

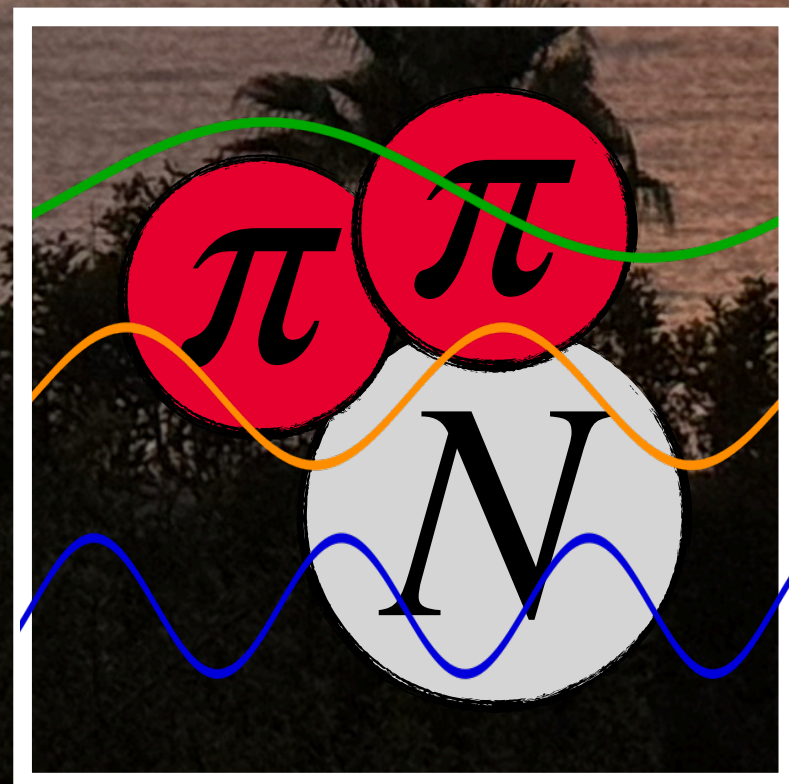
Baryon resonances from Lattice QCD

Fernando Romero-López

fernando.romero-lopez@unibe.ch

EINN

Cyprus, 30.10.2025



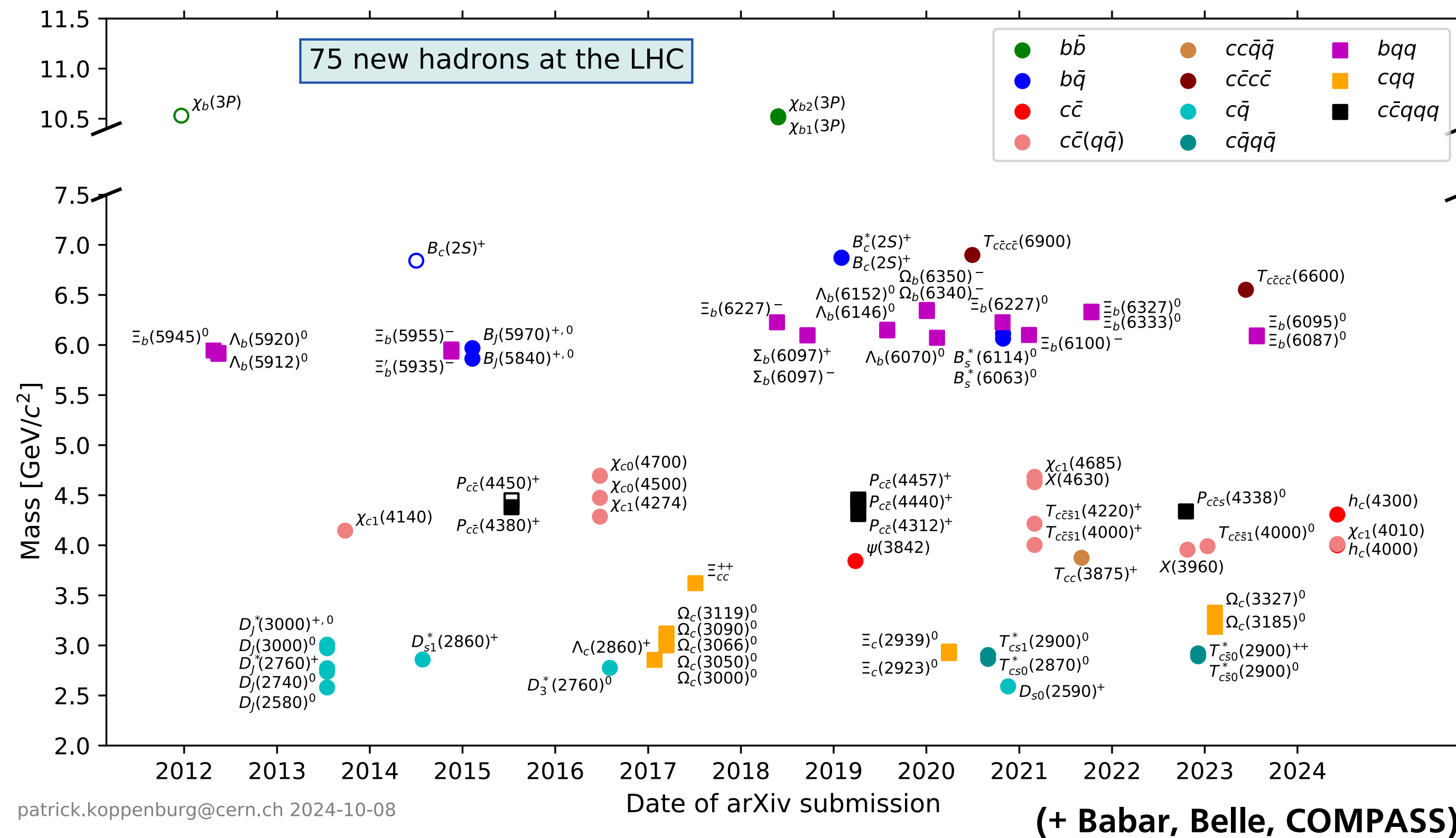
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UNIVERSITÄT
BERN

The Hadron Spectrum

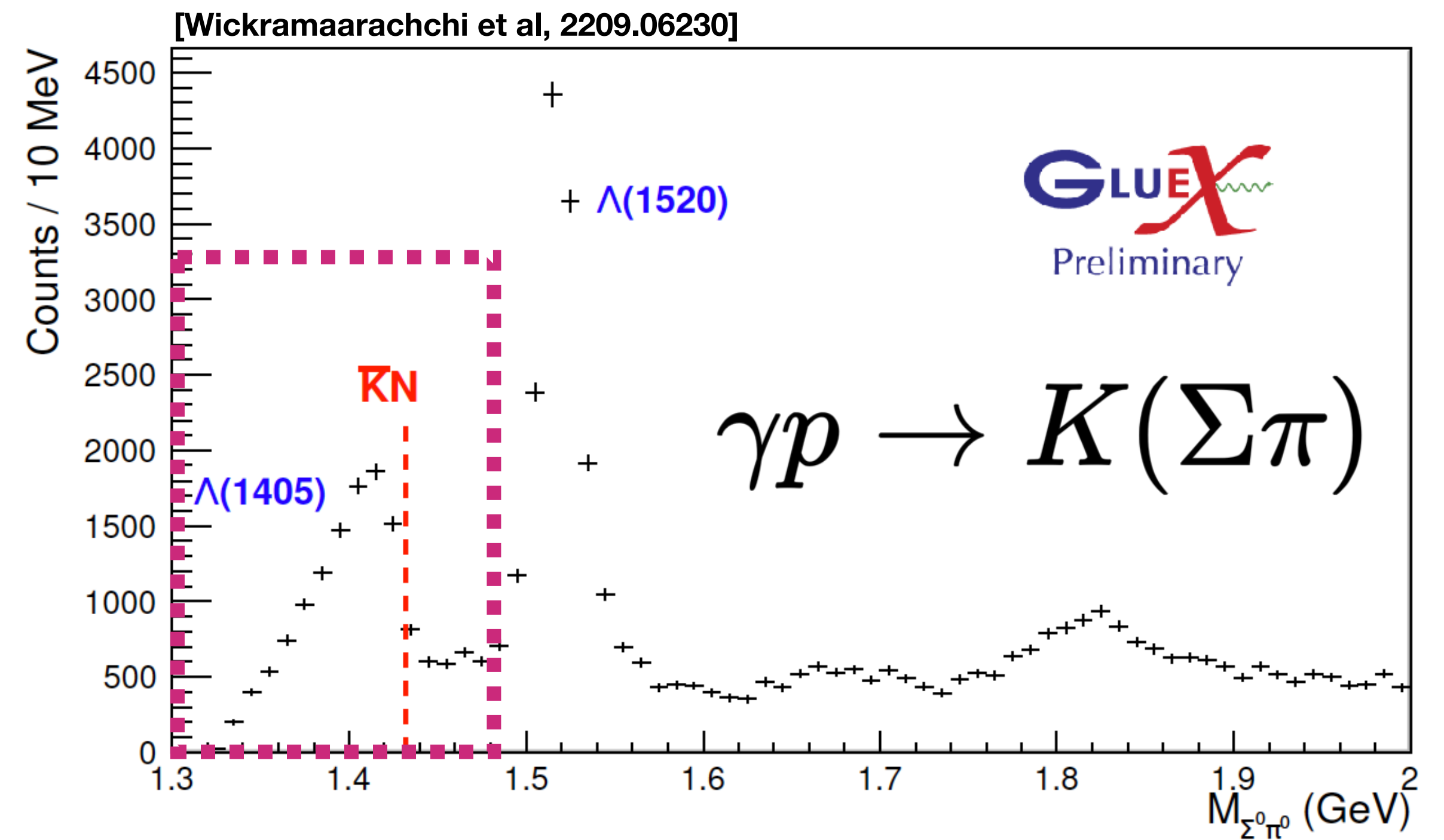
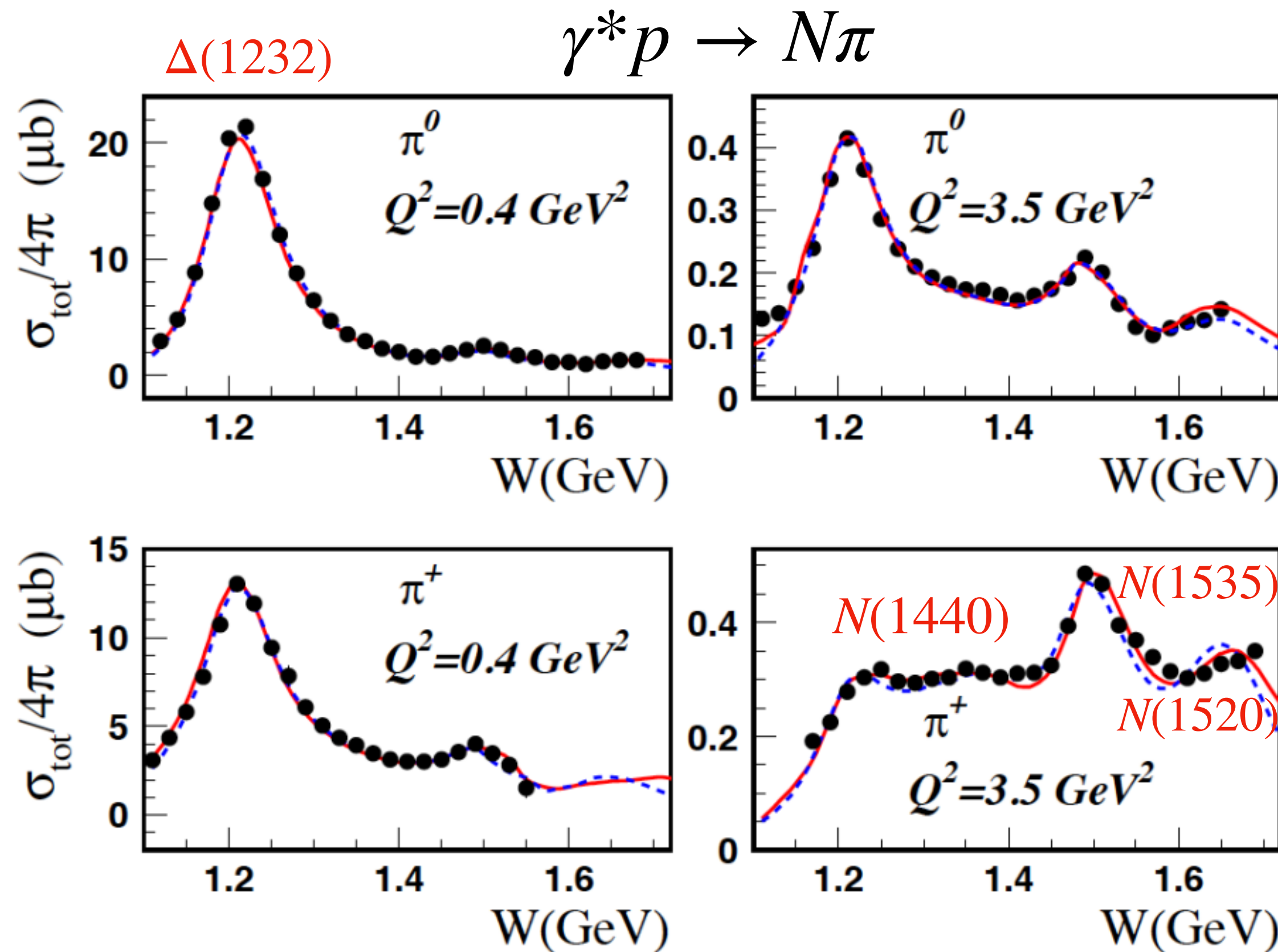
A growing hadron spectrum still requires first principles understanding

[<https://www.nikhef.nl/~pkoppenb/particles.html>]



The Baryonic Sector

Many baryonic excitations still not well understood from first-principles QCD



[Aznauryan et al, PRC80 2009] [Burkert, Roberts, 1710.02549]

(CLAS experiment data)

Hadronic resonances

○ Hadronic resonances typically manifest themselves as enhancements in cross-sections

☑ The rigorous definition of a hadronic resonance is a pole in the complex plane

$$\mathcal{M}_\ell \sim -\frac{g^2}{s - s_R}$$

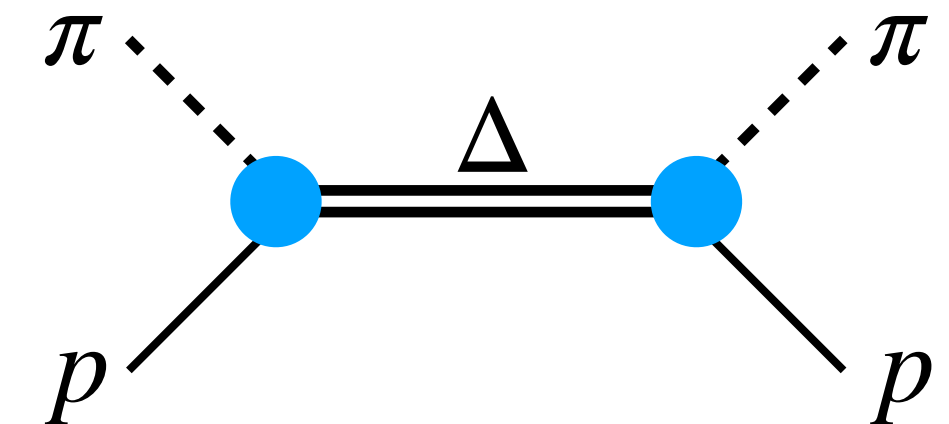
scattering amplitude

coupling

$$\sqrt{s_R} = M_R - i\frac{\Gamma}{2}$$

mass

width



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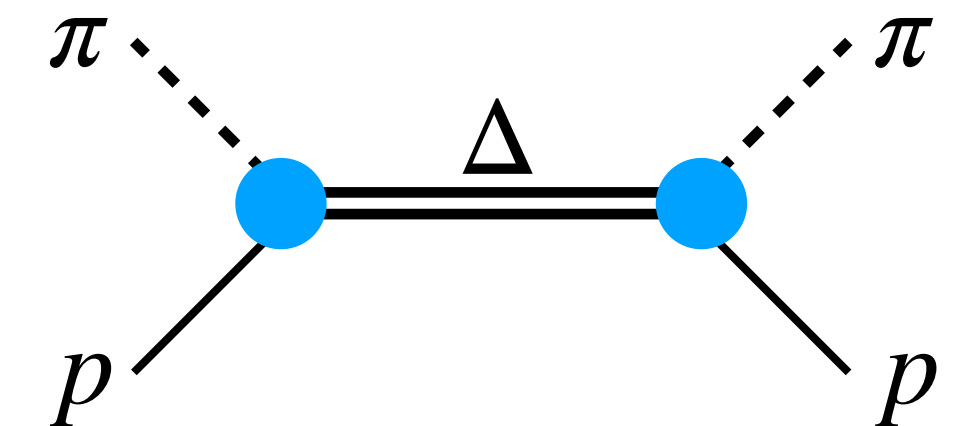
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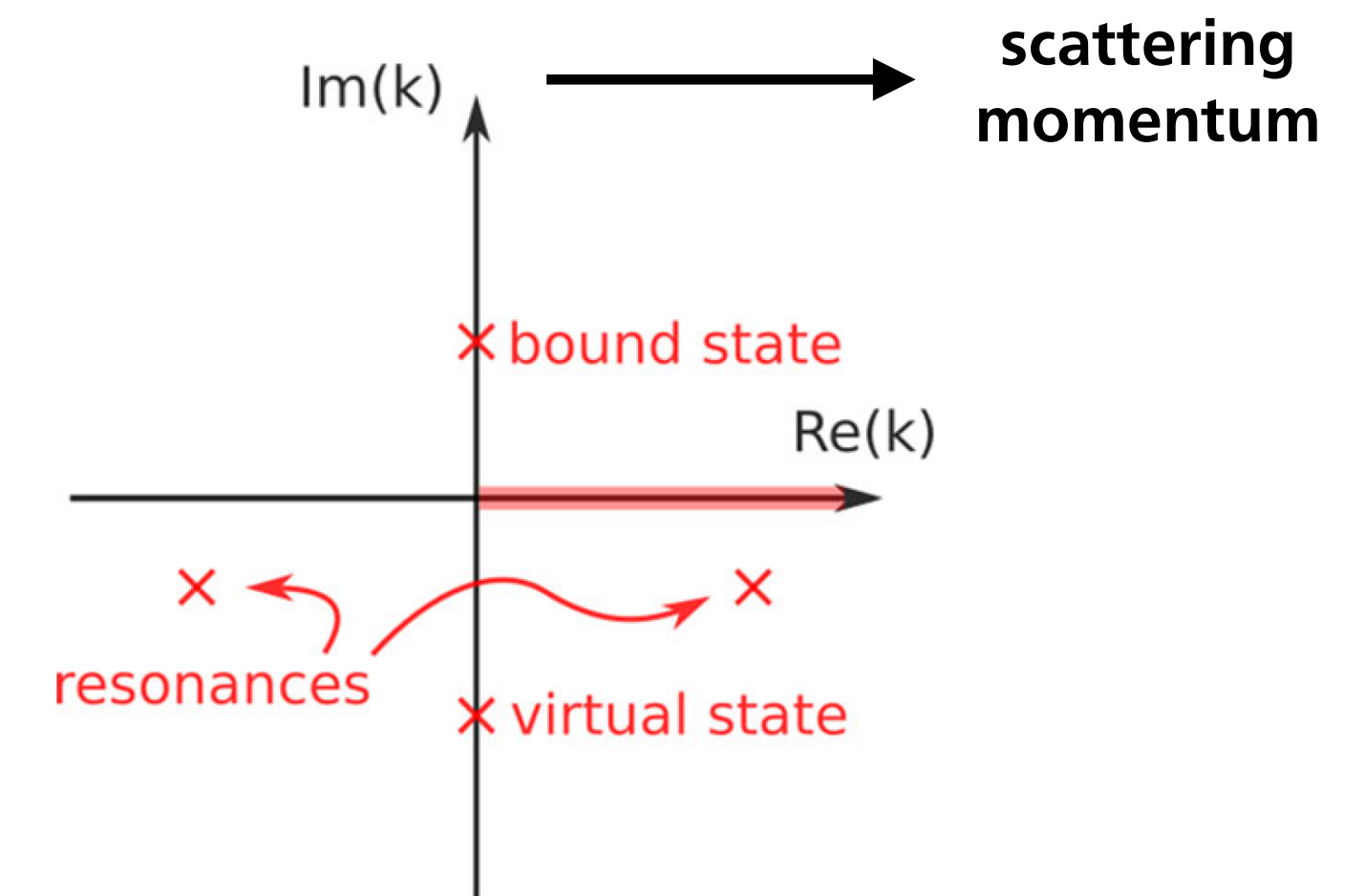
mass

scattering amplitude



○ Based on the location of the poles, they receive different names

- ▶ Bound states: stable particles, e.g. the deuteron is an NN bound state
- ▶ Resonances: unstable hadrons, e.g. the rho resonance
- ▶ Virtual states: "non-normalizable QM states", e.g. "dineutron"

