Status of baryon-baryon interactions from lattice QCD

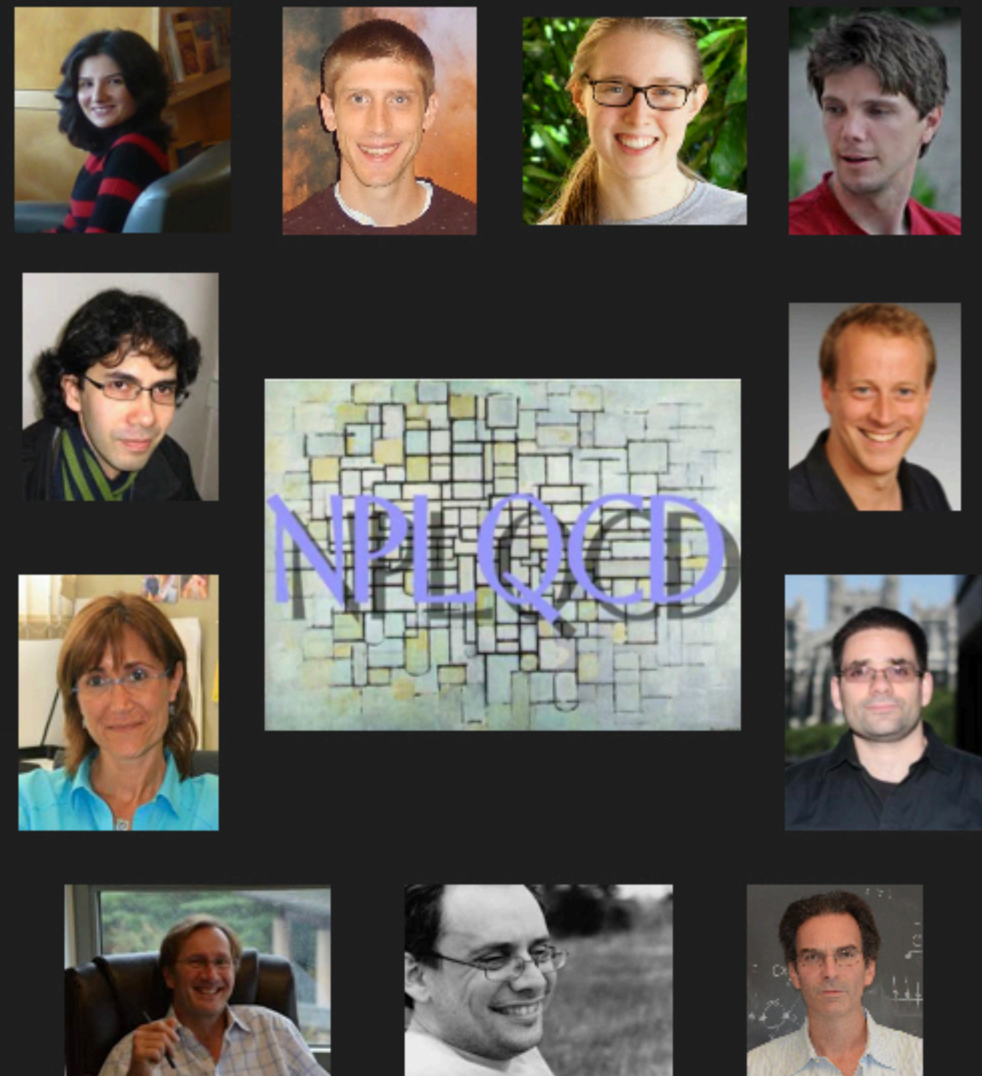
Silas Beane

CIPANP Palm Springs 6/1/2018

NPLQCD: UNPHYSICAL NUCLEI

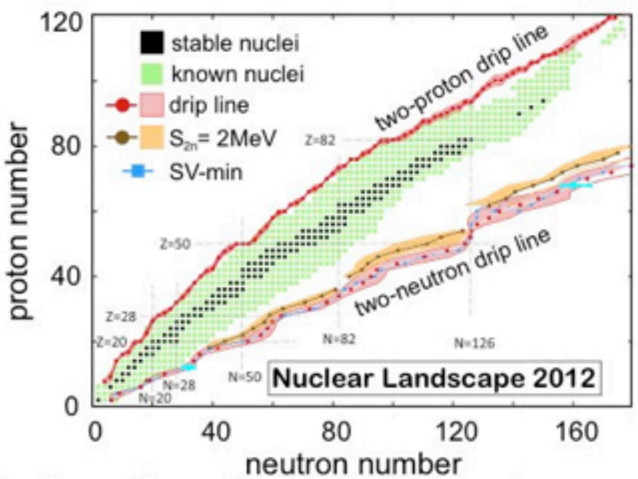
- Case study LQCD with unphysical quark masses (m_π~800 MeV, 450 MeV)

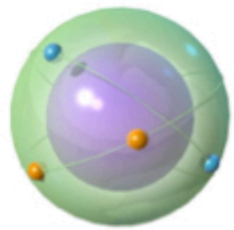
1. Spectrum and scattering of light nuclei (A<5) [PRD 87 (2013), 034506]
2. Nuclear structure: magnetic moments, polarisabilities (A<5) [PRL **113**, 252001 (2014), PRL **116**, 112301 (2016)]
3. Nuclear reactions: np→dγ [PRL **115**, 132001 (2015)]
4. Gamow-Teller transitions: pp→deν, $g_A(^3H)$ [PRL **119** 062002 (2017)]
5. Double β decay: pp→nn [PRL **119**, 062003 (2017)]
6. Gluon structure (A<4) [PRD **96** 094512 (2017)]
7. Scalar/tensor currents (A<4) [PRL **120** 152002 (2018)]



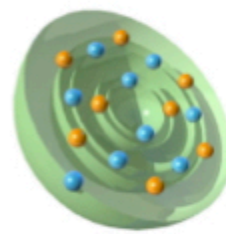
+ Arjun Gambhir (WM→LLNL)

★ Together with EW QCD must give:



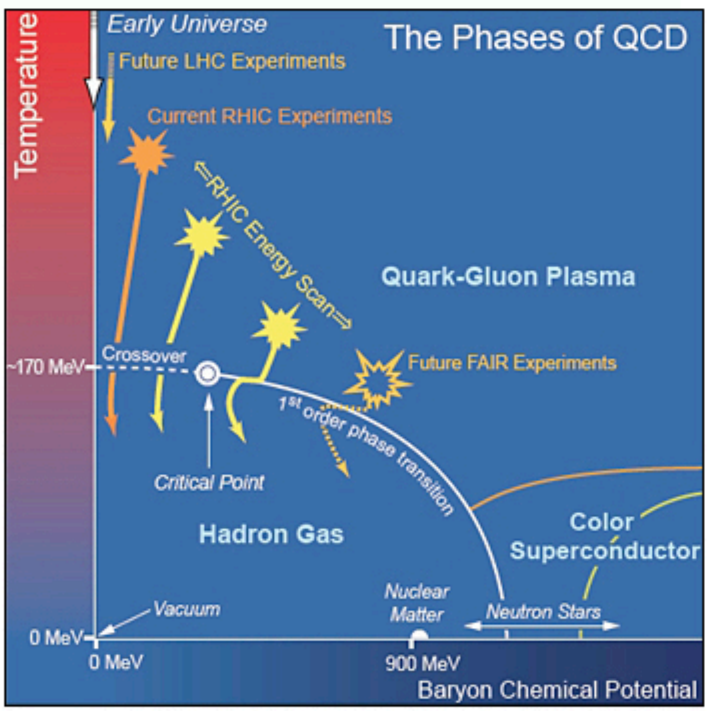


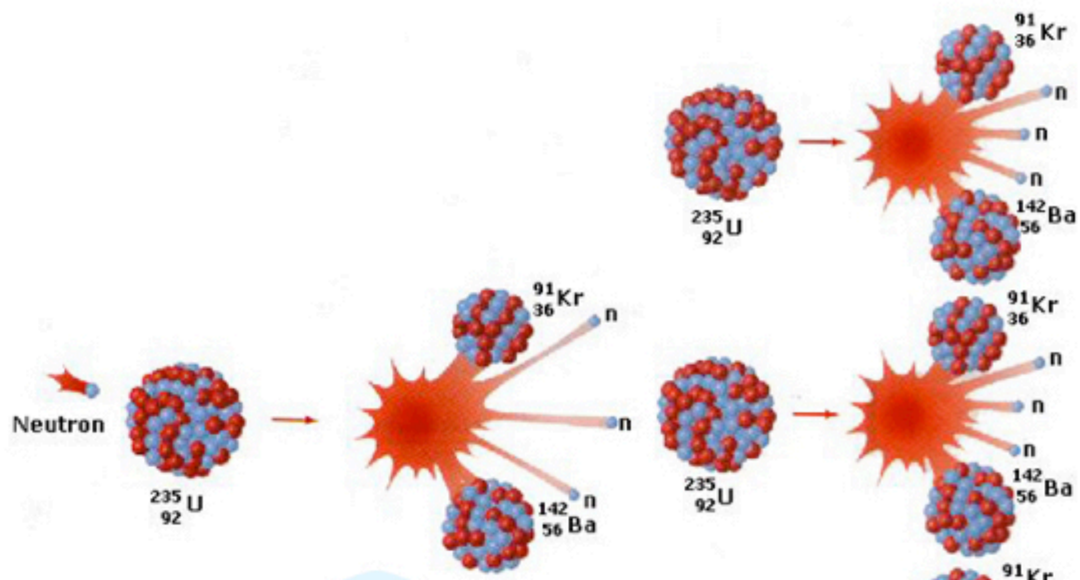
Spin-pairing

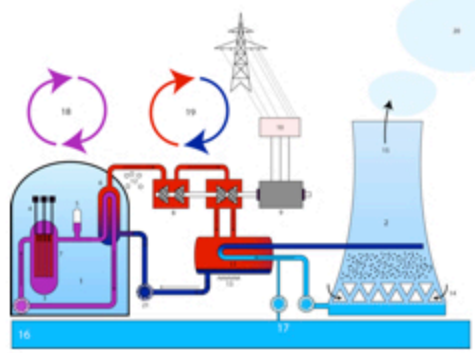


Shell-structure

Vibrational and rotational excitations

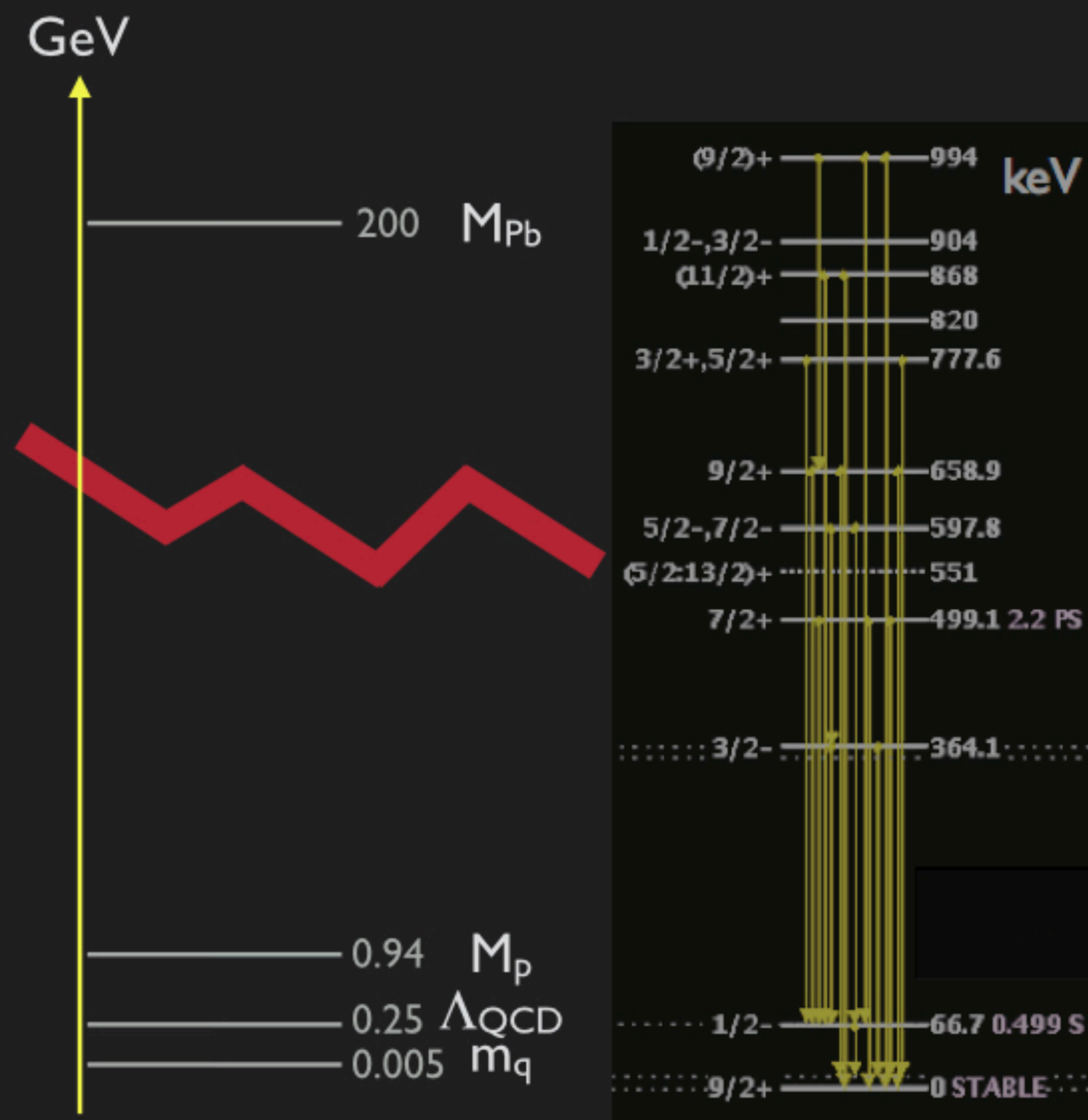






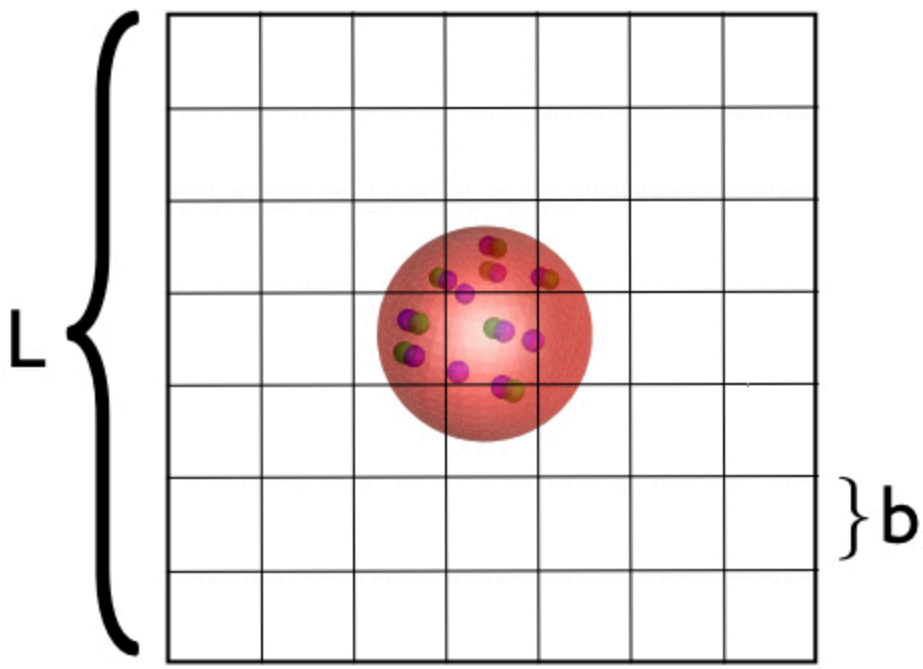
In principle can calculate properties of any nucleus from QCD and EW

Multi-scale physics with at least two exponentially difficult computational challenges



Lattice QCD = QCD on a grid or lattice

Non-perturbative definition of QCD



volume: $M_\pi L \gg 1$

infrared cutoff

lattice spacing: $b \ll M_N^{-1}$

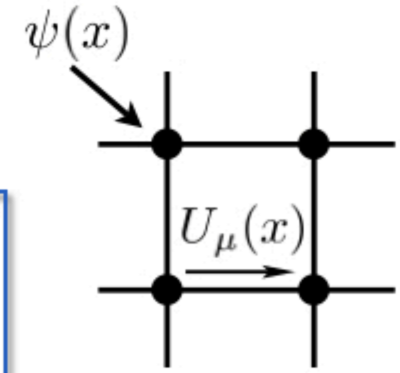
ultraviolet cutoff

Can use Effective Field Theory to extrapolate in L and b!

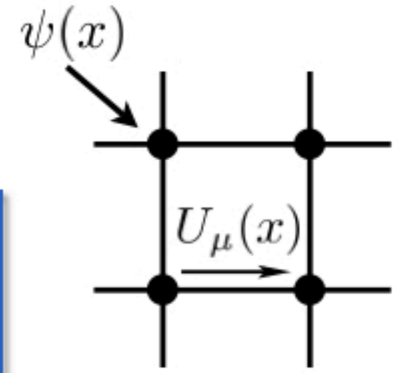
(systematic uncertainties from lattice artifacts are controlled)

QCD path integral with Montecarlo

$$\langle\mathcal{O}\rangle \sim \int dU_\mu \, d\bar{\psi} \, d\psi \; \mathcal{O}\left(U, \psi, \bar{\psi}\right) \; e^{-S_g(U) - \bar{\psi} D(U) \psi}$$



QCD path integral with Montecarlo



$$\langle \mathcal{O} \rangle \sim \int dU_\mu \, d\bar{\psi} \, d\psi \; \mathcal{O}\left(U, \psi, \bar{\psi}\right) \; e^{-S_g(U) - \bar{\psi} D(U) \psi}$$

propagators (detector)

N gauge configurations (accelerator)

$$\langle \mathcal{O} \rangle \sim \int dU_\mu \; \mathcal{O}(D(U)^{-1}) \;\; \det\left(f(U)\right) \;\; e^{-S_g(U)} \; = \lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} \mathcal{O}(D(U_i)^{-1})$$

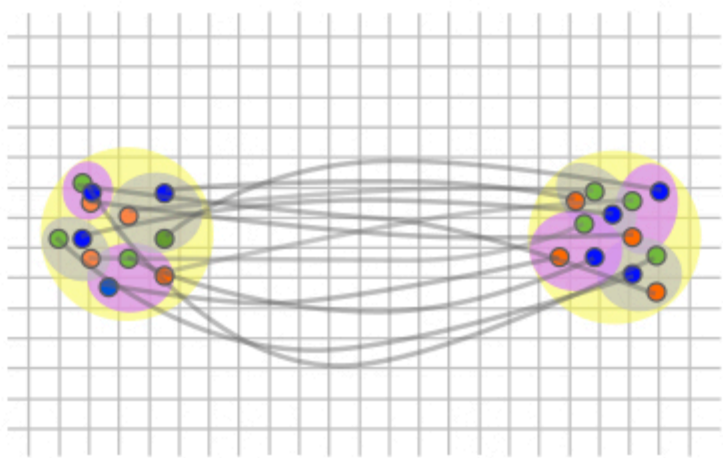
Estimate of $\mathcal{O}$ with $\sigma_{\mathcal{O}} \sim 1/\sqrt{N}$

Why is lattice QCD for nuclear physics hard ?

- Signal/noise (sign problem) and statistics

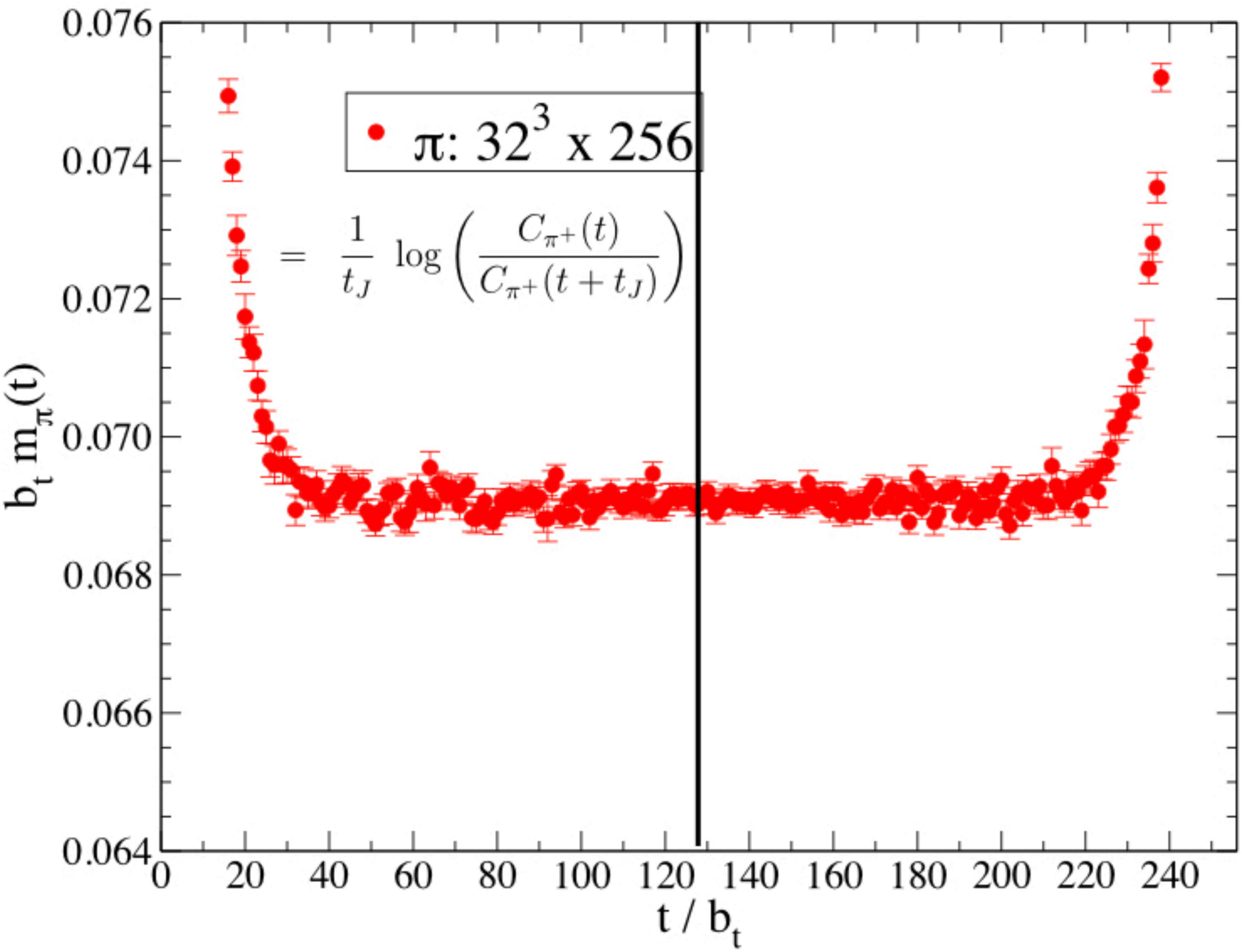
- Number of contractions

[Detmold,Orginos(2012),Doi,Endres(2012)]

