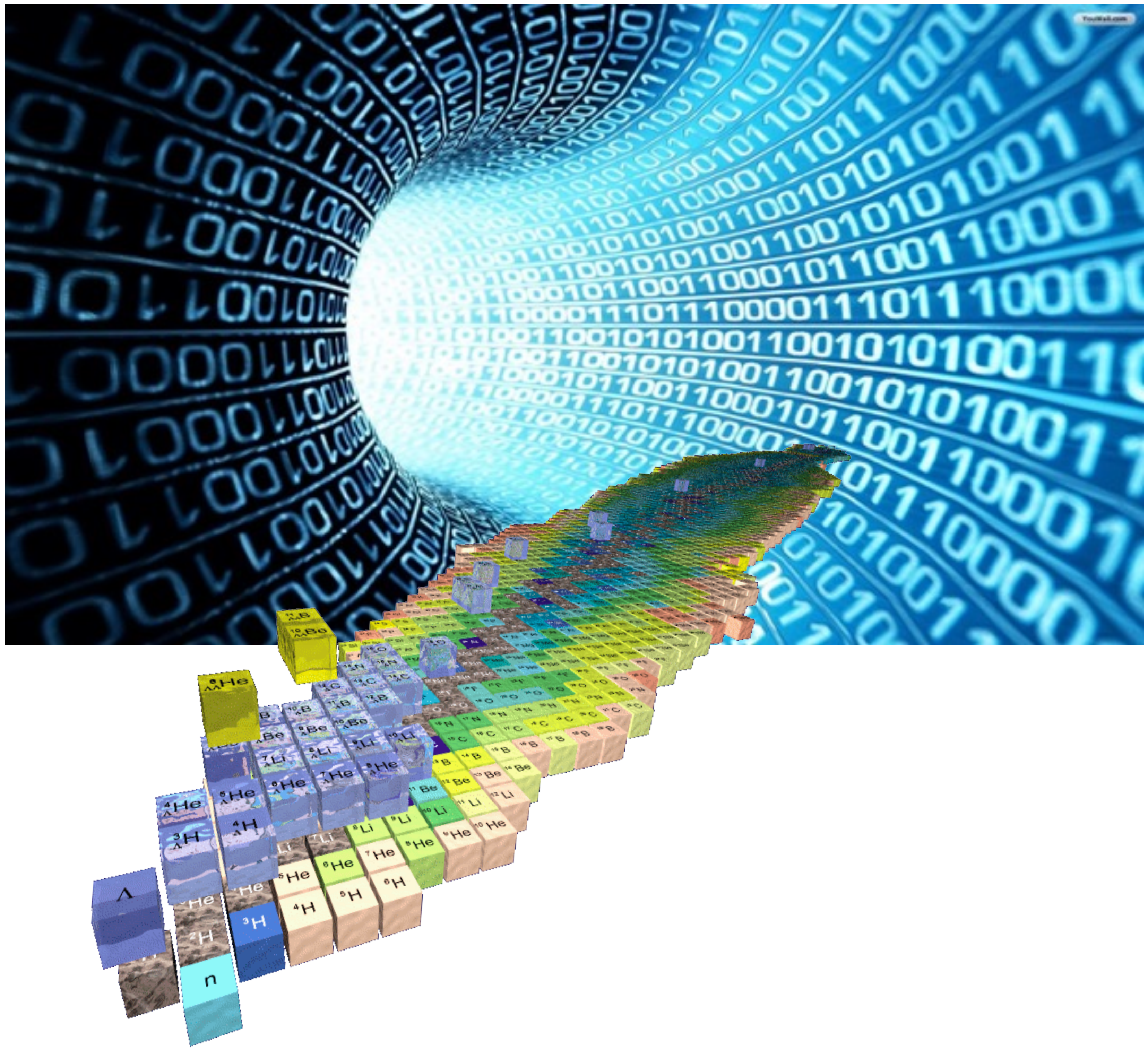


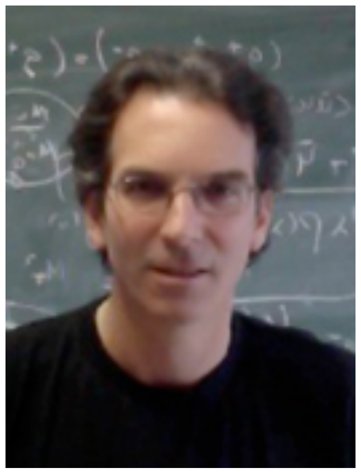
Exploring Nuclei and New Questions

Lattice Gauge Theory for the LHC and Beyond
KITP, Santa Barbara, August 2015

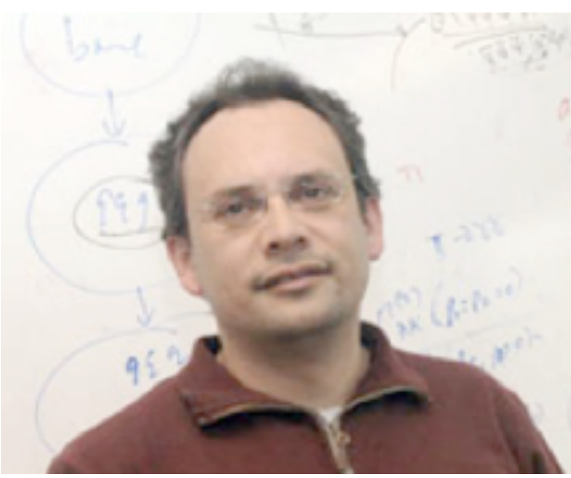
Martin J Savage

INSTITUTE for NUCLEAR THEORY

NPLQCD



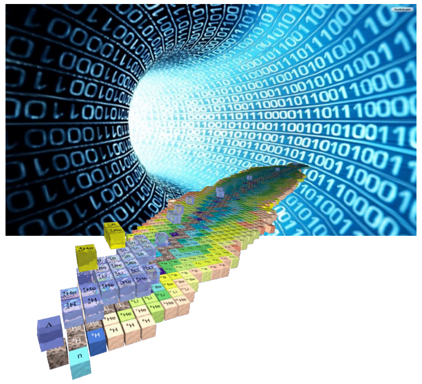

Brian Tiburzi
(CUNY/CCNY/RIKEN)



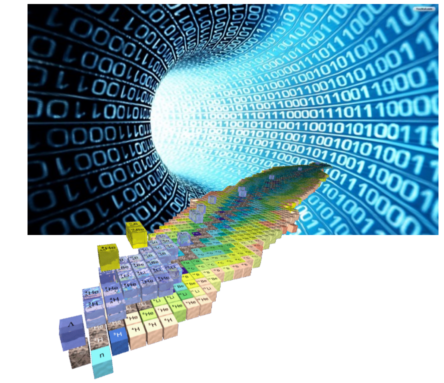
Silas Beane (UW)
William Detmold (MIT)
Assumpta Parreno (Barcelona)

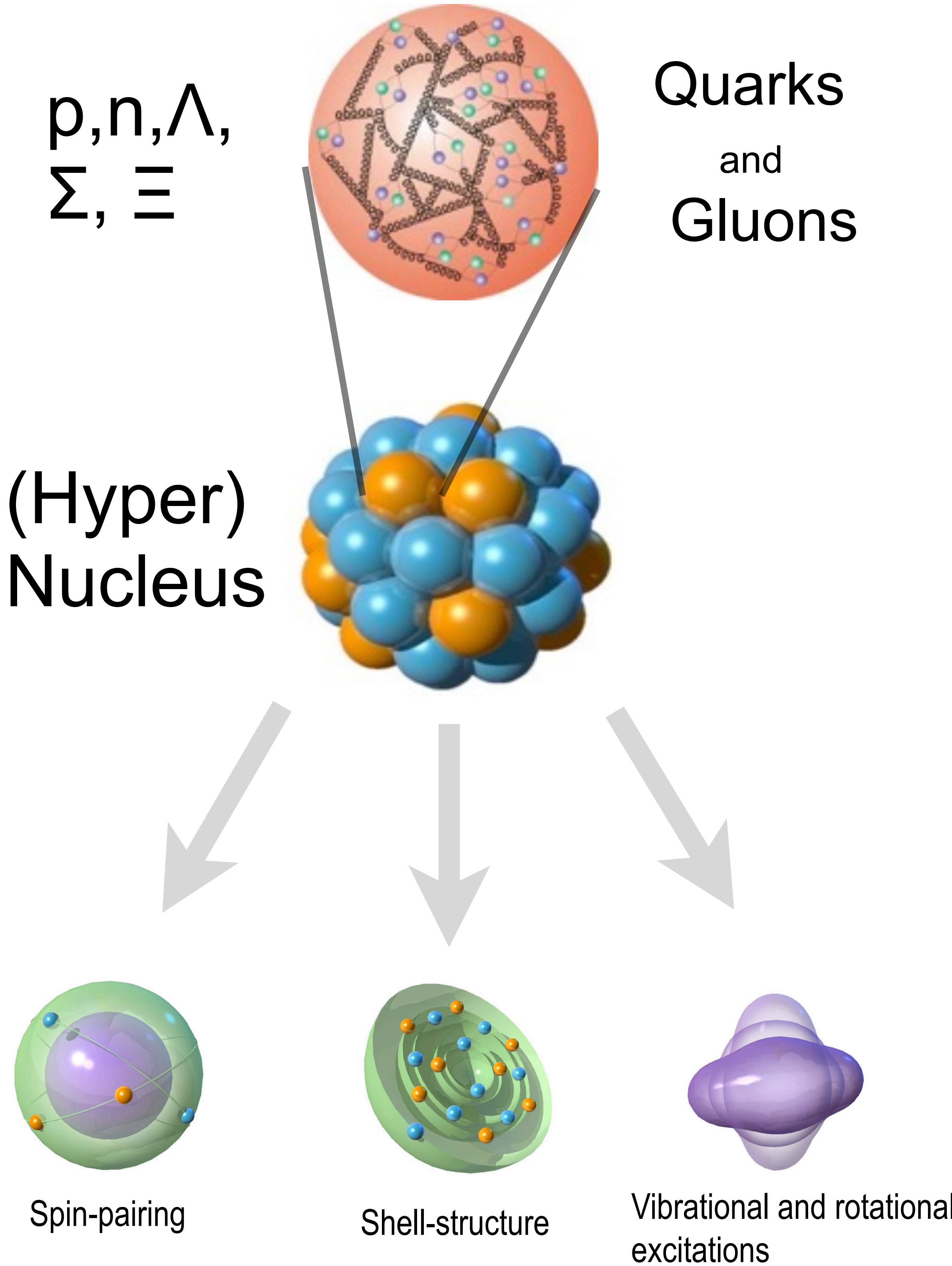
Emmanuel Chang (INT)
Kostas Orginos (WM/JLab)
Martin Savage (INT)

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



The Structure and Interactions of Matter from Quantum Chromodynamics





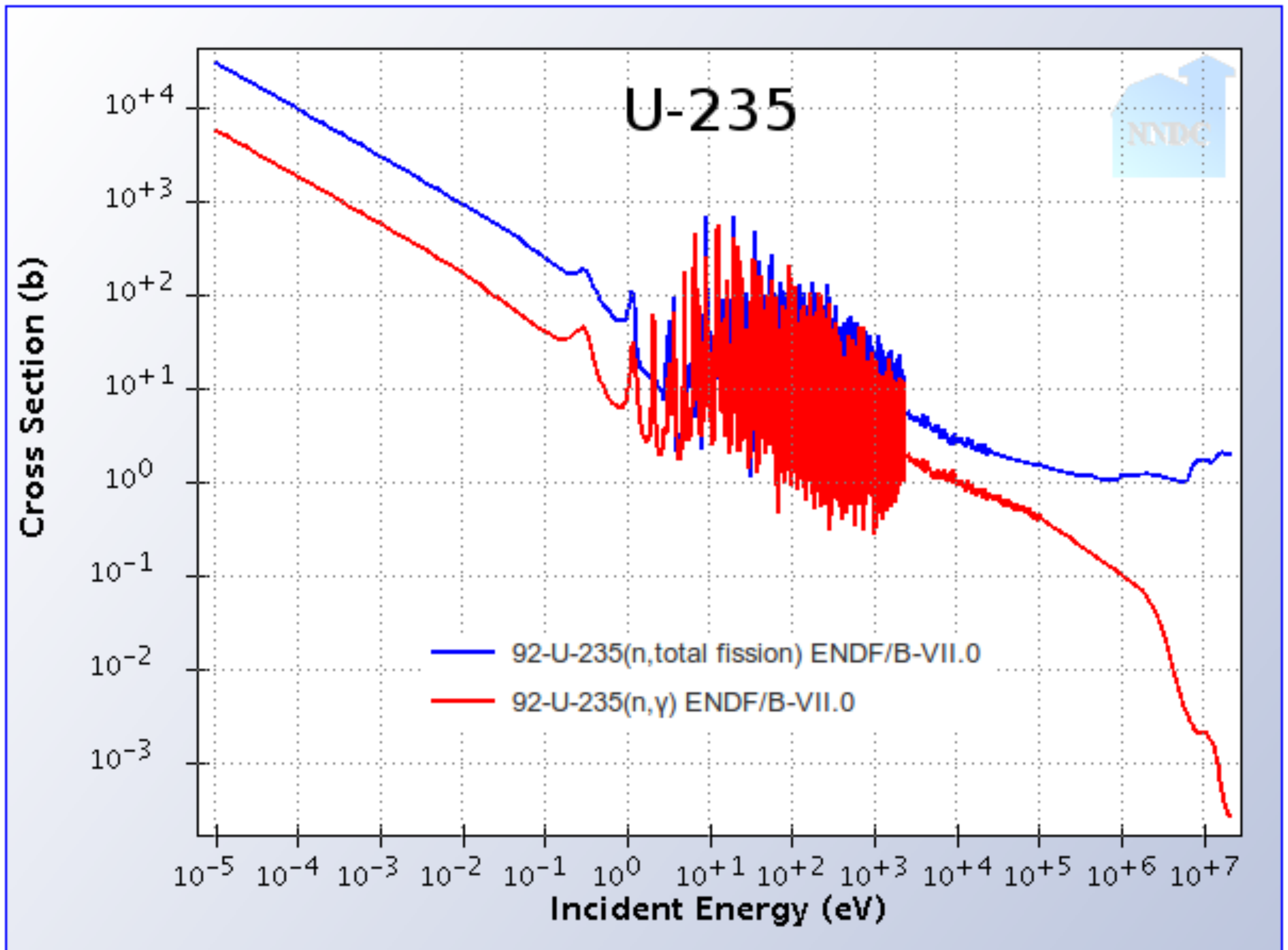
$$\Lambda_{\rm QCD}$$

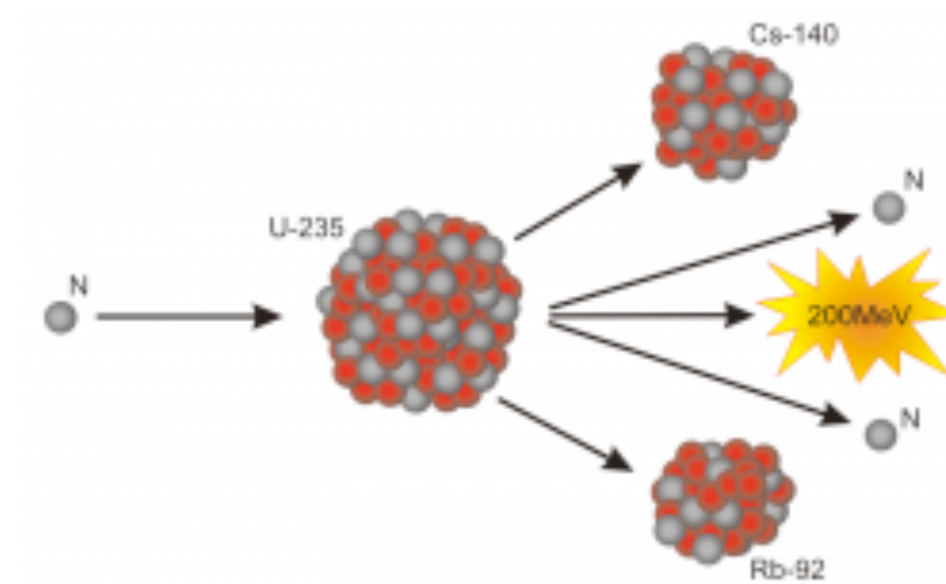
$$\frac{m_u}{\Lambda_{\rm QCD}} \quad \frac{m_d}{\Lambda_{\rm QCD}} \quad \frac{m_s}{\Lambda_{\rm QCD}}$$

$$\alpha_e$$

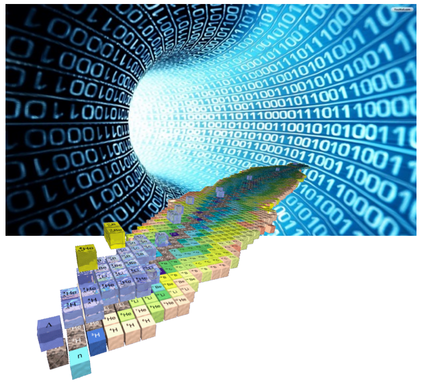
Small number of input parameters responsible for all of strongly interacting matter

QCD and EM Responsible for the Nuclear Energy Scales

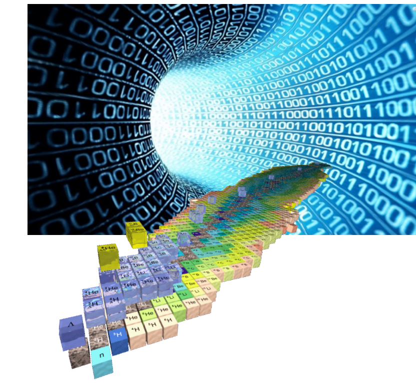




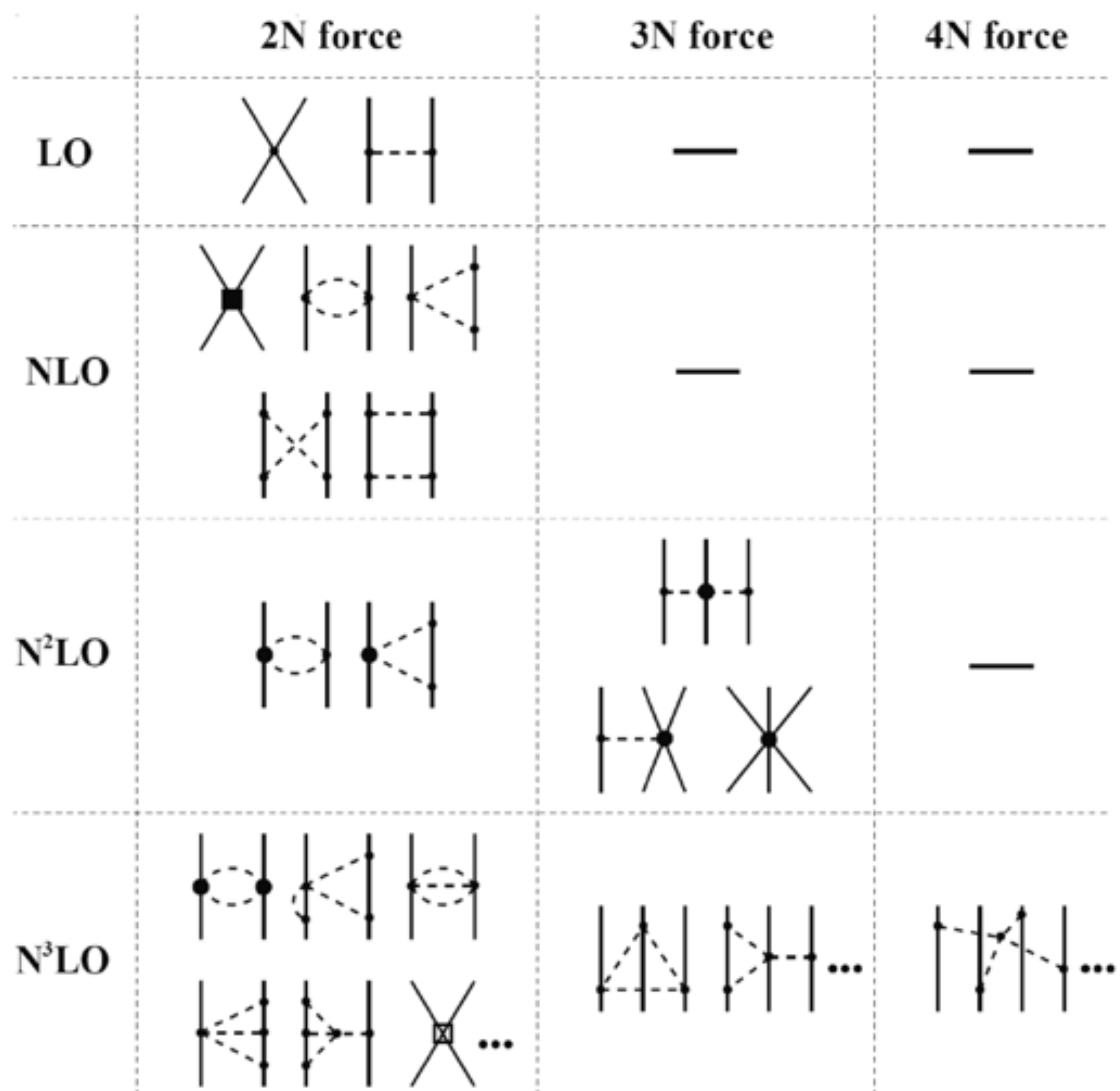
Mass ^{235}U ~ 220 900 MeV



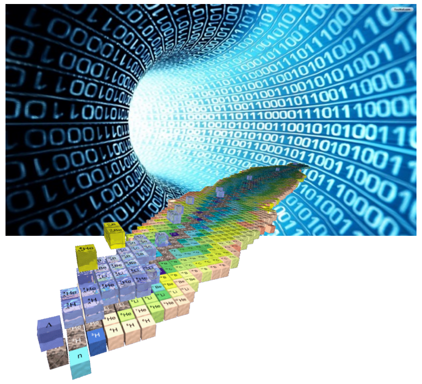
Organizing Nuclear Forces



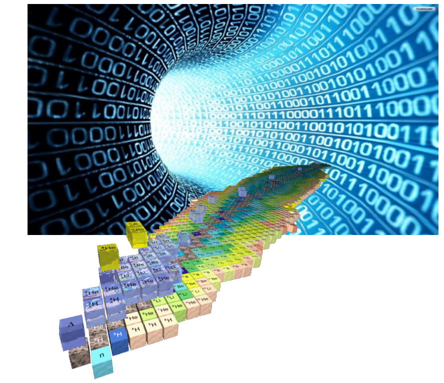
Effective Field Theory introduced by Weinberg in the early 1990's to systematize nuclear forces

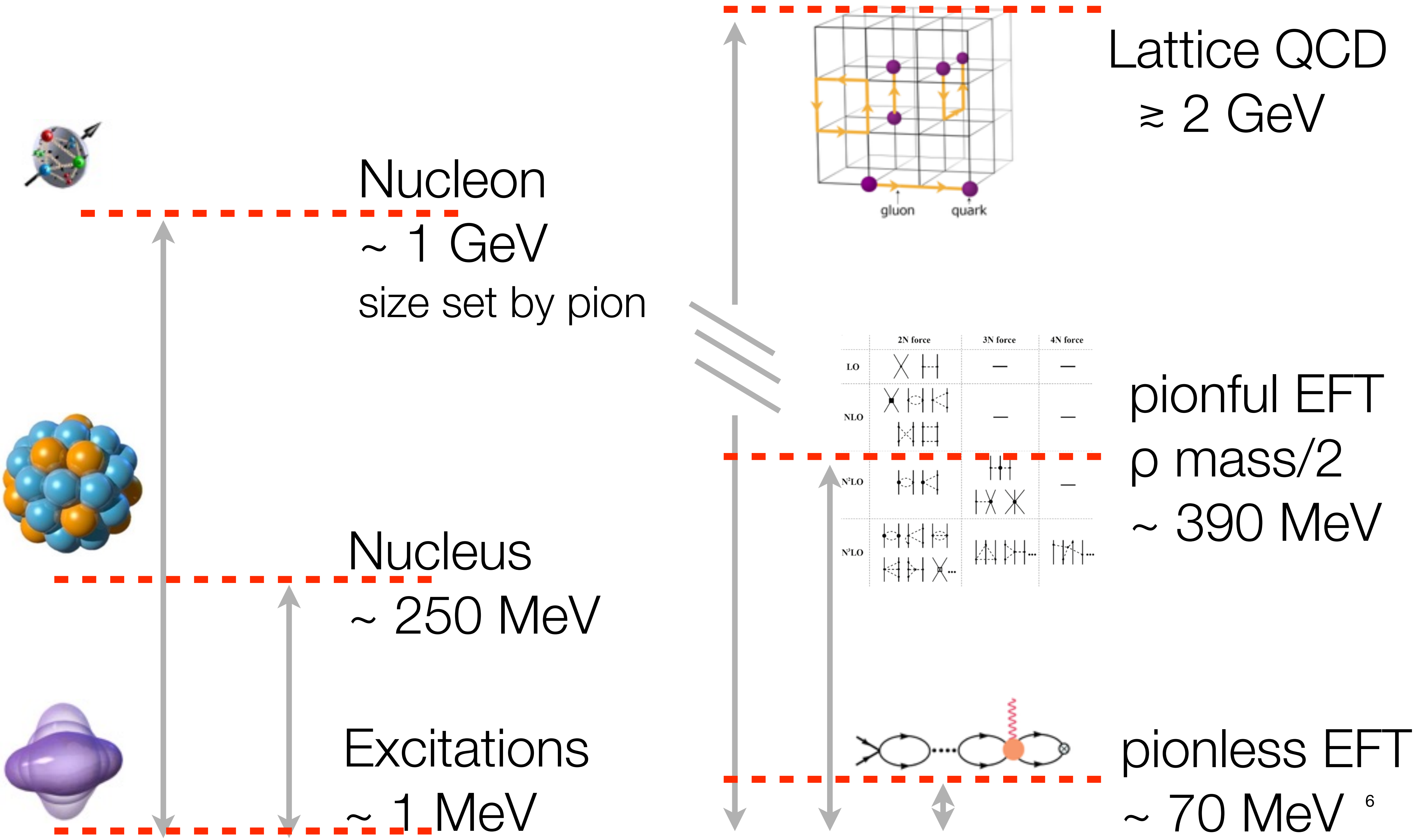


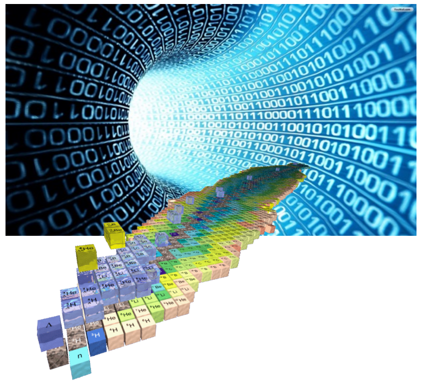
- Low-energy EFT of QCD
- Chiral symmetries of QCD
- Quark mass dependence
- Softer Interactions
  - V_{lowk} , SRG
  - many-body calcs

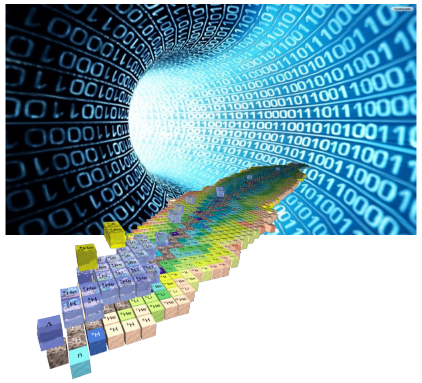


Energy Scales
Dynamical Degrees of Freedom

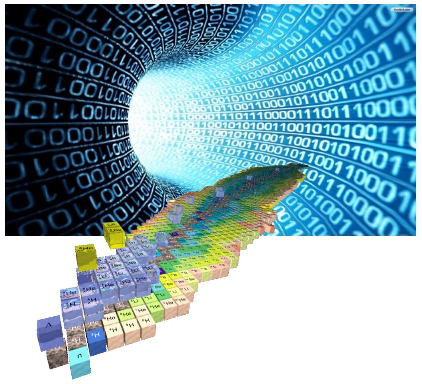




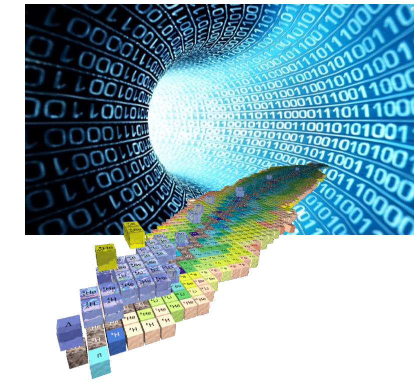


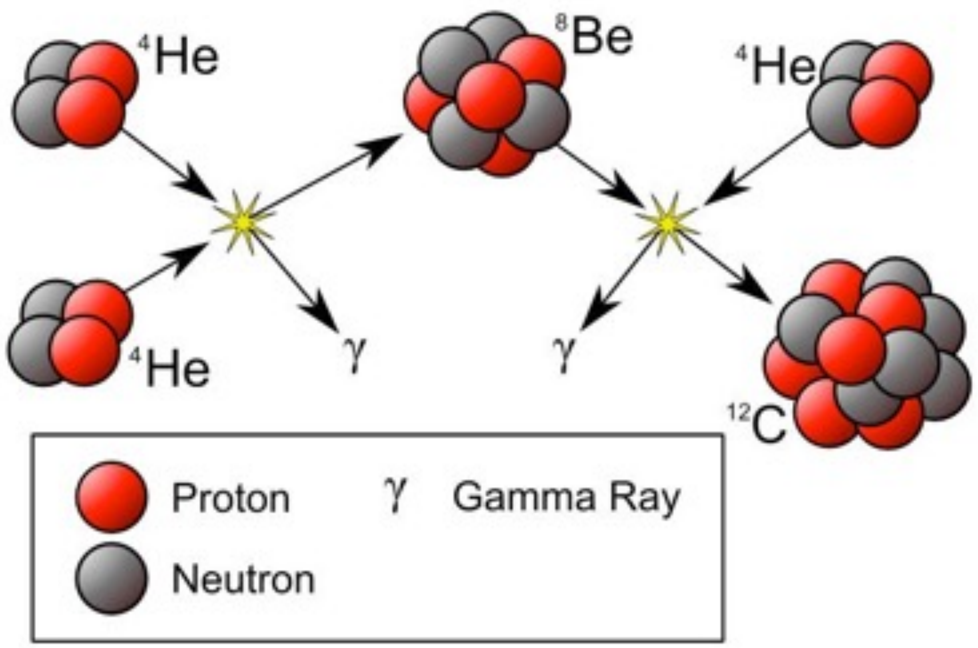


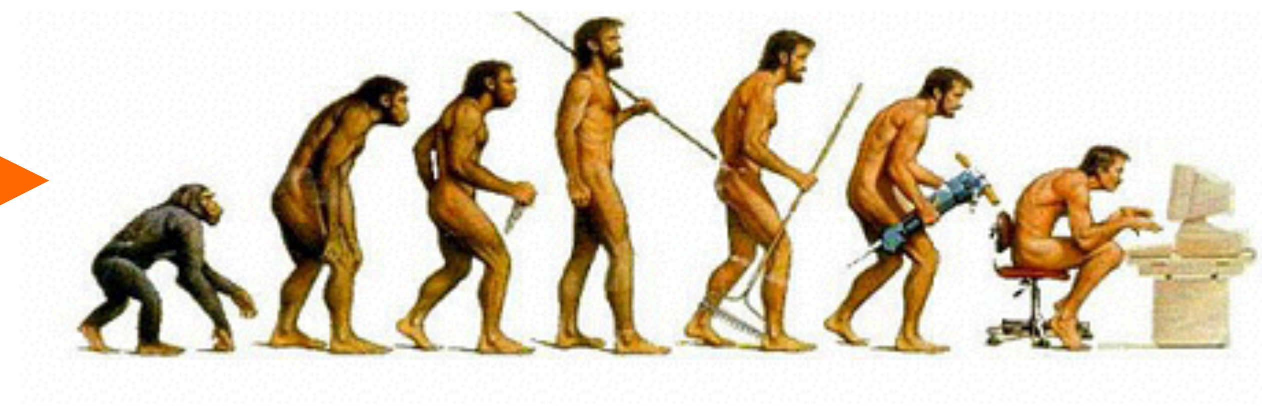
Fundamental Constants:
Nuclear Physics is Robust (?)



