Exotic Tetraquark in $cc\bar{q}_1\bar{q}_2$ channel

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Trends in Astroparticle and Particle Physics

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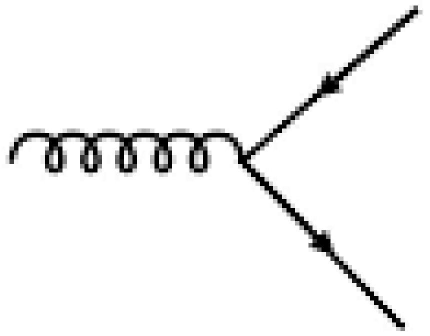
Quantum Chromodynamics

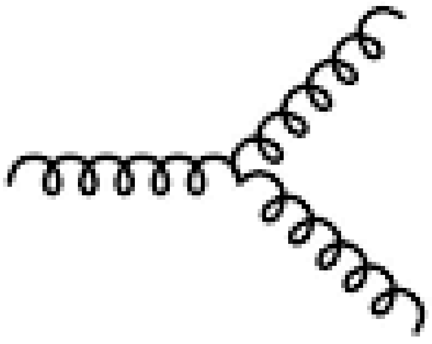
$$\mathcal{L}_{QCD} = \sum_i^{N_f} \bar{q}_i \left(D_\mu \gamma^\mu + m_i\right) q_i - \frac{1}{4g_s^2} G_{\mu\nu} G^{\mu\nu}$$

where, $D_\mu = \partial_\mu - i g_s \sum_{i=1}^{8} \lambda^a A_{a\mu}$

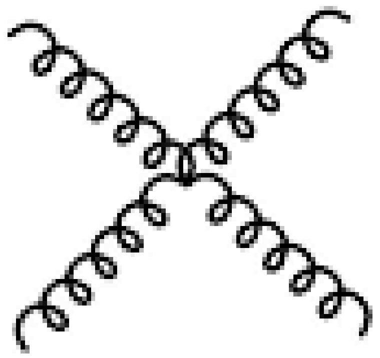
$$G_{\mu\nu} = [D_\mu, D_\nu]$$



Analogous to photon exchange of QED



3-gluon vertex



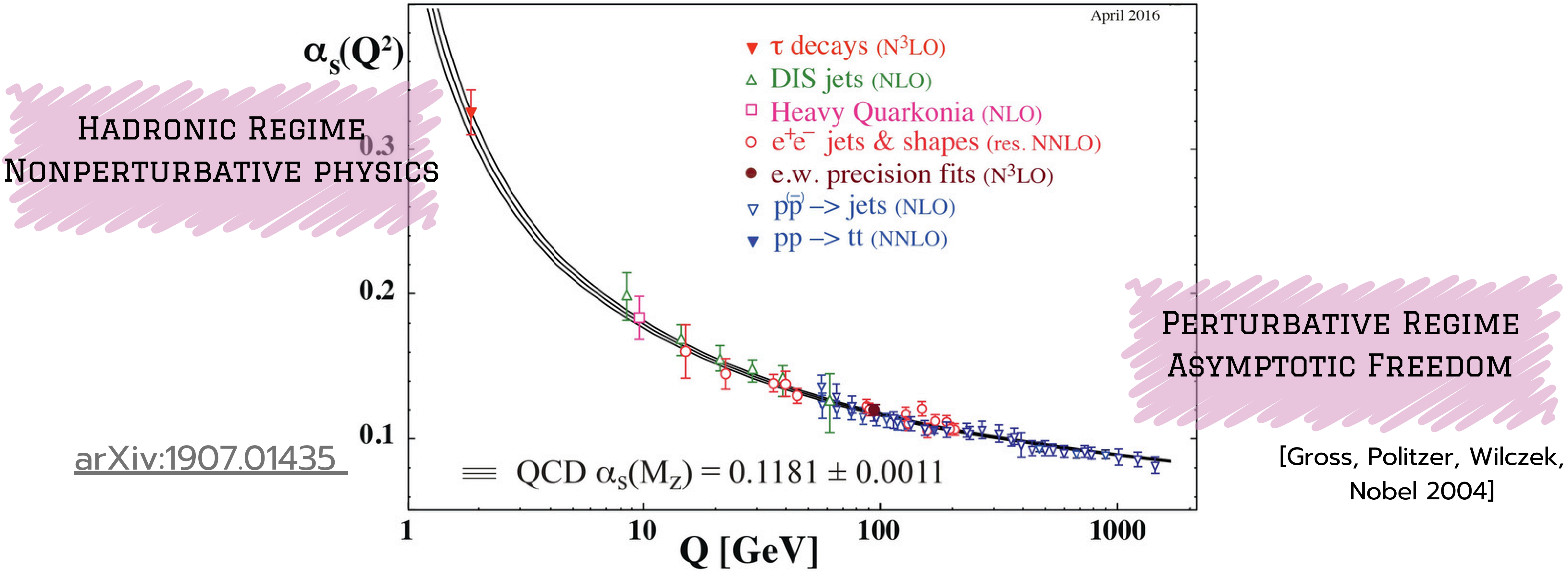
4-gluon vertex

Laure Massacrier
JRJC 2017

Fernando Romero-López
Lattice Practices 2024

The QCD coupling

Perturbative approaches fail in the hadronic regime.



arXiv:1907.01435

[Gross, Politzer, Wilczek, Nobel 2004]

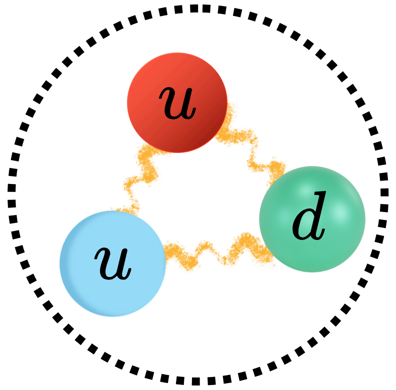
Nonperturbative approaches required for first principles investigation: Lattice QCD

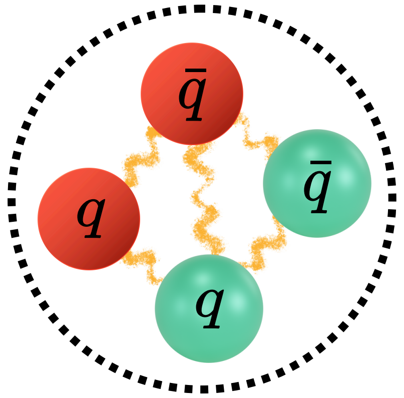
Hadrons

Composite subatomic particles made of quarks held together by the strong interaction.

