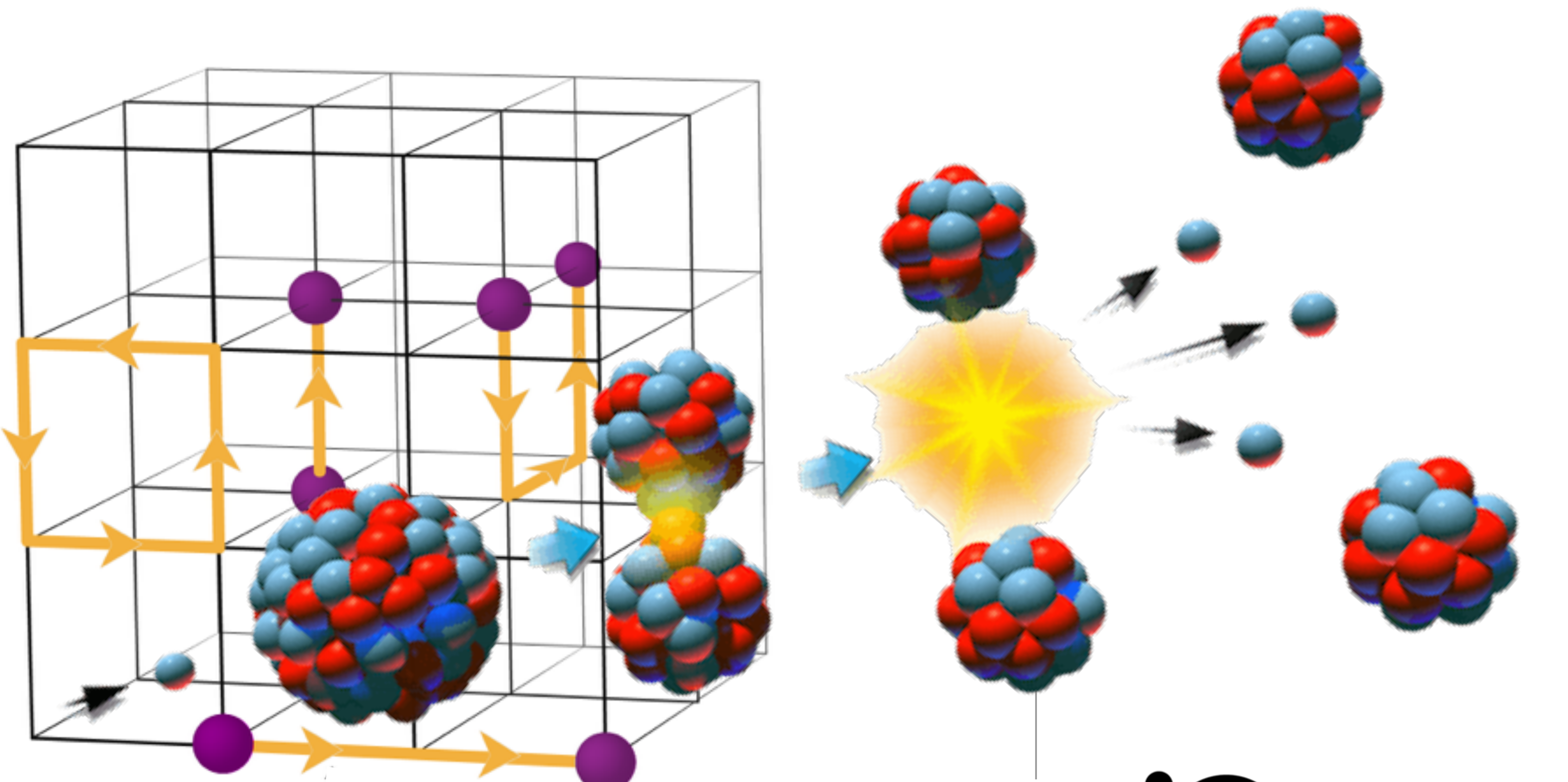
Nuclear Physics

Lattice 2016

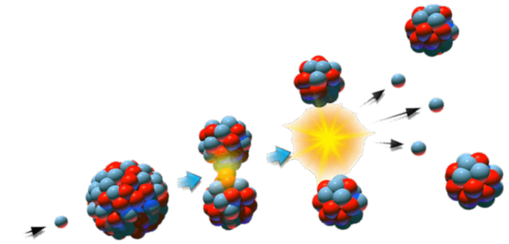
34th International Symposium on Lattice Field Theory, 24-30 July 2016



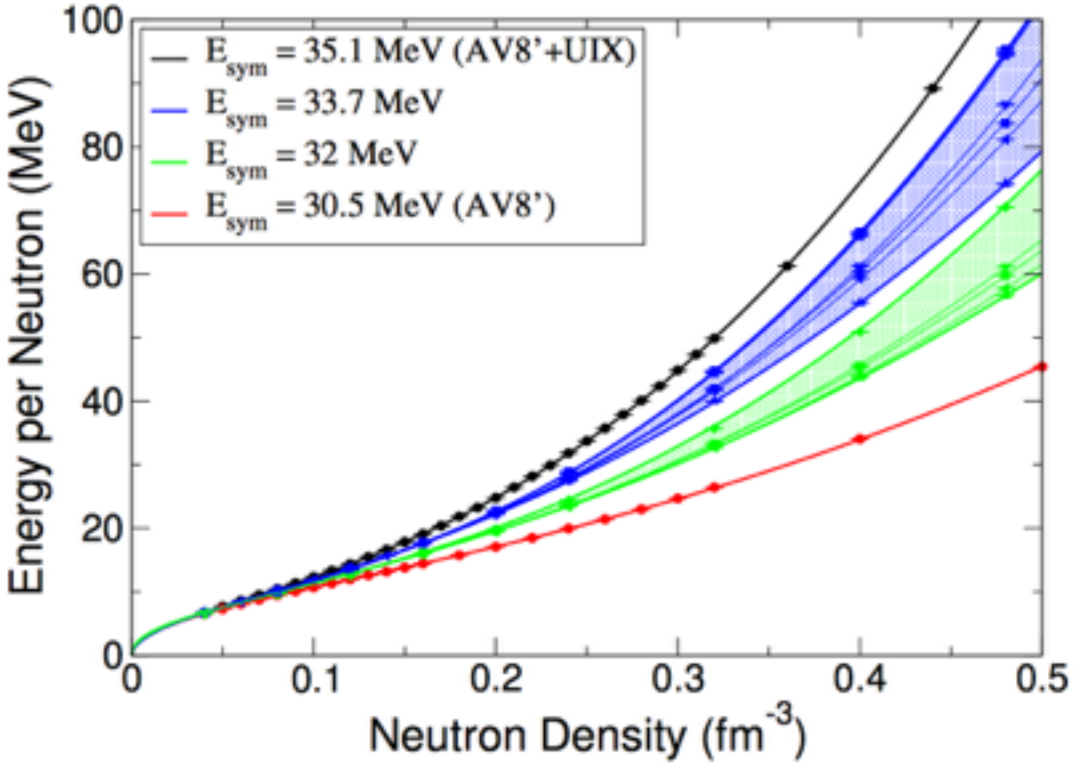
Martin J Savage

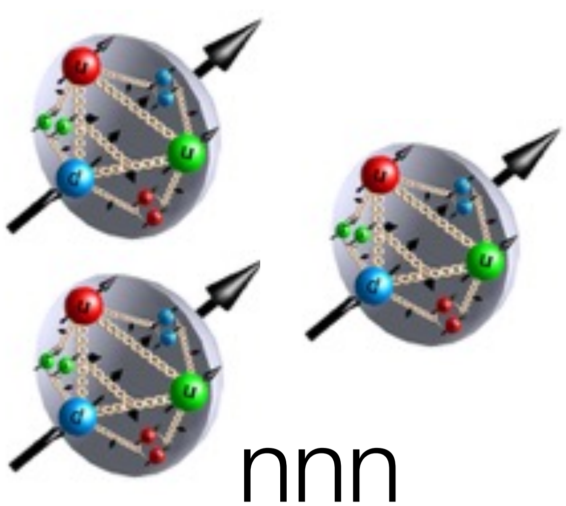
INSTITUTE for NUCLEAR THEORY

Nuclear Forces, Equation of State and Astrophysical Environments

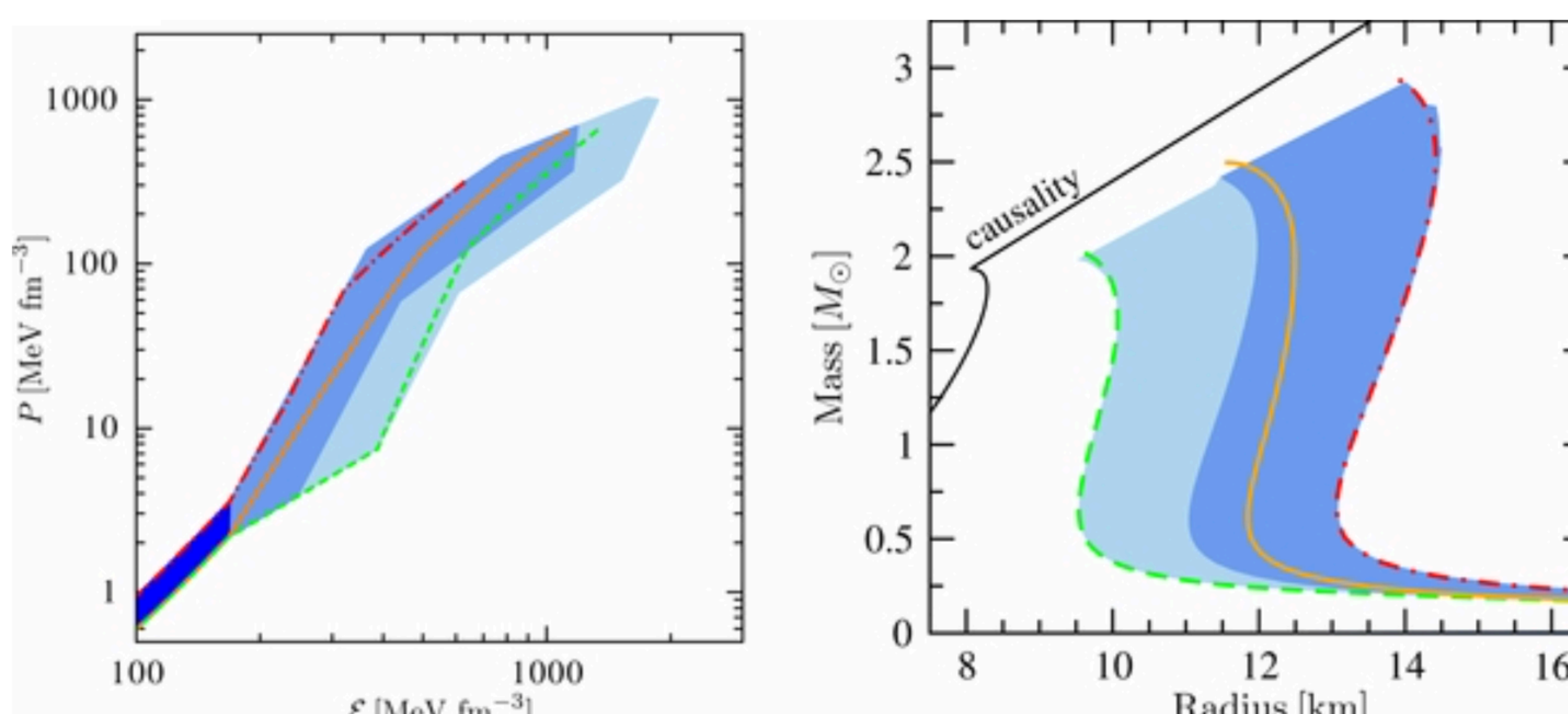


Gandolfi, Gezerlis and Carlson, Annual Reviews of Nuclear and Particle Science (2015)



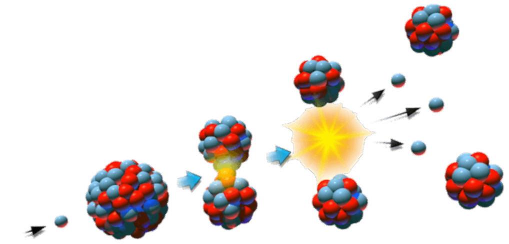


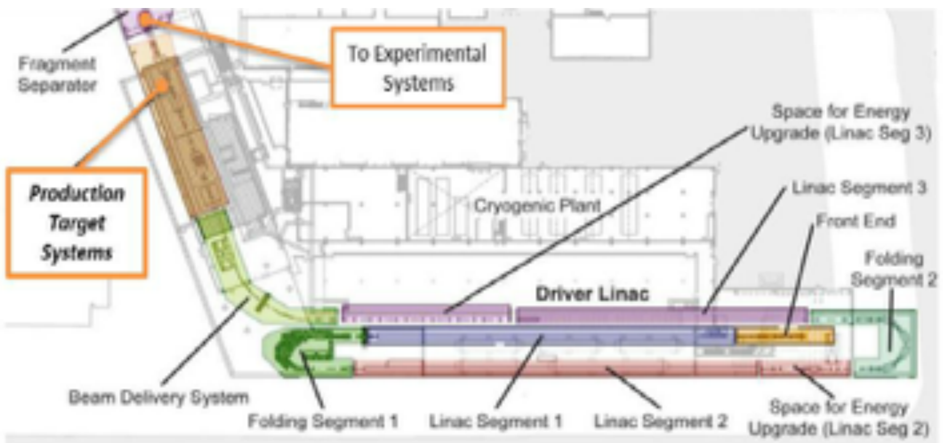
Hebeler, Lattimer, Pethick and Schwenk, Ap.J. 2013



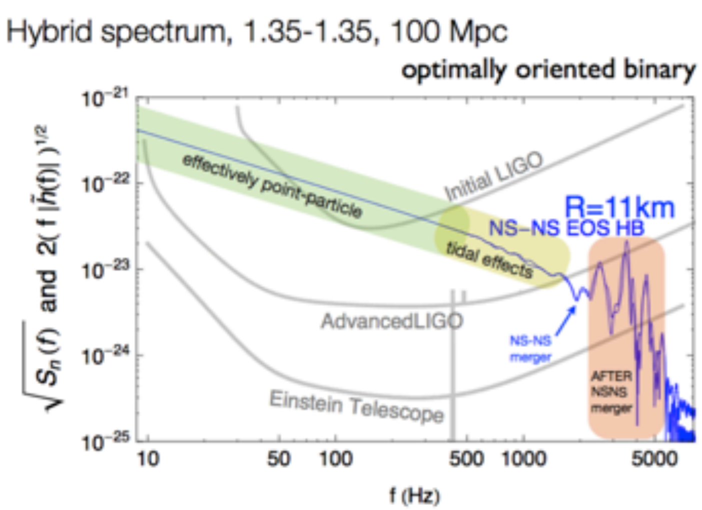
Rare Isotope Facilities

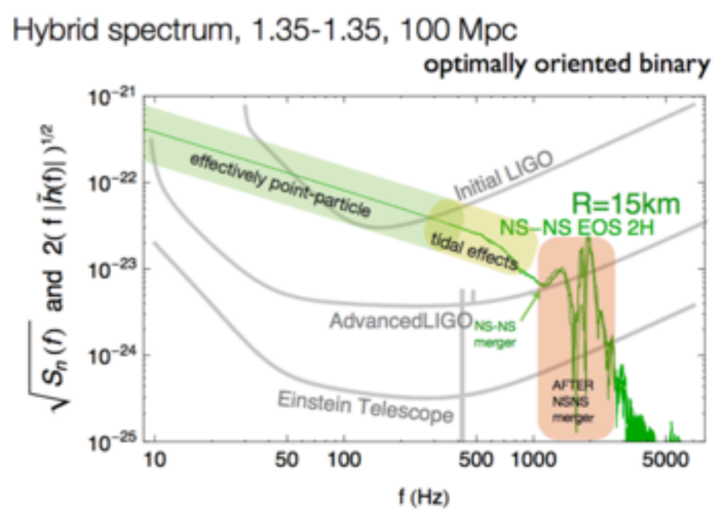
Canada, Germany, Japan, Korea, US, …

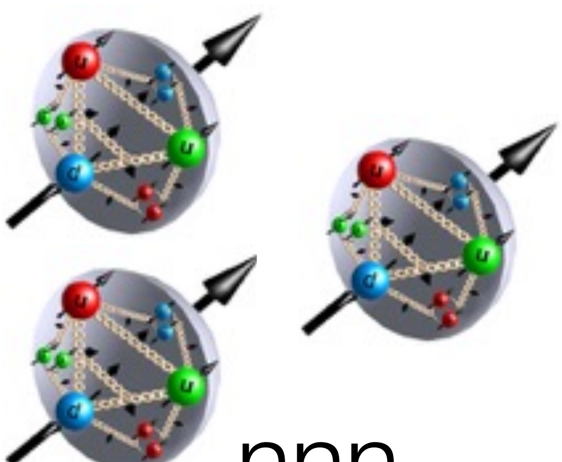




Experiment (US$ 730M) Theory Observation







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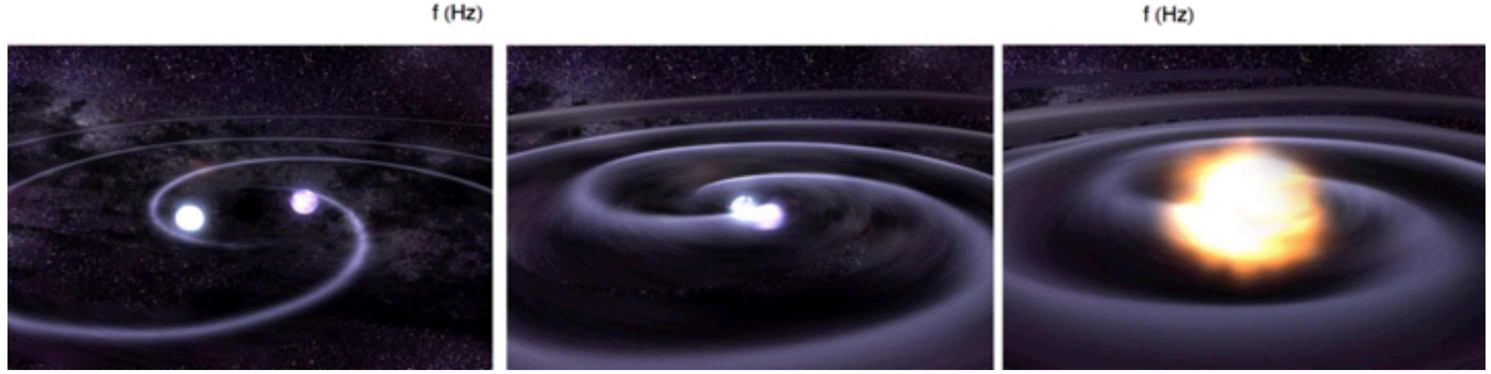

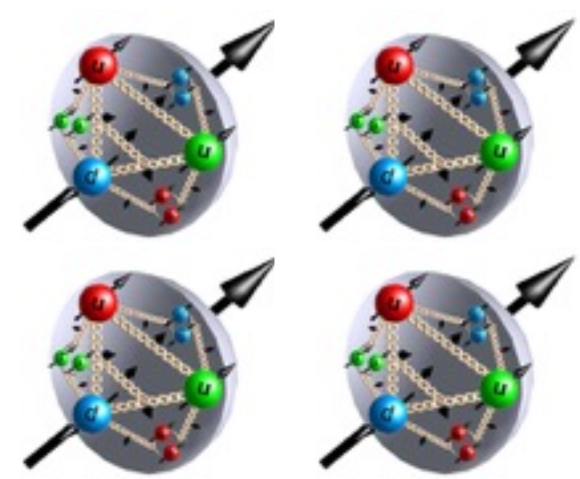

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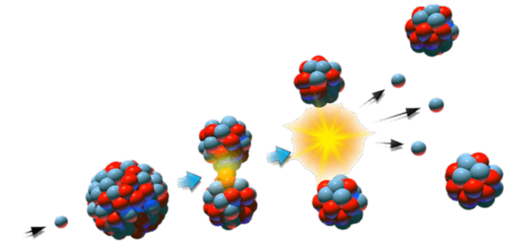
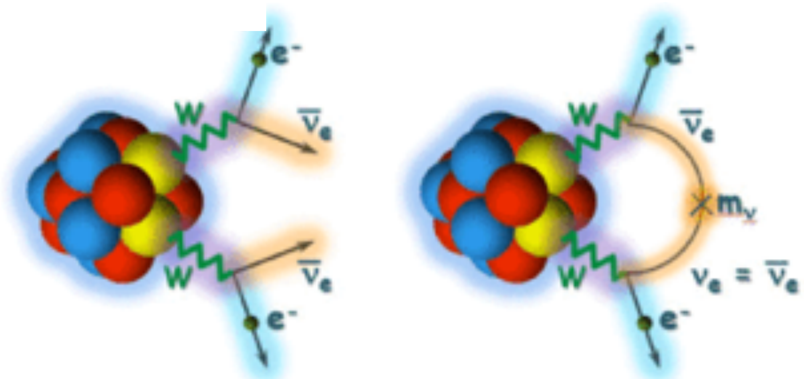
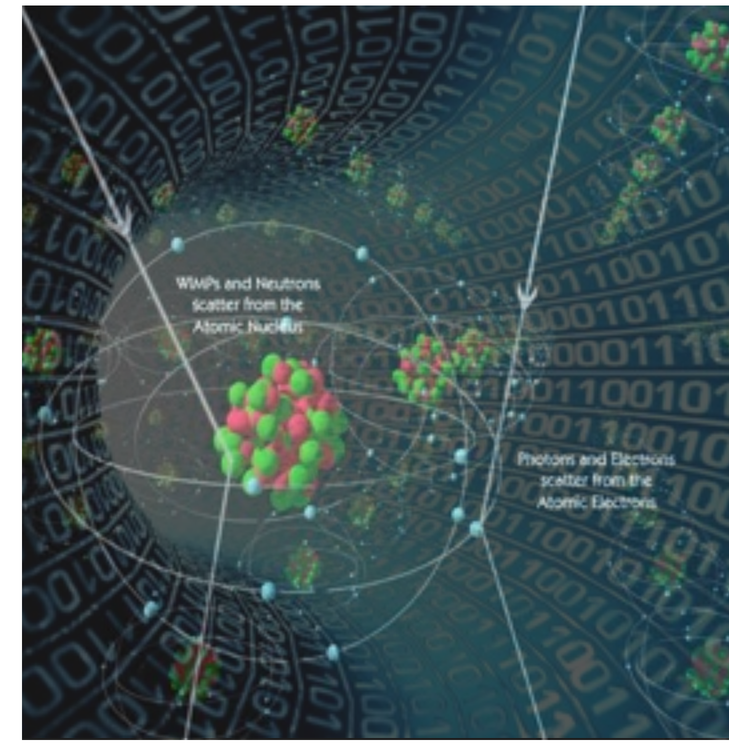
LIGO - Imprints Gravity Waves

Nuclear Matrix Elements

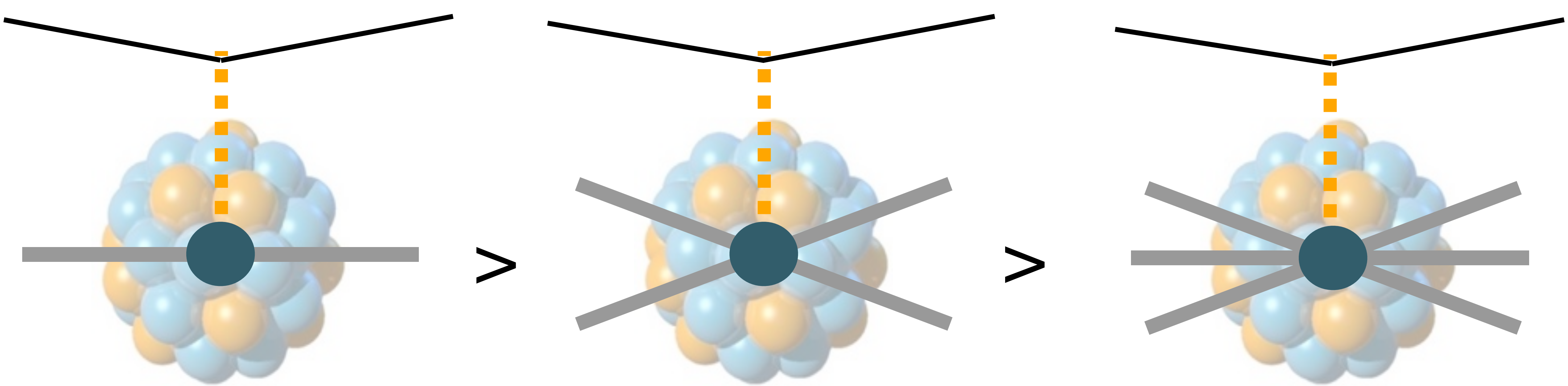




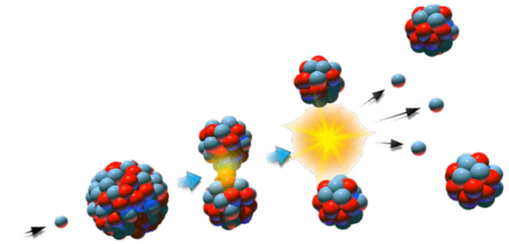
(Amy Nicholson, plenary later this week)



