Coupled-channel dynamics for baryon resonances from lattice QCD

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Introduction:

- Coupled-channel baryon dynamics necessary to understand many excited baryon resonances:
  - $N(1440)$
  - $\Lambda_c(2595)$
  - $\Lambda(1405)$ ← subject of today's talk
  - …

- Rich phenomenology:
  - Multiple poles
  - Anomalous thresholds, left-hand cuts, etc.

- Lattice QCD (starting to become) a valuable tool!
  - Finite-volume energies <=> scattering amplitudes

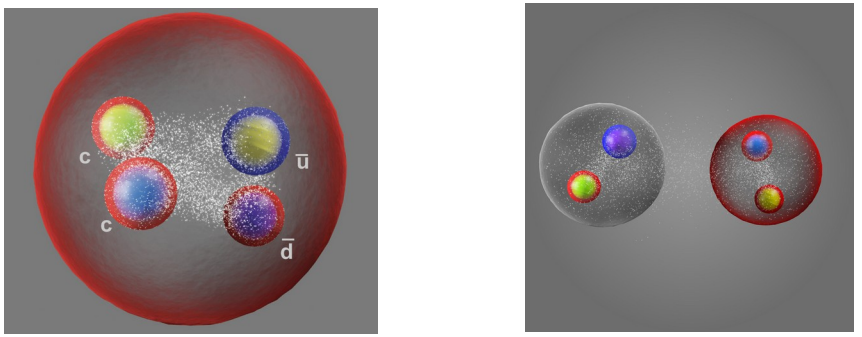
M. Lüscher, *Nucl. Phys.* **B354** (1991) 531

Exotic hadrons:

- How do you know if a hadron is exotic?
- Need a failure of the quark model. Examples:
  - Boson with two charm quarks: tetraquark/molecule

LHCb Collaboration, Nature Physics (2022)

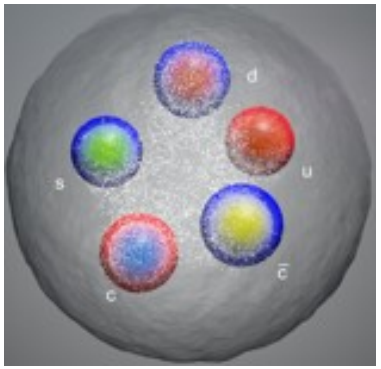
$T_{cc}^{+}(3875)$

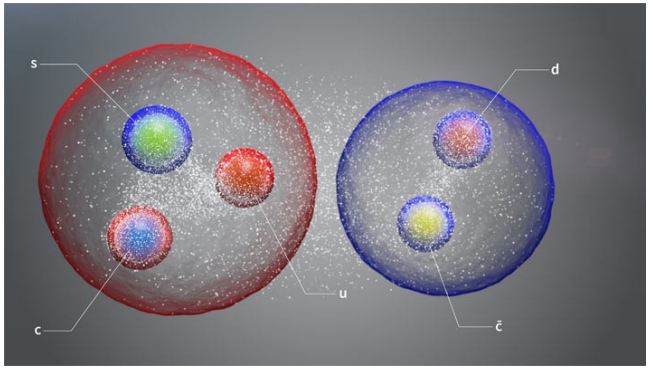


  - Fermion with charm-anticharm pair: pentaquark

LHCb Collaboration, Phys. Rev. Lett. 131, 031901 (2023)

