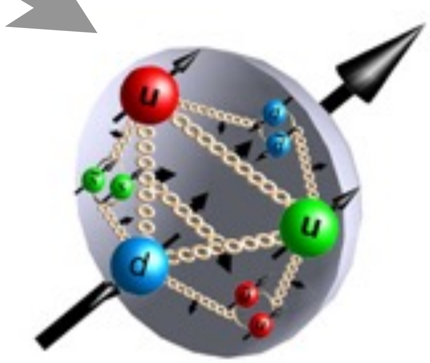
Electron Ion Collider

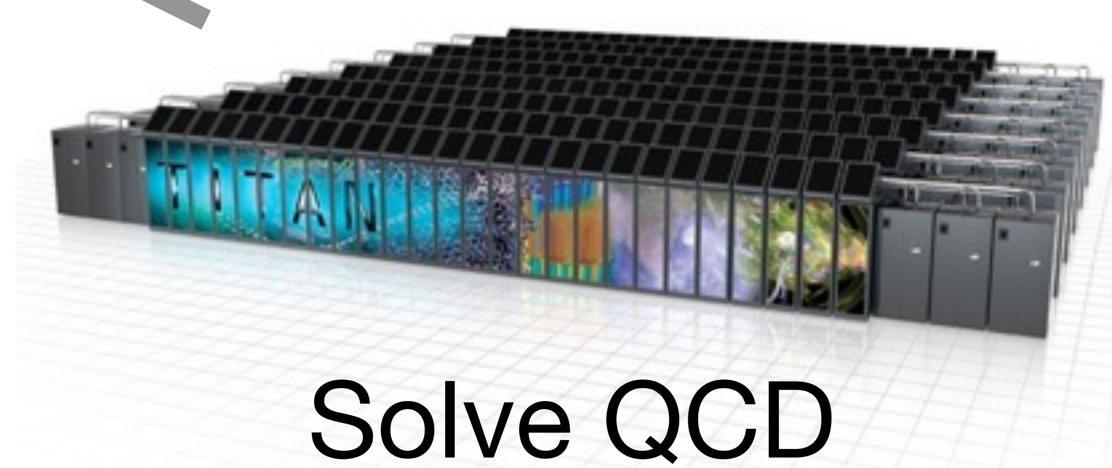
Many-Body Methods
e.g. SM, GFMC, NCSM, DFT,...



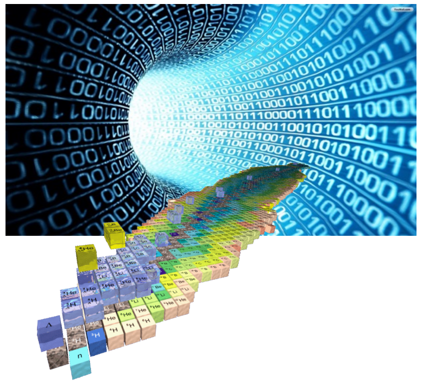
Nuclear Forces







Solve QCD



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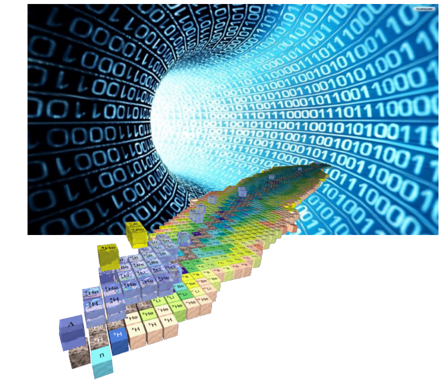
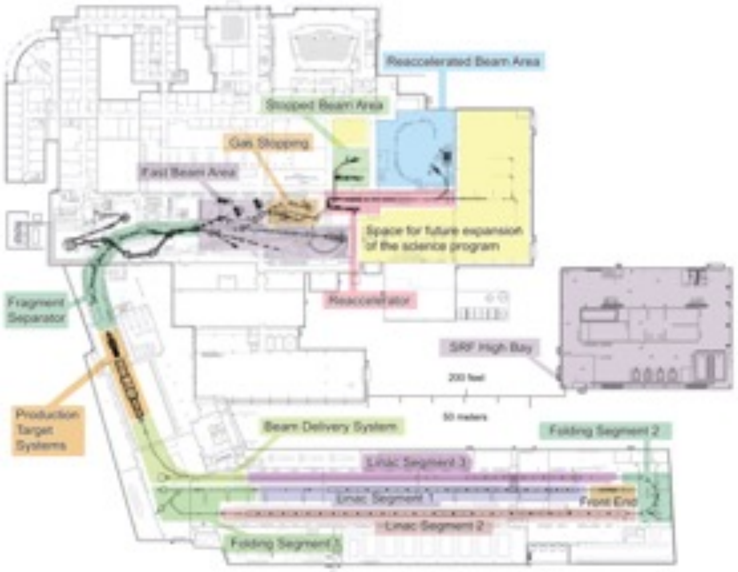
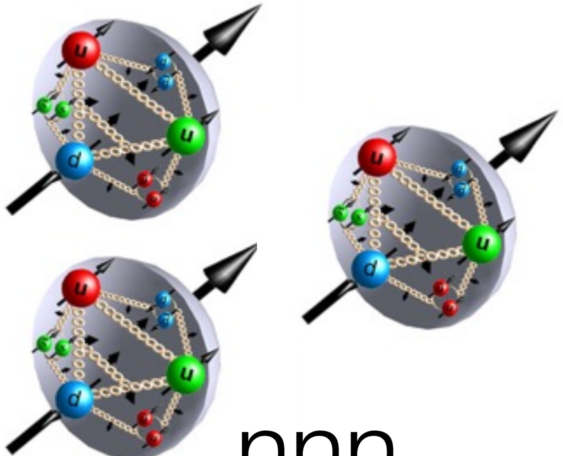




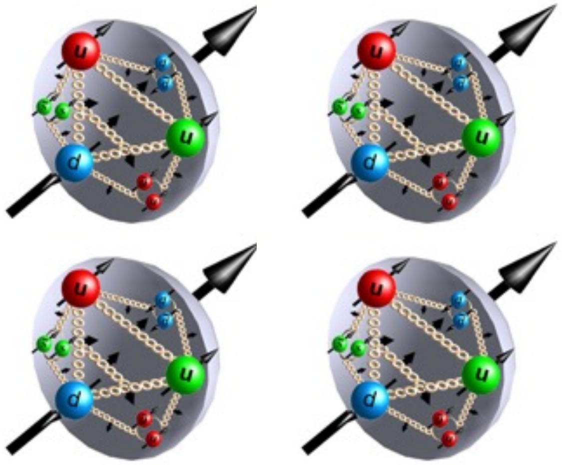
Experiment

Theory : NUCLEI

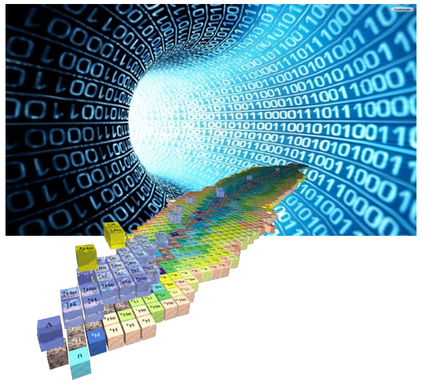


nnn

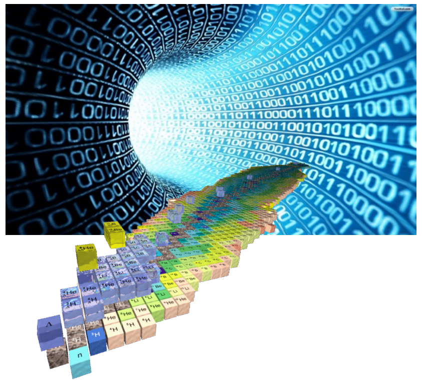
multi-neutron forces

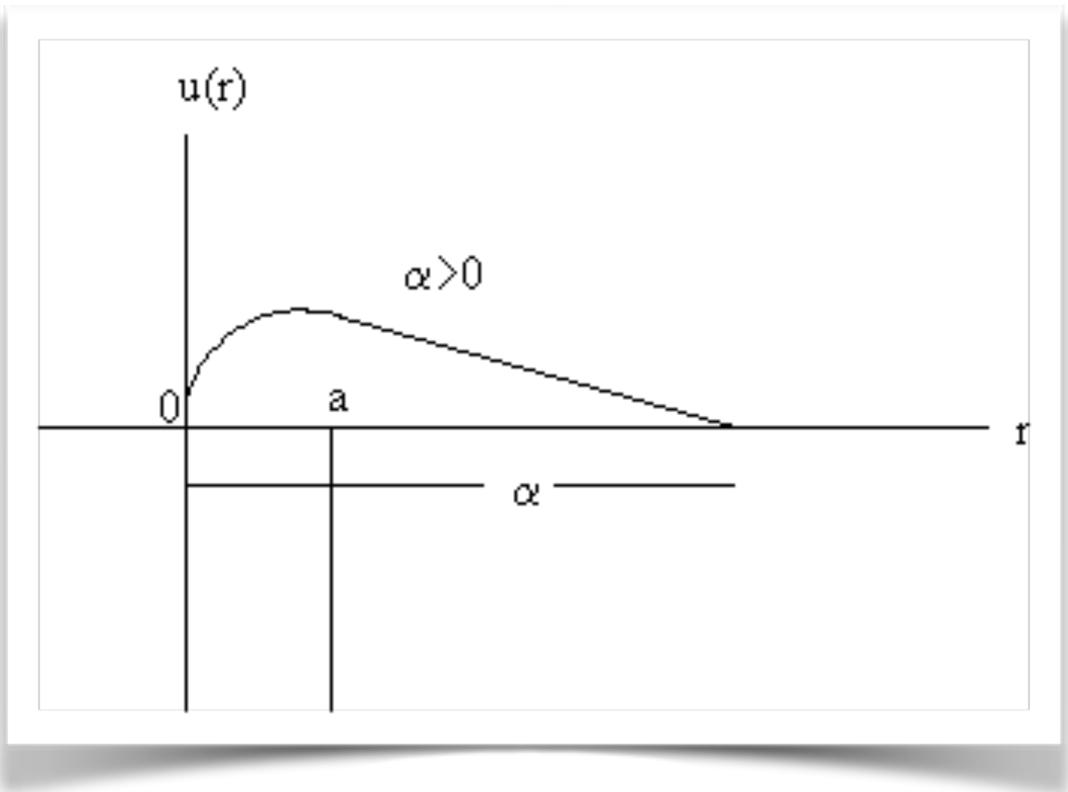


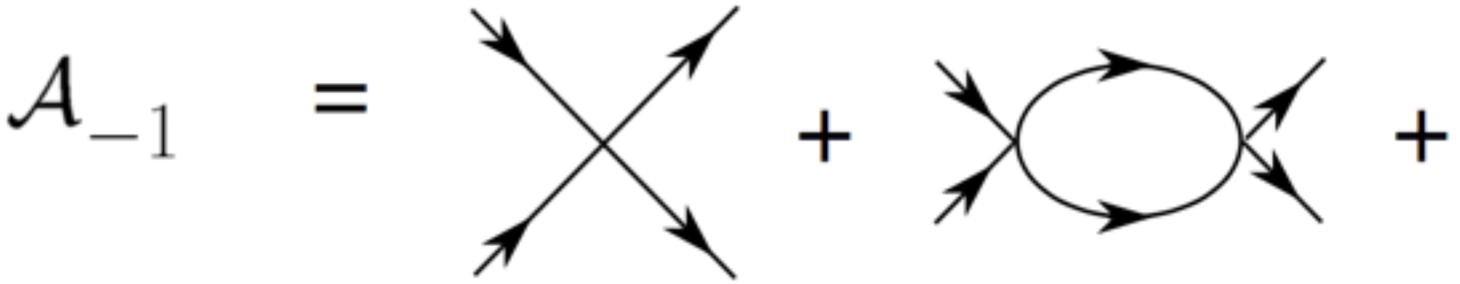
nnnn



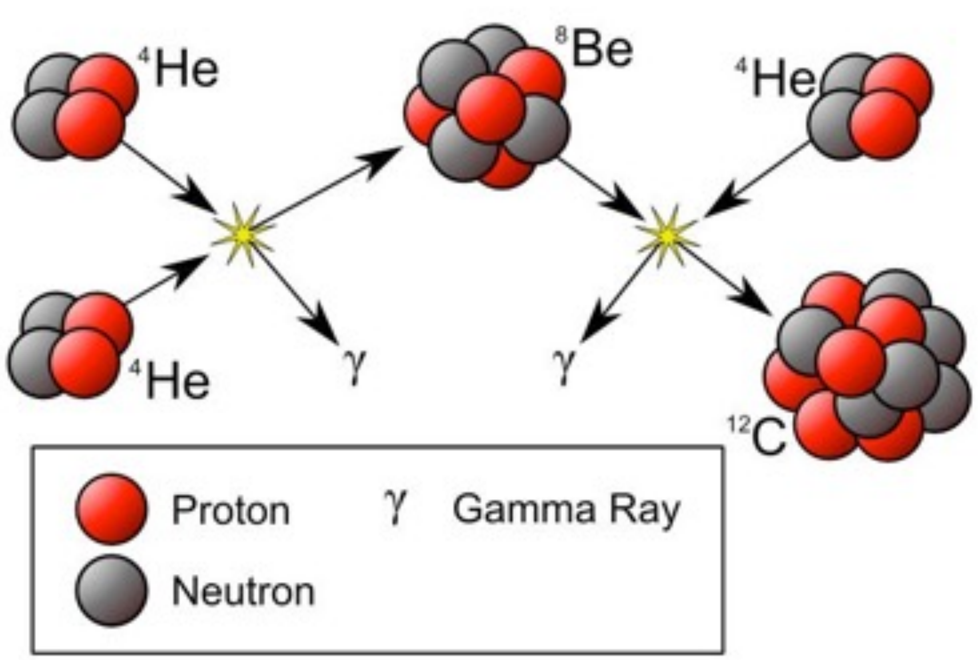
Fine-Tunings define our Universe

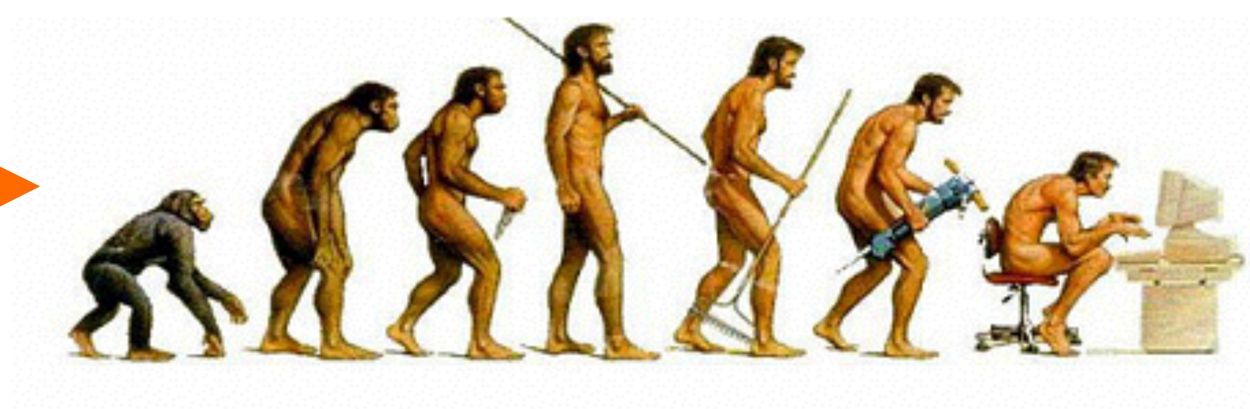


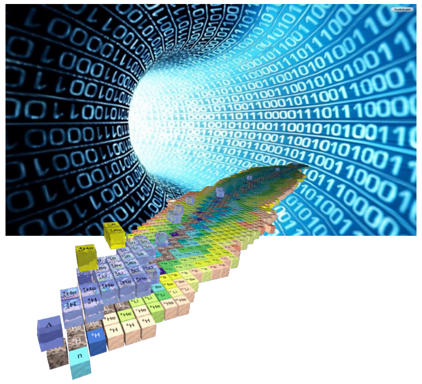




- Spin Independent up to $1/N_c^2$
  - SU(4) spin-flavor symmetry
- Near Unitarity

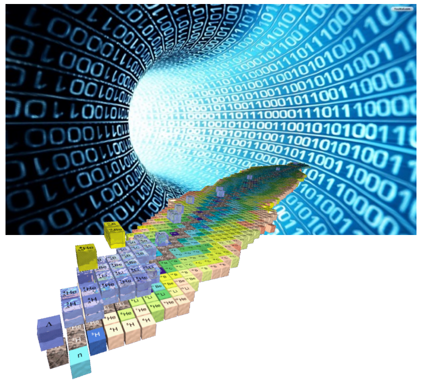


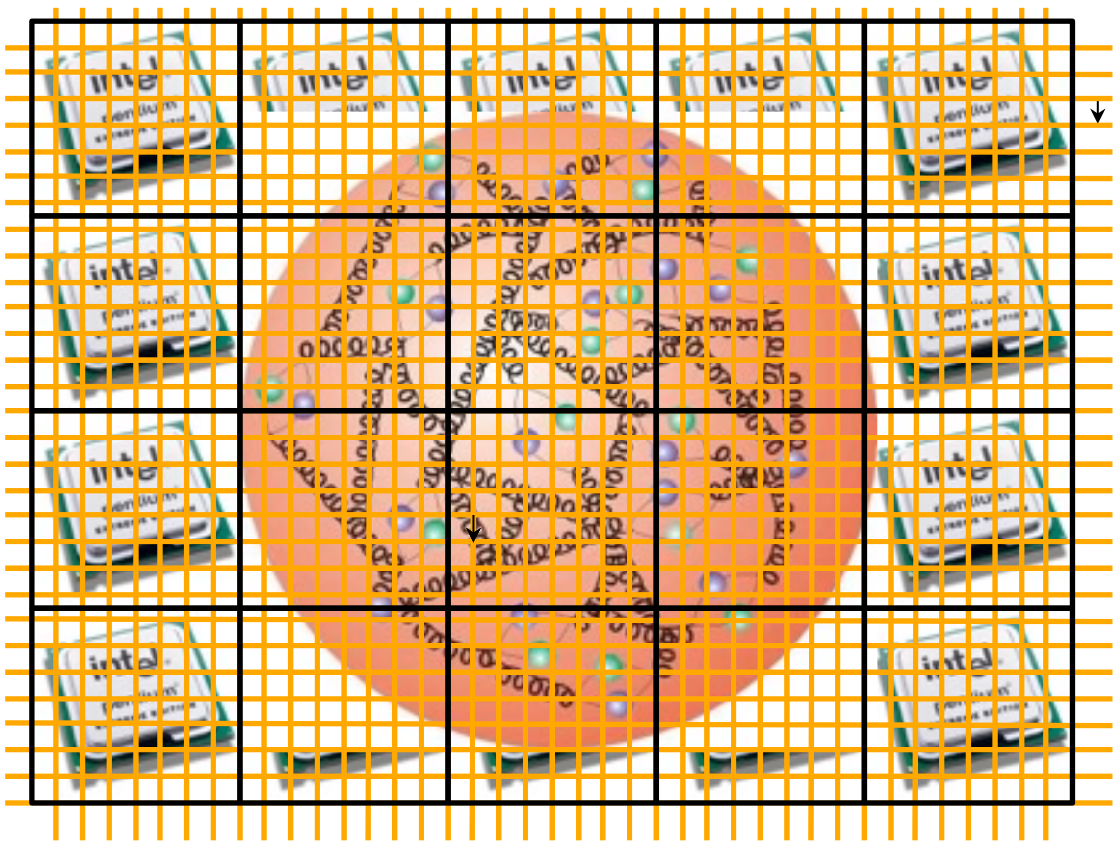




Lattice QCD

QFT in a Finite and Discretized Spacetime





Lattice Spacing :

$a << 1/\Lambda\chi$

(Nearly Continuum)

Lattice Volume :

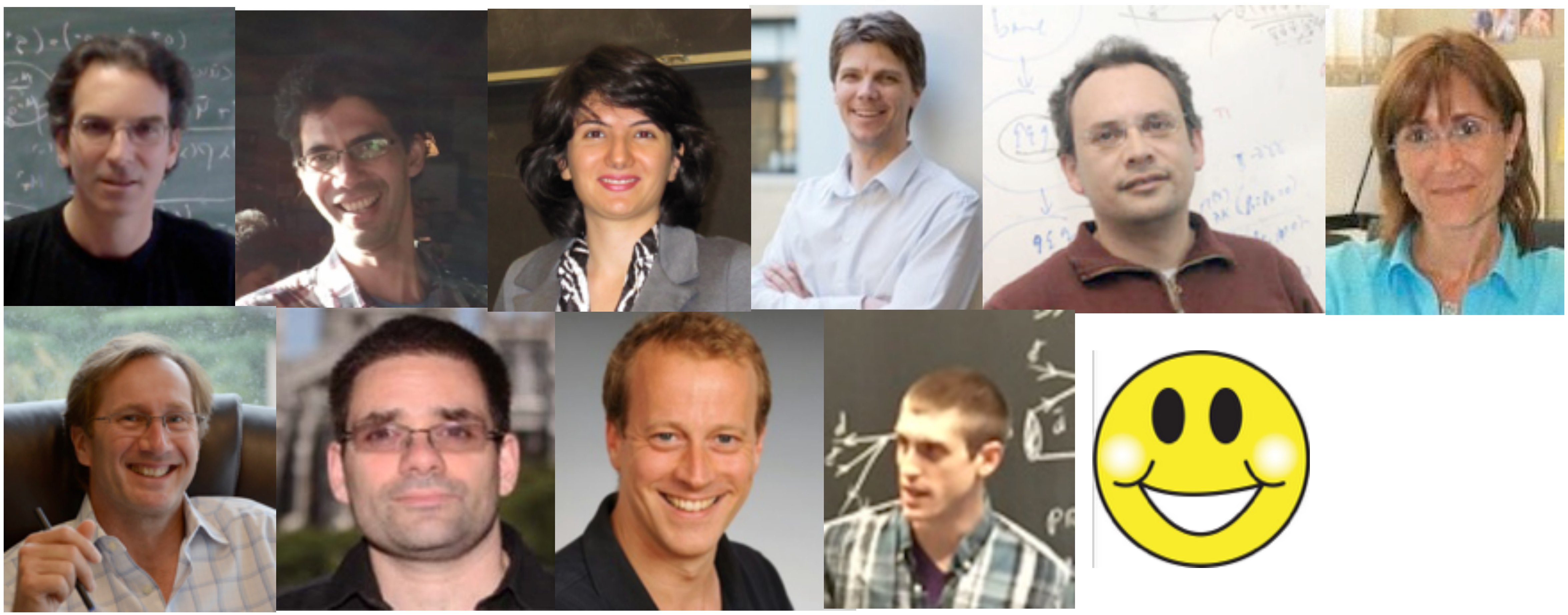
$m_\pi L >> 2\pi$

(Nearly Infinite Volume)

Extrapolate to $a = 0 \;\; \text{and} \;\; L = \infty$

Systematically remove non-QCD parts of calculation

NPLQCD



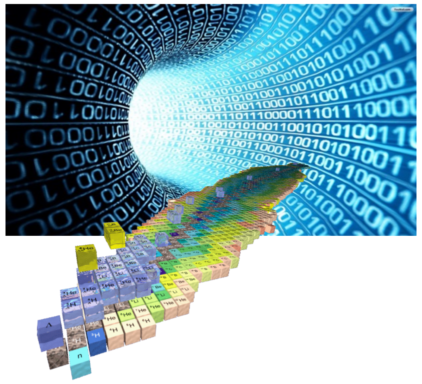
Silas Beane (UW)
Zohreh Davoudi (MIT)
Kostas Orginos (WM/JLab)
Martin Savage (INT)
Frank Winter (JLab)
Jonas Wilhelm (Geissen)

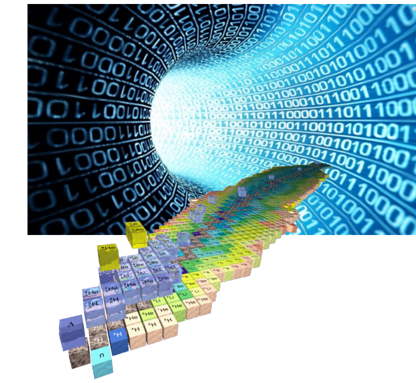
Emmanuel Chang (INT)
William Detmold (MIT)
Assumpta Parreno (Barcelona)
Brian Tiburzi (CCNY/BNL)
Michael Wagman (UW)