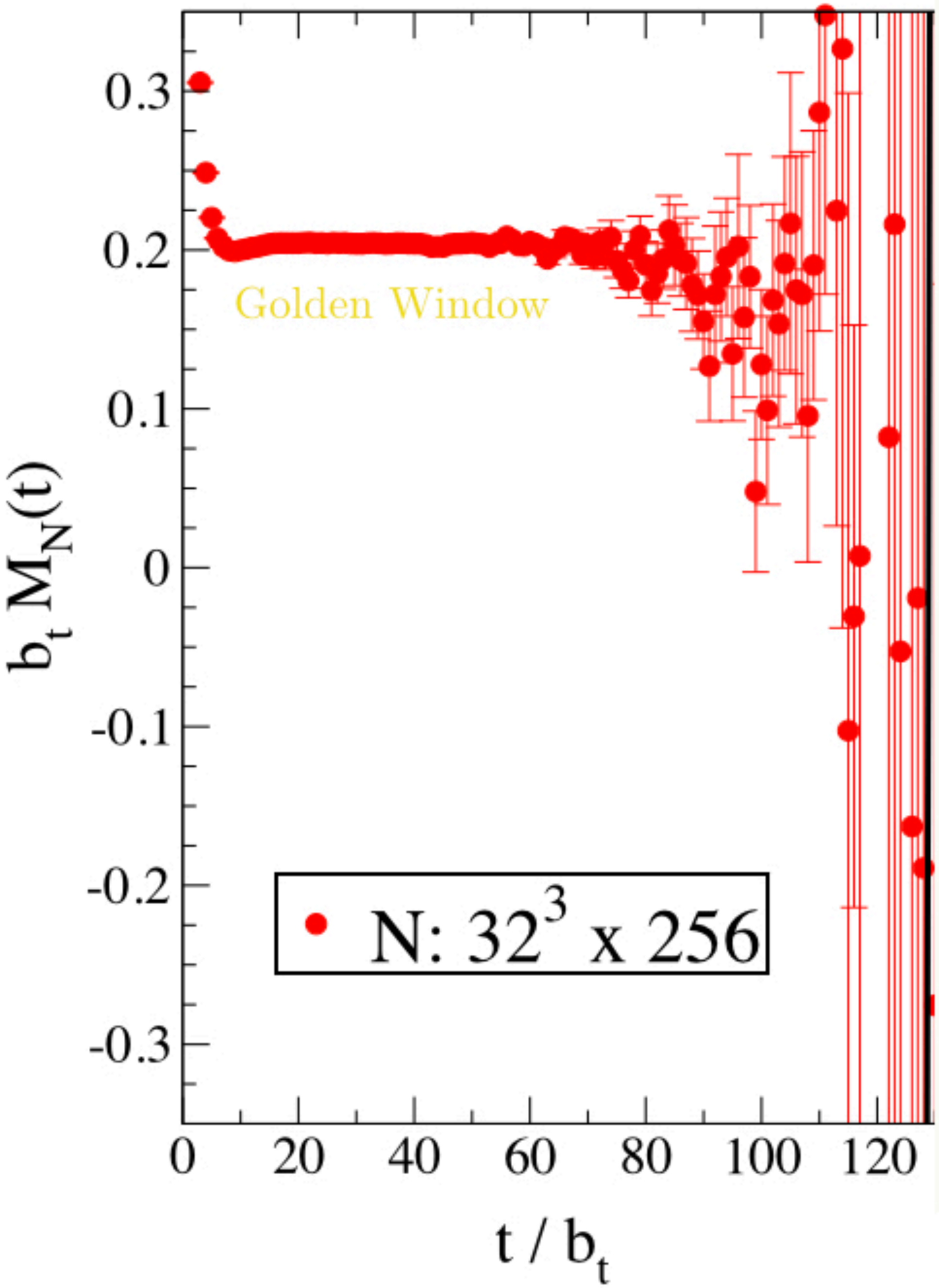


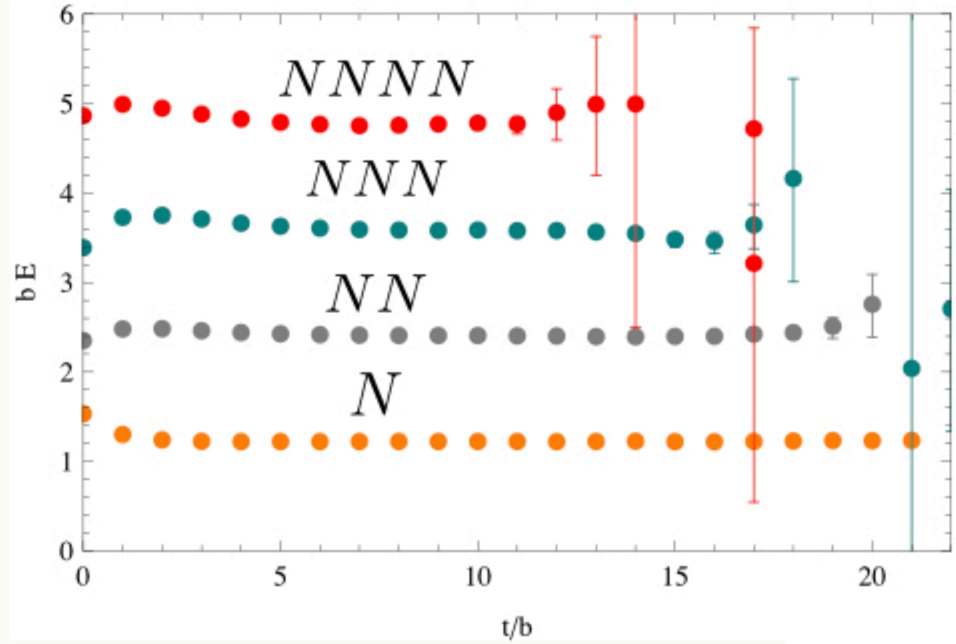
Signal/Noise Problem

$$C_{\pi^+}(t) \; = \; \sum_{\mathbf{x}} \langle 0| \; \pi^-(\mathbf{x},t) \; \pi^+(\mathbf{0},0) \; |0\rangle \longrightarrow e^{-m_\pi t} \quad \ldots$$



pions are easy! (i.e. cheap)



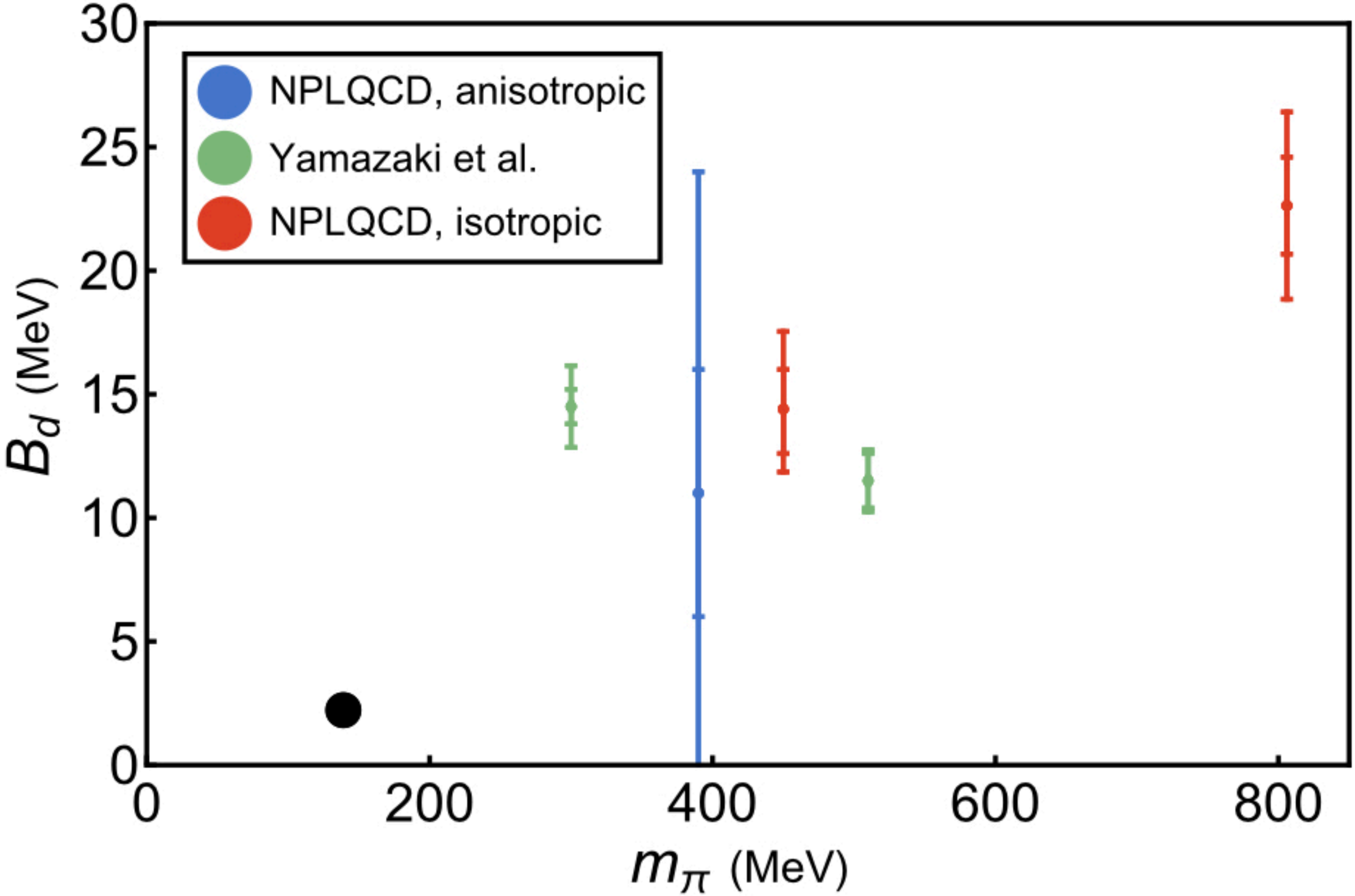


$$\frac{\text{noise}}{\text{signal}} \sim \frac{1}{\sqrt{N}}\, e^{A\left(m_p - \frac{3}{2} m_\pi\right)t}$$

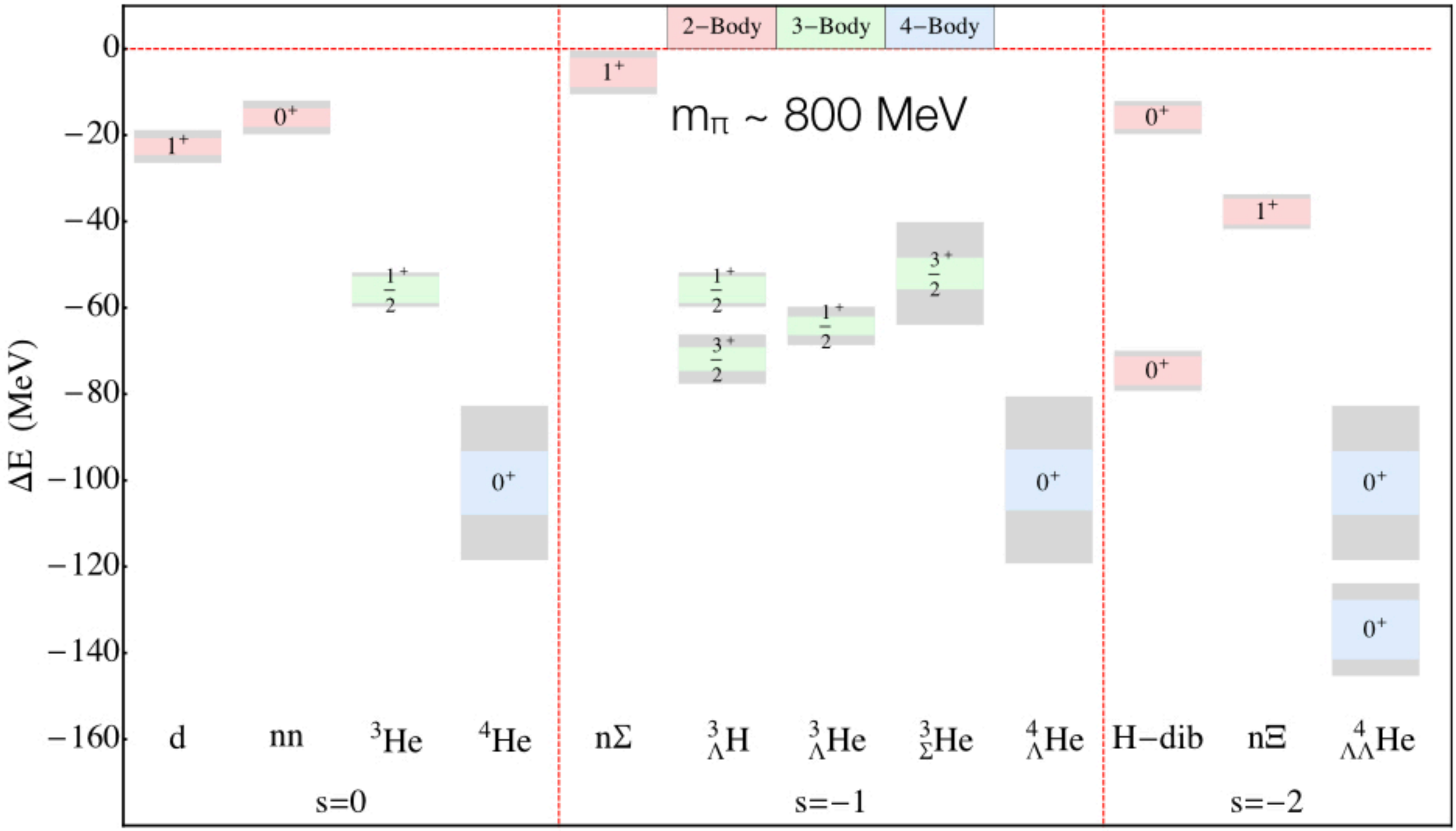
baryons are hard! (i.e. costly)

(Need quantum computers?)