$P_{\psi s}^{\Lambda}(4338)$



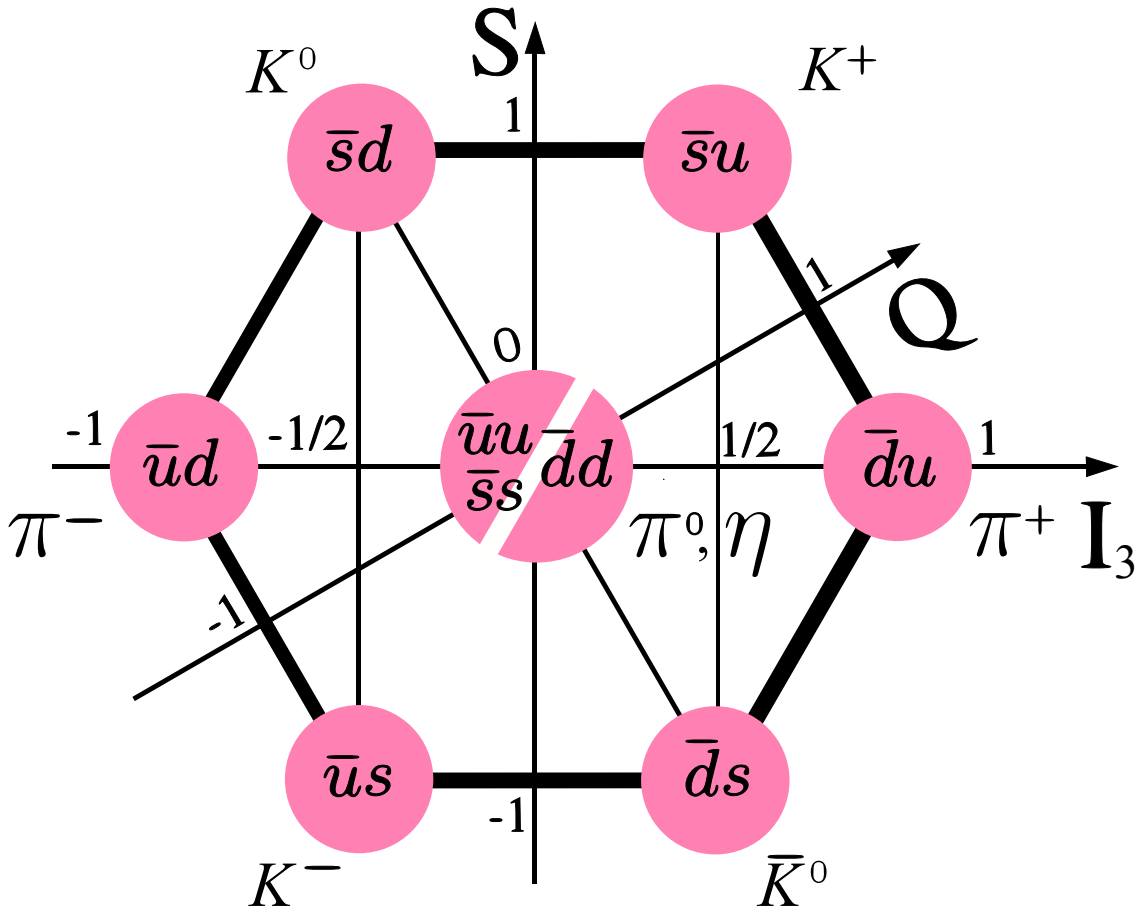


  - ***Extra/missing state compared to quark model multiplet

The Eightfold Way: meson singlet and octet

M. Gell-Mann, Y. Ne'emann '61

$$3 \otimes \bar{3} = 1 \oplus 8$$

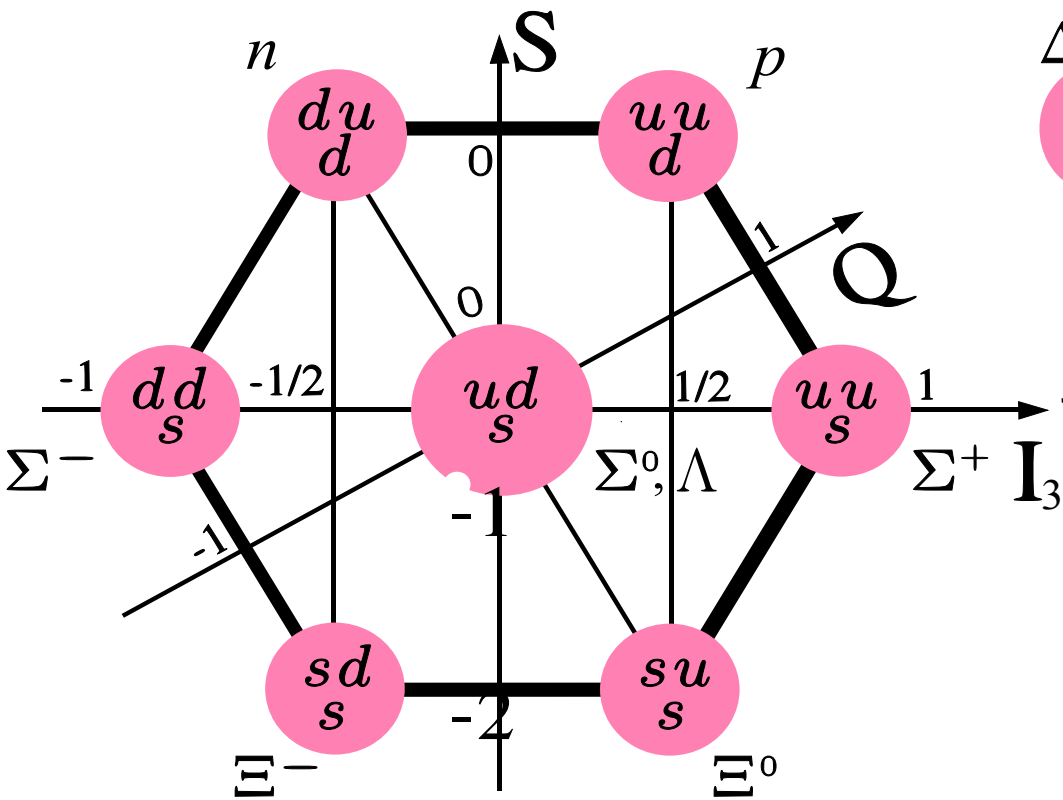


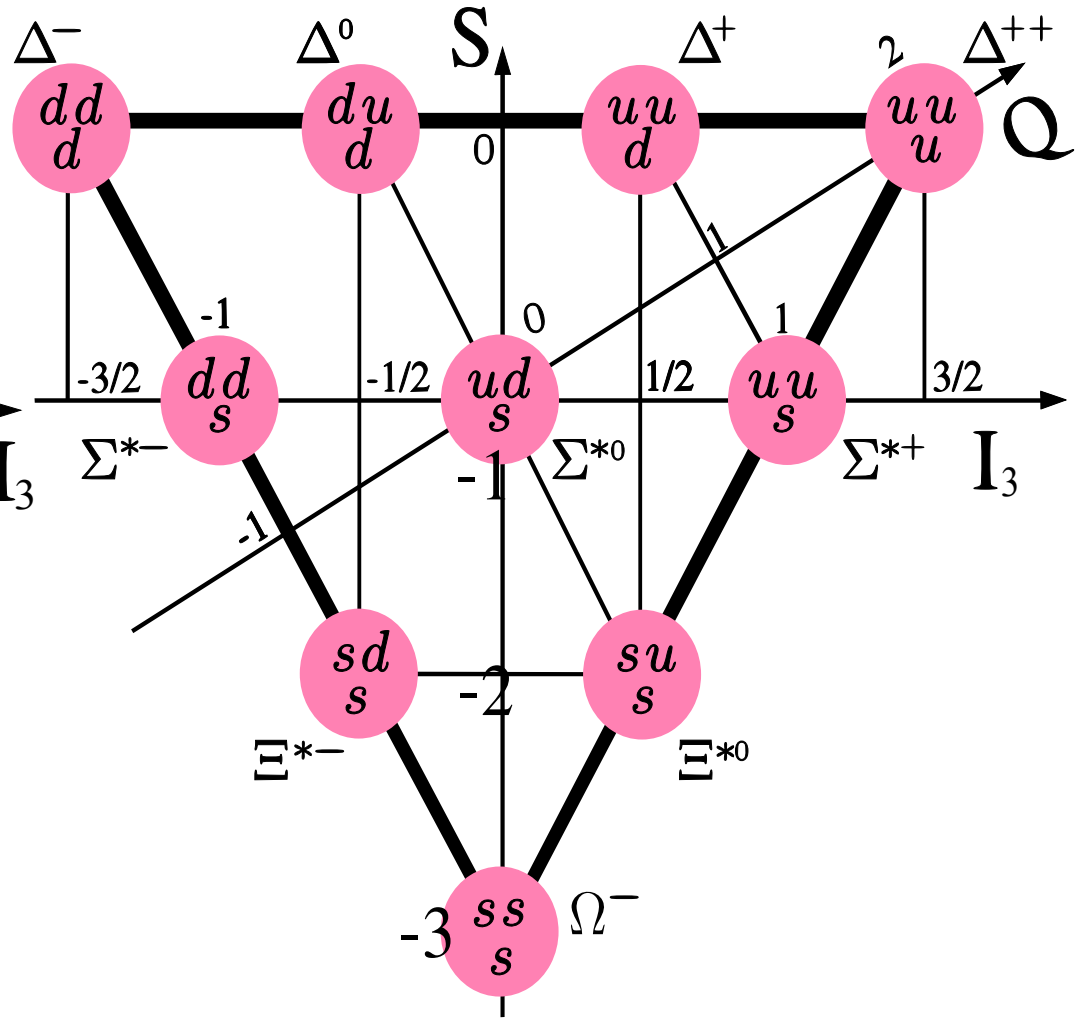
$(\bar{u}u,\ \bar{d}d,\ \bar{s}s)$

η'

The Eightfold Way: Baryon octet and decuplet:

$$3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$$





Question: does this work for hadron interactions?

The Curious Case of the $\Lambda(1405)$: the first 'exotic' hadron?

- Low-energy K+p interactions → sub-threshold S=-1 resonance.

  R. Dalitz. S.F. Tuan '59

- Now well-established: $\Lambda(1405)$ with $I(J^P) = 0(1/2^-)$

  CLAS Collaboration, Phys.Rev.Lett. 112 (2014) 8

- Three-quark interpretation difficult:
  - $1/2^-$ state should be ~500 MeV above $\Lambda(1115)$
  - Already have the $\Lambda(1670)$
  - Lighter than the N(1535)

- Is the $\Lambda(1405)$ an exotic meson-baryon bound state?

Meson-baryon interactions in SU(3) flavor:

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

- Low-energy interaction governed by chiral symmetry. At LO:
  - attraction in 8 and 1
  - repulsion in 27, no interaction in 10's

Weinberg, Tomozawa '66

→ two bound states!

U. Meissner, Symmetry 12 (2020) 6, 981
D. Jido, et al., Nucl.Phys.A 725 (2003) 181

- Confirmed by model:

chiral EFT + unitarization

Octet Baryons:

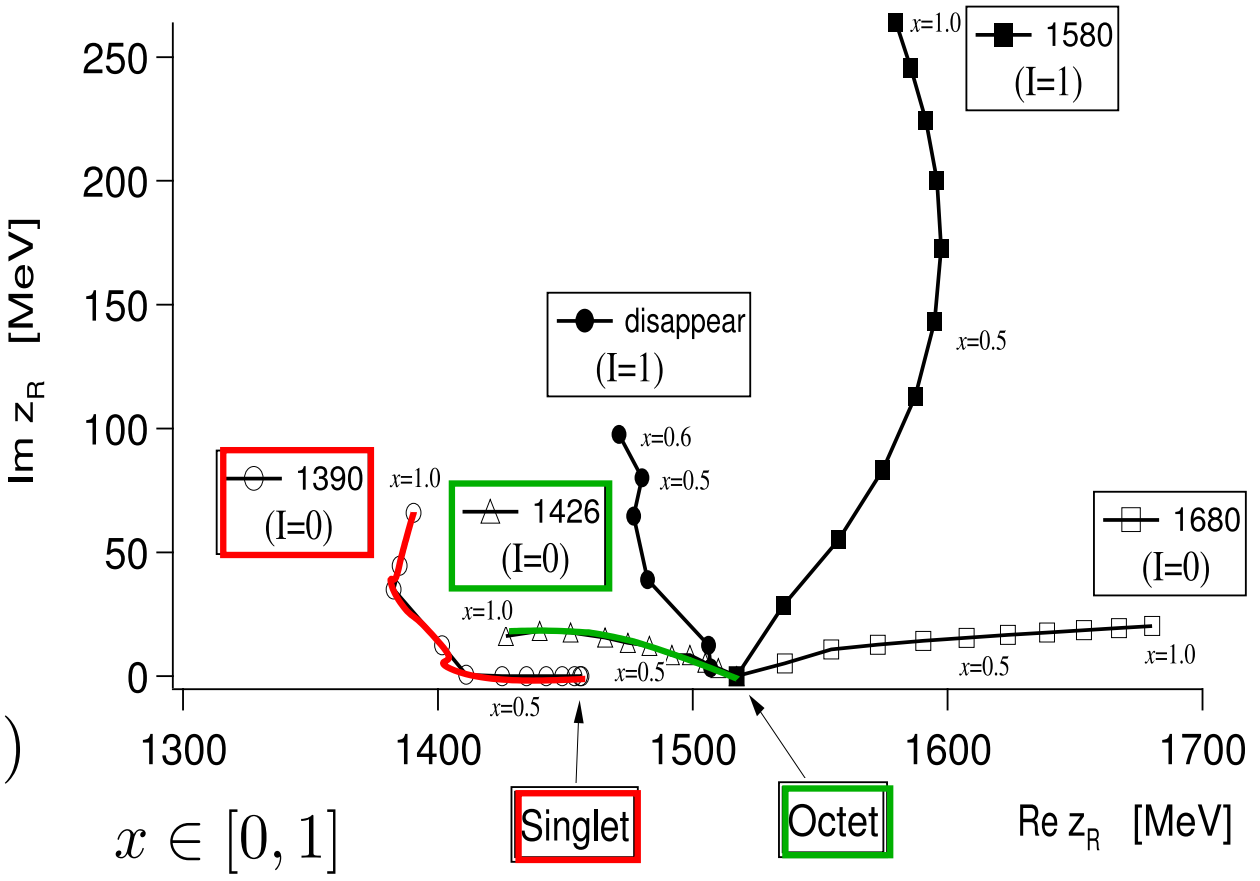
$$m_i(x) = m_0 + x(m_i - m_0)$$

$$m_0 = 1151\,\mathrm{MeV}$$

Octet mesons:

$$M_i^2(x) = M_0^2 + x(M_i^2 - M_0^2)$$

$$M_0 = 368\,\mathrm{MeV}$$

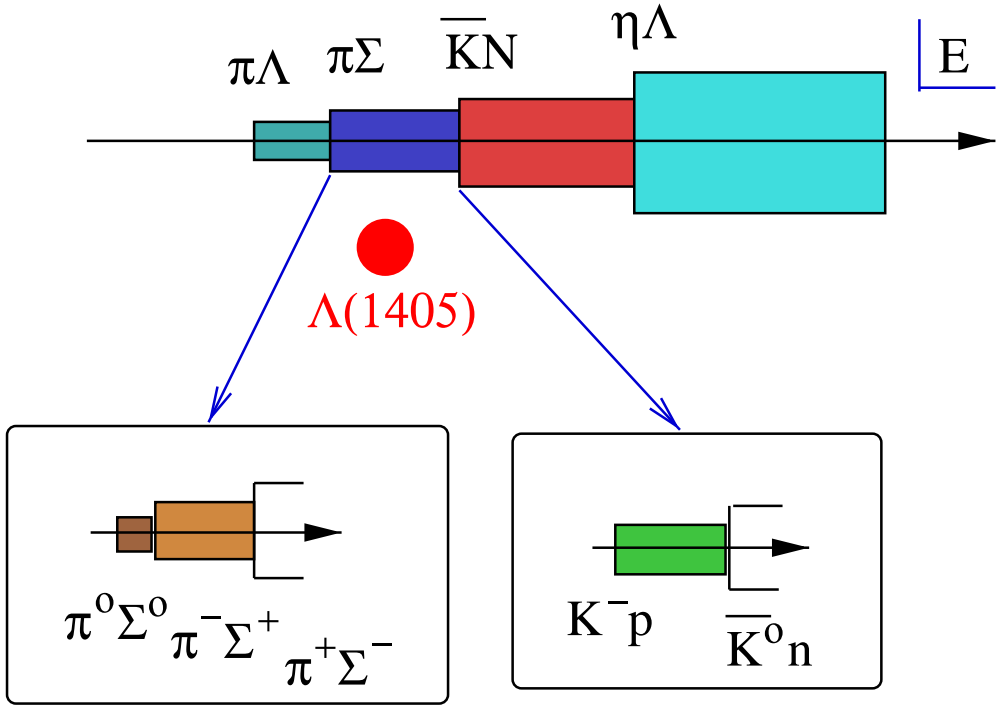


$x \in [0, 1]$

Quo Vadis?

- If three-quark: one state, but should be heavier
- If meson-baryon 'molecule': two states
- Particle Data Group lists $\Lambda(1405) : ****$ $\Lambda(1380) : **$
- Analytic continuation difficult. Many thresholds.

pole 1 [MeV]	pole 2 [MeV]
$1424^{+7}_{-23} - i\,26^{+3}_{-14}$	$1381^{+18}_{-6} - i\,81^{+19}_{-8}$
$1421^{+3}_{-2} - i\,19^{+8}_{-5}$	$1388^{+9}_{-9} - i\,114^{+24}_{-25}$
$1434^{+2}_{-2} - i\,10^{+2}_{-1}$	$1330^{+4}_{-5} - i\,56^{+17}_{-11}$
$1429^{+8}_{-7} - i\,12^{+2}_{-3}$	$1325^{+15}_{-15} - i\,90^{+12}_{-18}$

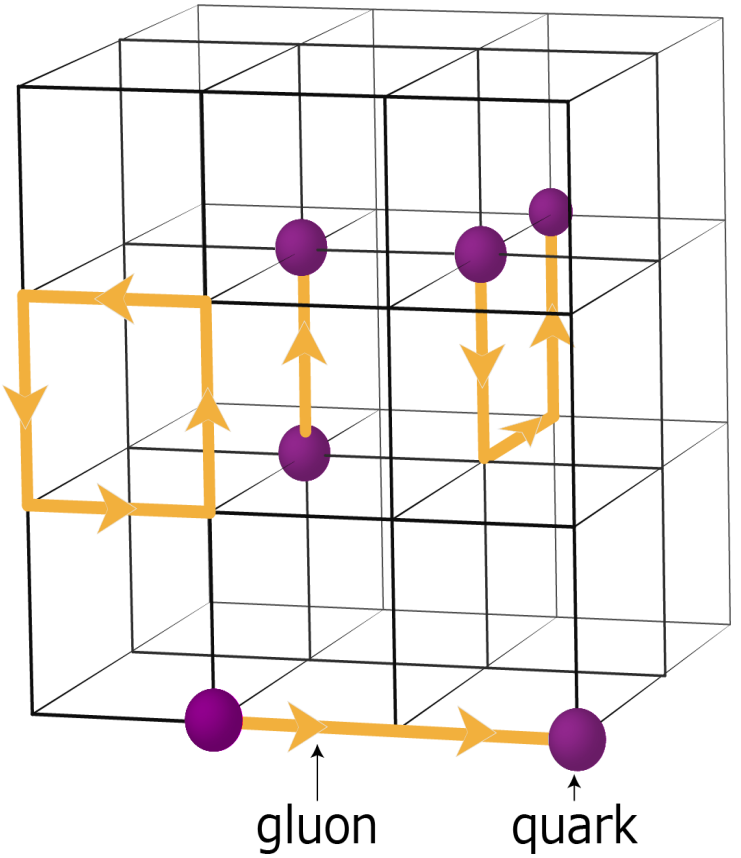


from T. Hyodo, U. Meissner, PDG '21

from U. Meissner, Symmetry 12 (2020) 6, 981

Lattice QCD: a bridge between high and low energies

- Monte Carlo sampling of QCD path integral



- Errors:
  - Monte Carlo statistics
  - Finite volume and lattice spacing

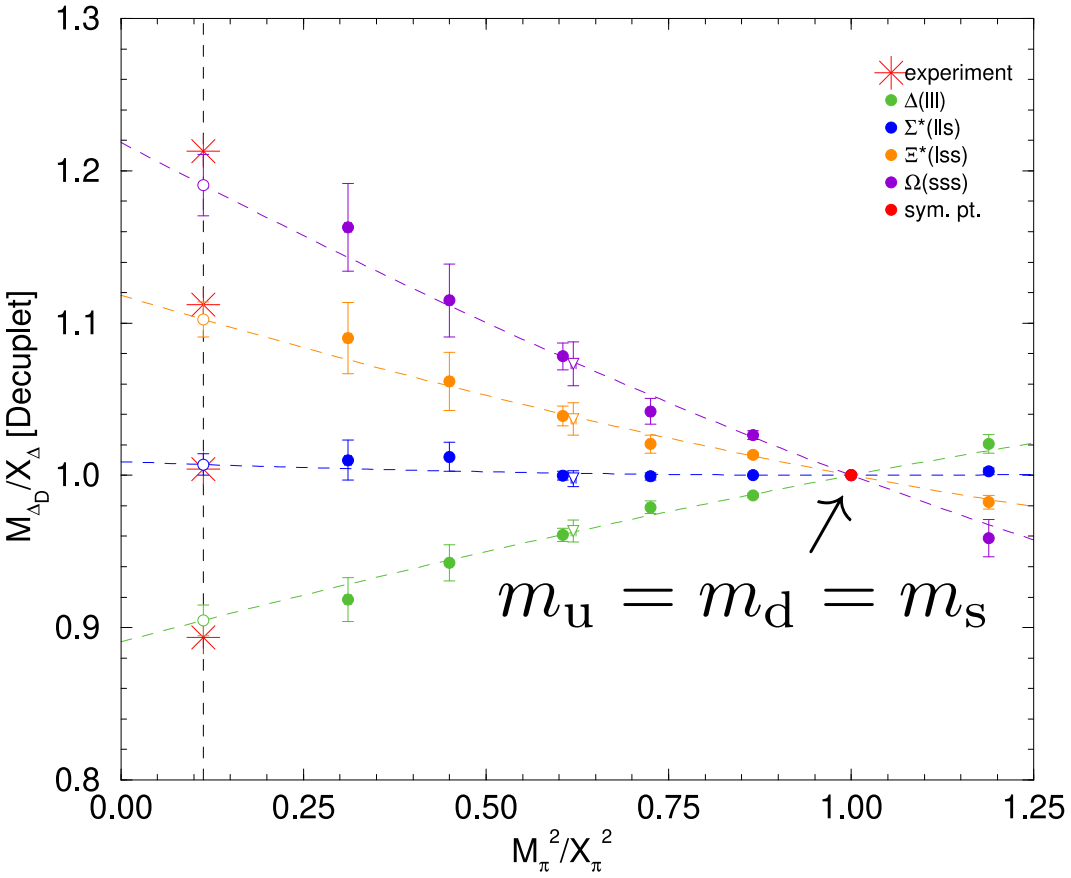
- Imaginary time required: $t \to i\tau$