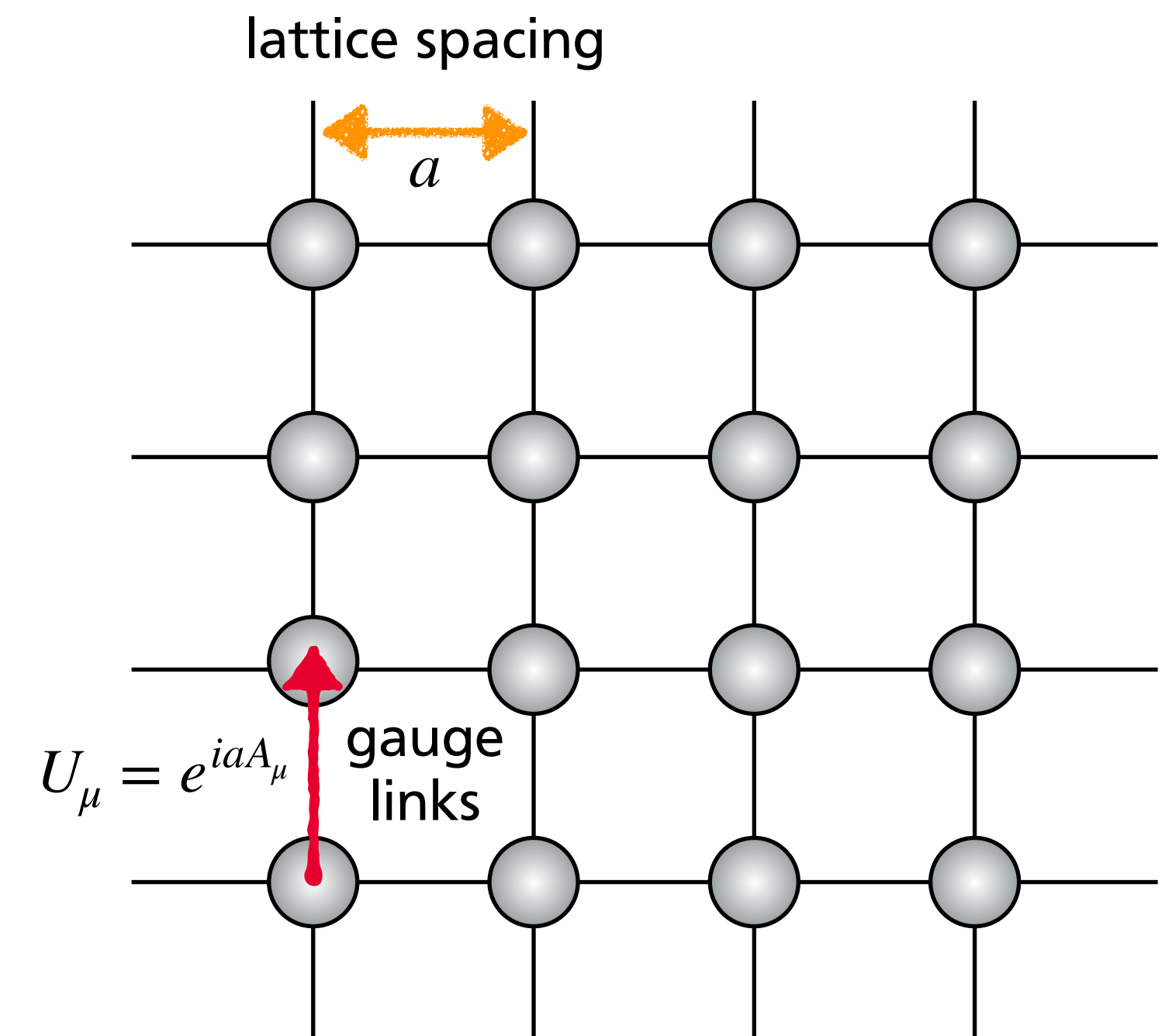


Lattice QCD

- Lattice QCD is a first-principles numerical approach to the strong interaction

$$\langle \mathcal{O}(t) \mathcal{O}(0) \rangle = \frac{1}{\mathcal{Z}} \int D\psi D\bar{\psi} DA \mathcal{O}(t) \mathcal{O}(0) e^{-S_E(\psi, \bar{\psi}, A_\mu)}$$

Euclidean
action



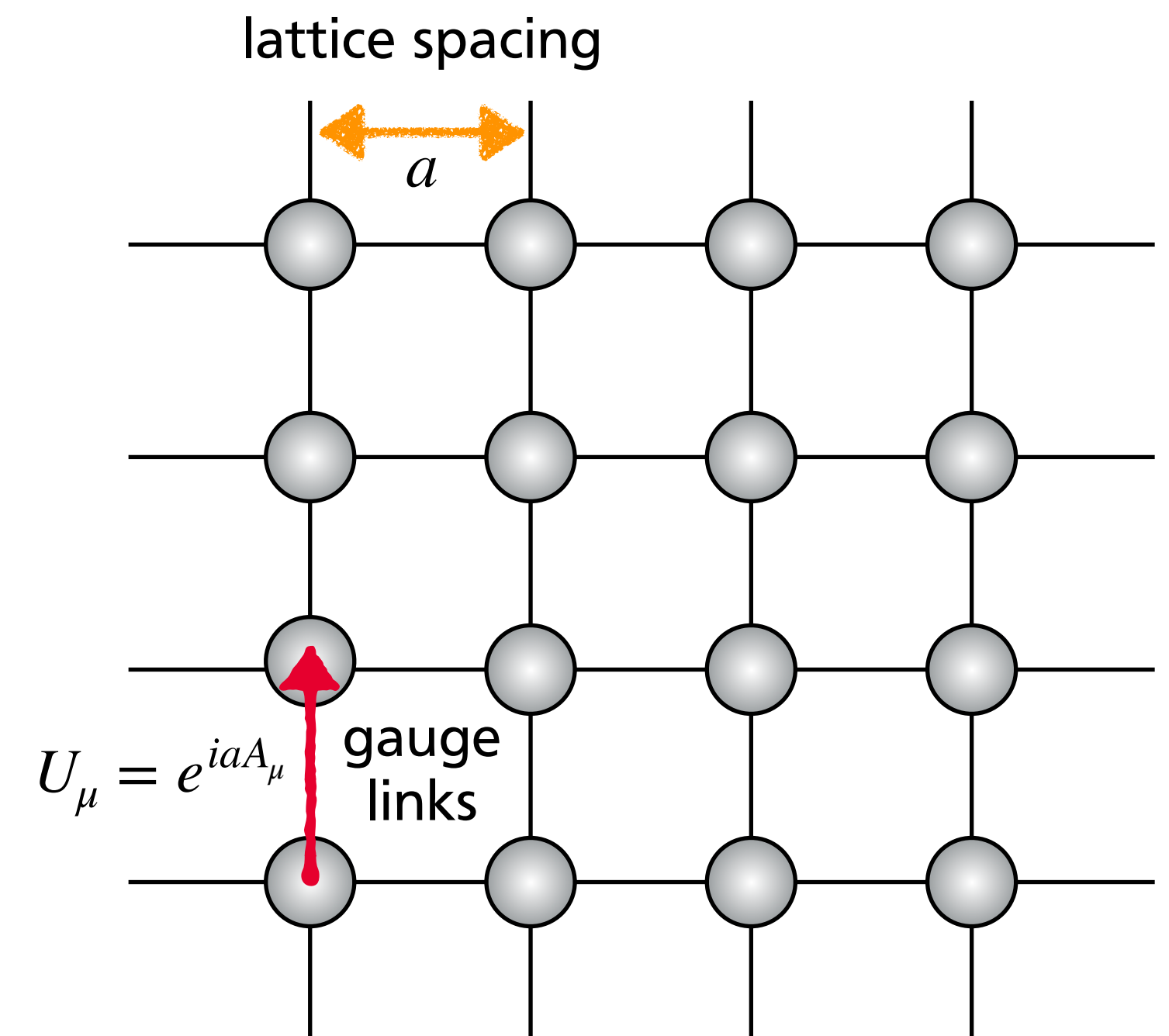
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Can we obtain scattering amplitudes and resonance properties from Euclidean correlation functions?



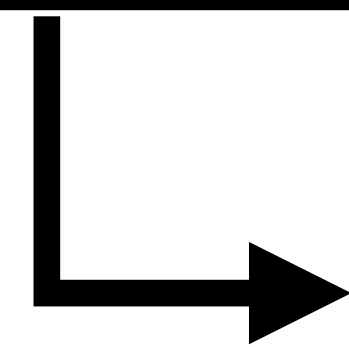
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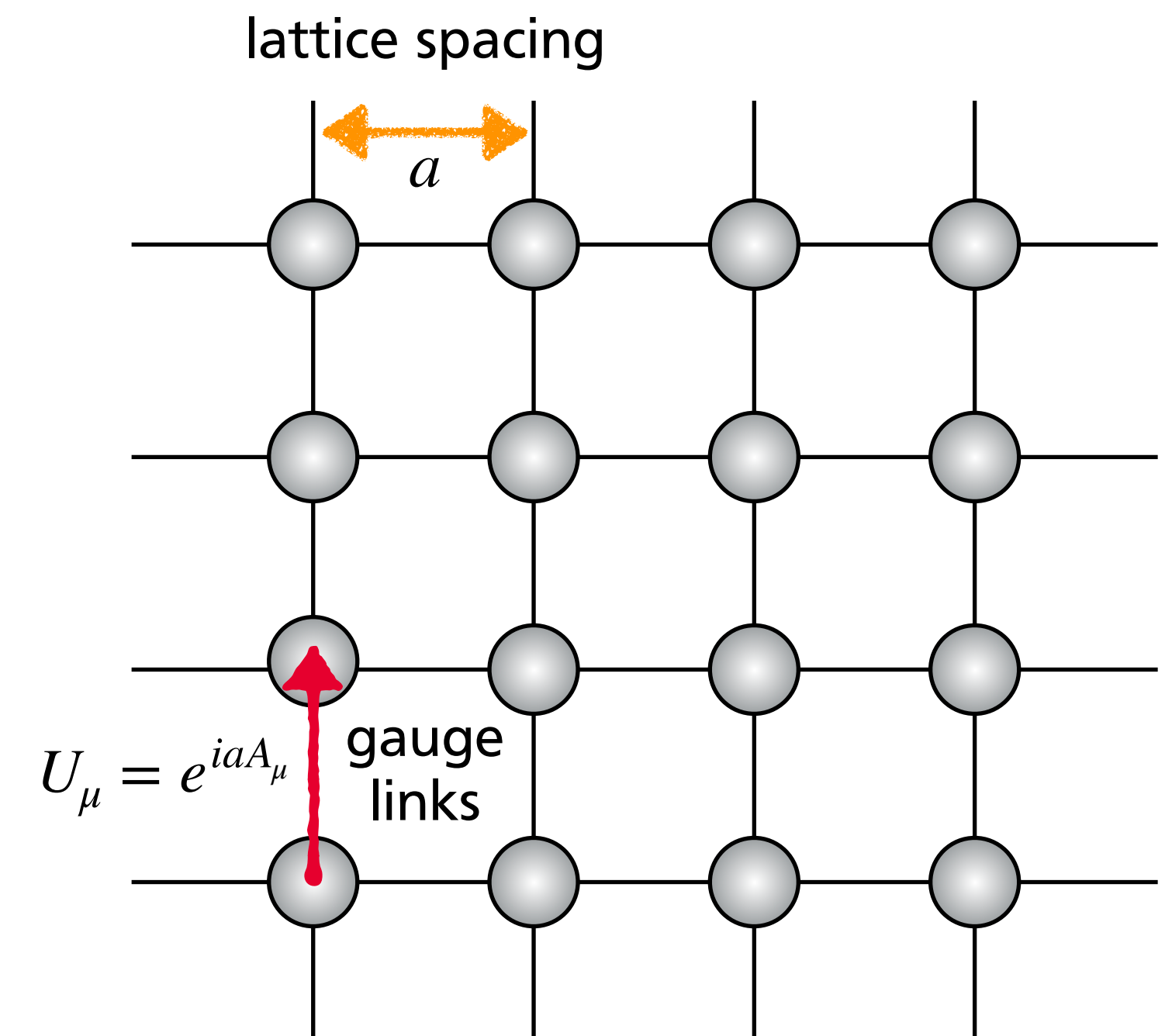
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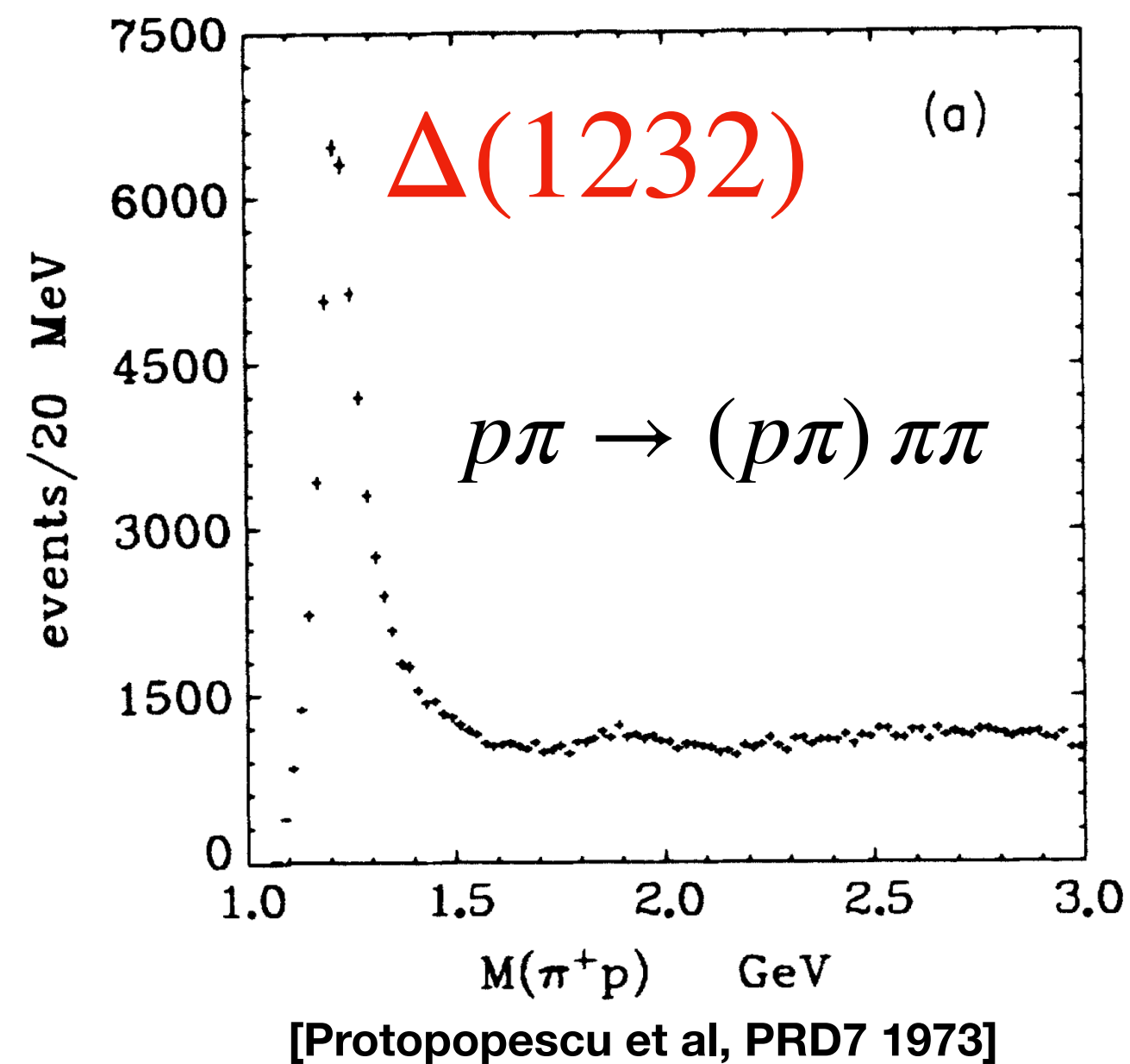
Yes, but not that simple!



