S = -1; I=3/2 Nucleon-Hyperon (NY) Interactions from LQCD

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(on behalf of Baryon-Scattering Collaboration; basc-collaboration.github.io)

Lattice 2026; University of Maryland
July 31, 2026

Collaborators!

About | News | Members | Publications | Talks

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Professor

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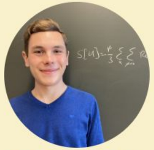

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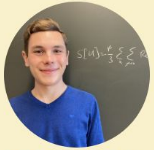

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Motivations for S=-1 Interactions

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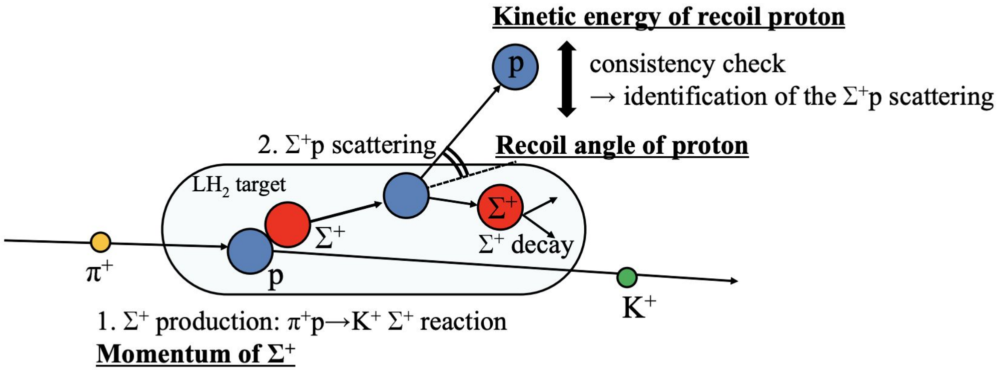
Renewed interest due to E40 J-PARC

- ~O(2500) events (100x more than state-of-the-art!) observed of p-Σ^+ (I=3/2) scattering in 2022 [1]! Made possible by J-PARC's high intensity pion beam



- Chiral EFT has been fit to the data [2]; recently used for light hypernuclear structure calculations [3]!

[1] J-PARC E40 Collaboration arXiv:2203.08393
[2] Haidenbauer, Meißner, Nogga, Le arXiv:2301.00722
[3] Haidenbauer, Meißner, Nogga arXiv:2508.05243

Motivations for S=-1 Interactions

Renewed interest due to E40 J-PARC (2022 experiment: [1], χEFT: [2, 3])

Historical application of the Pauli exclusion principle between quarks

- In 1980s, physicists identified this system as an example of a strongly repulsive interaction—they predicted phase shifts! [4]

[4] Oka, Shimizu, Yazaki; *Nucl. Phys. A 464 700 (1987)*

Motivations for S=-1 Interactions

Renewed interest due to E40 J-PARC (2022 experiment: [1], χEFT: [2, 3])

Historical application of the Pauli exclusion principle between quarks [4]

Recent LQCD progress (list likely incomplete)

- HALQCD analysis of S=-1 system [5]
- FV scattering of isospin 1/2 channel near the $N\Lambda$ threshold [6]

[5] Nemura (for HALQCD) *arXiv:1810.04046*
[6] Liu, Liu, Tan, Wang, Yan, Zhu *arXiv:2603.05854*

Outline of Talk

Goal of talk: comparison of isospin 3/2 N-Σ scattering between LQCD, quark model predictions, χEFT, and experiment

1. Ensembles + Finite Volume Energy Levels
2. Partial Wave Considerations
3. (Preliminary) Results for $^3S_1$—comparisons!
4. Ongoing/Future Work

Our ensembles and correlators

CLS ensemble [7]	D251
L^3 x T	64^3 x 192
a	0.063(1) fm
m_π	~ 280 MeV
$m_\pi L$	~ 6
m_K	~ 460 MeV
m_N	~ 1050 MeV
m_Σ	~ 1180 MeV
N_{cfg}	209

- Distillation is done using the QUDA-LapH codebase [8]
- In S=-1, isospin = 1/2 or 3/2
  - 3/2 is only NΣ (this talk)
  - 1/2 is coupled channel NΛ-NΣ (future work)
- Intuition by SU(3) flavor considerations: in this limit…
  - (l+s)-even (e.g. $^1S_0$, $^3P_0$, $^3P_1$, $^3P_2$, $^1D_2$, …) belong to 27-plet—same as NN I=1
  - (l+s)-odd (e.g. $^3S_1$, $^1P_1$, $^3D_1$, $^3D_2$, $^3D_3$, …) belong to 10-plet—expected to be repulsive from Pauli principle of quarks

[7] Bruno et al *arXiv:1411.3982*
[8] Morningstar - https://github.com/cosmon-collaboration/quda_laph

Model for Correlators: "Conspiracy Model" [9]

We obtain principal correlators, $C^{(BB)}$, by solving the GEVP: $C(t_d)\,V = C(t_0)\,V\,\Lambda_d$, and rotating the correlator matrix: $D(t) = V^\dagger\, C(t)\, V$.

The *"conspiracy model"* fits both $C^{(BB)}$ and two single-baryon correlators, $C^{(B)}$:

$$C^{(B_i)} = \sum_{n=0}^{N} \left(Z_n^{(B_i)}\right)^2 \exp\left[-E_n^{(B_i)} t\right] \qquad C^{(BB)} = \sum_{n_1,\, n_2} \left(Z_{n_1 n_2}^{(BB)}\right)^2 \exp\left[-\left(E_{n_1}^{(B_1)} + E_{n_2}^{(B_2)} + \delta_{n_1\, n_2}\right) t\right]$$

n_1 = # states in B_1 model; n_2 = # states in B_2 model

- If B_1 and B_2 are identical and have the same momentum, then BB correlator has N(N+1)/2 states
- Otherwise, N^2