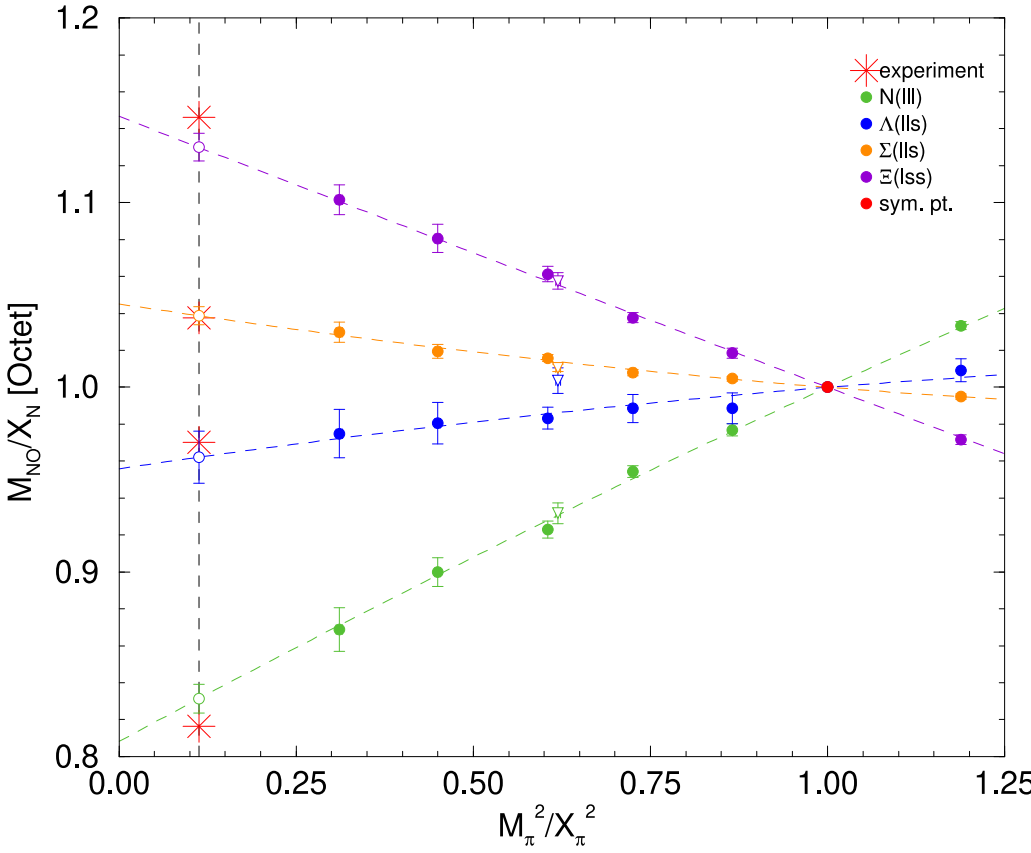
- Advantages of lattice QCD:
  - Turn off electroweak interactions
  - Vary quark masses
  - If $m_{\mathrm{u}} = m_{\mathrm{d}}$ then only two channels: $\pi\Sigma - \bar{K}N$

Varying quark masses: connection to The Eightfold Way

Lattice QCD results for baryon masses:

$$m_{\mathrm{u}} = m_{\mathrm{d}}, \qquad m_{\mathrm{u}} + m_{\mathrm{d}} + m_{\mathrm{s}} = \mathrm{phys.}$$





from QCDSF Collaboration, Phys.Rev.D 84 (2011) 054509

See also RQCD Collaboration, JHEP 05 (2023) 035

What about scattering in lattice QCD?:

Asymptotic limit of $\langle 0|\hat{\mathcal{O}}'(\tau_f)\hat{\mathcal{O}}^\dagger(\tau_i)|0\rangle$ contains no info about on-shell amplitudes.

→ ~~Haag-Ruelle~~

L. Maiani, M. Testa, *Phys. Lett.* **B245** (1990) 585
M. Bruno, M. T. Hansen, JHEP 06 (2021) 043

- Finite volume method: two-hadron energies below $n \geq 3$ hadron thresholds:

$$\det[K^{-1}(E^L_{\rm cm}) - B(E^L_{\rm cm})] = 0$$

M. Lüscher, *Nucl. Phys.* **B354** (1991) 531

For single channel:

$$K^{-1}_{\ell\ell'} = \delta_{\ell\ell'}\ \cot\delta_\ell$$

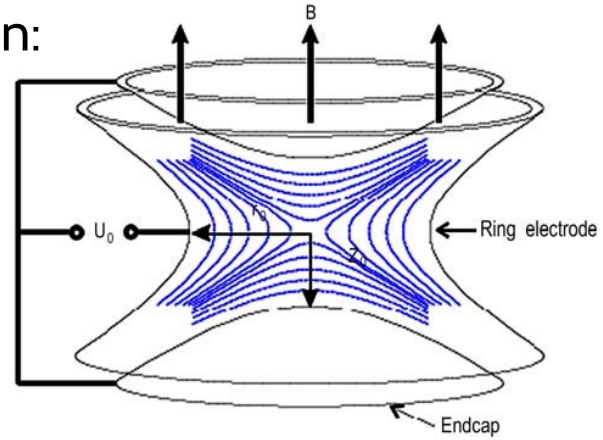
- Determinant over all partial waves and channels
  - Truncation at some $\ell_{\rm max}$ → systematic error

- Signal comes from interaction shift. Large-*L* threshold expansion:

$$\Delta E = E^{I=2}_{2\pi} - 2m_\pi = -\frac{4\pi a_0^{I=2}}{m_\pi L^3} + \mathrm{O}(L^{-4})$$

- For attractive *s*-wave interaction $E^L_{\rm cm} < E_{\rm thresh}$

  → direct constraints in complex plane!

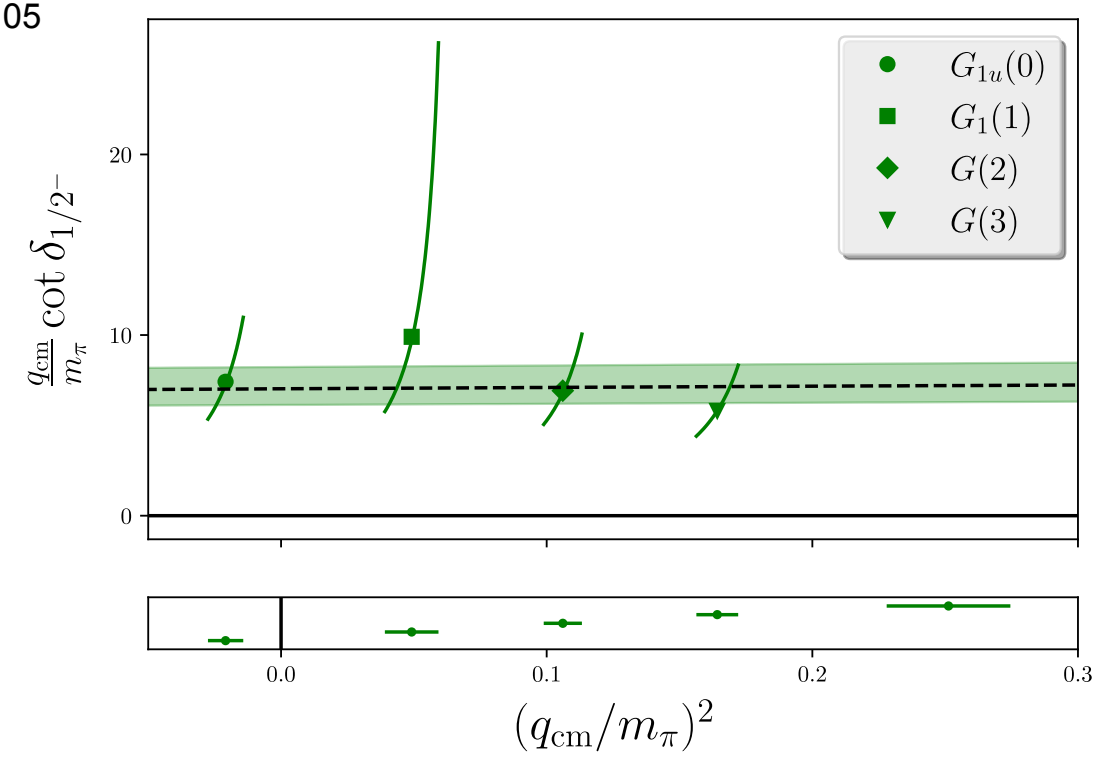


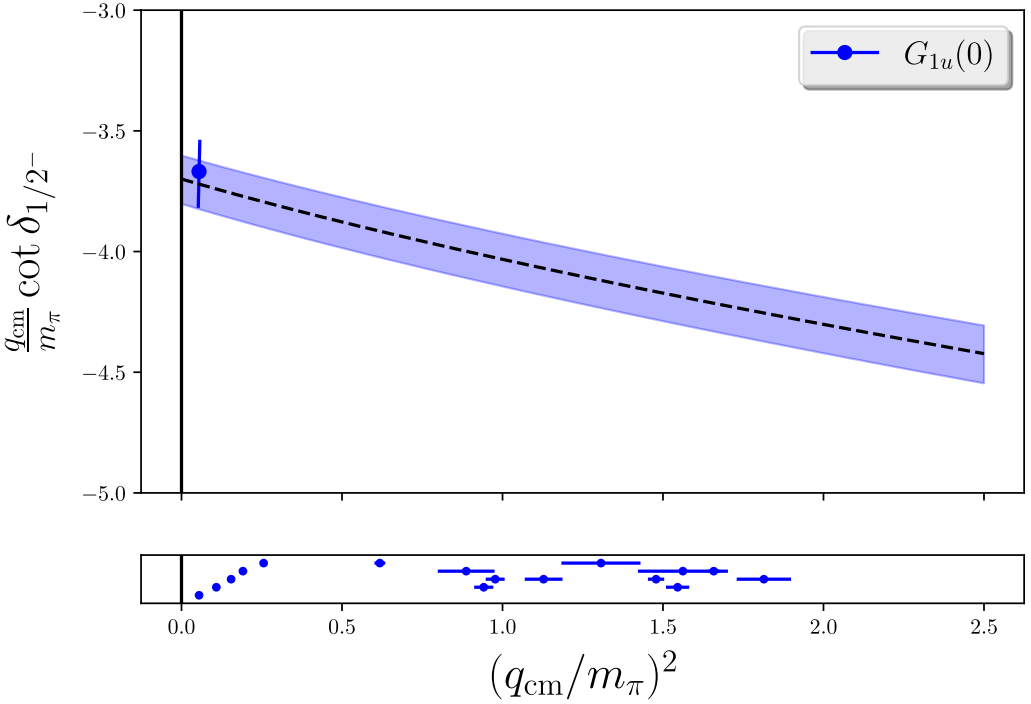
Analogy: two cold atoms in a trap
T. Busch, B.-G. Englert, K. Rzazewski, M. Wilkens, Found. Phys., 28 (1998)