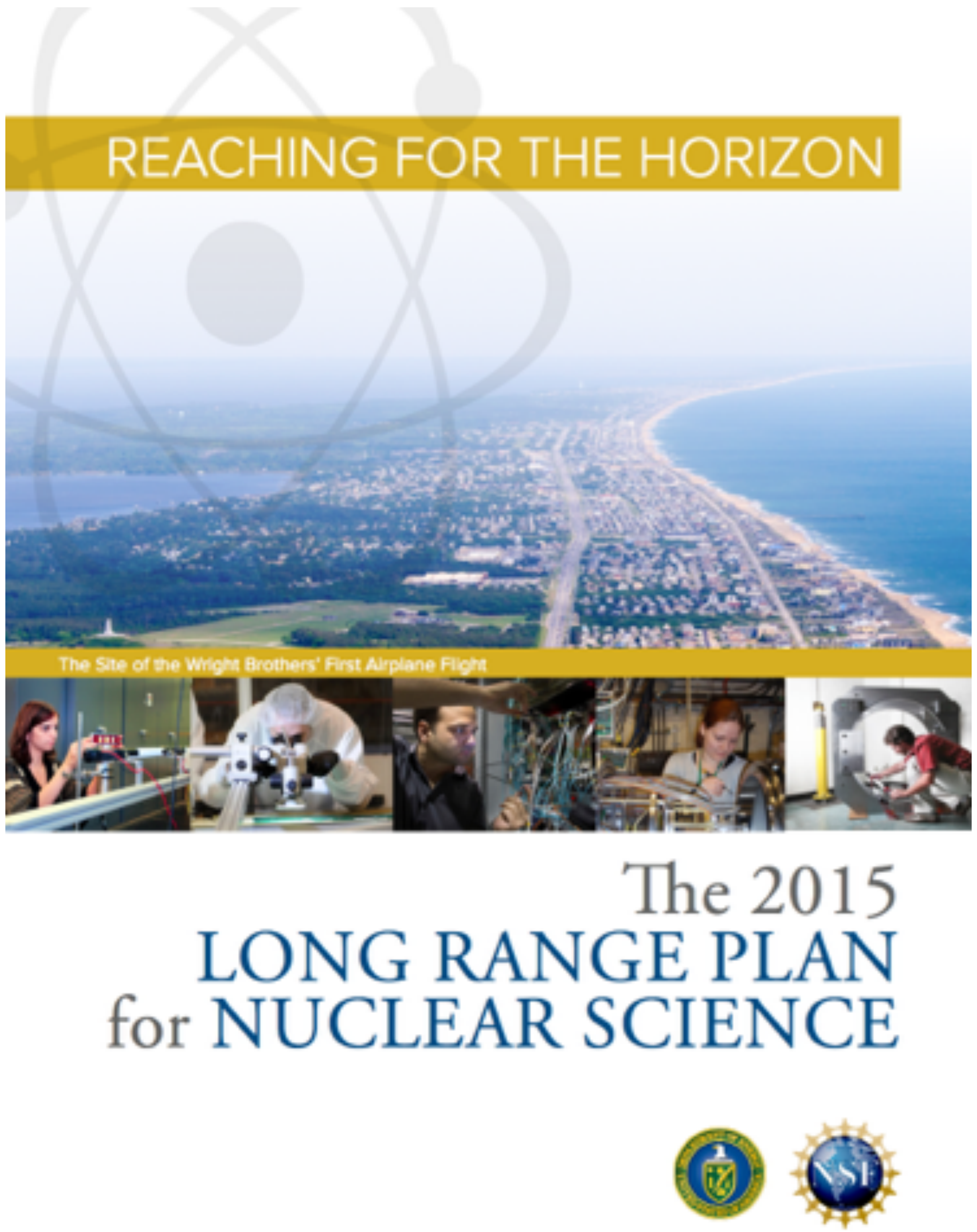
ν, e, μ, X - JLab, ν-experiments, DUNE, DM, edm, …



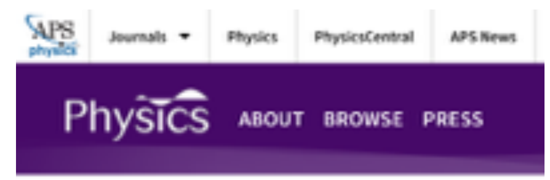
Gluons and an EIC

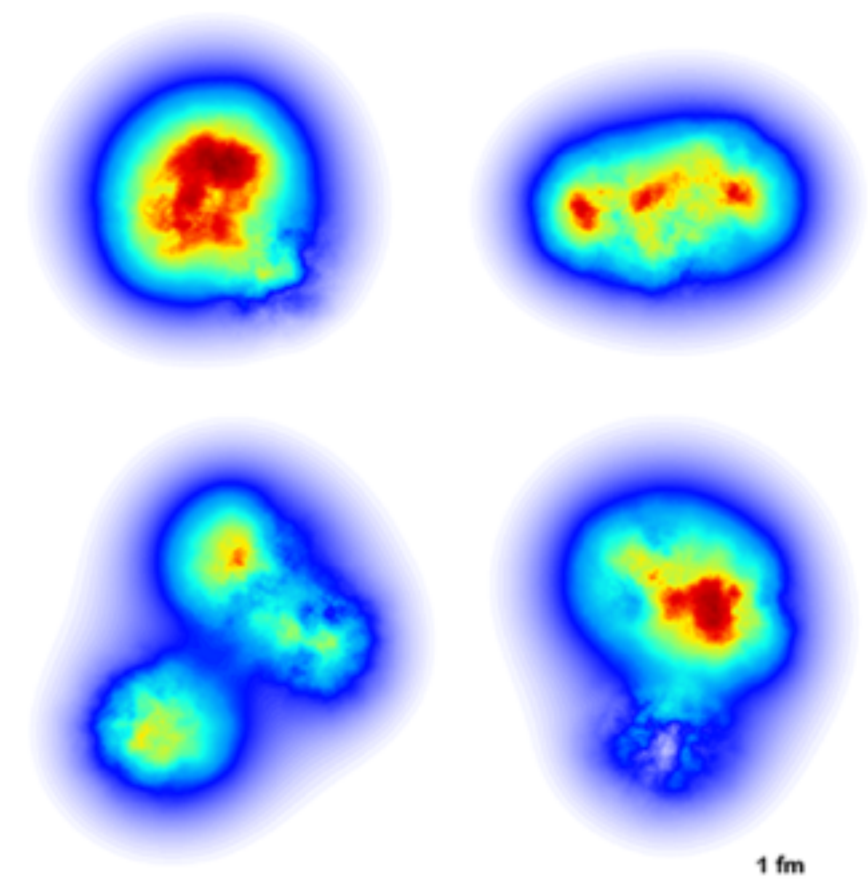


Future experimental QCD Program will be an Electron-Ion Collider ~ 2025



(H. Mäntysaari and B. Schenke)

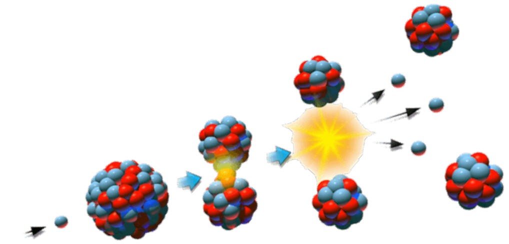


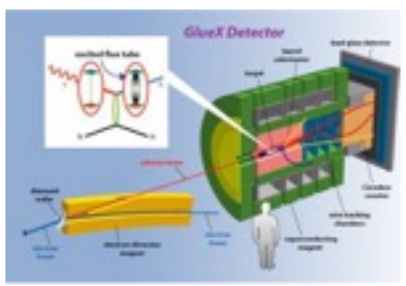


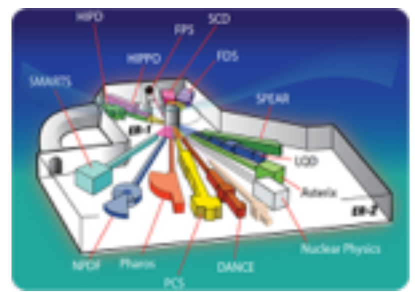
Gluon density in the nucleus at four different times.

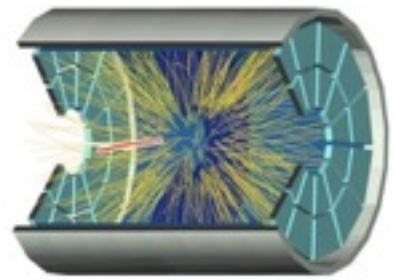
Phiala Shanahan, First Lattice QCD Study of Gluonic Transversity, later this week

