Hadron Spectroscopy and the $a_1(1260)$

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Outline

Motivation & Methods

Motivation

- Long-term goal to describe nuclear interactions and the hadron spectrum in terms of quark/gluon dynamics
- Exotics with forbidden quantum numbers
- GlueX, COMPASS, BESIII
- Give complementary information to experiments

Methods

- LQCD spectroscopy extracts the finite-volume spectrum
  scattering to extract scattering information

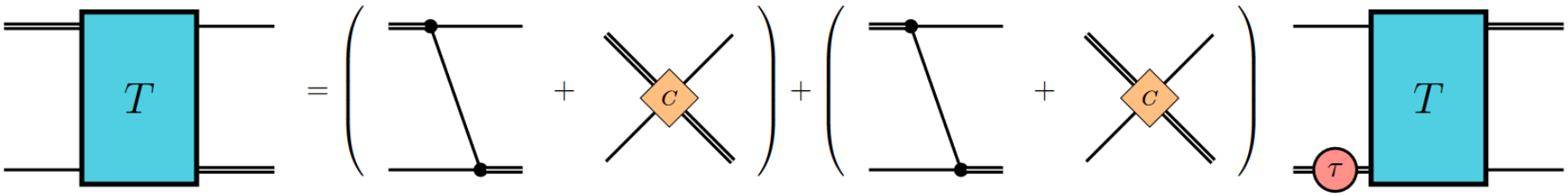
- Ignoring technical details of extracting a finite-volume spectrum

- Quantization Conditions - originally from Lüscher

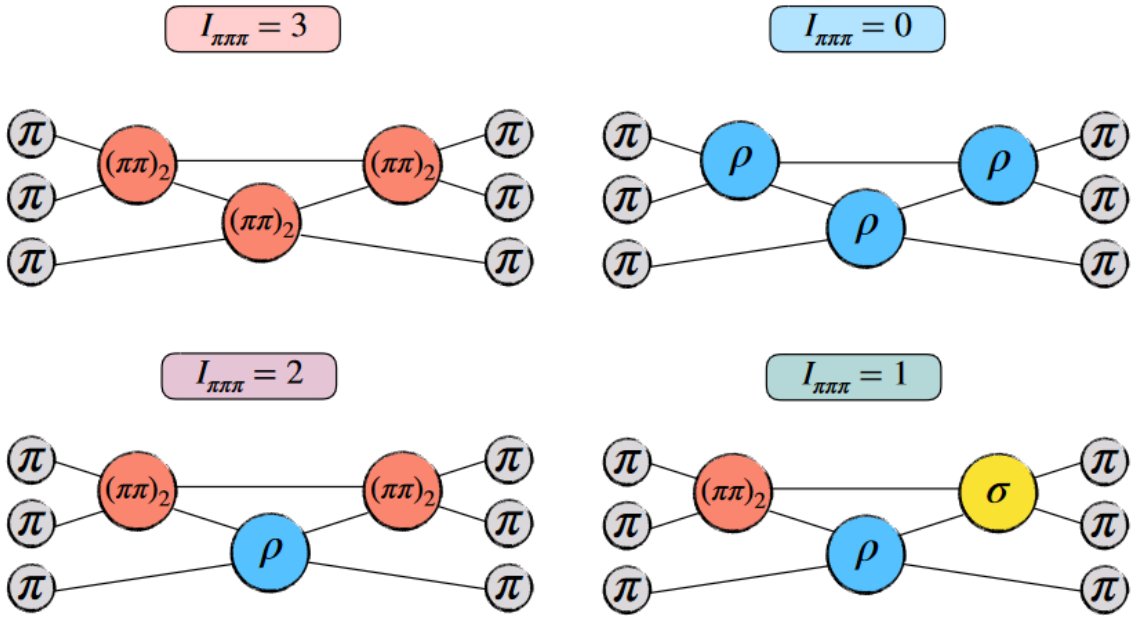
$$\det\left[\mathcal{M}^{-1}(\delta) + \mathcal{G}(E)\right] = 0$$

- HAL QCD Method - S. Aoki, T. Doi [2003.10730]
  Spectral Functions - J. Bulava, M. Hansen [1903.11735]
  Optical Potential - D. Agadjanov et al. [1603.07205]

Quantization Conditons



$$\det\left[B + C + \tau^{-1}\right] = 0$$



- Unitarity as a starting point - M. Mai, M. Döring [1709.08222]
- Relativistic, 3-π isospin channels - M. Hansen et al. [2003.10974]
- NREFT approach - H.Hammer et al. [1706.07700]

