recent progress on hadron spectroscopy from lattice QCD

Jozef Dudek

hadspec
hadron spectrum collaboration
hadspec.org

William & Mary
Chartered 1693

Jefferson Lab
Thomas Jefferson National Accelerator Facility

this presentation is dedicated to the memory of Mike Pennington,

scientist,

mentor,

friend

QCD, hadrons and the standard model

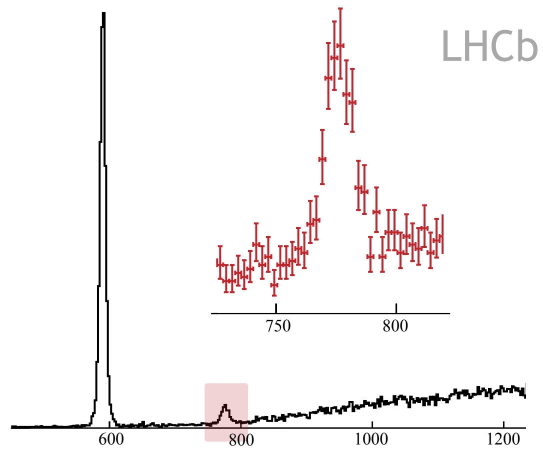
While **QCD** may be a solid part of the **standard model**, and **hadrons** are ubiquitous in HEP experiments, there remain significant mysteries in how **hadrons** are built from **quarks** and **gluons**

QCD, hadrons and the standard model

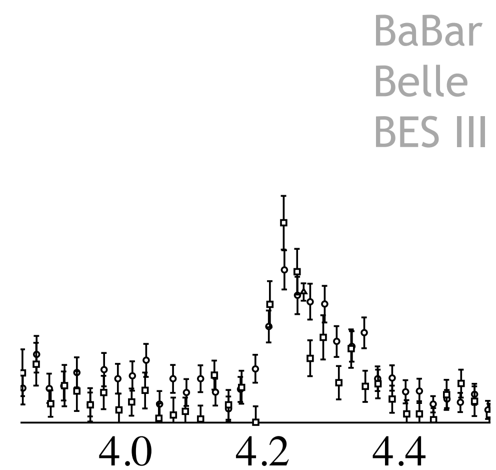
While **QCD** may be a solid part of the **standard model**, and **hadrons** are ubiquitous in HEP experiments, there remain significant mysteries in how **hadrons** are built from **quarks** and **gluons**

unexpected ?

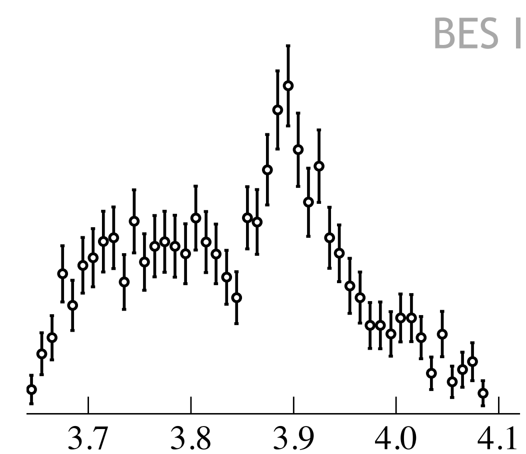
$X(3872) \to \pi\pi J/\psi$



$Y(4260) \to \pi\pi J/\psi$



$Z_c(3900) \to \pi^+ J/\psi$



While **QCD** may be a solid part of the **standard model**, and **hadrons** are ubiquitous in HEP experiments, there remain significant mysteries in how **hadrons** are built from **quarks** and **gluons**

unexplained ?

light scalar meson resonances

$f_0(500)$ or σ [g]
was $f_0(600)$

$I^G(J^{PC}) = 0^+(0^{++})$

Mass $m = (400\text{–}550)$ MeV
Full width $\Gamma = (400\text{–}700)$ MeV

$f_0(980)$ [j]

$I^G(J^{PC}) = 0^+(0^{++})$

Mass $m = 990 \pm 20$ MeV
Full width $\Gamma = 10$ to 100 MeV

$K_0^*(800)$
or κ

$I(J^P) = \frac{1}{2}(0^+)$

$a_0(980)$ [j]

