N*(1535) and N*(1650) from πN scattering and lattice QCD input

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Physics motivation

What builds the lowest S_{11} nucleon resonances?

$I = 1/2, J^P = 1/2^-$ { N*(1535), N*(1650) }

Three-quark components?
Meson-baryon dynamical generation?

πN scattering

Densely samples the energy dependence of Amp.
Incomplete coupled-channel information

Lattice QCD

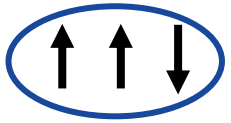
Few discrete spectra in finite volume
Sensitivity to operator structure

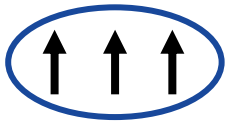
Nonperturbative Hamiltonian Framework (NPHF)

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$$H = H_0 + g + v$$

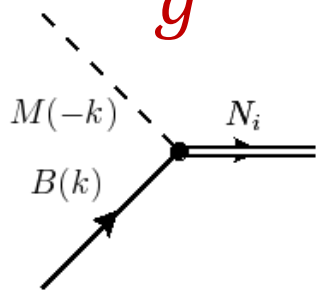
Two three-quark bare states

N_2: $S = 1/2$ 

N_4: $S = 3/2$ 

Both have $J^P = 1/2^-$

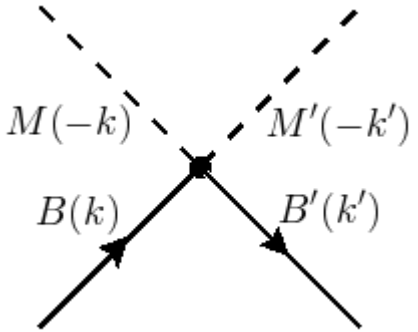
g



Four meson-baryon channels

$\pi N \quad \eta N \quad K\Lambda \quad \mathrm{K}\Sigma$

v: direct channel-channel interaction



- Infinite volume: scattering amplitudes and poles
- Finite volume: energy levels and elements' contributions

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Symmetry constraints

Weinberg-Tomozawa interaction

$$V_{\alpha\beta}^{WT} = -C_{\alpha\beta}\frac{g_0}{8\pi^2 f_\alpha f_\beta}\frac{\omega_M(k)+\omega_{M'}(k')}{\sqrt{2\omega_M(k)}\sqrt{2\omega_{M'}(k')}}u_\alpha(k)u_\beta(k')$$

Bare-state vertex

$$G_\alpha^{N_i}(k) = A_\alpha^{N_i}\frac{\sqrt{3}g_{N_i}}{2\pi f_\alpha}\sqrt{\omega_{\alpha_M}(k)}\mathrm{u}_\alpha(k)$$

SU(3) fixes relative channel strengths

$A_\alpha^{N_i}$	πN	ηN	$K\Lambda$	$K\Sigma$
Flavor-only	1	$1/5$	$-3/5$	$-1/5$
N_2	$\frac{\sqrt{2/3}}{3}$	$\frac{1}{3\sqrt{6}}$	$-\frac{1}{2\sqrt{6}}$	$\frac{1}{6\sqrt{6}}$
N_4	$\frac{1}{3\sqrt{6}}$	$-\frac{1}{3\sqrt{6}}$	**0**	$-\frac{\sqrt{2/3}}{3}$

Selection Rule

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Four Scenarios

Scenario 1: without bare states, 5 parameters — Dynamically generated

Scenario 2: with two bare states, without Channel-Channel coupling (WT int.), 6 parameters

Scenario 3: with one bare state, 8 parameters
- III(a): Just Flavor
- III(b): N_2
- III(c): N_4

Scenario 4: with two bare states and four coupled channels, 11 parameters
- IV(A): with mixing
- IV(B): $M_{N_2} < M_{N_4}$
- IV(C): $M_{N_2} > M_{N_4}$