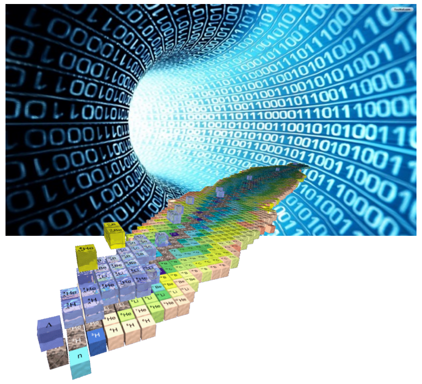
Fine-Tunings define our Universe



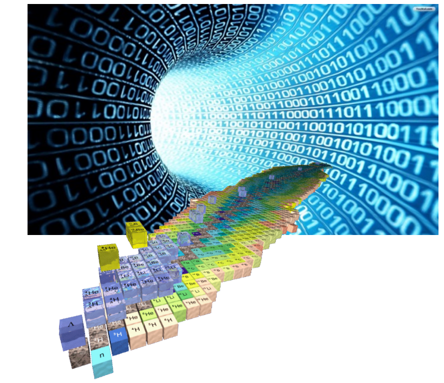


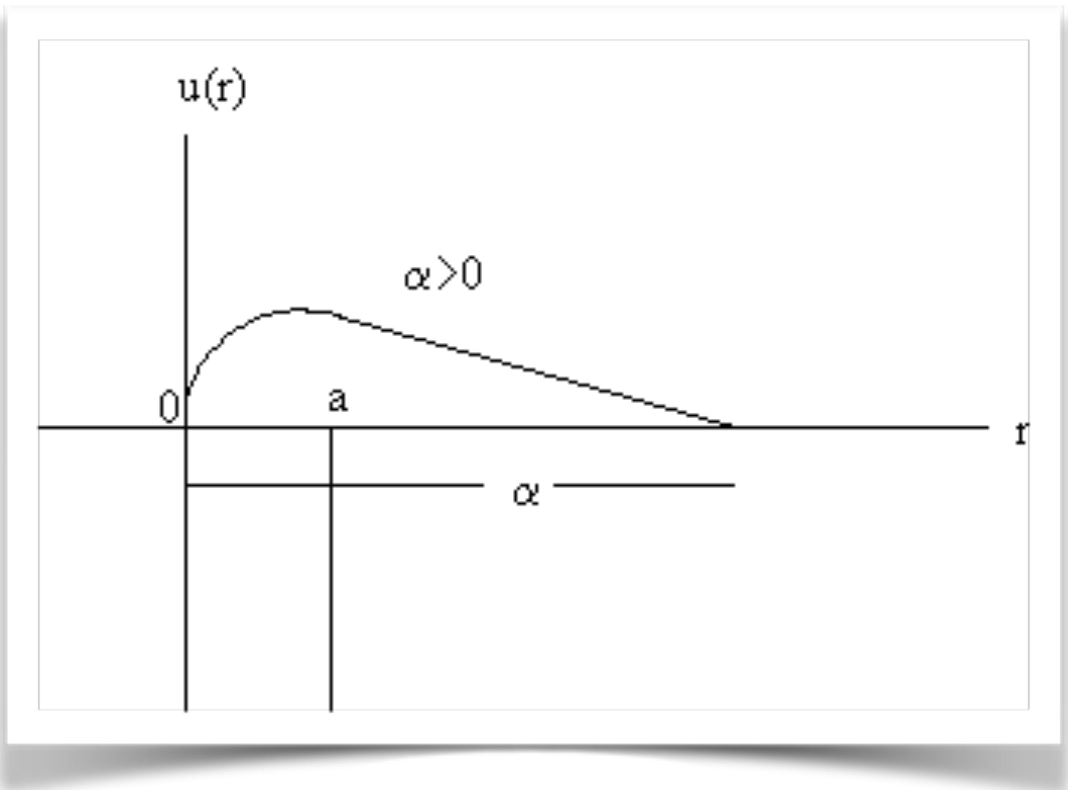


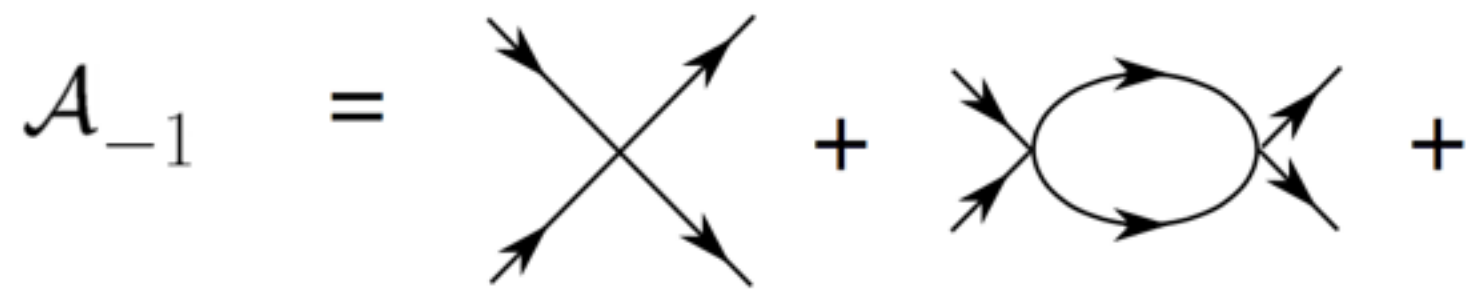
- Nuclear physics exhibits fine-tunings
  - *Why ?? Anthropic ?*
  - *Range of parameters to produce sufficient carbon ?*

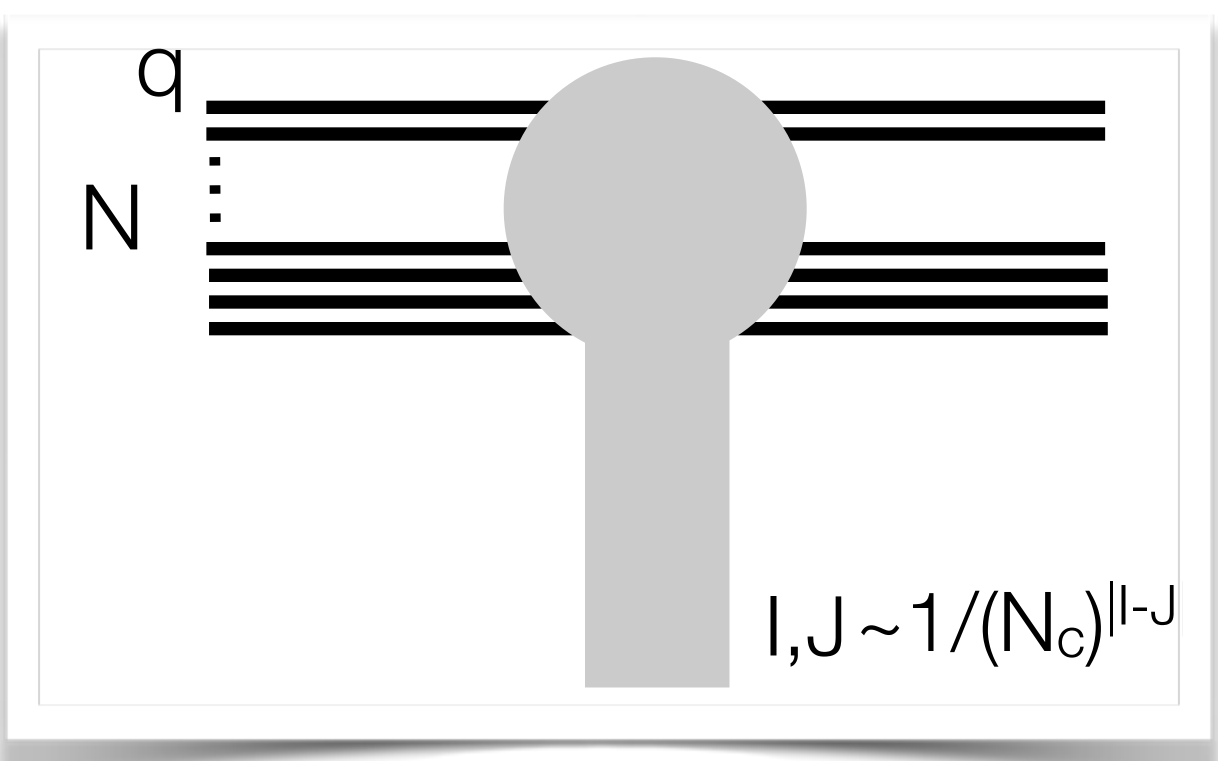


Fine-Tunings define our Universe

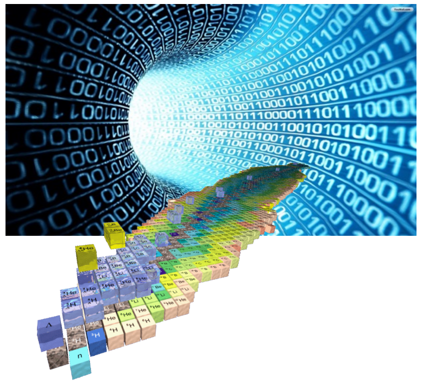




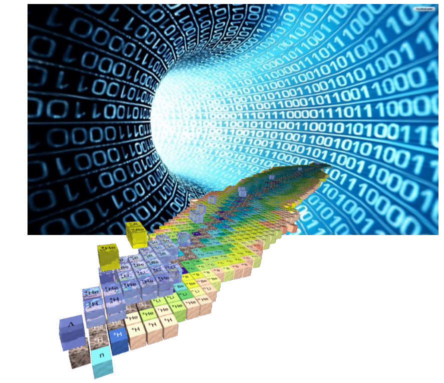




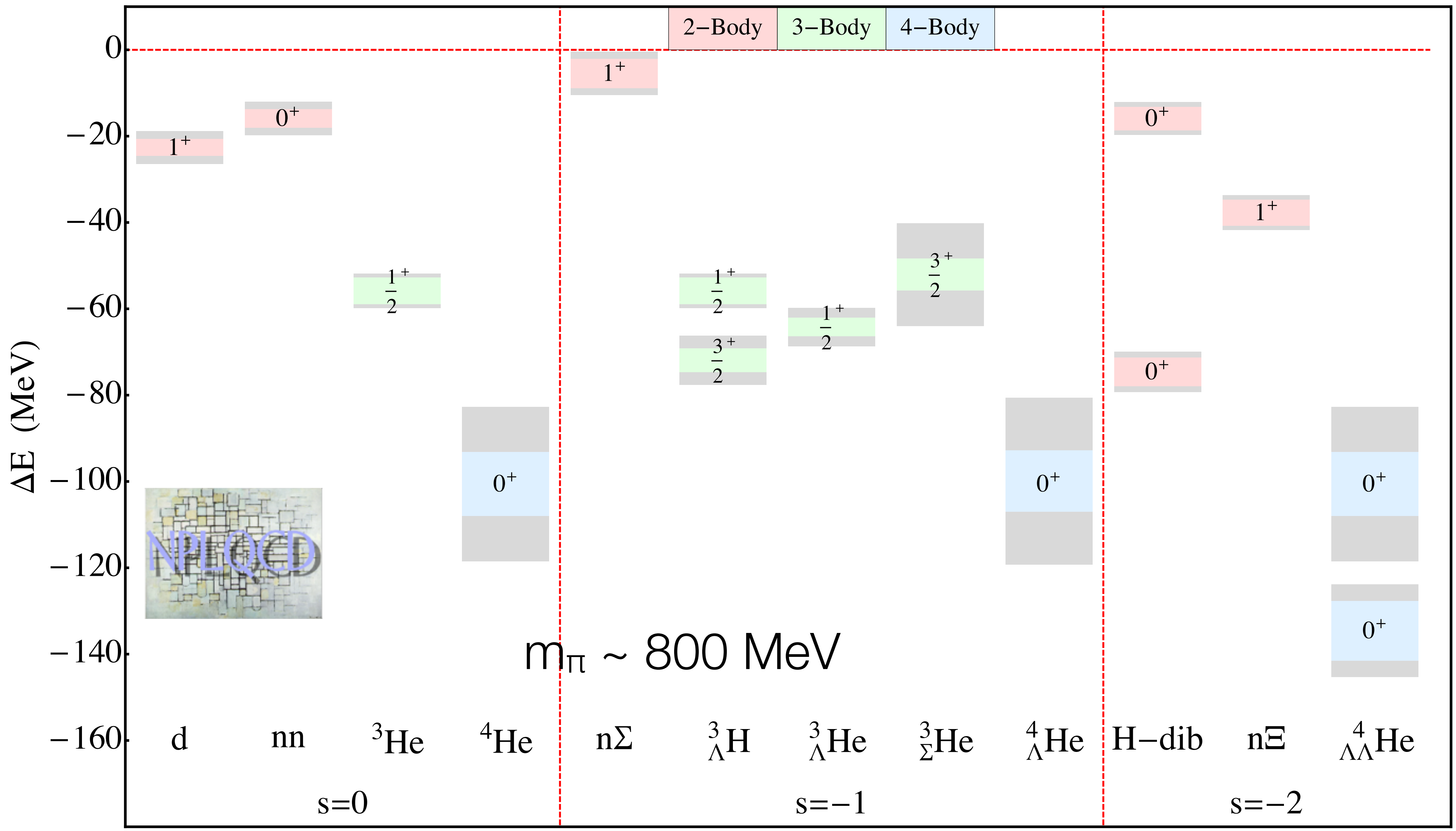
- Spin Independent up to $1/N_c^2$
  - SU(4) spin-flavor symmetry
- Near Unitarity
  - nontrivial UV fixed point



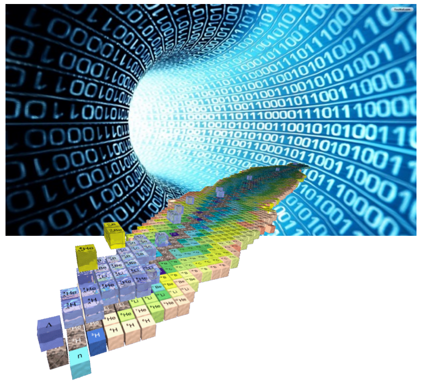
Nuclei from QCD



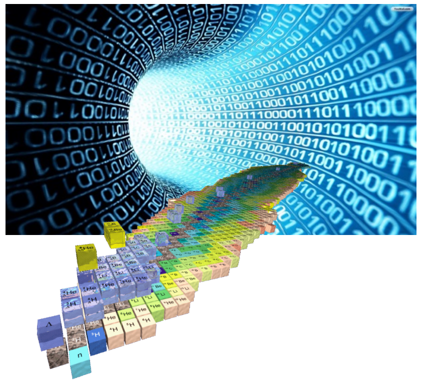
Beane *et al*, Phys.Rev. D87 (2013) 3, 034506, Phys.Rev. C88 (2013) 2, 024003

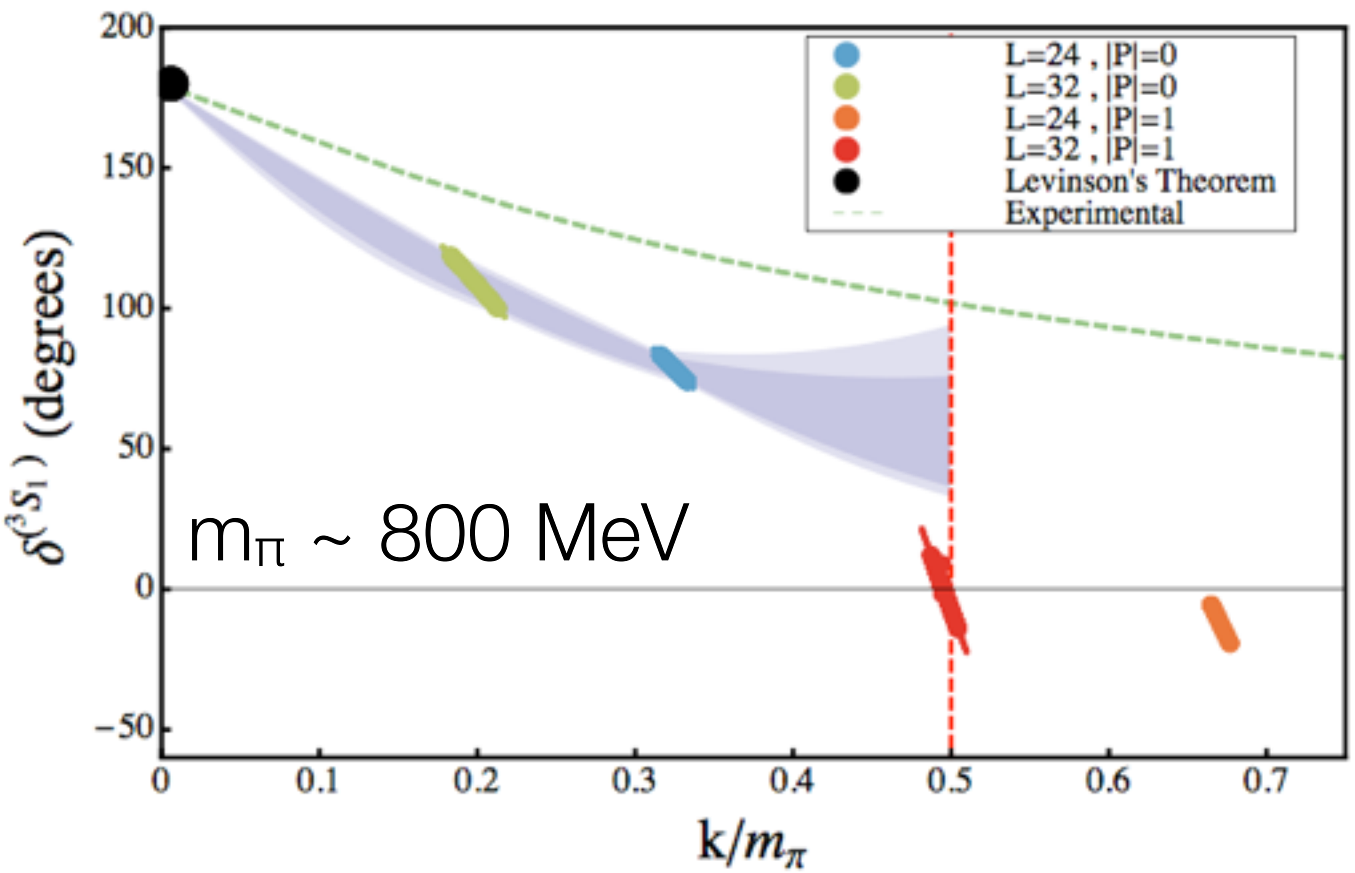


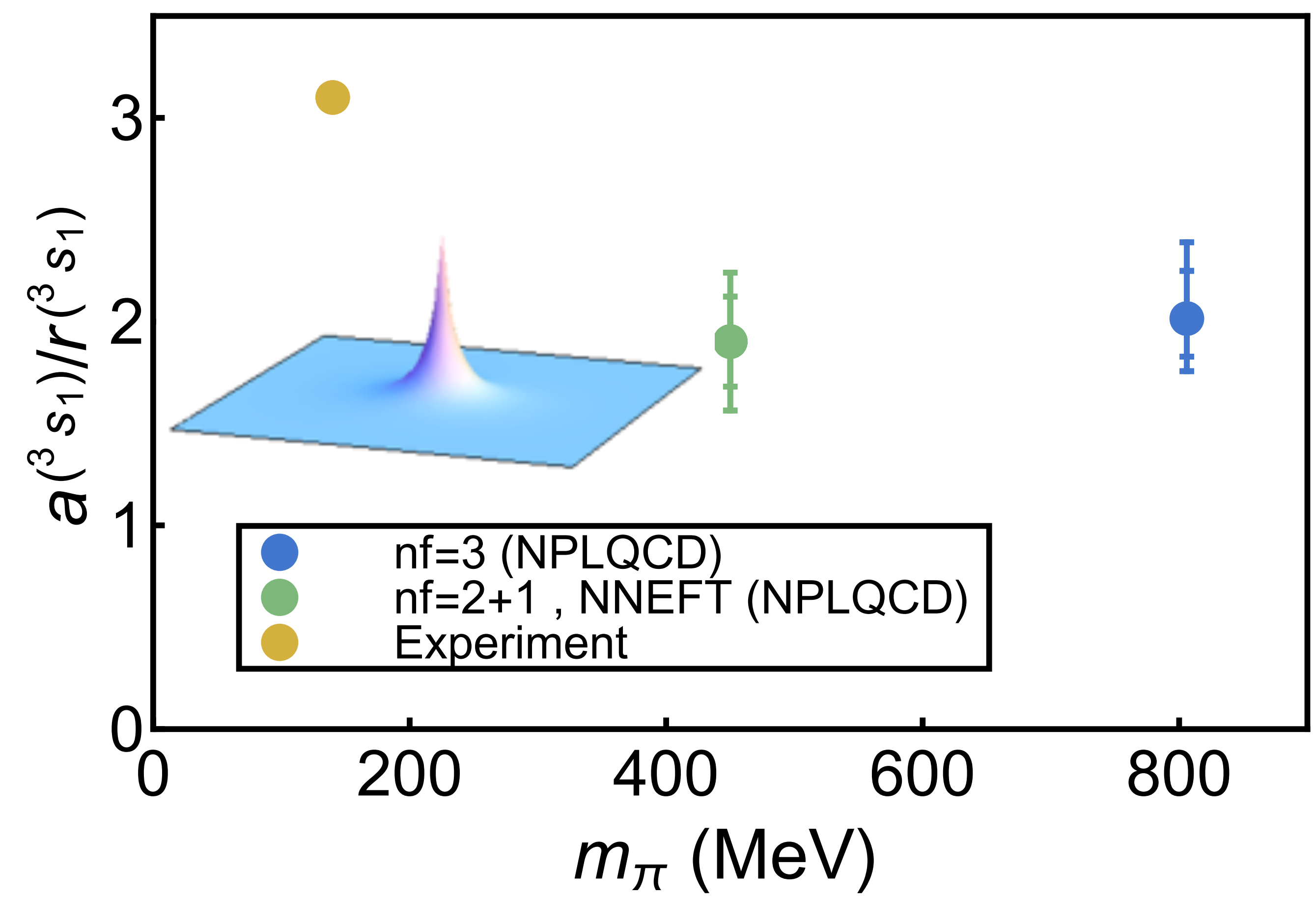
Extensive study of s-shell nuclei and hypernuclei, and baryon-baryon interactions at SU(3) symmetric point