$I^G(J^{PC}) = 1^-(0^{++})$

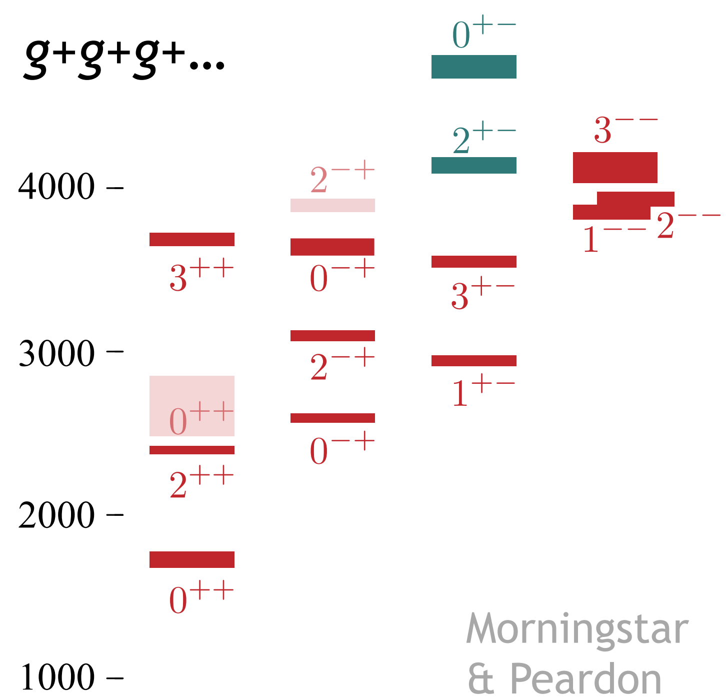
Mass $m = 980 \pm 20$ MeV
Full width $\Gamma = 50$ to 100 MeV

QCD, hadrons and the standard model

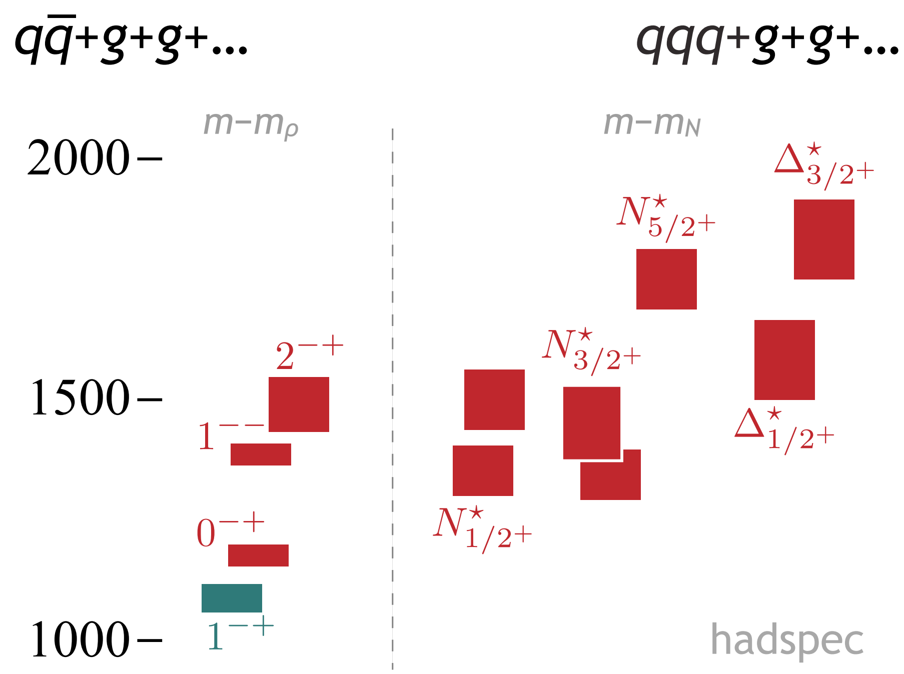
While **QCD** may be a solid part of the **standard model**, and **hadrons** are ubiquitous in HEP experiments, there remain significant mysteries in how **hadrons** are built from **quarks** and **gluons**

unobserved ?