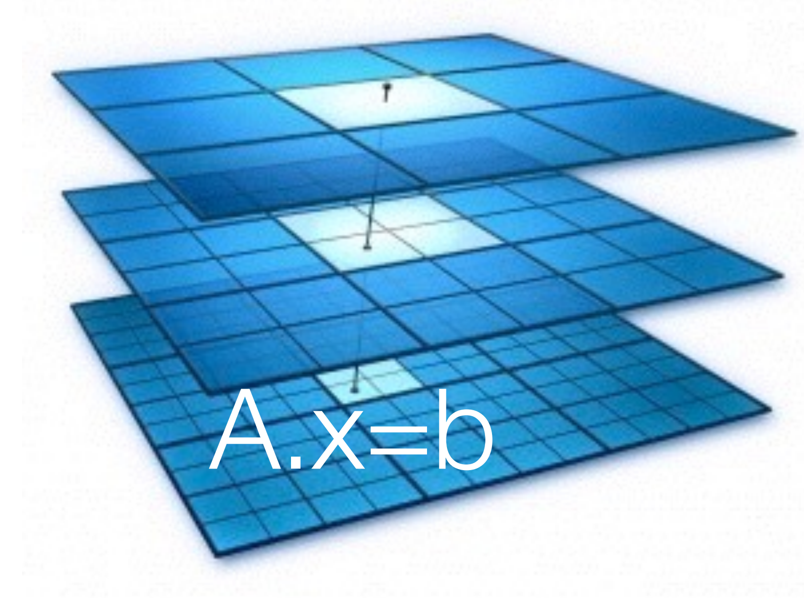
Past Collaborators
Saul Cohen
Pari Junnarkar
Huey-Wen Lin
Aaron Torok
Tom Luu
Andre Walker-Loud

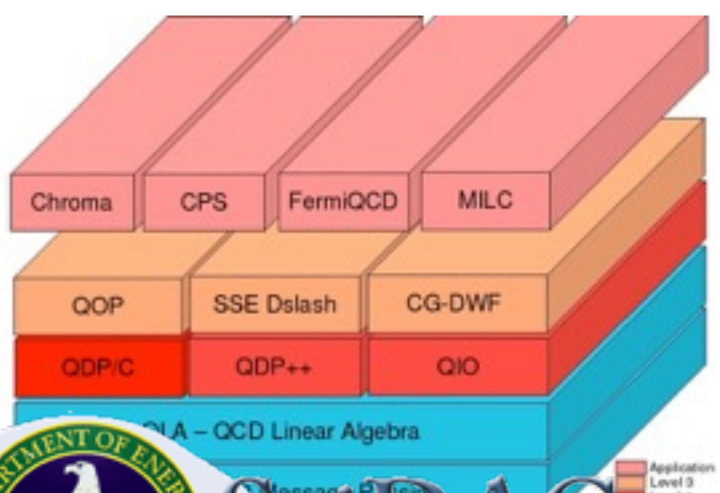
USQCD

A collaboration of collaborations

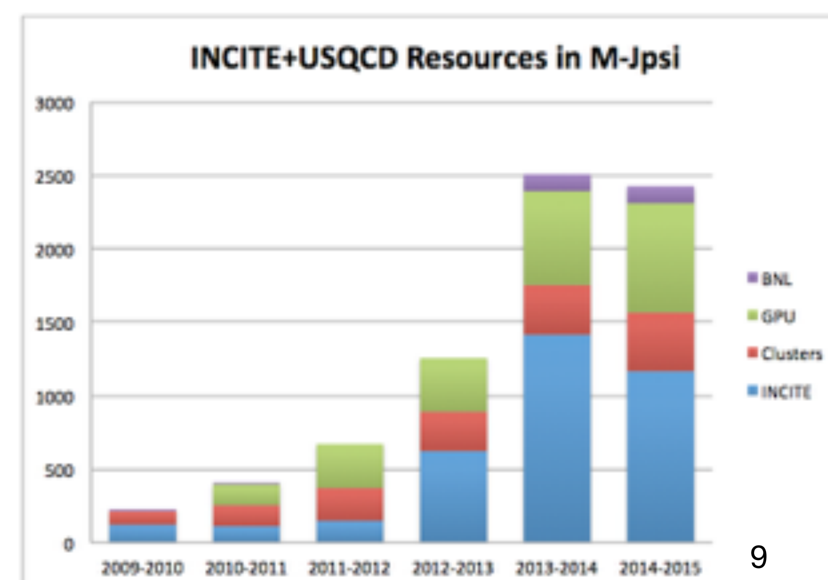


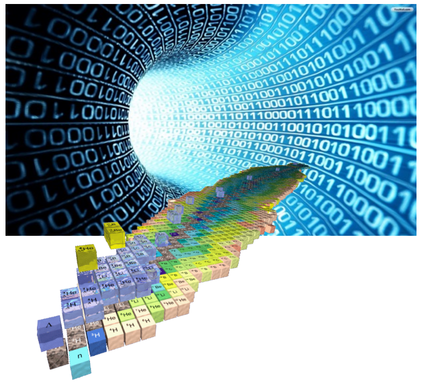




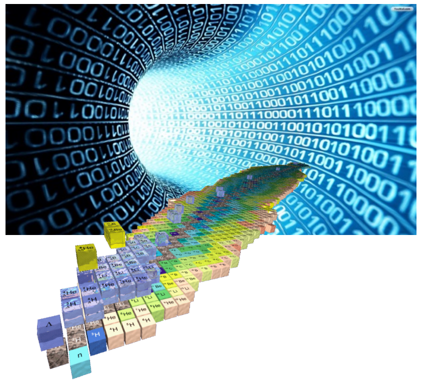


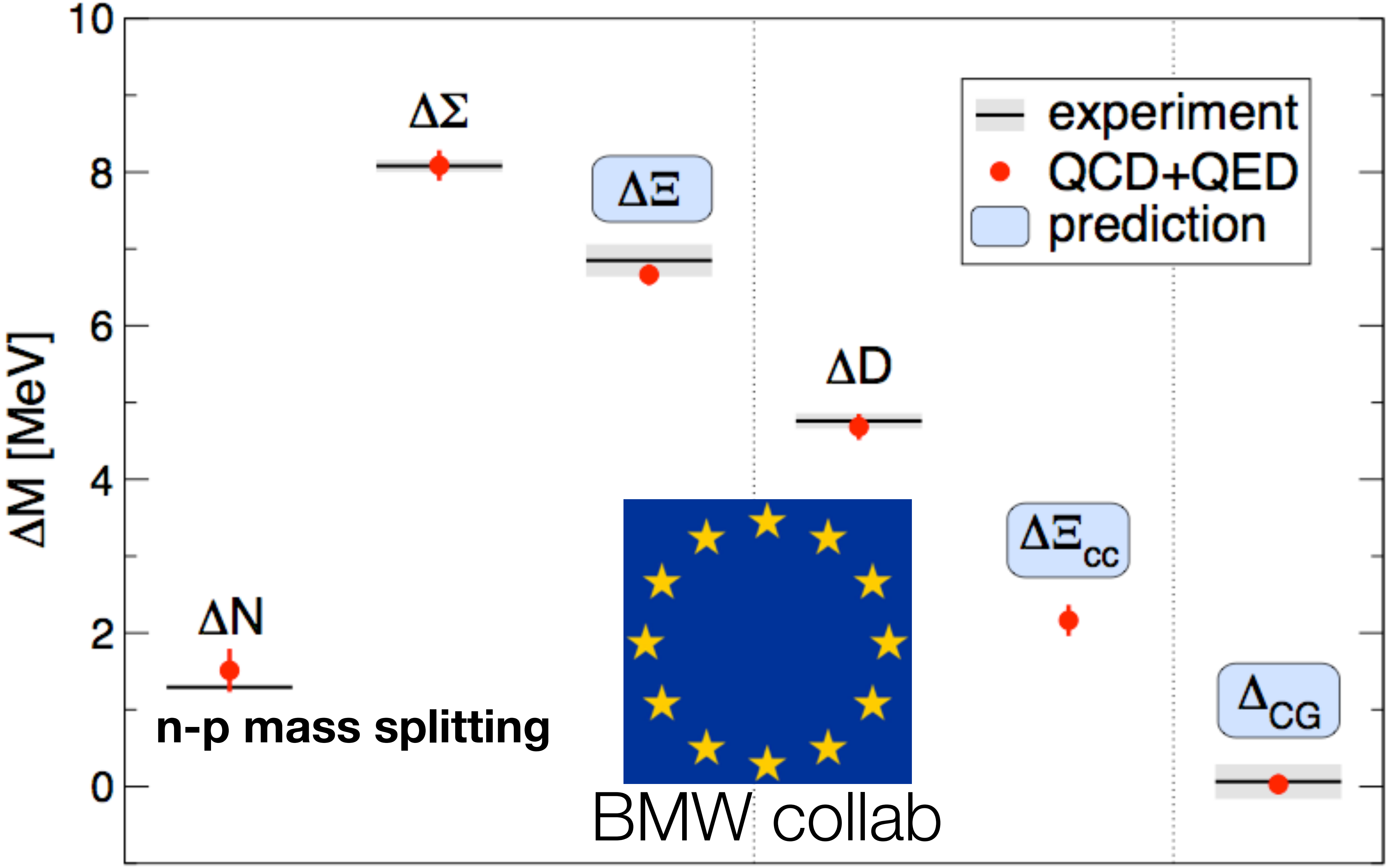
SciDAC
Scientific Discovery through Advanced Computing





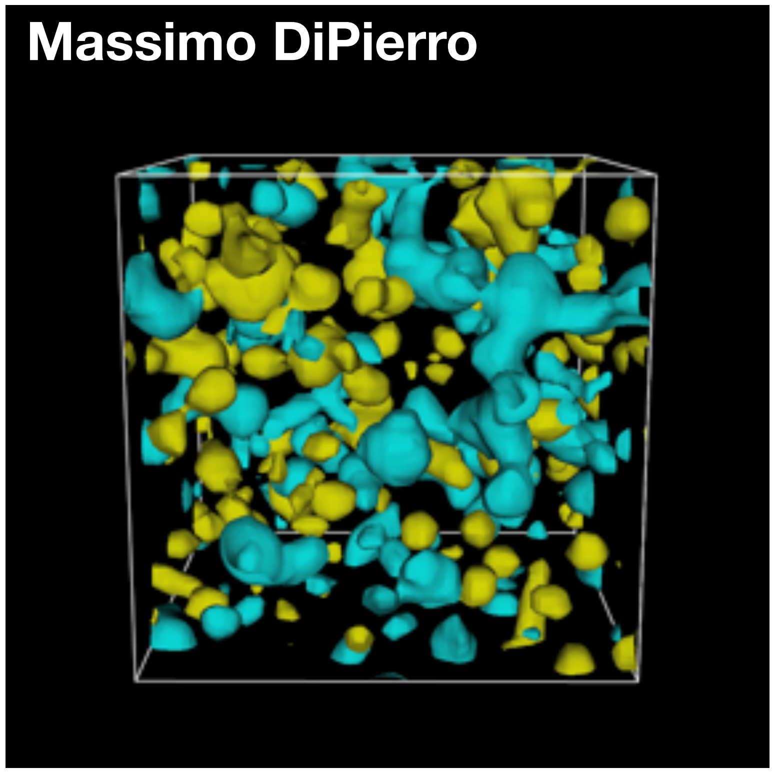
State-of-the-Art Lattice QCD





- Physical up, down, strange and charm quark masses
- Fully dynamical QCD+QED

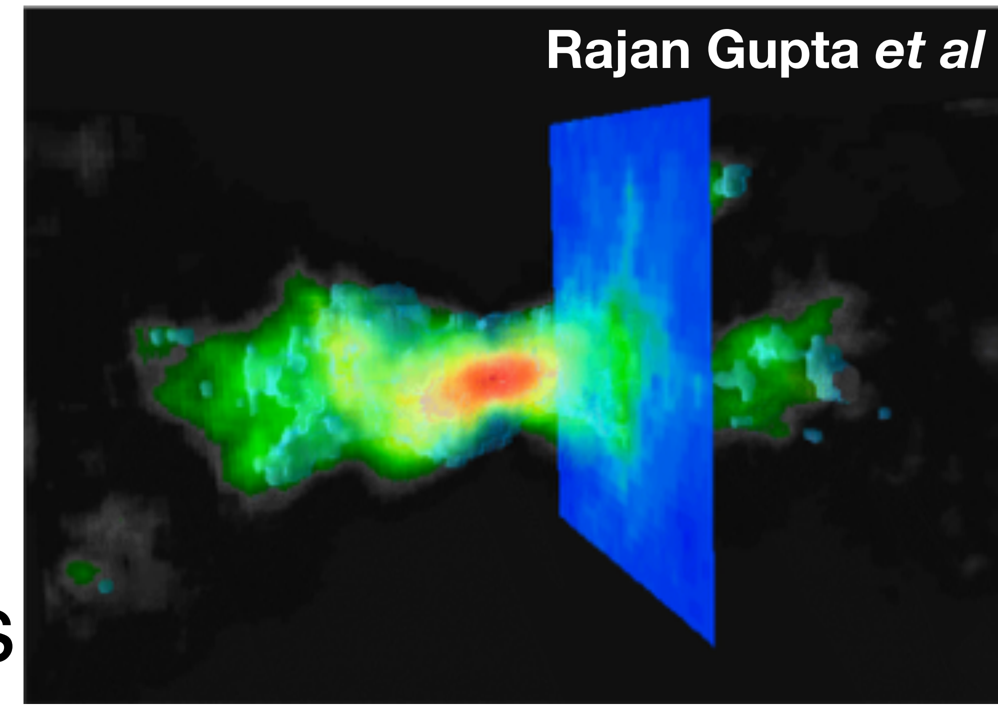
Gluons and Quarks

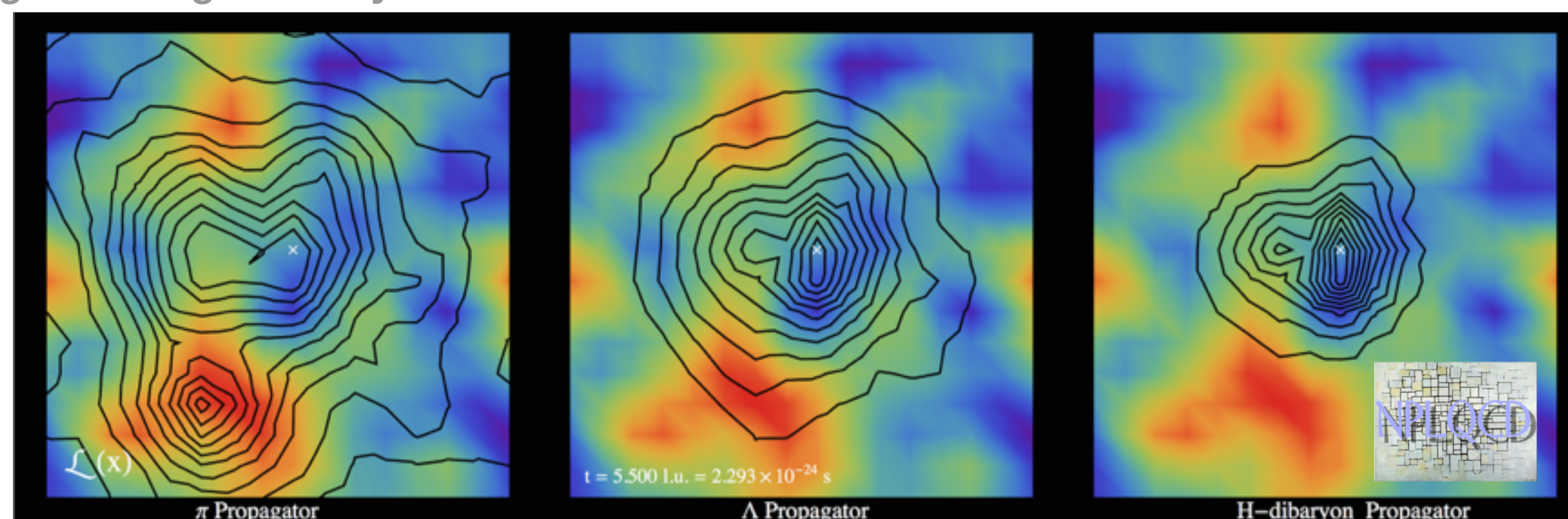


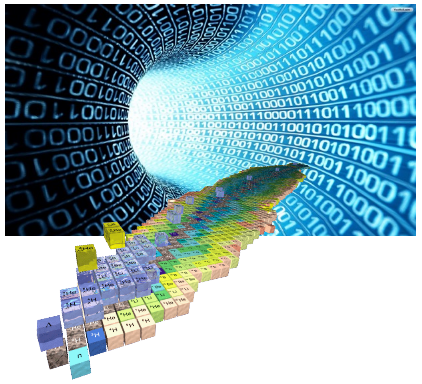
Topological Charge Density

Gluons

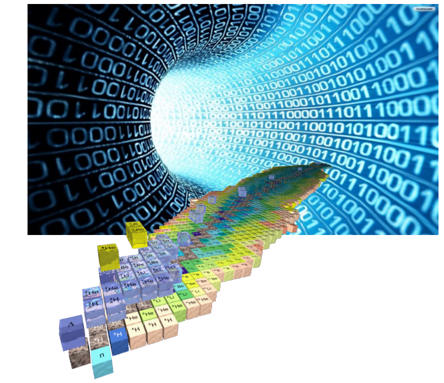
Quarks







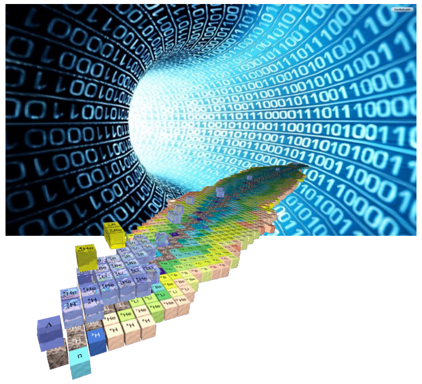
Sampling the Gluon Quantum Fluctuations and Designing Gauge Field Configurations



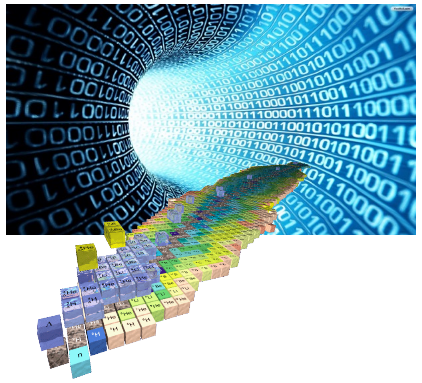
- Prior to WM/JLab/NPLQCD Clover program(s) lattices designed for particle physics (mesons)
  - spatial and temporal directions to small for nucleons
  - Domain-Wall on Staggered - expensive with exceptional - we did this for a while
  - Staggered on staggered - essentially impossible to isolate nucleons and nucleon

- Anisotropic clover
  - JLab program - spectroscopy requires precision short-time behavior
  - nuclear measurements expensive, more correlated in time

- Isotropic Clover
  - cheaper, permits ground states and a few higher
  - NPLQCD designed them for nuclei - longer time directions, larger spatial
  - Produced at pion masses of 800, 450, 300 MeV - proposed 220 and 140 MeV
  - Multiple volumes and lattice spacings
  - Upon request - can possibly be used by others for non-compete projects nucleon structure, parity violation



Isotropic Clover Configurations: Decision to Generate - 2010



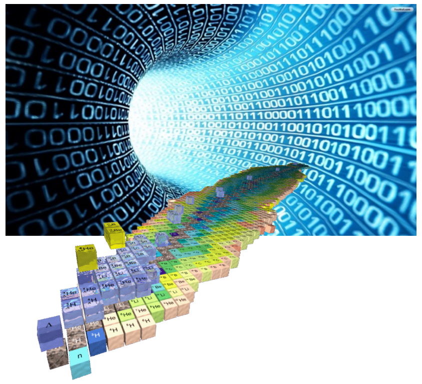
Committing future NPLQCD resources to generate isotropic clover gauge field configurations

isotropic lattices	
From:	William Detmold <wdetmold@wm.edu> Add
To:	"silas@itp.unibe.ch ITP" <silas@itp.unibe.ch>
Cc:	Kostas Orginos <kostas@jlab.org>, Martin Savage <mjs5@u.washington.edu>
Date:	Wed, 22 Dec 2010 00:01:24 -0500

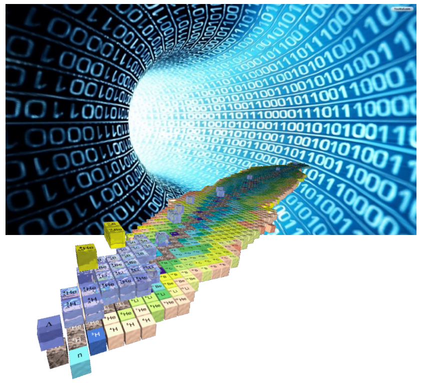
```
Hi Silas,

tomorrow AM, Kostas and I have a meeting with robert et al. We want to be in a position
to make the commitment outlined in my previous email or at least have a reasonable
expectation that there is serious discussion going on about doing so. Martin I believe
is on board with the proposed lattices. Can you send you initial thoughts to us as
quickly as possible?

Cheers,
Will
```

Not an obvious decision at the time - first time generating lattices, but the right decision in hindsight (20/20 vision)

Led to large scale production of SU(3) symmetric point (800 MeV), 450 MeV and 300 MeV (so far) ensembles in multiple volumes and lattice spacings.

