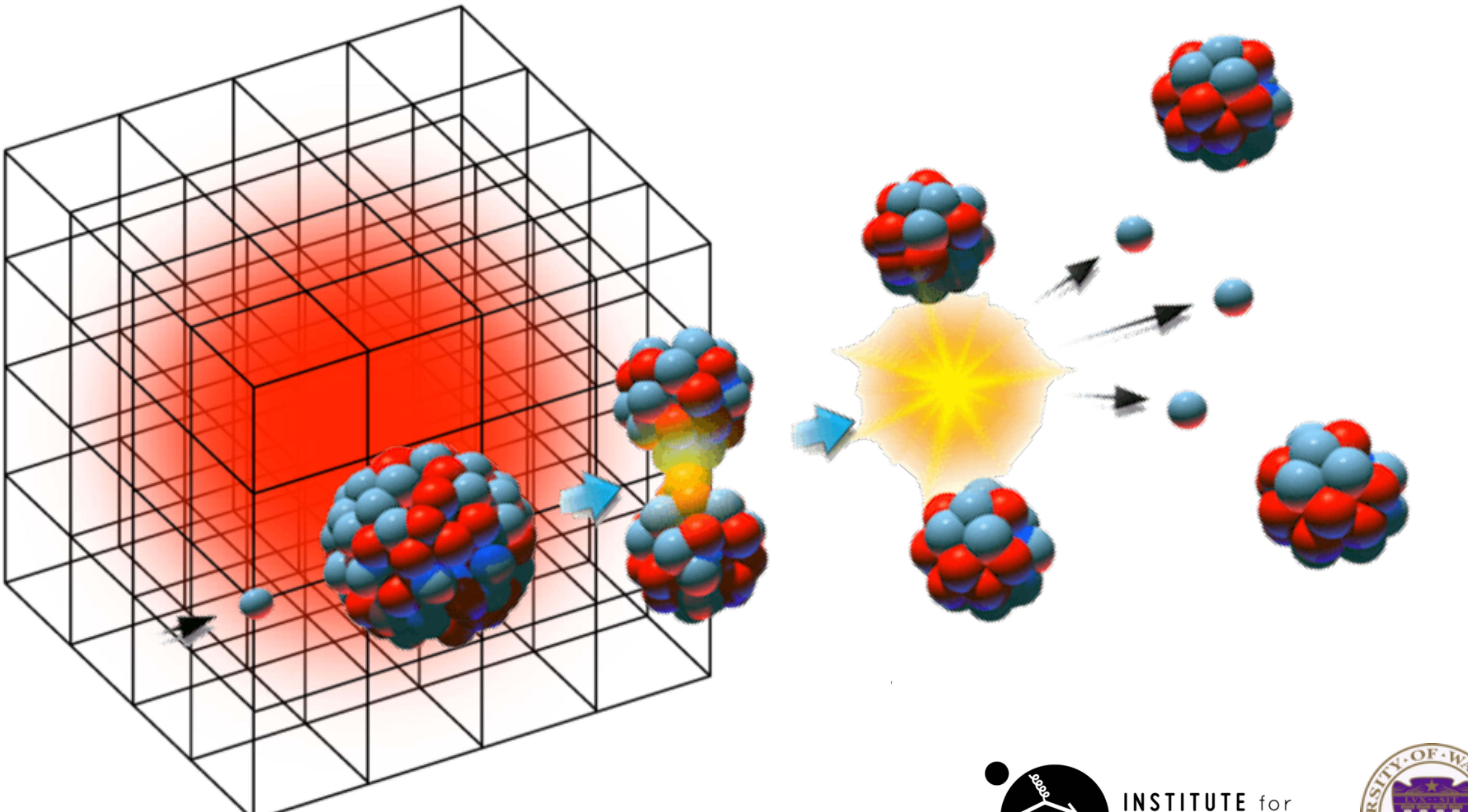
Kavli Institute for Theoretical Physics
University of California, Santa Barbara

Lattice QCD for Nuclear Physics

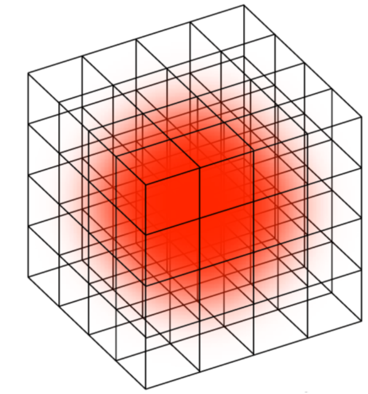


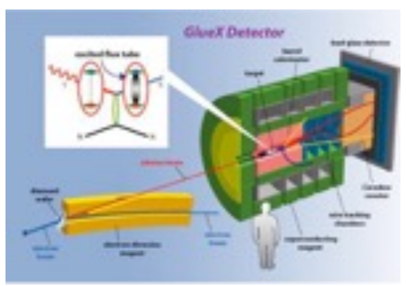
Martin J Savage

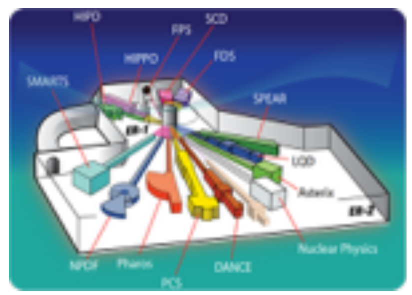
INSTITUTE for NUCLEAR THEORY

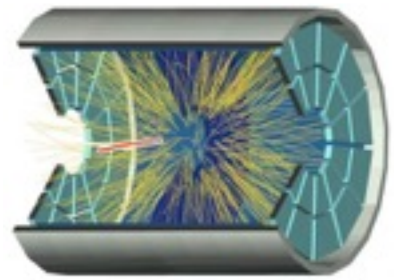
UNIVERSITY OF WASHINGTON · 1861

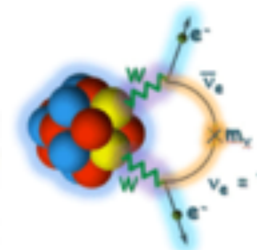
Low-Energy Nuclear Physics

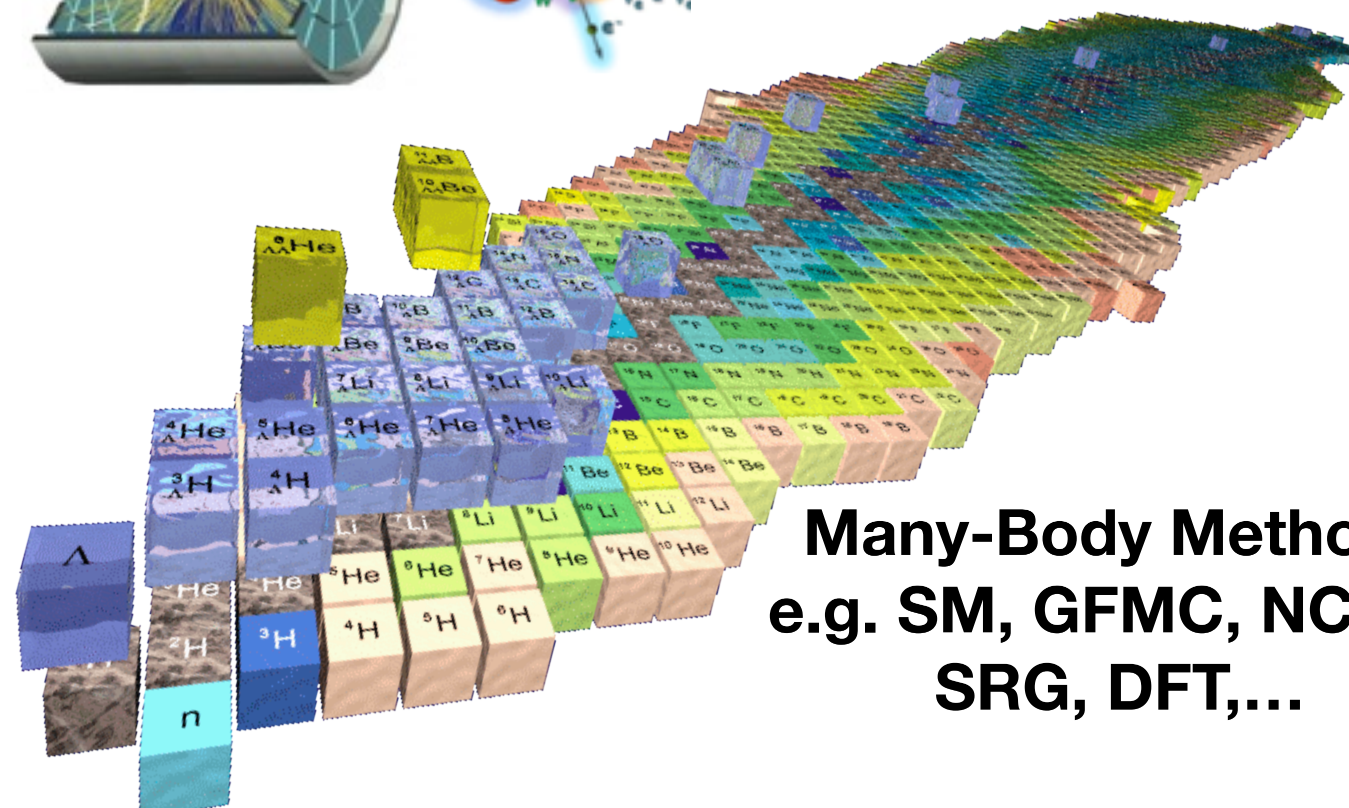




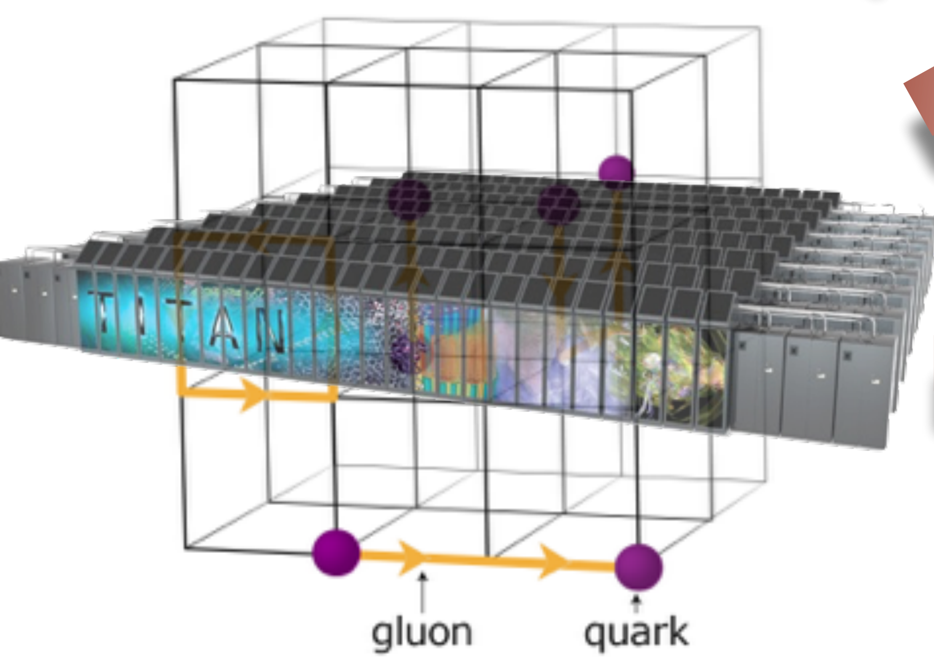


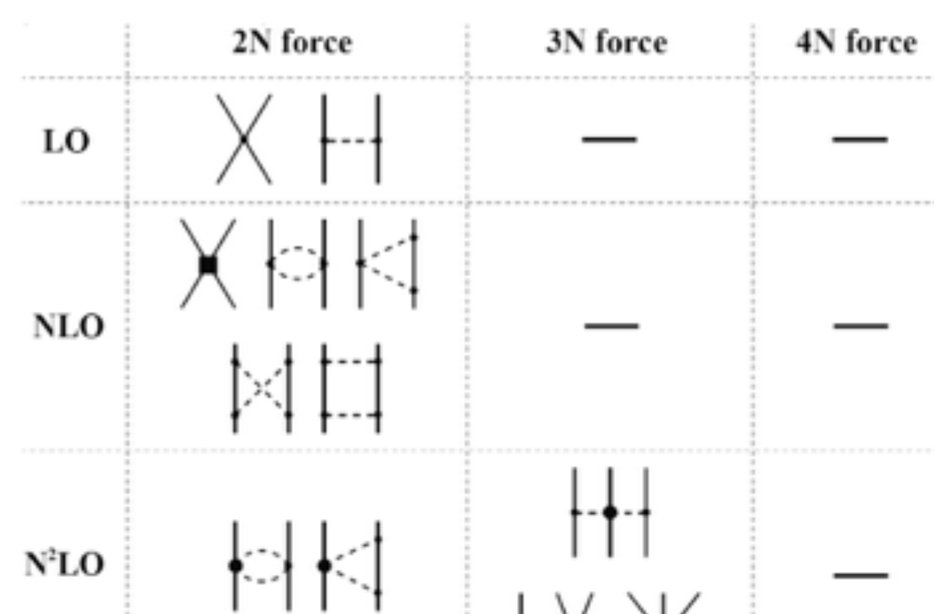




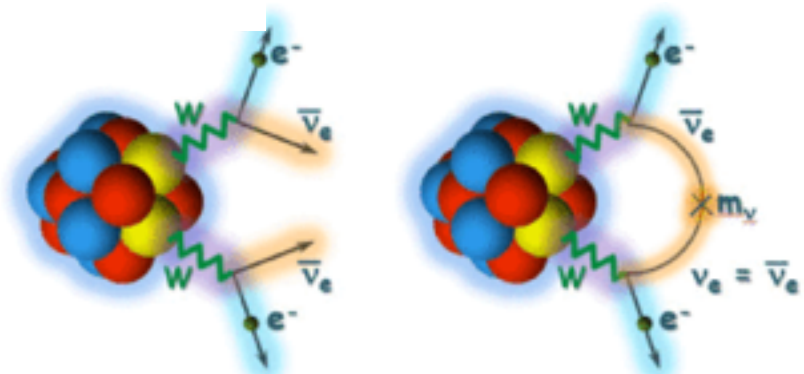


Many-Body Methods e.g. SM, GFMC, NCSM, SRG, DFT,…

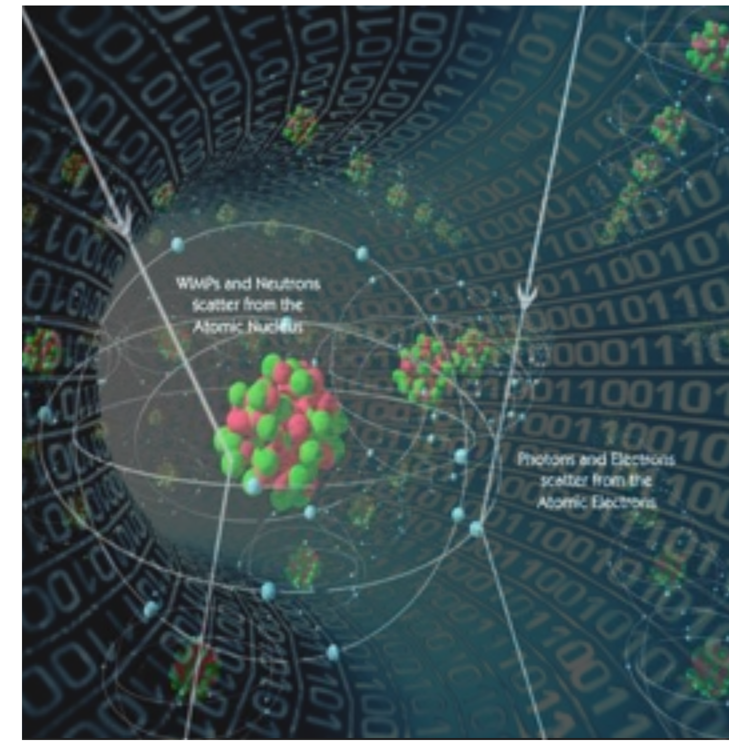




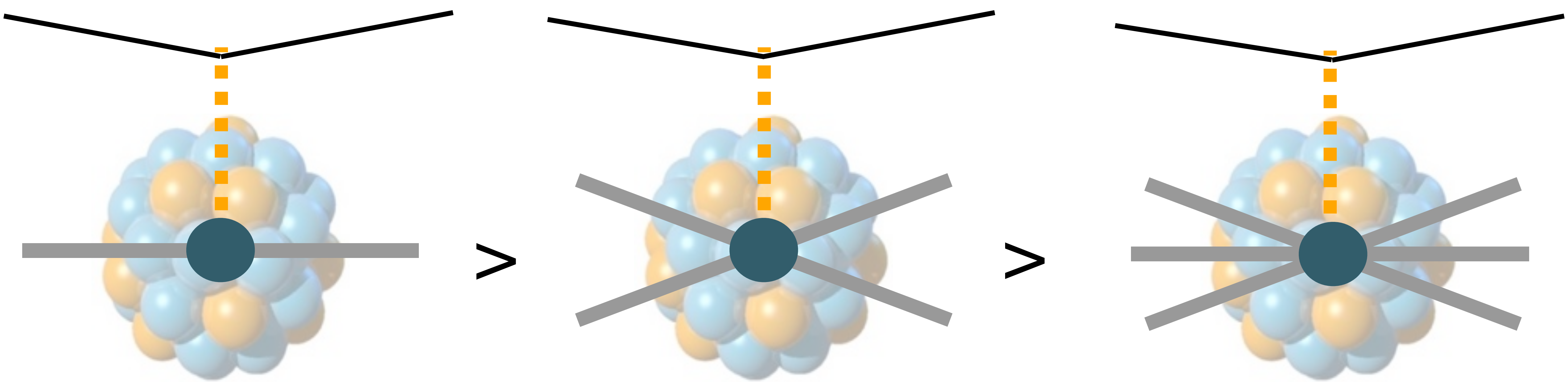
Facilitating
Experimental Discovery



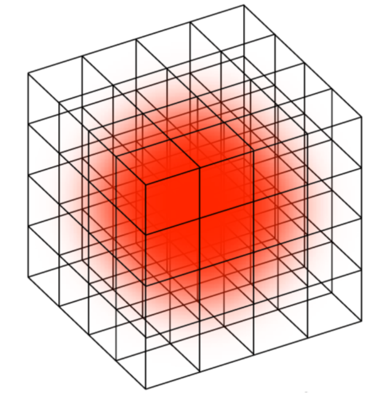
(Amy Nicholson, plenary later this week)

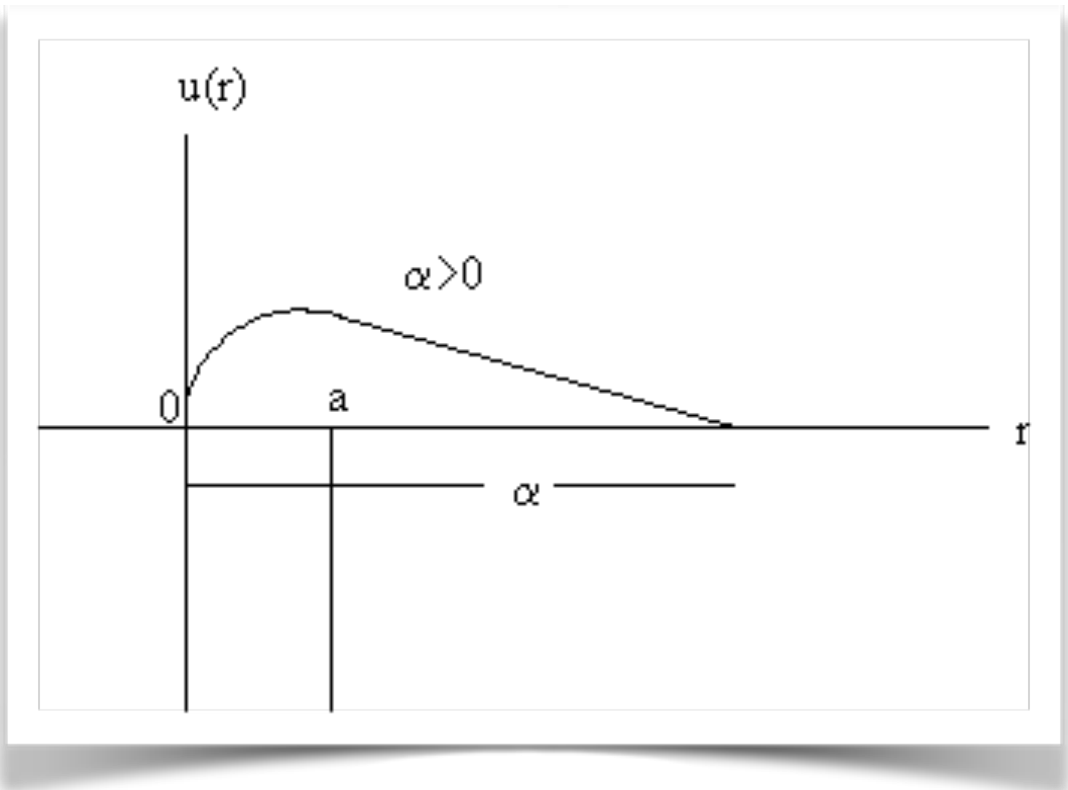


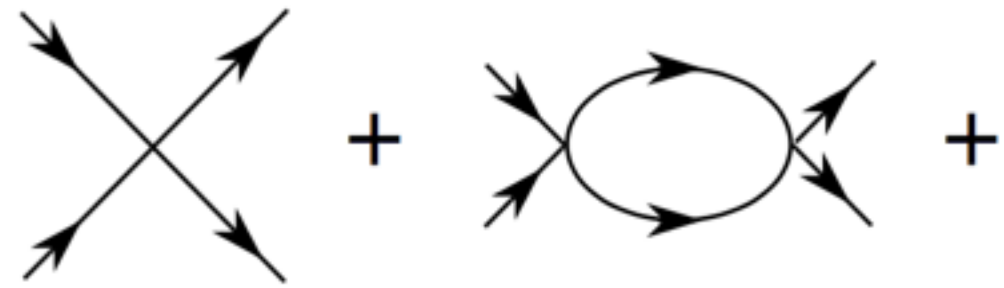
ν, e, μ, X - JLab, ν-experiments, DUNE, DM, edm, …



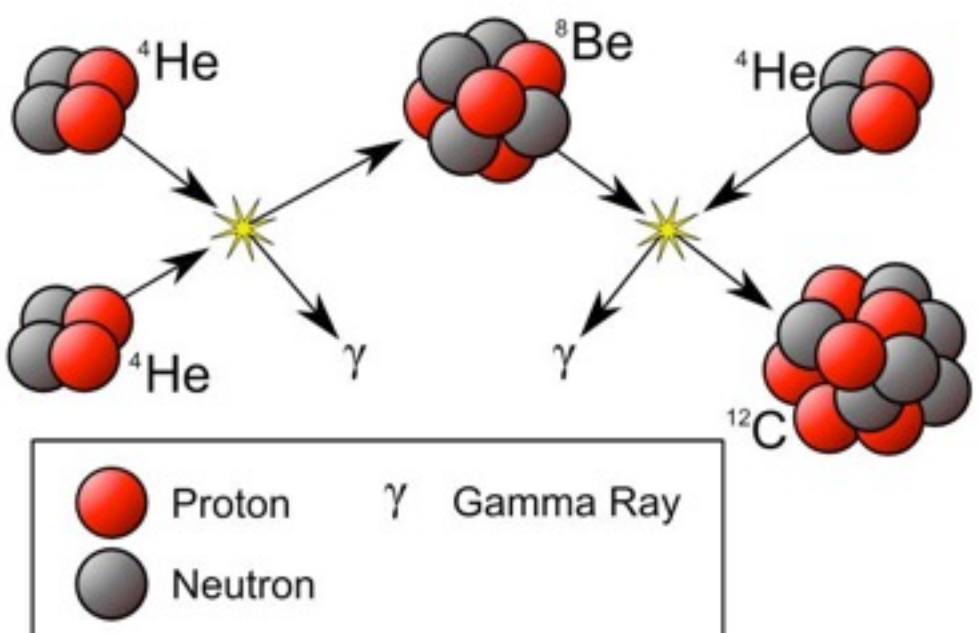
Understanding the Fine-Tunings define our Universe

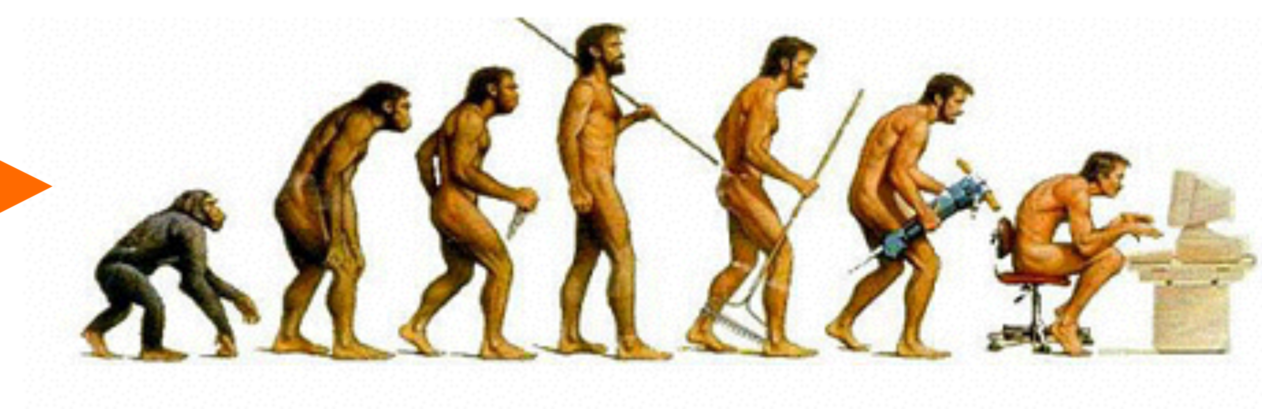




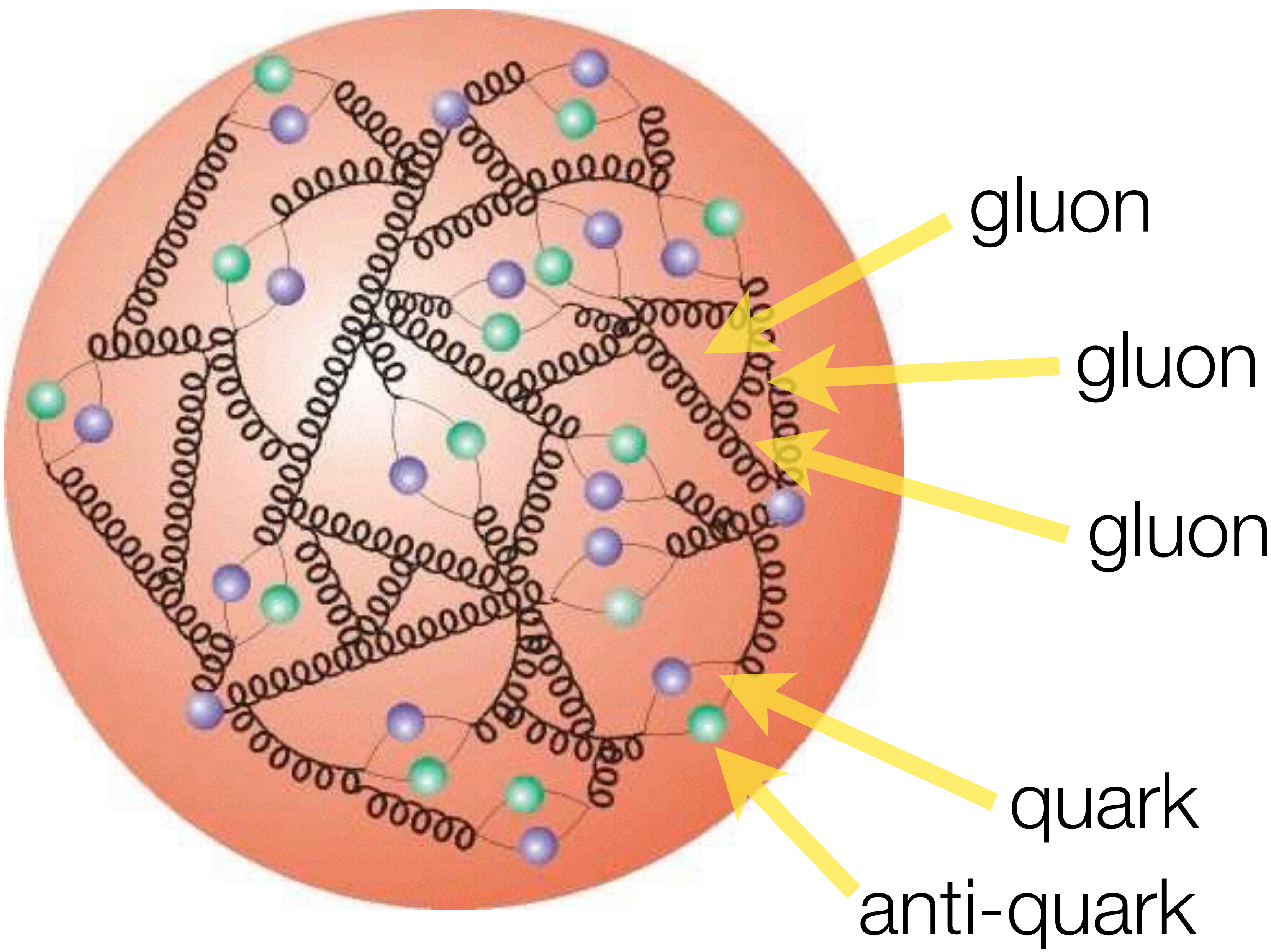
$\mathcal{A}_{-1} =$ 

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





The ``Reality” of QCD



Nucleon

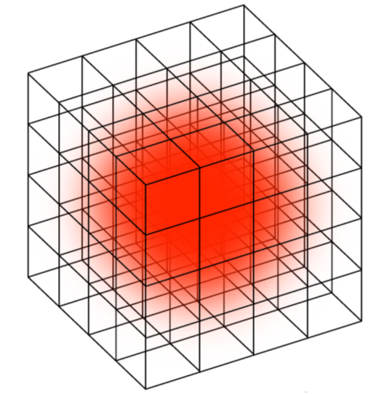
up-quark mass ~ 3 MeV
down-quark mass ~ 5 MeV
gluon mass = 0 MeV

