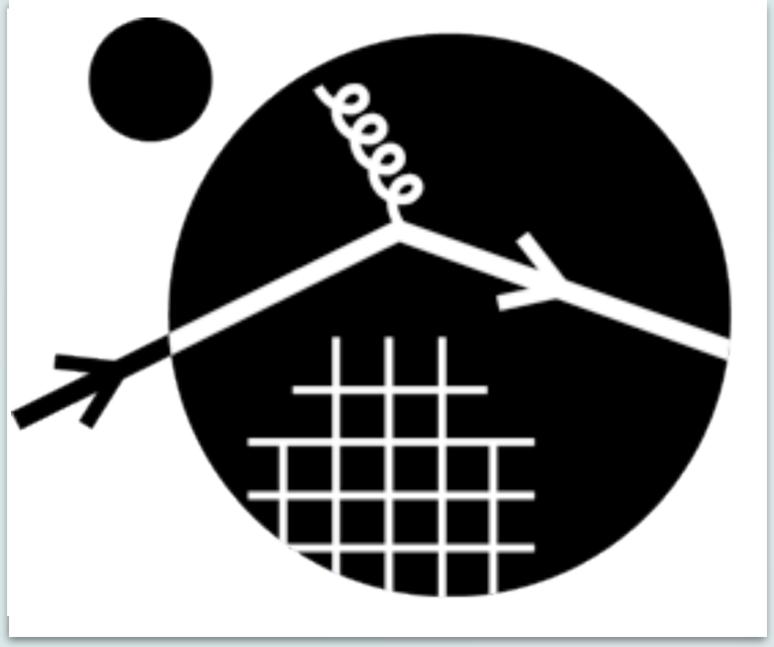
STATUS OF LQCD CALCULATIONS FOR MULTI-NUCLEON SYSTEMS

Zohreh Davoudi, MIT



Goals and impact

Challenges and Recent advances

Nuclei and hypernuclei from QCD

Nuclear matrix elements

Nuclear structure

Scattering and hadronic interactions

INT Workshop on
Lattice QCD Input for Neutrinoless Double-β Decay
July 6 - 7, 2017

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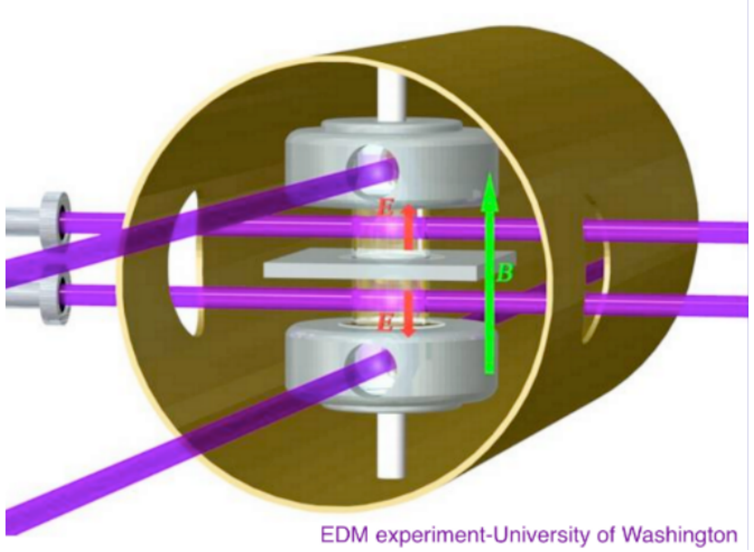
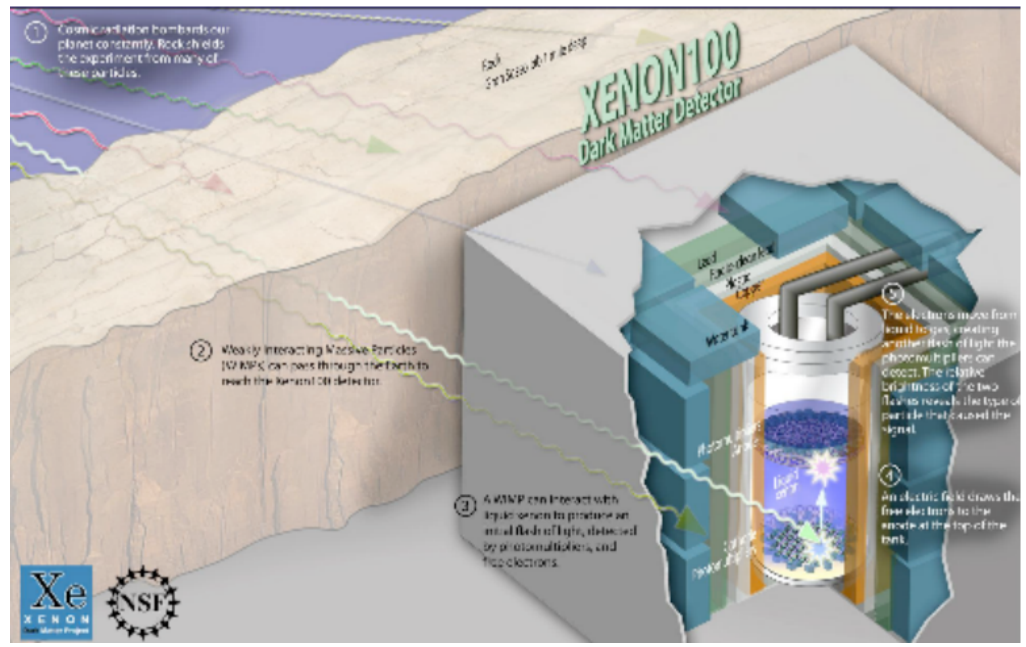
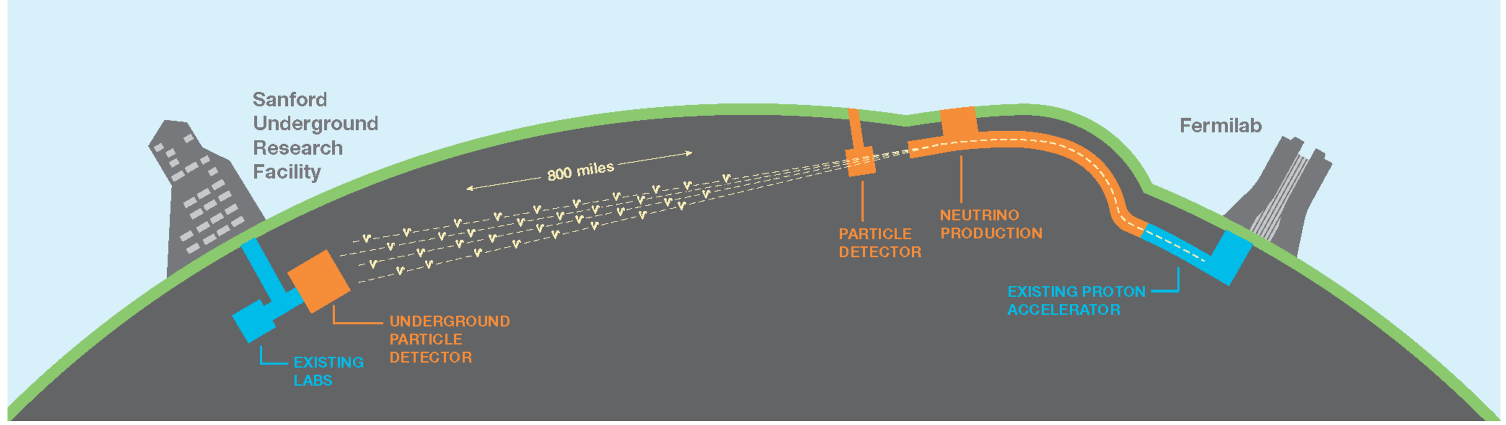
Nuclear matrix elements for tests of fundamental symmetries of nature…



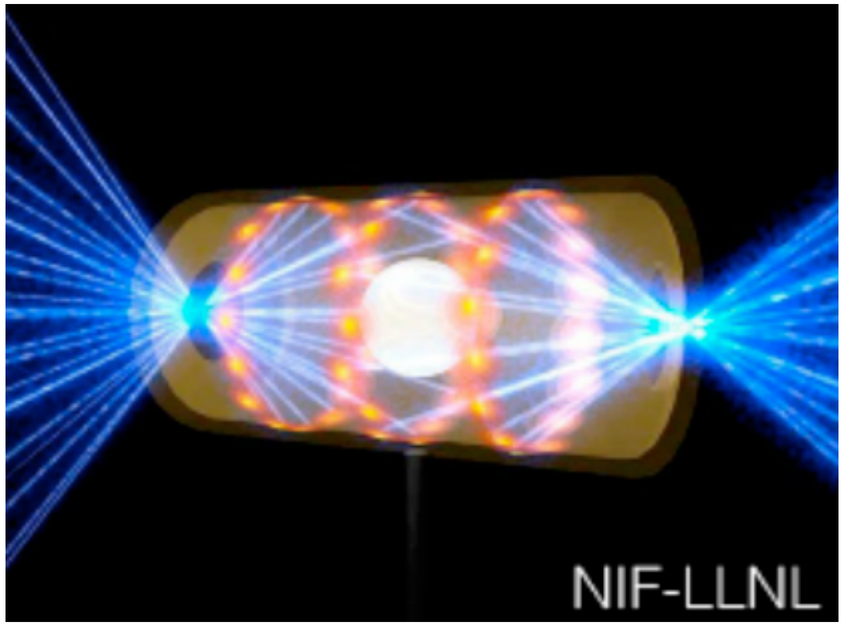
…and beyond the SM searches, neutrino experiments, etc.

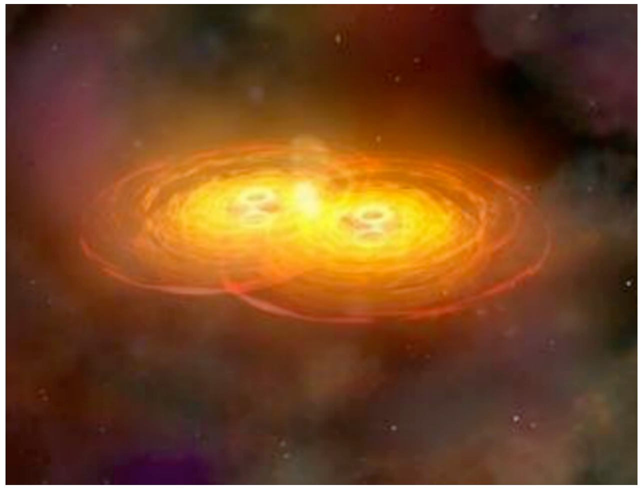


Deep Underground Neutrino Experiment

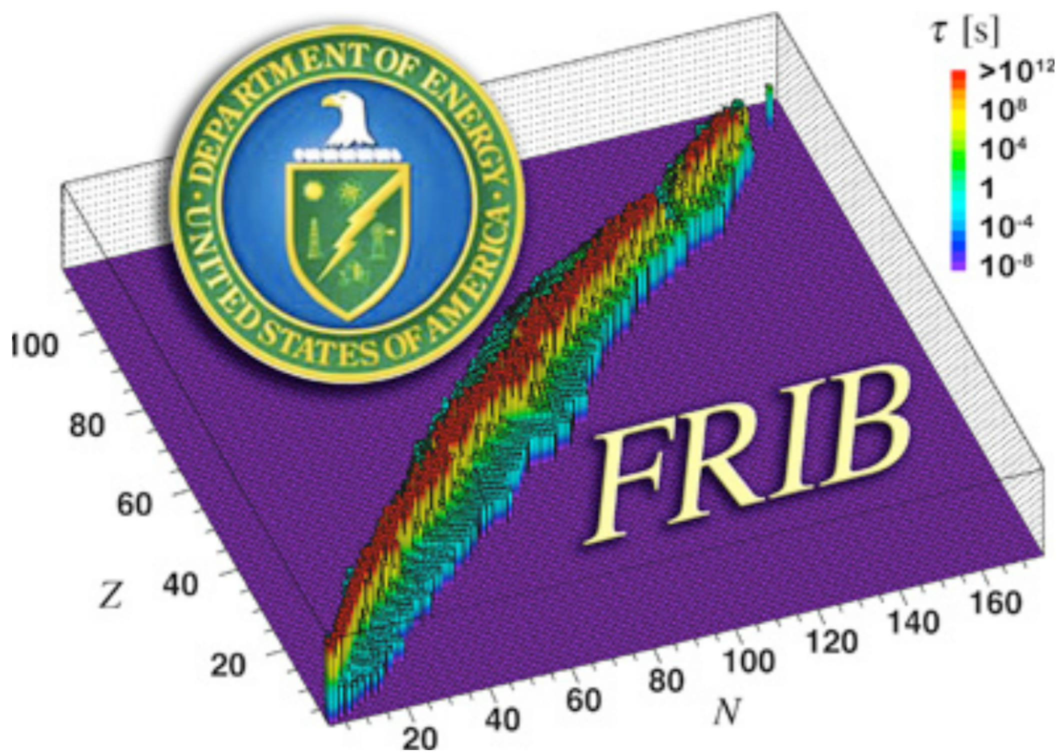


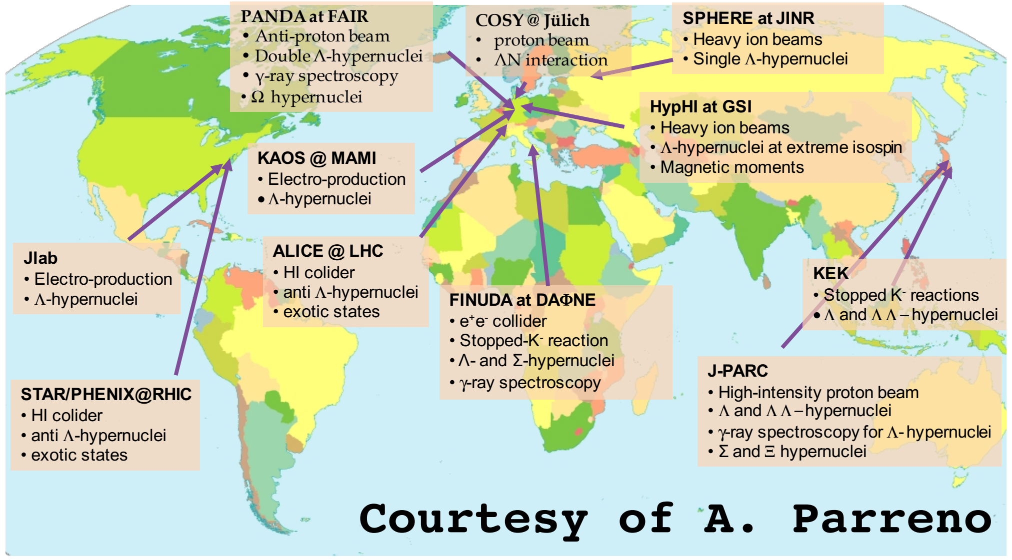
Nuclear reactions



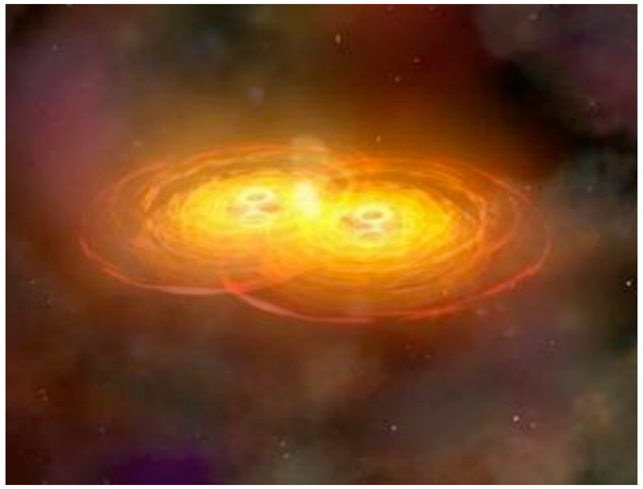


Nuclear and hypernuclear forces





updated from J. Pochodzalla, Int. Journal Modern Physics E, Vol 16, no. 3 (2007) 925-936



Quark and gluon structure of hadrons and nuclei

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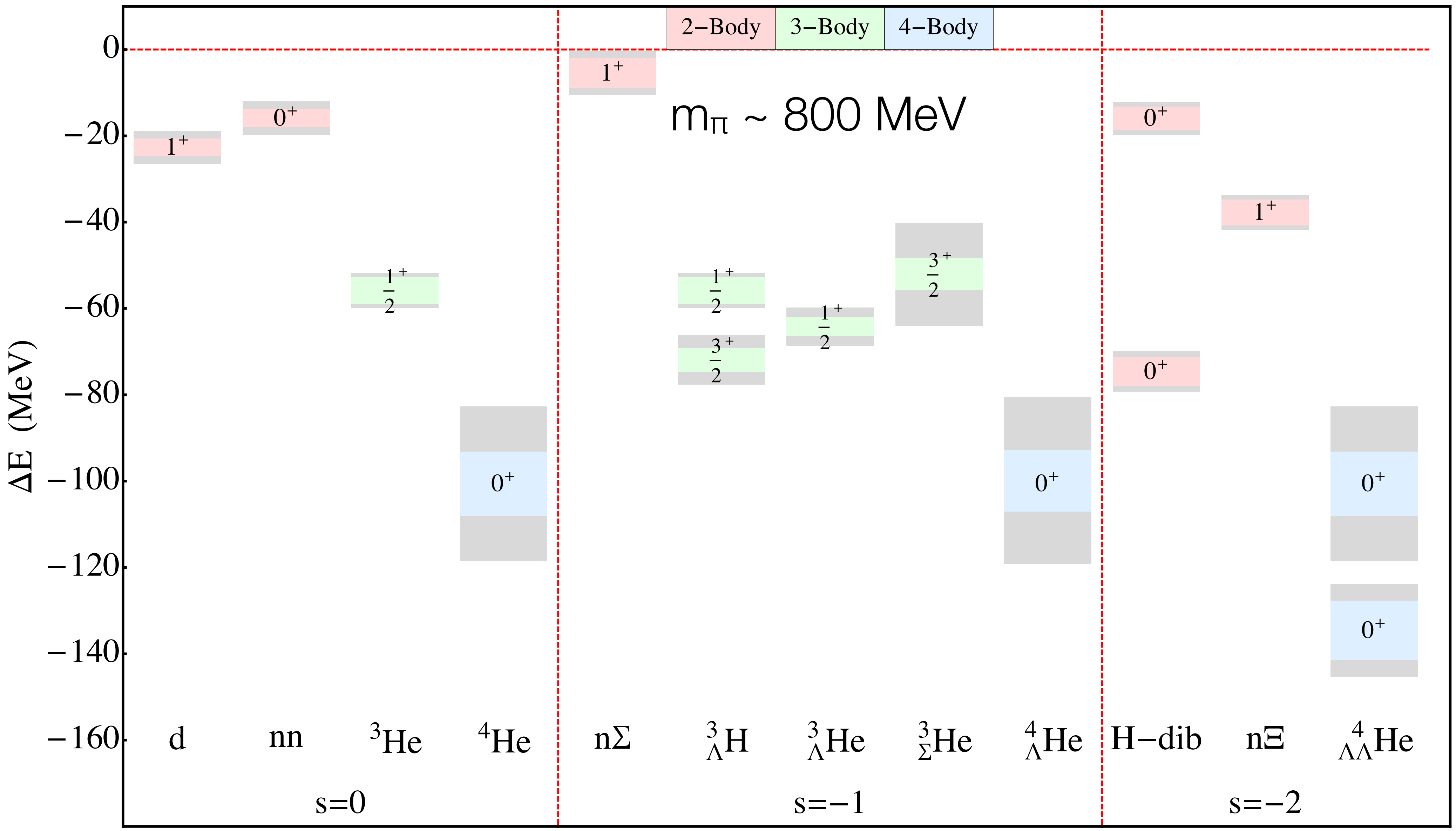
LIGHT NUCLEI AND HYPERNUCLEI
AT A FLAVOR-SYMMETRIC POINT

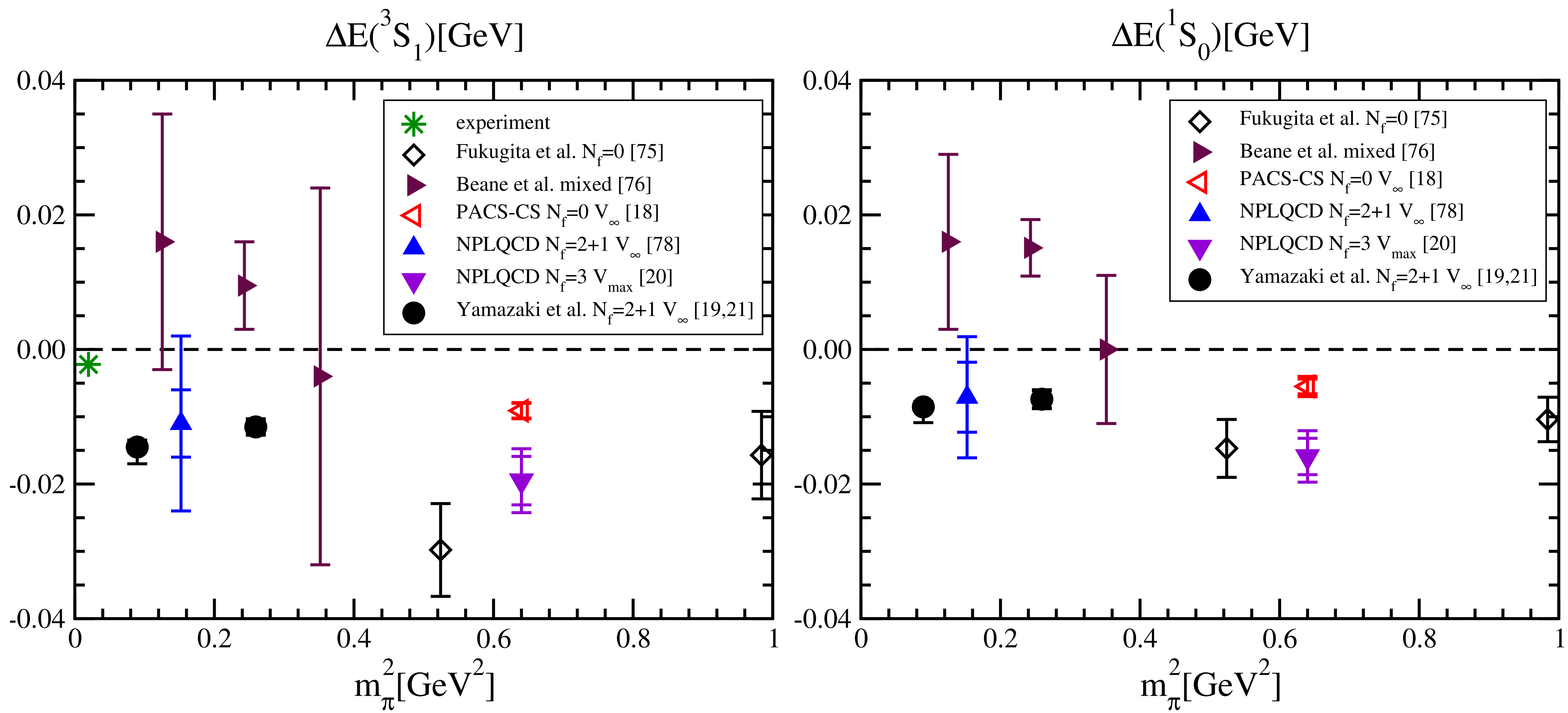
$$m_\pi = 806\ \text{MeV}$$

$N_f = 3, \;\; m_\pi = 0.806 \text{ GeV}, \;\; a = 0.145(2) \text{ fm}$



Beane et al (NPLQCD), Phys. Rev. D87, 034506 (2013).