pure YM glueballs

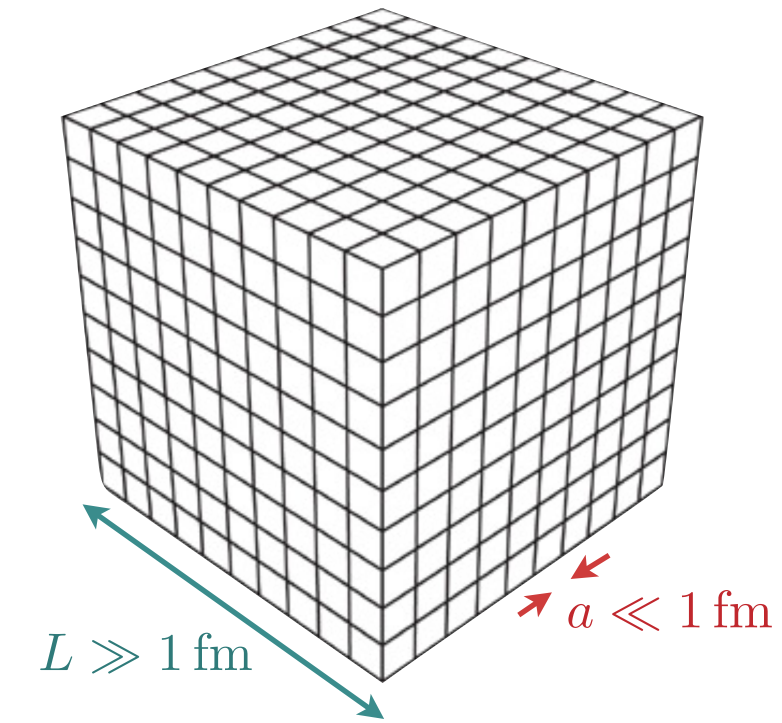


lqcd hybrid hadrons



quark & gluon fields on a **finite space-time grid** (in Euclidean time)

introduce: **lattice spacing**, **lattice volume**, often $m_q > m_q^{\text{phys}}$



Monte Carlo sample field configurations

hadron spectrum from two-point correlation functions

$$\langle 0 | \mathcal{O}'(t)\, \mathcal{O}(0) | 0 \rangle = \int \mathcal{D}\psi \mathcal{D}\bar{\psi} \mathcal{D}A \left[\mathcal{O}'(t)\, \mathcal{O}(0) \right] e^{-S[\psi, \bar{\psi}, A]}$$