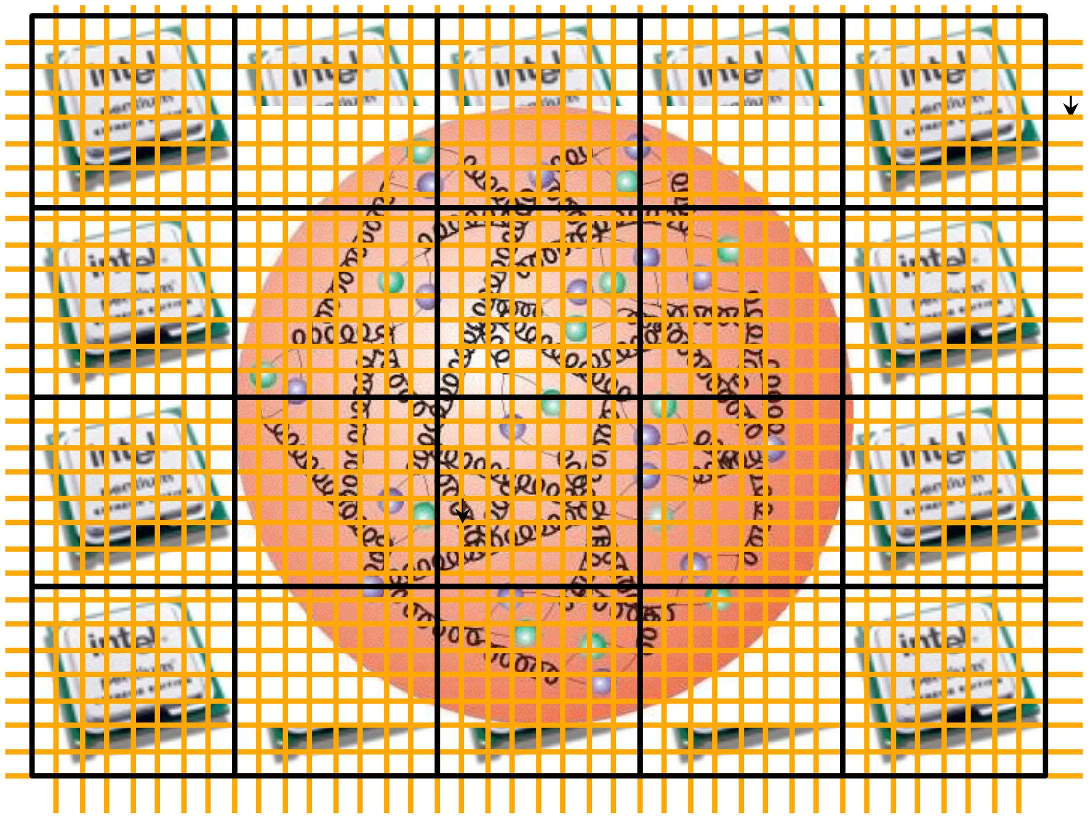
proton ~ 940 MeV

Nucleon is an entangled state of indefinite particle number with spin-1/2

quark masses defined in a scheme at a scale: e.g. Dim. Reg. with MSbar at μ=2 GeV

Lattice QCD:
A Discretized Euclidean Spacetime



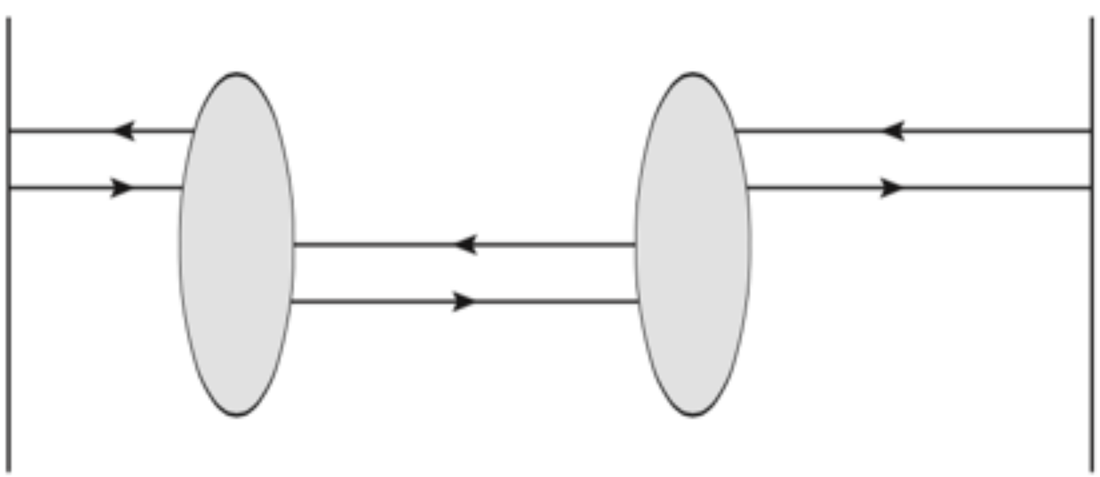


Lattice Spacing : $a << 1/\Lambda\chi$ (Nearly Continuum)

Lattice Volume : $m_\pi L >> 2\pi$ (Nearly Infinite Volume)

Extrapolation to $a = 0$ and $L = \infty$

Systematically remove non-QCD parts of calculation through the Symanzik action and p-regime effective field theories

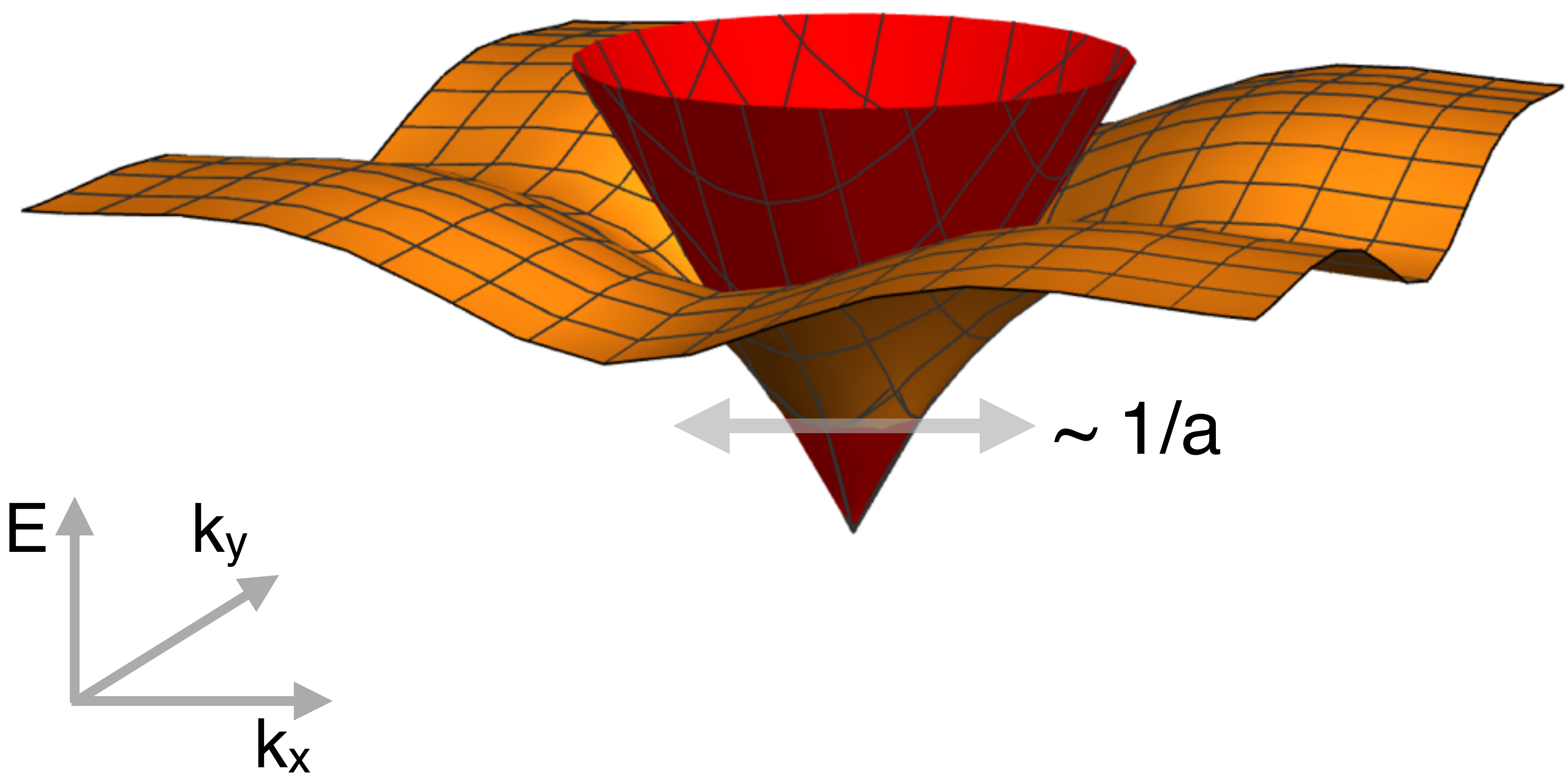


Thermal effects can be problematic, requires

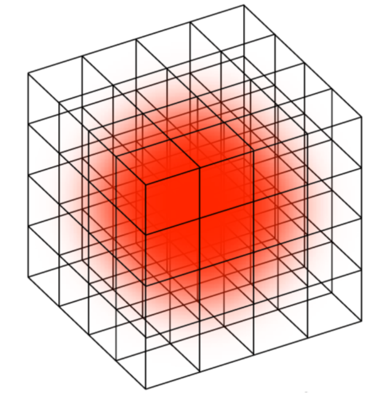
$$m_\pi T \gg 10$$

Lattice QCD:
Impact of Discretization

Dispersion Relation

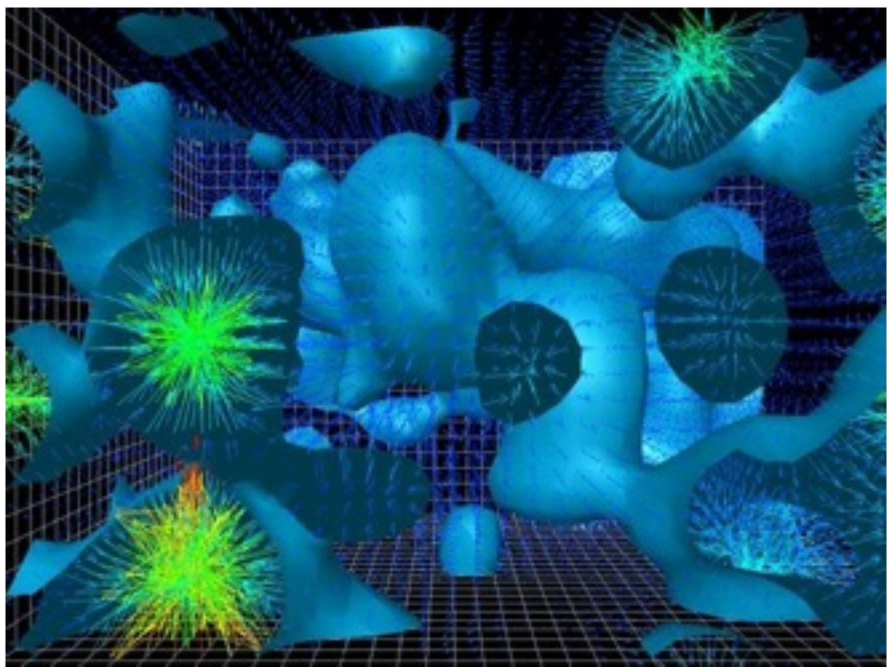


Gluons and Quarks



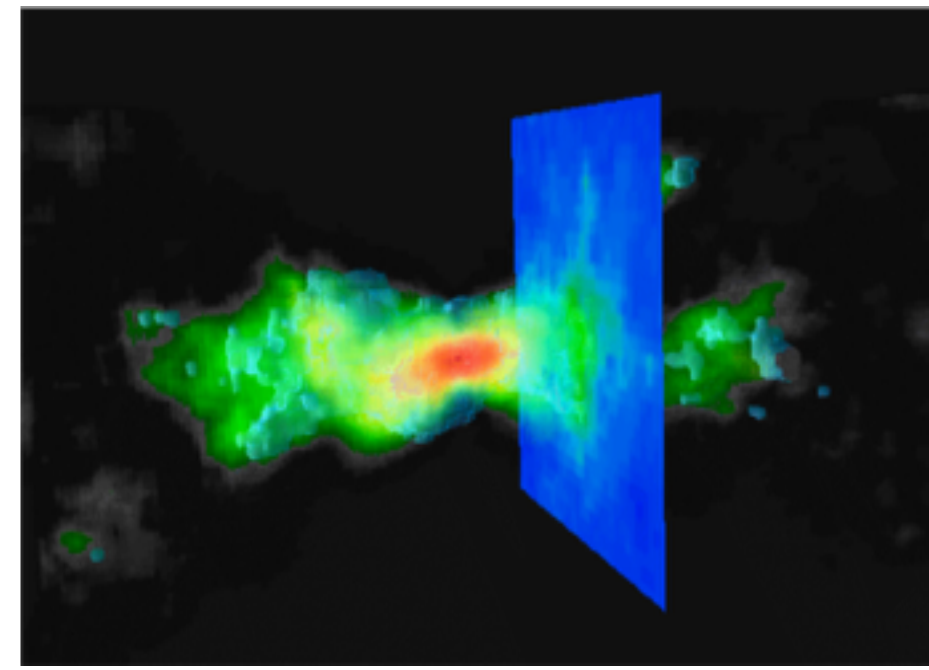
Derek Leinweber

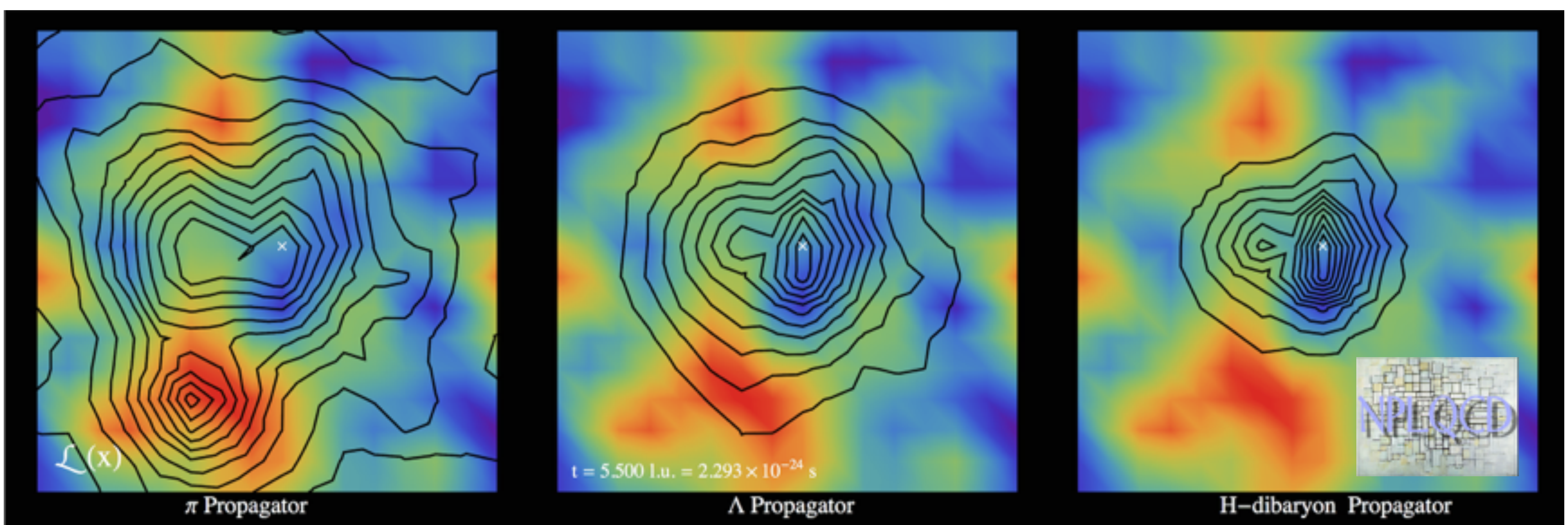
Rajan Gupta *et al*



Gluons

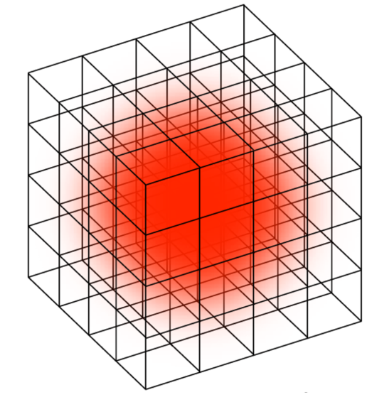
Quarks

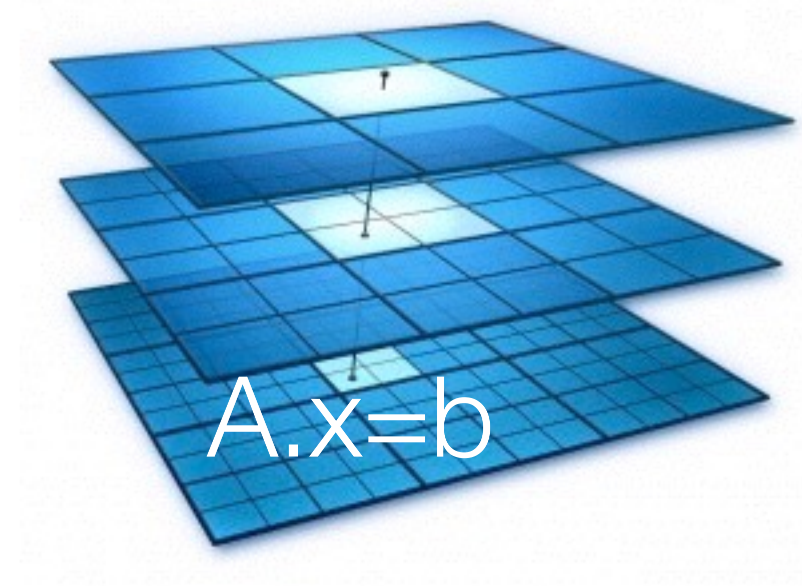


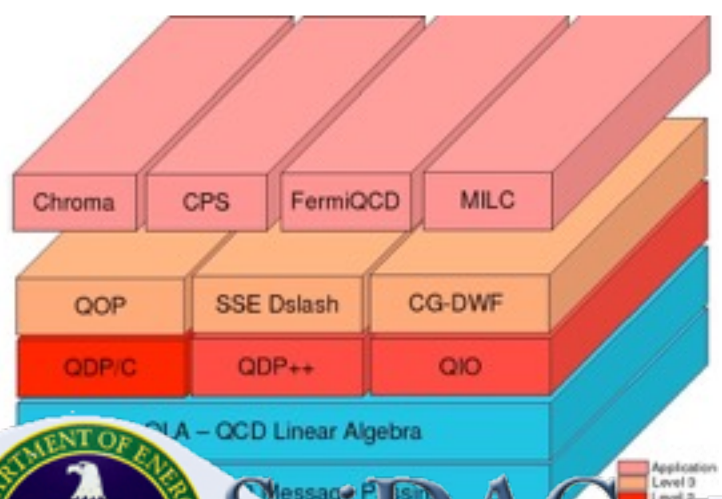


USQCD

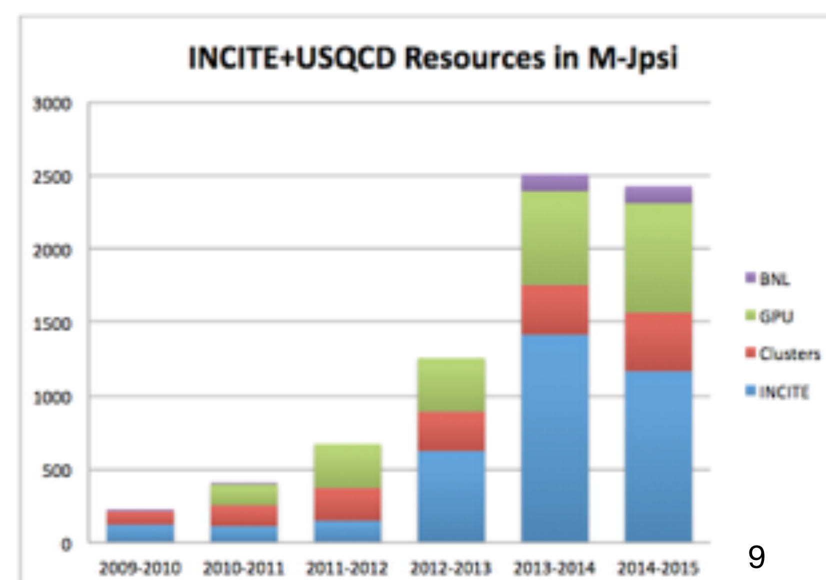
A collaboration of collaborations



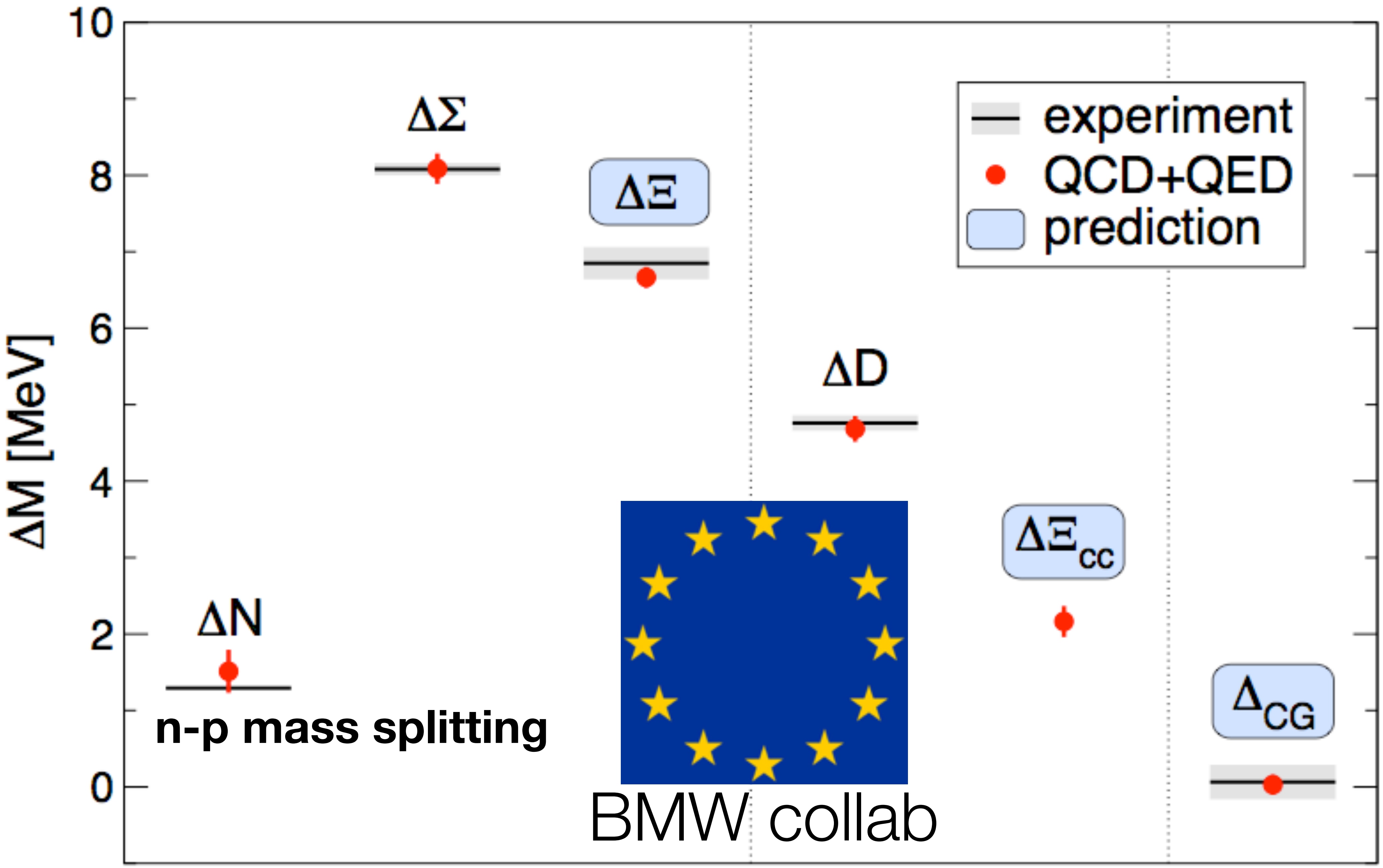




SciDAC
Scientific Discovery through Advanced Computing

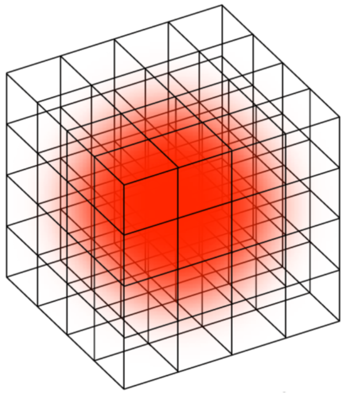


State-of-the-Art Lattice QCD



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

Methods and Difficulties
Correlators



DEUTSCHES ELEKTRONEN – SYNCHROTRON DESY

DESY 90-131
October 1990

受入
91-1-382

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

M. Lüscher
Deutsches Elektronen-Synchrotron DESY, Hamburg

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

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

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

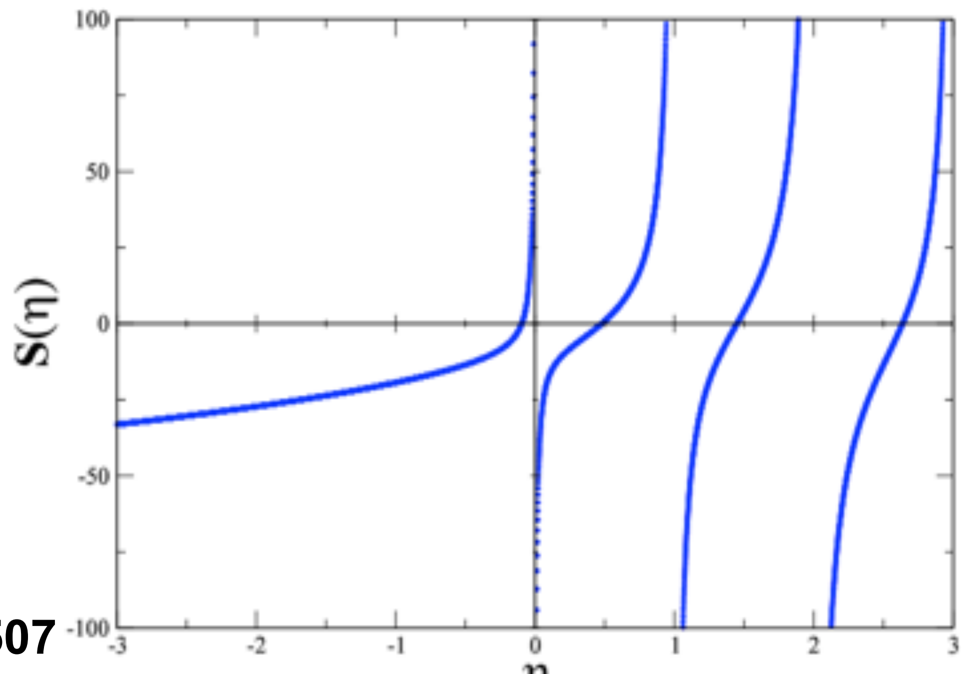
$$W = 2\sqrt{m^2 + mE}. \tag{7.2}$$

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 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

energy eigenvalue

e.g., A_1^+ irrep

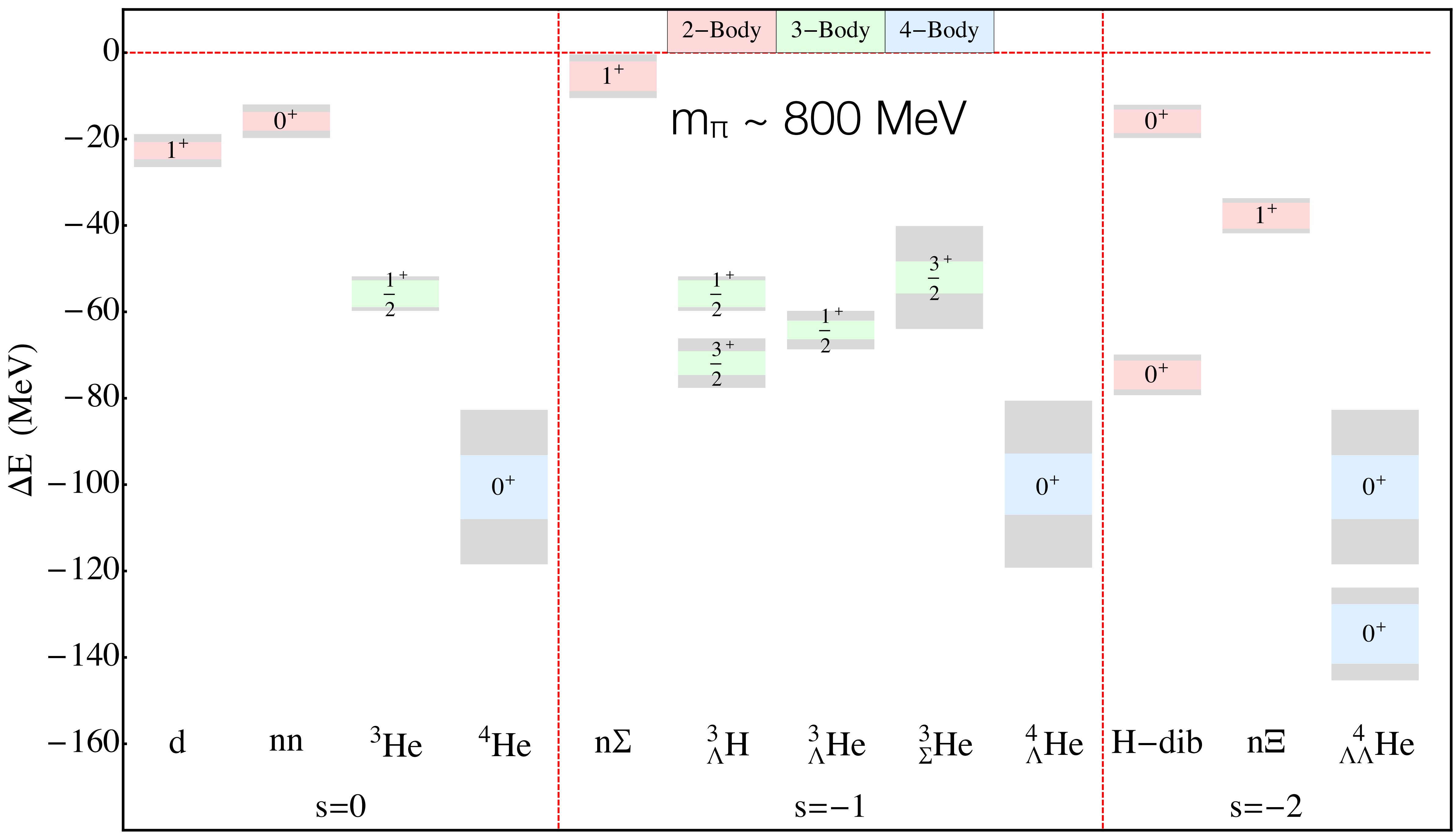
$$p\cot\delta(p) = \frac{1}{\pi L}\,\mathbf{S}\left(\left(\frac{Lp}{2\pi}\right)^2\right)$$



Extended to Coupled-Channels systems:

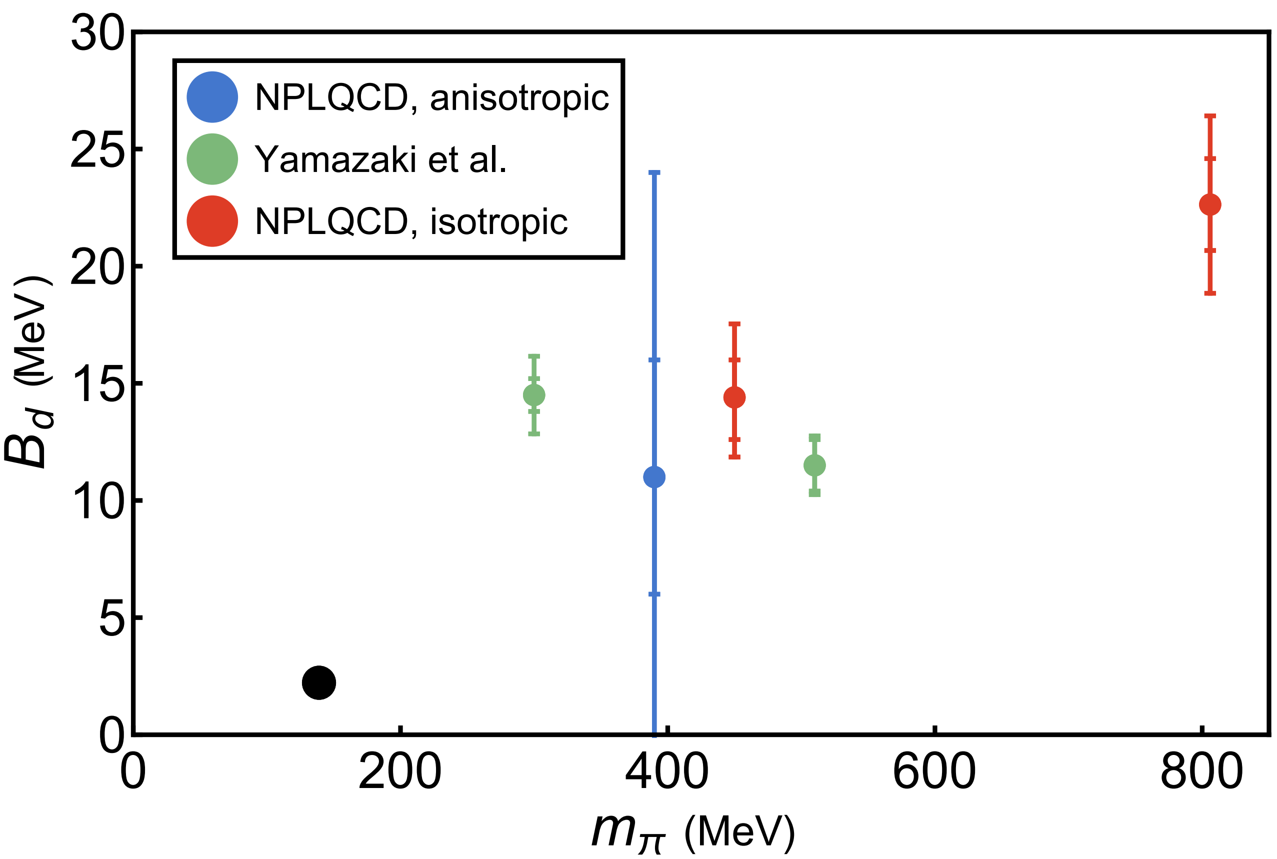
e.g., Raul Briceno and Zohreh Davoudi, Phys.Rev. D88 (2013) no.9, 094507

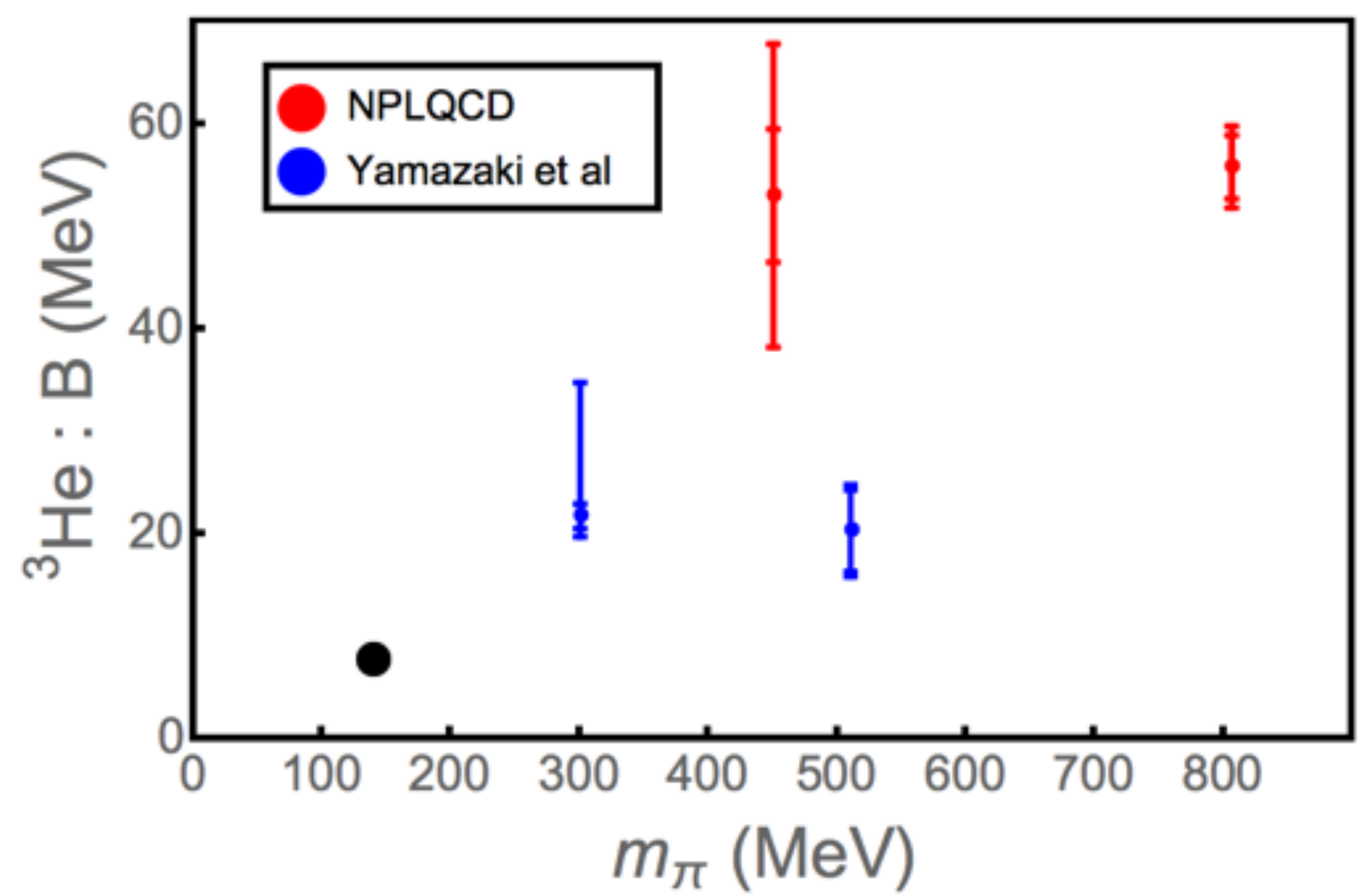
Nuclei from QCD



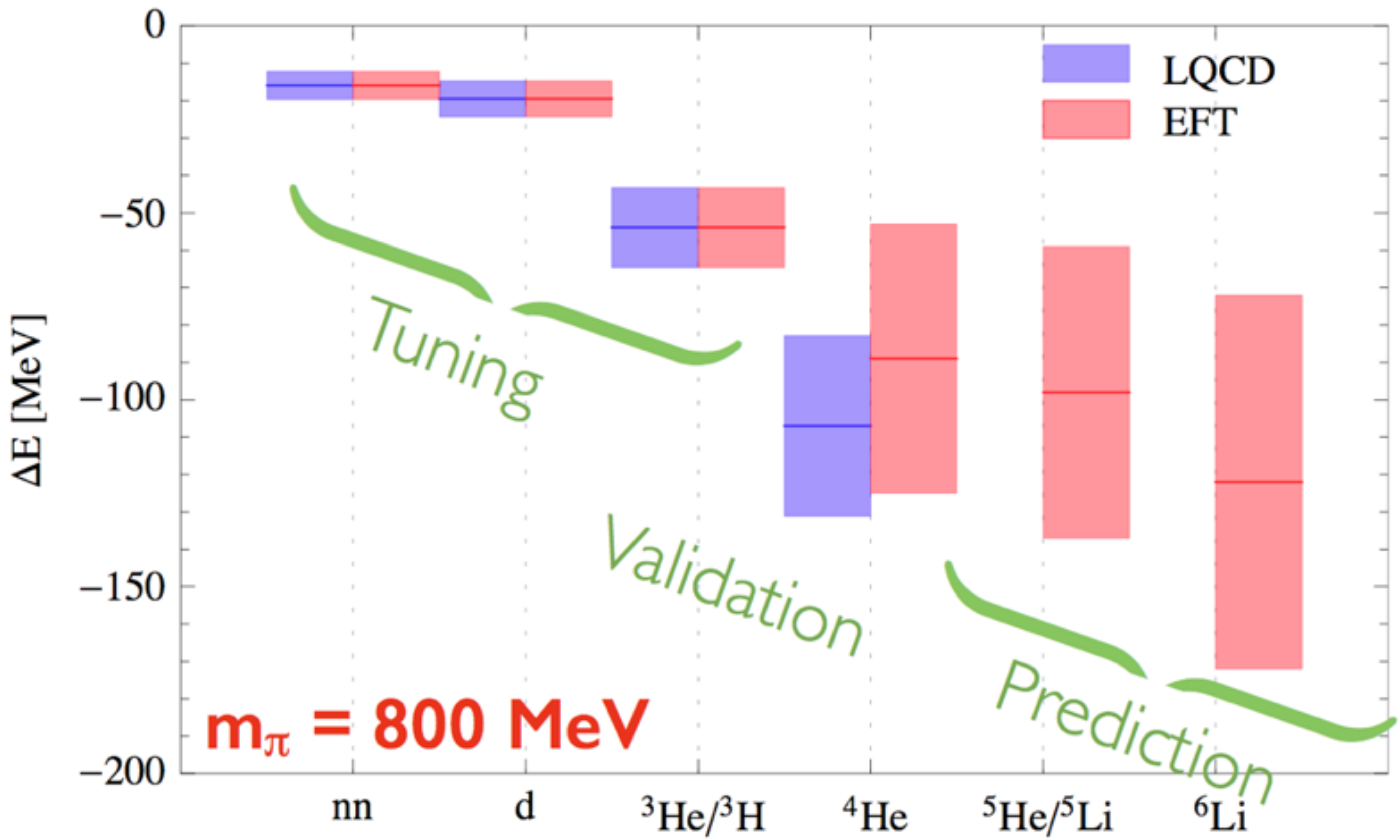
Beane *et al* (NPLQCD), Phys.Rev. D87 (2013) 3, 034506, Phys.Rev. C88 (2013) 2, 024003

Light Nuclei : Quark Mass Effects





The Periodic Table as a function of the quark masses

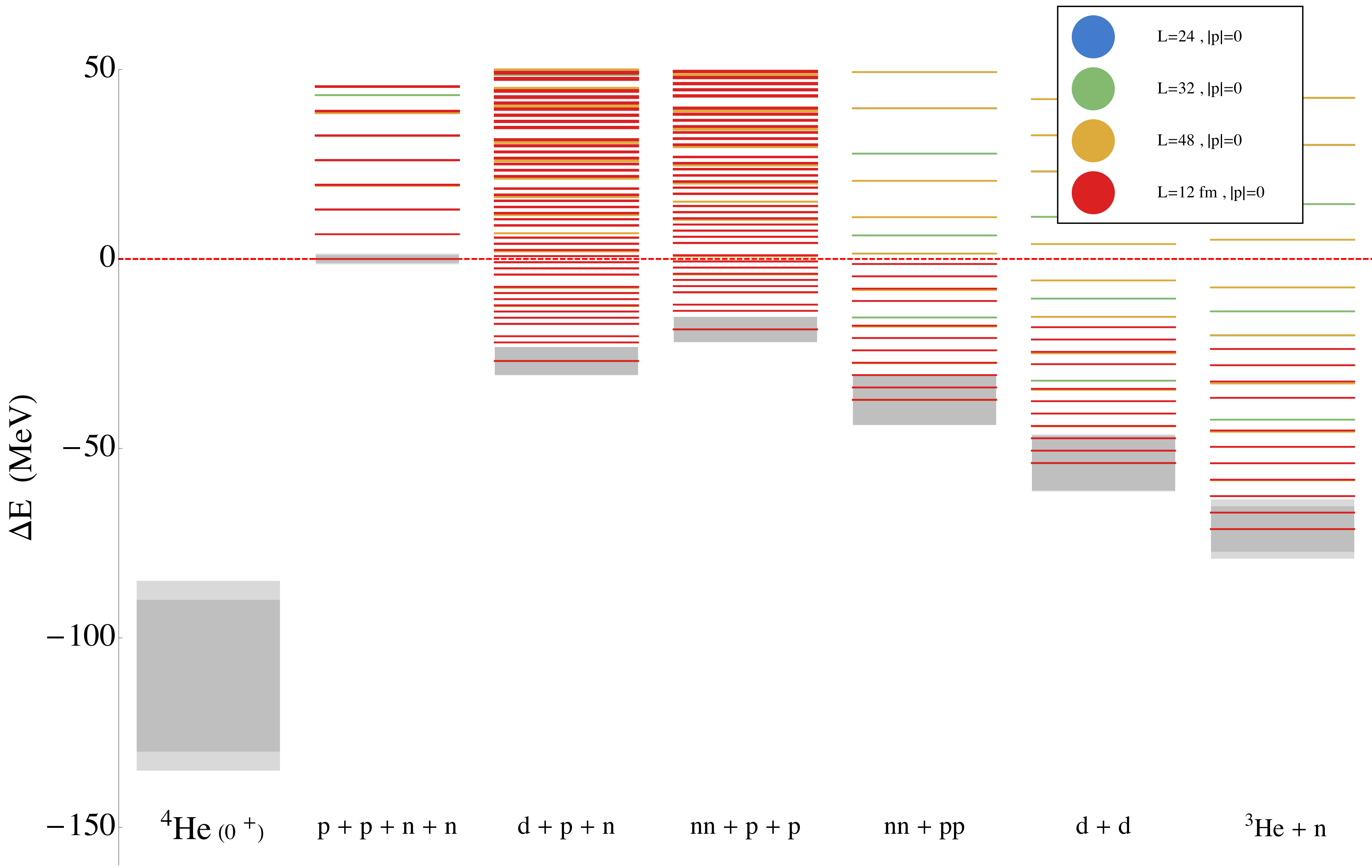


Enhances the scope of the Lattice Calculations

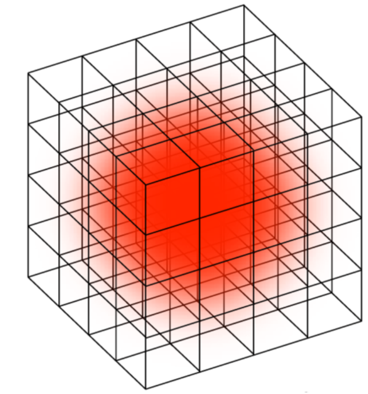
Effective Field Theory for Lattice Nuclei , N. Barnea et al, Nov 20, 2013. 5 pp. , Phys. Rev. Lett. 114 (2015) 5, 052501

Methods and Difficulties
Many-Body Spectra

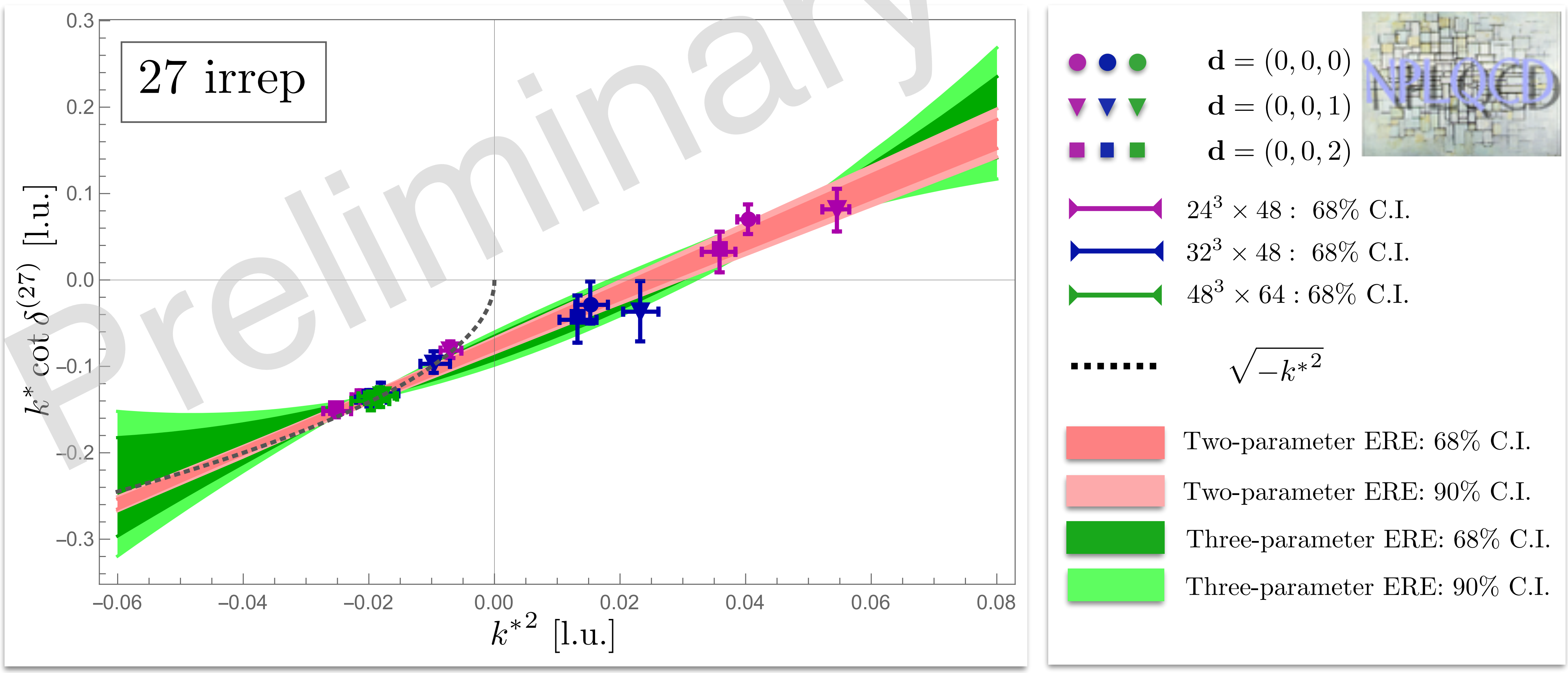
e.g., what was found and expected at $M_\pi \sim 800$ MeV

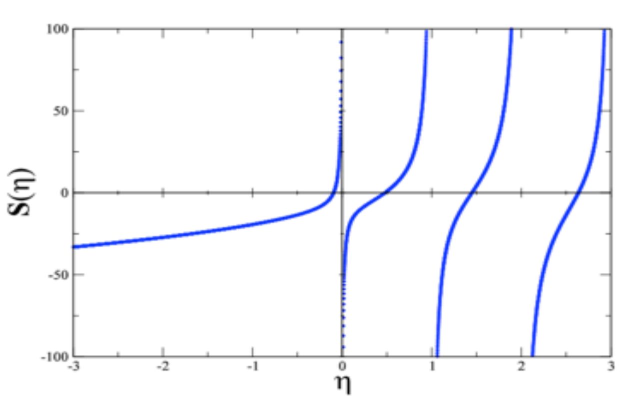


Methods and Difficulties
Correlators



Luscher's method(s): PACS, NPLQCD, Mainz,

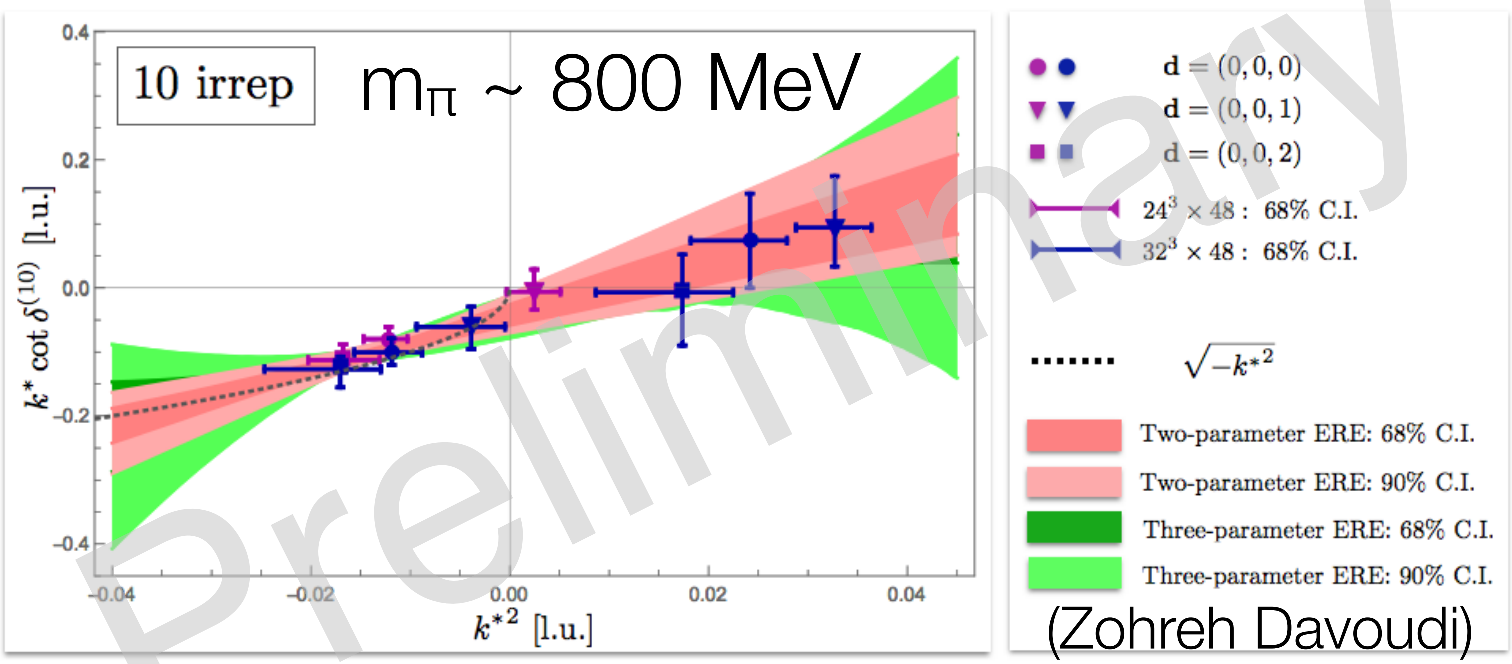




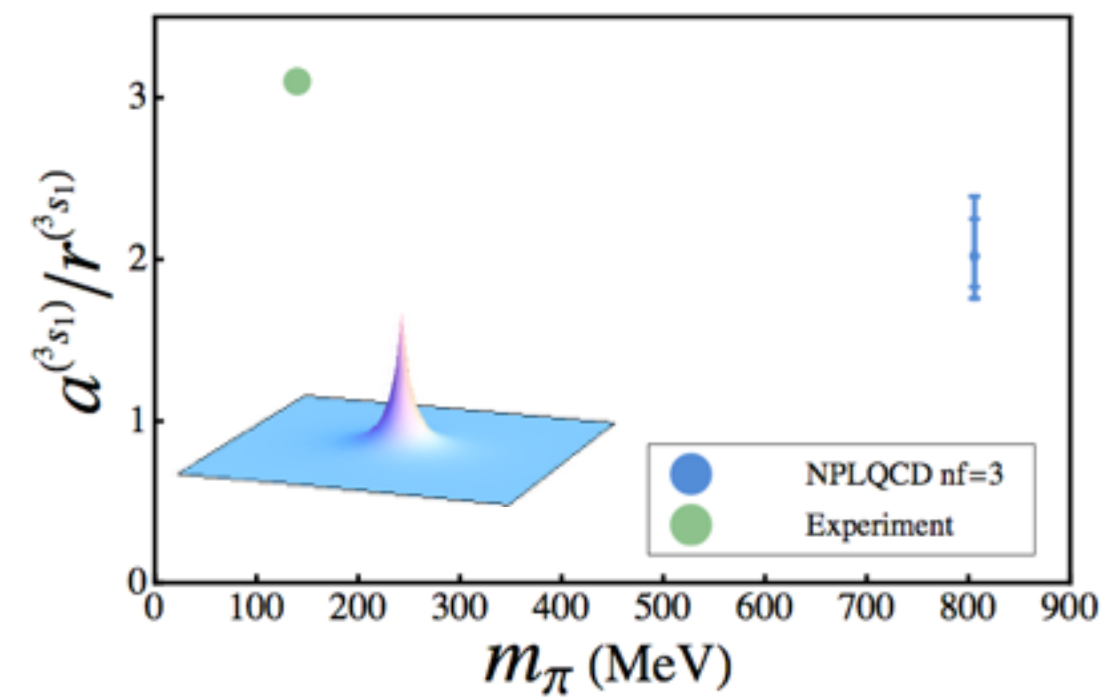
Applicable out to inelastic threshold, then can be extended by including other channels and S-matrix, $k^2 < m_\pi M_N$.

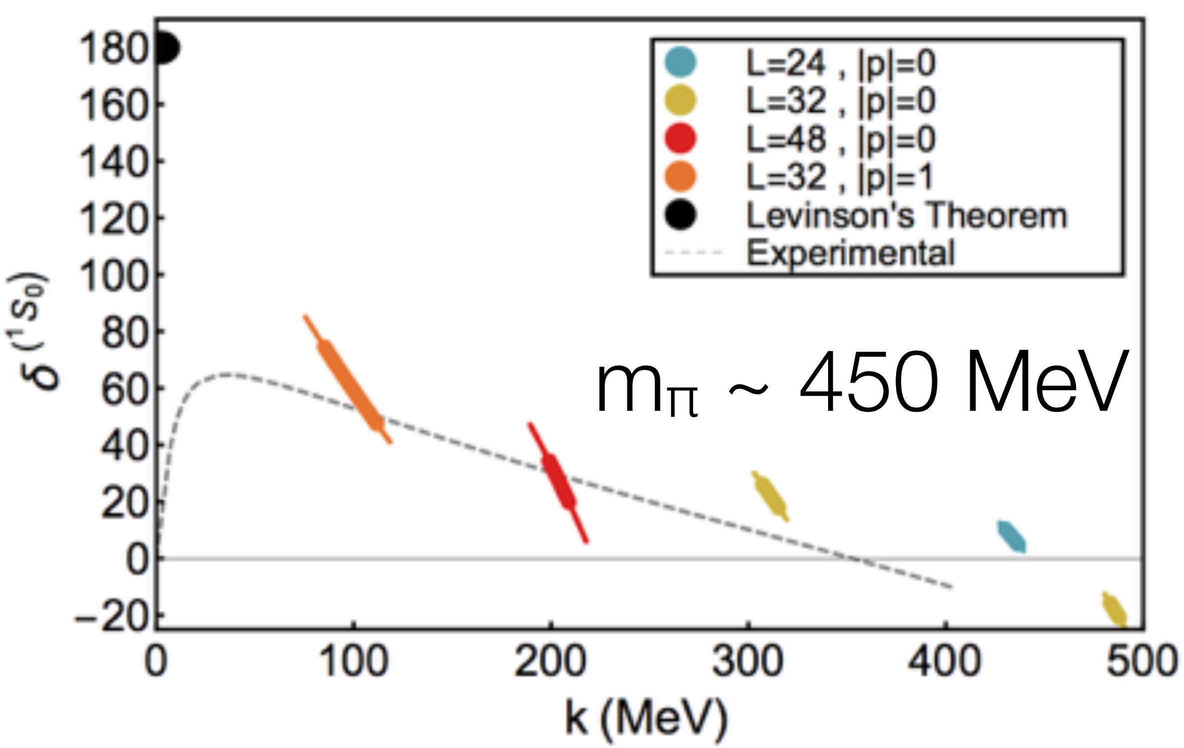
Effective Range Expansion valid below t-channel cut, $k < m_\pi/2$

NN Interactions



(Zohreh Davoudi)



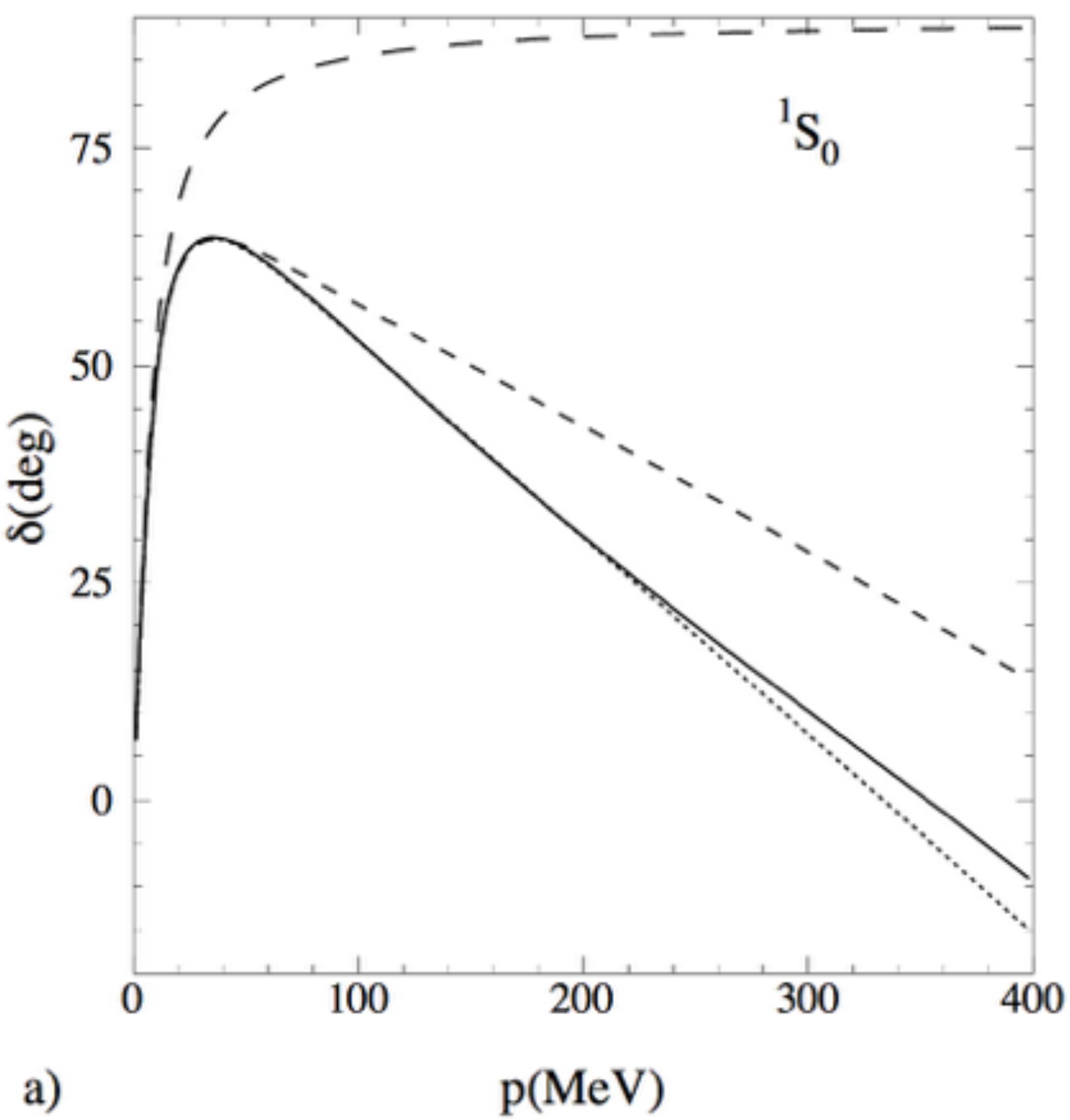


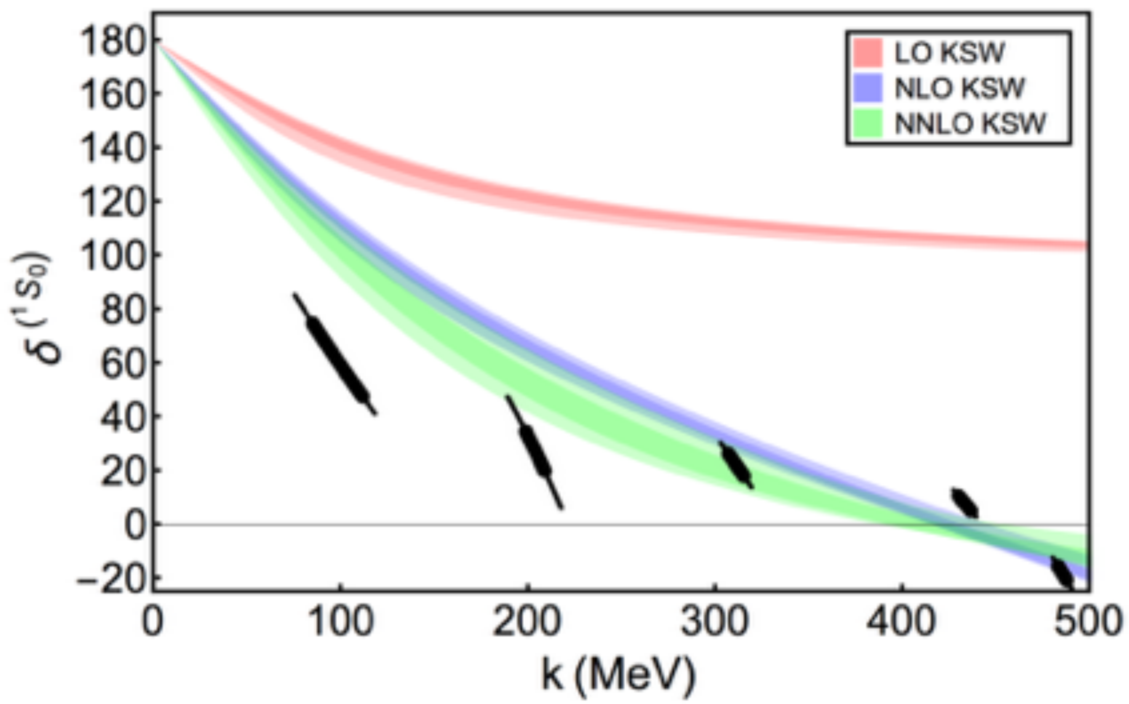
Deuteron appears to be unnatural but not finely-tuned ??