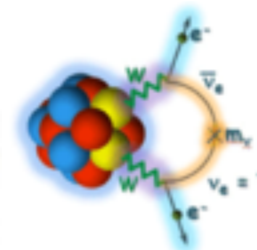
Low-Energy Nuclear Physics

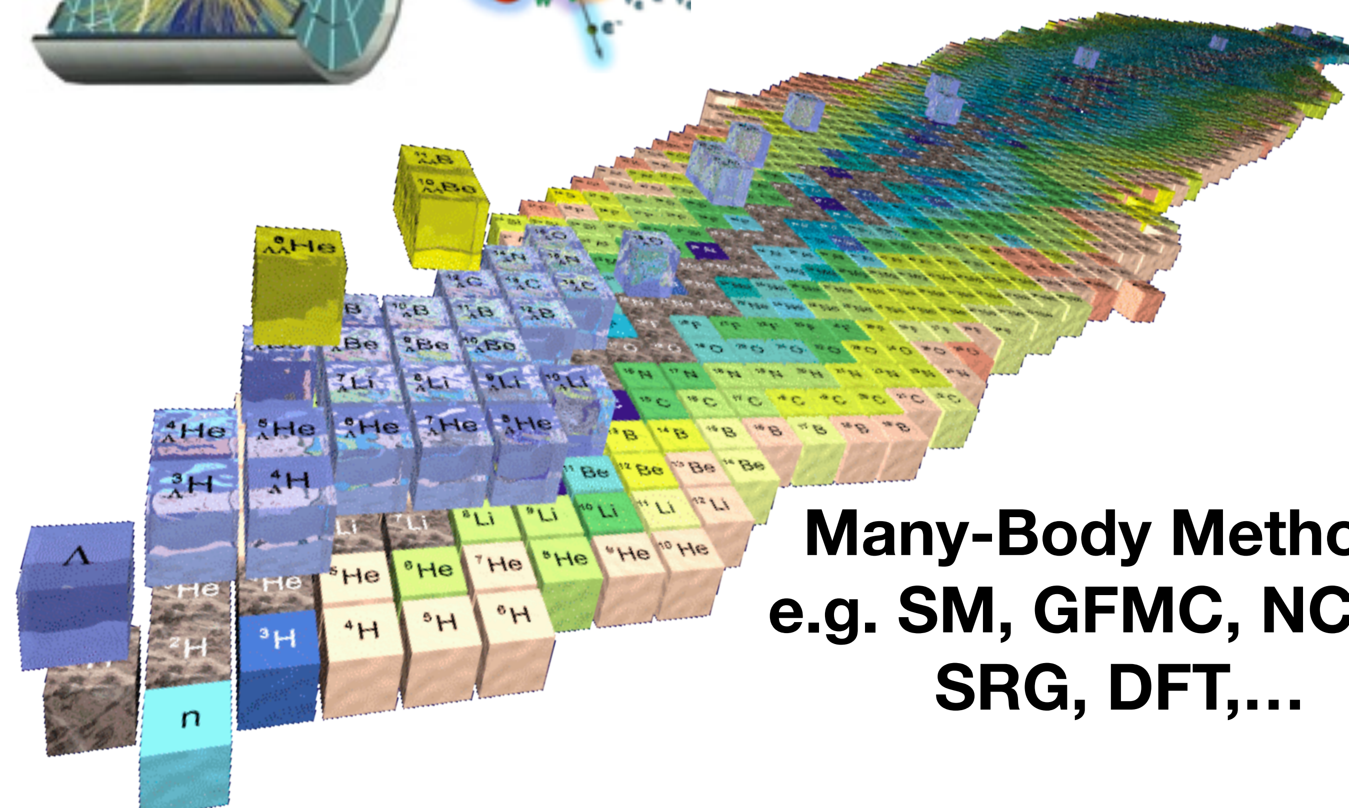




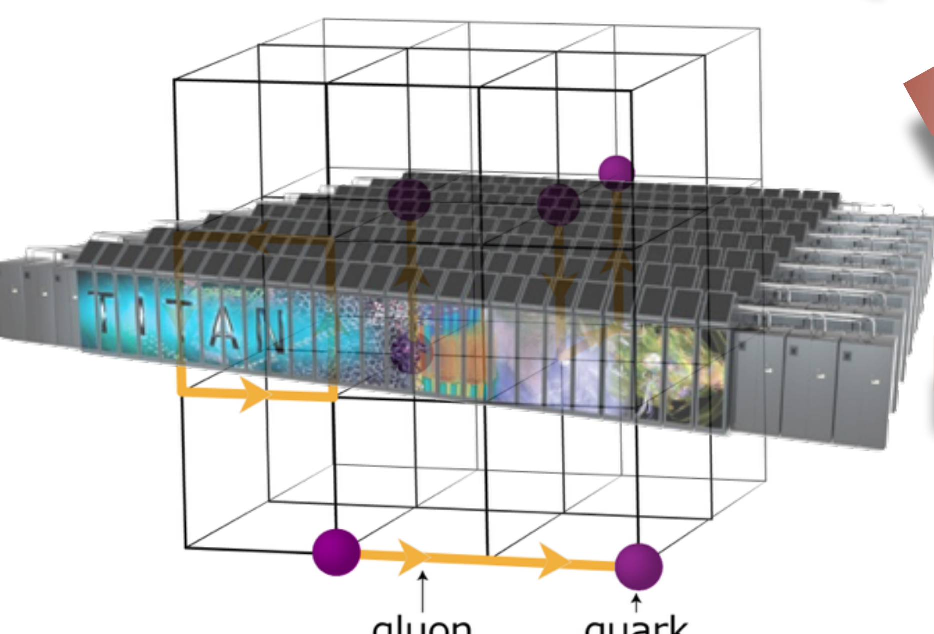


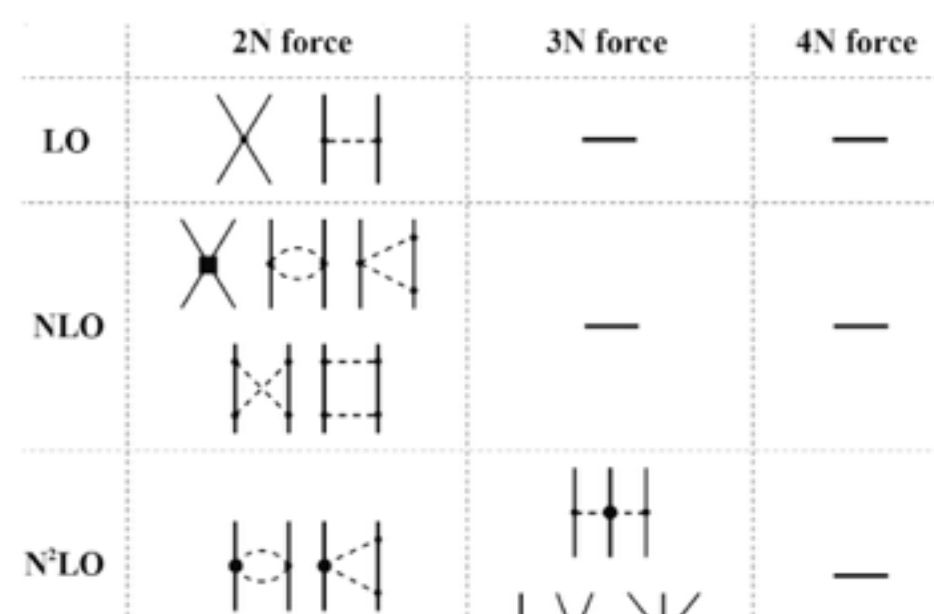




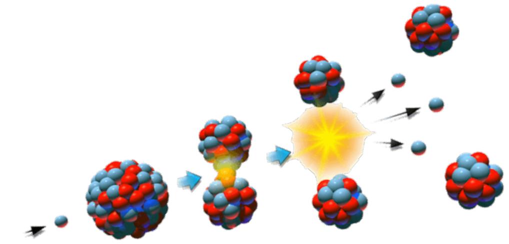


Many-Body Methods e.g. SM, GFMC, NCSM, SRG, DFT,…

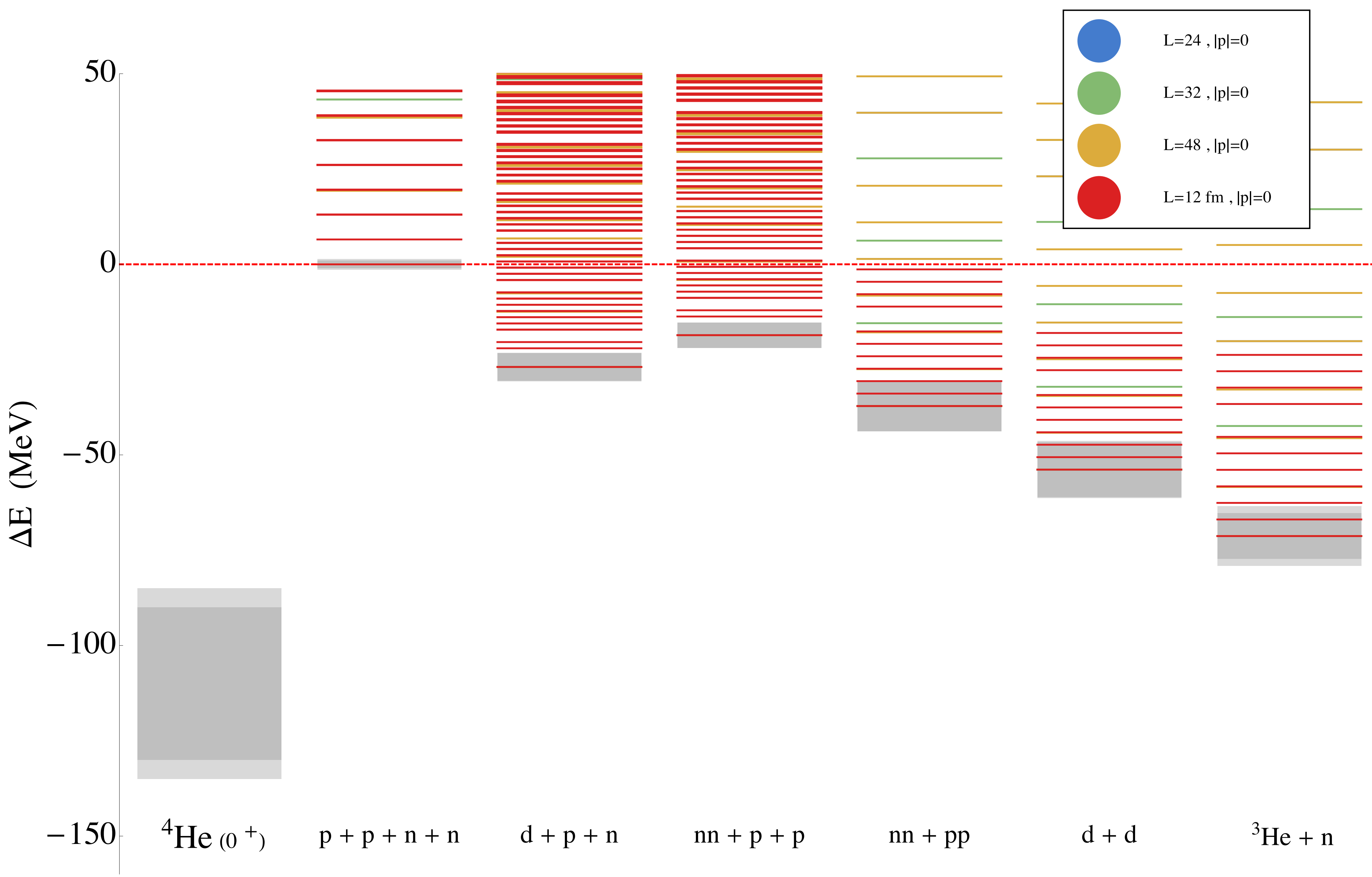


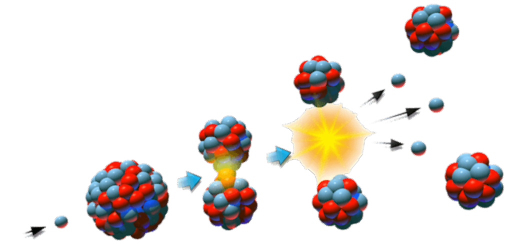


Methods and Difficulties
Many-Body Spectra



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



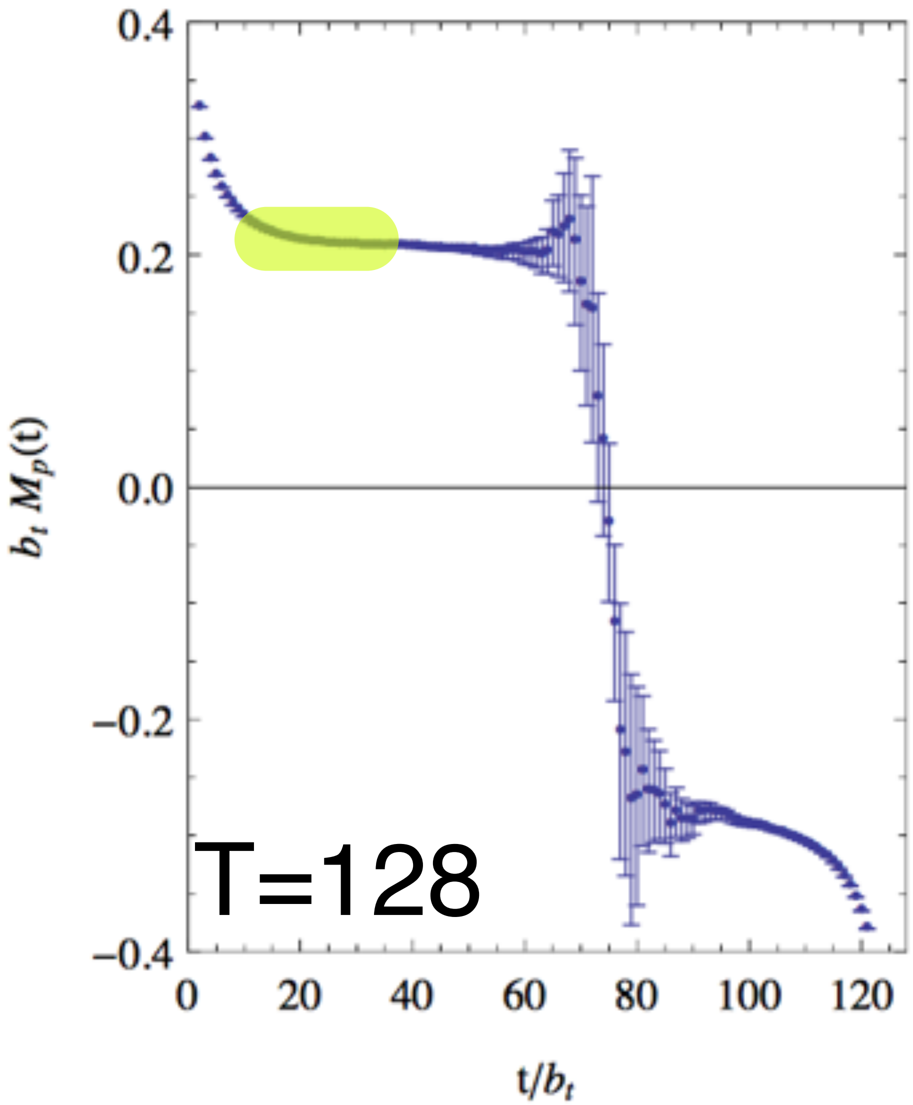


Methods and Difficulties
Signal-to-Noise

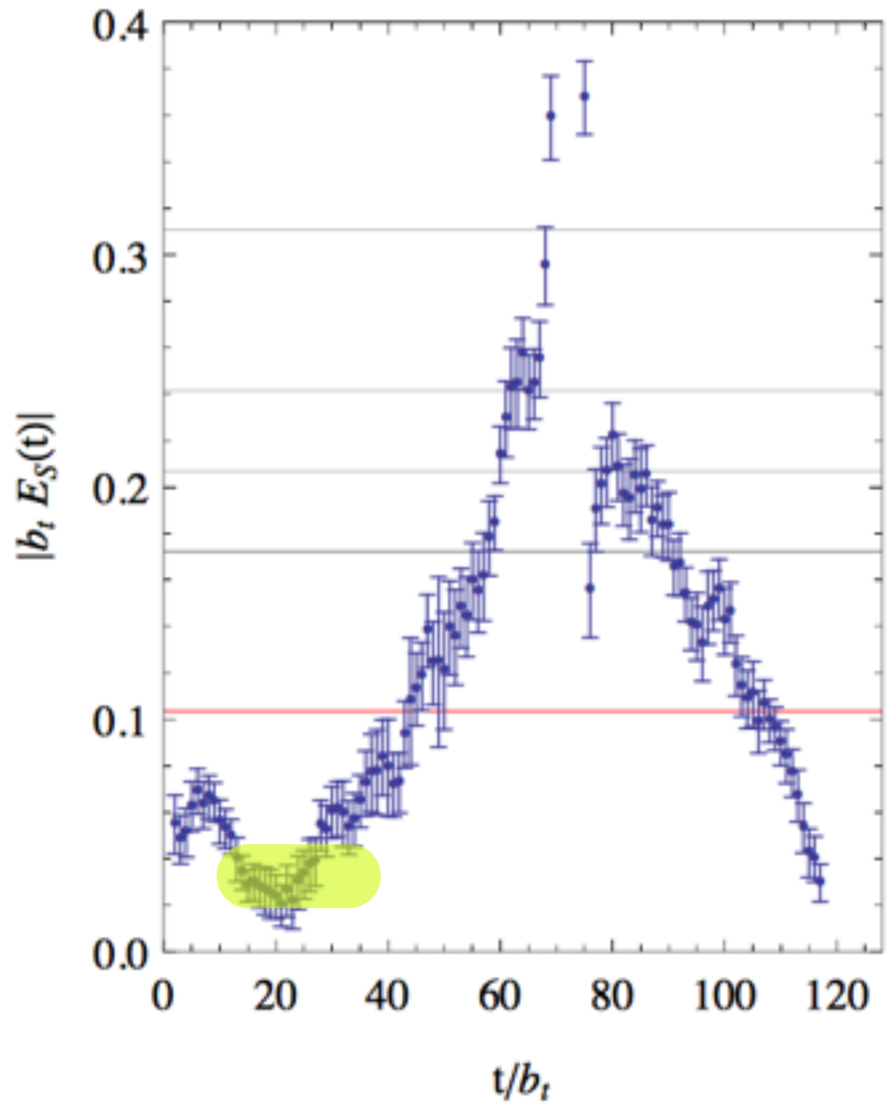
The Golden Window for Nuclei

dictated by source and sink structure

Nucleon Effective Mass



Noise-to-Signal Mass Scale

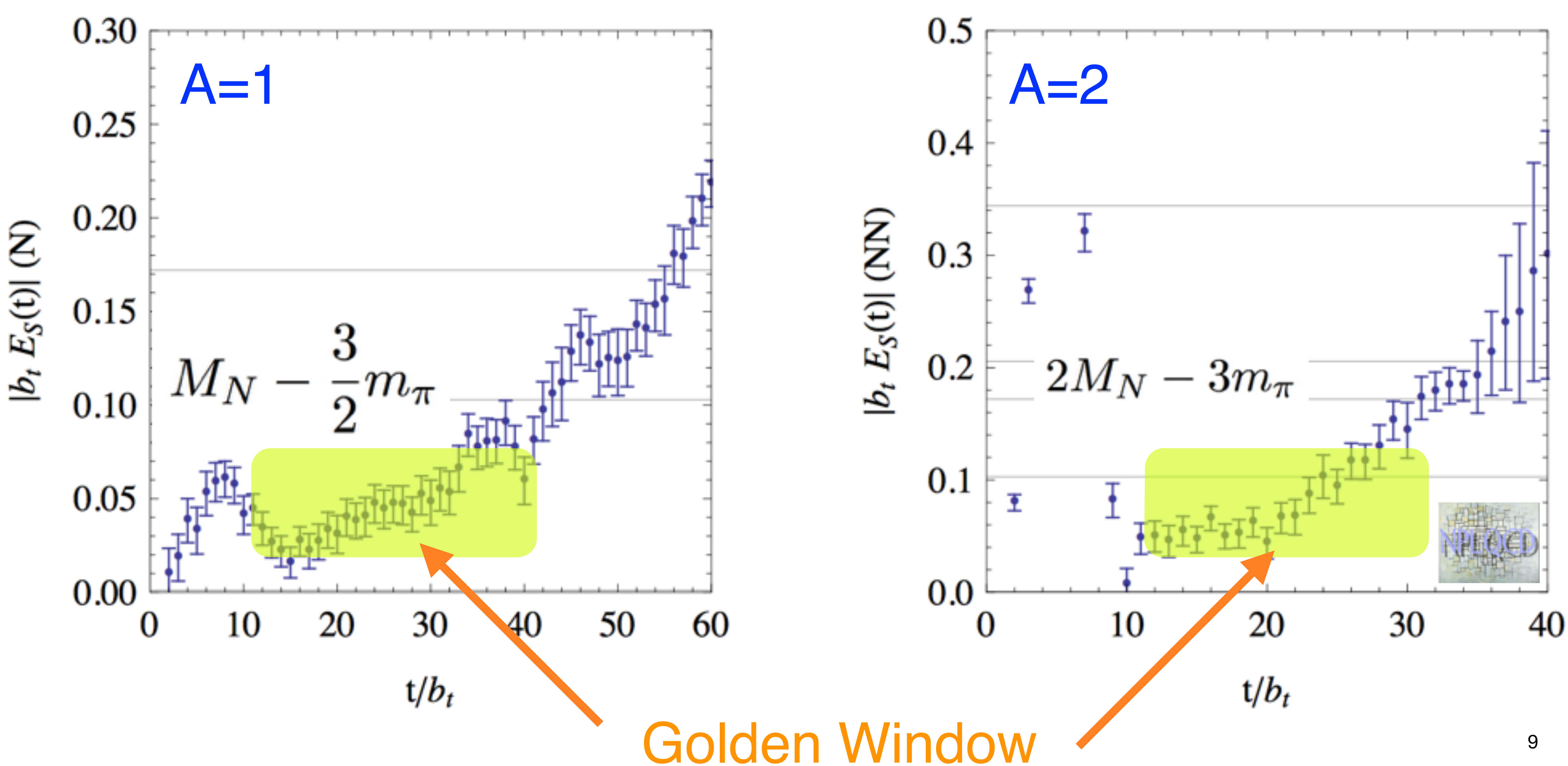


Lepage asymptotic

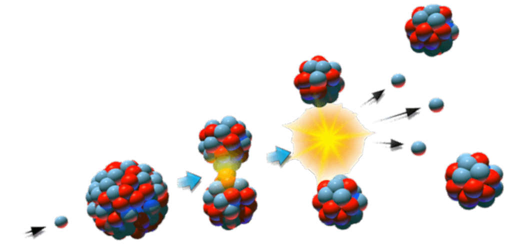
M_N - 3/2 M_π

Methods and Difficulties
Signal-to-Noise

Energy scale of the signal-to-noise ratio



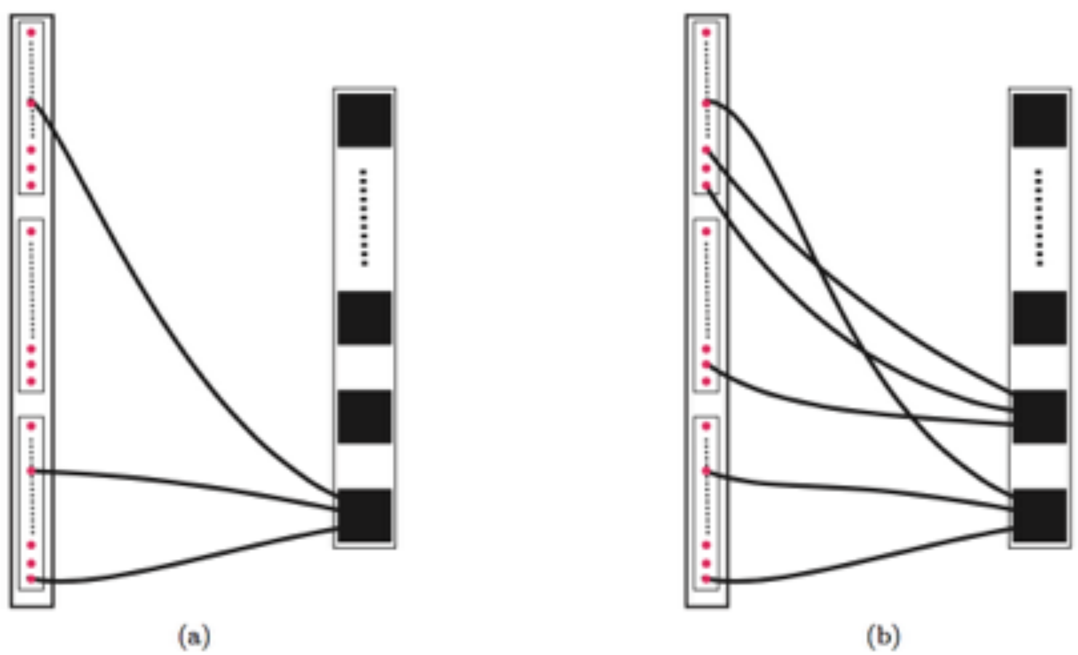
Methods and Difficulties Contractions

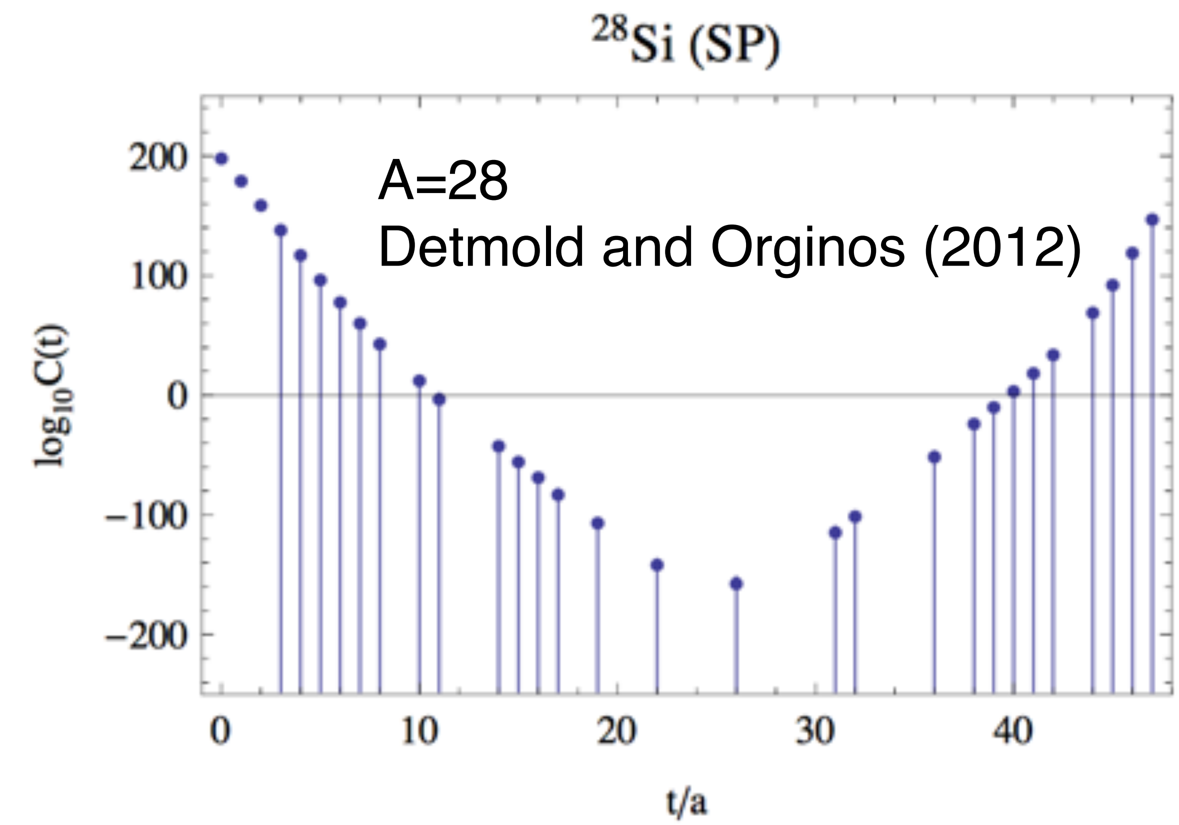


Detmold and Orginos (2011)
Yamazaki et al (2011)
Doi and Endres (2012)

Naively:
Proton : $N^{\text{cont}} = 2$
^{235}U : $N^{\text{cont}} = 10^{1494}$

Large number of contractions





Symmetries provide significant reduction
Automation, Recursion, … delay the problem but it remains

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

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

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

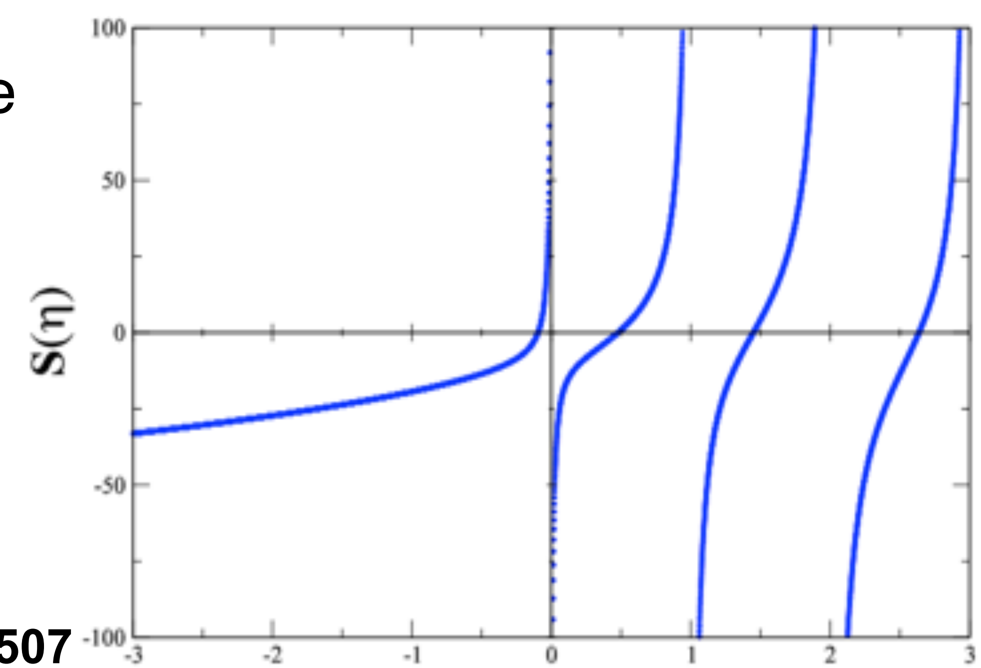
$$W = 2\sqrt{m^2 + mE}. \qquad (7.2)$$

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 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

e.g., A_1^+ irrep

energy eigenvalue

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

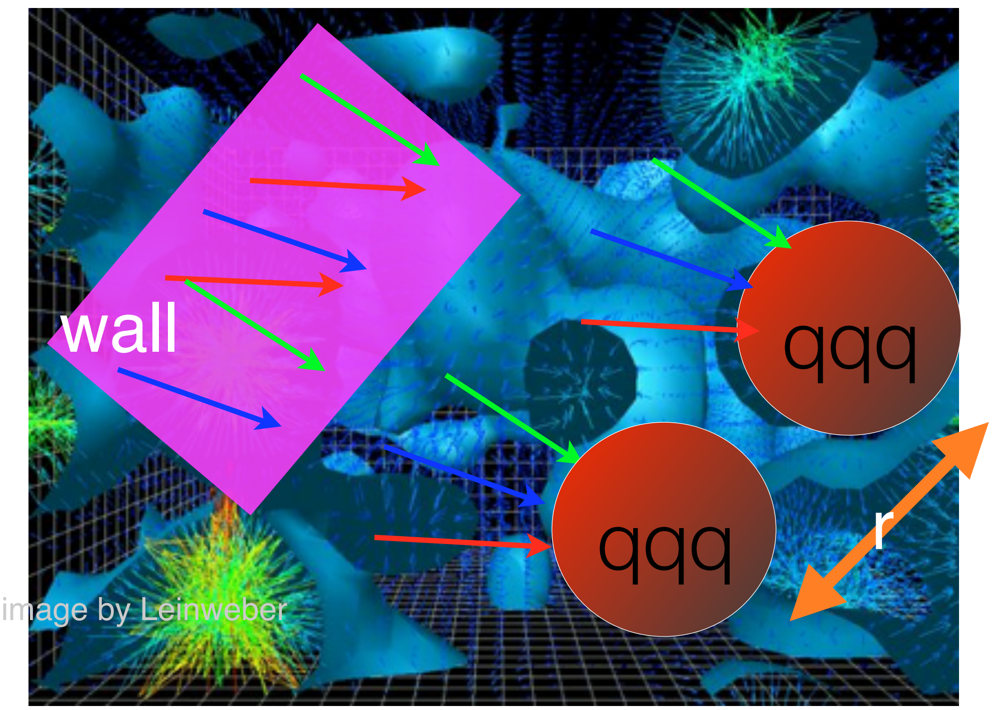


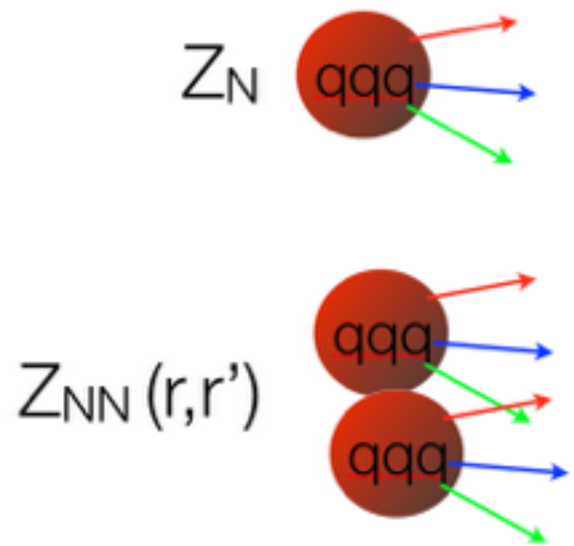
Extended to Coupled-Channels systems:

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

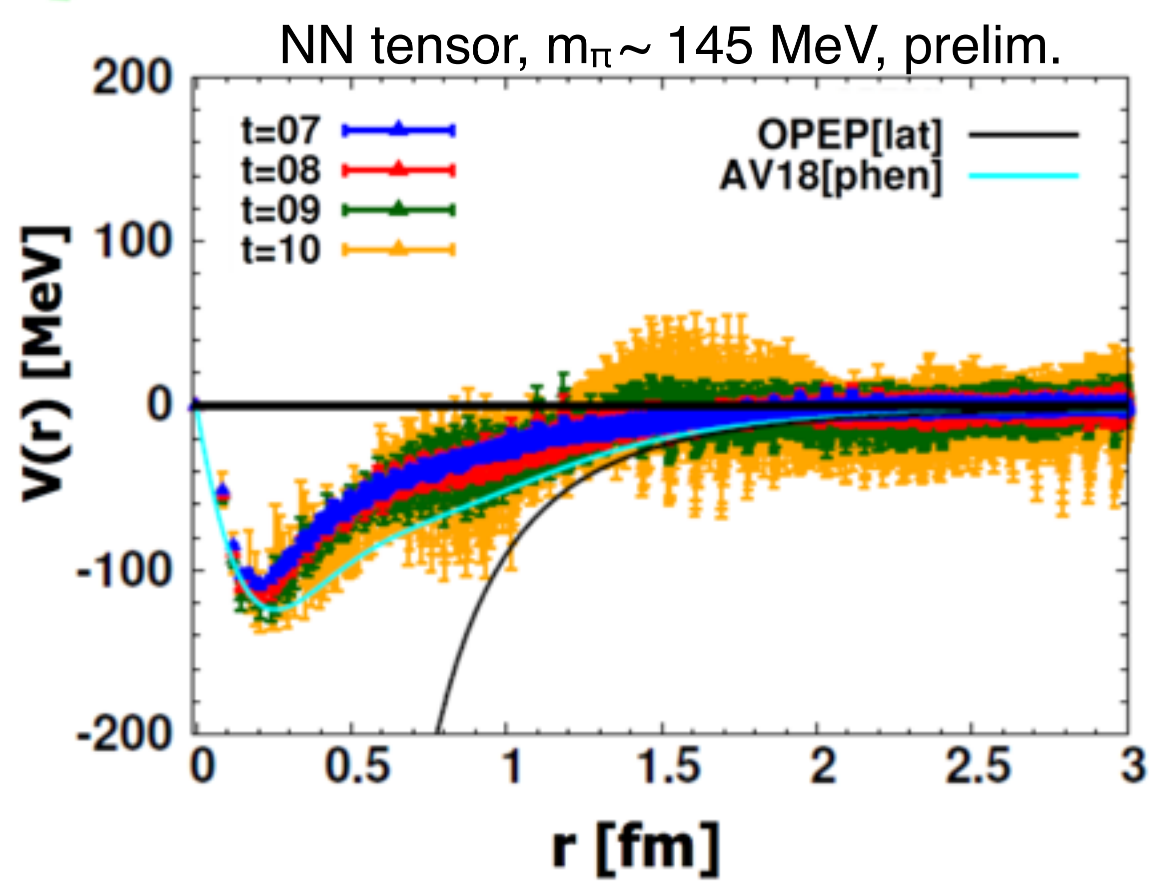
Methods and Difficulties
Correlators

HAL QCD method(s): HAL QCD



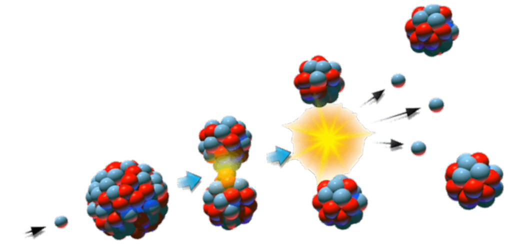


$U_E(r,r')$:
Expected to correctly reproduce S-matrix at energy eigenvalues

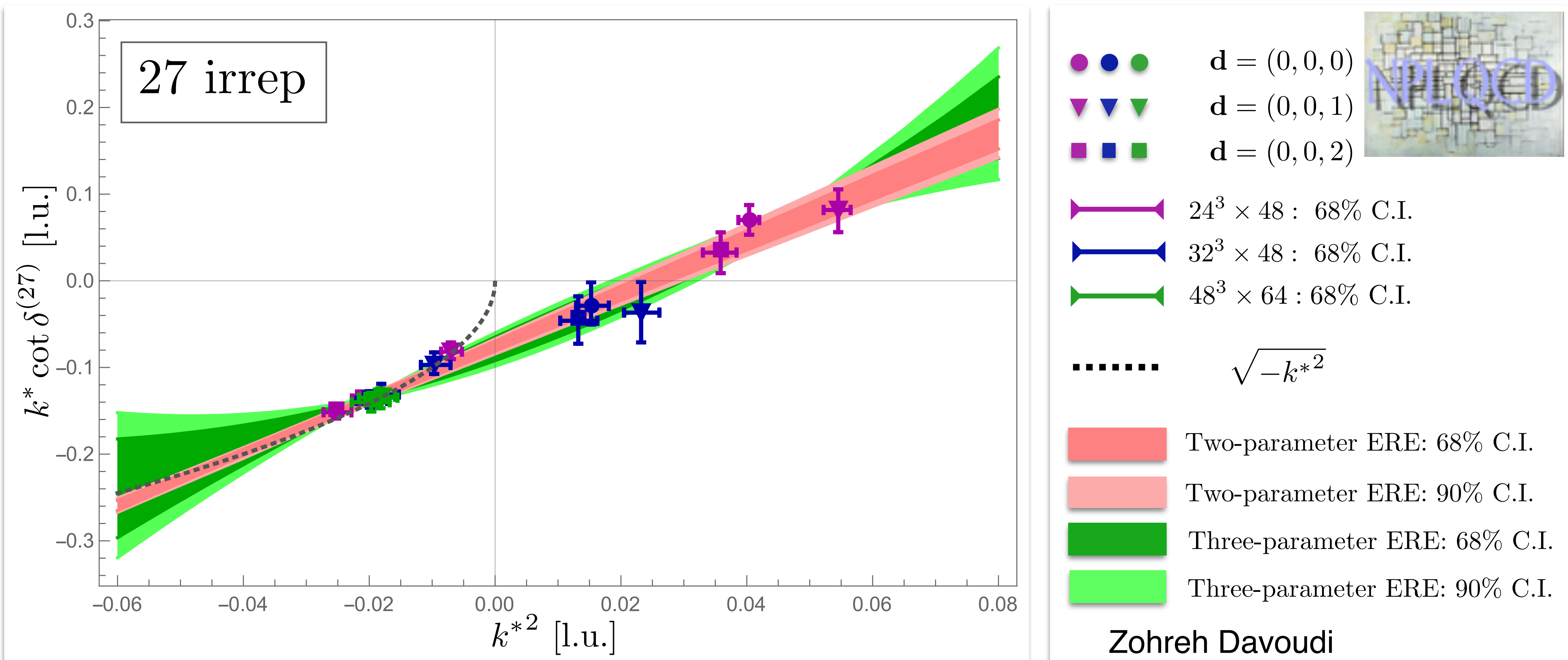


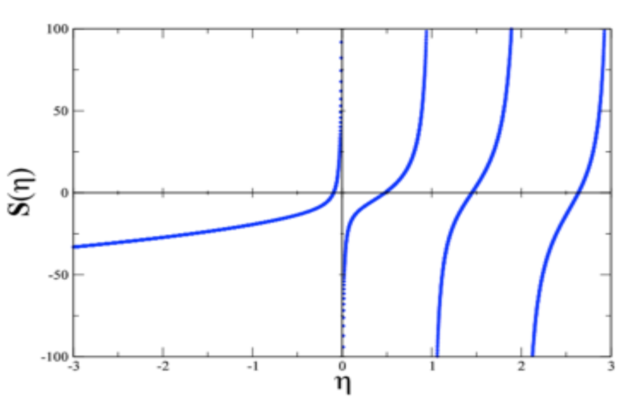
$U_E(r,r')$: assume -> $V(r-r')$ + …

Methods and Difficulties
Correlators



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

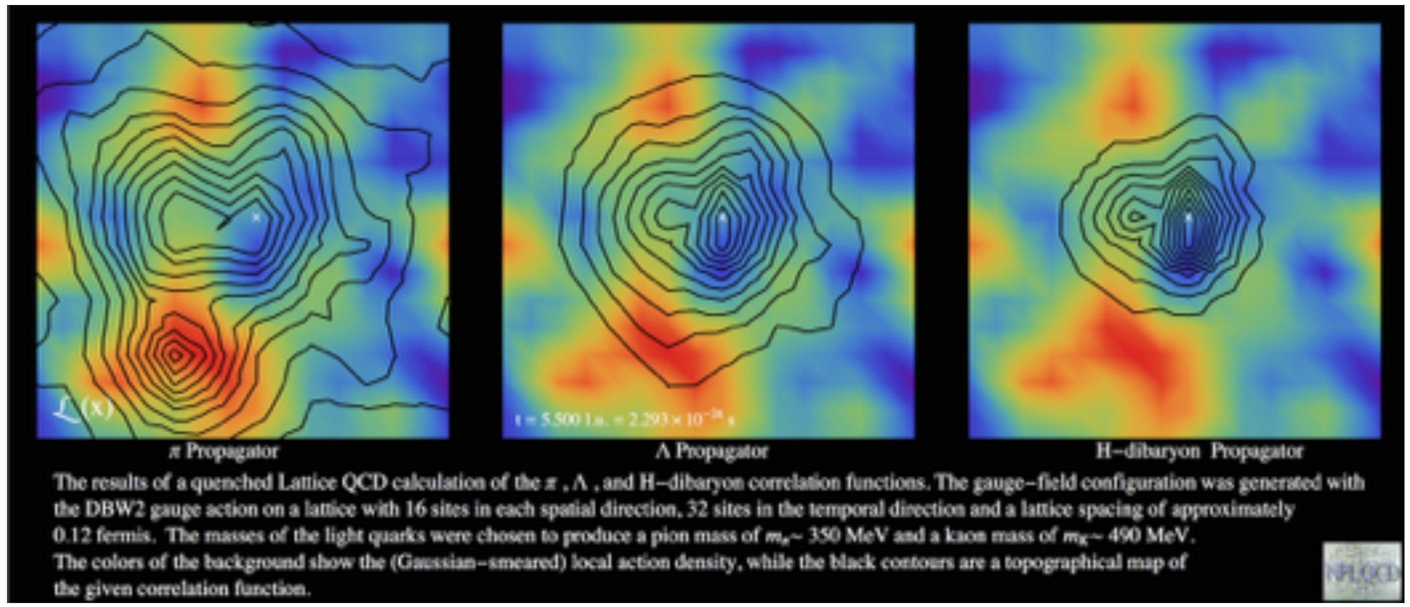




Applicable out to inelastic threshold, then can be extended by including other channels and S-matrix, $k^2 < m_\pi M_N$.