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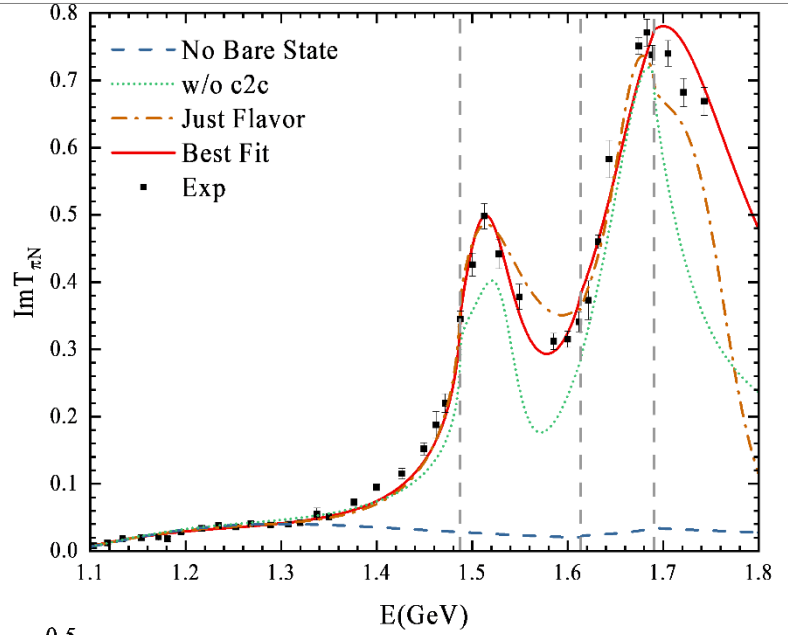
πN Scattering

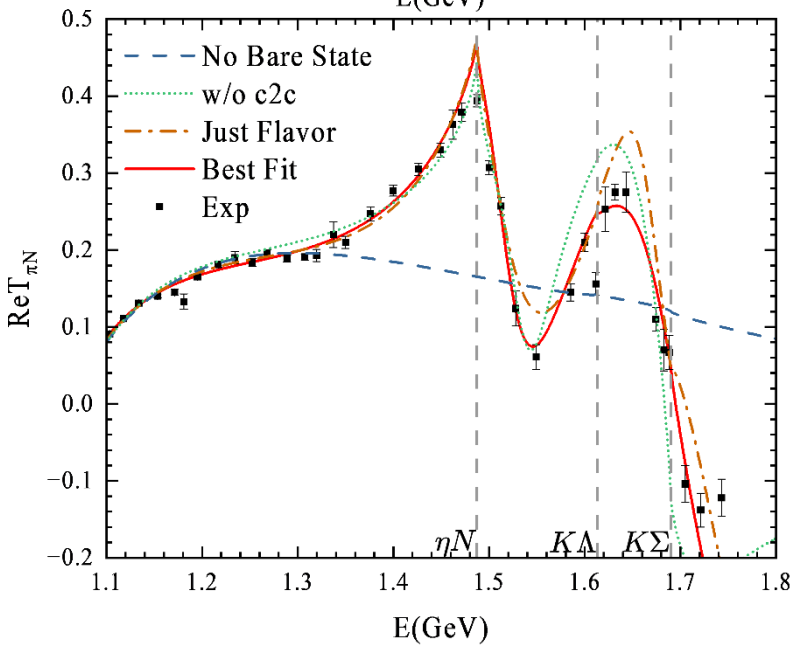
SAID πN S_{11} partial-wave amplitude

- 1.10-1.75 GeV
- 80 points (40 Re + 40 Im)

$$\chi^2 = \chi^2_{\mathrm{Re}T} + \chi^2_{\mathrm{Im}T}$$

- Scenario II (w/o c2c): $\chi^2/dof = 21.28$
- Scenario III:
  - Just Flavor: $\chi^2/dof = 7.65$
  - N_2: $\chi^2/dof = 12.89$
  - N_4: $\chi^2/dof = 57.32$





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πN Scattering

- Mixing: N_2, N_4 share the same quantum number

$$g_{B_1,\alpha} = \sqrt{1-\xi^2}\, A_\alpha^{N_2} g_{N_2} + \xi A_\alpha^{N_4} g_{N_4}$$

$$g_{B_2,\alpha} = -\xi A_\alpha^{N_2} g_{N_2} + \sqrt{1-\xi^2}\, A_\alpha^{N_4} g_{N_4}$$