Infinite vs finite volume

Experiments

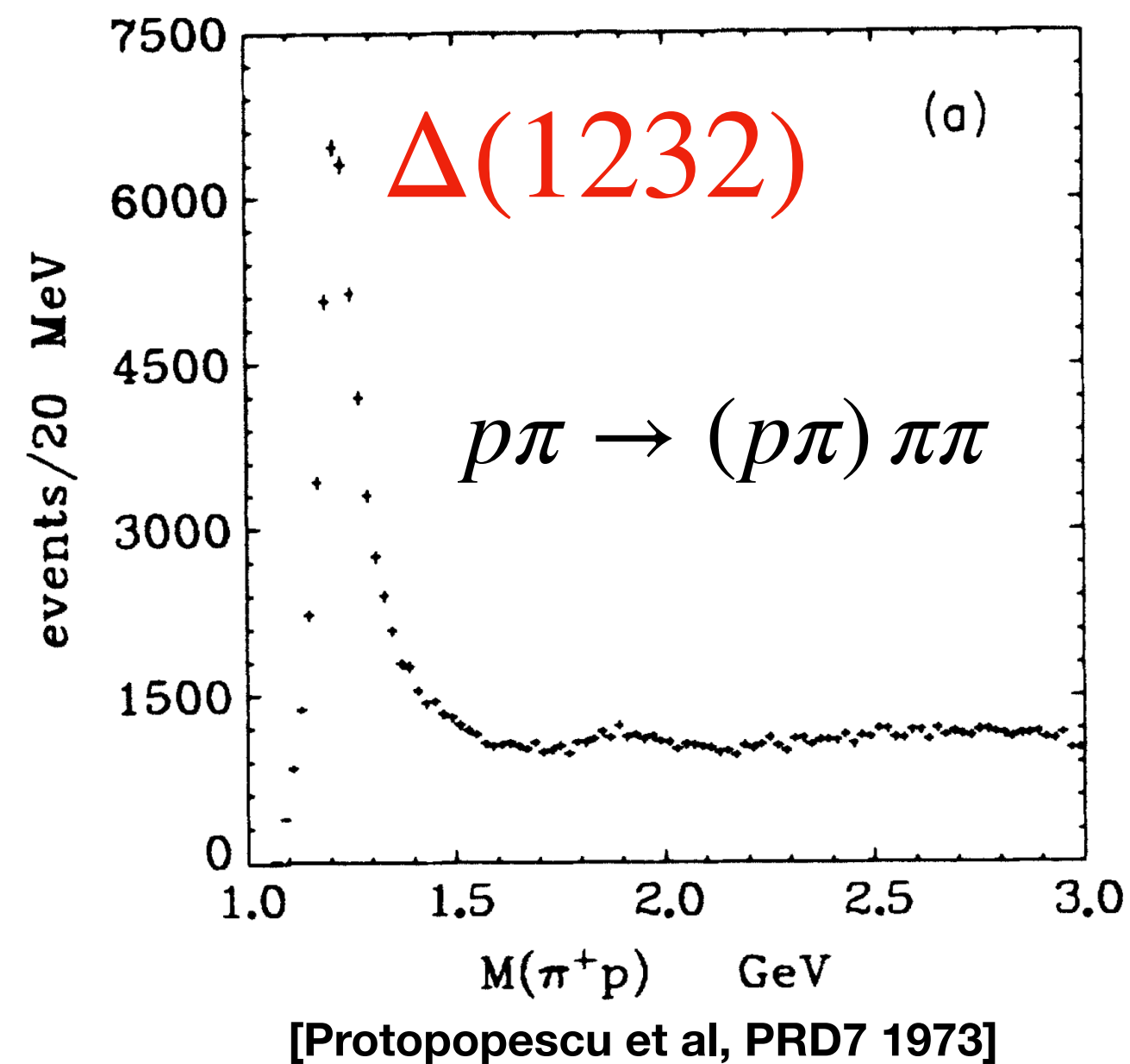
- Asymptotic states
- Direct access to scattering amplitudes



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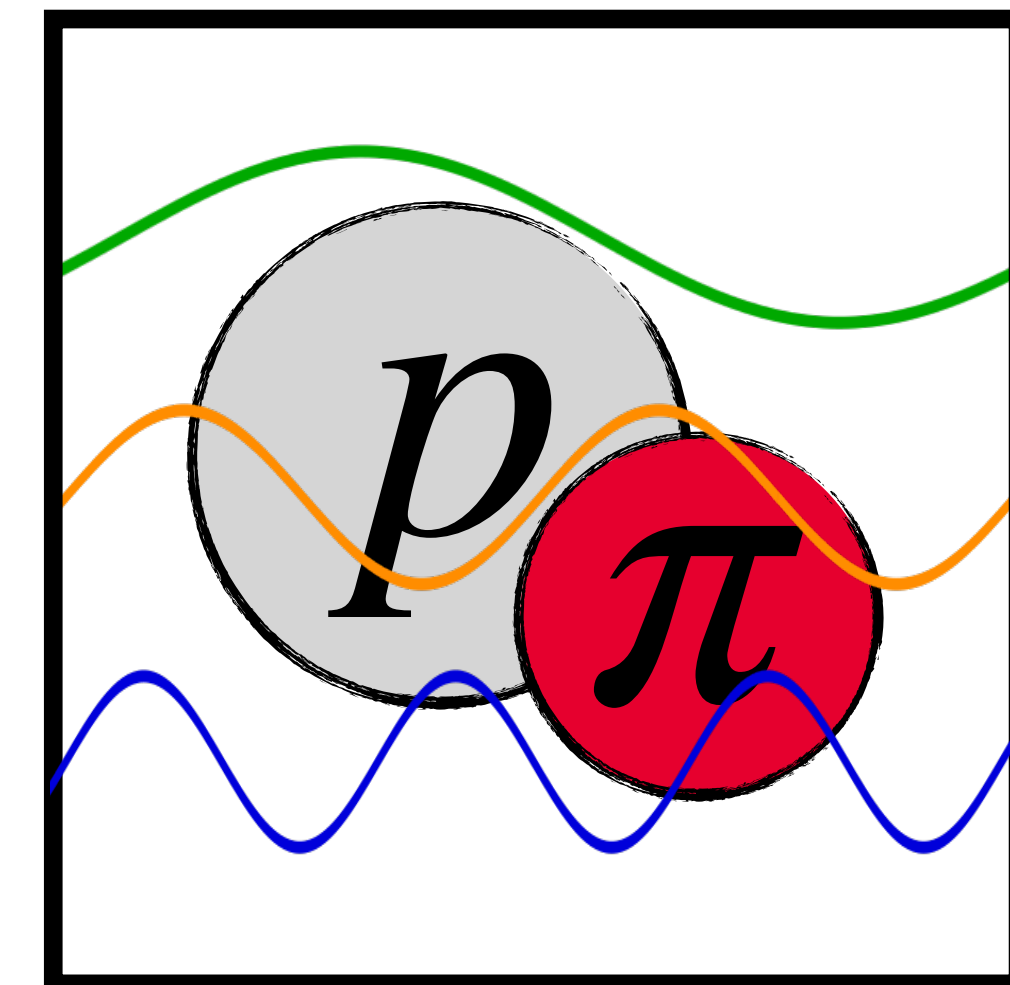
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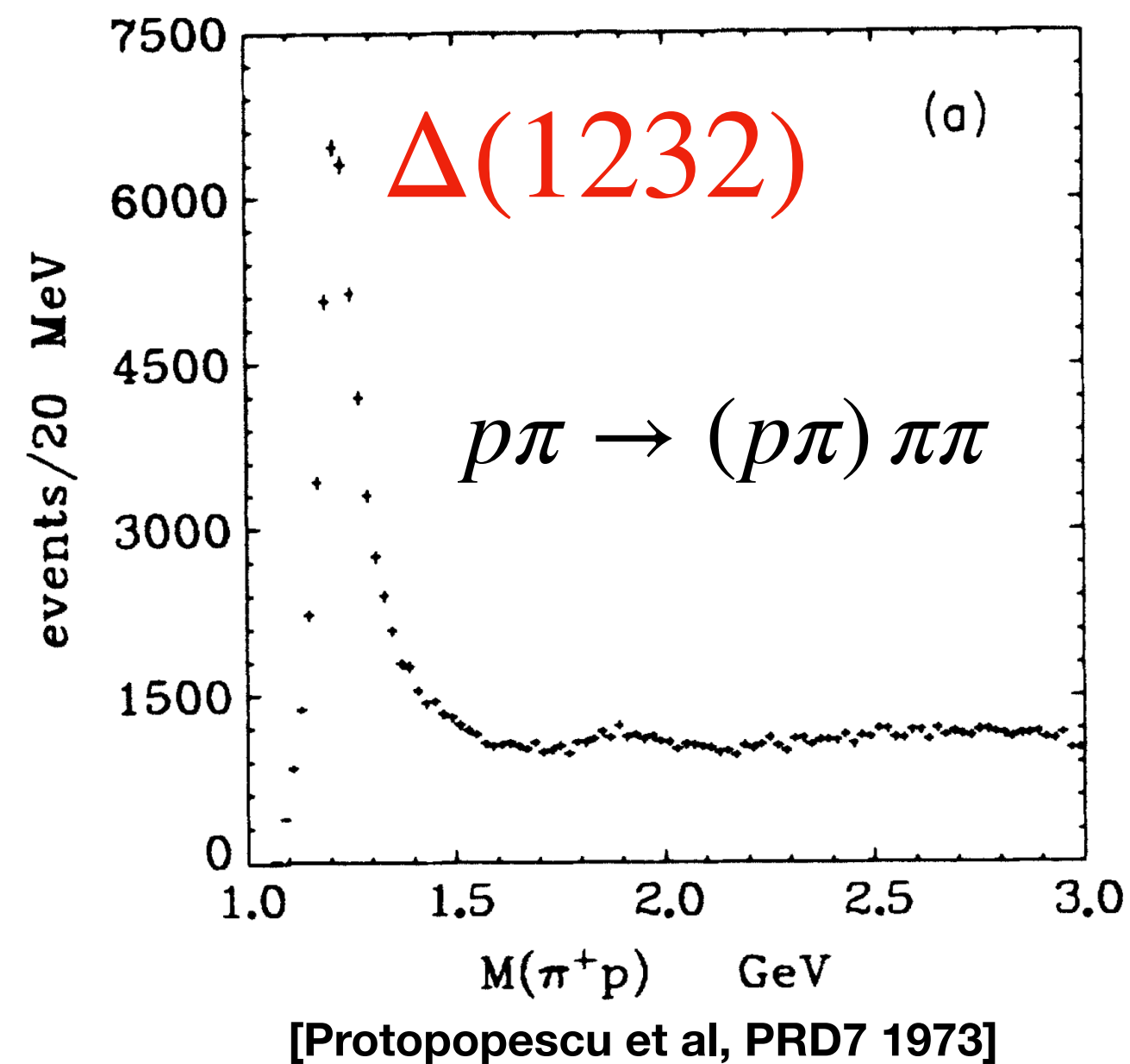
- Euclidean time
- Stationary states in a box



Infinite vs finite volume

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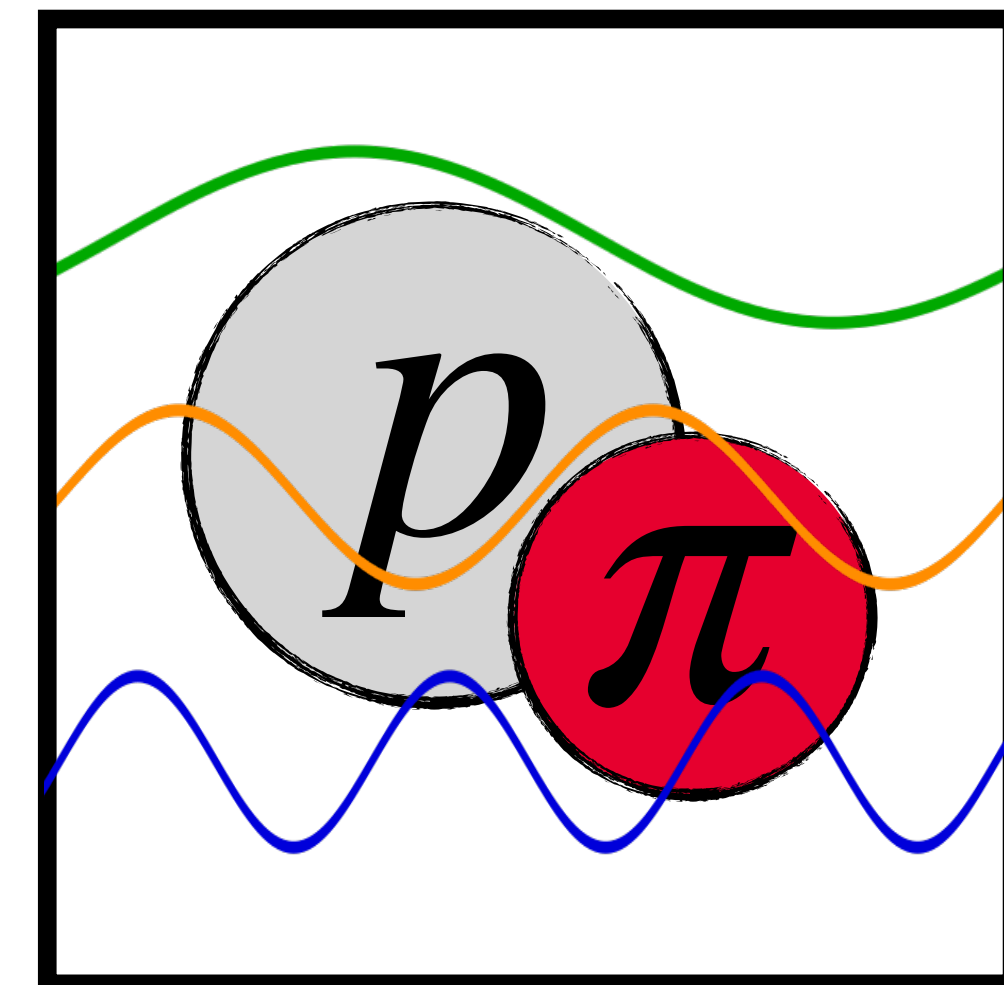
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Finite-volume formalism
[Lüscher, 89']

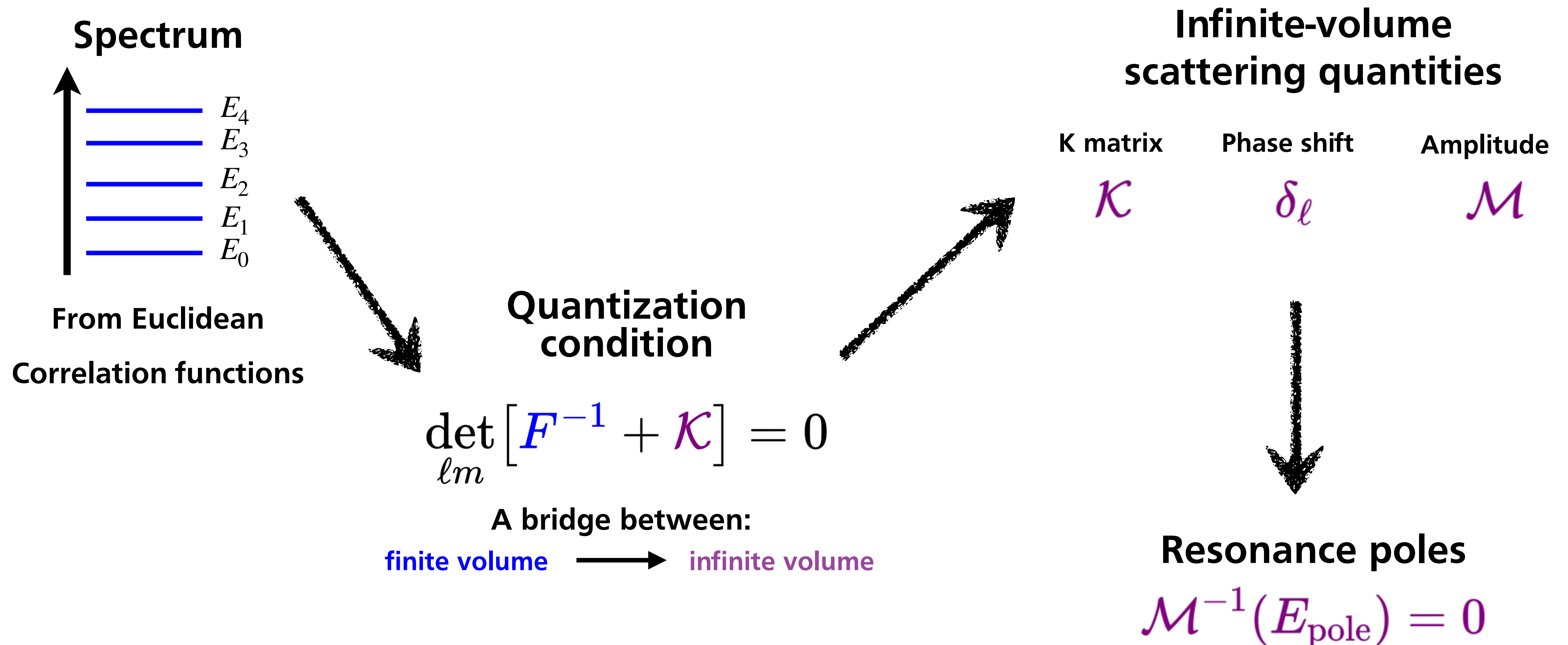
Lattice QCD

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Scattering amplitudes from Lattice QCD

The general strategy



Energy levels from lattice QCD

- The **energy levels** of the theory are measured from Euclidean correlation functions

$$C(t) = \langle \mathcal{O}(t) \mathcal{O}^\dagger(0) \rangle = \sum_n \left| \langle 0 | \mathcal{O}(0) | n \rangle \right|^2 e^{-E_n t}$$

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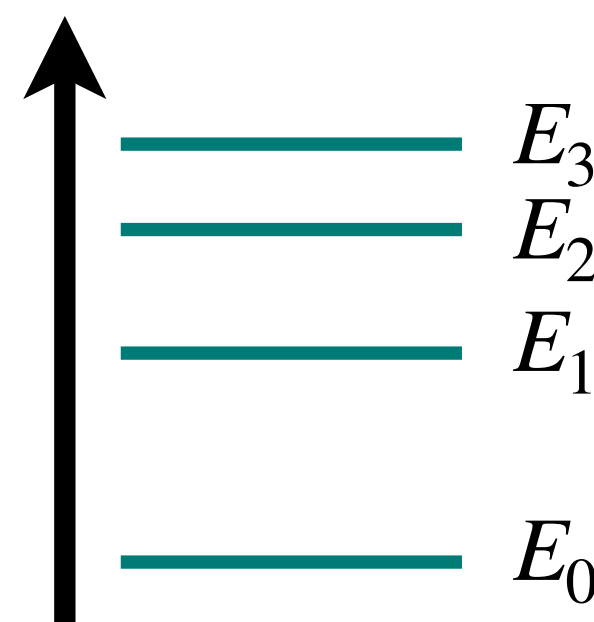
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- Multiple operators with the same quantum numbers to obtain several energy levels