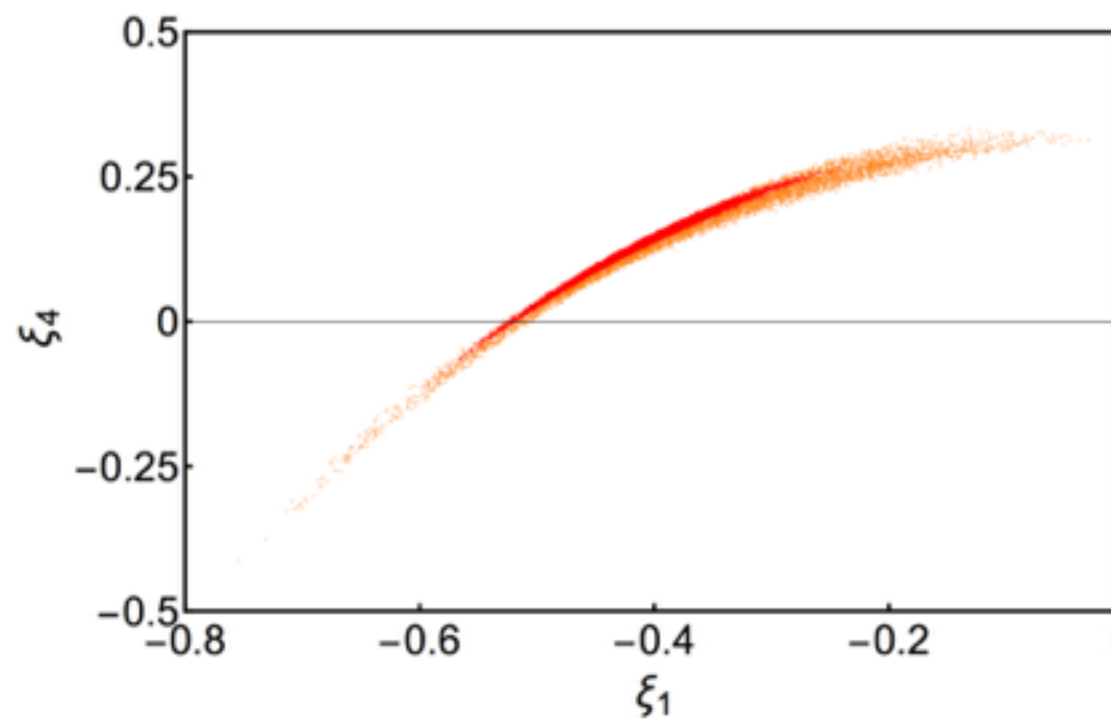
Generic feature of YM with n_f=3

NN Interactions

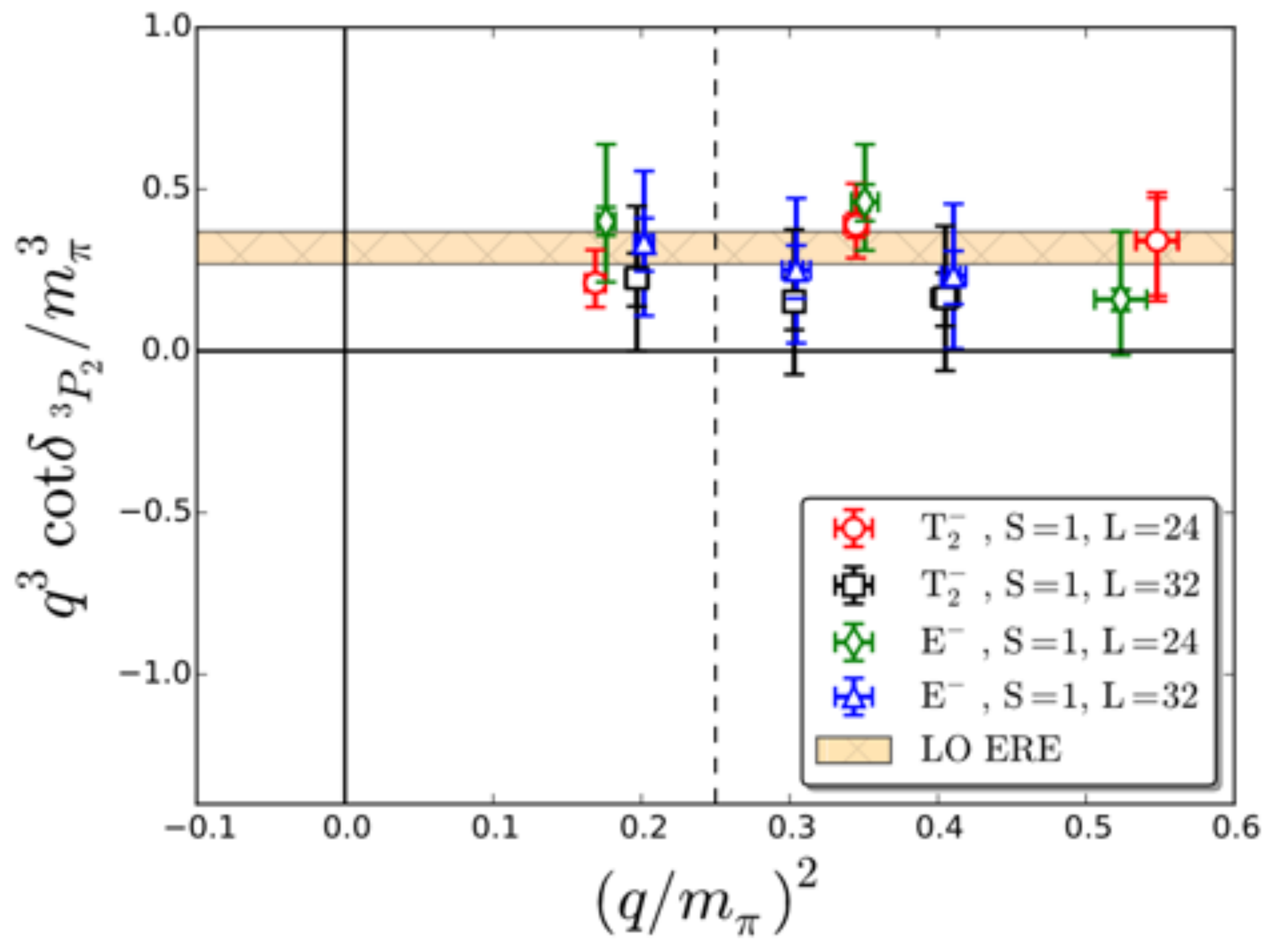
Fleming, Mehen. Stewart NNLO in KSW of NN 1S0
Convergence of perturbative pions in
spin singlet channels

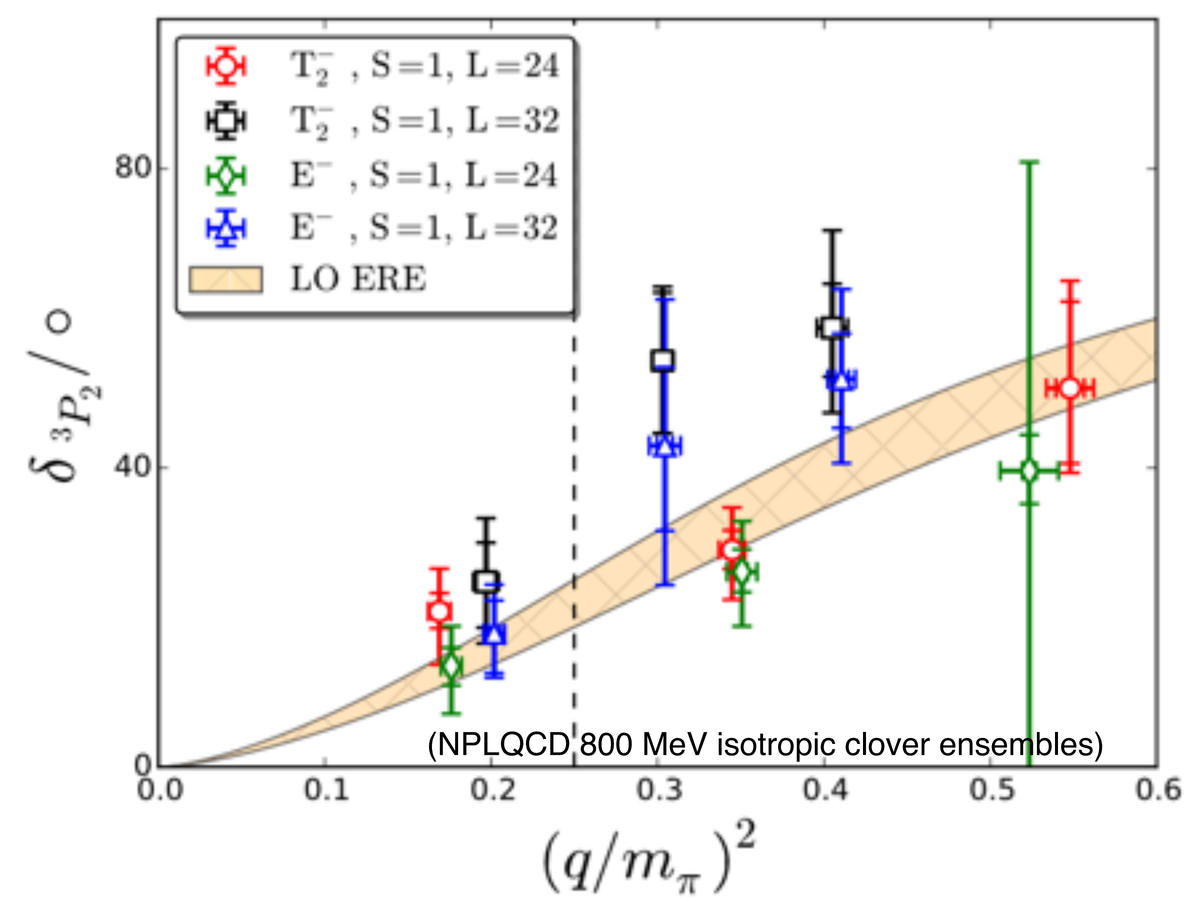






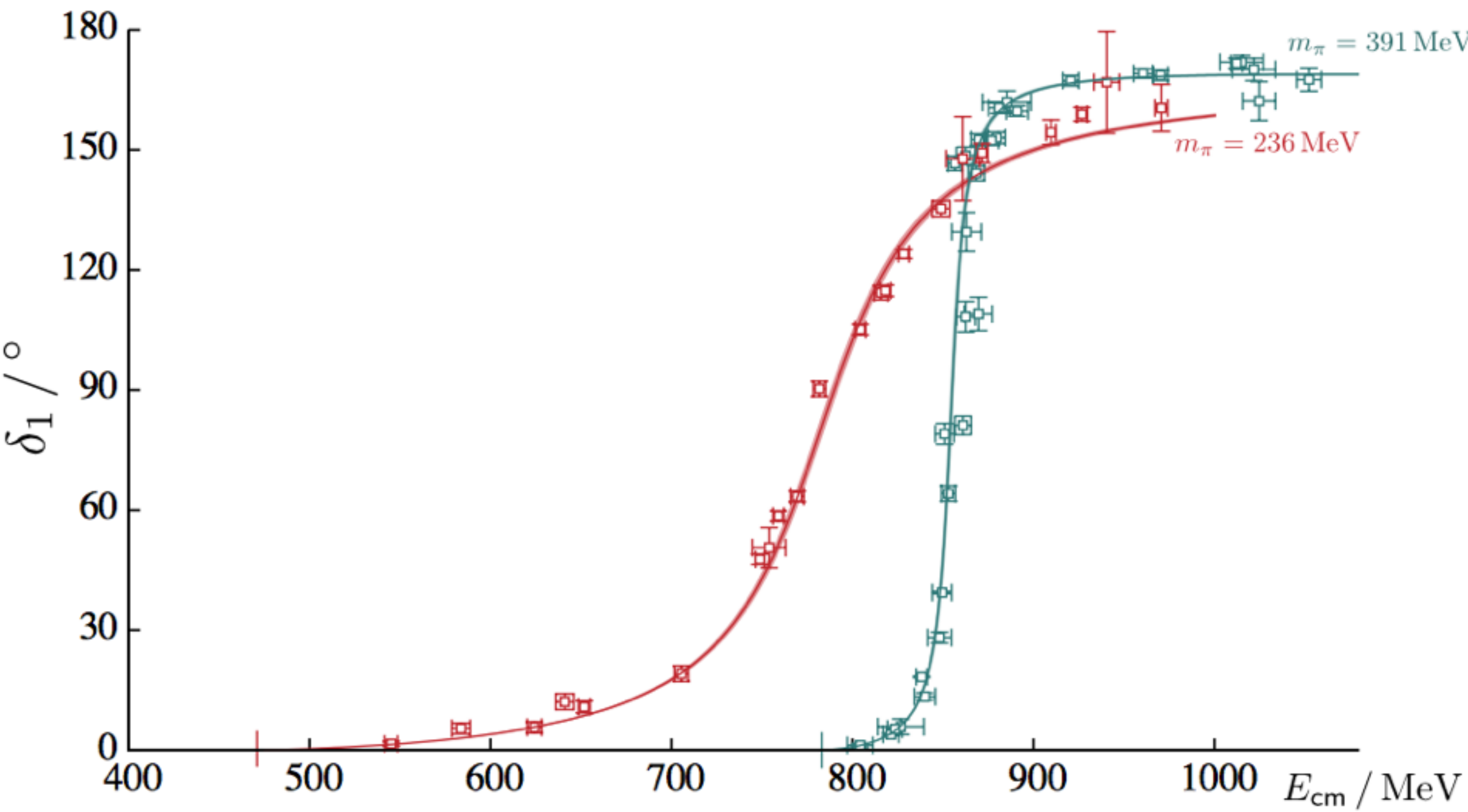
NN Higher Partial Waves





Amy Nicholson *et al* (CalLatt) - PoS LATTICE2015 (2016) 083

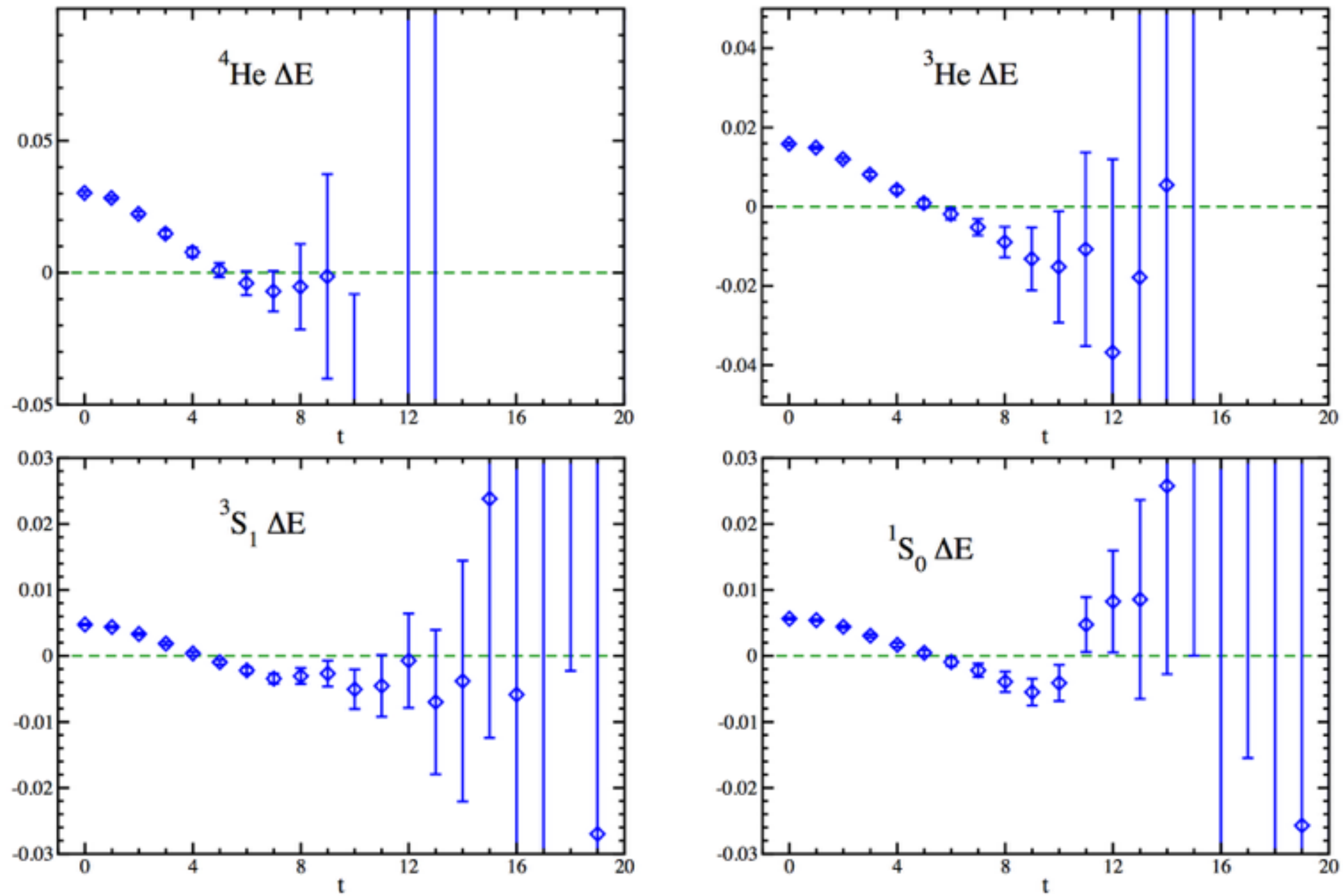
Resonances - mesons



David Wilson, Raul A. Briceno, Jozef J. Dudek, Robert G. Edwards and Christopher E. Thomas (Hadron Spectrum Collaboration)

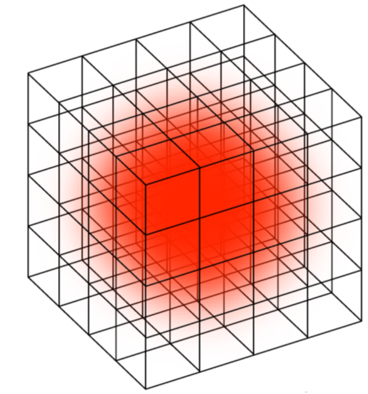
NN and Nuclei
PACS Collaboration

Multi-nucleon focus : nn, d, ^{3}He, ^{4}He $m_\pi \sim 145$ MeV

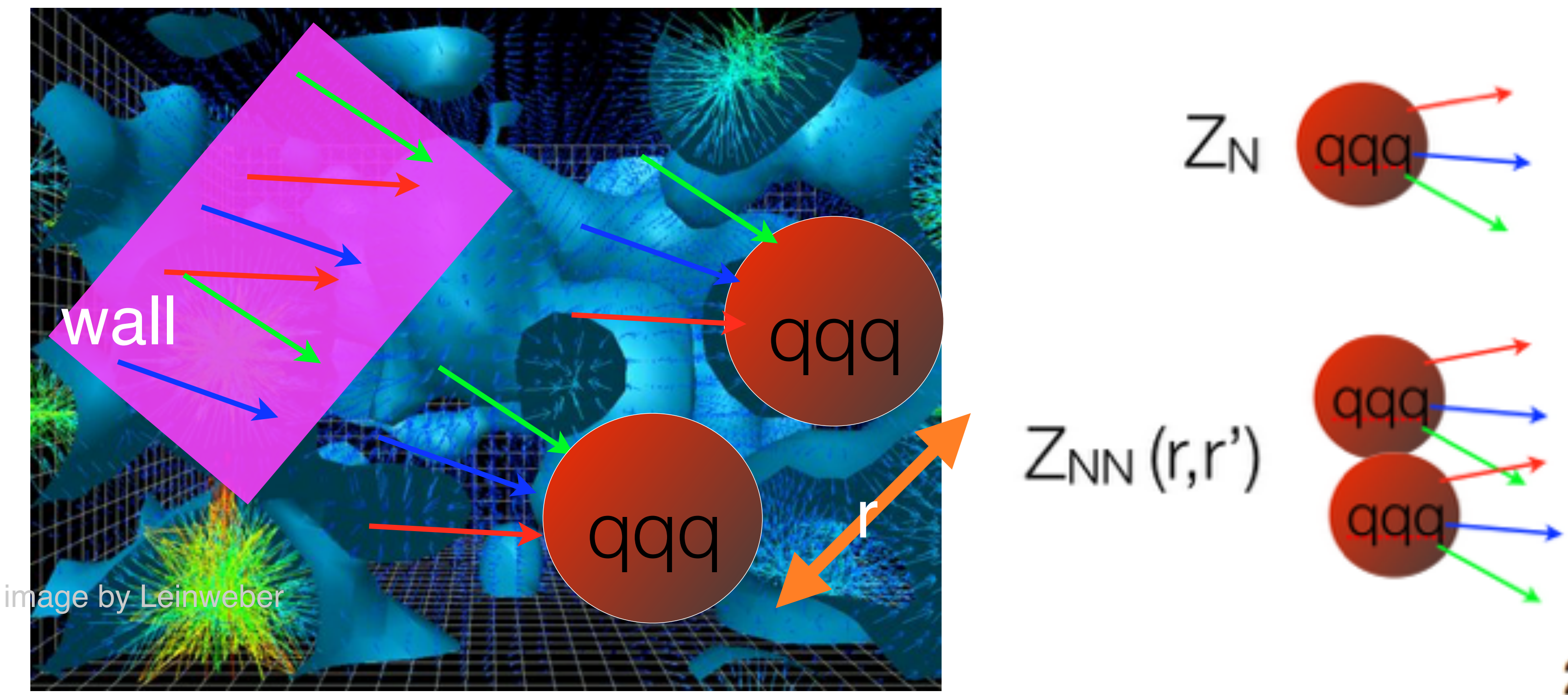


Talk by Takeshi Yamazaki

Methods and Difficulties
Correlators



HAL QCD method(s): HAL QCD

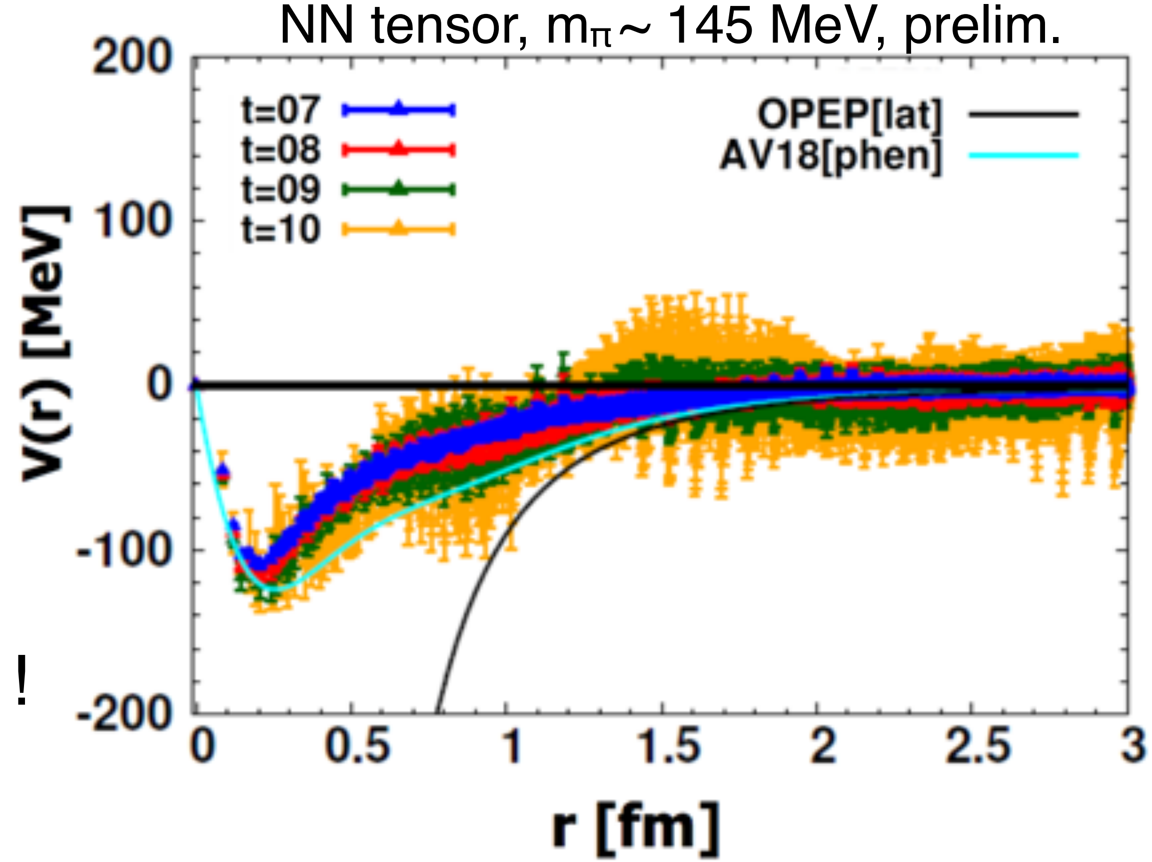


Explicitly, the stationary effective Schrödinger equation in the centre-of-mass frame reads

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

$U_E(r,r')$:
Expected to correctly reproduce S-matrix at energy eigenvalues

NN tensor, $m_\pi \sim$ 145 MeV, prelim.

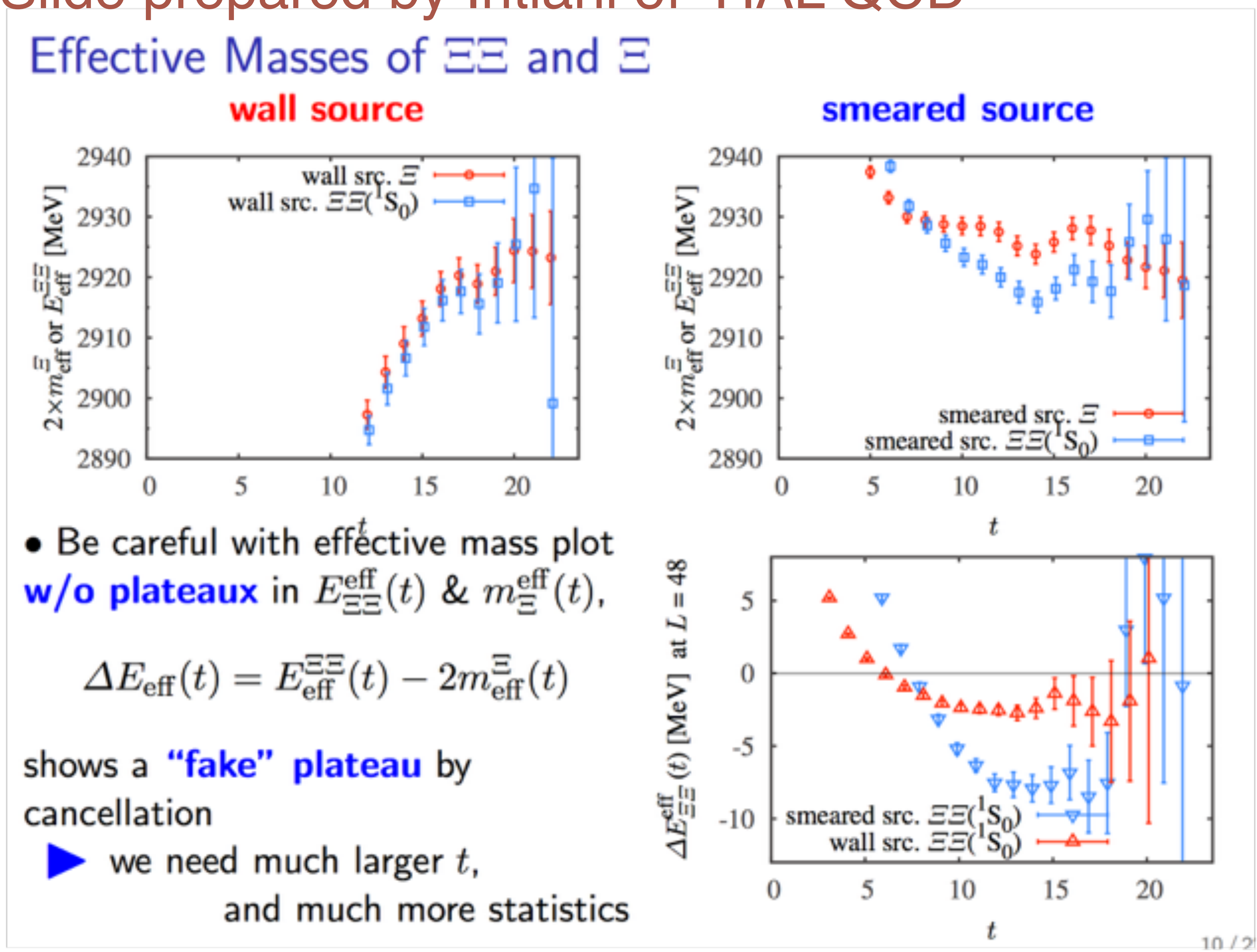


$U_E(r,r')$: assume -> $V(r-r')$ + …

NO nuclear bound states found with this method !
but likely not in plateau region.