Baryons

e.g. Proton





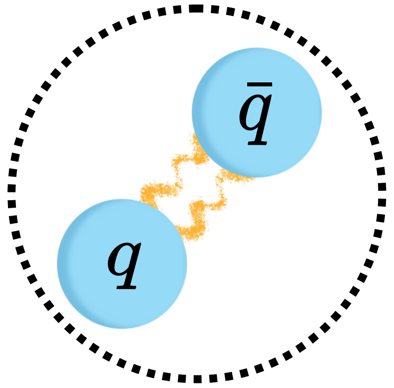
tetraquarks

Standard Hadrons

Exotic Hadrons

Mesons

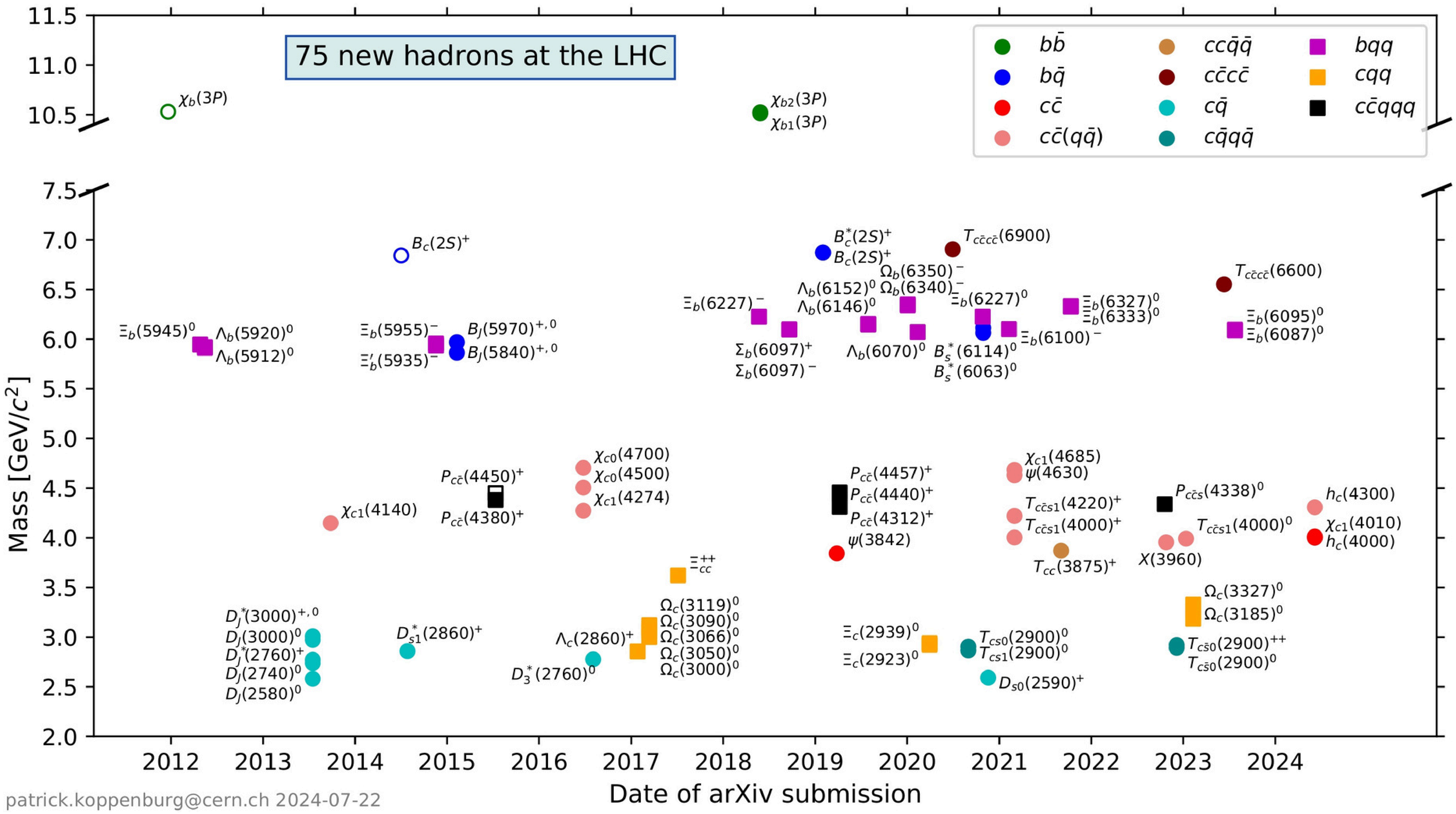
e.g. π, K



$+$ other structures

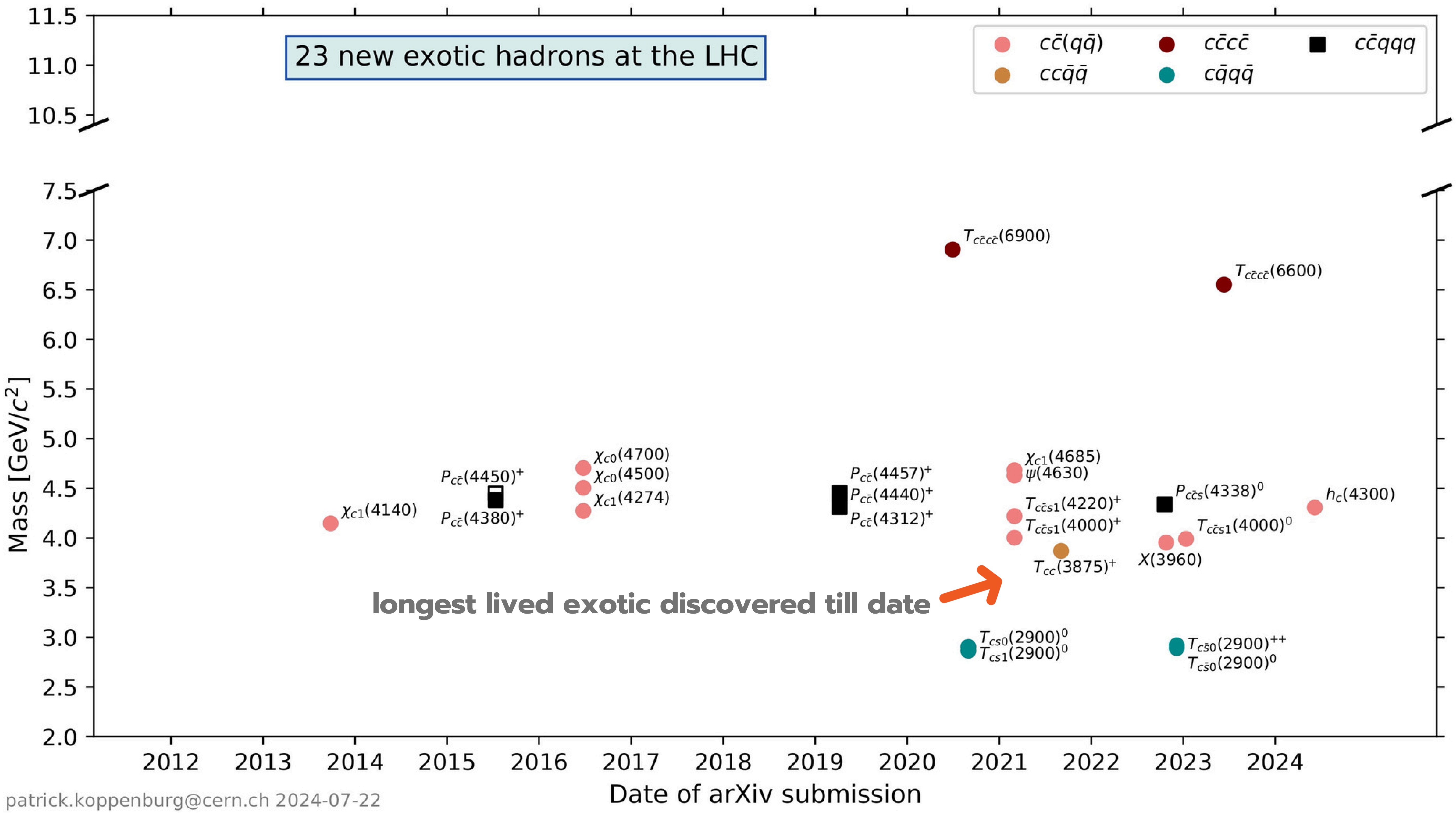
e.g. pentaquarks

We assume isospin symmetry and only strong interaction.



https://www.nikhef.nl/~pkoppenb/particles.html

Summary of LHC Discoveries



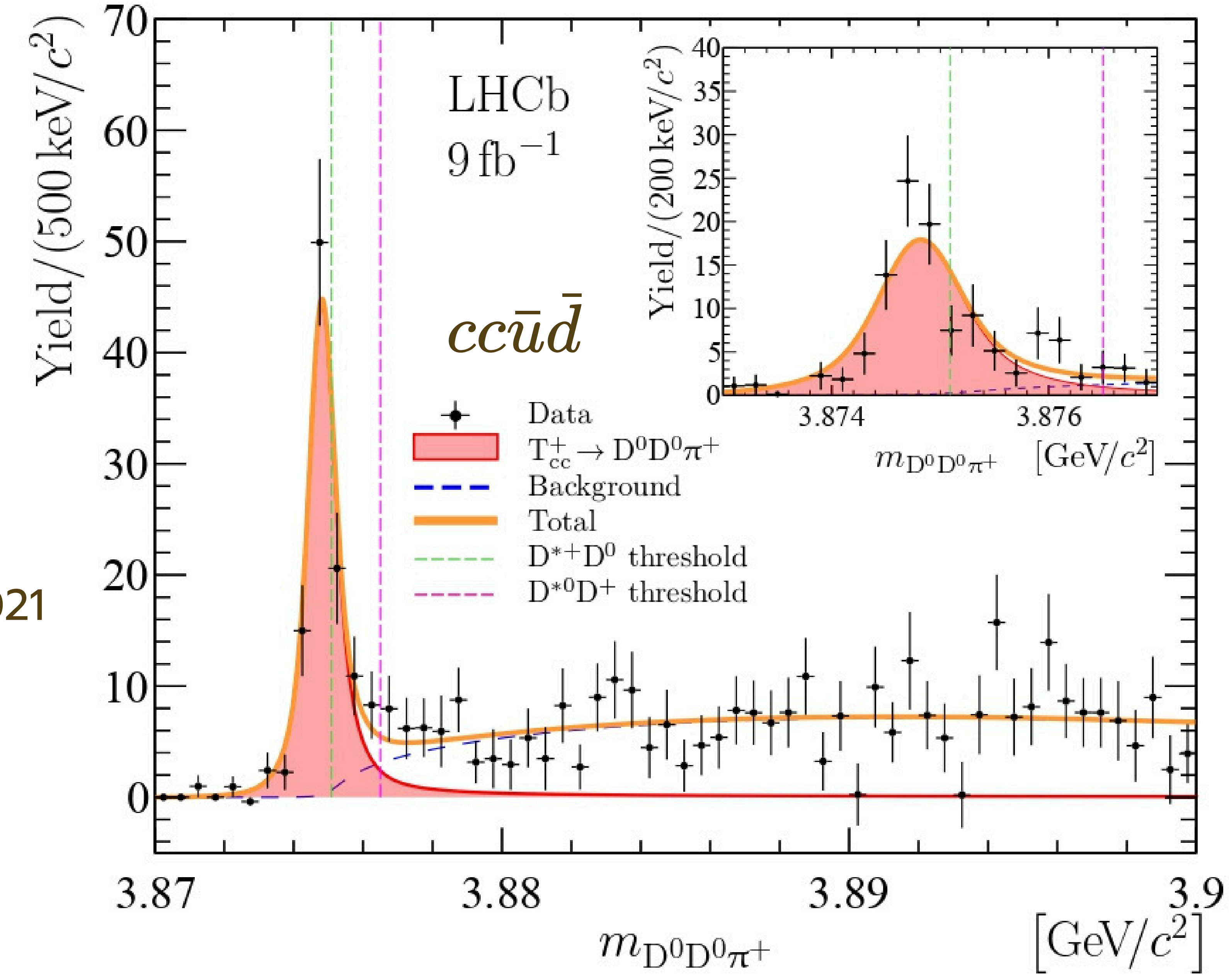
https://www.nikhef.nl/~pkoppenb/particles.html

Summary of Exotics Discovered

- **The LHCb collaboration discovered an exotic narrow resonance $T_{cc}^{+}(3875)$**
- **An isoscalar state with $J^P = 1^+$**
- **It is the longest lived exotic discovered till date.**
- **Many works on D^*D scattering including lattice calculations.**