A COMPILATION OF BINDING ENERGIES IN THE TWO-NUCLEON SECTOR (2014)

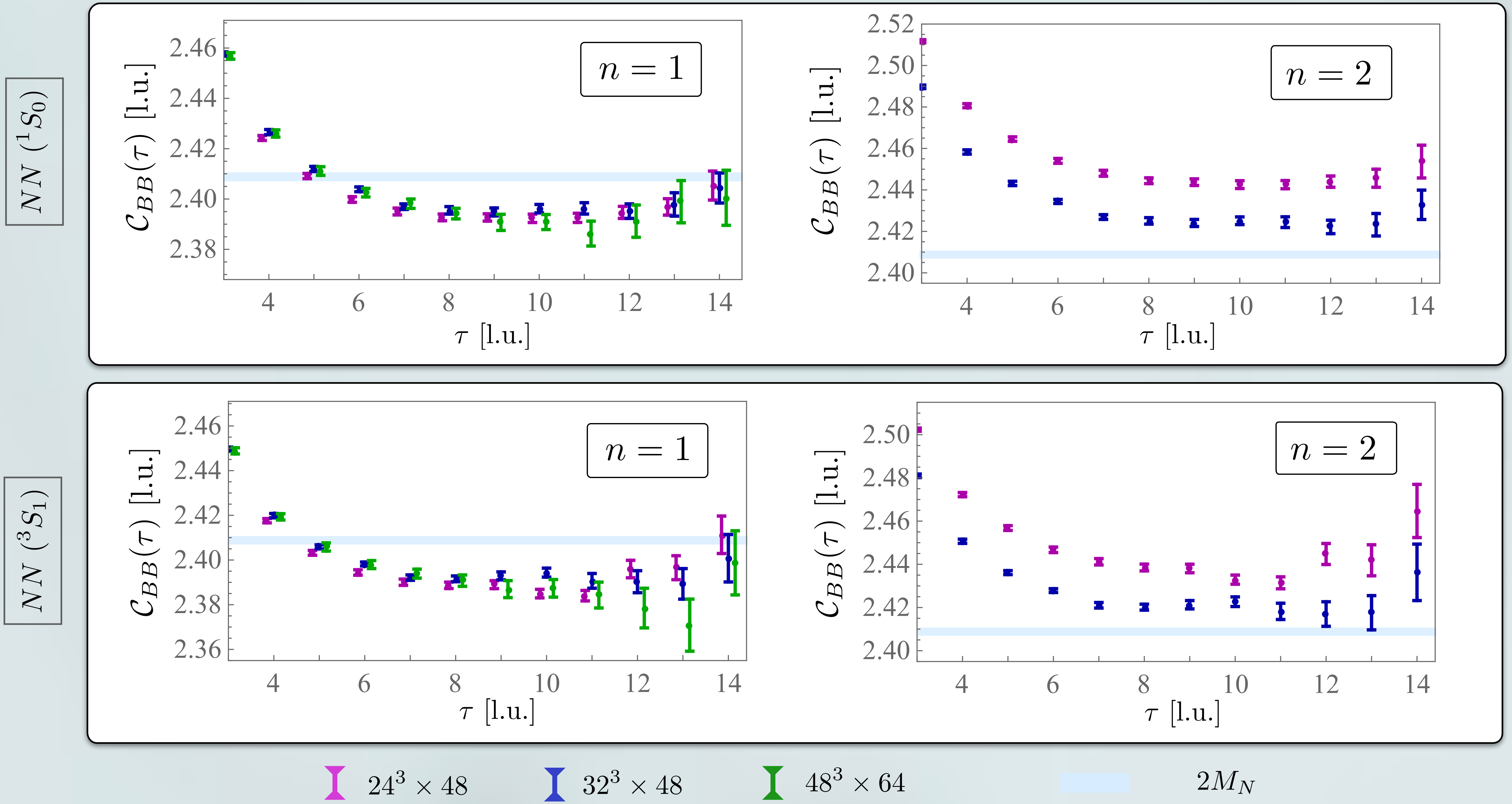


Yamazaki, PoS(LATTICE2014)009.

See also: Orginos et al (NPLQCD), Phys. Rev. D 92, 114512 (2015).
And: Berkowitz et al (CalLat), Phys. Lett. B, Volume 765, 10 (2017), 285.

ARE THESE BOUND STATES ROBUST?

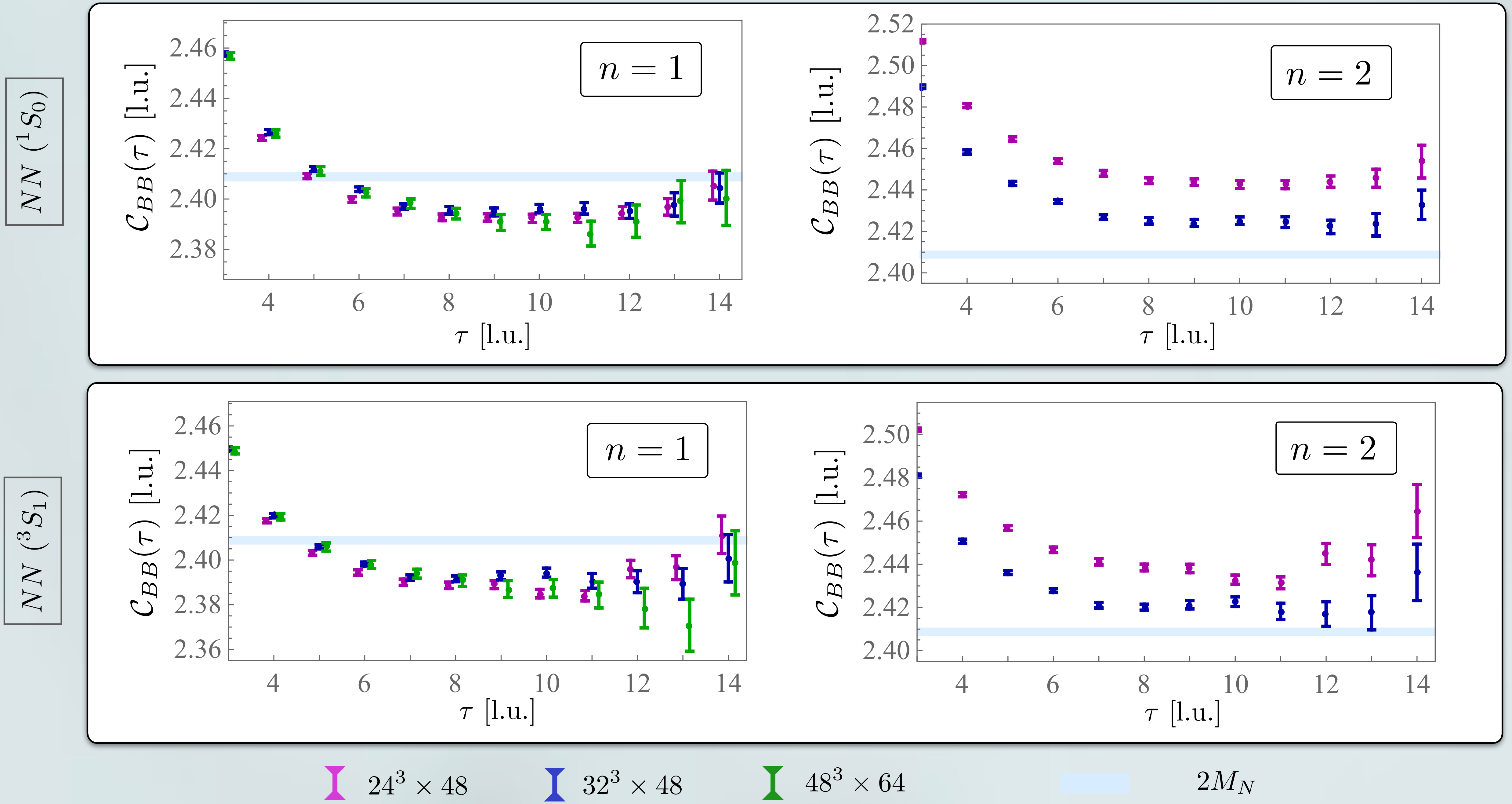
$N_f = 3,\ m_\pi = 0.806\ \text{GeV},\ a = 0.145(2)\ \text{fm}$



$$C_{\hat{\mathcal{O}},\hat{\mathcal{O}}'}(\tau;\mathbf{d}) \; = \; \sum_{\mathbf{x}} e^{2\pi i \mathbf{d}\cdot\mathbf{x}/L} \langle 0|\hat{\mathcal{O}}'(\mathbf{x},\tau)\hat{\mathcal{O}}^\dagger(\mathbf{0},0)|0\rangle = \mathcal{Z}_0'\mathcal{Z}_0^\dagger e^{-E^{(0)}\tau} + \mathcal{Z}_1'\mathcal{Z}_1^\dagger e^{-E^{(1)}\tau} + \ldots$$

Beane et al (NPLQCD), arXiv:1705.09239, Wagman et al (NPLQCD), arXiv:1706.06550.

$N_f = 3,\ m_\pi = 0.806\ \mathrm{GeV},\ a = 0.145(2)\ \mathrm{fm}$



Volume dependence unambiguously signals a bound ground state!

Beane et al (NPLQCD), arXiv:1705.09239, Wagman et al (NPLQCD), arXiv:1706.06550.

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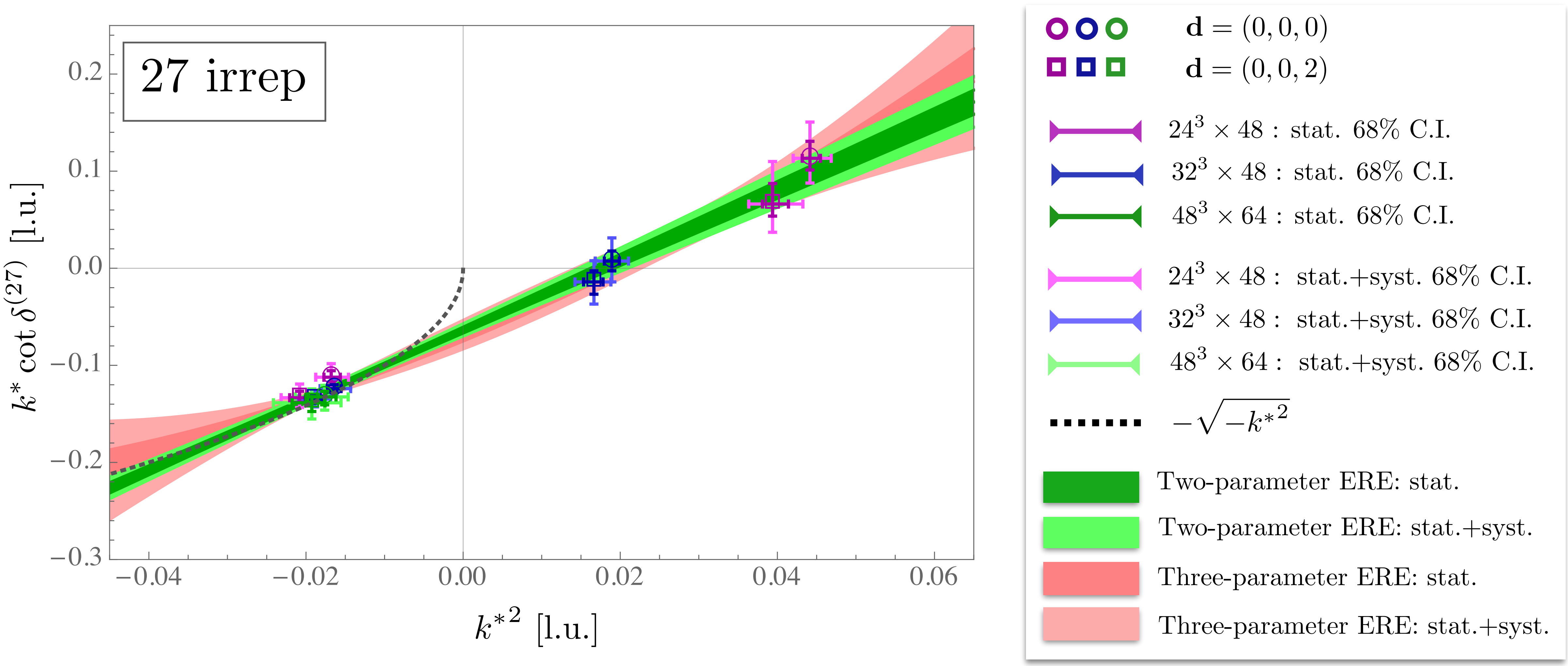
BARYON-BARYON SCATTERING AND LOW-ENERGY INTERACTIONS AT A FLAVOR-SYMMETRIC POINT

$m_\pi = 806 \text{ MeV}$

$N_f = 3,\ m_\pi = 0.806$ GeV, $a = 0.145(2)$ fm

Wagman et al (NPLQCD), arXiv:1706.06550.



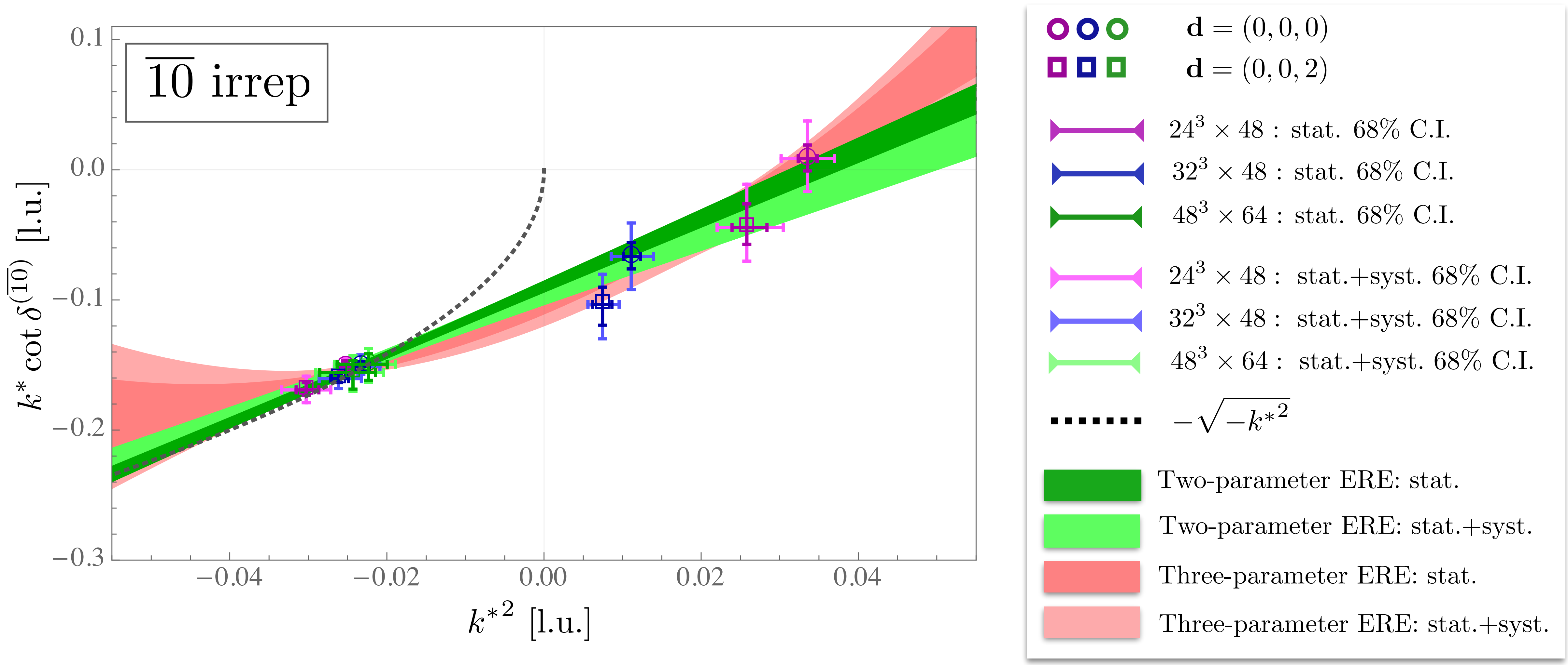
NPLQCD's conclusion: clear evidence for a bound state

Luescher (1986, 1990).

$$B = 20.6^{(+1.8)(+2.8)}_{(-2.4)(-1.6)} \text{ MeV}$$

$N_f = 3,\ m_\pi = 0.806\ \text{GeV},\ a = 0.145(2)\ \text{fm}$

Wagman et al (NPLQCD), arXiv:1706.06550.

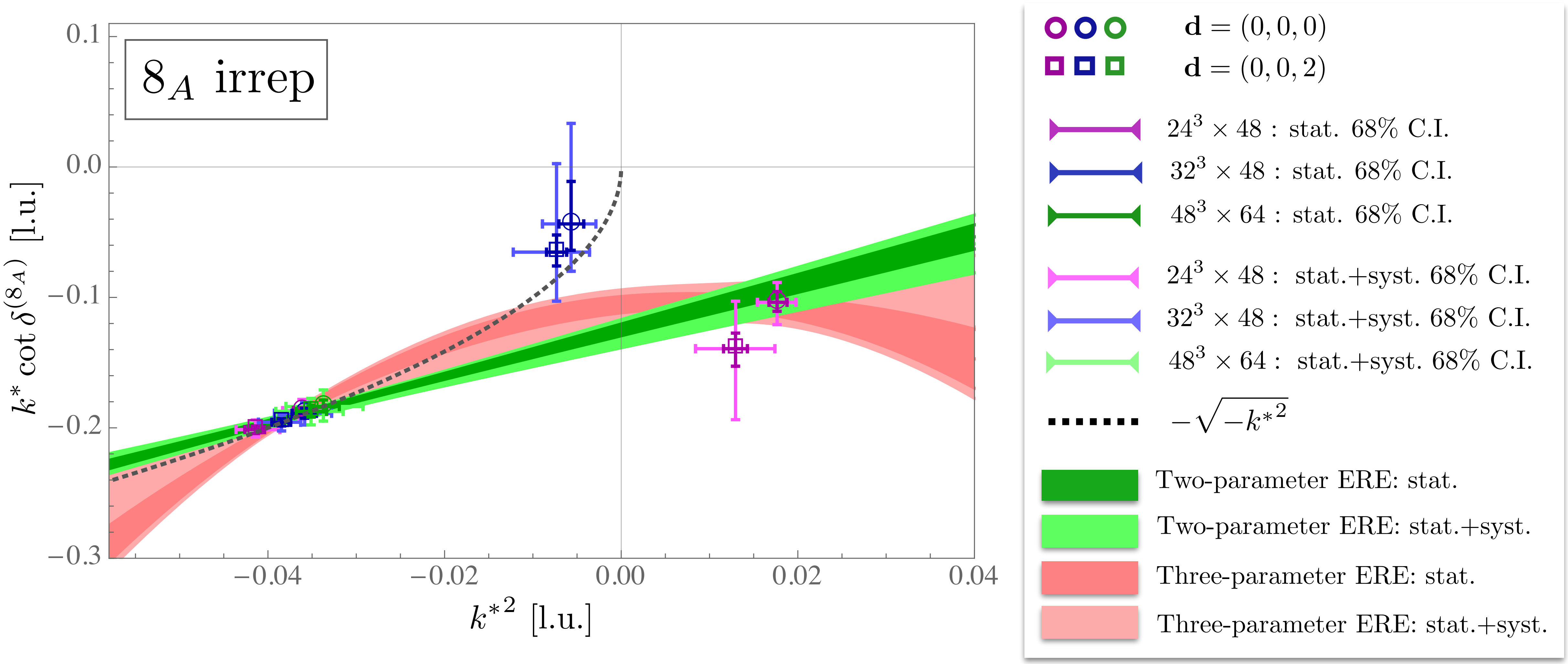


NPLQCD's conclusion: clear evidence for a bound state

$$B = 27.9^{(+3.1)(+2.2)}_{(-2.3)(-1.4)}\ \text{MeV}$$

$N_f = 3,\ m_\pi = 0.806$ GeV, $a = 0.145(2)$ fm

Wagman et al (NPLQCD), arXiv:1706.06550.

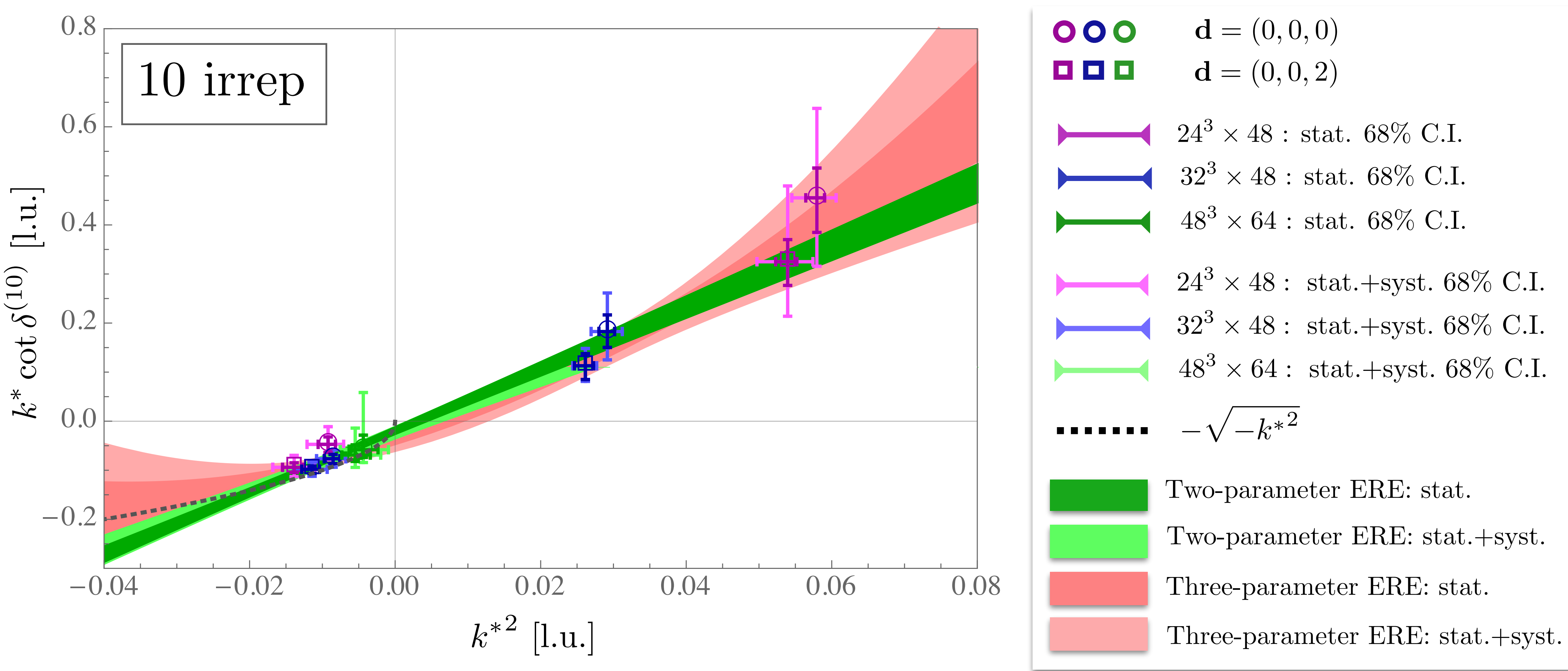


NPLQCD's conclusion: clear evidence for a bound state

$$B = 40.7^{(+2.1)(+2.4)}_{(-3.2)(-1.4)}\ \texttt{MeV}$$

$N_f = 3, \ m_\pi = 0.806 \text{ GeV}, \ a = 0.145(2) \text{ fm}$

Wagman et al (NPLQCD), arXiv:1706.06550.

