Baryon-Baryon Scattering

@ SU(3) Flavor-Symmetric Point

Higher partial waves **From Lattice QCD**

The 43rd International Symposium on Lattice Field Theory (Lattice 2026)

@NDB

Advancing Theory for Nuclear Double-Beta Decay

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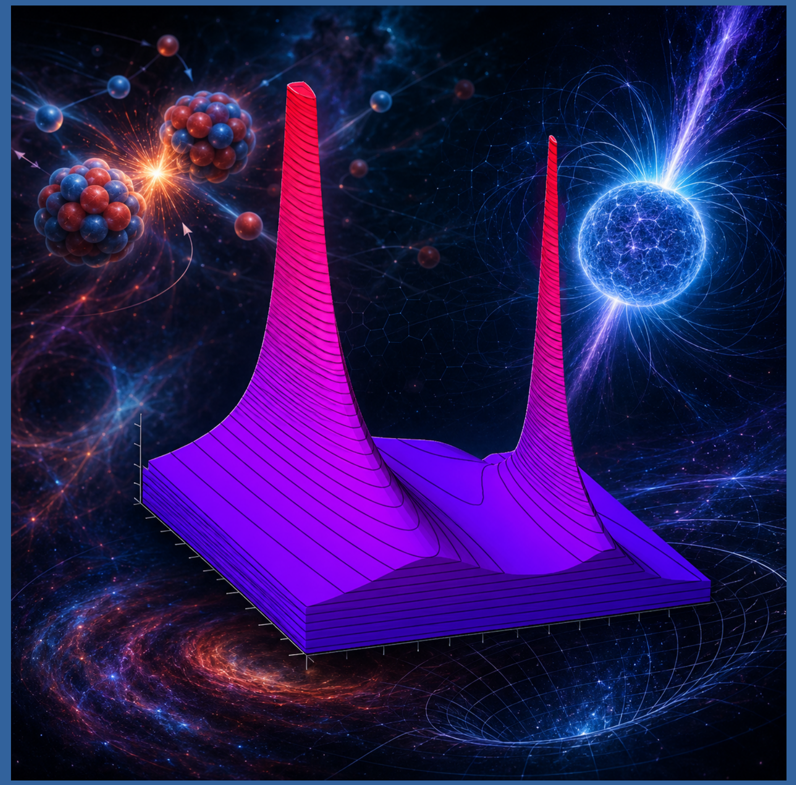

https://cosmon-collaboration.github.io/

BaSc

https://basc-collaboration.github.io/

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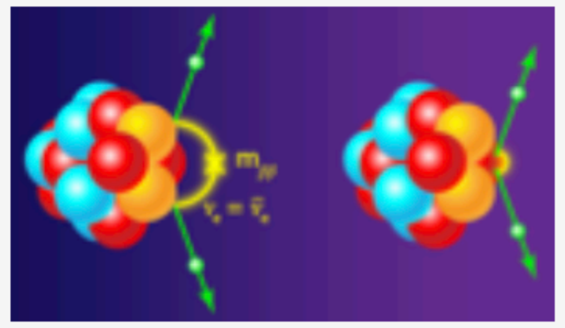

@NDB
Advancing Theory for Nuclear Double-Beta Decay

NN @ SU(3) Flavor-Symmetric Point

$m_u = m_d = m_s \Rightarrow$ flavor SU(3) is exact

$^1S_0(I=1) \in \mathbf{27}$
[arXiv:2505.05547, PRC]

$^3S_1 - {}^3D_1 - {}^3D_2 - {}^3D_3 \in \mathbf{\overline{10}}$

Beyond S waves: exploratory so far

- CalLat: *S,P,D,F* phases at $m_\pi \approx 800$ MeV — first $\ell > 0$ study [PLB 765 (2017)]
- NPLQCD: variational spectra incl. *D*-wave irreps [PRD 107, 094508]; HAL QCD: tensor potential V_T [Aoki, Hatsuda, Ishii, PTP 123 (2010) 89]
- ϵ_1 — *the* tensor-force observable — has never been resolved: the one finite-volume attempt was consistent with zero; [NPLQCD, PRD 92, 114512]

This talk

Systematic multi-wave analysis at the SU(3) flavor point — including the *first* nonzero Lüscher-based extraction of ϵ_1.

Dataset: C103 finite-volume spectra

- companion work, same dataset: di-nucleons do *not* bind at $m_\pi = m_K \approx 714$ MeV [arXiv:2505.05547, PRC]

stochastic LapH

Variational basis → GEVP

Di-nucleons do not form bound states at heavy pion mass

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(for the Baryon Scattering (BaSc) Collaboration)

Ensemble (CLS C103)
$N_f = 2{+}1$, SU(3) point,
$m_\pi = m_K \approx 714$ MeV
[CLS: Bruno et al., JHEP 02 (2015) 043; a: Bruno, Korzec, Schaefer, PRD 95 (2017)]

Volume & statistics
$48^3 \times 96$, $a \approx 0.085$ fm;
bootstrap spectra, $N = 1000$ samples
[spectra: BaSc, arXiv:2505.05547; Hörz et al., PRC 103, 014003 (2021)]

Frames & irreps
$P^2 = 0, \ldots, 4$ (O_h, C_{4v}, C_{2v}, C_{3v});
each level assigned to a parity tower first (→ next)

Dataset: C103 finite-volume spectra

All 232 measured levels, 25 frame/irrep spectra — *both* parity towers interleaved

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Isosinglet NN

Generalized Pauli: $(-1)^L(-1)^{S+1}(-1)^{I+1} = -1 \;\Rightarrow\; L + S + I$ odd. With $I = 0$: $L + S$ odd — two ways to satisfy it:

L even, $S = 1$ $\longrightarrow$ positive parity, spin triplet

$$\underbrace{{}^3S_1 \longleftrightarrow {}^3D_1}_{\text{tensor mixing } \epsilon_1}, \quad {}^3D_2, \quad {}^3D_3$$

- deuteron quantum numbers ($J^P = 1^+$)
- ϵ_1 = the tensor-force observable

L odd, $S = 0$ $\longrightarrow$ negative parity, spin singlet

$${}^1P_1\ (J=1), \quad {}^1F_3\ (J=3), \quad ({}^1H_5)$$

- no infinite-volume P–F mixing (different J)
- coupled only through shared finite-volume irreps

Energies to Amplitudes: Lüscher

$$\det\left[\widetilde{K}^{-1}(E^*) - B^{(\mathbf{P},\Lambda)}(E^*)\right] = 0$$

$$\widetilde{K}^{-1} = O(\theta)\begin{pmatrix}(k\cot\delta)_\alpha & 0 \\ 0 & (k\cot\delta)_\beta\end{pmatrix}O(\theta)^{\mathsf{T}},\quad \theta(p^2) = \epsilon_0 p^2$$

$\widetilde{K}_L^{-1} = p^{2L+1}\cot\delta_L$ (everything in units of m_N):

wave	$\widetilde{K}^{-1}$
$^3S_1$ (α)	$A + Bs + Cs^2,\quad s = E^{*2}$
$^3D_1$ (β), $^3D_3$	constant (β: $-1/a_D$)
$^3D_2$	$A + Bp^2$
$^1S_0$, $^1P_1$, $^1F_3$	$E^*\,(a + xr_1 + x^2r_2)$, $x = 4p^2$

$$B^{(\mathbf{P})}_{J'm'L'S';\,JmLS}$$

$$\delta_{S'S}\sum_{m_{L'},m_S,m_L}\langle J'm'|L'm_{L'},Sm_S\rangle\langle Lm_L,Sm_S|Jm\rangle\, W^{(\mathbf{P},\gamma)}_{L'm_{L'};\,Lm_L}(q^{*2})$$

- W: Rümmukainen–Gottlieb–Lüscher shifted zeta functions $\mathcal{Z}_{lm}$ per frame
- spin recoupling couples *all* (J, L) at fixed S: one irrep block mixes $^3S_1$, $^3D_1$, $^3D_2$, $^3D_3$

https://github.com/cjmorningstar10/TwoHadronsInBox

$$\chi^2 = \sum_{ij} r_i\,[C^{-1}]_{ij}\,r_j,\quad r_i = p_i^{*2}(\text{data}) - p_i^{*2}(\text{QC})$$

C = full data covariance (bootstrap); 24-start multistart; errors = bootstrap N=1000 percentiles

Energies to Amplitudes: Lüscher

Irrep and partial wave content (BDLS)