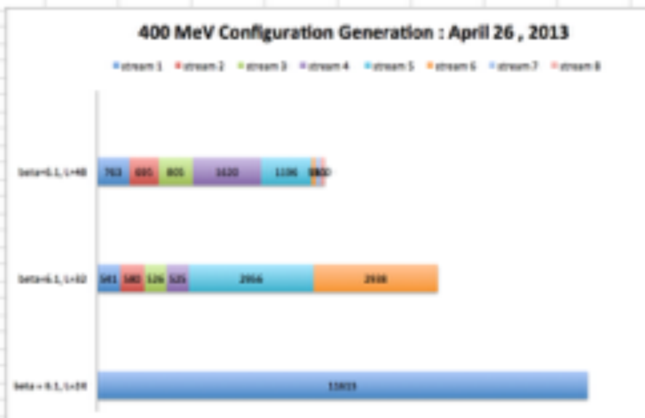


Isotropic Clover Configurations: Production Logistics

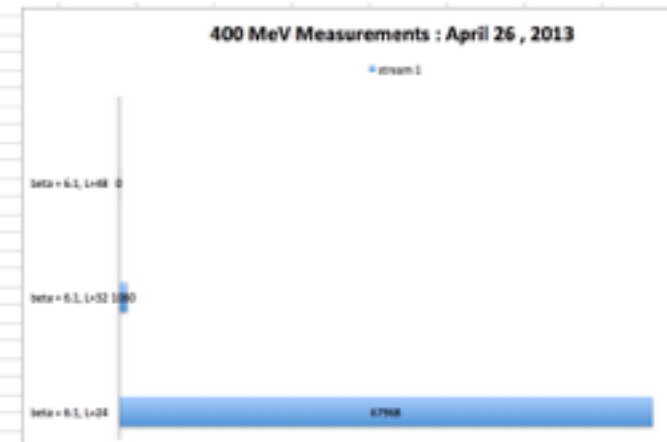


from my production log files

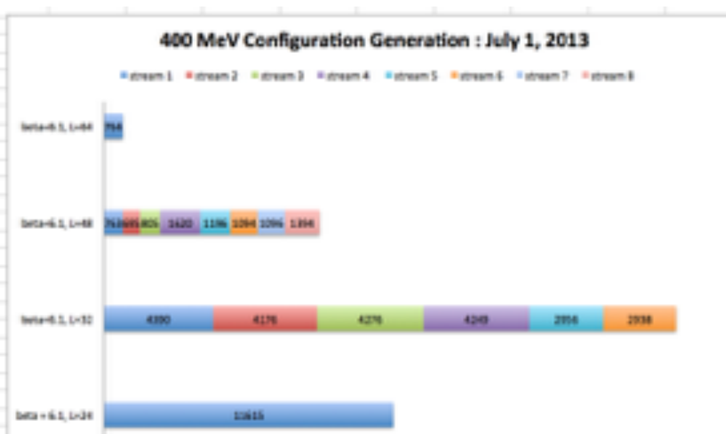
	beta = 6.1, L=24	ENSEMBLE beta=6.1, L=32	beta=6.1, L=48
tream 1	11615	541	763
tream 2		580	695
tream 3		526	805
tream 4		525	1620
tream 5		2956	1196
tream 6		2938	99
tream 7			111
tream 8			100
	11615	8066	5389



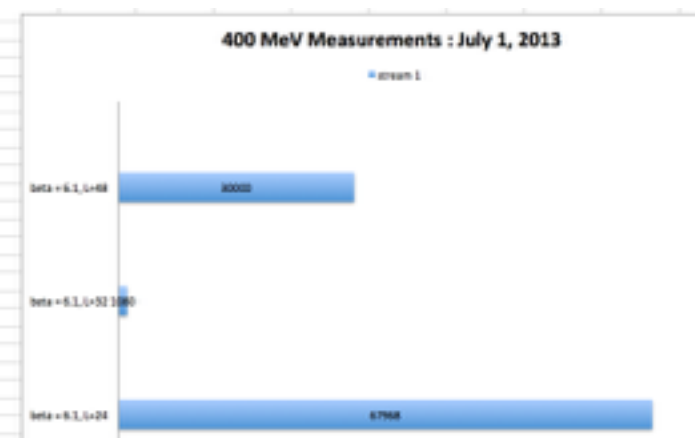
	beta = 6.1, L=24	beta = 6.1, L=32	beta = 6.1, L=48
tream 1	67968	1080	0

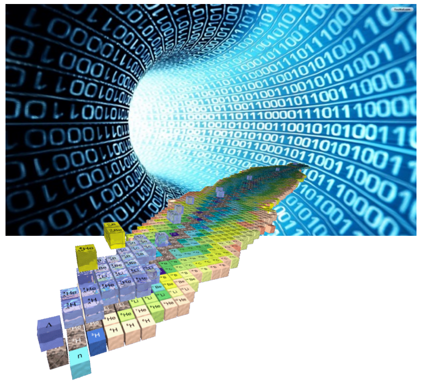


	beta = 6.1, L=24	ENSEMBLE beta=6.1, L=32	beta=6.1, L=48	beta=6.1, L=64
stream 1	11615	4390	763	764
stream 2		4176	695	
stream 3		4276	805	
stream 4		4249	1620	
stream 5		2956	1196	
stream 6		2938	1094	
stream 7			1096	
stream 8			1394	
	11615	22985	8663	764

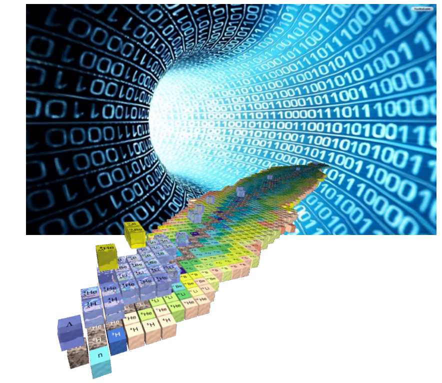


beta = 6.1, L=32	beta = 6.1, L=48
1080	30000





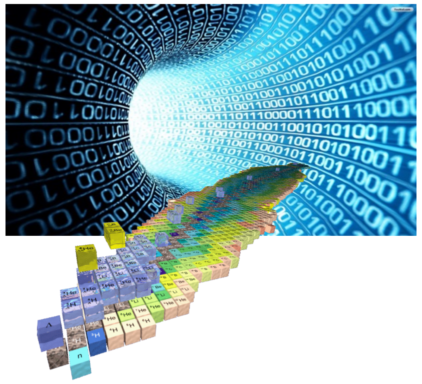
NPLQCD Nuclear Contraction Algorithm (2010-2011)



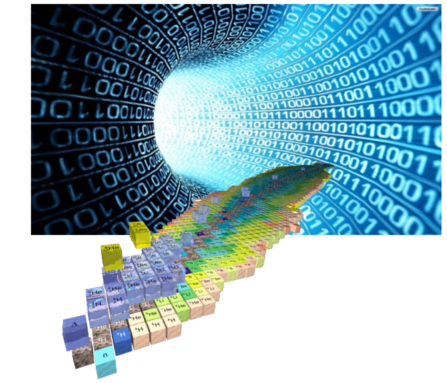
The Detmold and Orginos NPLQCD contraction algorithm in full production during 2011 e.g.

isotropic conclusions	Return to NPLQCD	
From:	mjs5@u.washington.edu Add	
To:	William Detmold <wdetmold@wm.edu>, Kostas Orginos <kostas@jlab.org>, Silas Beane <silas@physics.unh.edu>, andre walker-loud	
Cc:	Martin J. Savage <savage@phys.washington.edu>	
Date:	Sun, 11 Dec 2011 09:41:01 -0800 (PST)	Show Full Headers
Attachments:	Notes_Prelim_Analysis_Dec2011.docx (View | Download)	

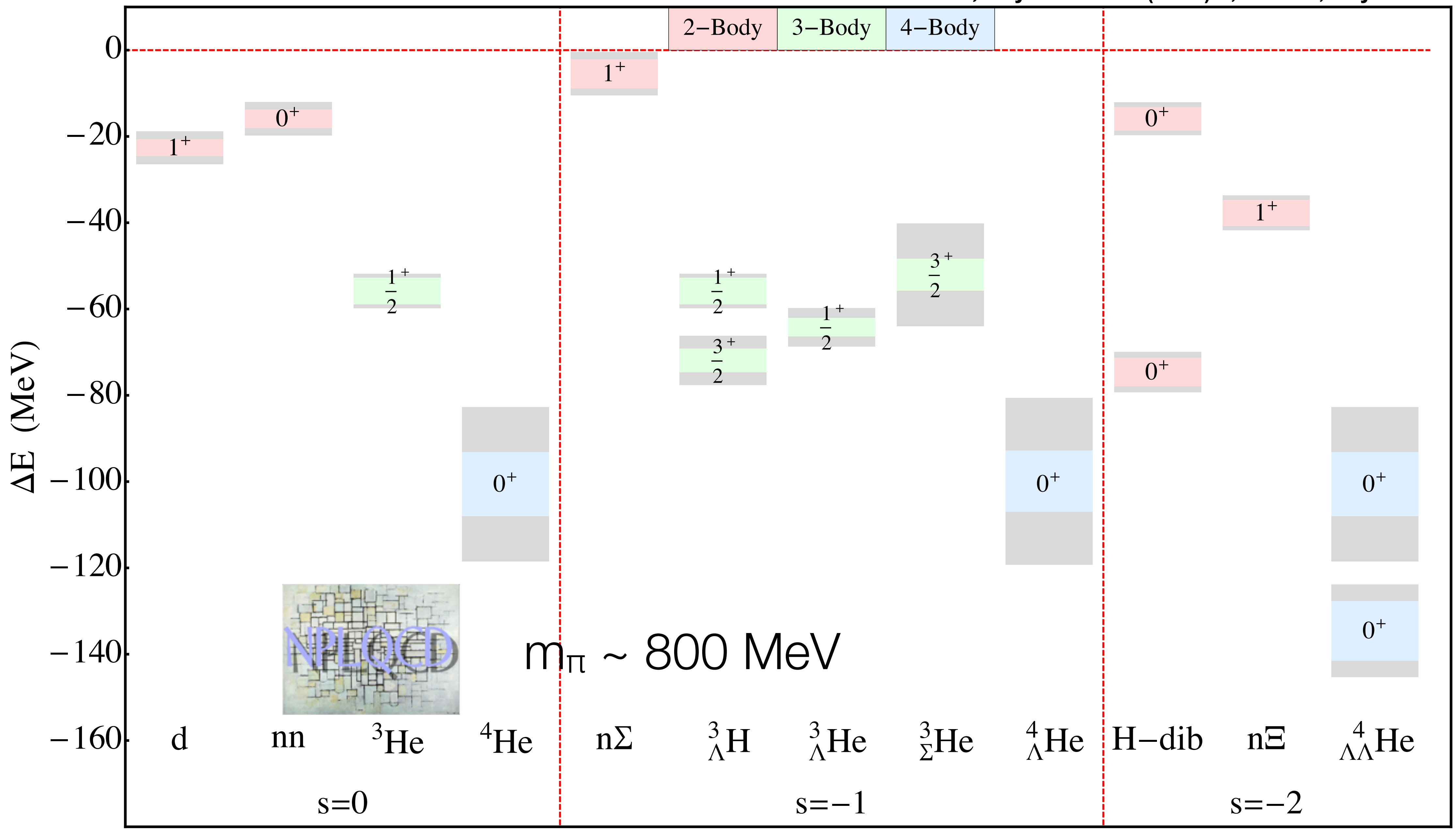
```
Guys,
     I have gone over the isotropic data that I have, using my standard methods (supplemented with some monte-carlo
sampling of coefficients in the linear combination of correlators to maximize the plateaau)
I can get one or two levels cleanly in most cases.

.........

Martin

Martin J Savage
Professor of Physics
University of Washington
```



Nuclei from QCD



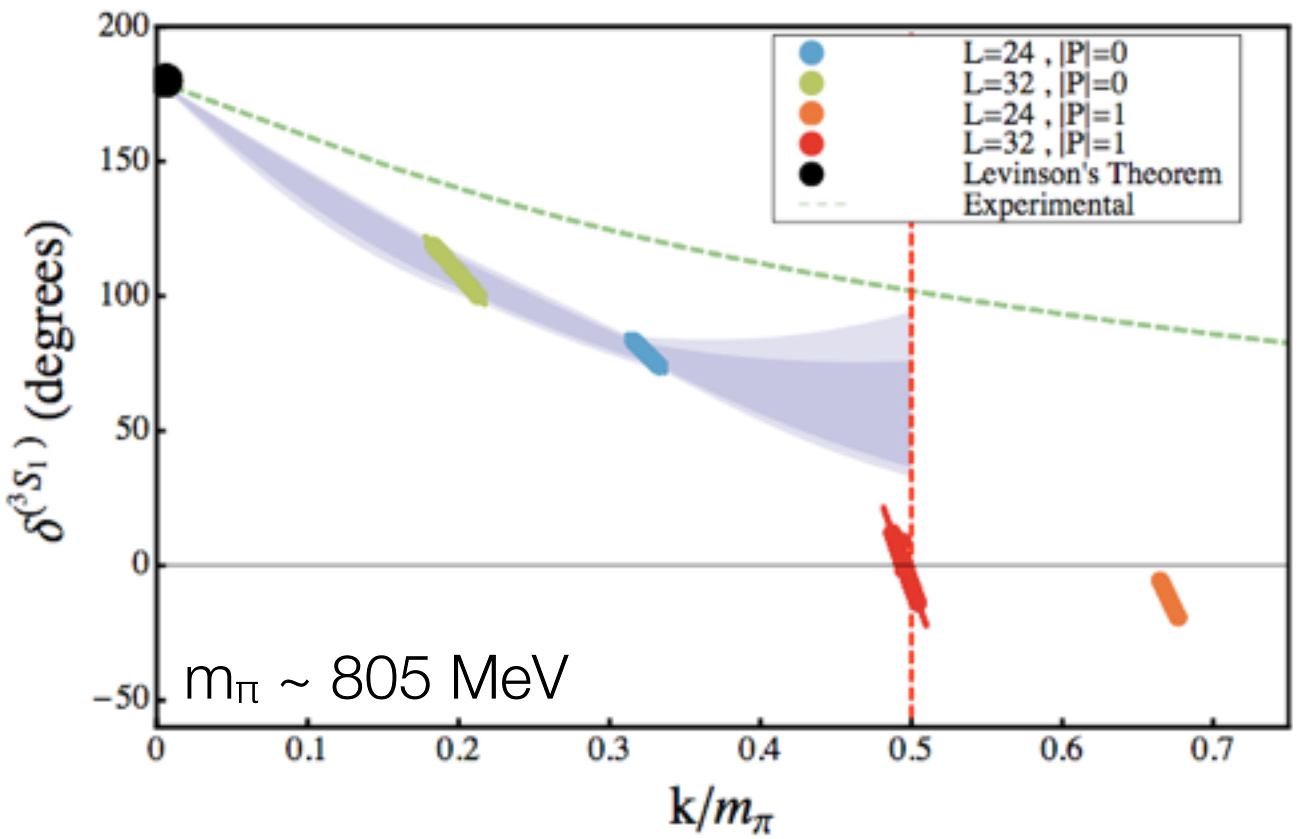
Beane *et al*, Phys.Rev. D87 (2013) 3, 034506, Phys.Rev. C88 (2013) 2, 024003

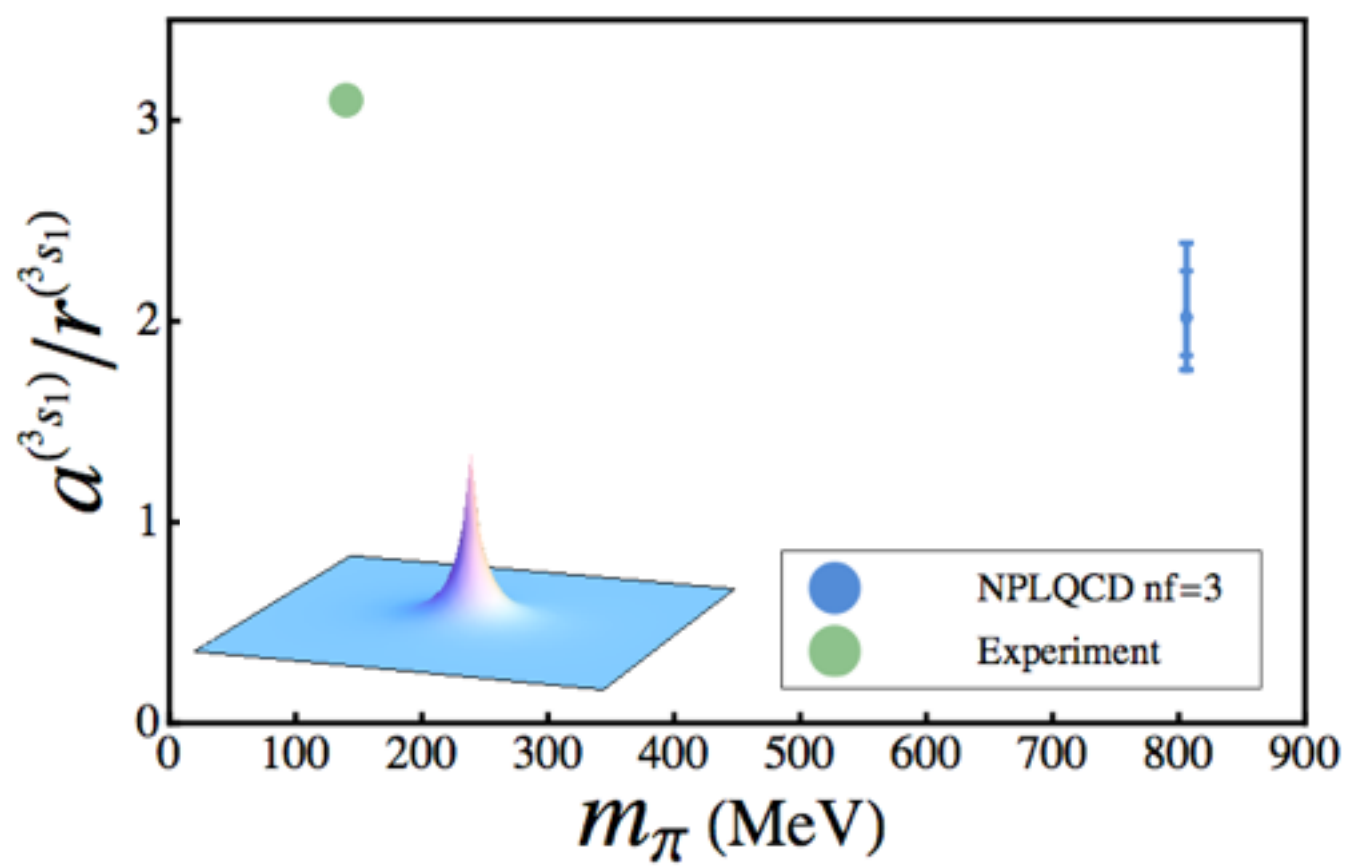


Extensive study of s-shell nuclei and hypernuclei, and baryon-baryon interactions at SU(3) symmetric point

NN Scattering

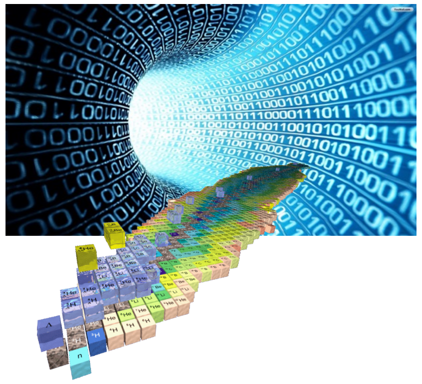
Beane *et al,* Phys.Rev. D87 (2013) 3, 034506, Phys.Rev. C88 (2013) 2, 024003



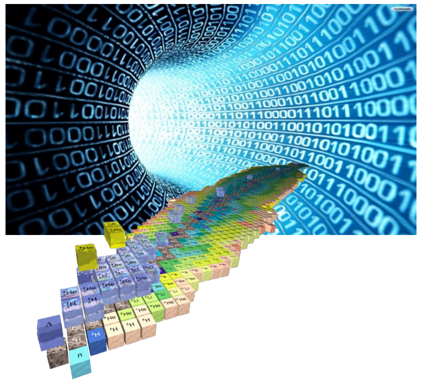


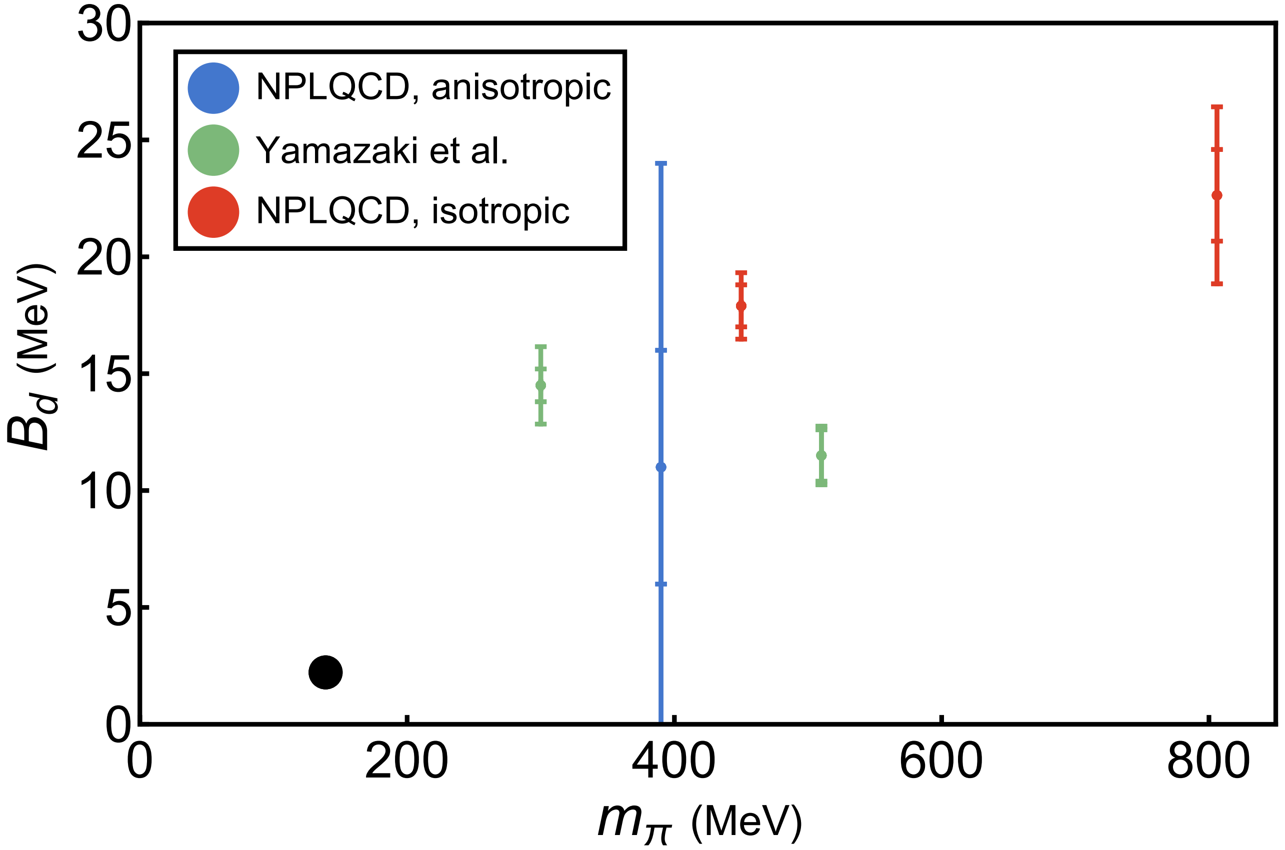
Deuteron appears to be unnatural but not finely-tuned ??