NN Interactions

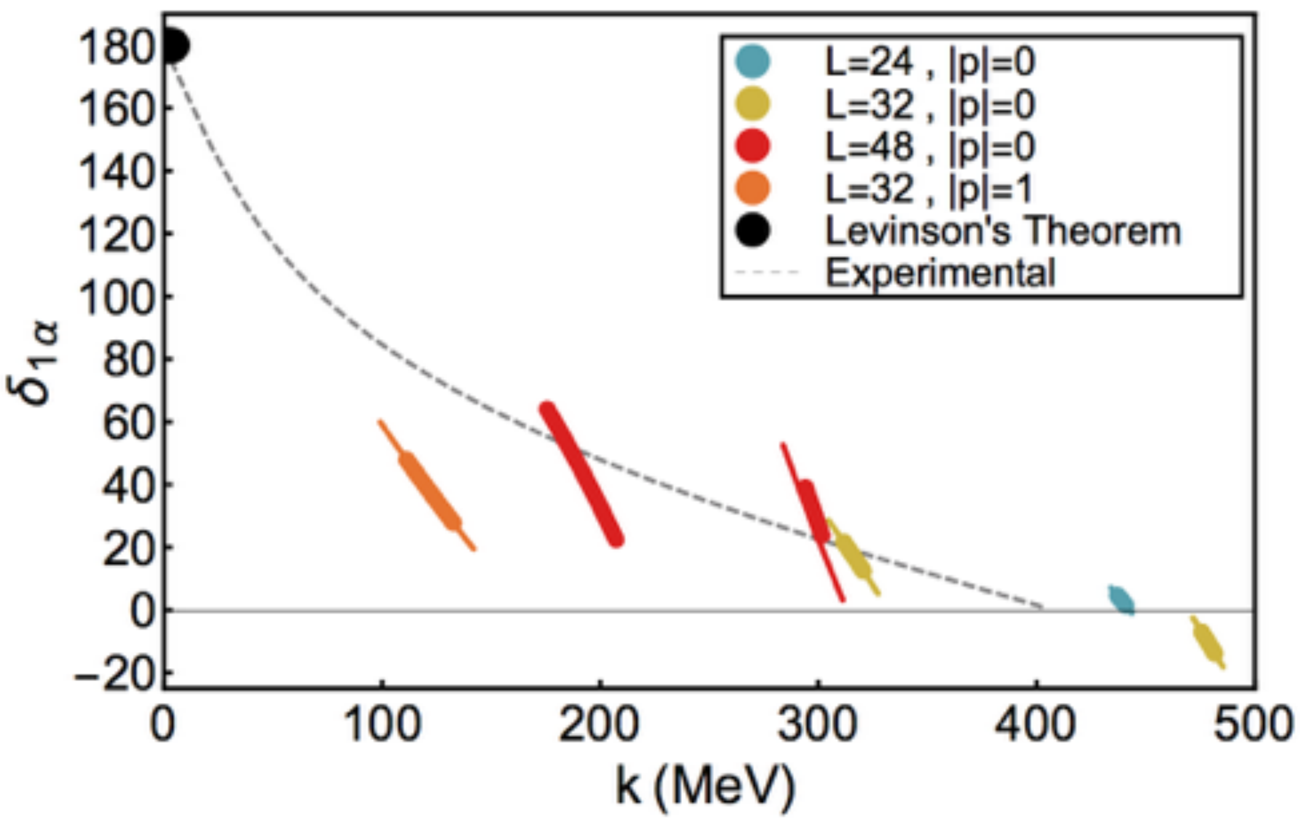


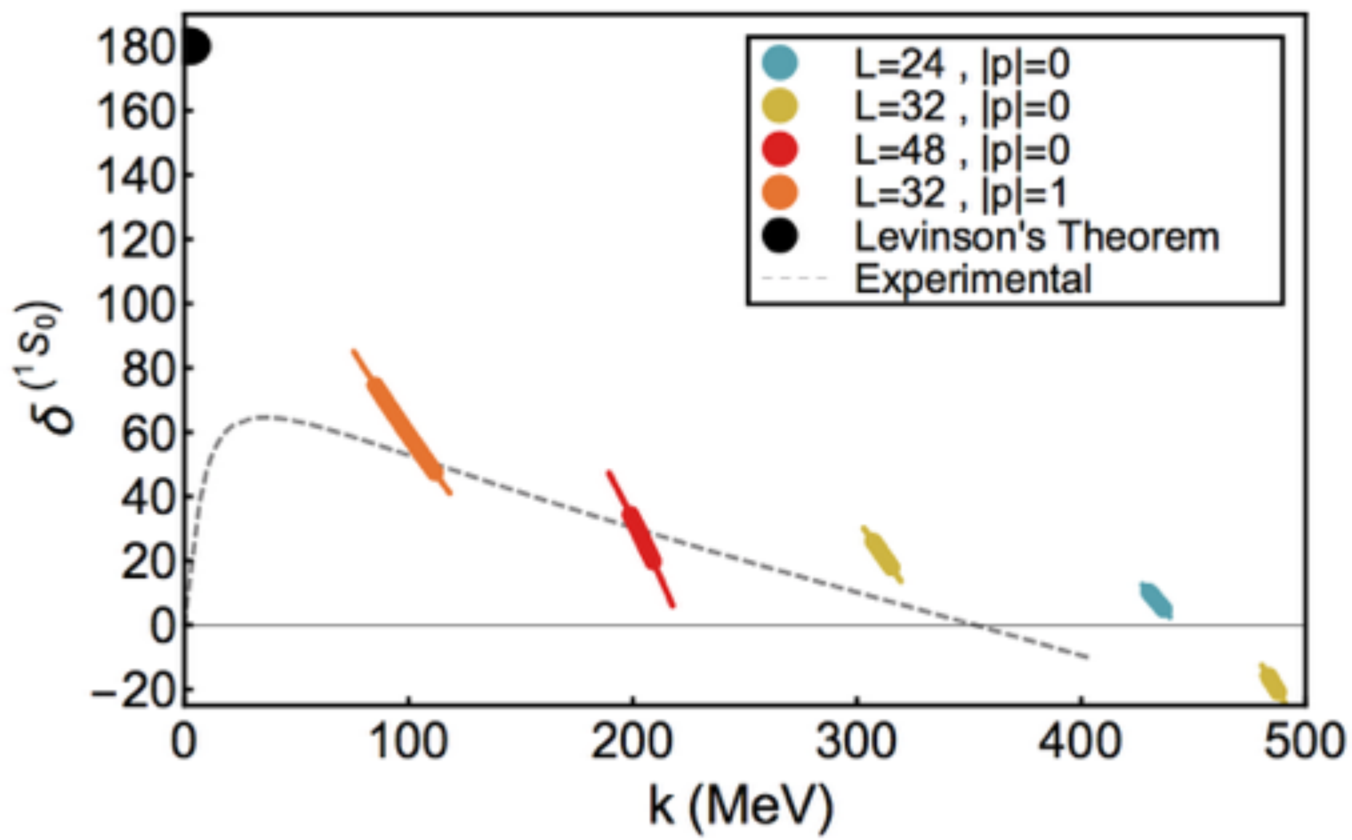




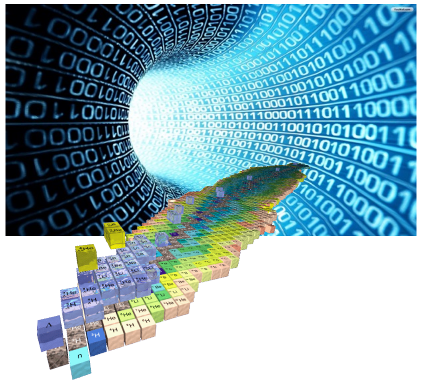
Deuteron appears to be (somewhat) unnatural
but not finely-tuned ??
Generic feature of YM with n_f=3

NN Interactions

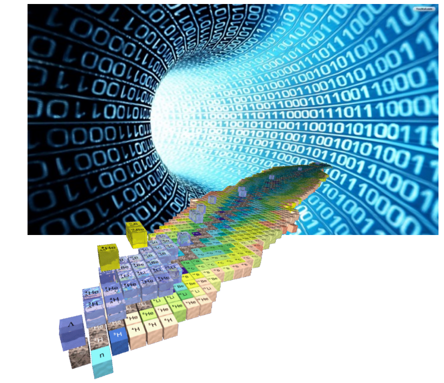


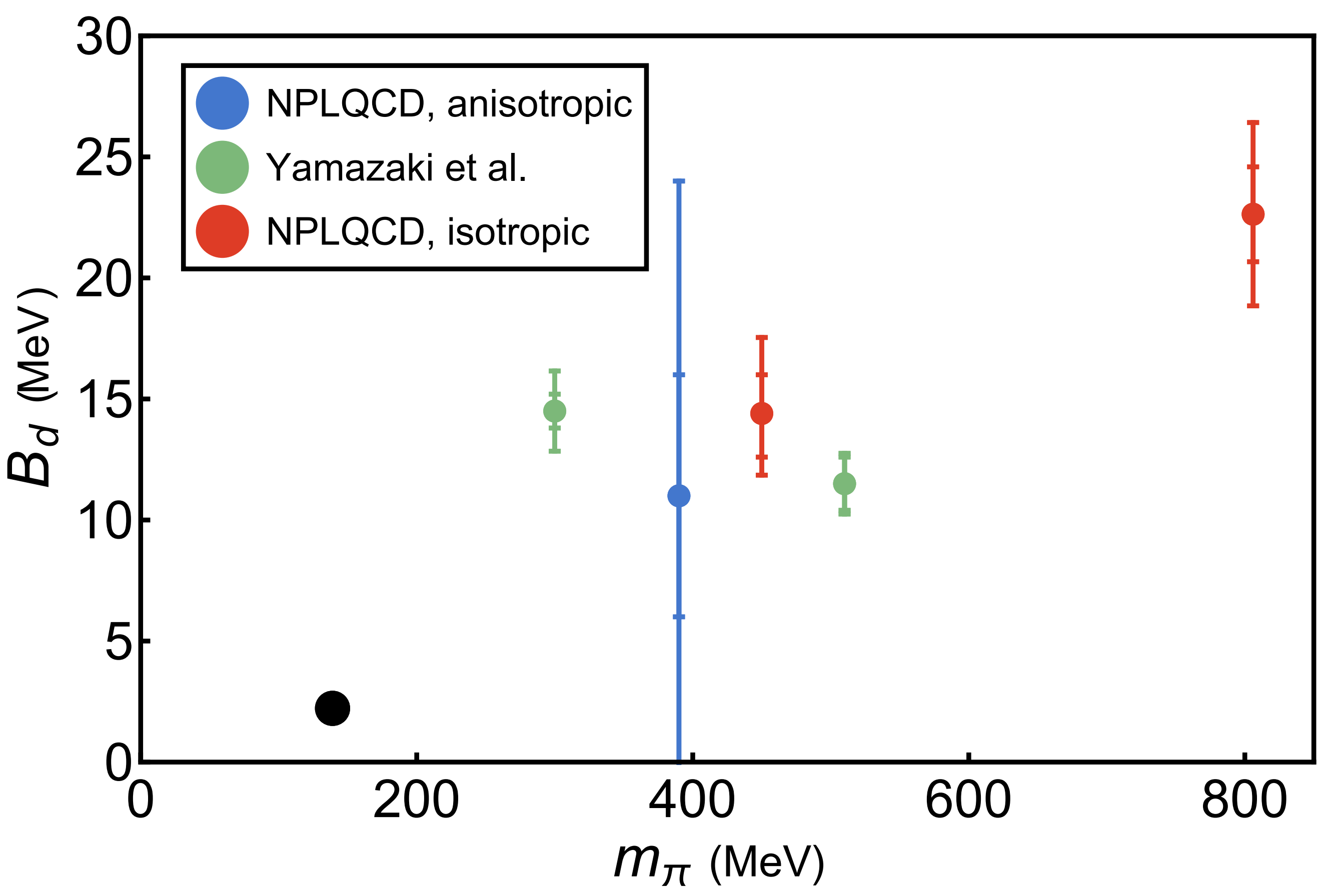


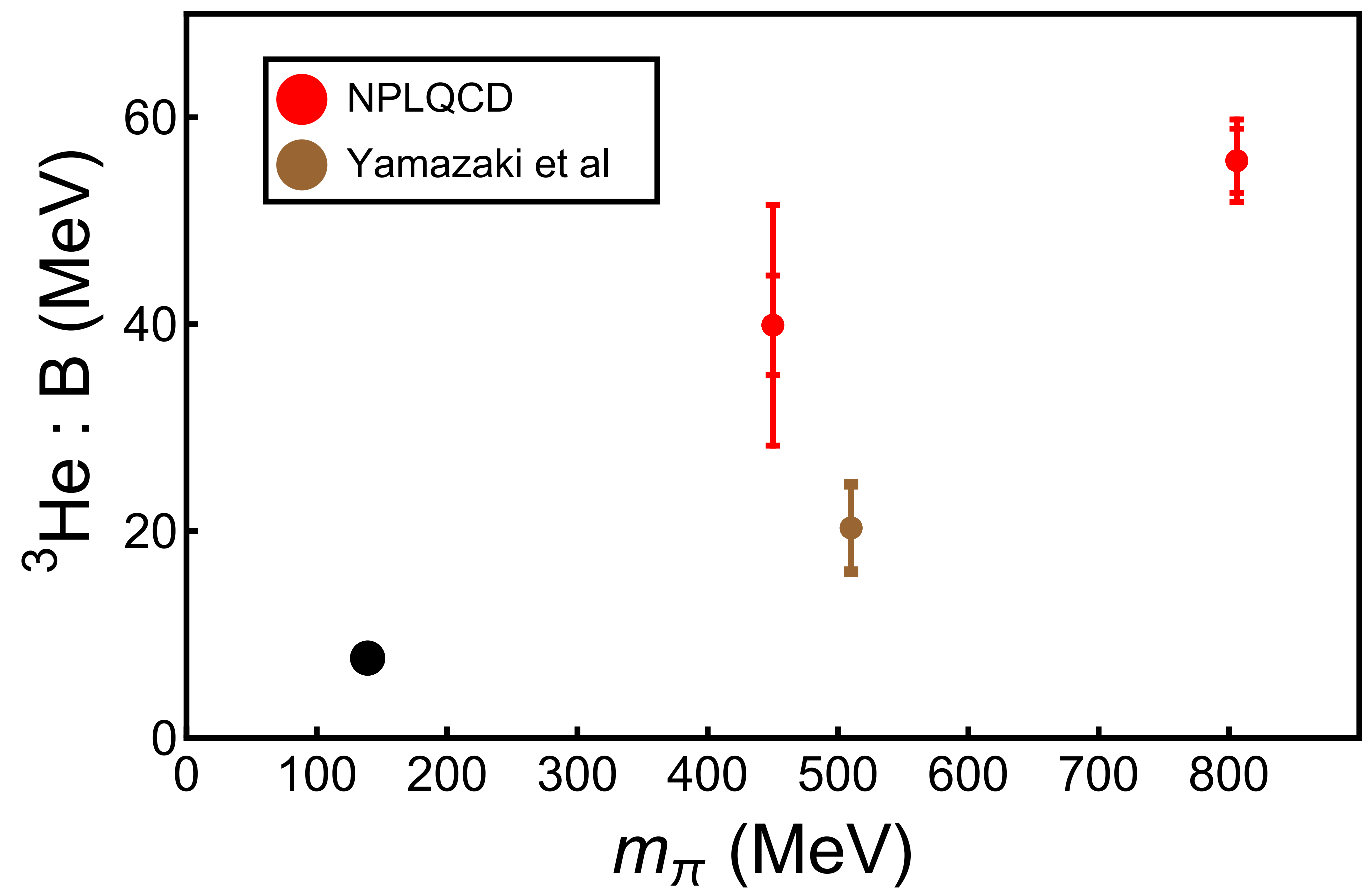
$m_\pi \sim 450$ MeV

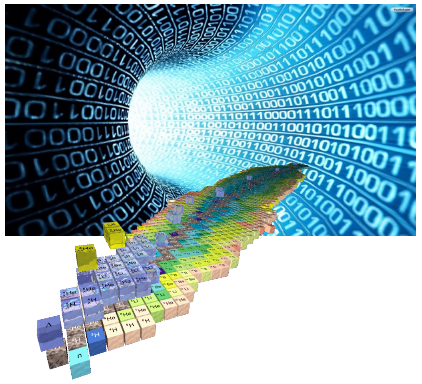


Light Nuclei :
Quark Mass Effects

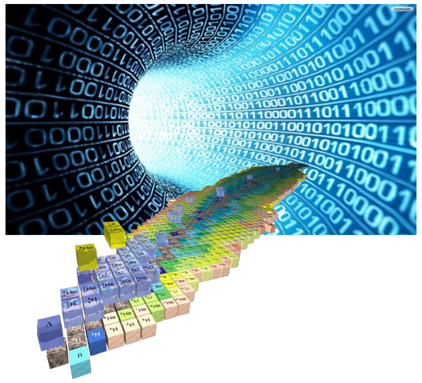




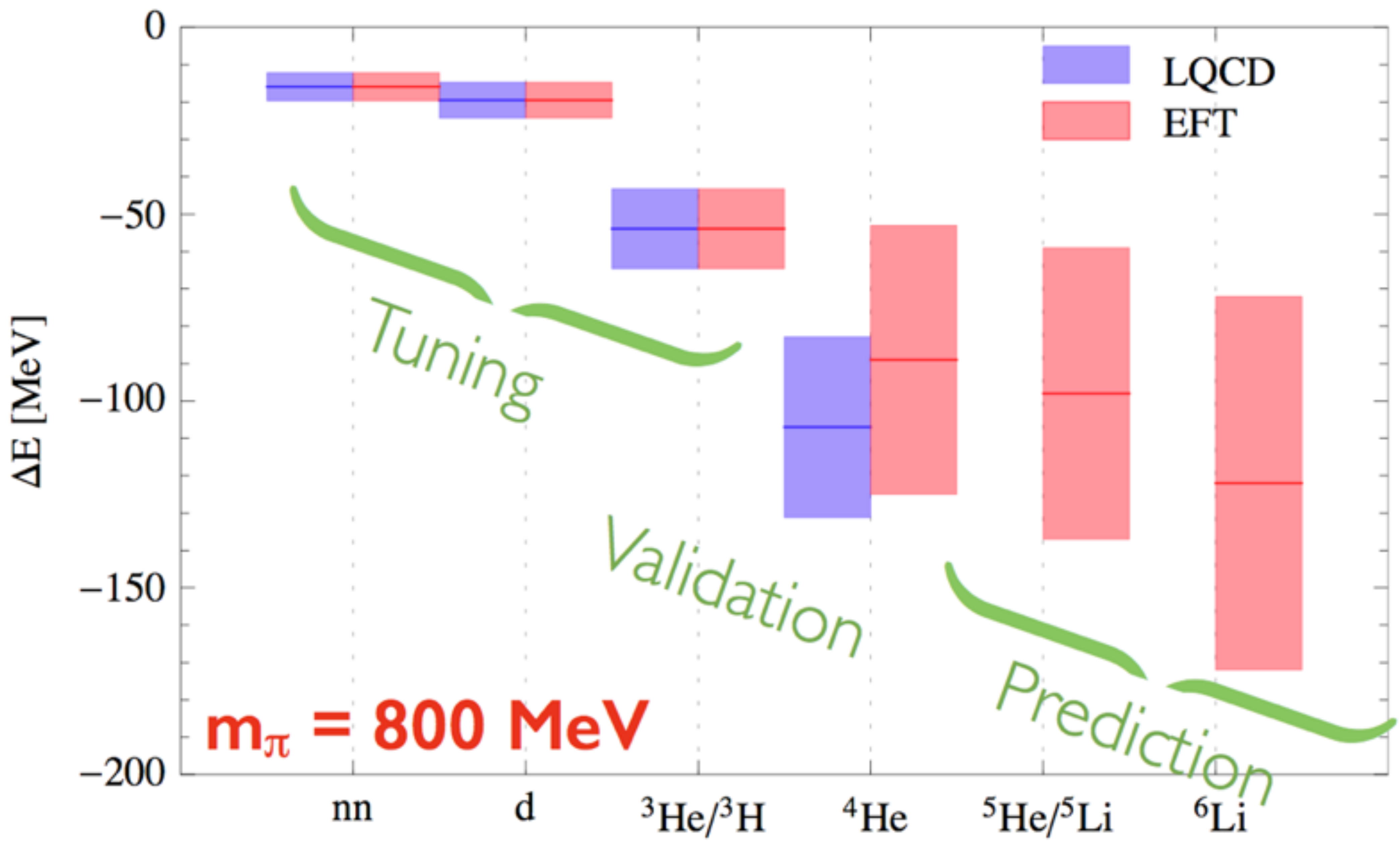




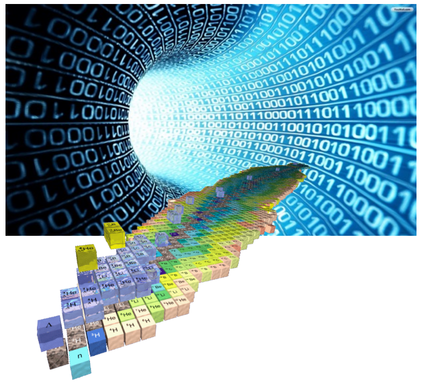
The Periodic Table as a function of the quark masses

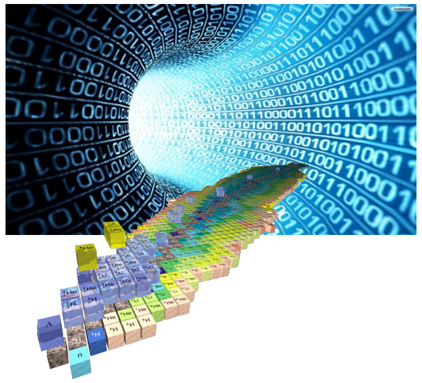


(Barnea *et al.*, Phys.Rev.Lett. 114 (2015) 5, 052501)

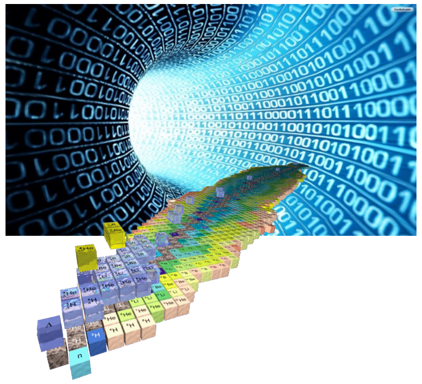


NNEFTs : Enhance scope of the Lattice Calculations

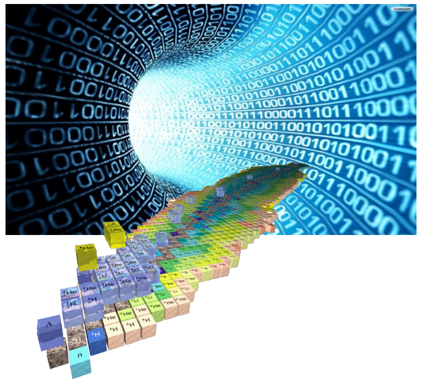




Nuclei are more than Nucleons !!



Deuteron Quadrupole Moment



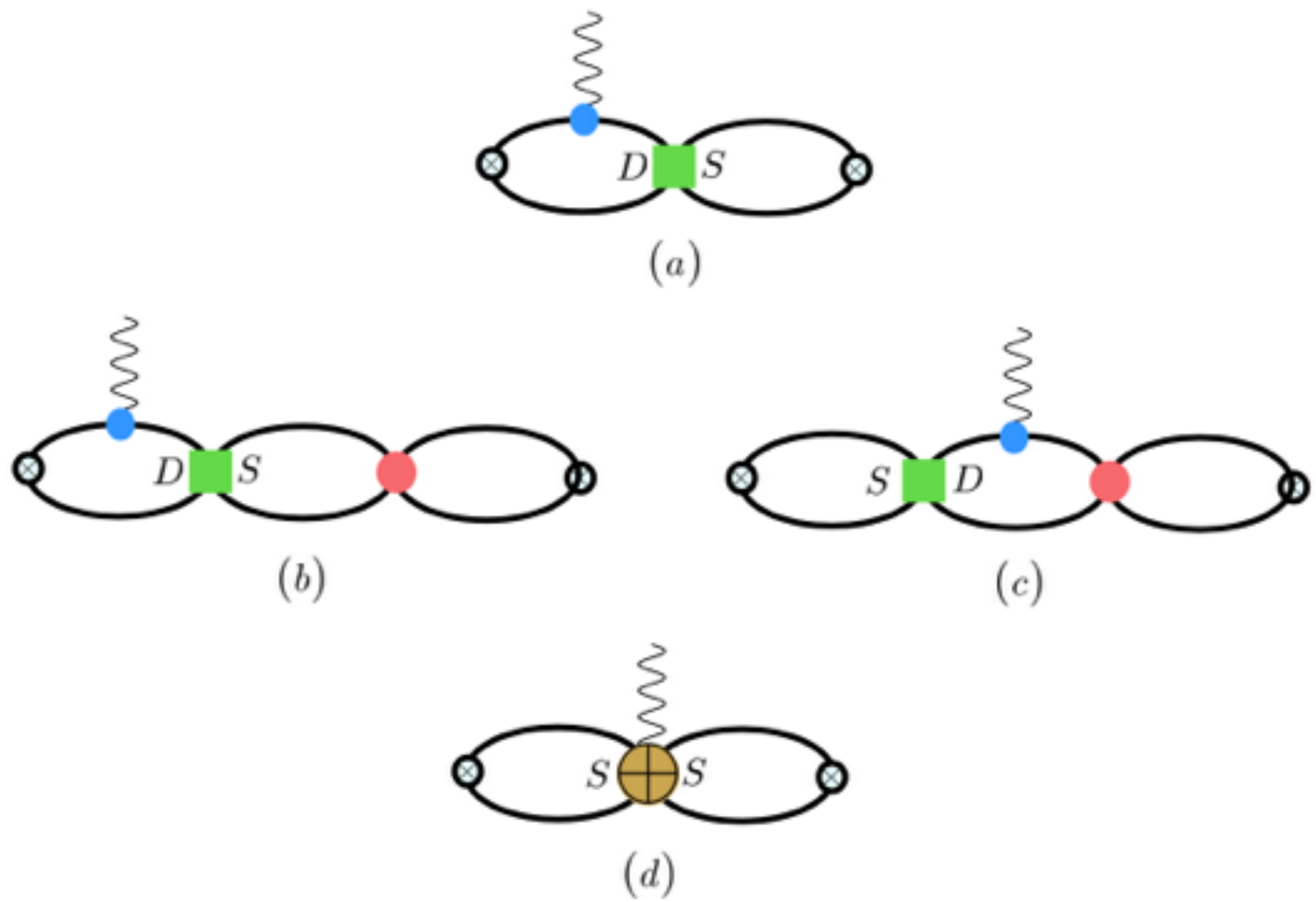


Figure 9: Some LO and NLO contributions to the deuteron quadrupole form factor. Diagrams of the form of (a) contribute at LO and higher. Diagrams of the form of (b) and (c) contribute at NLO and higher. At NLO there is a contribution from a local counterterm, diagram (d).

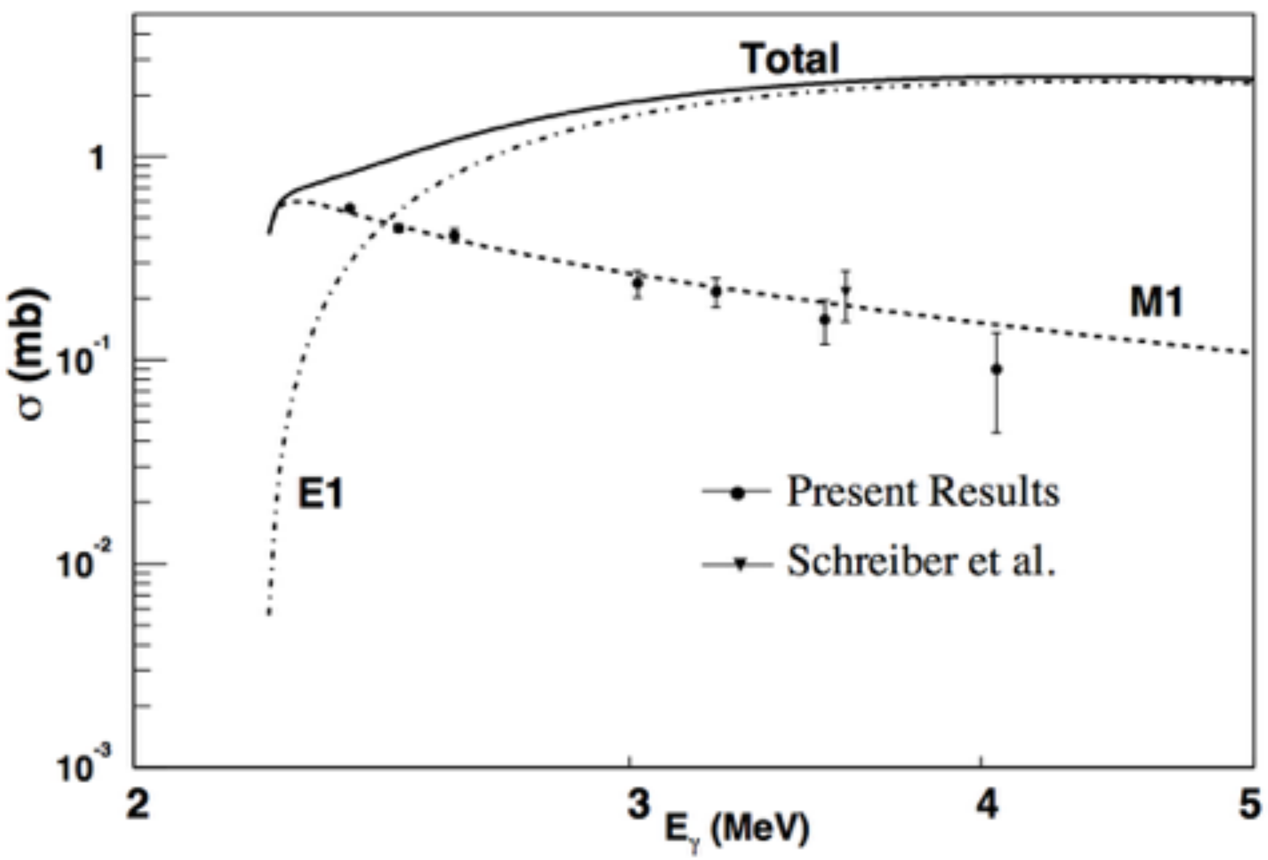
Contributions beyond single nucleon interactions

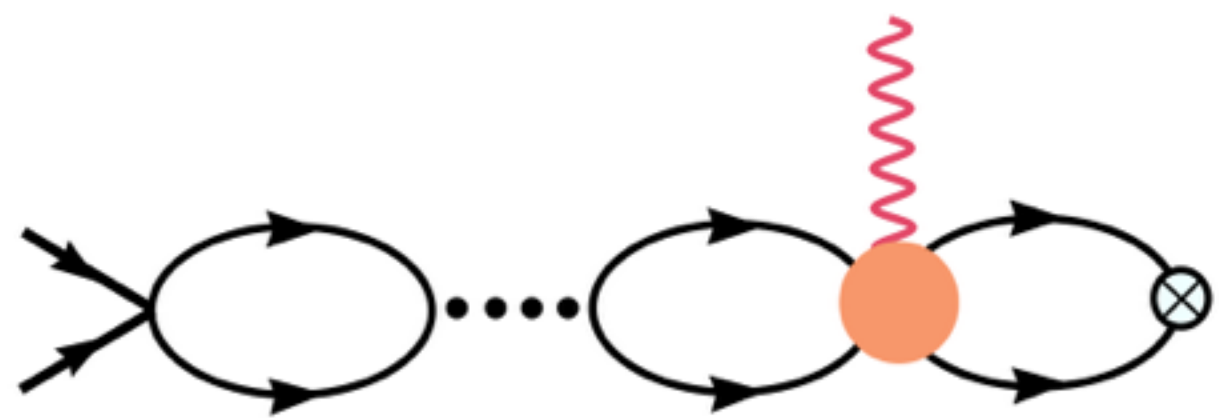
~5%

Radiative Capture :

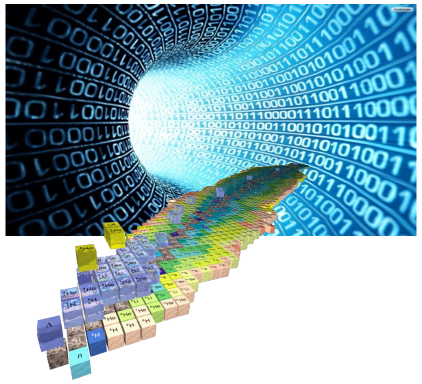
$$np \to d\gamma$$

Theory : Jiunn-Wei Chen and MJS Phys.Rev. C60 (1999) 06520
EXPT: Tornow et al, TUNL, Phys.Lett. B574 (2003) 8-13.



