IFIC Seminar
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The baryon-baryon interaction with unphysical quark masses

Marc Illa
Departament de Física Quàntica i Astrofísica, UB
Advisor: Assumpta Parreño

nplqcd.ub.edu

UNIVERSITAT DE BARCELONA

ICCUB

EXCELENCIA MARÍA DE MAEZTU

STRONG 2020

RES RED ESPAÑOLA DE SUPERCOMPUTACIÓN

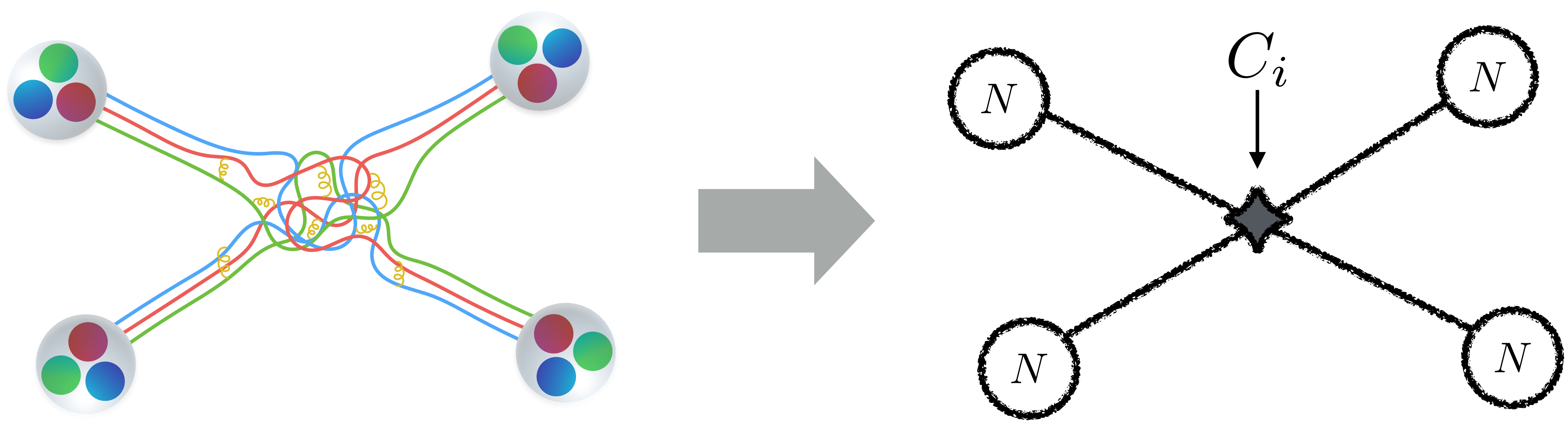
BSC Barcelona Supercomputing Center Centro Nacional de Supercomputación

NPLQCD

- Motivation
- Nuclear physics with Lattice QCD
- EFT for two-baryon systems
- Results for $m_\pi \sim 800 \text{ MeV}$
- Results for $m_\pi \sim 450 \text{ MeV}$

Motivation

☞ To constrain the low-energy coefficients from EFTs, we need data

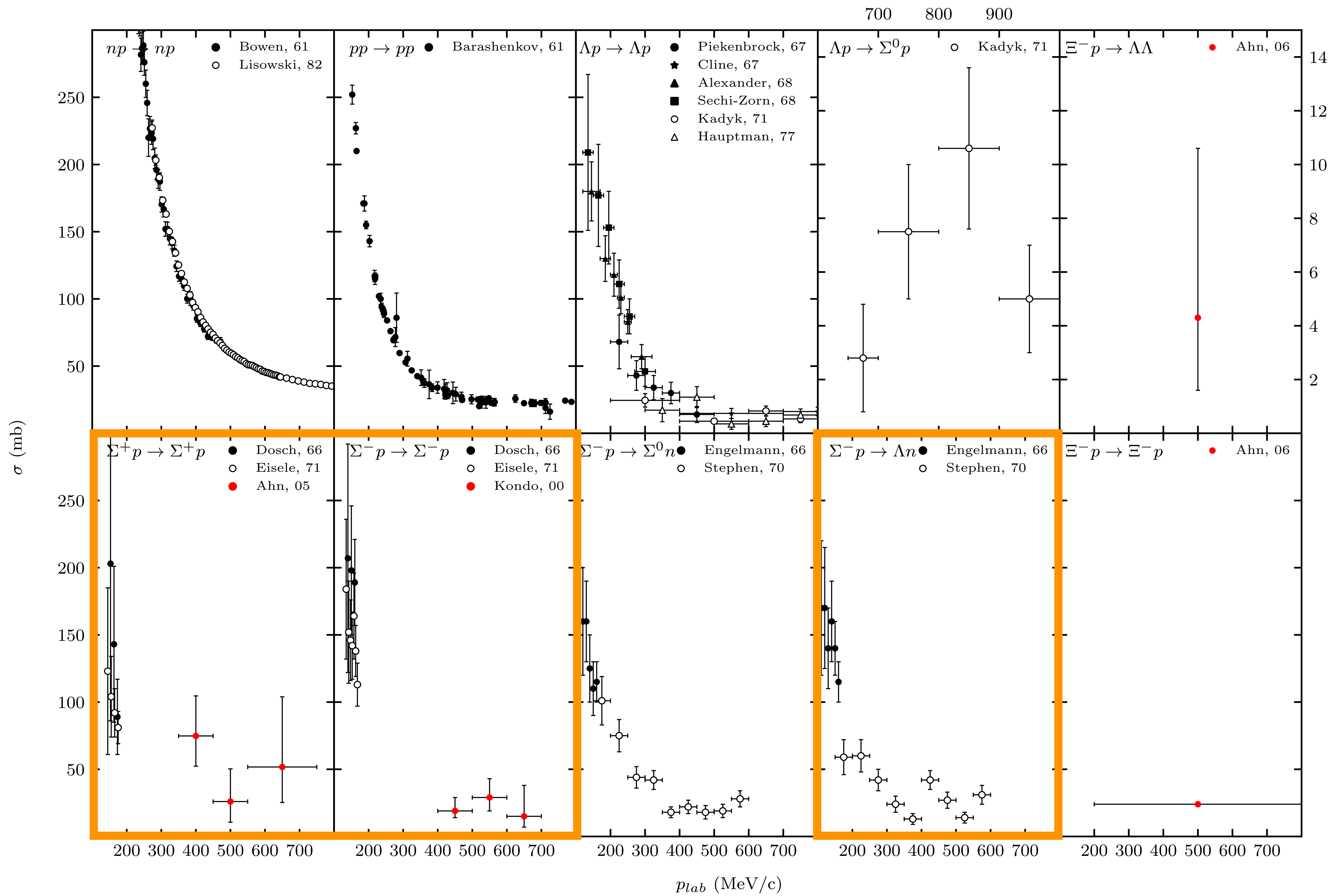


$\mathcal{L}_{QCD}[q, \bar{q}, A; m_q, \alpha_s]$ $\mathcal{L}_{EFT}[\pi, N, \ldots; m_\pi, m_N, \ldots, C_i]$

☞ Do we have experimental data for baryonic systems that contain strange quarks ($\Lambda/\Sigma/\Xi$)?

Motivation

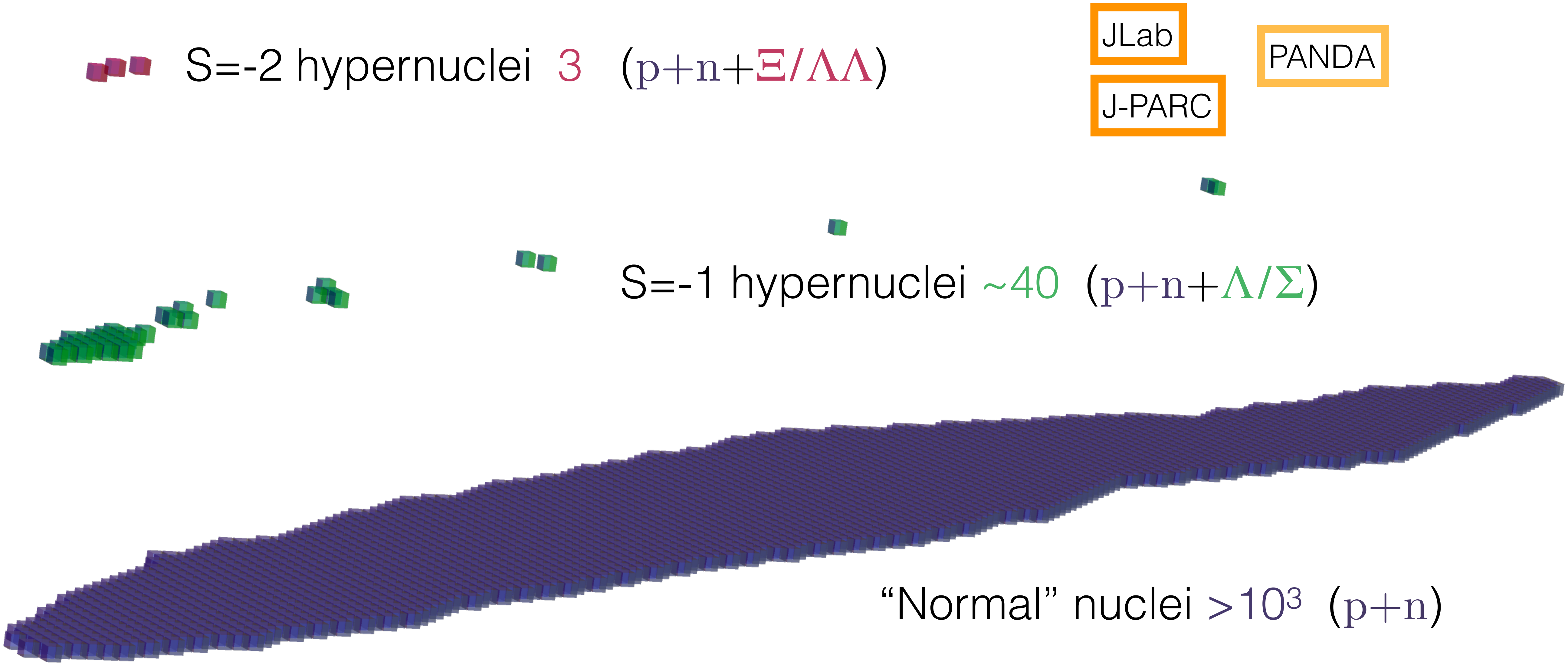
Before 1990s / After 1990s



E40 at J-PARC

Figure updated from
Dover and Feshback, Ann. Phys. 198 (1990)

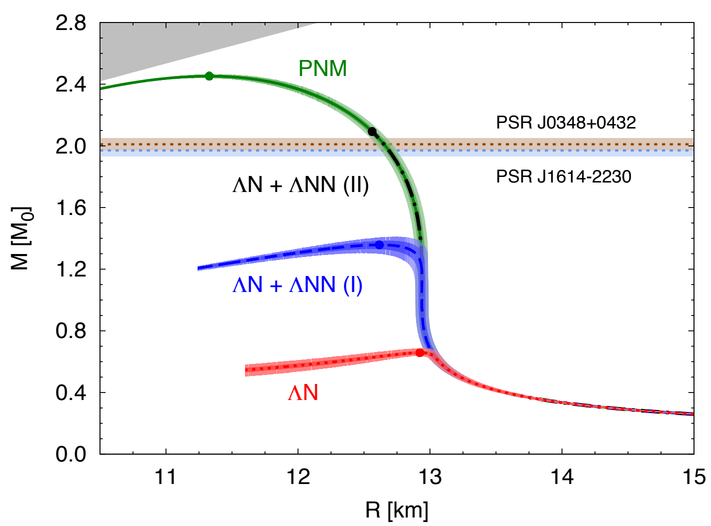
Motivation



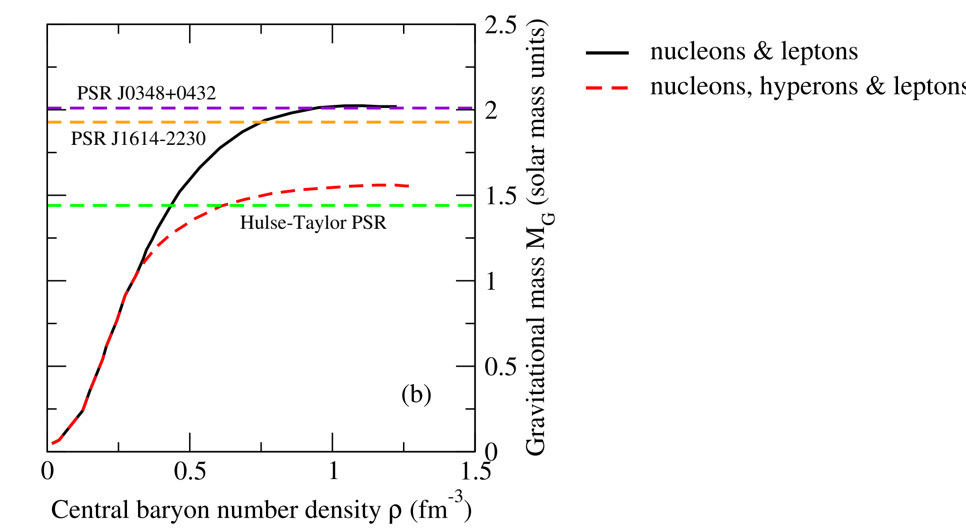
+ new constraints from momentum correlation functions (femtoscopy) at STAR (RHIC), ALICE (LHC) and HADES (GSI).

Motivation

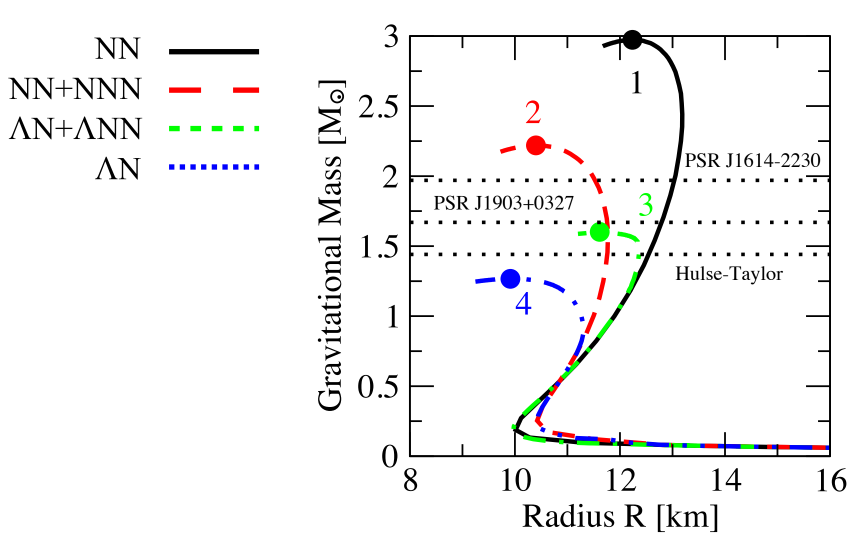
☞ Implications in several fields, like in nuclear astrophysics, with the hyperon puzzle



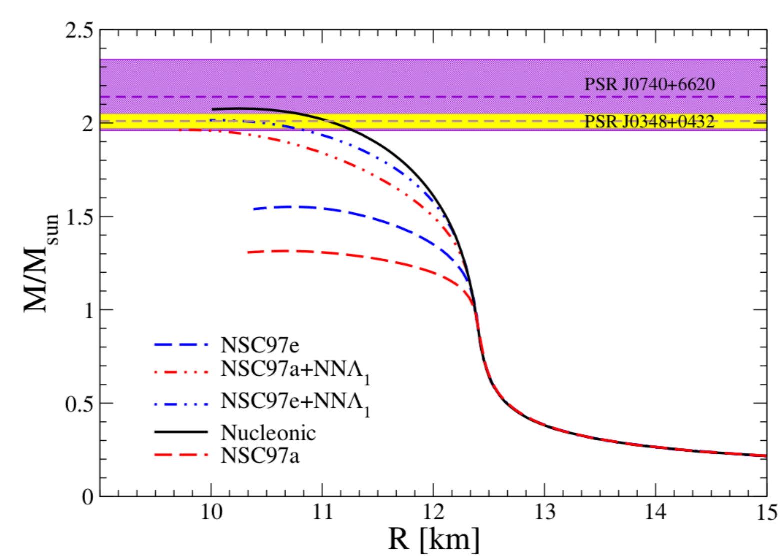
Lonardoni, Lovato, Gandolfi, Pederiva, Phys. Rev. Lett. 114 (2015)