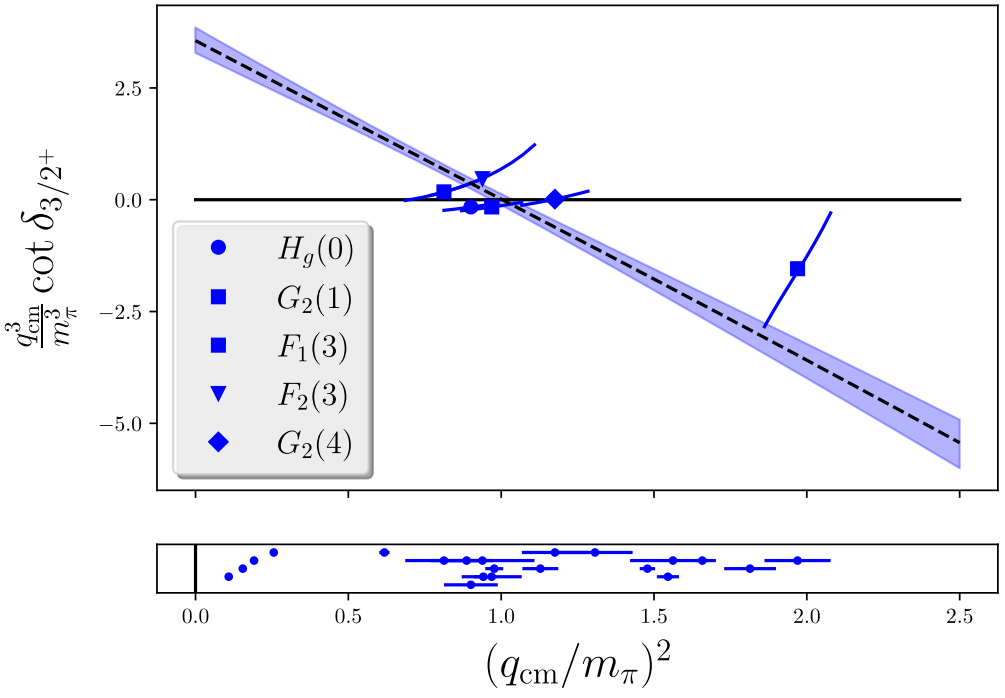
Single-channel Example: pion-nucleon scattering amplitudes

from JB, et al., Nucl.Phys.B 987 (2023) 116105

- Green: I = 1/2
- Blue: I = 3/2







Recent lattice computation of the $\pi\Sigma - \overline{K}N$ amplitude:

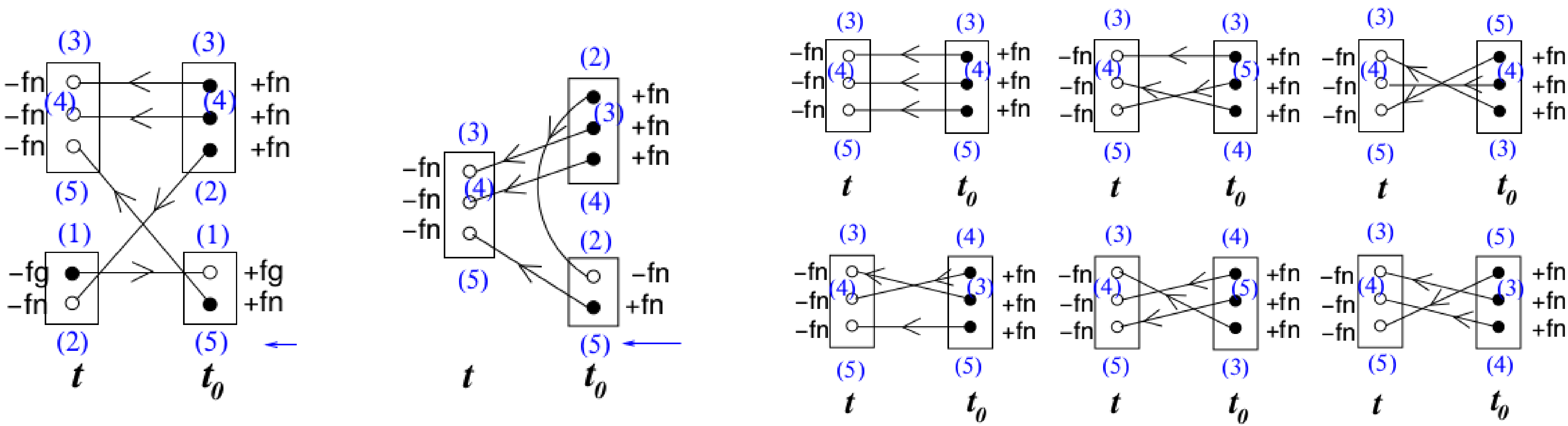
JB, B. Cid-Mora, A. Hanlon, B. Hoerz, D. Mohler, C. Morningstar, J. Moscoso, A. Nicholson, F. Romero-Lopez, A. Walker-Loud
(For the Baryon Scattering (BaSc) Collaboration) Phys.Rev.Lett. 132 (2024) 5, 051901 (Editor’s Suggestion)

- CLS (D200) lattice:

$$64^3 \times 128,\ a = 0.064\text{fm},\ m_\pi = 200\text{MeV},\ \frac{m_\pi^2}{m_X^2} = 0.23$$

$$m_\pi + m_\Sigma \approx 1380\,\text{MeV}$$

- Correlation functions from tensor contraction: inverse of large sparse Dirac matrix



- Factorization enabled by the distillation/stochastic LapH algorithms for quark propagation

M. Peardon et al. Phys.Rev.D 80 (2009) 054506; C. Morningstar et al. Phys.Rev.D 83 (2011) 114505

Baryon Scattering Collaboration (BaSC): comprehensive study of many channels

Flavor channel	Number of Correlators
$I = 0,\ S = 0,\ NN$	8357
$I = 0,\ S = -1,\ \Lambda, N\overline{K}, \Sigma\pi$	8143
$I = \frac{1}{2},\ S = 0,\ N\pi$	696
$I = \frac{1}{2},\ S = -1,\ N\Lambda, N\Sigma$	17816
$I = 1,\ S = 0,\ NN$	7945
$I = \frac{3}{2},\ S = 0,\ \Delta, N\pi$	3218
$I = \frac{3}{2},\ S = -1,\ N\Sigma$	23748
$I = 0,\ S = -2,\ \Lambda\Lambda, N\Xi, \Sigma\Sigma$	16086
$I = 2,\ S = -2,\ \Sigma\Sigma$	4589
Single hadrons (SH)	33

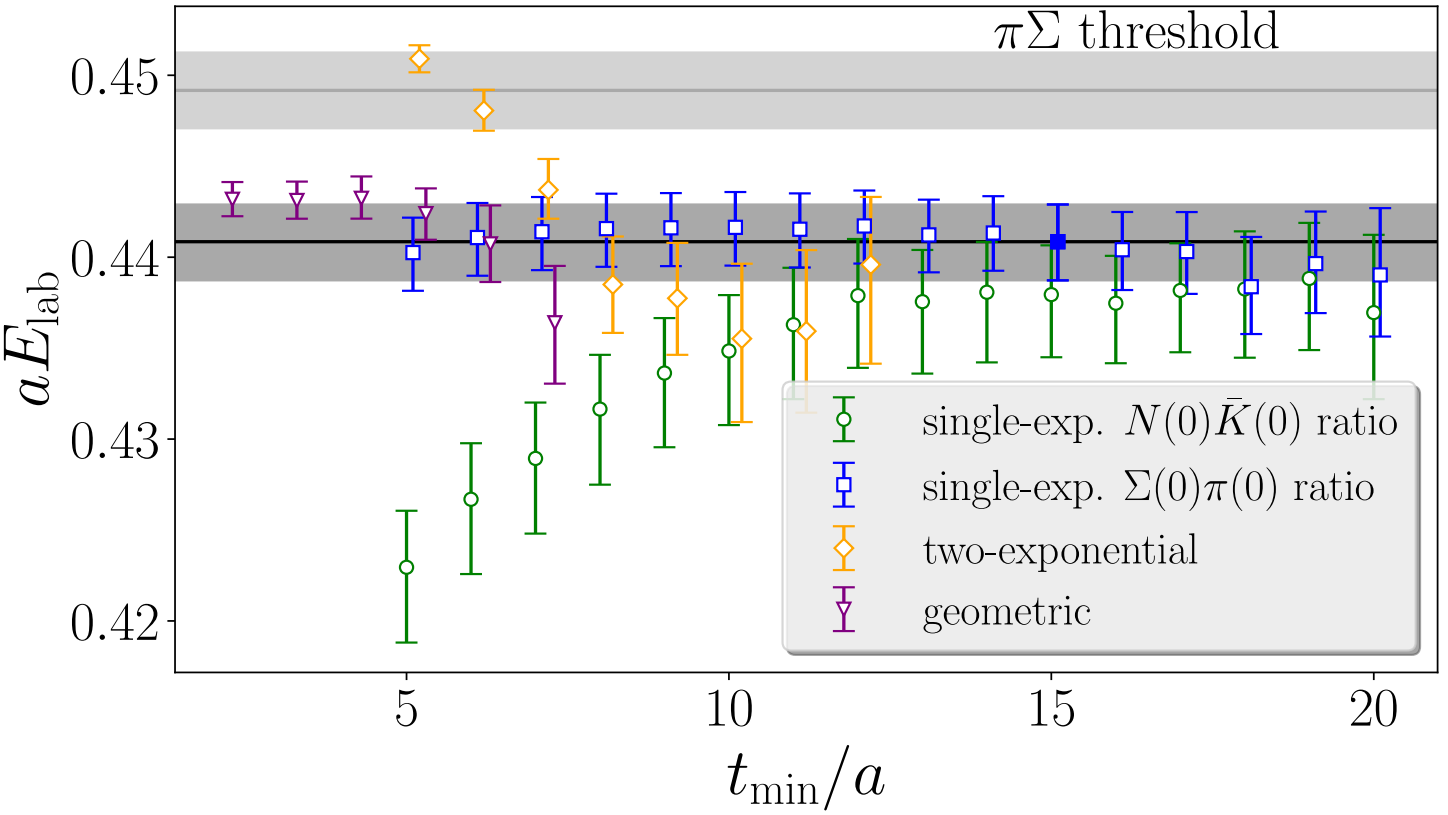
- 25M core-hr on JUQUEEN (JSC) and HIM
- 120M core-hr on Frontera (TACC)