Even parity ($S=1$)

frame	irrep	content	
$\mathbf{P}^2=0$	T_{1g}	$(^3S_1\text{–}^3D_1) \oplus {}^3D_3$	
	E_g	$^3D_2$	clean
	T_{2g}	$^3D_2 \oplus {}^3D_3$	
	A_{2g}	$^3D_3$	clean
$\mathbf{P}^2=1,4$	A_2	$(^3S_1\text{–}^3D_1) \oplus {}^3D_3$	
	E	$(^3S_1\text{–}^3D_1) \oplus {}^3D_2 \oplus 2\,{}^3D_3$	
	A_1	$^3D_2$	clean
	B_1, B_2	$^3D_2 \oplus {}^3D_3$	
$\mathbf{P}^2=2$	A_2, B_1, B_2	$(^3S_1\text{–}^3D_1) \oplus {}^3D_2 \oplus 2\,{}^3D_3$	
$\mathbf{P}^2=3$	A_2	$(^3S_1\text{–}^3D_1) \oplus 2\,{}^3D_3$	
	E	$(^3S_1\text{–}^3D_1) \oplus 2\,{}^3D_2 \oplus 2\,{}^3D_3$	

Odd parity ($S=0$)

frame	irrep	content	
$\mathbf{P}^2=0$	T_{1u}	$^1P_1 \oplus {}^1F_3$	
	A_{2u}, T_{2u}	$^1F_3$	clean
$\mathbf{P}^2=1,4$	A_1	$^1P_1 \oplus {}^1F_3$	
	E	$^1P_1 \oplus 2\,{}^1F_3$	
	B_1, B_2	$^1F_3$	clean
$\mathbf{P}^2=2,3$	$A_1, B/E$	$^1P_1 \oplus 2\,{}^1F_3$	
	A_2	$^1F_3$	clean

No irrep isolates the deuteron block: wherever $J^P=1^+$ $(^3S_1\text{–}^3D_1)$ appears, $^3D_3$ — and in moving frames $^3D_2$ — ride along $\Rightarrow$ the fits must treat $^3S_1\text{–}^3D_1\text{–}^3D_2\text{–}^3D_3$ together.

Methodology

Even parity ($S = 1$)

frame	irrep	content	
$\mathbf{P}^2=0$	T_{1g}	$({}^3S_1\text{–}{}^3D_1) \oplus {}^3D_3$	
	E_g	${}^3D_2$	clean
	T_{2g}	${}^3D_2 \oplus {}^3D_3$	
	A_{2g}	${}^3D_3$	clean
$\mathbf{P}^2=1,4$	A_2	$({}^3S_1\text{–}{}^3D_1) \oplus {}^3D_3$	
	E	$({}^3S_1\text{–}{}^3D_1) \oplus {}^3D_2 \oplus 2\,{}^3D_3$	
	A_1	${}^3D_2$	clean
	B_1, B_2	${}^3D_2 \oplus {}^3D_3$	
$\mathbf{P}^2=2$	A_2, B_1, B_2	$({}^3S_1\text{–}{}^3D_1) \oplus {}^3D_2 \oplus 2\,{}^3D_3$	
$\mathbf{P}^2=3$	A_2	$({}^3S_1\text{–}{}^3D_1) \oplus 2\,{}^3D_3$	
	E	$({}^3S_1\text{–}{}^3D_1) \oplus 2\,{}^3D_2 \oplus 2\,{}^3D_3$	

- equal masses $\Rightarrow$ relative inversion is exact even in moving frames $\Rightarrow$ the QC block-diagonalizes into even-L and odd-L sectors: no dynamical parity mixing
- but moving-frame little groups carry no parity label: both towers populate the *same* irrep spectrum $\Rightarrow$ every measured level must be assigned to a tower *before* any fit

$$\det\left[\widetilde{K}^{-1}(E^*) - B^{(\mathbf{P},\Lambda)}(E^*)\right] = 0$$

The bottleneck

every optimizer step re-scanned $\Omega(E) = \det[\widetilde{K}^{-1}(E) - B(E)]$ on a fine energy grid, and every Ω recomputed the box matrix $B(E)$ — the Lüscher zeta part, ~ 0.3 ms a call, thousands per χ^2.

The observation

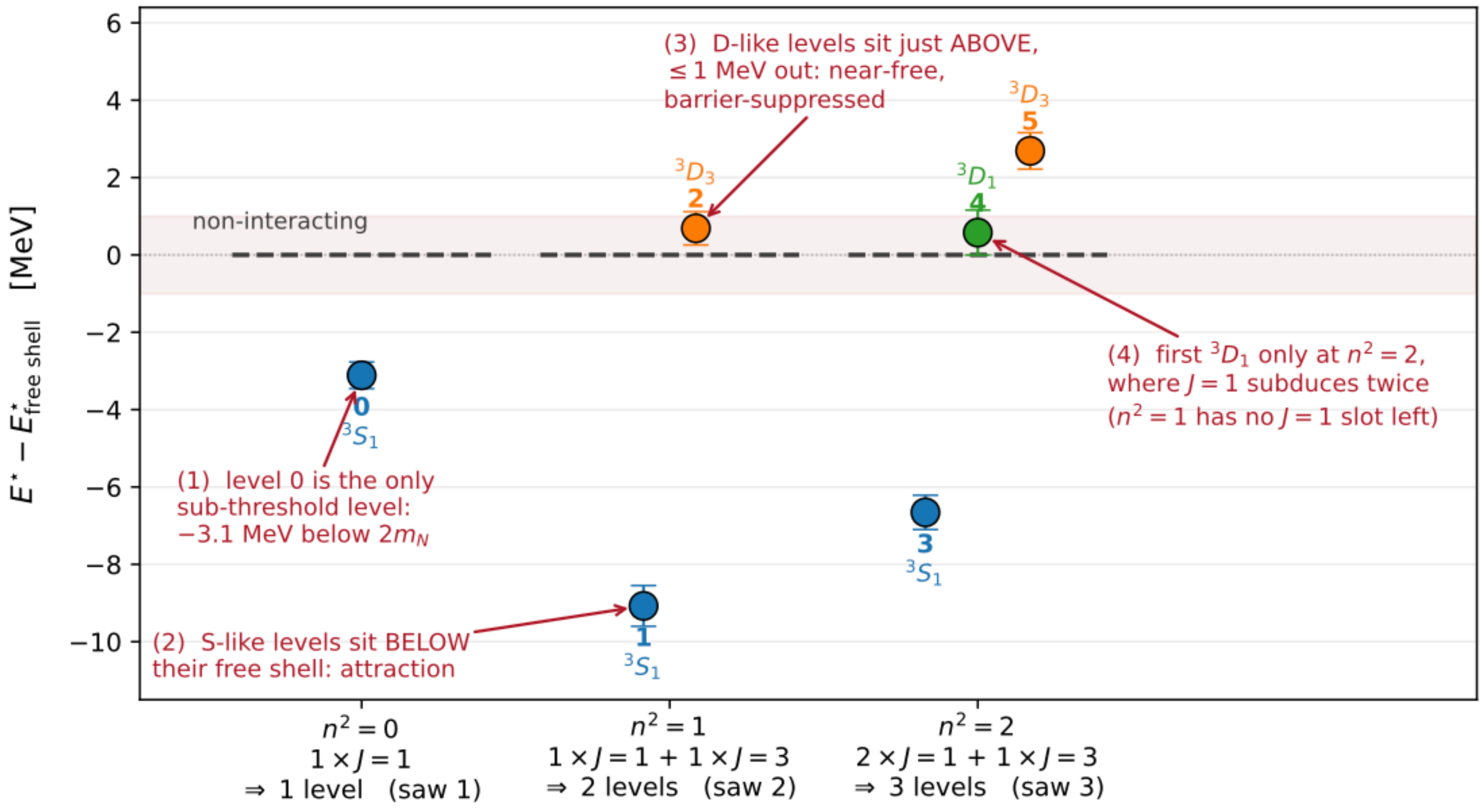
$B(E)$ is parameter-independent. Tabulate it once on Chebyshev–Lobatto nodes per $(\boldsymbol{P}^2, \Lambda)$ window between free levels, poles divided out *exactly* ($h = B\prod(E - E_{\mathrm{NI}})$) so the interpolant is good to $\sim 10^{-12}$.

Per step

rebuild $\widetilde{K}^{-1}$ vectorized; Ω from a batched eigen-decomposition; roots by vectorized bracket subdivision *on the smooth interpolant* — no grid step limits the resolution.