Q: Is there a Plateau Crisis ?
A: Only for Wall Sources

Slide prepared by Iritiani of HAL QCD

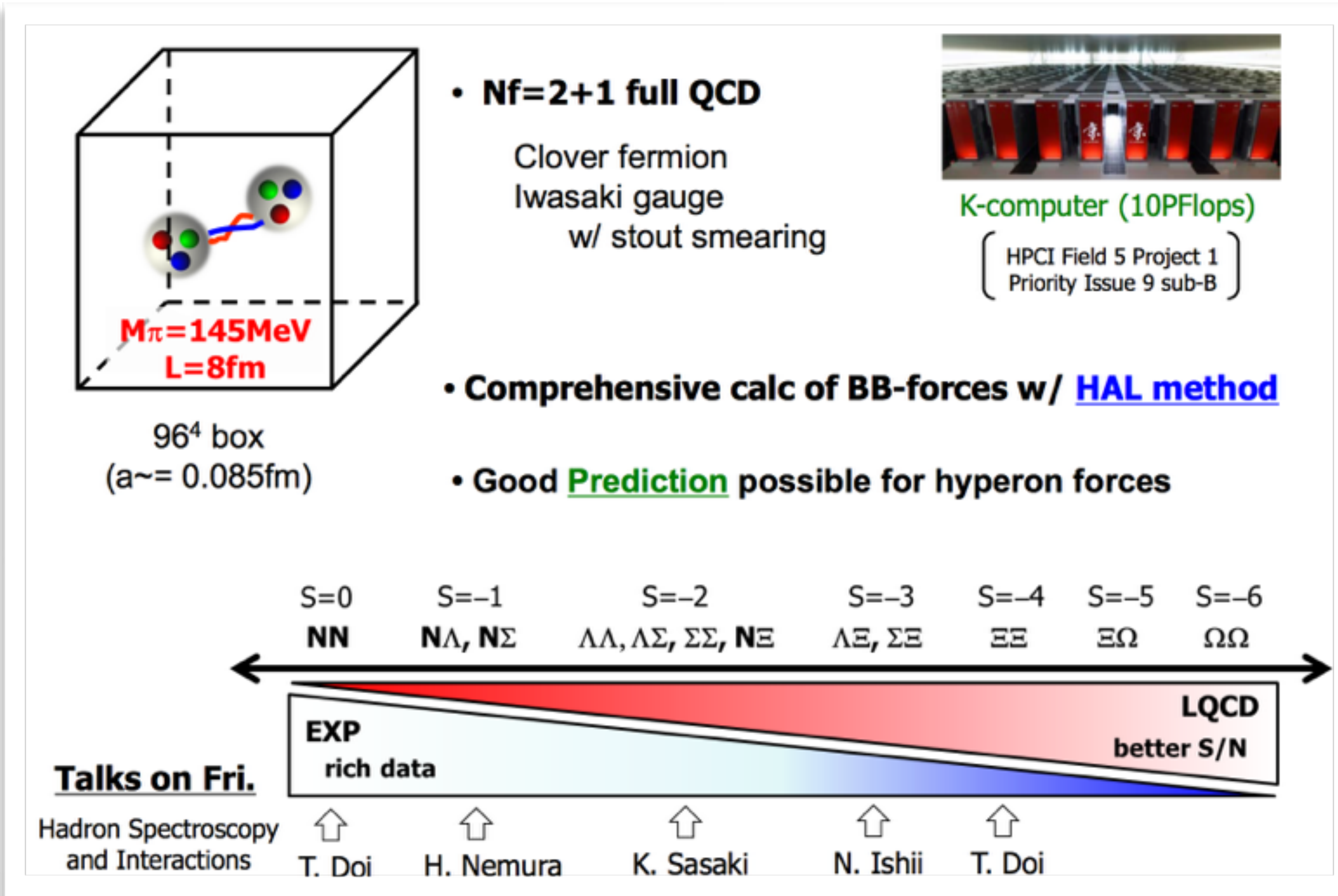


Slides from Yamazaki on their careful comparisons - thank you.

Needs much higher statistics in this study

All states need to be in their ground states before any calculations of ground state properties of multi-baryon systems are meaningful - including taking ratios of C(t). This applies to all methods.

BB Interactions
HAL QCD



Towards Lattice QCD Baryon Forces at the Physical Point: First Results
Takumi Doi *et al.* (HAL QCD). arXiv:1512.04199 [hep-lat]

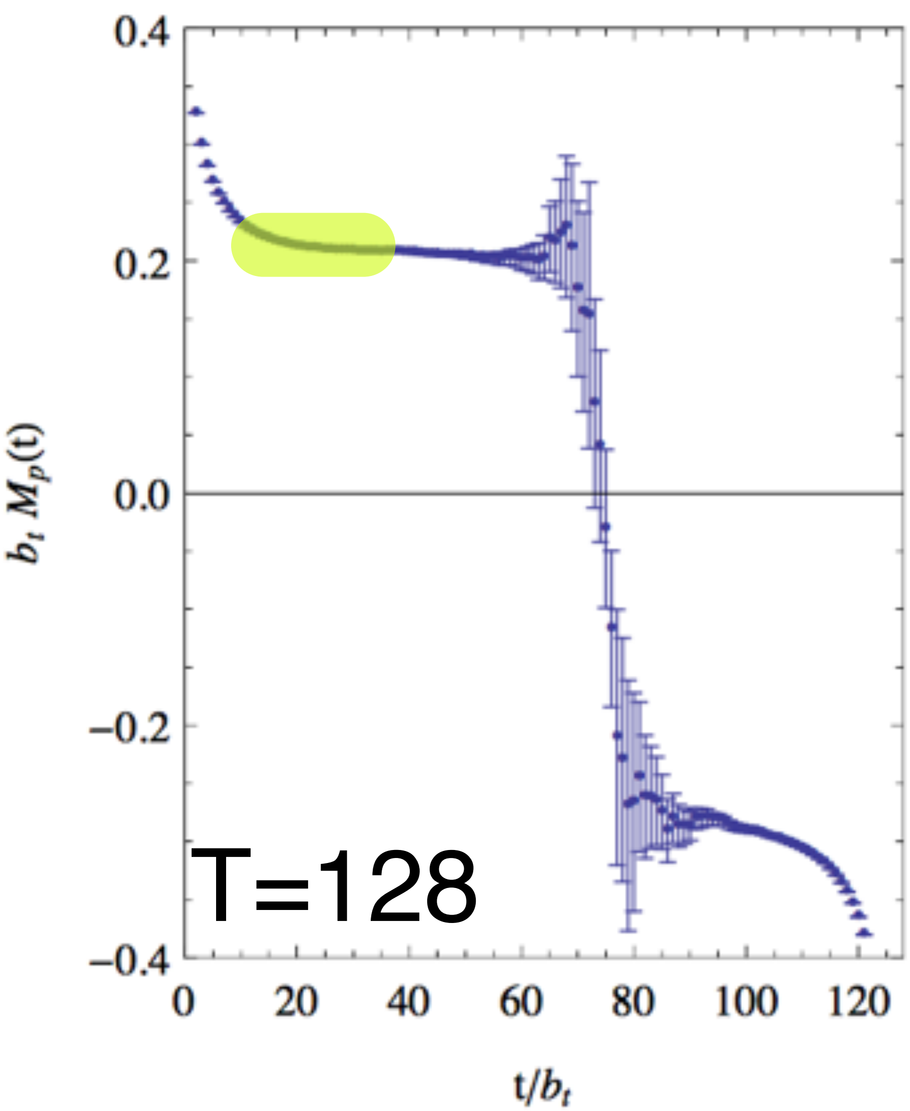
Slide prepared by T. Doi

Methods and Difficulties
Signal-to-Noise

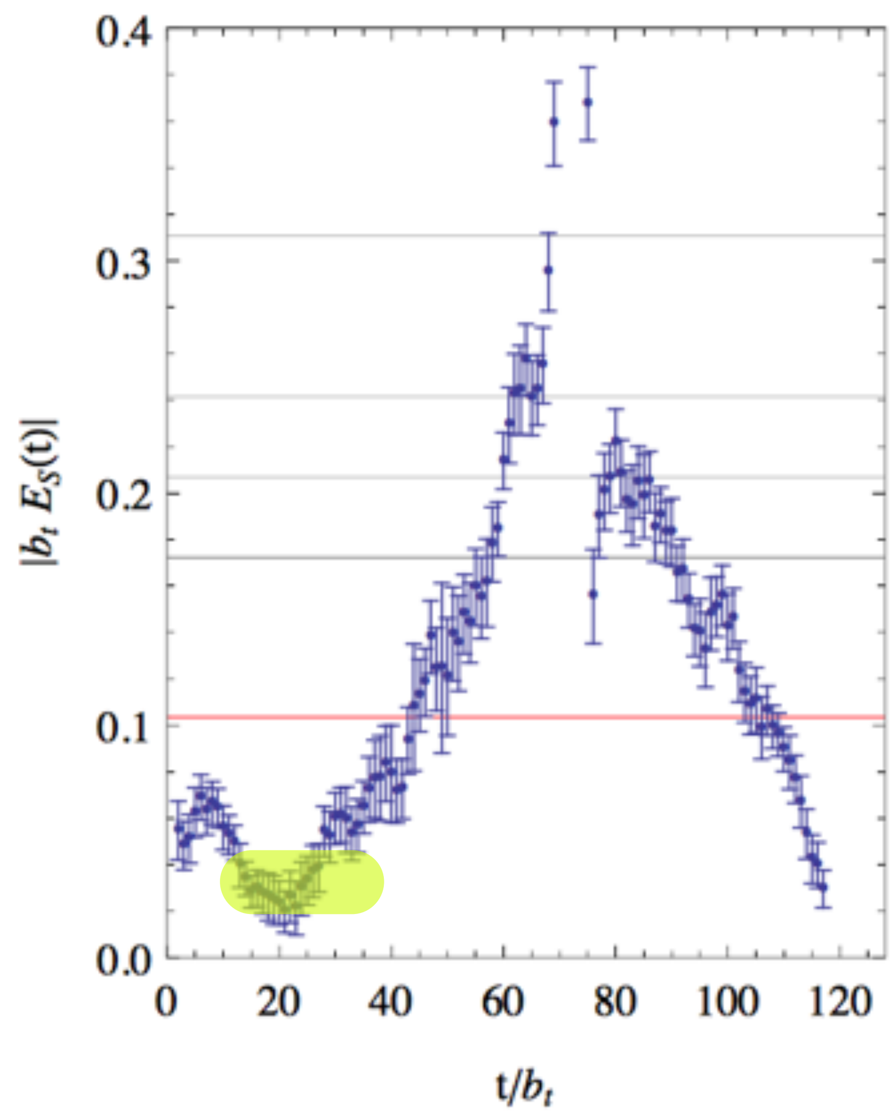
The Golden Window for Nuclei

dictated by source and sink structure

Nucleon Effective Mass



Noise-to-Signal Mass Scale

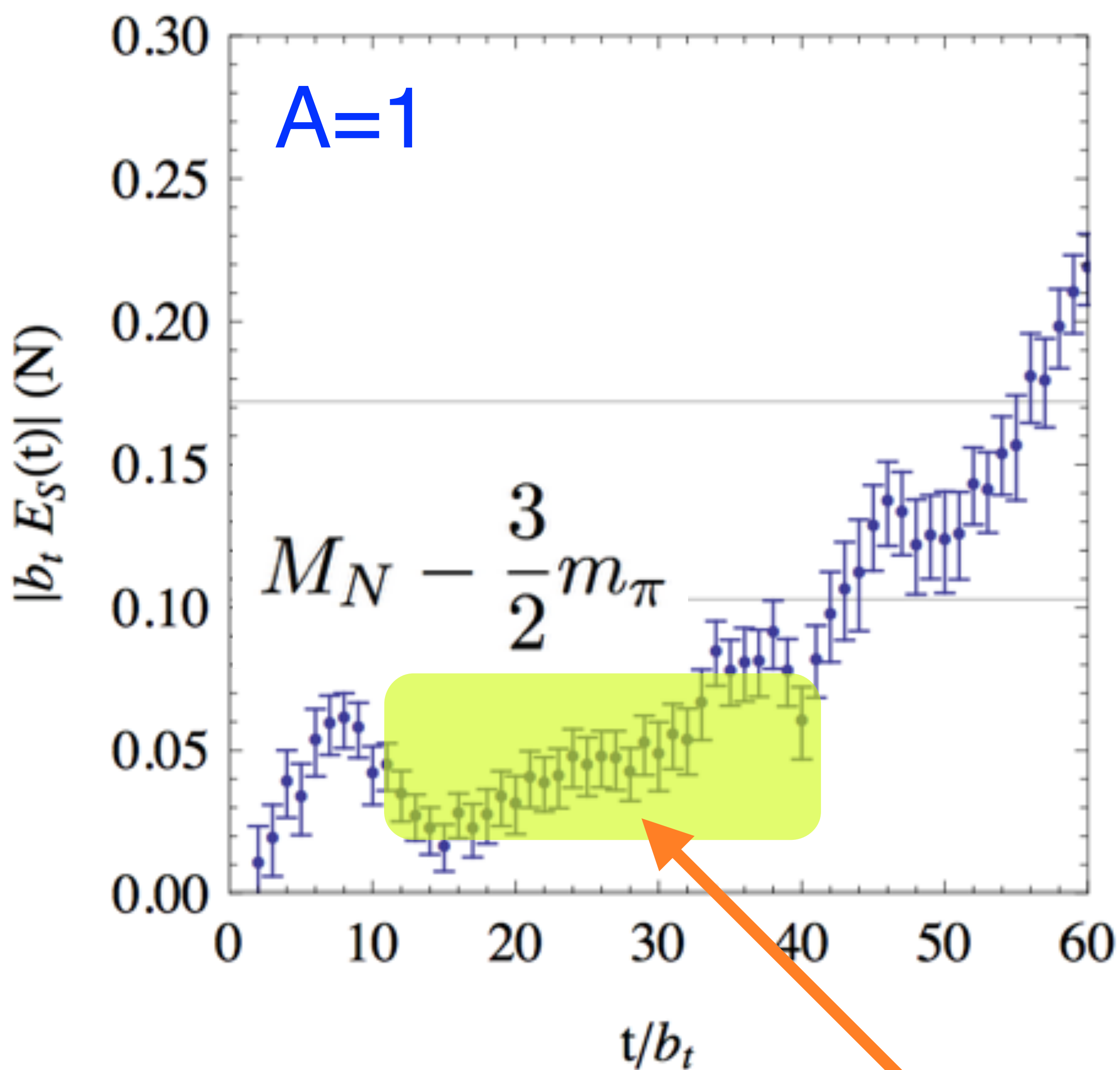


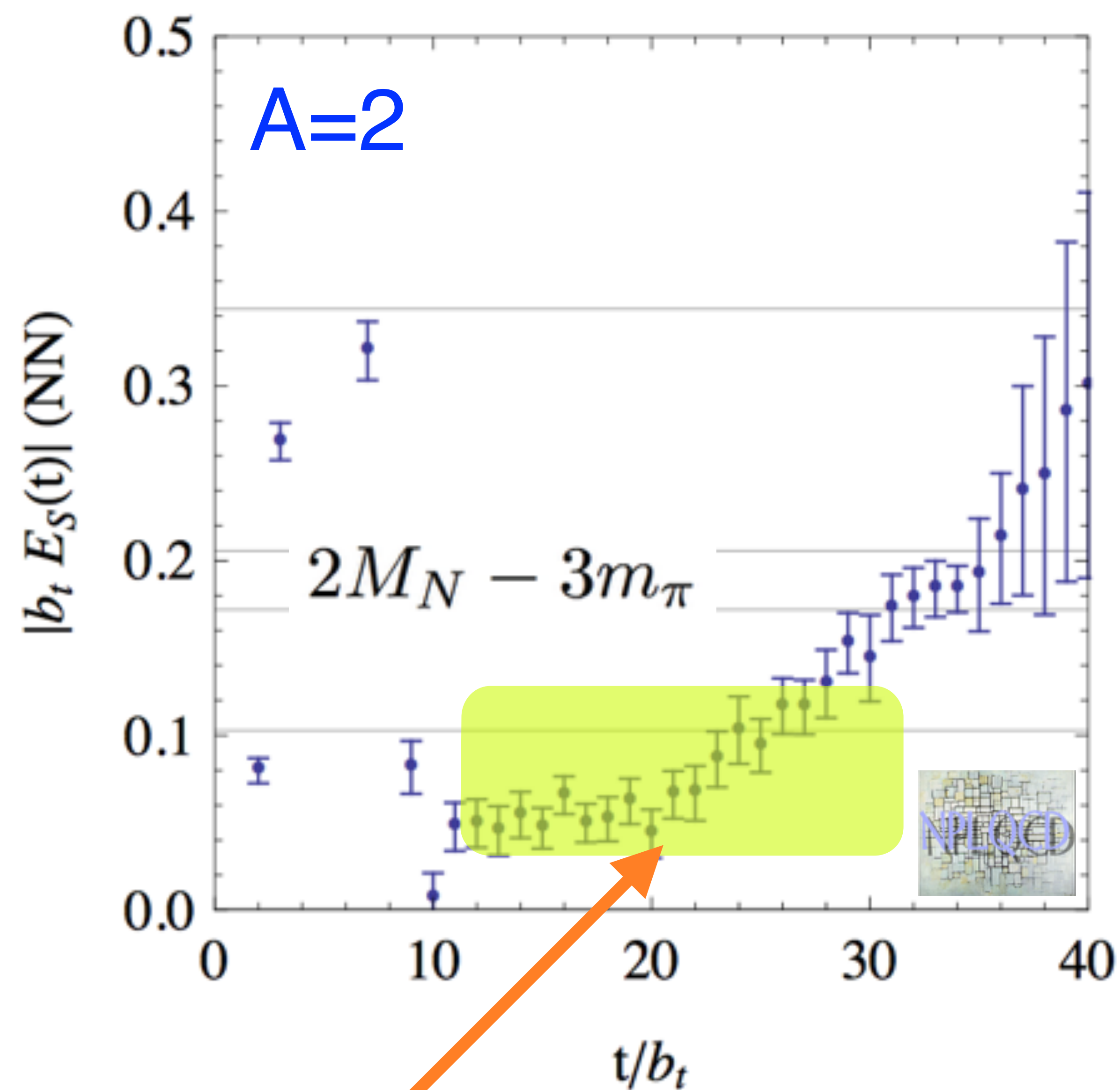
Lepage asymptotic
$M_N - 3/2\, M_\pi$

NPLQCD

Methods and Difficulties
Signal-to-Noise

Energy scale of the signal-to-noise ratio





Golden Window

Methods and Difficulties
Contractions

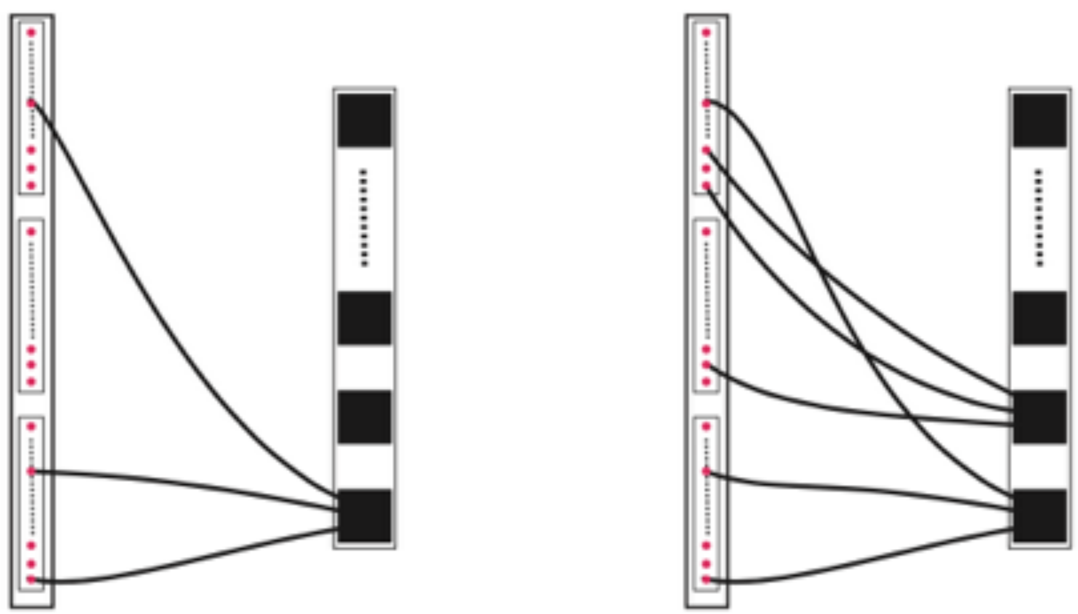
Detmold and Orginos (2011)
Yamazaki et al (2011)
Doi and Endres (2012)

Naively:

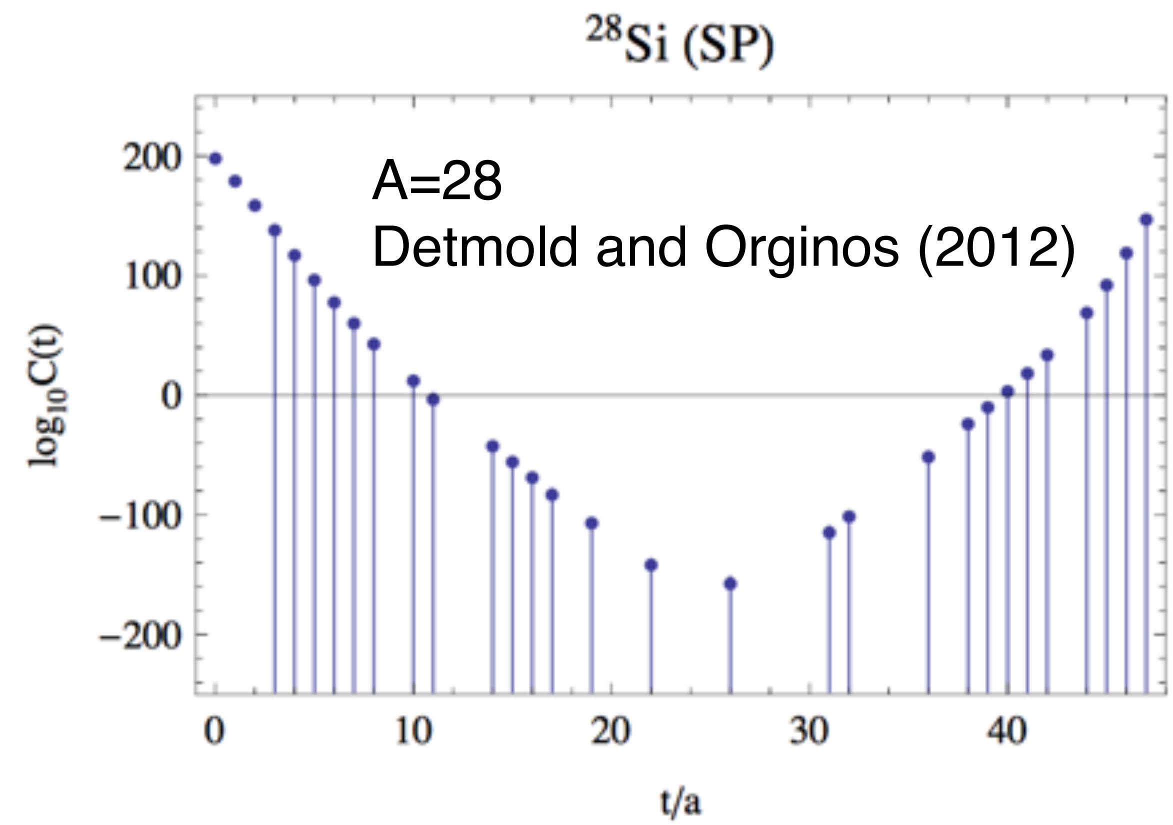
Proton : $N^{\text{cont}} = 2$

^{235}U : $N^{\text{cont}} = 10^{1494}$

Large number of contractions



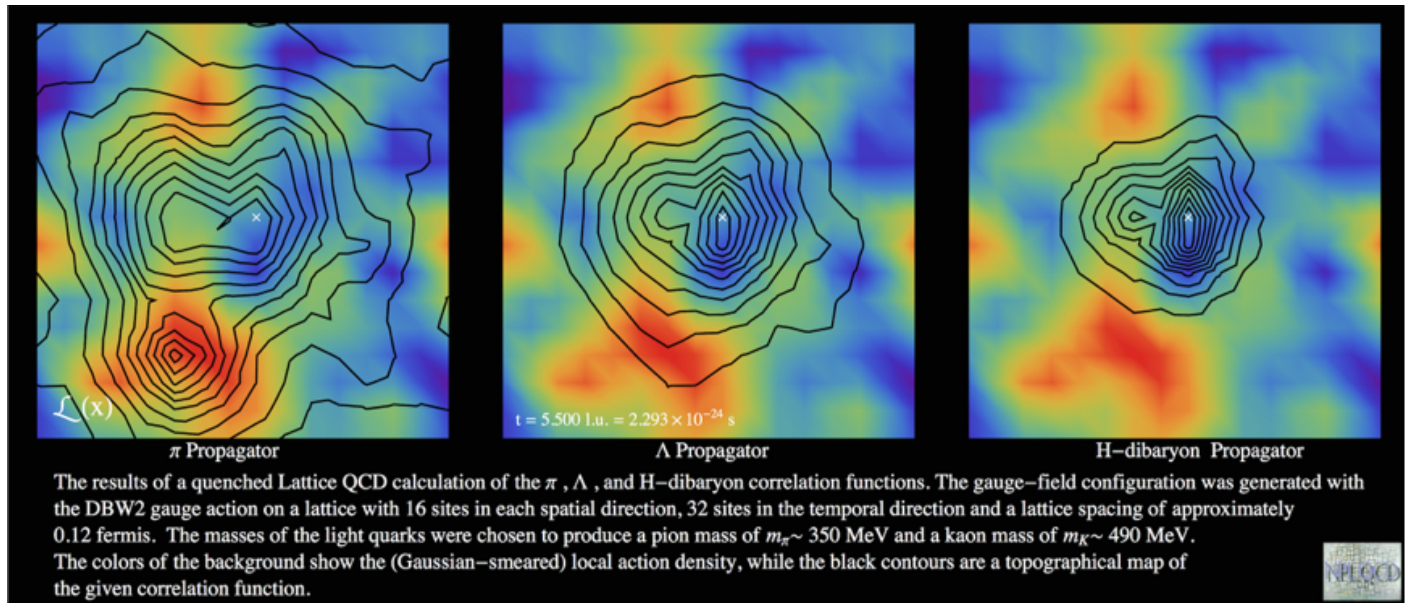
(a) (b)



Symmetries provide significant reduction

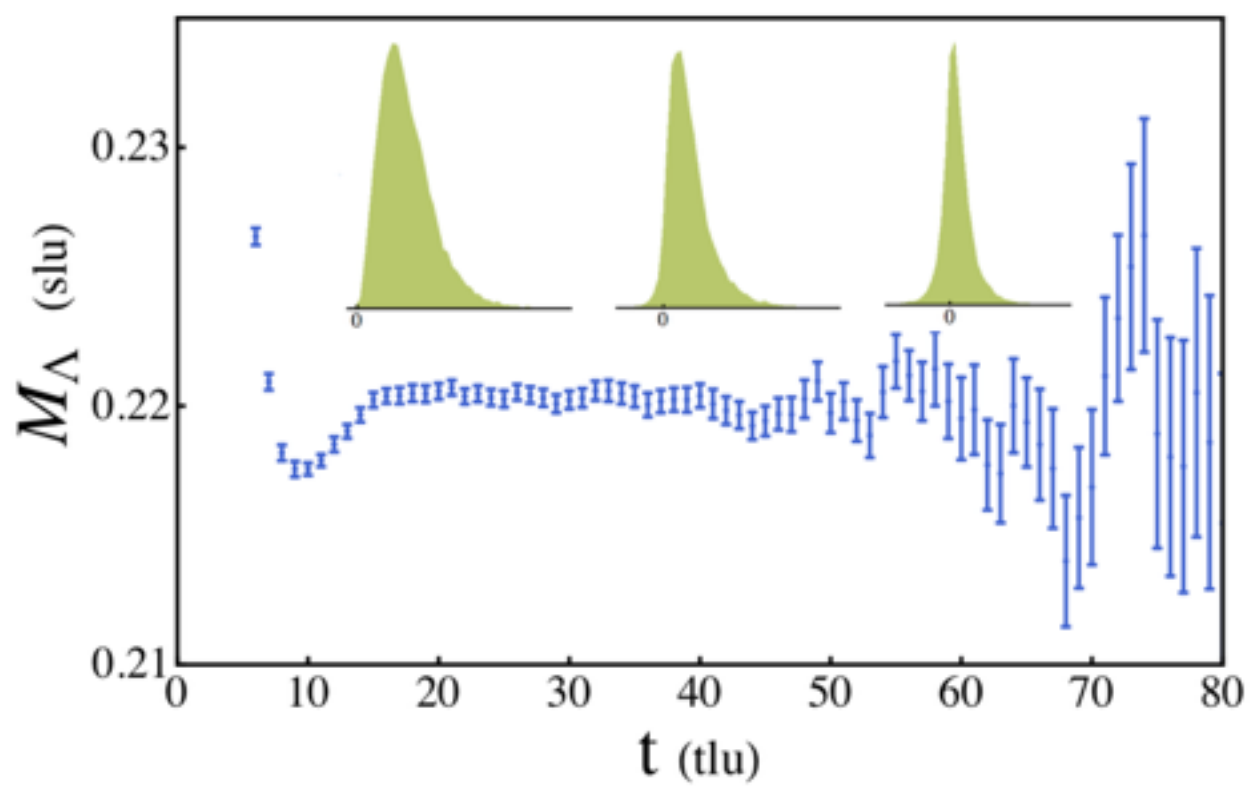
Automation, Recursion, … delay the problem but it remains

Statistics of Correlation Functions



The results of a quenched Lattice QCD calculation of the π, Λ, and H−dibaryon correlation functions. The gauge−field configuration was generated with the DBW2 gauge action on a lattice with 16 sites in each spatial direction, 32 sites in the temporal direction and a lattice spacing of approximately 0.12 fermis. The masses of the light quarks were chosen to produce a pion mass of $m_\pi \sim$ 350 MeV and a kaon mass of $m_K \sim$ 490 MeV. The colors of the background show the (Gaussian−smeared) local action density, while the black contours are a topographical map of the given correlation function.