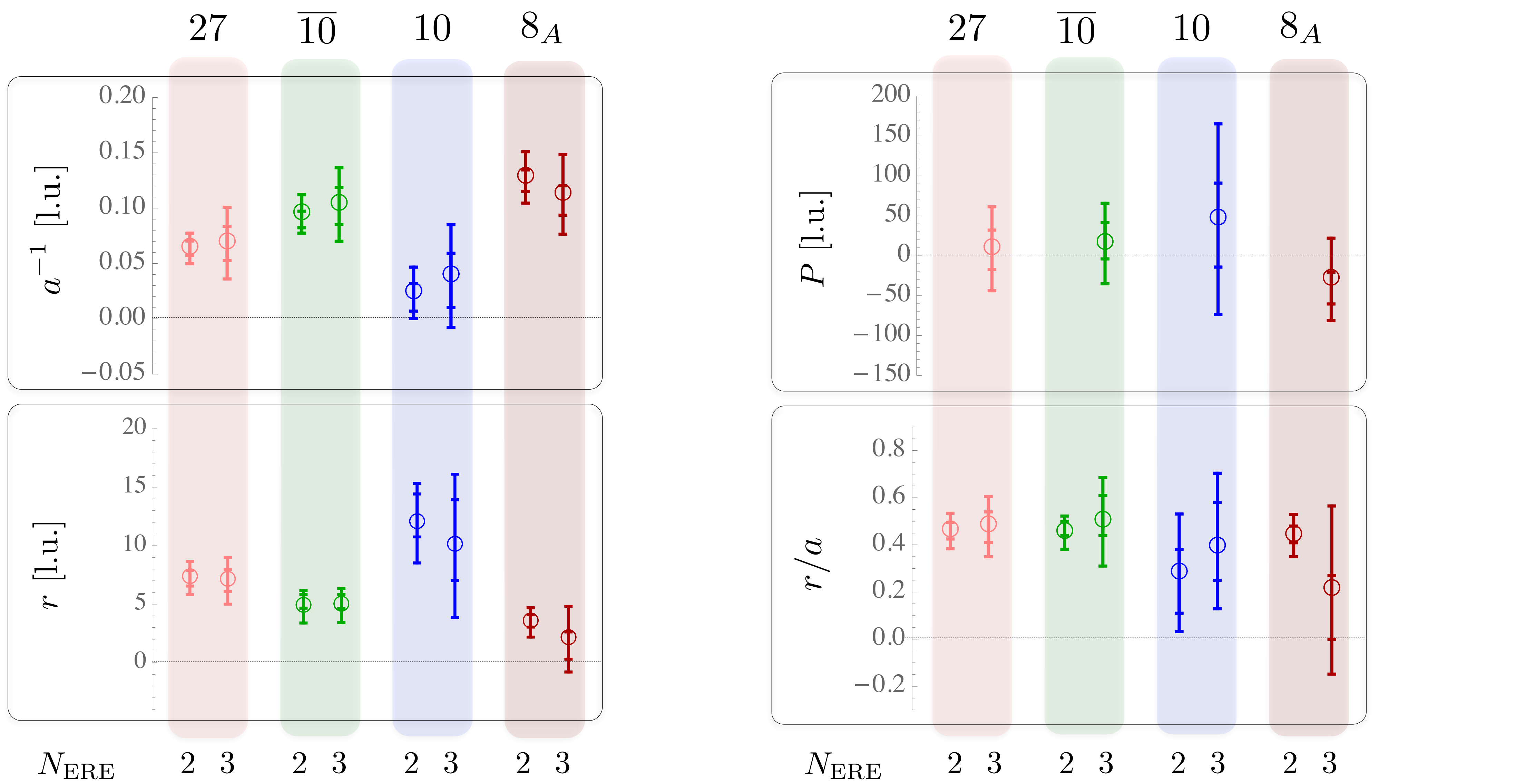


NPLQCD's conclusion: bound state not conclusive

$$B = 6.7^{(+3.3)(+1.8)}_{(-1.9)(-6.2)} \ \texttt{MeV}$$

$N_f = 3, \ m_\pi = 0.806 \text{ GeV}, \ a = 0.145(2) \text{ fm}$

Wagman et al (NPLQCD), arXiv:1706.06550.



Evidence for $SU(6)$ spin-flavor symmetry predicted at large N_c

Kaplan and Savage, Phys.Lett.B365:244-251,1996.

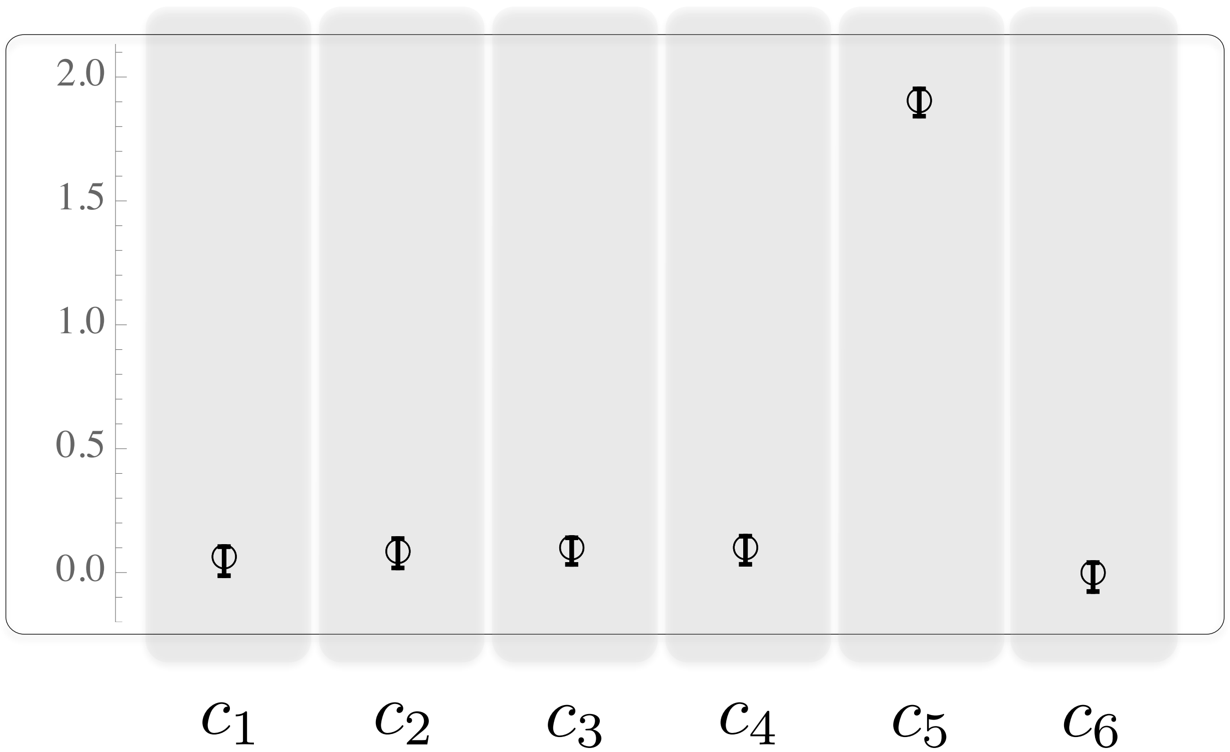
$N_f = 3,\ m_\pi = 0.806\ \text{GeV},\ a = 0.145(2)\ \text{fm}$

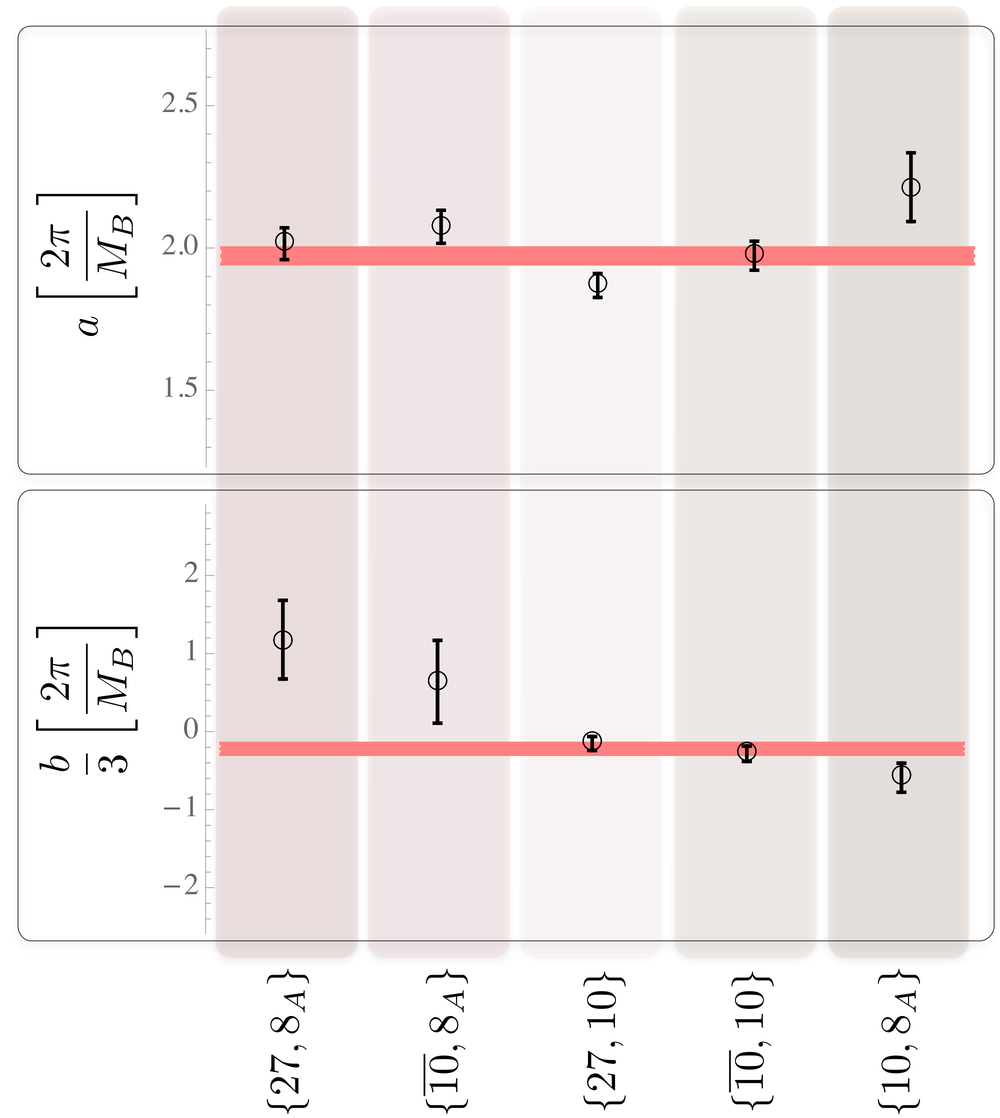
Wagman et al (NPLQCD), arXiv:1706.06550.

$$\mathcal{L}^{(0)}_{BB} = -c_1 \text{Tr}(B_i^\dagger B_i B_j^\dagger B_j) - c_2 \text{Tr}(B_i^\dagger B_j B_j^\dagger B_i) - c_3 \text{Tr}(B_i^\dagger B_j^\dagger B_i B_j) - c_4 \text{Tr}(B_i^\dagger B_j^\dagger B_j B_i) - c_5 \text{Tr}(B_i^\dagger B_i)\text{Tr}(B_j^\dagger B_j) - c_6 \text{Tr}(B_i^\dagger B_j)\text{Tr}(B_j^\dagger B_i).$$

Savage and Wise, Phys.Rev. D53 (1996) 349.

Unnatural case @ $\mu = m_\pi$





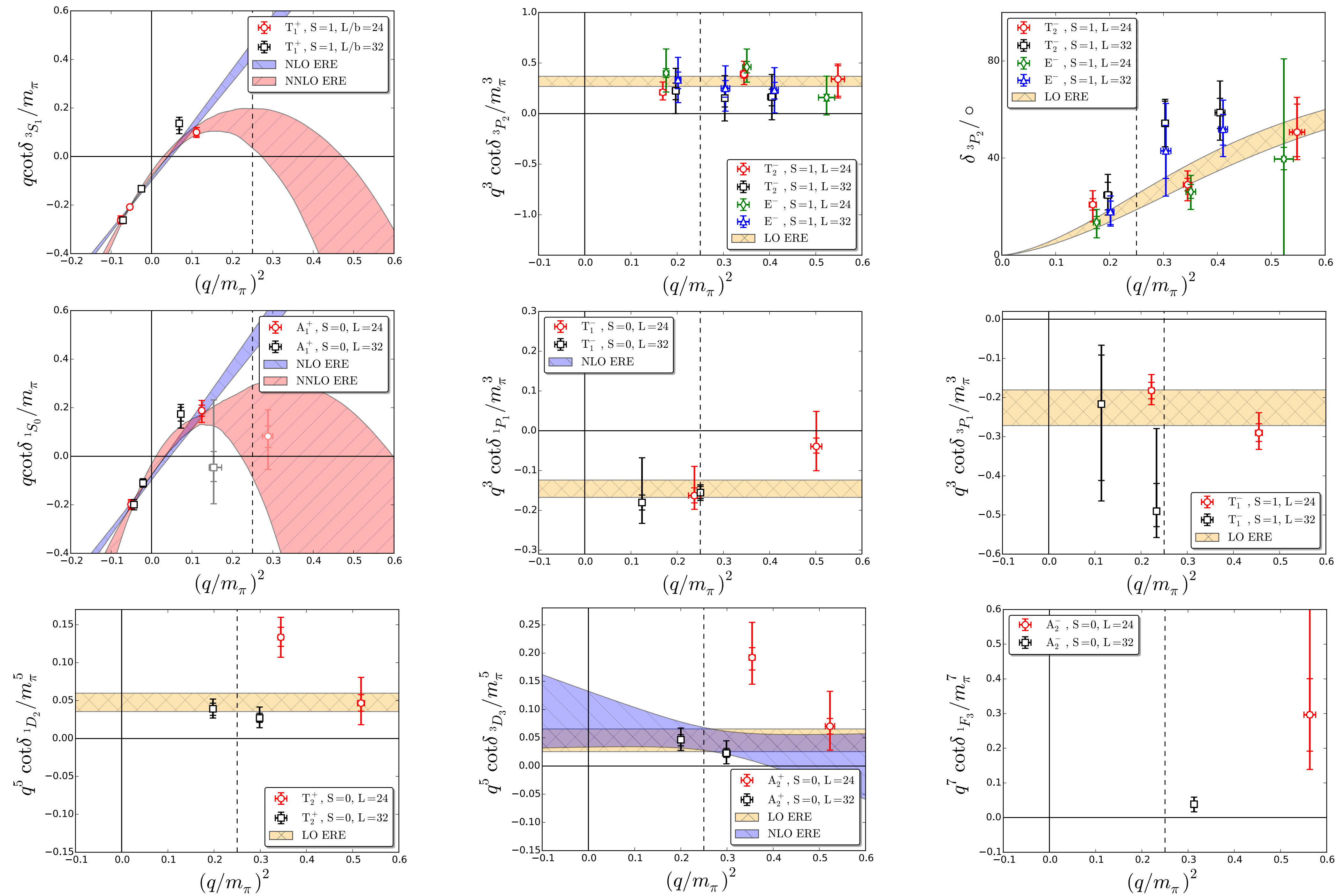
$SU(3) \longrightarrow SU(6) \longrightarrow SU(16)$

Kaplan and Savage, Phys.Lett.B365:244-251,1996.

NUCLEON-NUCLEON SCATTERING IN HIGHER PARTIAL WAVES AT A FLAVOR-SYMMETRIC POINT

$m_\pi = 806$ MeV

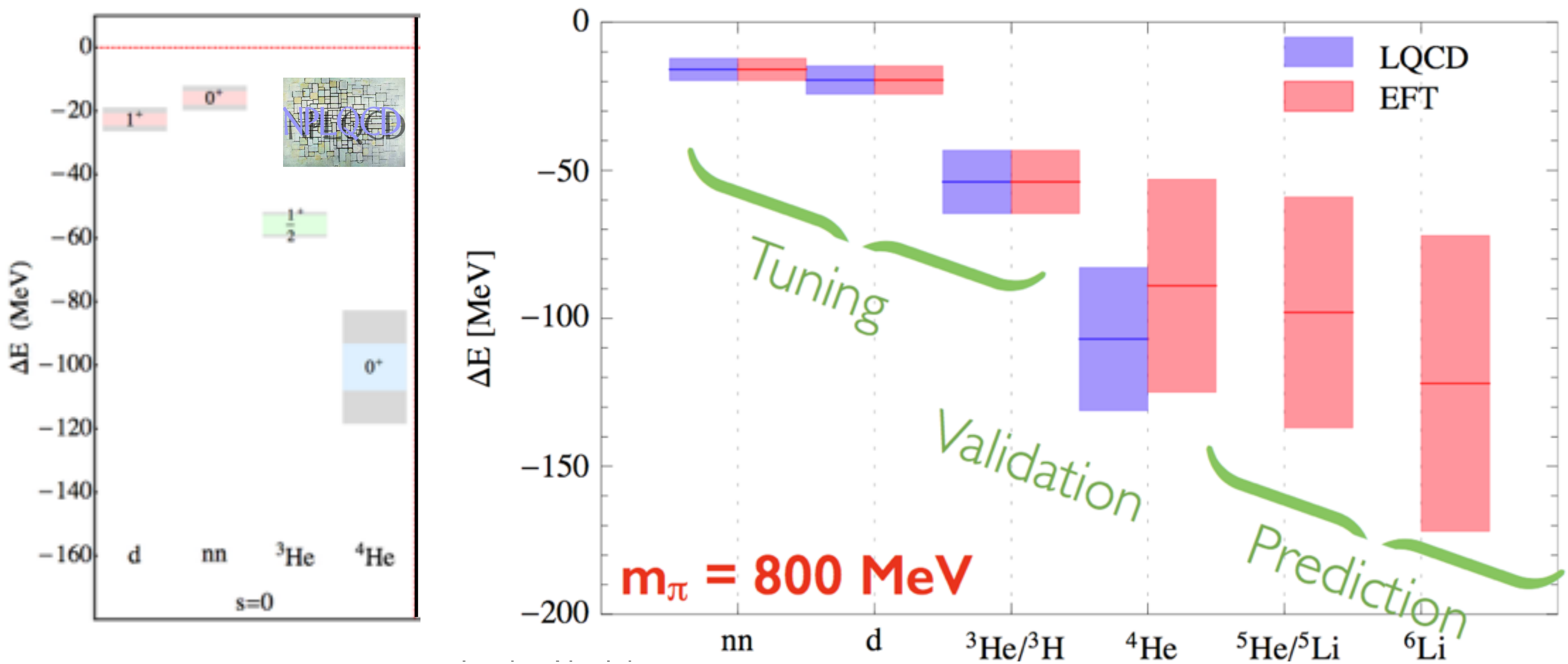
$N_f = 3,\ m_\pi = 0.806$ GeV$,\ a = 0.145(2)$ fm



Berkowitz et al (CalLat), Phys. Lett. B, Volume 765, 10 (2017), 285.

THE IMPACT ON AB INITIO NUCLEAR MANY-BODY CALCULATIONS

Effective Field Theory for Lattice Nuclei,
Barnea et al, Phys.Rev.Lett. 114 (2015) no.5, 052501

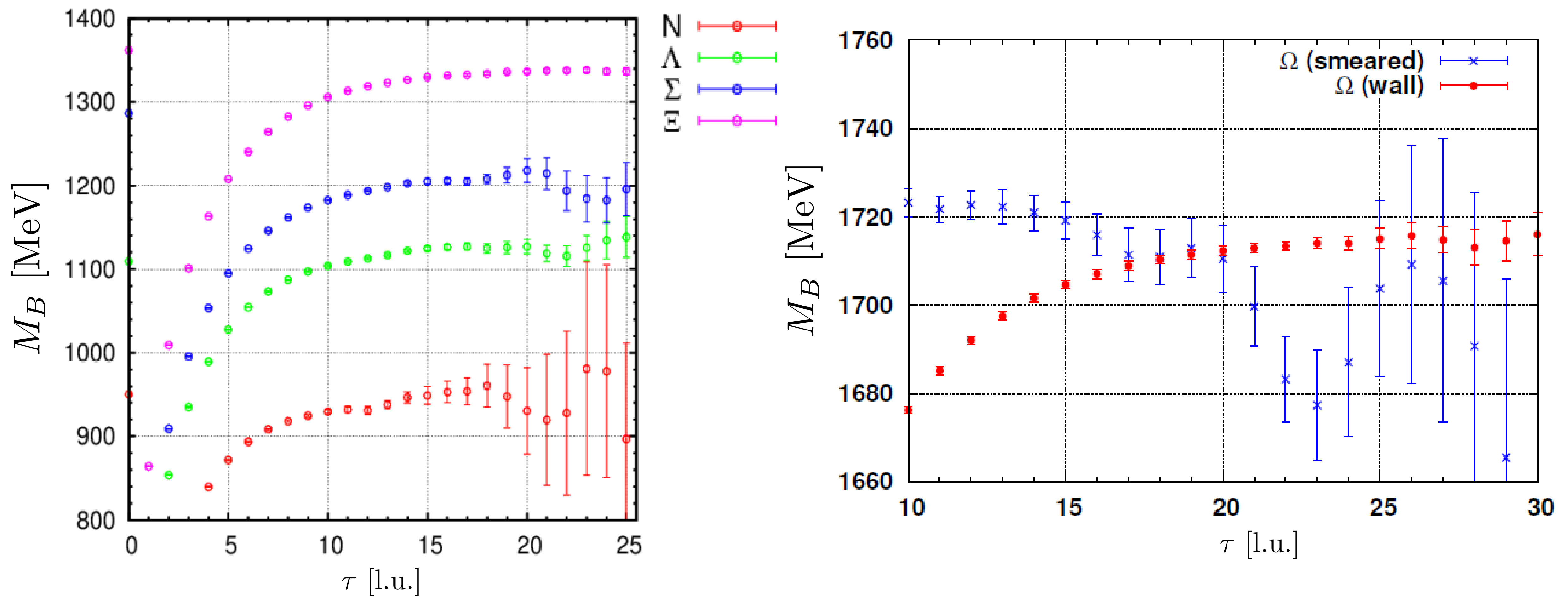


QCD input → Few-body EFT interactions → Many-body calculations of nuclei and hypernuclei

Ground-State Properties of 4He and 16 O Extrapolated from Lattice QCD with Pionless EFT
Contessi et al, arXiv:1701.06516.