[9] Bulava et al (BaSc) *arXiv:2505.05547*

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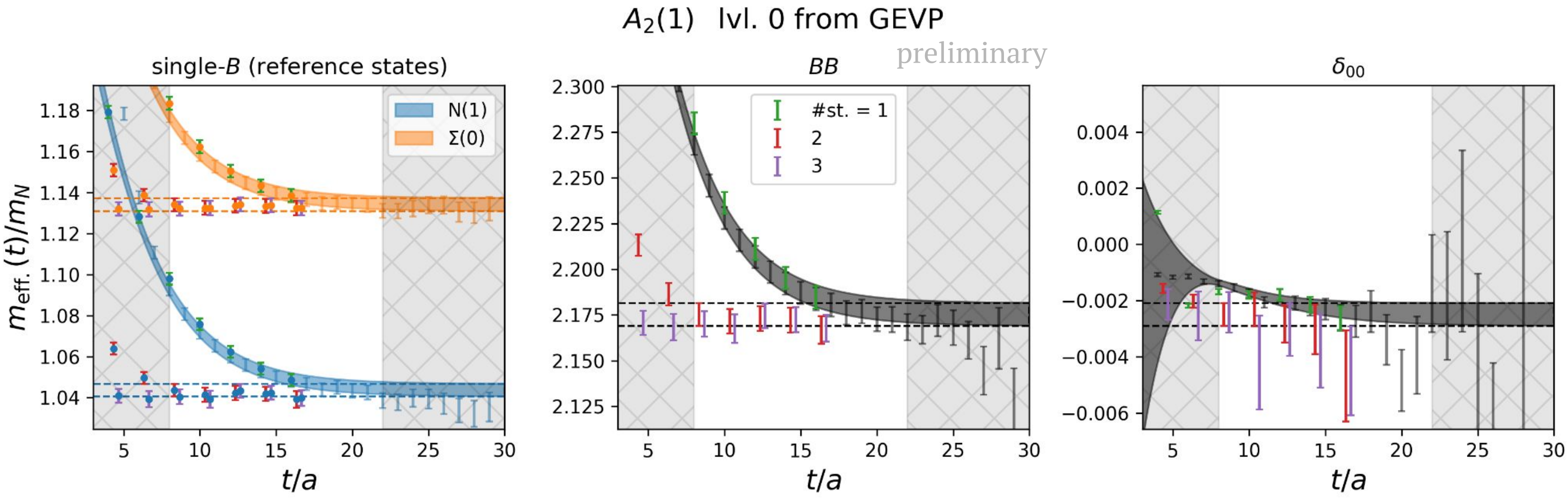

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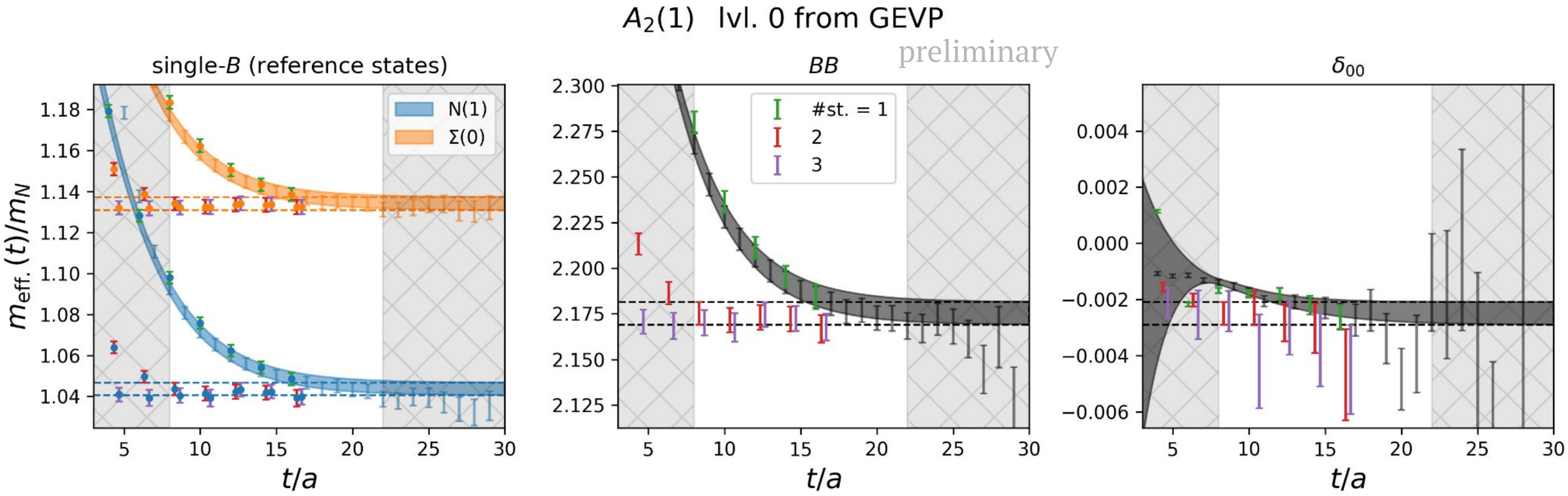
Construct FV Energy Levels with Continuum Dispersion

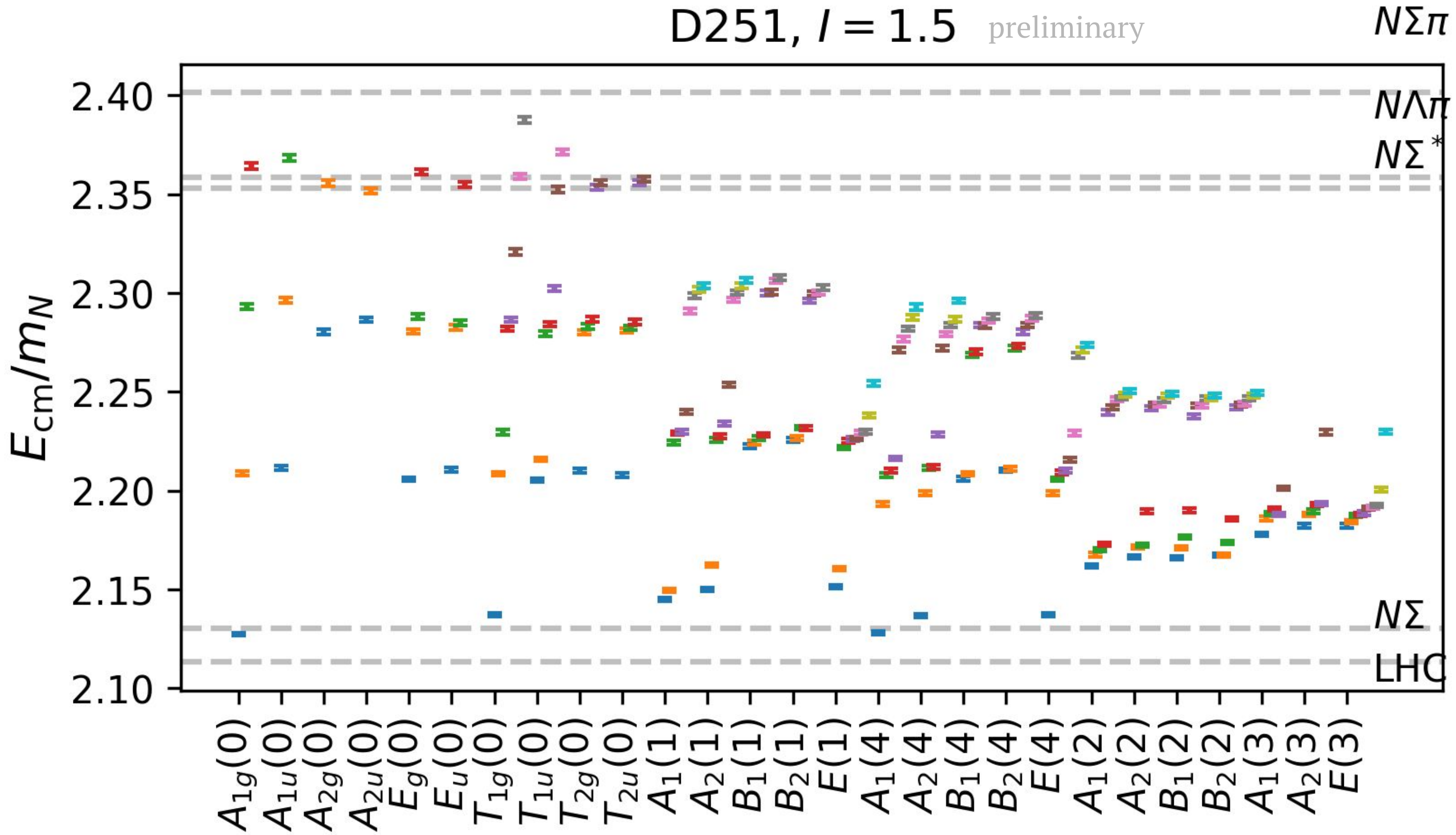


We take the FV energy level to be $E_{BB} = \sqrt{m_N^2 + \left(\frac{2\pi}{L}\vec{P}_N\right)^2} + \sqrt{m_\Sigma^2 + \left(\frac{2\pi}{L}\vec{P}_\Sigma\right)^2} + \delta_{00}$