Quark model: $|\theta_s| = 32^o \rightarrow \xi = sin\theta_s = 0.53$

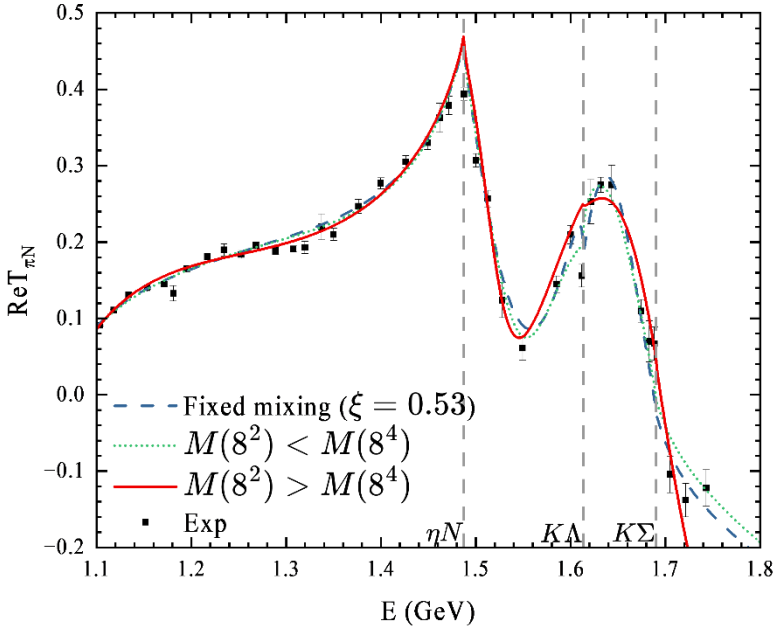
  - Scenario IV(A): $\chi^2/dof = 5.17$ $g_0 < 0$

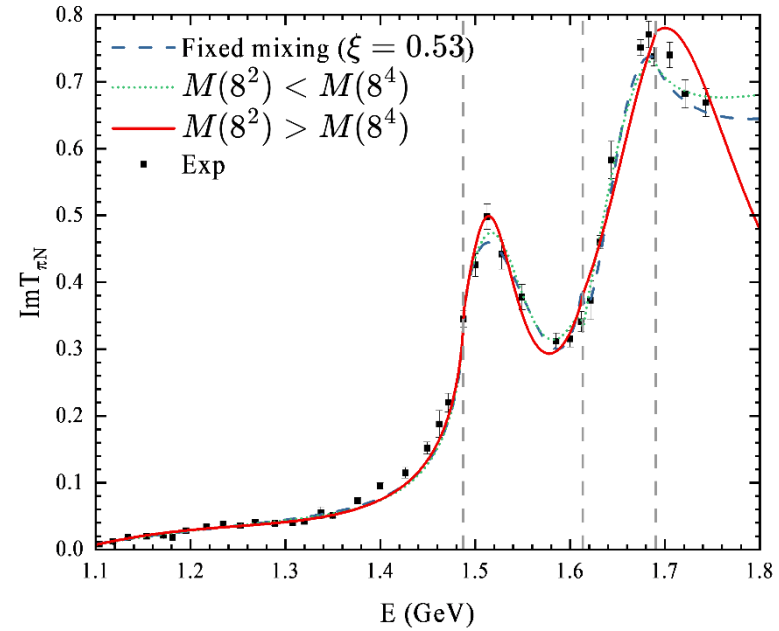
    Poles: 1.5123-0.1273i, 1.4664-0.0405i $(--++)$
    1.6459-0.0579i $(---+)$

- Without Mixing: $M_{N_2} < M_{N_4}$

  - Scenario IV(B): $\chi^2/dof = 4.9$ $g_0 < 0$

    Poles: 1.5176-0.0611i $(--++)$ g_0: WT strength
    1.6491-0.0787i $(---+)$

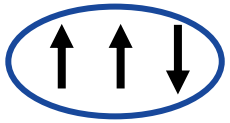




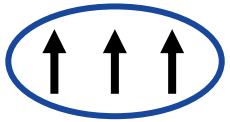
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Bare-mass inversion

- Bare-mass inversion: $M_{N_2} > M_{N_4}$



S=1/2 —— N_2 ➡ N*(1650)