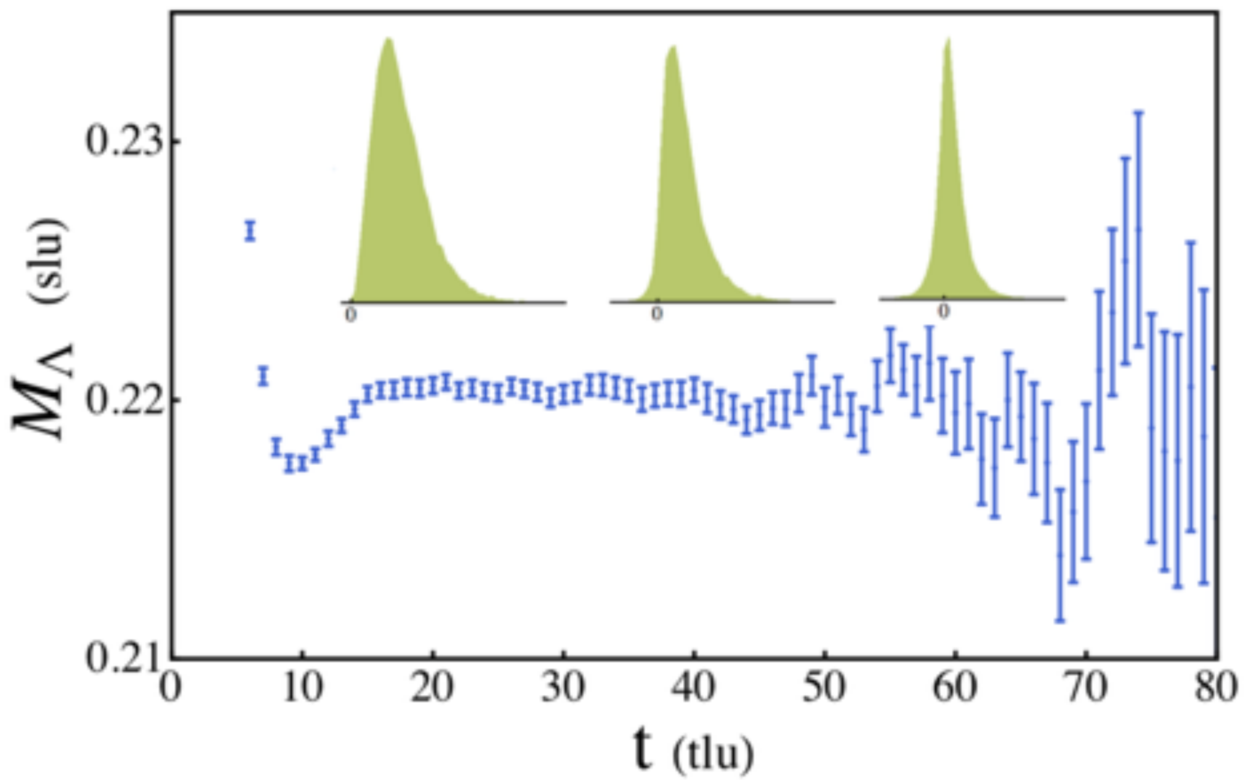
Effective Range Expansion valid below t-channel cut, $k < m_\pi/2$

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



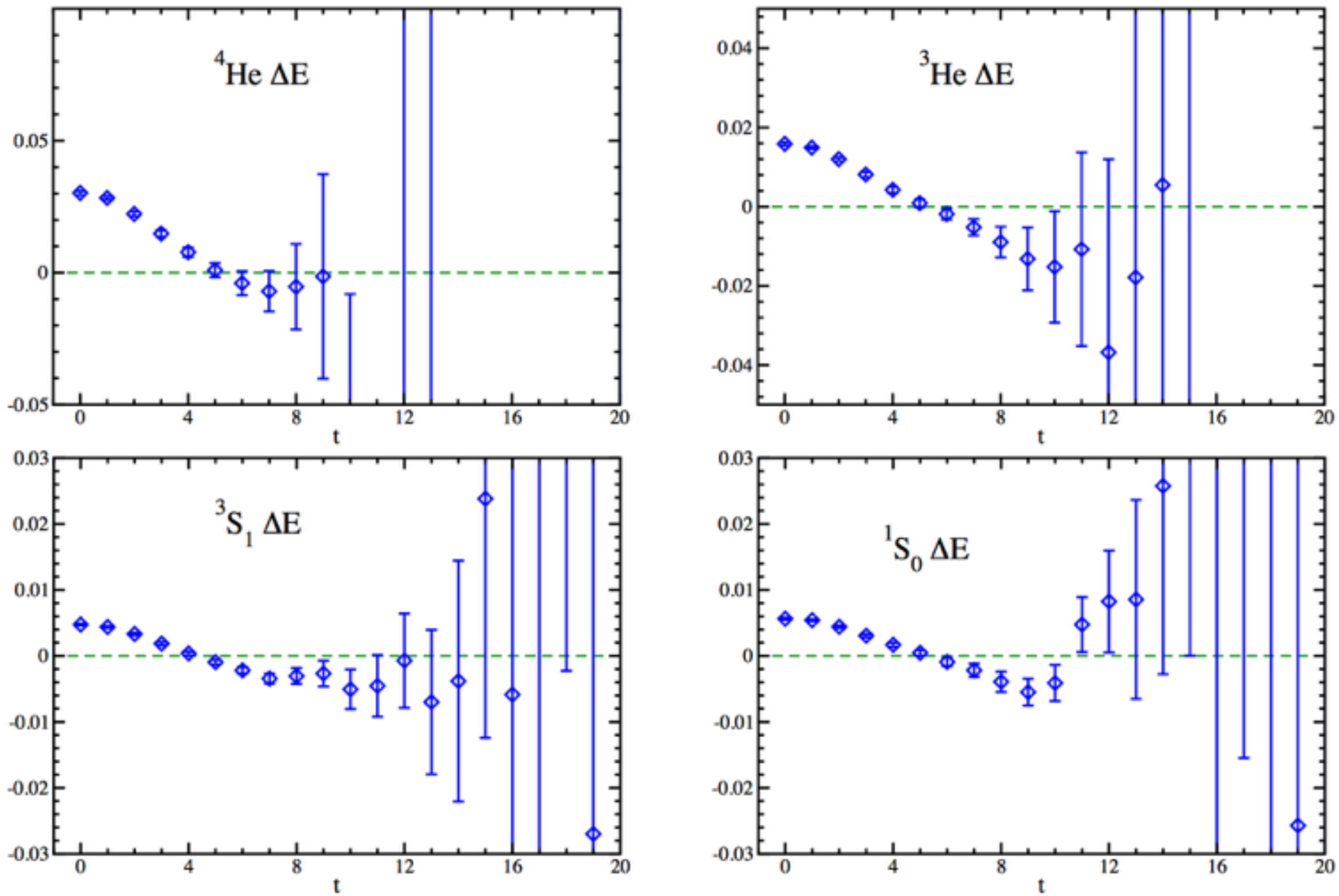
outliers

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

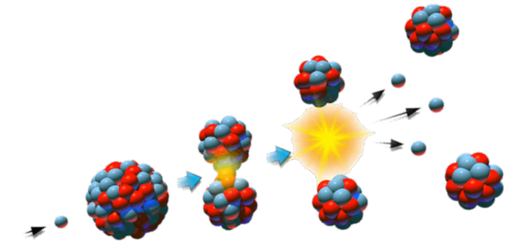
NN and Nuclei
PACS

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



Talk by Takeshi Yamazaki

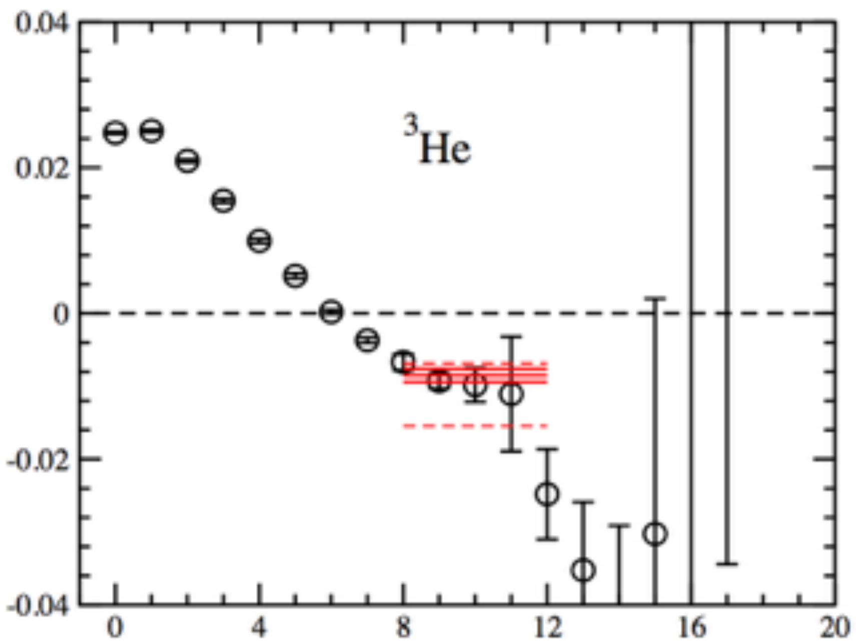
NN and Nuclei
PACS

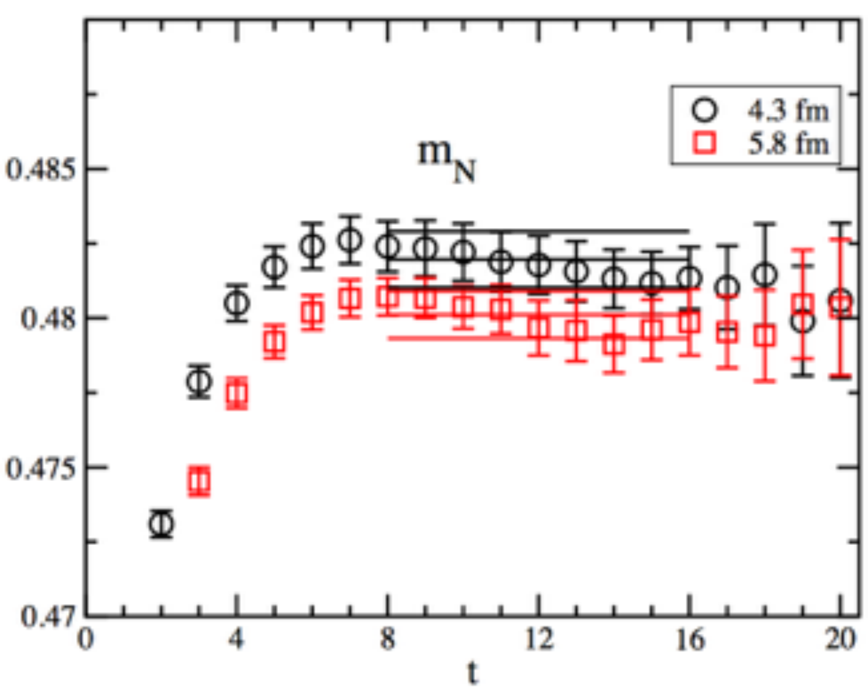


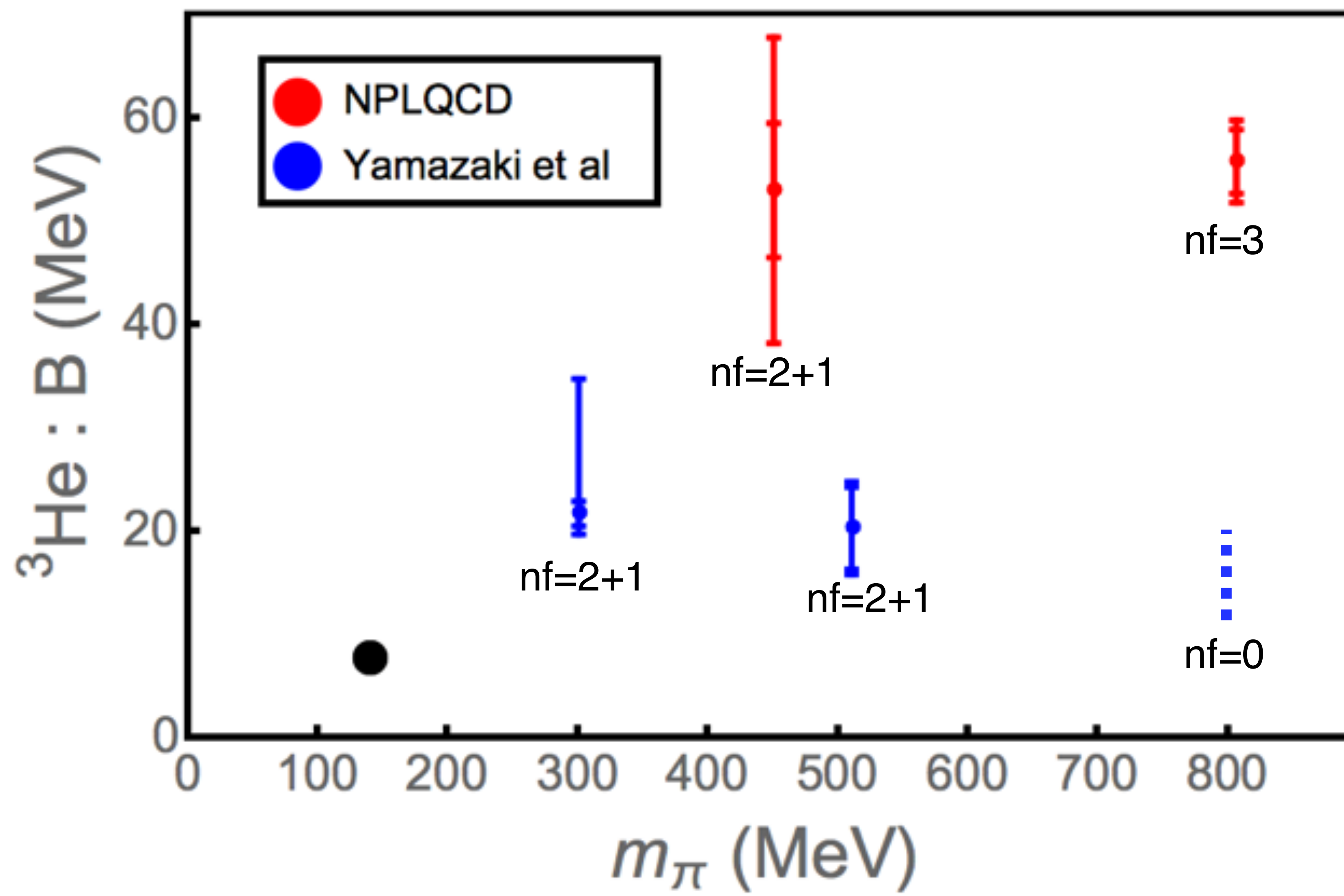
Multi-nucleon focus : nn, d,^{3}He, ^{4}He

m_π ~ 300 MeV

m_π ~ physical in process

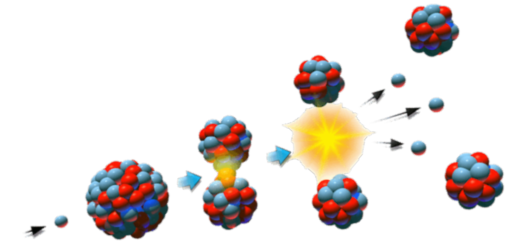


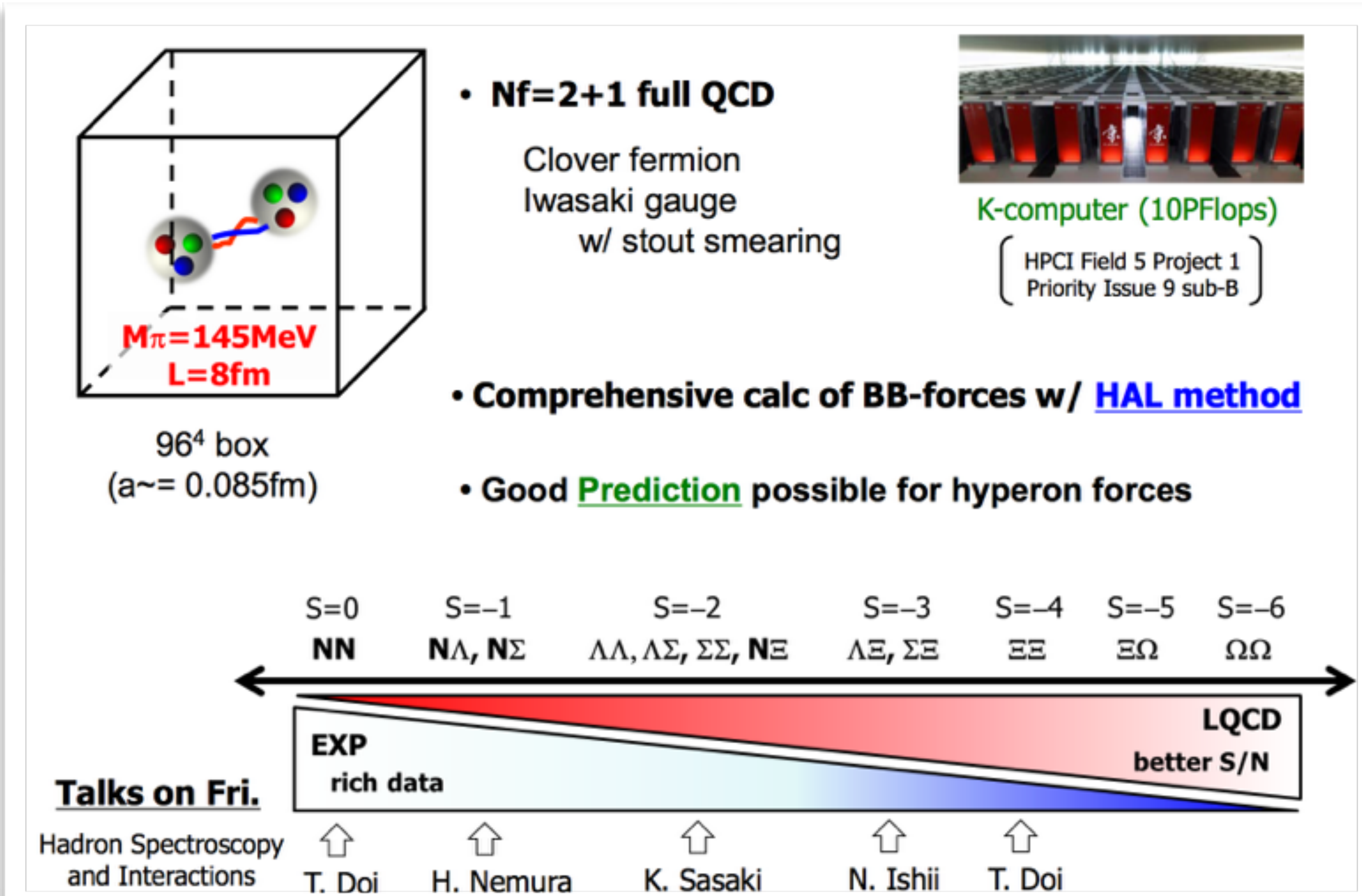




Takeshi Yamazaki, Ken-ichi Ishikawa, Yoshinobu Kuramashi, Akira Ukawa, Phys.Rev. D92 (2015) no.1, 014501

BB Interactions
HAL QCD

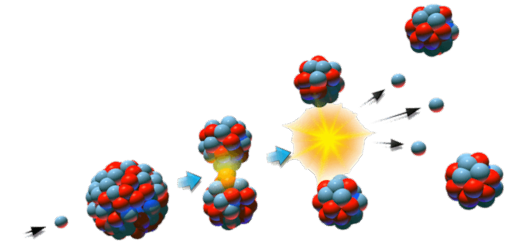


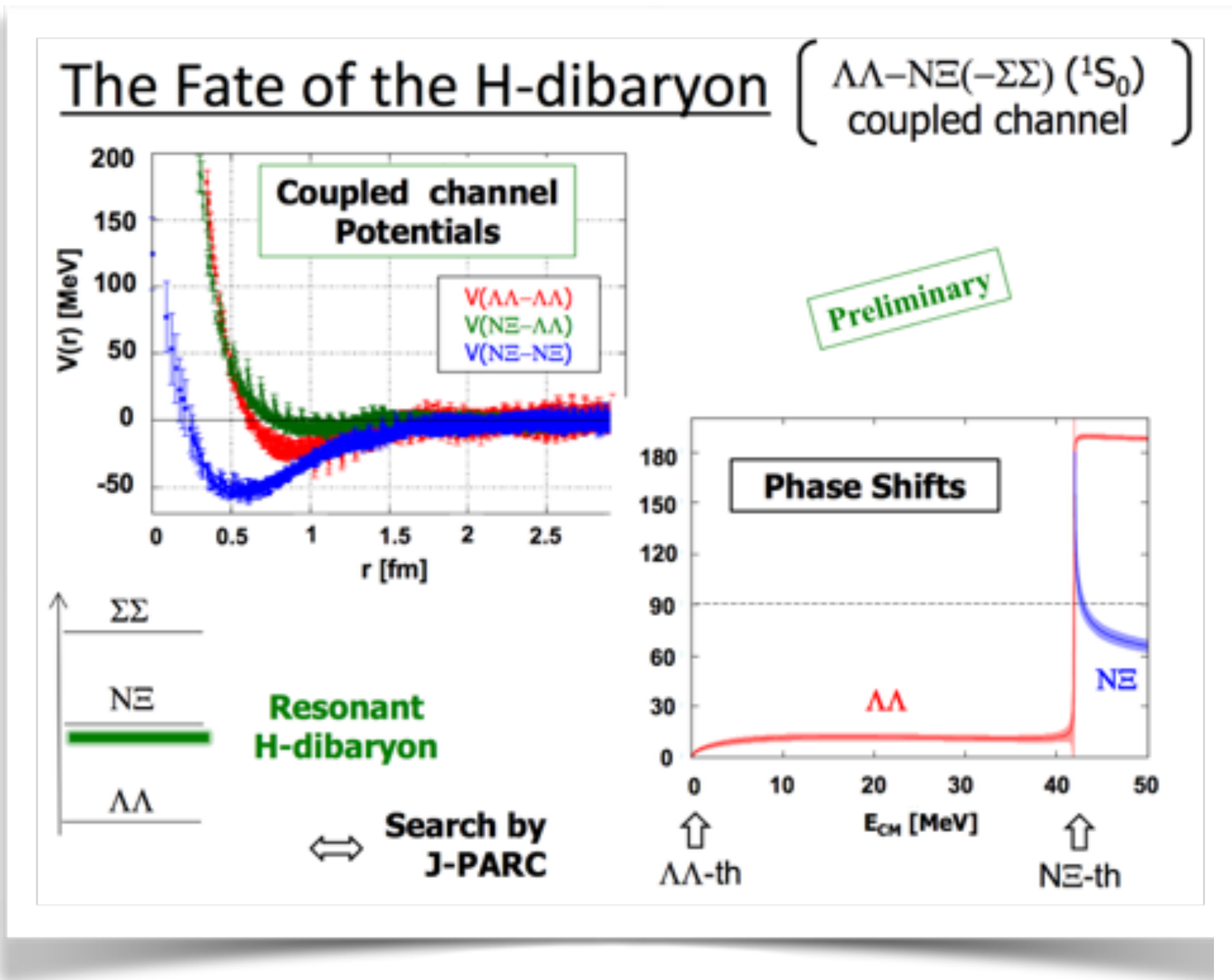


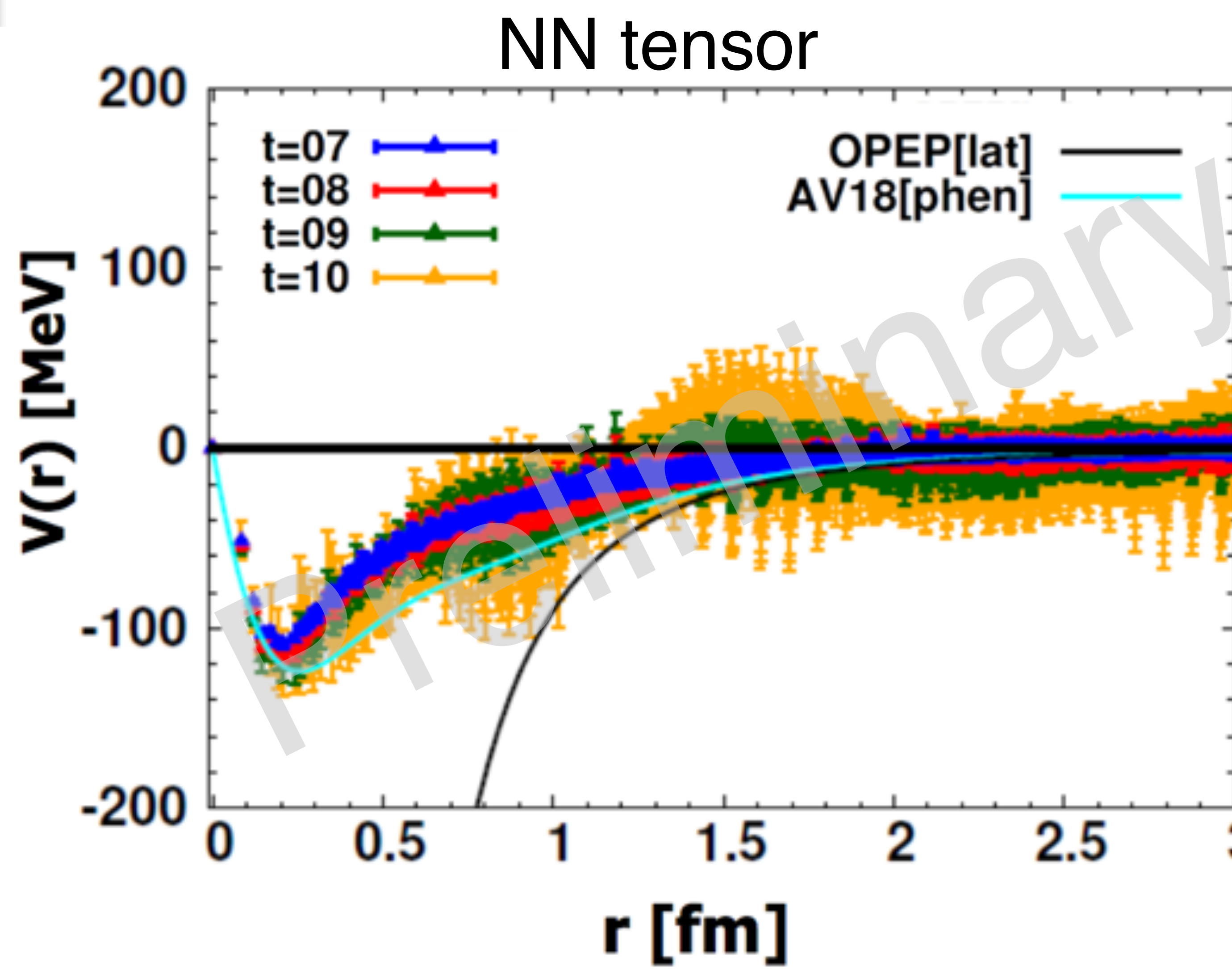
Towards Lattice QCD Baryon Forces at the Physical Point: First Results
Takumi Doi *et al.* (HAL QCD). arXiv:1512.04199 [hep-lat]