ONGOING WORK IN BARYON-BARYON SCATTERING AT THE PHYSICAL POINT

$N_f = 2+1,\ m_\pi = 146\ \text{MeV},\ a \approx 0.085\ \text{fm},\ L \approx 8\ \text{fm}$

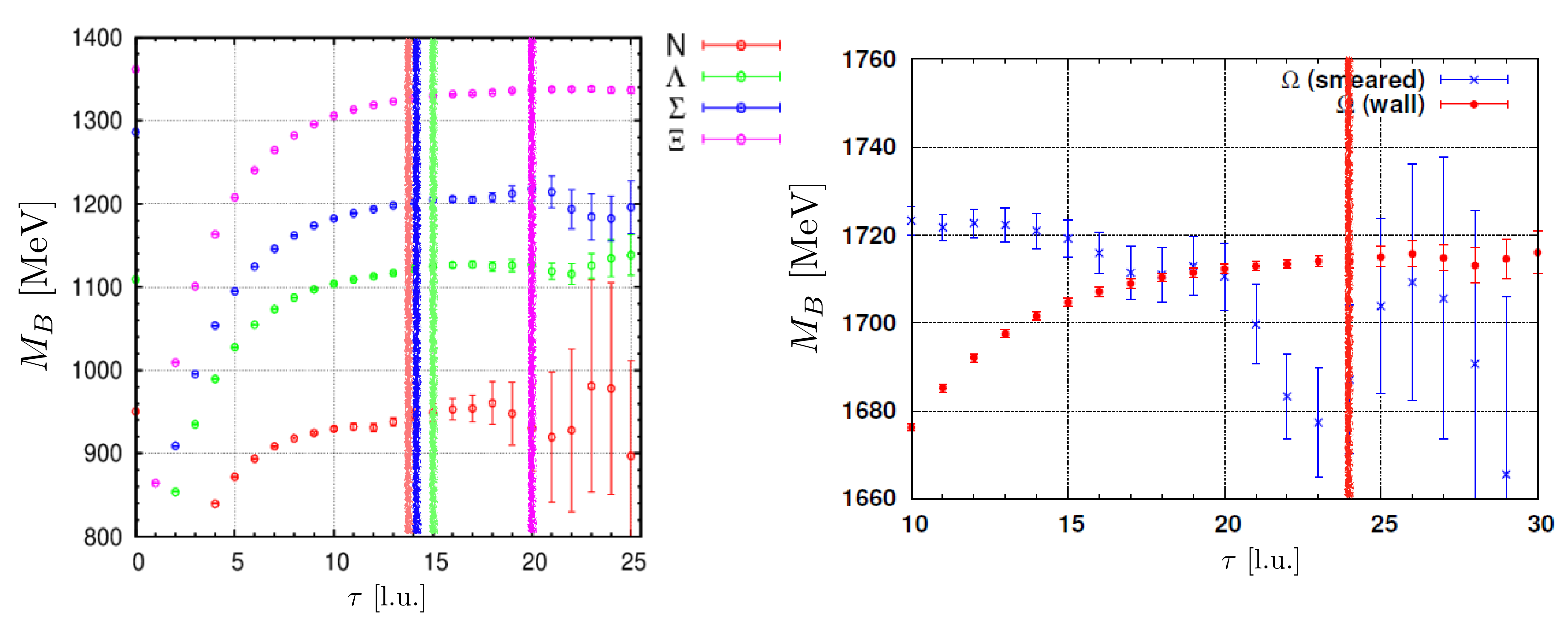


Lattice 2017: Talk by T. Doi

Potential method of HALQCD is used. Systematic uncertainties?

Detmold, Orginos and Savage, Phys. Rev. D76, 114503 (2007).
Beane, Detmold, Orginos and Savage, Prog.Part.Nucl.Phys.66,1 (2011).

$N_f = 2+1,\ m_\pi = 146\ \text{MeV},\ a \approx 0.085\ \text{fm},\ L \approx 8\ \text{fm}$



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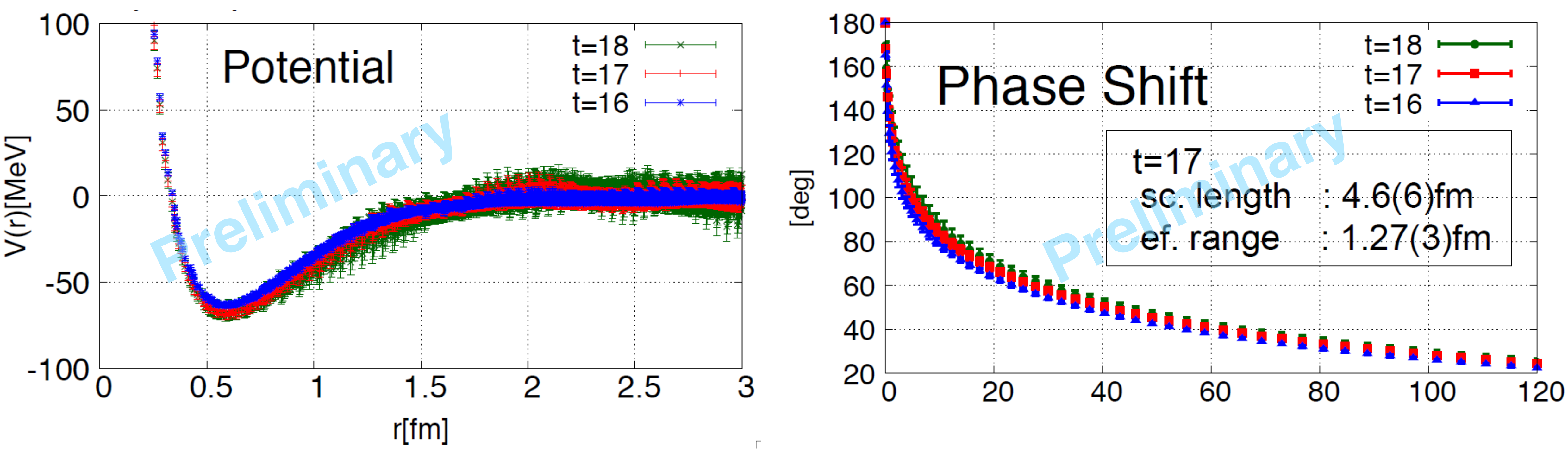
Potential method of HALQCD is used. Systematic uncertainties?

Detmold, Orginos and Savage, Phys. Rev. D76, 114503 (2007).
Beane, Detmold, Orginos and Savage, Prog.Part.Nucl.Phys.66,1 (2011).

$N_f = 2+1,\ m_\pi = 146\ \text{MeV},\ a \approx 0.085\ \text{fm},\ L \approx 8\ \text{fm}$

$\Omega\Omega$ system ($^1S_0$)



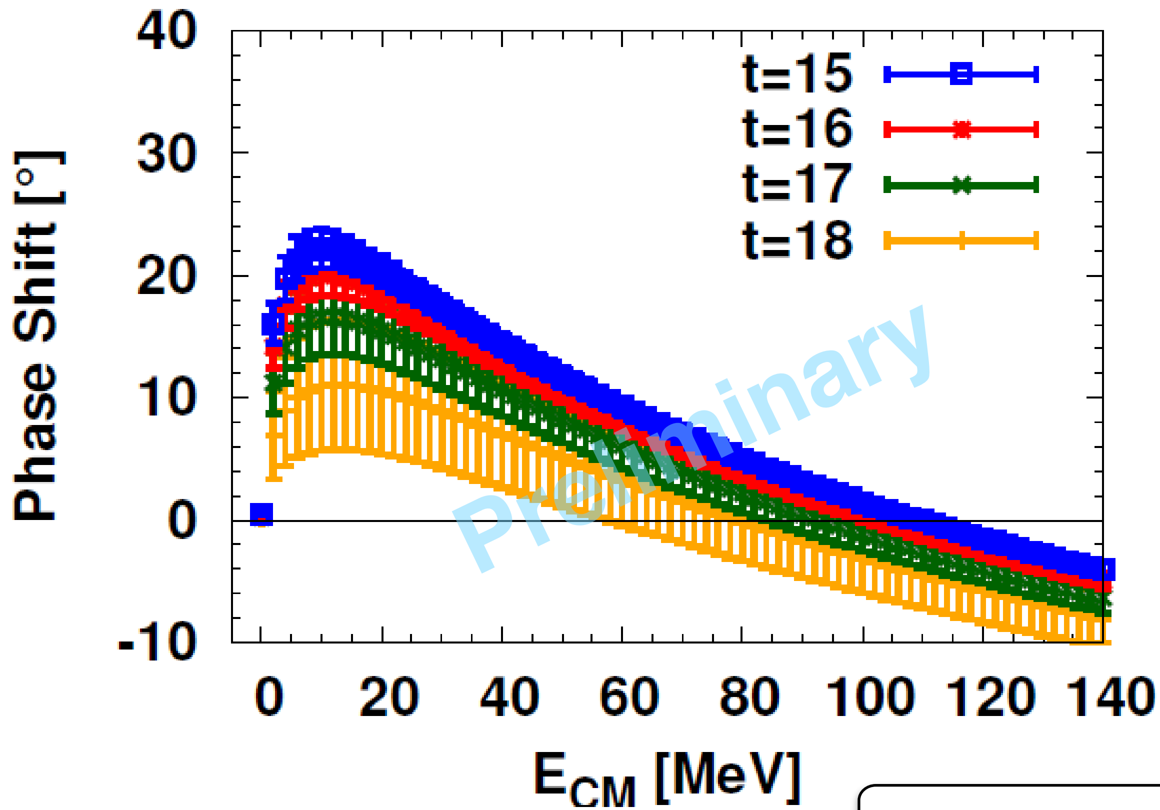
$t > 23$

HALQCD's conclusion: Strong interactions in both $\Omega\Omega(^1S_0)$ and $N\Omega(^5S_2)$ channels

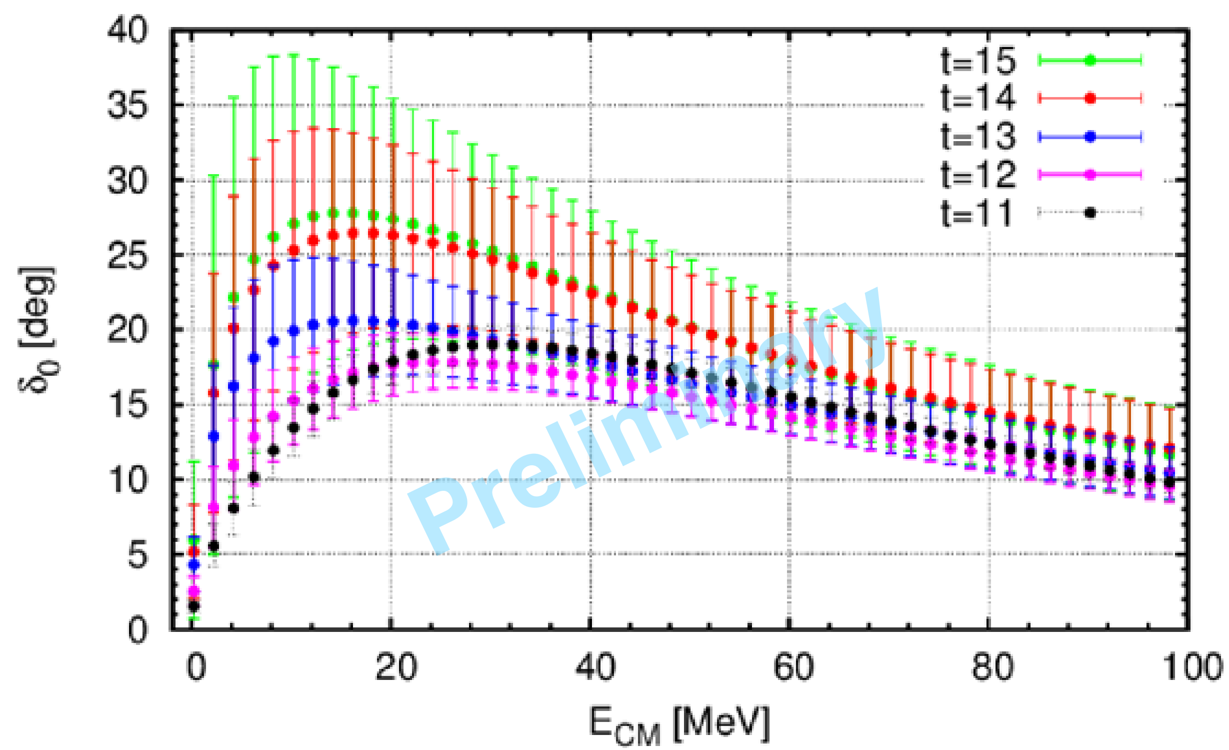
Lattice 2017: Talk by T. Doi

$N_f = 2+1,\ m_\pi = 146\ \text{MeV},\ a \approx 0.085\ \text{fm},\ L \approx 8\ \text{fm}$

ΞΞ (I=1, $^1S_0$)



ΞΣ (I=3/2, $^1S_0$)



$t > 20$

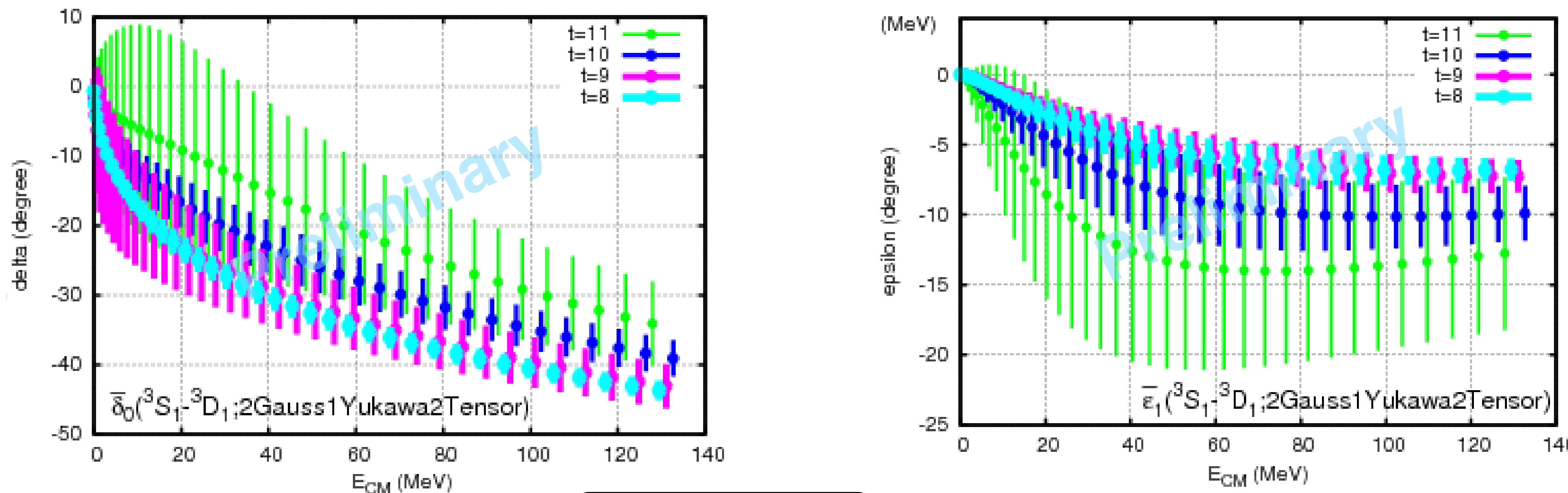
$t > 20$

HALQCD's conclusion: Strong interactions in these channels but no bound state

Lattice 2017: Talks by N. Ishii and T. Doi

$N_f = 2+1,\ m_\pi = 146\ \mathrm{MeV},\ a \approx 0.085\ \mathrm{fm},\ L \approx 8\ \mathrm{fm}$

$N\Sigma(^3S_1)$



$t > 14$

Lattice 2017: Talk by H. Nemura

See also:
Lattice 2017: Talk by K. Sasaki

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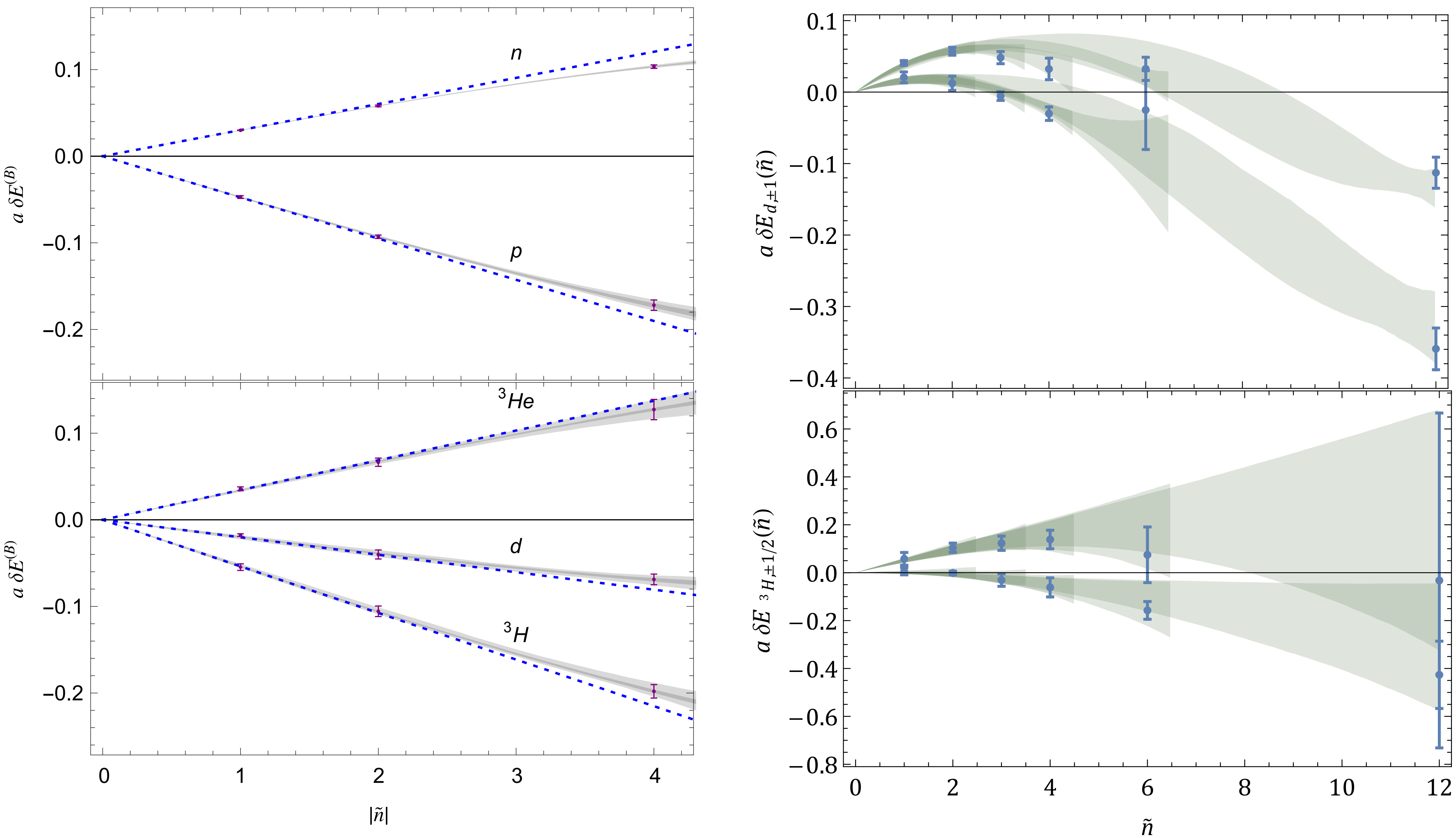
ELECTROMAGNETIC PROBES OF STRUCTURE

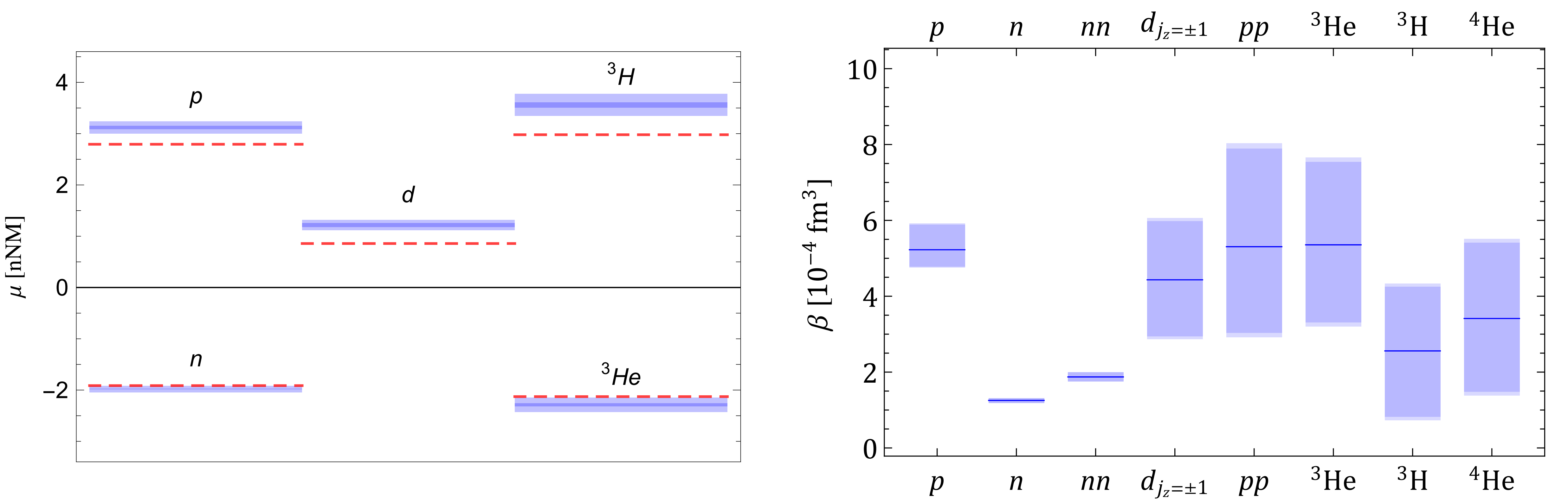
$$N_f = 3,\ m_\pi = 0.806\ \text{GeV},\ a = 0.145(2)\ \text{fm}$$



Chang et al (NPLQCD), Phys. Rev. Lett. 113, 252001 (2014), and Phys. Rev. D 92, 114502 (2015).

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

$N_f = 3,\ m_\pi = 0.806\ \text{GeV},\ a = 0.145(2)\ \text{fm}$



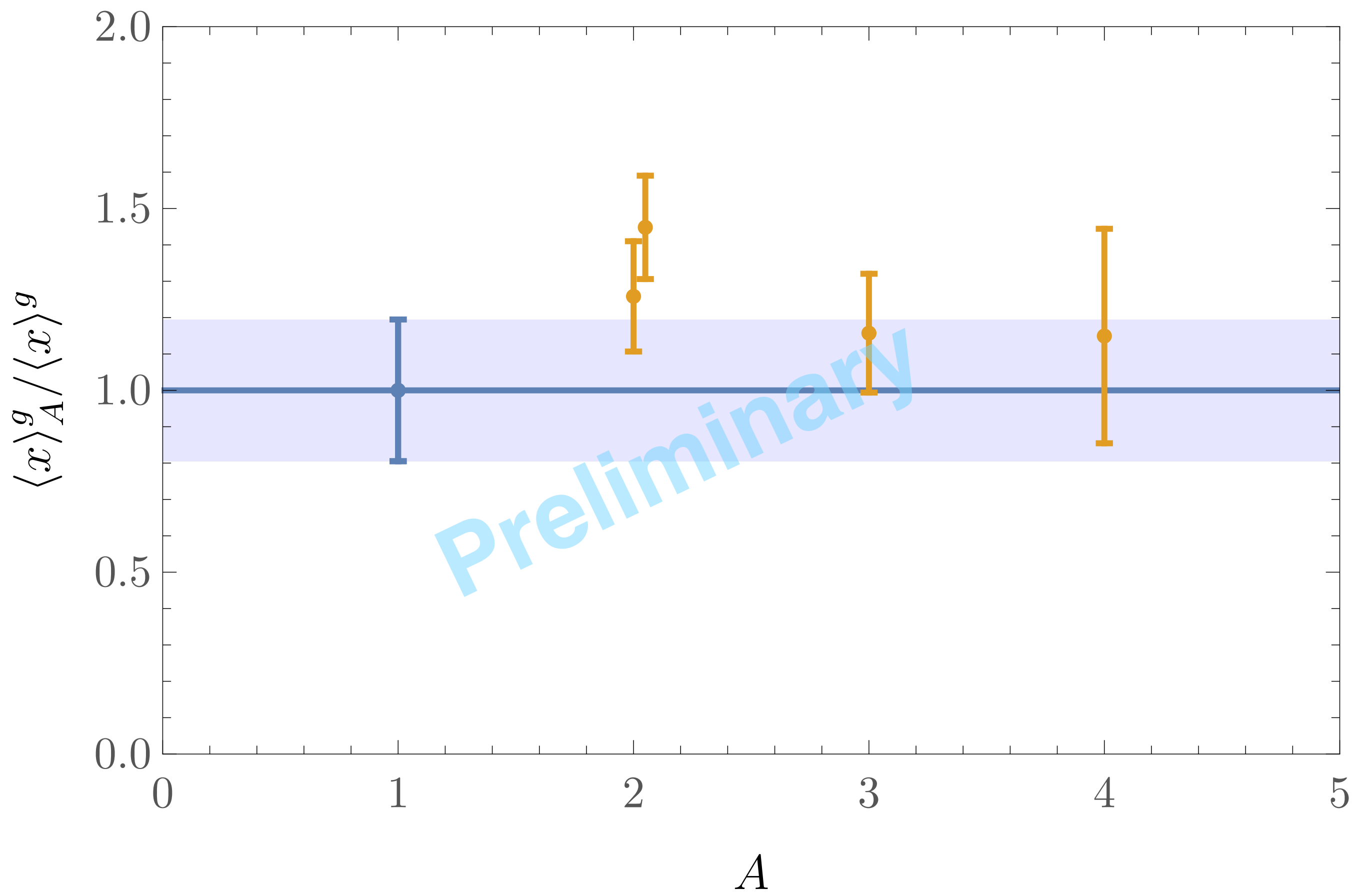
Chang et al (NPLQCD), Phys. Rev. Lett. 113, 252001 (2014), and Phys. Rev. D 92, 114502 (2015).