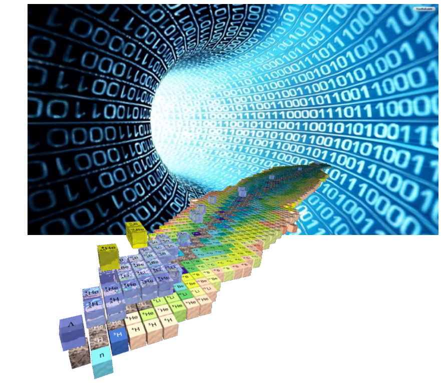


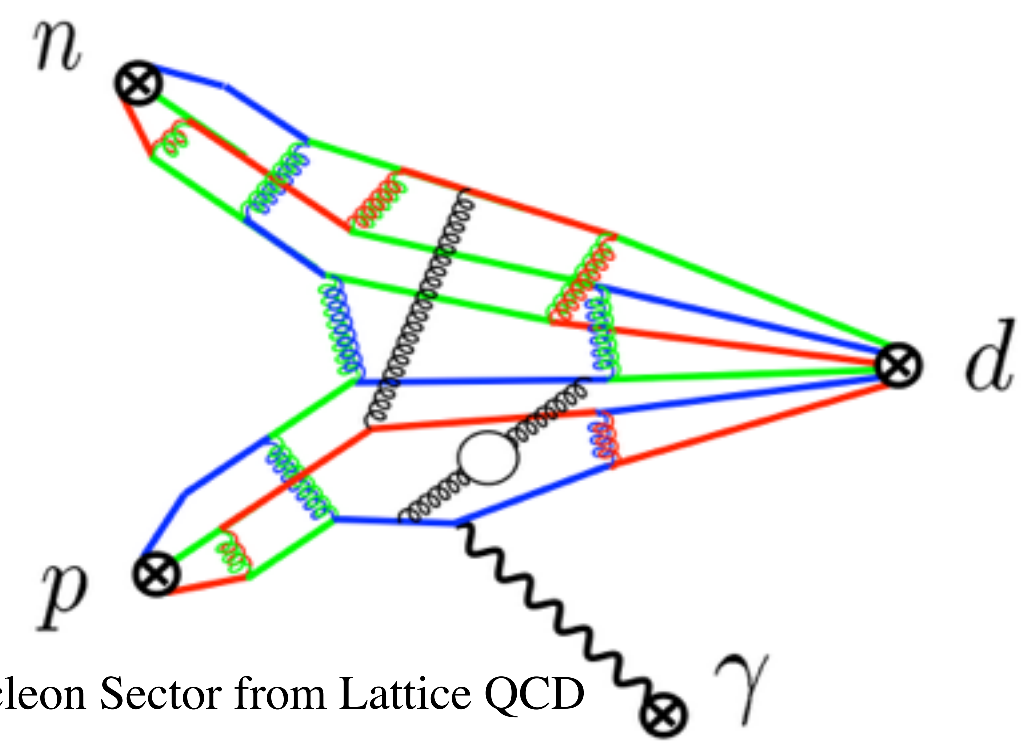
Contributions beyond single nucleon interactions
~10%

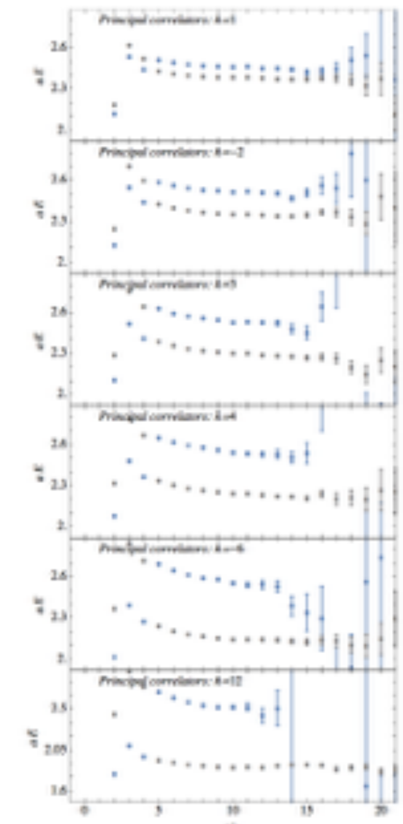


Radiative Capture :

$$np \rightarrow d\gamma$$







Electroweak Matrix Elements in the Two-Nucleon Sector from Lattice QCD
William Detmold and MJS,
Nucl. Phys. A 743, 170 (2004). hep-lat/0403005.

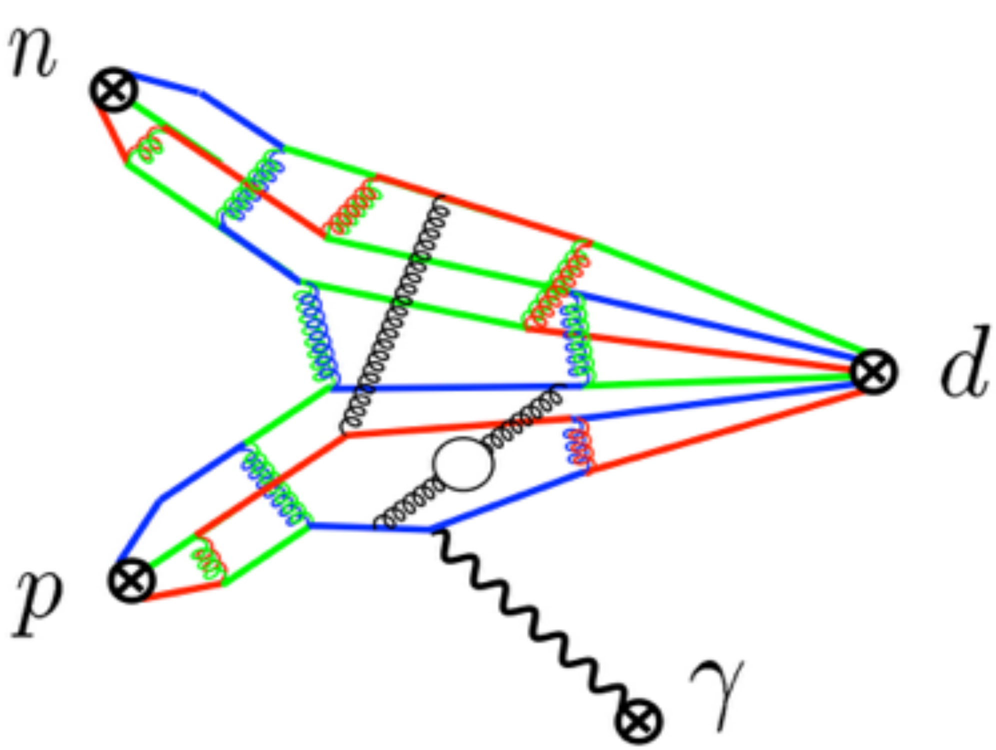
$$\left[p\cot\delta_1 - \frac{S_+ + S_-}{2\pi L} \right] \left[p\cot\delta_3 - \frac{S_+ + S_-}{2\pi L} \right] = \left[\frac{|e\mathbf{B}| l_1}{2} + \frac{S_+ - S_-}{2\pi L} \right]^2$$

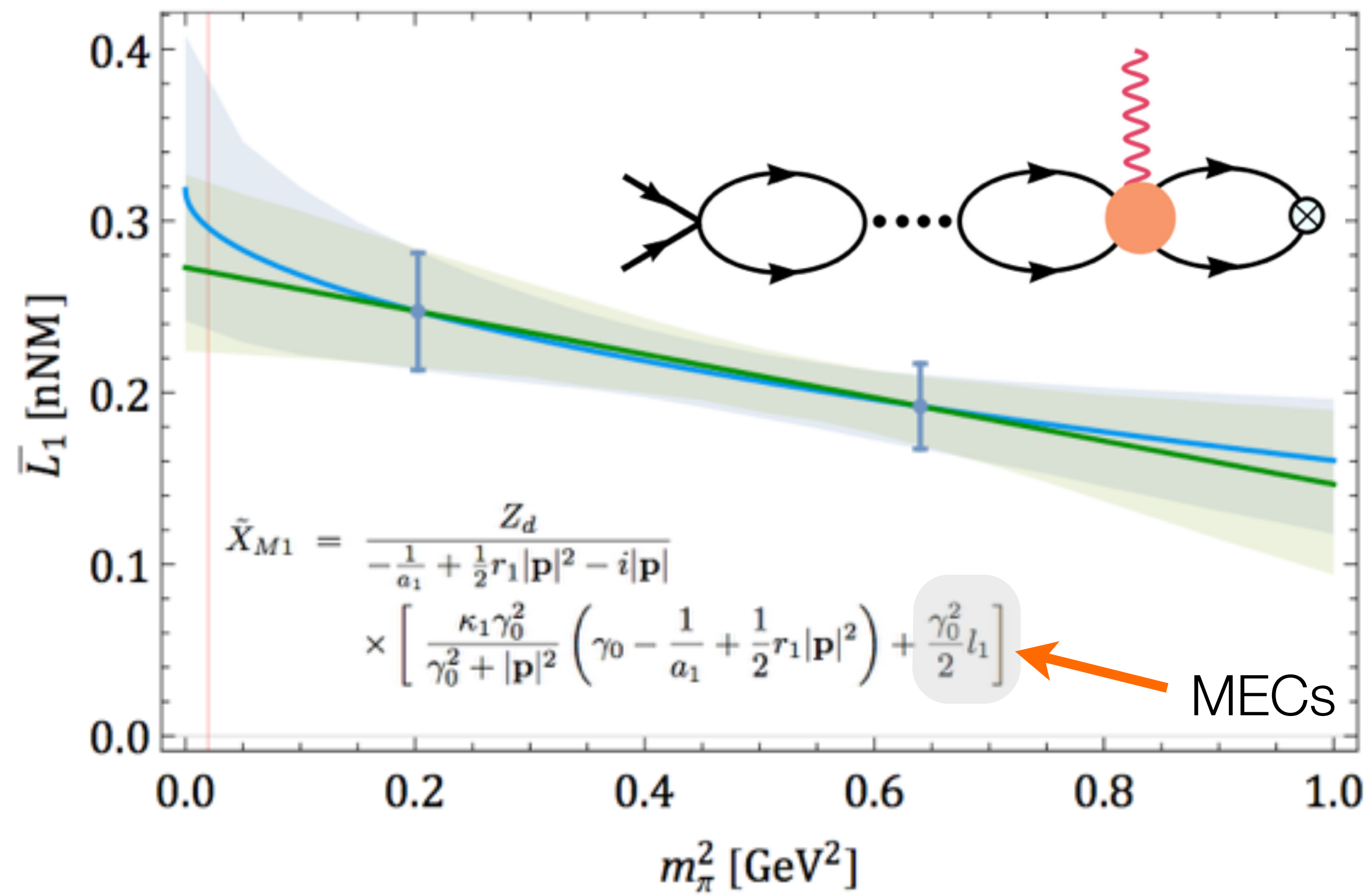
$$S_\pm \equiv S\left(\frac{L^2}{4\pi^2} (p^2 \pm |e\mathbf{B}|\kappa_1) \right)$$

$$\Delta E_{^3S_1, ^1S_0} = \mp Z_d^2 (\kappa_1 + \gamma_0 l_1) \frac{|e\mathbf{B}|}{M} + \ldots = \mp (\kappa_1 + \overline{L}_1) \frac{|e\mathbf{B}|}{M} + \ldots$$

Radiative Capture : $np \to d\gamma$

Ab Initio Calculation of the np → dγ Radiative Capture Process
NPLQCD, arXiv:1505.02422



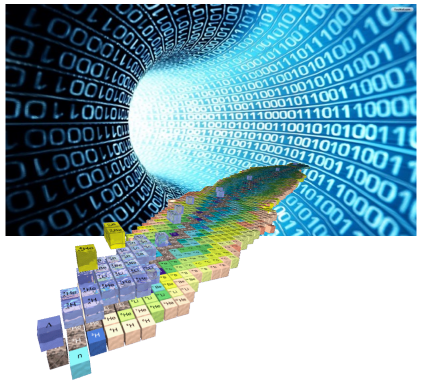


physical point:

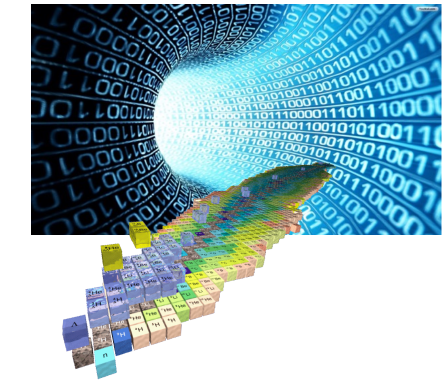
$$\sigma^{\mathrm{lqcd}} = 332.4\left({}^{+5.4}_{-4.7} \right)\ \mathrm{mb} \qquad v = 2,200\ \mathrm{m/s}$$

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

[306 mb single nucleons alone]



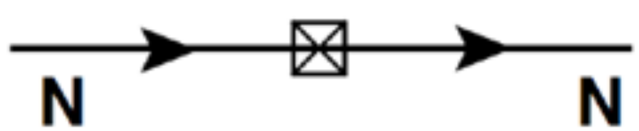
Nuclear σ-Terms and Dark Matter Interactions

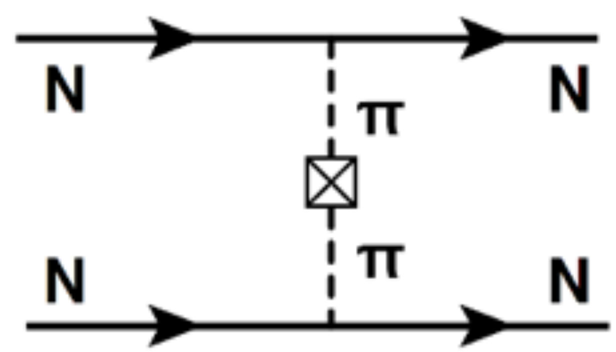


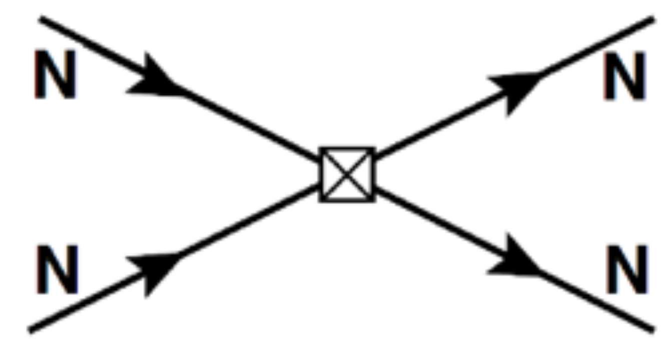
NPLQCD : Phys.Rev. D89 (2014) 074505 , arXiv:1306.6939 (2013)

$$\mathcal{L} = G_F\, \overline{\chi}\chi \sum_q a_S^{(q)}\, \overline{q}q \;=\; G_F\, \overline{\chi}\chi\, \overline{q} a_S q$$

$$= \frac{G_F}{2}\, \overline{\chi}\chi \left[(a_S^{(u)} + a_S^{(d)})\overline{q}q \;+\; (a_S^{(u)} - a_S^{(d)})\overline{q}\tau^3 q \;+\; 2\, a_S^{(s)}\overline{s}s \;+\; \ldots \right]$$

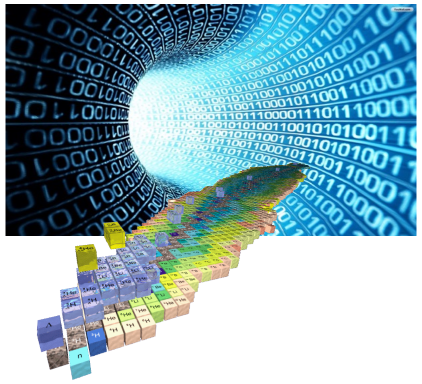




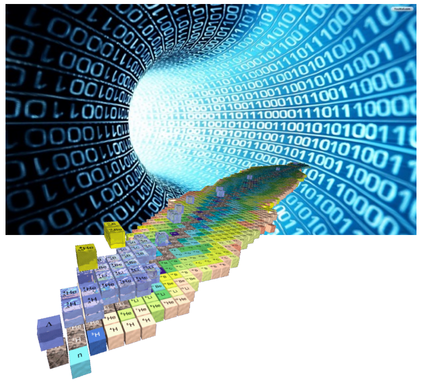


Usual assumption

Required by QCD !
How big ??



Nuclear σ-Terms and Dark Matter Interactions



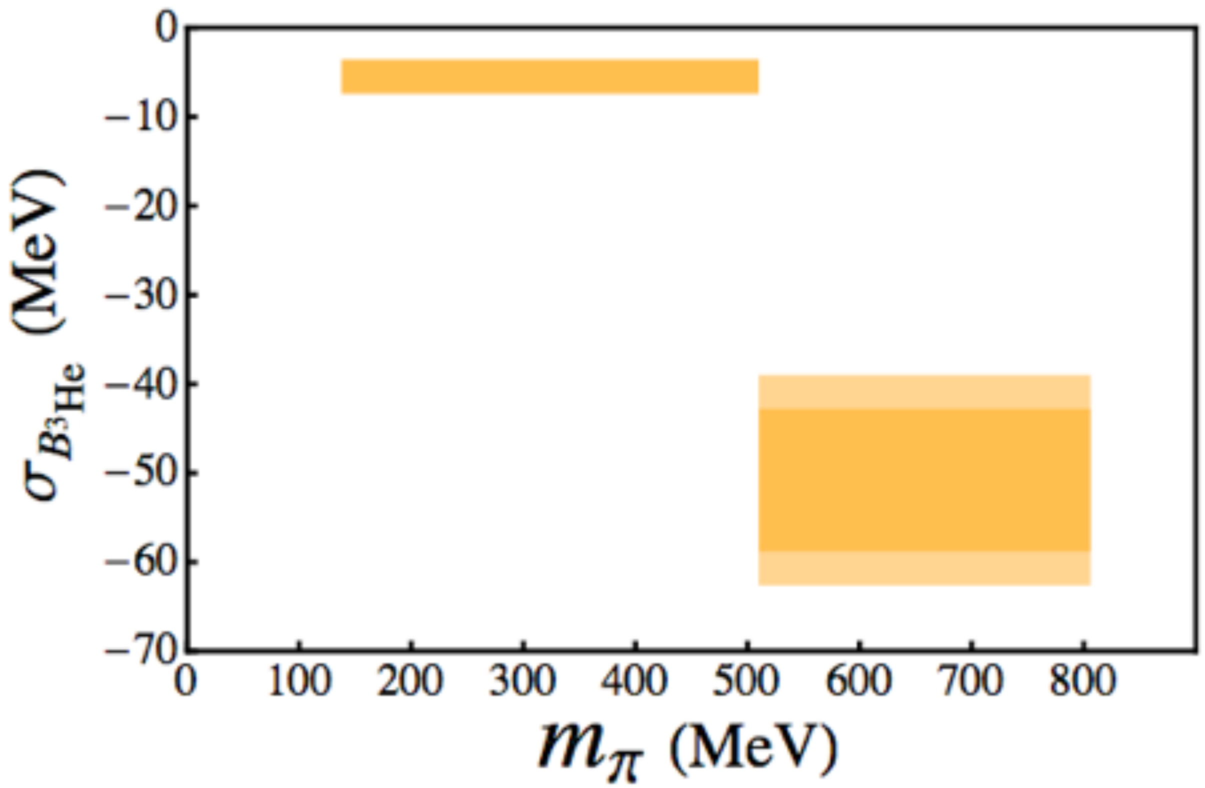
NPLQCD : Phys.Rev. D89 (2014) 074505 , arXiv:1306.6939 (2013)

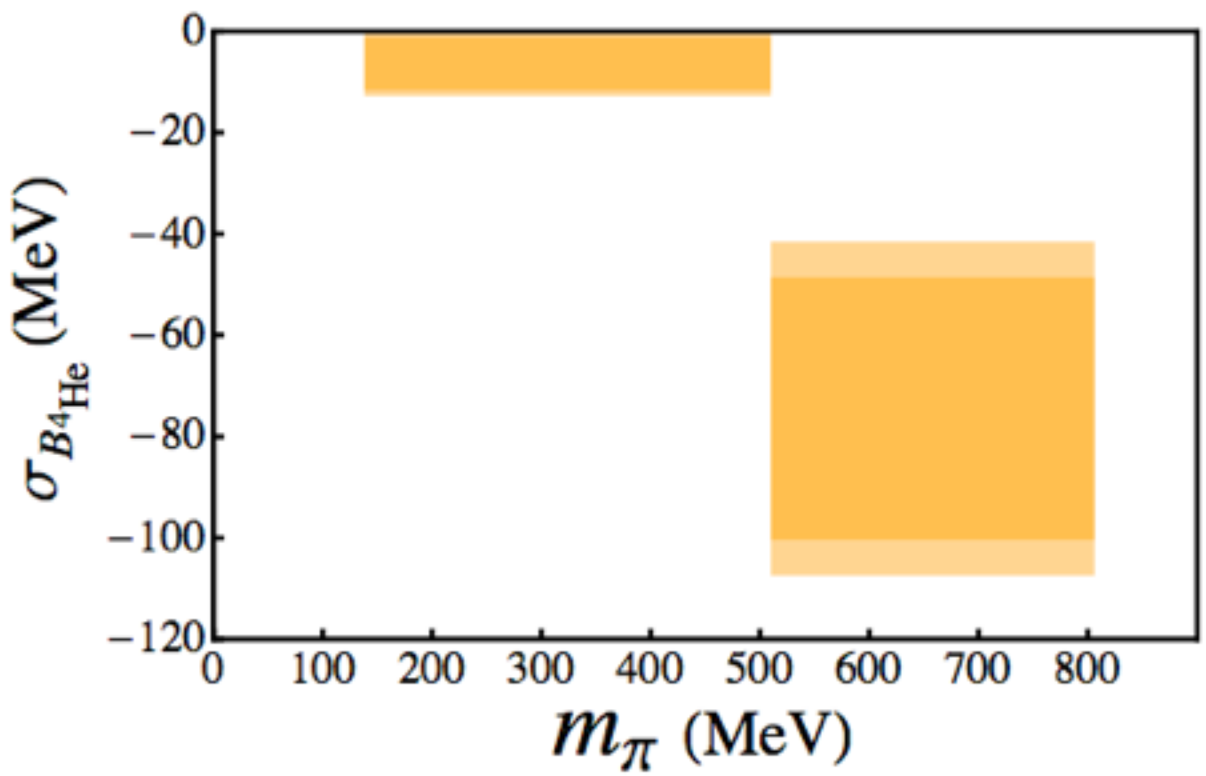
Nuclear σ-terms

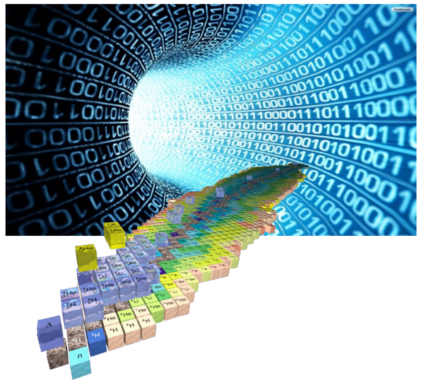
$$\sigma_{Z,N} = \overline{m}\langle Z,N(\mathrm{gs})|\ \overline{u}u + \overline{d}d\ |Z,N(\mathrm{gs})\rangle = \overline{m}\frac{d}{d\overline{m}}E^{(\mathrm{gs})}_{Z,N}$$

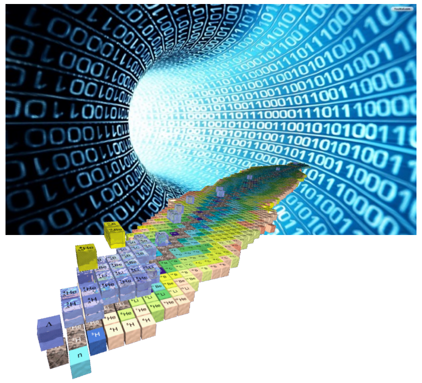
$$= \left[\ 1\ +\ \mathcal{O}\left(m_\pi^2\right)\ \right]\frac{m_\pi}{2}\frac{d}{dm_\pi}E^{(\mathrm{gs})}_{Z,N}$$