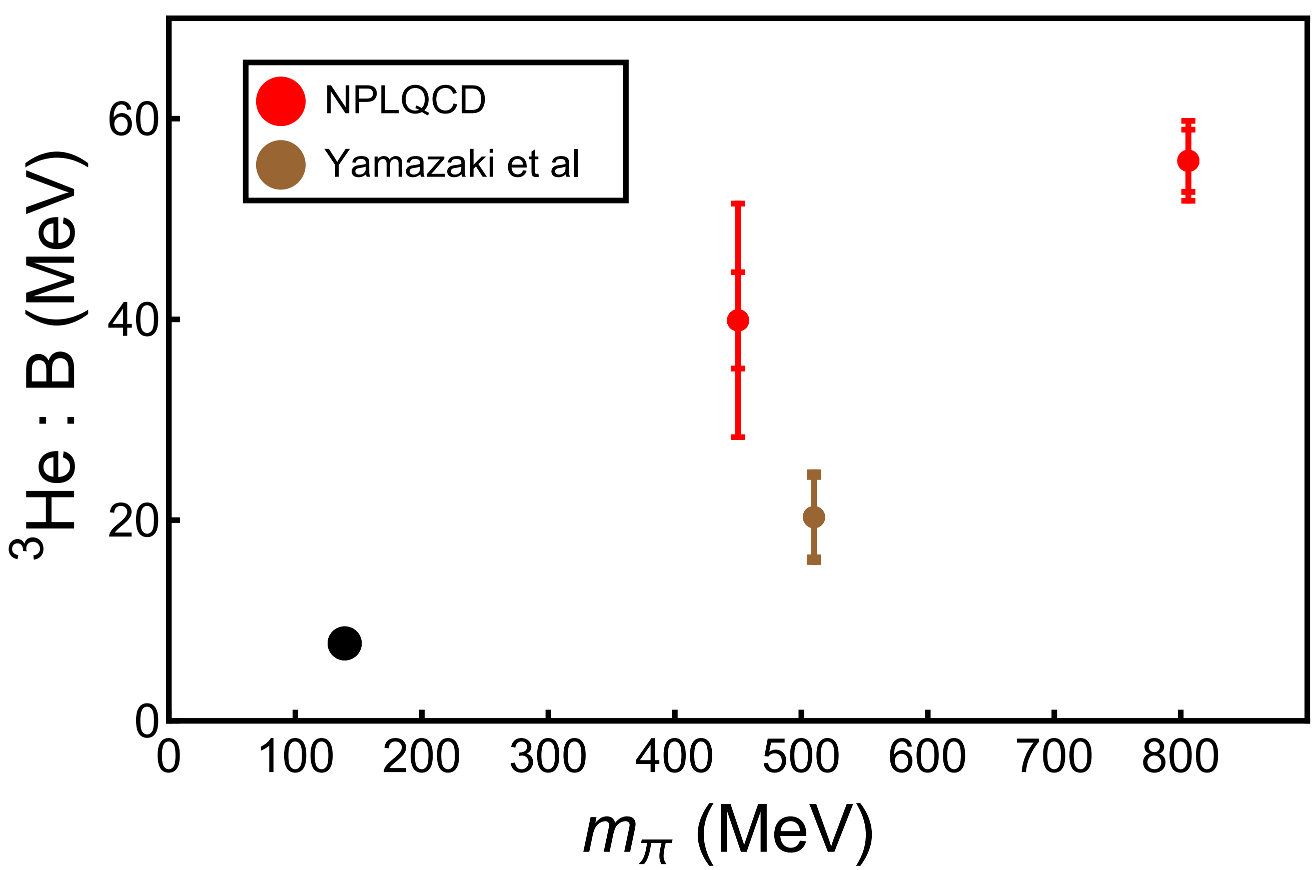
Generic feature of YM with n_f=3

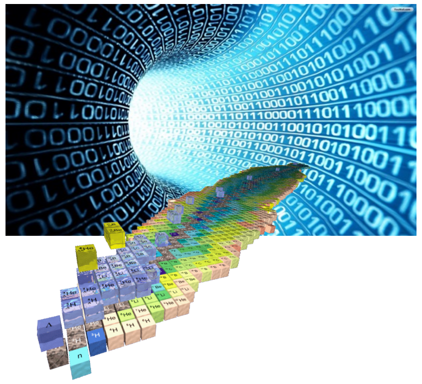


Light Nuclei : Quark Mass Effects

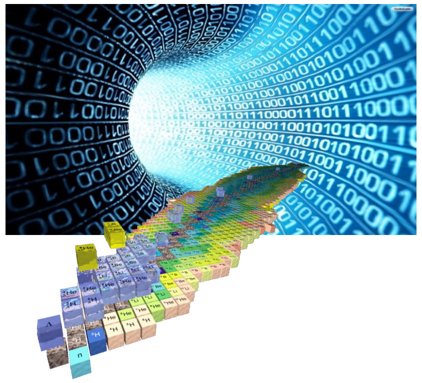




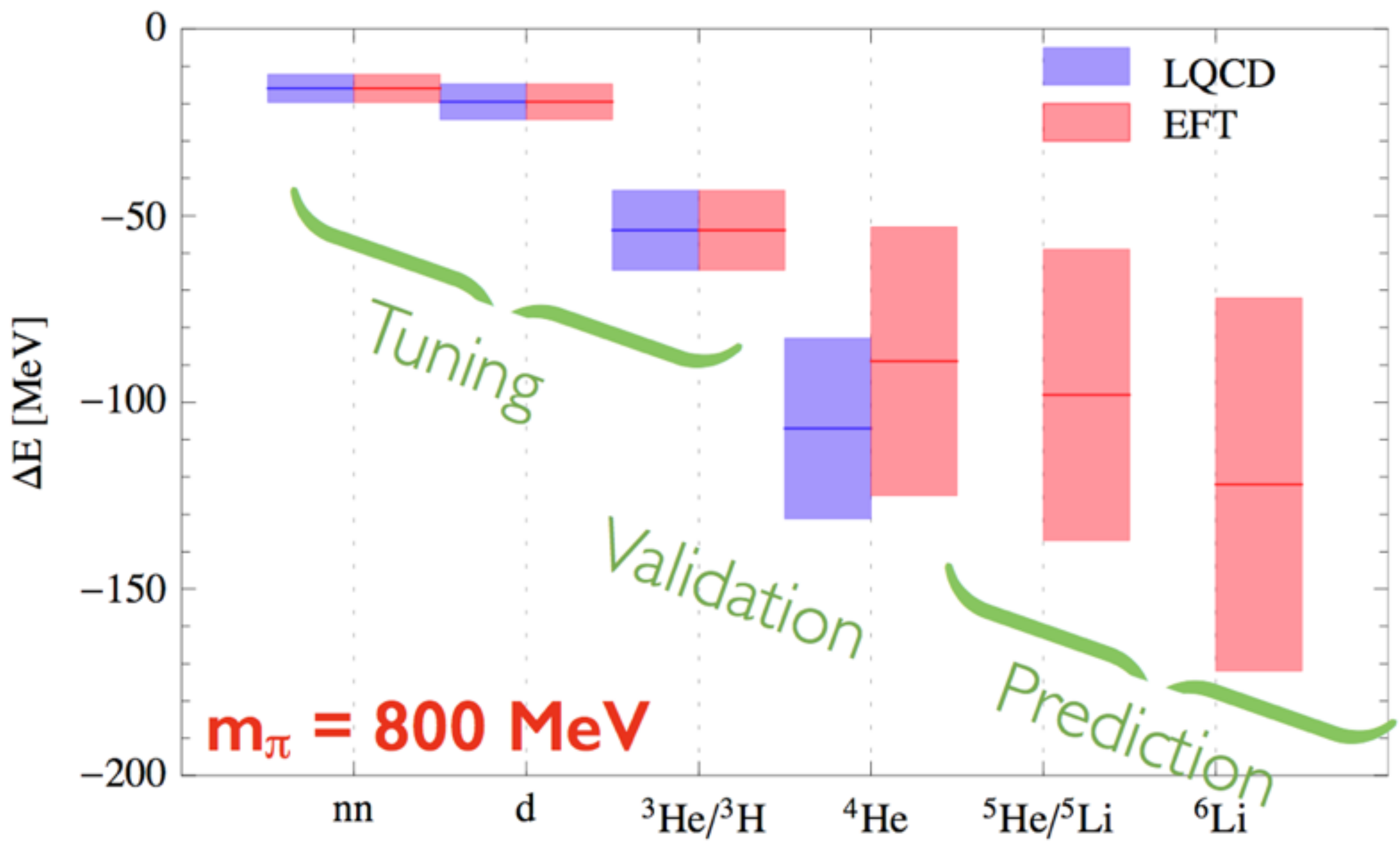


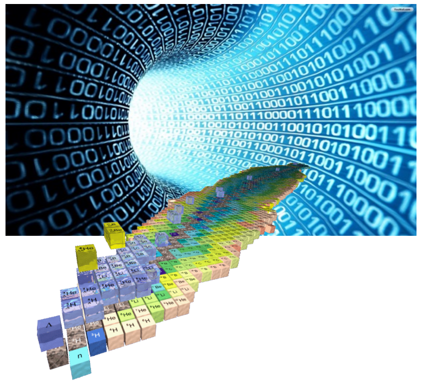


The Periodic Table as a function of the quark masses

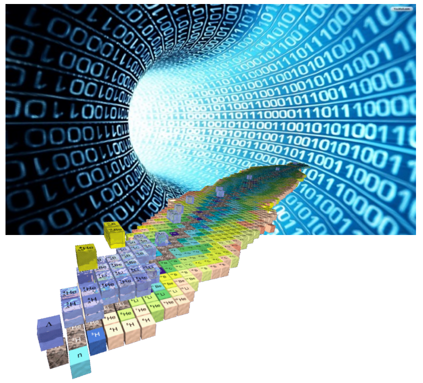


(Barnea *et al.*, Phys.Rev.Lett. 114 (2015) 5, 052501)

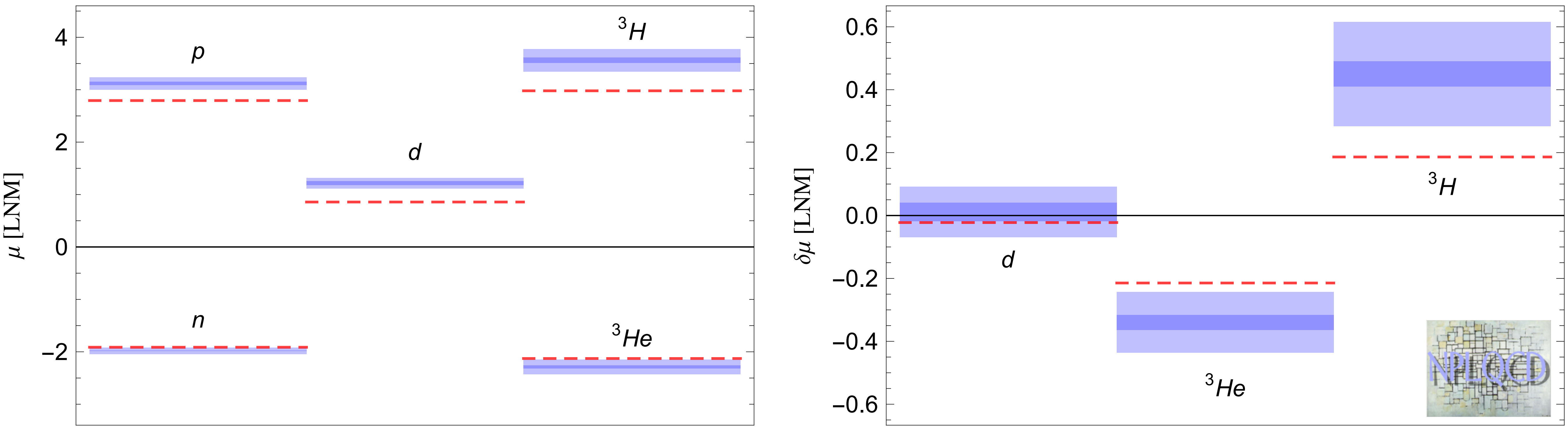


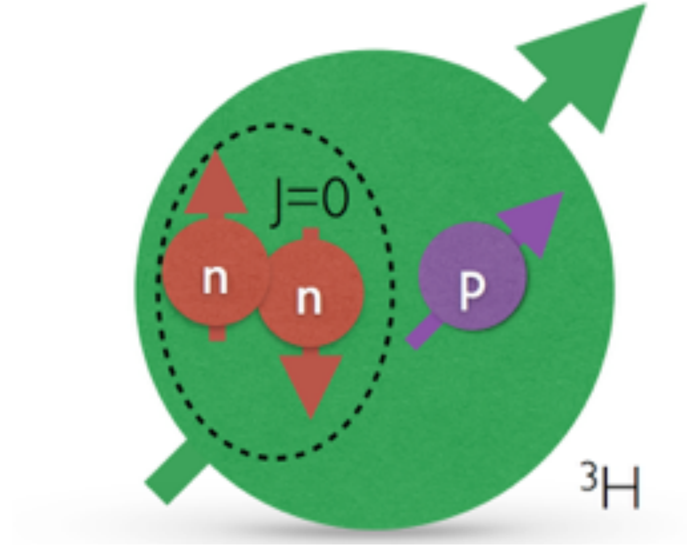


The Magnetic Structure of Nuclei : Magnetic Moments



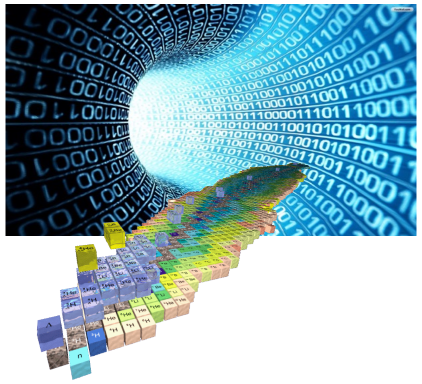
S.R. Beane *et al.*, Phys.Rev.Lett. 113 (2014) 25, 252001



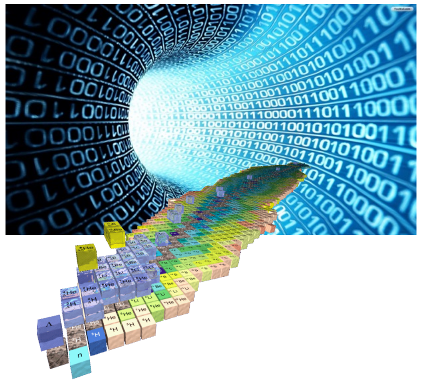


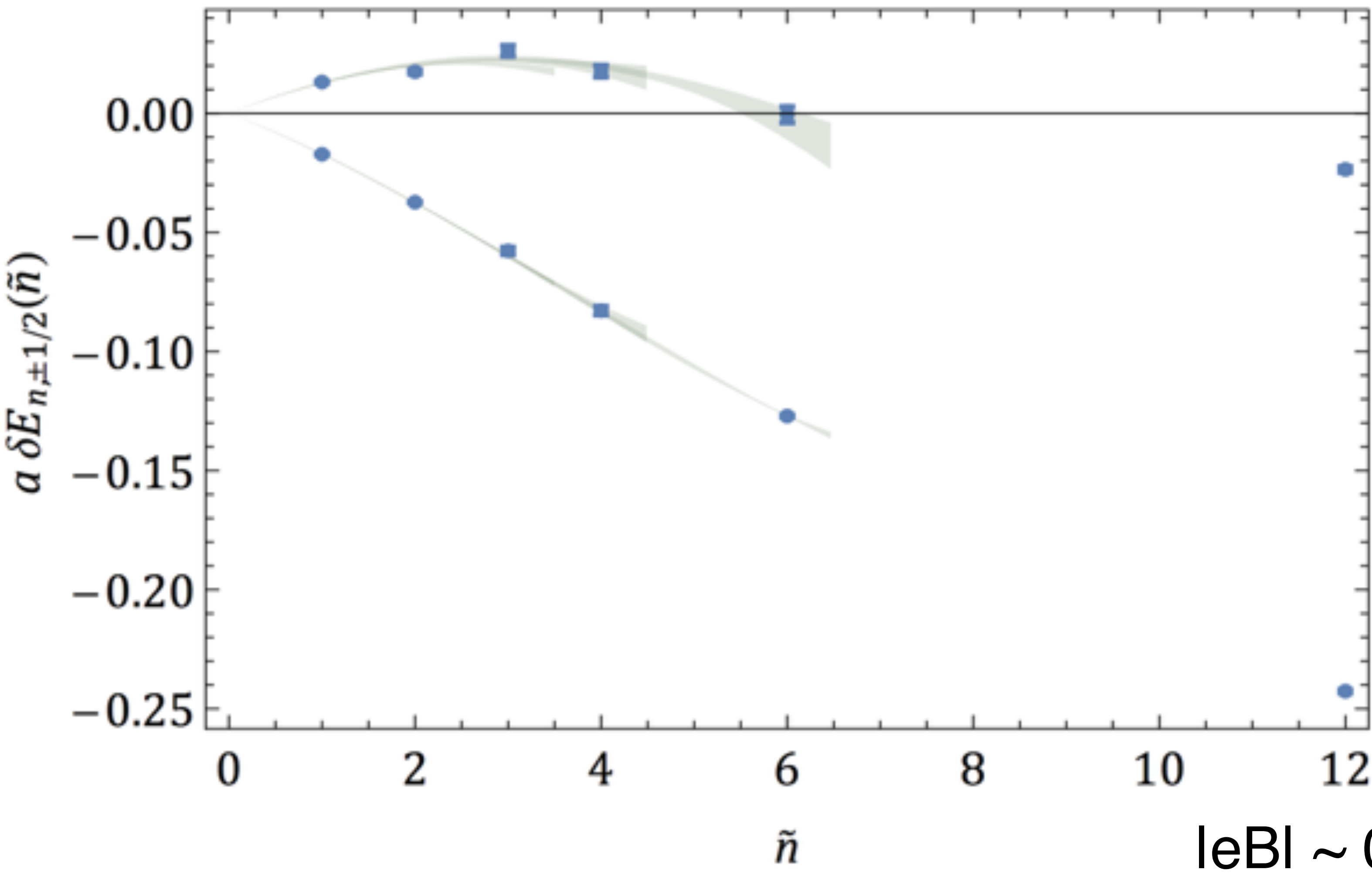
m_π ~ 800 MeV Vs Nature

Nuclei are (nearly) collections of nucleons
- shell model phenomenology!



Magnetic Moments
Neutron Spin States



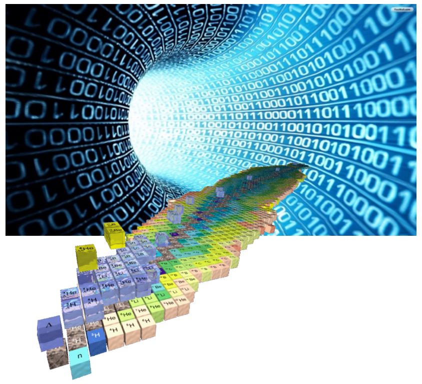


400 MeV

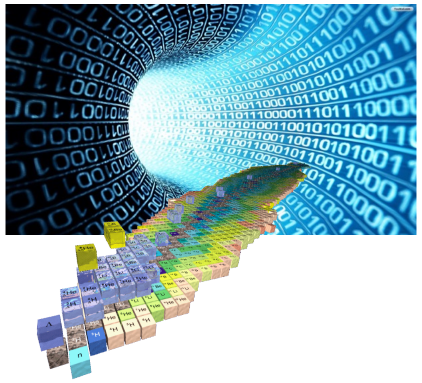
|eB| ~ 0.7 GeV²

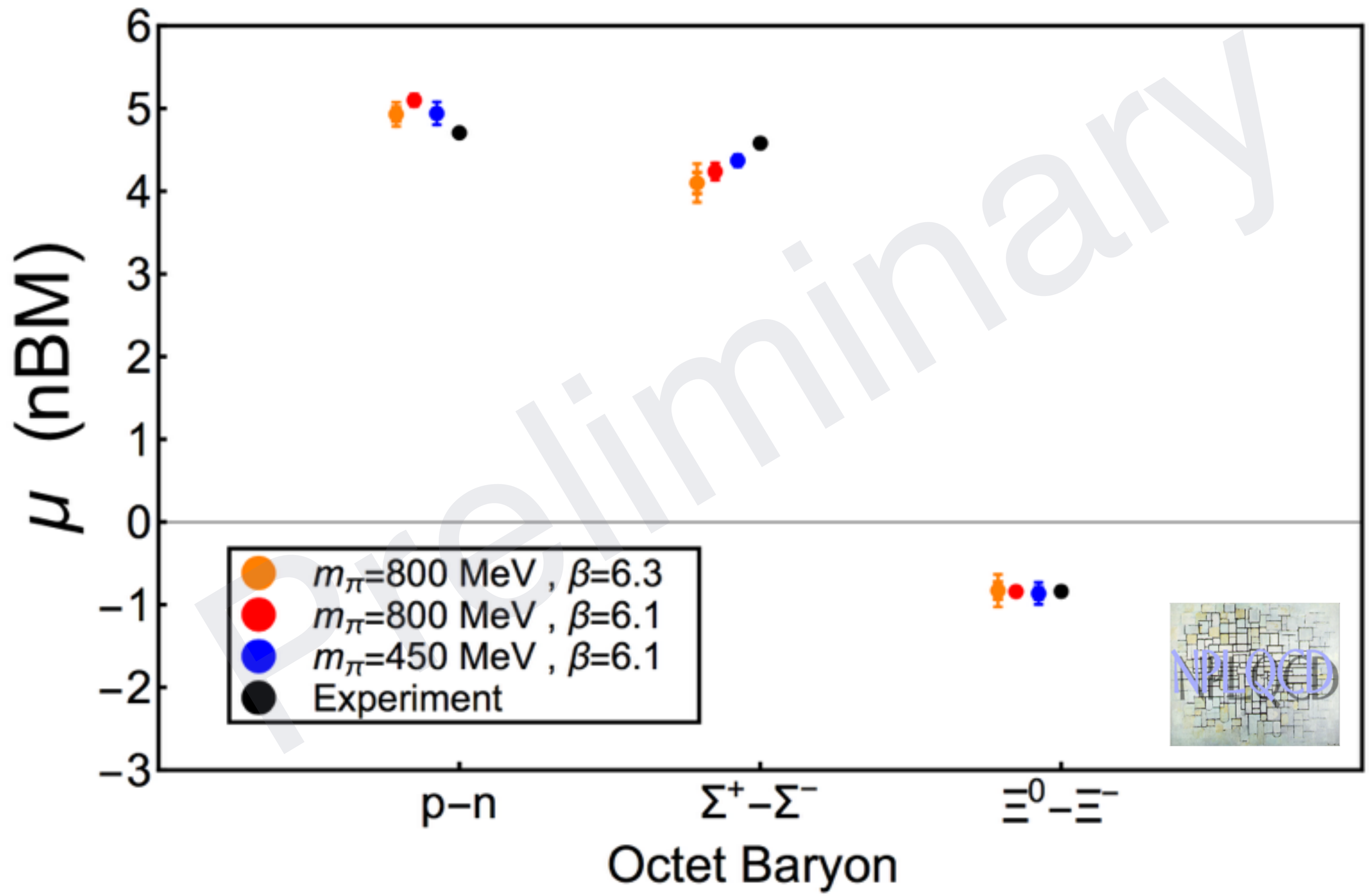
~ 10^{20} Gauss

- Lower state depends essentially linearly on B
- Polarizability results from upper level (essentially)
- Spin-dependences highly correlated



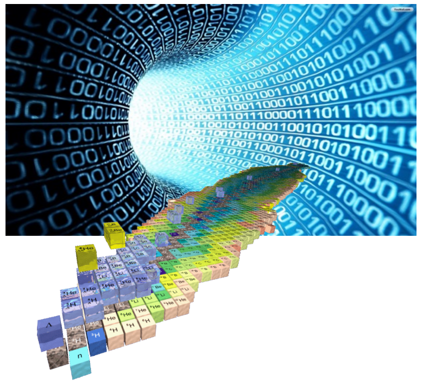
Magnetic Moments





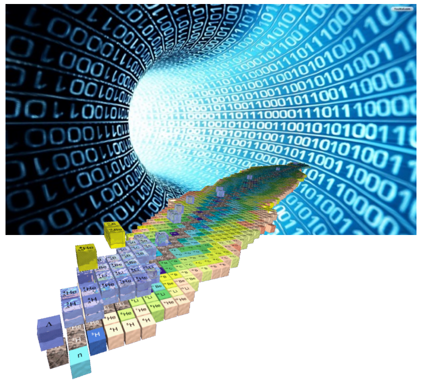
$$\frac{e}{2M(m_\pi)}$$

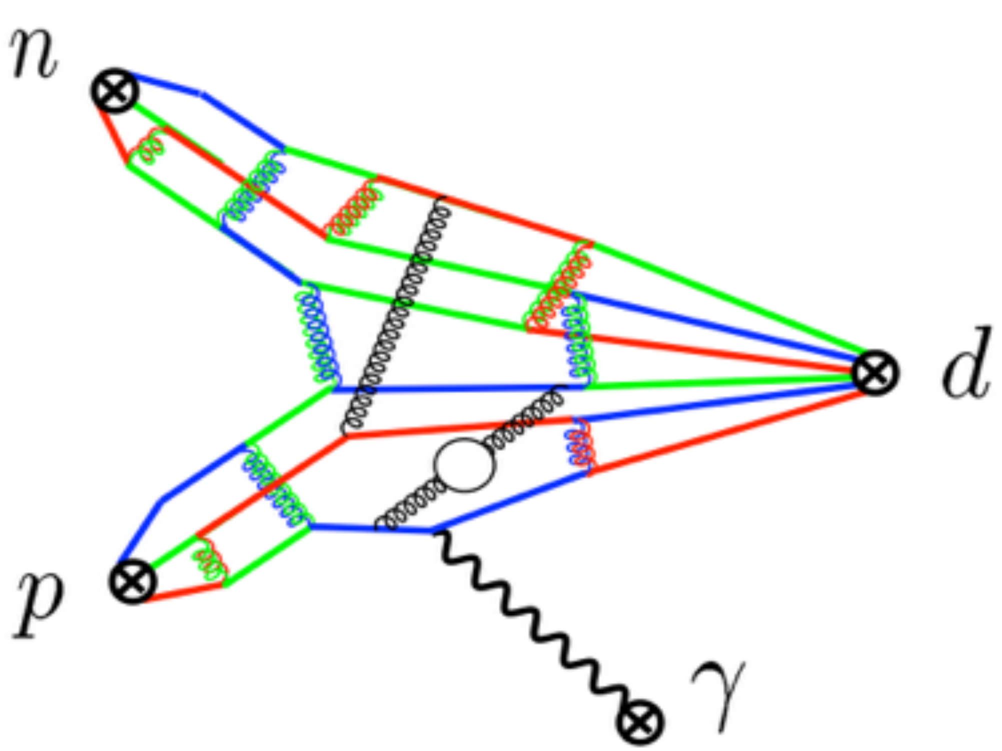
Essentially ALL quark mass dependence of nucleon magnetic moments is due to the nucleon mass