Log Normal in plateau region evolves into symmetric but non-Gaussian at late times

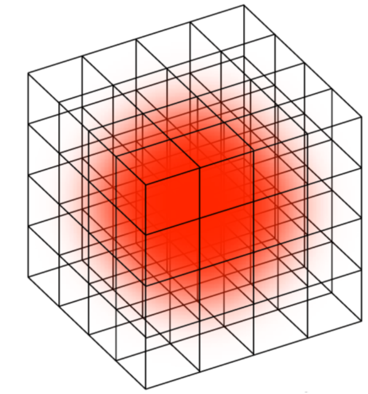


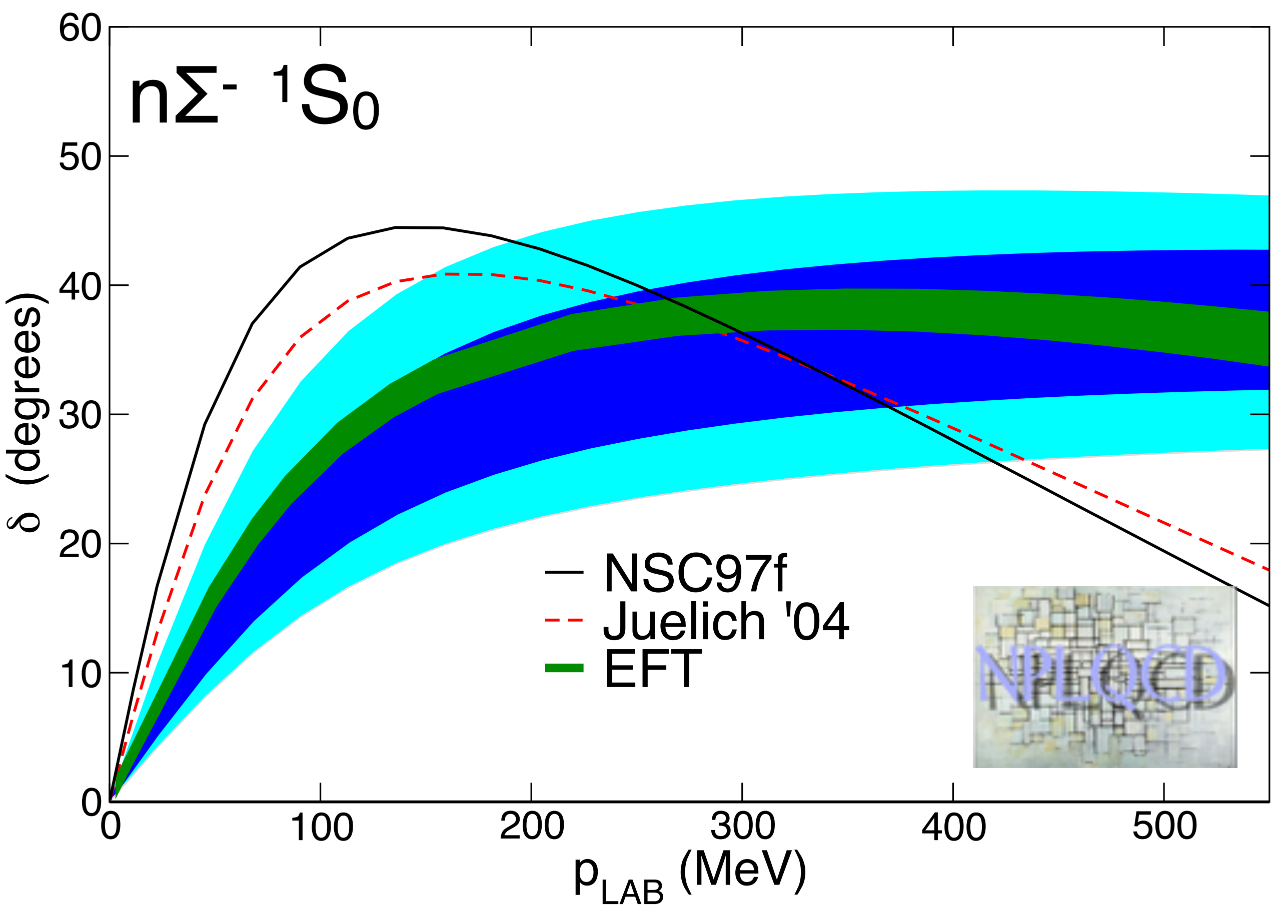
outliers

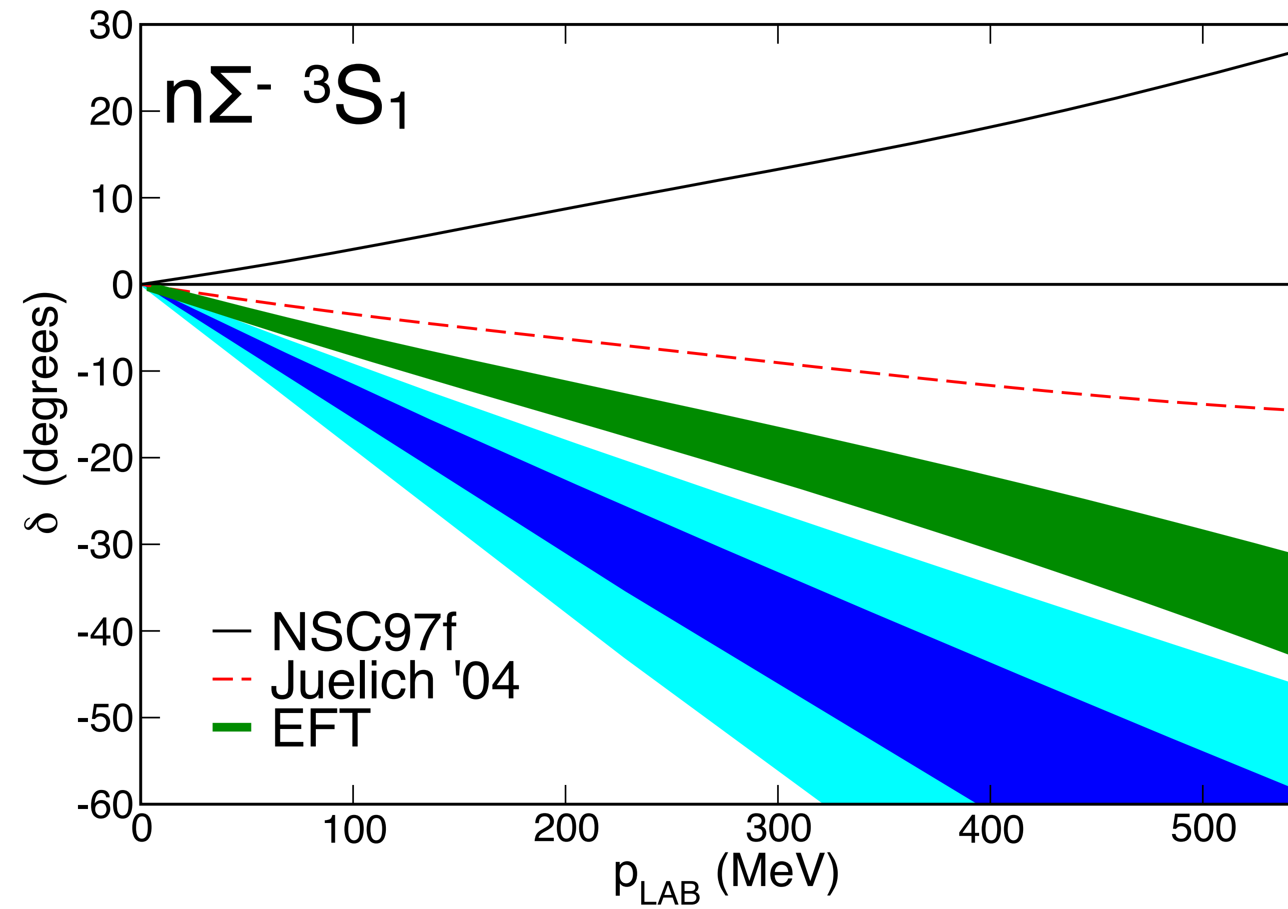
Noise, sign problems, and statistics, Michael G. Endres, David B. Kaplan, Jong-Wan Lee, Amy N. Nicholson, Phys.Rev.Lett. 107 (2011) 201601

Distribution of Canonical Determinants in QCD, Andrei Alexandru, C. Gattringer, H. -P. Schadler, K. Splittorff, J.J.M. Verbaarschot, Phys.Rev. D91 (2015) no.7, 074501

NN Interactions
NPLQCD



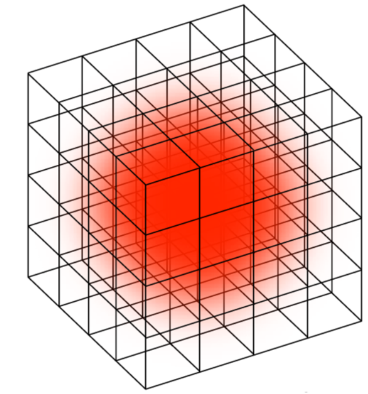


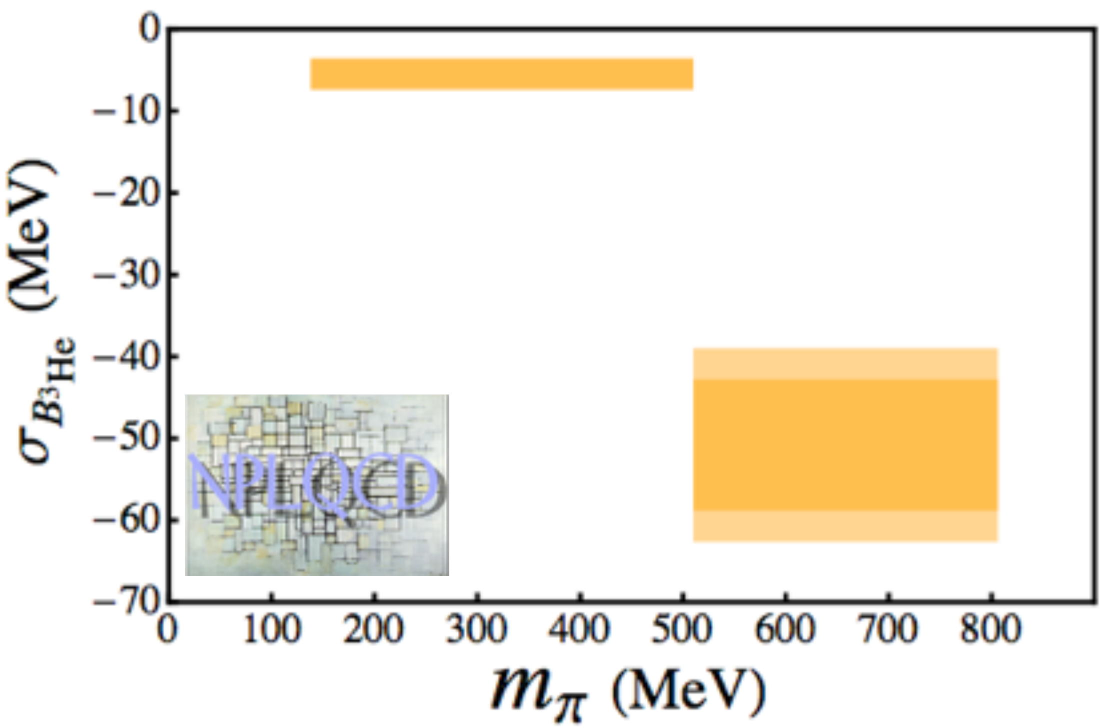


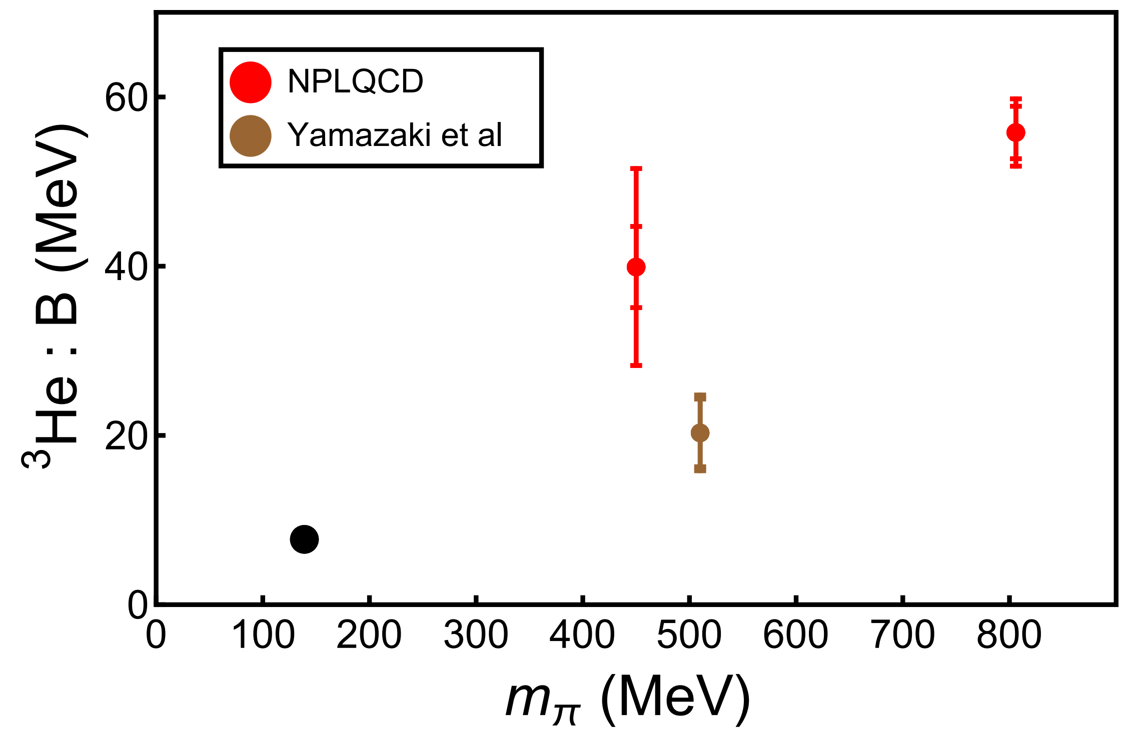
- Extrapolation to physical point with NNEFT
- Cancellation between channels in dense matter energy-shift of hyperon
- Fit LO chiral Effective Hamiltonian by explicit diagonalization in momentum space.
- Reproduces S-matrices obtained using Luscher's method at energy eigenvalues - but large radius of interaction in $^3S_1$
- In process of being refined

Hyperon-Nucleon Interactions and the Composition of Dense Nuclear Matter from Quantum Chromodynamics, Beane *et al* (NPLQCD), Phys.Rev.Lett. 109 (2012) 172001

Decomposition of Nuclear Masses and Bindings



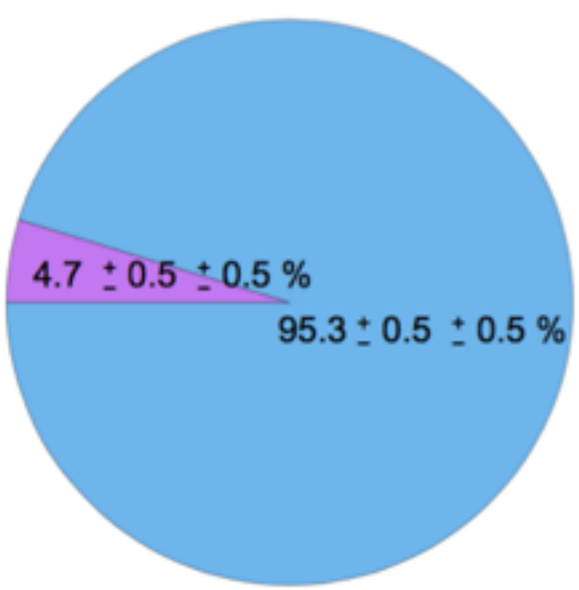




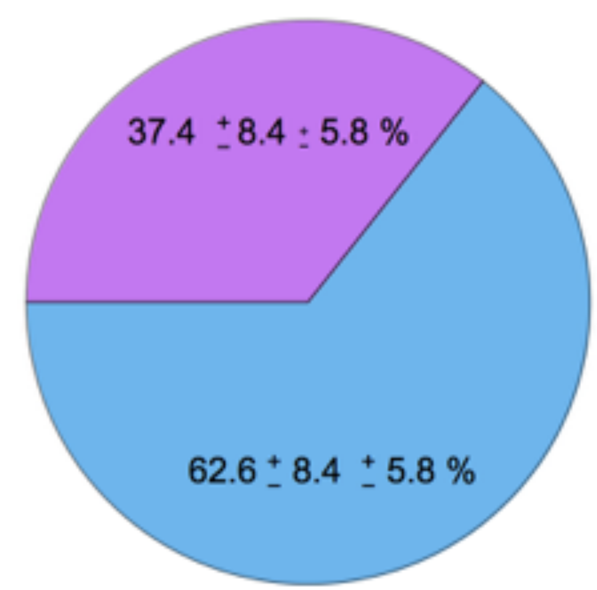
Nucleon Mass

Binding ^{3}He (m_π=450 MeV)

Dictates a Class Dark Matter Interactions

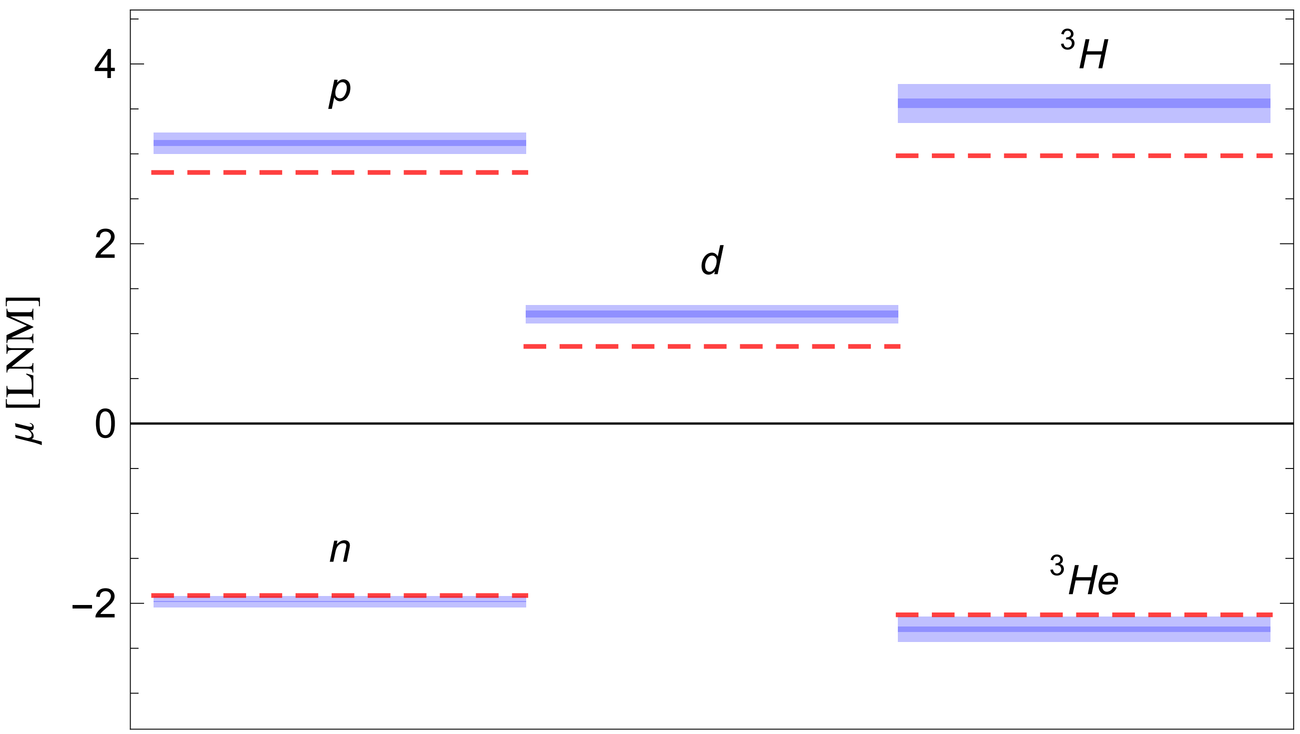


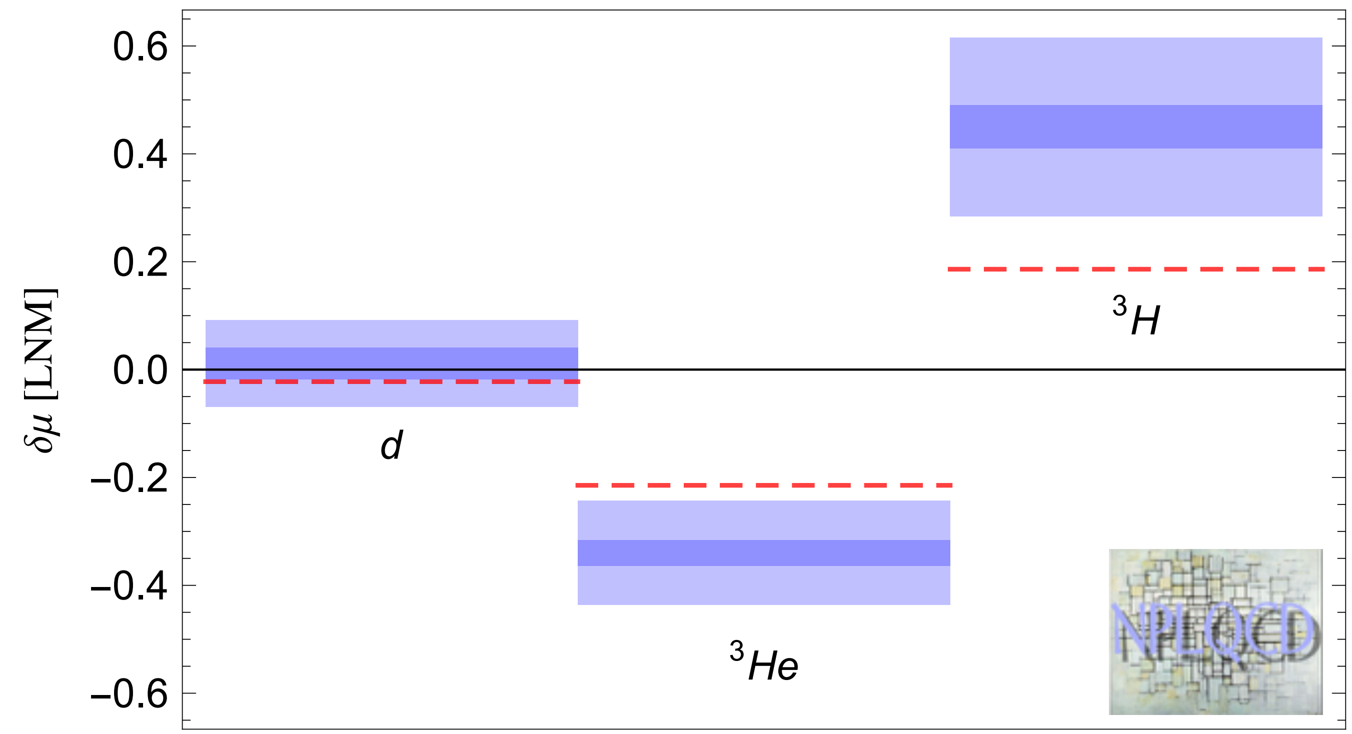
- Explicit U and D Quark−Mass Contributions: σ_{ud}−Term
- Explicit Anomalous Contribution

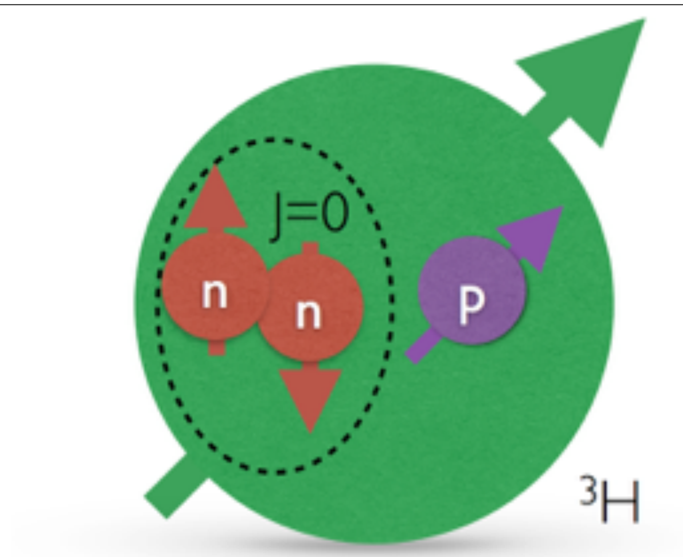


The Magnetic Structure of Nuclei : Magnetic Moments

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





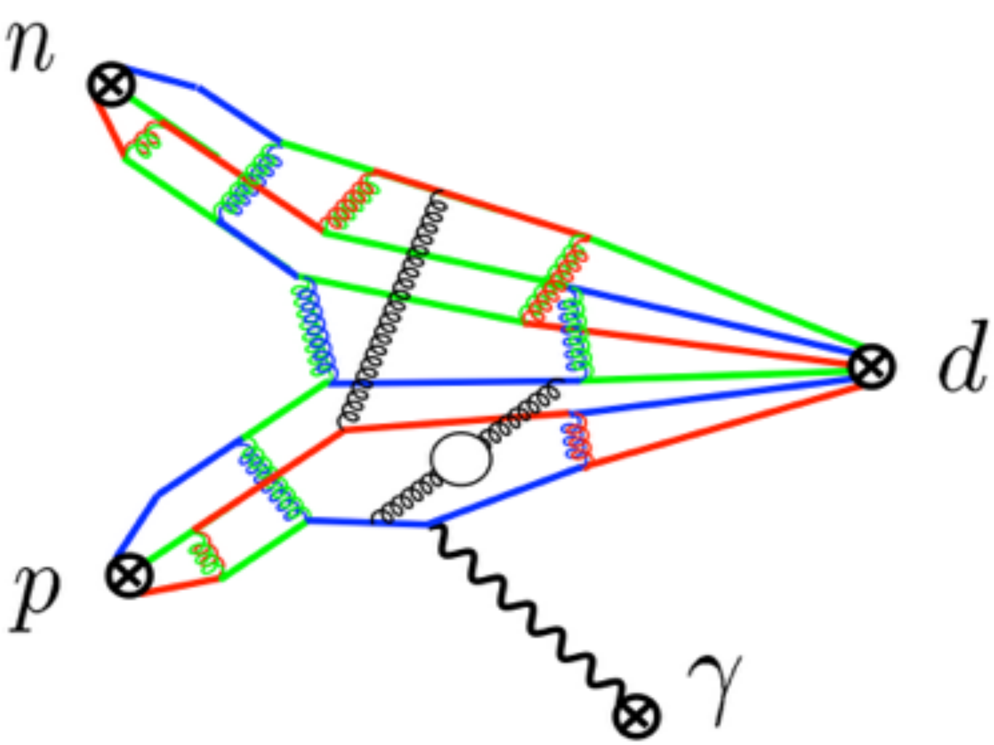


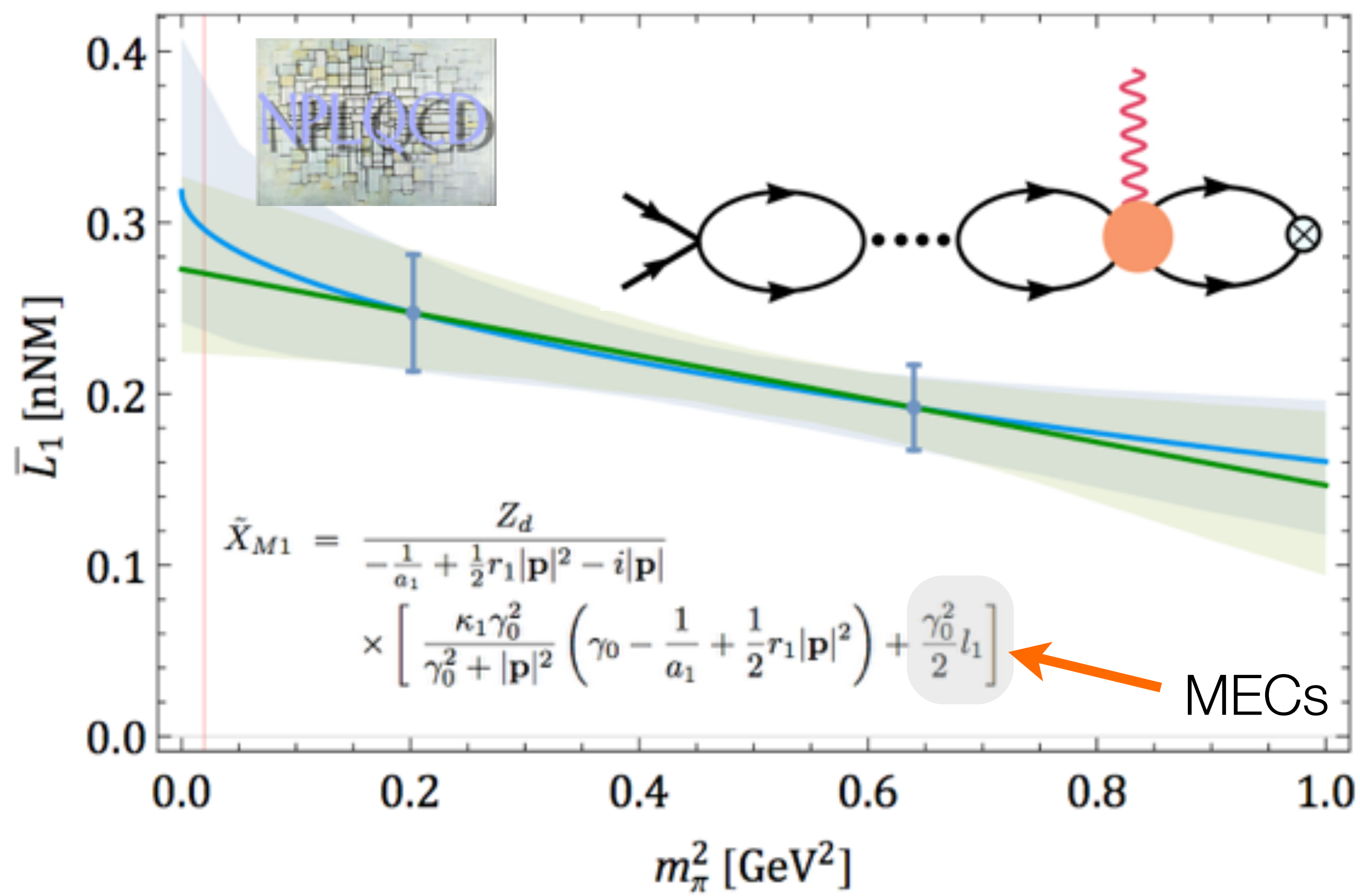
m_π ~ 800 MeV   Vs   Nature

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

First Inelastic Nuclear Reaction :

$$np \to d\gamma$$





physical point:

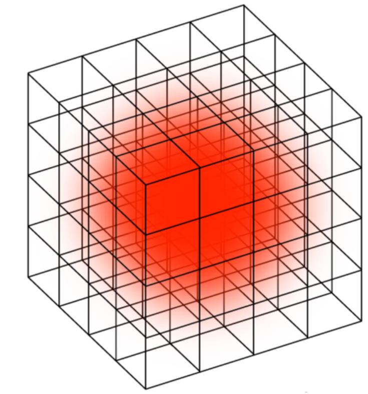
$\sigma^{\text{LQCD}} = 334.9(5.3)$ mb $\quad v = 2,200 \text{ m/s}$

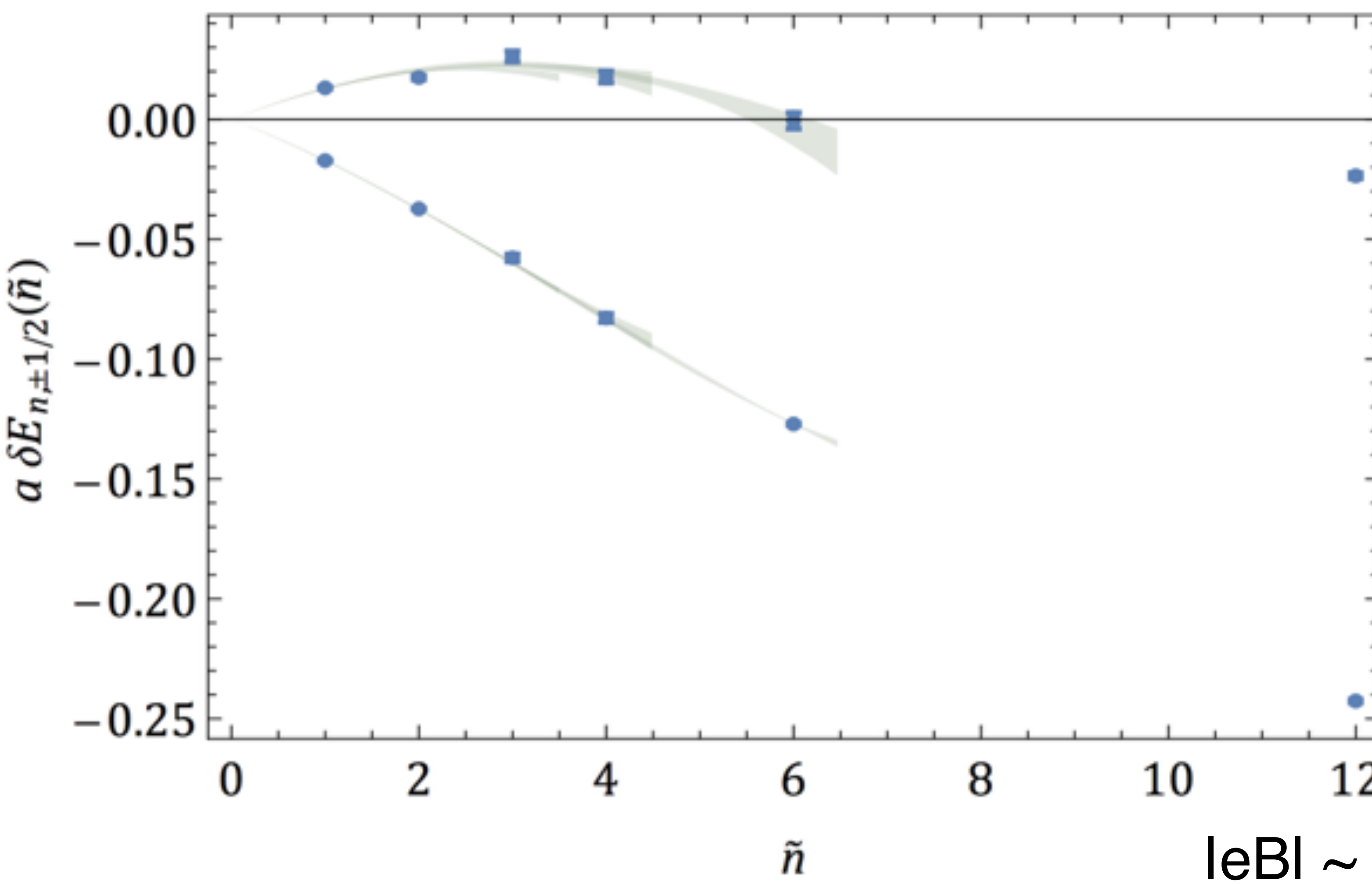
$\sigma^{\text{expt}} = 334.2(0.5)$ mb

[306 mb single nucleons alone]