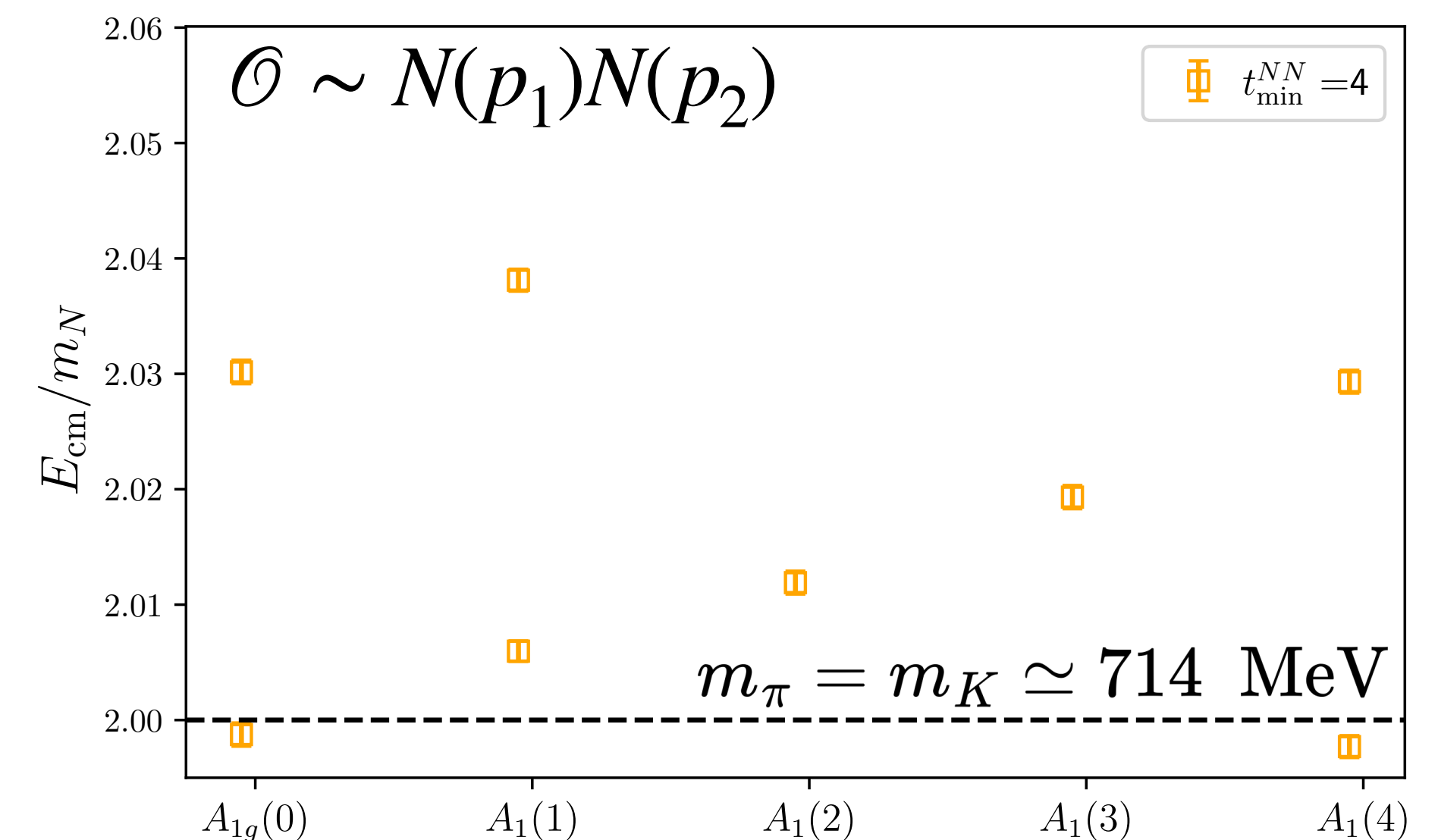
► **Generalized EigenValue Problem (GEVP)**
[Lüscher, Wolff, 90']

$$C_{ij}(t) = \langle \mathcal{O}_i(t) \mathcal{O}_j^\dagger(0) \rangle$$

$$C_{ij}(t) = \langle 0 | \mathcal{O}_i | n \rangle \langle n | \mathcal{O}_j | 0 \rangle^* e^{-E_n t}$$



Finite-volume energies of two neutrons in finite-volume

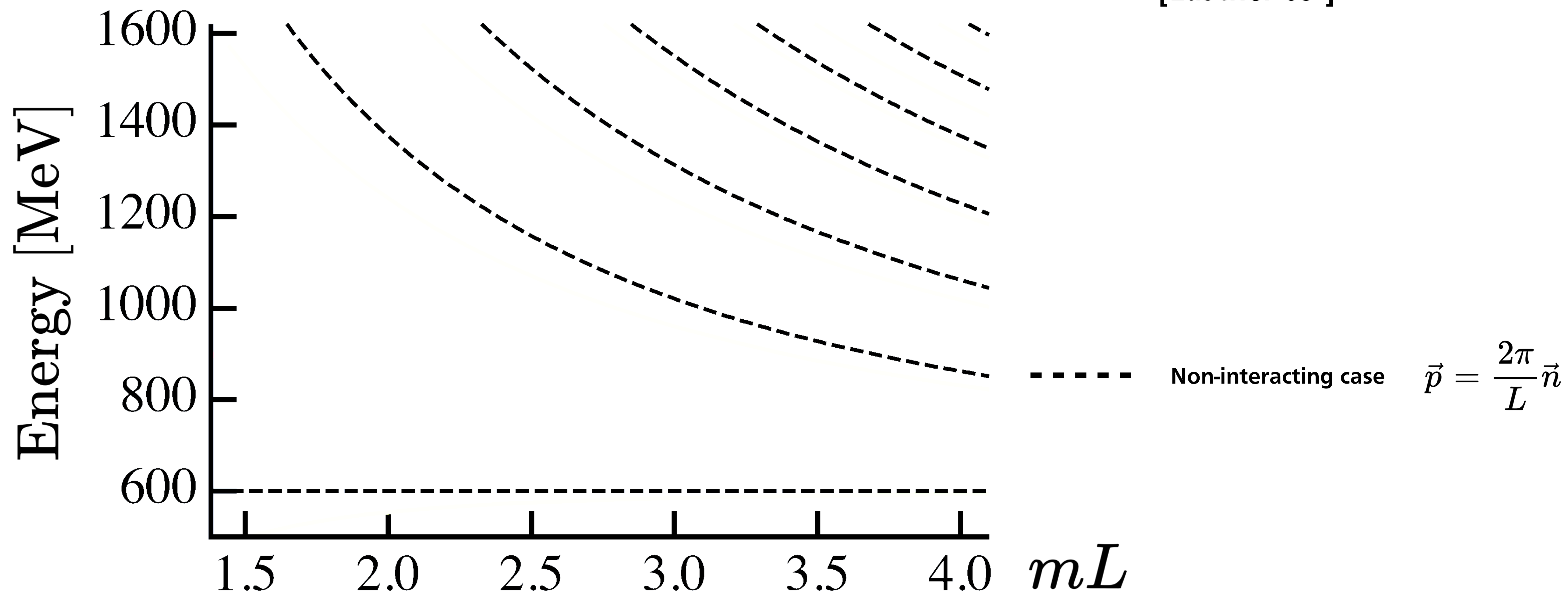


[Baryon Scattering Collaboration, arXiv:2505.05547]

Key insight

Volume dependence of finite-volume energy states contains scattering information

[Lüscher 89']

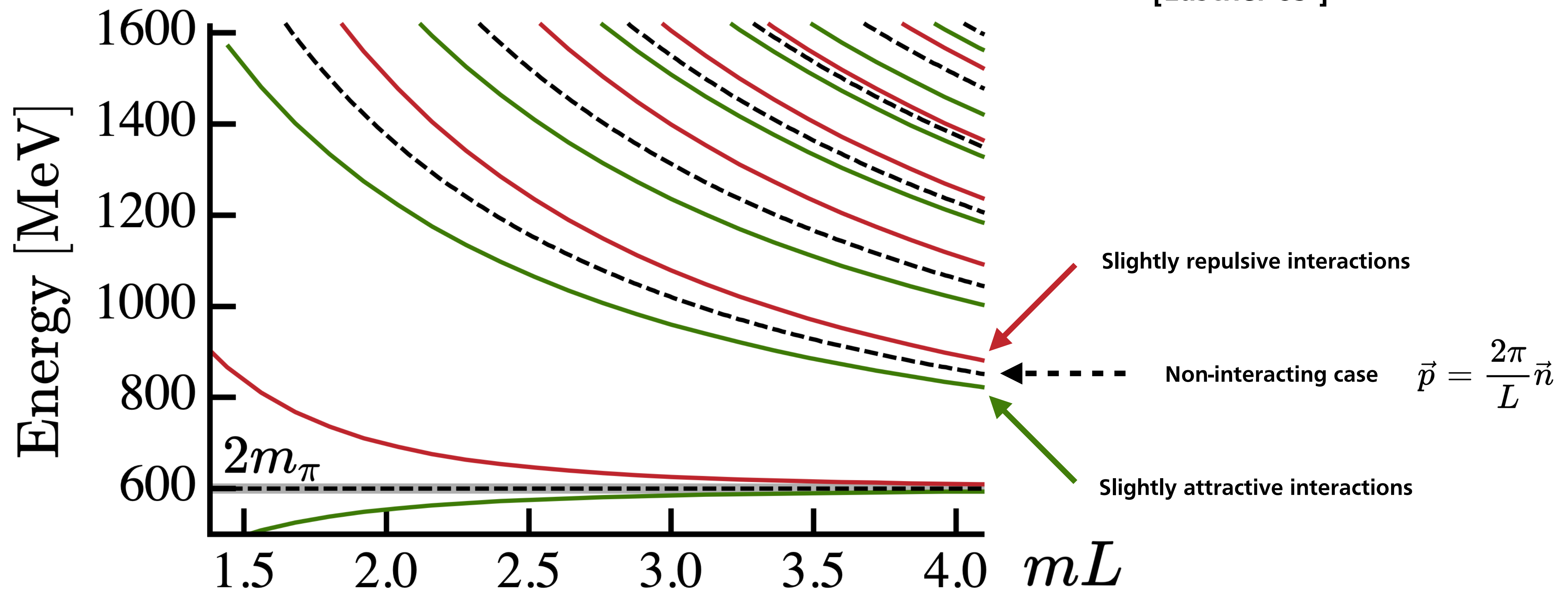


[Briceño, Dudek, Young, arXiv:1706.06223]

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Example: two neutrons

Two hadrons in an s wave

$$k \cot \delta_0(E_n) = \frac{1}{\pi L} \mathcal{Z}_{00}(E_n, \vec{P}, L)$$

one energy level $\rightarrow$ a phase shift point

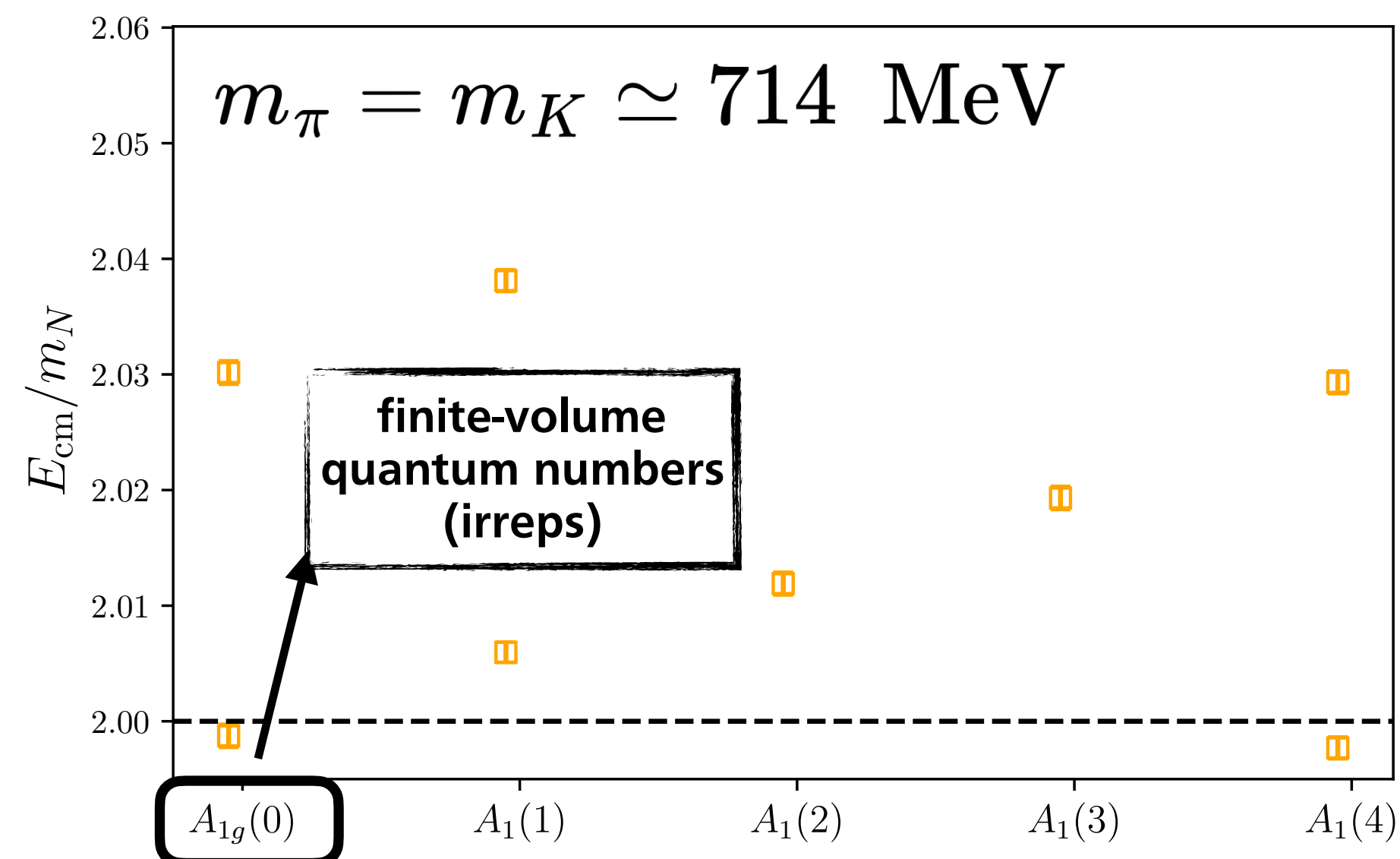
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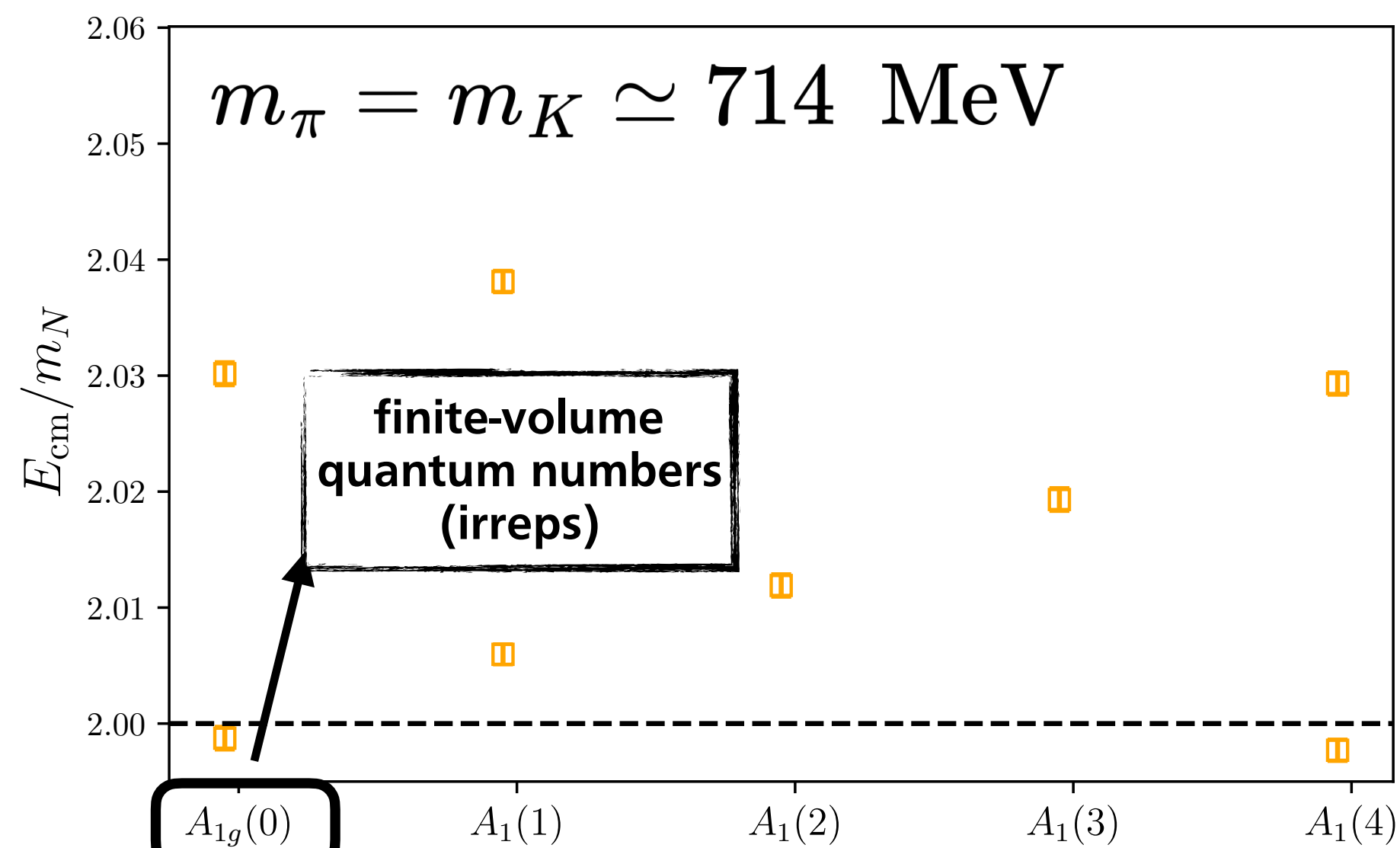
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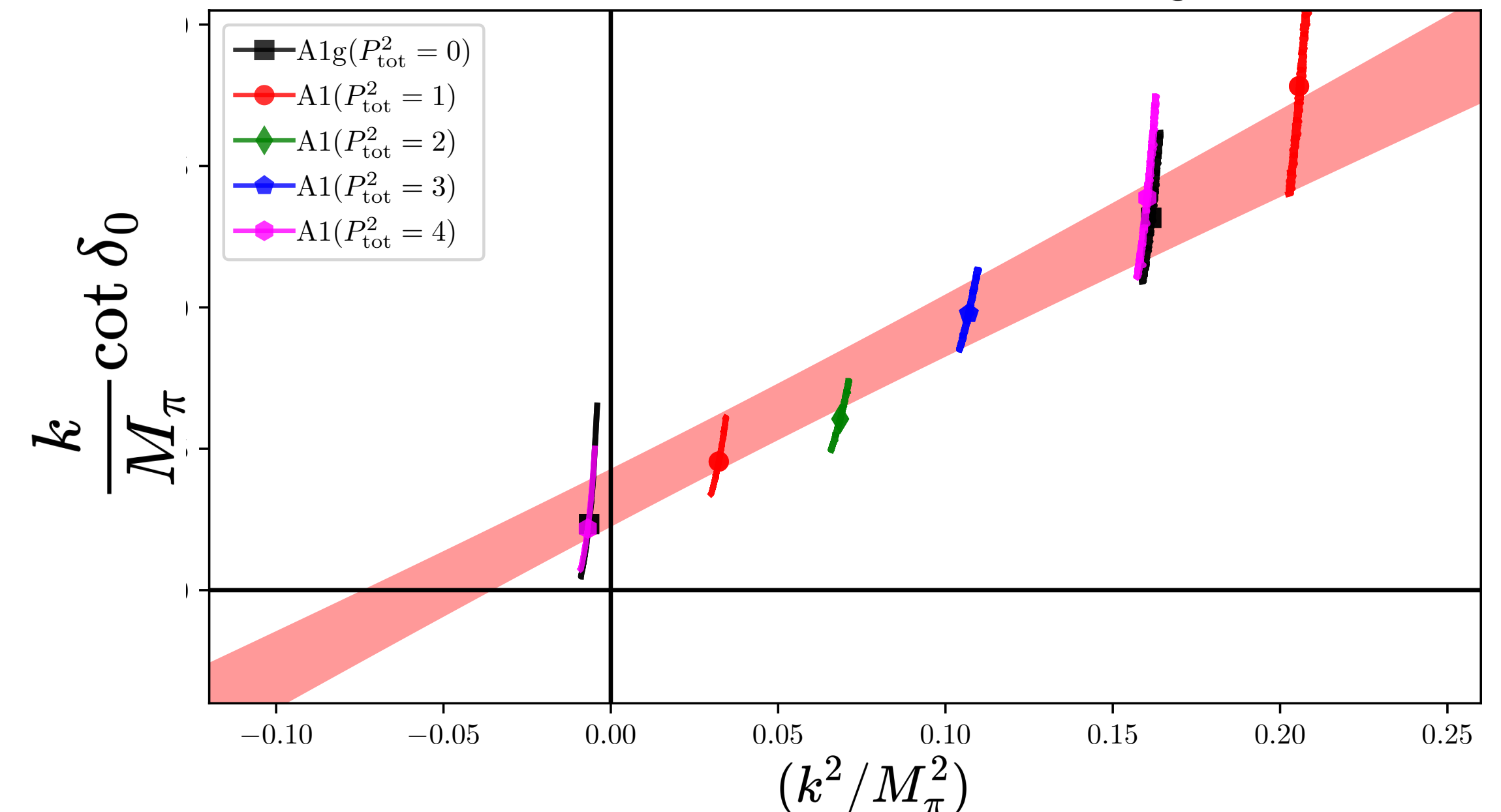
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Phase shift of two-neutron scattering