Discretization artifacts cancel in the difference $\delta_{00} = E_{BB} - E_{B_1} - E_{B_2}$ (at leading order) [9, 10]

[9] Bulava et al (BaSc) *arXiv:2505.05547*
[10] Hansen, Peterken *arXiv:2408.07062*

$N\Sigma$; $I = 3/2$ Spectrum at $m_\pi \approx 280$, $m_K \approx 460$ MeV (D251)



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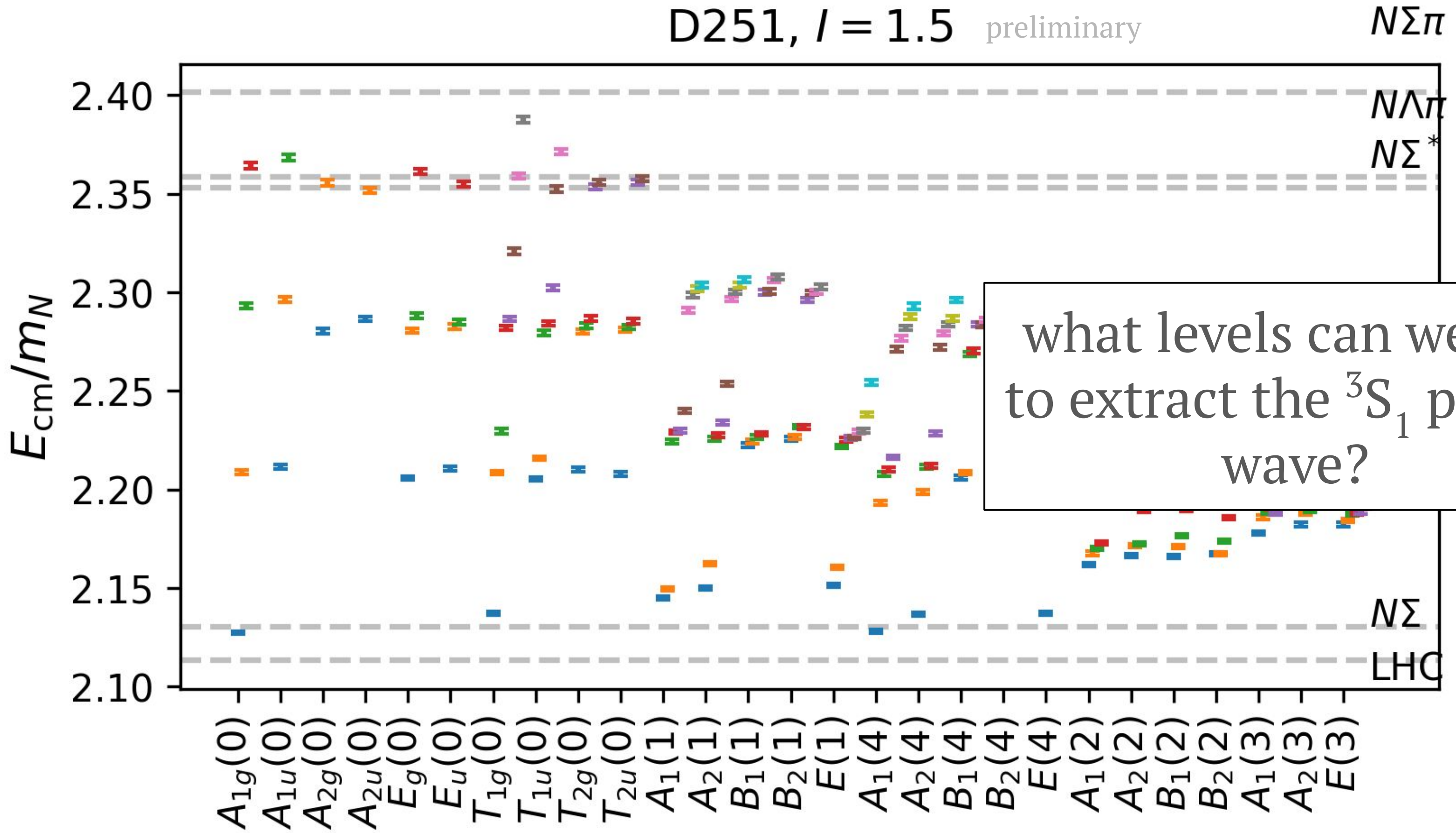


what levels can we use to extract the $^3S_1$ partial wave?

Irrep Consideration for $^3S_1$ Partial Wave

$^3S_1$	$T_{1g}(0)$, $A_2(1,2,3,4)$, $E(1,3,4)$, $B_1(2)$, $B_2(2)$
$^3D_1$	$T_{1g}(0)$, $A_2(1,2,3,4)$, $E(1,3,4)$, $B_1(2)$, $B_2(2)$

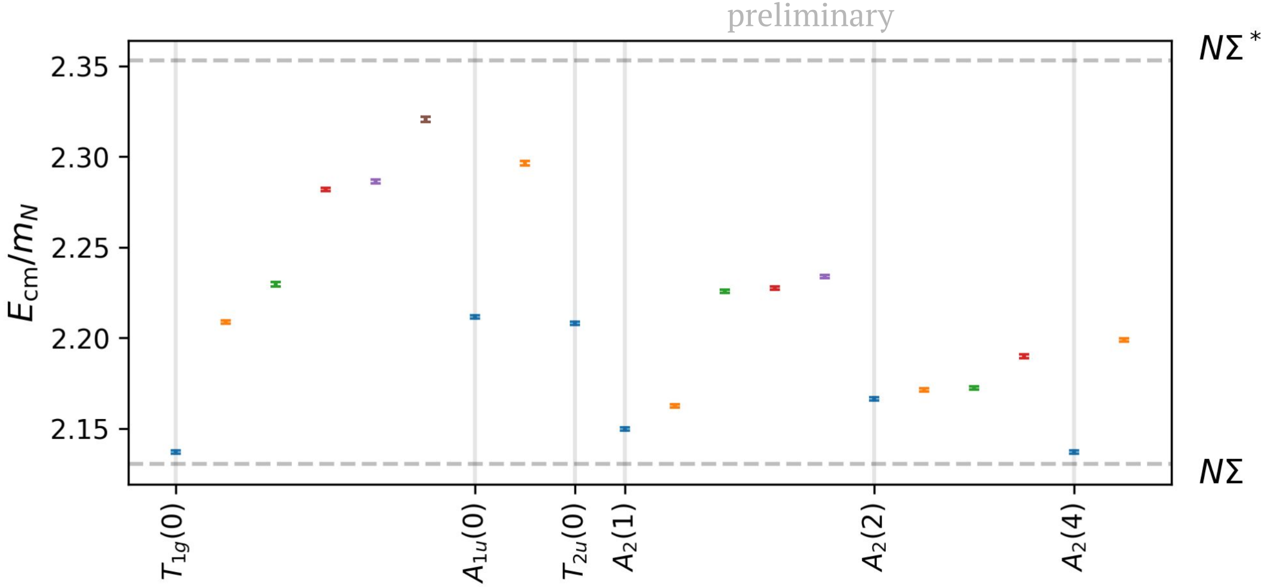
$T_{1g}(0)$	$^3S_1$,	$^3D_1$,	$^3D_3$,	$\cdots G_{\ldots}$,	$\ldots$