Phys. Rev. Lett. 129, 032002 (2022): First extraction of amplitude

R.Aaij *et. al.* 2021
2109.01038

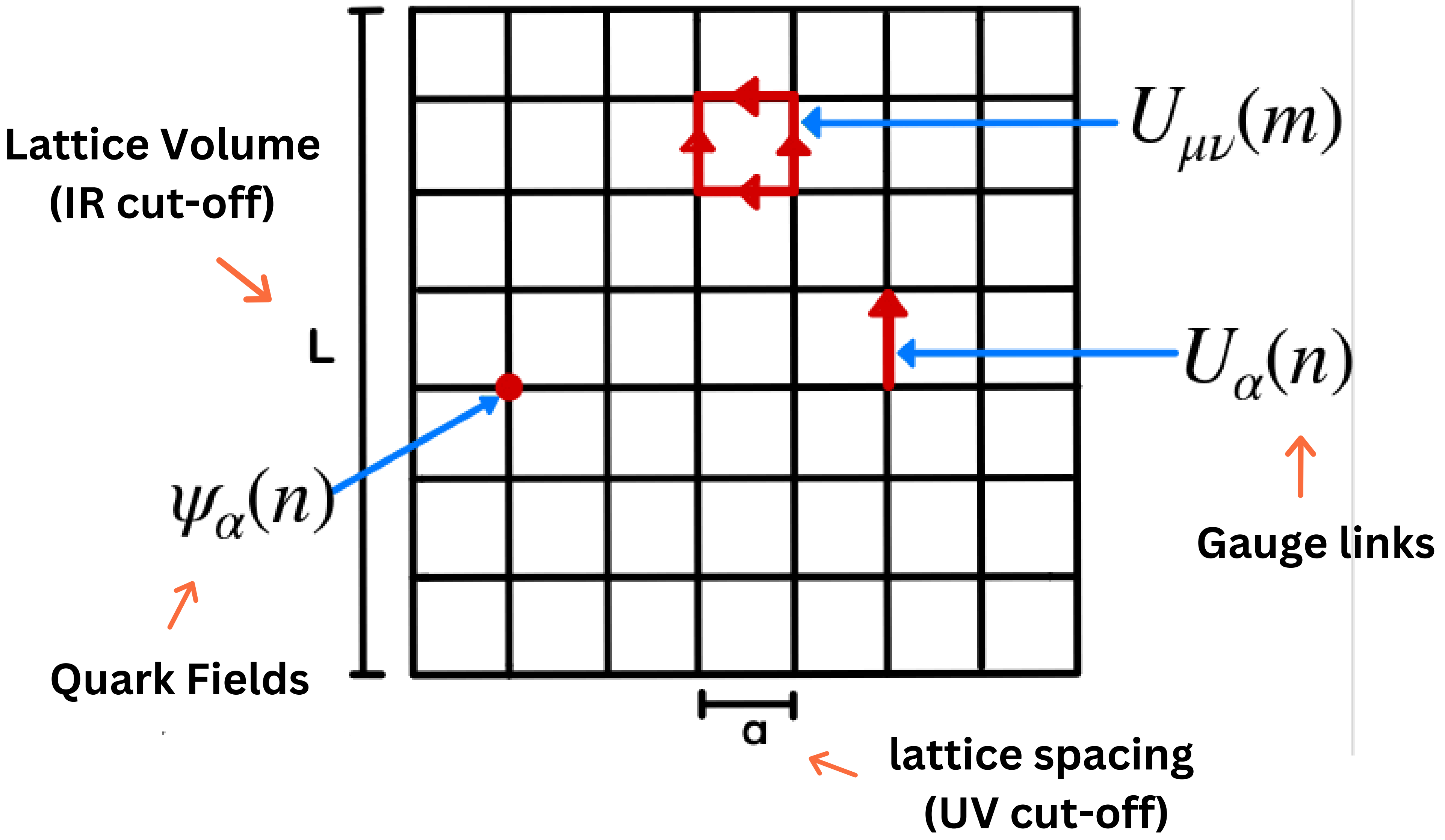


- **The next potential candidate could be a tetraquark with flavor content**

$$cc\bar{u}\bar{s}$$

Lattice QCD: theoretical aspects

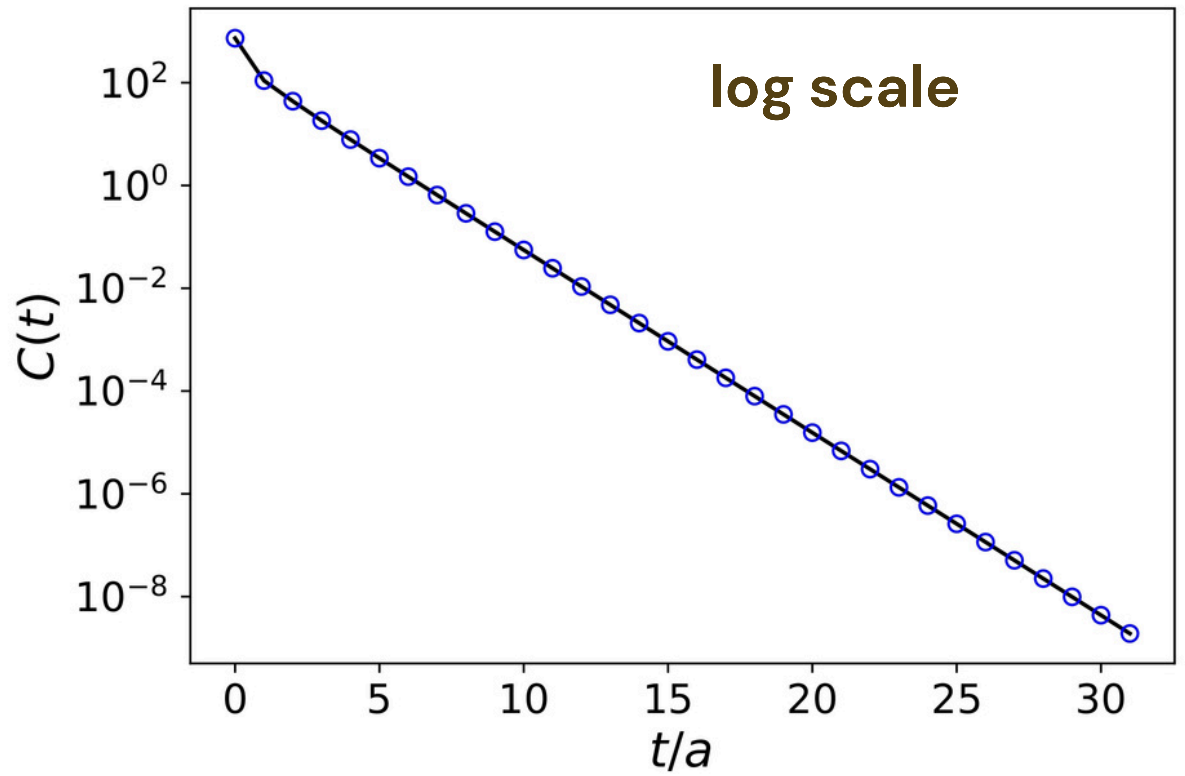
- A non-perturbative, gauge invariant *regulator* for the QCD path integrals.
- Redefine the theory on a discretized Euclidean space-time.
- The phase space is sampled using importance sampling procedures such as Markov Chain Monte Carlo algorithms.



Energies from Correlations

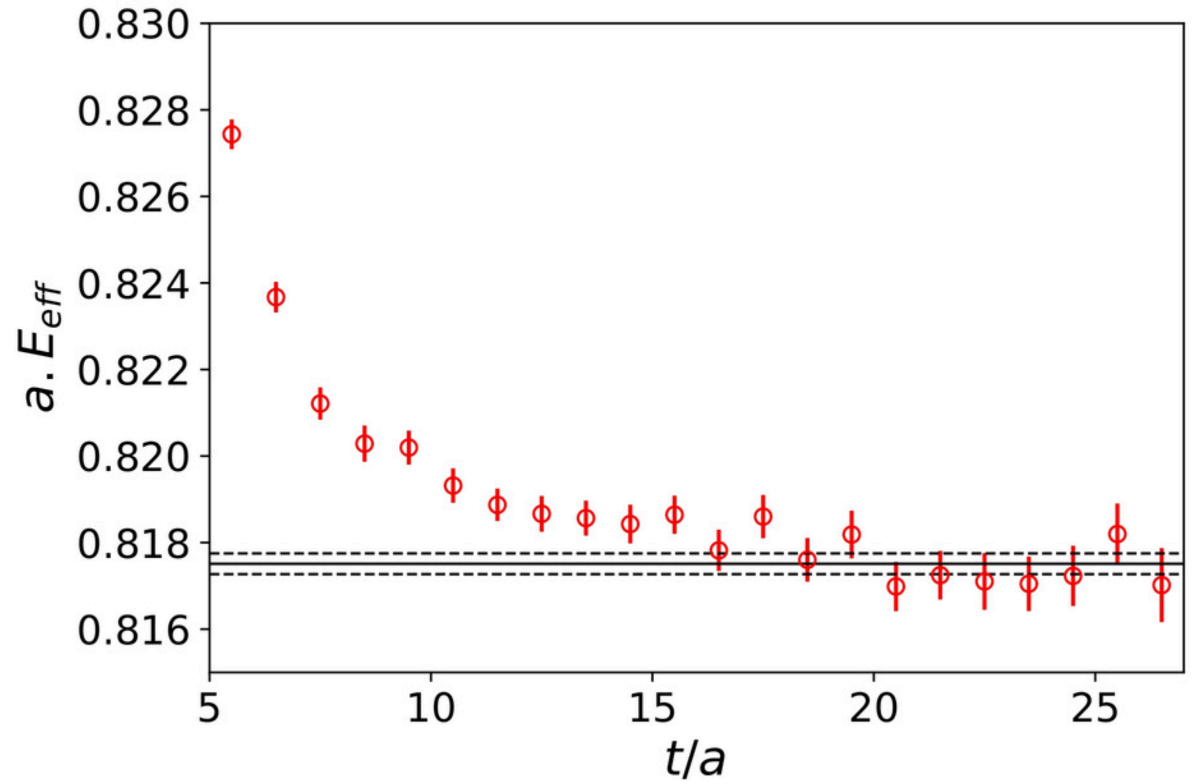
Spectral-Decomposition

$$\mathcal{C}(t) = \langle \hat{\phi}^\dagger(t)\hat{\phi}(0)\rangle = \sum_n \langle 0|\hat{\phi}^\dagger(t)|n\rangle\langle n|\hat{\phi}(0)|0\rangle$$
$$= \sum_n \langle 0|e^{i\mathcal{H}t}\hat{\phi}^\dagger(0)e^{-i\mathcal{H}t}|n\rangle\langle n|\hat{\phi}(0)|0\rangle$$
$$= \sum_n |\langle 0|\hat{\phi}(0)|n\rangle|^2 e^{-\mathcal{E}_n t}$$