Vidaña, Proc. Roy. Soc. Lond. A 474 (2018)



Vidaña, Logoteta, Providência, Polls, Bombay, EPL 94 (2011)



Logoteta, Vidaña, Bombaci, Eur. Phys. J. A 55 (2019)

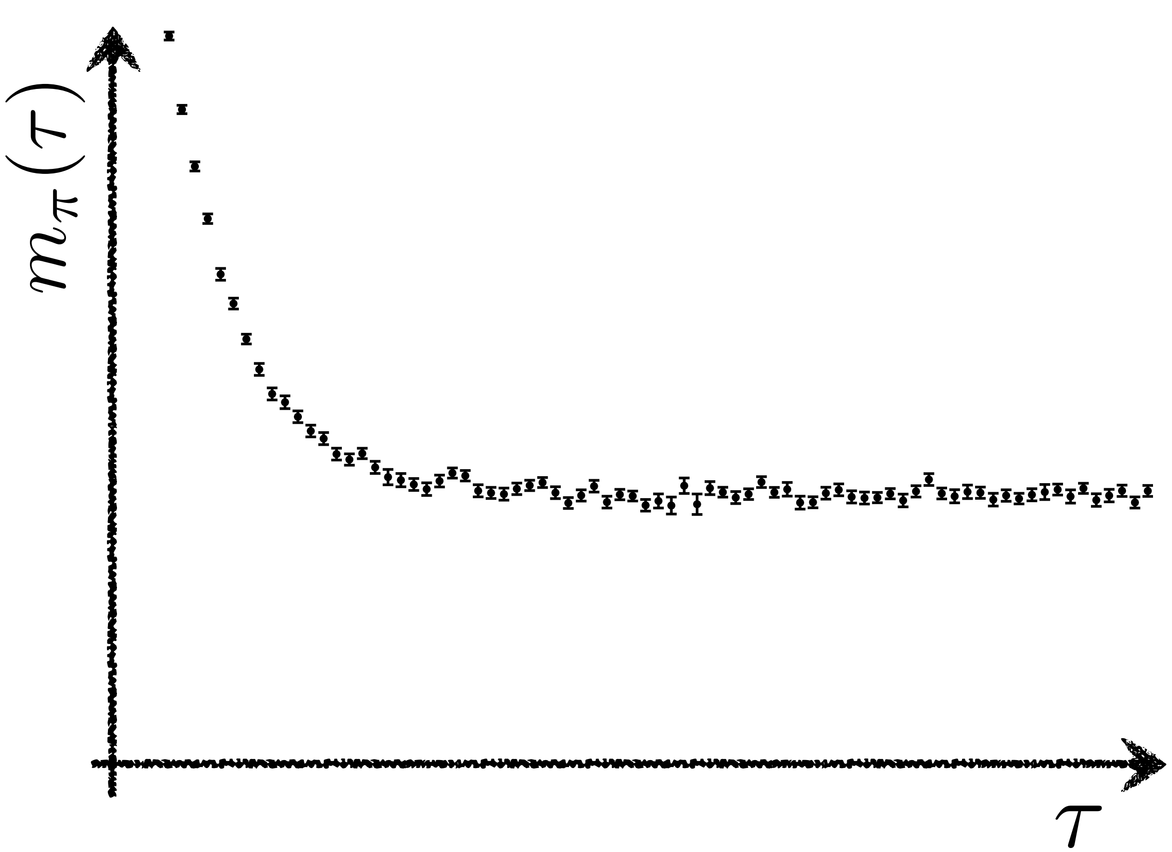
Nuclear physics with Lattice QCD

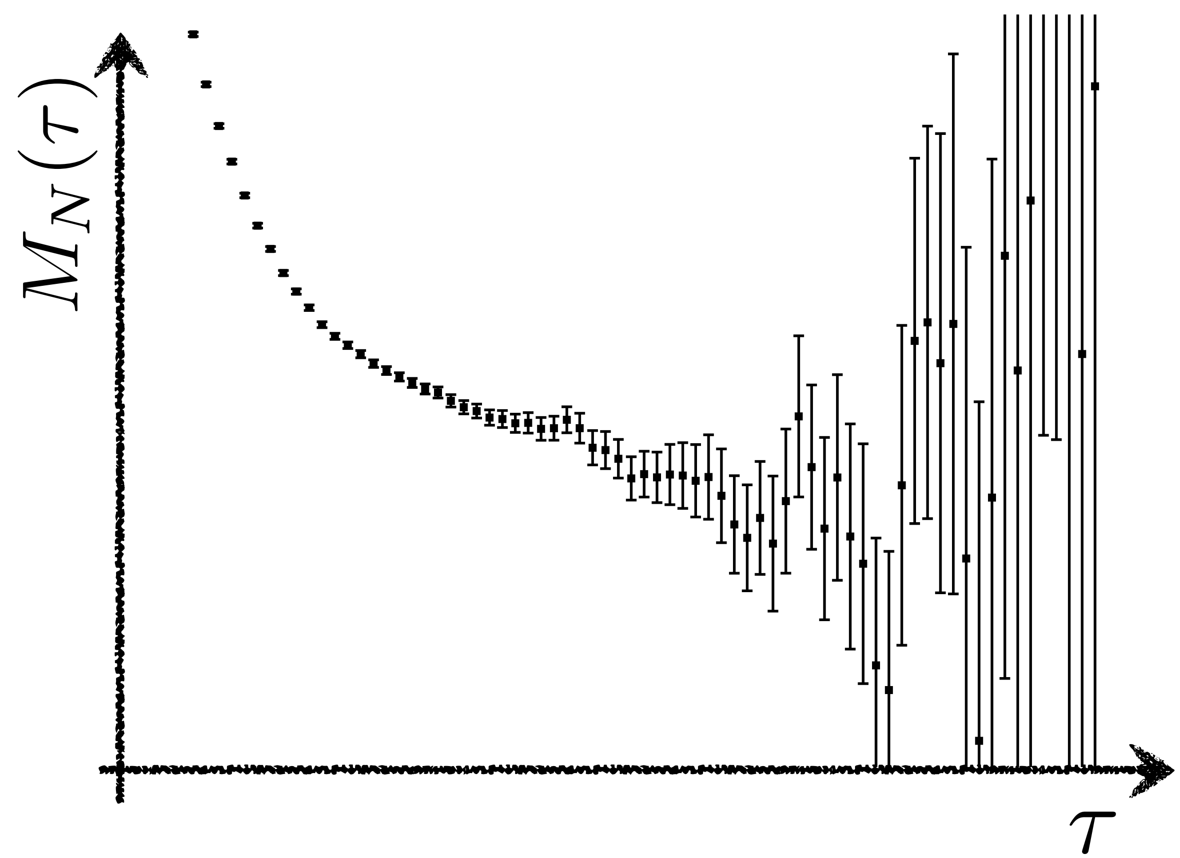
☞ To complement experimental data, we can use lattice QCD

But why most of the results are obtained with heavier-than-physical quark masses?

(NPLQCD, PACS-CS, CalLat, Mainz, HAL QCD)

$$C(\tau) = \langle O(\tau) O^\dagger(0) \rangle = \sum_n Z_n e^{-E_n \tau} \longrightarrow E(\tau) = \ln \frac{C(\tau)}{C(\tau+1)} \xrightarrow{\tau \to \infty} E_0$$





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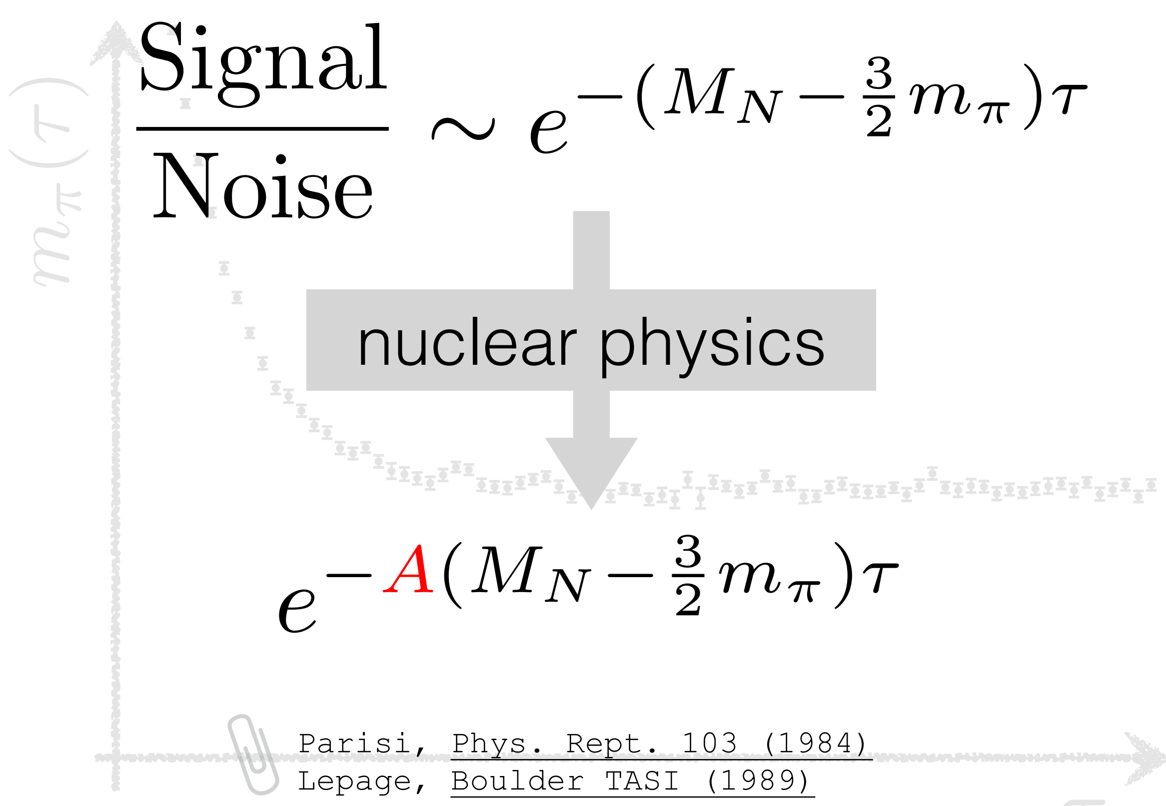
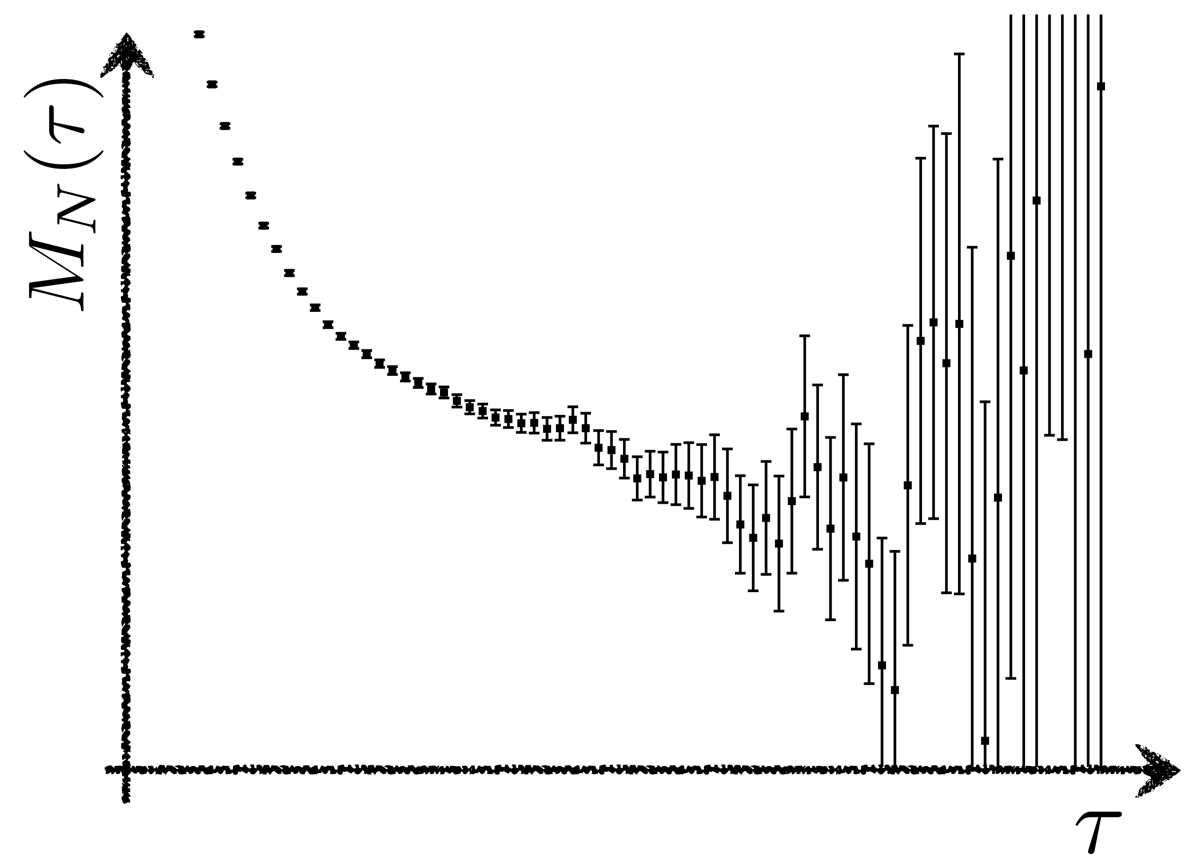


$$\frac{\text{Signal}}{\text{Noise}} \sim e^{-(M_N - \frac{3}{2} m_\pi)\tau}$$

nuclear physics

$$e^{-A(M_N - \frac{3}{2} m_\pi)\tau}$$

Parisi, Phys. Rept. 103 (1984)
Lepage, Boulder TASI (1989)
Wagman and Savage, Phys. Rev. D 96 (2017)



Nuclear physics with Lattice QCD

Signal-to-noise problem

Increase statistics

Compute more propagators: $M\psi = \eta$

cost $\propto \dfrac{1}{m_q}$

$$M_N - \frac{3}{2}m_\pi \sim 700 \text{ MeV} \quad @ \text{ phys}$$

$$M_N - \frac{3}{2}m_\pi \sim 400 \text{ MeV} \quad @ \, m_\pi \sim 800 \text{ MeV}$$

Contract propagators to form correlation functions

naïve: $n_u!n_d!n_s!$ →

Detmold and Orginos,
Phys. Rev. D 87 (2013)
Doi and Endres,
Comput. Phys. Commun. 184 (2013)

NPLQCD,
arXiv:1908.07050 [hep-lat]