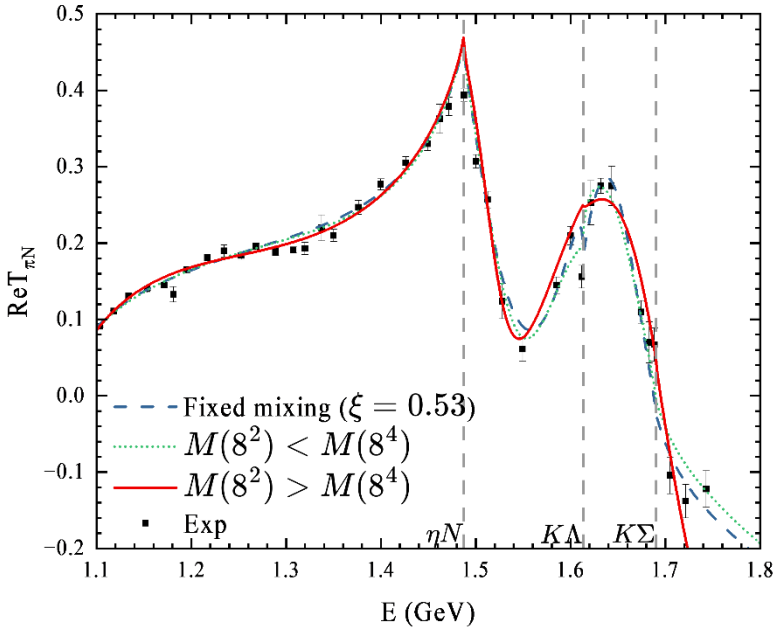
S=3/2 —— N_4 ➡ N*(1535)

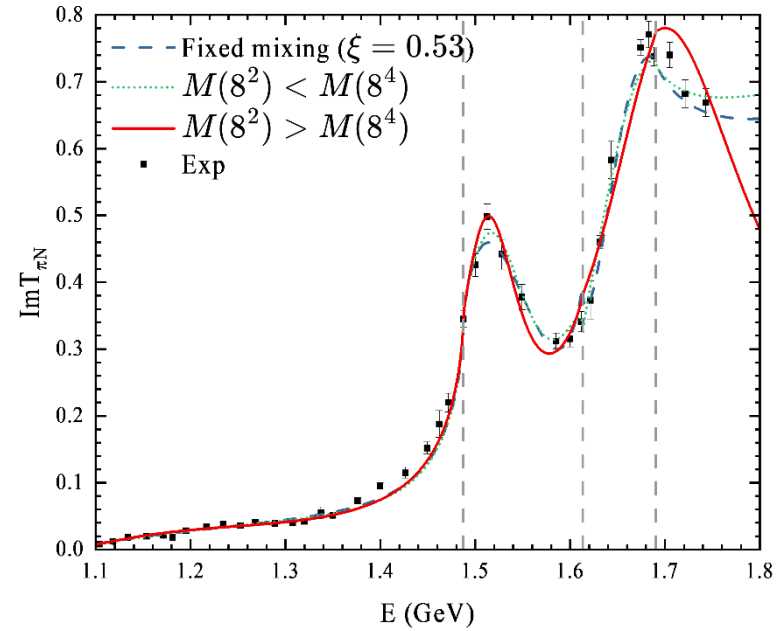
N*(1535) → $K\Lambda$ suppressed

N*(1650) → $K\Lambda$ more strongly

➢ Scenario IV(C): $\chi^2/dof = 5.87$ $g_0 > 0$

Poles: 1.5122-0.0436i (−−+ +)
1.6911-0.0919i (−−− +)





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Finite Volume

- Finite volume $\vec{k}_n = \frac{2\pi}{L}\vec{n}$ $\det(H - E_i\mathbb{I}) = 0$
- Physical pion mass: Fixed from scattering
- Unphysical pion mass: Hadron chiral extrapolation

$$m_M^2(m_\pi^2) = m_M^2\,|_{phys} + \alpha_M(m_\pi^2 - m_\pi^2\,|_{phys})$$

$$m_B(m_\pi^2) = m_B\,|_{phys} + \alpha_B(m_\pi^2 - m_\pi^2\,|_{phys})$$

α_M, α_B: determined by PACS-CS

Bare-state: $m_{N_i}^0(m_\pi^2) = m_{N_i}^0\,|_{phys} + \alpha_{N_i}(m_\pi^2 - m_\pi^2\,|_{phys})$

$\alpha_{N_2}, \alpha_{N_4}$: fitted to both volumes

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Spectrum near $L = 3$ fm and 2 fm