One Irrep View: T_{1g} example

Constraining sensitive waves: rest frame



Shift of each level from *its own* free shell, in MeV. T_{1g} subduces J=1 once and J=3 once, so each shell's J content fixes how many levels to expect — and that is the count observed.

$$\det\left[\widetilde{K}^{-1}(E^*) - B^{(\mathbf{P},\Lambda)}(E^*)\right] = 0$$

Stiff quantization condition

- weak interactions ⇒ roots pinned near noninteracting energies; $\widetilde{K}^{-1} \sim p^{2L+1}$ is steep — fine root scans required (parallel engine, ~ 500× faster per χ^2)
- multistart + basin audit: χ^2 landscape has false minima

One Irrep View: T_{1g} example

Identifying levels after fitting

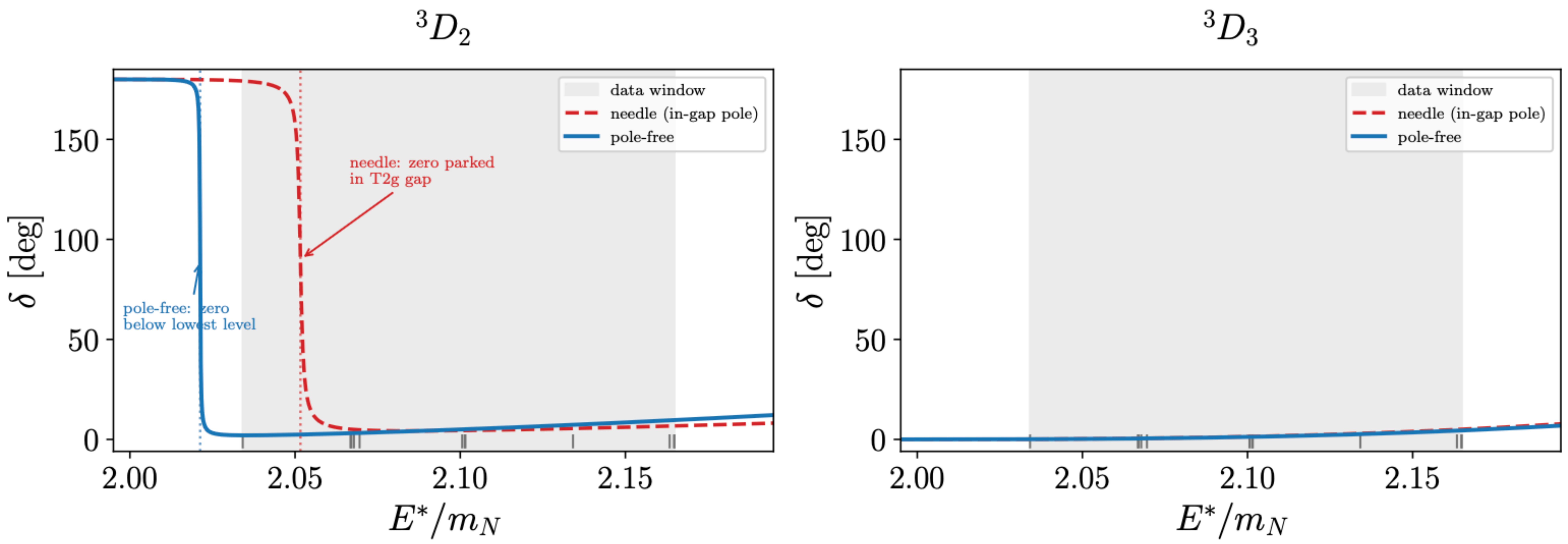
At each QC root, $\Omega(E^*)v = 0$, $\Omega = B - \widetilde{K}$; wave i gets its slope-participation weight

$$w_i \propto \left| v_i \left(\frac{d\Omega}{dE} v \right)_i \right|$$

- = share of the Hellmann–Feynman energy slope: how much the level *moves* when wave i's phase is displaced — invariant under barrier-factor rescalings, unlike the raw eigenvector weights $|v_i|^2$ used previously for channel identification [Woss, Wilson, Dudek, PRD 101, 114505 (2020)] (⟶ backup)
- same machinery tags every level of both towers ⟶ frozen level tables

level	E^*/m_N	$\lvert v_i\rvert^2$ says	slope w_i says	assignment
0	1.998	98% $^3D_1$	99.8% $^3S_1$	$^3S_1$ (thresh.)
1	2.029	98% $^3D_1$	99.3% $^3S_1$	S
2	2.035	99% $^3D_3$	85.0% $^3D_3$	$^3D_3$
3	2.064	97% $^3D_1$	79.8% $^3S_1$	S
4	2.069	83% $^3D_1$	72.9% $^3D_1$	$^3D_1$
5	2.070	99% $^3D_3$	97.1% $^3D_3$	$^3D_3$

$^3D_2 - ^3D_3$: the needle trap



Rest-frame D-dominated selection: $E_g[0\text{–}2]$, $A_{2g}[0\text{–}1]$, $T_{2g}[0\text{–}6]$ (12 levels, N1000) — same data, two $^3D_2$ parametrizations.

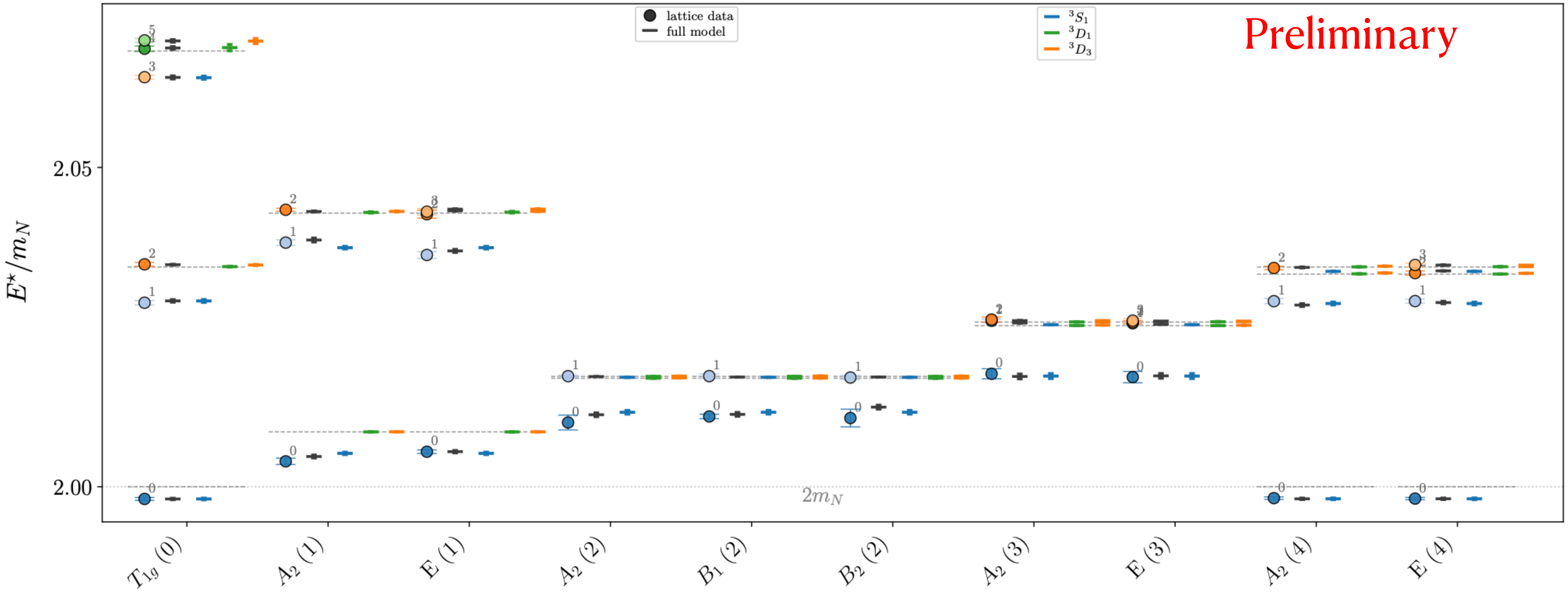
Pole-free (adopted): $\chi^2/\text{dof} = 25.8/9$; $A_{^3D_2} = -0.489(75)$, $B = 0.120(18)$, $A_{^3D_3} = 0.156(67)$; $\delta = 90°$ crossing at $\sqrt{s_0} = 2.021(7)\, m_N$ — *below* the lowest level

Needle (rejected): crossing at $\sqrt{s_0} = 2.052$, parked inside the T_{2g} gap; buys $\Delta\chi^2 = 5.6$ from an $\mathcal{O}(p^5)$-narrow feature no level can resolve

Fix: pole-free parametrizations — build $\widetilde{K}^{-1}$ so the crossing cannot enter the window (e.g. $\widetilde{K}^{-1} = E\,a$, zero pinned sub-threshold; adopted for P–F); profile every crossing before believing a $\Delta\chi^2$