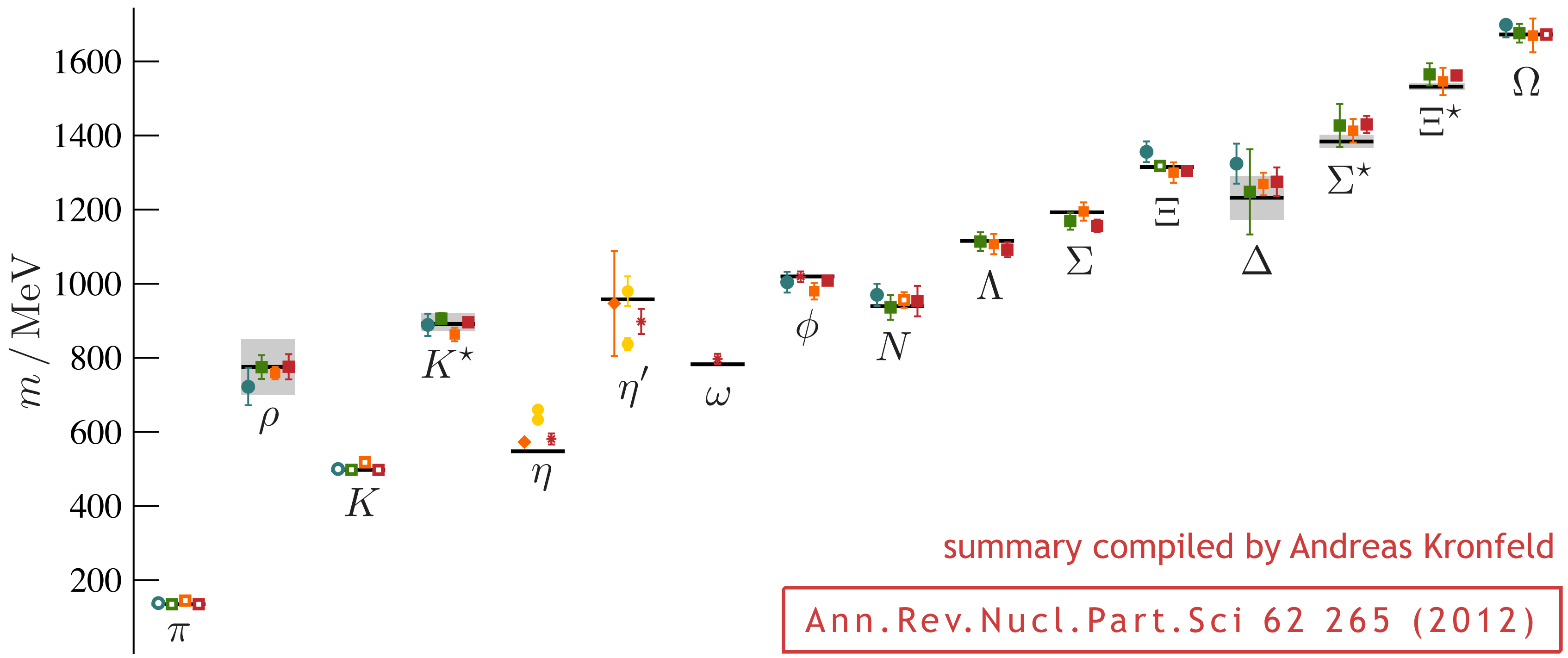
field configuration probability

$$\langle 0 | \mathcal{O}'(t)\, \mathcal{O}(0) | 0 \rangle = \sum_{\mathfrak{n}} A'_{\mathfrak{n}}\, A_{\mathfrak{n}}\, e^{-E_{\mathfrak{n}} t}$$

spectrum of QCD eigenstates

precise spectroscopy of stable hadrons

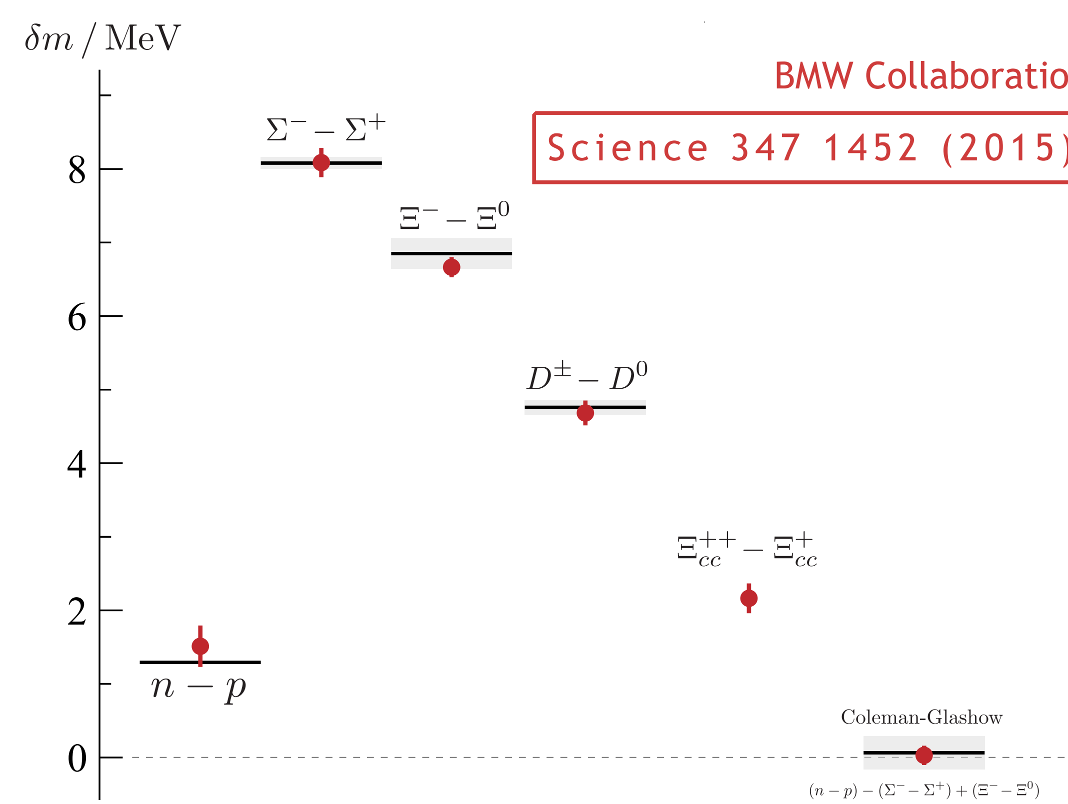
lattice qcd light hadron spectrum



summary compiled by Andreas Kronfeld

Ann.Rev.Nucl.Part.Sci 62 265 (2012)