Slides prepared by T. Doi - thank you

BB Interactions
HAL QCD

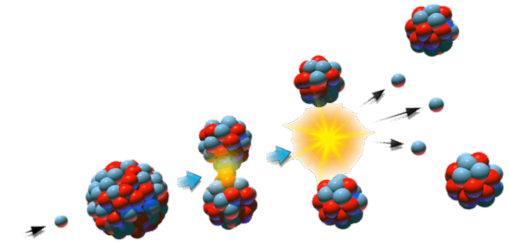






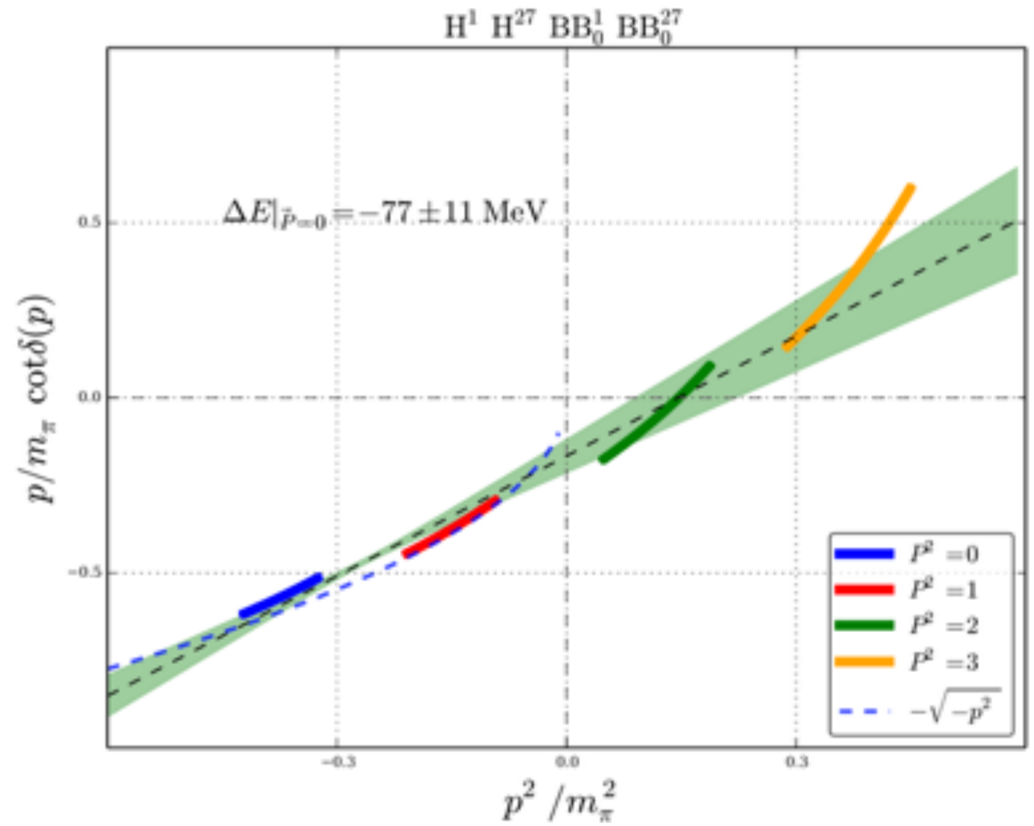
Do not use plateaus in EMPs to extract $U_E(r,r')$

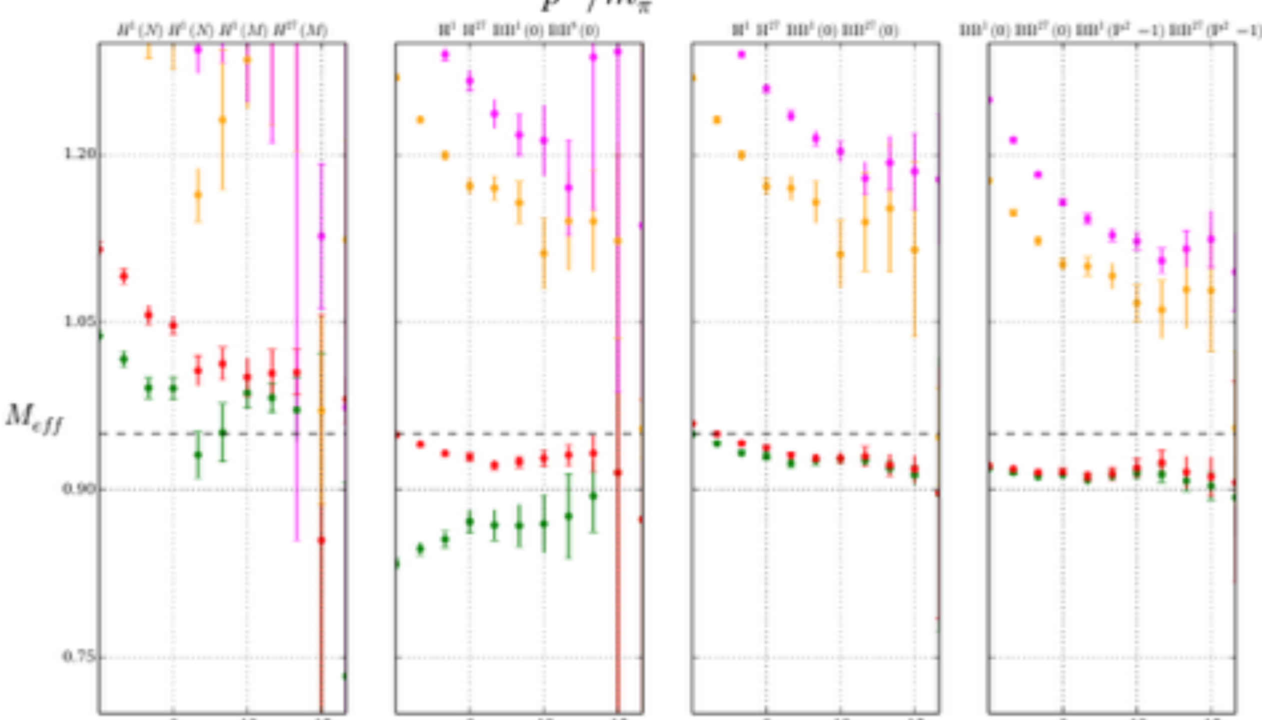
BB Interactions
Mainz

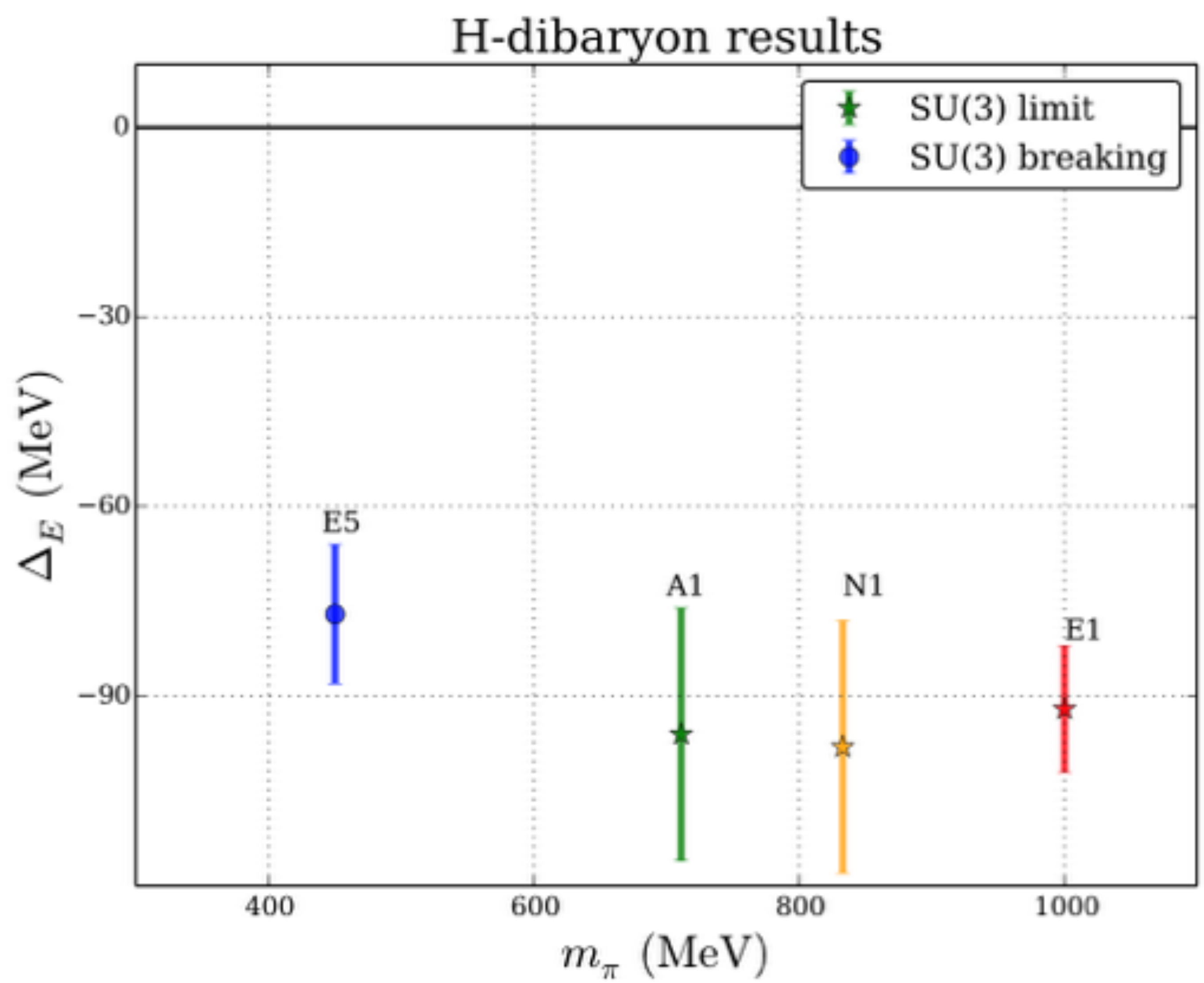


H-dibaryon is focus

4 pion masses

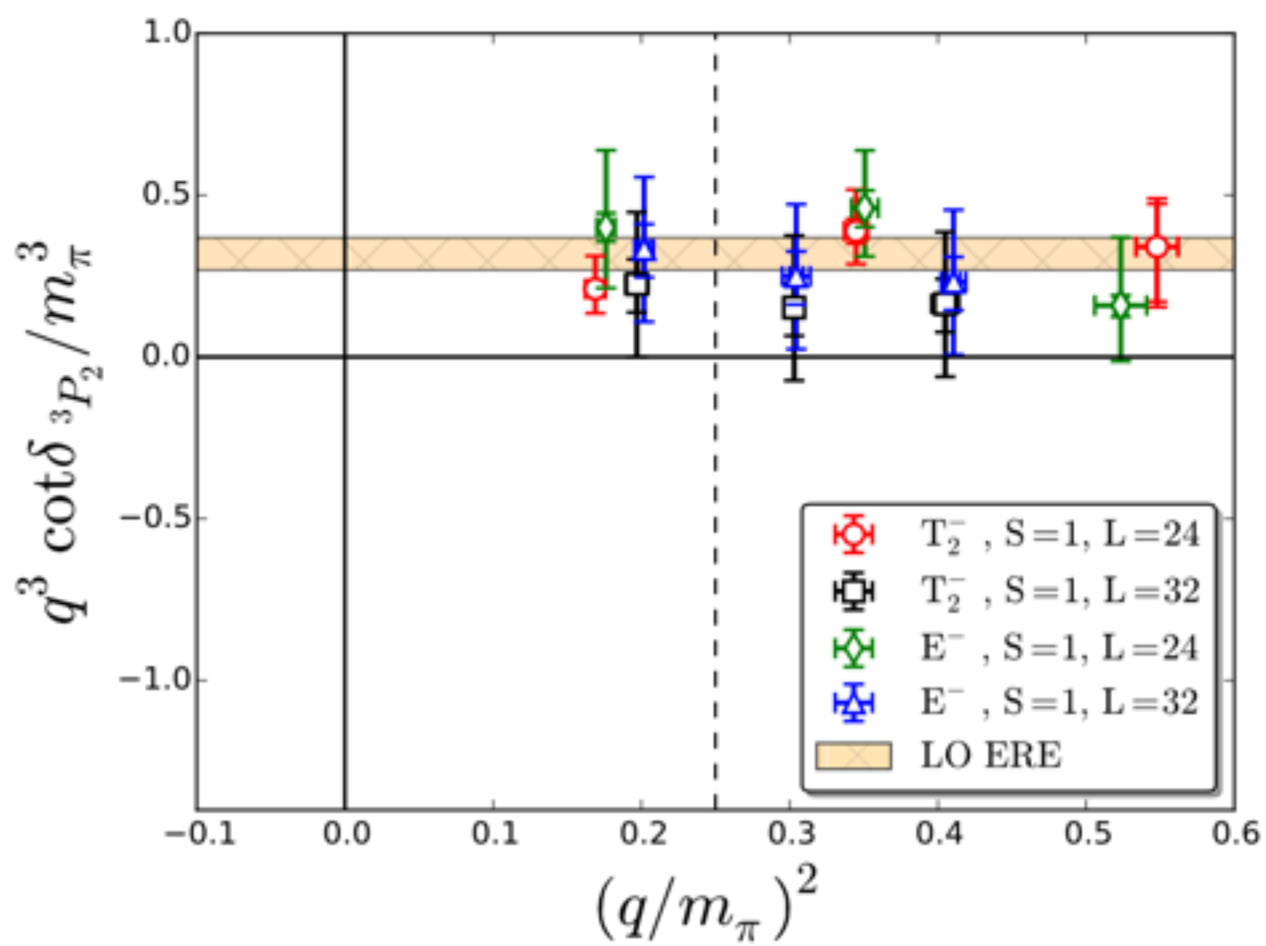


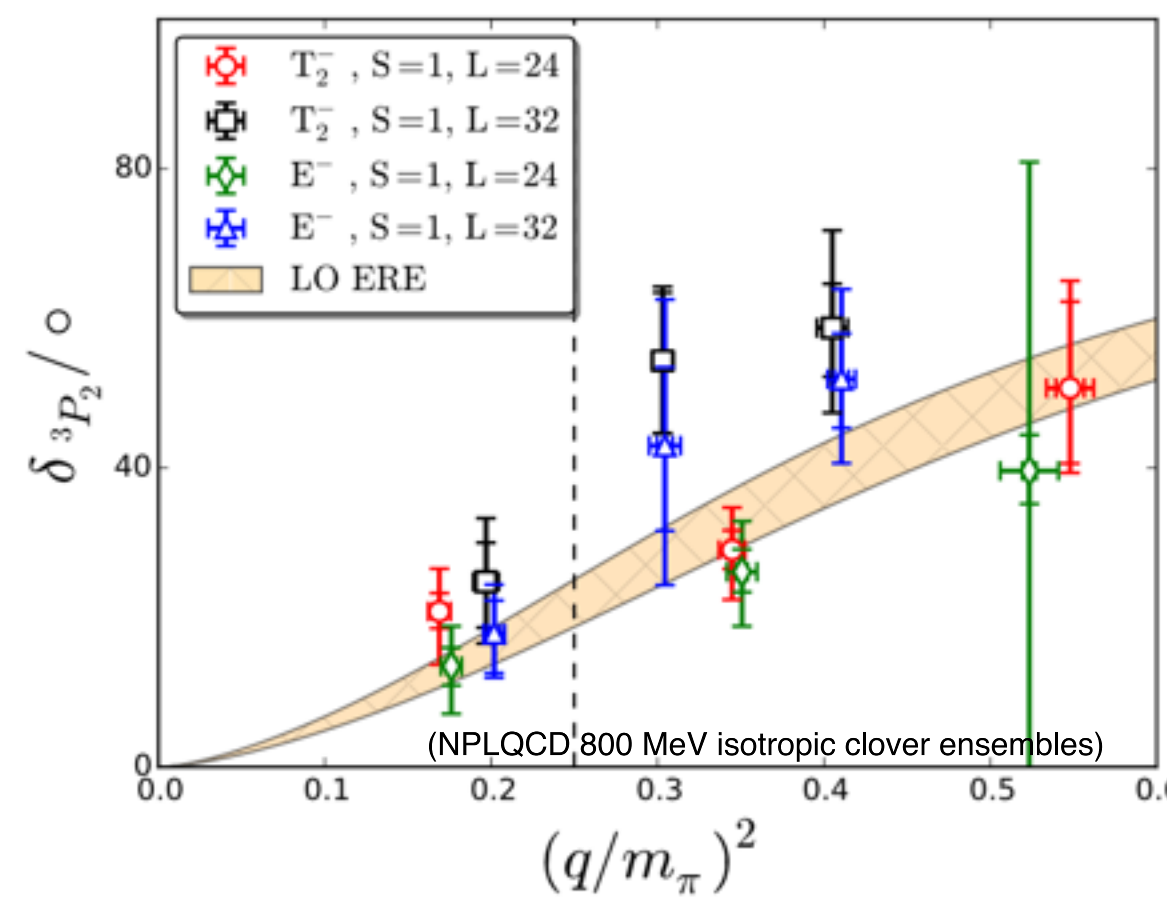




Parikshit Junnarkar, Anthony Francis, Jeremy Green, Chuan Miao, Thomas Rae, Hartmut Wittig, PoS CD15 (2015) 079, PoS LATTICE2015 (2016)