$^3D_1$ (β), $^3D_3$	constant (β: $-1/a_D$)
$^3D_2$	$A + Bp^2$

$^3S_1 - ^3D_1 - 3D_3$: $\chi^2/\mathbf{dof} = 19.6/27$



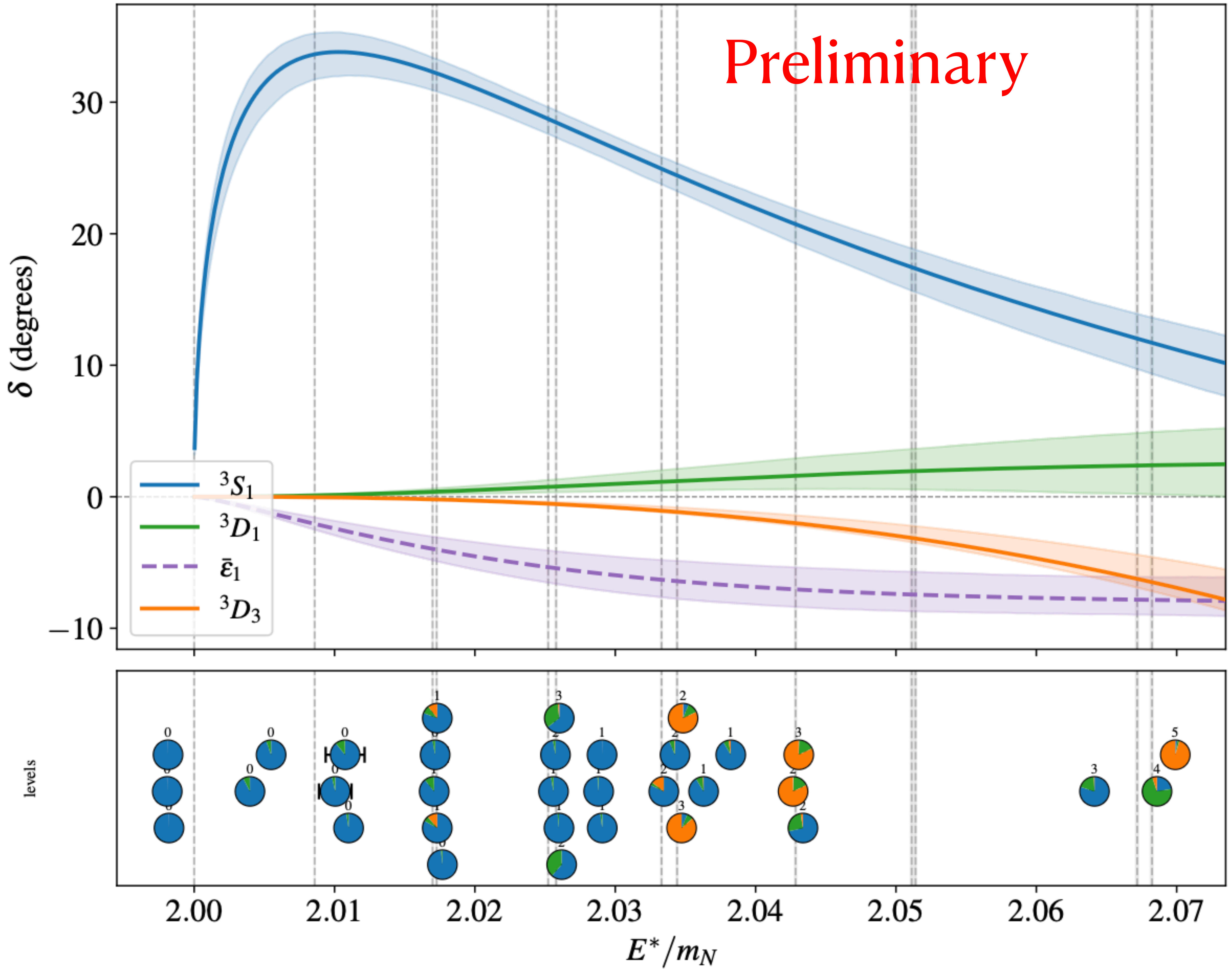
Best fit vs. data: measured levels (coloured points), full-model roots (grey ticks), each wave *alone* (coloured ticks).

Model (best χ^2/dof of the ladder): $k\cot\delta(^3S_1)$ 3-term poly in s; $^3D_1$ constant $\widetilde{K}^{-1}$; $\theta = \epsilon_0 p^2$; $^3D_3$ spectator

$^3D_2$ **test**: full 4-wave fit gives $\Delta\chi^2 = 0.00$, shared params unchanged — J=1 levels carry no $^3D_2$ weight → dropped (pinned by the D-wave fit)

Fit quality: extended even-parity dataset; $\chi^2/\text{dof} = 19.6/27$

$^3S_1 - ^3D_1$: the tensor force lives!



Stapp (bar) convention: $\bar{\delta}(^3S_1)$, $\bar{\delta}(^3D_1)$, $\bar{\epsilon}_1$ — the PWA-comparable quantities. Bands: pointwise 68% from N=1000 bootstrap, converted *per draw*.

- $^3S_1$ attractive, δ peaks $\sim 33°$ — **no bound state**, but a virtual state at −7.5 MeV (→ next slide), consistent with the companion S-wave result
- $^3D_1$ small

Mixing angle

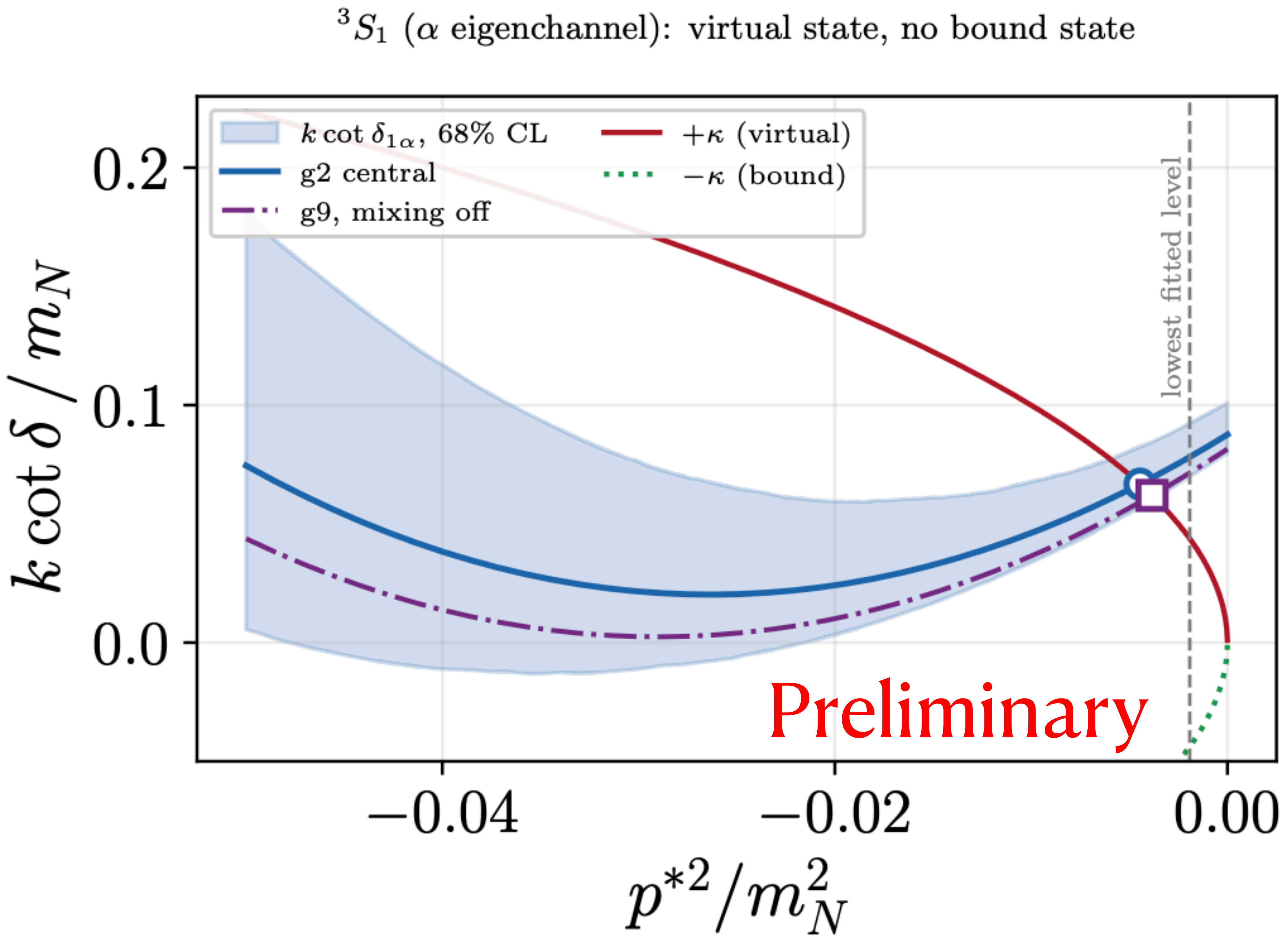
fitted (BB): $\epsilon_0 = -7.55$, 68% CL $[-9.37, -5.68]$ — nonzero at $\approx 4\sigma$; no mixing costs $\Delta\chi^2 = 16.7$ (33-level refit)

shown after $\sin 2\bar{\epsilon}_1 = \sin 2\epsilon_1 \sin(\delta_{1\alpha} - \delta_{1\beta})$:

BB $\epsilon_1 \to -33°$ across the window, while $\bar{\epsilon}_1$ saturates near $-8°$

- converted to Stapp (bar) for PWA-comparable results: $\bar{\delta}_S + \bar{\delta}_D = \delta_{1\alpha} + \delta_{1\beta}$, $\sin 2\bar{\epsilon}_1 = \sin 2\epsilon_1 \sin(\delta_{1\alpha} - \delta_{1\beta})$ (e.g. $\epsilon_1 \simeq -33° \to \bar{\epsilon}_1 \simeq -8°$)

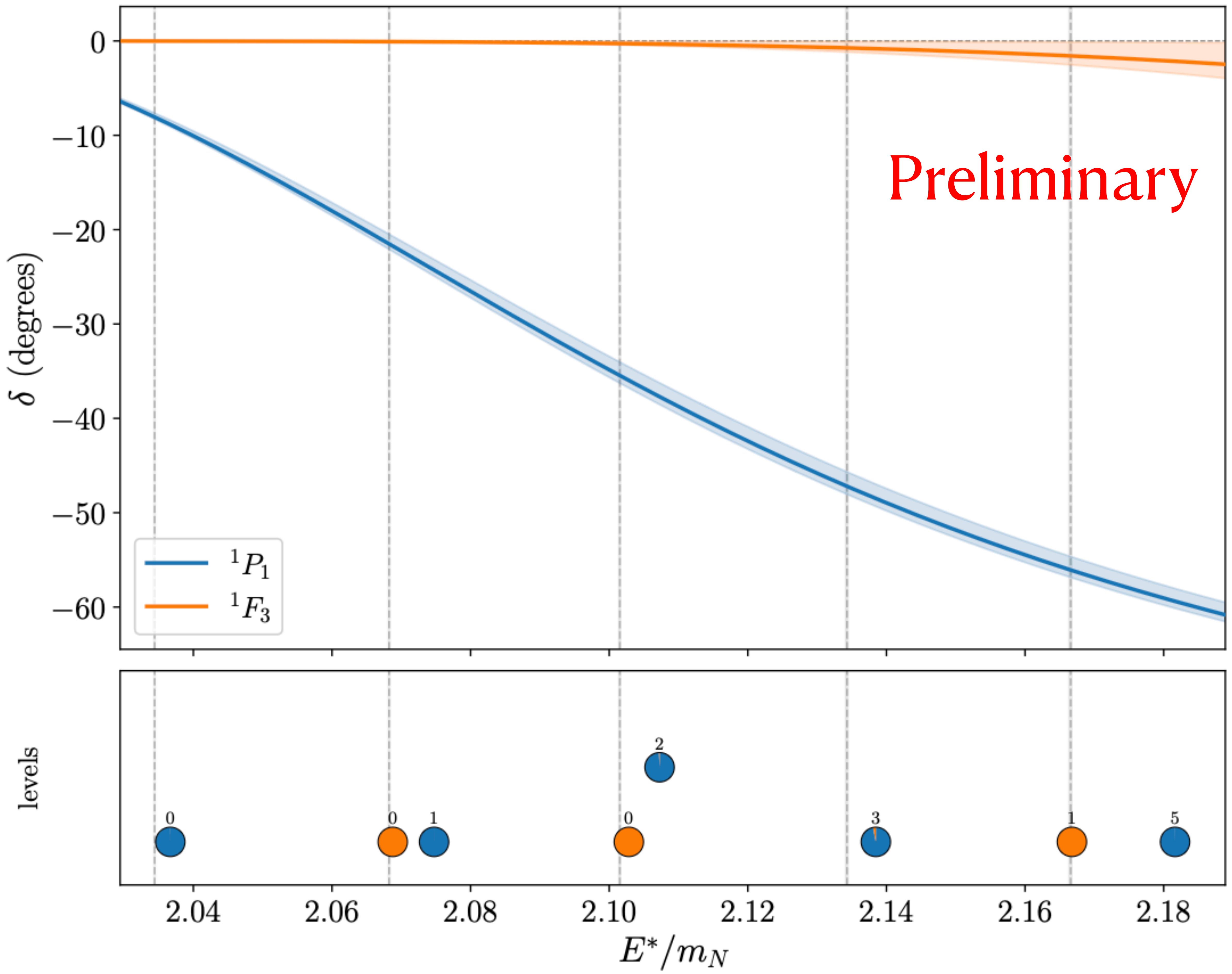
$^3S_1 - ^3D_1$: the tensor force lives!



- $^3S_1$ attractive, δ peaks $\sim 33°$ — **no bound state**, but a virtual state at -7.5 MeV (→ next slide), consistent with the companion S-wave result
- $^3D_1$ small
- continuing $p \longrightarrow \mp i\kappa$: $k \cot \delta = \mp\kappa$ for bound / virtual

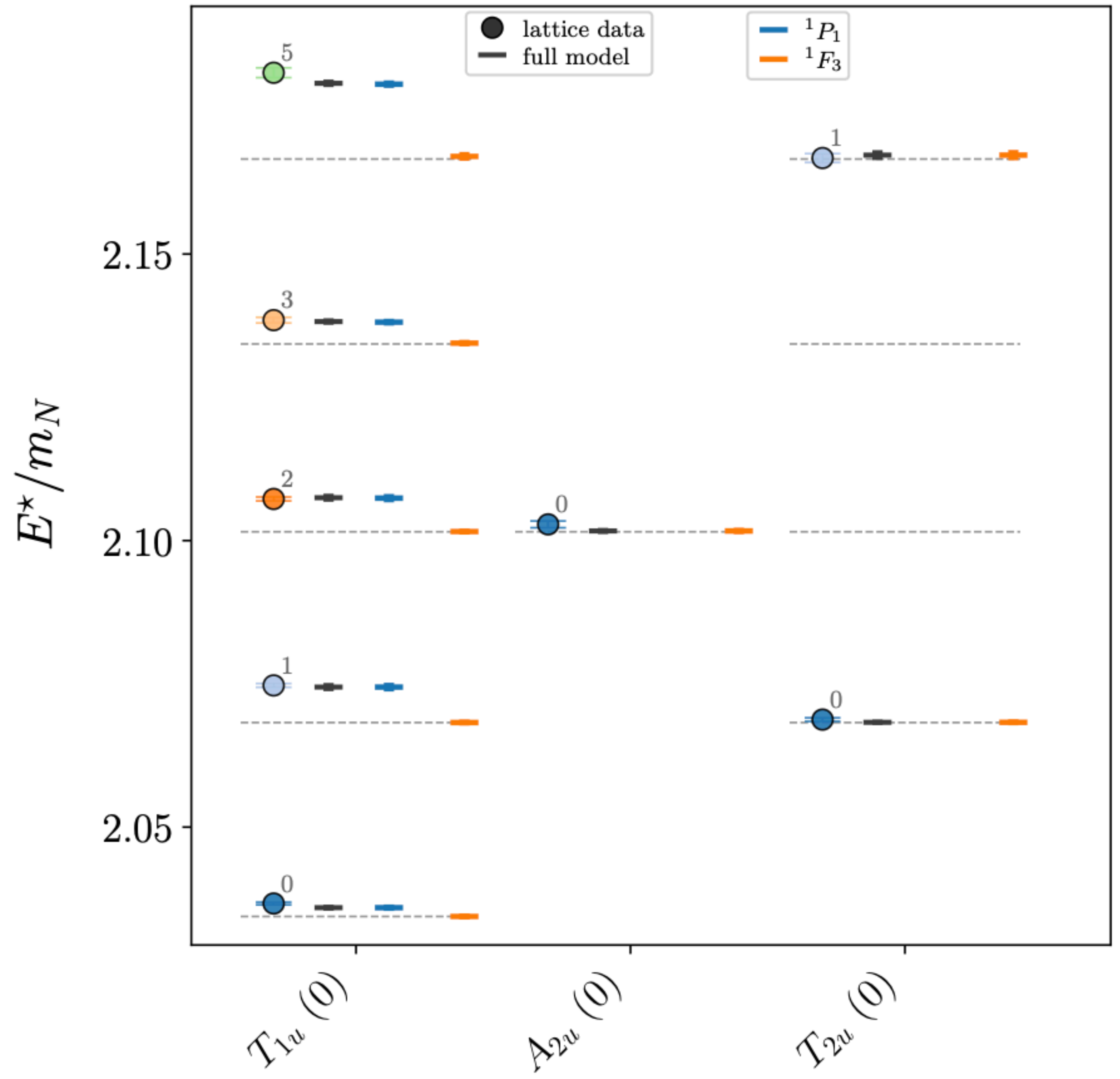
Result (N=1000 bootstrap)
$E^* - 2m_N = -7.5$ MeV, 68% CL $[-9.7, -6.0]$
$\kappa = 110$ MeV · $a(^3S_1) = -1.39$ fm
0/1000 samples bind