Ground State

$$\lim_{t\to\infty} \mathcal{C}(t) = \mathcal{A}_0 e^{-\mathcal{E}_0 t}$$



Beyond Ground State

Compute matrix of Euclidean correlations using a basis of operators with desired quantum numbers.

$$\mathcal{C}_{ij}(t) = \langle \hat{\phi}_i(t)\hat{\phi}_j^{\dagger}(0)\rangle = \sum_n e^{-\mathcal{E}_n t}\langle 0|\hat{\phi}_i(0)|n\rangle\langle n|\hat{\phi}_j^{\dagger}(0)|0\rangle$$

Variationally determine the optimal linear combinations to describe the time evolution of excited states.

Variational procedure (Generalised EigenValue Problem) →

Adjoint sources in lattice gauge theory
C. Michael (1985)

ELSEVIER

Nuclear Physics B

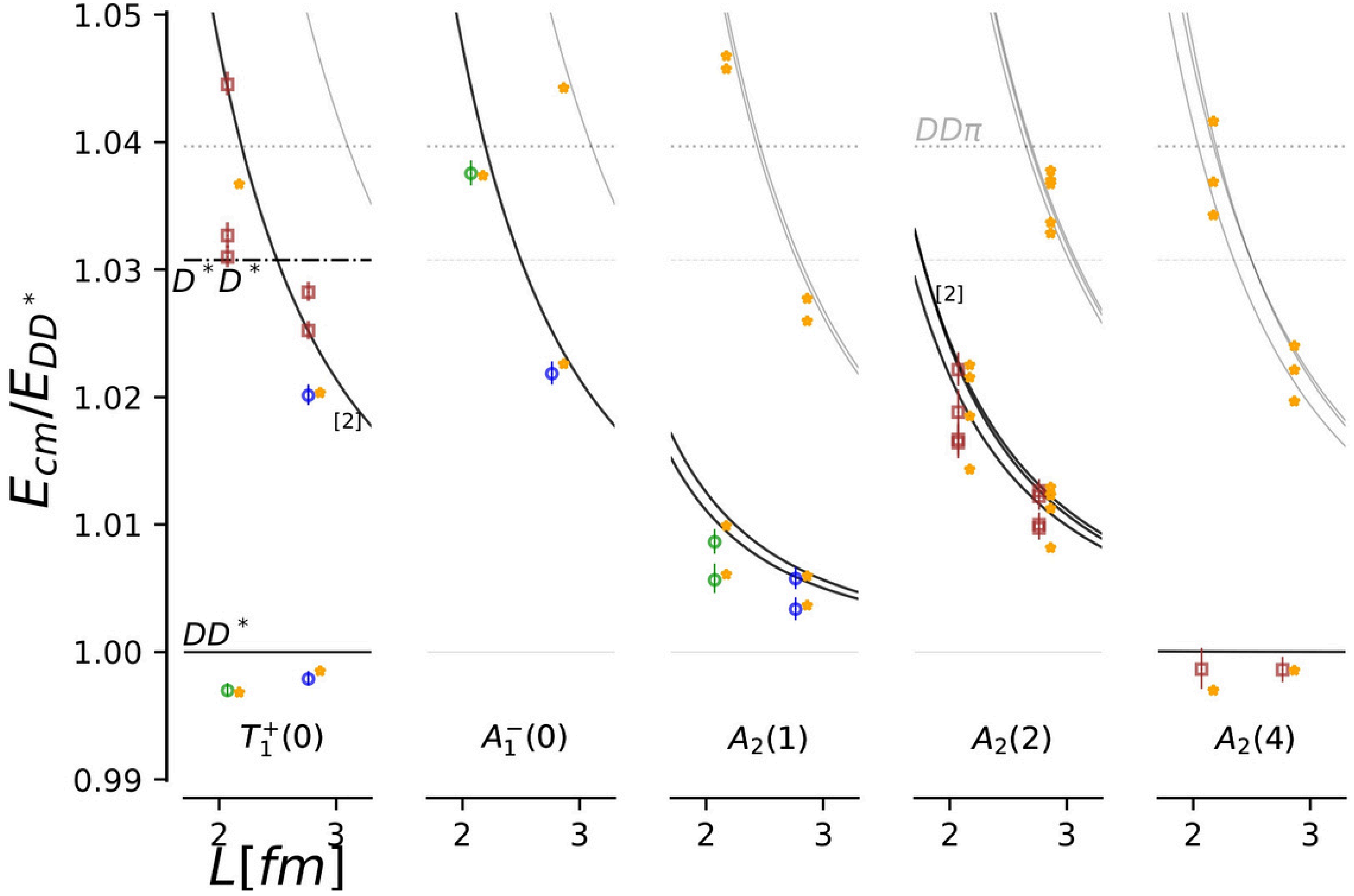
Volume 339, Issue 1, 23 July 1990, Pages 222-252

How to calculate the elastic scattering matrix in two-dimensional quantum field theories by numerical simulation

Martin Lüscher, Ulli Wolff [a b]

Finite-Volume Spectrum

- **Positive shift w.r.t non-interacting level $\implies$ repulsive interaction.**
- **Negative shift w.r.t non-interacting level $\implies$ attractive interaction.**

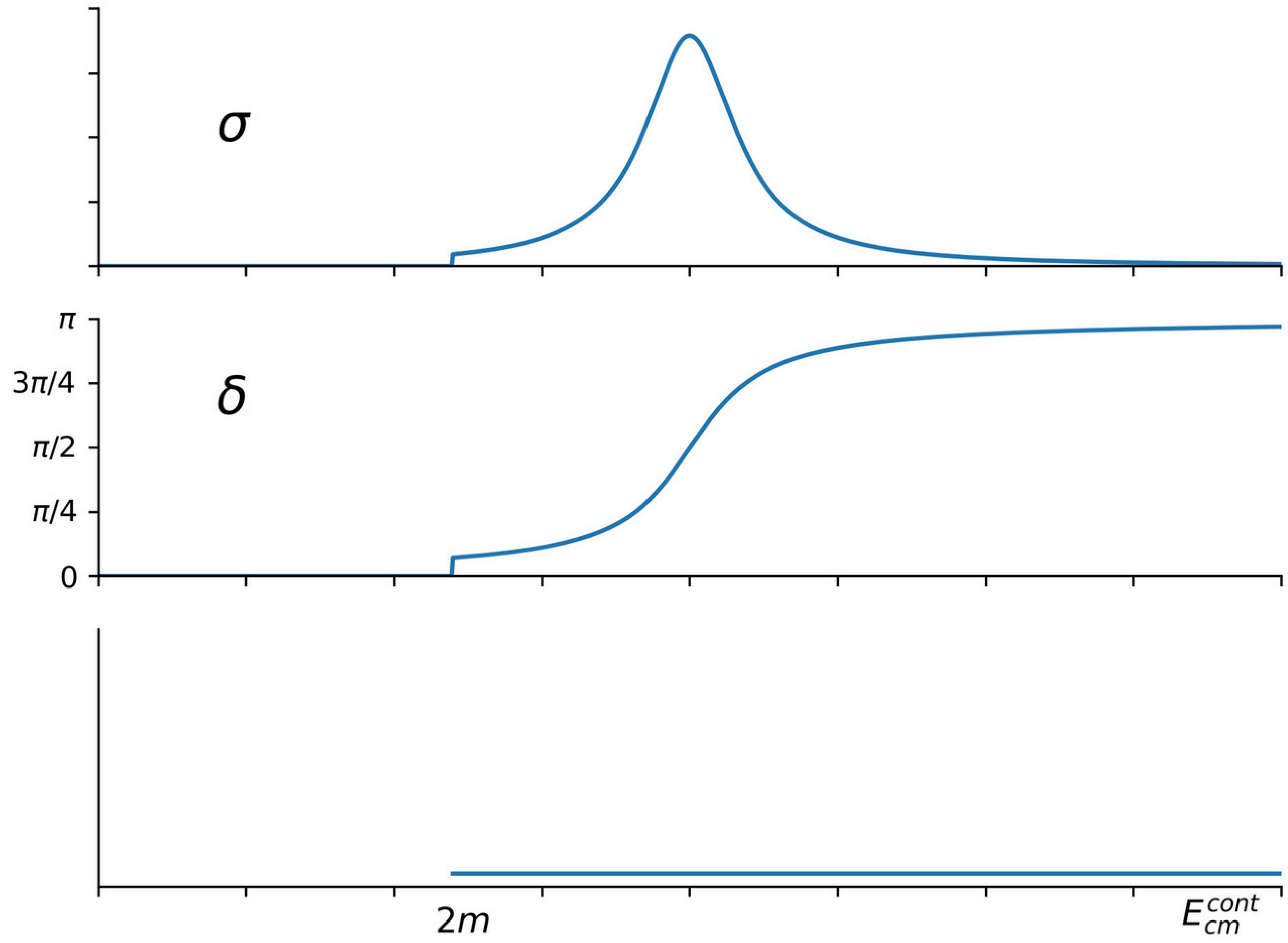


These are "finite-volume" energy levels. Associating them with infinite volume physics: not straightforward