Moving irreps break parity + non-identical particles = many coupled partial waves!

$A_2(1)$	$^3S_1$,	$^3P_0$,	$^3P_2$,		$^3D_1$,		$^3D_3$,	$\cdots F_{\ldots}$,	$\cdots G_{\ldots}$,	$\ldots$
$A_2(2)$	$^3S_1$,	$^3P_0$,	$^3P_2$,	$^1D_2$,	$^3D_1$,	$^3D_2$,	$^3D_3$,	$\cdots F_{\ldots}$,	$\cdots G_{\ldots}$,	$\ldots$

$\vdots$

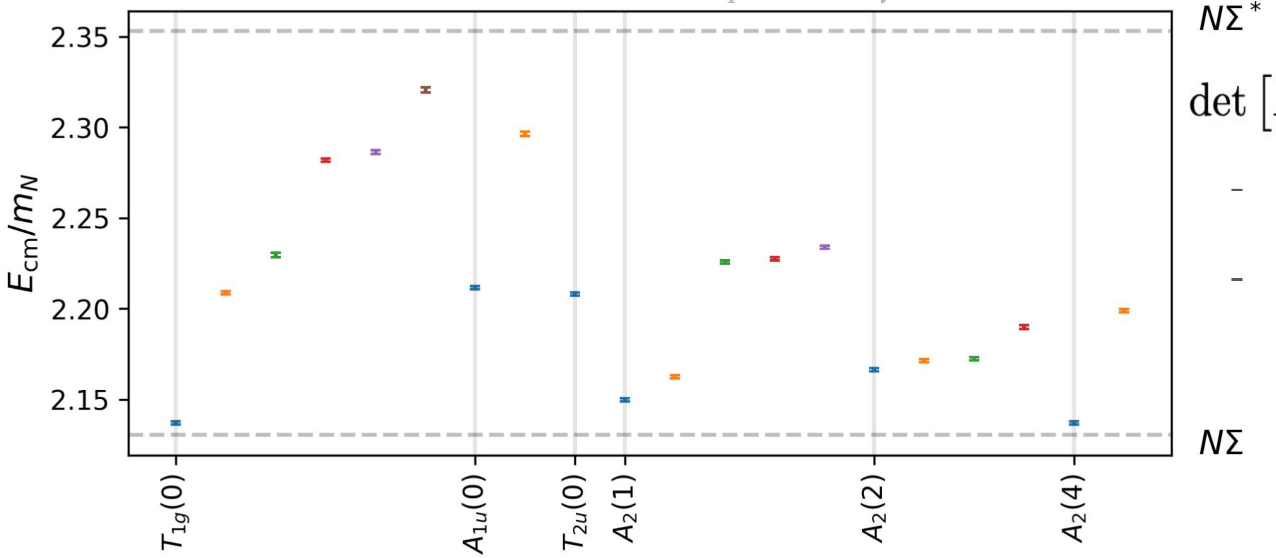
$N\Sigma$; $I = 3/2$ Spectrum at $m_\pi \approx 280$, $m_K \approx 460$ MeV (D251)



[11] Morningstar et al *arXiv:1707.05817*

$N\Sigma$; $I = 3/2$ Spectrum at $m_\pi \approx 280$, $m_K \approx 460$ MeV (D251)

preliminary



[11]

$$\det\left[K^{-1}(E;\{p_i\}) - B(E)\right]_{\Gamma(P^2)} = 0$$

- Predicts a FV spectrum, given a set of $\{p_i\}$
- tune $\{p_i\}$ to match FV energies E

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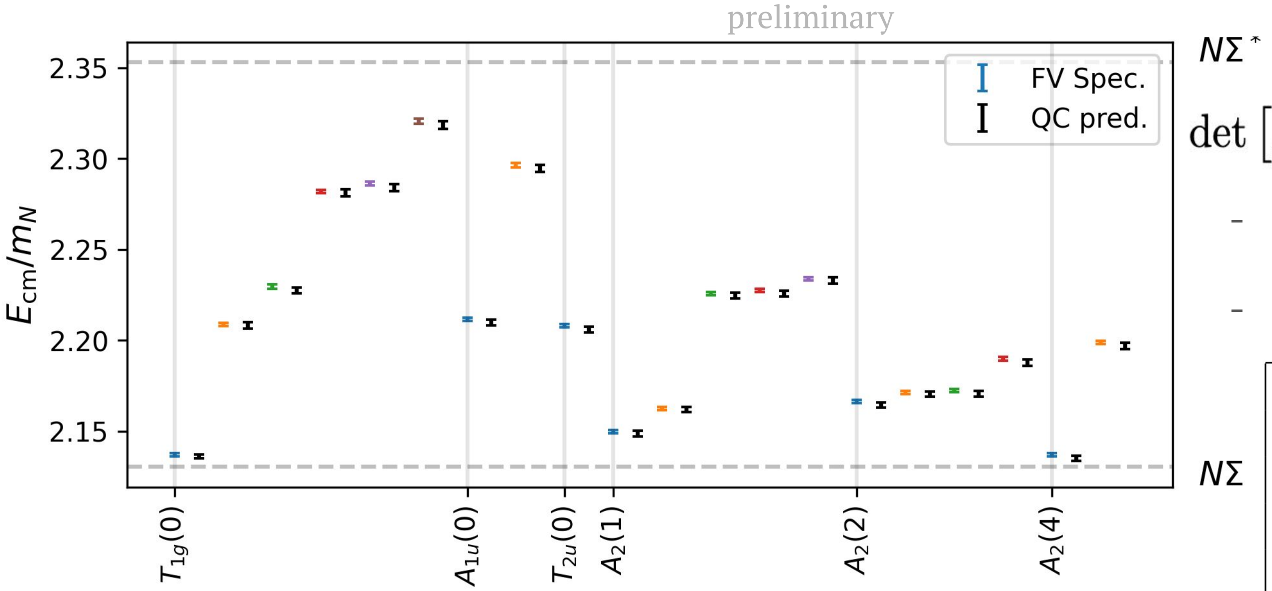