Odd Parity: $^1P_1$ repulsive, $^1F_3$ free



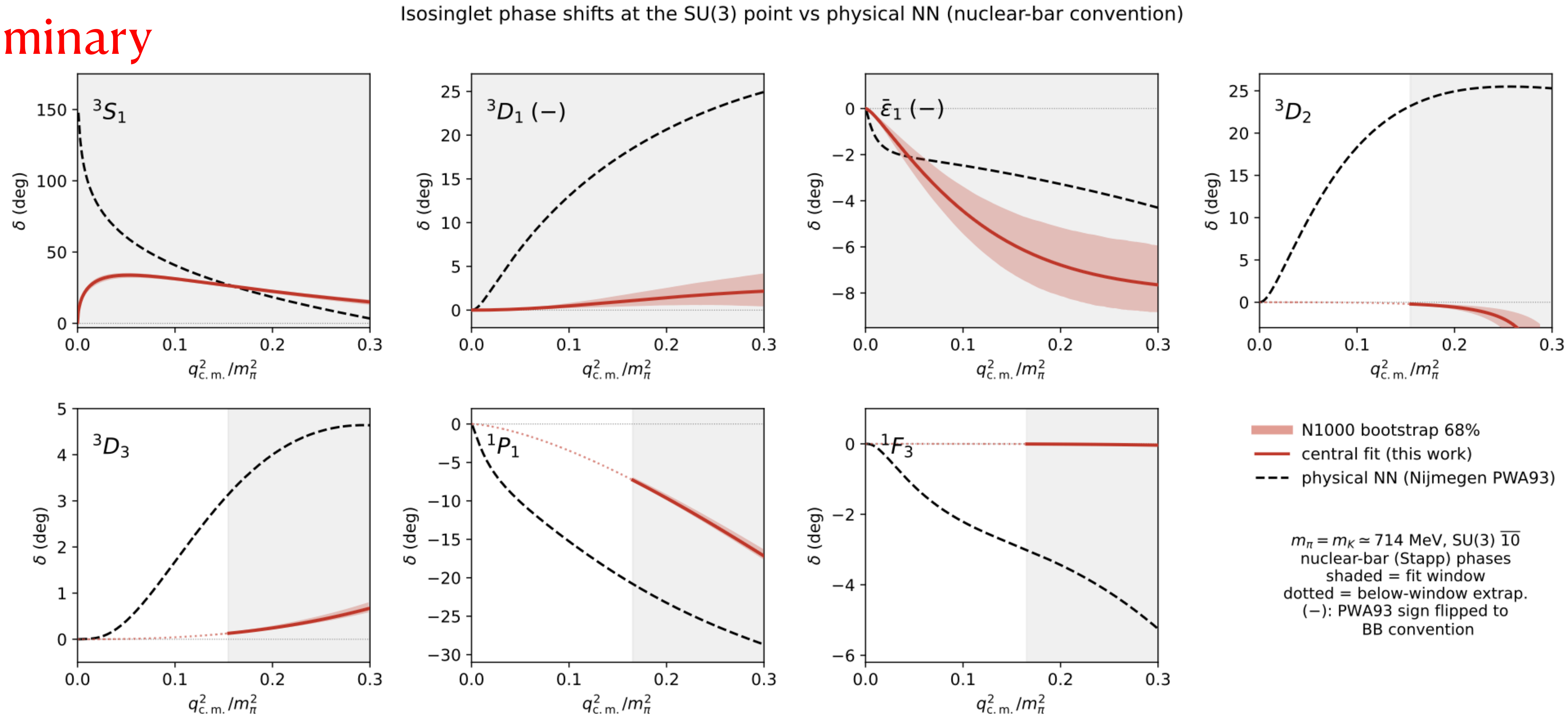
Central fit: rest-frame 8 levels; one *pole-free* coefficient per wave ($\widetilde{K}^{-1} = E\, a$)

$^1P_1$
$a(^1P_1) =$ -0.0224, 68% $[-0.0237, -0.0218]$ $\delta(^1P_1)$ reaches $\approx -60°$: repulsive



Seven Waves against physical NN (Nijmegen)

Preliminary



Nuclear-bar (Stapp) phases vs. q^{*2}/m_π^2; shaded = fit window, dotted = below-window extrapolation. (−): PWA93 sign flipped to our convention. Same signs and ordering as the physical point, with muted magnitudes and no binding: the heavy quark mass weakens, but does not reorganize, the NN interaction.

Conclusion & Outlook

Conclusions

- Systematic NN higher-partial-wave analysis at the SU(3) flavor point — including the first Lüscher-based extraction of ϵ_1 — on the dataset that settled the di-nucleon question
- ϵ_1 nonzero at $\approx 4\sigma$; ${}^1P_1$ repulsive; ${}^3D_2$, ${}^3D_3$ constrained by dedicated D-wave fits (${}^3D_2$ decouples from the J=1 fit); ${}^1F_3$ free within errors

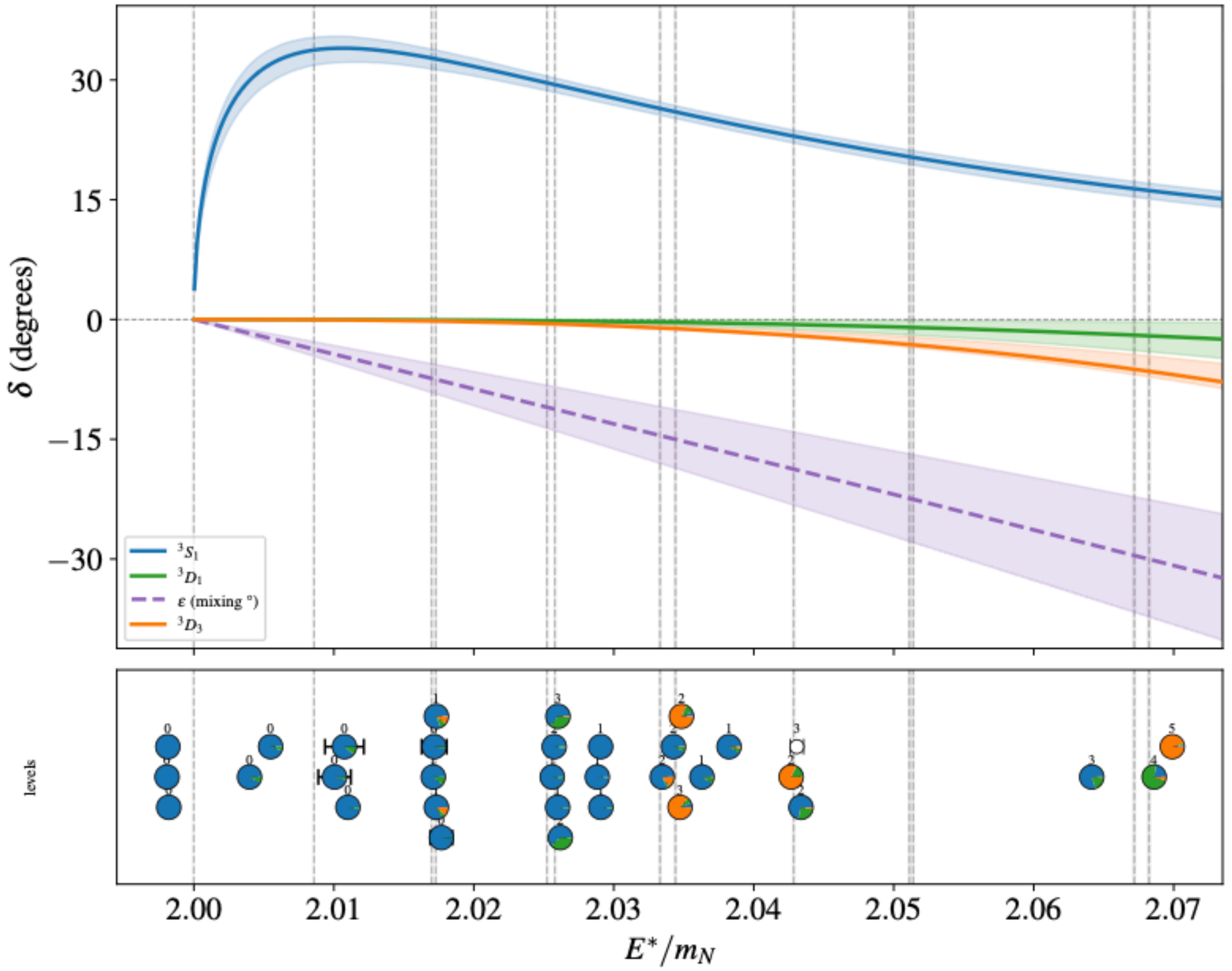
Outlook

- Isotriplet campaign: ${}^1S_0$ companion waves ${}^1D_2$, ${}^3P_{0,1,2}$ spin–orbit splittings, ϵ_2 candidate
- p^4 term in the mixing-angle energy dependence; joint H-wave fits
- Lighter pion masses along the CLS trajectory; matching to pionless/chiral EFT for quark-mass extrapolation