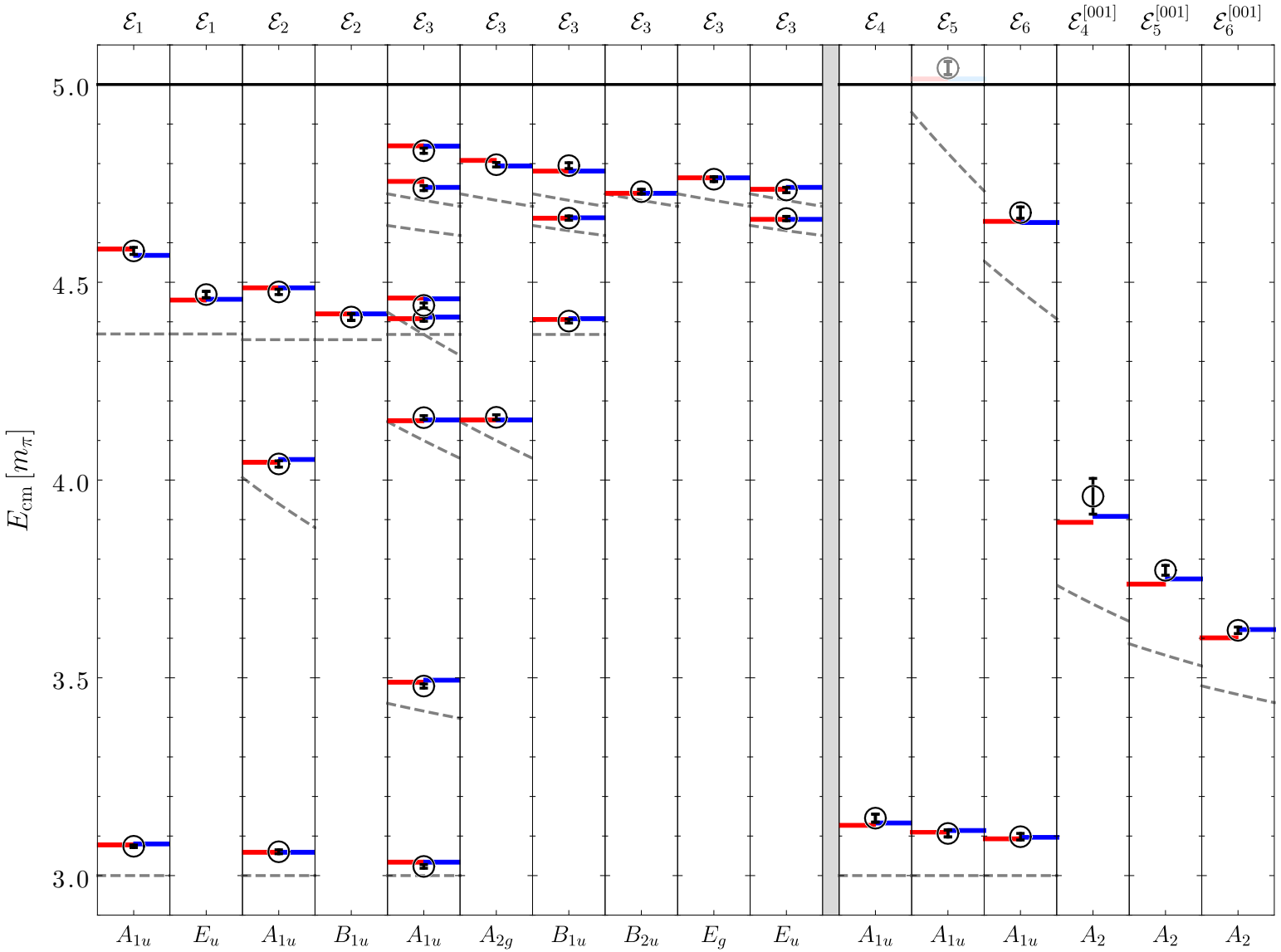
Top figure from [2002.12431], bottom figure from [2003.10974]