Finite-volume spectrum at 280 MeV pion mass for T_{cc}

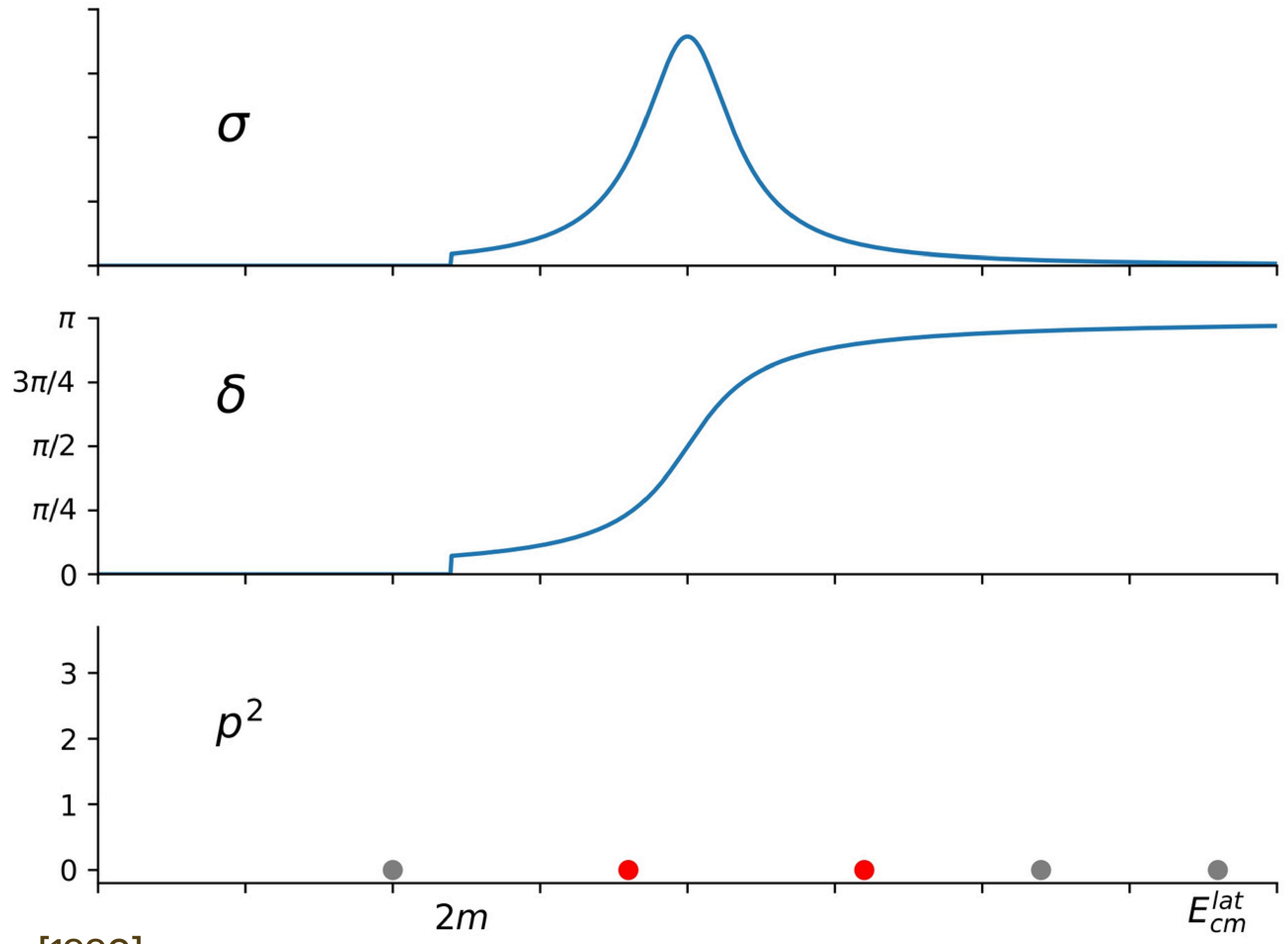
Phys. Rev. Lett. 129, 032002 (2022)

Infinite Volume Scattering



Schematic picture for illustration. Should not be taken quantitatively

Finite Volume Scattering



Maiani-Testa no-go theorem [1990]

Schematic picture for illustration. Should not be taken quantitatively

- **In continuum for any physical scattering we have the following relation,**

$$S = 1 + i(2\rho^{\frac{1}{2}} T \rho^{\frac{1}{2}}) \text{ where } \rho_{l,a} = \frac{2k_a}{E_{cm}}$$

and from the K-matrix formalism we can write,

$$S = (1 + iK)(1 - iK)^{-1}$$

from which one could write,

$$T^{-1} = \frac{2\tilde{K}^{-1}}{E_{cm}} - i\rho \text{ where, } \tilde{K}^{-1}_{l'a;,la} = k_{a'}^{l+\frac{1}{2}} K^{-1}_{l'a;,la} k_a^{l'+\frac{1}{2}}$$

- **The infinite-volume physics can be extracted from the finite-volume spectra following the Lüscher's two-particle prescription for the finite-volume.**

Related to Infinite-volume scattering amplitudes

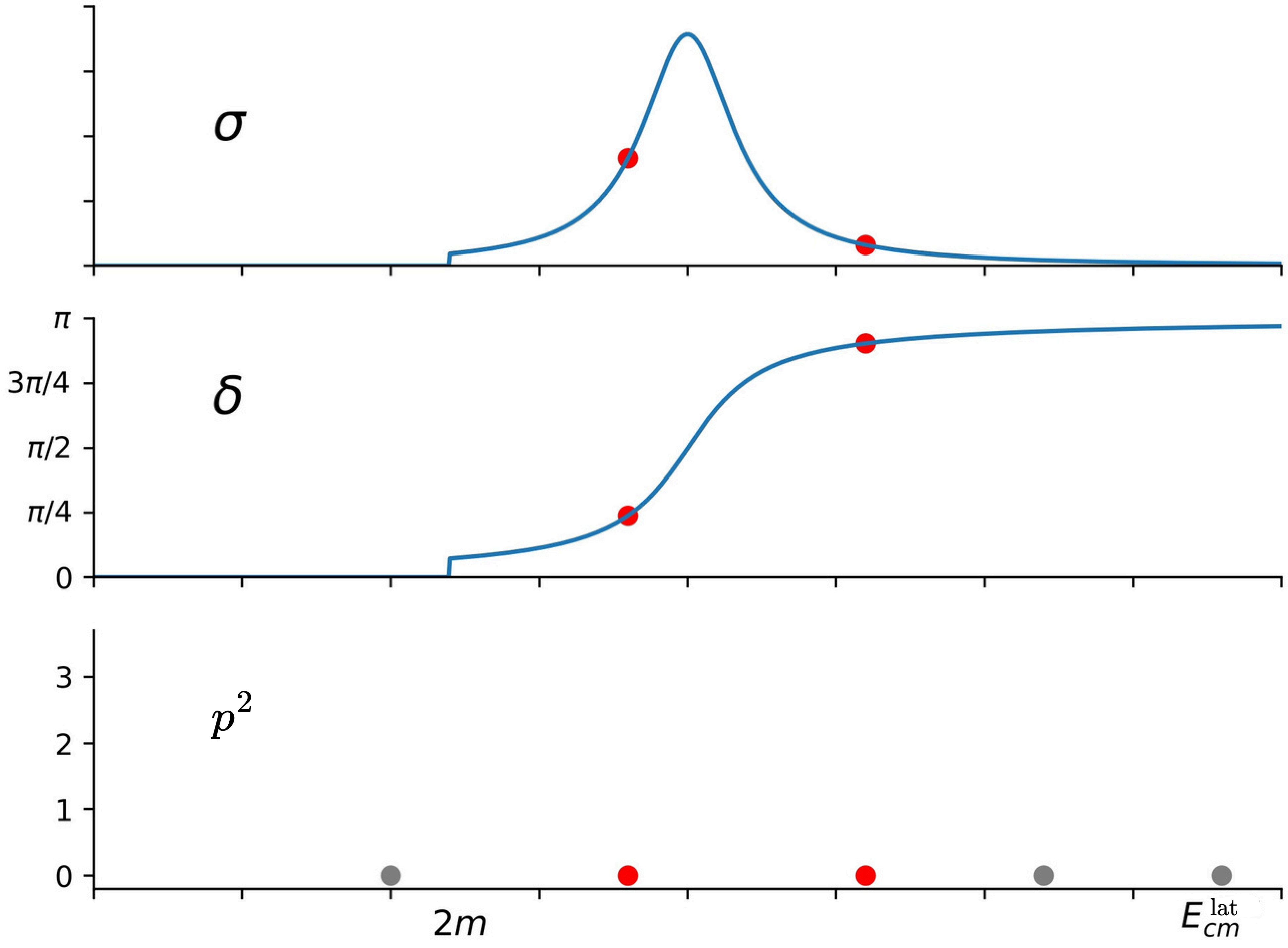
Determinant over angular momenta and channel space

$$det[\tilde{K}(s)^{-1} - B(\mathbf{P}, L)] = 0$$

Known mathematical functions of energy and volume

Lüscher[1991]