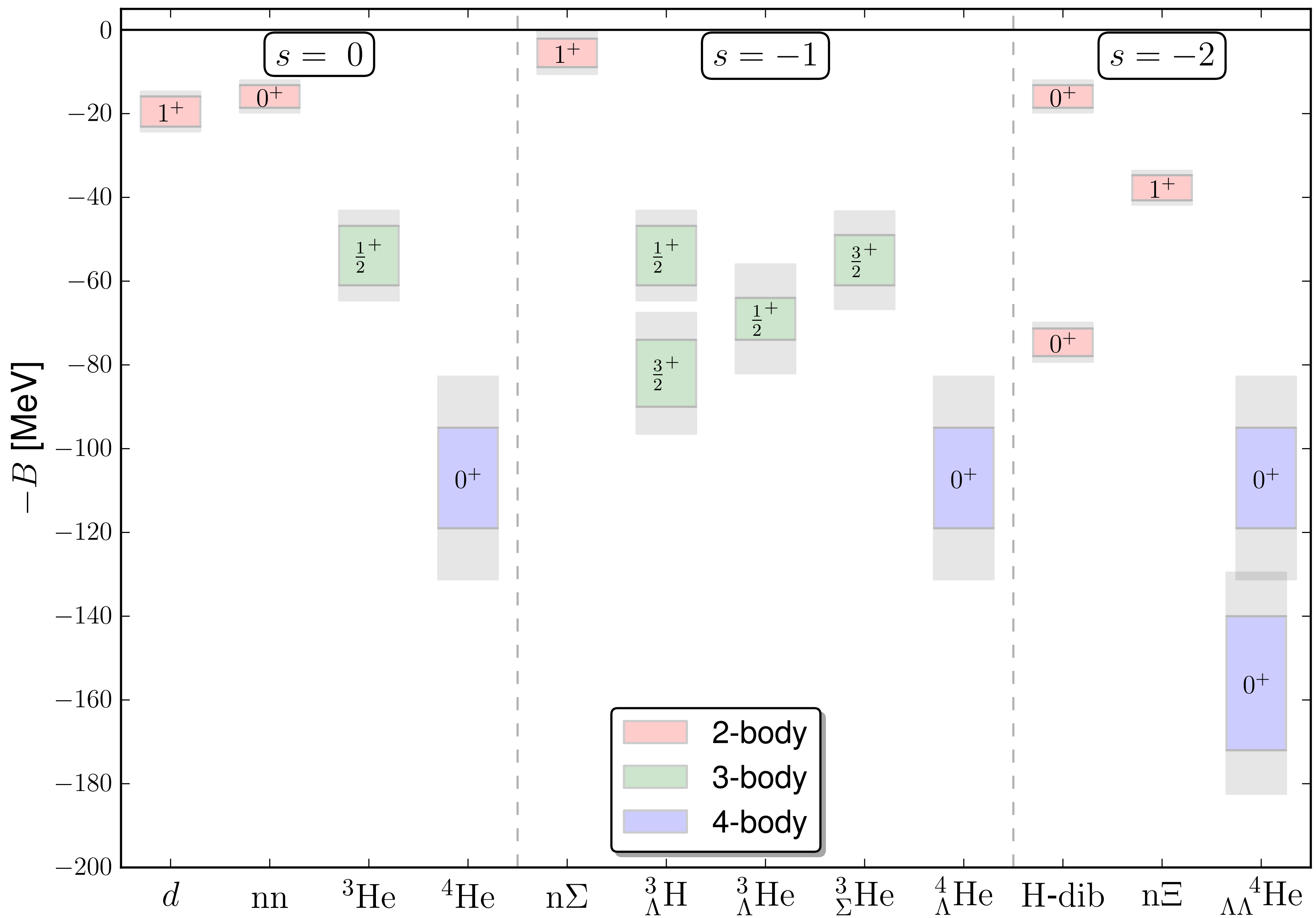
Unphysical quark masses

Nuclear physics with Lattice QCD

☞ A world with $m_\pi \sim 800\ \mathrm{MeV}$ and exact $SU(3)_f$ symmetry:

NPLQCD, Phys. Rev. D 87 (2012)

(no e.m.)



Nuclear physics with Lattice QCD

☞ What if we want to go beyond 4-body systems?

NPLQCD, Phys. Rev. D 87 (2012)
Barnea, Contessi, Gazit, Pederiva, van Kolck, Phys. Rev. Lett. 114 (2015)

$$V^{LO} = C^0_{2-body} + C^1_{2-body}\vec{\sigma_1}\vec{\sigma_2} + D_{3-body}$$

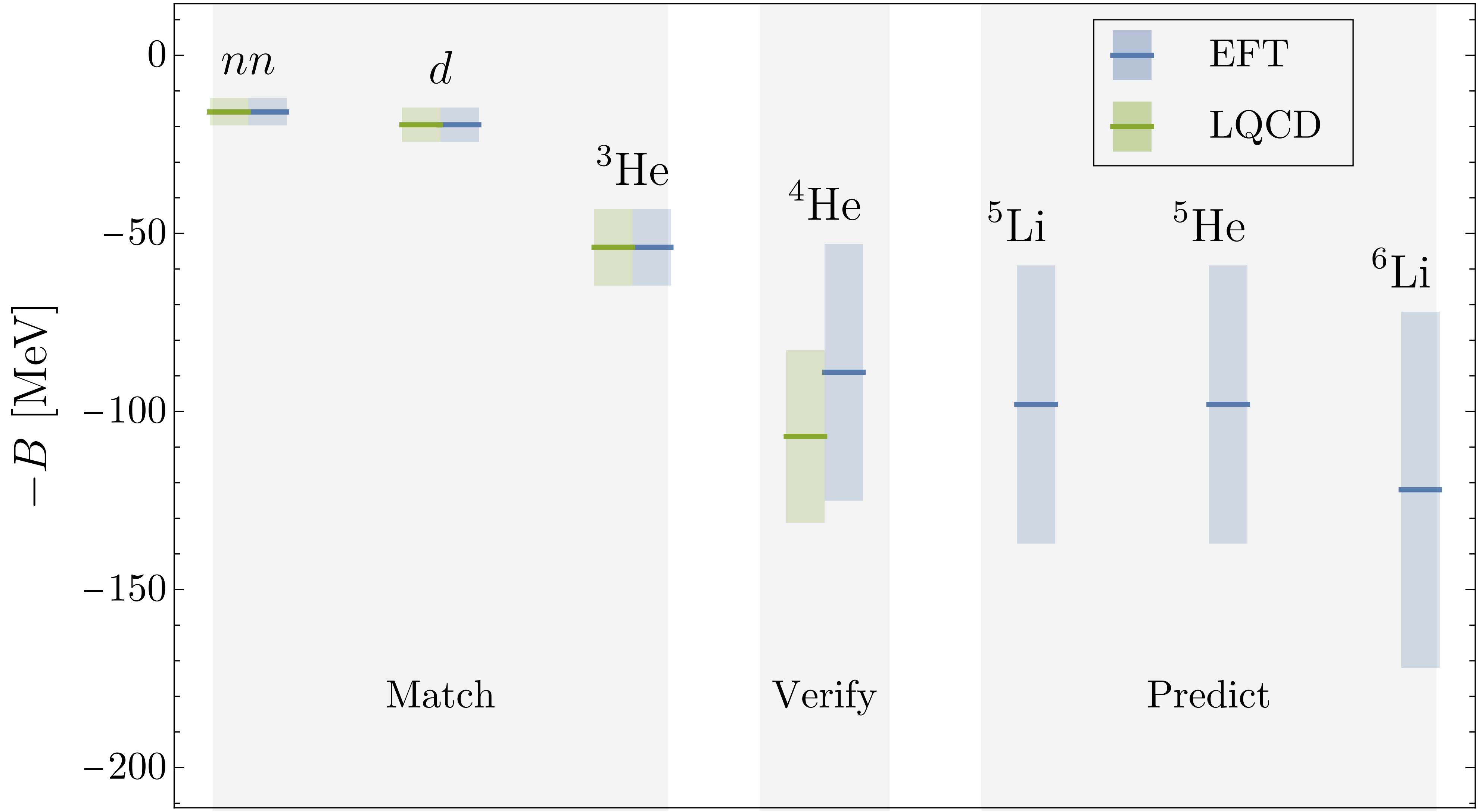


Figure from
Davoudi, Detmold, Shanahan, Orginos, Parreño, Savage, Wagman, Phys. Rept. 900 (2021)

Baryon-Baryon Interactions and Spin-Flavor Symmetry from Lattice Quantum Chromodynamics

Michael L. Wagman,[1,2] Frank Winter,[3] Emmanuel Chang, Zohreh Davoudi,[4]
William Detmold,[4] Kostas Orginos,[5,3] Martin J. Savage,[1,2] and Phiala E. Shanahan[4]
(NPLQCD Collaboration)

Phys. Rev. D 96 (2017)

(Re-analysis and extension of Phys. Rev. D 87 (2013), Phys. Rev. C 88 (2013))

Low-energy Scattering and Effective Interactions of Two Baryons at $m_\pi \sim 450$ MeV from Lattice Quantum Chromodynamics

Marc Illa,[1] Silas R. Beane,[2] Emmanuel Chang, Zohreh Davoudi,[3,4]
William Detmold,[5] David J. Murphy,[5] Kostas Orginos,[6,7] Assumpta Parreño,[1]
Martin J. Savage,[8] Phiala E. Shanahan,[5] Michael L. Wagman,[9] and Frank Winter[7]
(NPLQCD Collaboration)

arXiv:2009.12357 [hep-lat]

(Re-analysis and extension to the 3-flavor sector of Phys. Rev. D 92 (2015))

Baryon-Baryon Interactions and Spin-Flavor Symmetry from Lattice Quantum Chromodynamics

$$m_u = m_d = m_s \longrightarrow m_\pi = m_K \sim 800 \text{ MeV}$$

Michael L. Wagman,[1,2] Frank Winter,[3] Emmanuel Chang, Zohreh Davoudi,[4]
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Phys. Rev. D 96 (2017)

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Low-energy Scattering and Effective Interactions of Two Baryons at $m_\pi \sim 450$ MeV from Lattice Quantum Chromodynamics

$$m_u = m_d \neq m_s \longrightarrow m_\pi \sim 450 \text{ MeV},\ m_K \sim 600 \text{ MeV}$$

Marc Illa,[1] Silas R. Beane,[2] Emmanuel Chang, Zohreh Davoudi,[3,4]
William Detmold,[5] David J. Murphy,[5] Kostas Orginos,[6,7] Assumpta Parreño,[1]
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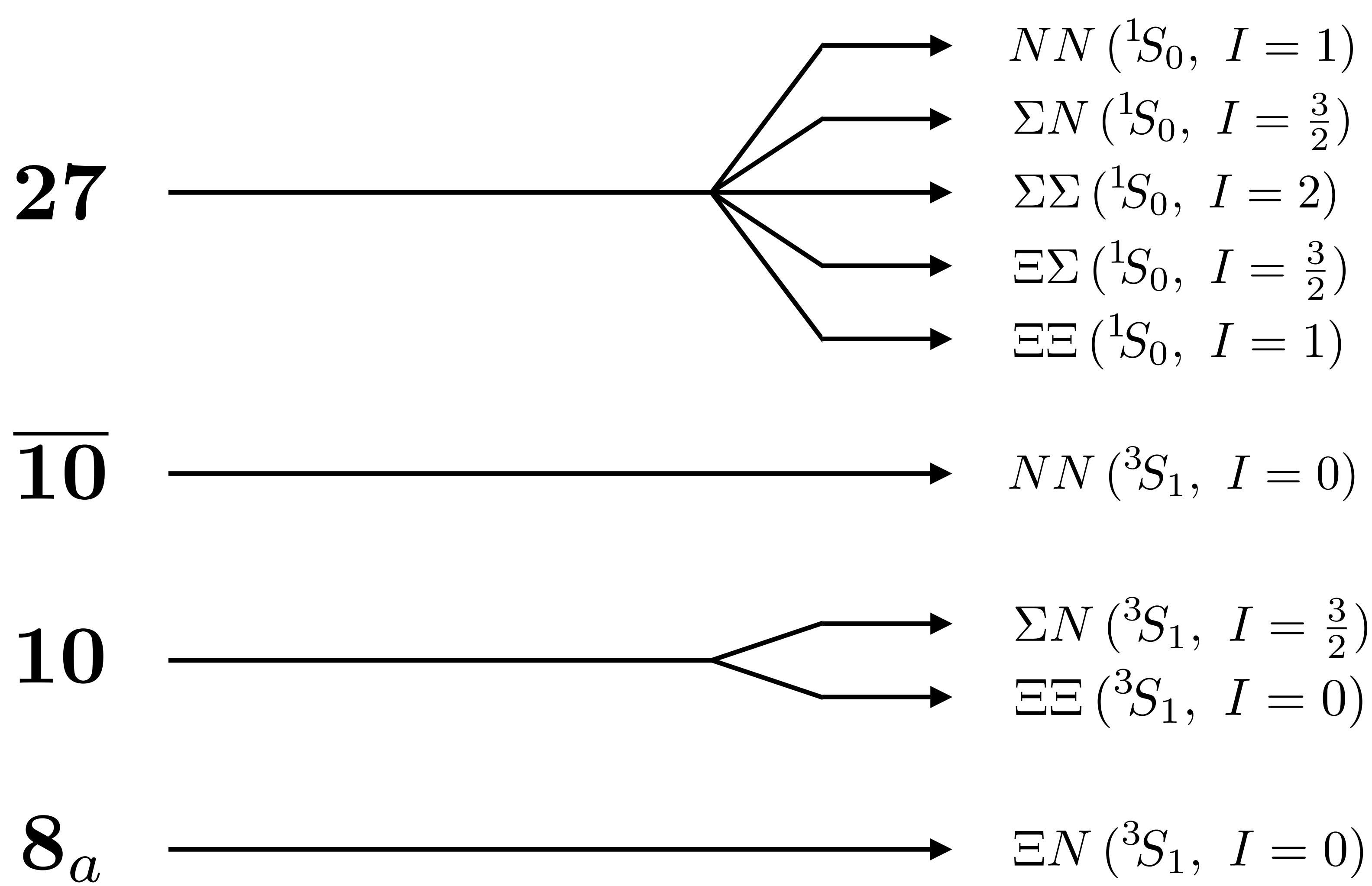
arXiv:2009.12357 [hep-lat]

(Re-analysis and extension to the 3-flavor sector of Phys. Rev. D 92 (2015))

Baryon-baryon systems $(J^P = \frac{1}{2}^+)$

$$\mathbf{8} \otimes \mathbf{8} = \mathbf{27} \oplus \mathbf{8}_s \oplus \mathbf{1} \oplus \overline{\mathbf{10}} \oplus \mathbf{10} \oplus \mathbf{8}_a$$

$m_\pi \sim 800$ MeV $\qquad\qquad m_\pi \sim 450$ MeV



EFT for two-baryon systems

☞ At very low energies, we can use pionless EFT to study the baryon-baryon interaction

At leading order:

$$\mathcal{L}_{BB}^{(0),\,SU(3)} = -\,c_1 \mathrm{Tr}(B_i^\dagger B_i B_j^\dagger B_j) - c_2 \mathrm{Tr}(B_i^\dagger B_j B_j^\dagger B_i) - c_3 \mathrm{Tr}(B_i^\dagger B_j^\dagger B_i B_j) - c_4 \mathrm{Tr}(B_i^\dagger B_j^\dagger B_j B_i) - c_5 \mathrm{Tr}(B_i^\dagger B_i)\mathrm{Tr}(B_j^\dagger B_j) - c_6 \mathrm{Tr}(B_i^\dagger B_j)\mathrm{Tr}(B_j^\dagger B_i)$$

$$B = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ \Xi^- & \Xi^0 & -\sqrt{\frac{2}{3}}\Lambda \end{pmatrix} \qquad i, j \in \{\uparrow, \downarrow\}$$

$$c_1, \ldots, c_6 \longrightarrow c^{(27)}, \ldots, c^{(8_a)}$$

Savage and Wise, Phys. Rev. D 53 (1996)

EFT for two-baryon systems

☞ At very low energies, we can use pionless EFT to study the baryon-baryon interaction

At next-to-leading order:

$$\begin{aligned}\mathcal{L}_{BB}^{(2),\,SU(3)} =& -\tilde{c}_1 \mathrm{Tr}(B_i^\dagger \nabla^2 B_i B_j^\dagger B_j + \mathrm{h.c.}) - \tilde{c}_2 \mathrm{Tr}(B_i^\dagger \nabla^2 B_j B_j^\dagger B_i + \mathrm{h.c.}) \\ & -\tilde{c}_3 \mathrm{Tr}(B_i^\dagger B_j^\dagger \nabla^2 B_i B_j + \mathrm{h.c.}) - \tilde{c}_4 \mathrm{Tr}(B_i^\dagger B_j^\dagger \nabla^2 B_j B_i + \mathrm{h.c.}) \\ & -\tilde{c}_5 [\mathrm{Tr}(B_i^\dagger \nabla^2 B_i)\mathrm{Tr}(B_j^\dagger B_j) + \mathrm{h.c.}] - \tilde{c}_6 [\mathrm{Tr}(B_i^\dagger \nabla^2 B_j)\mathrm{Tr}(B_j^\dagger B_i) + \mathrm{h.c.}]\end{aligned}$$

$$\tilde{c}_1, \ldots, \tilde{c}_6 \longrightarrow \tilde{c}^{(27)}, \ldots, \tilde{c}^{(8_a)}$$