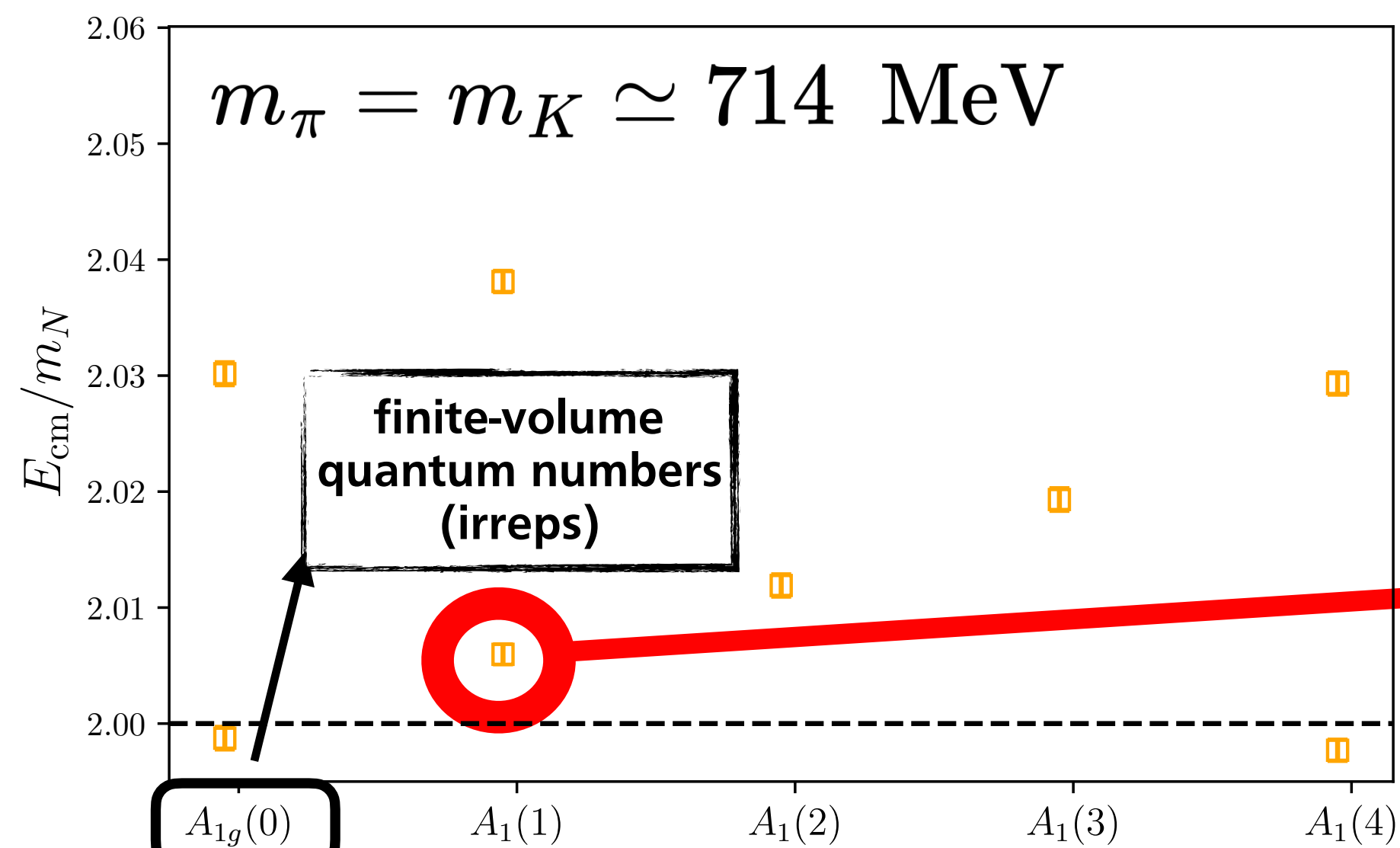
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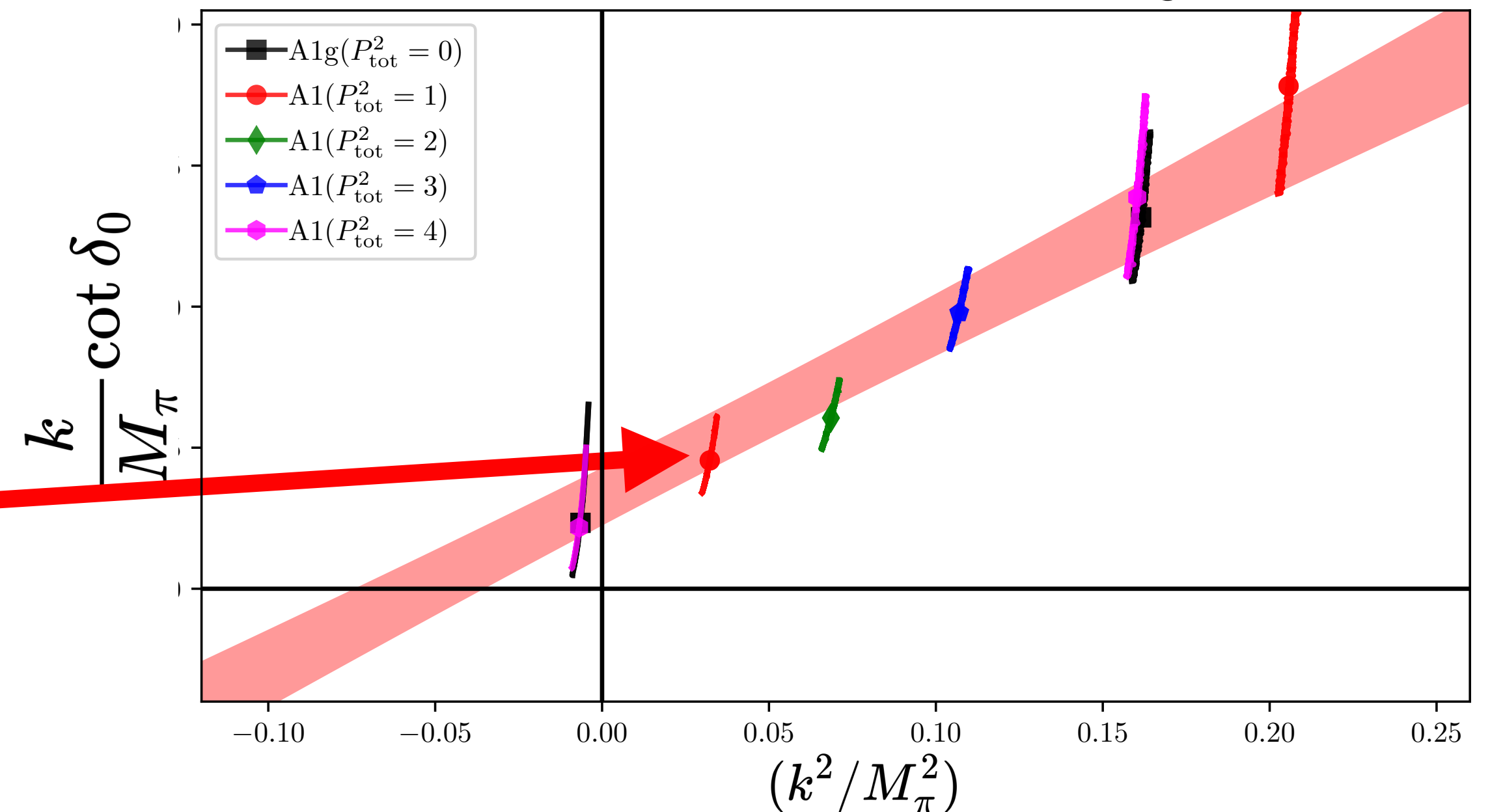
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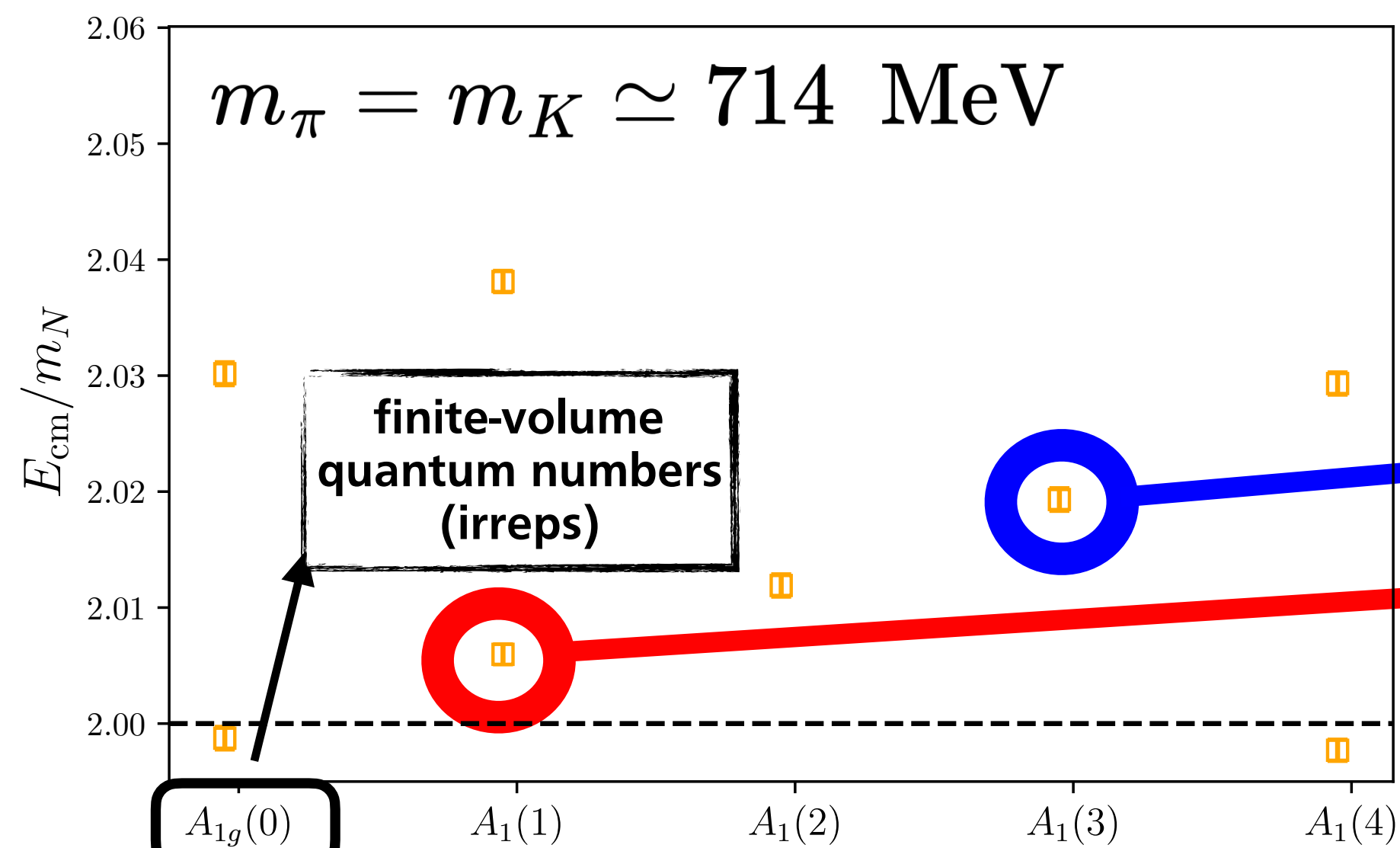
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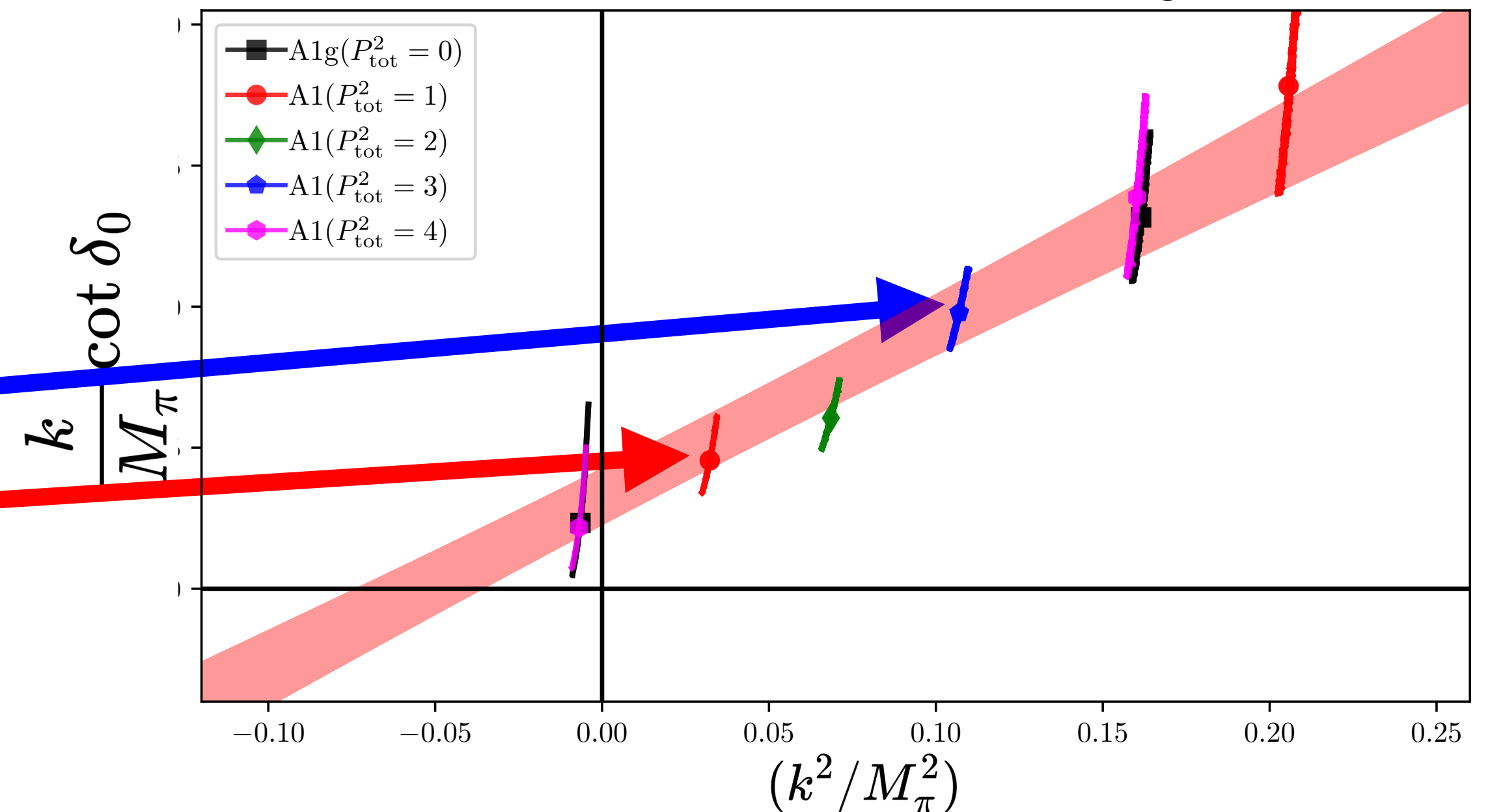
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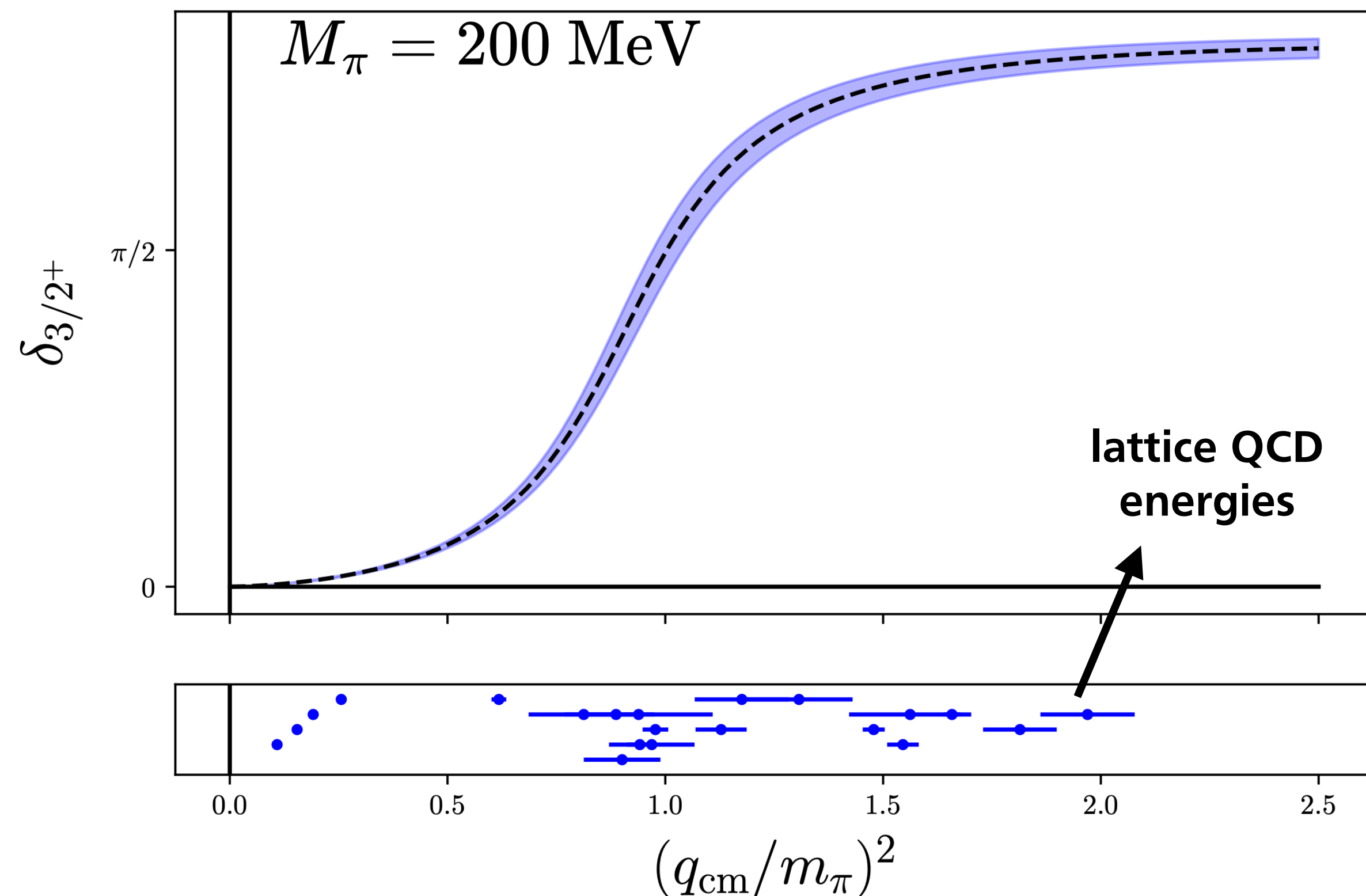
The $\Delta(1232)$ resonance