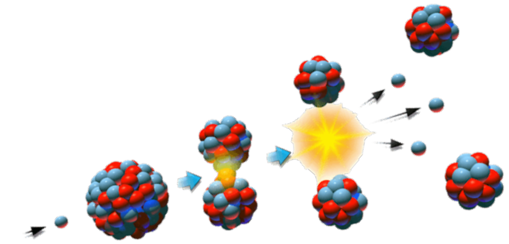
NN Higher Partial Waves

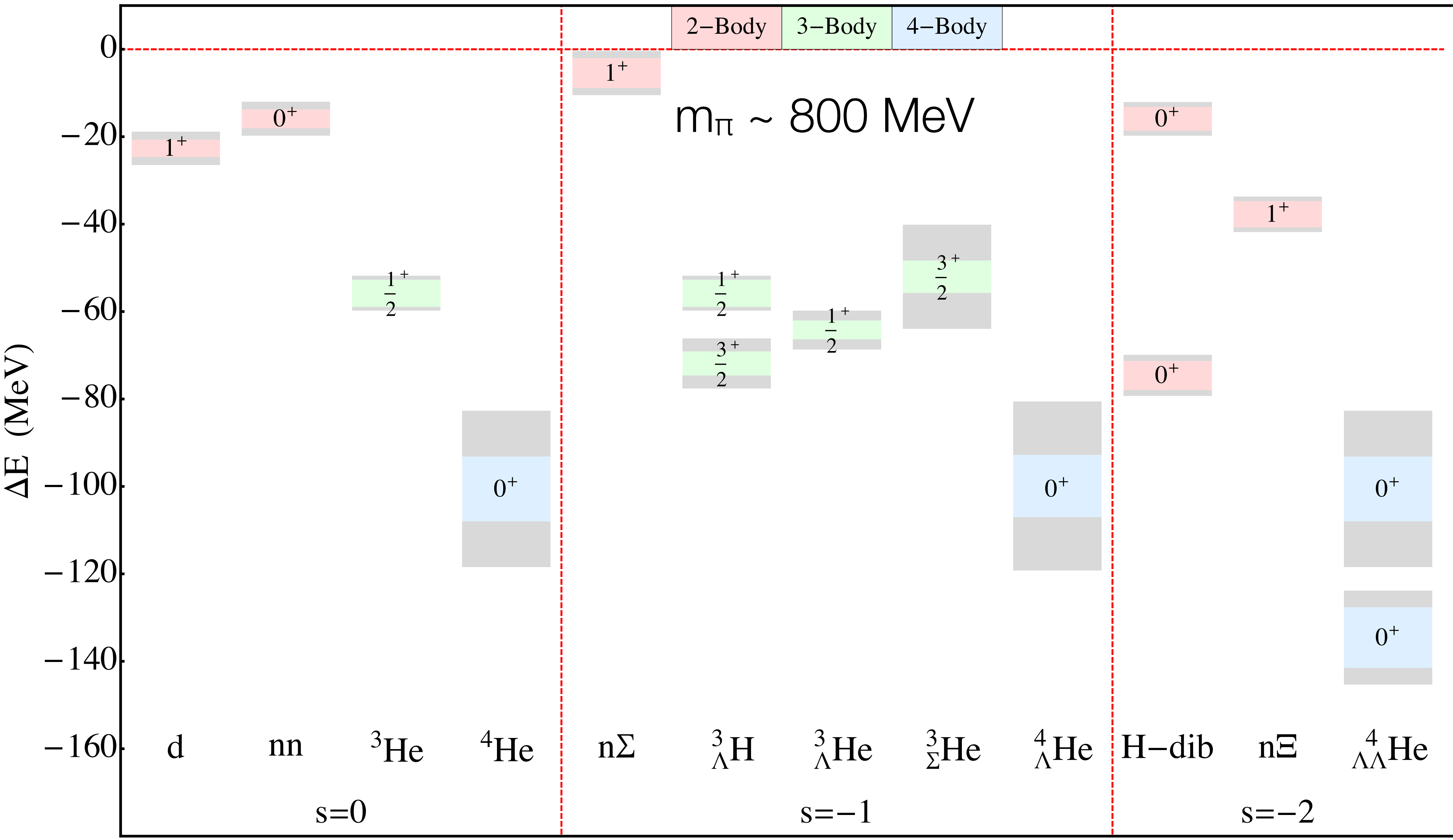




Amy Nicholson *et al* (CalLatt) - PoS LATTICE2015 (2016) 083

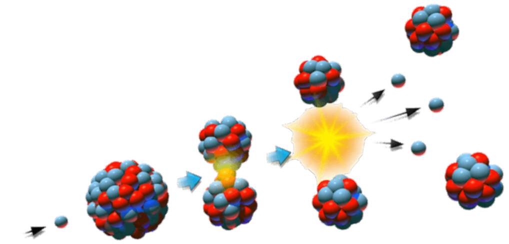
Nuclei from QCD

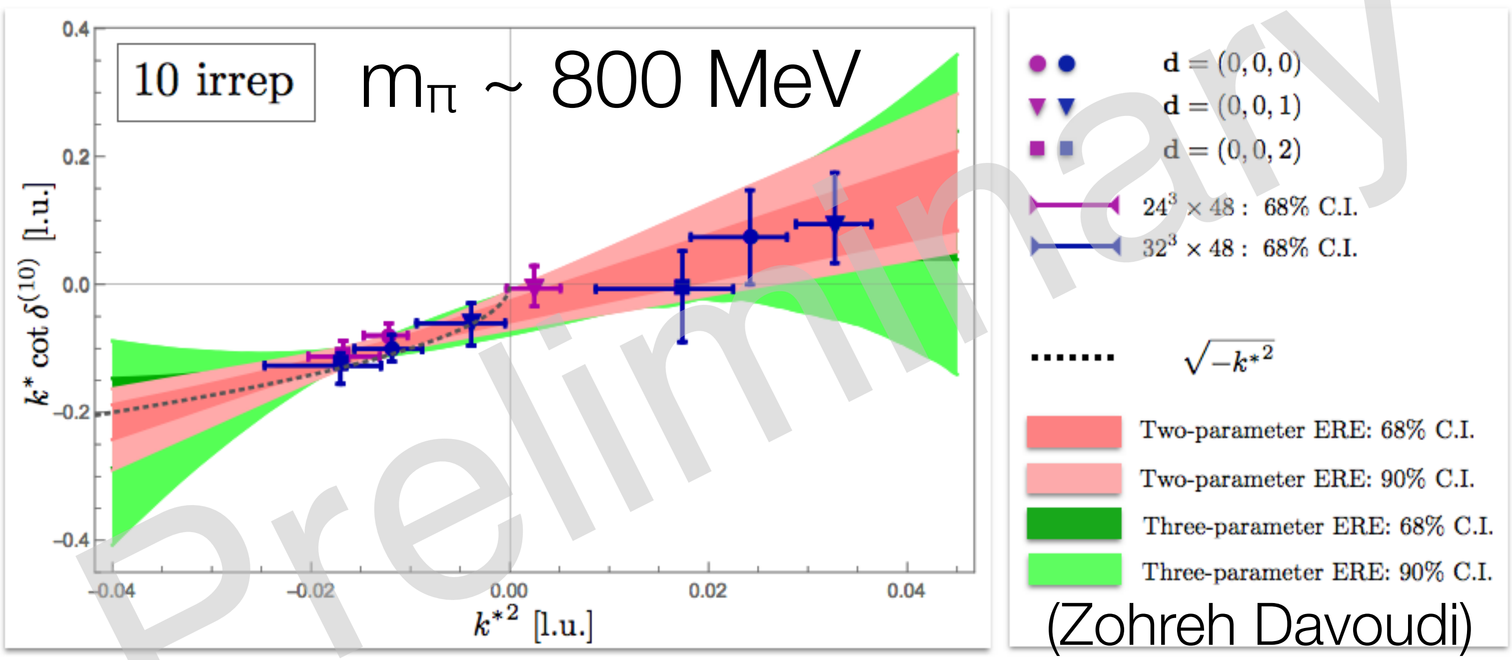


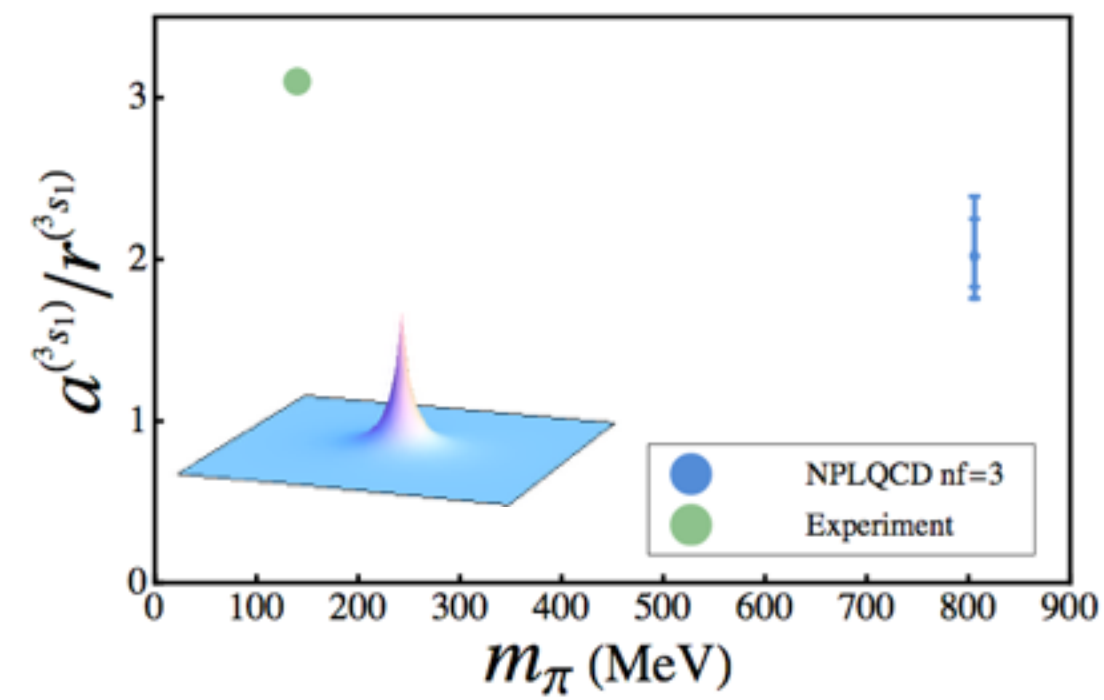


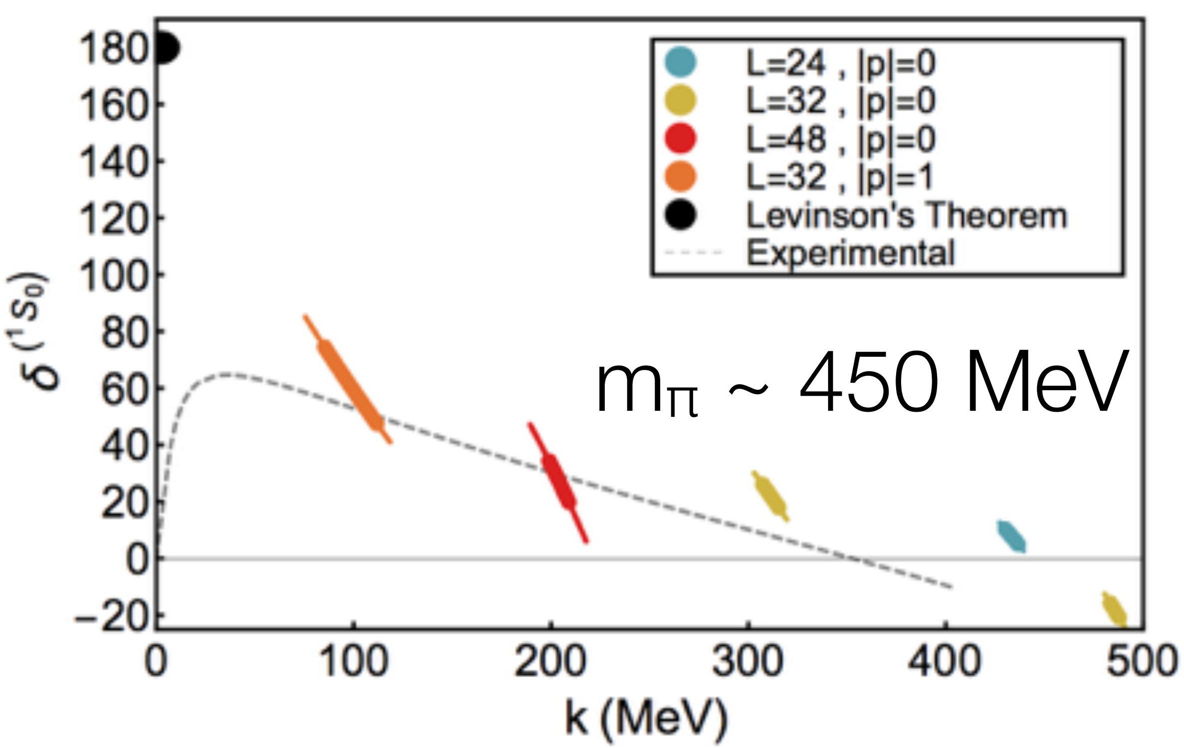
Beane *et al* (NPLQCD), Phys.Rev. D87 (2013) 3, 034506, Phys.Rev. C88 (2013) 2, 024003

NN Interactions
NPLQCD





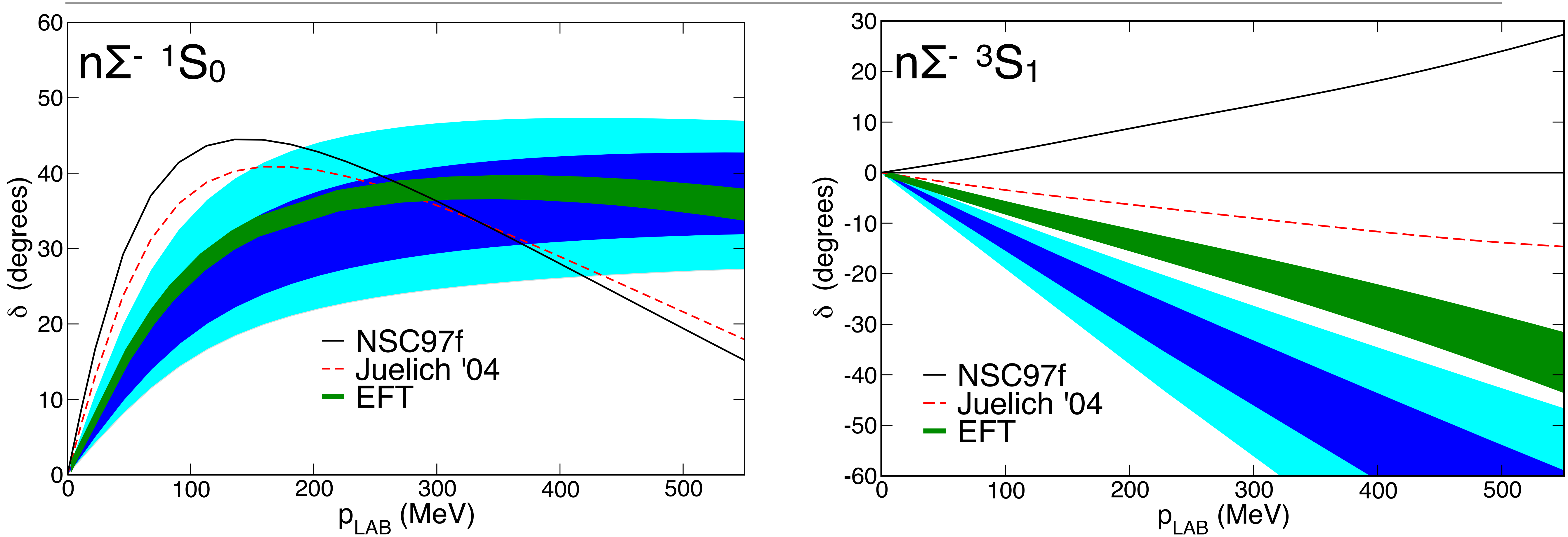




Deuteron appears to be unnatural but not finely-tuned ??

Generic feature of YM with $n_f=3$

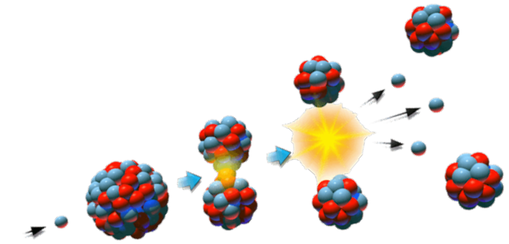
NN Interactions
NPLQCD



- 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

Is there a Plateau Crisis ?



Recently, HAL QCD has suggested that practitioners of Luscher's method have been seduced by false plateaus !

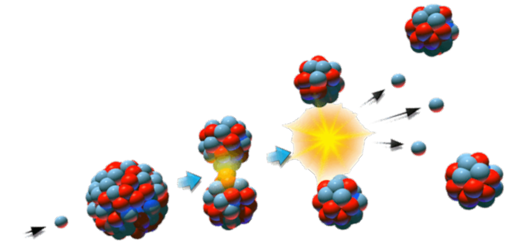
Possible for non-isolated states - will become an increasing problem toward the physical point

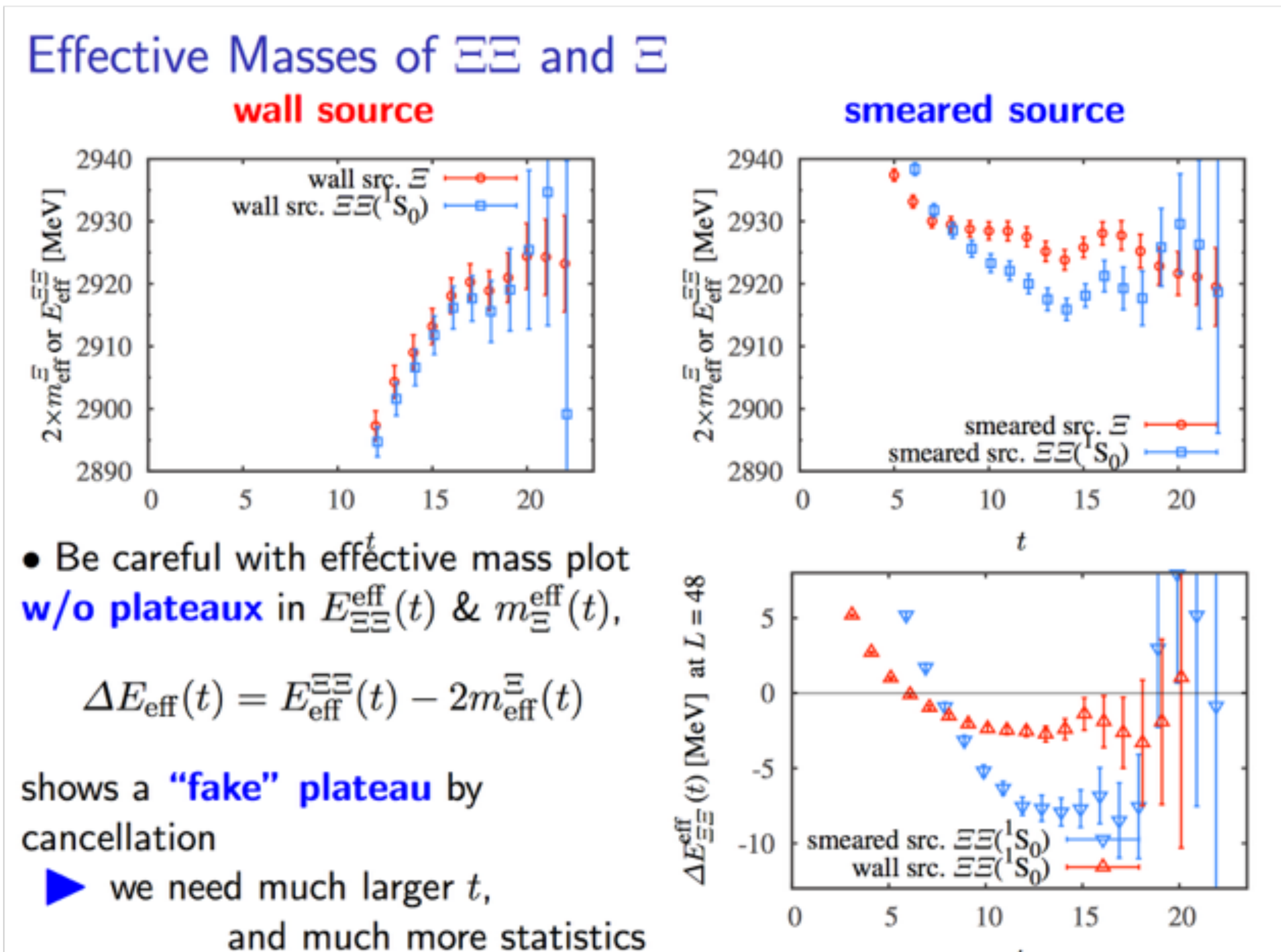
Signal-to-noise problem presents challenge for establishing ground states

HAL QCD and PACS have performed tests with Wall-sources and localized sources.

e.g.,
Mirage in Temporal Correlation functions for Baryon-Baryon Interactions in Lattice QCD, **Takumi Iritani *et al.*. arXiv:1607.06371**

Is there a Plateau Crisis ?





Slide prepared by Iritiani of HAL QCD - thank you. [Aoki, Doi]

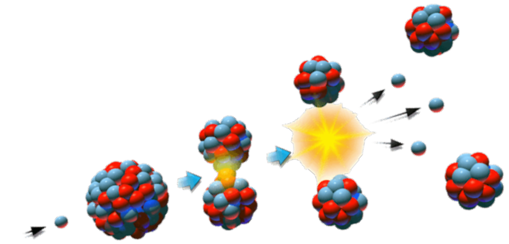
Slides from Yamazaki on their careful comparisons - thank you.

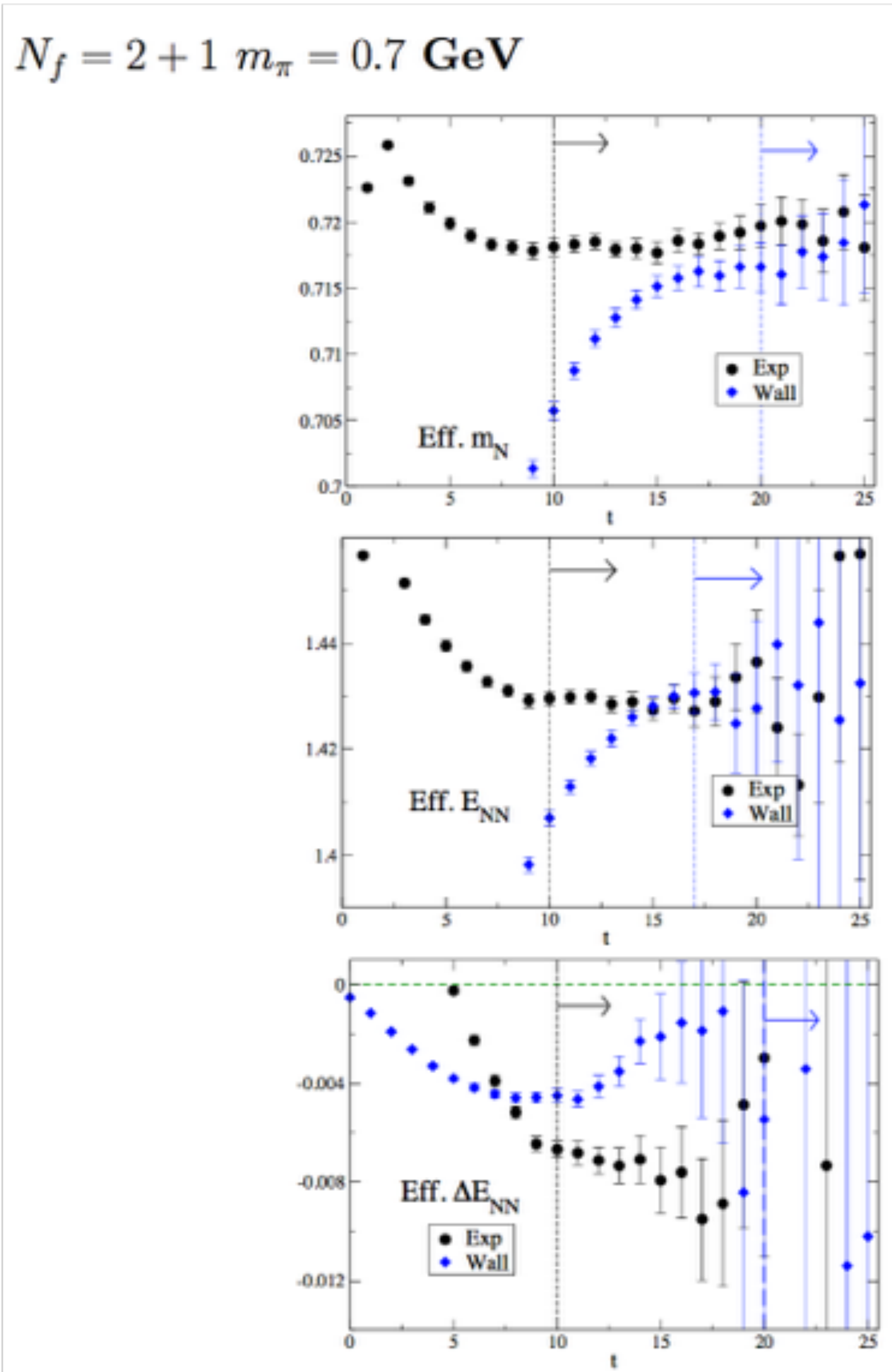
Needs much higher statistics in this study

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.

LATTICE 2016

Is there a Plateau Crisis ?





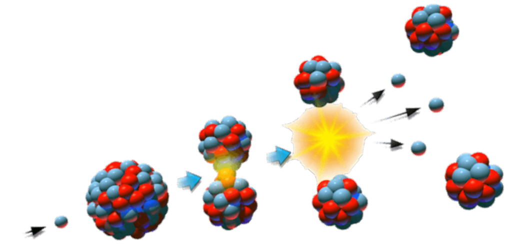
PACS : Yamazaki et al (2016)

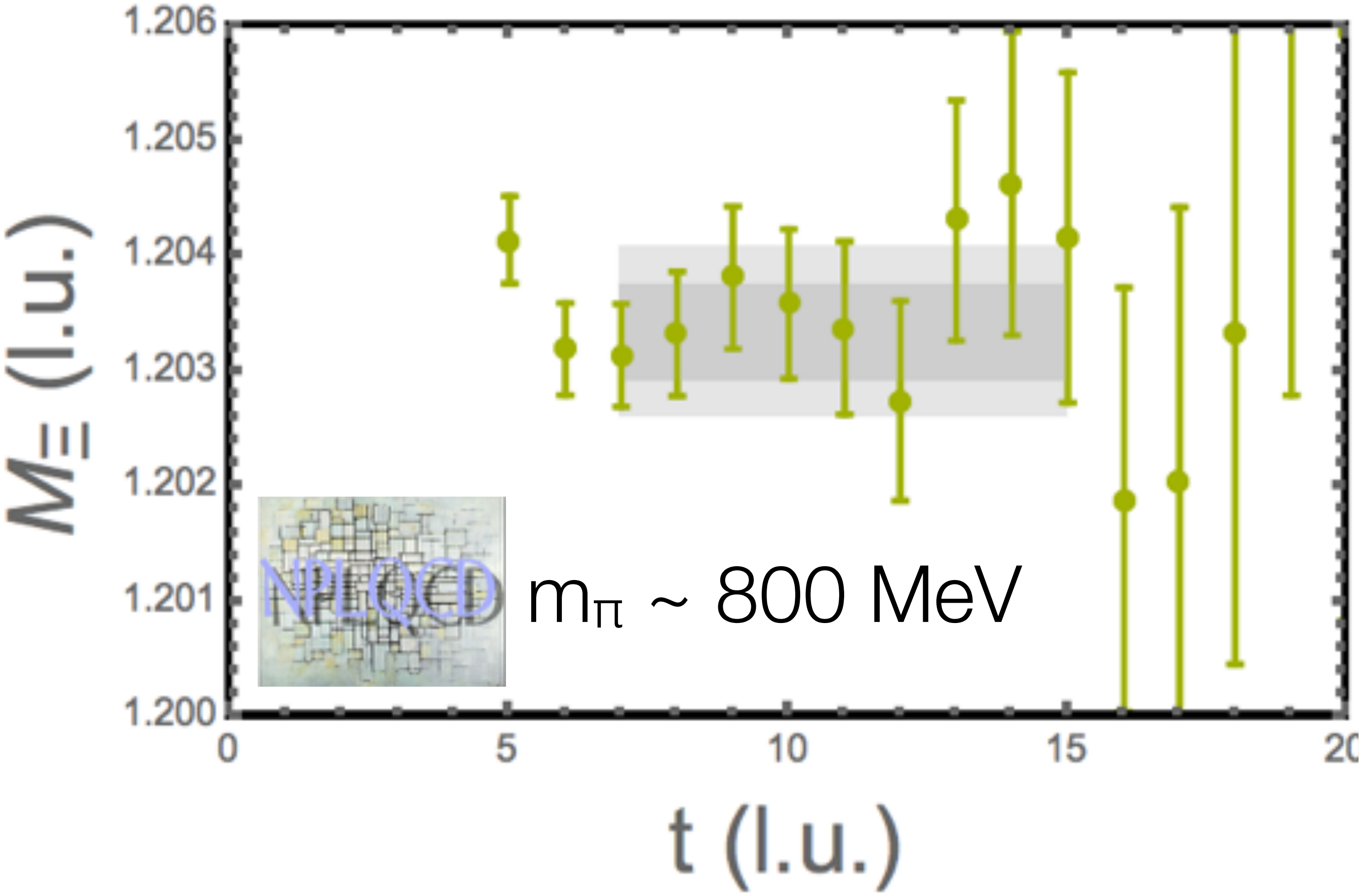
Slide prepared by Yamasaki of PACS-CS - thank you.

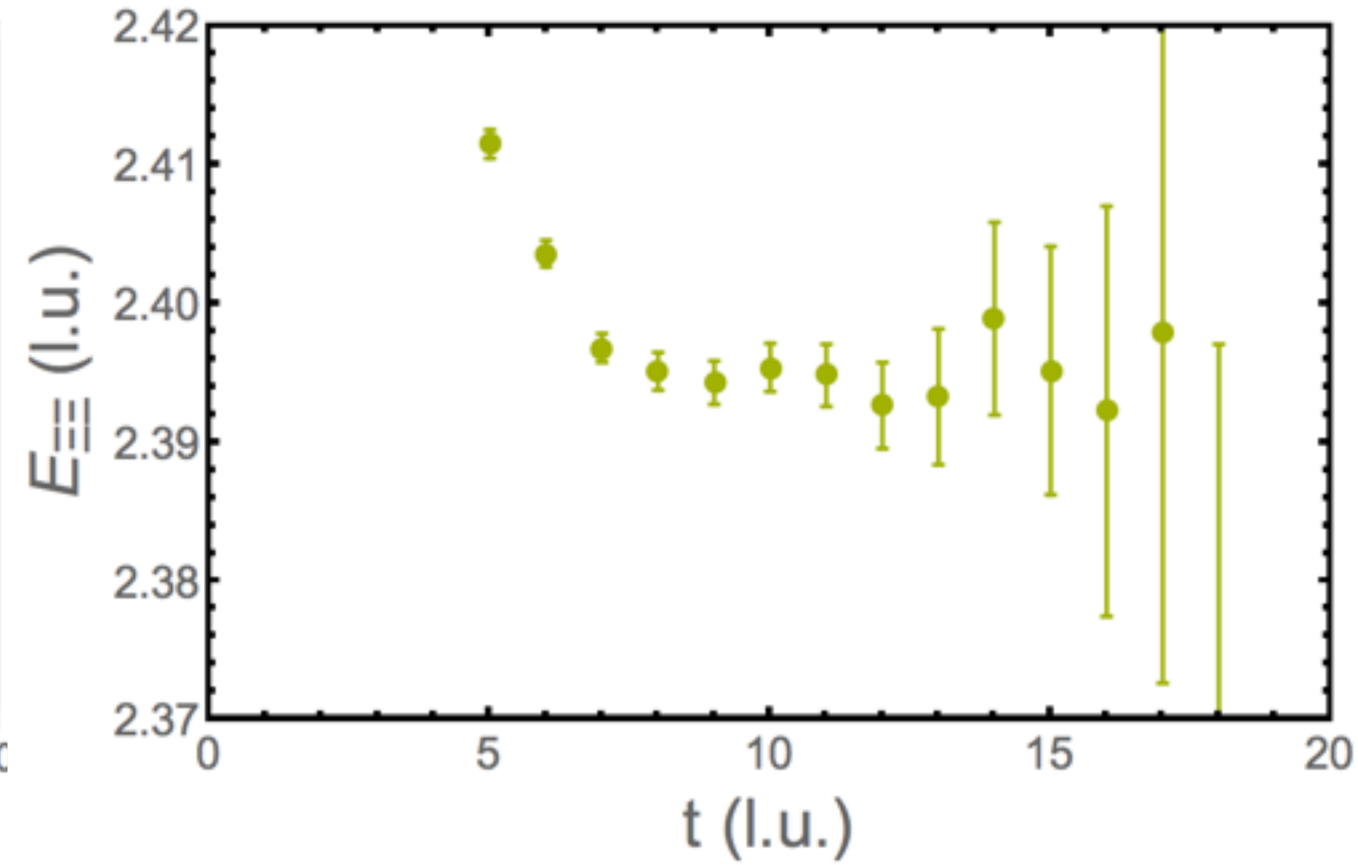
Observations:

- the Smeared Source plateaus earlier than the Wall
- when the Wall eventually plateaus, they are consistent

Is there a Plateau Crisis ?