QCD+QED mass shifts



BMW Collaboration

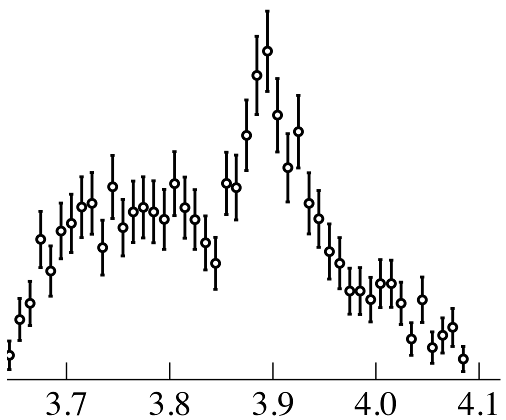
Science 347 1452 (2015)

excited spectroscopy

but much of the excitement in hadron spectroscopy is in **heavier states**

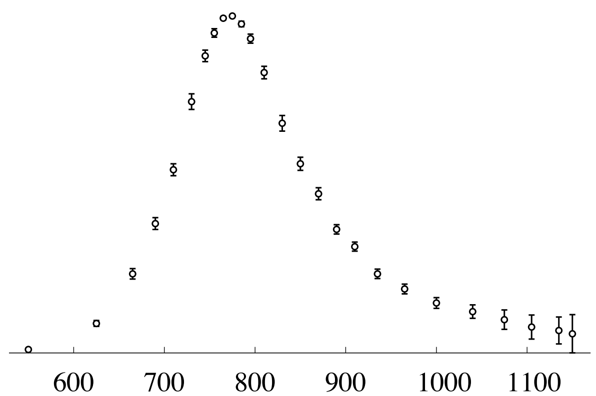
and they are **resonances** observed through their decays

$Z_c(3900) \to \pi^+ J/\psi$



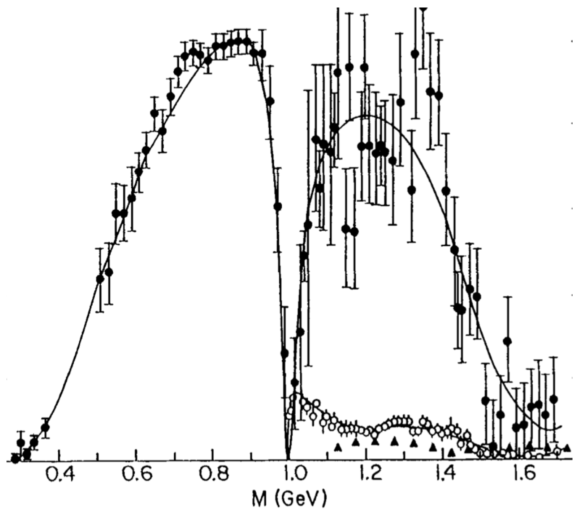
exotic

$\rho \to \pi\pi$



familiar

$\pi\pi \to \pi\pi, K\bar{K}, \eta\eta$



non-trivial

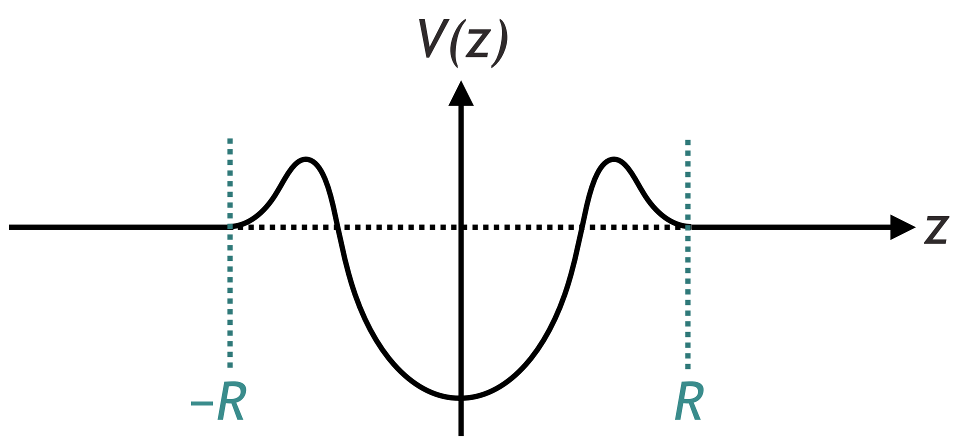
same non-perturbative dynamics **binds** and causes the **decay** – can't be separated within QCD ...