The $\Delta(1232)$ from LQCD

Lowest-lying baryon resonance

Lattice QCD

[Bulava, Hanlon, Hörz, Morningstar, Nicholson,
FRL, Skinner, Vranas, Walker-Loud, 2208.03867]

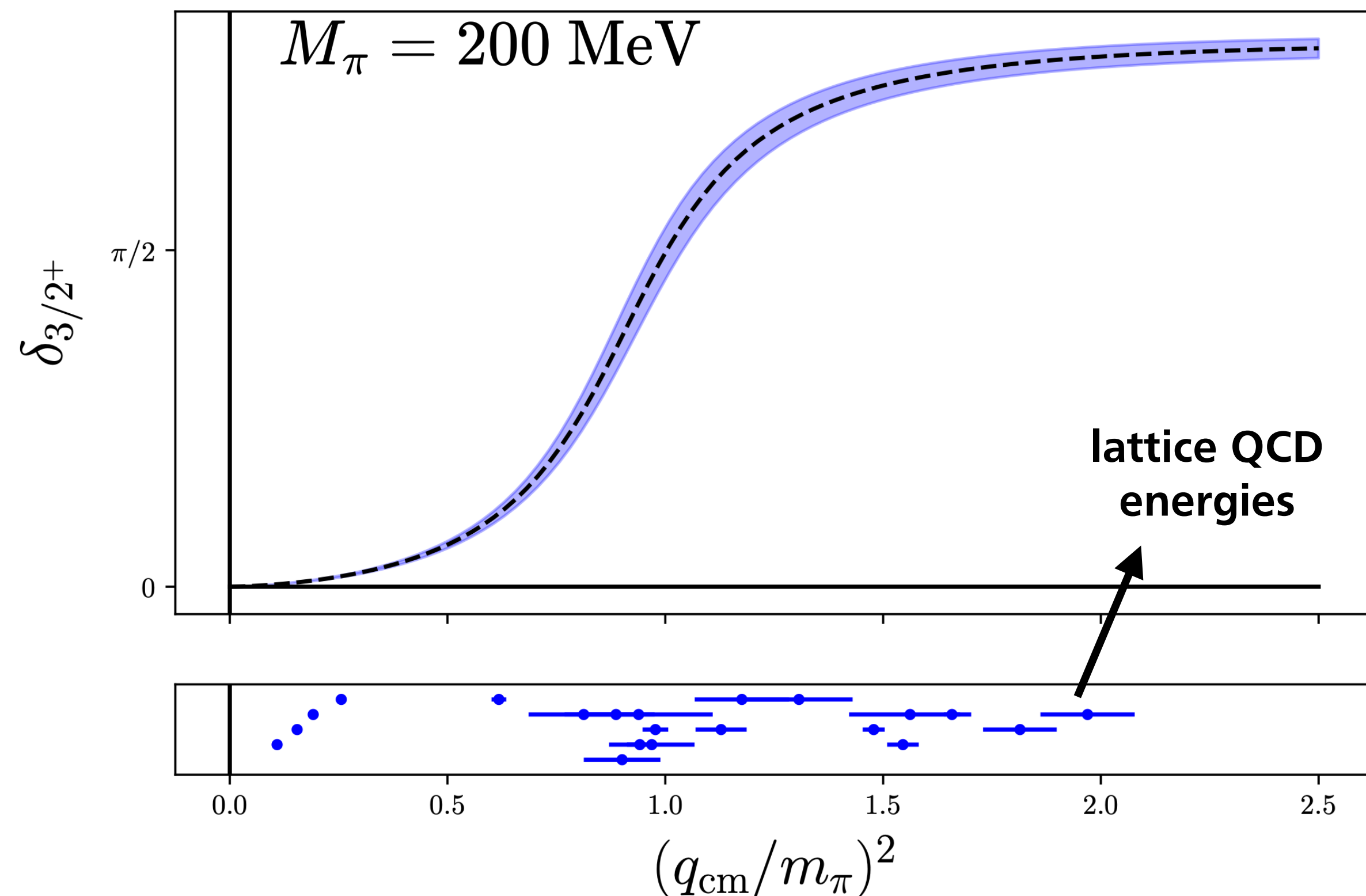


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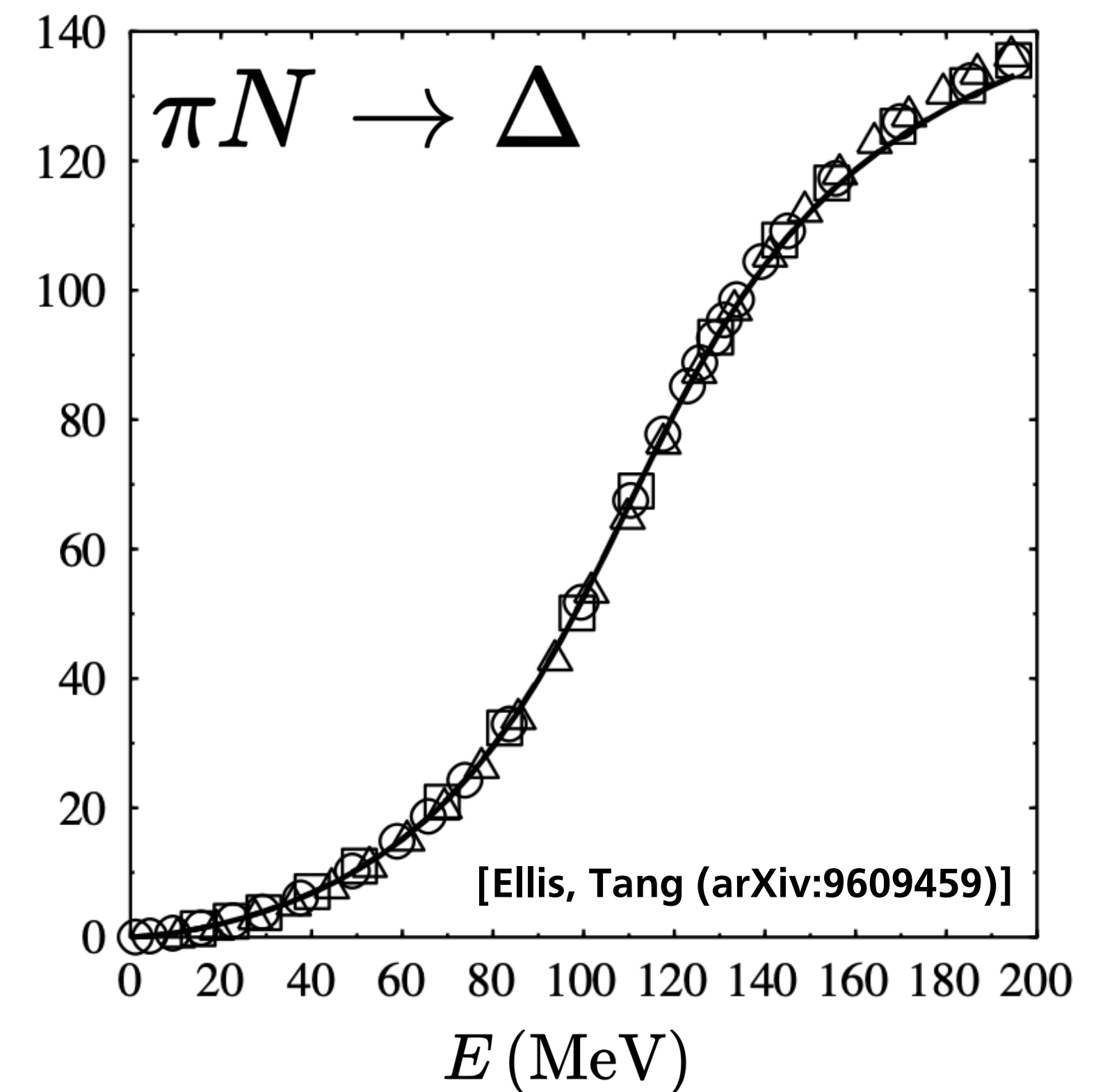
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scattering
phase δ_{P33} (deg)

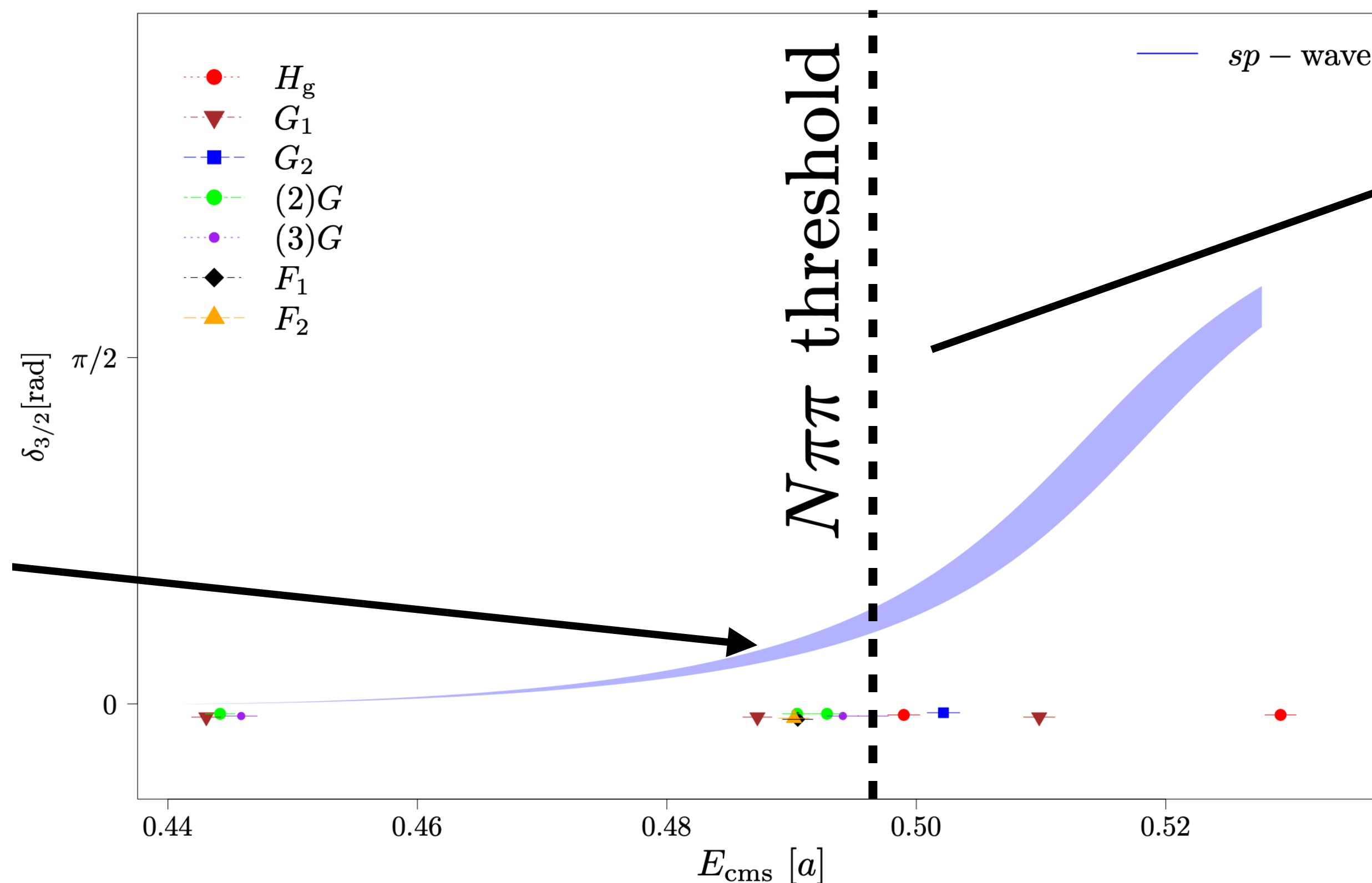
Experiment



The $\Delta(1232)$ from LQCD

Physical point calculation by the ETMC collaboration

[Alexandrou et al, 2307.12846]



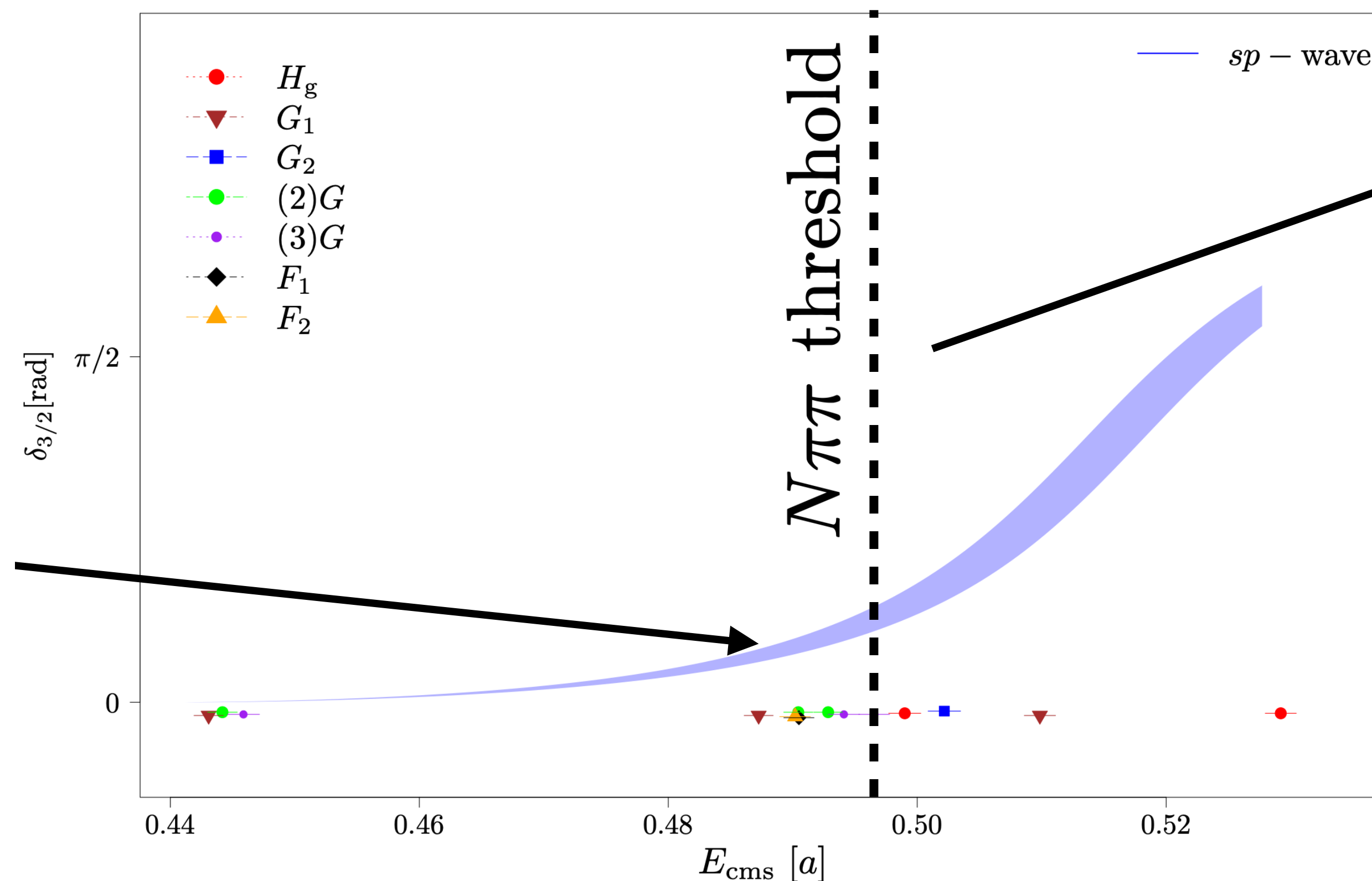
$M_R = 1269 (39)_{\text{Stat.}} (45)_{\text{Total}} \text{ MeV}$
 $\Gamma_R = 144 (169)_{\text{Stat.}} (181)_{\text{Total}} \text{ MeV},$

Inelastic threshold
makes physical-point
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Inelastic threshold
makes physical-point
calculations difficult

Still need formal
developments!

Coupled $\Sigma\pi$ -KN scattering & the $\Lambda(1405)$ resonance

[Bulava, Cid Mora, Hanlon, Hörz, Mohler, Morningstar, Moscoso, Nicholson, FRL, Skinner, Walker-Loud (Baryon Scattering Collaboration), 2307.13471 & 2307.10413]

PRL and PRD Editor's suggestion!

One or two resonances?