σ-terms from the binding energy only



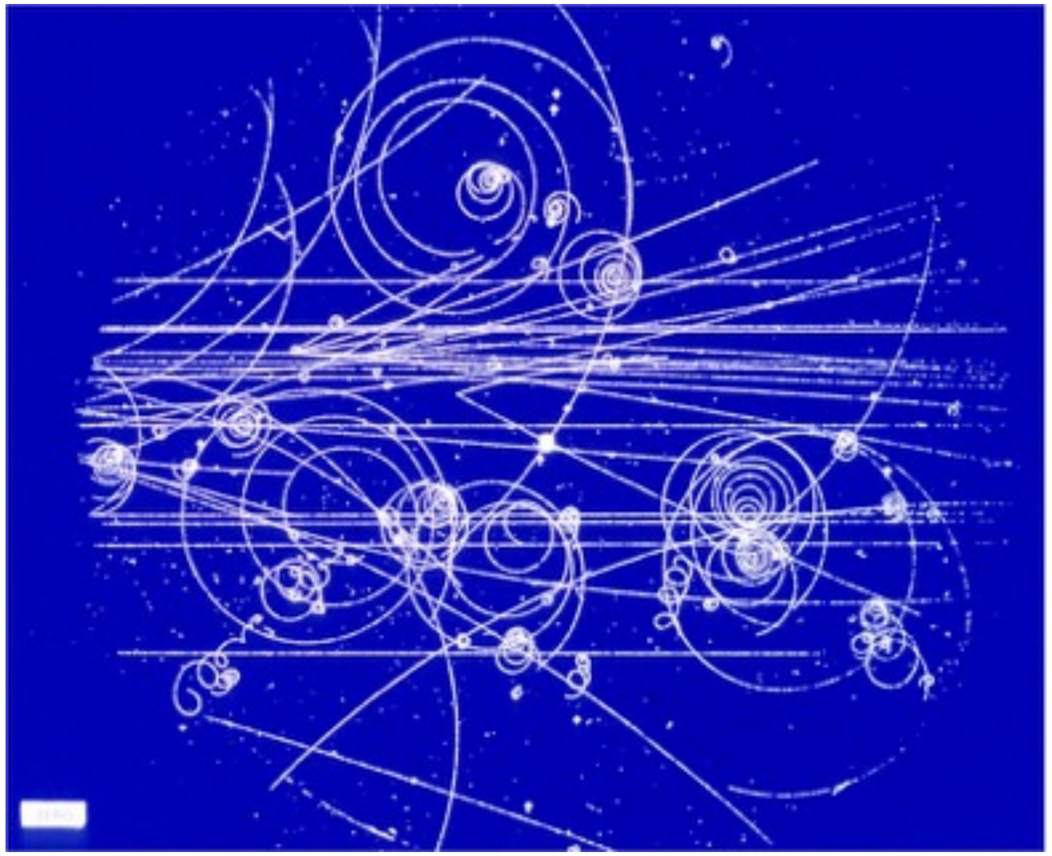






Nuclei in Large Magnetic Fields

Magnetic Moments
Expectations and Landau Levels



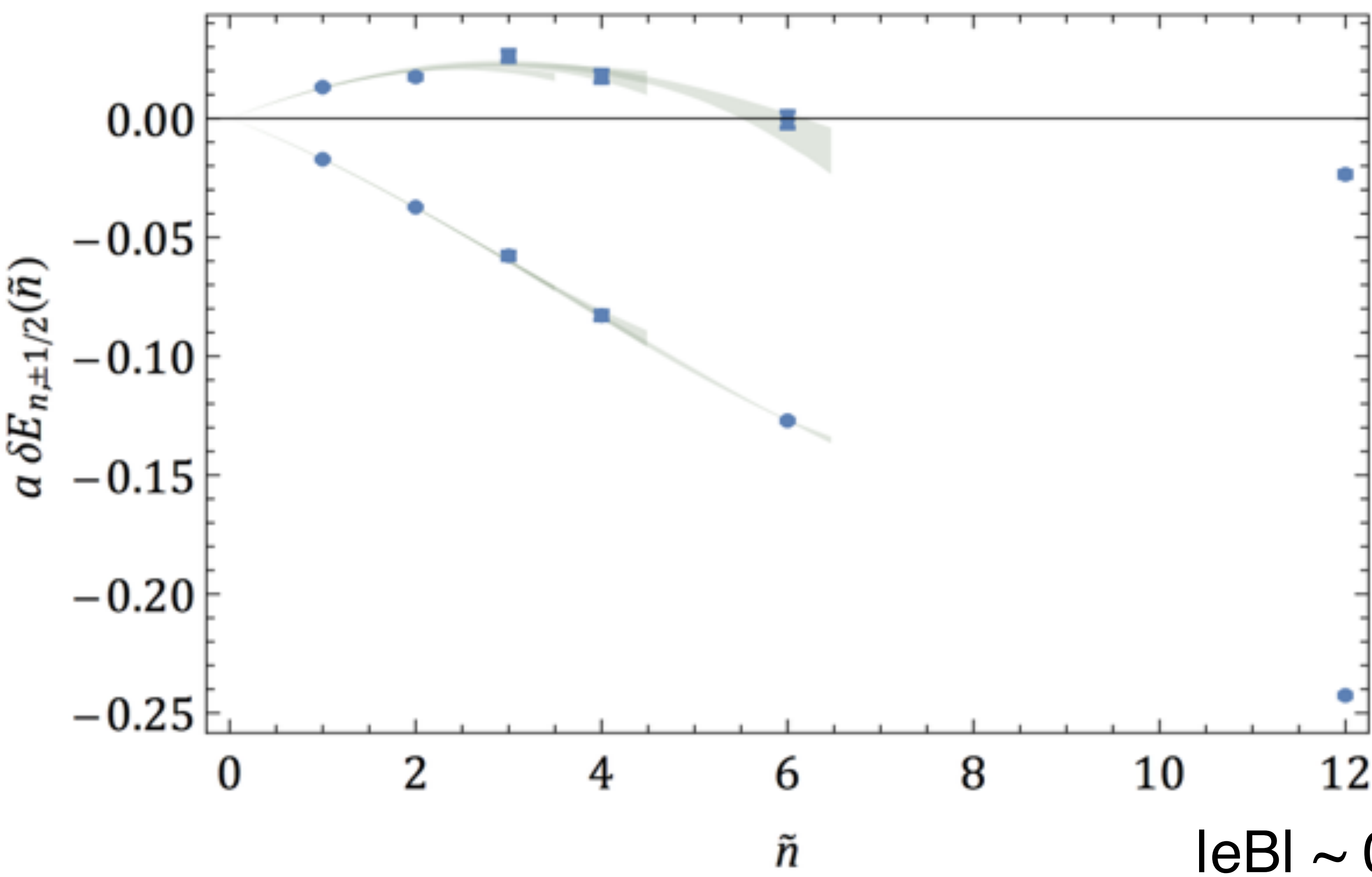
$$E_{h;j_z}(\mathbf{B}) \;=\; \sqrt{M_h^2 + P_{\|}^2 + (2n_L+1)|Q_h e\mathbf{B}|} - \boldsymbol{\mu}_h \cdot \mathbf{B} - 2\pi\beta_h^{(M0)}|\mathbf{B}|^2 - 2\pi\beta_h^{(M2)}\langle \hat{T}_{ij} B_i B_j\rangle + \ldots$$

$$\hat{T}_{ij} \;=\; \frac{1}{2}\left[\;\hat{J}_i\hat{J}_j + \hat{J}_j\hat{J}_i - \frac{2}{3}\delta_{ij}\hat{J}^2\;\right]$$

Landau levels present for charged particles contaminate the extraction of polarizabilities

Magnetic Moments
Neutron Spin States

$m_\pi \sim 800$ MeV

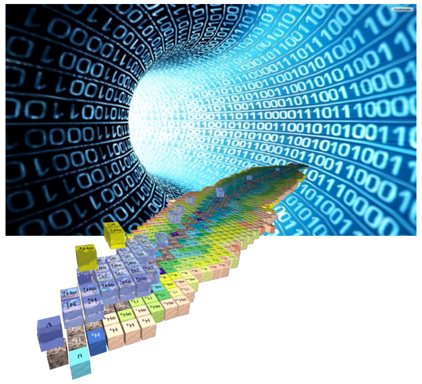


400 MeV

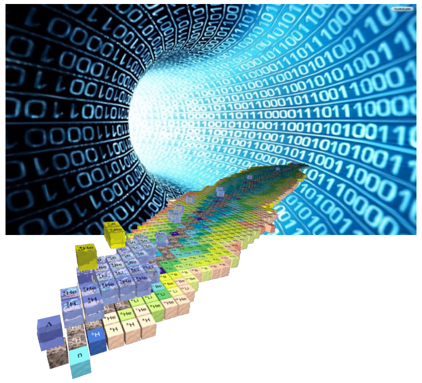
$|eB| \sim 0.7\ \mathrm{GeV}^2$

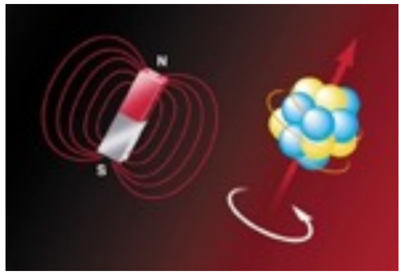
$\sim 10^{20}$ Gauss

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



Magnetic Moments

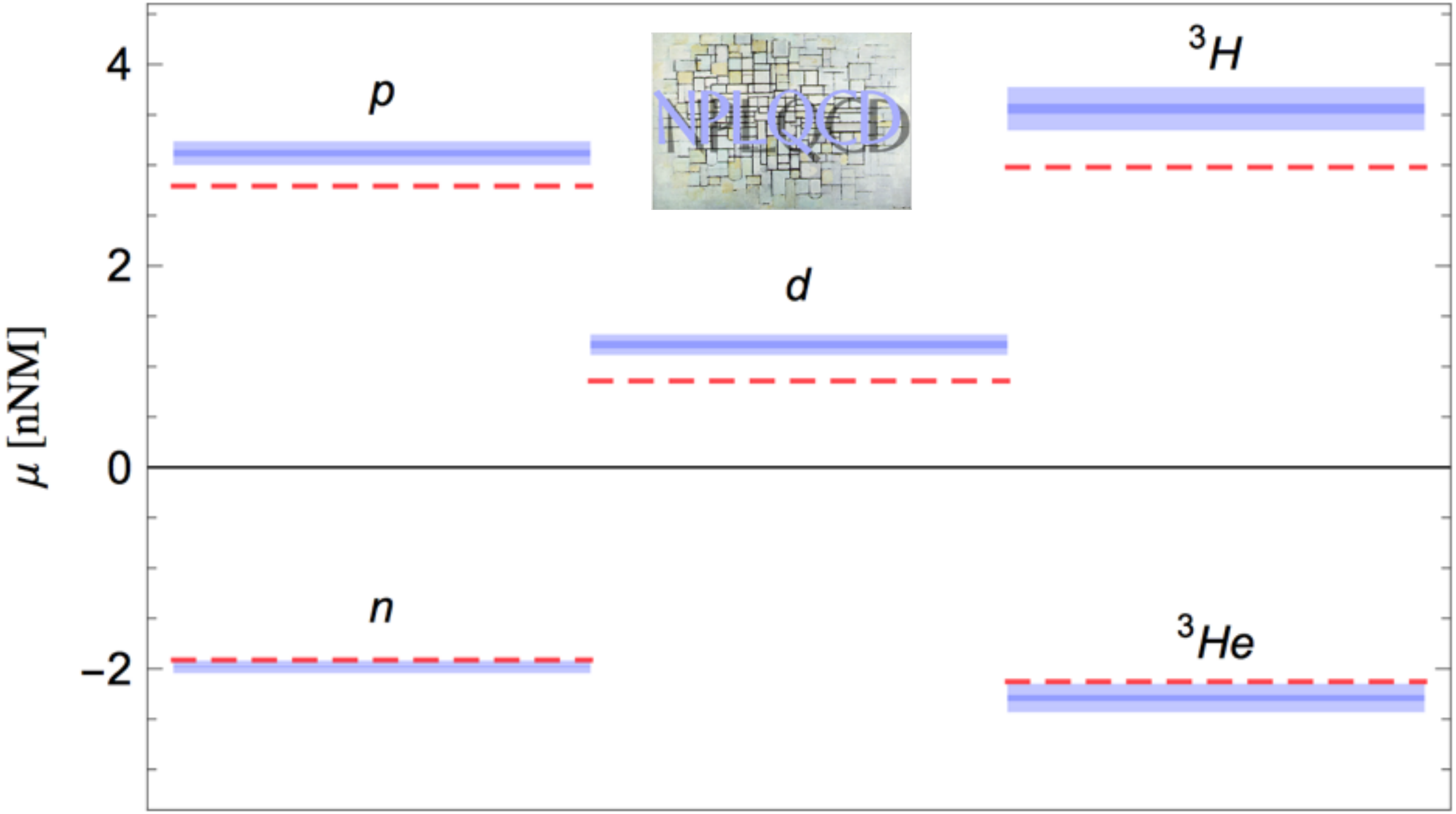




Magnetic moments of light nuclei from lattice quantum chromodynamics

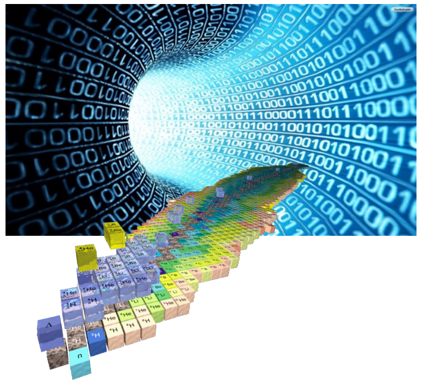
S.R. Beane, E. Chang, S. Cohen, W. Detmold, H.W. Lin, K. Orginos, A. Parreno, M.J. Savage, B.C. Tiburzi

Published in **Phys.Rev.Lett. 113 (2014) 25, 252001**
e-Print: **arXiv:1409.3556 [hep-lat]**

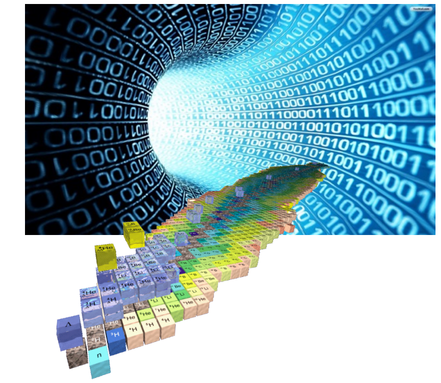


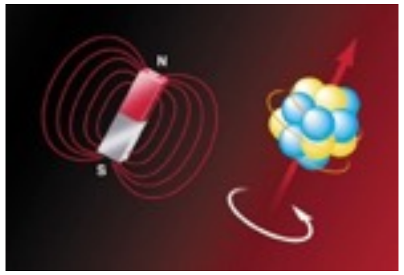
$$\frac{e}{2M(m_\pi)}$$

m_π ~ 800 MeV   Vs   Nature



Magnetic Moments





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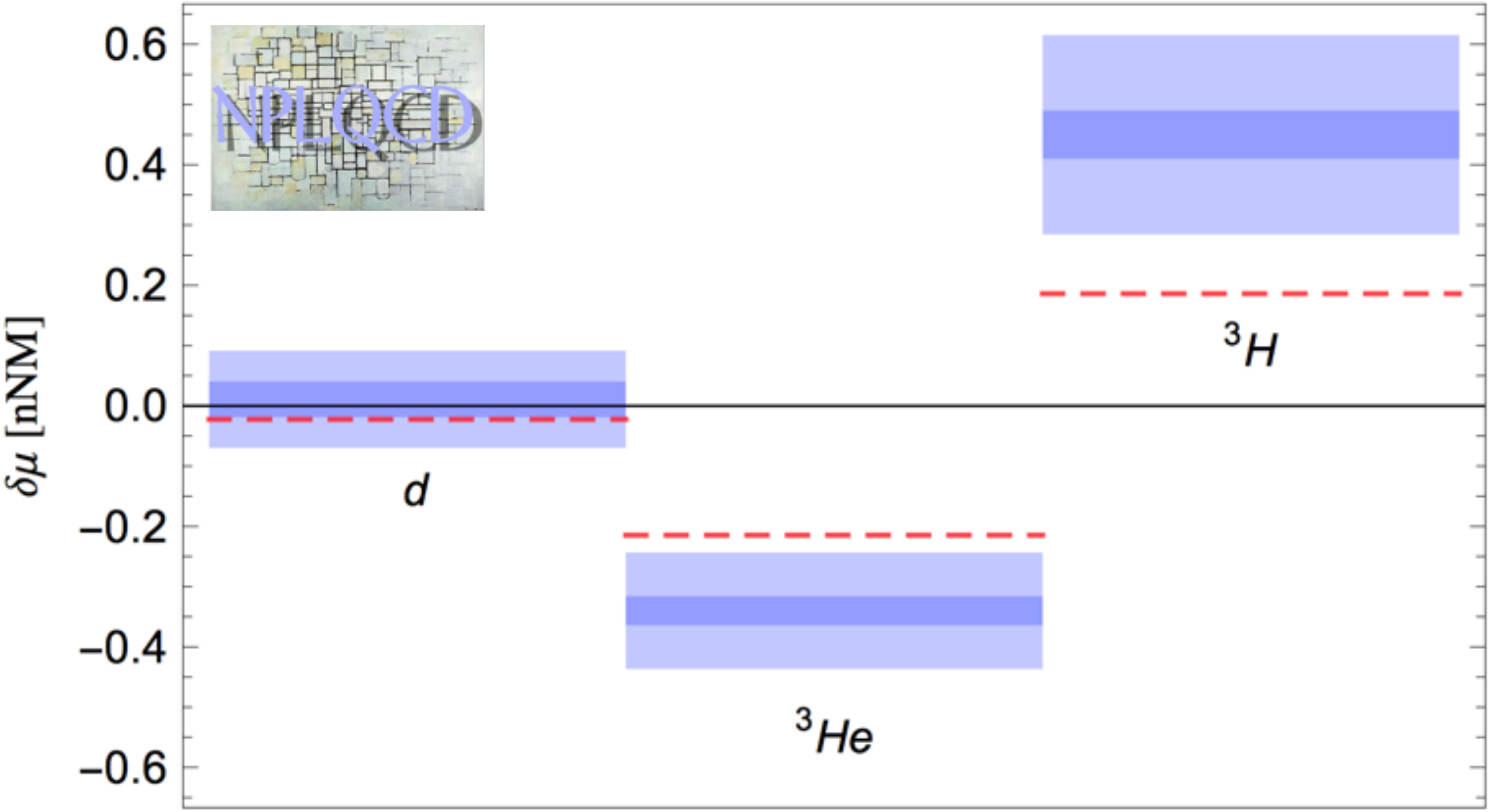
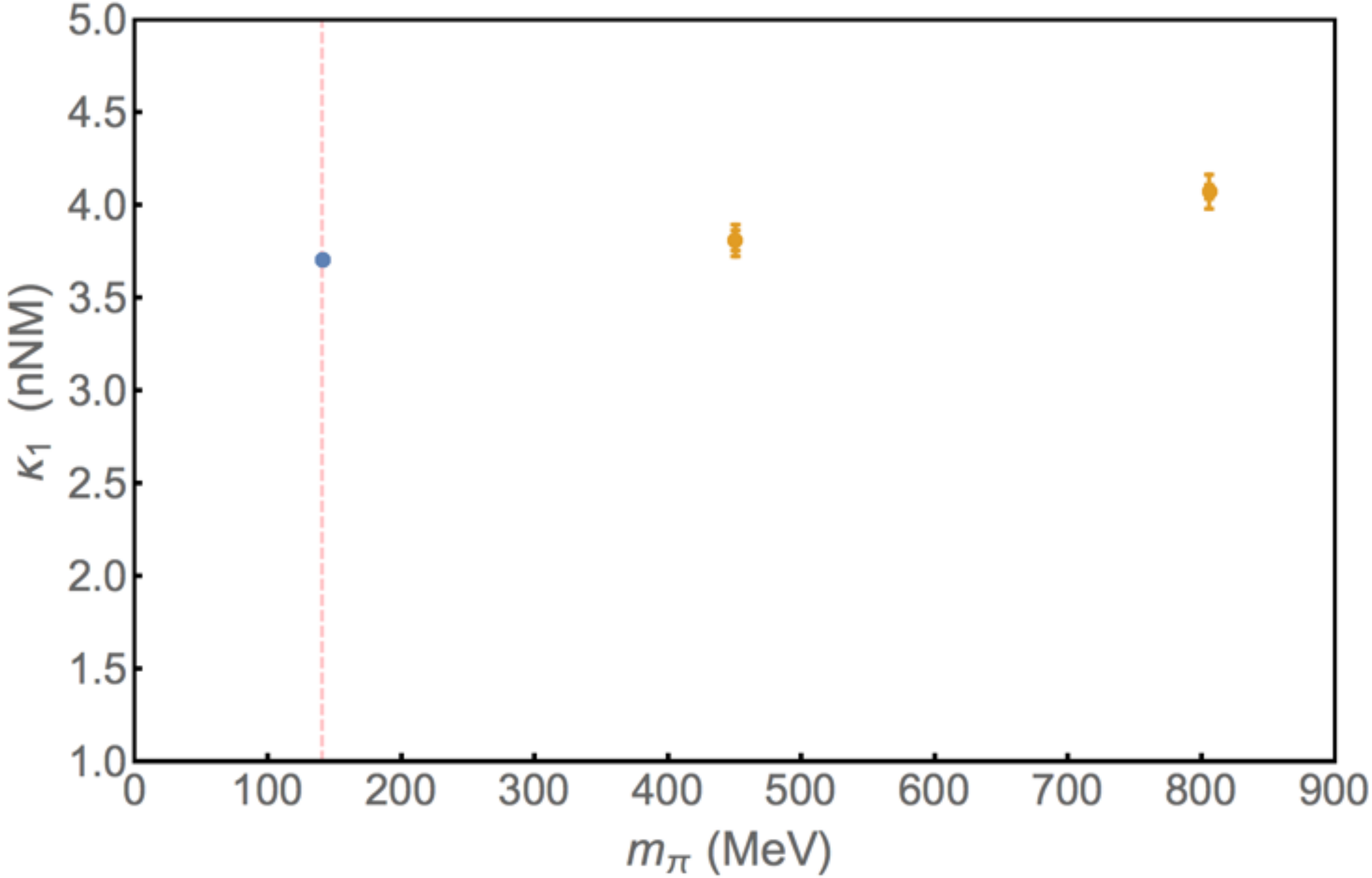


$$\frac{e}{2M(m_\pi)}$$

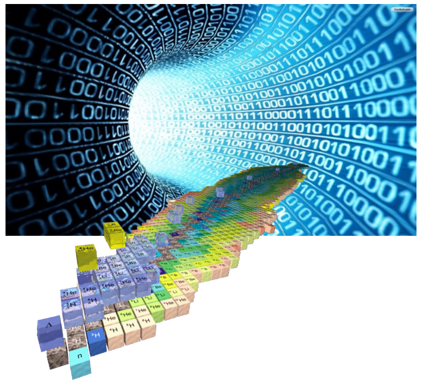
m_π ~ 800 MeV Vs Nature

Magnetic Moments

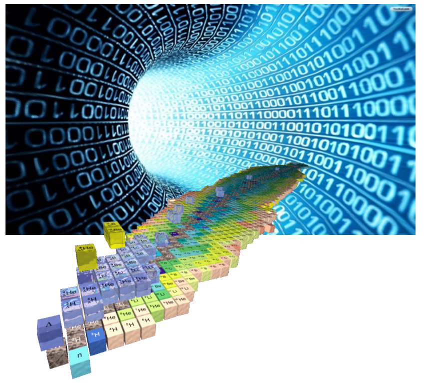


$$\frac{e}{2M(m_\pi)}$$

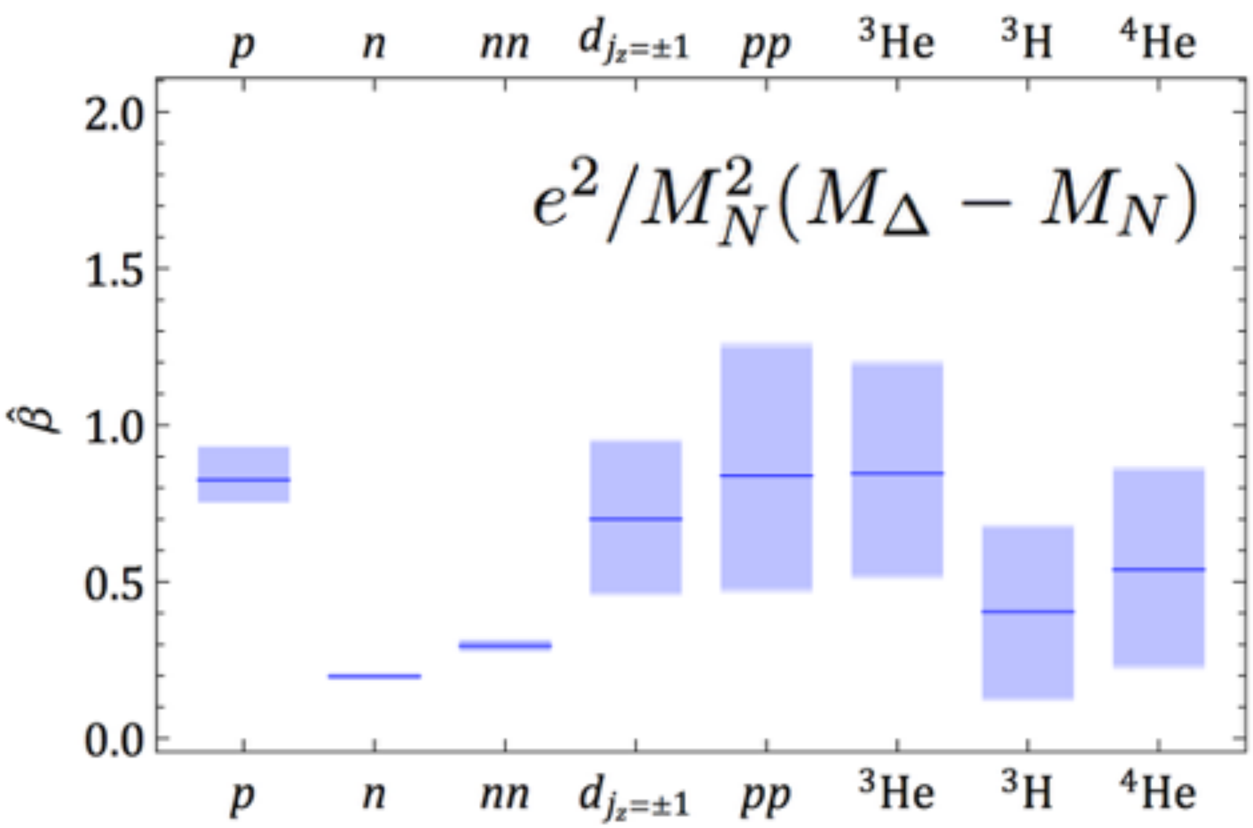
Essentially ALL quark mass dependence of nucleon magnetic moments is due to the nucleon mass