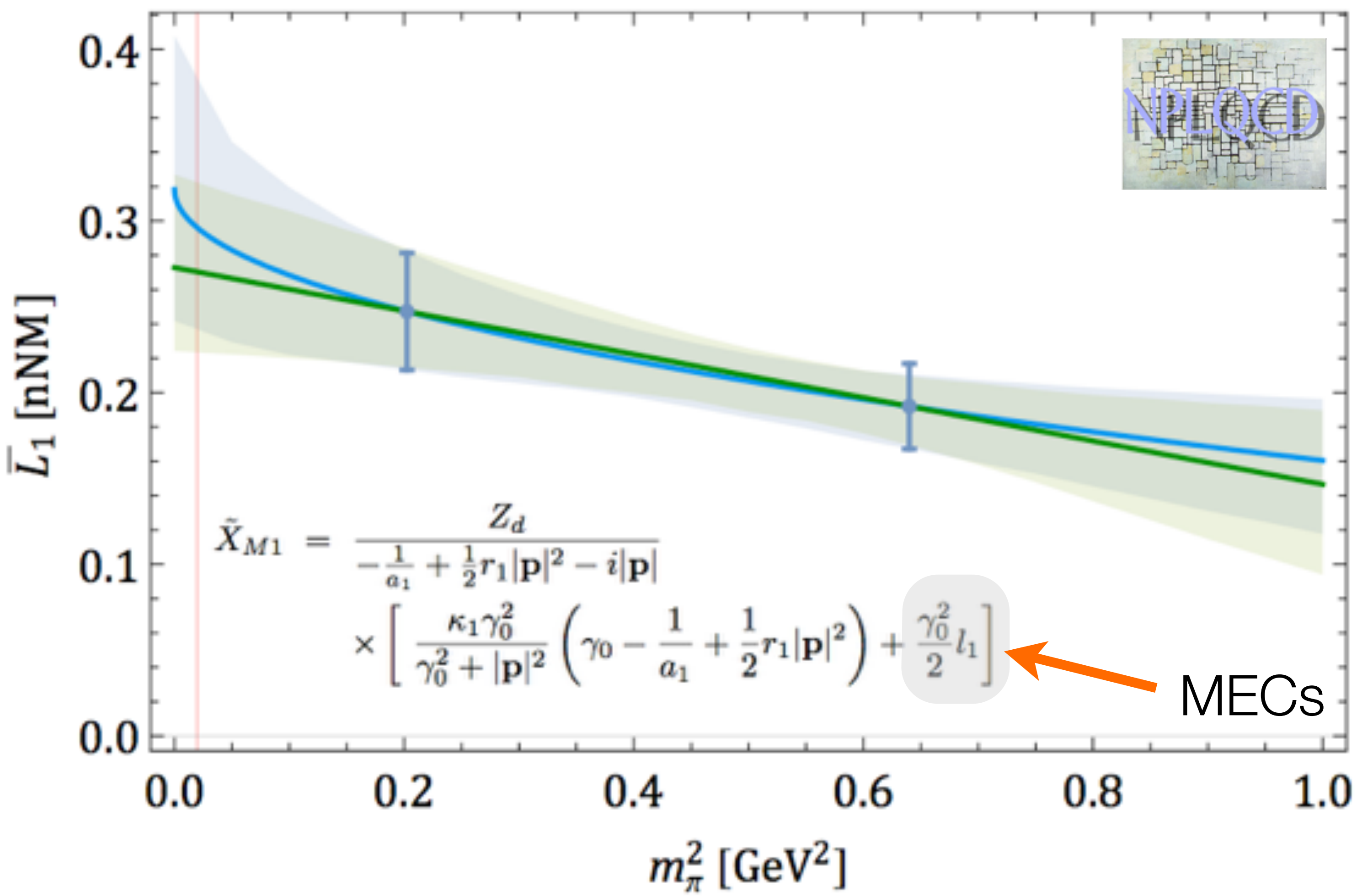


Radiative Capture :

$$np \to d\gamma$$







CIPANP 2000, Quebec City **(nucl-th/0007023)**

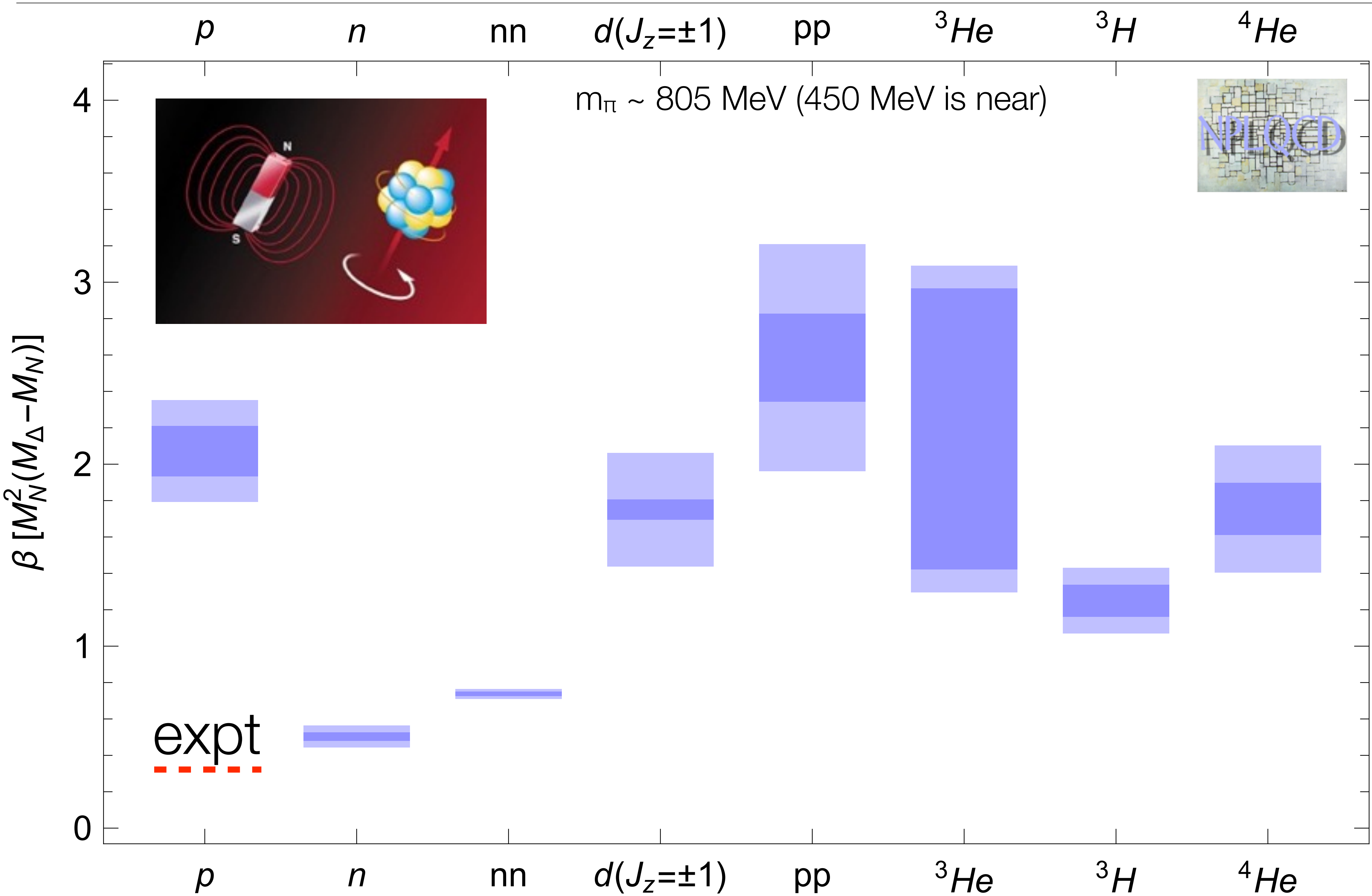
I was pessimistic about LQCD for this process

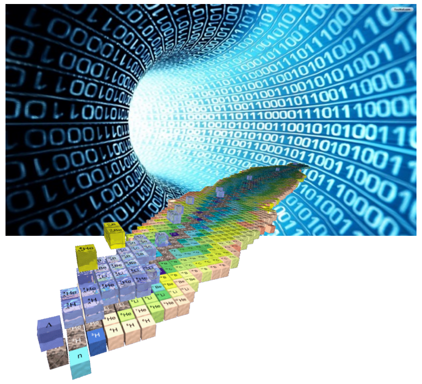
postdiction at the physical point (verification) :

$$\sigma^{\rm lqcd} = 334.9\left({}^{+5.4}_{-4.7} \right)\ {\rm mb} \qquad v = 2,200\ {\rm m/s}$$

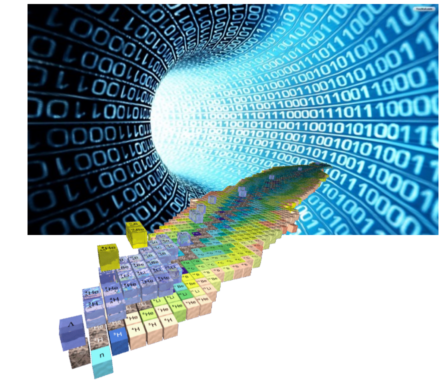
$$\sigma^{\rm expt}(np \to d\gamma) = 334.2(0.5)\ {\rm mb}$$

The Magnetic Structure of Nuclei : Polarizabilities

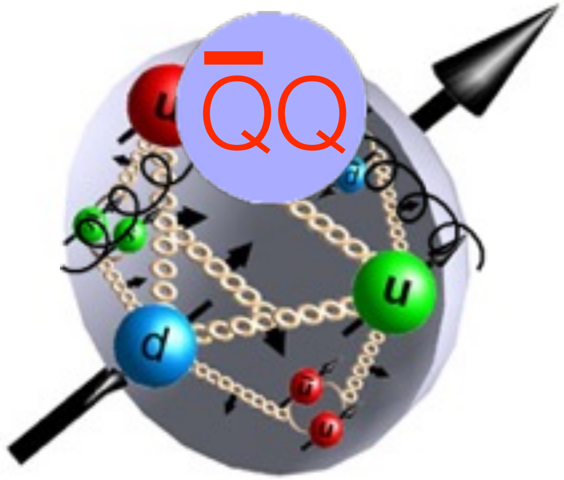


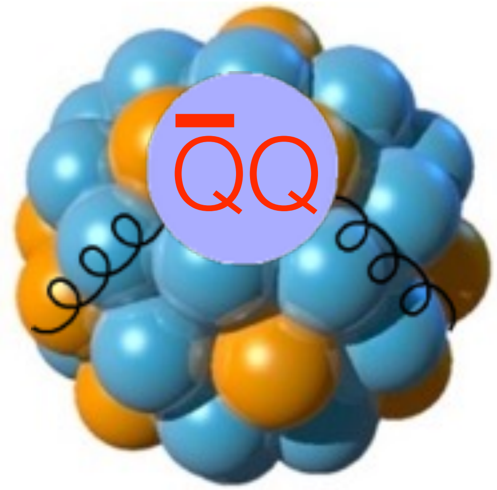


Exotic Nuclei - Quarkonia

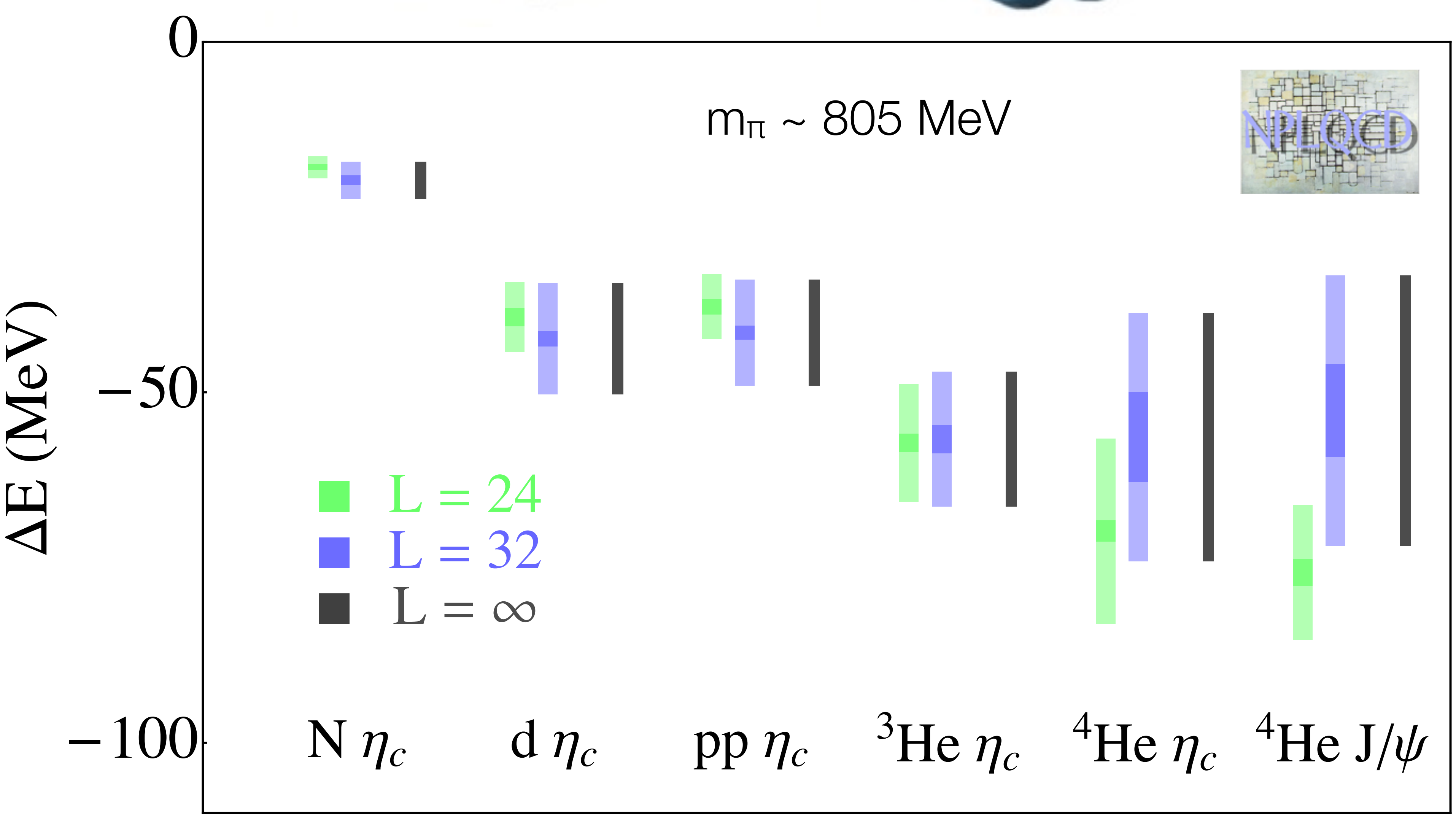


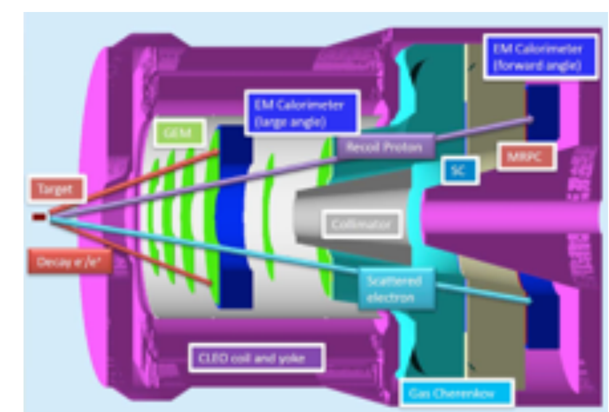
(Beane *et al.*, arXiv:1410.7069)





Gluonic matrix elements - DM - technibaryons?

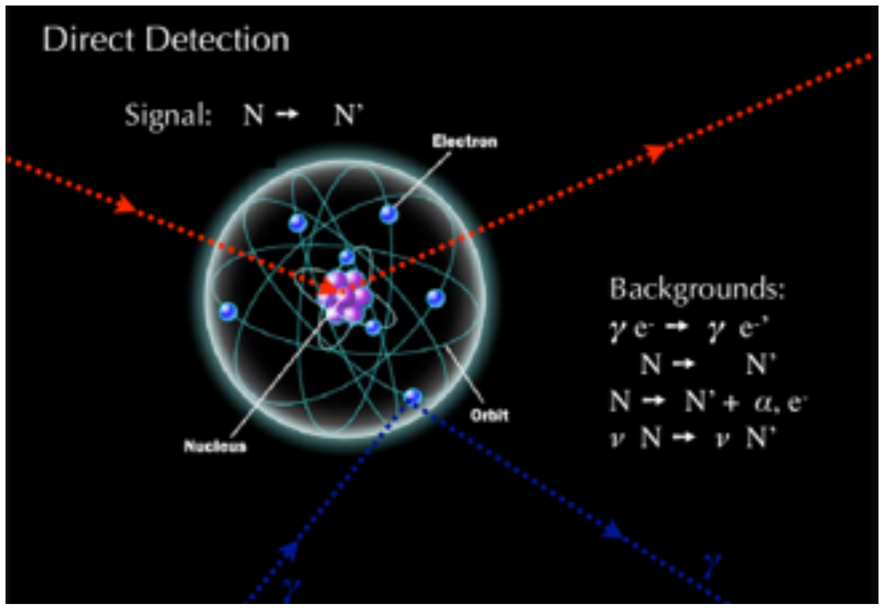




Athenna

Jefferson Lab
EXPLORING THE NATURE OF MATTER

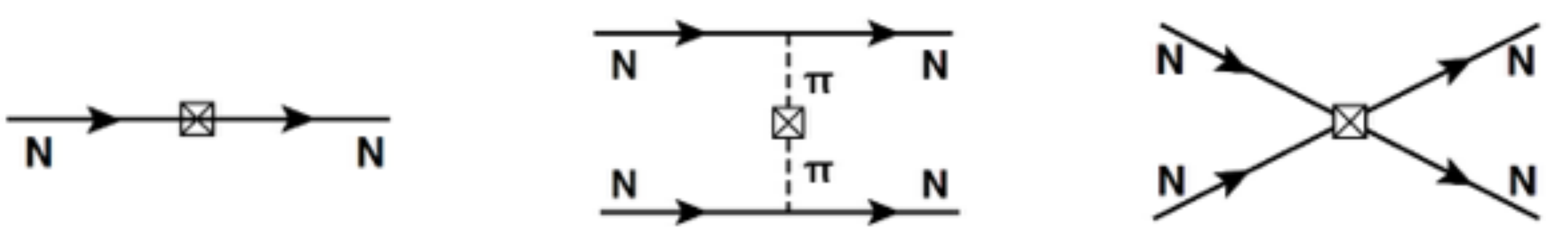
Nuclear σ-Terms and Dark Matter Interactions

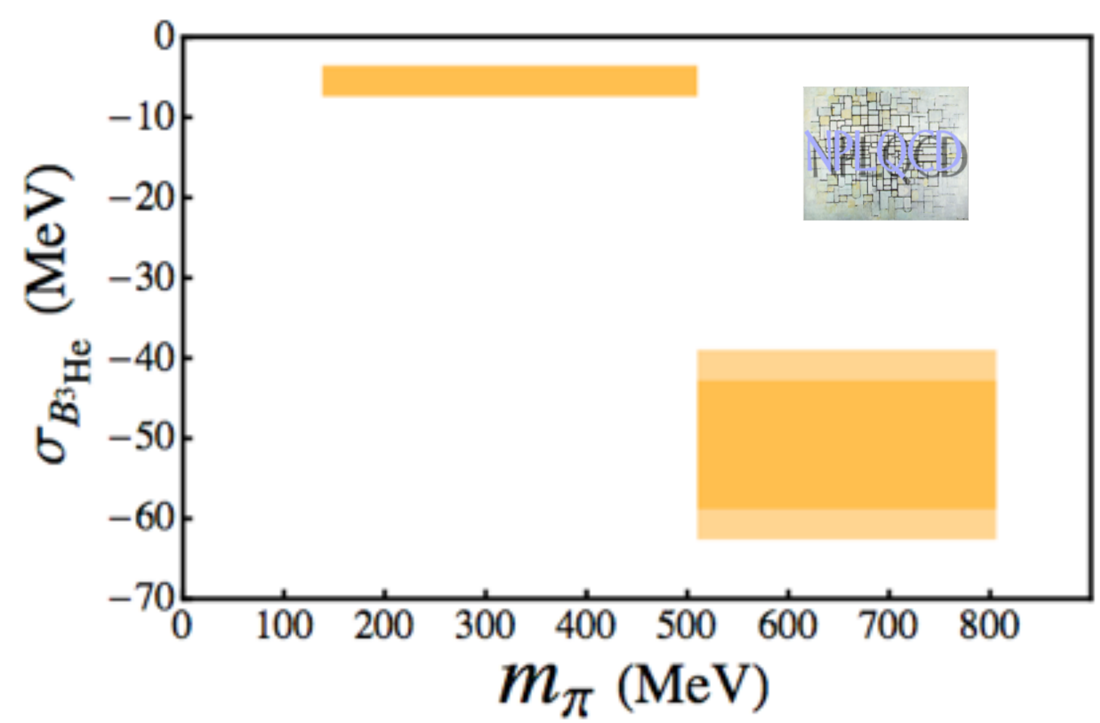


Nuclear σ-terms

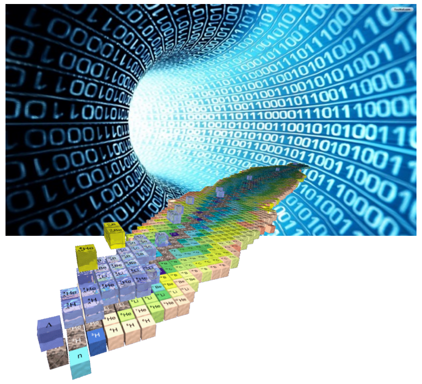
$$\sigma_{Z,N} = \overline{m}\langle Z,N(\mathrm{gs})|\ \overline{u}u+\overline{d}d\ |Z,N(\mathrm{gs})\rangle = \overline{m}\frac{d}{d\overline{m}}E^{(\mathrm{gs})}_{Z,N}$$

$$= \left[\,1\ +\ \mathcal{O}\left(m_\pi^2\right)\,\right]\frac{m_\pi}{2}\frac{d}{dm_\pi}E^{(\mathrm{gs})}_{Z,N}$$



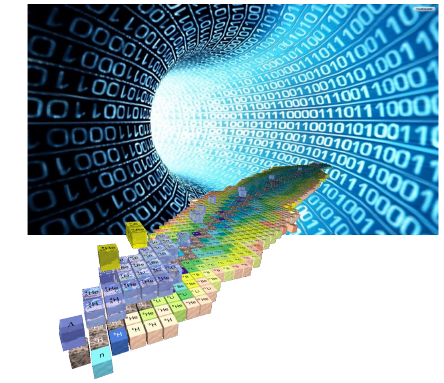


(Beane *et al*, Phys.Rev. D89 (2014) 074505)



Future Computational Needs

Physics Objectives



2007-2014 ...

Structure of the Nucleon

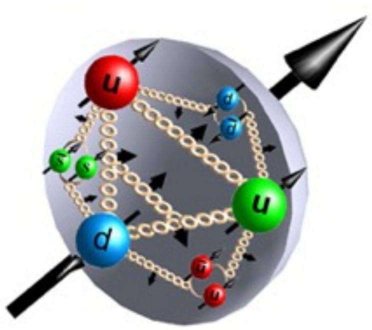
multiple L,T, lattice spacings
multiple discretizations
N predictions for mq(phys)

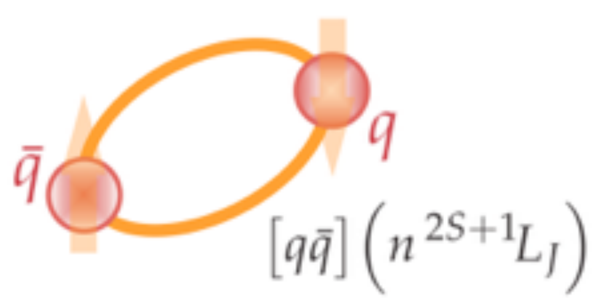
Meson and Baryon Spectroscopy

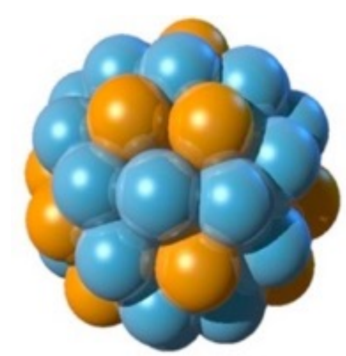
multiple L,T
one lattice spacing
resolved spectrum
mapped out resonances

Nuclei and Nuclear Forces

multiple L,T
one lattice spacing
light (hyper-)nuclei, scattering
simple properties of nuclei

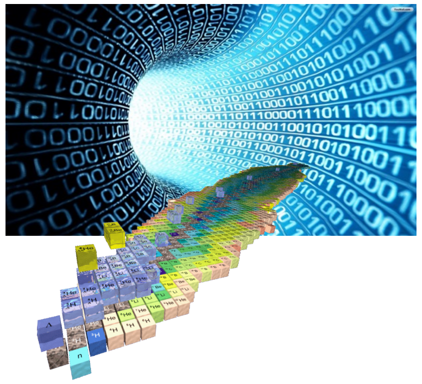






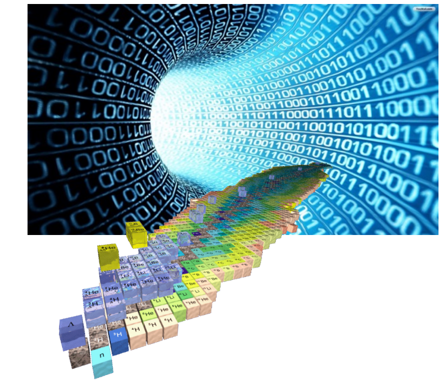
140 MeV | 300 MeV | 800 MeV

Pion Mass

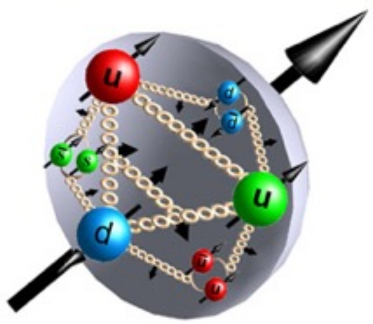


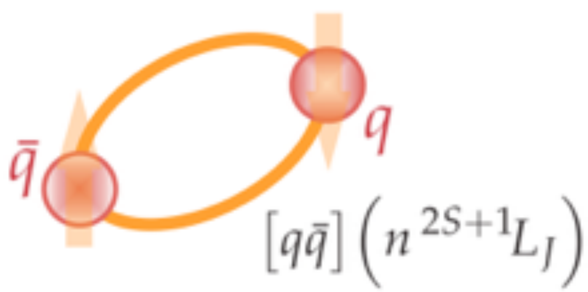
Future Computational Needs

Physics Objectives



In the Exascale Era:

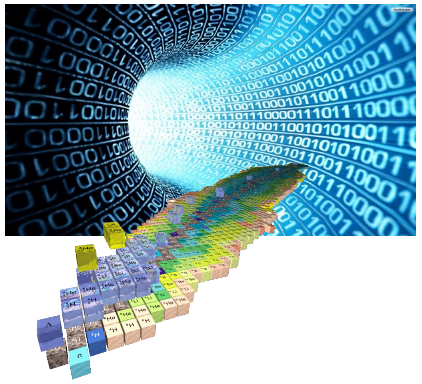




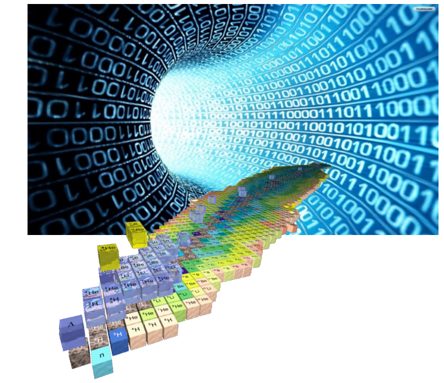
- physical pion mass with $n_f = 1+1+1+1$
- electromagnetism
- precision calculations
- multiple lattices volumes with large T
- multiple lattice spacings
- multiple discretizations
- fully quantified uncertainties
- complement experimental program
- guide future experimental program
- provide critical inputs for theory

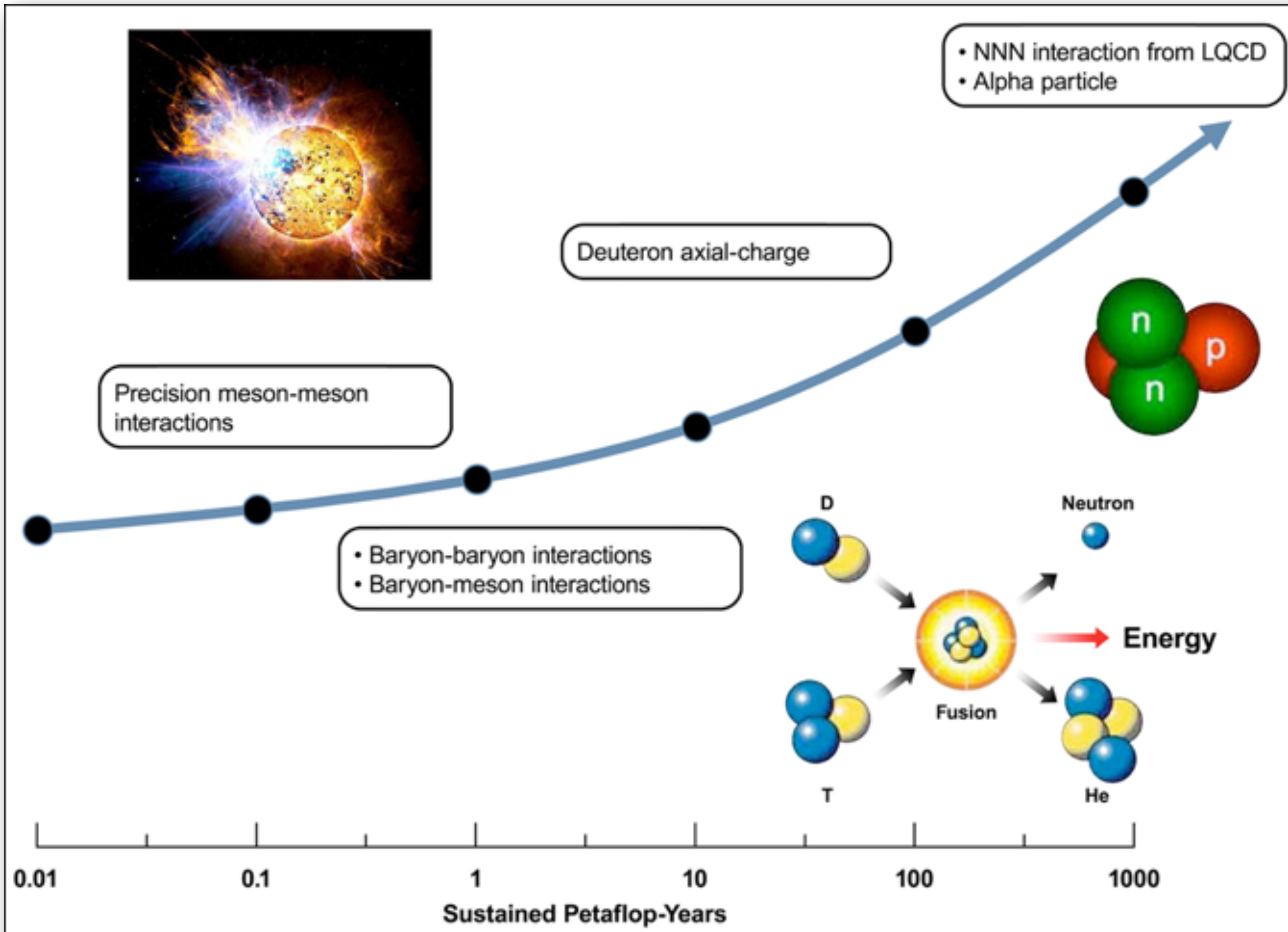
140 MeV   300 MeV   800 MeV

Pion Mass



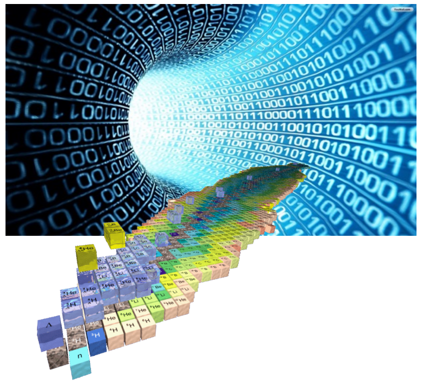
Exascale Resources Required



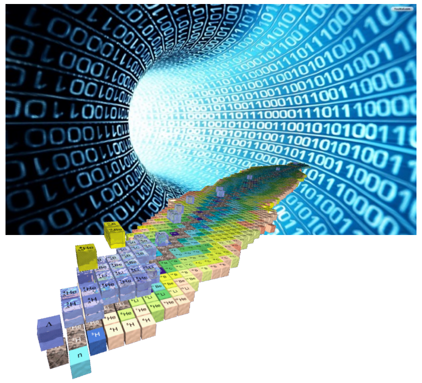


- Physical quark masses
- QED
- Continuum extrapolation
- Volume extrapolations

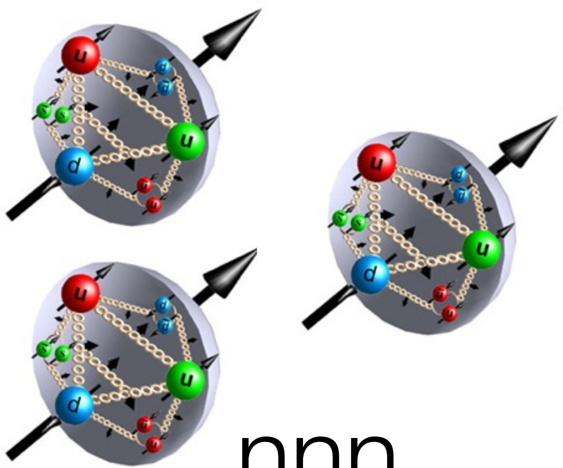
Estimates from 2009 which are in the process of being refined.



Important Things to do Next

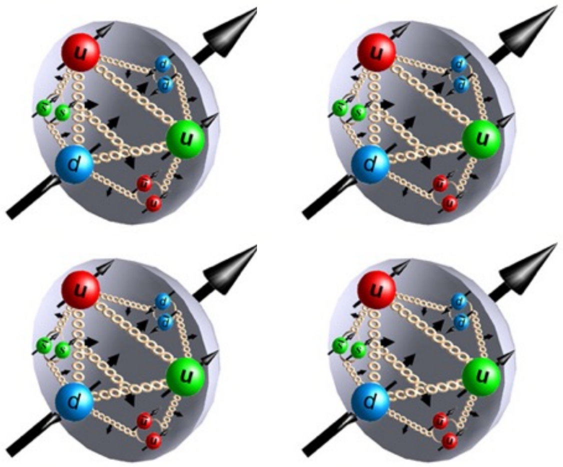


FRIB



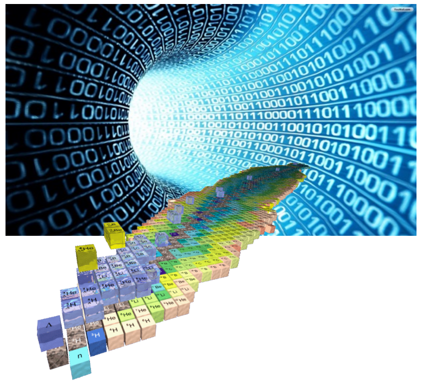
nnn

multi-neutron forces

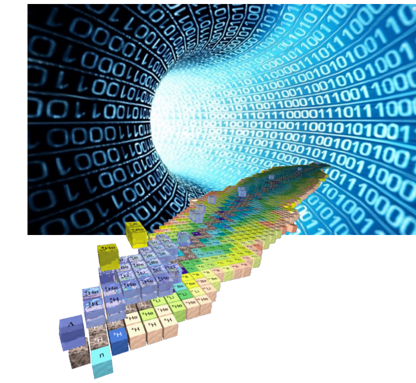


nnnn

- LQCD needs guidance from many-body calculations of systems in FV
- Determine the FV effects from many-body -subtract from LQCD to access UV physics to be input into many-body calcs.
- Collaboration required for optimal progress



Important Things to do Next



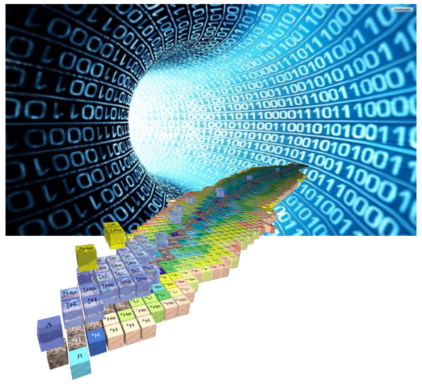
Directly related is:

- How to extract S-matrix elements from N-body systems?
  - 3-nucleon systems are (easier below inelastic thresholds) than, say, 3-mesons - which can couple to 2-mesons
  - Want to understand what to calculate with LQCD to refine multi-baryon processes
  - 4-body after 3-body - if at all practical

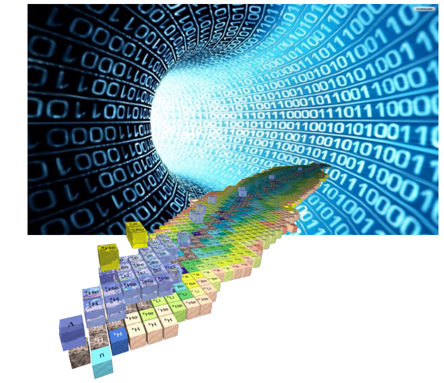
(Briceno, Davoudi, Hansen, Sharpe, Beane, Detmold, MJS, Rusetsky, Meissner, …)

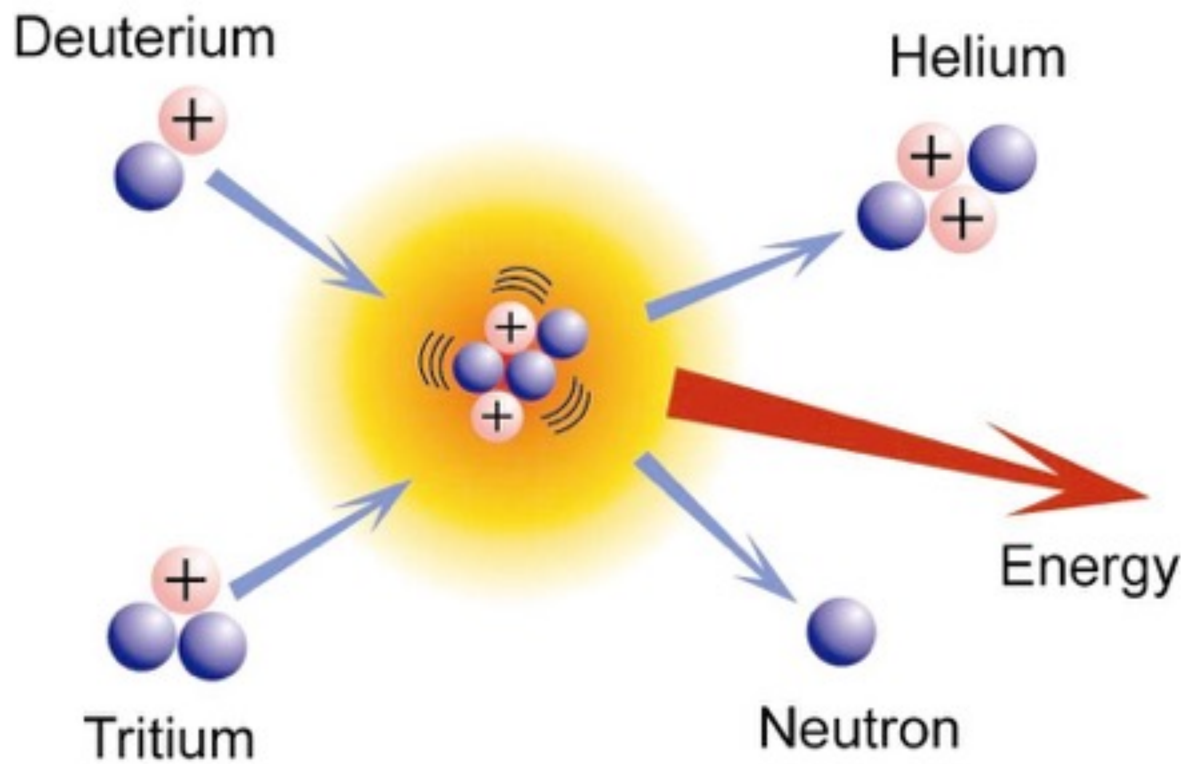
- Constrain underlying effective Hamiltonian responsible for S-matrix from FV calculations
  - This would be how nuclear many-body systems will be refined (previous slide)
  - N-body systems are ``easier" using this framework
  - Don't need S-matrix elements directly to refine nuclear physics predctive capabilities

(NPLQCD, …)



Why must we think about Lattice QCD and Nuclear Many-Body efforts together?



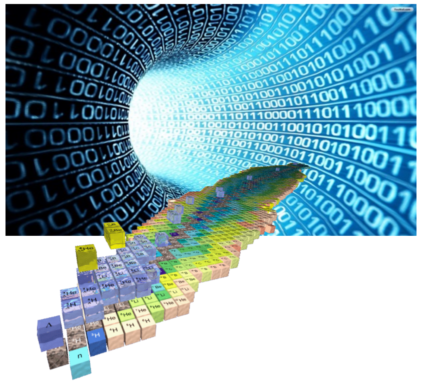


Don’t know the nuclear forces to sufficient precision from experiment for calculations in important systems.

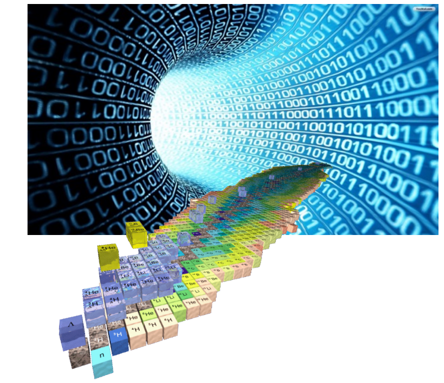
But what is the most important quantity to calculate?

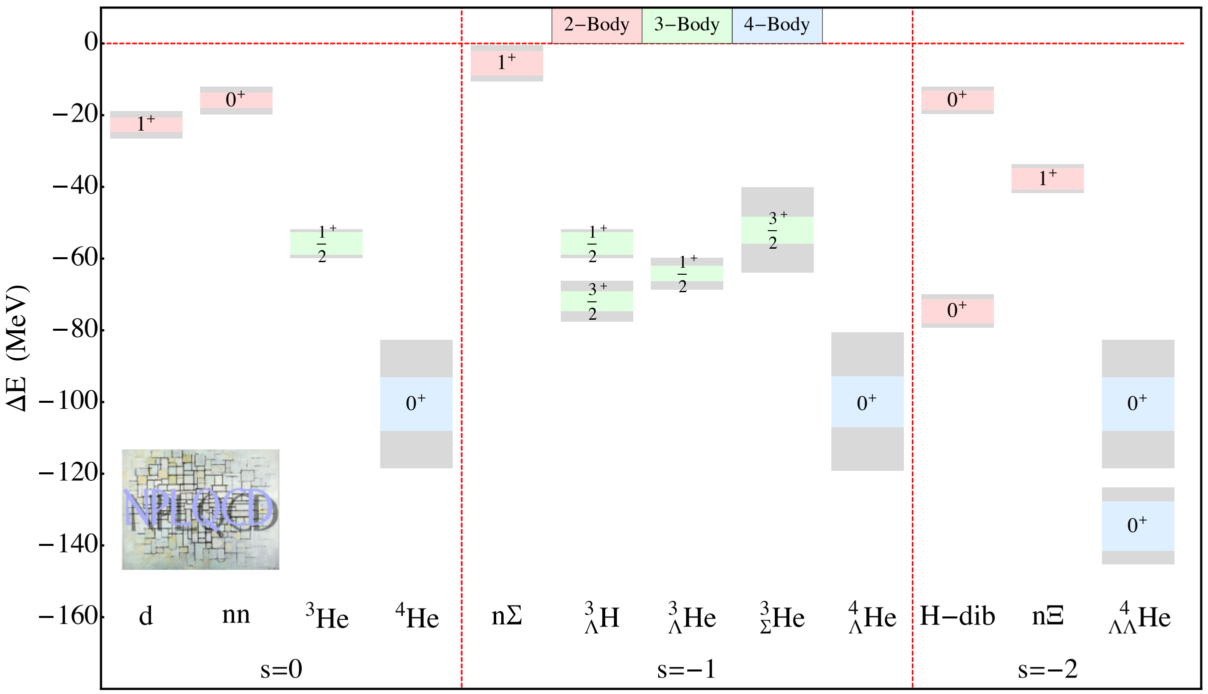
Meson-exchange currents unrelated to scattering (i.e. multi-nucleon-multi-gauge-field operators)

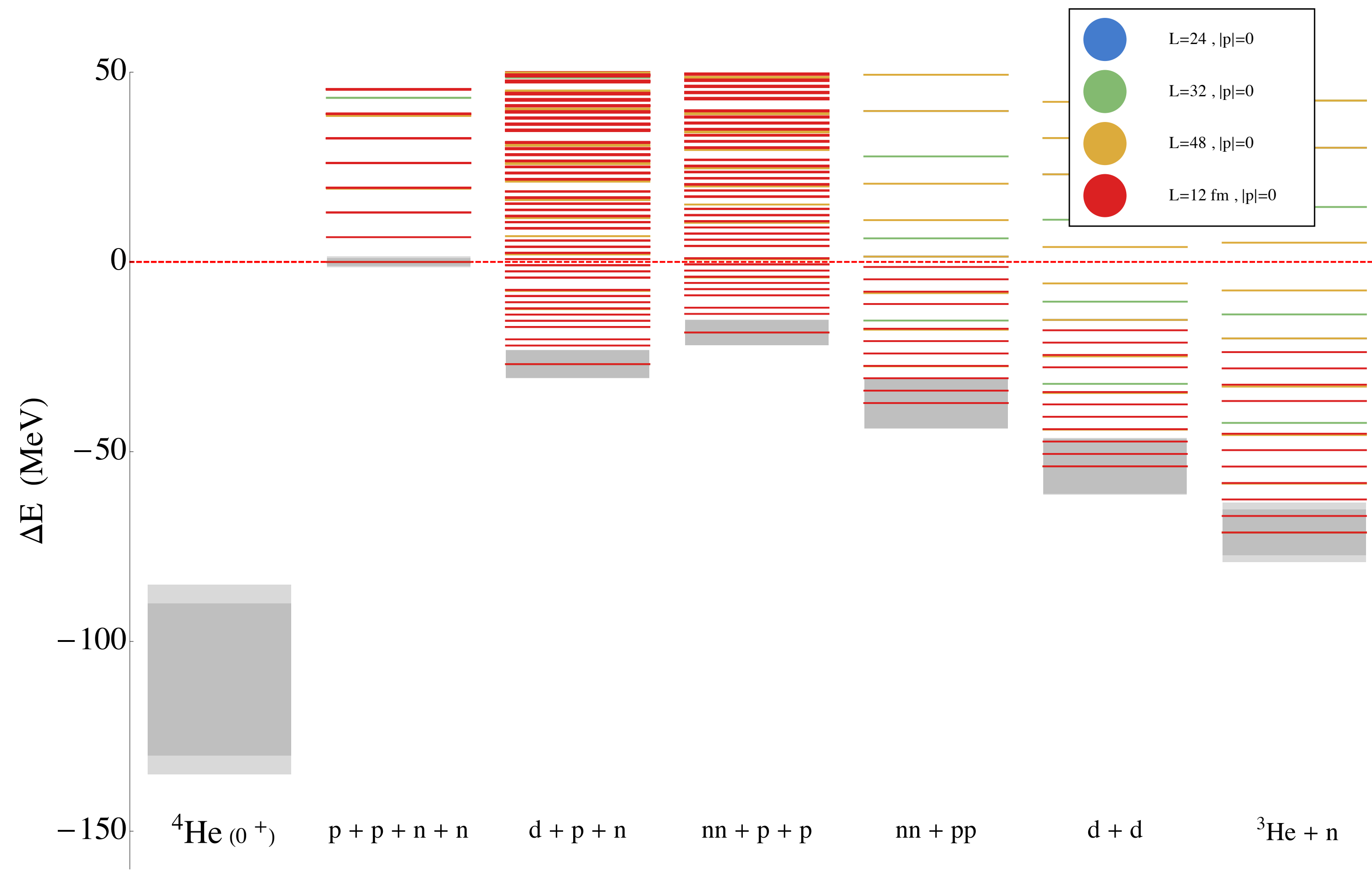
Neutron-rich, Hyperon systems for extreme environments