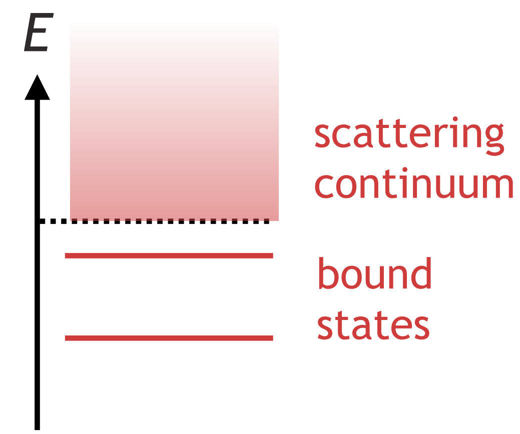
a faithful QCD calculation should give **all the scattering physics** at once ...

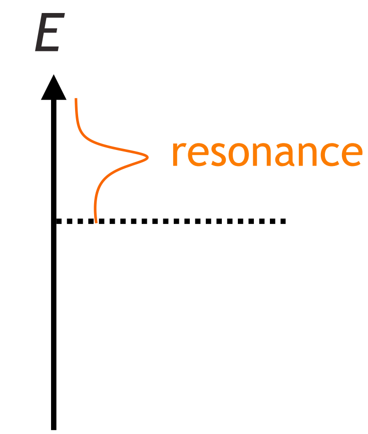
resonances on the lattice ?

the approach can be illustrated within **one-dimensional quantum mechanics**

imagine two identical bosons separated by a distance *z*
interacting through a finite-range potential *V(z)*

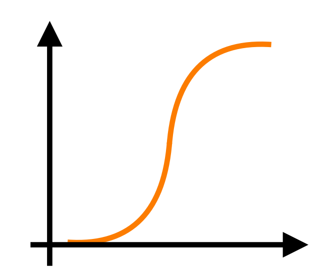






$$\psi(|z|>R) \sim \cos\left(p\,|z| + \delta(p)\right)$$

phase-shift



‘scattering’ in a finite-volume

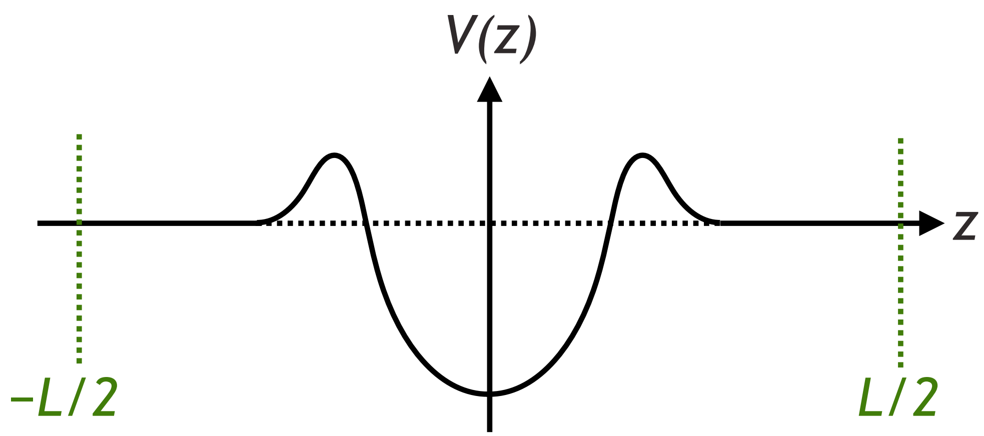
now put the system in a ‘box’ — periodic boundary condition at $z = \pm L/2$