Petschauer and Kaiser, Nuc. Phys. A 916 (2013)

EFT for two-baryon systems

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At next-to-leading order:

$$
\begin{aligned}
\mathcal{L}_{BB}^{(2),\,SU(3)} = &- \tilde{c}_1 \mathrm{Tr}(B_i^\dagger \nabla^2 B_i B_j^\dagger B_j + \text{h.c.}) - \tilde{c}_2 \mathrm{Tr}(B_i^\dagger \nabla^2 B_j B_j^\dagger B_i + \text{h.c.}) \\
&- \tilde{c}_3 \mathrm{Tr}(B_i^\dagger B_j^\dagger \nabla^2 B_i B_j + \text{h.c.}) - \tilde{c}_4 \mathrm{Tr}(B_i^\dagger B_j^\dagger \nabla^2 B_j B_i + \text{h.c.}) \\
&- \tilde{c}_5 [\mathrm{Tr}(B_i^\dagger \nabla^2 B_i)\mathrm{Tr}(B_j^\dagger B_j) + \text{h.c.}] - \tilde{c}_6 [\mathrm{Tr}(B_i^\dagger \nabla^2 B_j)\mathrm{Tr}(B_j^\dagger B_i) + \text{h.c.}]
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}_{BB}^{(2),\,\cancel{SU(3)}} = &- c_1^\chi \mathrm{Tr}(B_i^\dagger \chi B_i B_j^\dagger B_j) - c_2^\chi \mathrm{Tr}(B_i^\dagger \chi B_j B_j^\dagger B_i) - c_3^\chi \mathrm{Tr}(B_i^\dagger B_i \chi B_j^\dagger B_j) \\
&- c_4^\chi \mathrm{Tr}(B_i^\dagger B_j \chi B_j^\dagger B_i) - c_5^\chi \mathrm{Tr}(B_i^\dagger \chi B_j^\dagger B_i B_j + \text{h.c.}) - c_6^\chi \mathrm{Tr}(B_i^\dagger \chi B_j^\dagger B_j B_i + \text{h.c.}) \\
&- c_7^\chi \mathrm{Tr}(B_i^\dagger B_j^\dagger \chi B_i B_j) - c_8^\chi \mathrm{Tr}(B_i^\dagger B_j^\dagger \chi B_j B_i) - c_9^\chi \mathrm{Tr}(B_i^\dagger B_j^\dagger B_i B_j \chi) \\
&- c_{10}^\chi \mathrm{Tr}(B_i^\dagger B_j^\dagger B_j B_i \chi) - c_{11}^\chi \mathrm{Tr}(B_i^\dagger \chi B_i)\mathrm{Tr}(B_j^\dagger B_j) - c_{12}^\chi \mathrm{Tr}(B_i^\dagger \chi B_j)\mathrm{Tr}(B_j^\dagger B_i)
\end{aligned}
$$

Petschauer and Kaiser, Nuc. Phys. A 916 (2013)

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$$- \tilde{c}_3 \mathrm{Tr}(B_i^\dagger B_j^\dagger \nabla^2 B_i B_j + \mathrm{h.c.}) - \tilde{c}_4 \mathrm{Tr}(B_i^\dagger B_j^\dagger \nabla^2 B_j B_i + \mathrm{h.c.})$$
$$- \tilde{c}_5 [\mathrm{Tr}(B_i^\dagger \nabla^2 B_i)\mathrm{Tr}(B_j^\dagger B_j) + \mathrm{h.c.}] - \tilde{c}_6 [\mathrm{Tr}(B_i^\dagger \nabla^2 B_j)\mathrm{Tr}(B_j^\dagger B_i) + \mathrm{h.c.}]$$

$$\chi = \begin{pmatrix} m_\pi^2 & 0 & 0 \\ 0 & m_\pi^2 & 0 \\ 0 & 0 & 2m_K^2 - m_\pi^2 \end{pmatrix}$$

$$\mathcal{L}_{BB}^{(2),\,\cancel{SU(3)}} = - c_1^\chi \mathrm{Tr}(B_i^\dagger \chi B_i B_j^\dagger B_j) - c_2^\chi \mathrm{Tr}(B_i^\dagger \chi B_j B_j^\dagger B_i) - c_3^\chi \mathrm{Tr}(B_i^\dagger B_i \chi B_j^\dagger B_j)$$
$$- c_4^\chi \mathrm{Tr}(B_i^\dagger B_j \chi B_j^\dagger B_i) - c_5^\chi \mathrm{Tr}(B_i^\dagger \chi B_j^\dagger B_i B_j + \mathrm{h.c.}) - c_6^\chi \mathrm{Tr}(B_i^\dagger \chi B_j^\dagger B_j B_i + \mathrm{h.c.})$$
$$- c_7^\chi \mathrm{Tr}(B_i^\dagger B_j^\dagger \chi B_i B_j) - c_8^\chi \mathrm{Tr}(B_i^\dagger B_j^\dagger \chi B_j B_i) - c_9^\chi \mathrm{Tr}(B_i^\dagger B_j^\dagger B_i B_j \chi)$$
$$- c_{10}^\chi \mathrm{Tr}(B_i^\dagger B_j^\dagger B_j B_i \chi) - c_{11}^\chi \mathrm{Tr}(B_i^\dagger \chi B_i)\mathrm{Tr}(B_j^\dagger B_j) - c_{12}^\chi \mathrm{Tr}(B_i^\dagger \chi B_j)\mathrm{Tr}(B_j^\dagger B_i)$$

Petschauer and Kaiser, Nuc. Phys. A 916 (2013)

EFT for two-baryon systems

☞ At very low energies, we can use pionless EFT to study the baryon-baryon interaction

In the limit of large number of colors, there is an $SU(6)$ spin-flavor symmetry

$$\mathcal{L}_{BB}^{(0),SU(6)} = -a(\Psi^\dagger_{\mu\nu\rho}\Psi^{\mu\nu\rho})^2 - b\Psi^\dagger_{\mu\nu\sigma}\Psi^{\mu\nu\tau}\Psi^\dagger_{\rho\delta\tau}\Psi^{\rho\delta\sigma}$$

$$\Psi^{\mu\nu\rho} = \Psi^{(i\alpha)(j\beta)(k\gamma)} = \frac{1}{\sqrt{18}}\left(B^\alpha_{\omega,i}\epsilon^{\omega\beta\gamma}\epsilon_{jk} + B^\beta_{\omega,j}\epsilon^{\omega\gamma\alpha}\epsilon_{ik} + B^\gamma_{\omega,k}\epsilon^{\omega\alpha\beta}\epsilon_{ij}\right)$$

(in the 2-flavor sector, the SU(4) Wigner symmetry is observed)

Kaplan and Savage, Phys. Lett. B 365 (1996)

EFT for two-baryon systems

☞ How can we compute the values of the coefficients?

$$\left[-\frac{1}{a_{B_1 B_2}} + \mu\right]^{-1} = \frac{\overline{M}_{B_1 B_2}}{2\pi}\left(c^{(\mathrm{irrep})} + \boldsymbol{c}^{\chi}_{B_1 B_2}\right)$$

$\boldsymbol{c}^{\chi}_{B_1 B_2}$ ← $c^{\chi}_{B_1 B_2}(m_K^2 - m_\pi^2)$

$$\frac{r_{B_1 B_2}}{2}\left[-\frac{1}{a_{B_1 B_2}} + \mu\right]^{-2} = \frac{\overline{M}_{B_1 B_2}}{2\pi}\,\tilde{c}^{(\mathrm{irrep})}$$

Kaplan, Savage and Wise, Phys. Lett. B 424 (1998)
Nuc. Phys. B 534 (1998)
van Kolck, Nucl. Phys. A 645 (1999)

☞ Are the baryon-baryon channels natural?

$$NN\ (^3S_1) : r/a \sim 0.32 \qquad\qquad NN\ (^1S_0) : r/a \sim -0.12$$

Results for $m_\pi \sim 800$ MeV

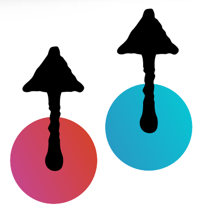
Phys. Rev. D 96 (2017)

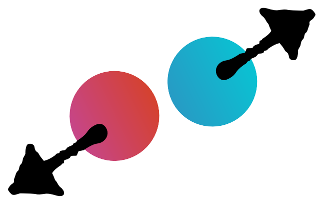
$n_f = 3,\ m_\pi = 806(5)\ \text{MeV},\ b = 0.145(2)\ \text{fm}$

$L \in \{3.4,\ 4.5,\ 6.7\}\ \text{fm} \quad T \in \{6.7,\ 6.7,\ 9.0\}\ \text{fm}$

Different smearings: SP and SS

Boosted systems ($\mathbf{d}$) and back-to-back momenta





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Phys. Rev. D 96 (2017)

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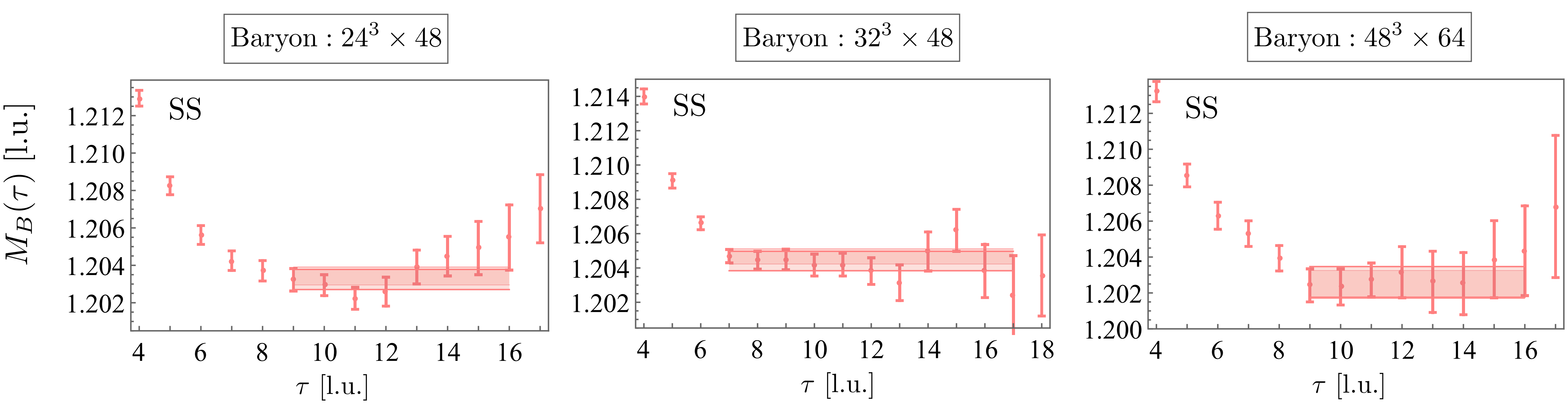
Different smearings: SP and SS

Boosted systems ($\mathbf{d}$) and back-to-back momenta

☞ At the $SU(3)$ flavor-symmetric point, all baryons have the same mass

$$M_N = M_\Lambda = M_\Sigma = M_\Xi \sim 1.6 \text{ GeV}$$



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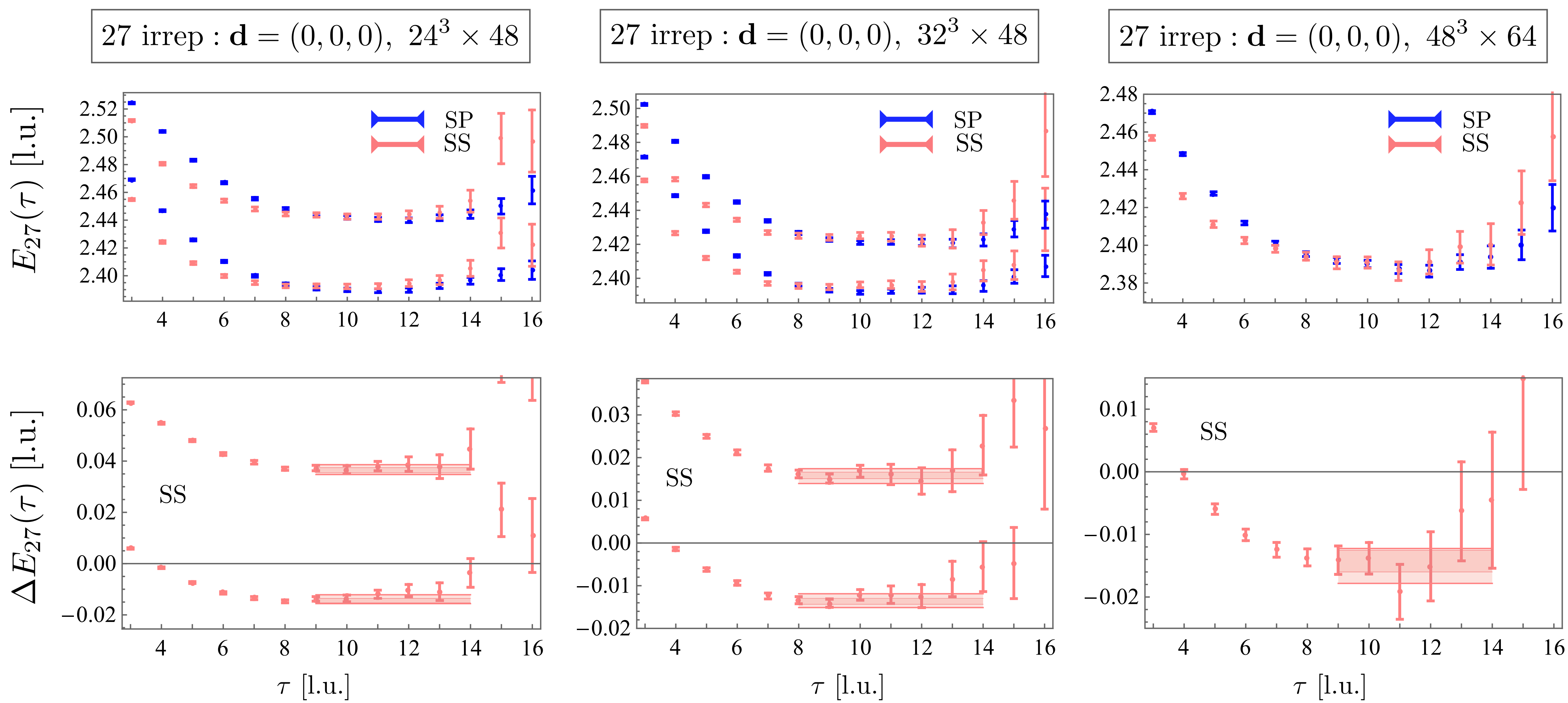
Different smearings: SP and SS