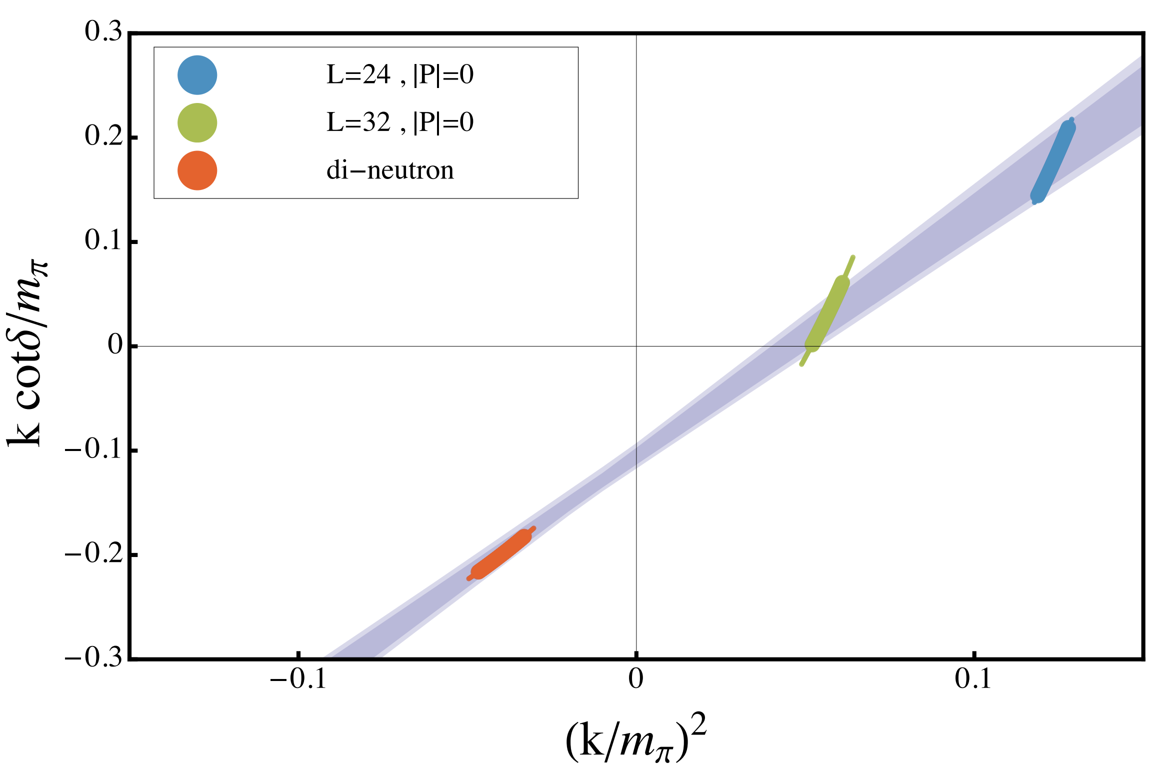


Light Nuclei and Hypernuclei
SU(3) limit, 800 MeV pions

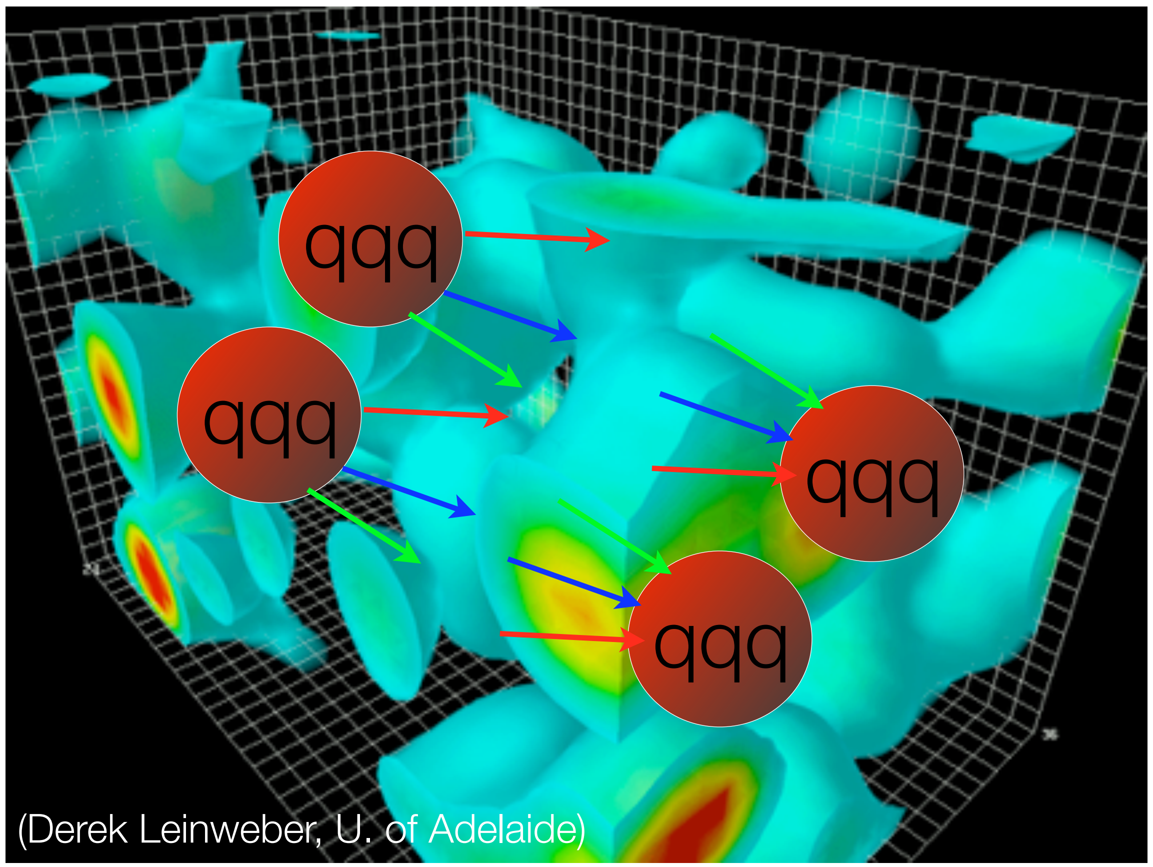


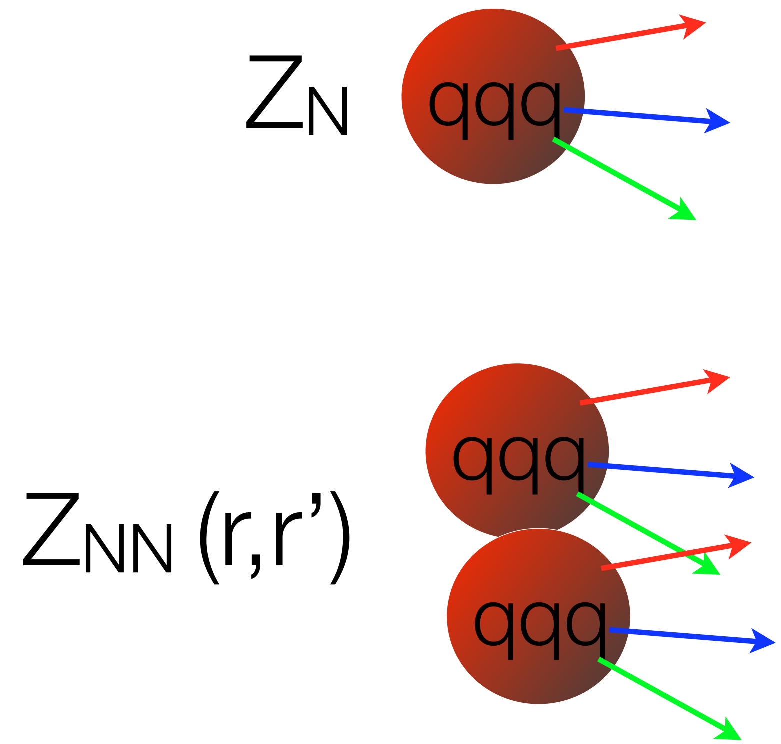






HALQCD "Potentials" ?

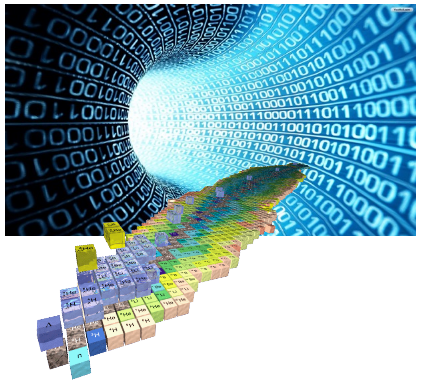




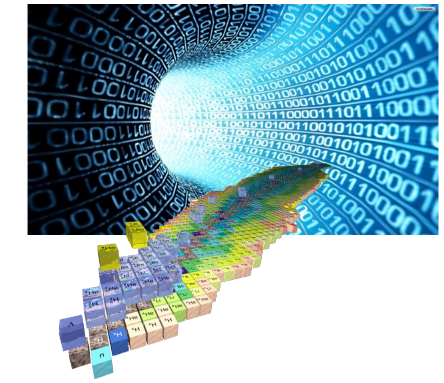
1) Maiani-Testa Theorem

2) Luscher : Measure energy-eigenvalues of the two-hadron system

3) Can nuclear potentials with meaning be extracted ?



A Primer -
1990 : Luscher says ....



Explicitly, the stationary effective Schrödinger equation in the centre-of-mass frame reads

$$-\frac{1}{2\mu}\Delta\psi(\mathbf{r}) + \frac{1}{2}\int \mathrm{d}^3r'\, U_E(\mathbf{r},\mathbf{r}')\psi(\mathbf{r}') = E\psi(\mathbf{r}), \qquad (7.1)$$

where the parameter E is related to the true energy W of the system through

$$W = 2\sqrt{m^2 + mE}. \qquad (7.2)$$

The "potential" $U_E(\mathbf{r},\mathbf{r}')$ is the Fourier transform of the modified Bethe-Salpeter kernel $\hat{U}_E(\mathbf{k},\mathbf{k}')$ introduced in ref.[3]. It depends analytically on

38

E in the range $-m < E < 3m$ and is a smooth function of the coordinates $\mathbf{r}$ and $\mathbf{r}'$, decaying exponentially in all directions †. Furthermore, the potential

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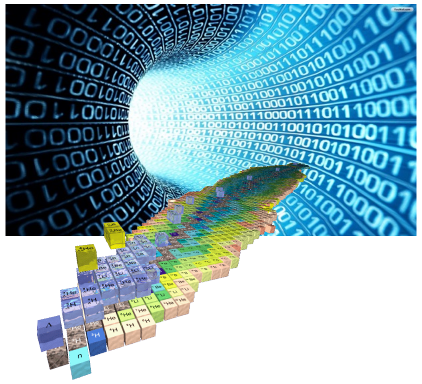
Two-Particle States on a Torus and their Relation to the Scattering Matrix

M. Lüscher

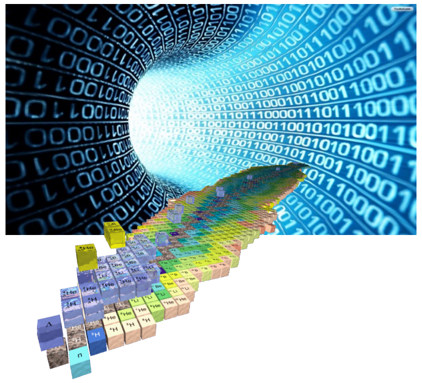
Deutsches Elektronen-Synchrotron DESY, Hamburg

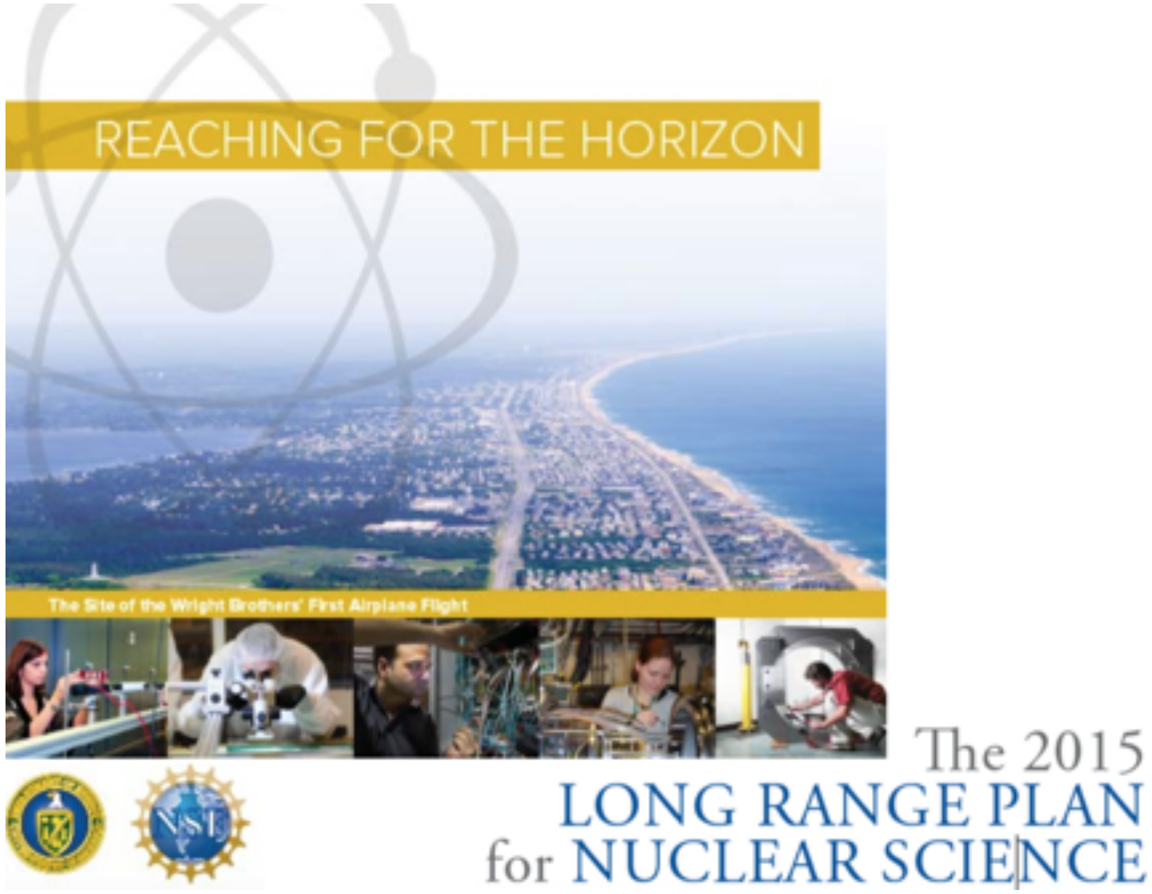
It therefore follows that....

Taking U to be energy-independent is a model-dependent assertion and not a QCD prediction



Important Things to do Next Gluonic Structure





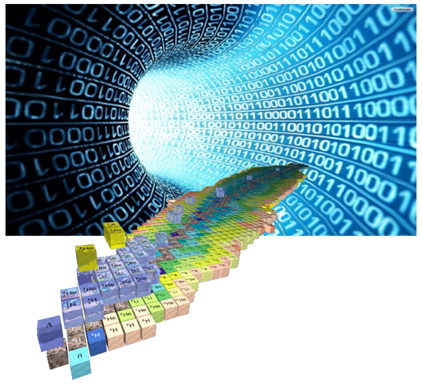
RECOMMENDATION III

Gluons, the carriers of the strong force, bind the quarks together inside nucleons and nuclei and generate nearly all of the visible mass in the universe. Despite their importance, fundamental questions remain about the role of gluons in nucleons and nuclei. These questions can only be answered with a powerful new electron ion collider (EIC), providing unprecedented precision and versatility. The realization of this instrument is enabled by recent advances in accelerator technology.

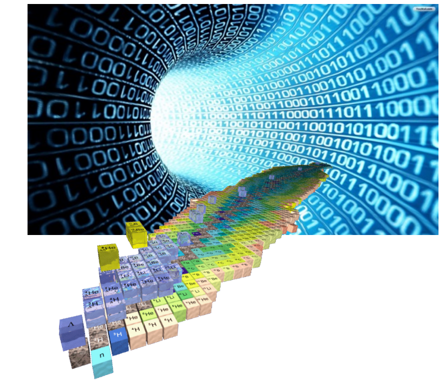
We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

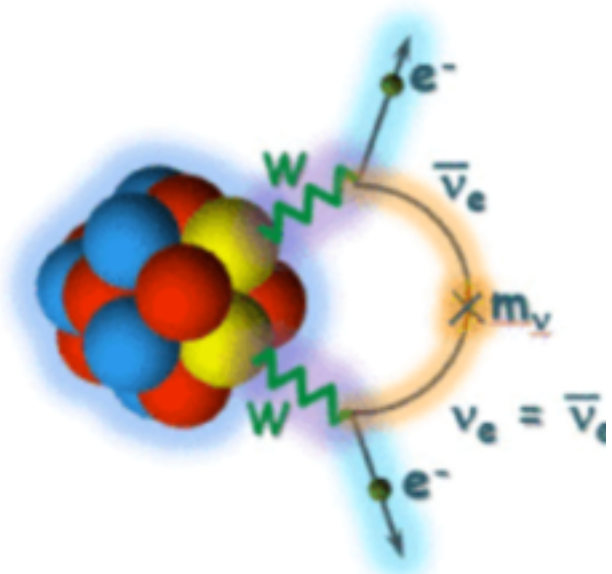
The EIC will, for the first time, precisely image gluons in nucleons and nuclei. It will definitively reveal the origin of the nucleon spin and will explore a new quantum chromodynamics (QCD) frontier of ultra-dense gluon fields, with the potential to discover a new form of gluon matter predicted to be common to all nuclei. This science will be made possible by the EIC's unique capabilities for collisions of polarized electrons with polarized protons, polarized light ions, and heavy nuclei at high luminosity.

The vision of an EIC was already a powerful one in the 2007 Long Range Plan. The case is made even more compelling by recent discoveries. This facility can lead to the convergence of the present world-leading QCD programs at CEBAF and RHIC in a single facility. This vision for the future was expressed in the 2013 NSAC report on the implementation of the 2007 Long Range Plan with the field growing towards two major facilities, one to study the quarks and gluons in strongly interacting matter and a second, FRIB, primarily to study nuclei in their many forms. Realizing the EIC will keep the U.S. on the cutting edge of nuclear and accelerator science.



Important Things to do Next
Fundamental Symmetries





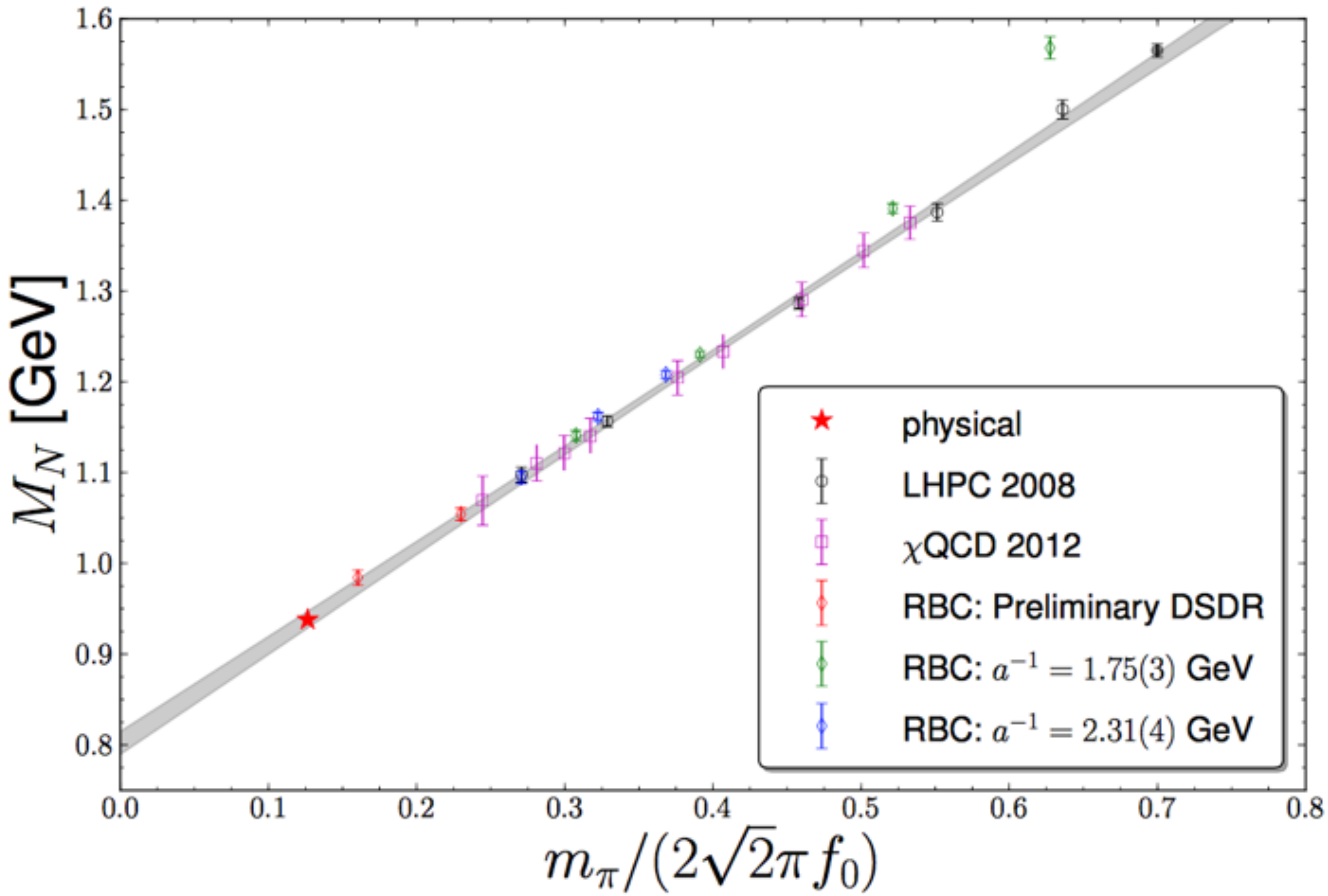
RECOMMENDATION II

The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding of the matter-antimatter mystery.

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

A ton-scale instrument designed to search for this as-yet unseen nuclear decay will provide the most powerful test of the particle-antiparticle nature of neutrinos ever performed. With recent experimental breakthroughs pioneered by U.S. physicists and the availability of deep underground laboratories, we are poised to make a major discovery.

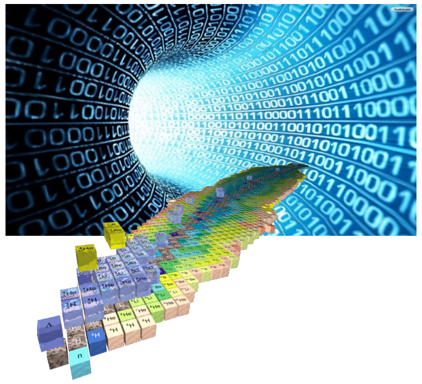
Puzzle 1
Nucleon Mass



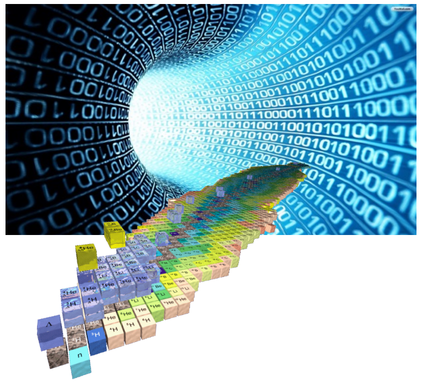
For pions about about 250 MeV:

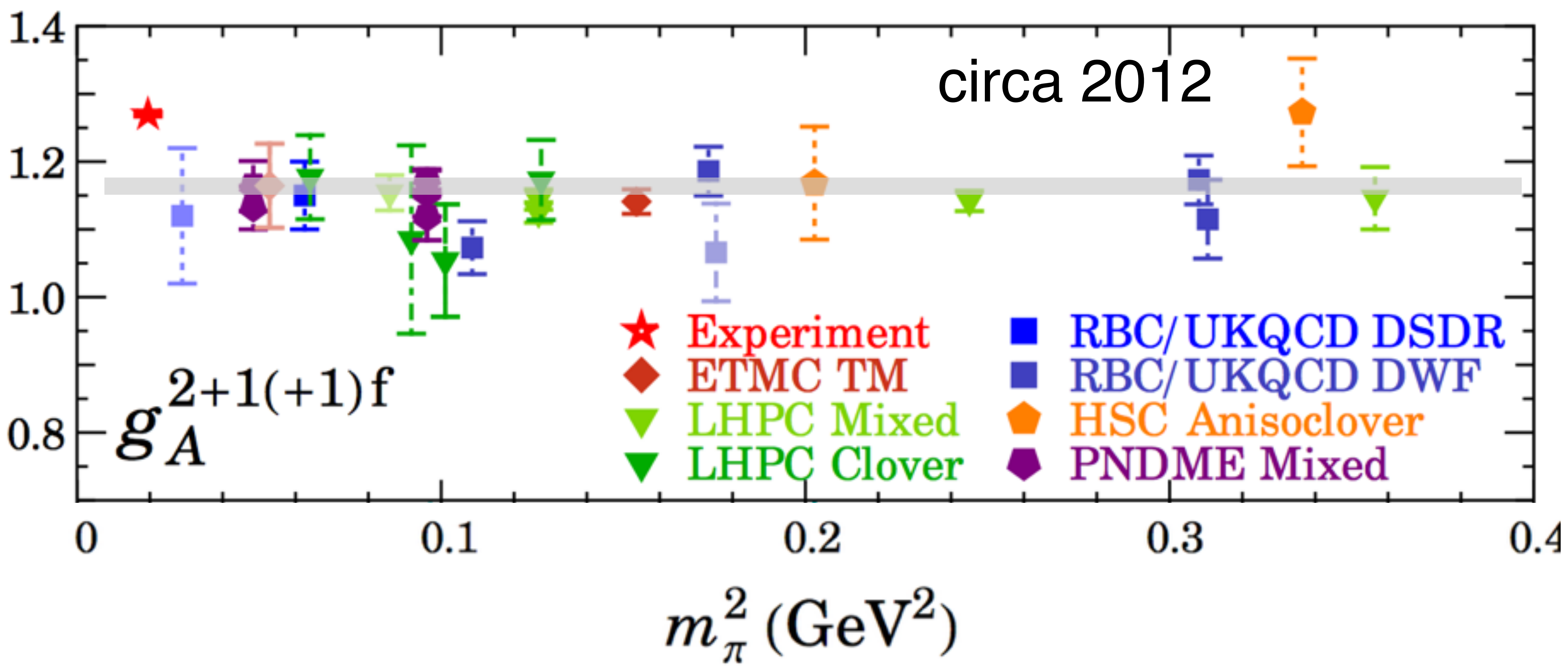
$$M_N \; = \; 800 \text{ MeV} \; + \; m_\pi$$

Unexpected behavior !!