Determination of finite-volume spectrum:

- Direct determination of interacting shifts from ratios:

$$R(t) = \frac{C(t)}{C_1(t)C_2(t)} \approx A\mathrm{e}^{-\Delta E t}$$

- Single-exp. fits over range $[t_{\mathrm{min}}, t_{\mathrm{max}}]$



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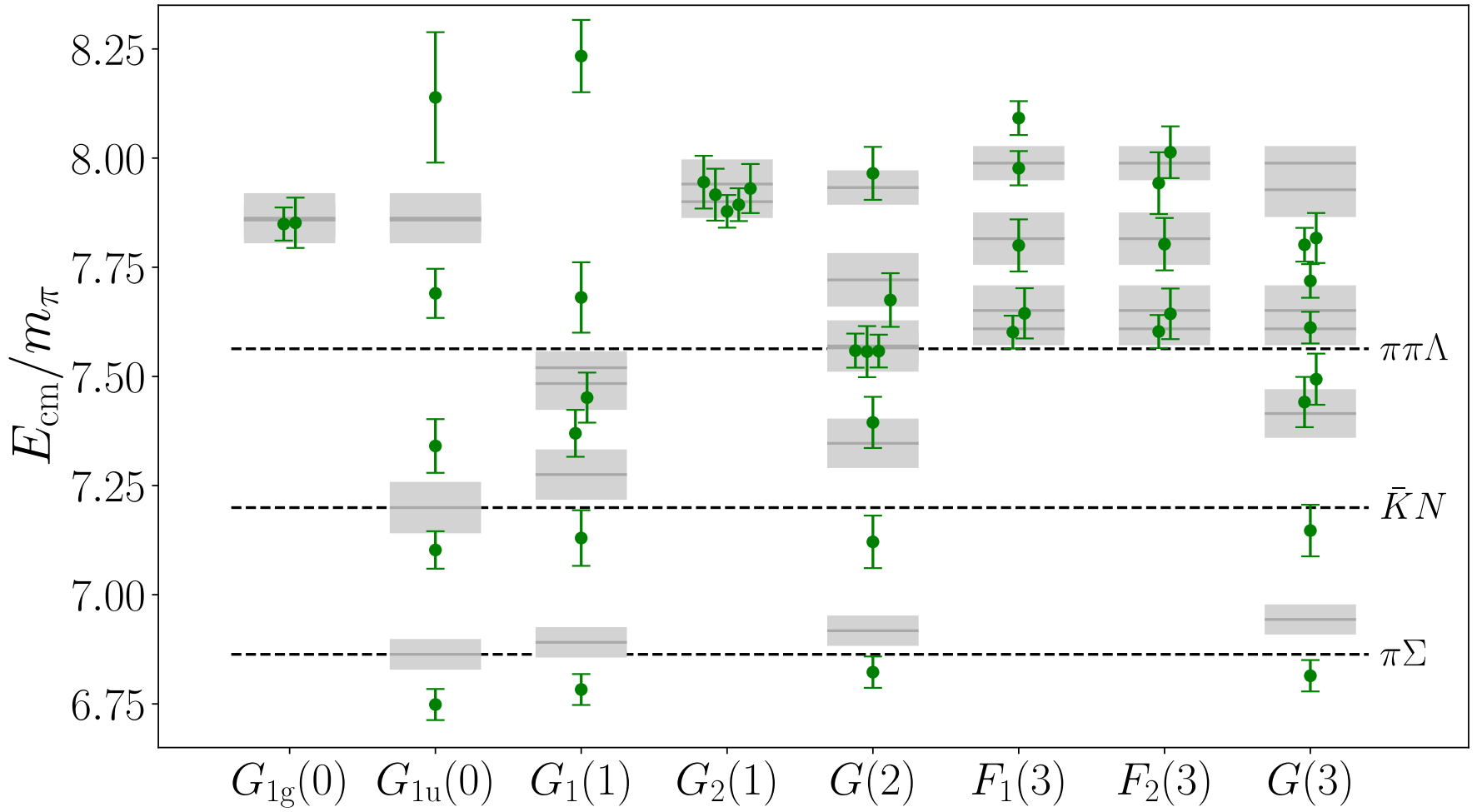
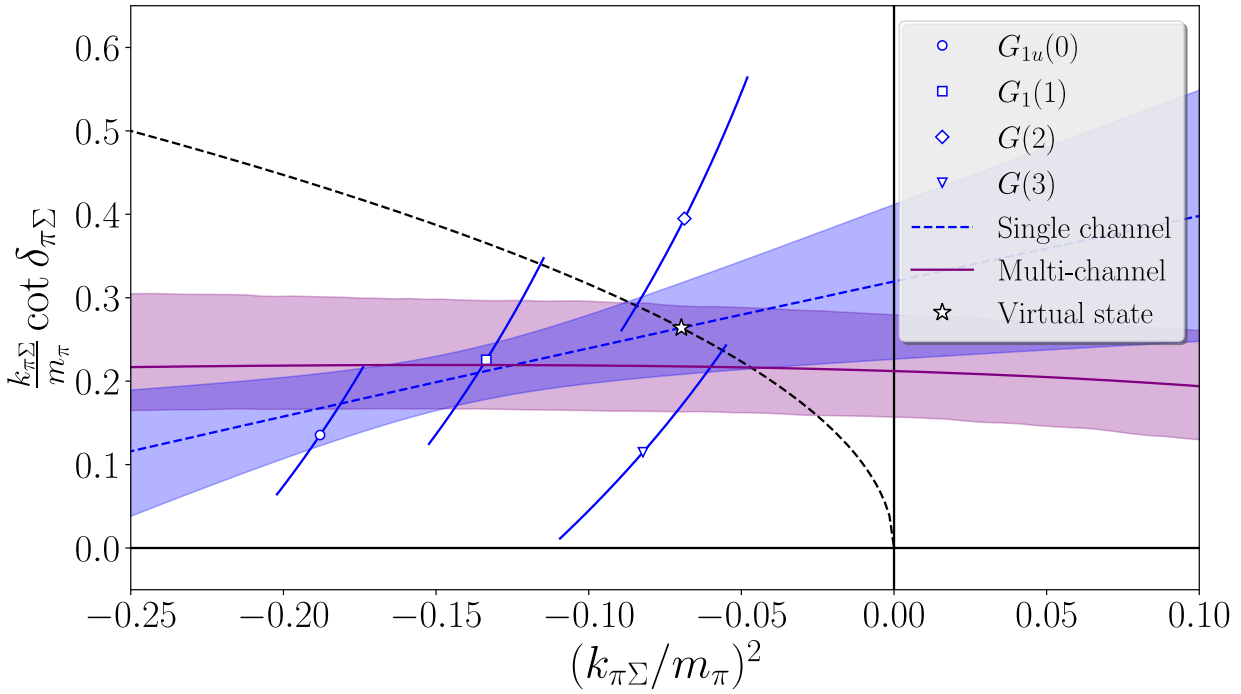


Elastic Sigma-pion scattering: below nucleon-kaon threshold

- Single-partial wave approximation: $k \cot \delta = B(E^L_{\rm cm})$
- Effective range parametrization: $k \cot \delta = A + Bk^2$
- Analytic continuation: pole occurs when $k \cot \delta = ik$
- Pole for pure-imaginary, negative *k* → virtual bound state



Coupled-channel scattering: below three-hadron threshold

- Simple amplitude parametrizations (no chiral symmetry constraints)

  Variants of:

$$K_{ij}^{-1} = A_{ij} + B_{ij}\Delta(E_{\mathrm{cm}})$$

  as well as for *K* and Blatt-Biedenharn

- Analytic continuation: find zeroes of

$$t^{-1} = K^{-1} - i\hat{k}$$

- No nearby left- or right-hand cuts!