Boosted systems ($\mathbf{d}$) and back-to-back momenta



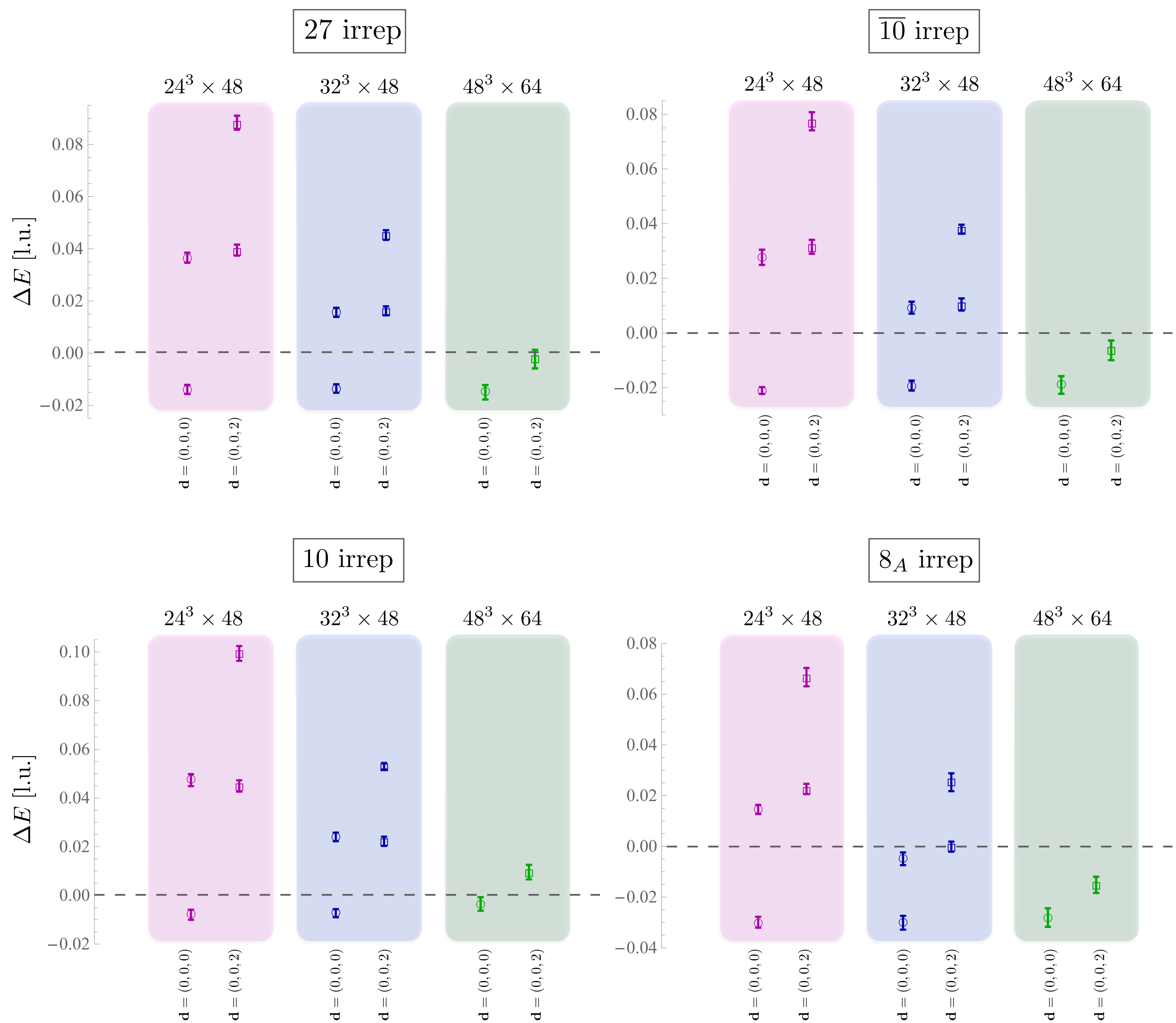
Results for $m_\pi \sim 800$ MeV

Phys. Rev. D 96 (2017)

- A total of 10 kinematic points per system
- All show negative ground-state energies

↓

How can we compute scattering parameters and binding energies?



Results for $m_\pi \sim 800$ MeV

Phys. Rev. D 96 (2017)

☞ Use Lüscher's formalism

Lüscher, Commun. Math. Phys. 105 (1986), Nucl. Phys. B 354 (1991) + many more

$$k^* \cot\delta = \frac{2}{\gamma L\sqrt{\pi}} \sum_{\mathbf{n}\in\mathbb{Z}^3} \frac{1}{[\hat{\gamma}^{-1}(\mathbf{n}-\alpha\mathbf{d})]^2 - (\frac{k^* L}{2\pi})^2}$$

In the negative k^{*2} region, it can be expanded to find the binding momenta $\kappa^{(\infty)}$:

Beane, Bedaque, Parreño, Savage, Phys. Lett. B 585 (2004)
Davoudi and Savage, Phys. Rev. D 84 (2011)

$$B = m_1 + m_2 - \sqrt{m_1^2 - \kappa^{(\infty)2}} - \sqrt{m_2^2 - \kappa^{(\infty)2}}$$

$$B_{27} = 20.6^{(+1.8)(+2.8)}_{(-2.4)(-1.6)}\ \mathrm{MeV} \qquad B_{10} = 6.7^{(+3.3)(+1.8)}_{(-1.9)(-6.2)}\ \mathrm{MeV}$$

$$B_{\overline{10}} = 27.9^{(+3.1)(+2.2)}_{(-2.3)(-1.4)}\ \mathrm{MeV} \qquad B_{8_a} = 40.7^{(+2.1)(+2.4)}_{(-3.2)(-1.4)}\ \mathrm{MeV}$$

☞ All systems are bound

Results for $m_\pi \sim 800$ MeV

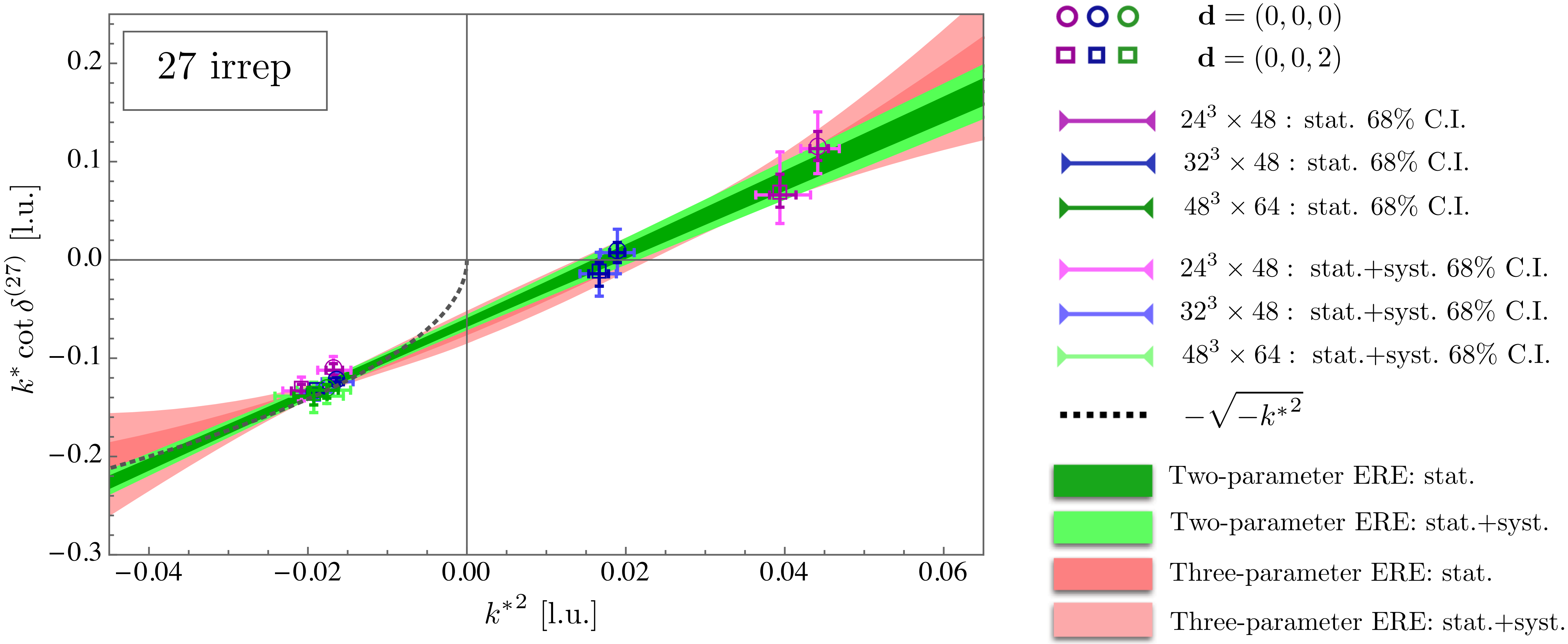
Phys. Rev. D 96 (2017)

☞ Use Lüscher's formalism

Lüscher, Commun. Math. Phys. 105 (1986), Nucl. Phys. B 354 (1991) + many more

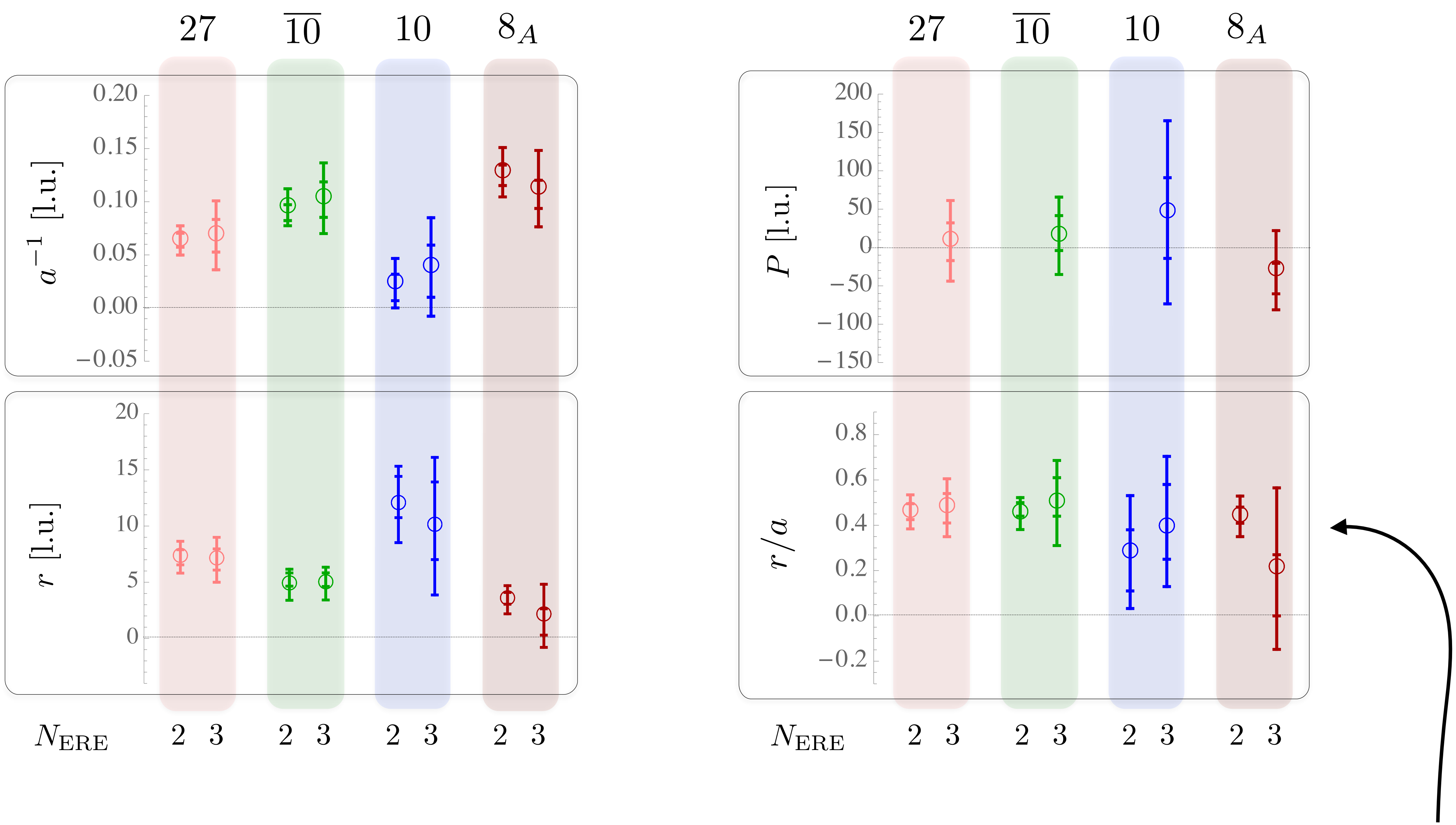
Since all points are below the t-channel cut $(k^* = \frac{m_\pi}{2})$, we can use the effective range expansion (ERE) to extract the scattering parameters

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



Results for $m_\pi \sim 800$ MeV

Phys. Rev. D 96 (2017)

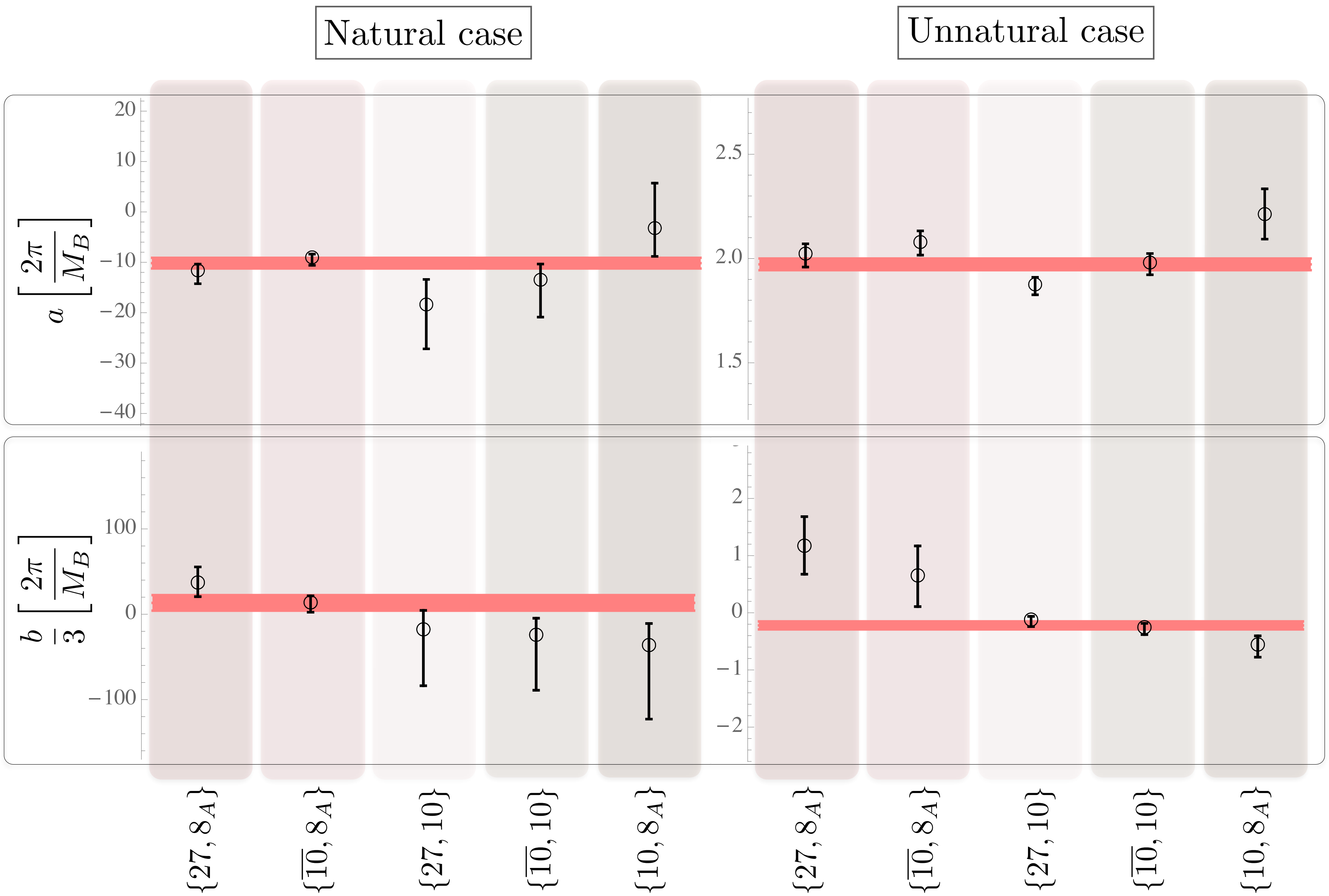


All systems show unnaturalness

Results for $m_\pi \sim 800$ MeV

Phys. Rev. D 96 (2017)

$$c^{(27)} = 2a - \frac{2b}{27} \qquad c^{(\overline{10})} = 2a - \frac{2b}{27} \qquad c^{(10)} = 2a + \frac{14b}{27} \qquad c^{(8_a)} = 2a + \frac{2b}{27}$$