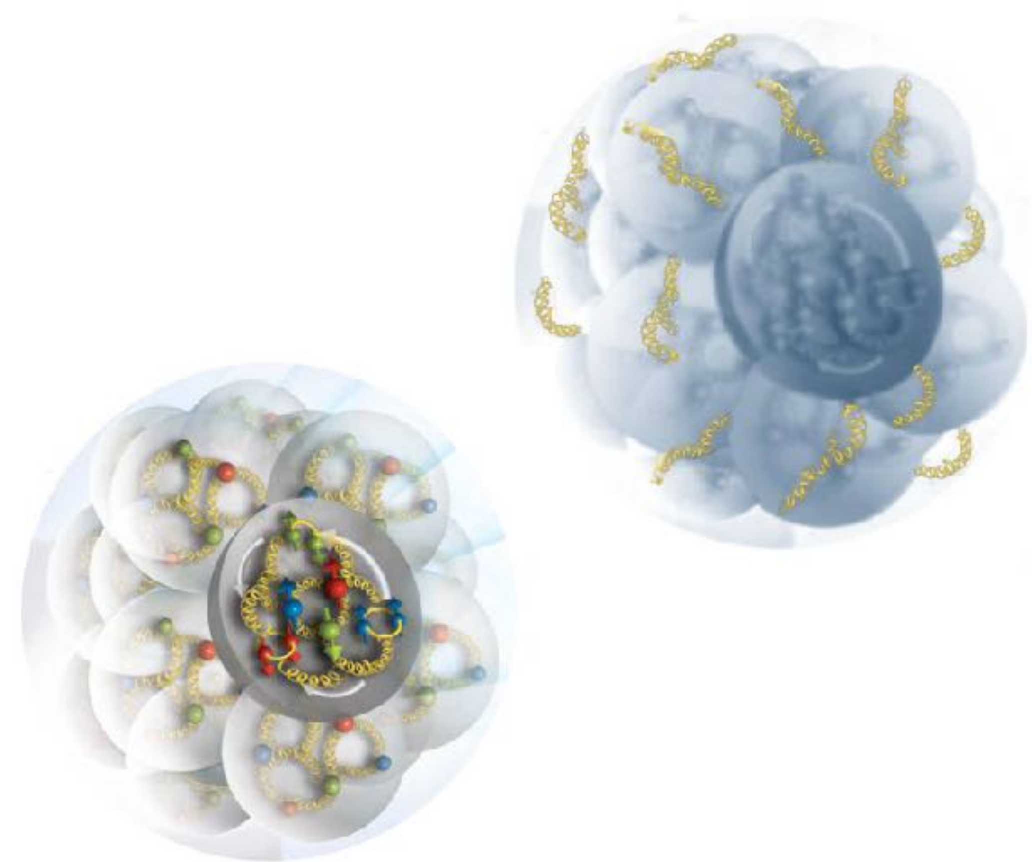
Shell Model is a good description of light nuclei even at heavy values of quark masses.

See also Krischer et al, arXiv:1702.07268 [nucl-th].

GLUONIC PROBES OF STRUCTURE

$N_f = 2+1$, $m_\pi \approx 450$ MeV, $a \approx 0.12$ fm





Spin-independent structure function shows no EMC effect with current precision

Lattice 2017: Talk by P. Shanahan.

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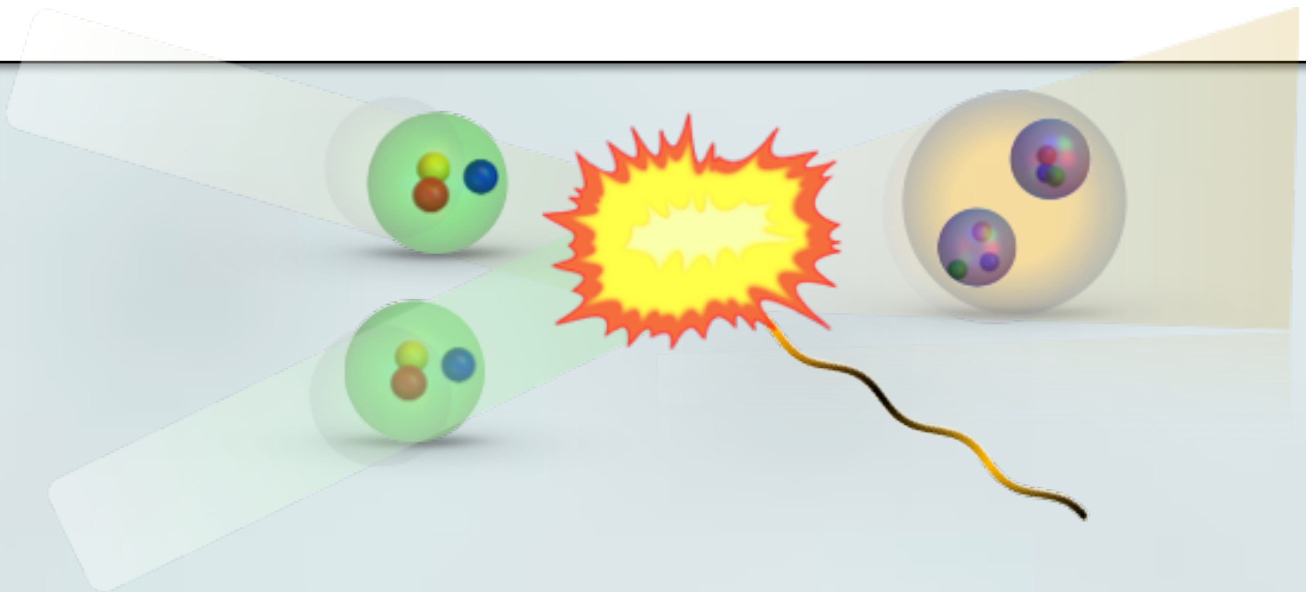
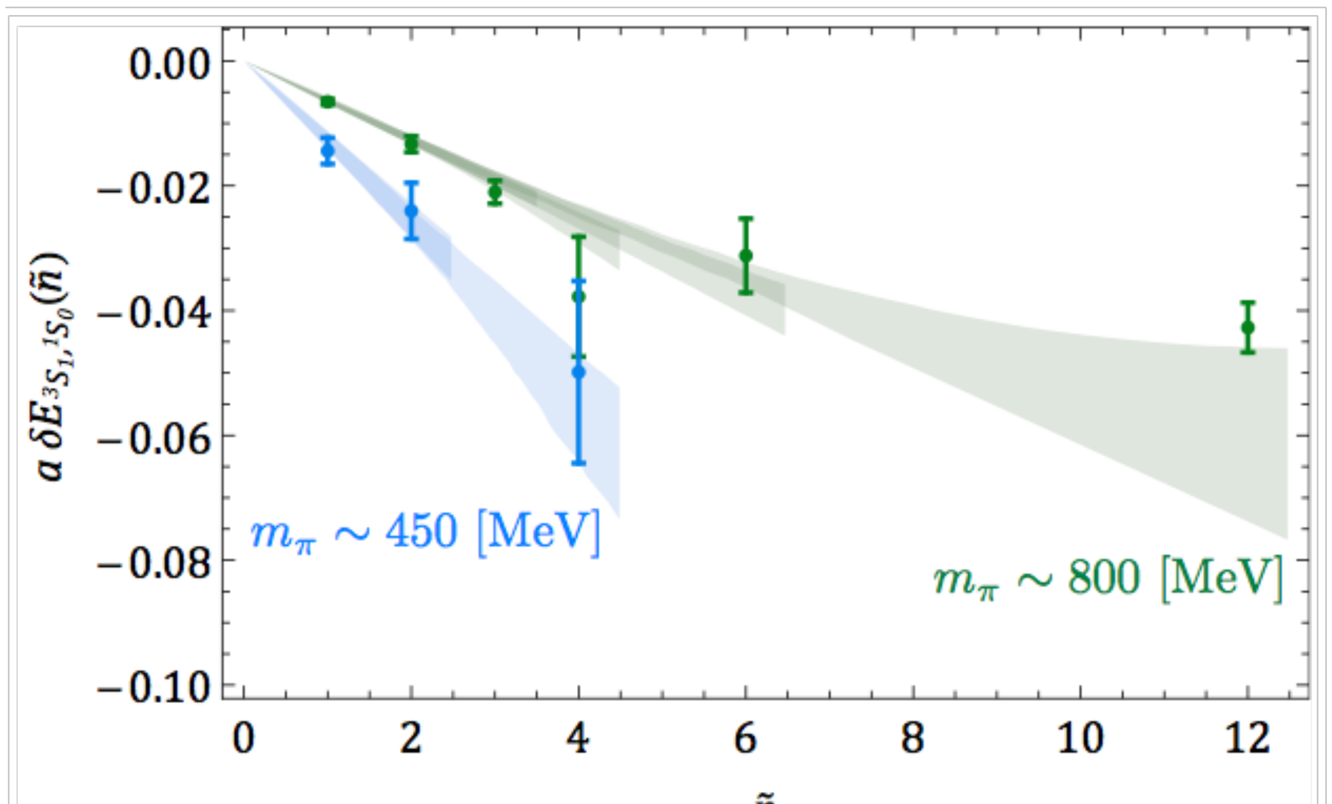
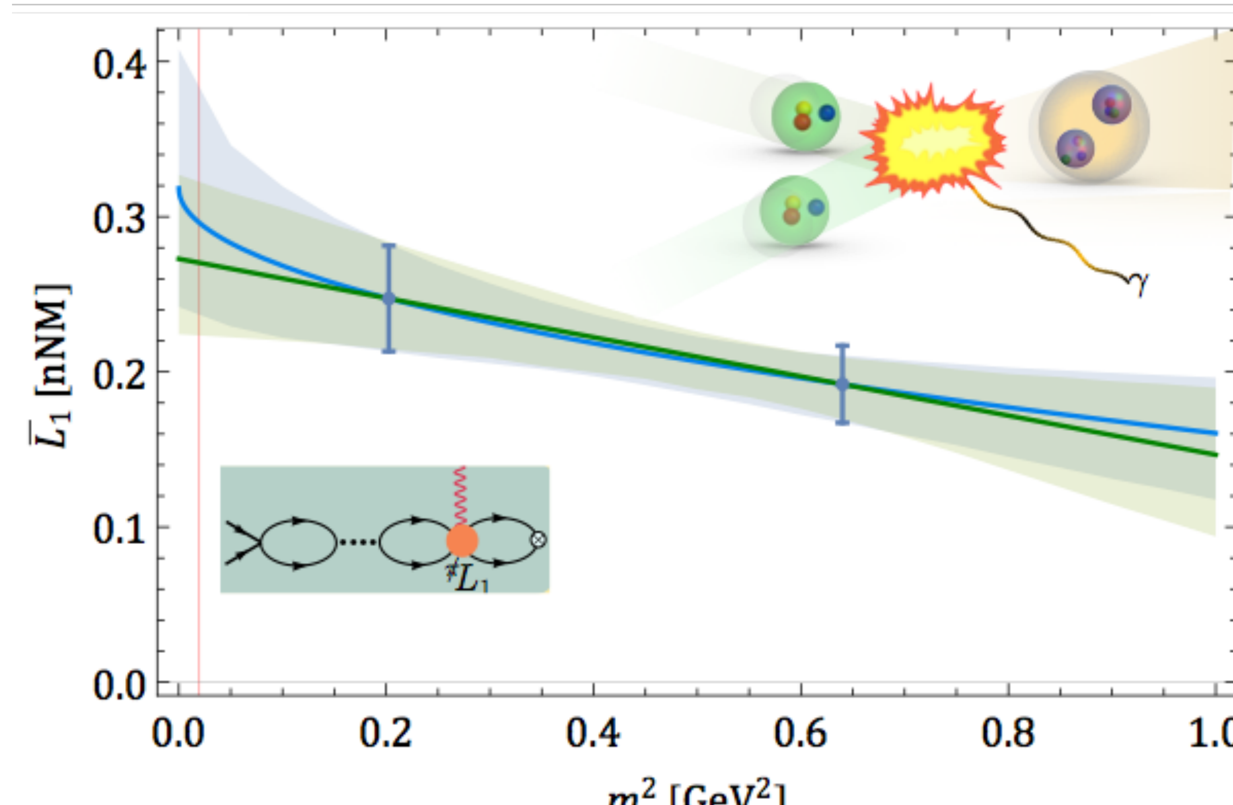
A RADIATIVE CAPTURE PROCESS



Beane et al (NPLQCD), Phys. Rev. Lett. 115, 132001 (2015).

$$\mathbf{C}(t;\mathbf{B}) = \begin{pmatrix} C^{^3S_1,^3S_1}(t;\mathbf{B}) & C^{^3S_1,^1S_0}(t;\mathbf{B}) \\ C^{^1S_0,^3S_1}(t;\mathbf{B}) & C^{^1S_0,^1S_0}(t;\mathbf{B}) \end{pmatrix} \longrightarrow \delta R_{^3S_1,^1S_0}(t;\mathbf{B}) = \frac{\lambda_+(t;\mathbf{B})}{\lambda_-(t;\mathbf{B})}\frac{C_{n,\uparrow}(t;\mathbf{B})C_{p,\downarrow}(t;\mathbf{B})}{C_{n,\downarrow}(t;\mathbf{B})C_{p,\uparrow}(t;\mathbf{B})}$$





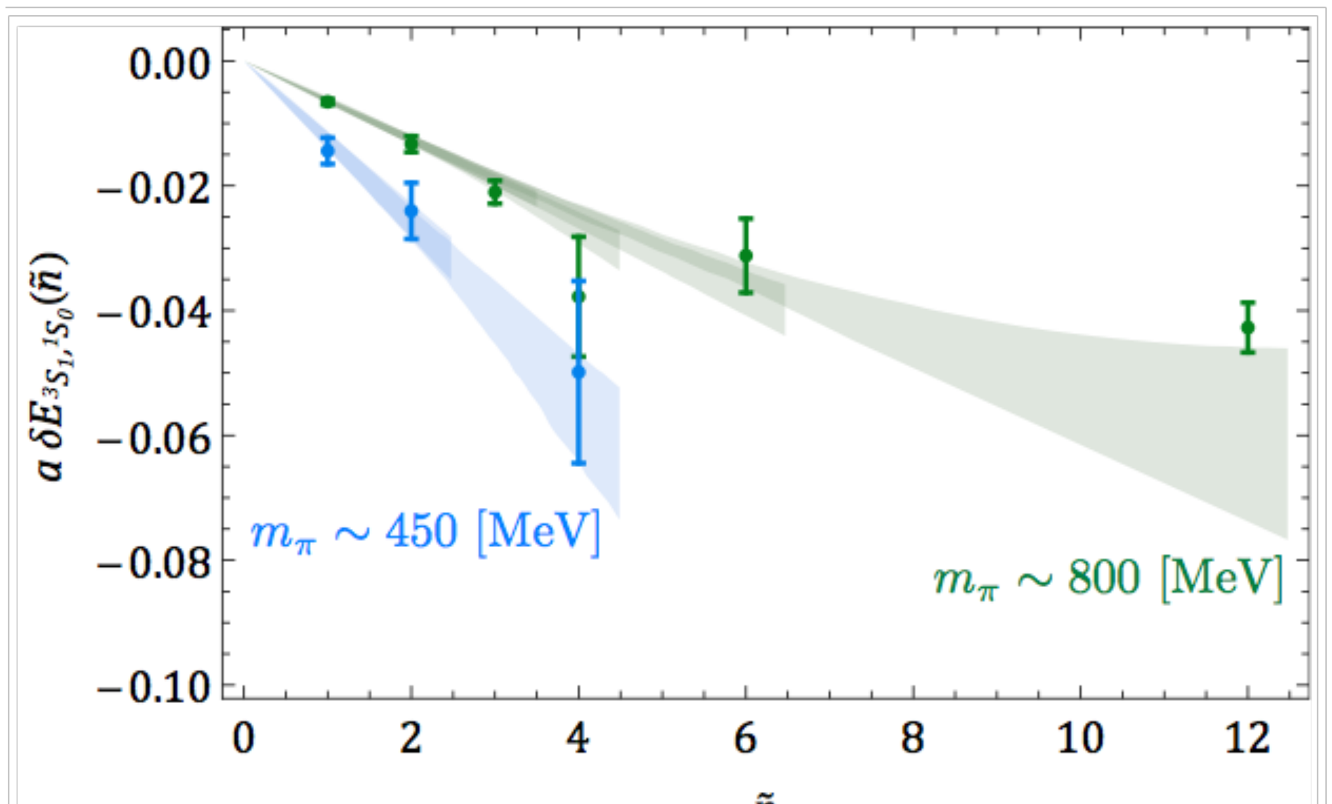
$$\delta E_{^3S_1,^1S_0} \equiv \Delta E_{^3S_1,^1S_0} - [E_{p,\uparrow} - E_{p,\downarrow}] + [E_{n,\uparrow} - E_{n,\downarrow}] \longrightarrow 2\overline{L}_1|e\mathbf{B}|/M + \mathcal{O}(\mathbf{B}^2)$$

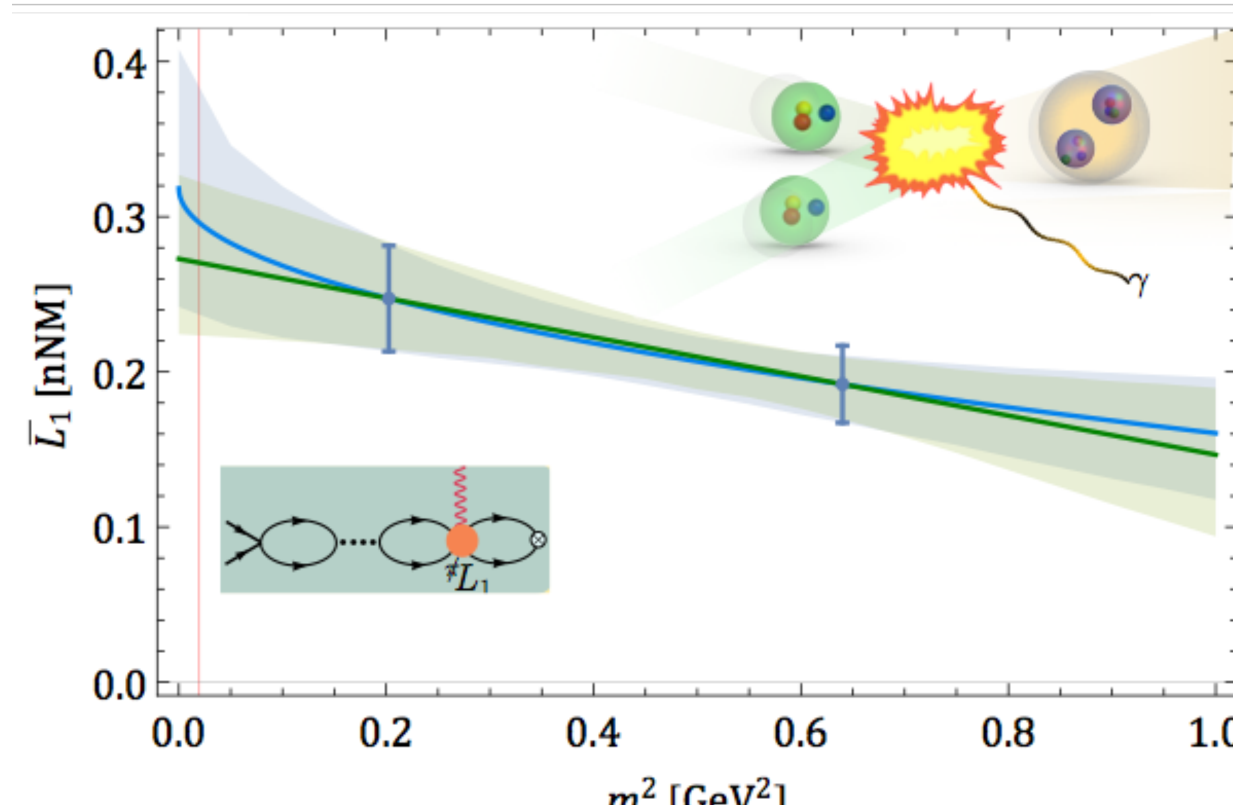
Detmold and Savage, Nucl.Phys. A743 (2004) 170.

$$\sigma(np \to d\gamma) = \frac{e^2(\gamma_0^2 + |\mathbf{p}|^2)^3}{M^4\gamma_0^3|\mathbf{p}|}|\tilde{X}_{M1}|^2 + \ldots$$

Beane et al (NPLQCD), Phys. Rev. Lett. 115, 132001 (2015).

$$\mathbf{C}(t;\mathbf{B}) = \begin{pmatrix} C^{^3S_1,^3S_1}(t;\mathbf{B}) & C^{^3S_1,^1S_0}(t;\mathbf{B}) \\ C^{^1S_0,^3S_1}(t;\mathbf{B}) & C^{^1S_0,^1S_0}(t;\mathbf{B}) \end{pmatrix} \longrightarrow \delta R_{^3S_1,^1S_0}(t;\mathbf{B}) = \frac{\lambda_+(t;\mathbf{B})}{\lambda_-(t;\mathbf{B})}\frac{C_{n,\uparrow}(t;\mathbf{B})C_{p,\downarrow}(t;\mathbf{B})}{C_{n,\downarrow}(t;\mathbf{B})C_{p,\uparrow}(t;\mathbf{B})}$$