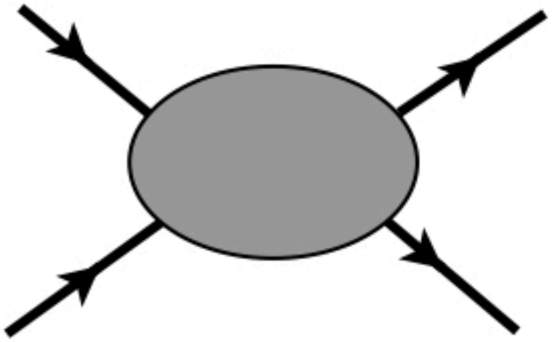
Deuteron binding energy from LQCD



Light (Hyper)Nuclei at SU(3) point



Nucleon-nucleon scattering



$$k \cot \delta = -\frac{1}{a} + \frac{1}{2} r |\mathbf{k}|^2 + P |\mathbf{k}|^4 + \mathcal{O}\left(|\mathbf{k}|^6\right)$$

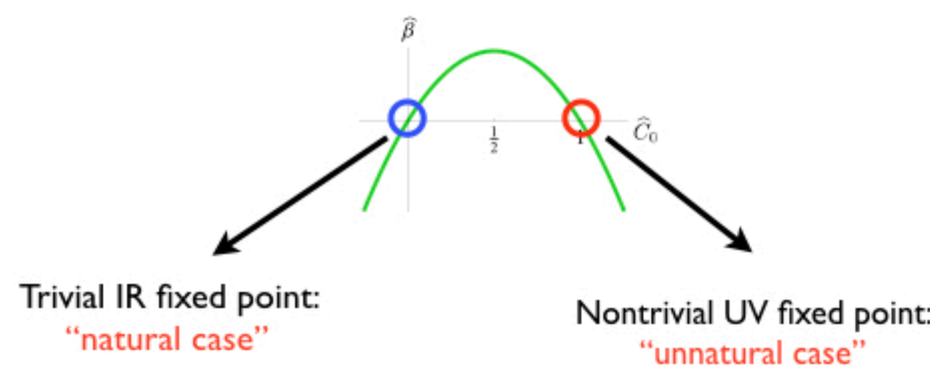
effective range: range of interaction

scattering length: unbounded

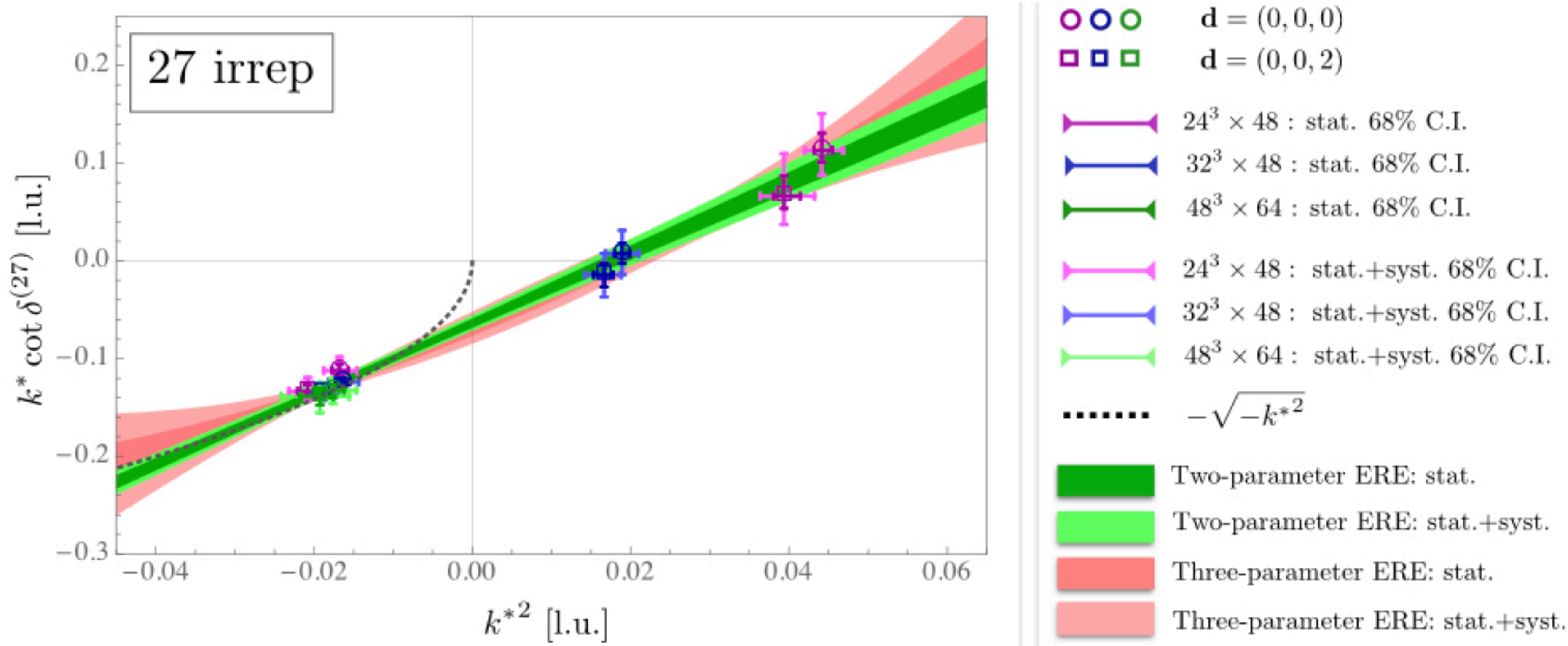
EXPERIMENT:

$$a^{(^1S_0)} = -23.71 \text{ fm} \qquad a^{(^3S_1)} = 5.43 \text{ fm}$$
$$r^{(^1S_0)} = 2.73 \text{ fm} \qquad r^{(^3S_1)} = 1.75 \text{ fm}$$

$$a^{(^1S_0)} \gg \Lambda_{QCD}^{-1}$$

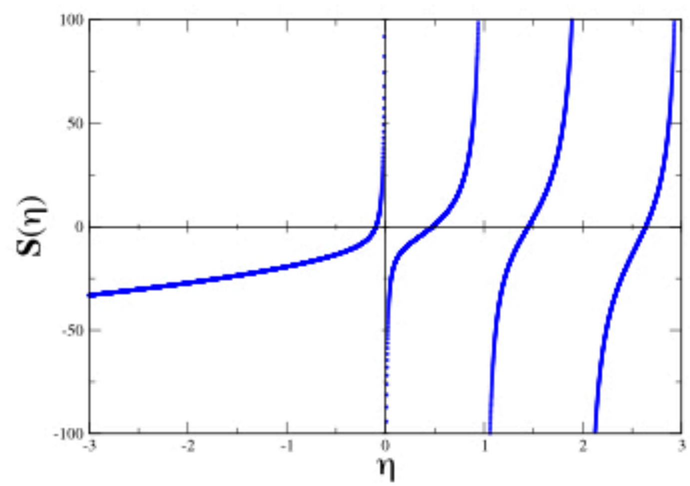


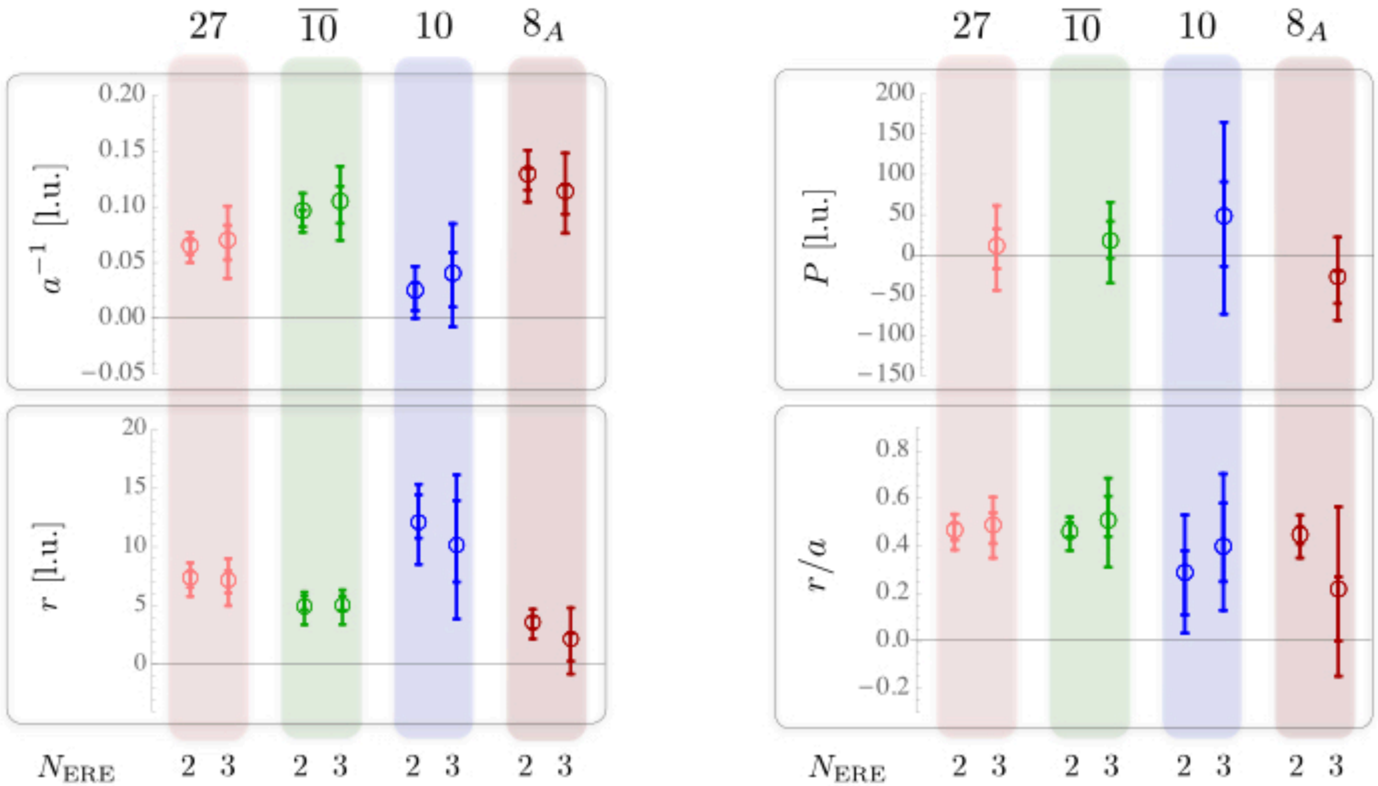
Baryon-Baryon S-wave phase shifts



$$p \cot \delta \ = \ \frac{1}{\pi L} \mathcal{S}(\tilde{p})$$

$$\mathcal{S}\left(x\right) \ \equiv \ \sum_{\mathbf{n}}^{\Lambda_n} \frac{1}{|\mathbf{n}|^2 - x^2} \ - \ 4\pi\Lambda_n$$