Current Status of Hadron Spectroscopy

Two Hadron

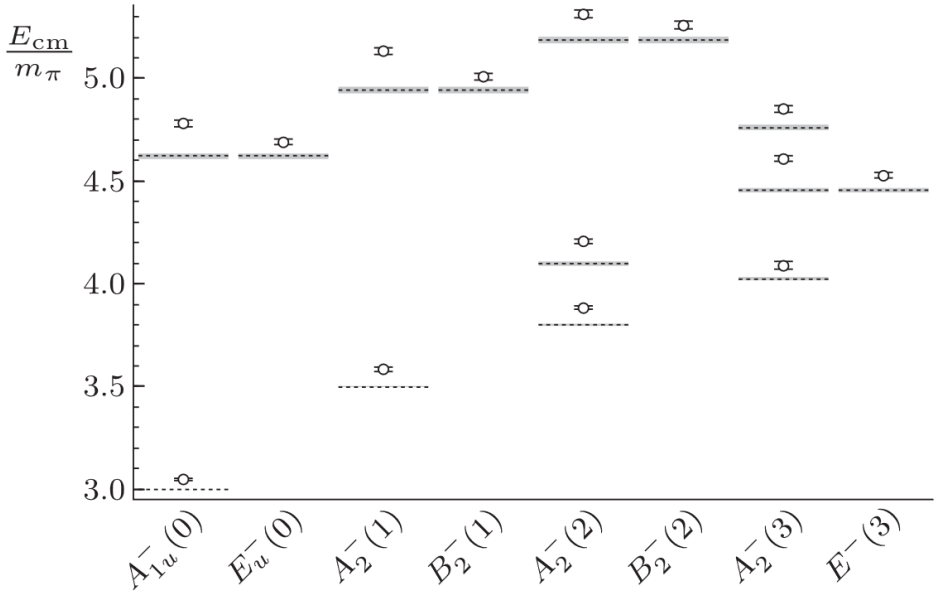
- Meson-Meson: Near physical pion mass, $N_f = 2 + 1 + 1$
  $\pi\pi, K\pi, \eta\pi, D\pi, \ldots$
- Meson-Baryon:
  $\Delta(1232), pK^+, nK^+, \ldots$
- Baryon-Baryon: Heavy pion masses
  (800 MeV NPLQCD, Preliminary 350 MeV CalLat)

$\pi^+\pi^+\pi^+$

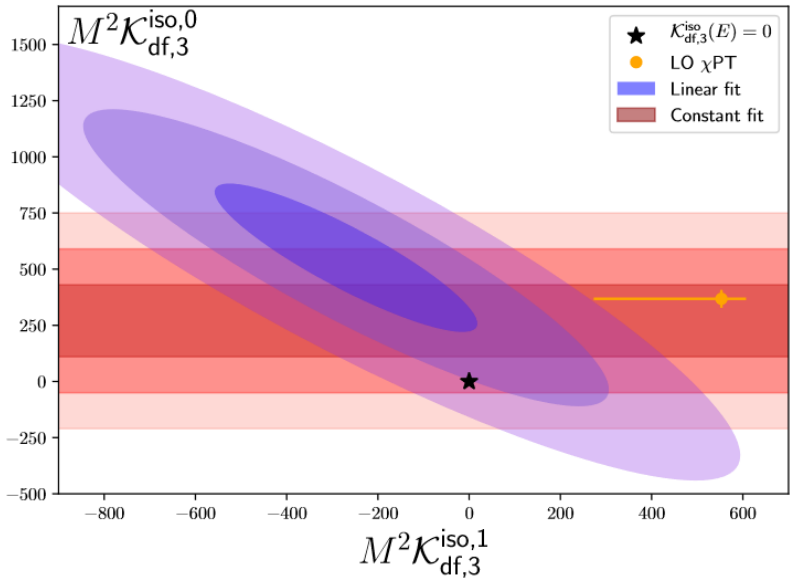


CC et al. [1911.09047]

$\pi^+\pi^+\pi^+$



B. Horz, A. Hanlon [1905.04277]



T. Blanton et al. [1909.02973]

GWU Analyis of the data found three-body term consistent with zero unless $\pi\pi$ energies included. Mai et al [1909.05749]

$a_1(1260)$

GWU Lattice Study of the $a_1(1260)$

- $I^G(J^{PC}) = 1^-(1^{++})$ $\qquad a_1 \to (\rho\pi, \sigma\pi) \to \pi\pi\pi$
- GWU has on the same set of ensembles, calculations of $\pi\pi$ in all isospin Have stored the LapH quark propagators
- Use $\bar{q}q, \rho\pi, \sigma\pi$ and $\pi\pi\pi$ operators
- Contractions more costly
  $I = 3$ - $\pi^+(p_1)\pi^+(p_2)\pi^+(p_3)$ - 36 Diagrams
  $I = 1$ - $\pi(p_1)\pi(p_2)\pi(p_3)$ - 206 Diagrams
- Expect to get from $P = [000]$ in T_1^g/A_2^g
  30 energy levels from 315 MeV ensembles
  17 energy levels from 220 MeV ensembles