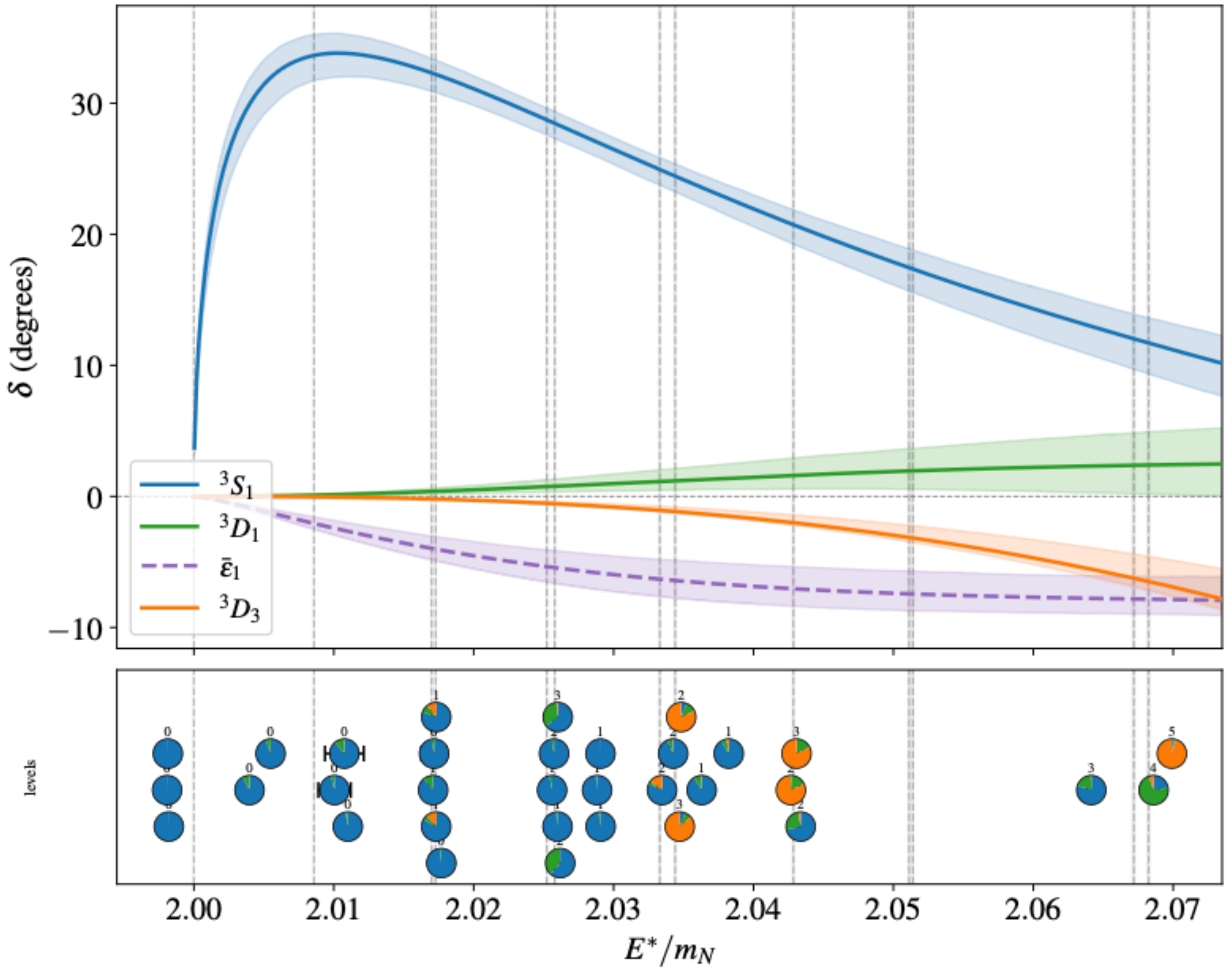
Thank you!

Backup

Backup: same fit, two conventions — BB vs. Stapp



Blatt–Biedenharn: $\delta_{1\alpha}, \delta_{1\beta}, \epsilon_1$ (as fitted)



Stapp (bar): $\bar{\delta}_S, \bar{\delta}_D, \bar{\epsilon}_1$, converted per draw

- sum rule at every energy: $\bar{\delta}_S + \bar{\delta}_D = \delta_{1\alpha} + \delta_{1\beta}$
- mixing suppression: $\sin 2\bar{\epsilon}_1 = \sin 2\epsilon_1 \sin(\delta_{1\alpha} - \delta_{1\beta})$ caps $|\bar{\epsilon}_1|$ as the eigenphases approach — $\epsilon_1 \to -33°$ while $\bar{\epsilon}_1$ saturates near $-8°$
- $\mathcal{O}(\epsilon^2)$ on the diagonal phases: $\delta_{1\beta} < 0$ everywhere, yet $\bar{\delta}_D$ slightly positive; uncoupled $^3D_3$ identical in both

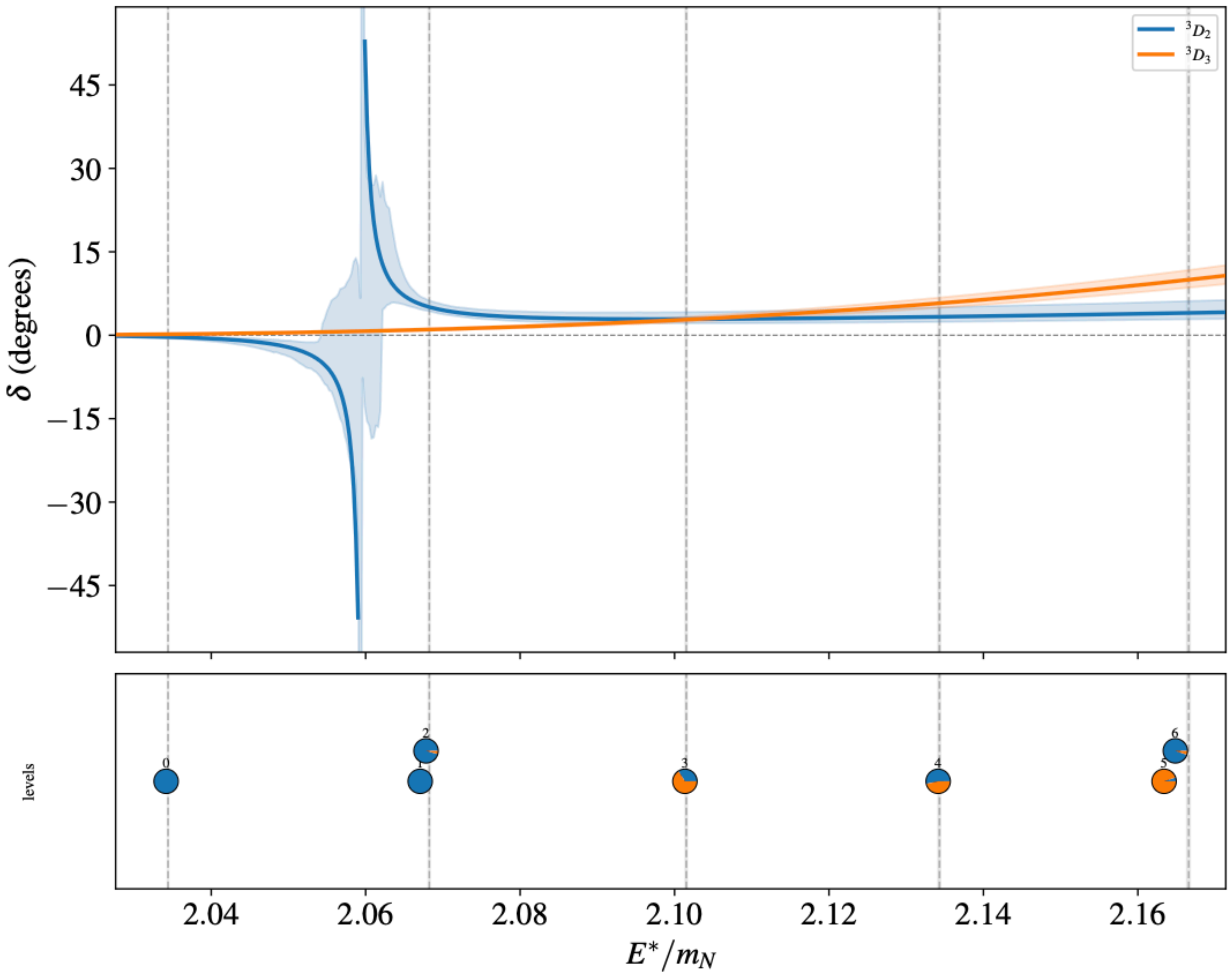
Backup: the "needle" lesson — phantom χ^2 gains