  J. R. Green, et al., Phys.Rev.Lett. 127 (2021) 24, 242003

- Parametrization-independent analytic continuation:

  M. Salg, F. Romero-Lopez, W. Jay, 2506.16161 [hep-lat]

Coupled-channel scattering: below three-hadron threshold

- Pole 1

$$E_1 = [1455(13)(2)(17) - i\,11.5(4.4)(4)(0.1)]\,\mathrm{MeV}$$

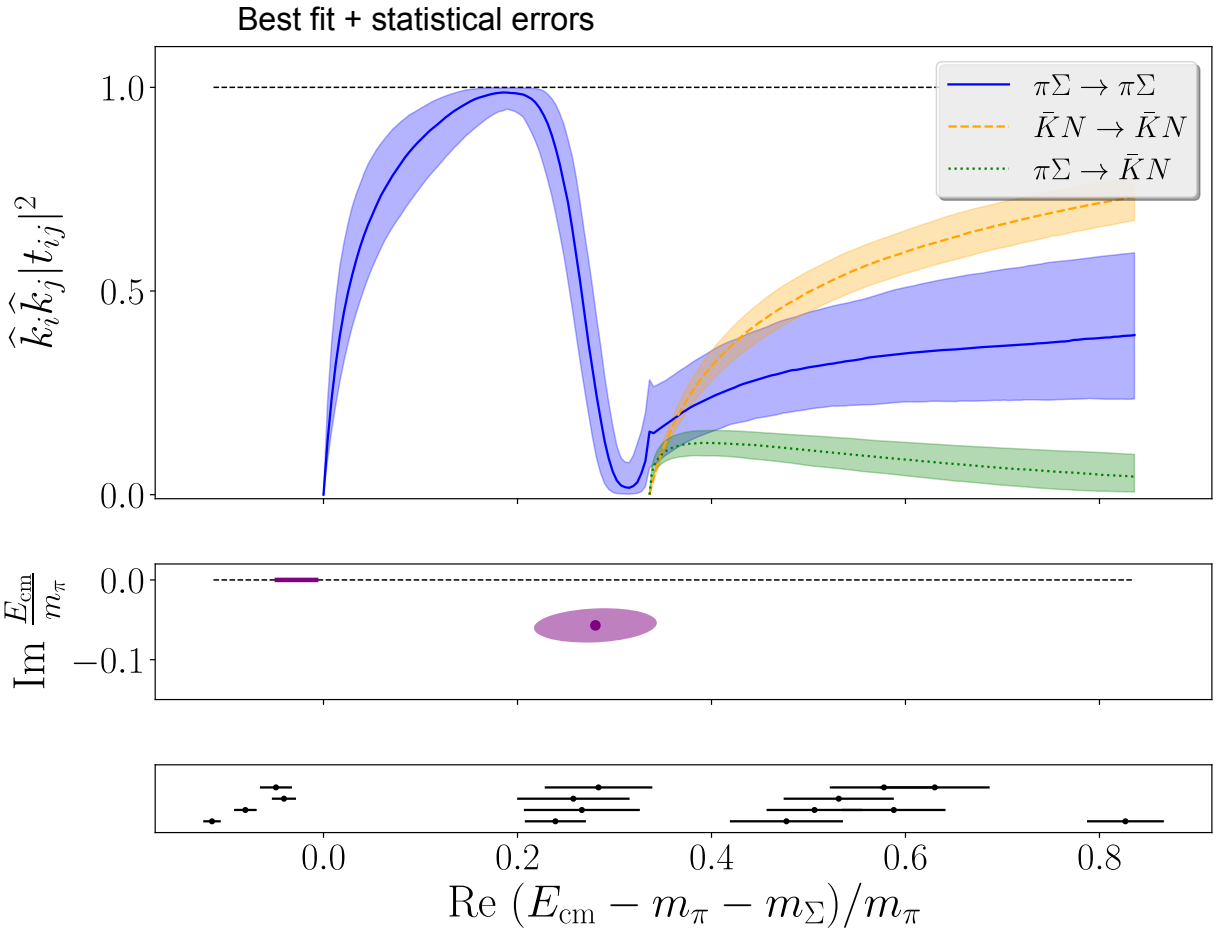
- Pole 2

$$E_2 = 1392(9)(2)(16)\,\mathrm{MeV}$$

- Residues:

$$\left|\frac{c^{(2)}_{\pi\Sigma}}{c^{(2)}_{\bar{K}N}}\right| = 1.9(4)(6)$$

$$\left|\frac{c^{(1)}_{\pi\Sigma}}{c^{(1)}_{\bar{K}N}}\right| = 0.53(9)(10)$$



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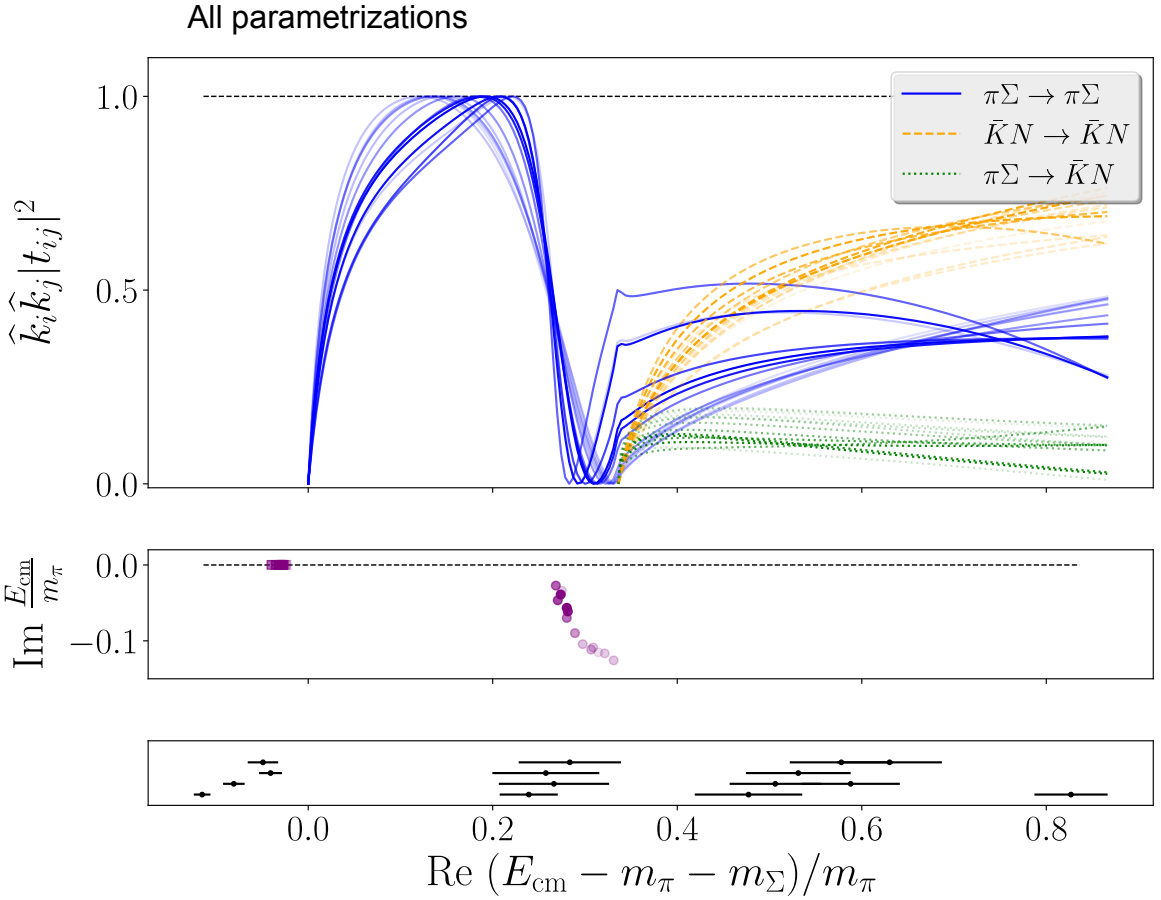
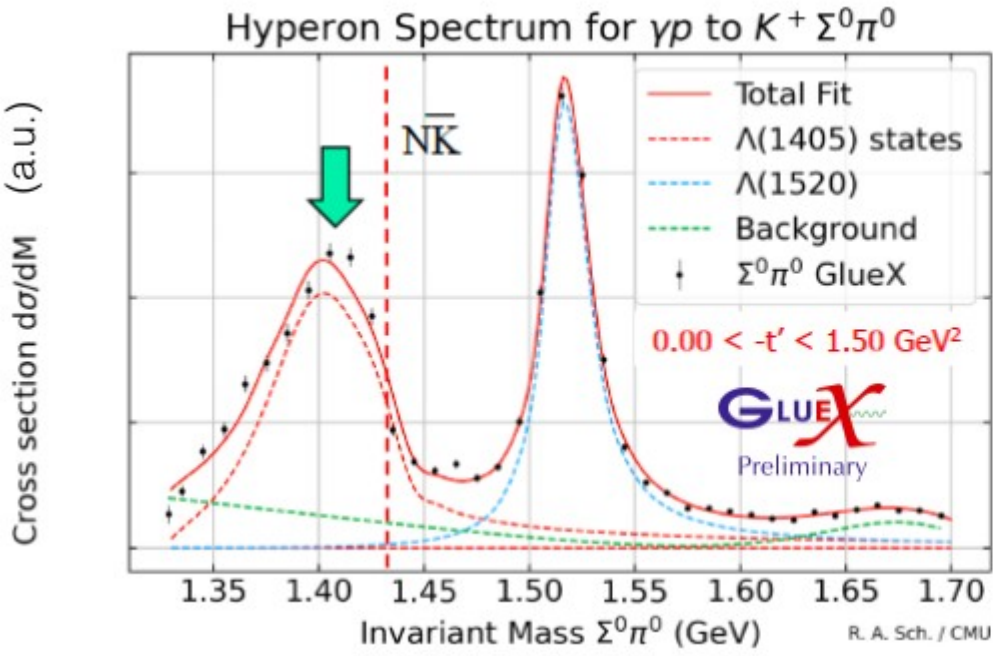
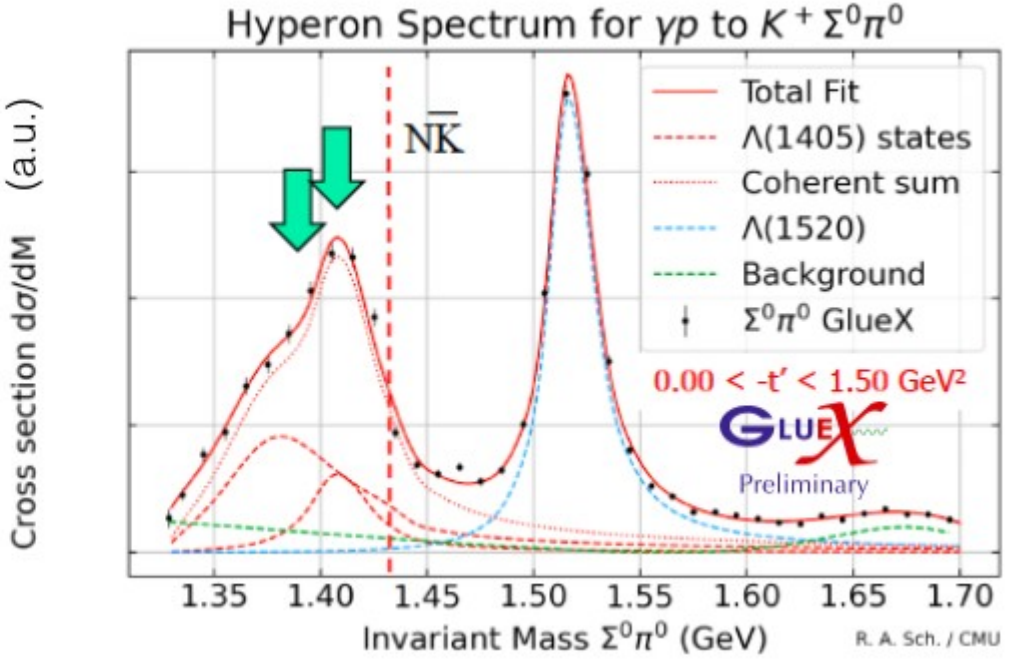