Lineshape

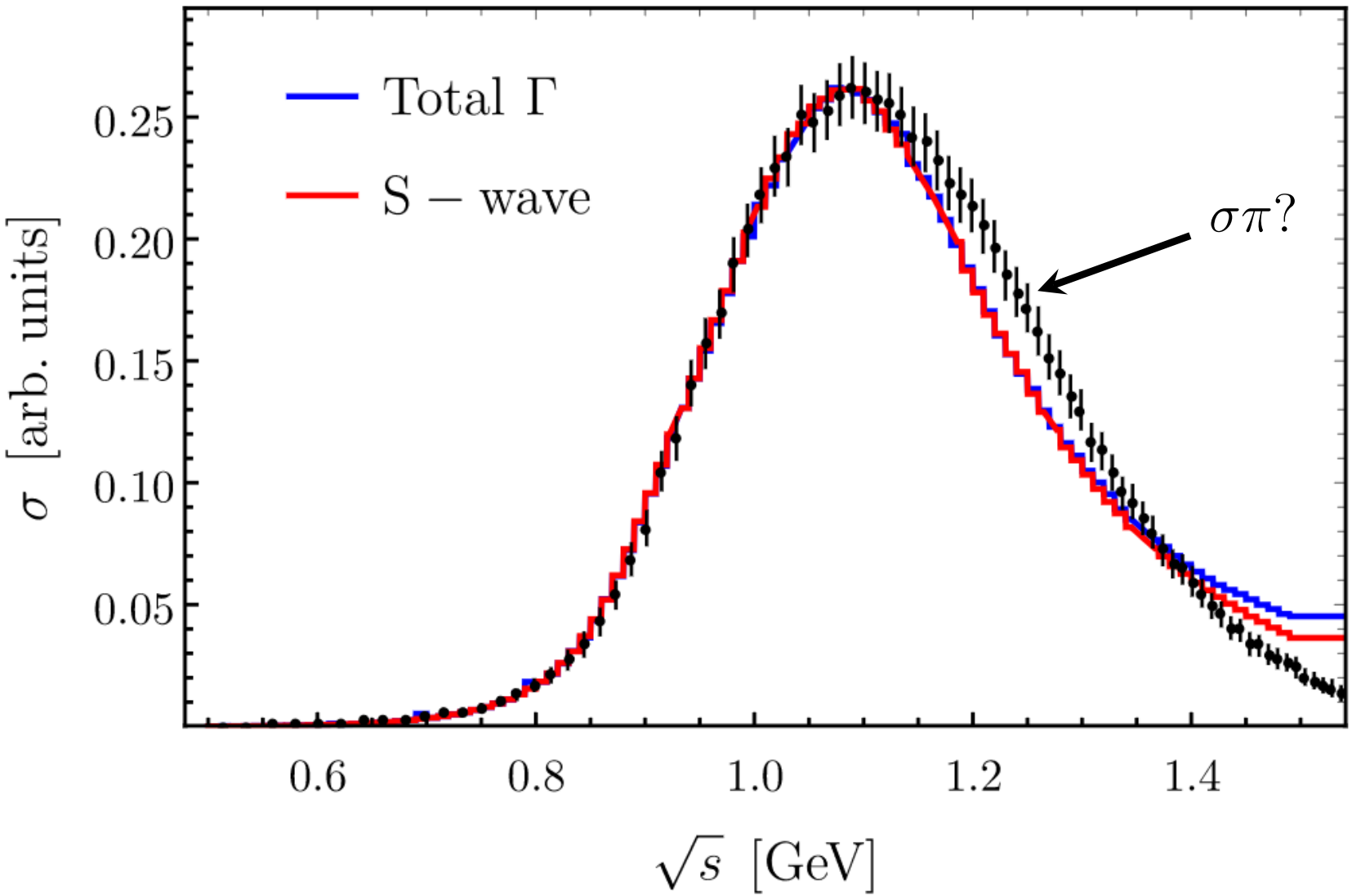


Figure from D. Sadasivan et al. [2002.12431]. Exp. data from ALEPH.