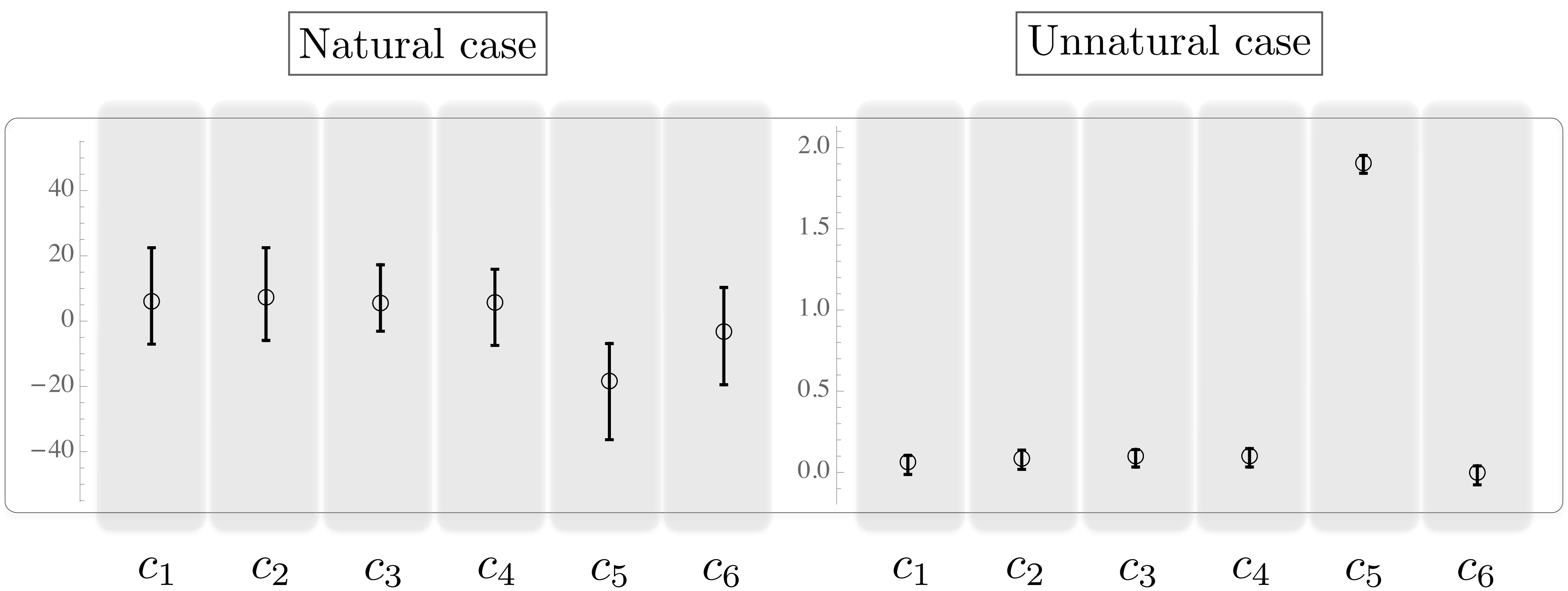
$SU(6)$ ✓

Results for $m_\pi \sim 800$ MeV

Phys. Rev. D 96 (2017)

☞ With the $SU(6)$ coefficients, we can compute all LO $SU(3)$ LECs:

$$c_1 = -\frac{7}{27}b \qquad c_2 = \frac{1}{9}b \qquad c_3 = \frac{10}{81}b \qquad c_4 = -\frac{14}{81}b \qquad c_5 = a + \frac{2}{9}b \qquad c_6 = -\frac{1}{9}b$$



$SU(16)$ ✔

☞ But where does $SU(16)$ come from?

Beane, Kaplan, Klco, Savage, Phys. Rev. Lett. 122 (2019) ⟶ New conjecture: entanglement suppression is a dynamical property of QCD

(A similar idea was previously used to constrain QED and weak interactions, but by imposing maximal entanglement)

Cervera-Lierta, Latorre, Rojo, Rottoli, SciPost Phys. 3 (2017)

Results for $m_\pi \sim 450$ MeV

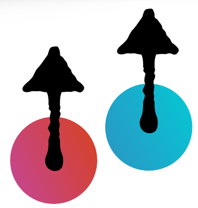
arXiv:2009.12357 [hep-lat]

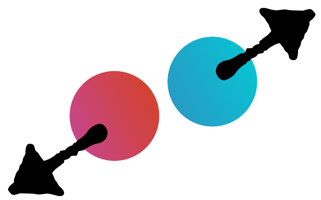
$n_f = 2+1,\ m_\pi = 450(5)\ \text{MeV},\ b = 0.117(2)\ \text{fm}$

$L \in \{2.8,\ 3.7,\ 5.6\}\ \text{fm} \quad T \in \{7.5,\ 11.2,\ 11.2\}\ \text{fm}$

Different smearings: SP and SS

Boosted systems ($\mathbf{d}$) and back-to-back momenta





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$n_f = 2+1,\ m_\pi = 450(5)\ \text{MeV},\ b = 0.117(2)\ \text{fm}$

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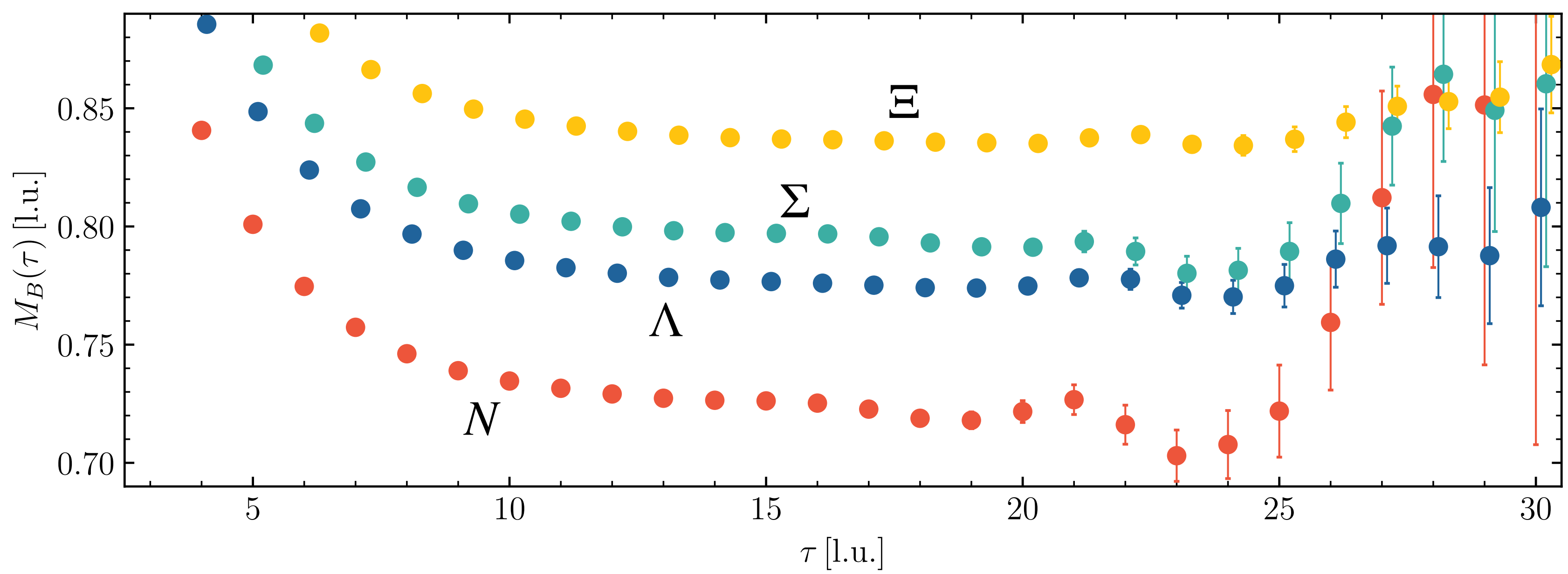
Different smearings: SP and SS

Boosted systems ($\mathbf{d}$) and back-to-back momenta

☞ With $SU(3)$ flavor symmetry being explicitly broken, the baryons will have different mass

$M_N \sim 1.23\ \text{GeV} \qquad M_\Lambda \sim 1.31\ \text{GeV} \qquad M_\Sigma \sim 1.35\ \text{GeV} \qquad M_\Xi \sim 1.41\ \text{GeV}$



Results for $m_\pi \sim 450$ MeV

arXiv:2009.12357 [hep-lat]

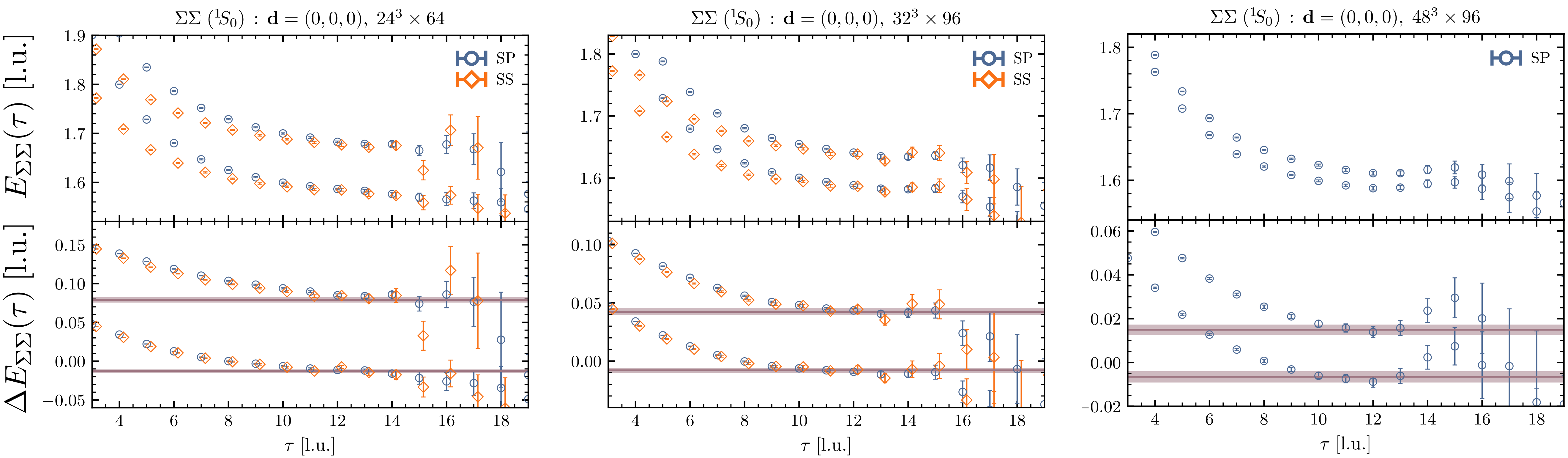
$n_f = 2+1,\ m_\pi = 450(5)$ MeV, $b = 0.117(2)$ fm

$L \in \{2.8,\ 3.7,\ 5.6\}$ fm $\quad T \in \{7.5,\ 11.2,\ 11.2\}$ fm

Different smearings: SP and SS

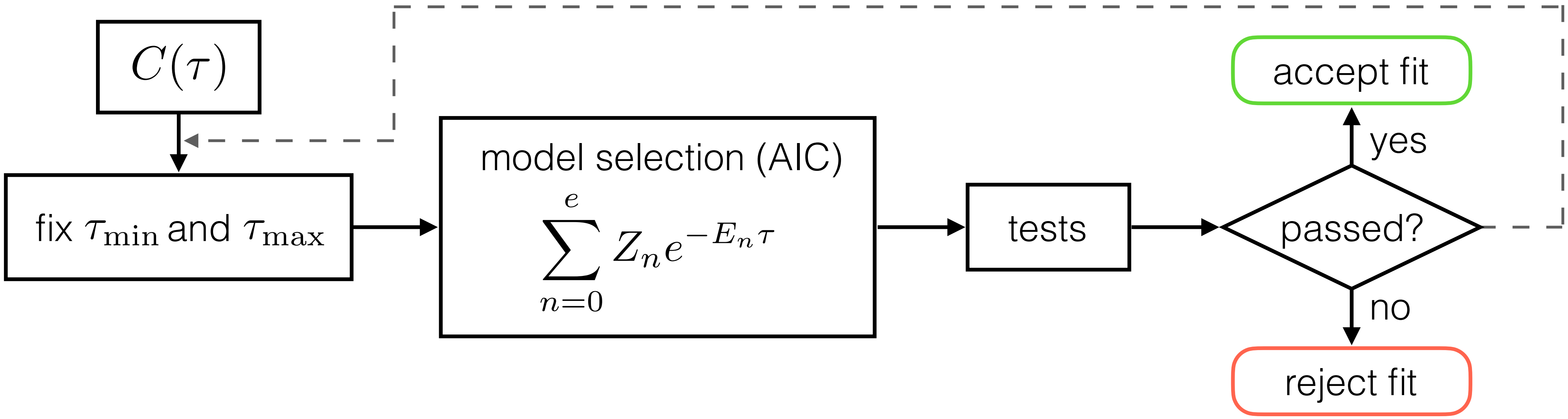
Boosted systems ($\mathbf{d}$) and back-to-back momenta

☞ Noisier correlation functions, so a more elaborated fitting strategy — NPLQCD+QCDSF, arXiv:2003.12130 [hep-lat]

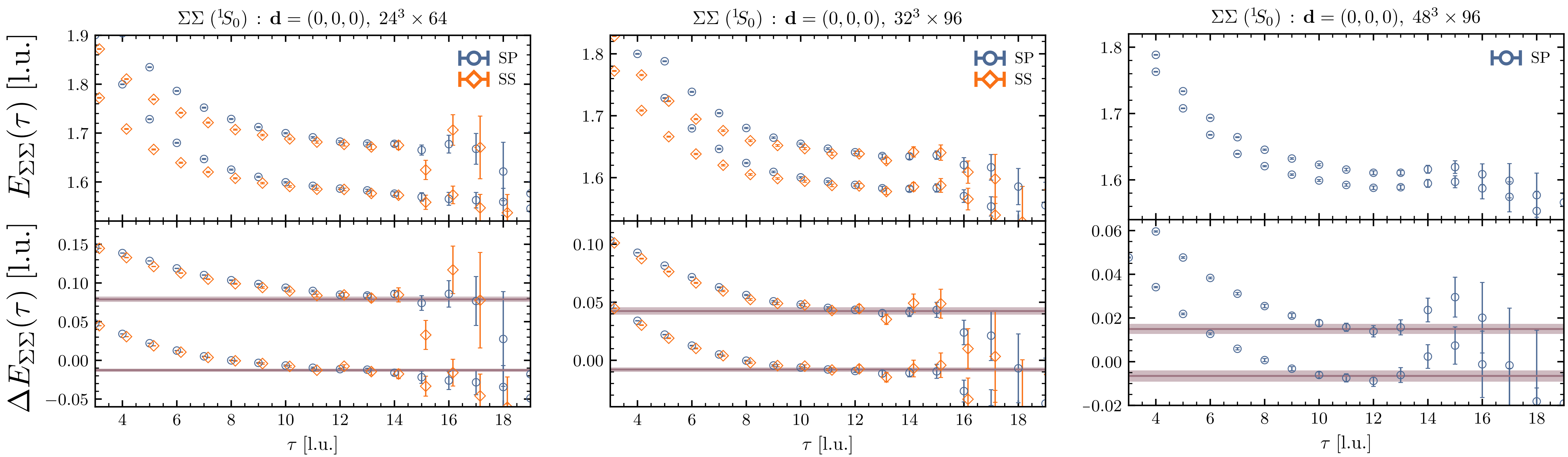


Results for $m_\pi \sim 450$ MeV

arXiv:2009.12357 [hep-lat]