- Appears in coupled-channel scattering

$$\begin{pmatrix} \pi\Sigma \rightarrow \pi\Sigma & \pi\Sigma \rightarrow Kp \\ Kp \rightarrow \pi\Sigma & Kp \rightarrow Kp \end{pmatrix}$$

- Latest PDG lists two resonances in the energy region

$\Lambda(1405) \ 1/2^-$

$I(J^P) = 0(\frac{1}{2}^-)$ Status: ****



$\Lambda(1380) \ 1/2^-$

$J^P = \frac{1}{2}^-$ Status: **



**** Existence is certain.

*** Existence is very likely.

** Evidence of existence is fair.

* Evidence of existence is poor.

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Experiment:

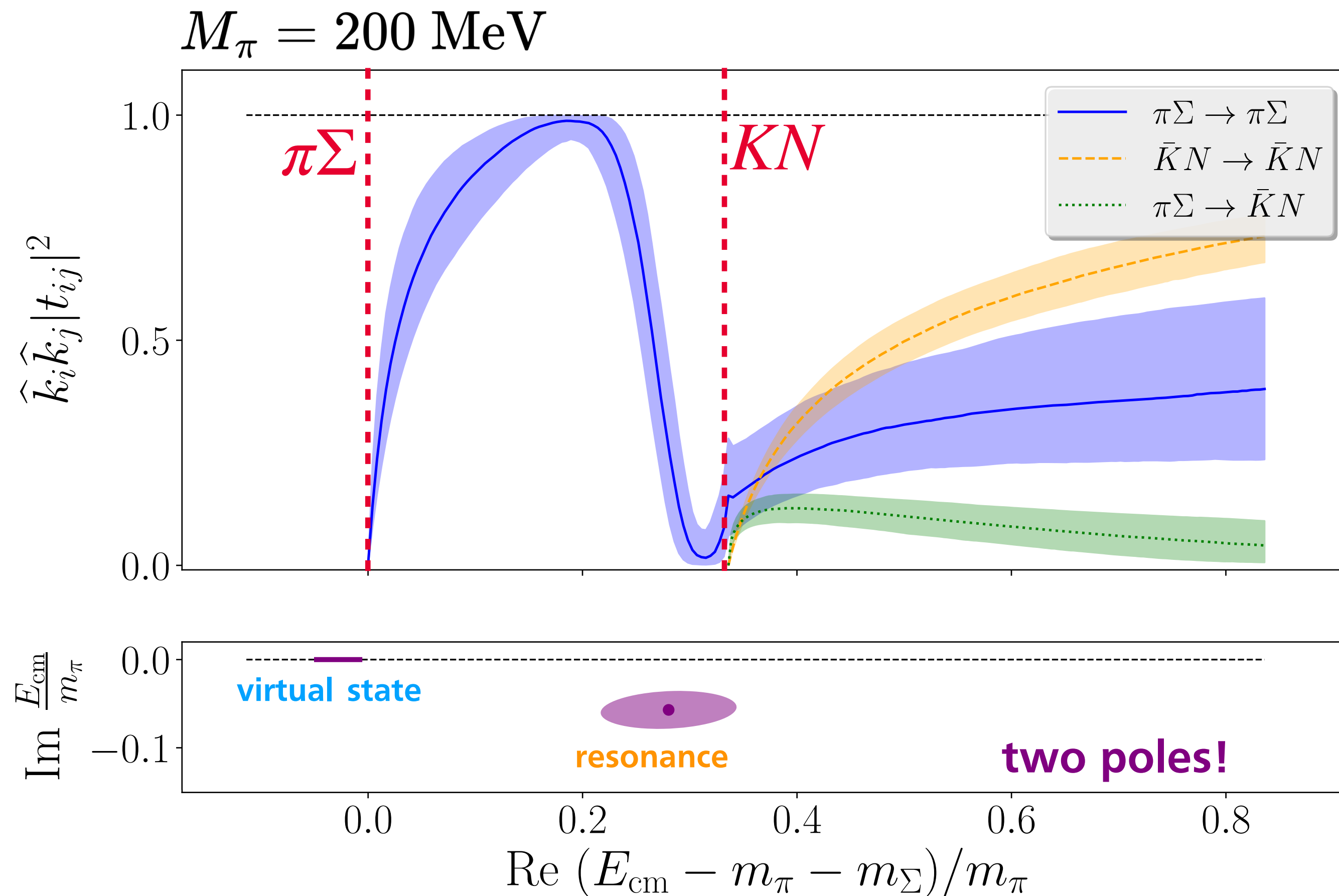
- ▶ CLAS, BGOOD, ALICE, GlueX favor **two poles**
[Mai, Meißner, EPJA 2014], [Roca, Oset, PRC 2013], [ALICE, arXiv:2205.15176]
[BGOOD, arXiv:2108.12235], [Wickramaarachchi et al, 2209.06230]
- ▶ J-PARC consistent with **one pole**. [arXiv:2209.08254]
- ▶ A multi-experiment analysis favors **one pole**
[Anisovich et al, EPJA 2020]

Theory:

- ▶ Simple quark models predict **one state**
[Isgur, Karl PRD 1987]
- ▶ Chiral Unitarity approach predicts **two poles**
[Oller, Meißner, hep-ph/0402261] See review: [Mai, arXiv:2010.00056]
- ▶ Lattice QCD studies, but no coupled scattering
[Gubler et al PRD 2016], [Menadue et al PRL 2012], [Engel et al PRD 2013],
[Hall et al, PRL 2015], [Takahashi, Oka, PRD 2010]

This work!

Amplitudes and two poles



[Bulava, Cid Mora, Hanlon, Hörz, Mohler, Morningstar, Moscoso, Nicholson, FRL, Skinner, Walker-Loud, 2307.13471 & 2307.10413]

Virtual bound state

$$E_1 = 1392(9)_{\text{stat}}(2)_{\text{model}}(16)_a \text{ MeV}$$

$$\left| \frac{c_{\pi\Sigma}^{(1)}}{c_{\bar{K}N}^{(1)}} \right| = 1.9(4)_{\text{stat}}(6)_{\text{model}}$$

Stronger coupling to $\pi\Sigma$

Resonance pole

$$E_2 = [1455(13)_{\text{stat}}(2)_{\text{model}}(17)_a - i \times 11.5(4.4)_{\text{stat}}(4.0)_{\text{model}}(0.1)_a] \text{ MeV}$$

$$\left| \frac{c_{\pi\Sigma}^{(2)}}{c_{\bar{K}N}^{(2)}} \right| = 0.53(9)_{\text{stat}}(10)_{\text{model}}$$

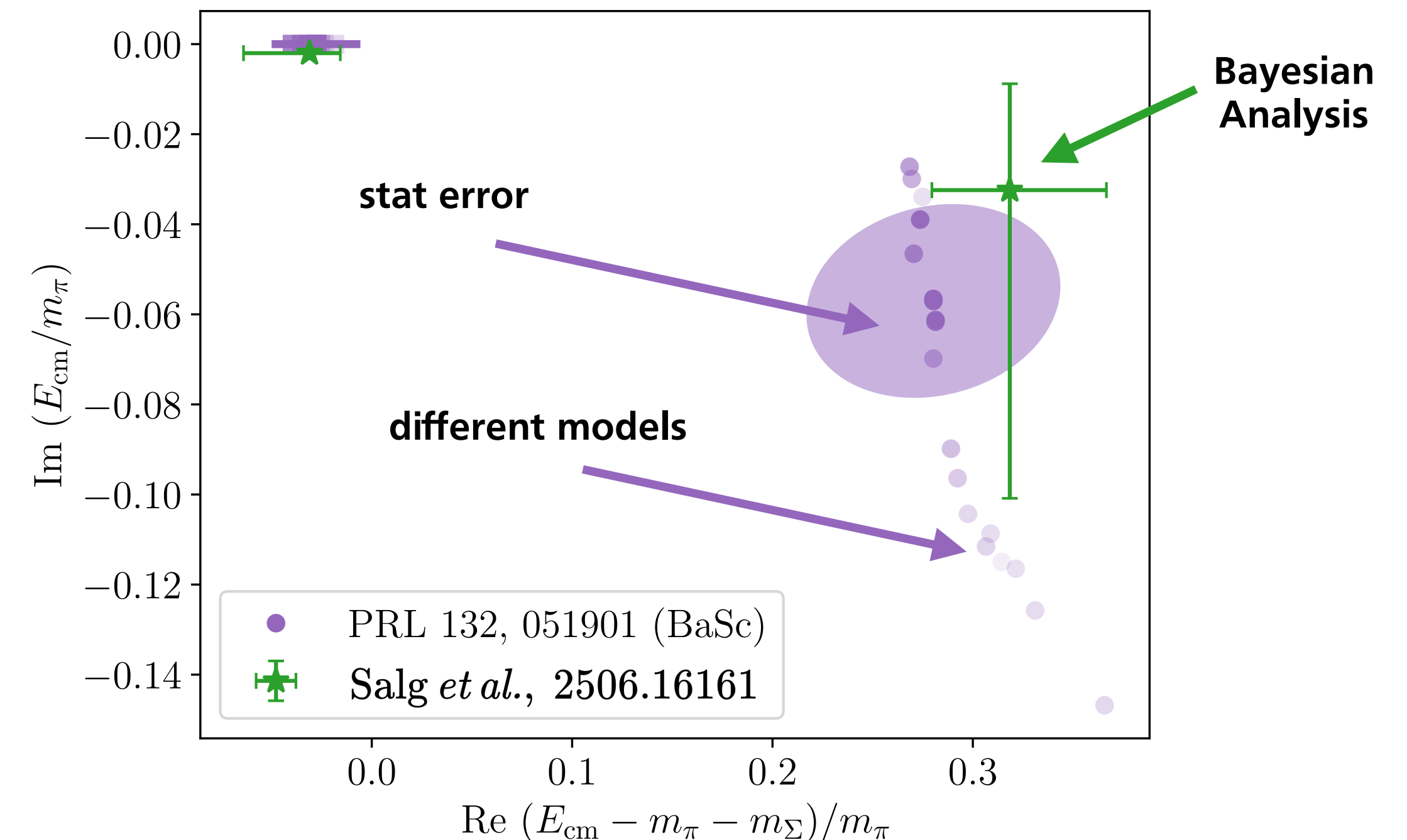
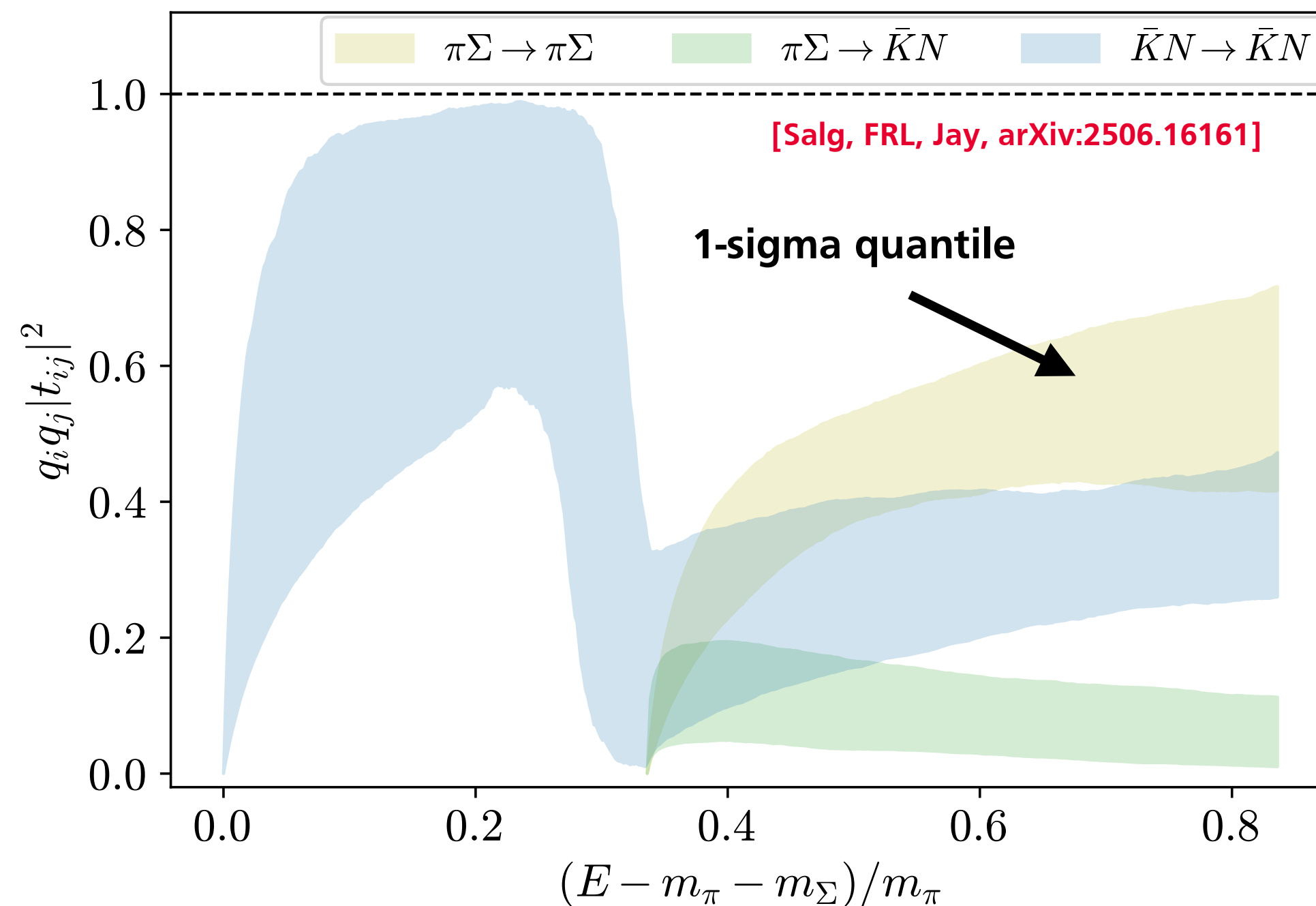
Stronger coupling to KN

Bayesian analysis

- Scattering calculations have significant model dependence
 - Bayesian framework for improved uncertainty quantification
 - Similar to Gaussian processes
 - Errors combine statistical error and model dependence



Led by Miguel Salg (Uni Bern)

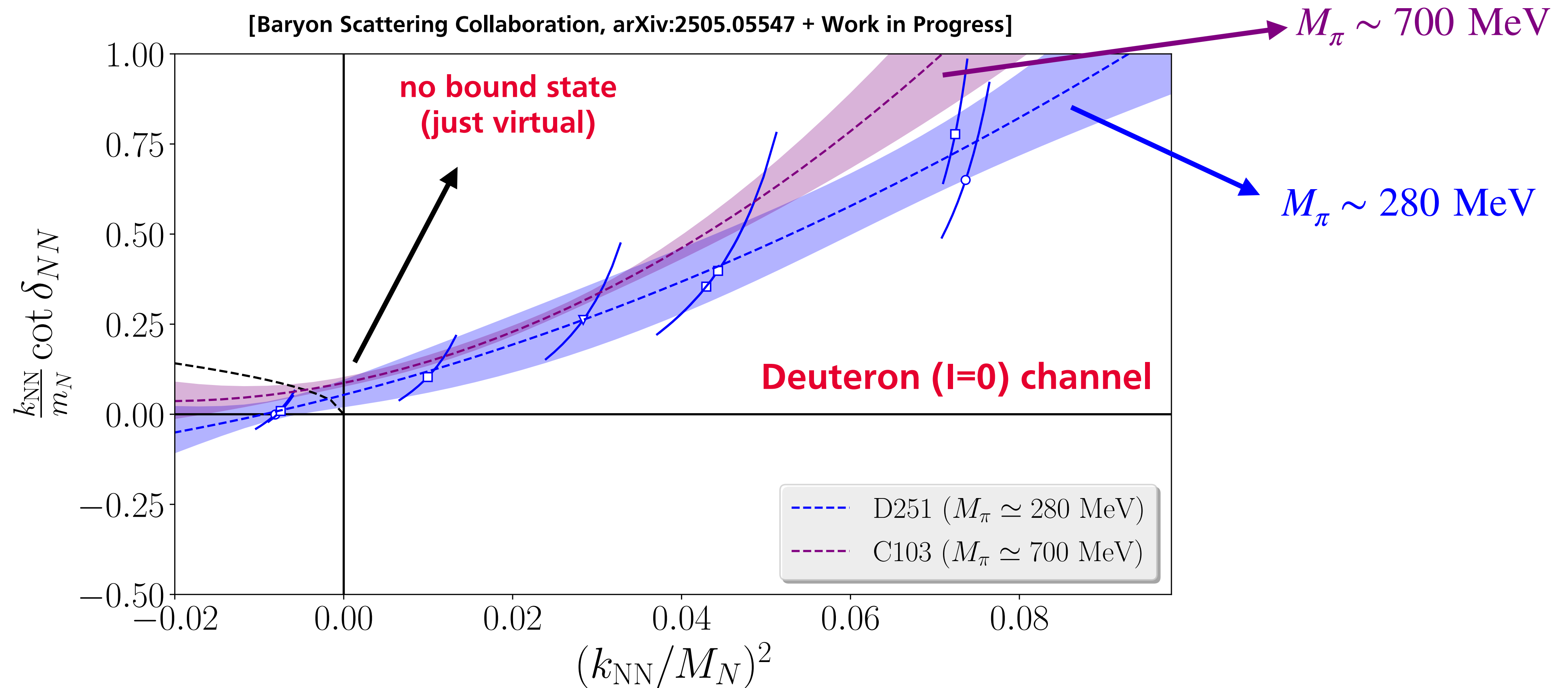


NN scattering

NN scattering

Lattice QCD Calculations of NN scattering advancing towards the physical point

[Baryon Scattering Collaboration, arXiv:2505.05547 + Work in Progress]



The three-hadron frontier from LQCD

Why three particles?

- Studying higher lying resonances needs the addition of three-body final states

- ▶ Roper: $N(1440) \rightarrow \Delta\pi \rightarrow N\pi\pi$

- Similarly, in many-body nuclear physics there are many relevant three-body effects:

- ▶ 3N force
 - ▶ Tritium nucleus

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- ☑ Major developments in the three-particle finite-volume formalism

[Hansen, Sharpe, PRD 2014 & 2015], [Hammer, Pang, Rusetsky, JHEP 2017] x 2

[Mai, Döring, EPJA 2017]

[...]