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- tune $\{p_i\}$ to match FV energies E

$a_{^3S_1}$	3.360(89)
$r_{^3S_1}$	1.59(17)
$a_{^3D_1}$	10.5(1.2)
$\theta(=\epsilon/q^2)$	-1.72(41)
$a_{^3D_3}$	-2.8(1.8)
$a_{^3P_0}$	8.1(1.4)
$r_{^3P_0}$	-0.46(29)
$a_{^3P_2}$	0.69(56)
χ^2/dof	$17.7/(20-8) \approx 1.5$

$$K^{-1} = \begin{bmatrix} \tilde{q}^3 \cot\delta_{^3P_0} & 0 & 0 & 0 & 0 \\ 0 & \multicolumn{2}{c}{} & 0 & 0 \\ 0 & \multicolumn{2}{c}{K^{-1}_{^3S_1{}^3D_1}} & 0 & 0 \\ 0 & 0 & 0 & \tilde{q}^3\cot\delta_{^3P_2} & 0 \\ 0 & 0 & 0 & 0 & \tilde{q}^5\cot\delta_{^3D_3} \end{bmatrix}$$

$$K^{-1}_{^3S_1{}^3D_1} = C(\epsilon)\cdot D\cdot C(\epsilon)^T$$

$$C = \begin{bmatrix} \cos\epsilon & -\frac{1}{\tilde{q}^2}\sin\epsilon \\ \tilde{q}^2\sin\epsilon & \cos\epsilon \end{bmatrix}$$

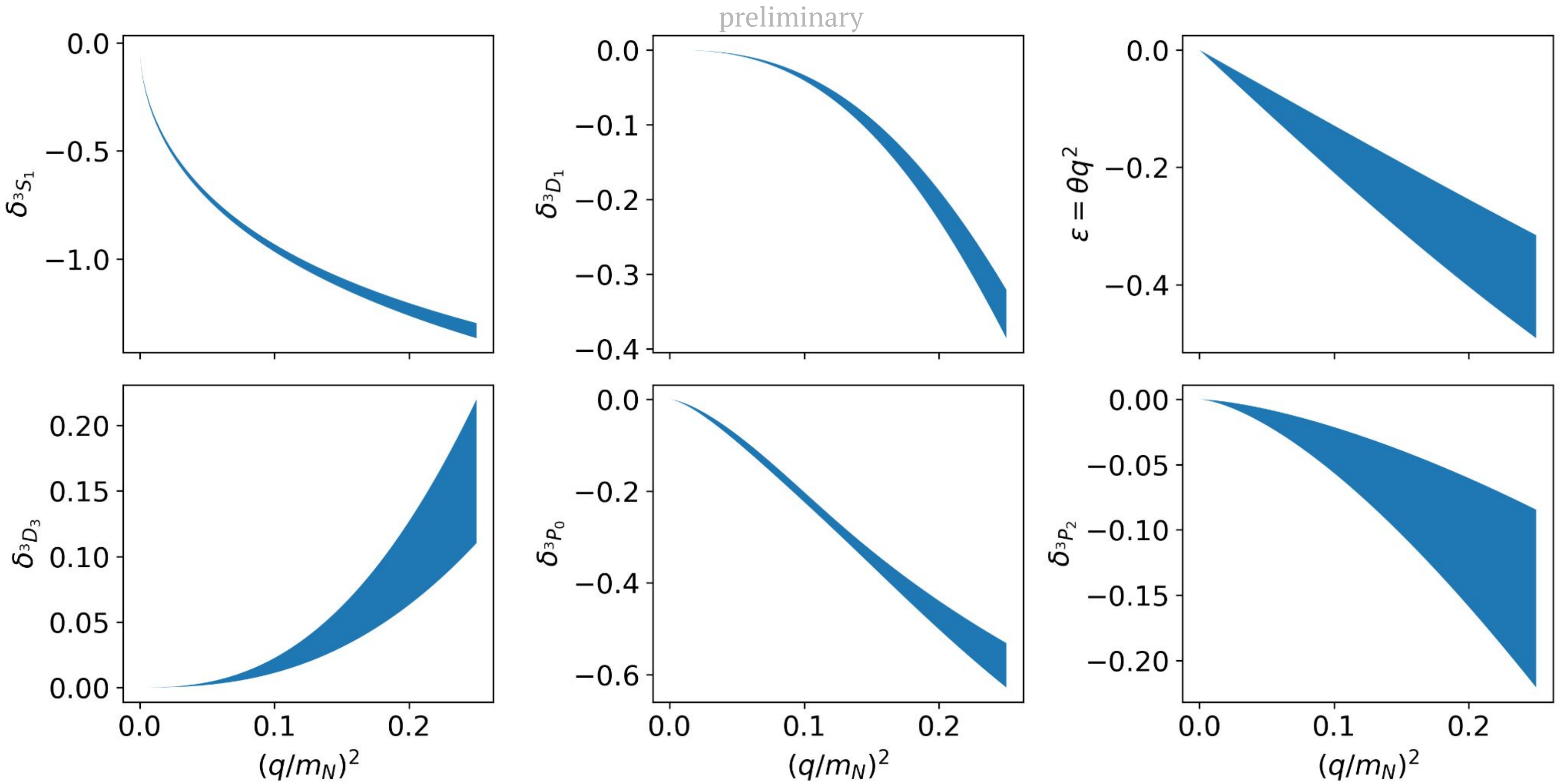
$$D = \begin{bmatrix} \tilde{q}\cot\delta_{^3S_1} & 0 \\ 0 & \tilde{q}^5\cot\delta_{^3D_1} \end{bmatrix}$$

$$\tilde{q}^{2\ell+1}\cot\delta_\ell = -1/a + \frac{1}{2}r\tilde{q}^2$$

$$\tilde{q} = q/m_N$$

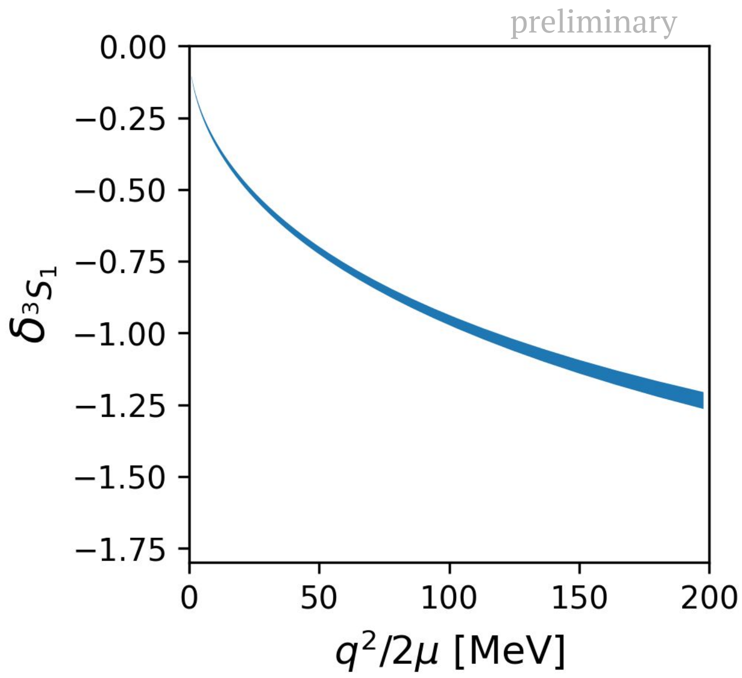
[11] Morningstar et al *arXiv:1707.05817*