- A 2-parameter ${}^1F_3$ model placed a $\delta_F = 90°$ crossing of width $\mathcal{O}(p^7)$ just below a data level — absorbing that level's pull and faking $\Delta\chi^2 \approx 11$
- Pole-free form forbids the 90° crossing but not the 0° one: wide-bound refit parks a $\delta_F = 0$ needle (width 0.0015 in p^2/m^2) exactly on another level
- χ^2 profile vs. pinned crossing position: flat plateau with $\Delta\chi^2 < 1$ dips centred on single data points ⇒ not physics

Practices adopted

pole-free parametrizations by construction; crossing-position profiling before accepting any $\Delta\chi^2$; explicit `param_bounds` in every bootstrap (auto-boxes fake a σ for flat directions)

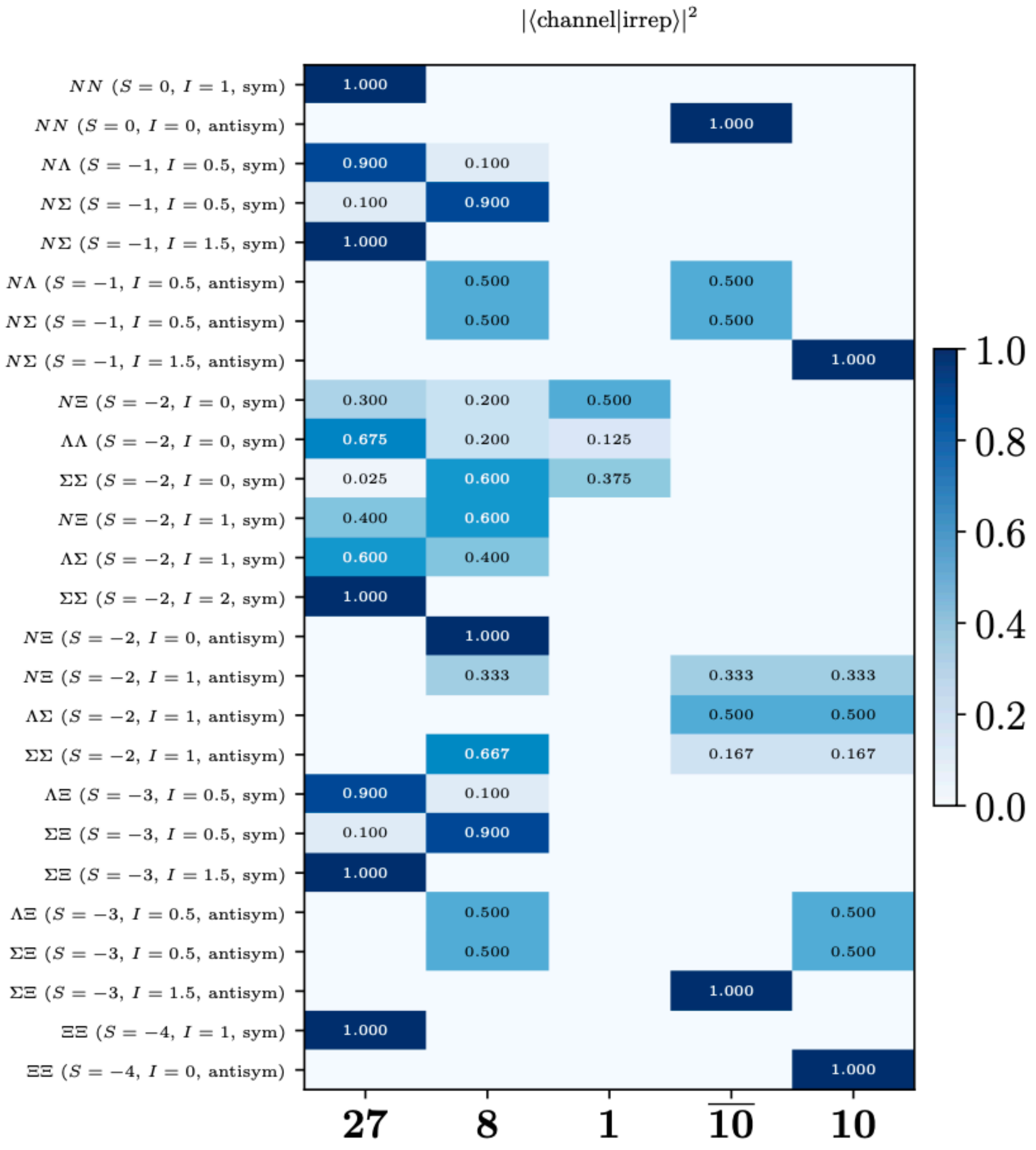
Backup: ${}^3D_2$–${}^3D_3$ phase shifts (dedicated fit)



Dedicated ${}^3D_2$–${}^3D_3$ bootstrap fit to the D-dominated levels.

- ${}^3D_3$ in the full J=1-sector fit: $\widetilde{K}^{-1}$ element = −0.0112, 68% [−0.0159, −0.0101] → small but clearly nonzero
- ${}^3D_2$: consistent with a free wave within the coupled fit
- splitting pattern among ${}^3D_1$, ${}^3D_2$, ${}^3D_3$ = tensor/spin–orbit information at heavy quark mass

Backup: full SU(3) channel × irrep decomposition



$|\langle \text{channel}|\text{irrep}\rangle|^2$ at $I_3 = I$. Rows with a single 1.000 are the single-irrep channels. Computed in `scripts/su3_bb_channels.py`; checks: $C_2(\mathbf{8}) = 3$, multiplicities 27/20/16/1, channel count = irrep count per sector.

SU(3): the same two amplitudes *are* hyperon-channel predictions

$\mathbf{8} \otimes \mathbf{8} = \mathbf{27} + \mathbf{8}_s + \mathbf{1}$ (sym) + $\mathbf{10} + \overline{\mathbf{10}} + \mathbf{8}_a$ (antisym) — one amplitude per irrep, shared by every channel containing it; $\sigma_{\text{flavour}} = (-1)^{L+S}$. We determine **27** (from $^1S_0$) and $\overline{\mathbf{10}}$ (from $^3S_1$–$^3D_1$, $^3D_2$, $^3D_3$, $^1P_1$, $^1F_3$).

Single-irrep channels

our phase shifts apply unchanged, zero SU(3) breaking

$\overline{\mathbf{10}}$ (odd $L+S$)	**27** (even $L+S$)
NN (I=0)	NN (I=1)
$\Sigma\Xi$ (I=3/2)	ΣN (I=3/2)
	$\Sigma\Sigma$ (I=2)
	$\Sigma\Xi$ (I=3/2)
	$\Xi\Xi$ (I=1)

Six hyperon-channel predictions, no free parameters. $\Sigma\Xi$(I=3/2) in *both* parities.

Partially constrained

we fix one component; weight = $|\langle \text{ch}|\text{irrep}\rangle|^2$

channel	$\overline{\mathbf{10}}$	**27**
ΛN	0.500	0.900
ΣN	0.500	0.100
$\Lambda\Sigma$	0.500	0.600
$N\Xi$	0.333	0.400
$\Lambda\Lambda$	—	0.675

ΛN–ΣN spin-triplet is exactly **half $\overline{\mathbf{10}}$**: half the ΛN interaction hypernuclear physics wants.

From the group theory (Casimir on the 64-dim pair space), not a table lookup — reproduces the standard H-dibaryon channel