$SU(6)$ from large-N_c

$$\left[-\frac{1}{a^{(27)}}+\mu\right]^{-1}=\frac{M_B}{2\pi}(a-\frac{b}{27})+\mathcal{O}\left(\frac{1}{N_c^2}\right),\qquad \left[-\frac{1}{a^{(\overline{10})}}+\mu\right]^{-1}=\frac{M_B}{2\pi}(a-\frac{b}{27})+\mathcal{O}\left(\frac{1}{N_c^2}\right),$$

$$\left[-\frac{1}{a^{(10)}}+\mu\right]^{-1}=\frac{M_B}{2\pi}(a+\frac{7b}{27})+\mathcal{O}\left(\frac{1}{N_c}\right),\qquad \left[-\frac{1}{a^{(8_A)}}+\mu\right]^{-1}=\frac{M_B}{2\pi}(a+\frac{b}{27})+\mathcal{O}\left(\frac{1}{N_c}\right),$$

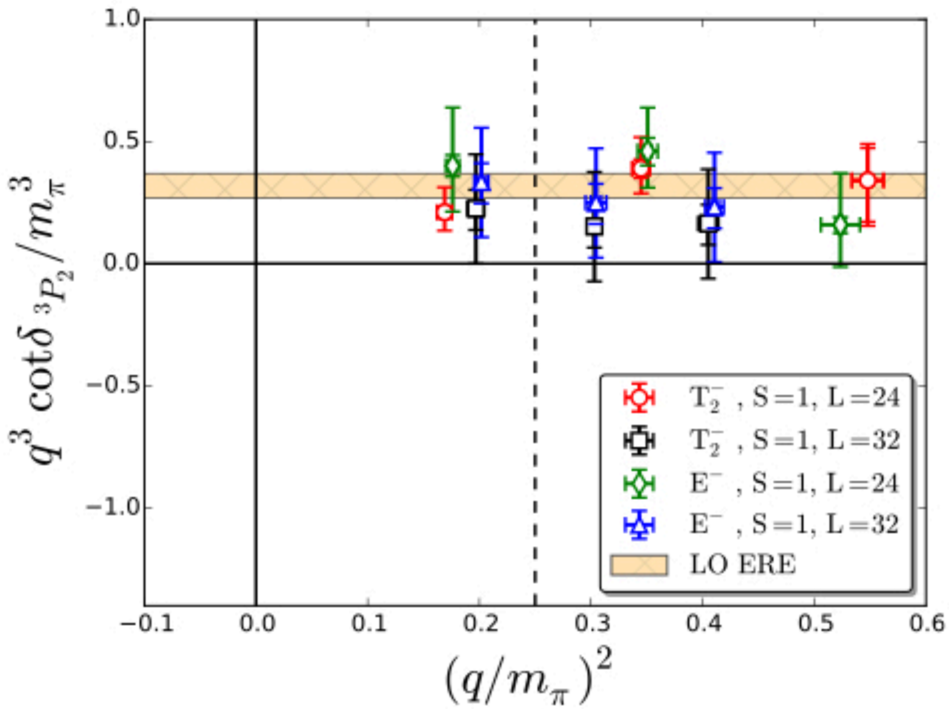
$$\left[-\frac{1}{a^{(8_S)}}+\mu\right]^{-1}=\frac{M_B}{2\pi}(a+\frac{b}{3})+\mathcal{O}\left(\frac{1}{N_c}\right),\qquad \left[-\frac{1}{a^{(1)}}+\mu\right]^{-1}=\frac{M_B}{2\pi}(a-\frac{b}{3})+\mathcal{O}\left(\frac{1}{N_c}\right),$$

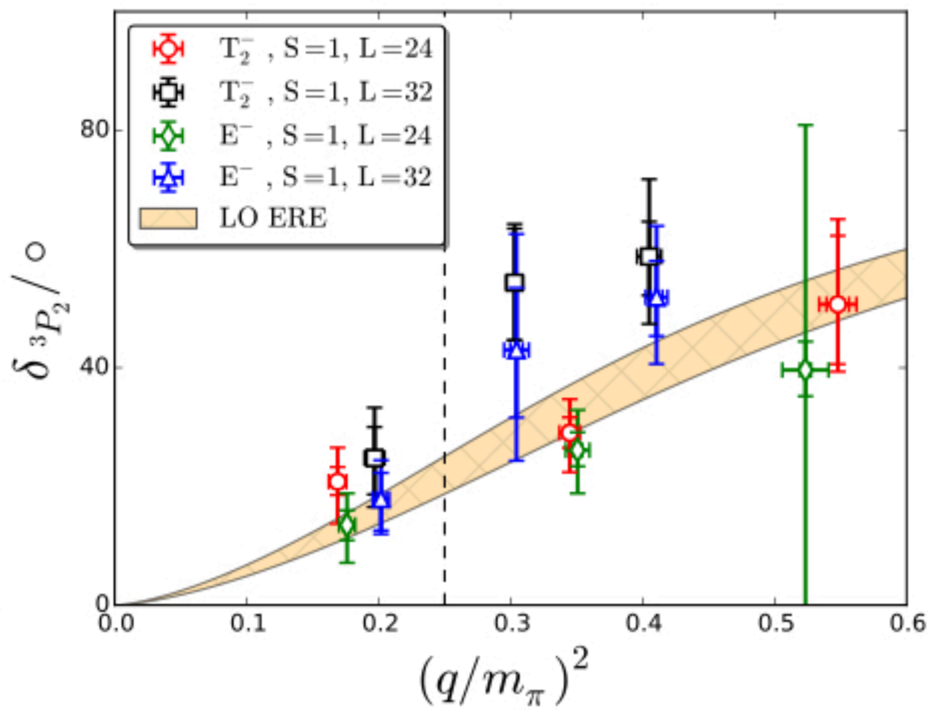
NN P-wave phase shifts

CalLat Collaboration (using NPLQCD resources)

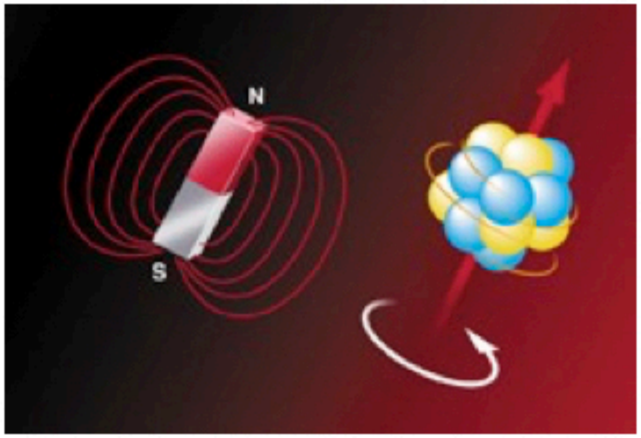
$m_\pi \sim 800$ MeV

Amy Nicholson *et al* (CalLatt)





Nuclear structure: magnetic moments



$U_Q(1)$ phase

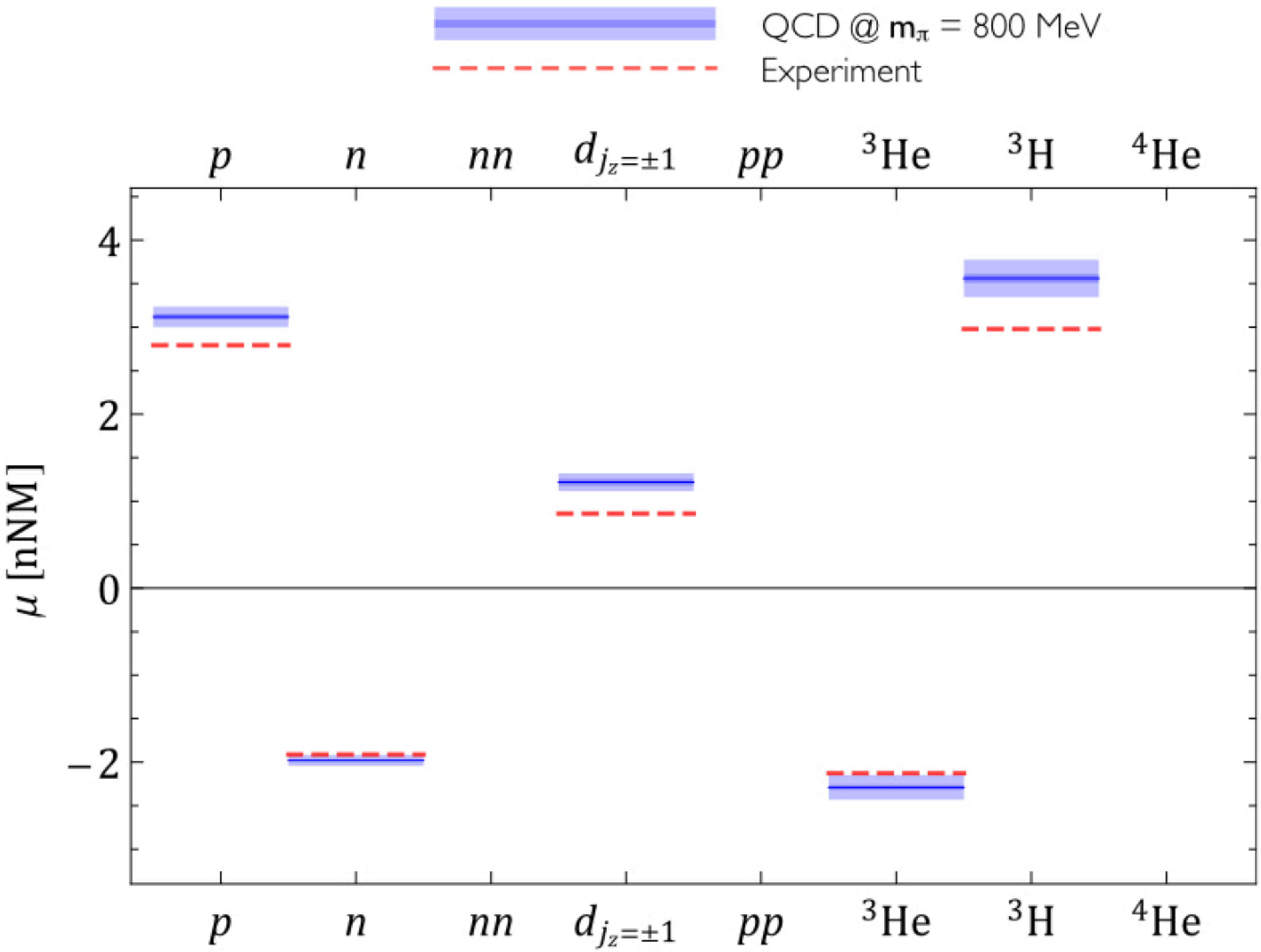
$$U_\mu(x) \;=\; e^{i\frac{6\pi Q_q \tilde{n}}{L^2} x_1 \delta_{\mu,2}} \times e^{-i\frac{6\pi Q_q \tilde{n}}{L} x_2 \delta_{\mu,1}\delta_{x_1,L-1}}$$

- Hadronic and nuclear correlation functions are modified in the presence of a background magnetic field:

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

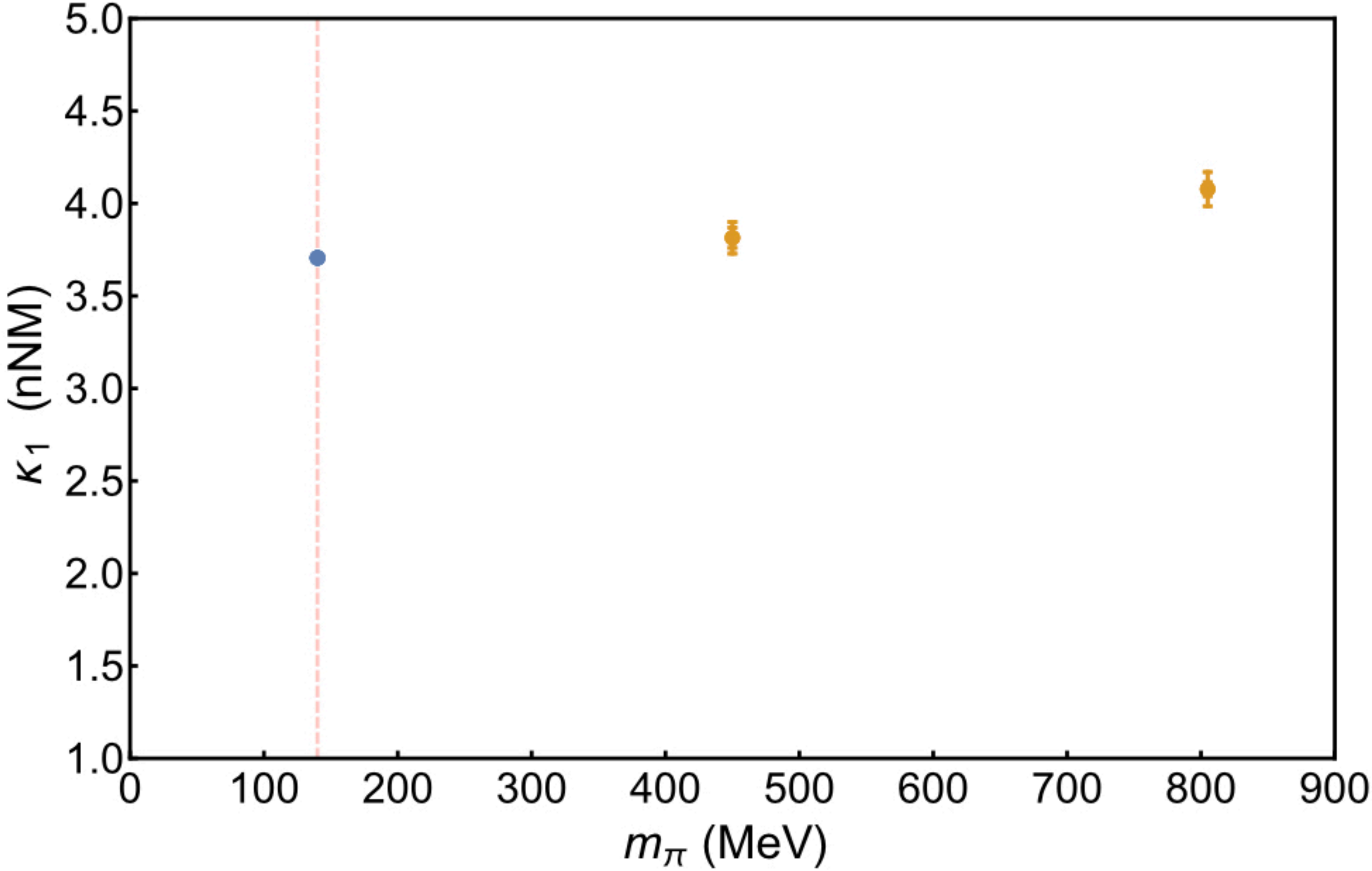
Landau level

- Can extract magnetic moments, polarizabilities, …
- Extendable to external electric fields, etc.