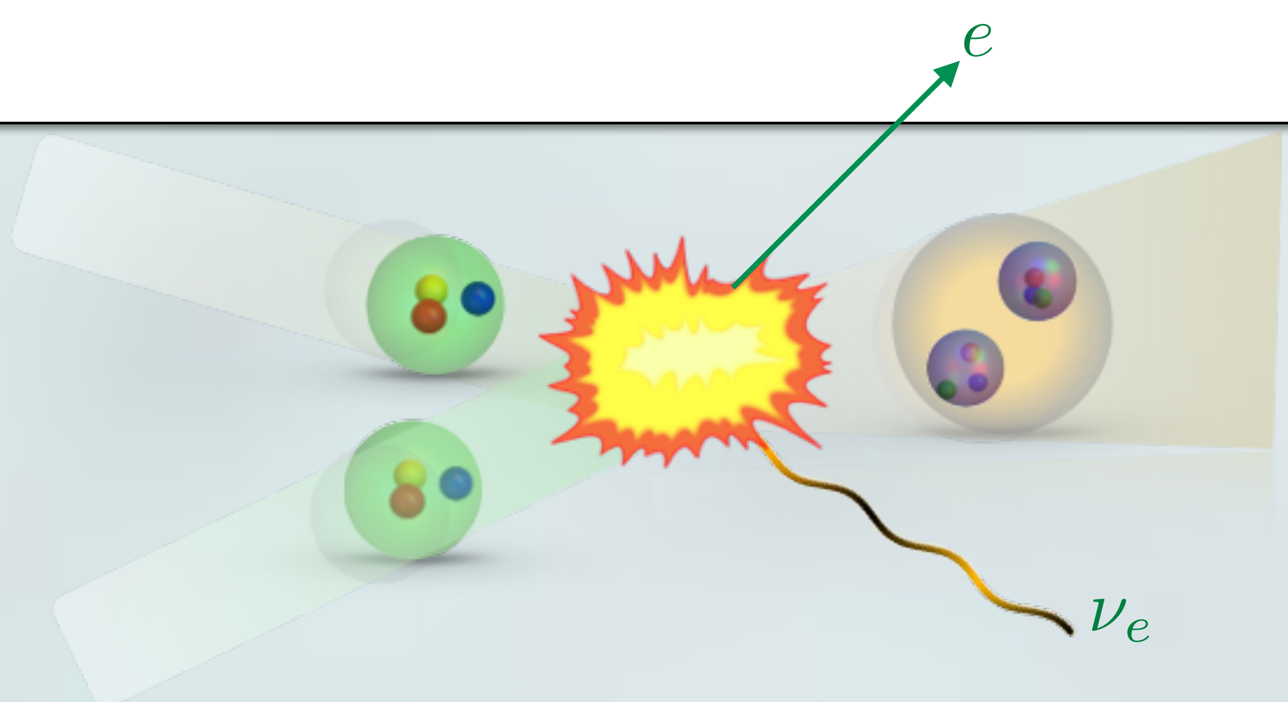
$$\delta E_{^3S_1,^1S_0} \equiv \Delta E_{^3S_1,^1S_0} - [E_{p,\uparrow} - E_{p,\downarrow}] + [E_{n,\uparrow} - E_{n,\downarrow}] \longrightarrow 2\bar{L}_1|e\mathbf{B}|/M + \mathcal{O}(\mathbf{B}^2)$$

Detmold and Savage, Nucl.Phys. A743 (2004) 170.

$$\sigma(np \to d\gamma) = \frac{e^2(\gamma_0^2 + |\mathbf{p}|^2)^3}{M^4\gamma_0^3|\mathbf{p}|}|\tilde{X}_{M1}|^2 + \ldots$$

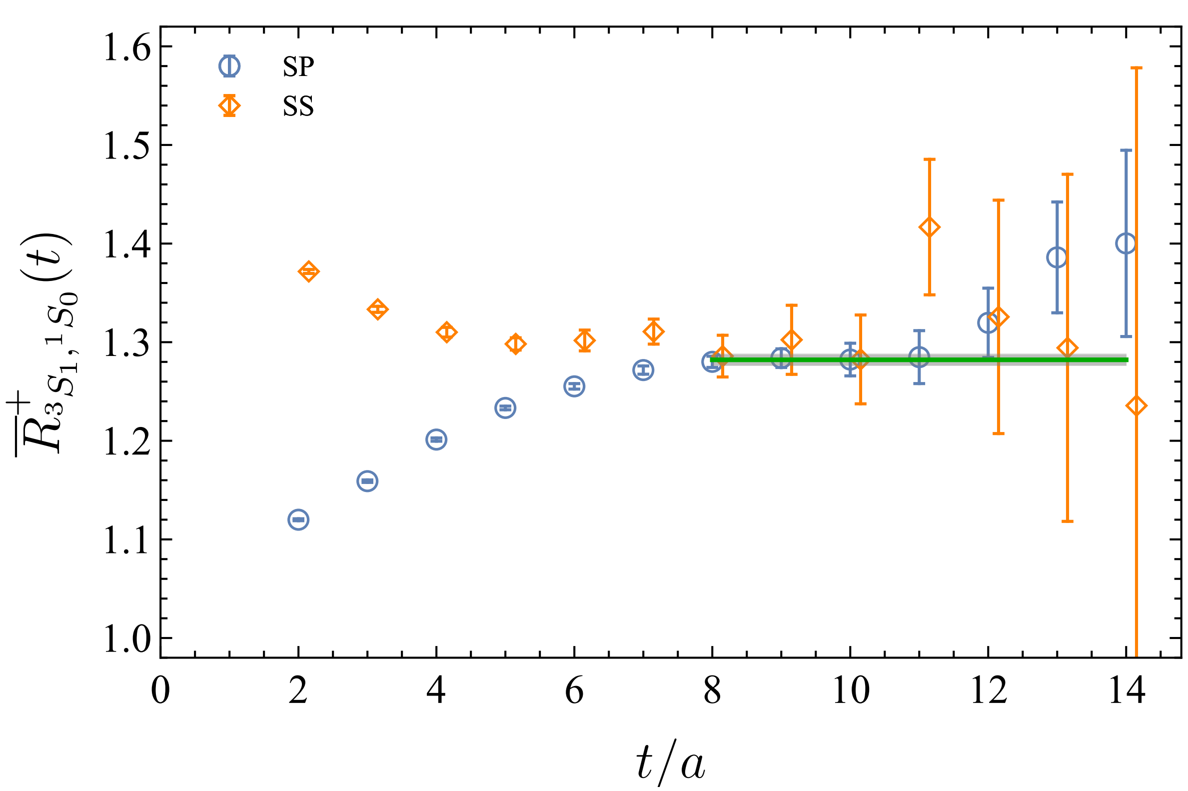
For formal aspects of a general matrix element calculation see e.g.: Detmold and Savage, Nucl.Phys. A743 (2004) 170, Briceno and ZD, Phys. Rev. D 88, 094507 (2013), Briceno and Hansen, Phys. Rev. D 94, 013008 (2016), Christ et al, Phys. Rev. D 91, 114510 (2015), Hansen et al, arXiv:1704.08993.

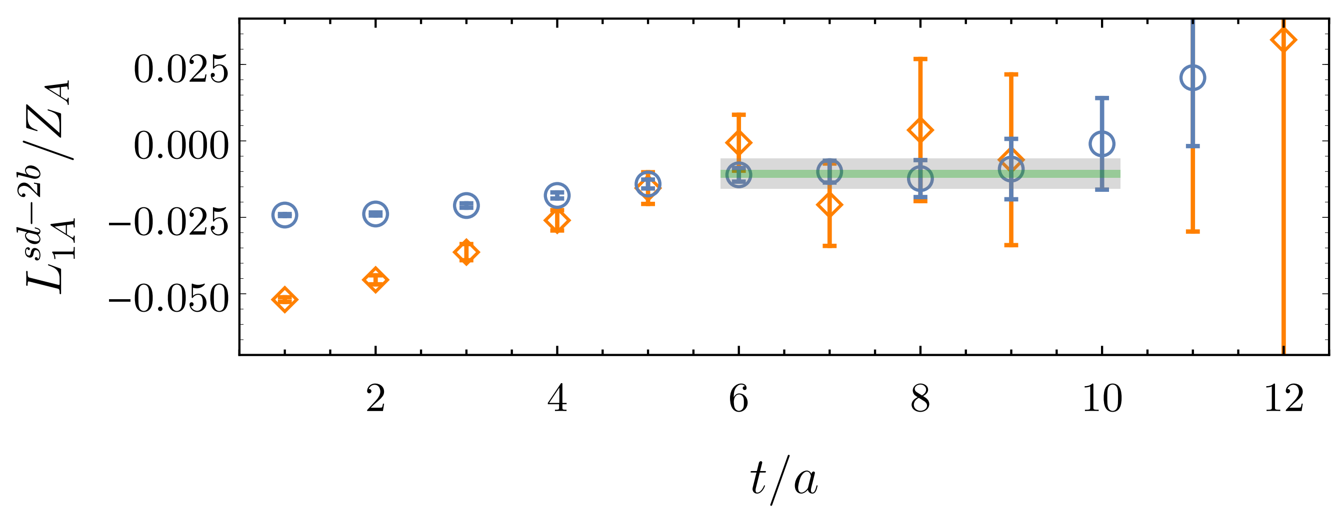
SINGLE-WEAK PROCESSES



$N_f = 3,\ m_\pi = 0.806\ \text{GeV},\ a = 0.145(2)\ \text{fm}$

Savage et al (NPLQCD), arXiv:1610.04545.





$$L_{1,A}^{sd-2b} \equiv \frac{|\langle pp|A_3^+|d\rangle| - g_A}{Z_A} = -0.011(01)(15)$$

Detmold and Savage, Nucl.Phys. A743 (2004) 170.
Briceno and ZD, Phys. Rev. D 88, 094507 (2013).

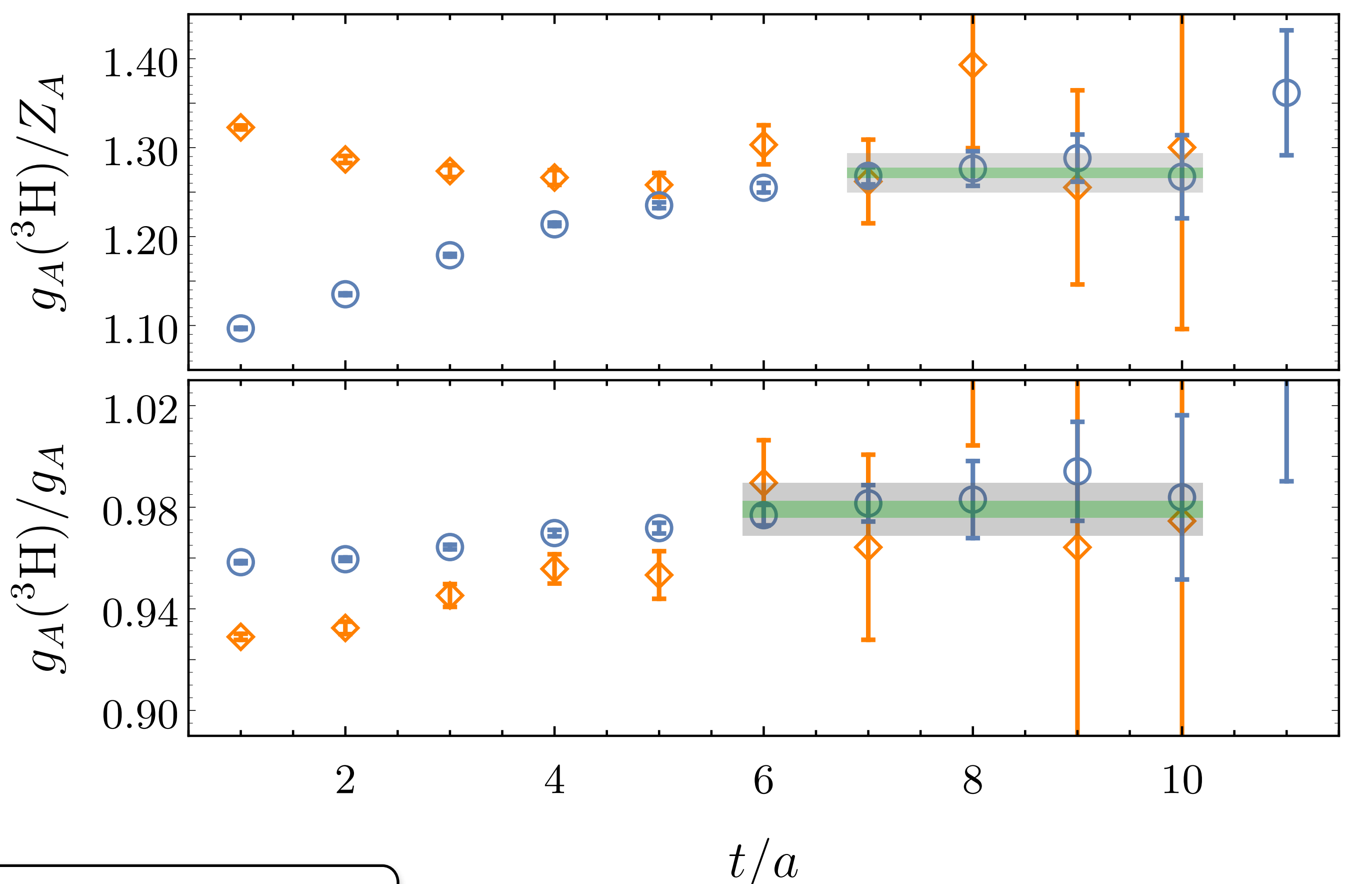
$$\left|\langle d; j\,|A_k^-|\,pp\rangle\right| \equiv g_A C_\eta \sqrt{\frac{32\pi}{\gamma^3}}\,\Lambda(p)\,\delta_{jk}$$

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

Chen et al, Phys.Rev. C67 (2003) 025801.

$N_f = 3,\ m_\pi = 0.806\ \text{GeV},\ a = 0.145(2)\ \text{fm}$

Savage et al (NPLQCD), arXiv:1610.04545.



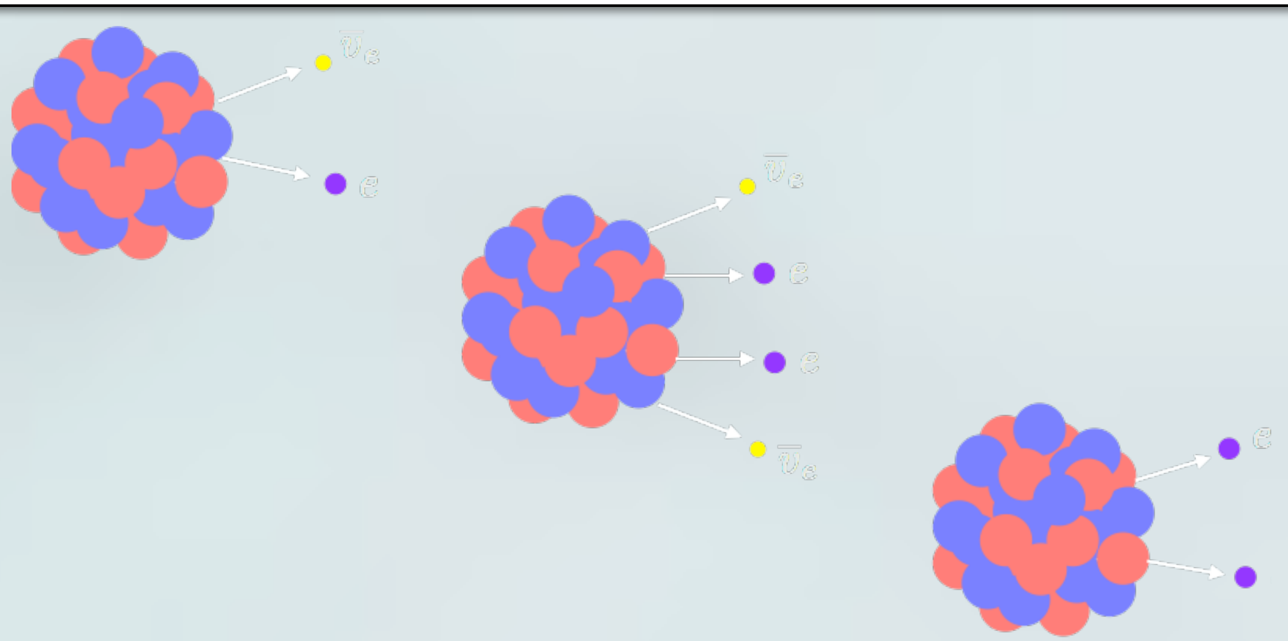
Axial charge of triton

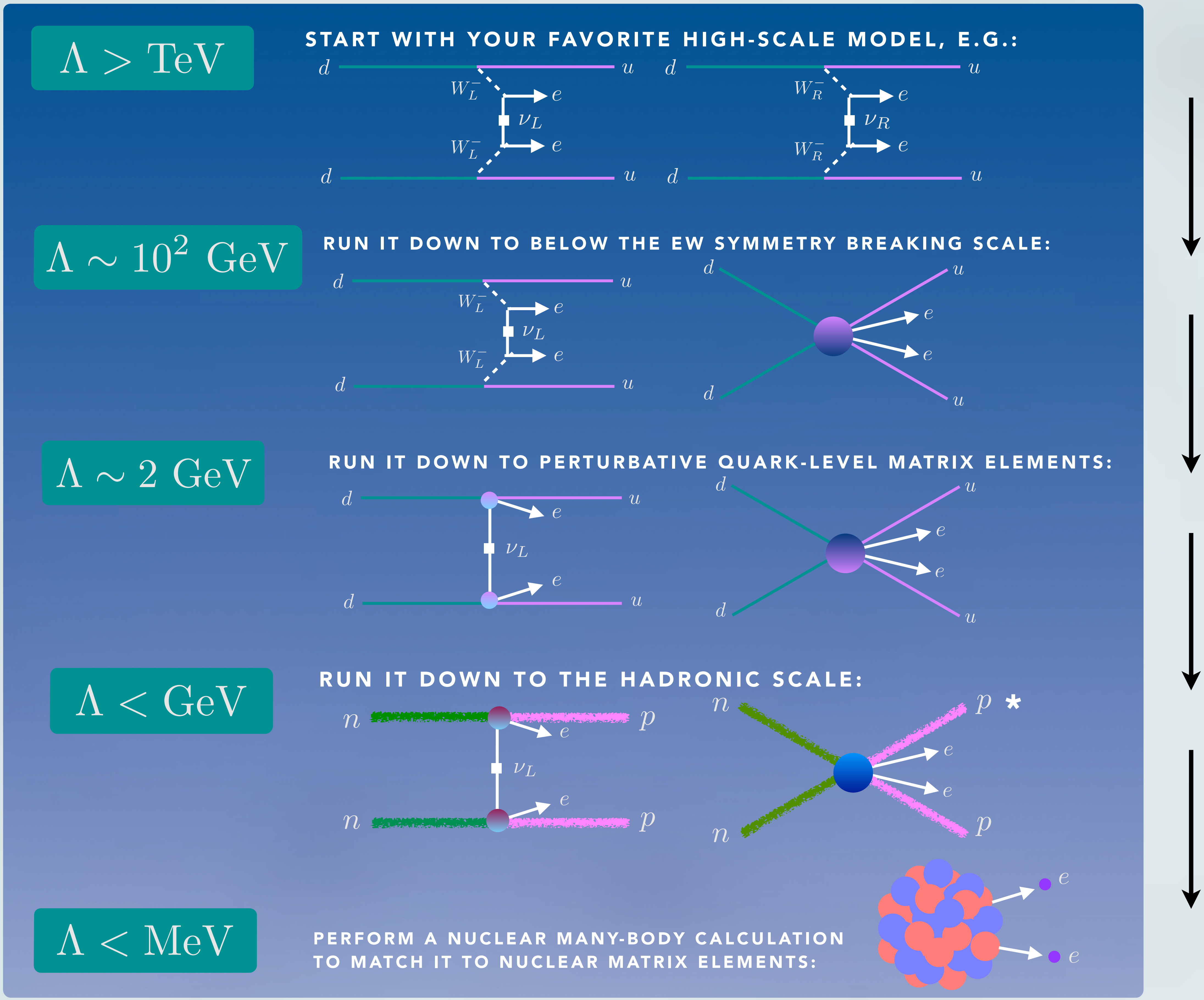
$$\langle ^3\text{He}|\overline{q}\gamma_k\gamma_5\tau^+ q|^3\text{H}\rangle = \overline{u}\gamma_k\gamma_5\tau^+ u\ g_A \langle \mathbf{GT}\rangle$$

$$\frac{(1+\delta_R) f_V}{K/G_V^2} t_{1/2} = \frac{1}{\langle \mathbf{F}\rangle^2 + f_A/f_V\ g_A^2 \langle \mathbf{GT}\rangle^2}$$

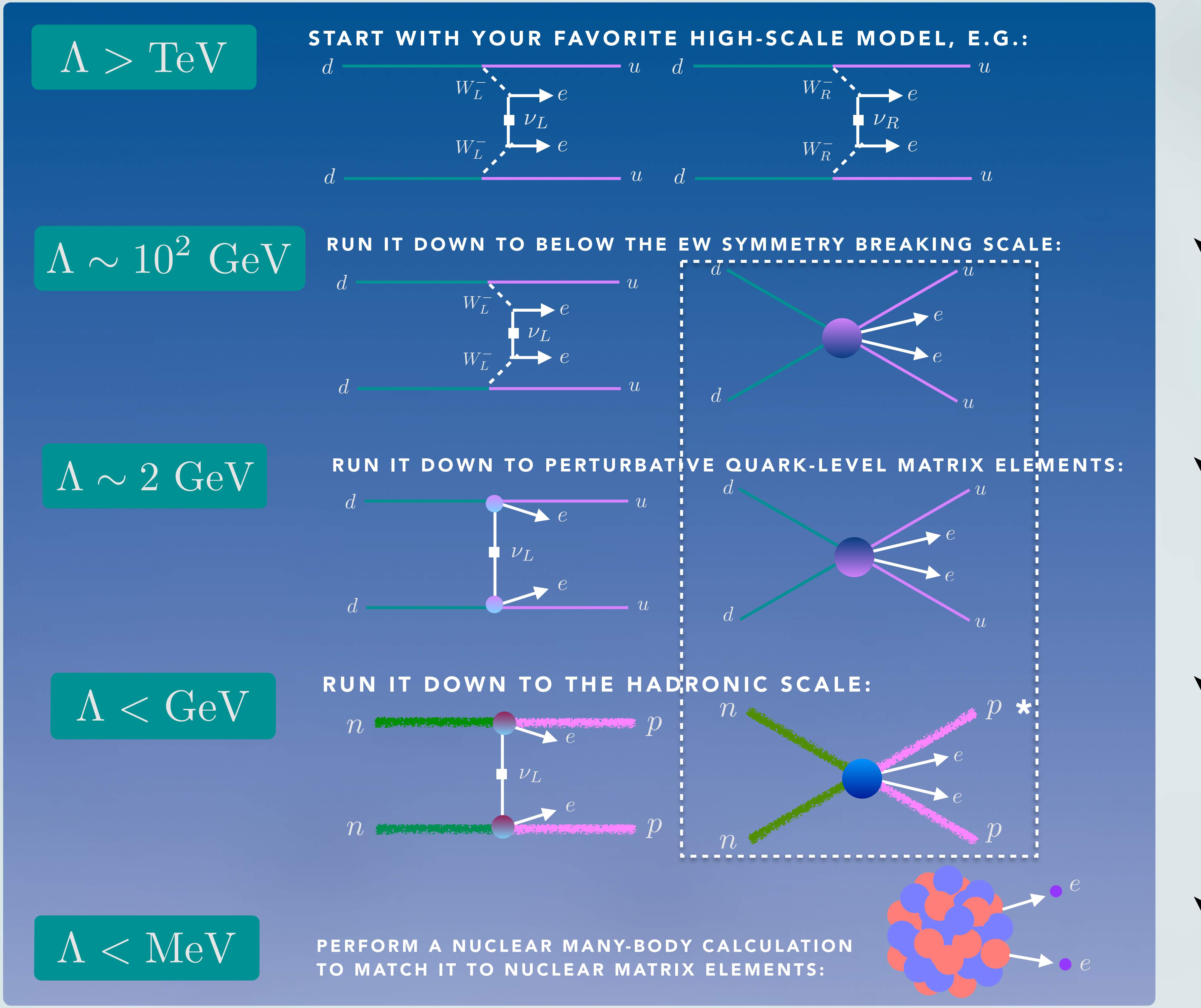
Schiavilla et al, Phys. Rev. C58, 1263 (1998).

DOUBLE-WEAK PROCESSES





Bottom-Up approach: Matching the high scale to low scale



Bottom-Up approach: Matching the high scale to low scale

Berkowitz et al (CalLat), arXiv:1608.04793.