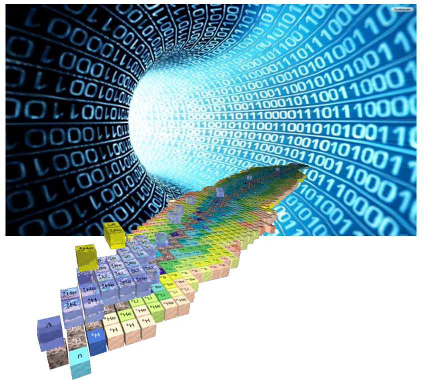


Puzzle 2
Nucleon Axial Charge

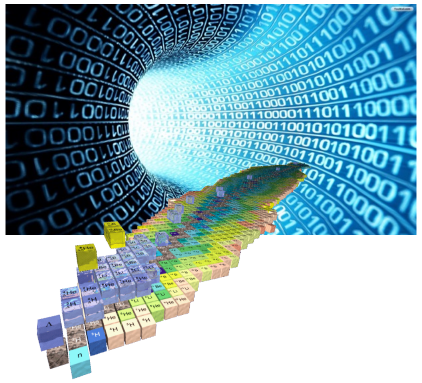


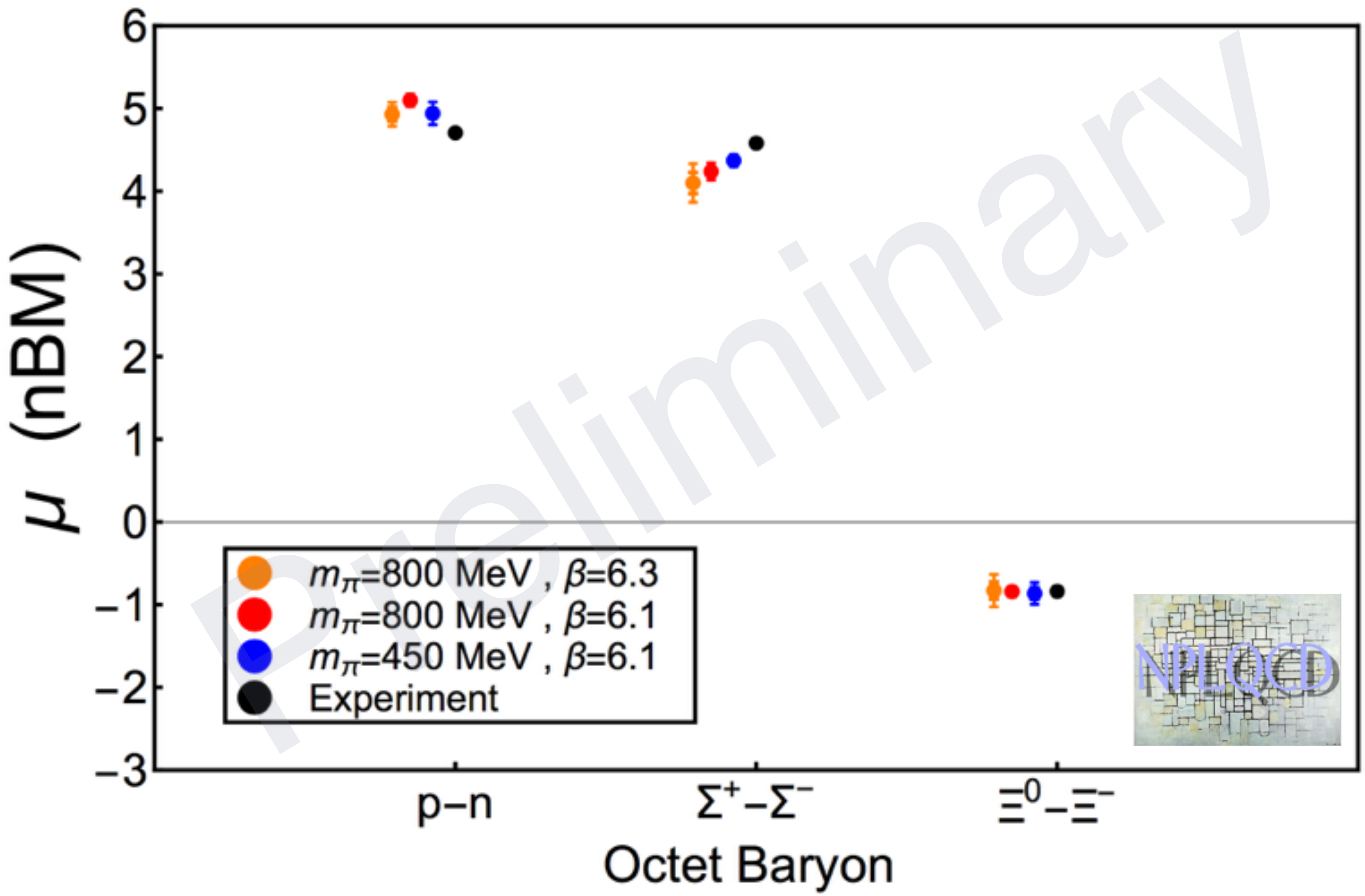


(compilation by H.W. Lin)



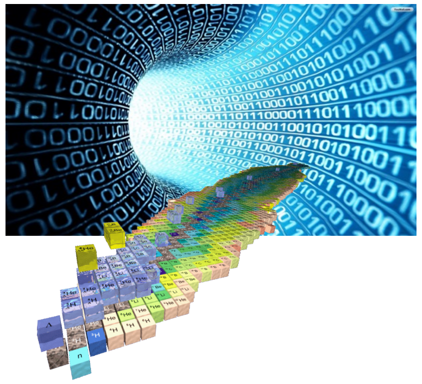
Puzzle 3
Nucleon Magnetic Moments



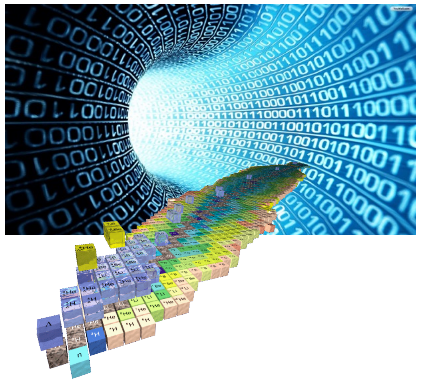


$$\frac{e}{2M(m_\pi)}$$

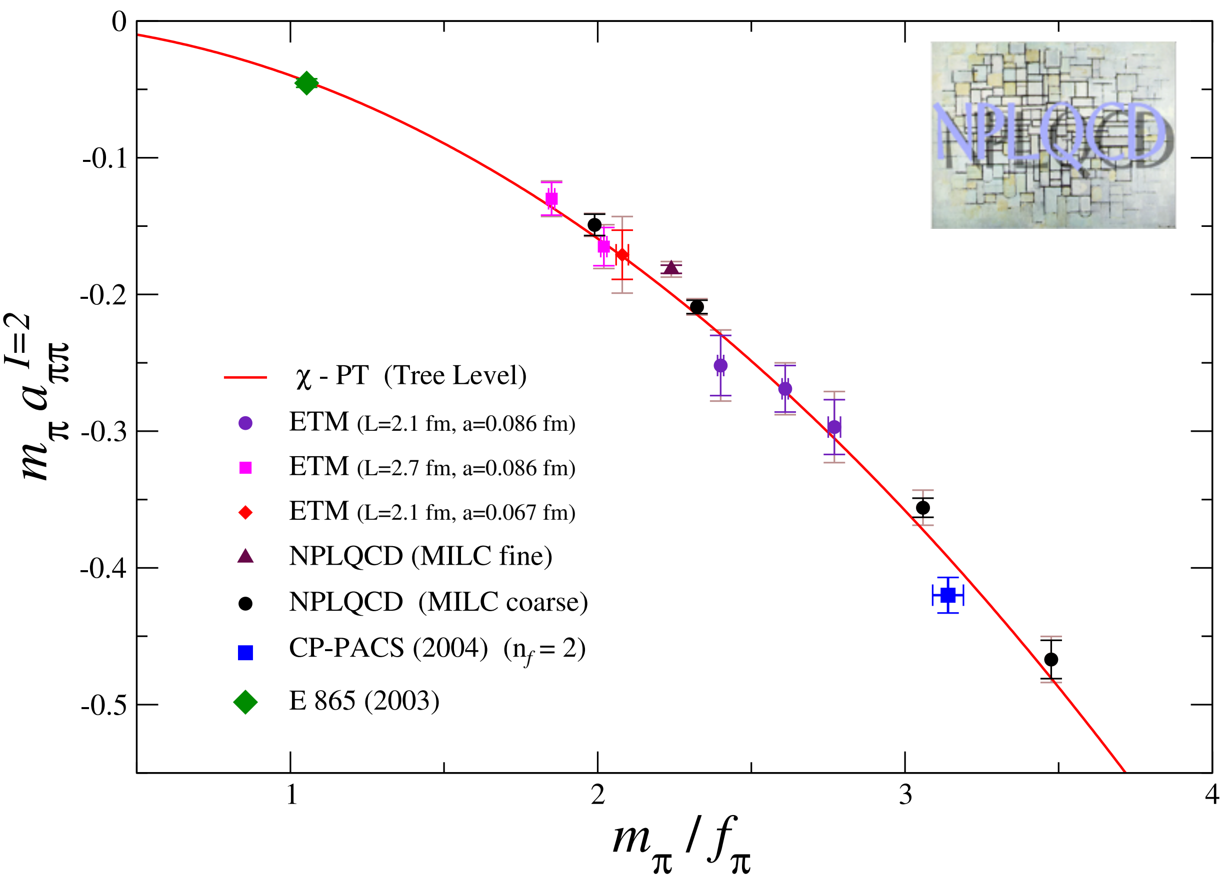
Essentially ALL quark mass dependence of nucleon magnetic moments is due to the nucleon mass



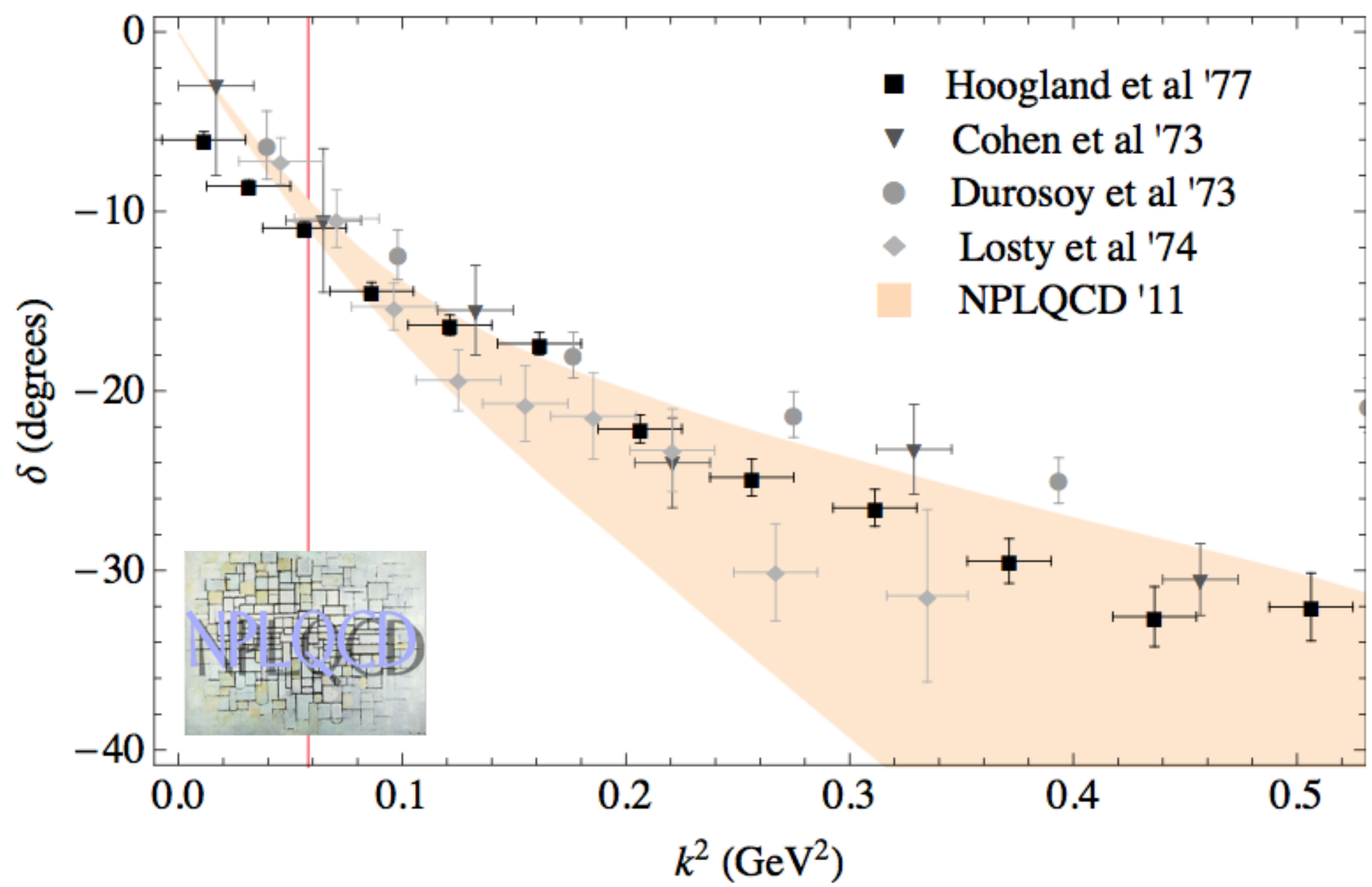
Puzzle 4
Meson Interactions



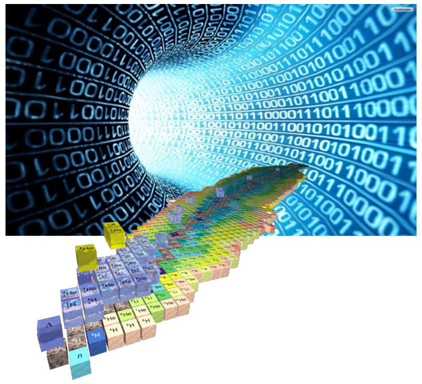
$\pi^+\pi^+$ $(I=2)$



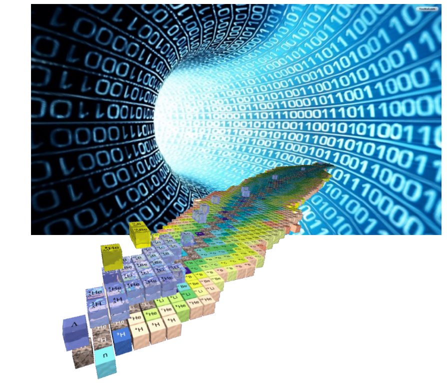
χPT extrapolation to nature

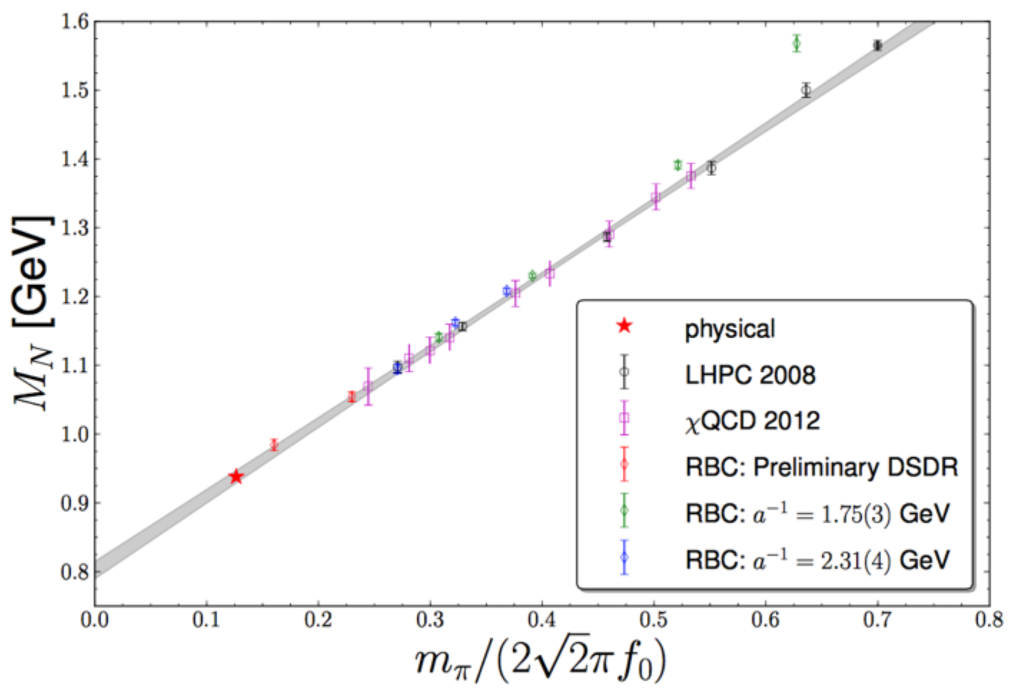


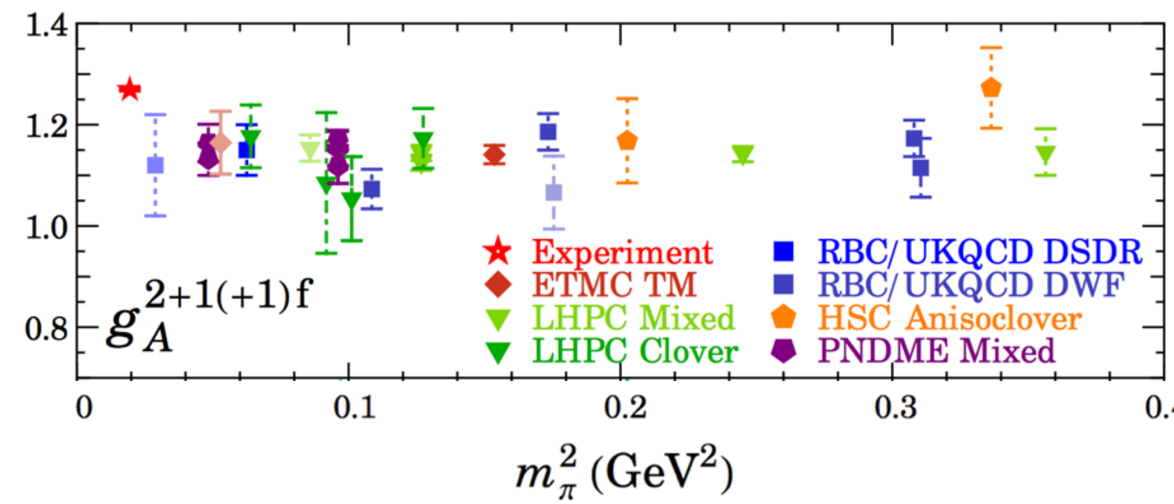
Red curve is tree-level chiral PT - Weinberg
- prediction and not fit

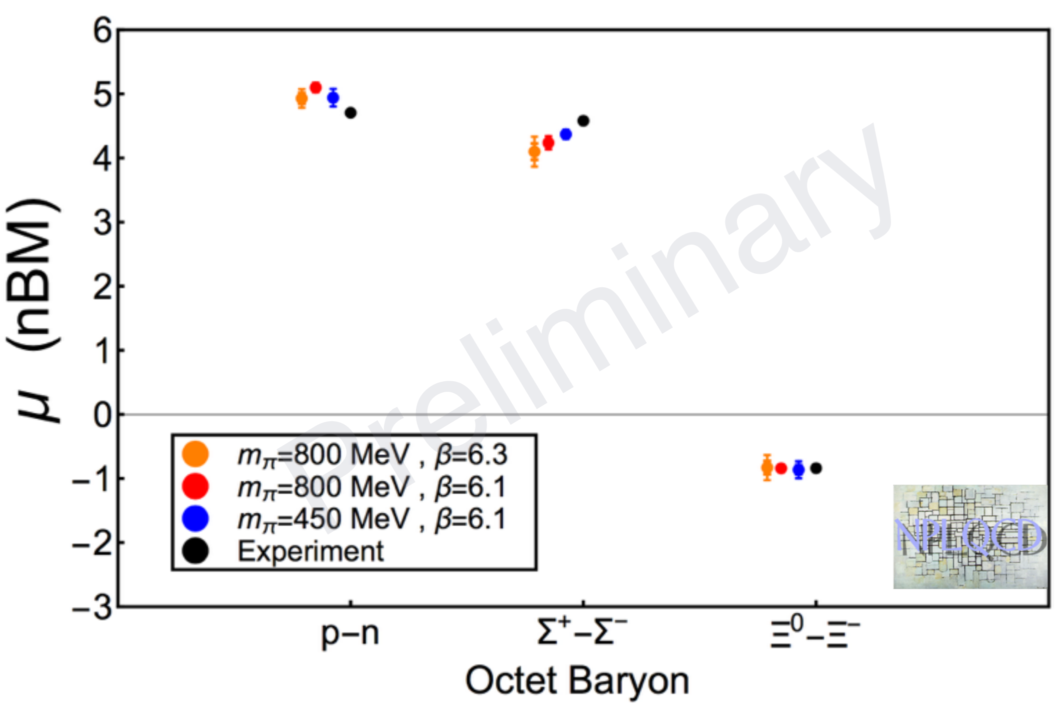


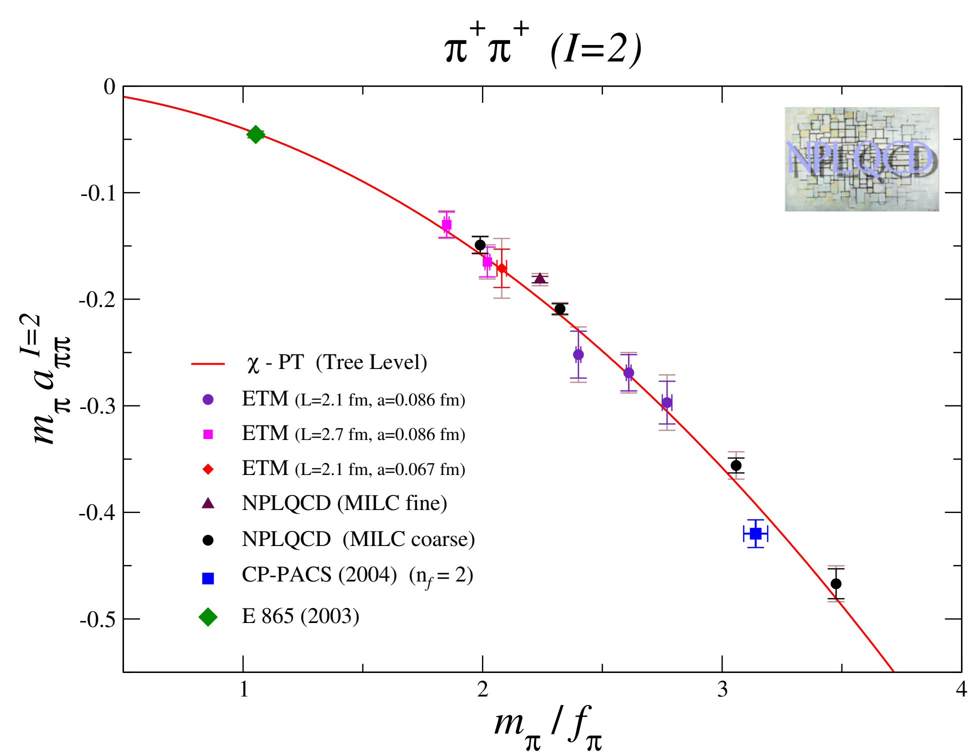
Lattice QCD:
What is the Underlying Structure ?



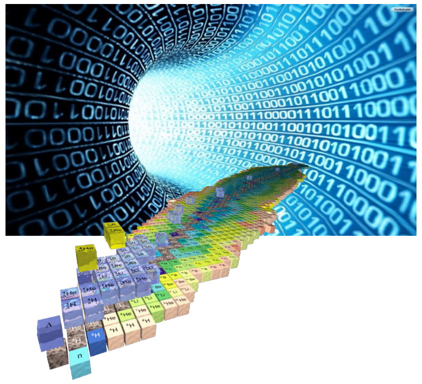




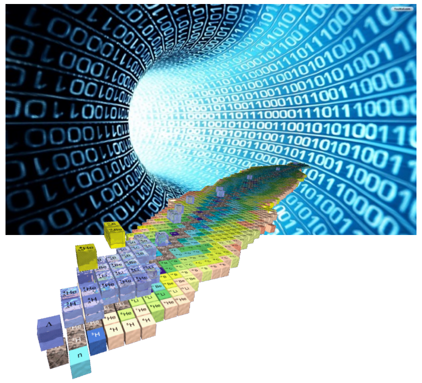




All unexpected results that Lattice QCD has revealed



Closing Remarks



Lattice QCD combined with nuclear many-body techniques is beginning to provide first principles predictive capabilities for nuclear physics.

Close collaborations with Nuclear Many-body theorists going forward are crucial in making optimal use of Lattice QCD resources to support the overall nuclear physics program

Exciting puzzles being revealed by Lattice calculations at unphysical parameters - feels like 1962 again! Such calculations are actually essential in dissecting the chiral nuclear forces!

FIN