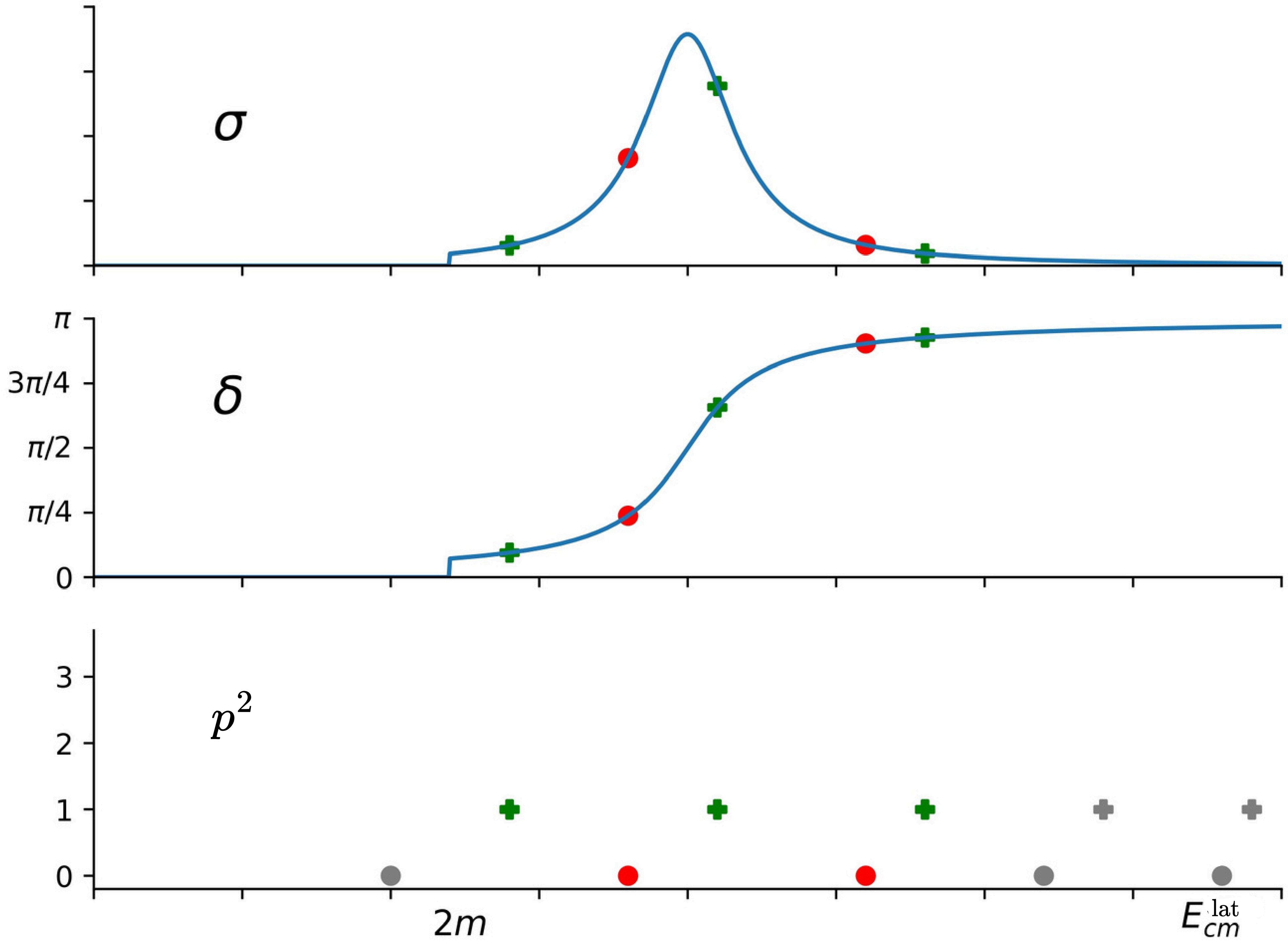
Finite Volume Scattering



For generalizations of Lüscher's framework, c.f. Briceño, Hansen 2014-15

Lüscher[1991]

Finite Volume Scattering



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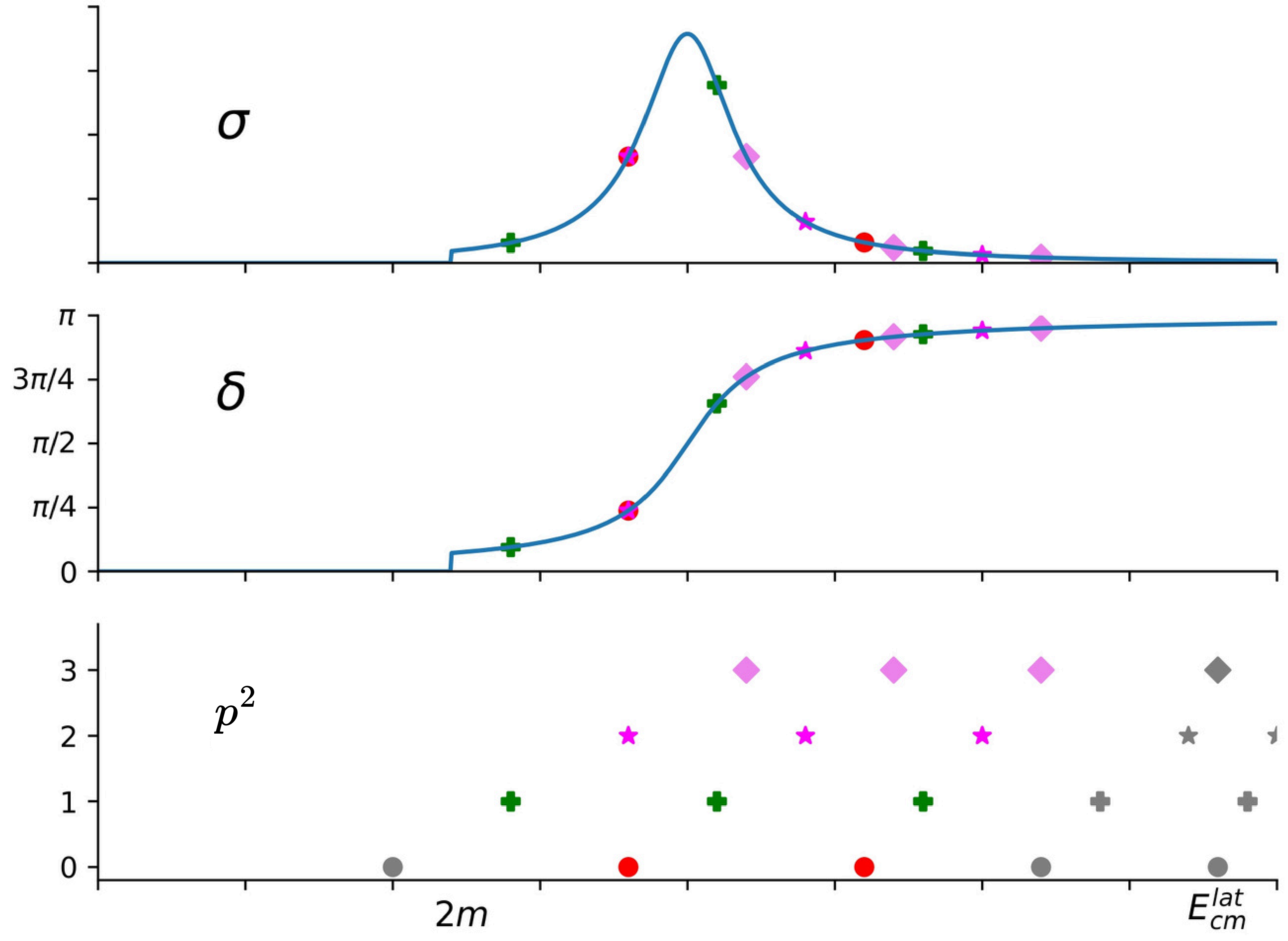
Lüscher[1991]