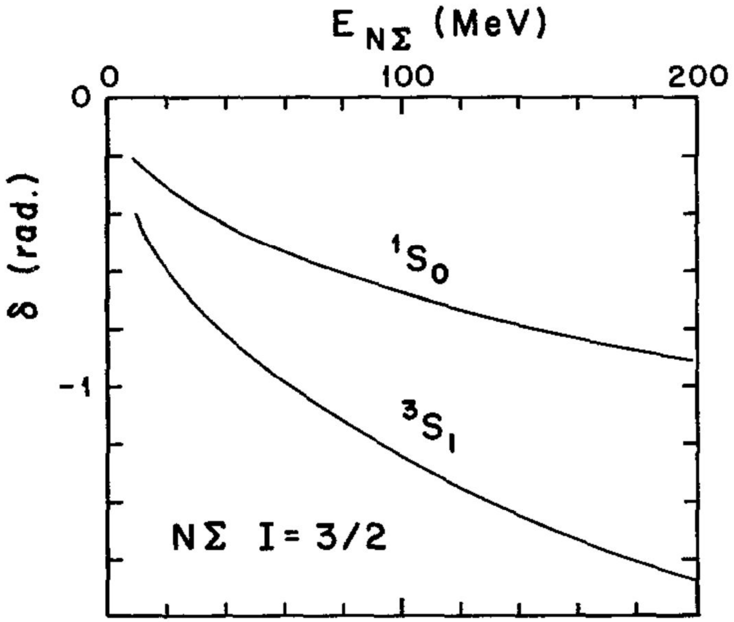
Phase Shift Results (**Preliminary**)



(all in radians)

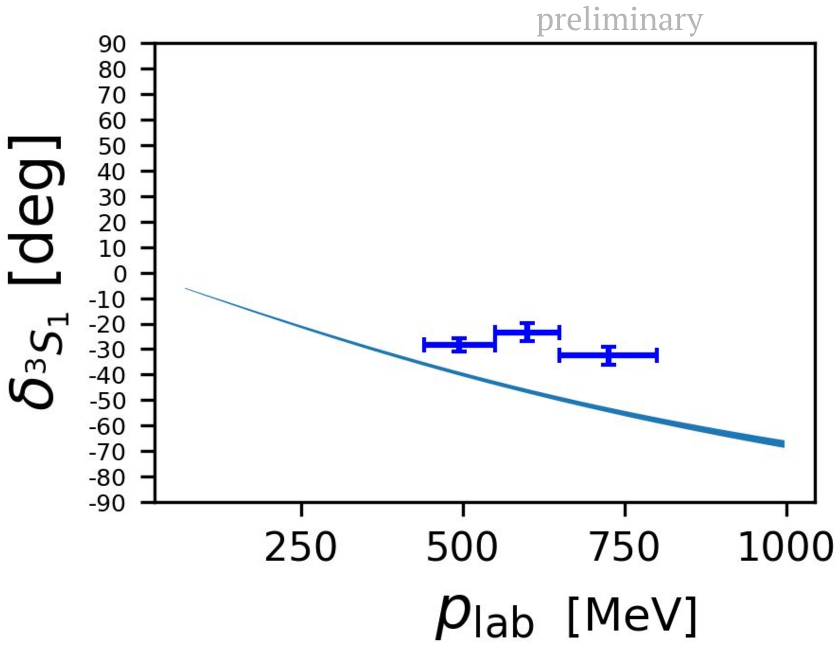
Comparison to Quark Model Prediction (**Preliminary**)

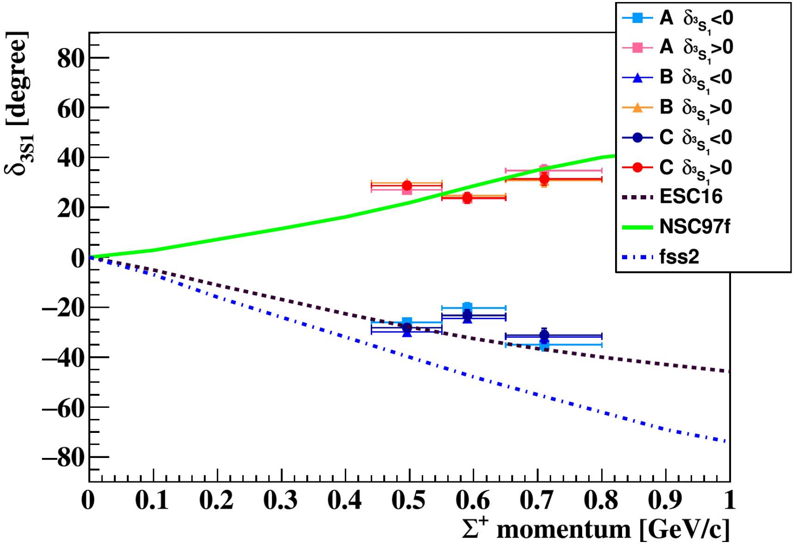




Prediction of a highly repulsive baryon-baryon interactions from the quark Pauli principle at SU(3) symmetric point! ([4] Oka, Shimizu, Yazaki (1987))

Comparison to Experiment (E40 J-PARC) (**Preliminary**)