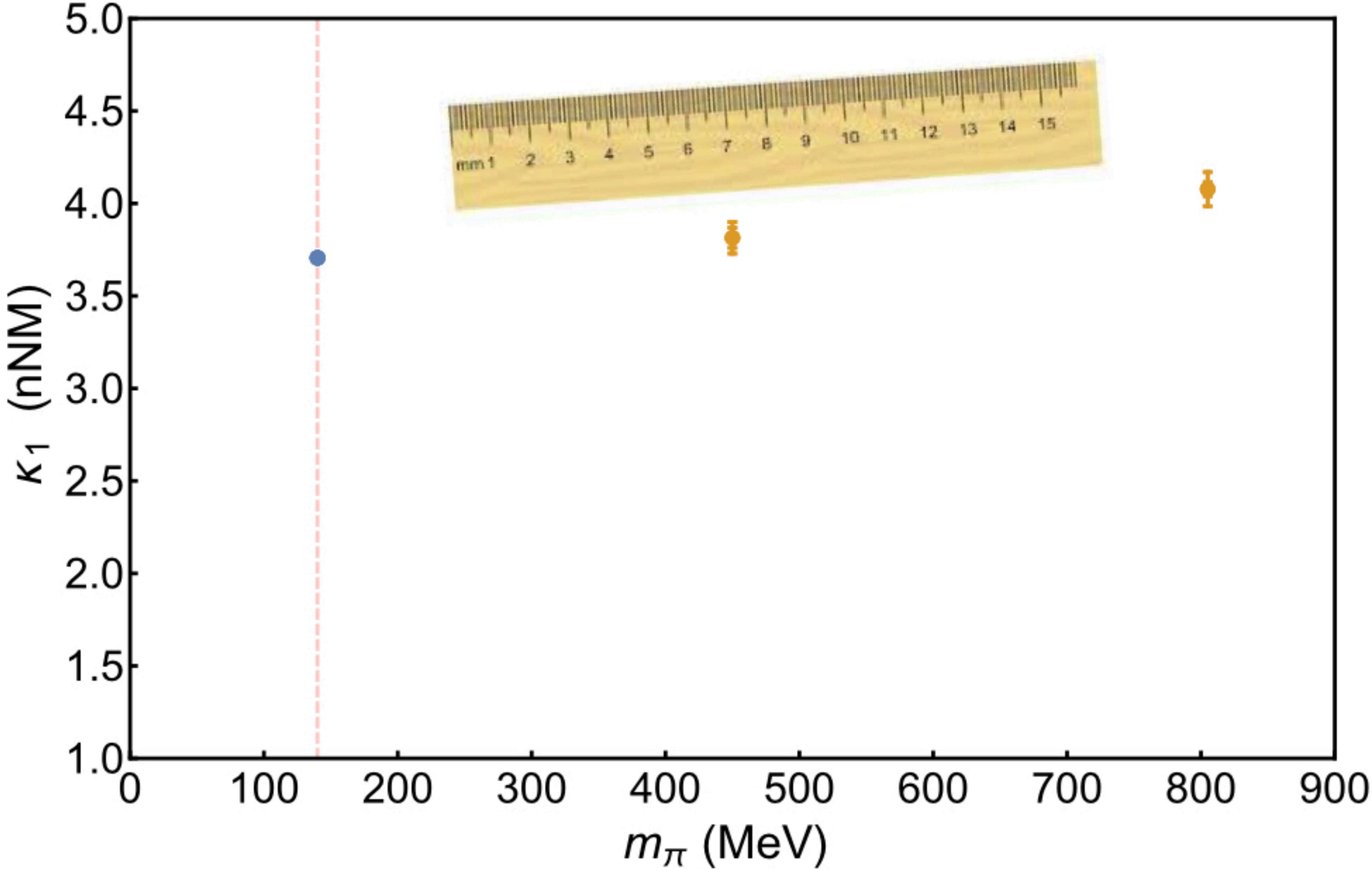


✦ Almost no quark mass dependence in units of $\dfrac{e}{2M(m_\pi)}$

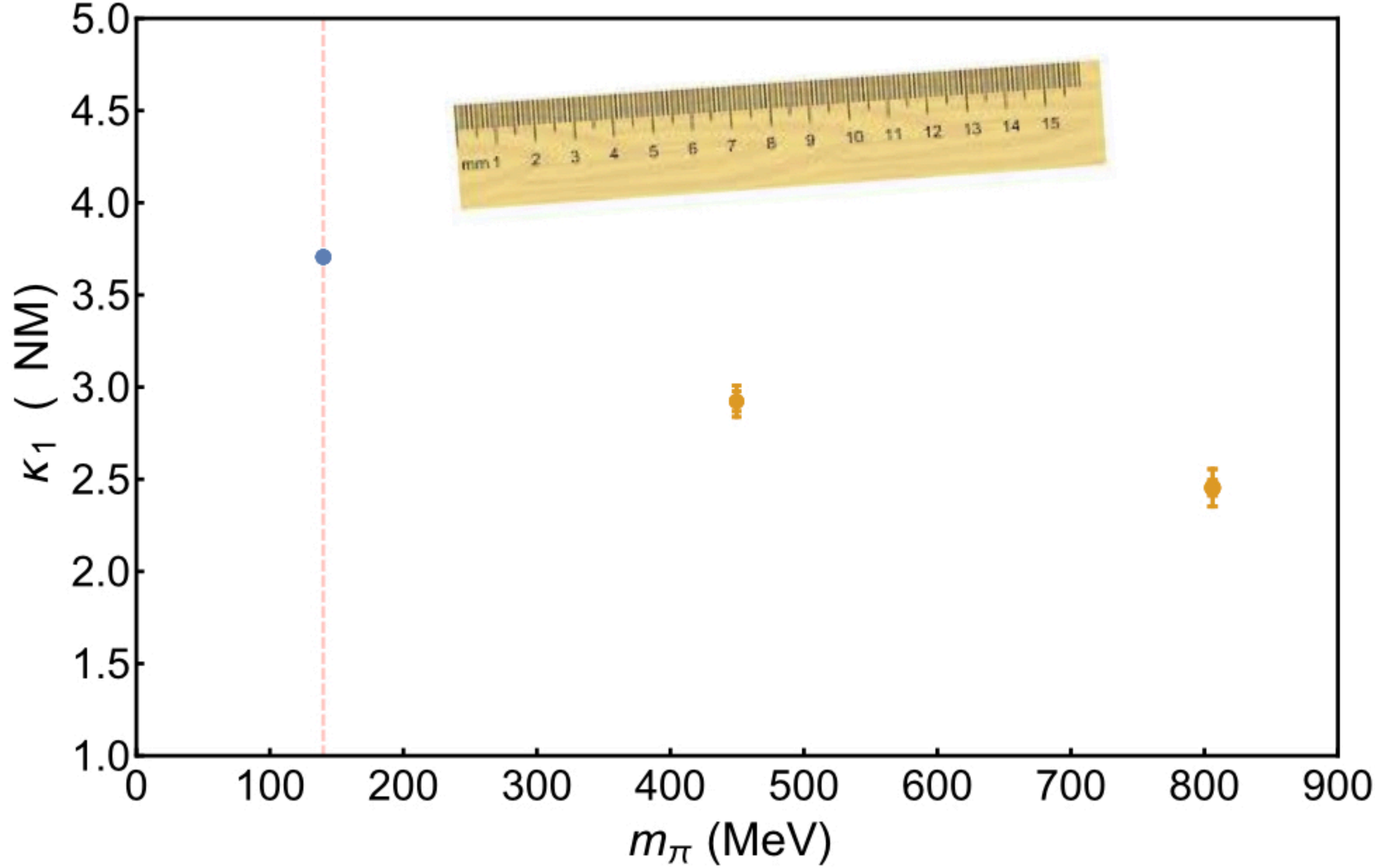
Nucleon isovector magnetic moment



Nucleon isovector magnetic moment

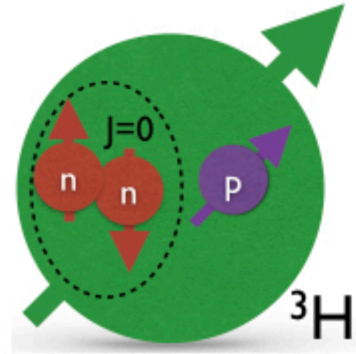


Nucleon isovector magnetic moment

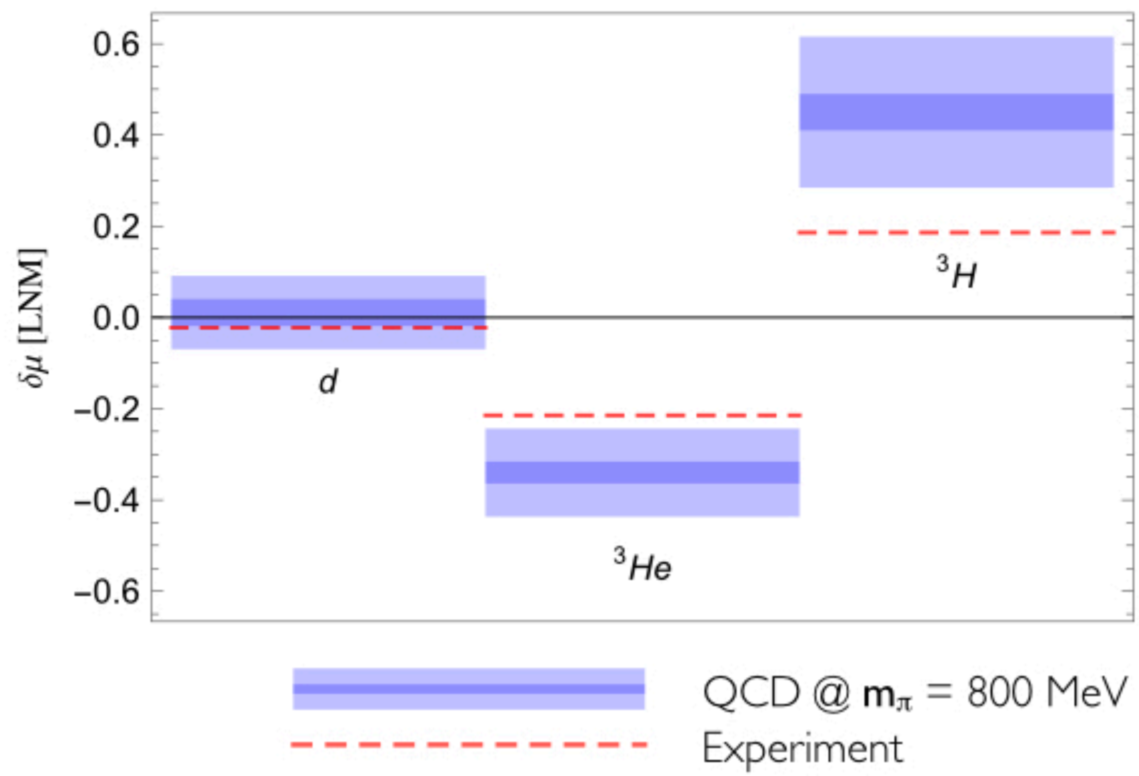


Nuclei as groupings of nucleons: shell model!

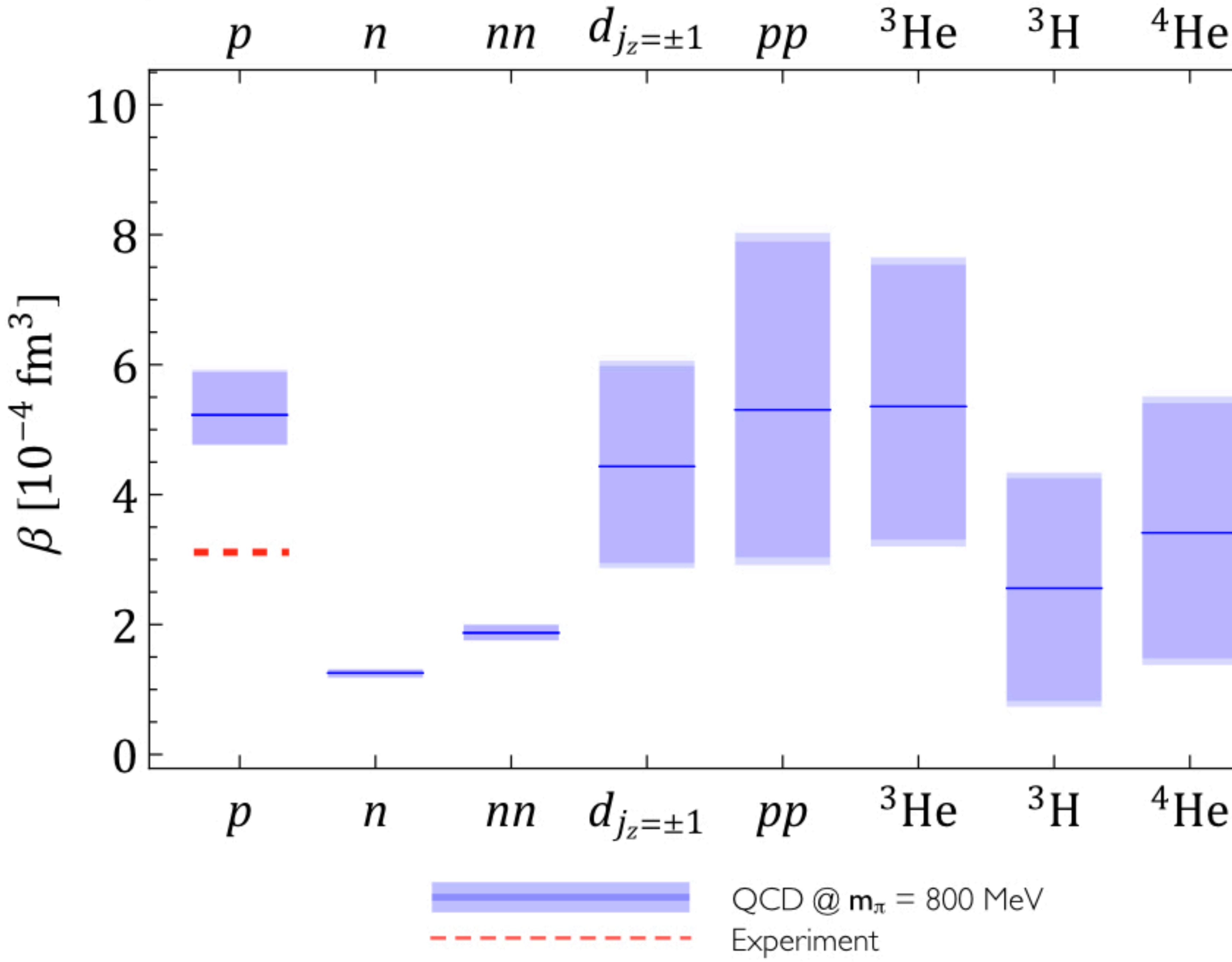
$$\mu_{^3\mathrm{H}} = \mu_p$$
$$\mu_{^3\mathrm{He}} = \mu_n$$
$$\mu_d = \mu_p + \mu_n$$



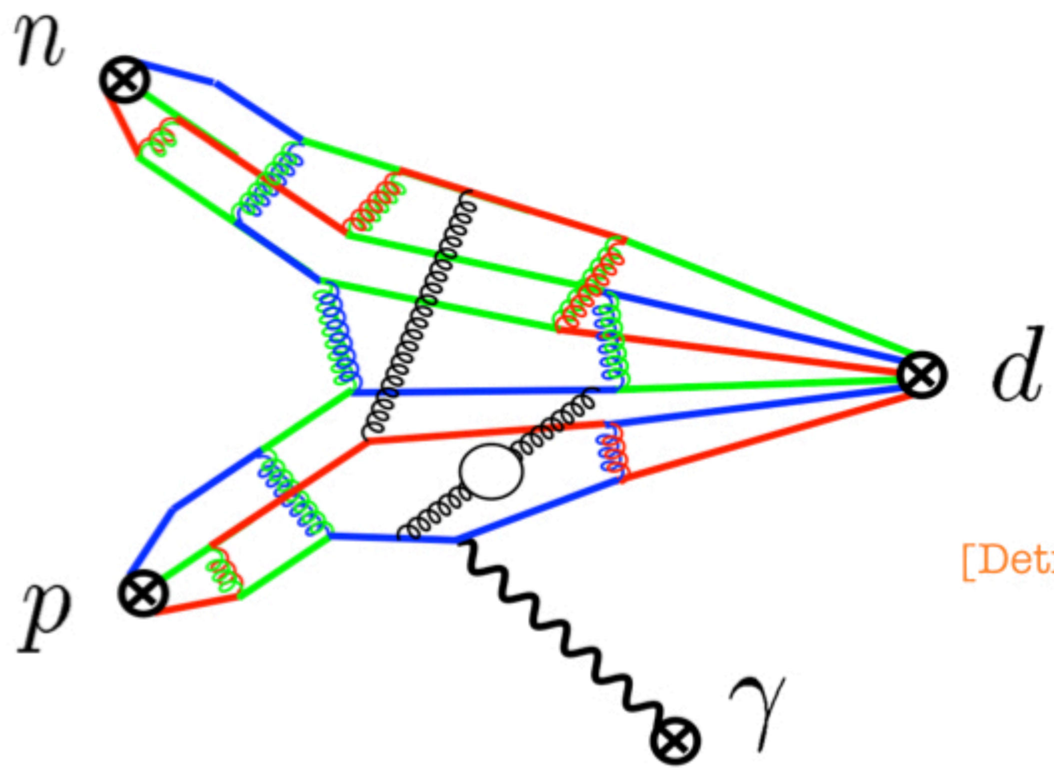
Difference between nuclear magnetic moments and shell model predictions



Nuclear structure: polarizabilities



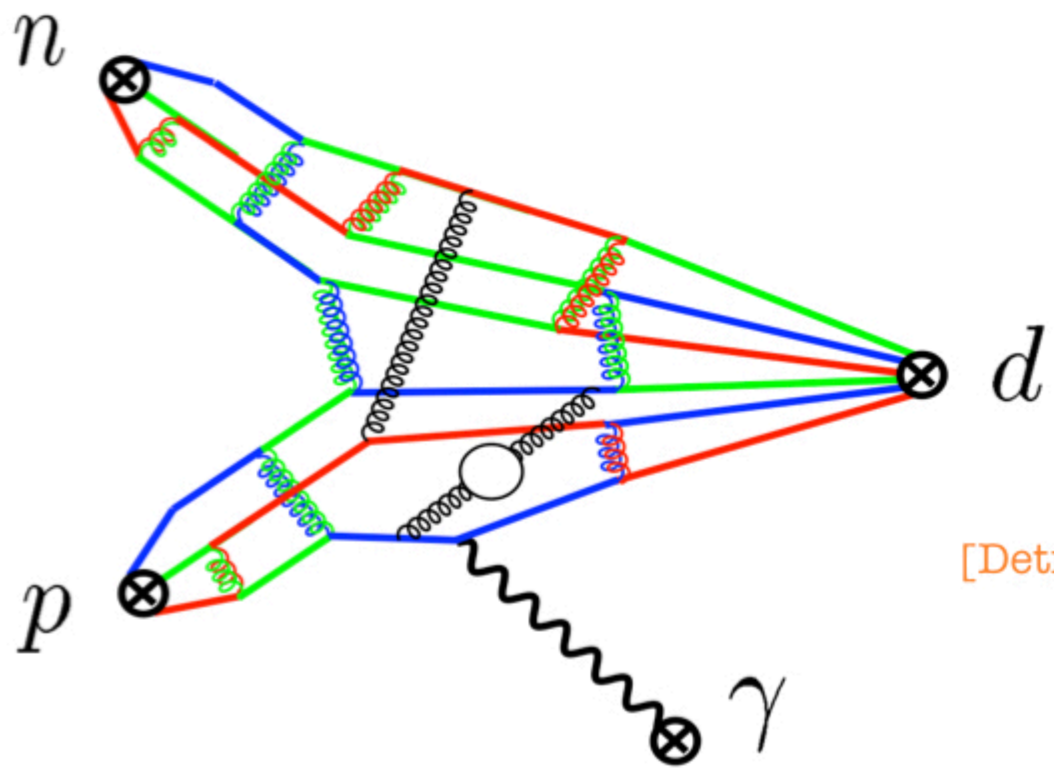
Nuclear reaction: $np \to d\gamma$



[Detmold and Savage (2004)]