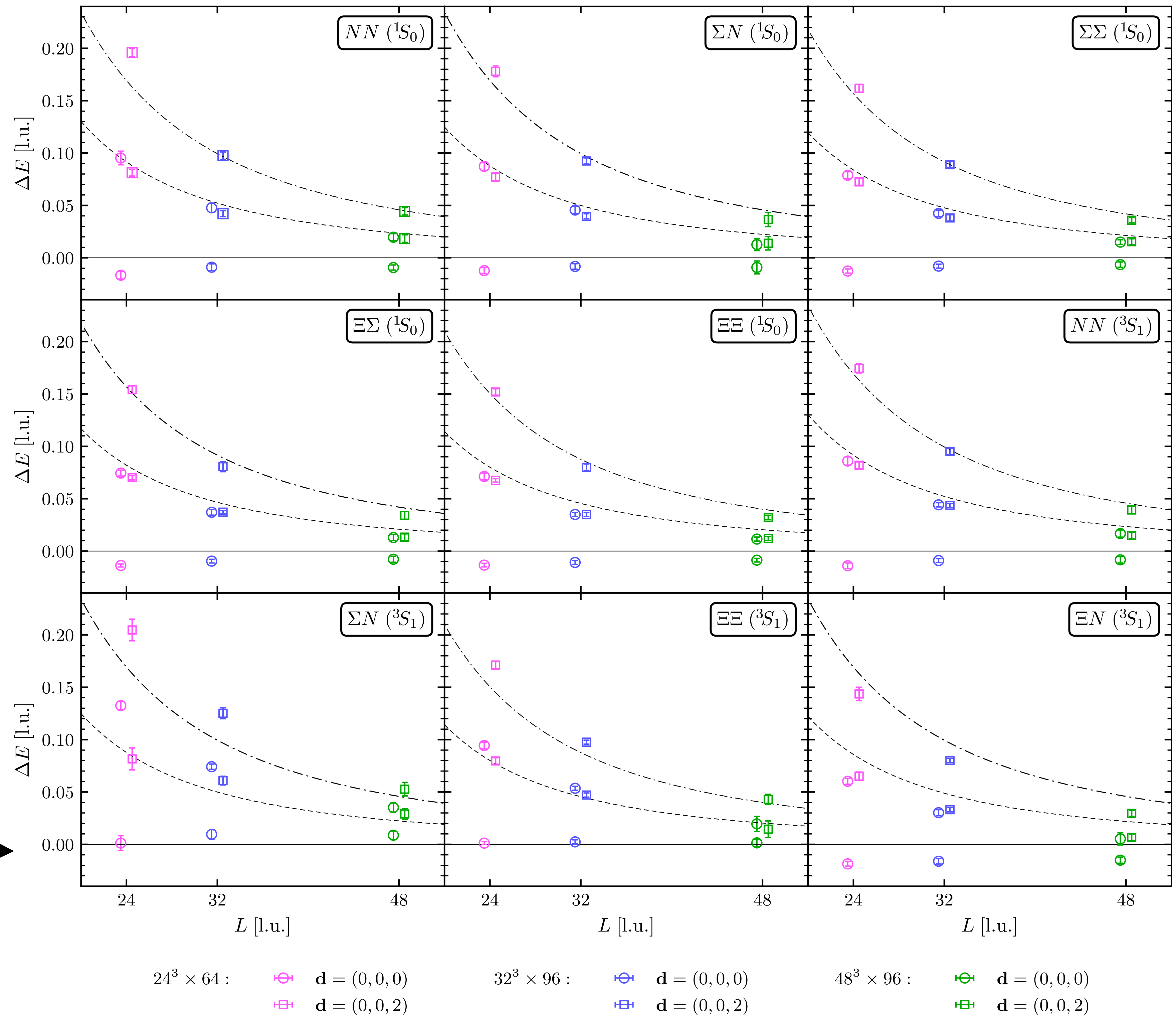
☞ Noisier correlation functions, so a more elaborated fitting strategy NPLQCD+QCDSF, arXiv:2003.12130 [hep-lat]



Results for $m_\pi \sim 450$ MeV

arXiv:2009.12357 [hep-lat]

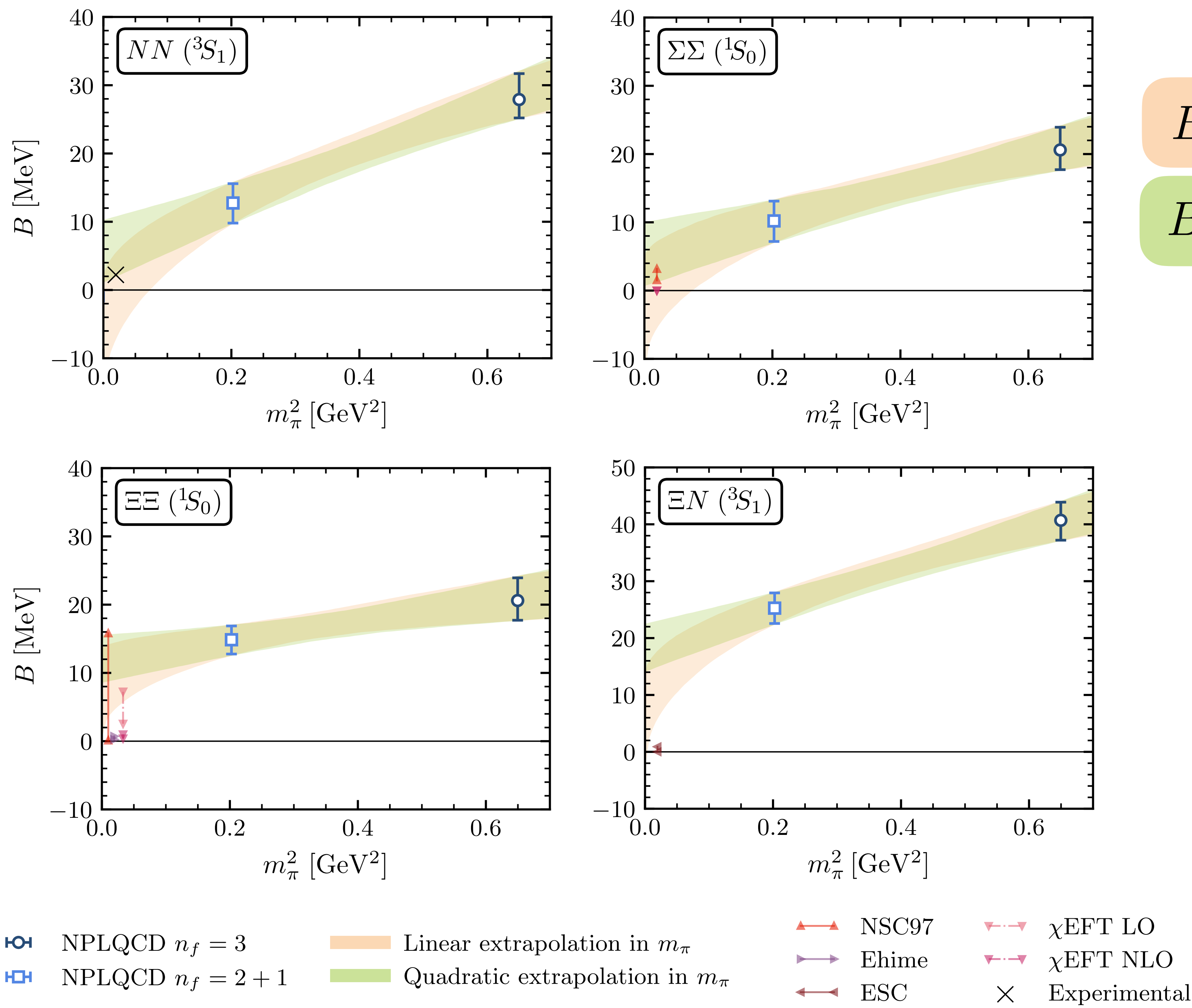
- ☞ A total of 12 kinematic points per system
- ☞ Not all systems show negative ground-state energies



Results for $m_\pi \sim 450$ MeV

arXiv:2009.12357 [hep-lat]

☞ Again, we use Lüscher's formalism to compute binding energies and scattering parameters.



$$B_{\text{lin}}(m_\pi) = B^{(0)}_{\text{lin}} + B^{(1)}_{\text{lin}} m_\pi$$

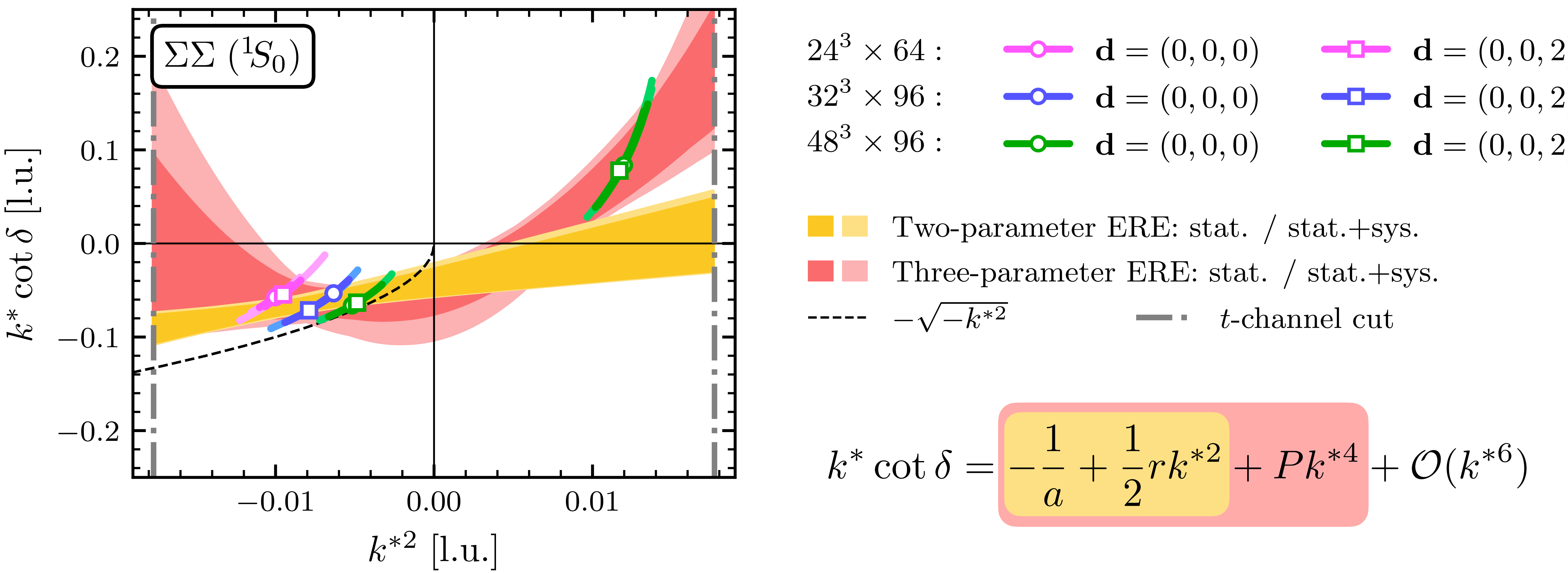
$$B_{\text{quad}}(m_\pi) = B^{(0)}_{\text{quad}} + B^{(1)}_{\text{quad}} m_\pi^2$$

Results for $m_\pi \sim 450$ MeV

arXiv:2009.12357 [hep-lat]

☞ Again, we use Lüscher's formalism to compute binding energies and scattering parameters.

Now not all the kinematic points fall inside the t-channel cut…

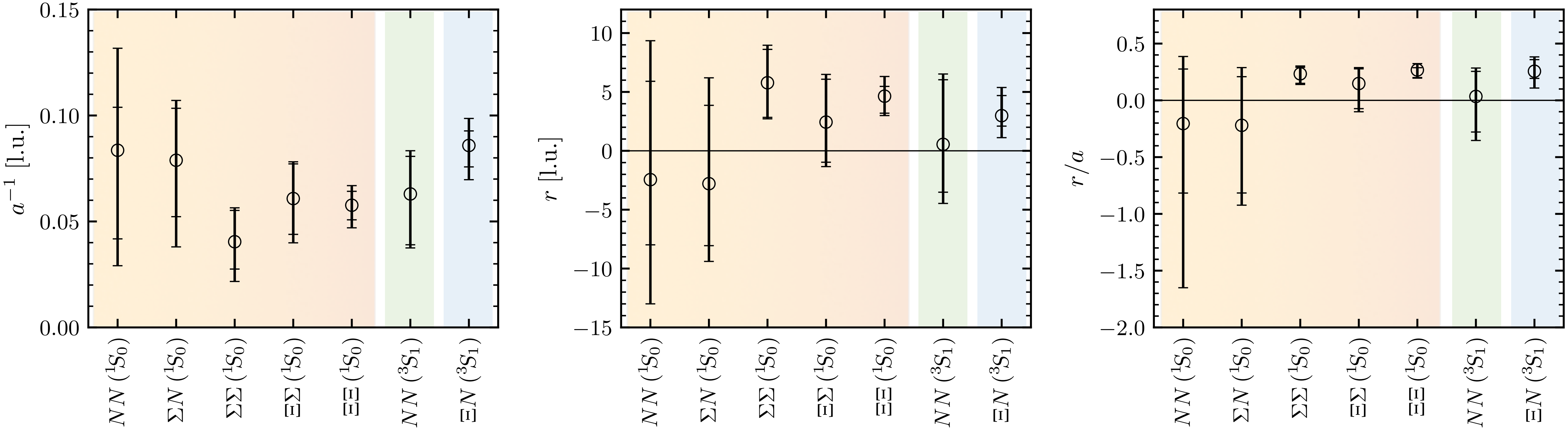


$$k^* \cot\delta = -\frac{1}{a} + \frac{1}{2} r k^{*2} + P k^{*4} + \mathcal{O}(k^{*6})$$

Results for $m_\pi \sim 450$ MeV

arXiv:2009.12357 [hep-lat]

Systems with resolved r/a show unnaturalness



☞ Compared to $m_\pi \sim 800$ MeV, we have now less points to fit with larger uncertainties

Can also compute the scattering length as: $a^{-1} = \kappa^{(\infty)}$

$$\mathcal{A} = \frac{2\pi}{\tilde{M}} \frac{i}{k^* \cot\delta - ik^*} \xrightarrow{k^* = i\kappa^{(\infty)}} k^* \cot\delta|_{k^*=i\kappa^{(\infty)}} + \kappa^{(\infty)} = 0$$

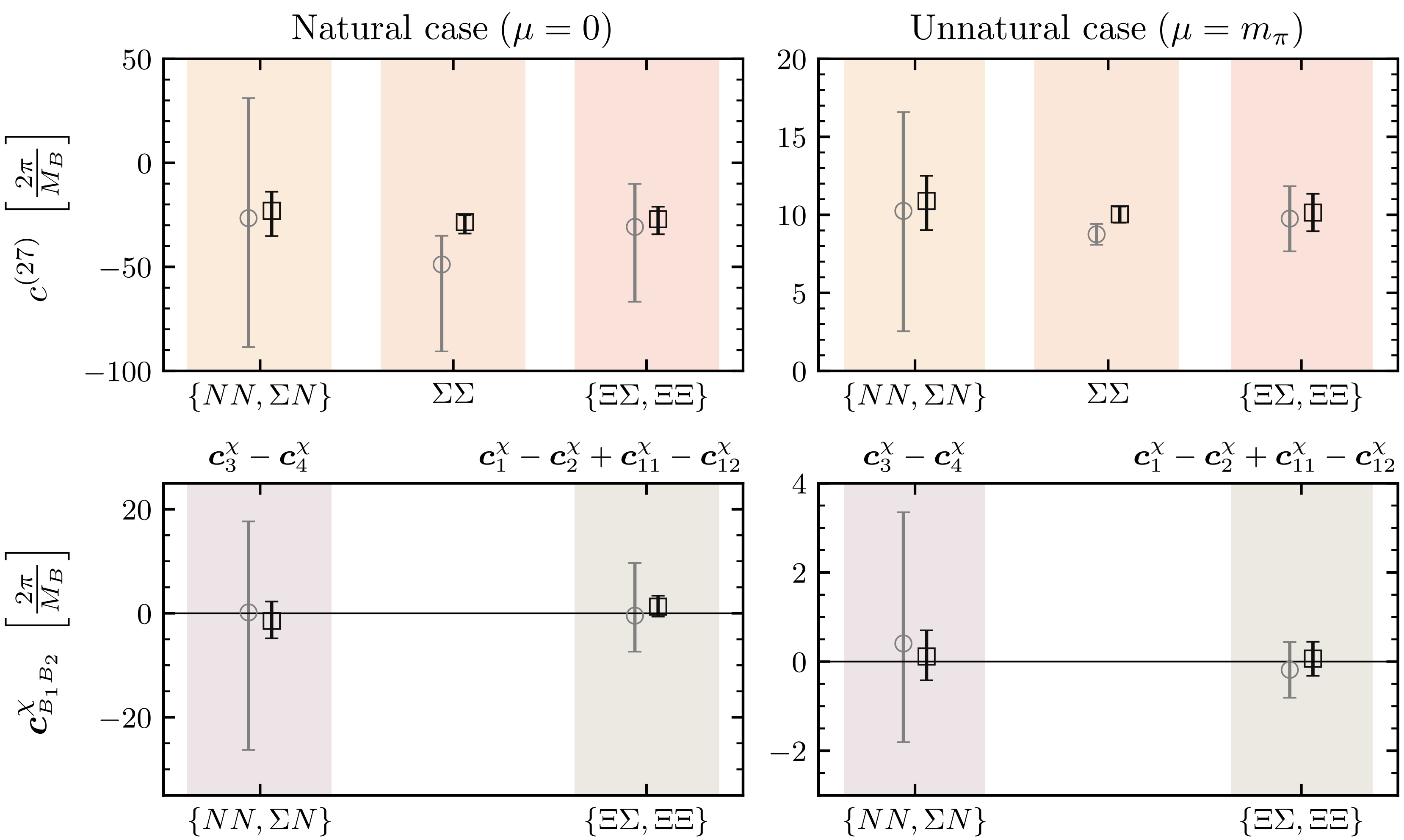
Results for $m_\pi \sim 450$ MeV

arXiv:2009.12357 [hep-lat]