L~3fm : CSSM & Cyprus L~2fm : Lang and Verduci & HSC

- Three-quark interpolator

$$\chi_1 = \epsilon^{abc}(u^{aT} C\gamma_5 d^b)u^c$$

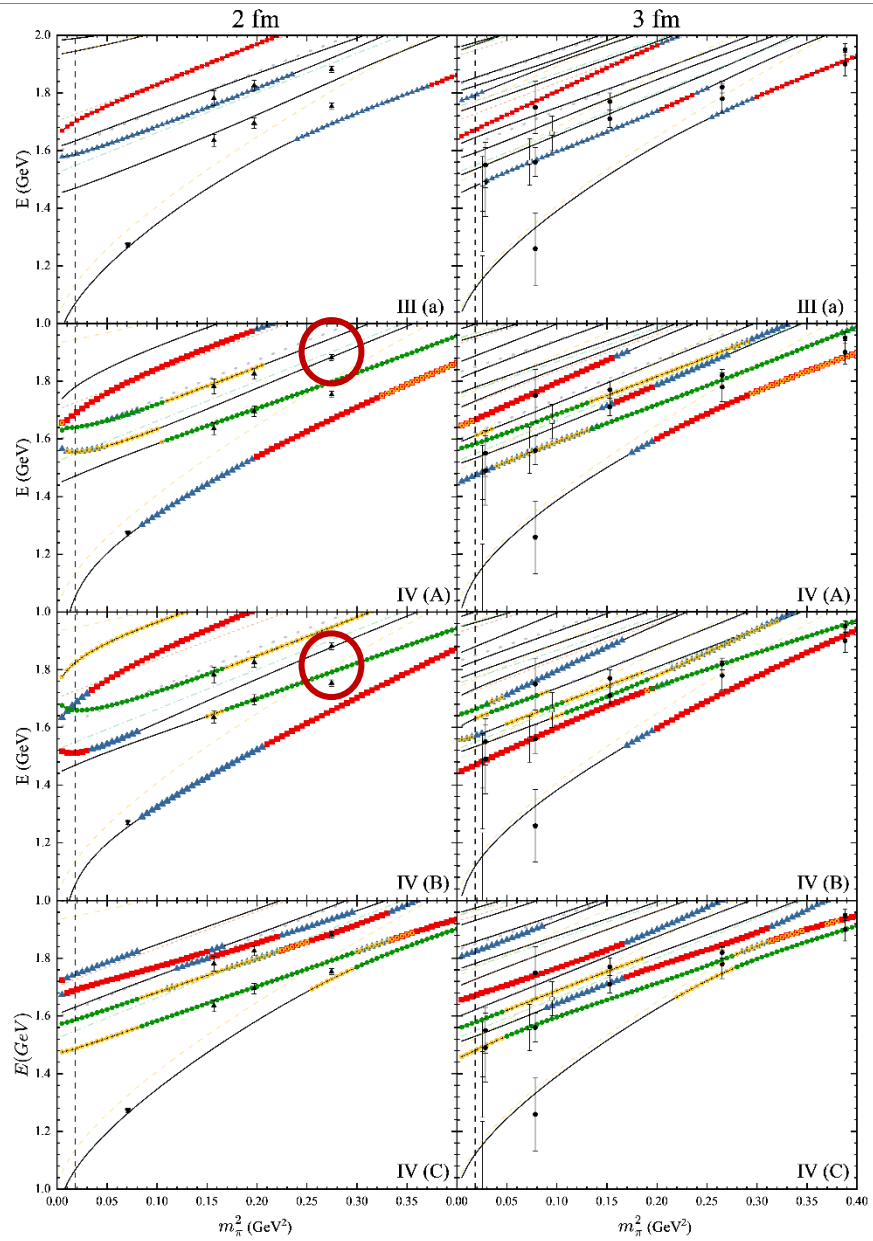
$$\chi_2 = \epsilon^{abc}(u^{aT} C d^b)\gamma_5 u^c$$