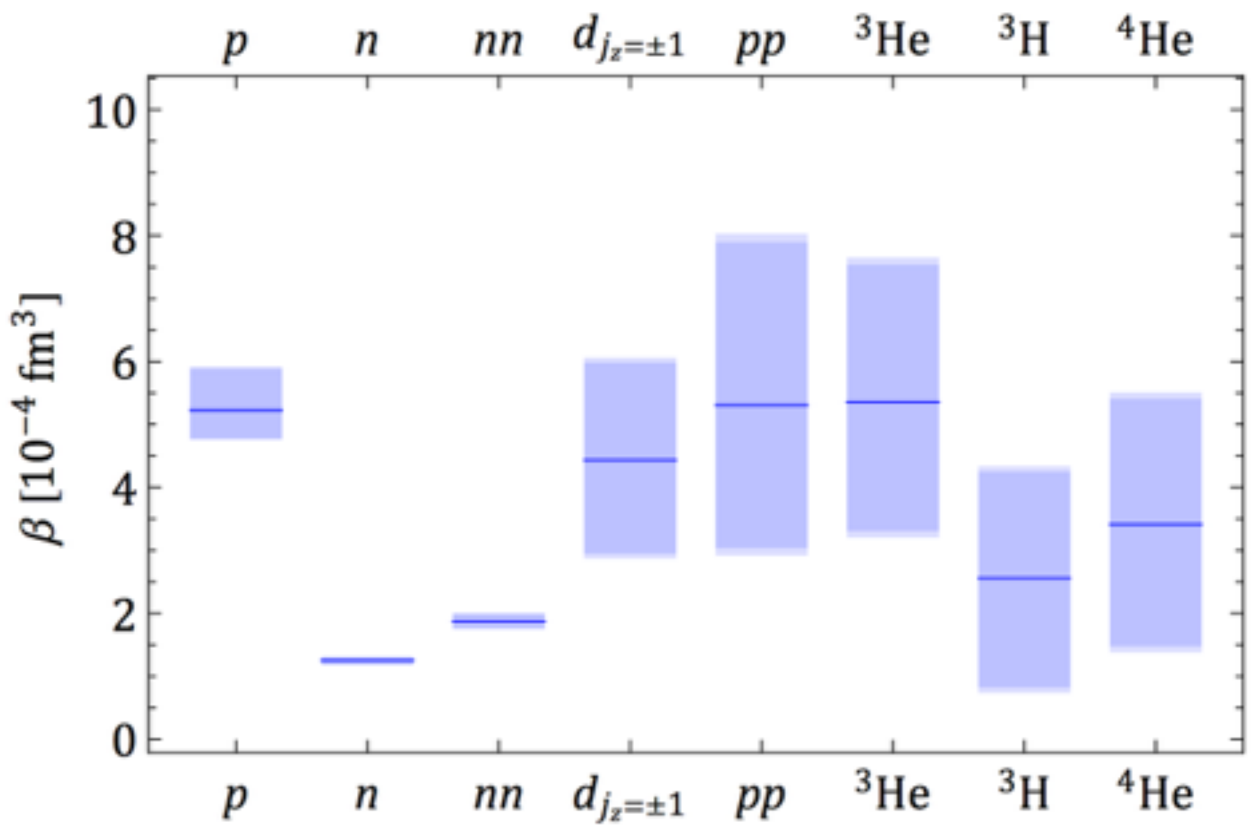


The Structure of Nuclei : Polarizabilities

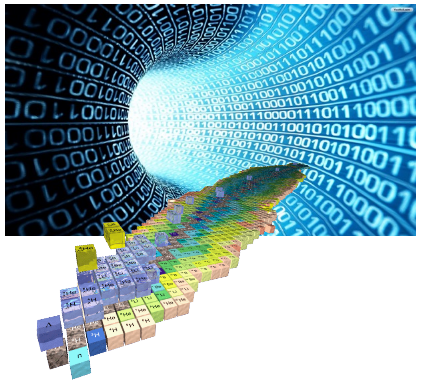


$m_\pi \sim 800$ MeV

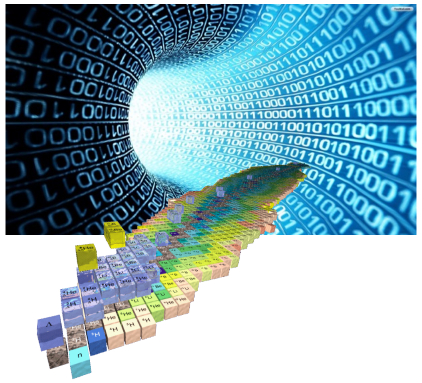


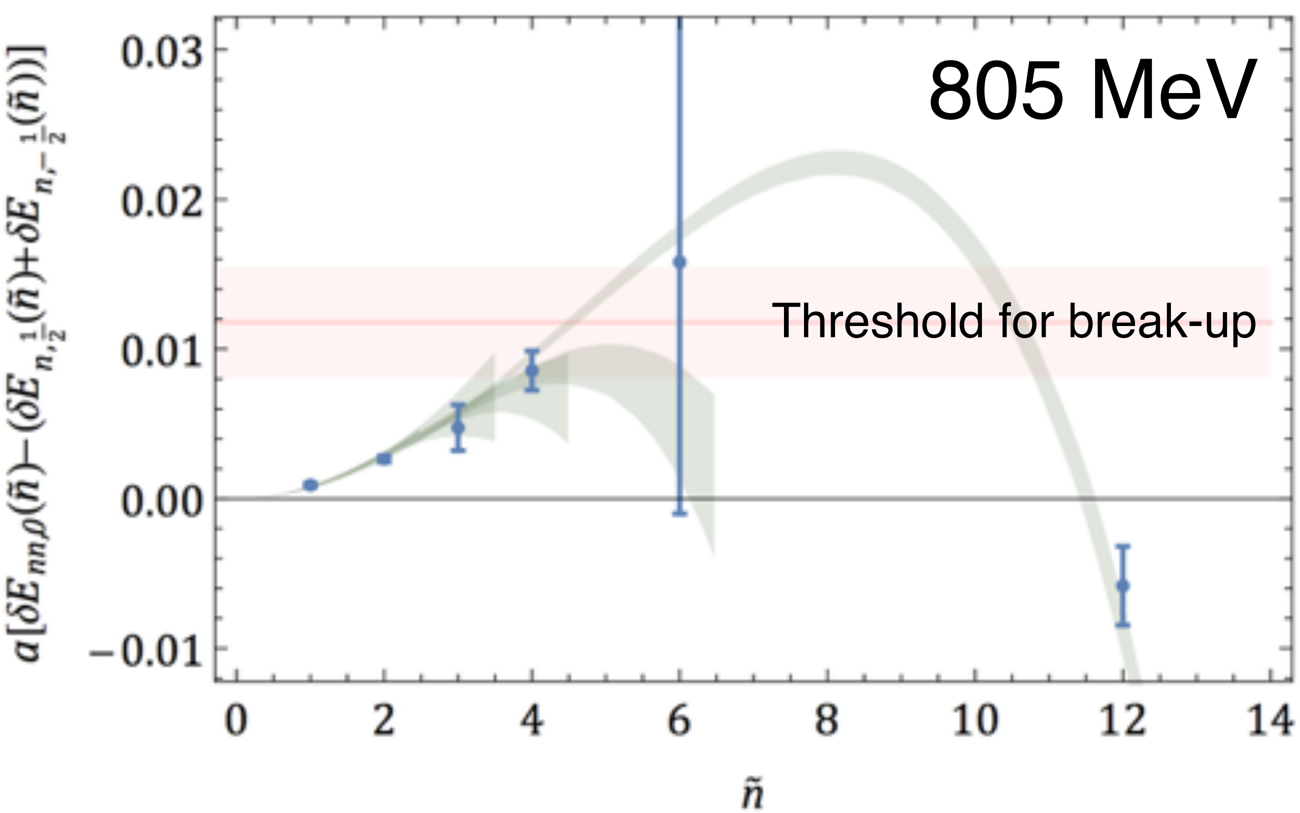


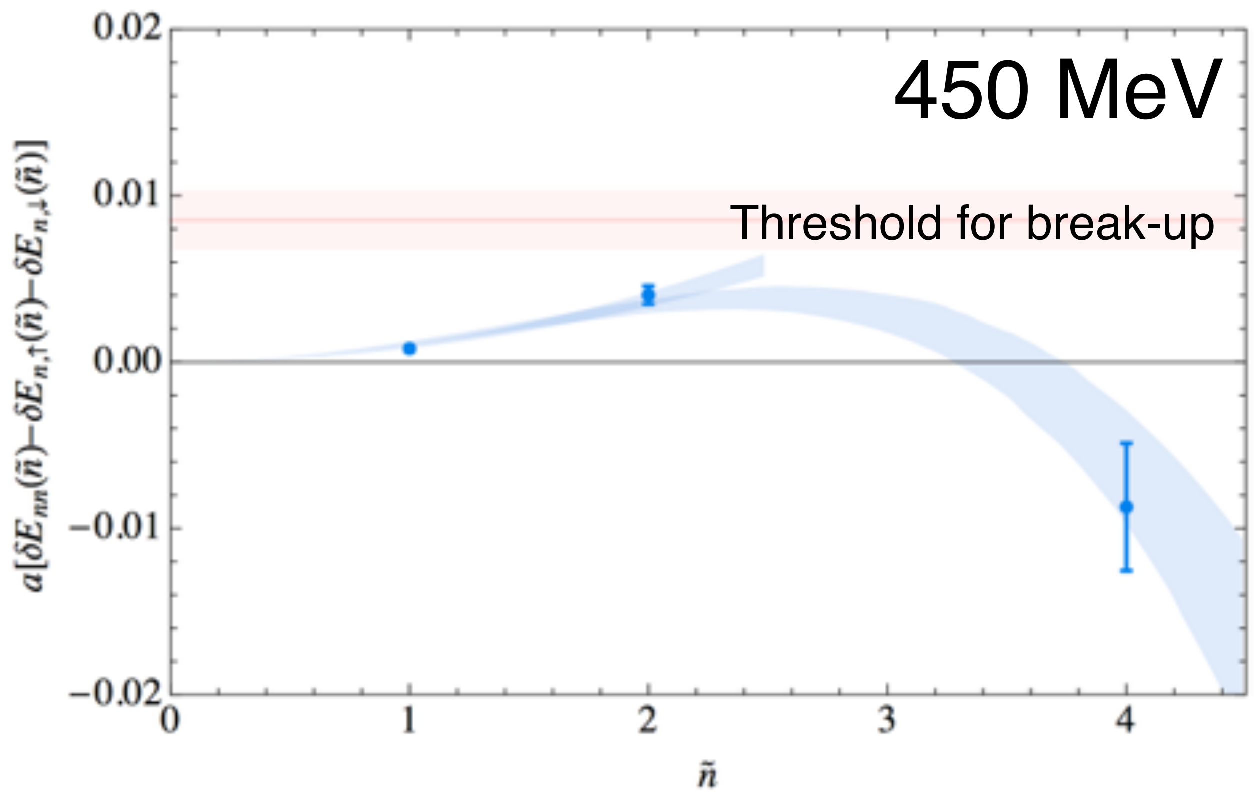
Large isovector nucleon polarizability
Nuclear polarizabilities are similar to proton polarizability



The Structure of Nuclei : Feshbach Resonances



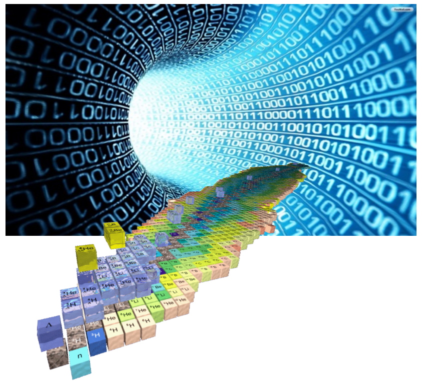


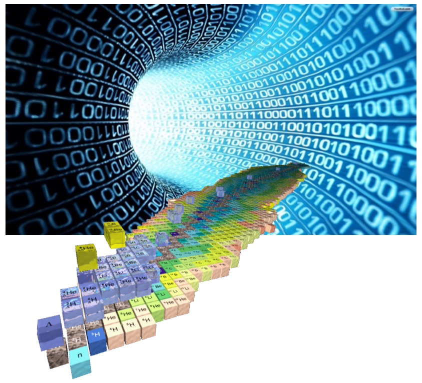


Increasing B tends to dissociate dineutron

- if trend survives to physical point then neutron stars do not want to spontaneously generate B-fields

Possible Feshbach resonance of deuteron and pp-system at the physical point - system with infinite scattering length

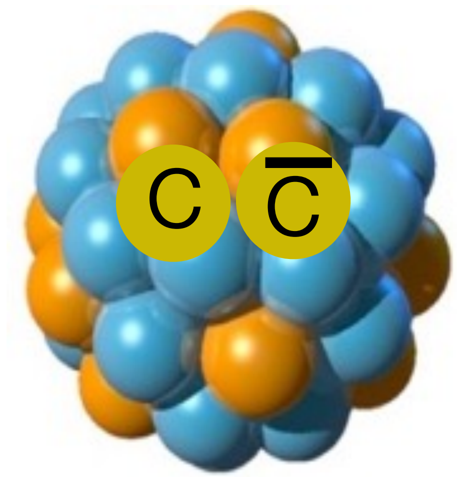




Exotic Nuclei :
Penta-Quarks, Octa-Quarks and Beyond

Modeling Interactions with Nuclei

- Brodsky, Schmidt and deTeramond (1989)
  - multi-gluon exchange modeled by Pomerons
  - large binding energies, scaling with A

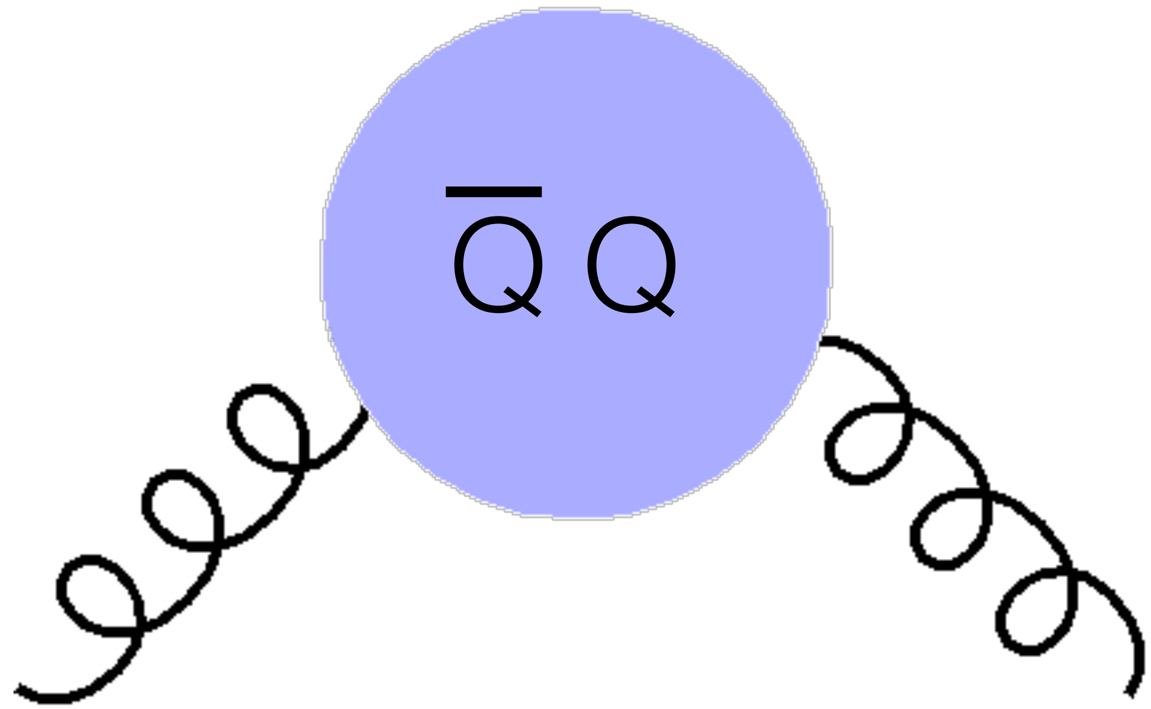


- Wasson (1991)
  - Saturation due to finite range interaction

Ref.	Binding Energy (MeV)			Binding Energy (MeV)	
	^{3}He η_c	^{4}He η_c	NM η_c	^{4}He J/ψ	NM J/ψ
[1]	19	140			
[2]	0.8	5	27		
[3]			10		10
[5]	*	*	9		
[6]					5
[7]				5	18
[8]				15.7	

[1] S. J. Brodsky, I. Schmidt, and G. de Teramond, Phys.Rev.Lett. **64**, 1011 (1990).
[2] D. Wasson, Phys.Rev.Lett. **67**, 2237 (1991).
[3] M. E. Luke, A. V. Manohar, and M. J. Savage, Phys.Lett. **B288**, 355 (1992), hep-ph/9204219.
[4] S. J. Brodsky and G. A. Miller, Phys.Lett. **B412**, 125 (1997), hep-ph/9707382.
[5] G. F. de Teramond, R. Espinoza, and M. Ortega-Rodriguez, Phys.Rev. **D58**, 034012 (1998), hep-ph/9708202.
[6] S. H. Lee and C. Ko, Phys.Rev. **C67**, 038202 (2003), nucl-th/0208003.
[7] K. Tsushima, D. Lu, G. Krein, and A. Thomas, Phys.Rev. **C83**, 065208 (2011), 1103.5516.
[8] A. Yokota, E. Hiyama, and M. Oka, PTEP **2013**, 113D01 (2013), 1308.6102.

Quarkonium
Symmetries and Interactions



(Luke, Manohar, MJS)

Only spin-0 and spin-2 , no spin-1 (requires 3 gluons)

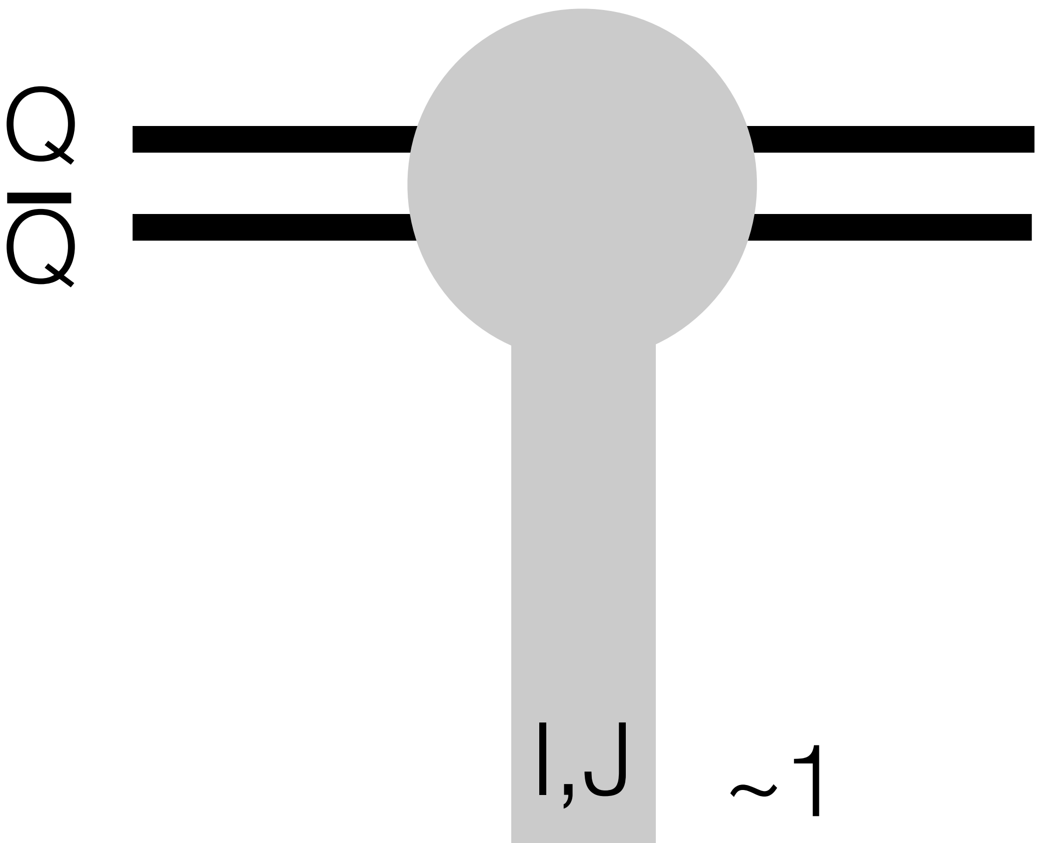
$G_{\mu\nu} G^{\mu\nu}$, $G_{0\alpha} G_0{}^{\alpha}$ $O(1)$

$G_{i\alpha} G_j{}^{\alpha}$ symmetrized, traceless $O(1/M_Q)$

Matrix elements of gluonic operators - exploring the glue structure of nuclei
A new and nice probe - hopefully

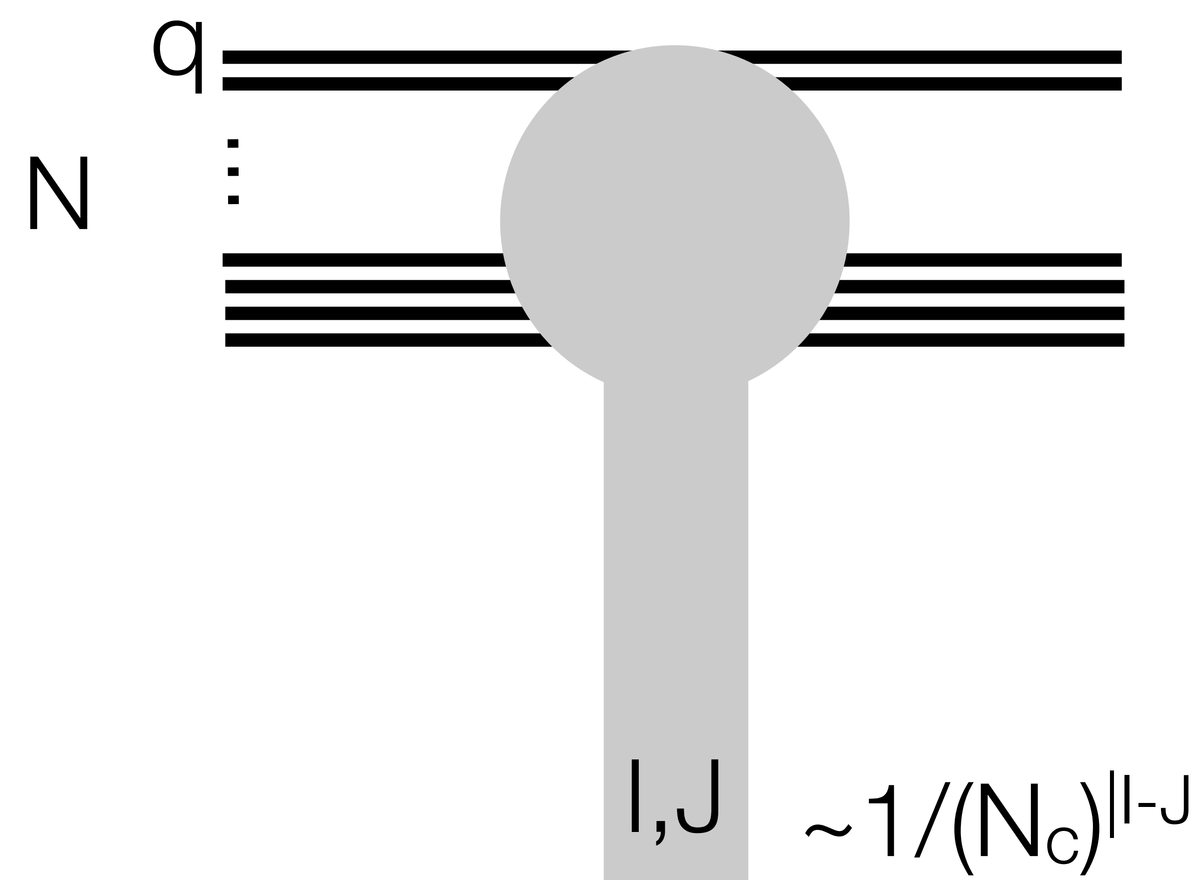
Techni-baryons with colored constituents have similar forms - same at LO

Quarkonium
Symmetries and Interactions



Large-Nc Limit

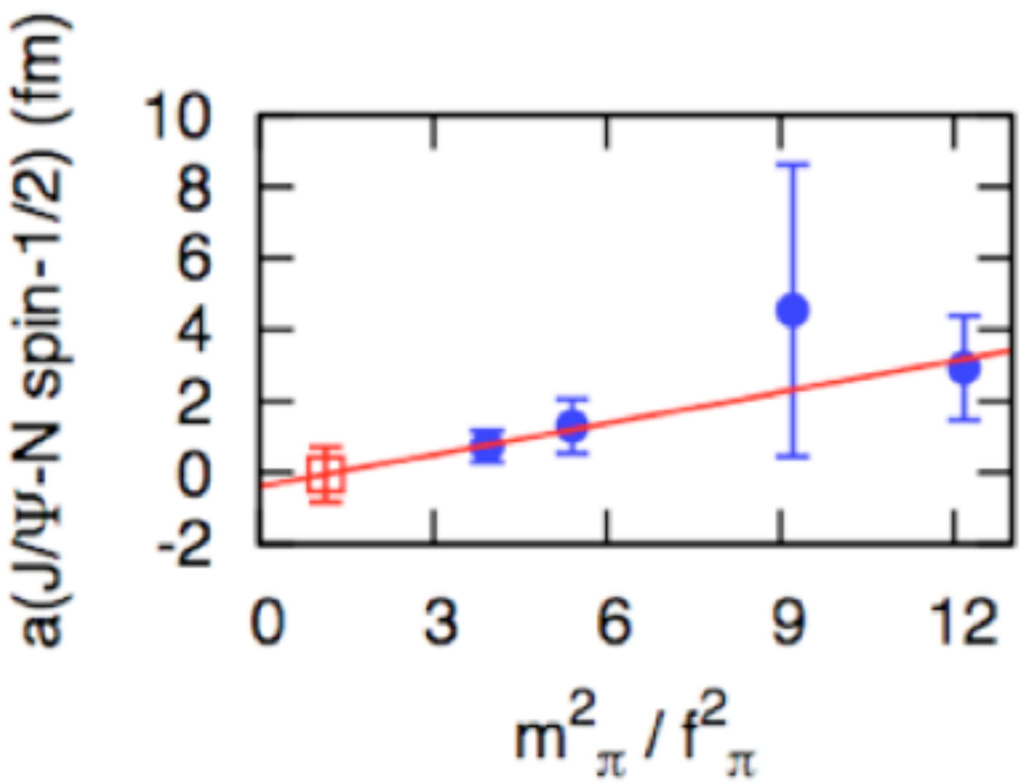
ηc and J/ψ have spin-independent interactions up to $1/M_Q$

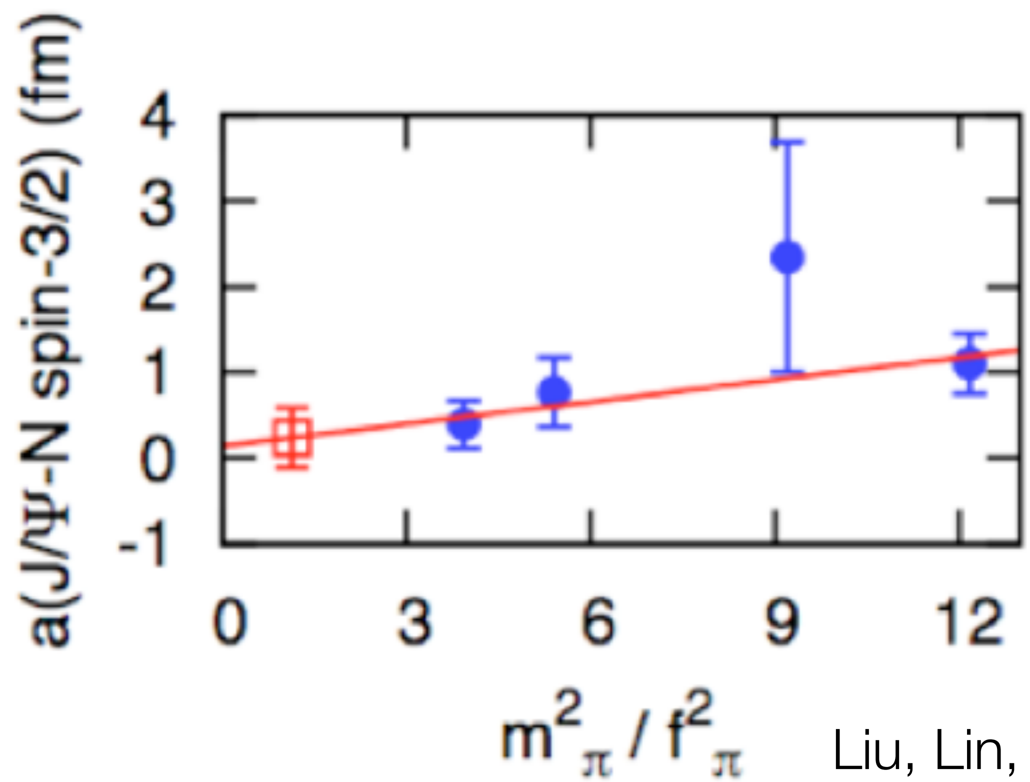


Nuclei have 1/Nc suppressions that depend on t-channel quantum numbers

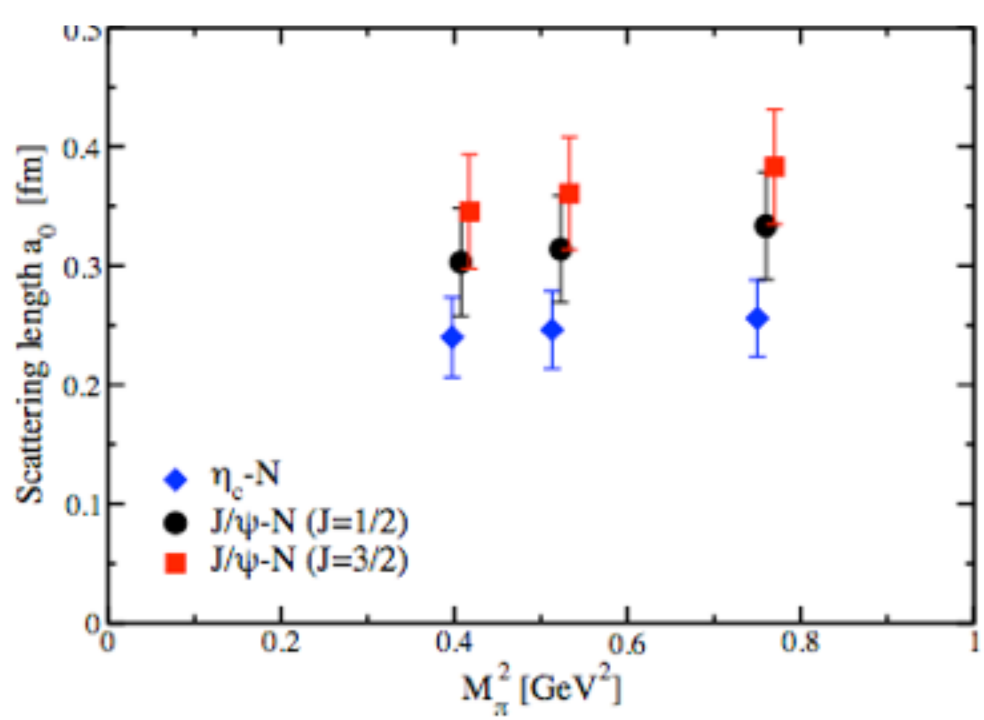
Charmonium-Nucleon

Previous Calculations



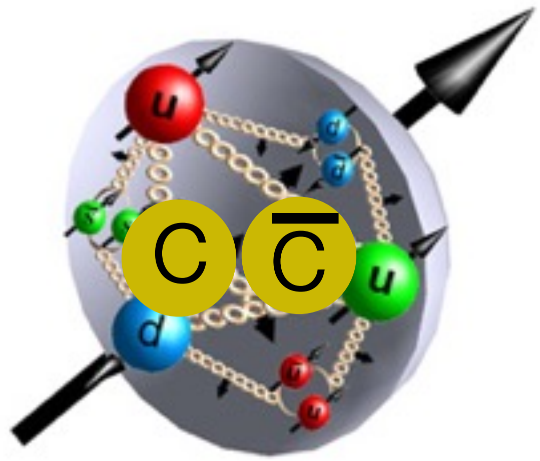


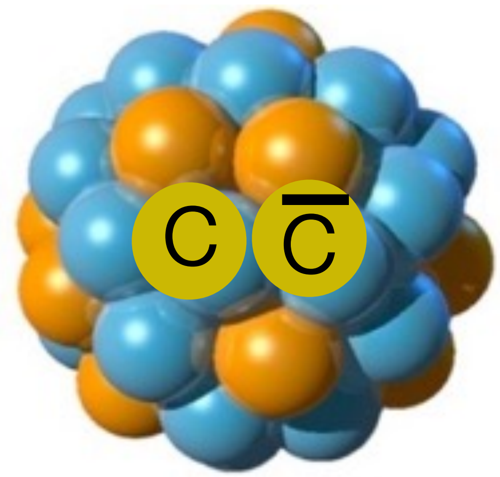
Liu, Lin, Orginos, (2008)