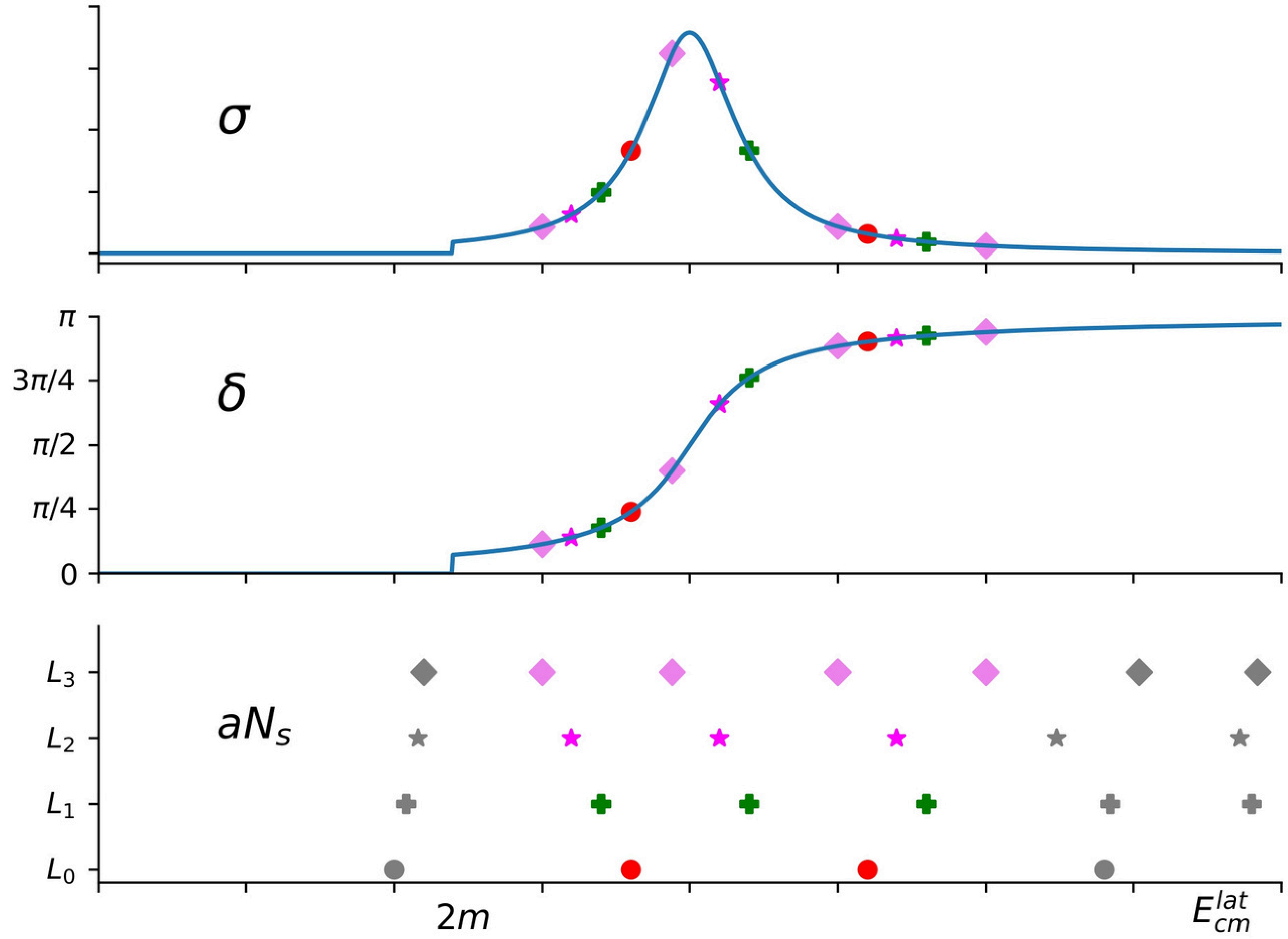
Finite Volume Scattering



For generalizations of Lüscher's framework, c.f. Briceño, Hansen 2014-15

Lüscher[1991]

Finite Volume Scattering



For generalizations of Lüscher's framework, c.f. Briceño, Hansen 2014-15

Lüscher[1991]

- **Once the infinite-volume scattering matrix is extracted, various physical quantities can be extracted from that amplitude.**
- **Employing these techniques, the first lattice calculation for T_{cc} was performed at 280 MeV pion mass in reference :**

Signature of a Doubly Charm Tetraquark Pole in DD^* Scattering on the Lattice

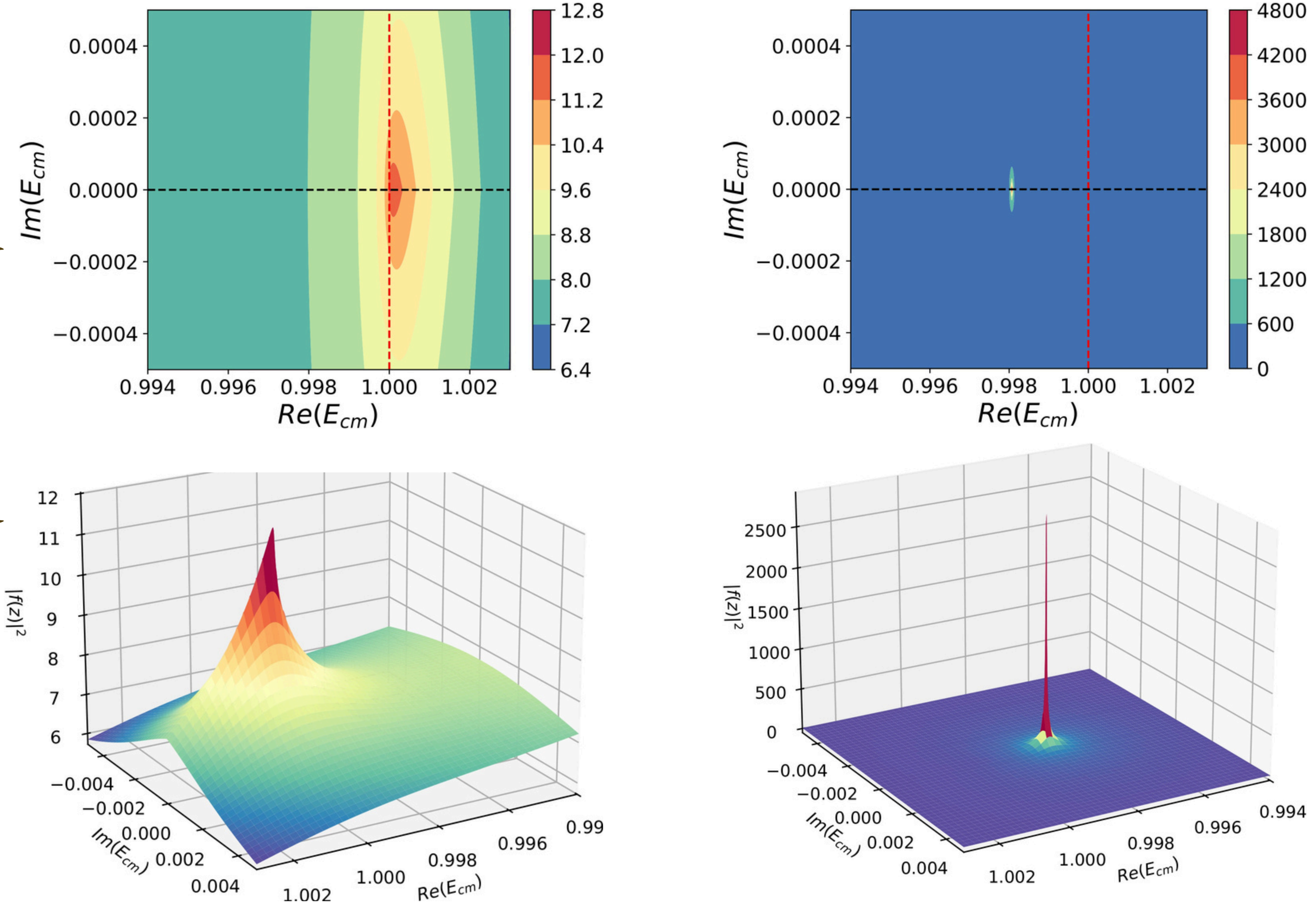
Phys. Rev. Lett. **129**, 032002 – Published 12 July 2022

- **The authors identified a pole singularity in the amplitude, linked to the physical state observed in experiments. They examined various Riemann sheets associated with the unitary branch cut.**

But can we predict existence of any such solutions (T_{ccus}) in the $cc\bar{u}\bar{s}$ quark configuration?

T_{cc} as a pole in DD^* amplitude

Physical Sheet

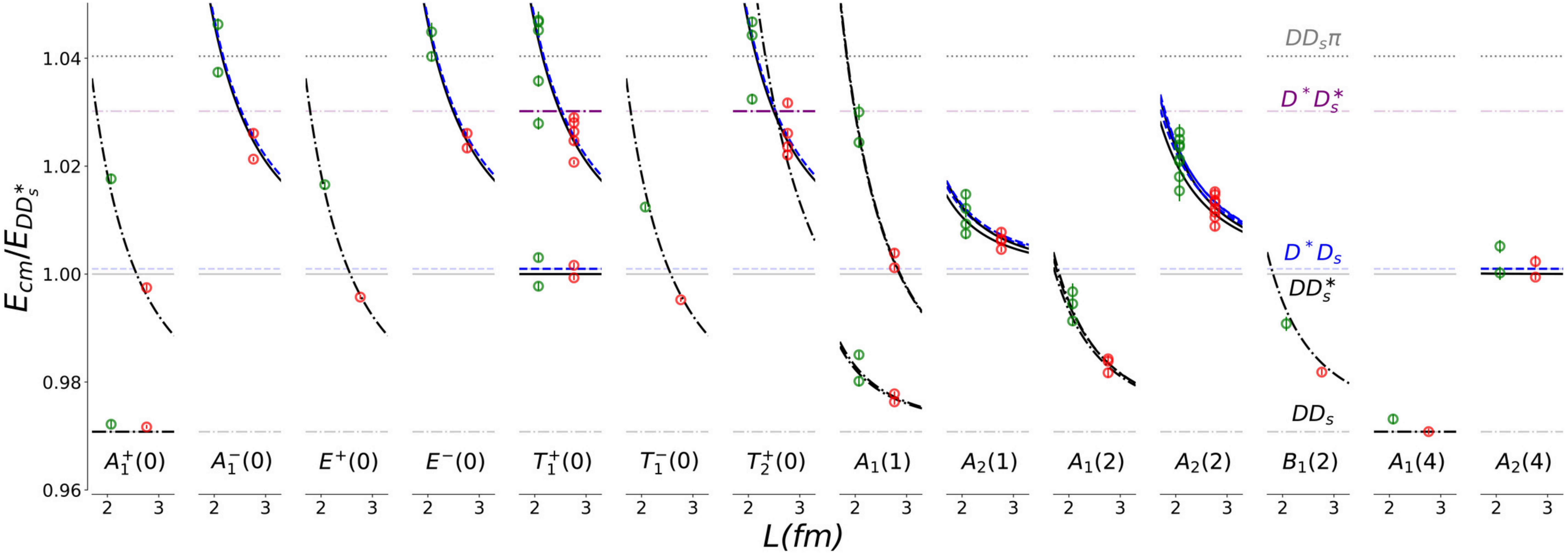


Unphysical Sheet

Phys. Rev. Lett. 129, 032002 (2022)