Recent (preliminary) experimental results:

- Preliminary analysis from the Glue-X collaboration

N. Wickramaarachchi, R. A. Schumacher, G. Kalicy, arXiv:2209.06230 [nucl-ex]
J. Rittman, talk at Chiral Dynamics `24





- First hint of two poles in experimental data?

- Another important experimental input: Kbar-N scattering length from SIDDARTHA2

JINST 19 (2024) 11, P11006

Conclusions

- Meson-baryon coupled-channel dynamics can be studied with lattice QCD
  - ➔ First example: Lambda(1405) support for two-pole picture

- Much to do:
  - ➔ Lattice spacing effects
  - ➔ Variation of quark masses: connection to Chiral models + SU(3) flavor symmetry

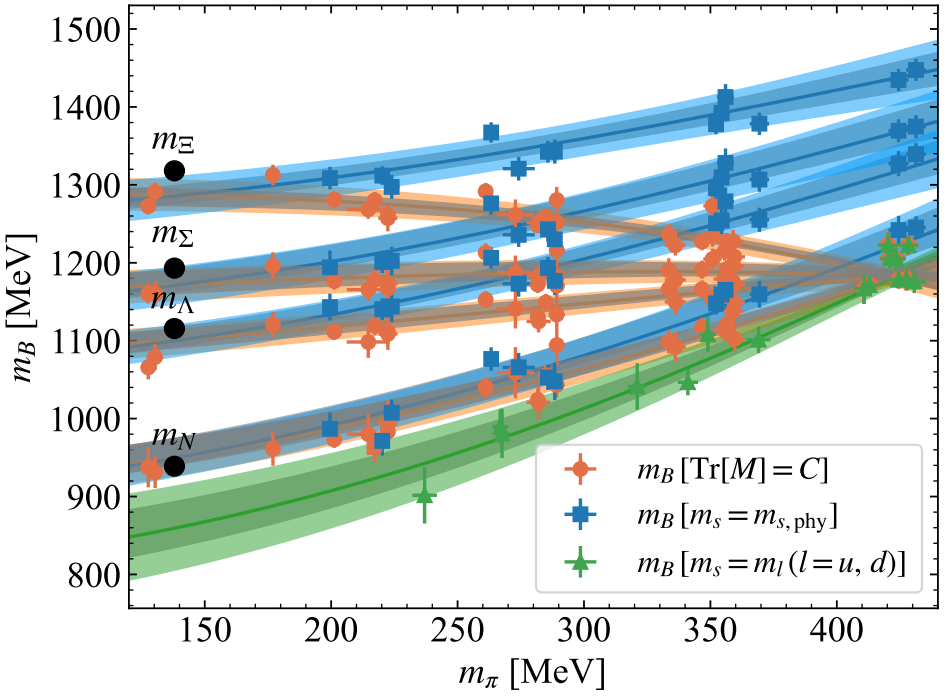
- Difficulties to be addressed:
  - ➔ Left- and right-hand cuts as $m_\pi \to m_\pi^{\rm phys}$
  - ➔ Are pentaquark interpolating operators needed?
  - ➔ Addition of $\eta\Lambda$ channel

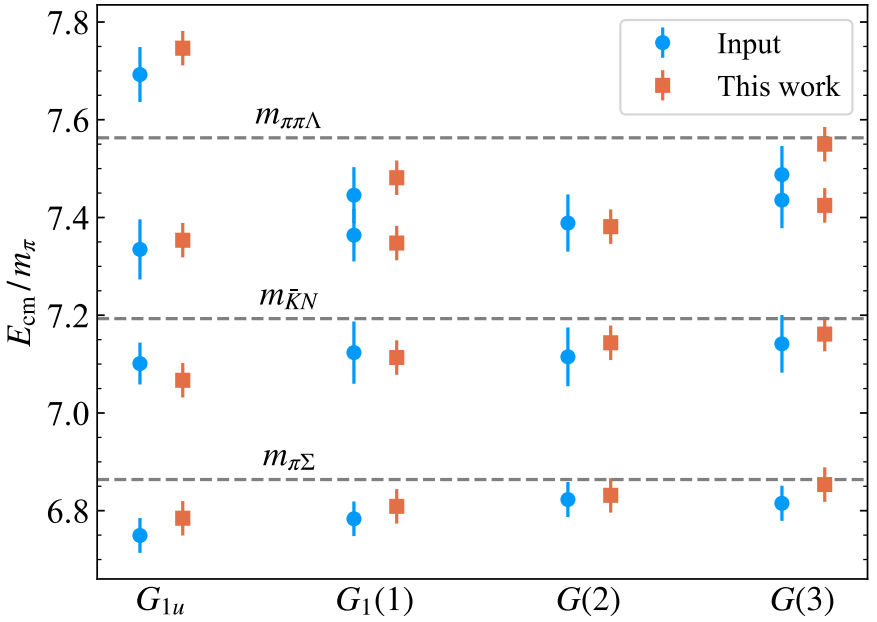
- Other systems: $N(1440),\ \Lambda_c(2595), \ldots$

UchPT+Lattice: approach the physical point

Zhuang, et al., Sci.Bull. 70 (2025) 1953-1961

- Fix model parameters at higher quark masses
- Use model to go $m_\pi \to m_\pi^{\rm phys}$





$$z_1 = 1376(10)(10) - i142(19)(5)\,\mathrm{MeV}, \quad z_2 = 1418(11)(2) - i11(6)(3)\,\mathrm{MeV}$$

- See also:

Pittler, et al., Phys.Rev.D 112 (2025) 7, 074037
Xiu-Lei Ren (Talk on Thurs.) Phys.Lett.B 855 (2024) 138802
Bruns+Cieply, Eur.Phys.J.A 61 (2025) 3, 44
F.-K. Guo, et al., Phys.Lett.B 846 (2023) 138264

Another worry: local multi-quark interpolating operators

- In principle: all interpolating operators approach the lowest states
- In practice: signal-to-noise ratio decays, could lead to plateau misidentification

- A warning from the Tcc: study effect of

  A. Stump, J. R. Green, 2510.26459 [hep-lat]

  - Two-meson operators
  - Tetraquark operators