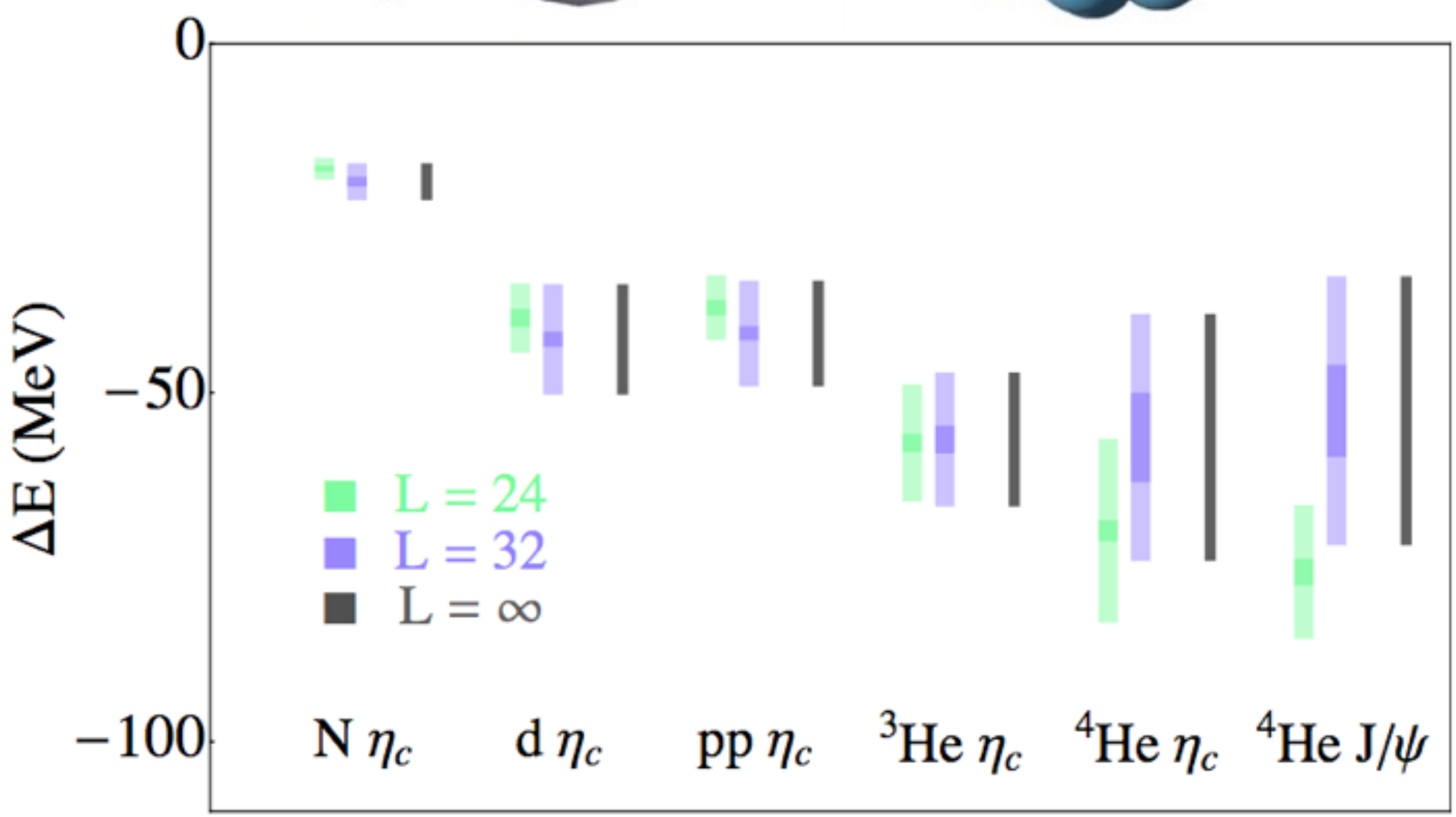
Kawanai, Sasaki, (2010)

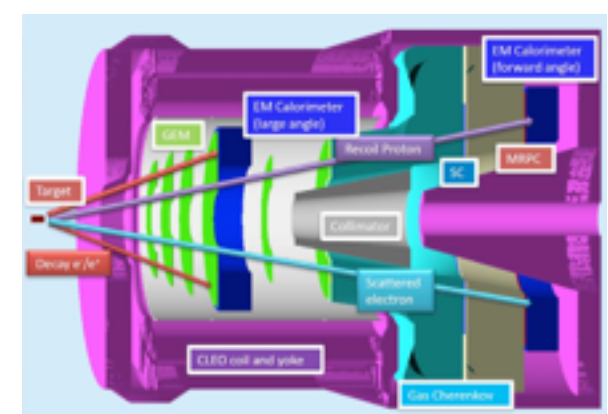
Charmonium-Nuclei
$m_\pi \sim 800$ MeV





NPLQCD



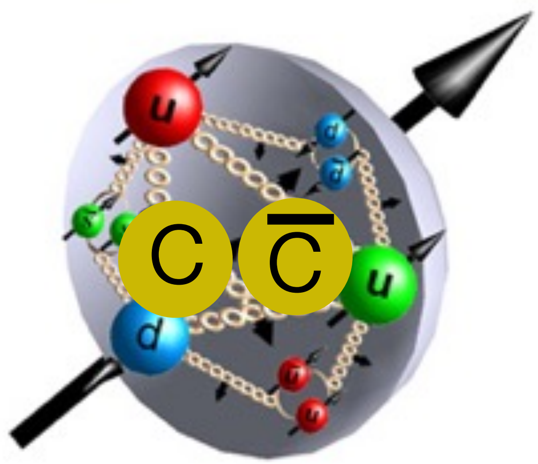


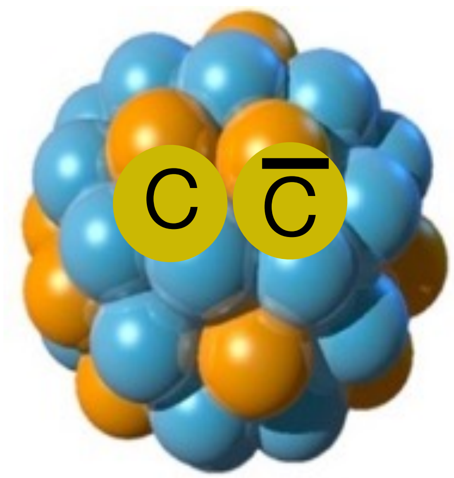
Athenna

Jefferson Lab
EXPLORING THE NATURE OF MATTER

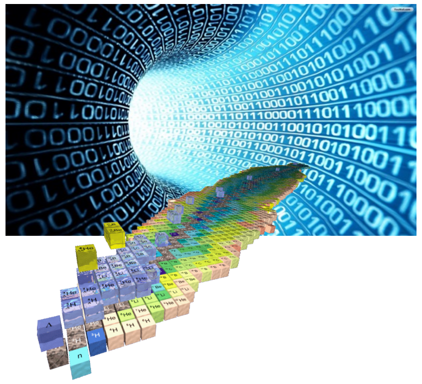
(Beane, Chang, Cohen, Detmold, Lin, Orginos, Parreno, MJS ,
Phys.Rev. D91 (2015) 11, 114503, arXiv:1410.7069)

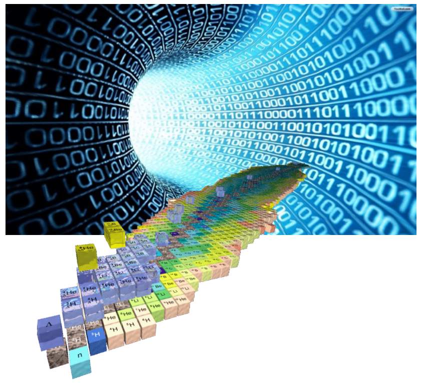
Charmonium-Nuclei
Extrapolation to Nature





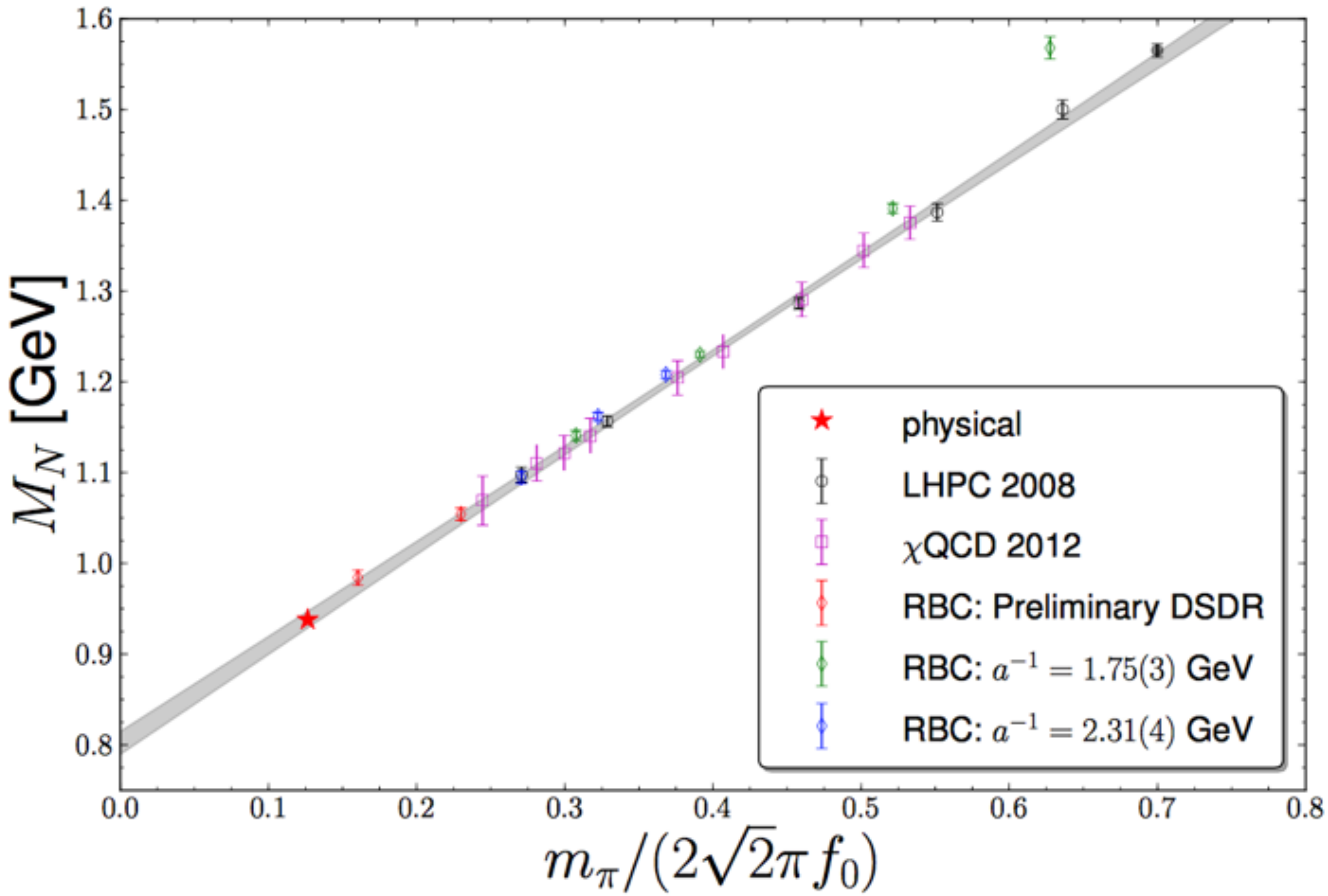
- Leading Gluonic Matrix Element ~ M_N
  - B~60 MeV @ m_π = 800 MeV extrapolates to B~40 MeV @ m_π = 140 MeV
- Calculations at lighter masses underway





Puzzle(s)

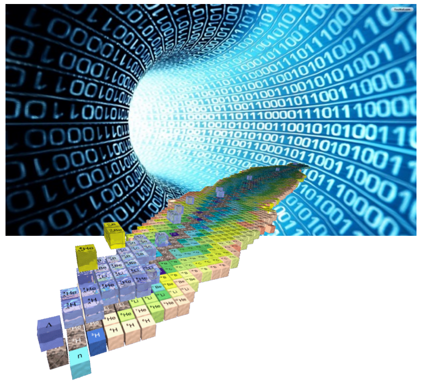
Lattice QCD:
Results - Nucleon



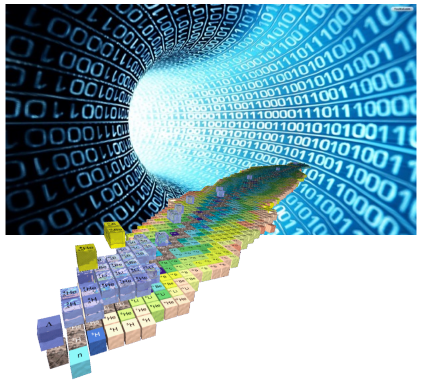
(Walker-Loud)

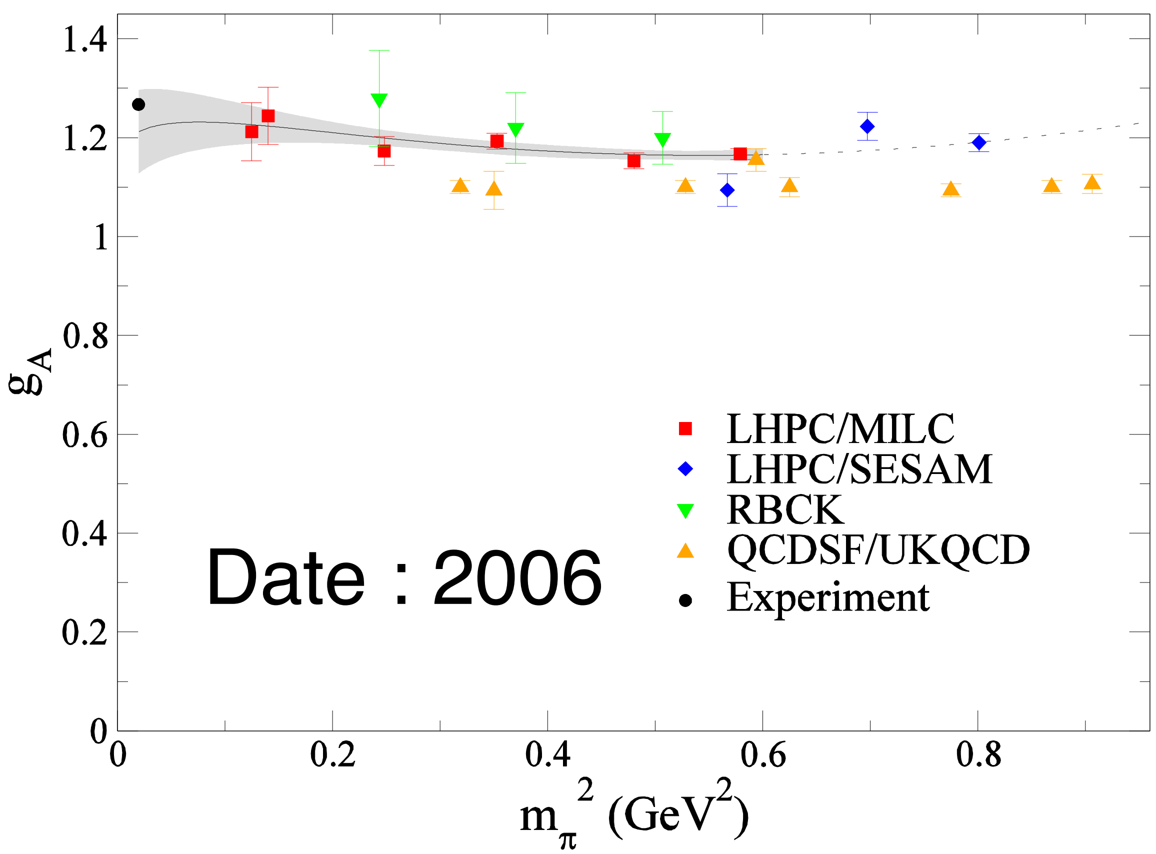
$$M_N = 800 \text{ MeV} + m_\pi$$

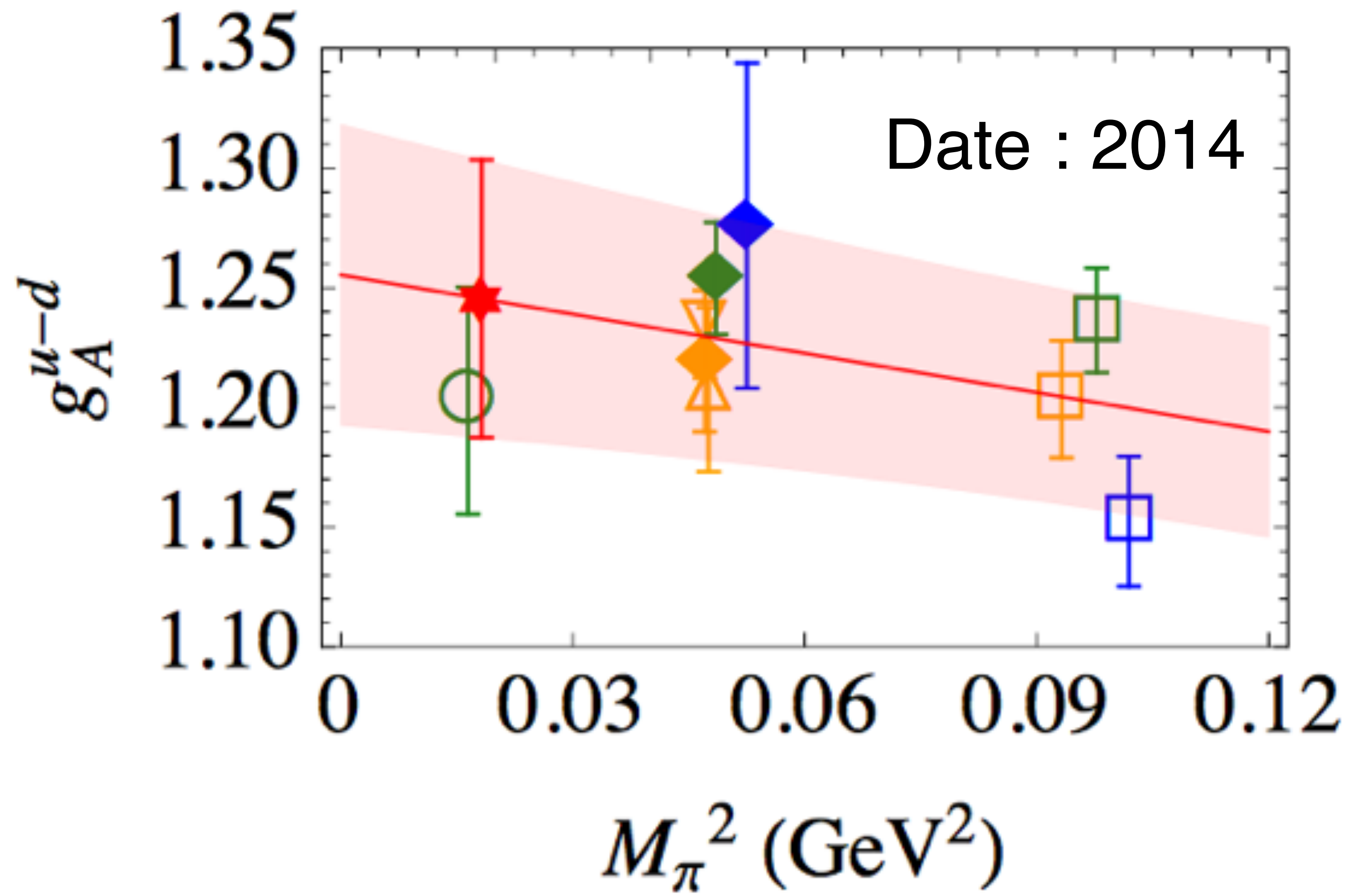
Unexpected behavior !!

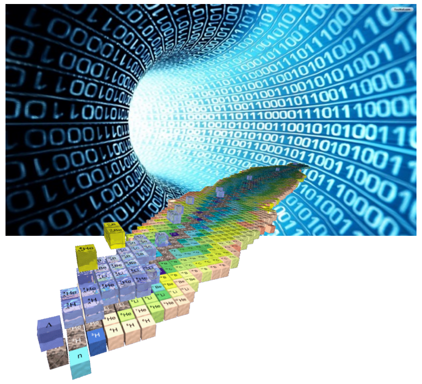


Lattice QCD:
Results - Nucleon Axial Charge

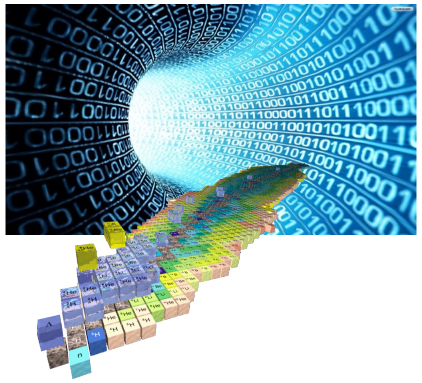


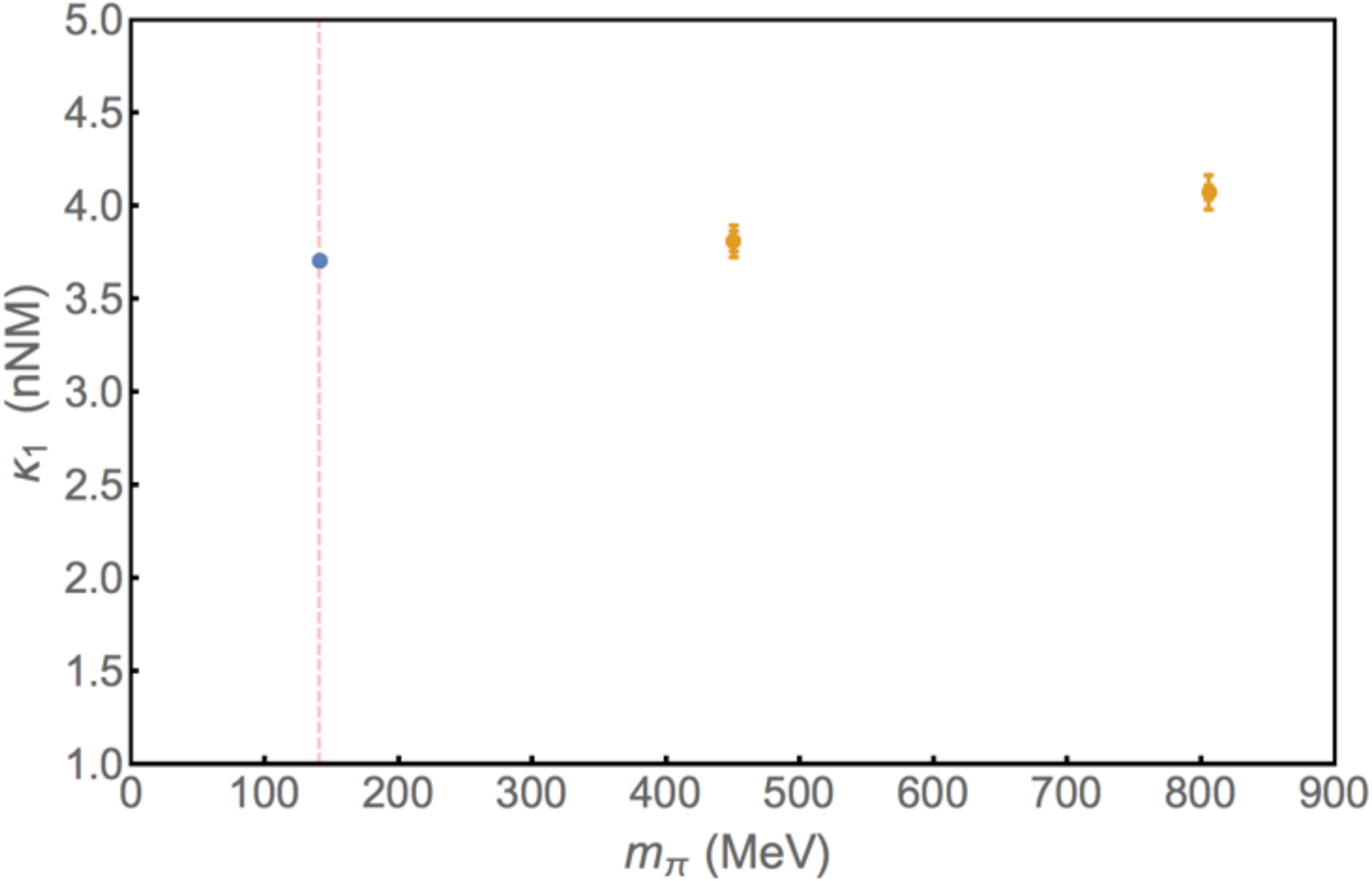






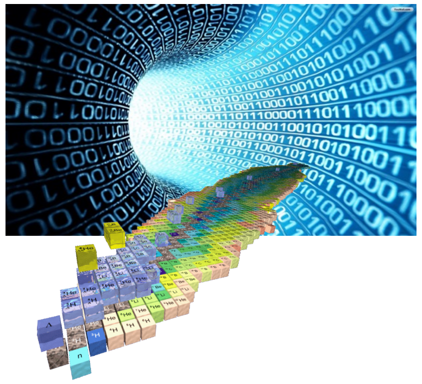
Lattice QCD:
Results - Magnetic Moments

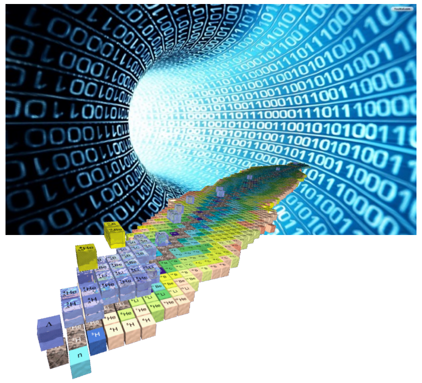




$$\frac{e}{2M(m_\pi)}$$

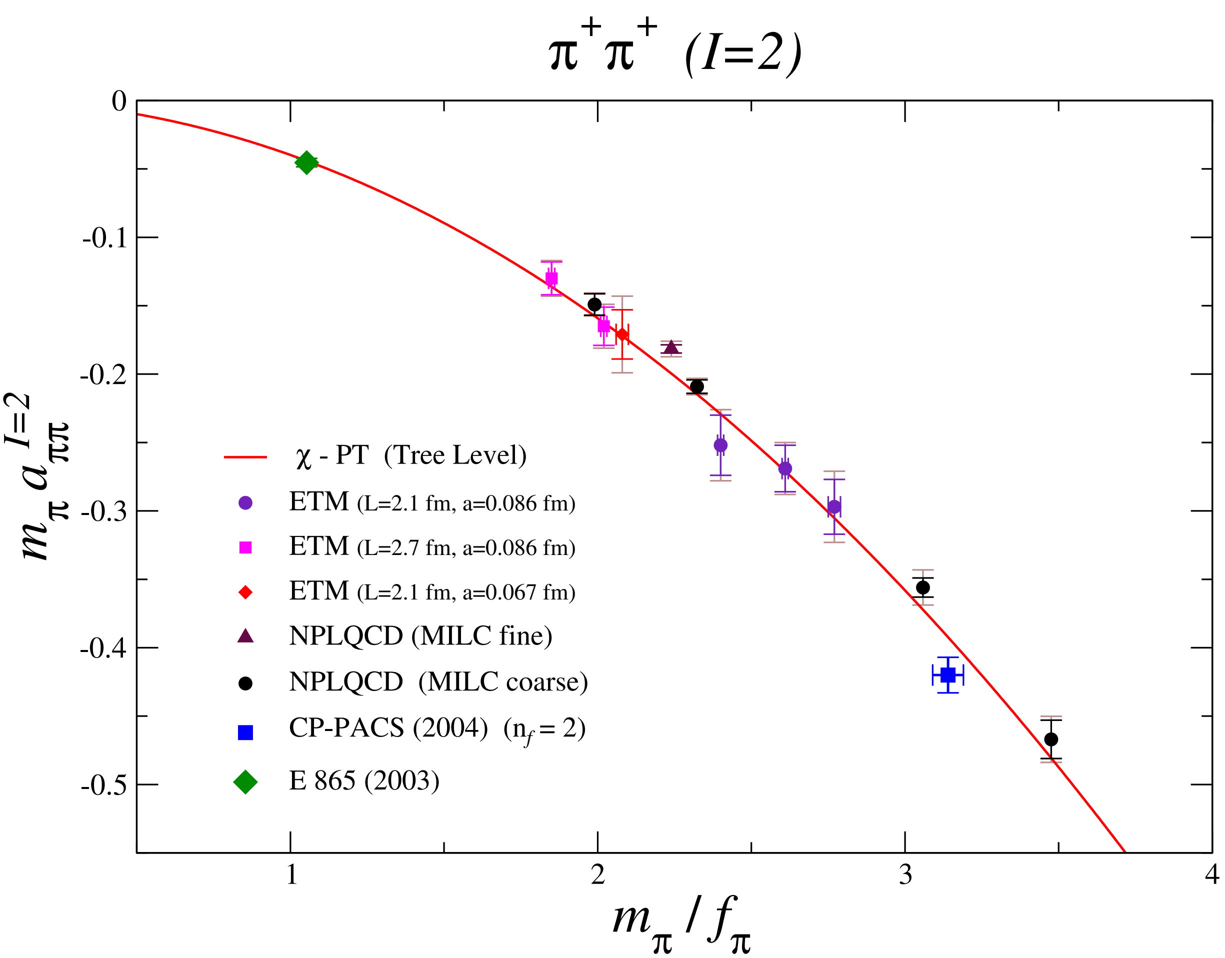
Essentially ALL quark mass dependence of nucleon magnetic moments is due to the nucleon mass