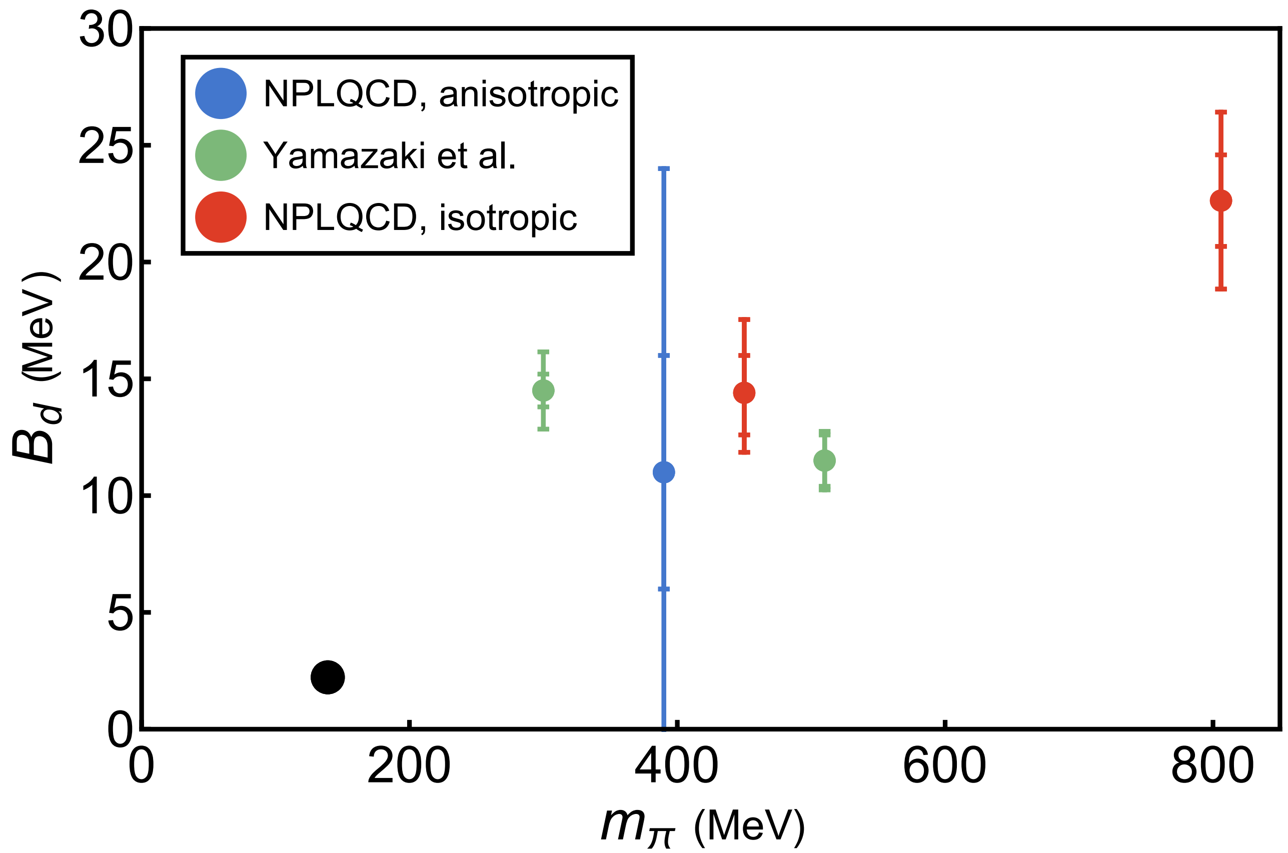


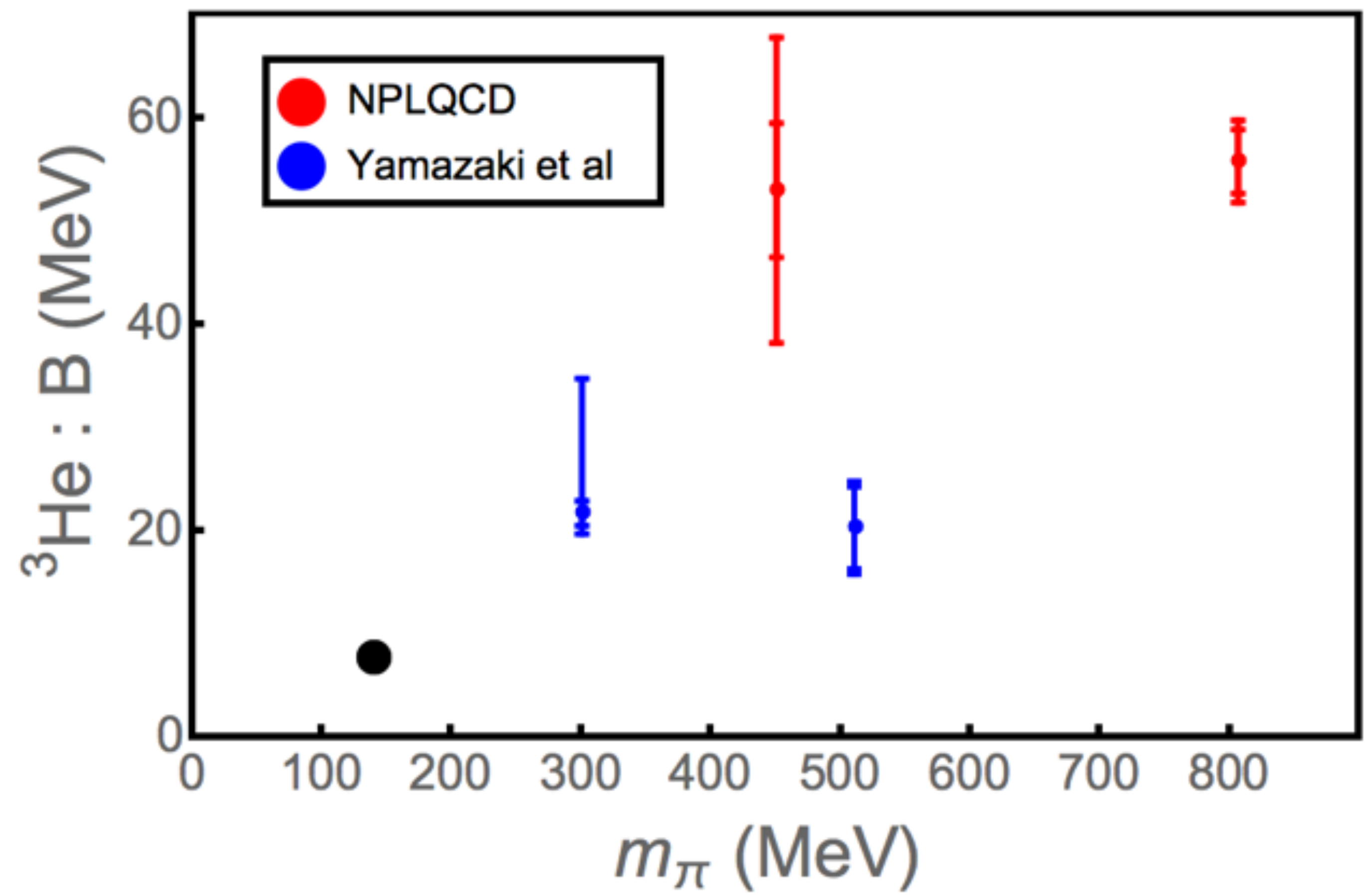
Light Nuclei and Hypernuclei from Quantum Chromodynamics in the Limit of SU(3) Flavor Symmetry
NPLQCD Collaboration, Phys.Rev. D87 (2013) no.3, 034506

Thoughts:

- Wall-Sources are not great for these calcs.
- Publications could show all involved correlators for clarity

Light Nuclei : Quark Mass Effects

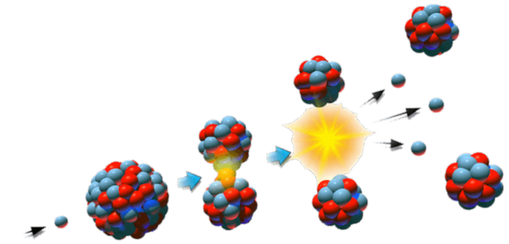


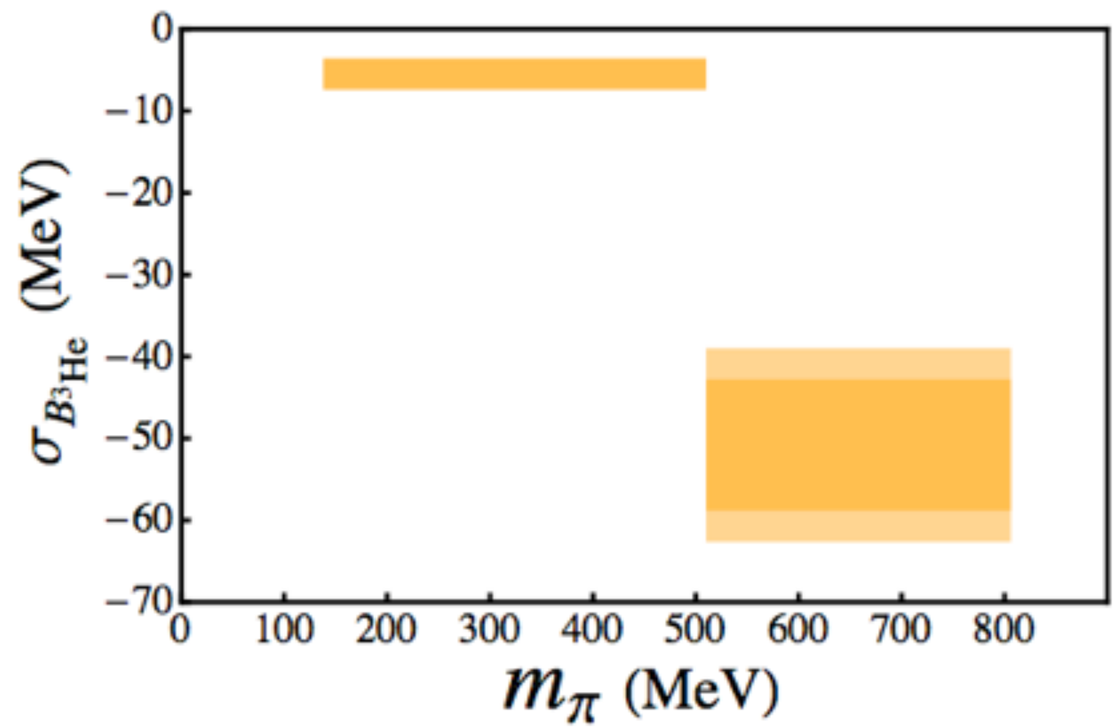


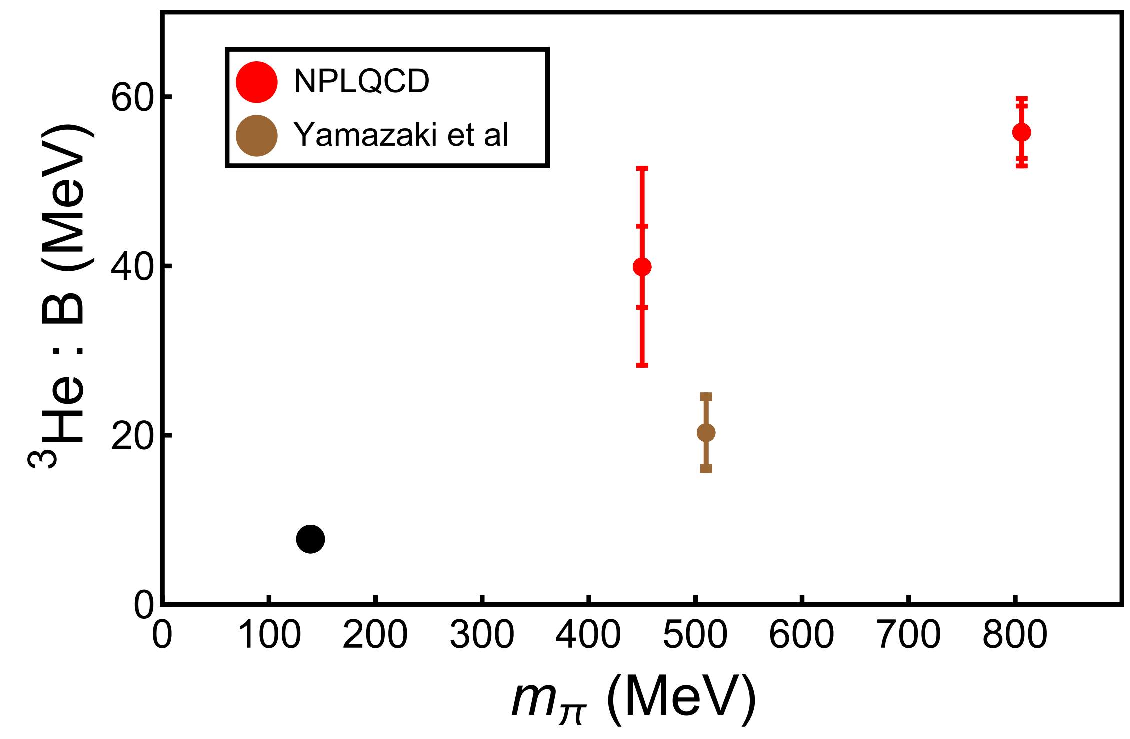
Note:

- HAL QCD's method does not yield bound states.
  - Would like to see results near the physical point and understand the quark mass dependence

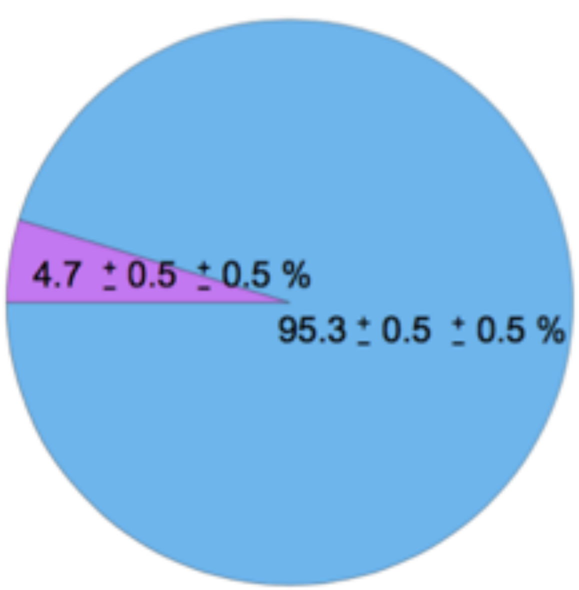
Decomposition of Nuclear Masses and Bindings



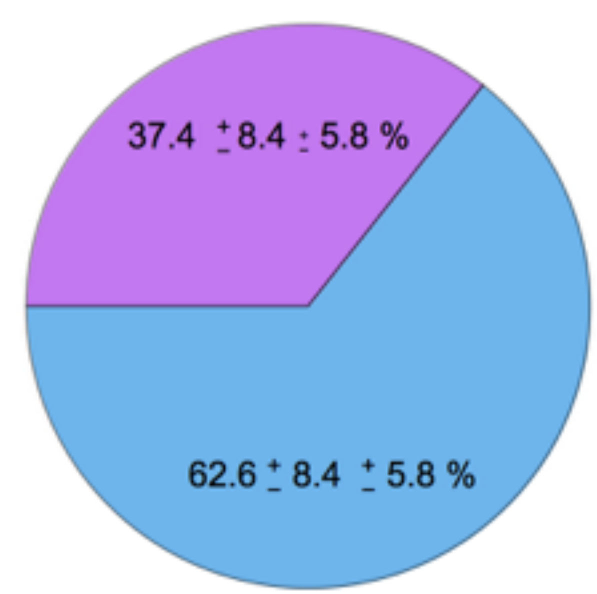




Nucleon Mass



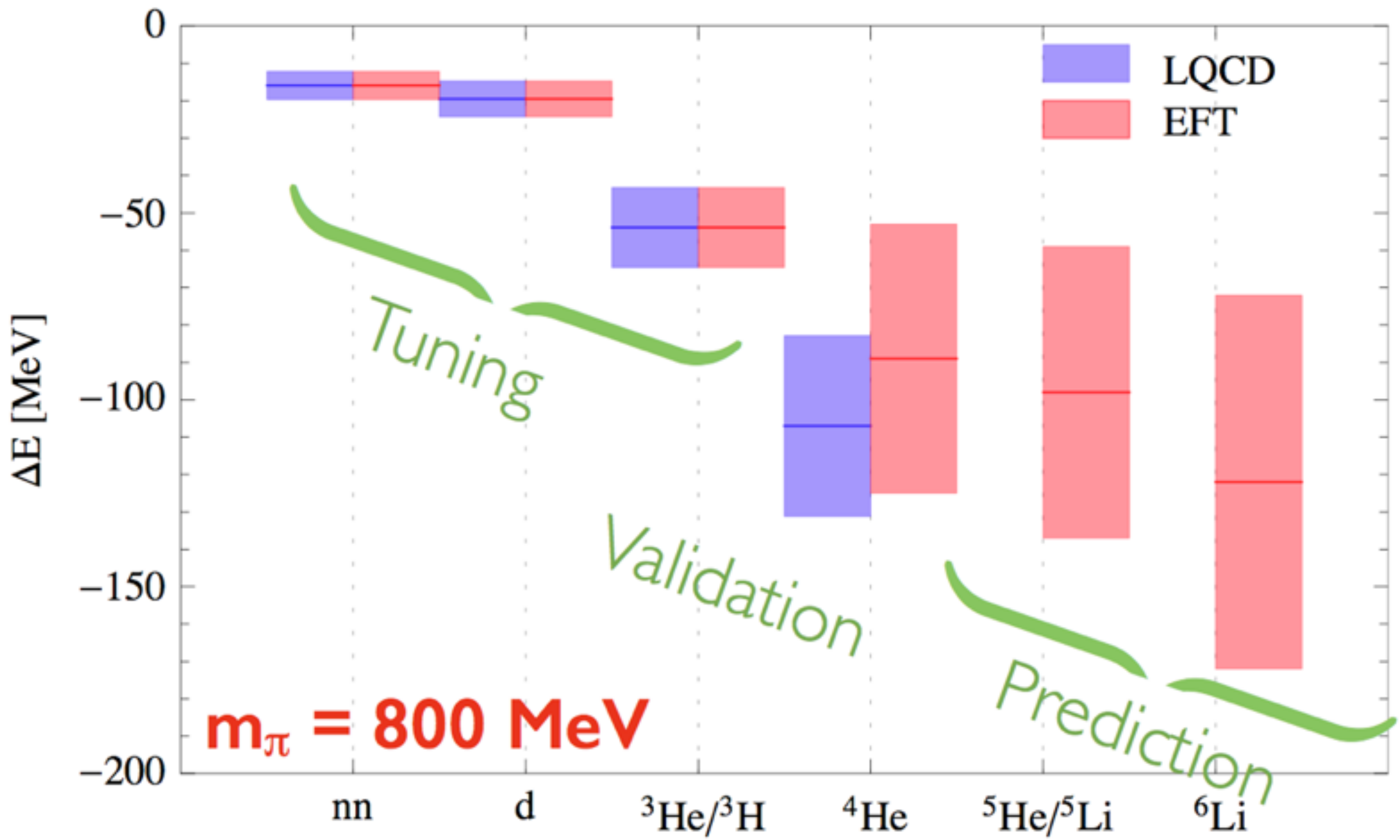
Binding ^{3}He (m_π=450 MeV)



Dictates a Class Dark Matter Interactions

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

The Periodic Table as a function of the quark masses

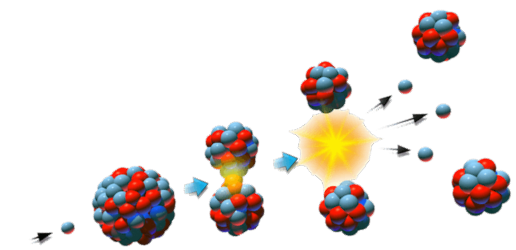


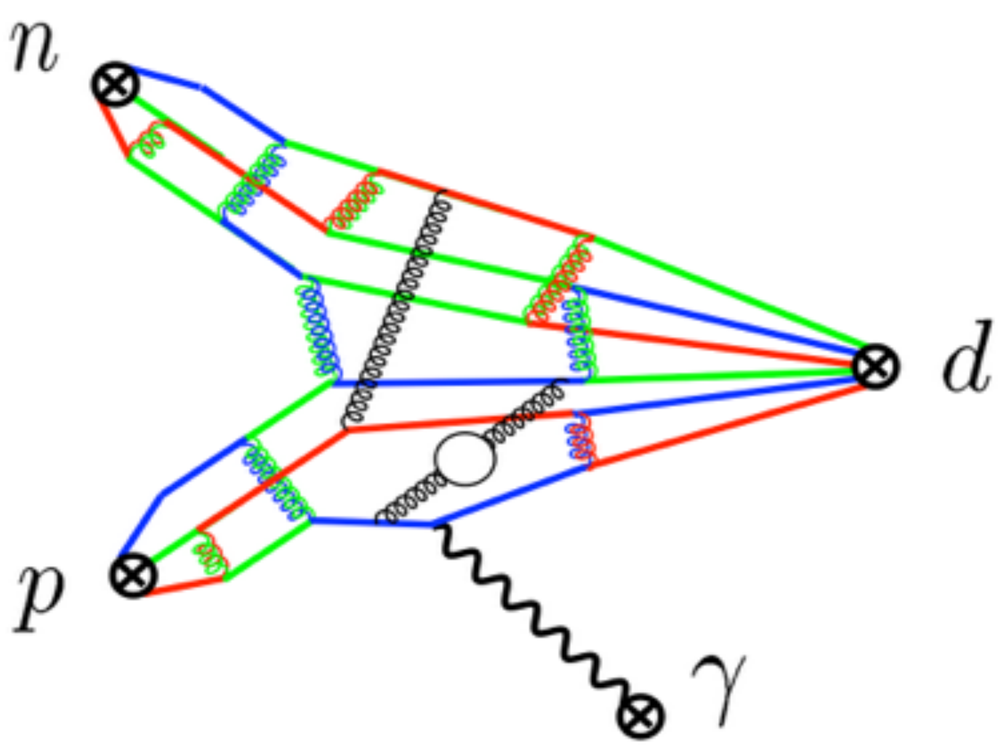
Enhances the scope of the Lattice Calculations

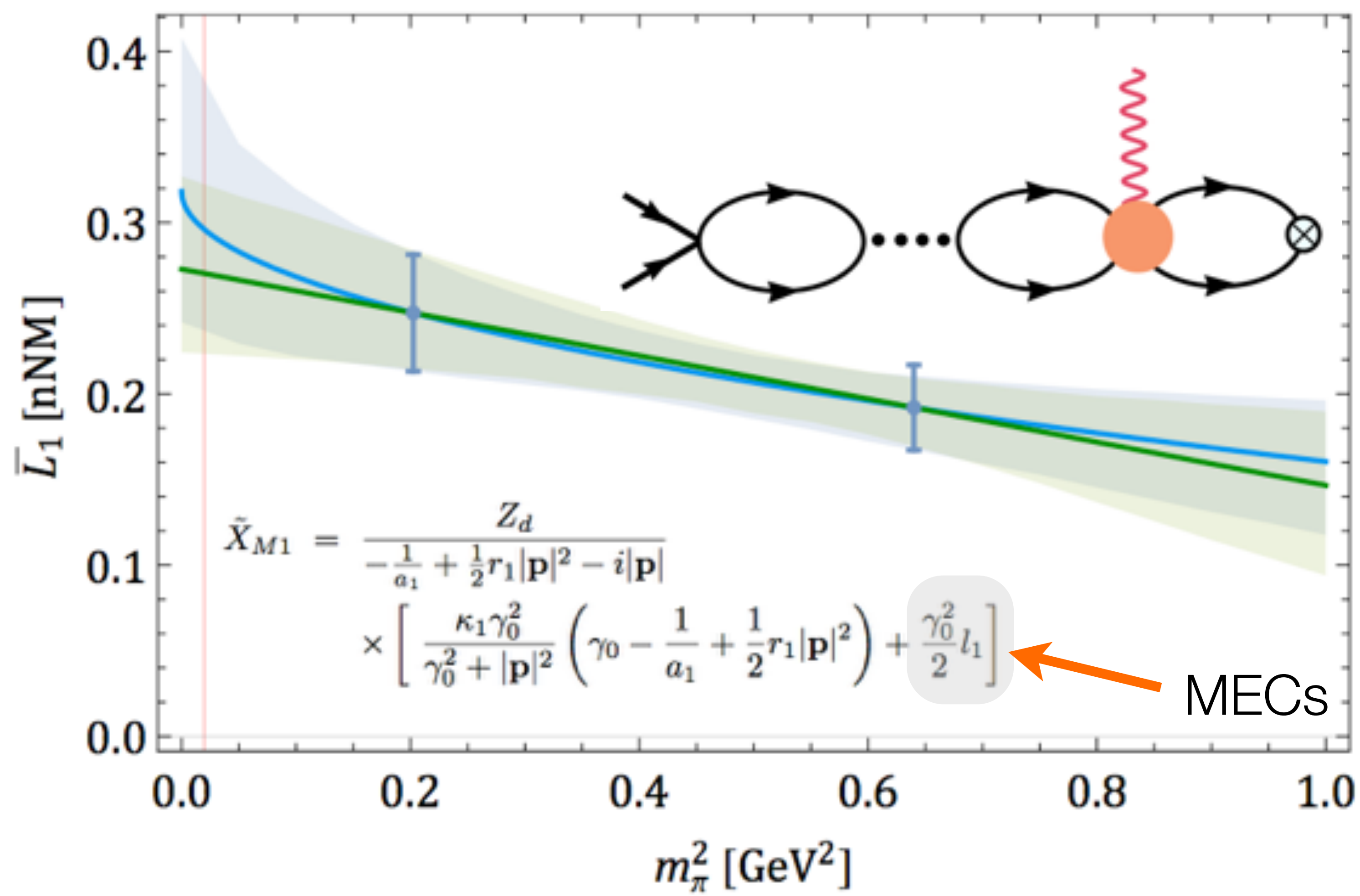
Effective Field Theory for Lattice Nuclei , N. Barnea et al, Nov 20, 2013. 5 pp. , Phys. Rev. Lett. 114 (2015) 5, 052501