Conclusion

Conclusion

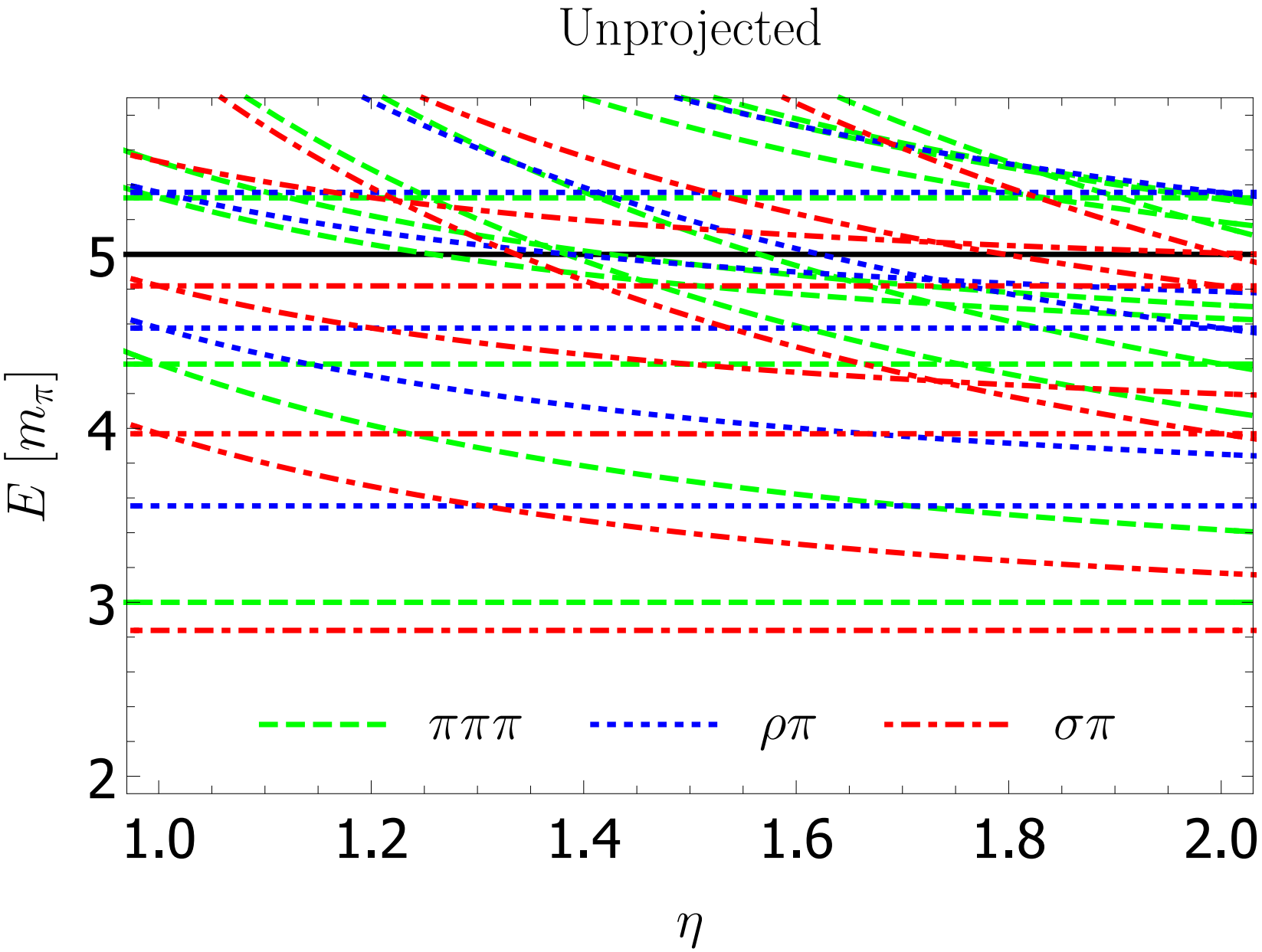
- $a_1(1260)$ is a prime candidate for significant three-body dynamics
- Contributions from all $\pi\pi$ channels in isobars
- We have the QC's, need finite volume spectra and input from phenomonology
- Continuing to push up the hadron spectrum requires three-body dynamics

Ensemble Details

Label	$N_t \times N_{x,y}^2 \times N_z$	η	a[fm]	N_{cfg}	am_π
$\mathcal{E}_1$	$48 \times 24^2 \times 24$	1.00	0.1210(2)(24)	300	0.1931(4)
$\mathcal{E}_2$	$48 \times 24^2 \times 30$	1.25	–	–	0.1944(3)
$\mathcal{E}_3$	$48 \times 24^2 \times 48$	2.00	–	–	0.1932(3)
$\mathcal{E}_4$	$64 \times 24^2 \times 24$	1.00	0.1215(3)(24)	400	0.1378(6)
$\mathcal{E}_5$	$64 \times 24^2 \times 28$	1.17	–	–	0.1374(5)
$\mathcal{E}_6$	$64 \times 24^2 \times 32$	1.33	–	–	0.1380(5)

- Lüscher-Weis gauge action
- $N_f = 2$ nHYP-smeared clover fermions
- $N_v = 100$ LapH Eigenvectors

315 MeV Non-Interacting Levels



220 MeV Non-Interacting Levels