$D^{(*)} D_s^{(*)}$ Spectrum

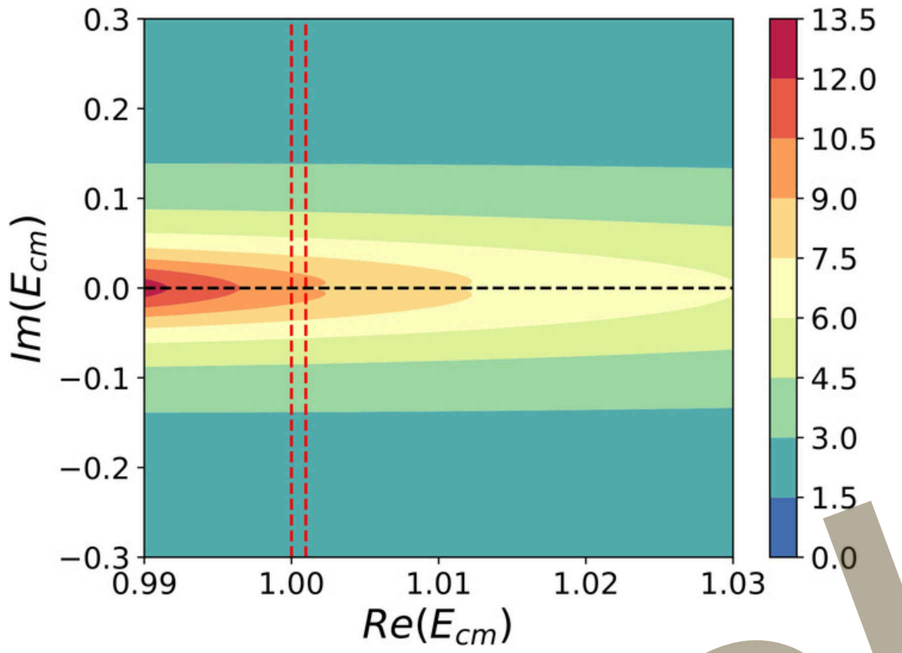
- **Relatively difficult system: multiple final state two-meson configurations possible.**
- **Potential mixture of attractive and repulsive interactions observed.**
- **Further complications from coupled channel scattering amplitudes.**



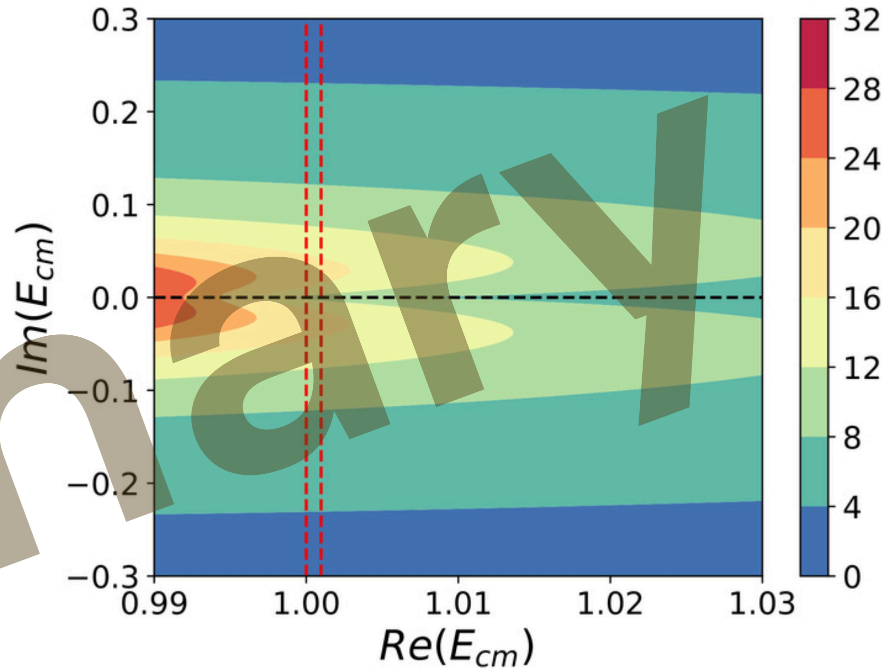
$DD_s^* - D^*D_s$ Amplitude

This is an ongoing analysis and the analytic structure of the scattering amplitude across complex energy plane is being investigated.

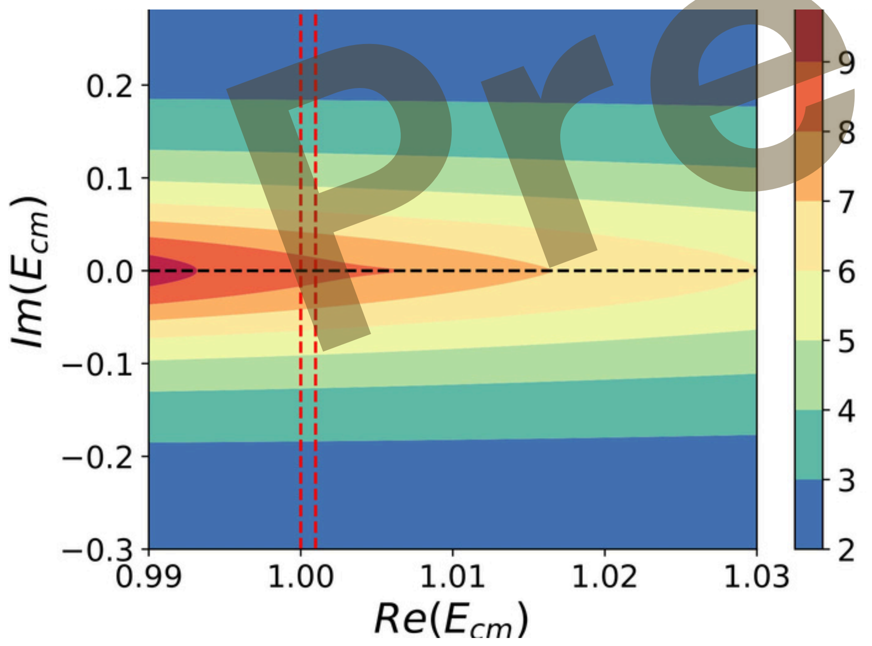
Sheet 1
[1,1]



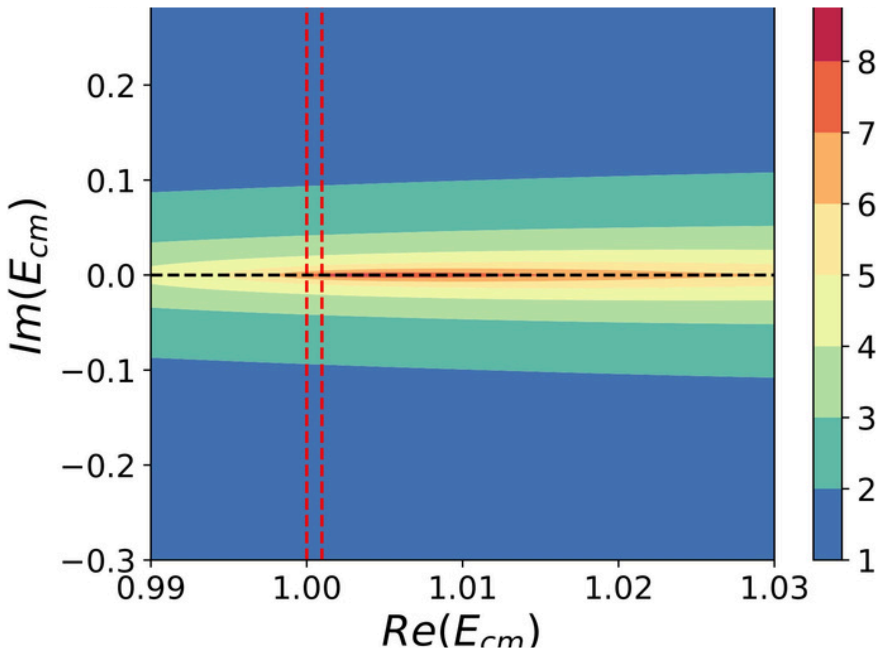
Sheet 2
[−1,1]



Sheet 3
[−1,−1]



Sheet 4
[1,−1]



Summary

- There's a lot of experimental activity going on, and exciting news of hadron discoveries keeps us motivated and active.

- Lattice QCD is the one of the powerful non-perturbative first principles approach for studying hadrons.

Prof. MVN Murthy TAPP-2024

Lattice QCD Evidence that the $\Lambda(1405)$ Resonance is an Antikaon-Nucleon Molecule

Jonathan M. M. Hall, Waseem Kamleh, Derek B. Leinweber, Benjamin J. Menadue, Benjamin J. Owen, Anthony W. Thomas, and Ross D. Young
Phys. Rev. Lett. **114**, 132002 – Published 1 April 2015

- Various details on extracting finite-volume spectrum are discussed.

- Using Lüscher’s prescription infinite-volume scattering amplitudes are determined from the finite-volume spectrum.

- Results for T_{cc} and for ongoing $D^{(*)}D_s^{(*)}$ scattering studies have been discussed.

Thank You