HISQ ensembles, $m_\pi \approx 310,\ 220,\ 135$ MeV, 0.09 fm $\leq a \leq 0.15$ fm

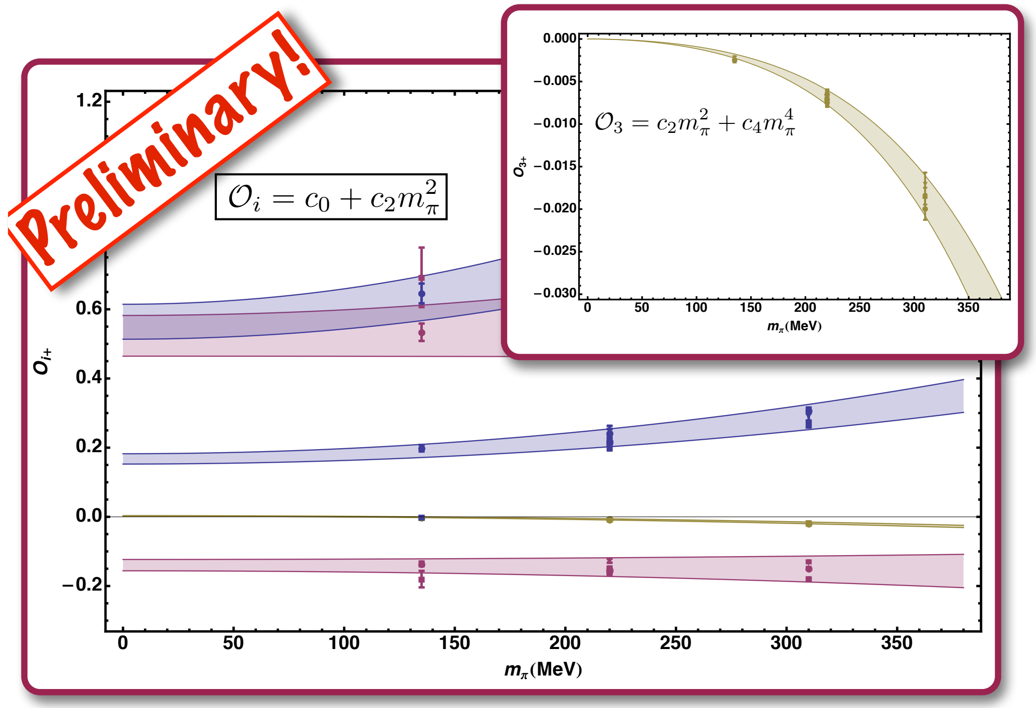
$$\mathcal{O}_{1+}^{++} = (\bar{q}_L \tau^- \gamma^\mu q_L)\,[\bar{q}_R \tau^- \gamma_\mu q_R]$$

$$\mathcal{O}'^{++}_{1+} = (\bar{q}_L \tau^- \gamma^\mu q_L]\,[\bar{q}_R \tau^- \gamma_\mu q_R)$$

$$\mathcal{O}_{2+}^{++} = (\bar{q}_R \tau^- q_L)\,[\bar{q}_R \tau^- q_L] + (\bar{q}_L \tau^- q_R)\,[\bar{q}_L \tau^- q_R]$$

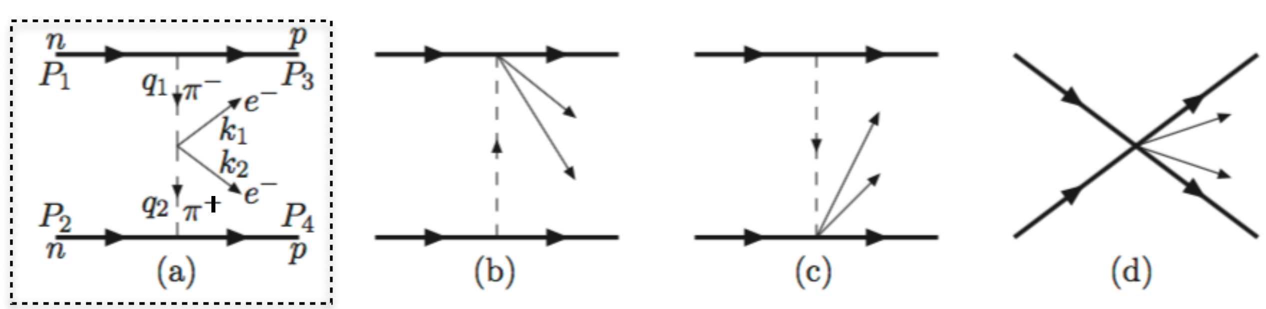
$$\mathcal{O}'^{++}_{2+} = (\bar{q}_R \tau^- q_L]\,[\bar{q}_R \tau^- q_L) + (\bar{q}_L \tau^- q_R]\,[\bar{q}_L \tau^- q_R)$$

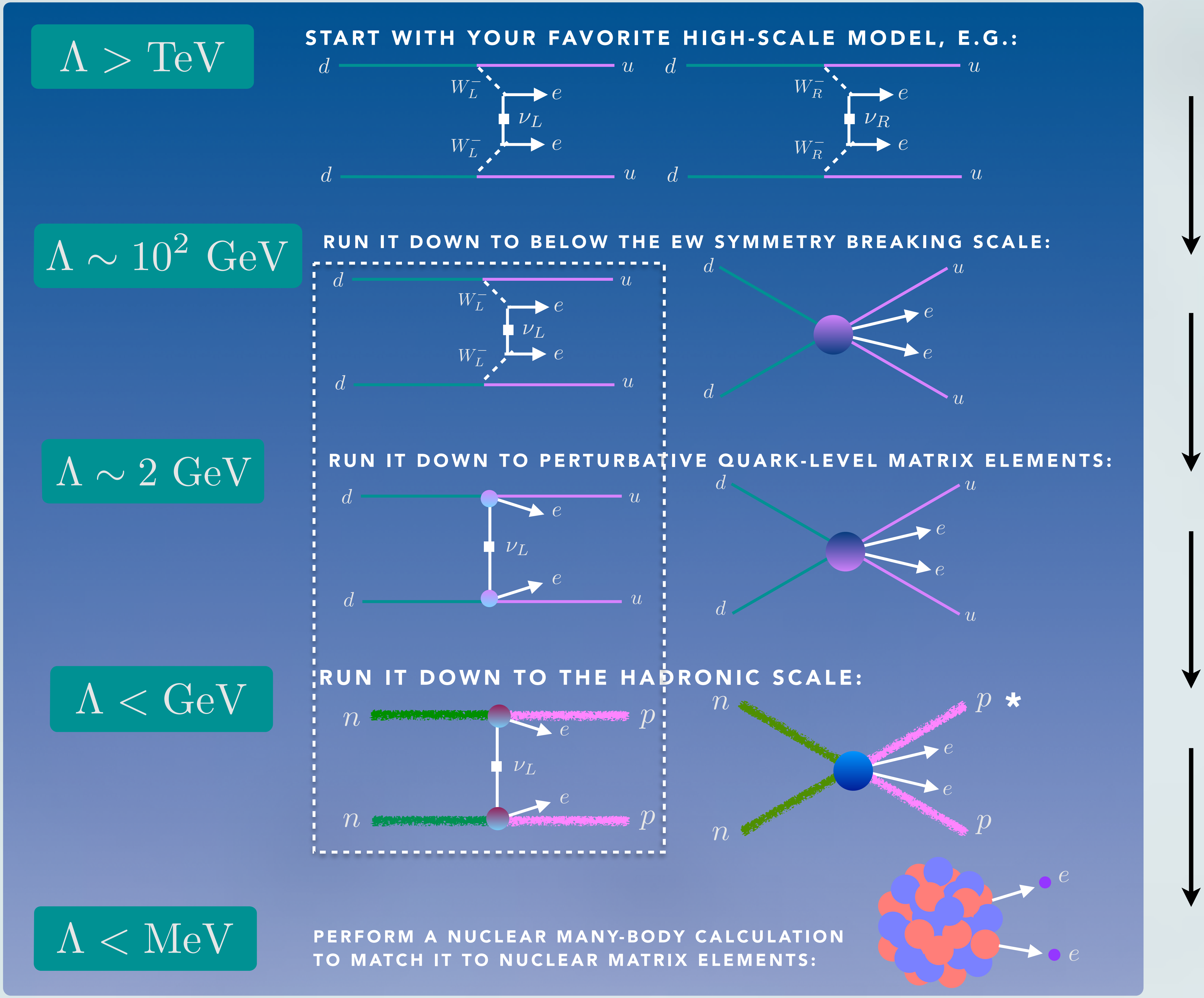
$$\mathcal{O}_{3+}^{++} = (\bar{q}_L \tau^- \gamma^\mu q_L)\,[\bar{q}_L \tau^- \gamma_\mu q_L] + (\bar{q}_R \tau^- \gamma^\mu q_R)\,[\bar{q}_R \tau^- \gamma_\mu q_R]$$



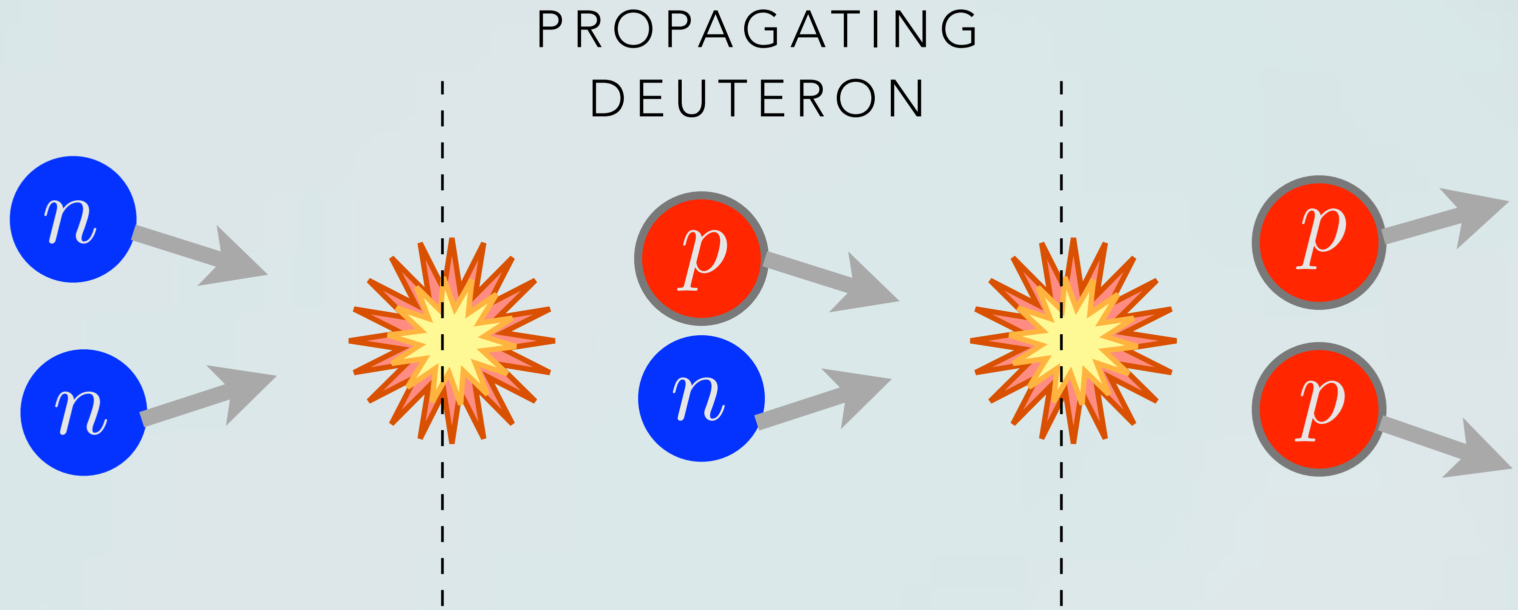
Pionic matrix elements of $\Delta I_3 = 2$ four-quark operators

Prezeau, Ramsey-Musolf and Vogel, Phys.Rev. D68 03401 (2003), Savage, Phys. Rev. C59, 2293 (1999), Cirigliano, Dekens, Graesser and Mereghetti, arXiv:1701.01443 [hep-ph].

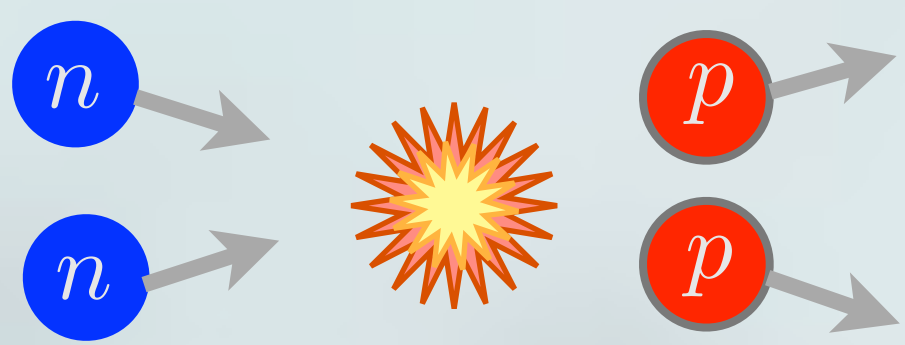




Bottom-Up approach: Matching the high scale to low scale



LONG-DISTANCE PIECE



SHORT-DISTANCE PIECE

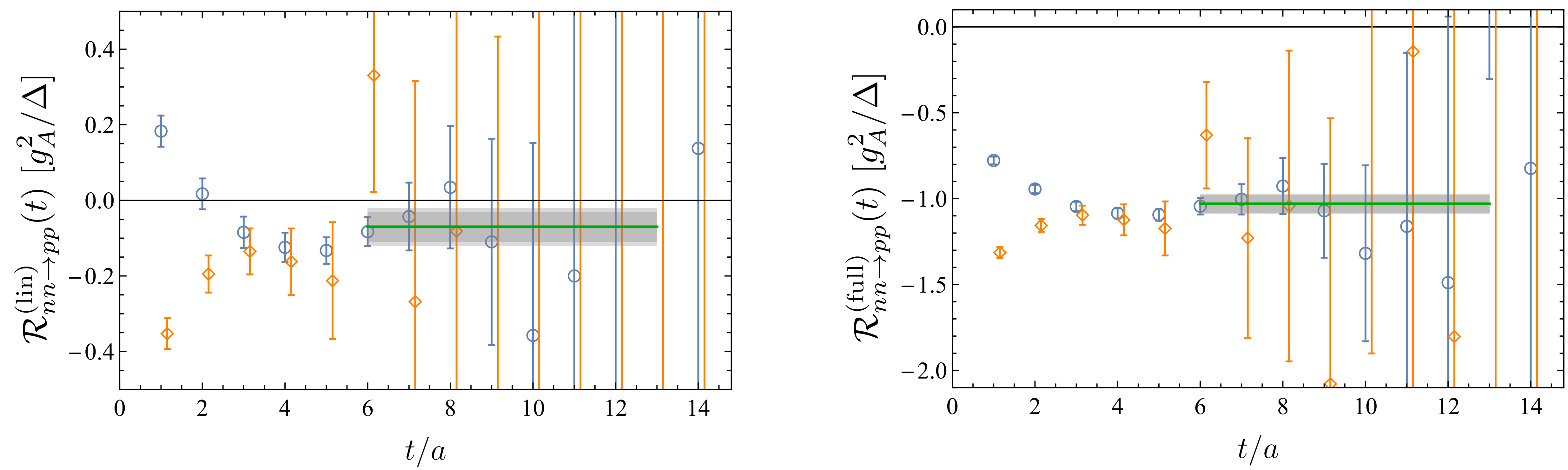
$$\mathcal{R}_{nn\to pp}(t) = \frac{C_{nn\to pp}(t)}{2C^{(nn)}_{0;0}(t)}$$

See RBPC's recent developments in KL-KS.

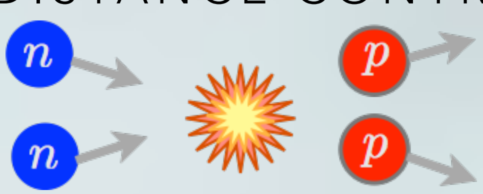
$$a^2\mathcal{R}_{nn\to pp}(t) = \left[-t + \frac{e^{\Delta t}-1}{\Delta}\right] \frac{\langle pp|\tilde{J}^+_3|d\rangle\langle d|\tilde{J}^+_3|nn\rangle}{\Delta} + t \sum_{\mathfrak{l}'\neq d} \frac{\langle pp|\tilde{J}^+_3|\mathfrak{l}'\rangle\langle \mathfrak{l}'|\tilde{J}^+_3|nn\rangle}{\delta_{\mathfrak{l}'}} + C + D\, e^{\Delta t} + \mathcal{O}(e^{-\delta t}, e^{-\delta' t})$$

$N_f = 3,\ m_\pi = 0.806$ GeV, $a = 0.145(2)$ fm

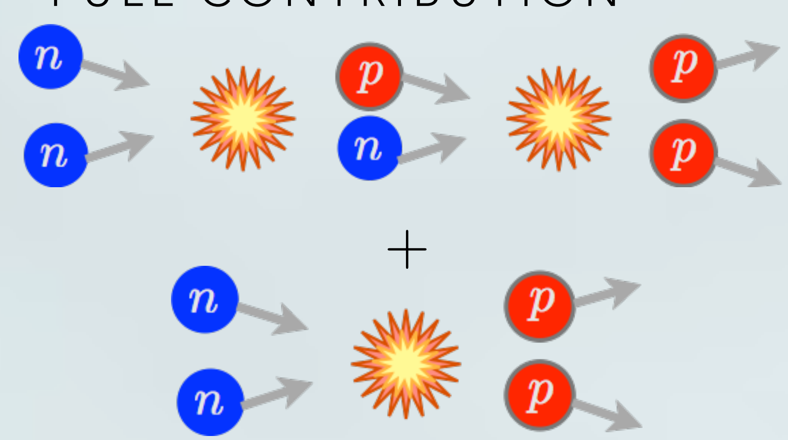
Shanahan et al (NPLQCD), arXiv:1701.03456.
Tiburzi et al (NPLQCD), arXiv:1702.02929.



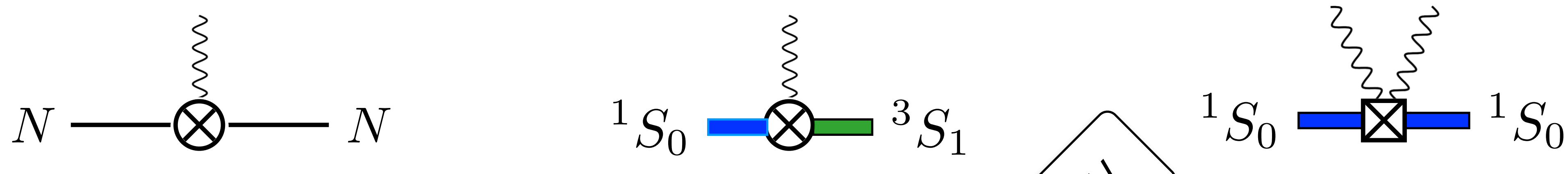
SHORT-DISTANCE CONTRIBUTION



FULL CONTRIBUTION



Shanahan et al (NPLQCD), arXiv:1701.03456.
Tiburzi et al (NPLQCD), arXiv:1702.02929.



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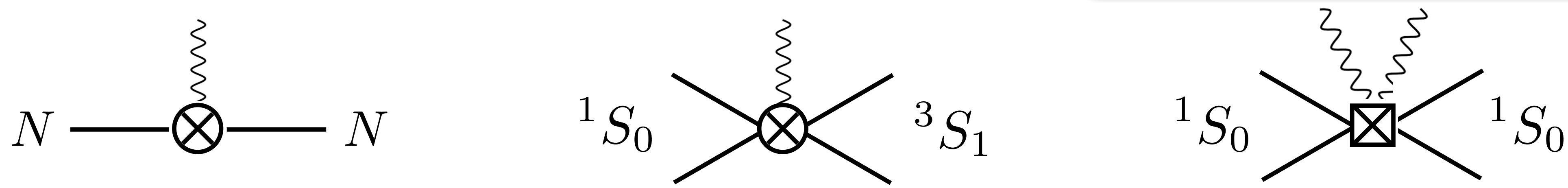


NEW

$$\mathbb{H}_{2,S} = 4.7(1.3)(1.8)\ \mathrm{fm}$$
$$@\ m_\pi = 806\ \mathrm{MeV}$$

Isotensor axial polarizability could be comparable to quenching of axial charge, and can only be constrained with lattice QCD.

STATUS OF LQCD CALCULATIONS FOR MULTI-NUCLEON SYSTEMS

Zohreh Davoudi, MIT

Challenges and Recent advances

Goals and impact

Nuclei and hypernuclei from QCD

Scattering and hadronic interactions

Nuclear matrix elements

Nuclear structure

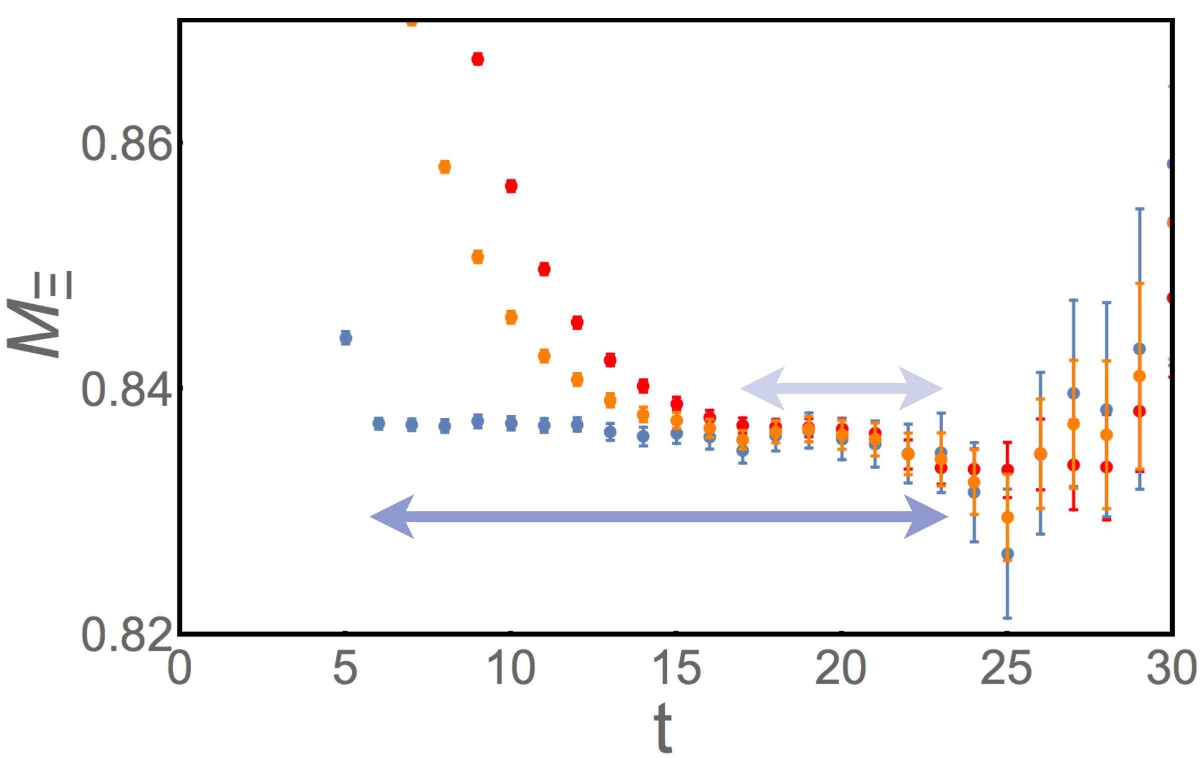
INT Workshop on
Lattice QCD Input for Neutrinoless Double-β Decay
July 6 - 7, 2017

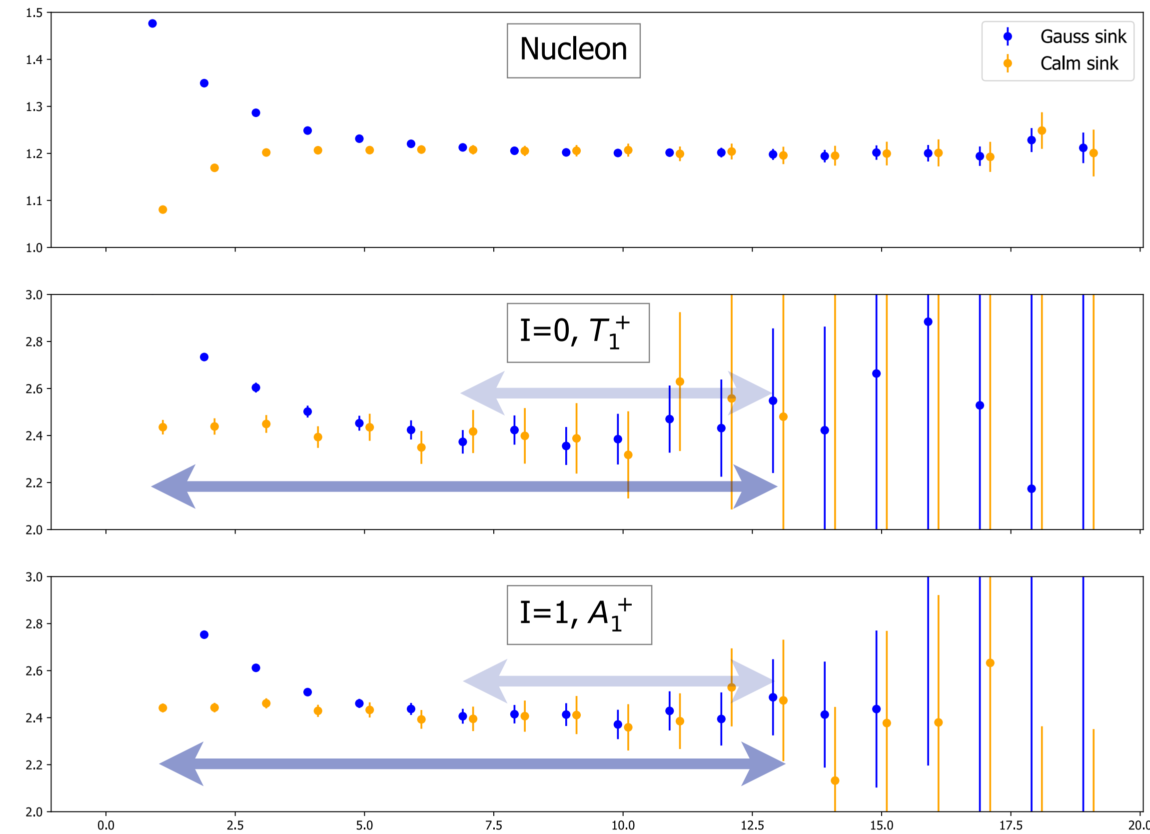
Extending the “Golden Window”

Beane et al (NPLQCD), Phys.Rev.D79:114502,2009.