- Overlap from NPHF

Bare-state: $|< B_j \mid E_i >|^2$

Meson-baryon Channel: $\sum_n |< \alpha(k_n) \mid E_i >|^2$

➢ Colored marks: largest and second-largest bare-state overlap



Flavor only

With mixing

w/o mixing

M_{N_i} inversion

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Contamination

- Three-quark interpolator for an odd-parity nucleon

$$\chi_1 = \epsilon^{abc}(u^{aT} C\gamma_5 d^b)u^c$$ Scalar diquark

$$\chi_2 = \epsilon^{abc}(u^{aT} C d^b)\gamma_5 u^c$$

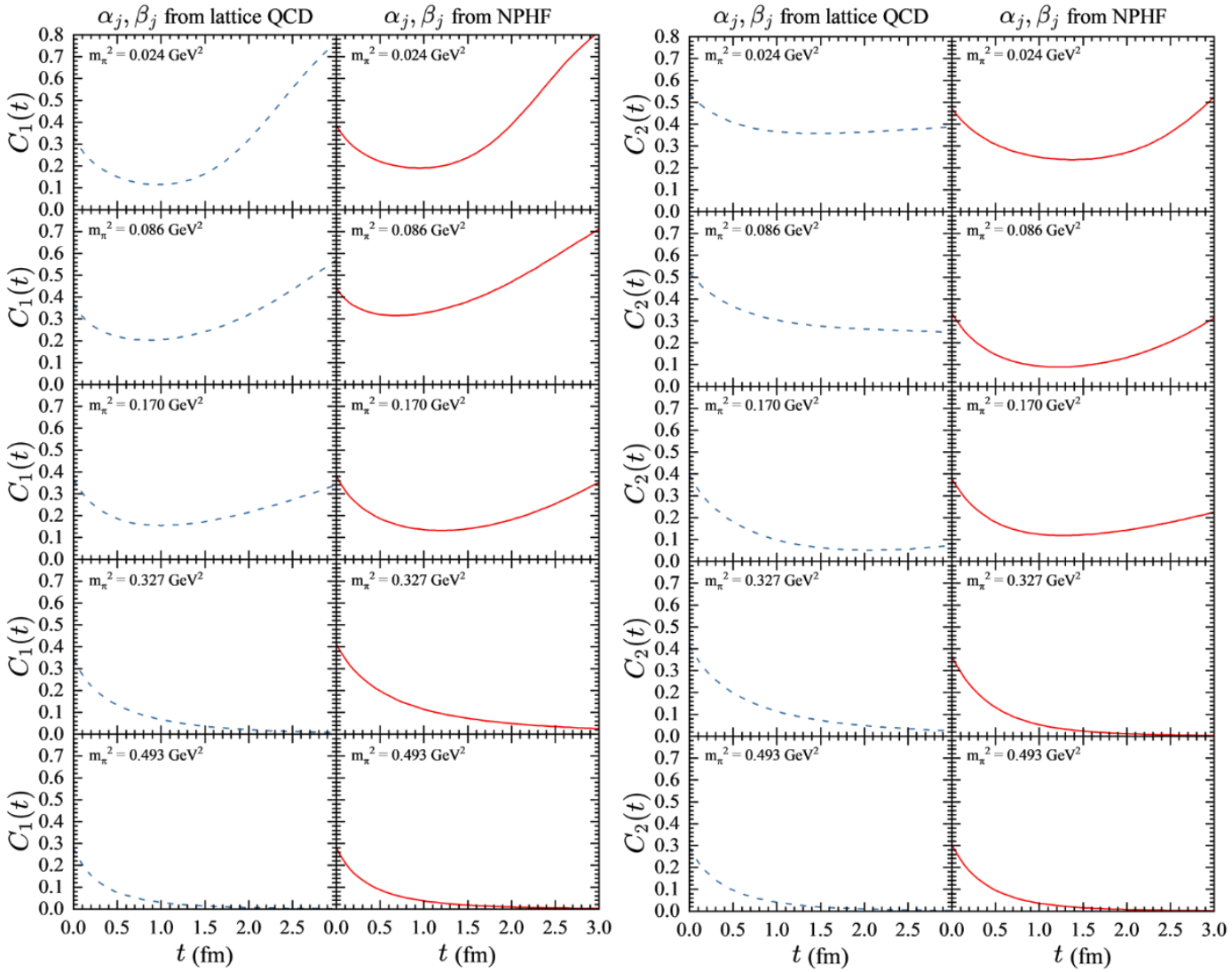
$$(\alpha\bar{\chi}_1 + \beta\bar{\chi}_2)|\Omega> = \alpha\,|N_2> + \beta\,|N_4>$$

- Contamination function

$$C_j(t) = \frac{1}{G_j(t)} \sum_{n \notin \{n_2^{(1,2)}, n_4^{(1,2)}\}} \left|\alpha_j \langle N_2 | E_n\rangle + \beta_j \langle N_4 | E_n\rangle\right|^2 e^{-E_n t}$$

Relativistic node structure is compatible with the proposed ordering

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Scenario IV(C): Bare-mass inversion

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Summary

- πN S_{11} scattering data with finite-volume lattice QCD spectra

  Full information for energy dependence and coupled channels

- Flavor and spin symmetry constraints

  Internal structure of nucleon resonances

- Two bare states and the dynamics of four coupled channels

  Four scenarios were discussed

- Bare-mass inversion is favored

  $M_{N_2} > M_{N_4}$ and $N_2 \rightarrow$ N*(1650), $N_4 \rightarrow$ N*(1535)

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