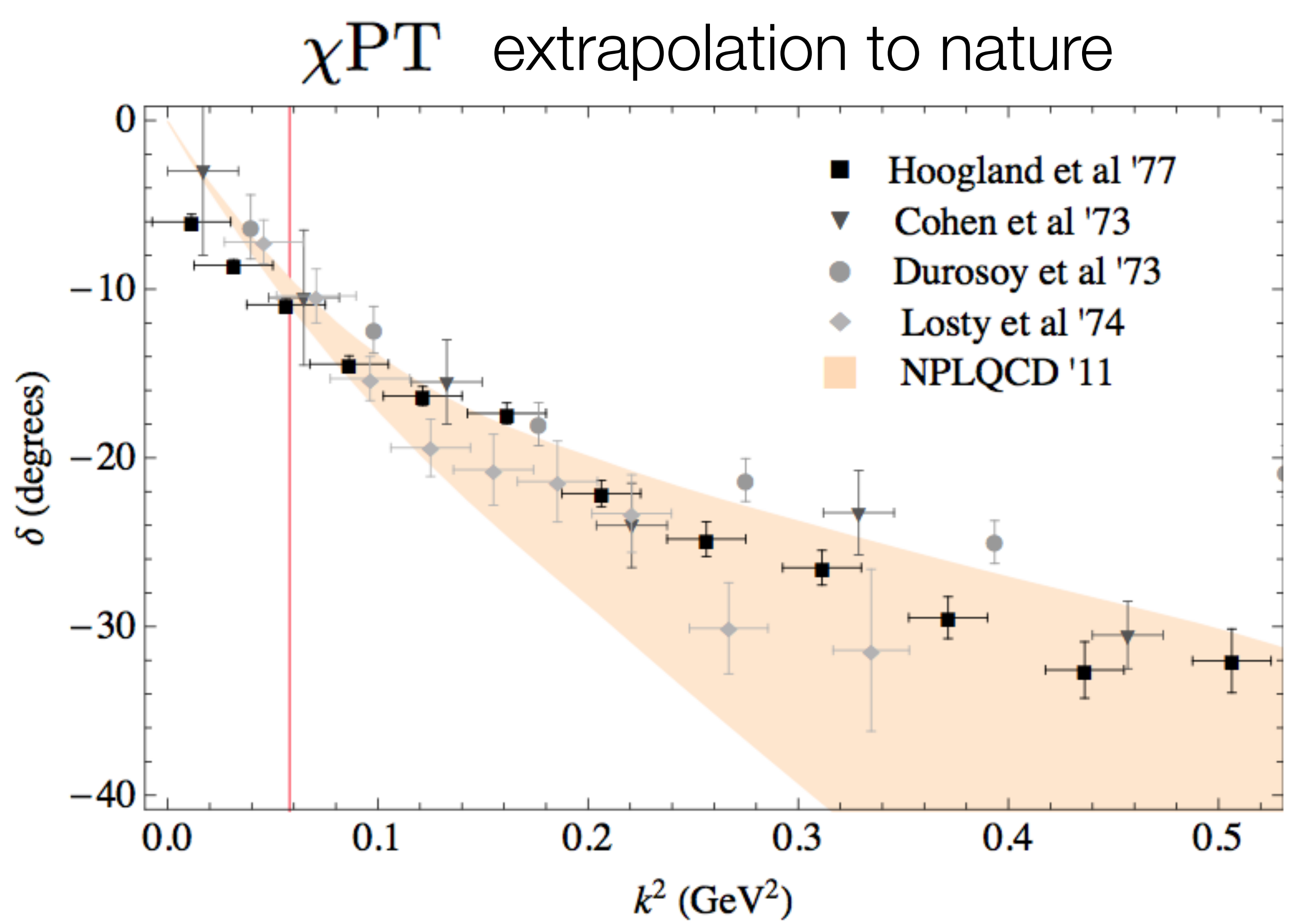




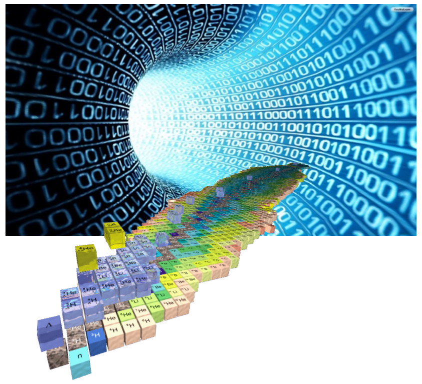
Lattice QCD:

Results - meson-meson scattering



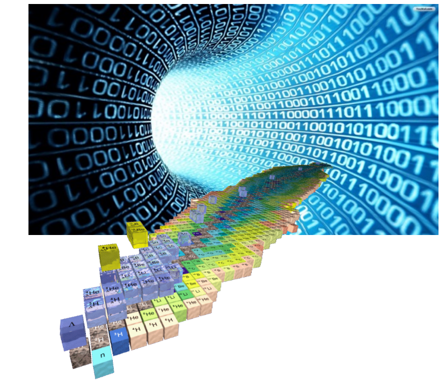


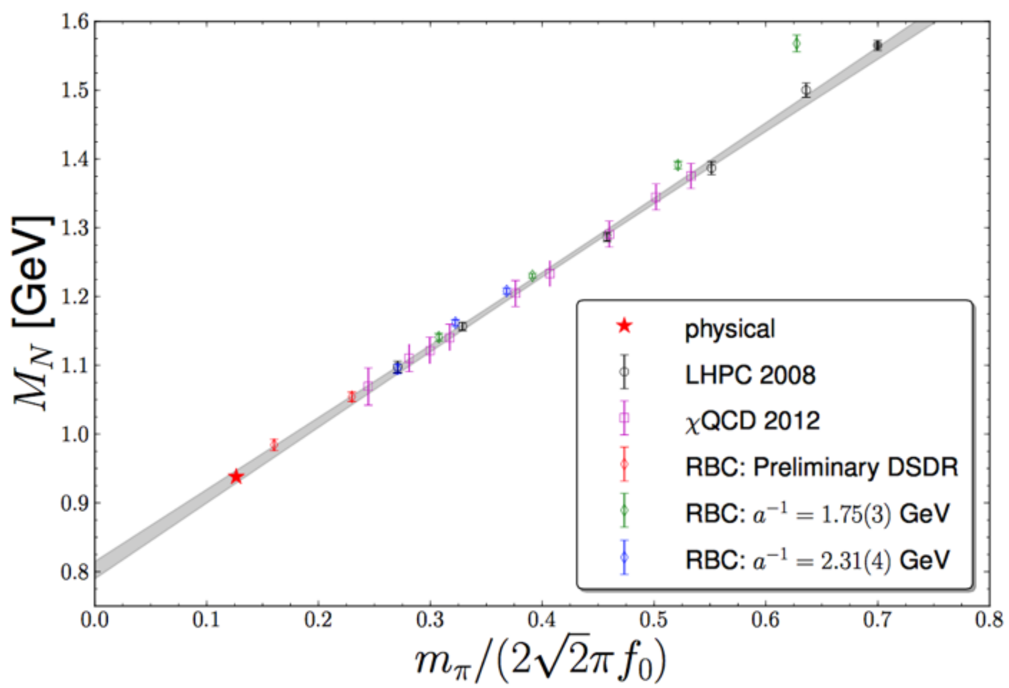
Red curve is tree-level chiral PT - Weinberg
- prediction and not fit

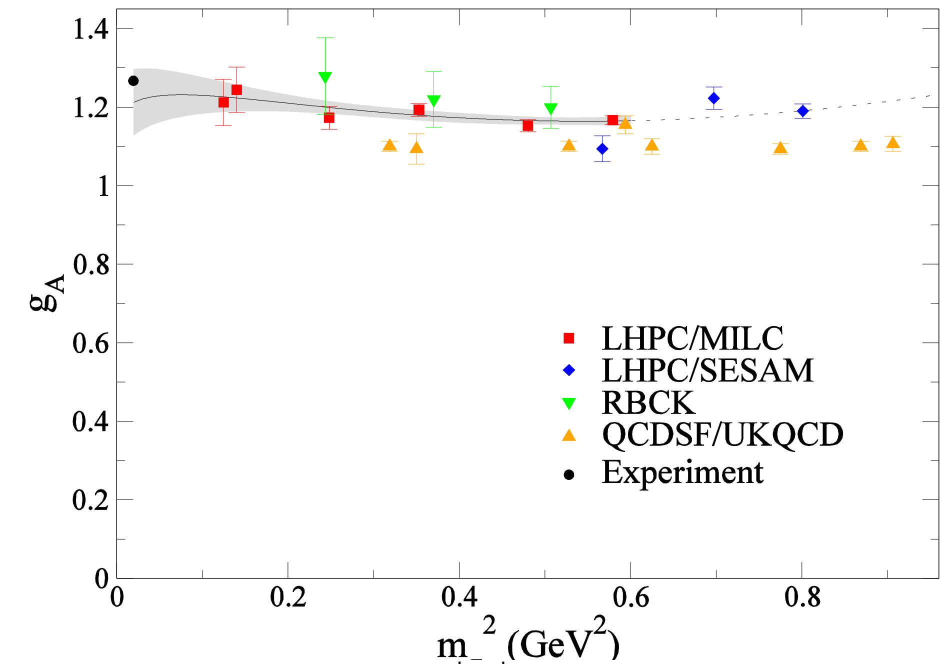


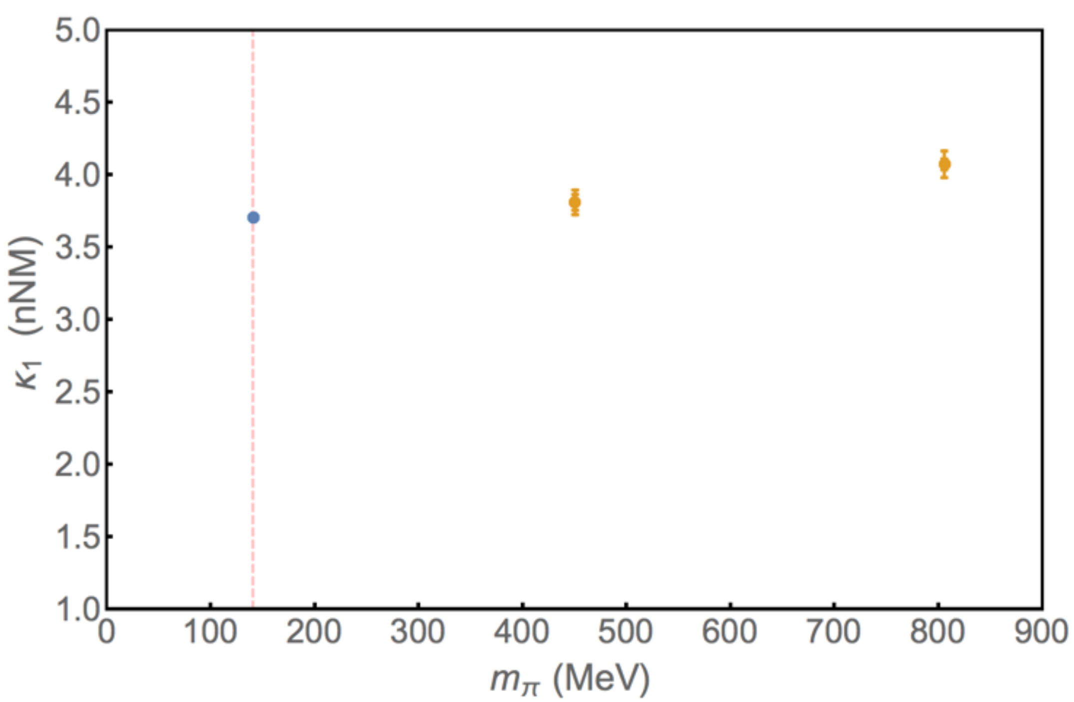
Lattice QCD:

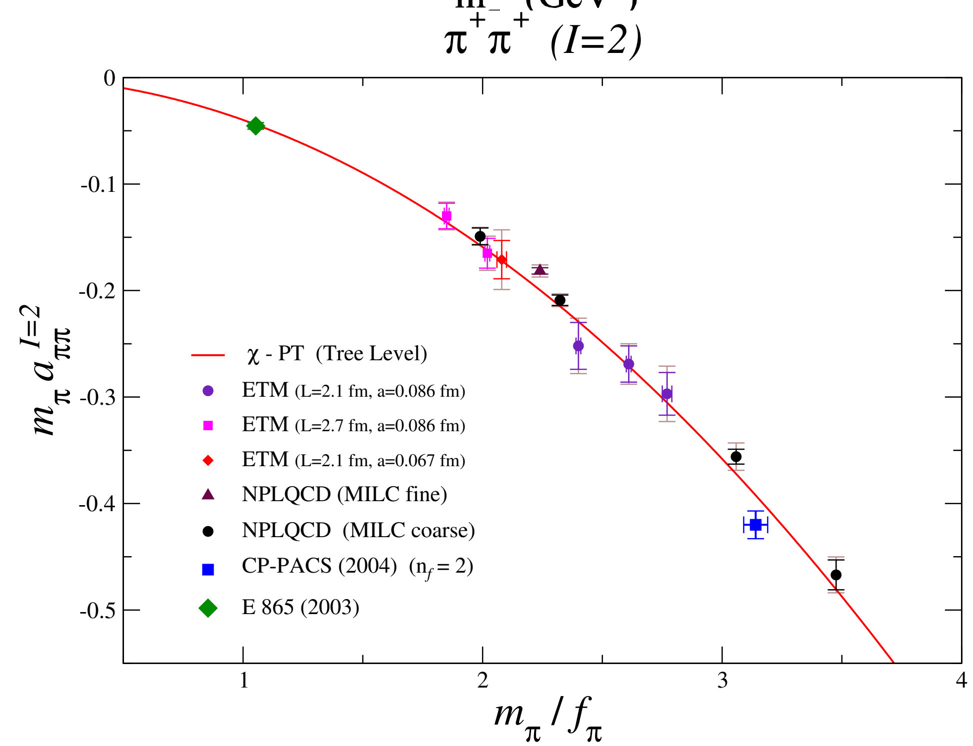
What is the Underlying Structure ?



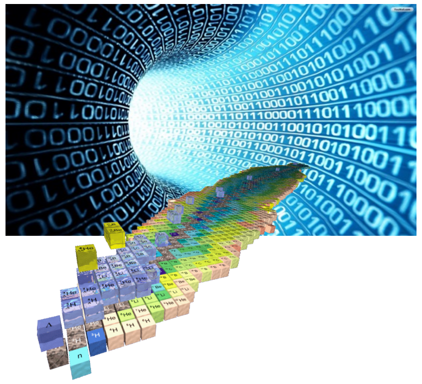




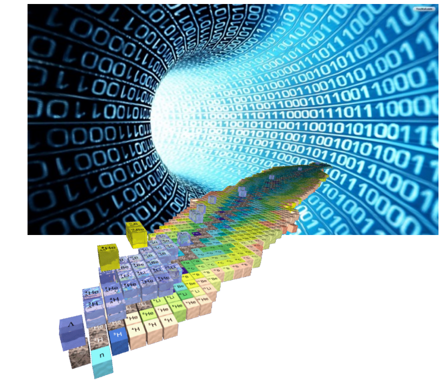


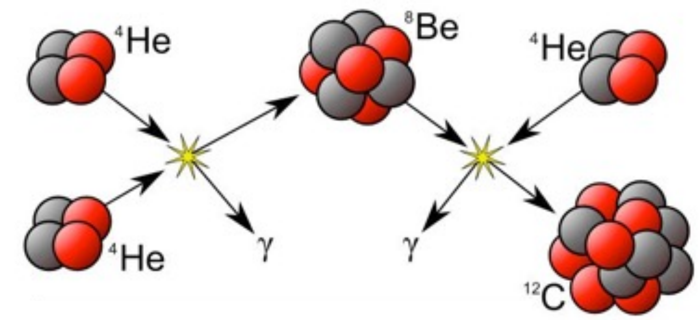


All unexpected results that Lattice QCD has revealed

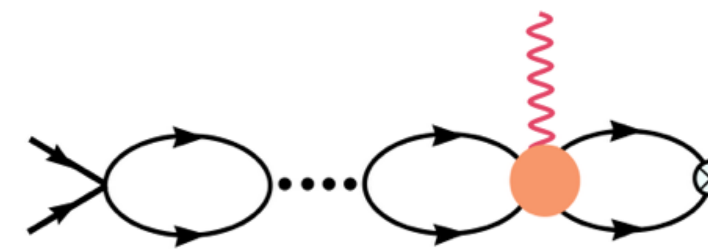


Closing Remarks

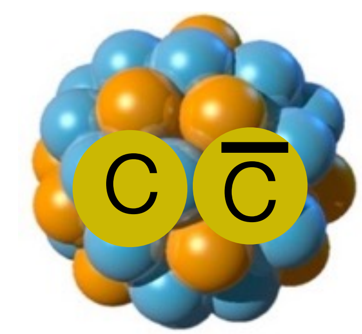




- Nuclear Physics is unnatural
  - Nuclear Theory interesting and challenging !!
  - Interesting to explore stability and de-tuning
  - Is it finely tuned ?

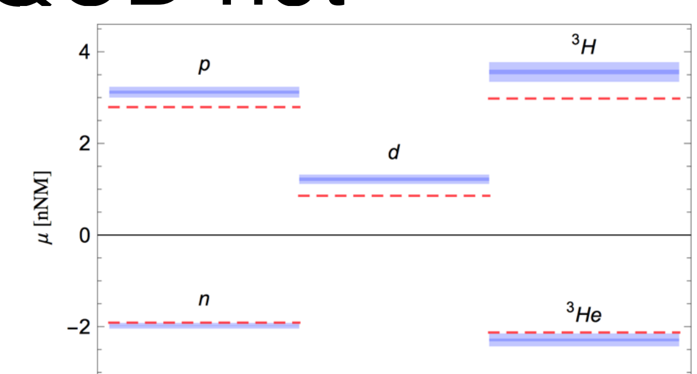


- Nuclei are more than nucleons
  - correlated multi-nucleon-probe(s) interactions contribute



- Exotic Nuclei - penta-quarks, octa-quarks, …

- Hadronic/nuclear structure revealed by Lattice QCD not understood



END

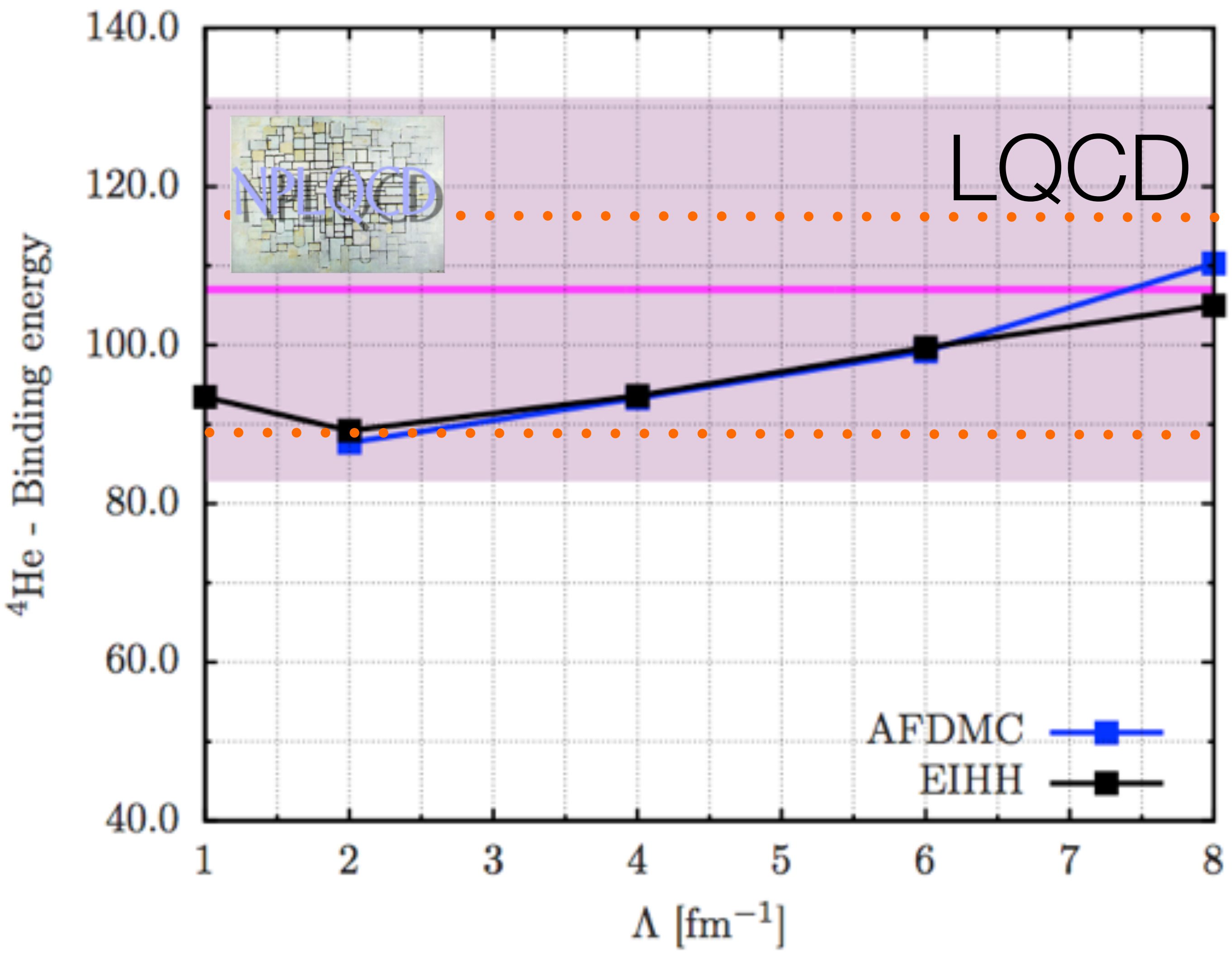
LQCD to Pionless EFT to Nuclei

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

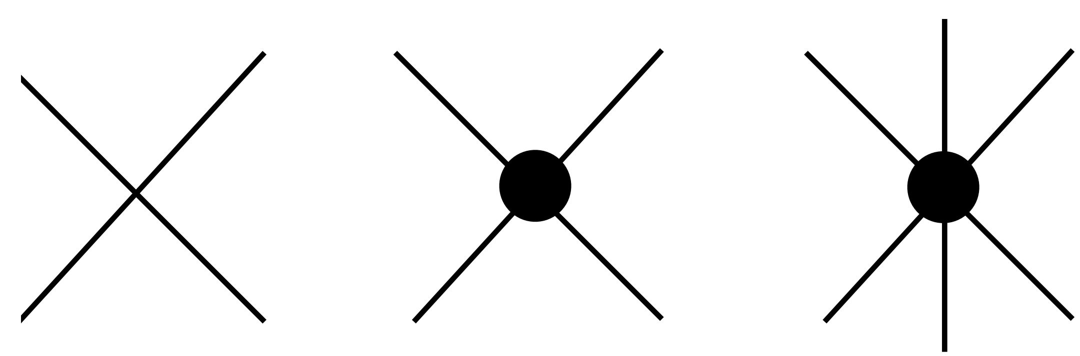
LQCD Nuclei for 800 MeV pions

- Fit 2-body and 3-body LQCD bindings
- Predict 4-body, c/w LQCD prediction

pionless EFT valid for nuclei



``First Contact``



Weak Capture/Breakup

arXiv:nucl-th/0210073v2 31 Oct 2002

Constraining the Leading Weak Axial Two-body Current by SNO and Super-K

Jiunn-Wei Chen
Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139 and Department of Physics, University of Maryland, College Park, MD 20742
jwchen@lns.mit.edu

Karsten M. Heeger
Lawrence Berkeley National Laboratory, Berkeley, CA 94720 and Department of Physics and Center for Experimental Nuclear Physics and Astrophysics, University of Washington, Seattle, WA 98195
KMHeeger@lbl.gov

R.G. Hamish Robertson
Department of Physics and Center for Experimental Nuclear Physics and Astrophysics, University of Washington, Seattle, WA 98195
rghr@u.washington.edu

Abstract

We analyze the Sudbury Neutrino Observatory (SNO) and Super-Kamiokande (SK) data on charged current (CC), neutral current (NC) and neutrino electron elastic scattering (ES) reactions to constrain the leading weak axial two-body current parameterized by $L_{1,A}$. This two-body current is the dominant uncertainty of every low energy weak interaction deuteron breakup process, including SNO's CC and NC reactions. Our method shows that the theoretical inputs to SNO's determination of the CC and NC fluxes can be self-calibrated, be calibrated by SK, or be calibrated by reactor data. The only assumption made is that the total flux of active neutrinos has the standard ^8B spectral shape (but distortions in the electron neutrino spectrum are allowed). We show that SNO's conclusion about the inconsistency of the no-flavor-conversion hypothesis does not contain significant theoretical uncertainty, and we determine the magnitude of the active solar neutrino flux.

TABLE II. Determinations of the NNLO $L_{1,A}$ (at renormalization scale m_π) from different processes. The higher order theoretical systematics are expected to be absorbed by shifting $L_{1,A}$ by $\sim +2$ to $+3$ fm^3 thus is not included in this table. Note that the CC, NC & ES combined analysis assumes the standard ^8B shape for the active neutrino flux. The tritium β decay analysis assumes the three-body current is negligible. The helioseismology analysis does not include the uncertainties from the solar model. The last two entries are theoretical determinations. EFT dimensional analysis gives $|L_{1,A}| \sim 6$ (fm^3) which is denoted as $[-6, 6]$ as its expected range.

Processes	$L_{1,A}$ (fm^3)	References
CC, NC & ES	4.0 ± 6.3	[this work]
Reactor $\bar{\nu}$-d	3.6 ± 4.6	[3]
Tritium β decay	4.2 ± 0.1	[29](see also [16,3,30])
Helioseismology	4.8 ± 5.9	[31]
Dimensional analysis	$\sim [-6, 6]$	[2]
Potential model	4.0	[24]