Ab Initio Calculation of the np → dγ Radiative Capture Process, NPLQCD, Phys. Rev. Lett. 115 (2015) 13, 132001

Magnetic Moments
Neutron Spin States





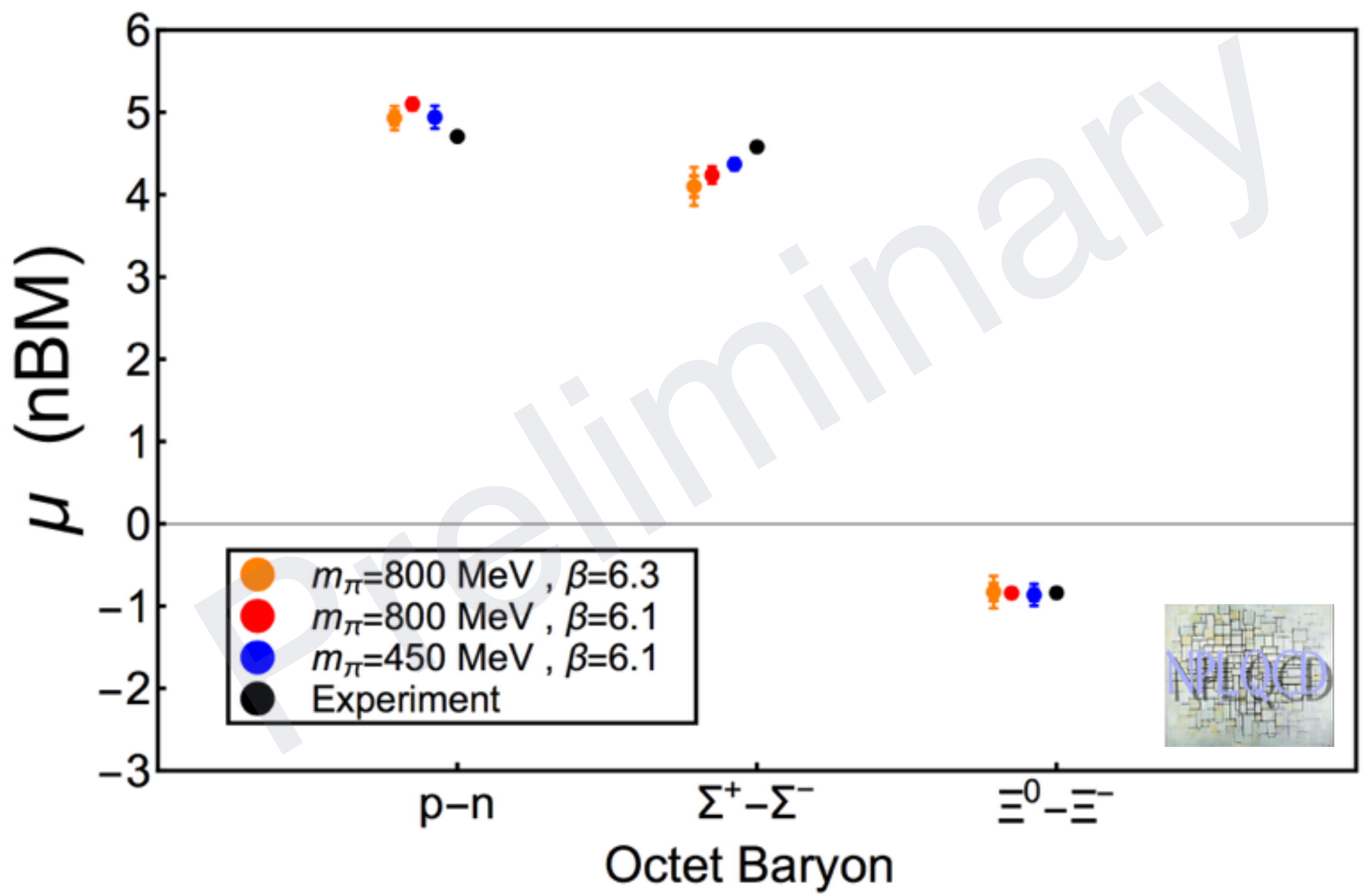
400 MeV

|eB| ~ 0.7 GeV^2

~ 10^{20} Gauss

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

Magnetic Moments



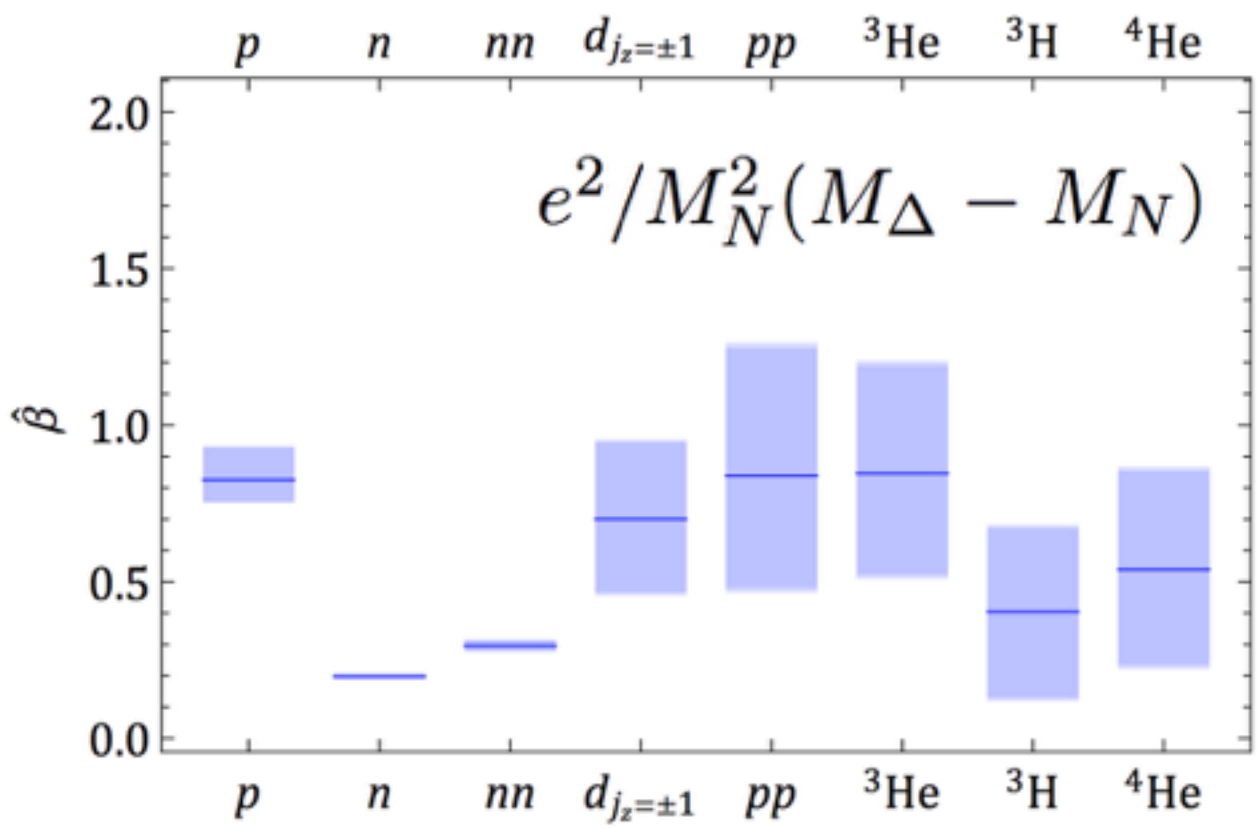
$$\frac{e}{2M(m_\pi)}$$

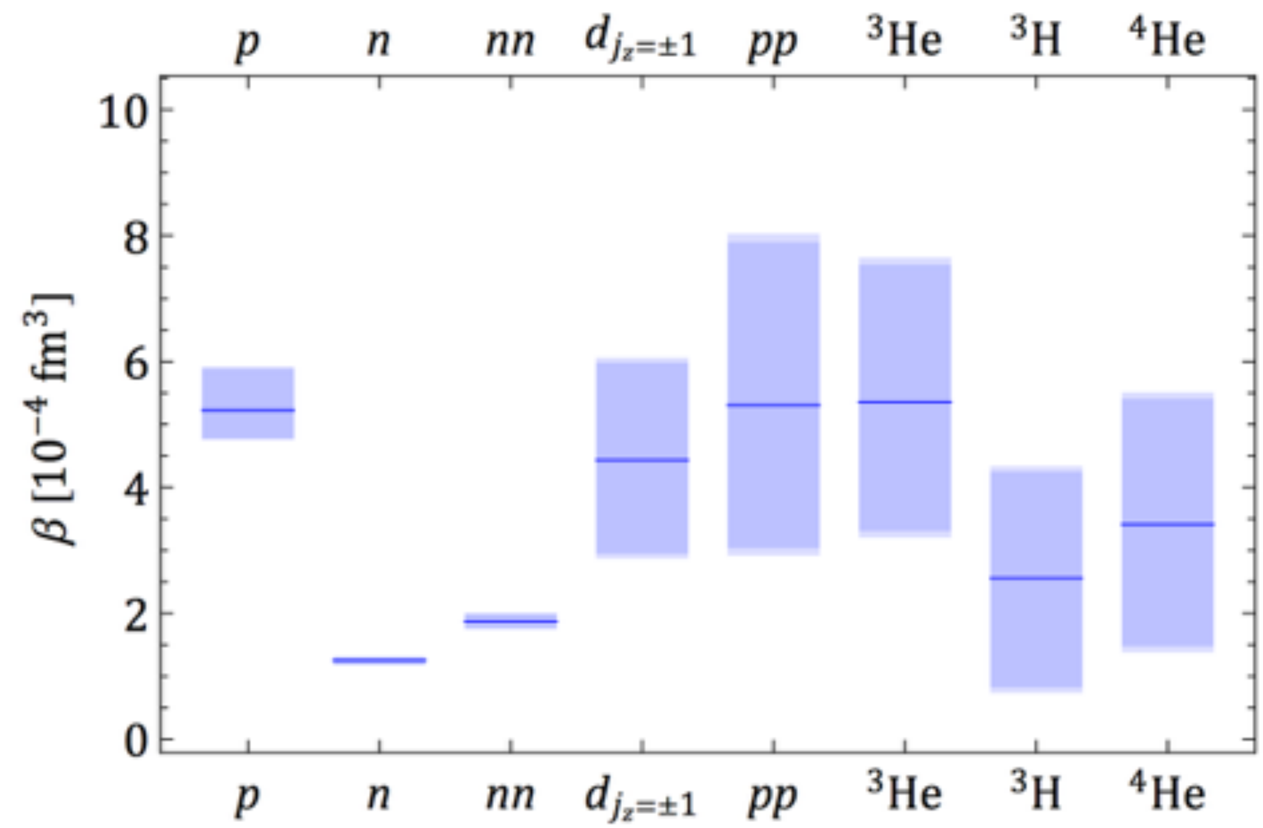
Essentially ALL quark mass dependence of nucleon magnetic moments is due to the nucleon mass

Magnetic Structure Polarizabilities

$m_\pi \sim 800$ MeV

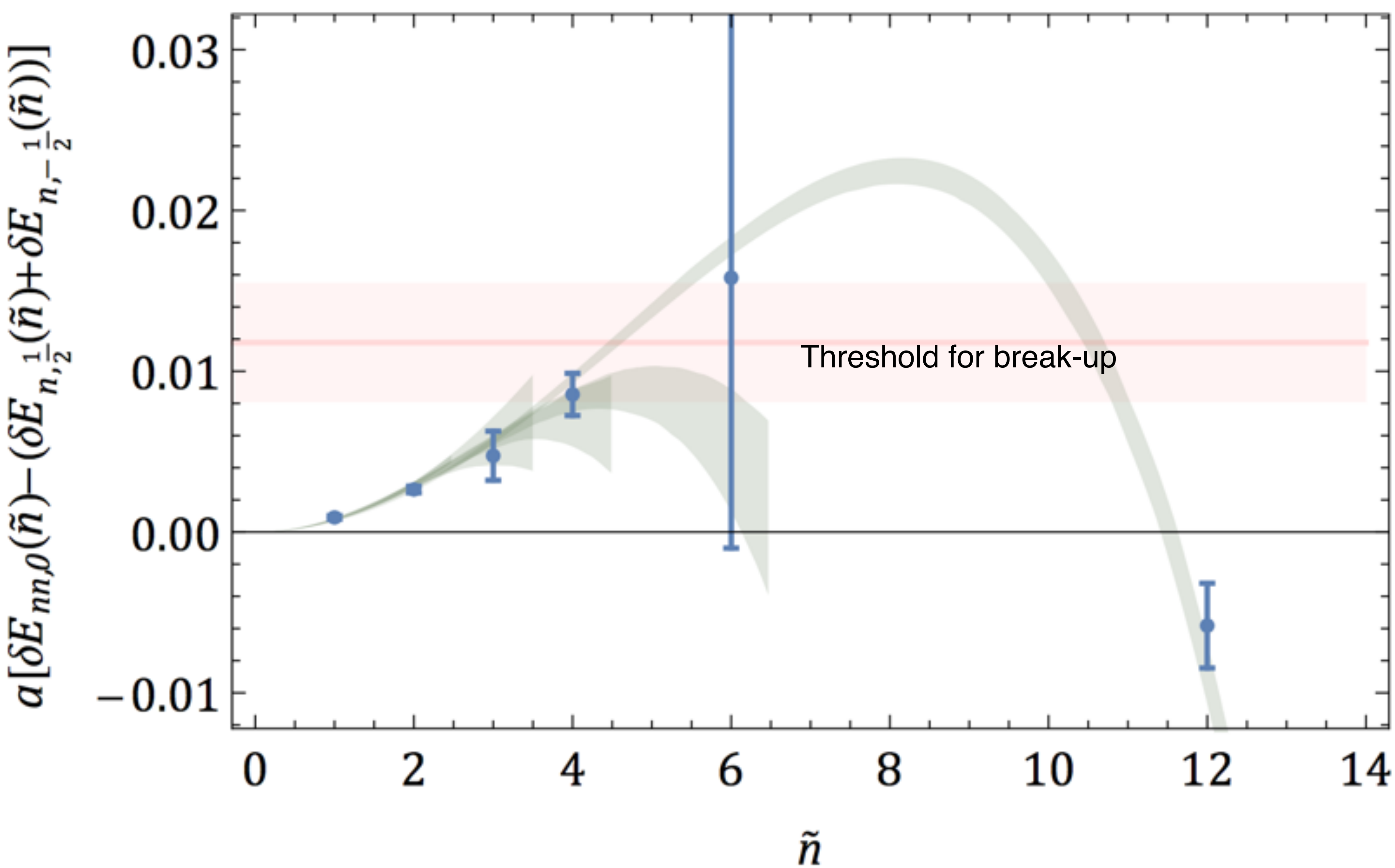
The Magnetic Structure of Light Nuclei from Lattice QCD
Emmanuel Chang et al., Jun 17, 2015. 49 pp.
e-Print: **arXiv:1506.05518 [hep-lat]**





Large isovector nucleon polarizability
Nuclear polarizabilities are similar to proton polarizability

Magnetic Moments
States at Threshold



NPLQCD, Phys.Rev.Lett. 113 (2014) no.25, 252001 and Phys.Rev. D92 (2015) no.11, 114502

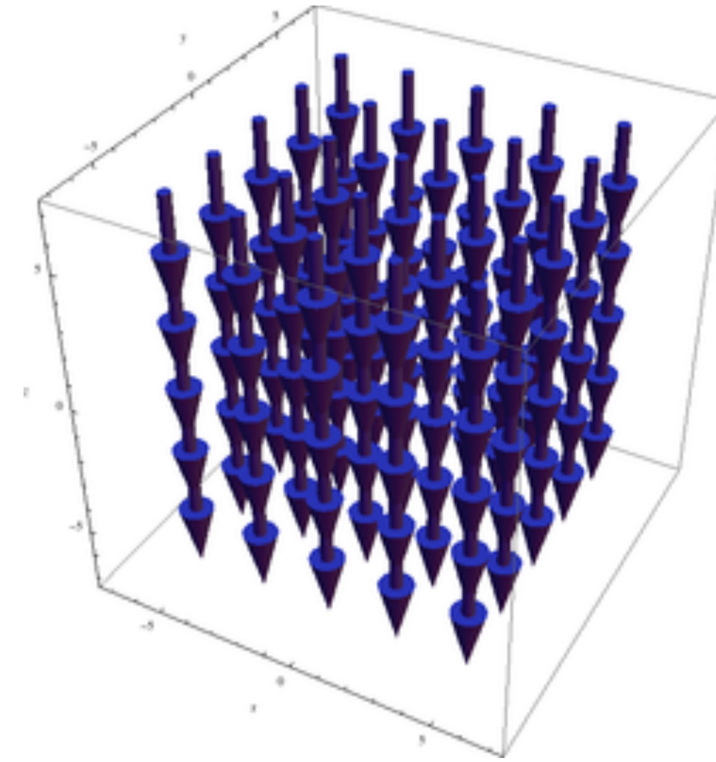
Axial-Current Matrix Elements

Formalism developed in

Electroweak matrix elements in the two nucleon sector from lattice QCD

William Detmold, MJS

Nucl. Phys. A743 (2004) 170-193



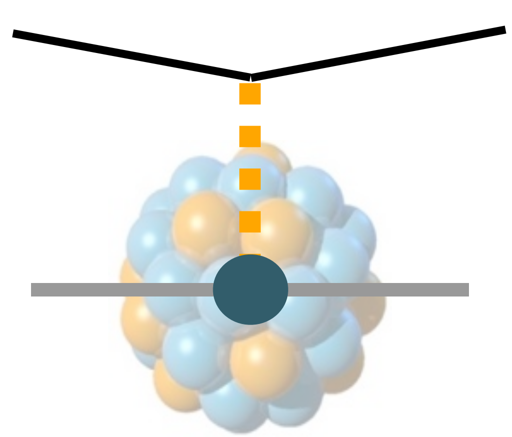
quark-level interactions

$$\delta\mathcal{L} \;=\; -\frac{1}{2} gW\left(\overline{u}\gamma^z\gamma_5 u - \overline{d}\gamma^z\gamma_5 d\right)$$

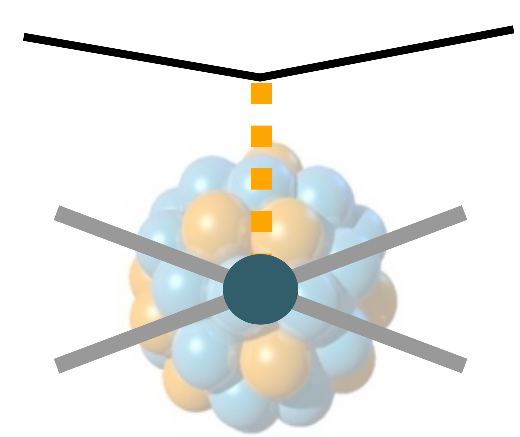
hadronic-level interactions

$$\delta\mathcal{L} \;=\; -gW\,\frac{g_A}{2}\,N^\dagger\sigma^z\tau^3 N \;-\; \frac{gW\;l_{1,A}}{2M\sqrt{r_1 r_3}}\,\left[t_3^\dagger s_3 + \mathrm{h.c.}\right] \;+\;\ldots$$