Linear combos. at the level of correlation functions

Lattice 2017: Talk by E. Berkowitz





Linear combos. at the level of sink construction

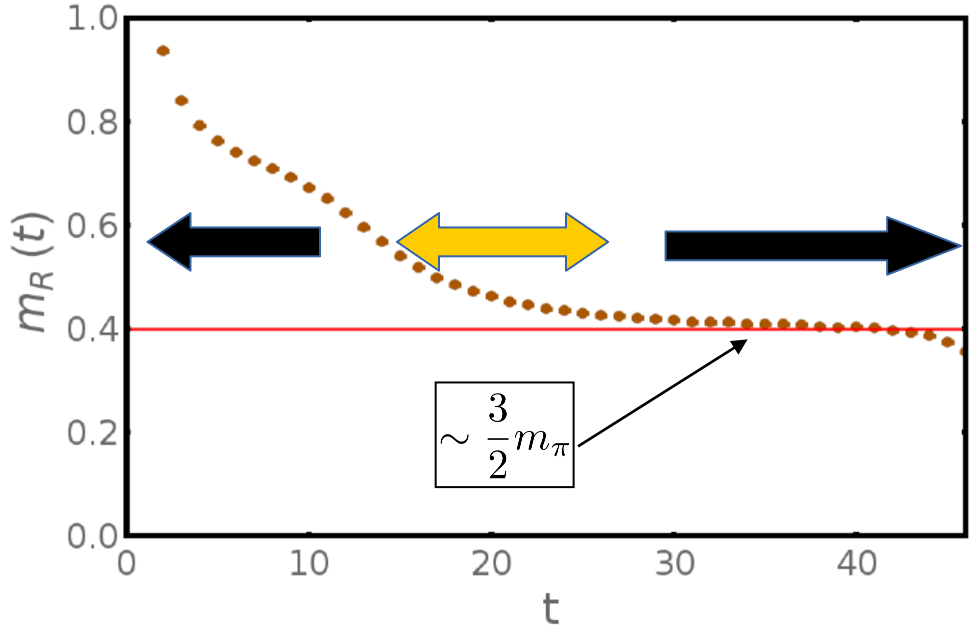
$$C_{\hat{\mathcal{O}},\hat{\mathcal{O}}'}(\tau;\mathbf{d}) \;=\; \sum_{\mathbf{x}} e^{2\pi i\mathbf{d}\cdot\mathbf{x}/L}\langle 0|\hat{\mathcal{O}}'(\mathbf{x},\tau)\hat{\mathcal{O}}^\dagger(\mathbf{0},0)|0\rangle = \mathcal{Z}_0'\mathcal{Z}_0^\dagger e^{-E^{(0)}\tau} + \mathcal{Z}_1'\mathcal{Z}_1^\dagger e^{-E^{(1)}\tau} + \ldots$$

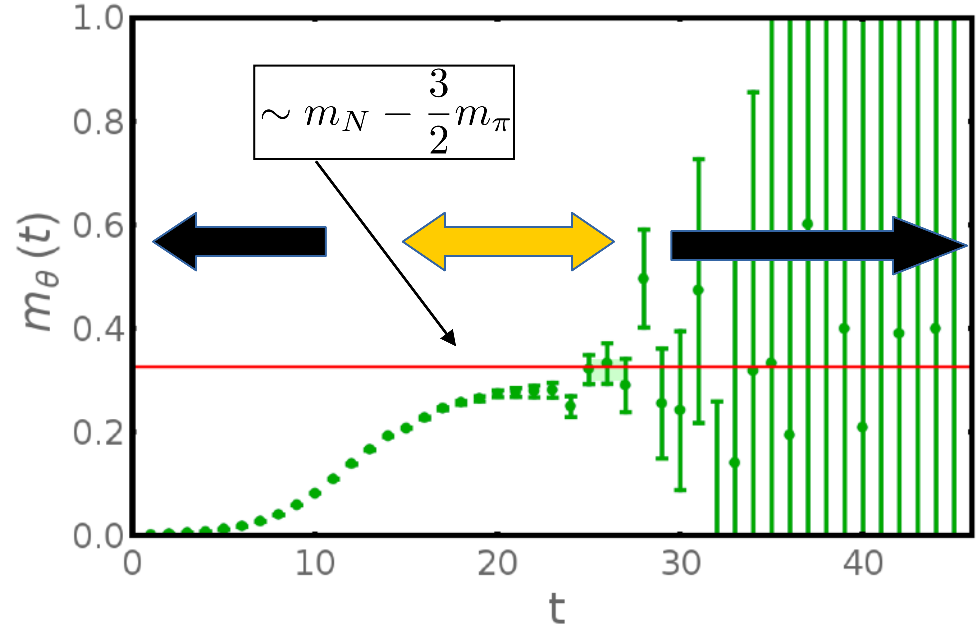
Going beyond the "Golden Window"

Wagman and Savage, arXiv:1611.07643, arXiv:1704.07356.

$$\text{StN} \sim e^{-(m_N - \frac{3}{2}m_\pi)\Delta t}$$

$$C_i(t) = e^{R_i(t) + i\theta_i(t)}$$



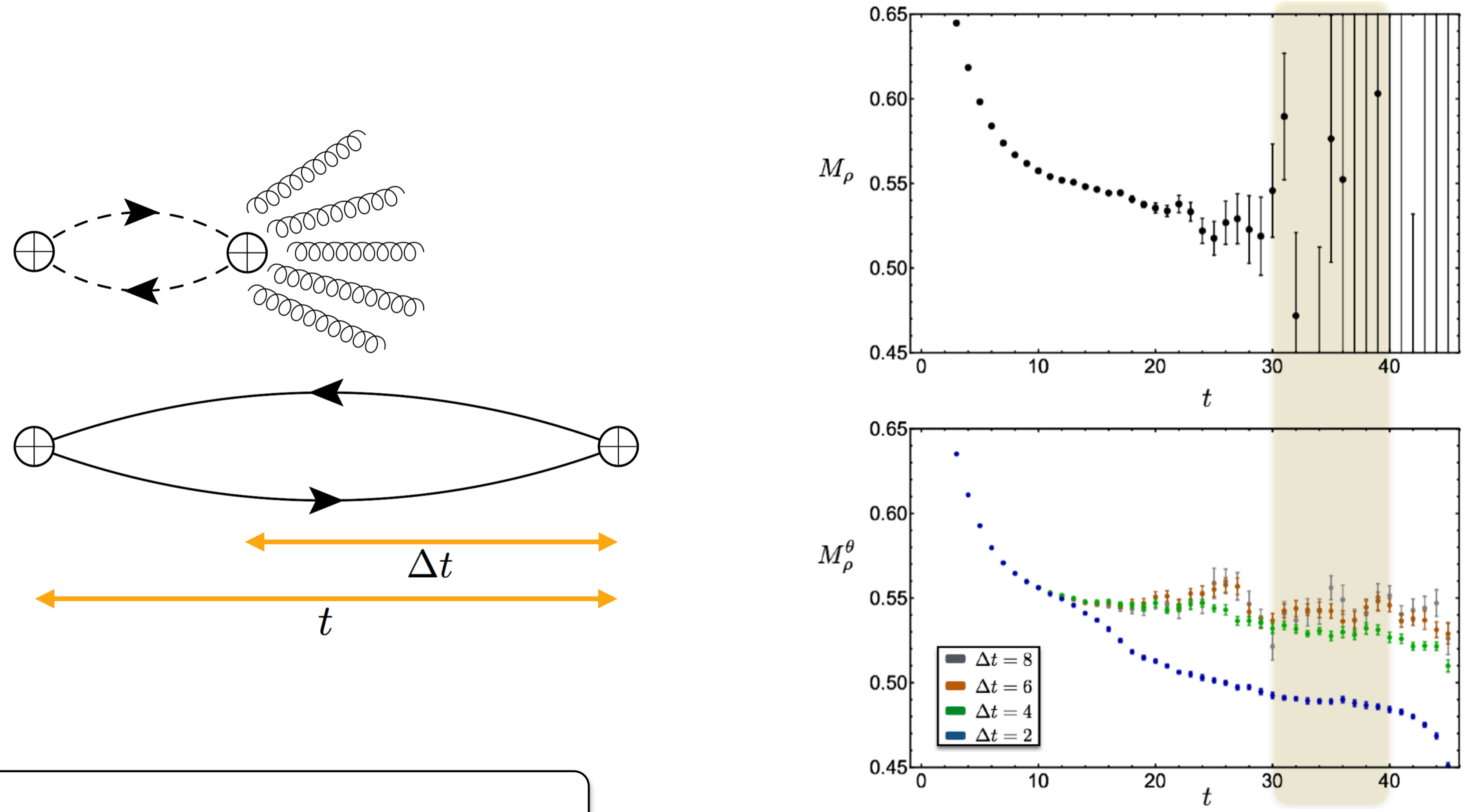


$$m_R(t) = \ln\left(\frac{\langle e^{R_i(t)}\rangle}{\langle e^{R_i(t+1)}\rangle}\right)$$

$$m_\theta(t) = \ln\left(\frac{\langle e^{i\theta_i(t)}\rangle}{\langle e^{i\theta_i(t+1)}\rangle}\right)$$

Time derivates approach time-independent stable and wrapped stable distributions at late times.

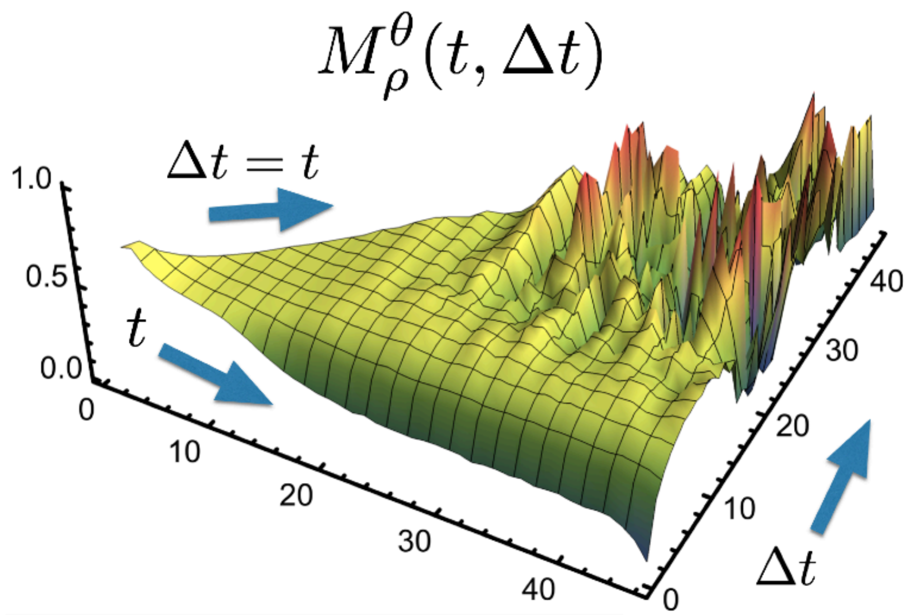
Wagman and Savage, arXiv:1611.07643, arXiv:1704.07356.

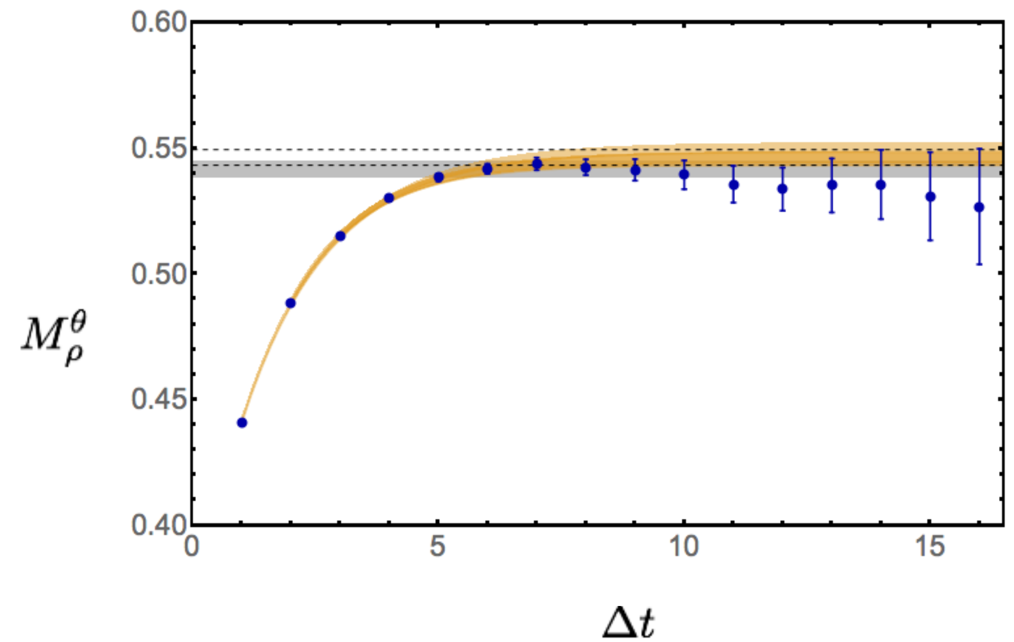


A phase reweighting method

Similar physics of decorrelation between spacetime subvolumes exploited in: Ce, Giusti and Schaefer, Phys.Rev. D93 (2016).

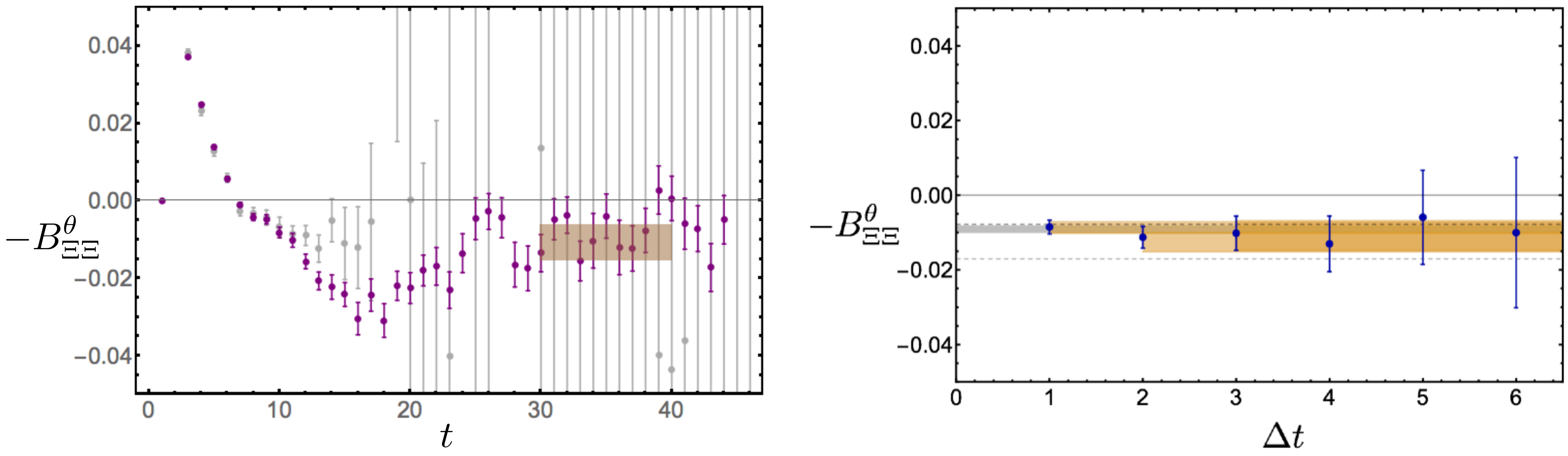
Wagman and Savage, arXiv:1611.07643, arXiv:1704.07356.





$$M_\rho^\theta(t, \Delta t) = M_\rho + c\,\delta M_\rho e^{-\delta M_\rho \Delta t} + \ldots$$

Wagman and Savage, arXiv:1611.07643, arXiv:1704.07356.



A nice demonstration of the consistency between GW result and the phase reweighed result.

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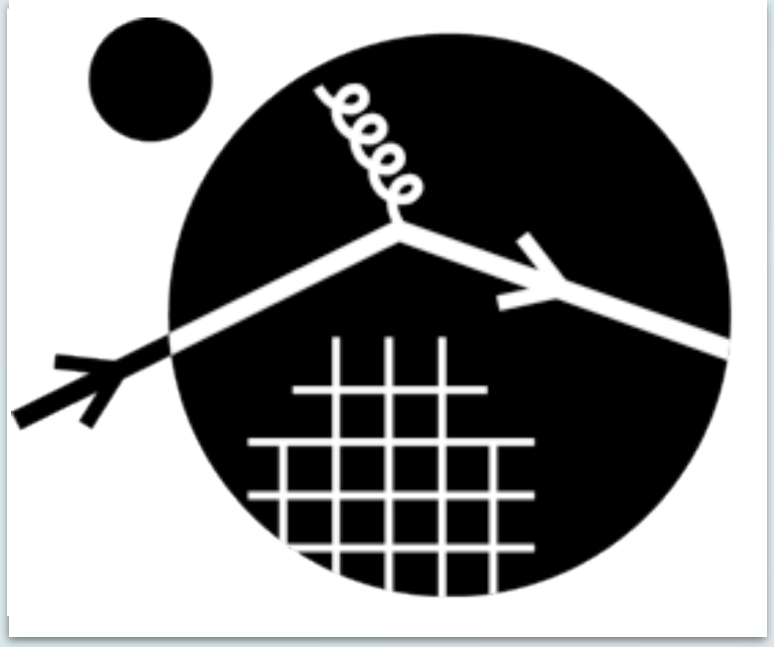

Nuclei and hypernuclei from QCD

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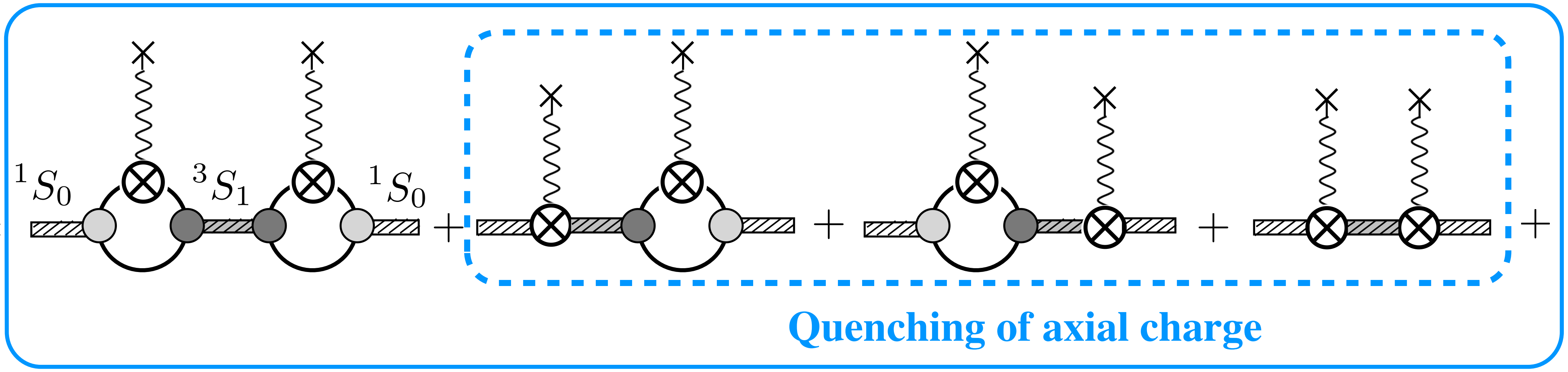
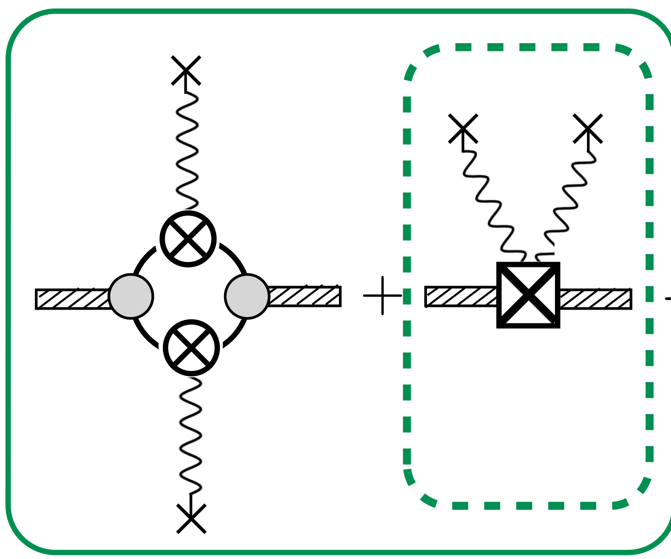
BACKUP SLIDES

EFT correlation function

$$i\mathcal{C}_{nn\to pp} =$$



Give partly the dominant long-range contribution



$$+\ \mathcal{O}\left(\lambda^4\right)$$

A short-range contribution not accounted for before

$$M_{nn\to pp} = -\frac{|M_{pp\to d}|^2}{\Delta} + \frac{M g_A^2}{4\gamma_s^2} - \mathbb{H}_{2,S}$$

$$M_{pp\to d} = g_A(1+S) + \mathbb{L}_{1,A}$$