First Inelastic Nuclear Reaction :

$$np \to d\gamma$$







physical point:

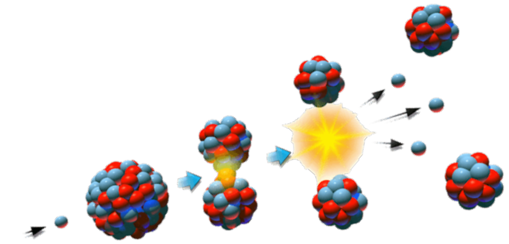
σ^{LQCD} = 334.9(5.3) mb $\quad v = 2,200\ \mathrm{m/s}$

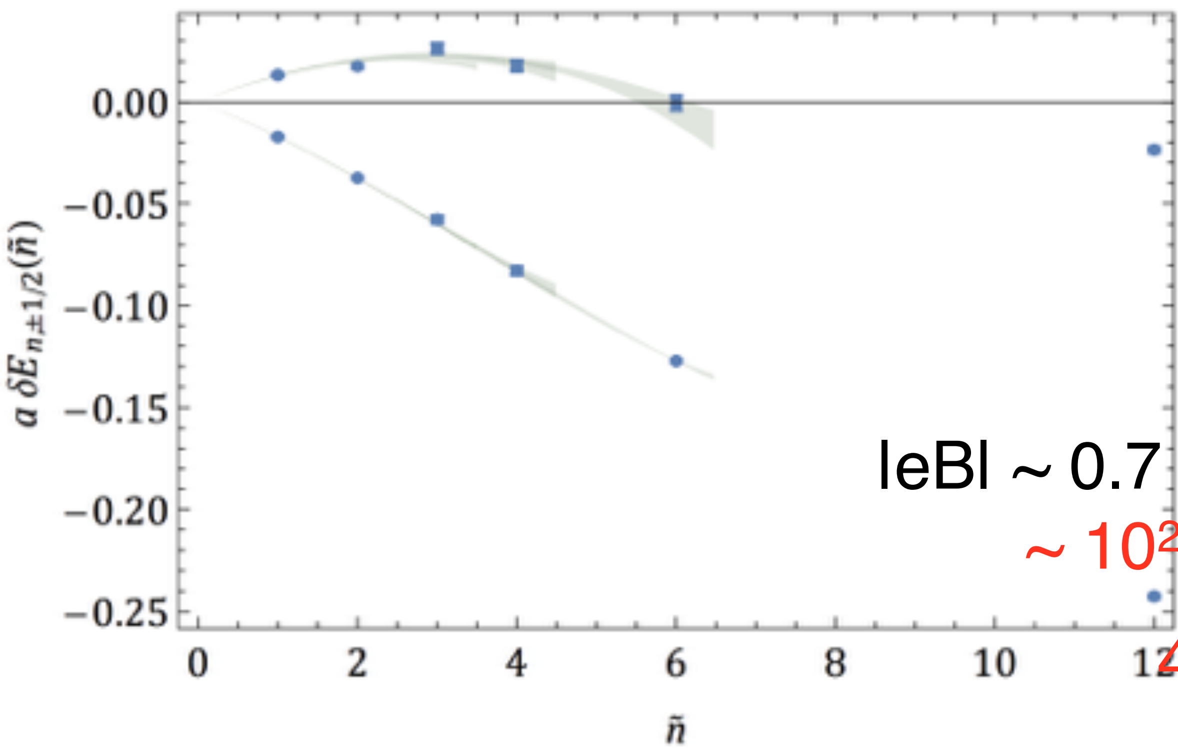
σ^{expt} = 334.2(0.5) mb

[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

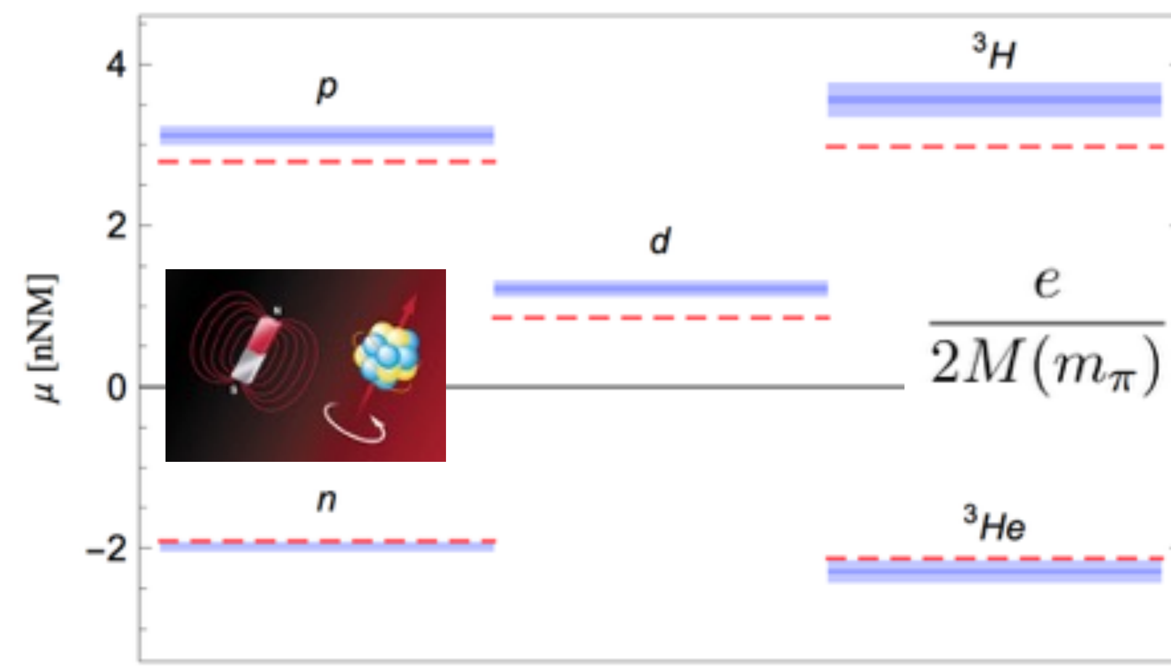


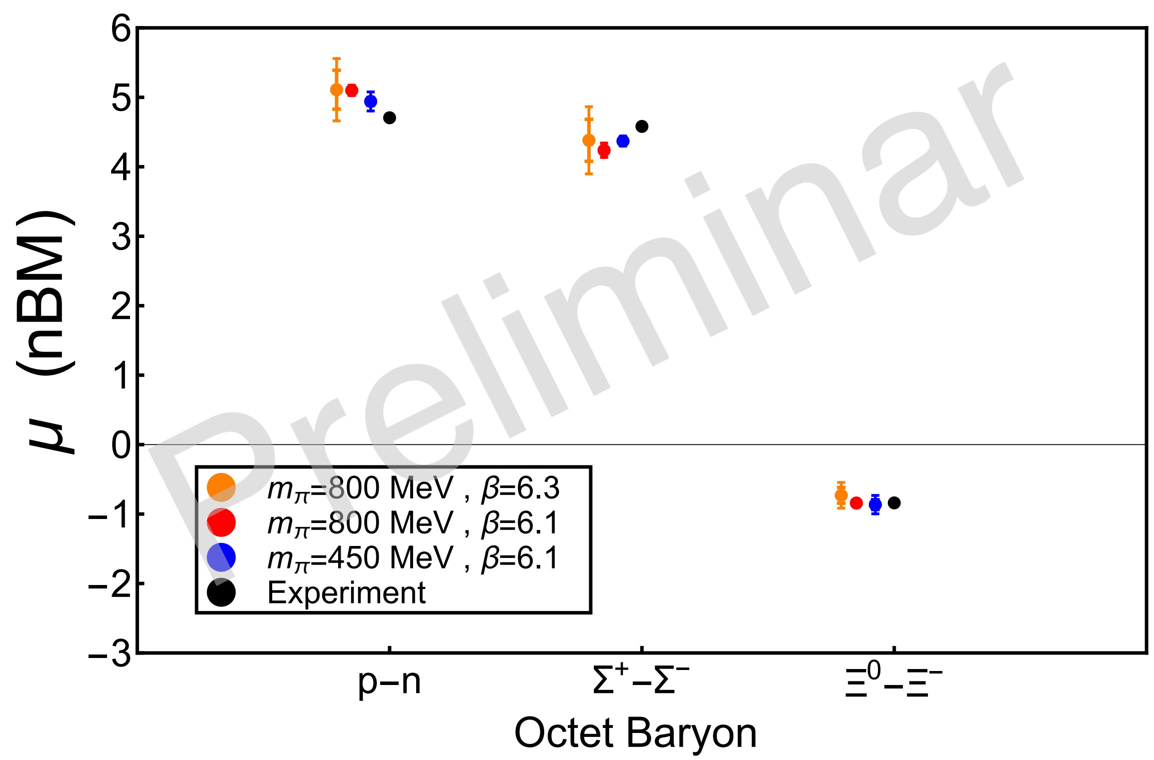


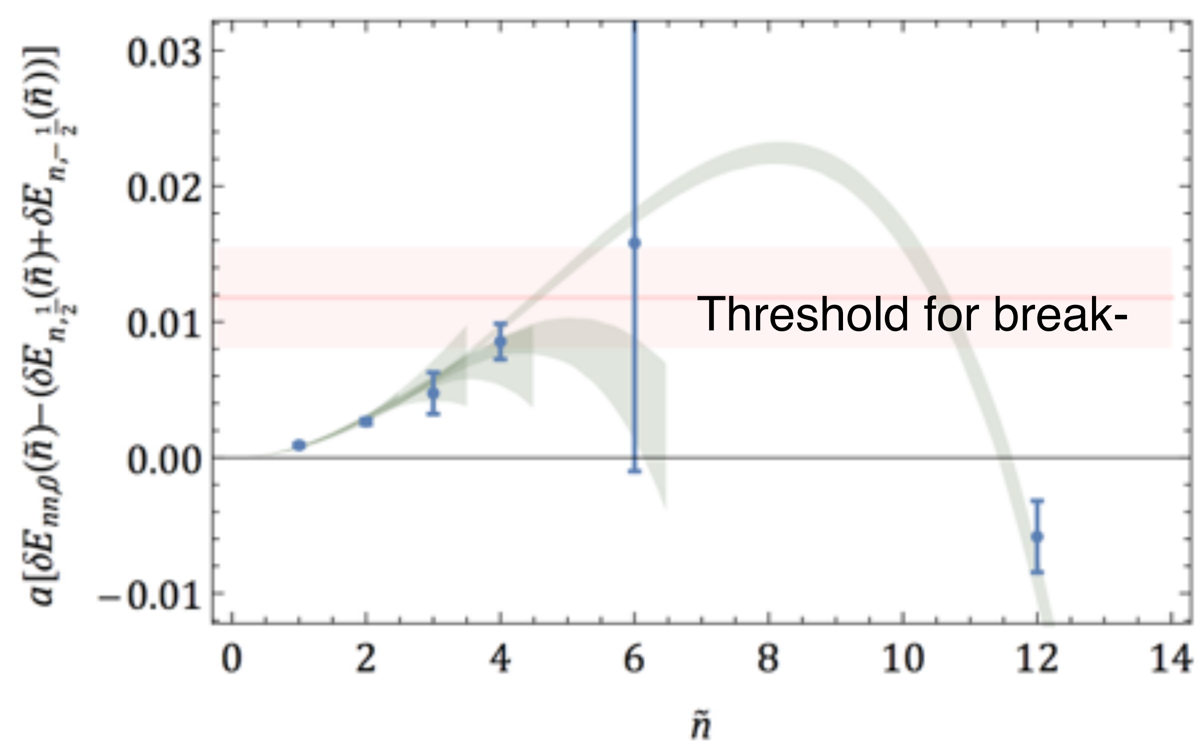
|eB| ~ 0.7 GeV^2

~ 10^{20} Gauss

400 MeV

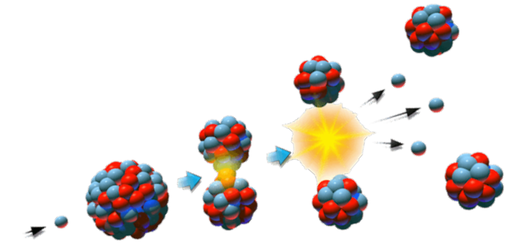




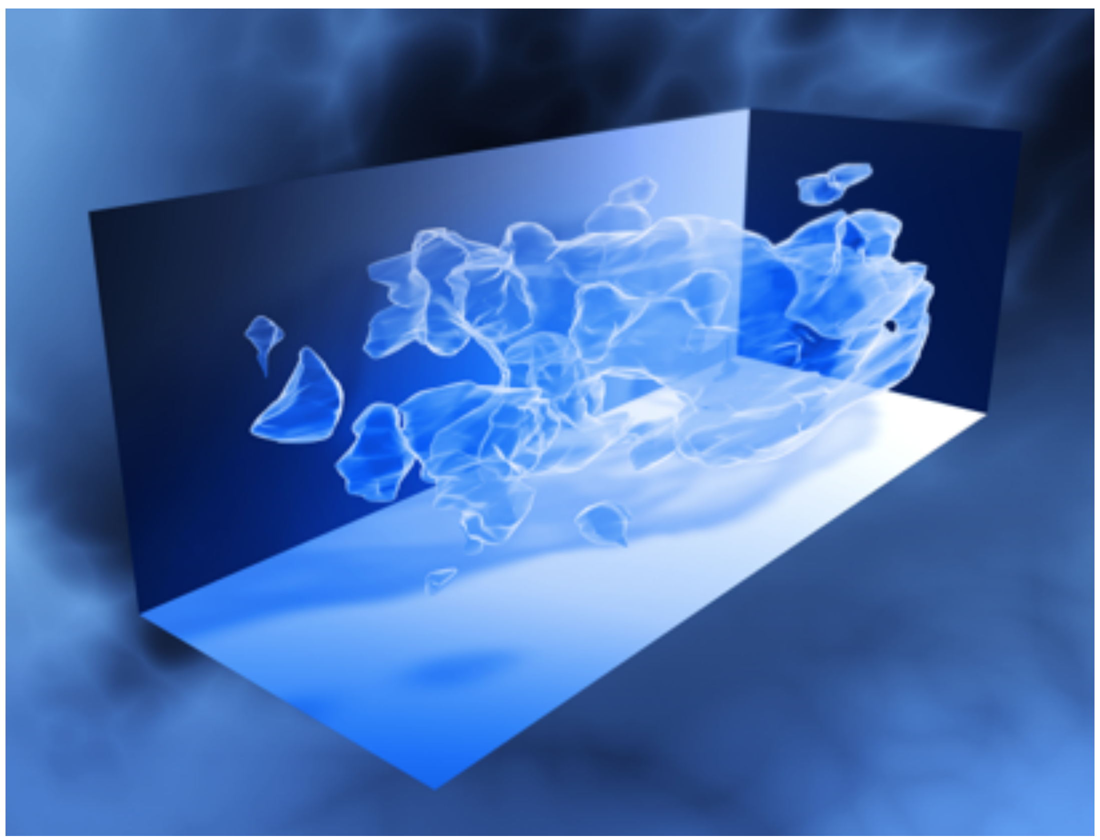


NPLQCD, Phys.Rev.Lett. 113 (2014) no.25, 252001 and Phys.Rev. D92 (2015) no.11, 114502

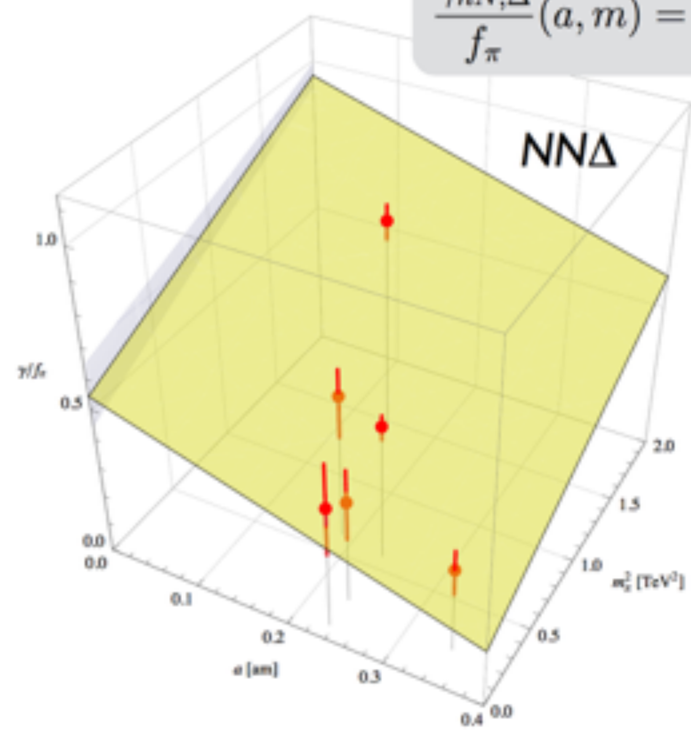
Dark Nuclei

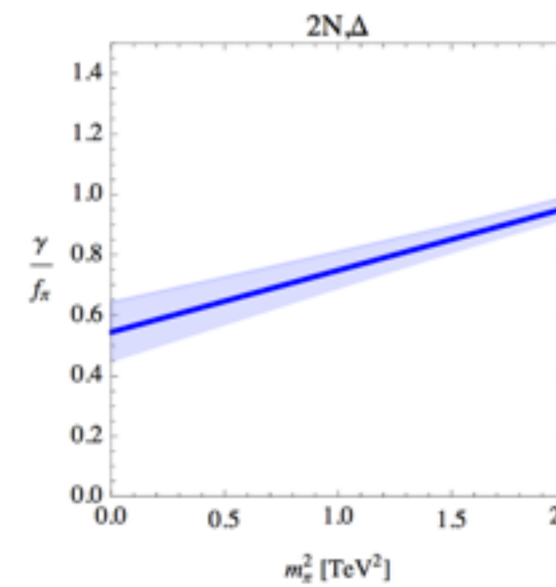


BSM Nuclei as Dark Matter ?



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

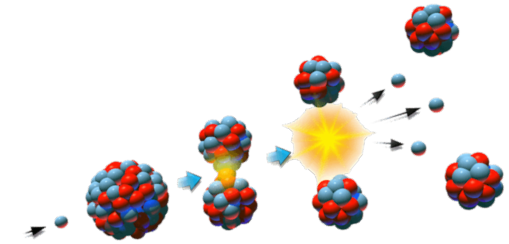




Use QCD technology for SU(2) color - bound states.

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

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

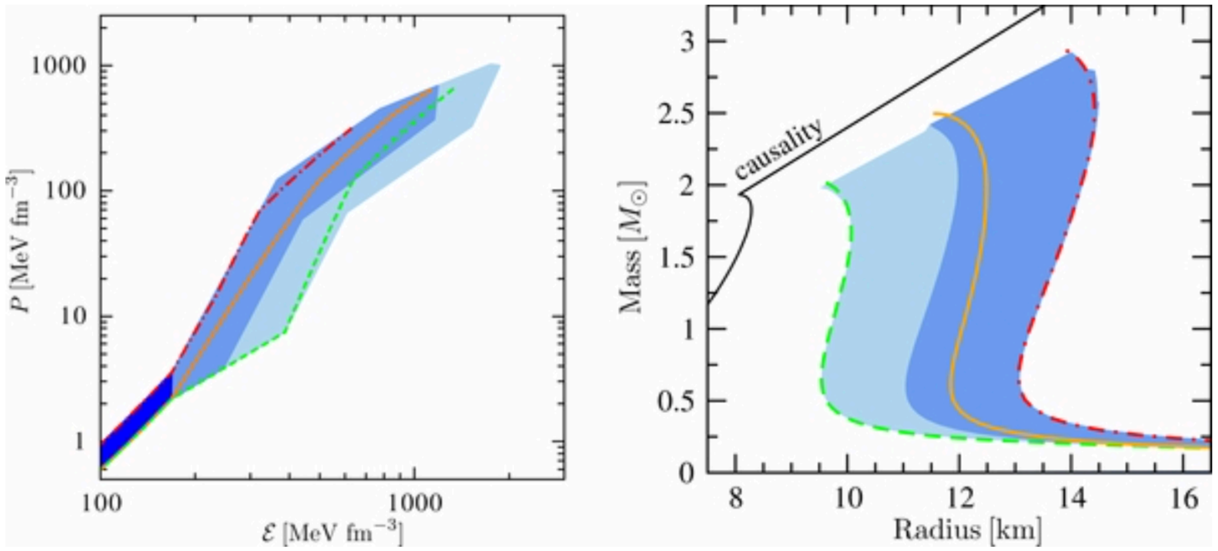
Magnetic and Axial moments and polarizabilities,

A>4 : p-shell nuclei

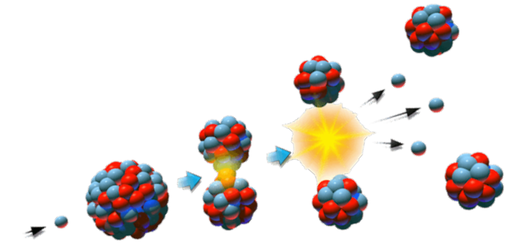
Bound states and continuum states, matching to NNEFT and phenomenological nuclear methods

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



Closing Remarks

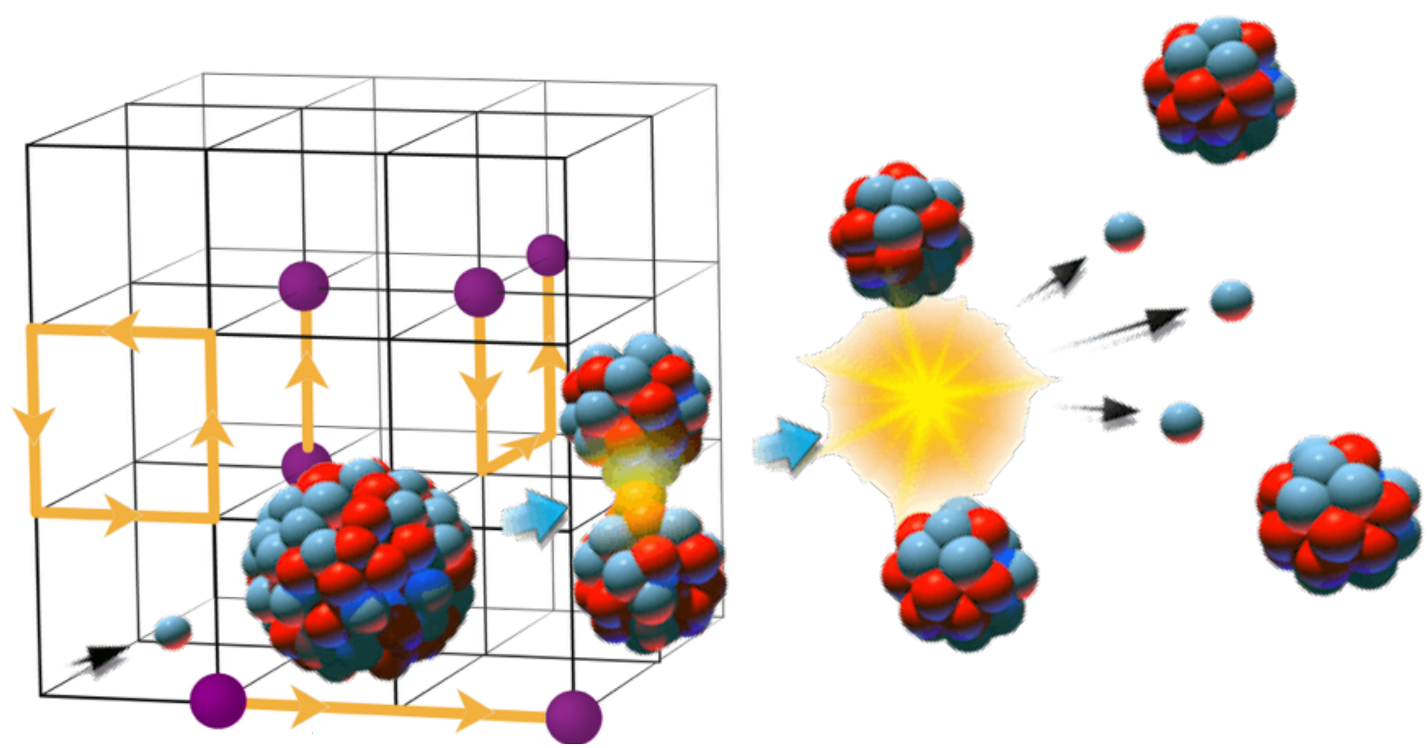


- Light Nuclei, nuclear forces and the structure of matter are emerging directly from Quantum Chromodynamics

- Exciting progress on the path to supporting and complementing the experimental programs in NP and HEP

- Some groups at the physical point already!
  - Away from physical point calculations are also required to refine chiral nuclear forces
    - reveal interesting features of the strong interactions

- (Known) challenges lie ahead



Thanks to Organizers !!

FIN