single-nucleon interaction

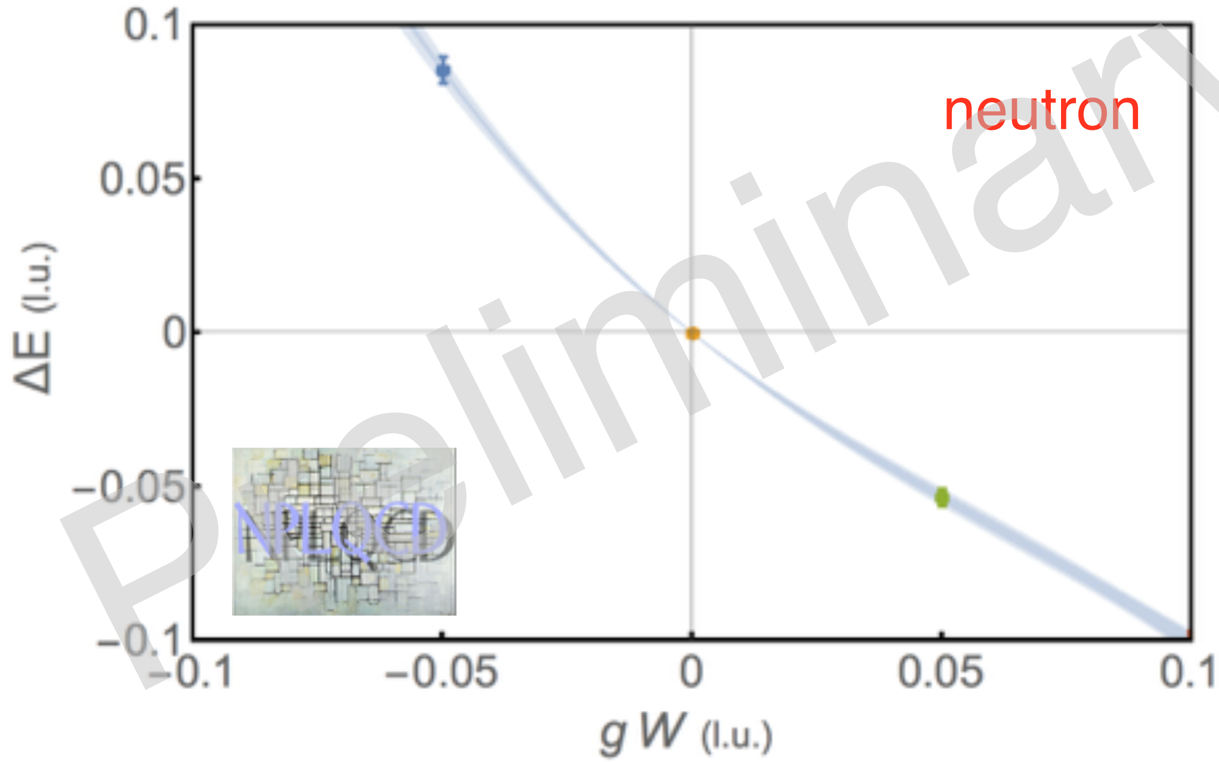


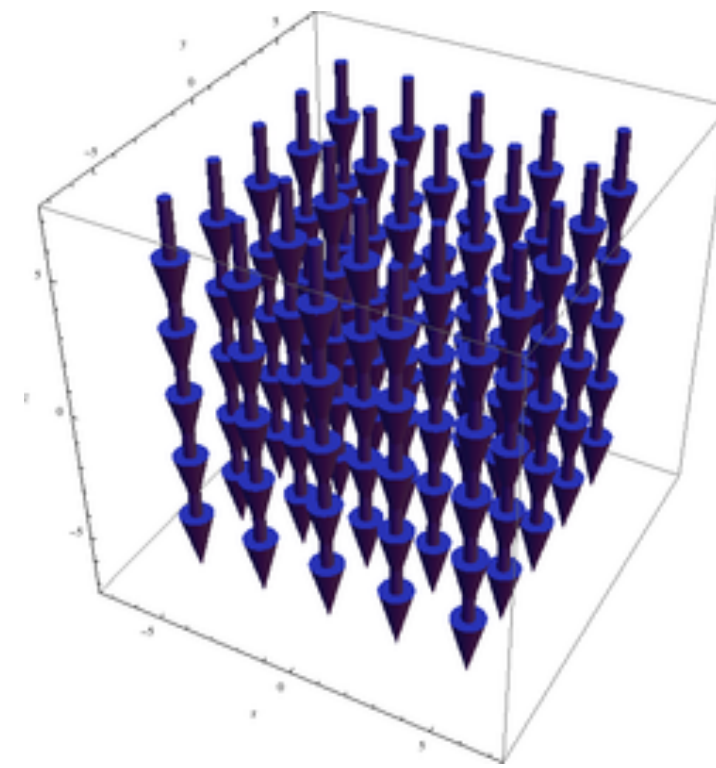
leading two-nucleon interaction

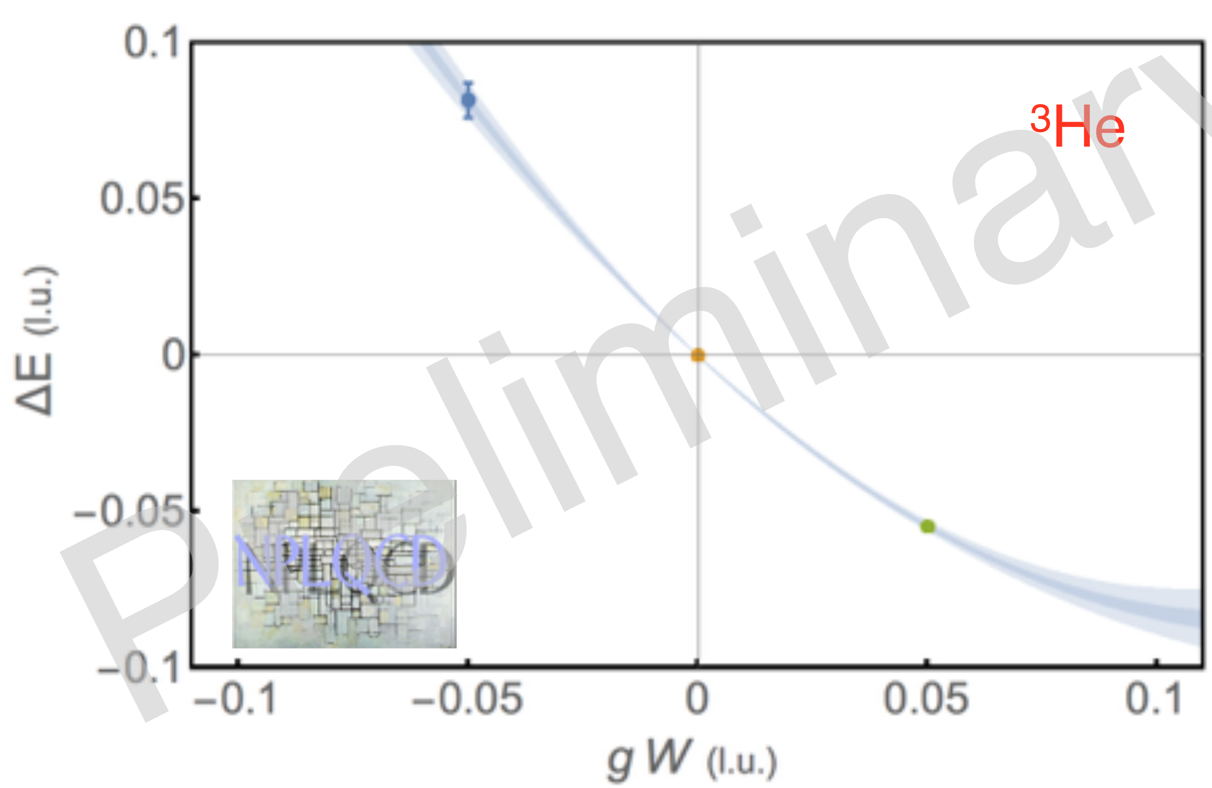


Axial-Current Matrix Elements

$M_\pi \sim 800$ MeV





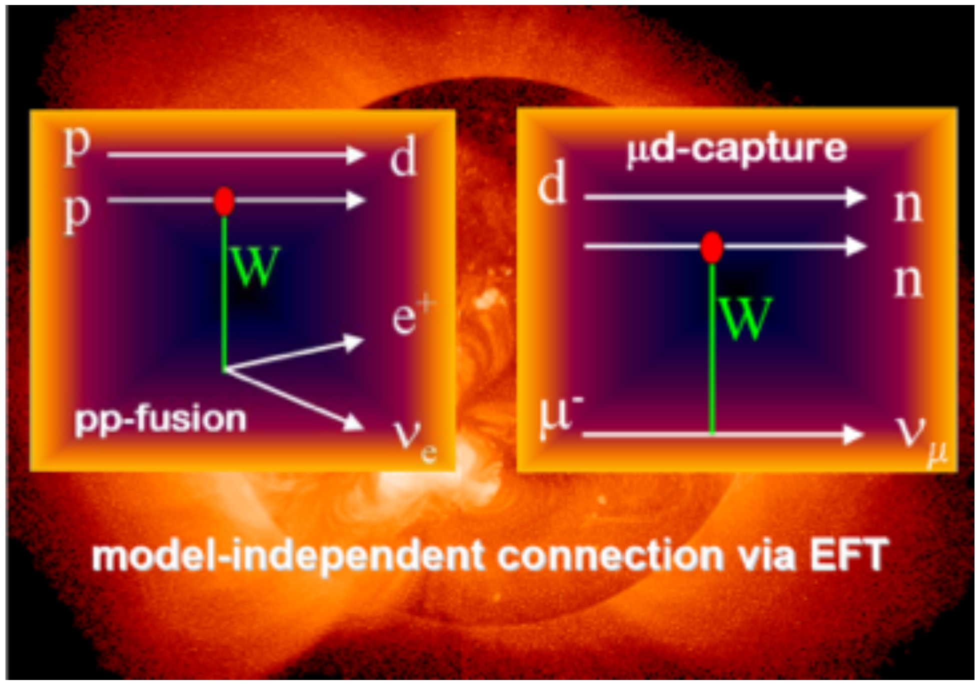


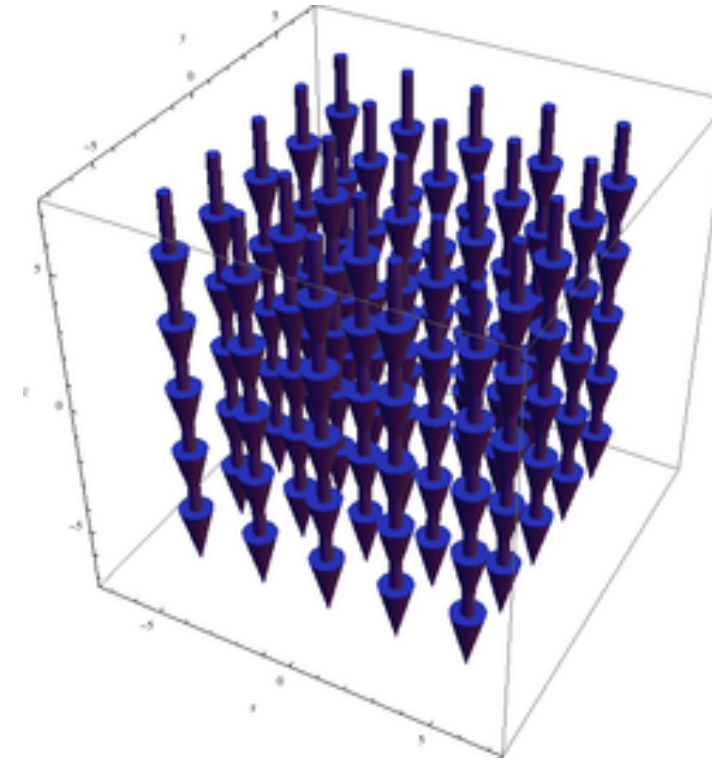
p : $g_A \sim 1.2$

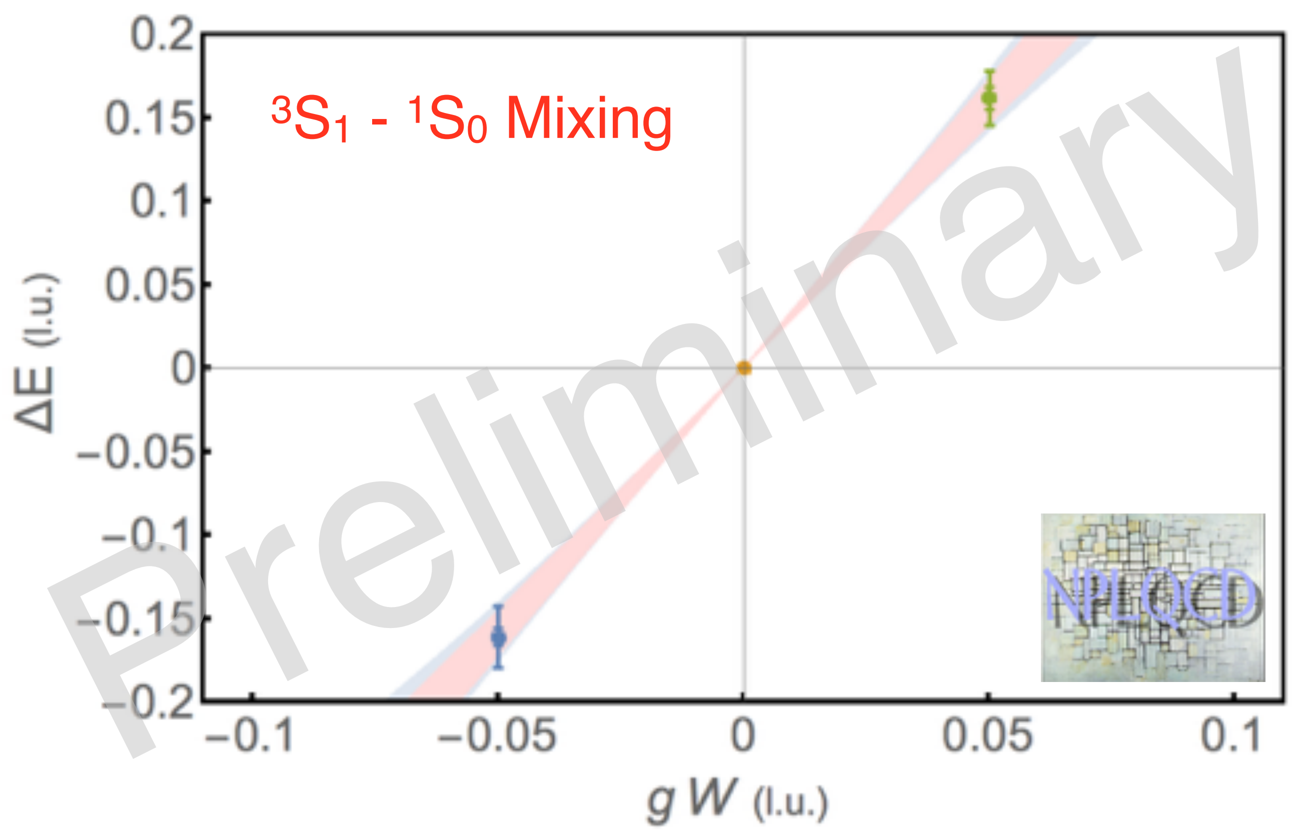
^{3}He : $g_A \sim 1.2$

Axial-Current Matrix Elements

$M_{\pi} \sim 800$ MeV



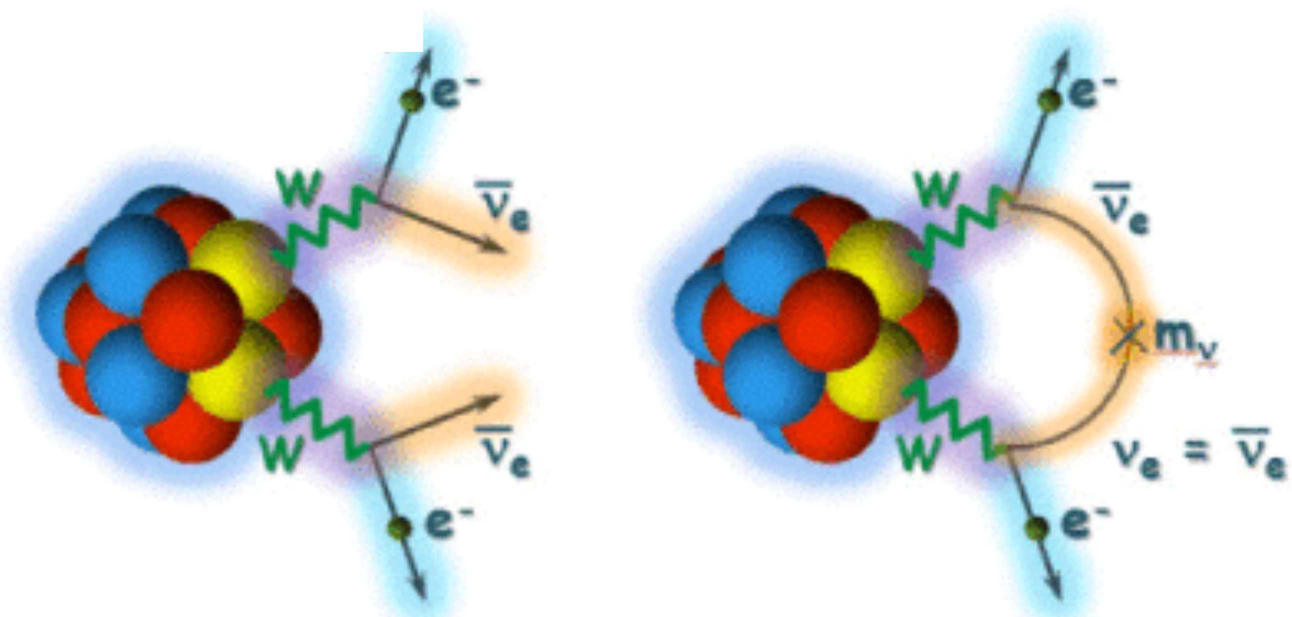


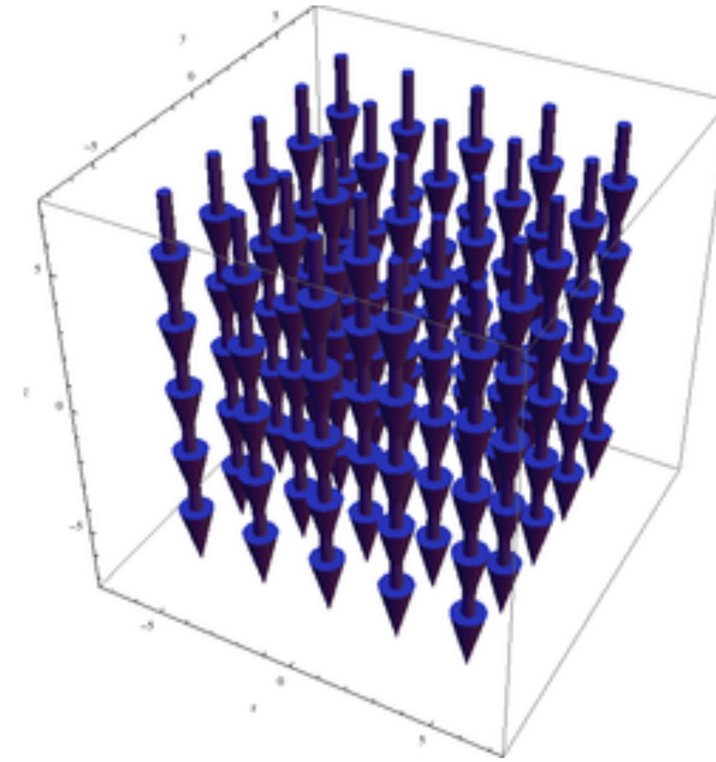


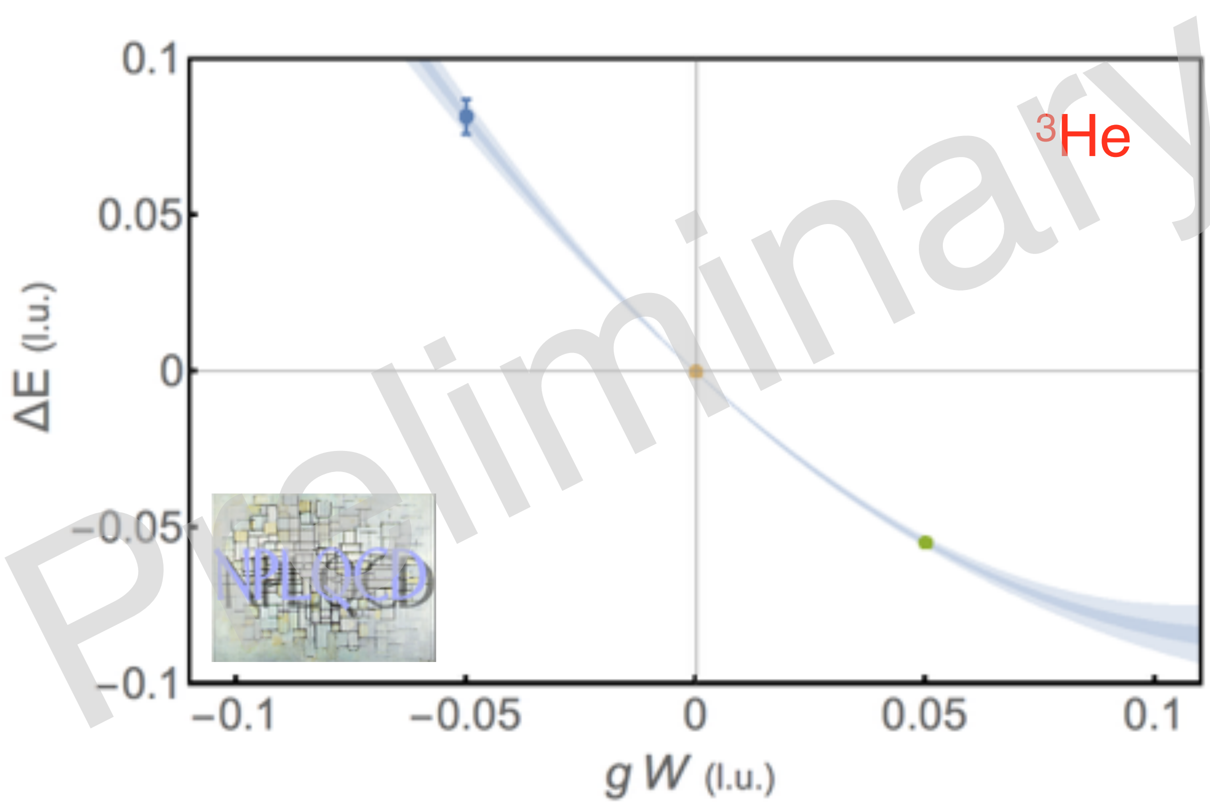
Extract the correlated two-nucleon interaction with axial field : L_{1A}

(aka - meson-exchange currents)

Axial Polarizabilities and 0νββ-decay rates







Curvature determined by Axial Polarizabilities.

Long-distance contribution to 0νββ-decay matrix elements

In Process

A=2 : NN, NΛ, NΣ, ΛΛ… ΞΞ, ΩΩ

S-matrix : Bound states and s-wave and higher scattering,
Luscher’s method for S-matrix, HAL QCD’s methods, Effective Hamiltonians

Magnetic and Axial moments and polarizabilities, Four-quark operators, reactions

A=3, 4 : ^{3}He, nnn, NNΛ, …, ΞΞΞ,

S-matrix : Bound states, HAL QCD’s methods, matching to NNEFT and phenomenological nuclear methods

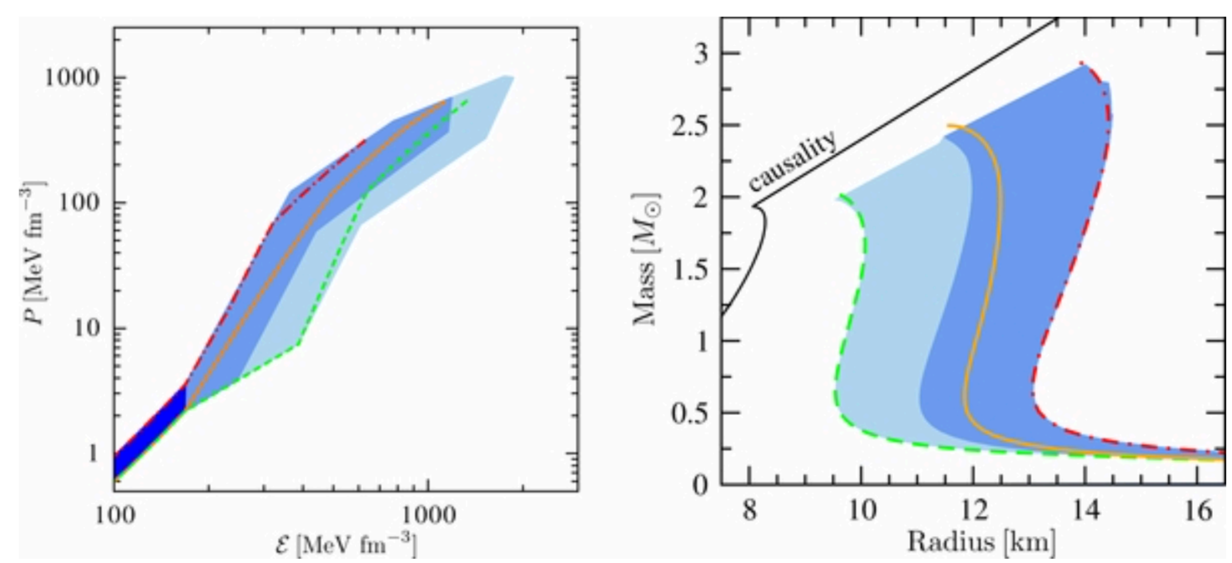
Magnetic and Axial moments and polarizabilities,

A>4 : p-shell nuclei

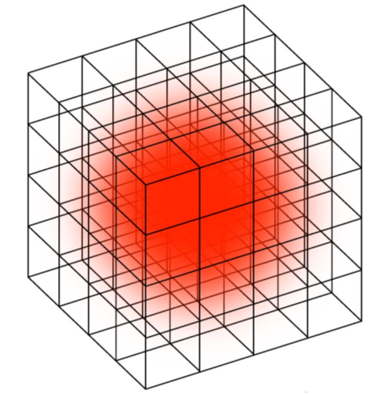
Bound states and continuum states, matching to NNEFT and phenomenological nuclear methods

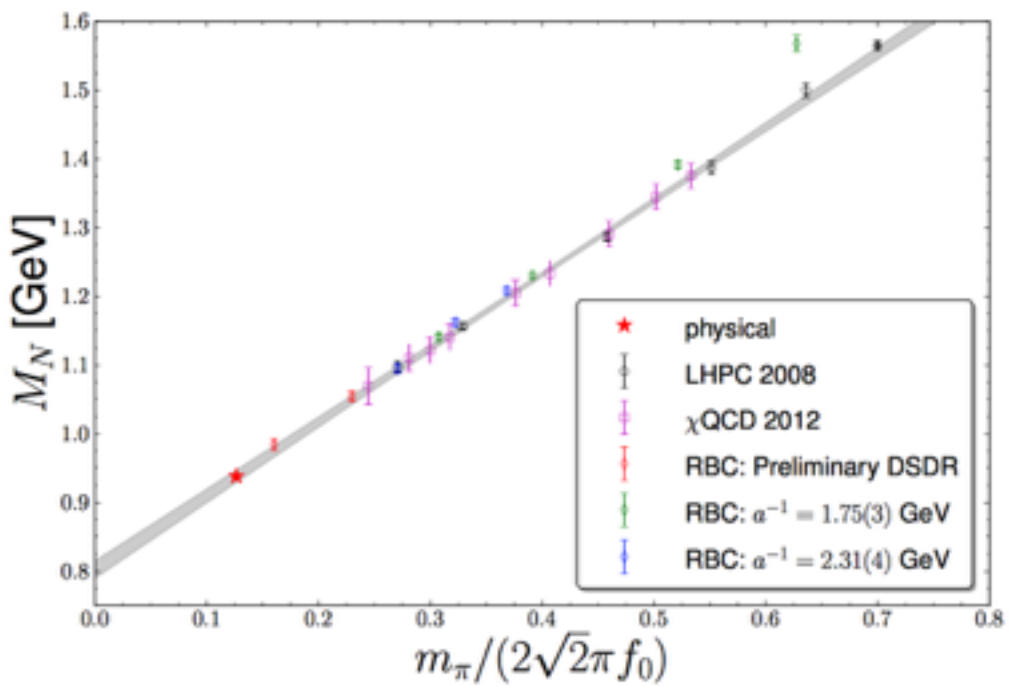
Anticipated Progress

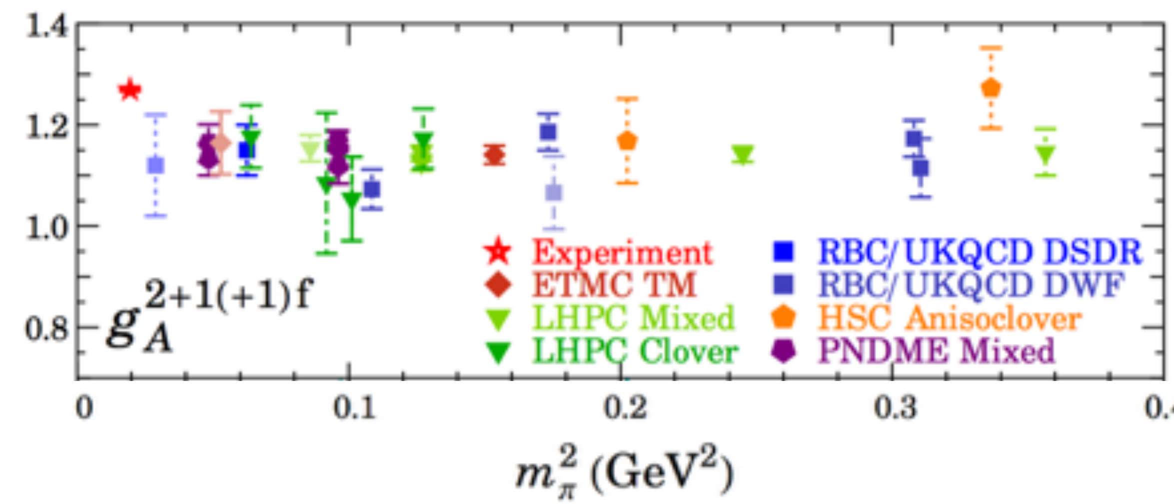
- Lighter pion masses
  - groups already at physical point
- Higher precision
  - needed at all masses
- Multi-nucleon forces
- P-shell and SD-shell nuclei
- Matrix elements

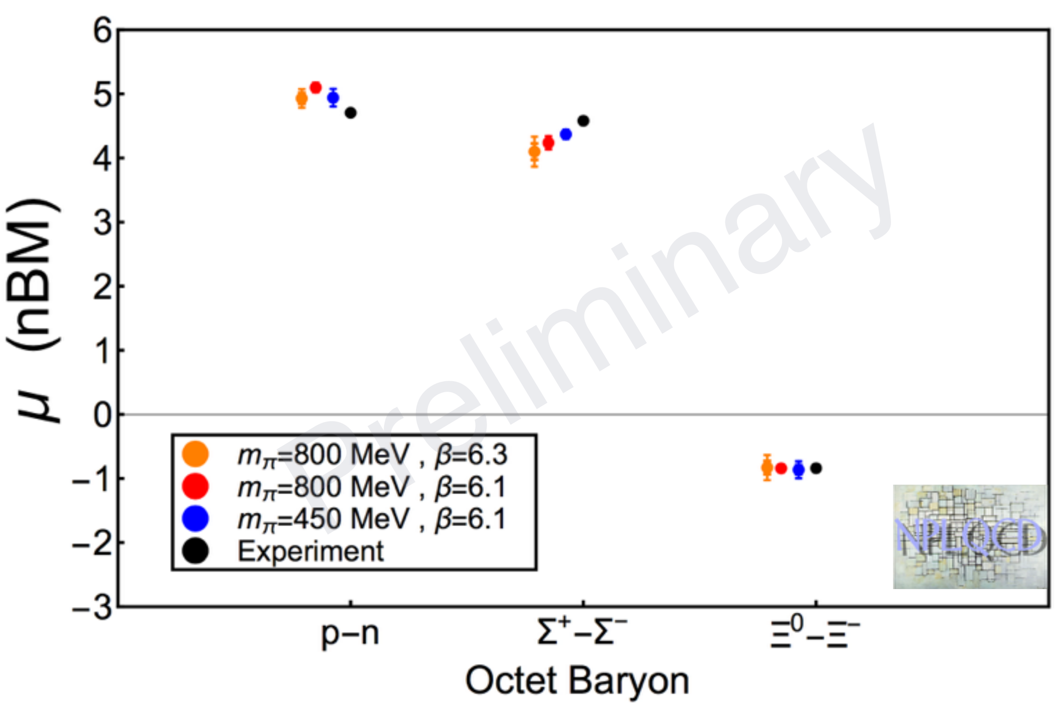


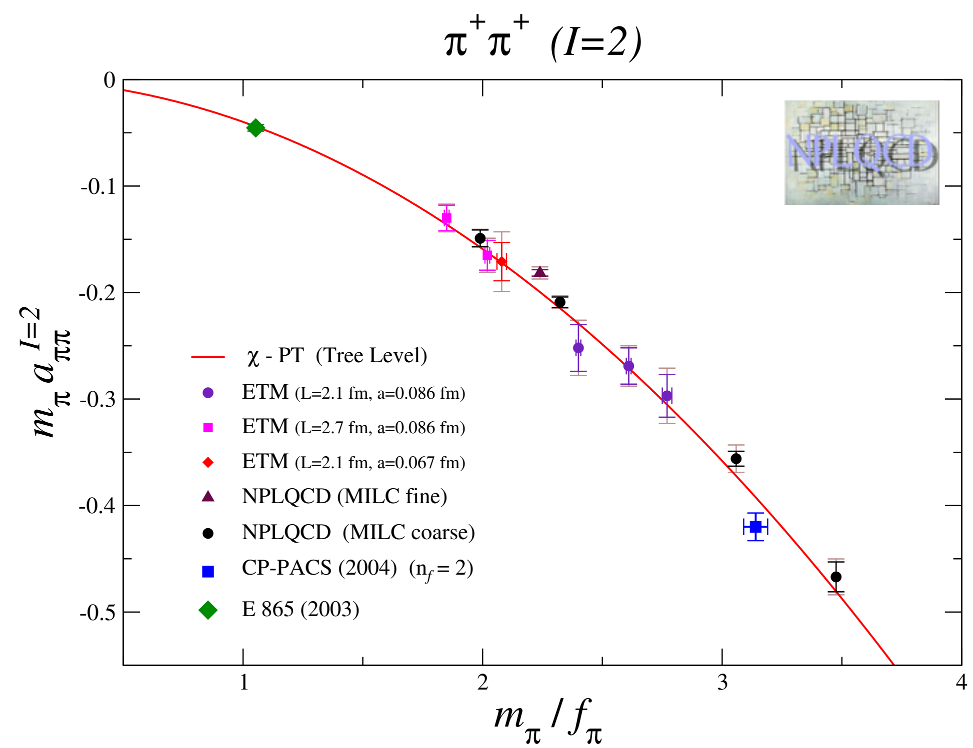
Lattice QCD: What is the Underlying Structure ?









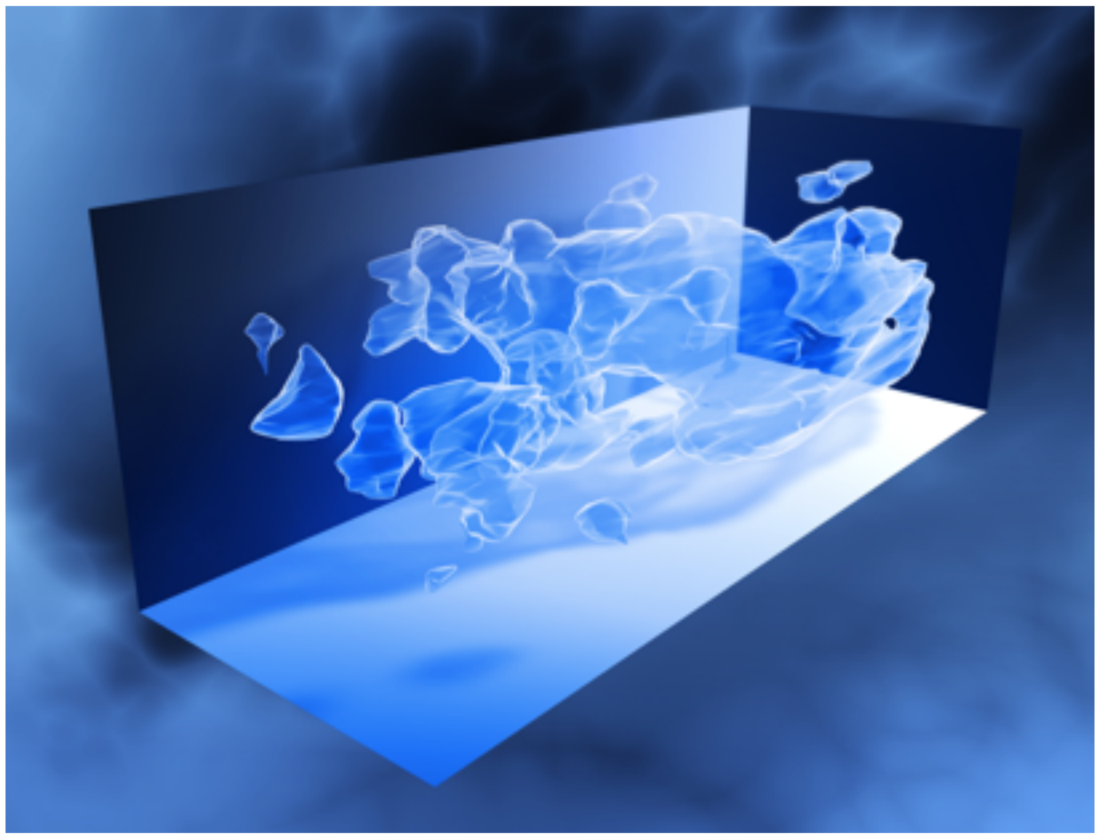


All unexpected results that Lattice QCD has revealed

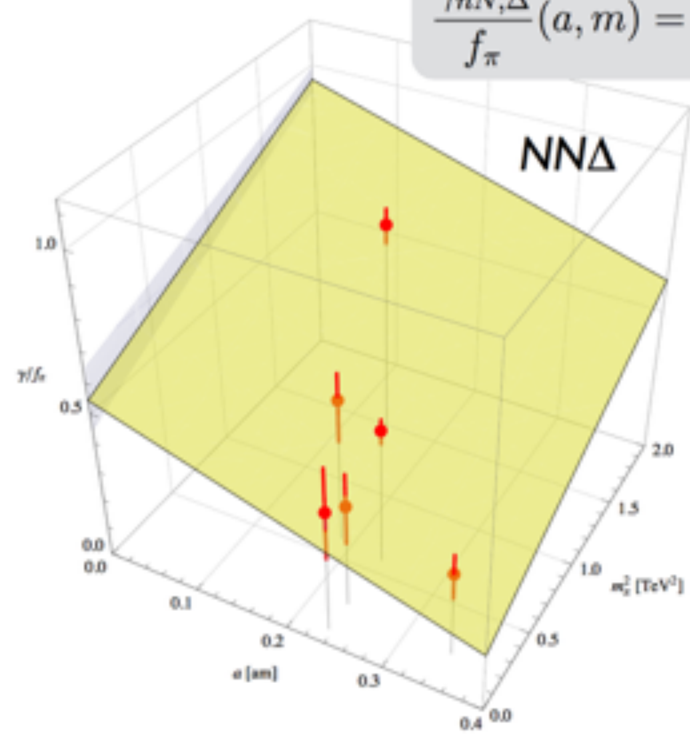
Dark Nuclei
A (Possible) Challenge for NEFTs

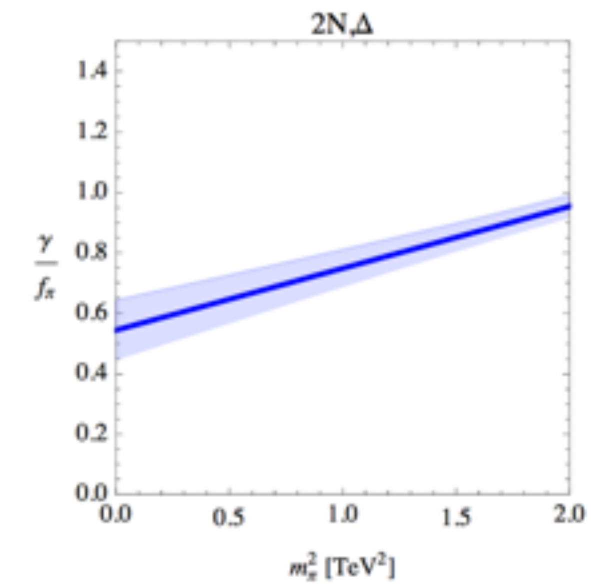
BSM Nuclei as Dark Matter ?

William Detmold, Matthew McCullough, and Andrew Pochinsky, Phys. Rev. D **90**, 115013 (2014), Phys. Rev. D **90**, 114506 (2014).



$$\frac{\gamma_{nN,\Delta}}{f_\pi}(a,m) = \gamma^{(0)}_{nN,\Delta} + a\ \delta^{(a)}_n + m_\pi{}^2\delta^{(m)}_n$$

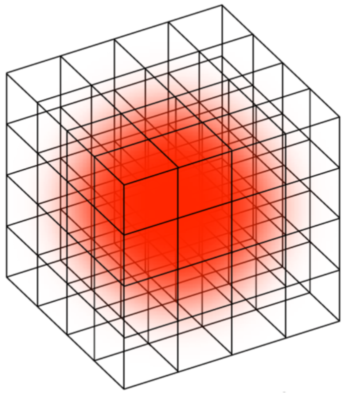




Use QCD technology for $SU(2)_c$ color - bound states.

1/ Define NEFT for $SU(2)_c$
2/ Extract counterterms from limited LQCD results
3/ Predict Periodic Table and cross sections (with error bars)
4/ Compare with complete LQCD results

Closing Remarks



Lattice QCD combined with nuclear many-body techniques is beginning to provide first principles predictive capabilities for nuclear physics - some groups already at the physical point.

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. Such calculations are actually essential in dissecting the chiral nuclear forces!

Known challenges lie ahead

FIN