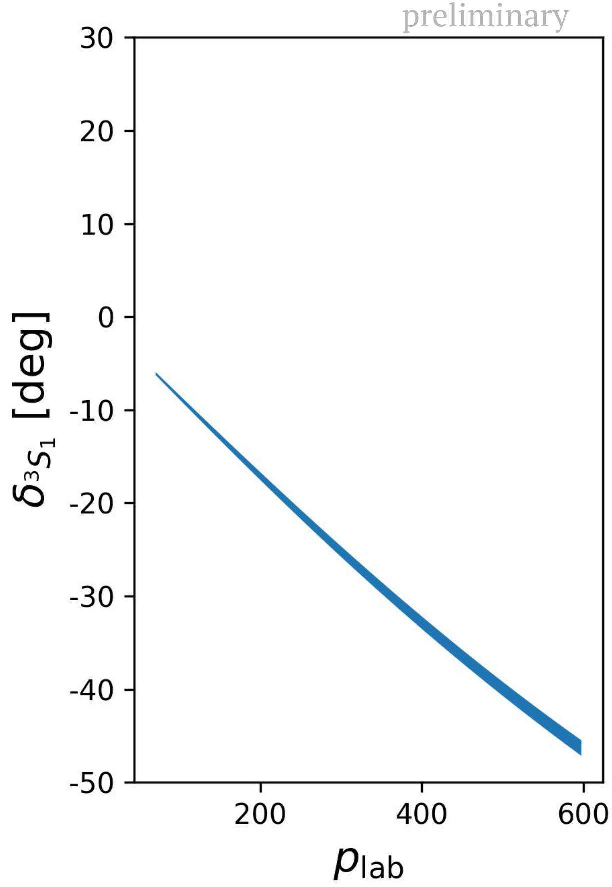


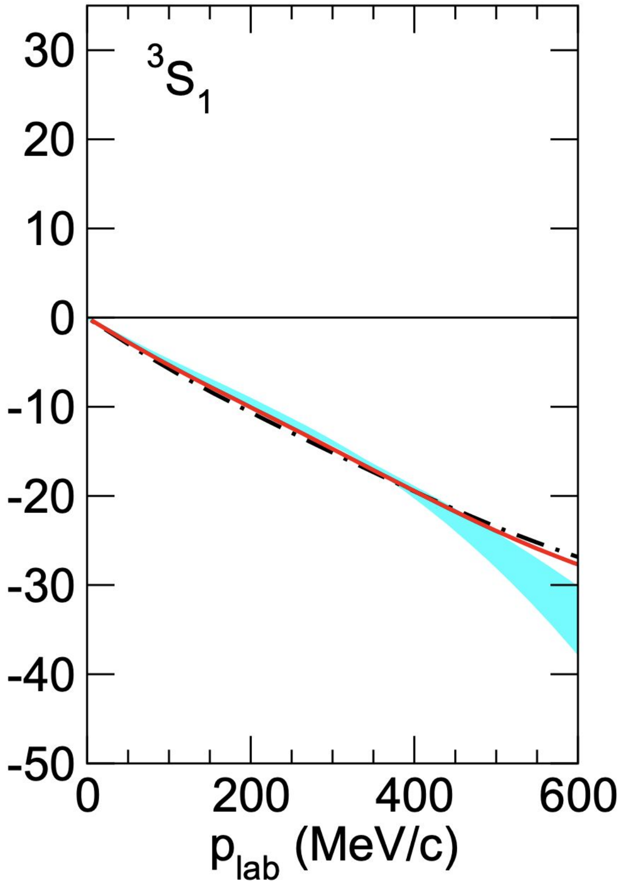


(a) $\delta_{^3S_1}$

Results from J-PARC E40 partial wave analysis [1]

Comparison to χEFT (**Preliminary**)



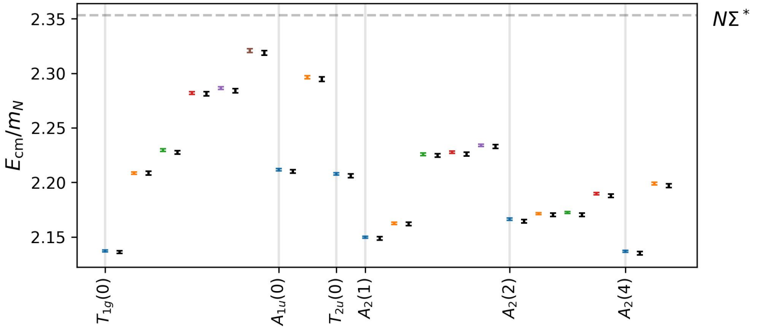


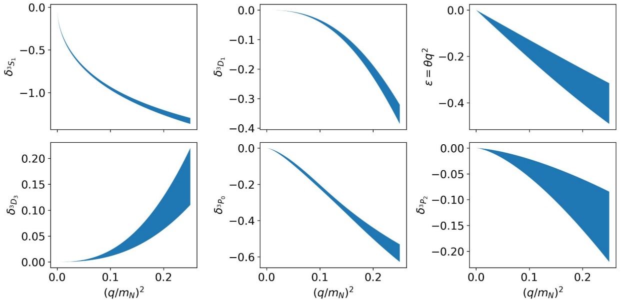
Summary and Conclusions

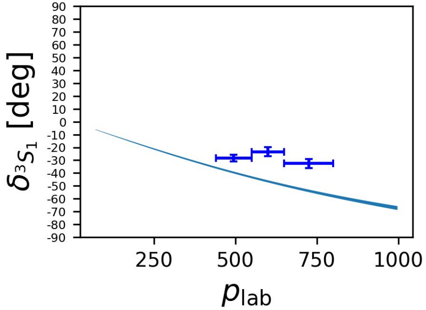
- S=-1 (I=3/2): promising analysis of $^3S_1$

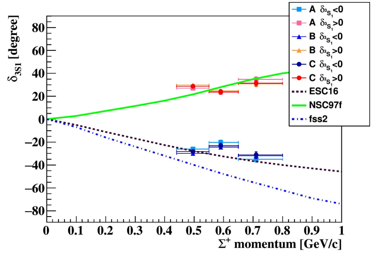
- Ongoing:
  - Attempt $^1P_1$ for I = 3/2 (then publish!)

- Up next:
  - I = 1/2









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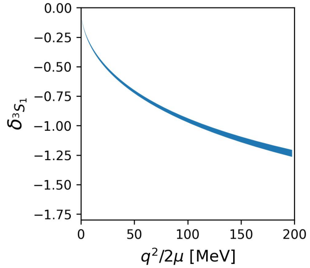

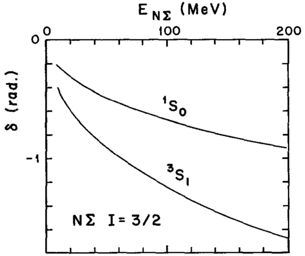

References

[1] Measurement of differential cross sections for $\Sigma^+ p$ elastic scattering in the momentum range 0.44-0.80 GeV/c - Nanamura et al; *Prog. Theor. Exp. Phys.* ***2022****, 093-01*

[2] Hyperon-nucleon interaction in chiral effective field theory at next-to-next-to-leading order - Haidenbauer, Meißner, Noga, Le *Eur. Phys. J. A* ***59****, 63 (2023)*

[3] *Ab initio* description of hypernuclei - Haidenbauer, Meißner, Nogga (*Prog. Part. Nucl. Phys. 149 (2026) 104242*)

[4] Hyperon-nucleon and hyperon-hyperon interaction in a quark model - Oka, Shimizu, Yazaki; *Nucl. Phys. A 464 700 (1987)*

[5] Hyperon-nucleon interaction from lattice QCD at $(m_\pi, m_K) \approx (146, 525)$ MeV - Nemura et al (HALQCD) *AIP Conf. Proc. 2130 (1): 040005* (2019)

[6] A Lattice QCD study of p-Λ scattering in continuum and chiral limits - Liu et al (*arXiv:2603.05854*)

[7] Simulation of QCD with Nf = 2 + 1 flavors of non-perturbatively improved Wilson fermions - Bruno et al *JHEP 2015, 43 (2015).*

[8] Morningstar - https://github.com/cosmon-collaboration/quda_laph

[9] Di-nucleons do not form bound states at heavy pion mass - Bulava et al (BaSc); Phys. Rev. C 113, 024002 (2026)

[10] Discretization effects in finite-volume 2 -> 2 scattering - Hansen, Peterken arXiv:2408.07062

[11] Estimating the two-particle K-matrix for multiple partial waves and decay channels from finite-volume energies - Morningstar et al Nucl Phys B 924 (2017) 477