[Draper, Hansen, FRL, Sharpe, JHEP 2023]: **Formalism for three nucleons**

[Hansen, FRL, Sharpe, JHEP 2024]: **Formalism for the T_{cc}**

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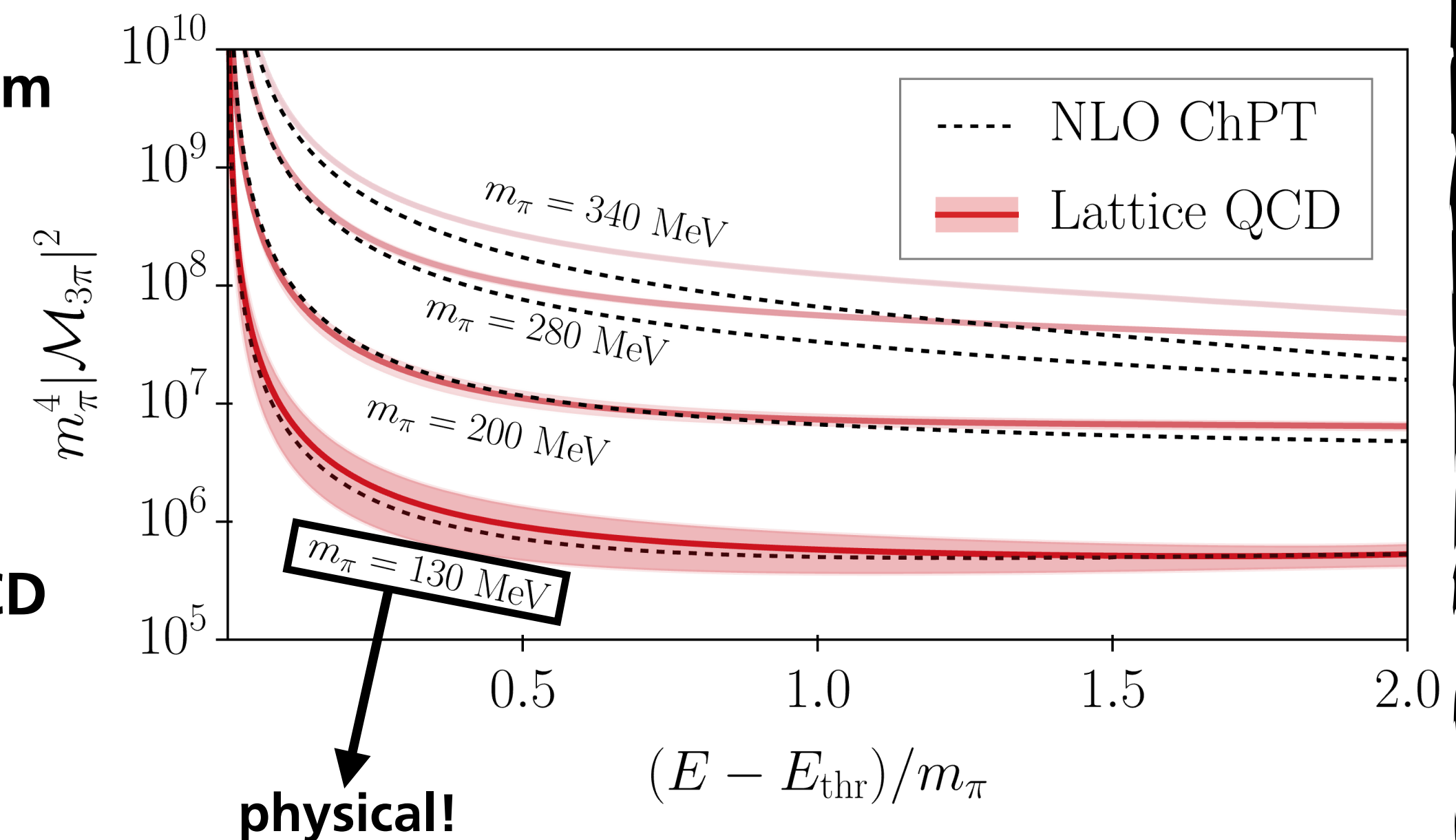
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- ☑ Determination of the physical three-meson amplitude from LQCD

[Dawid, Draper, Hanlon, Hörz, Morningstar, FRL, Sharpe, Skinner, arXiv:2502.17976,2502.13978]



Towards $N\pi\pi$ systems

- $N\pi\pi$ effects are crucial to understand nucleon excitations.
- Accessing the Roper Resonance is a long-standing challenge for lattice QCD
 - ▶ Complete finite-volume formalism not ready yet

$$N(1440) \rightarrow N\pi + N\pi\pi$$

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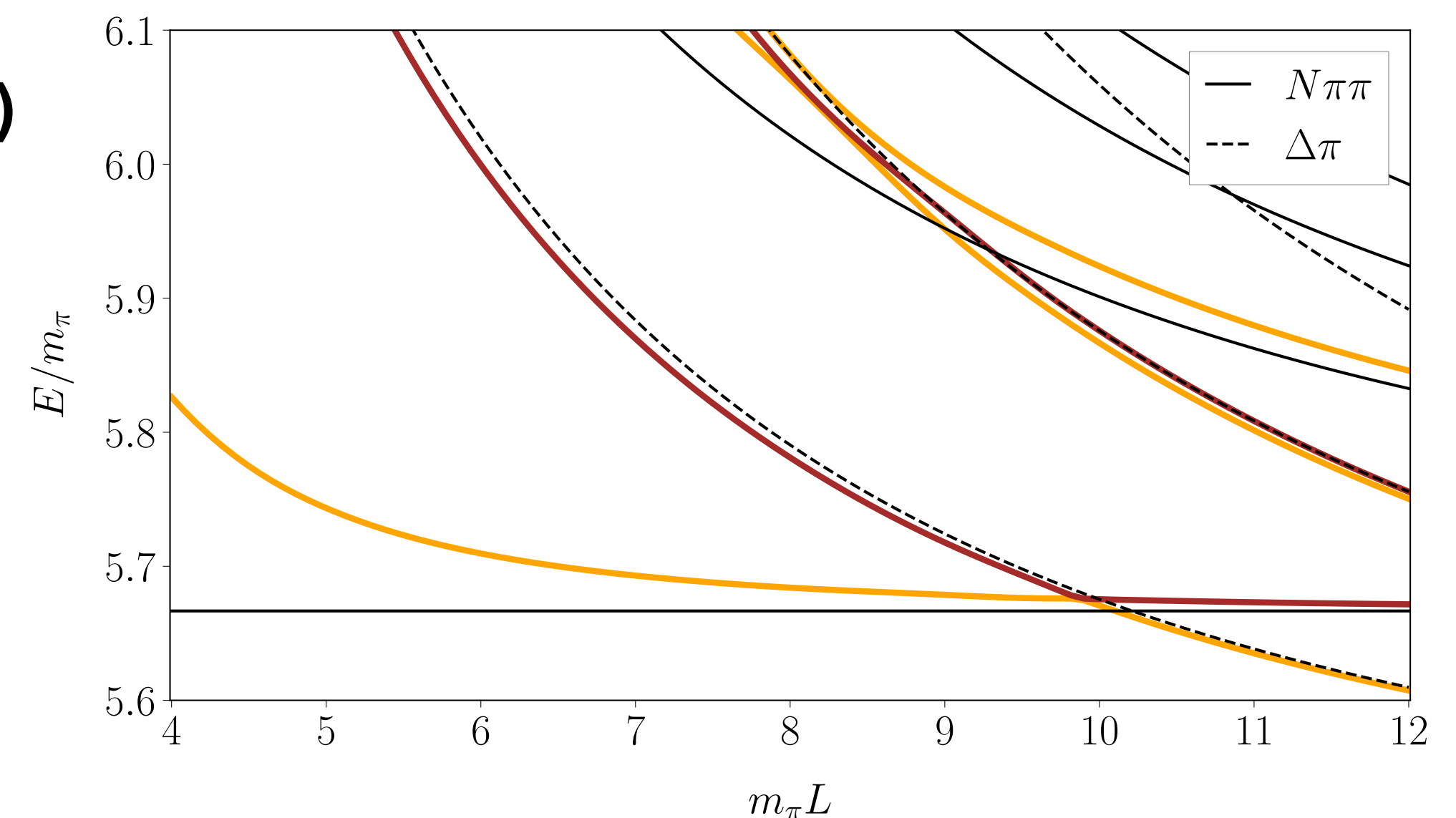
$$N(1440) \rightarrow N\pi + N\pi\pi$$

- First step, formalism for systems at maximal isospin ($p\pi^+\pi^+$)

- No mixing with two-hadron systems
- But Δ baryon contributes ($\Delta\pi$ scattering)

Toy implementation:

mimics $M_\pi \sim 300$ MeV case with stable Δ

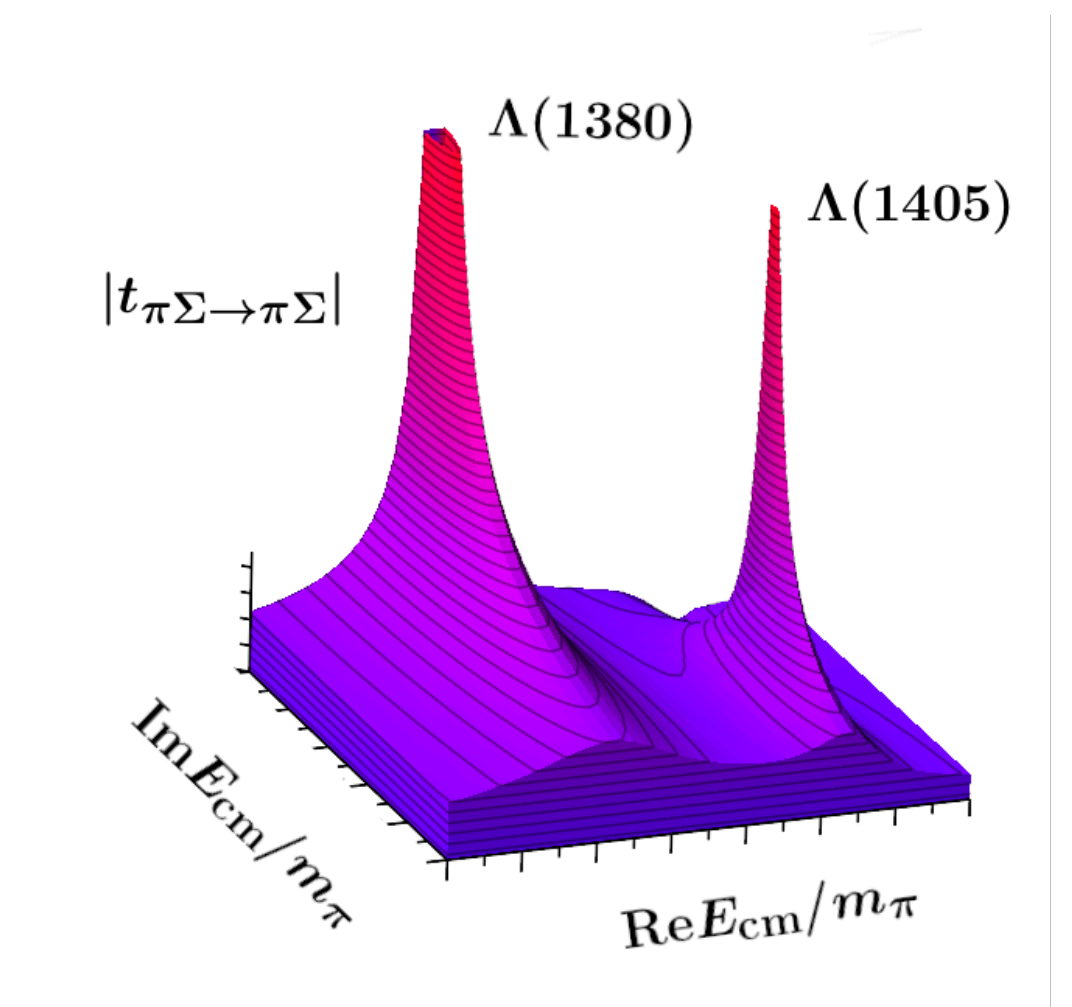


[Hansen, FRL, Sharpe, arXiv:2509.24778]

Summary and Outlook

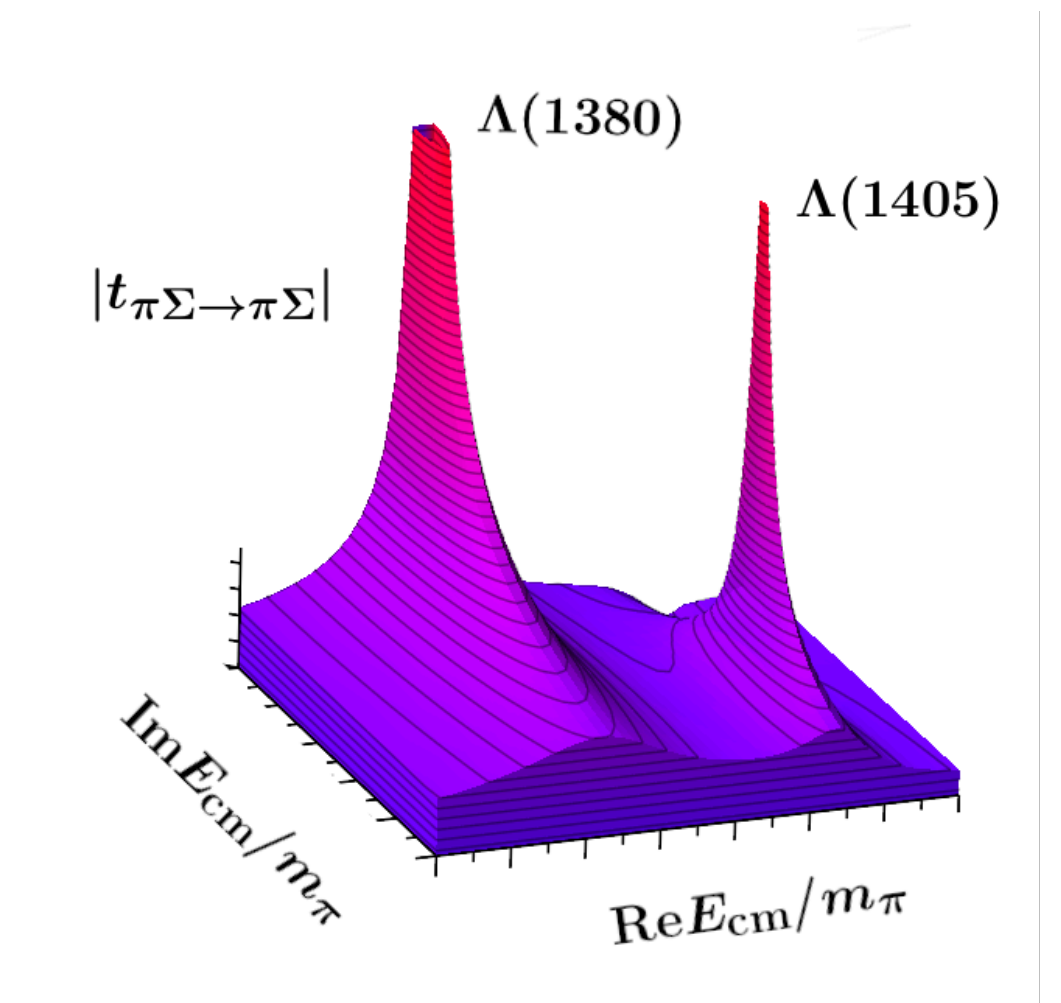
Summary and outlook

- ✓ Lattice QCD provides a first-principle tool to investigate the hadron spectrum
- ✓ Results for two-hadron systems: NN , $\Delta(1232)$, $\Lambda(1405)$.
- ✓ First results on three-particle scattering amplitudes
- ✓ Formalism towards $N\pi\pi$ systems



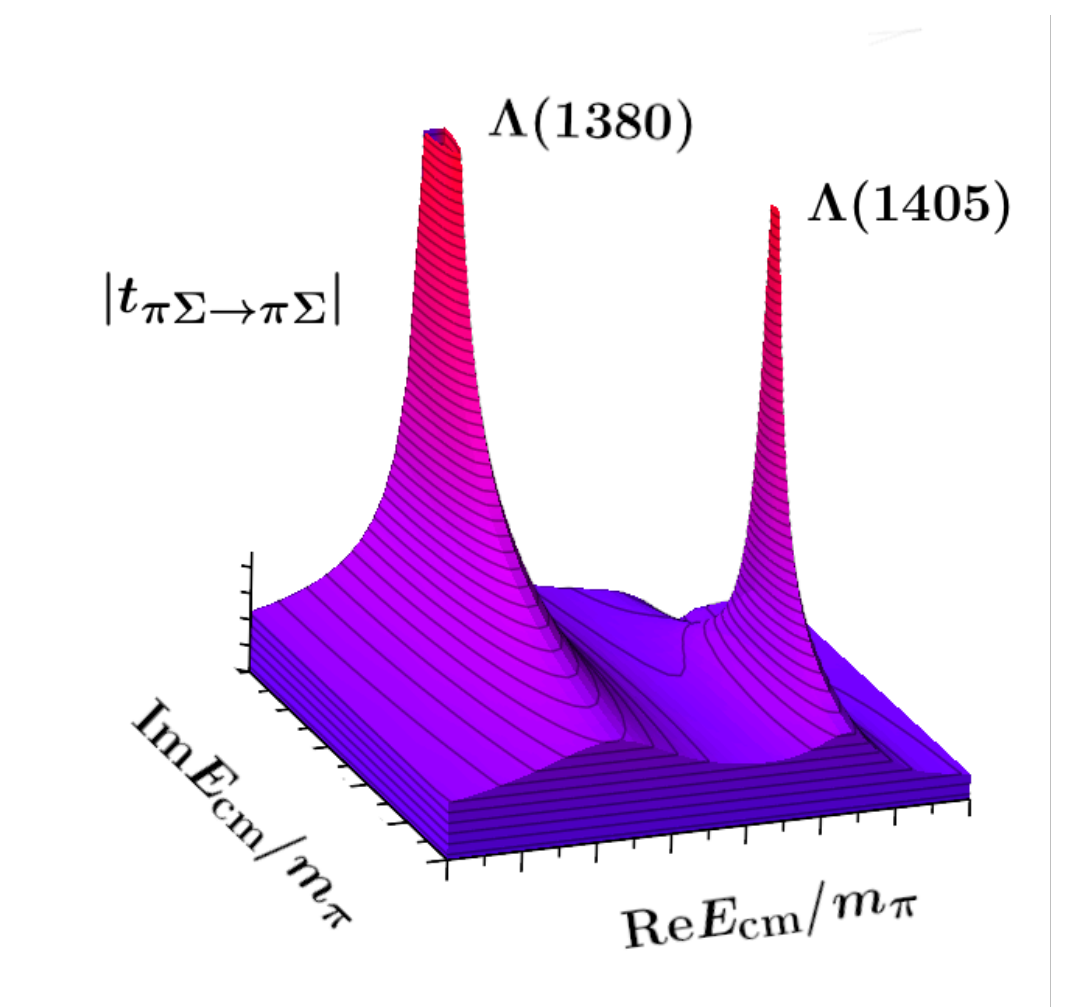
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- ✓ Formalism towards $N\pi\pi$ systems
- Present frontier: lattice data for baryon systems with physical quark masses
 - ➡ Work in progress with the Baryon Scattering Collaboration (BaSc)
- Further theoretical developments & applications are necessary!
 - ➡ Roper resonance $N(1440) \rightarrow N\pi, N\pi\pi$
 - ➡ Four or more particle resonances



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- ✓ Formalism towards $N\pi\pi$ systems
- Present frontier: lattice data for baryon systems with physical quark masses
 - ➡ Work in progress with the Baryon Scattering Collaboration (BaSc)
- Further theoretical developments & applications are necessary!
 - ➡ Roper resonance $N(1440) \rightarrow N\pi, N\pi\pi$
 - ➡ Four or more particle resonances



Thanks!