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

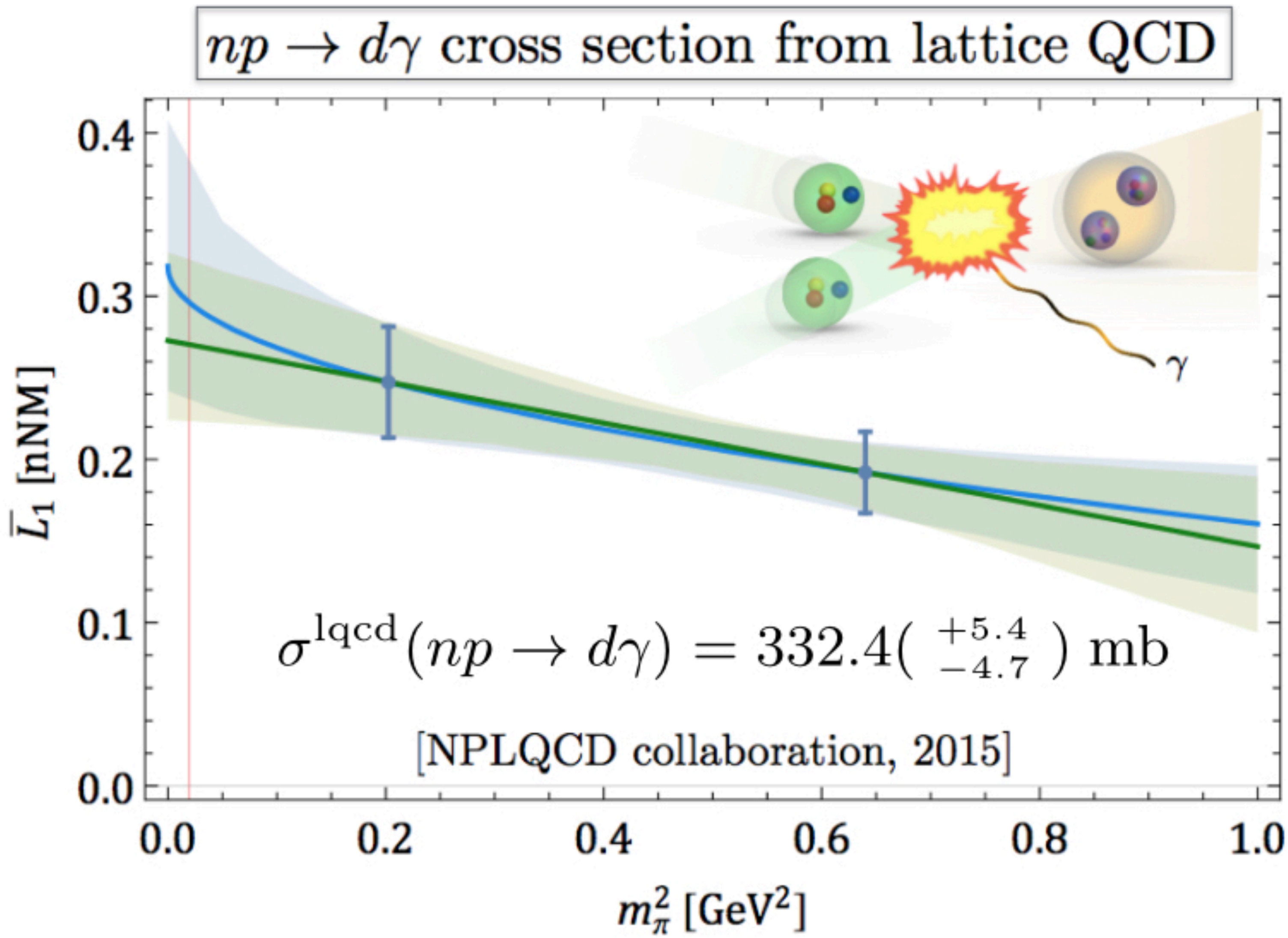
Nuclear reaction: $np \to d\gamma$



[Detmold and Savage (2004)]

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

$np \to d\gamma$

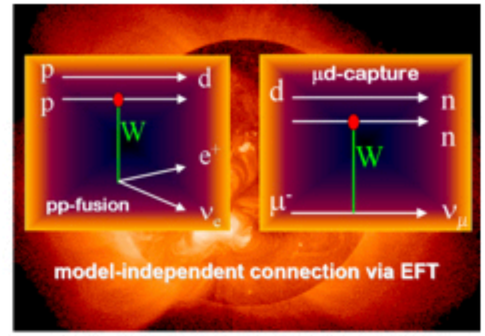


$$\sigma^{\mathrm{expt}}(np \to d\gamma) = 334.2(0.5)\ \mathrm{mb}$$

Nuclear structure: axial transitions

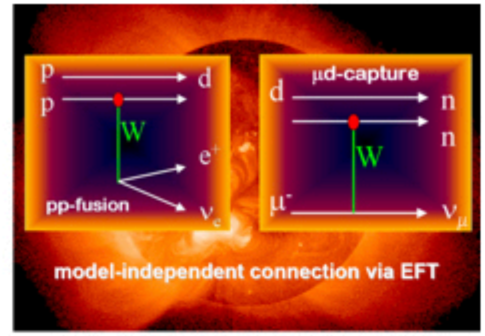
- Axial coupling to the NN system
  - $\mu^- d \to nn\nu_\mu$: MuSun @ PSI
  - $\nu d \to e^+ nn$: SNO
  - *"calibrating the sun"* $pp \to de^+\nu_e$

MuSun



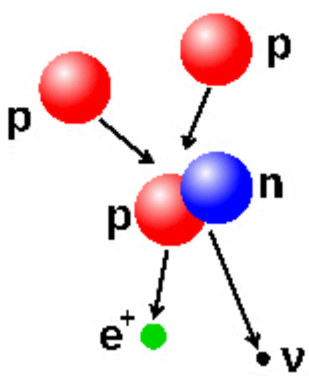
Nuclear structure: axial transitions

MuSun

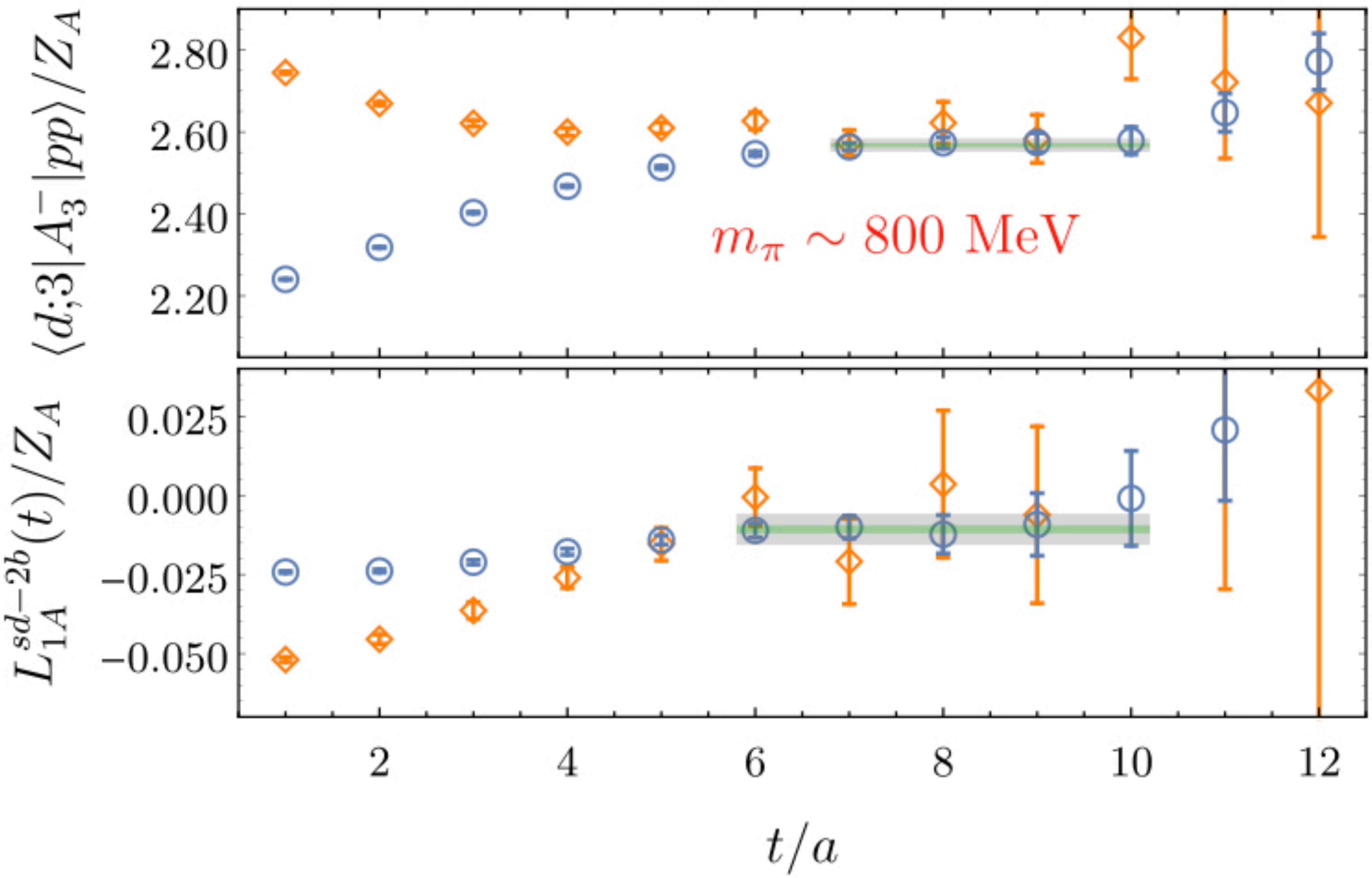


- Axial coupling to the NN system
  - $\mu^- d \to n n \nu_\mu$: MuSun @ PSI
  - $\nu d \to e^+ n n$: SNO
  - *"calibrating the sun"* $pp \to d e^+ \nu_e$

$$\left|\langle d; j \,|A_k^-|\, pp\rangle\right| \equiv g_A C_\eta \sqrt{\frac{32\pi}{\gamma^3}}\,\Lambda(p)\,\delta_{jk}$$



$$\Lambda(0) = \frac{1}{\sqrt{1-\gamma\rho}}\{e^\chi - \gamma a_{pp}[1 - \chi e^\chi E_1(\chi)] + \frac{1}{2}\gamma^2 a_{pp}\sqrt{r_1\rho}\} - \frac{1}{2g_A}\gamma a_{pp}\sqrt{1-\gamma\rho}\; L_{1,A}^{sd-2b}$$



$$\frac{L_{1,A}^{sd,2b}}{Z_A} = \frac{\langle {}^3S_1; J_z = 0 \left| A_3^3 \right| {}^1S_0; I_z = 0 \rangle - 2g_A}{2Z_A} = -0.0107(12)(48)$$

$$\Lambda(0)_{lqcd} = 2.6585(6)(71)(25) \qquad \Lambda(0)_{exp} = 2.652(2)$$

- Progress has been made in benchmarking lattice QCD calculations of nucleon-nucleon interactions.
- An important goal of lattice QCD is to generate hyperon-nucleon and hyperon-hyperon interactions with *fully-controlled* uncertainties.
- Prospect of a quantitative connection to QCD makes this an exciting time for nuclear physics.

USQCD US Lattice Quantum Chromodynamics

NSF Jefferson Lab Exploring the Nature of Matter OLCF Oak Ridge Leadership Computing Facility

NERSC National Energy Research Scientific Computing Center

Department of Energy United States of America