Back-Up

Summary and Conclusions

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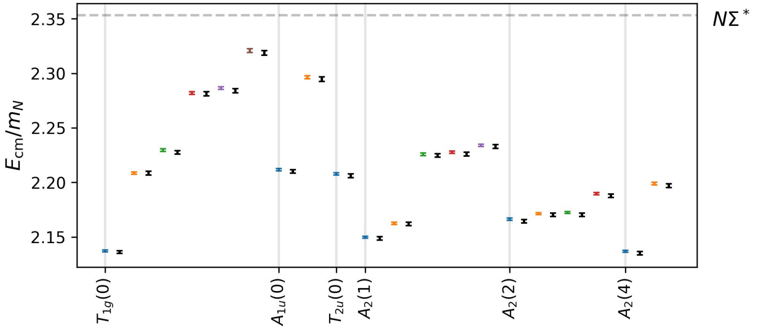
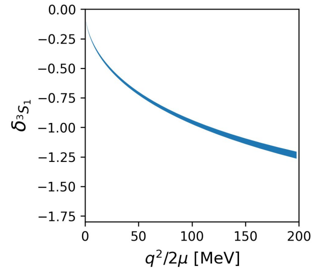
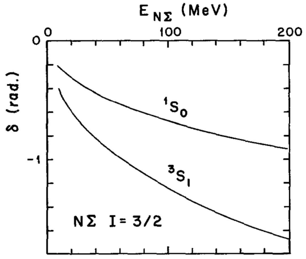
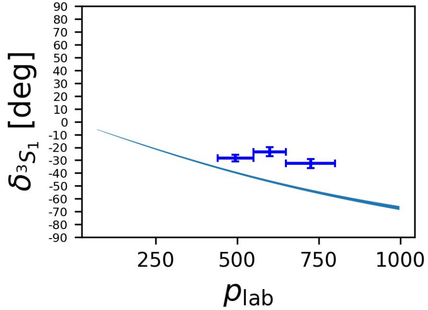


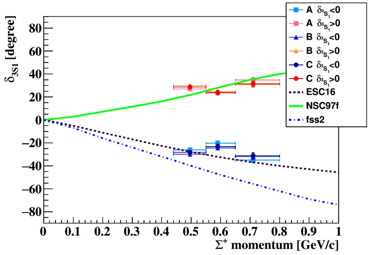




Thank you for your attention

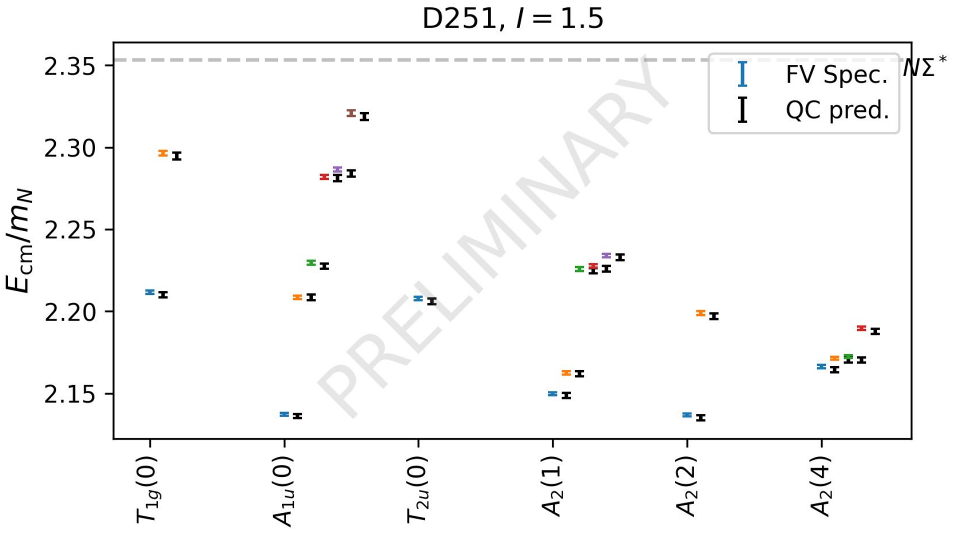
🙂🥳

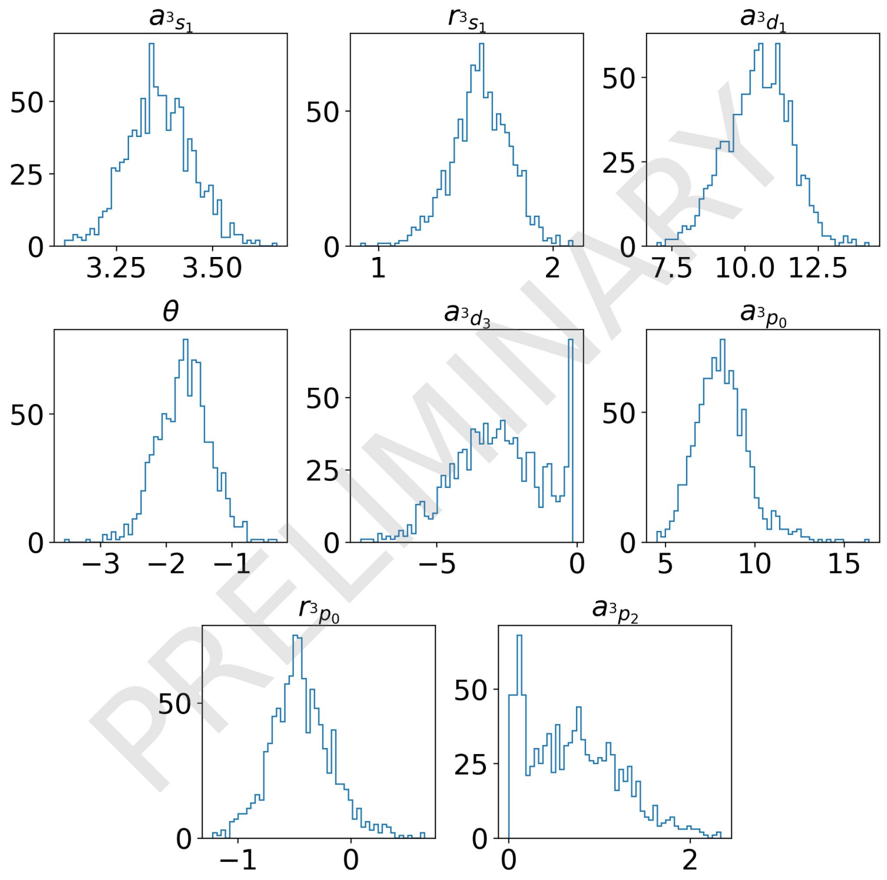




(a) $\delta_{^3S_1}$

Spectrum Method Results (*Pre*





Lüscher Analysis Results (**Preliminary**)

$$T = \left[C\,D\,C^T - iq\right]^{-1}$$

$$C = \begin{bmatrix} \cos\epsilon & -\sin\epsilon \\ \sin\epsilon & \cos\epsilon \end{bmatrix}$$

$$D = \begin{bmatrix} q\cot\delta_{{}^3S_1} & 0 \\ 0 & q\ \cot\delta_{{}^3D_1} \end{bmatrix}$$