☞ If we want to study $SU(6)$, first we have to check $SU(3)$

For the 27-plet systems:

$$\begin{Bmatrix} NN : c^{(27)} + 4(\boldsymbol{c}_3^\chi - \boldsymbol{c}_4^\chi) \\ \Sigma N : c^{(27)} + 2(\boldsymbol{c}_3^\chi - \boldsymbol{c}_4^\chi) \end{Bmatrix} \qquad \begin{Bmatrix} \Sigma\Sigma : c^{(27)} \end{Bmatrix} \qquad \begin{Bmatrix} \Xi\Sigma : c^{(27)} + 2(\boldsymbol{c}_1^\chi - \boldsymbol{c}_2^\chi + \boldsymbol{c}_{11}^\chi - \boldsymbol{c}_{12}^\chi) \\ \Xi\Xi : c^{(27)} + 4(\boldsymbol{c}_1^\chi - \boldsymbol{c}_2^\chi + \boldsymbol{c}_{11}^\chi - \boldsymbol{c}_{12}^\chi) \end{Bmatrix}$$



Results for $m_\pi \sim 450$ MeV

arXiv:2009.12357 [hep-lat]

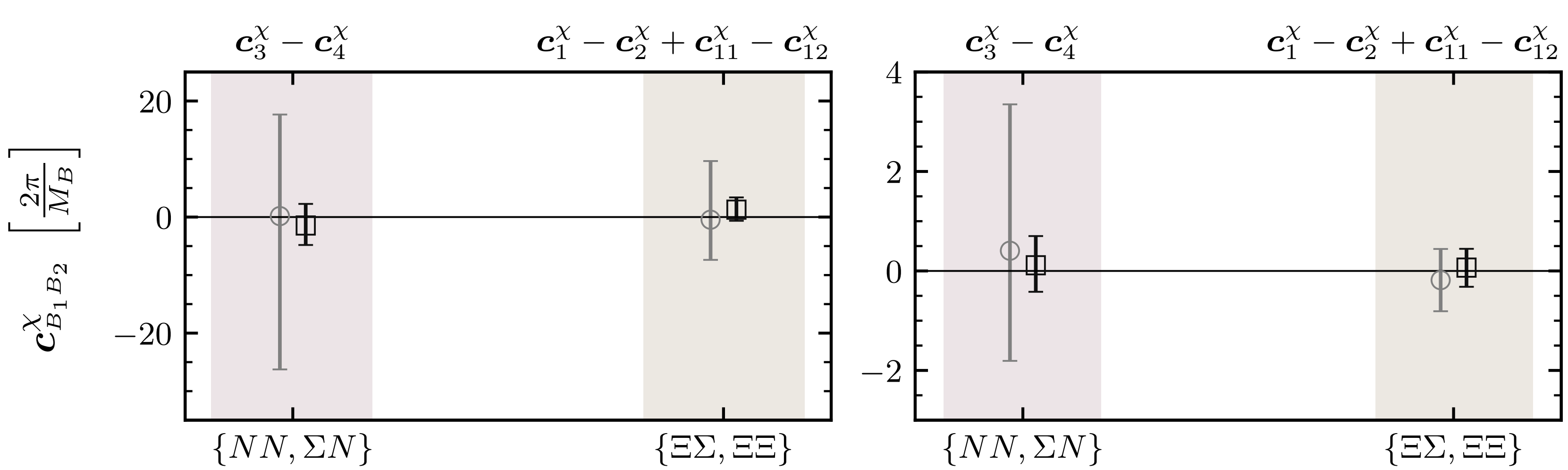
☞ If we want to study $SU(6)$, first we have to check $SU(3)$

For the 27-plet systems:

☞ Similarities between the binding energies and scattering parameters of the systems within the same irrep

☞ The violation of the Gell-Mann-Okubo mass relation is an order of magnitude smaller compared to the experimental value

$$\frac{M_N + M_\Xi}{2} = \frac{3M_\Lambda + M_\Sigma}{4}$$

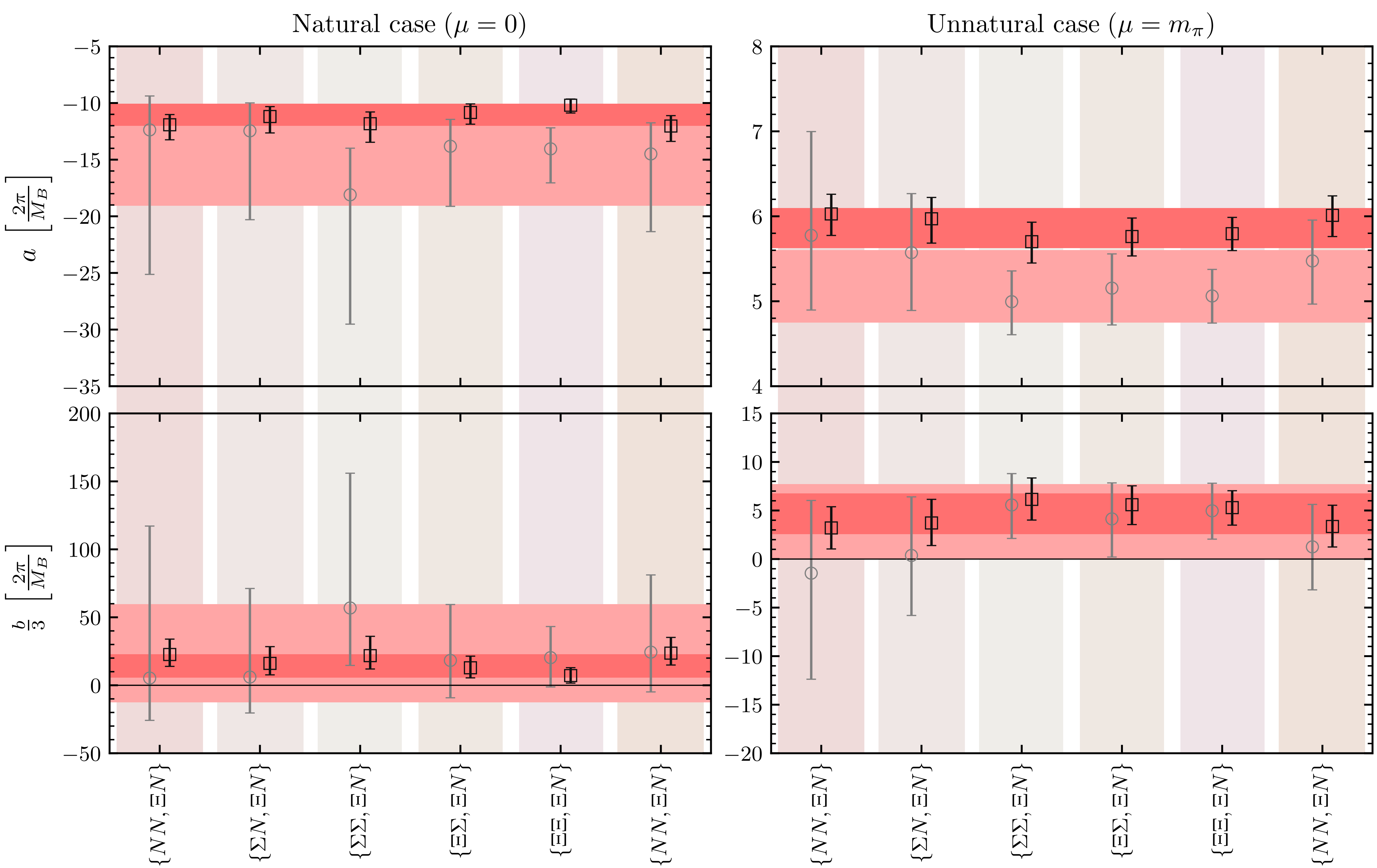


$SU(3)$ ✓

Results for $m_\pi \sim 450$ MeV

arXiv:2009.12357 [hep-lat]

$$c^{(27)} = 2a - \frac{2b}{27} \qquad c^{(\overline{10})} = 2a - \frac{2b}{27} \qquad c^{(8_a)} = 2a + \frac{2b}{27}$$



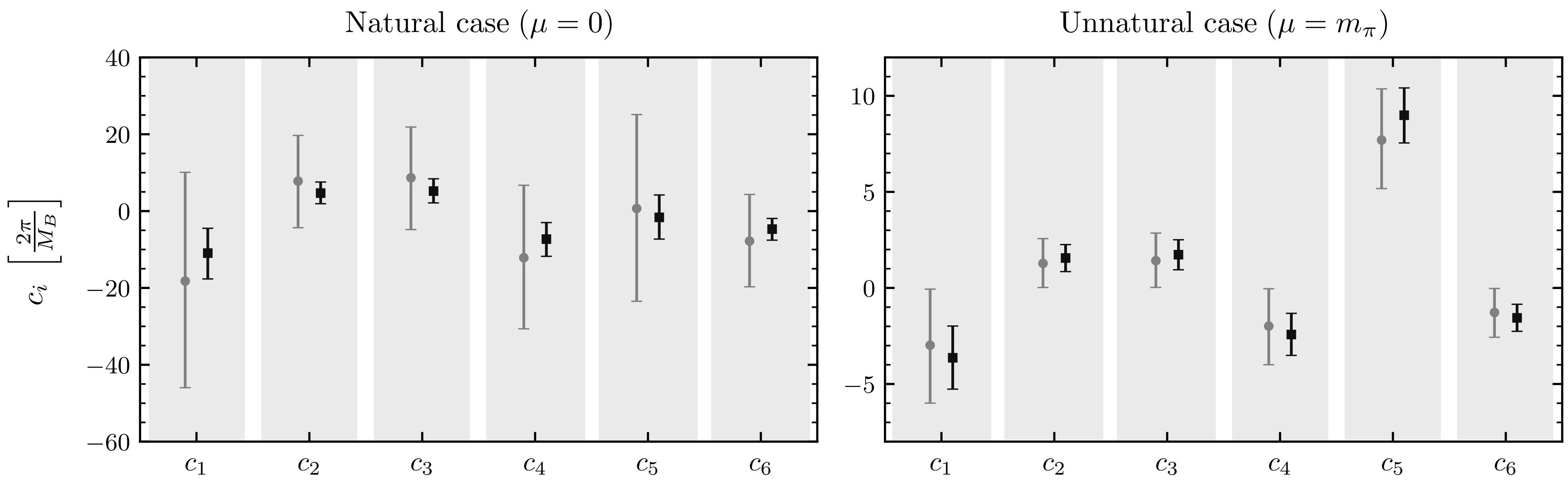
$SU(6)$ ✓

Results for $m_\pi \sim 450$ MeV

arXiv:2009.12357 [hep-lat]

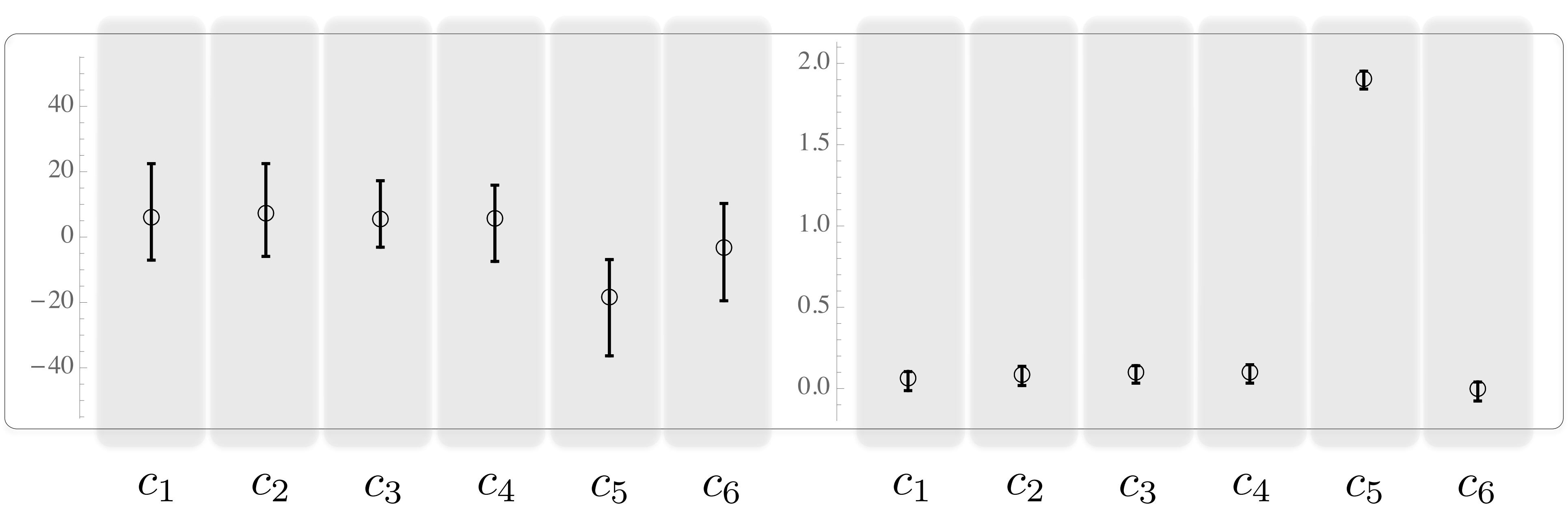
$$c_1 = -\frac{7}{27}b \qquad c_2 = \frac{1}{9}b \qquad c_3 = \frac{10}{81}b \qquad c_4 = -\frac{14}{81}b \qquad c_5 = a + \frac{2}{9}b \qquad c_6 = -\frac{1}{9}b$$

$m_\pi \sim 450$ MeV



$SU(16)$

$m_\pi \sim 800$ MeV



$SU(16)$

Summary

☞ LQCD can be used to help constrain EFTs when there are no experimental data

☞ Although calculations are not @ physical point, they are useful to reveal the symmetries more clearly

At $800\ \mathrm{MeV}$, there is an accidental $SU(16)$ symmetry, and at $450\ \mathrm{MeV}$, despite the quarks having different masses, $SU(3)$ and $SU(6)$ are still approximate

☞ Discrepancies between different methods (variational, HAL QCD) need to be understood

☞ Calculations near the physical pion mass are being performed

Other projects:

☞ Interaction of hadrons with external currents: momentum fraction, axial charge…

arXiv:2009.05522 arXiv:2102.03805

☞ Spectrum of 3-body hypernuclei

Thank you!

NPLQCD

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