$$\psi(|z| > R) \sim \cos\big(p\,|z| + \delta(p)\big)$$

$$\psi(L/2) = \psi(-L/2)$$
$$\frac{d\psi}{dz}(L/2) = \frac{d\psi}{dz}(-L/2)$$

momentum quantization condition

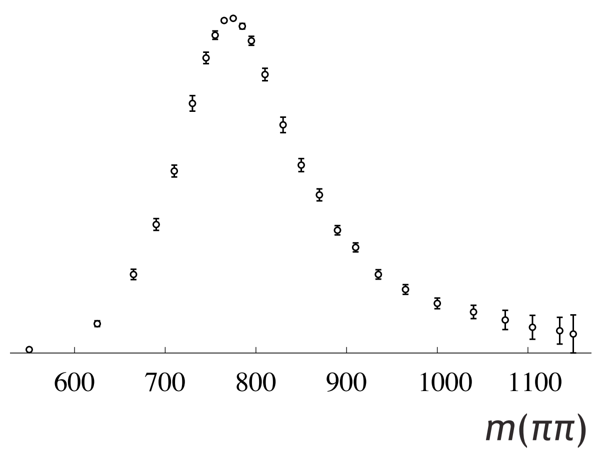
$$p = \frac{2\pi}{L}n - \frac{2}{L}\delta(p)$$



reversing the logic:

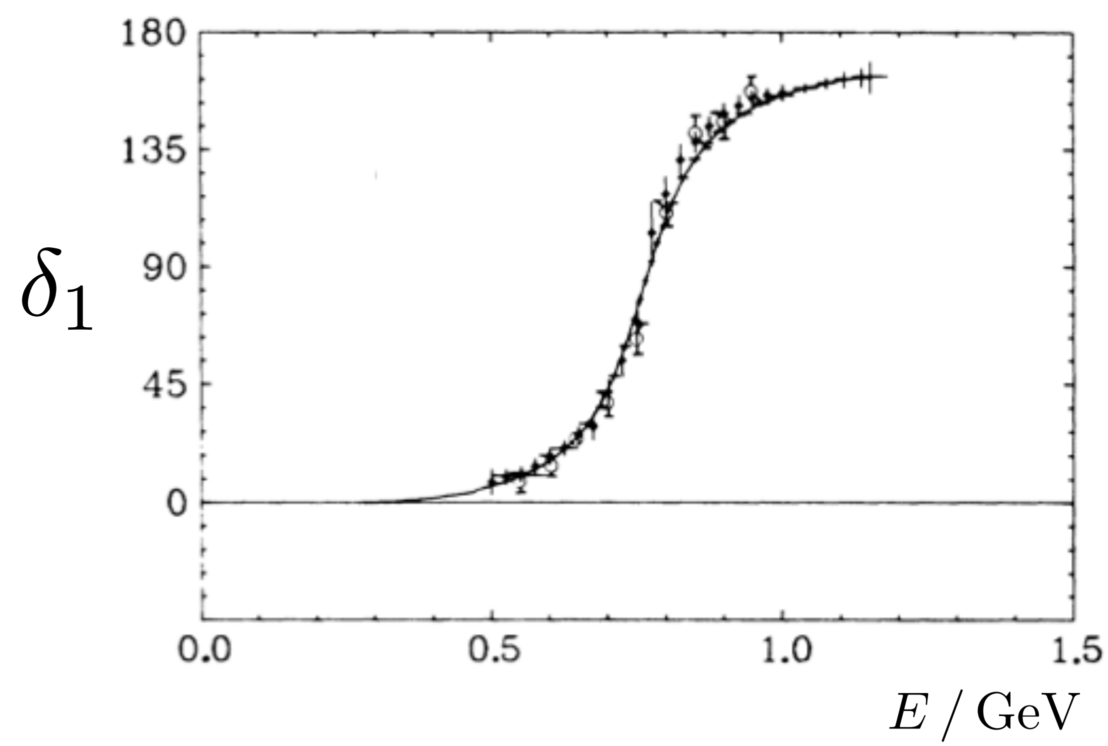
if you can compute the **discrete finite-volume spectrum** in a quantum theory, you can find the **scattering amplitude**

an elastic resonance — the ρ in $\pi\pi$



canonical resonance 'bump'
described by a rapidly rising phase-shift

scattering phase-shift



PHYSICAL REVIEW D VOLUME 7, NUMBER 5 1 MARCH 1973

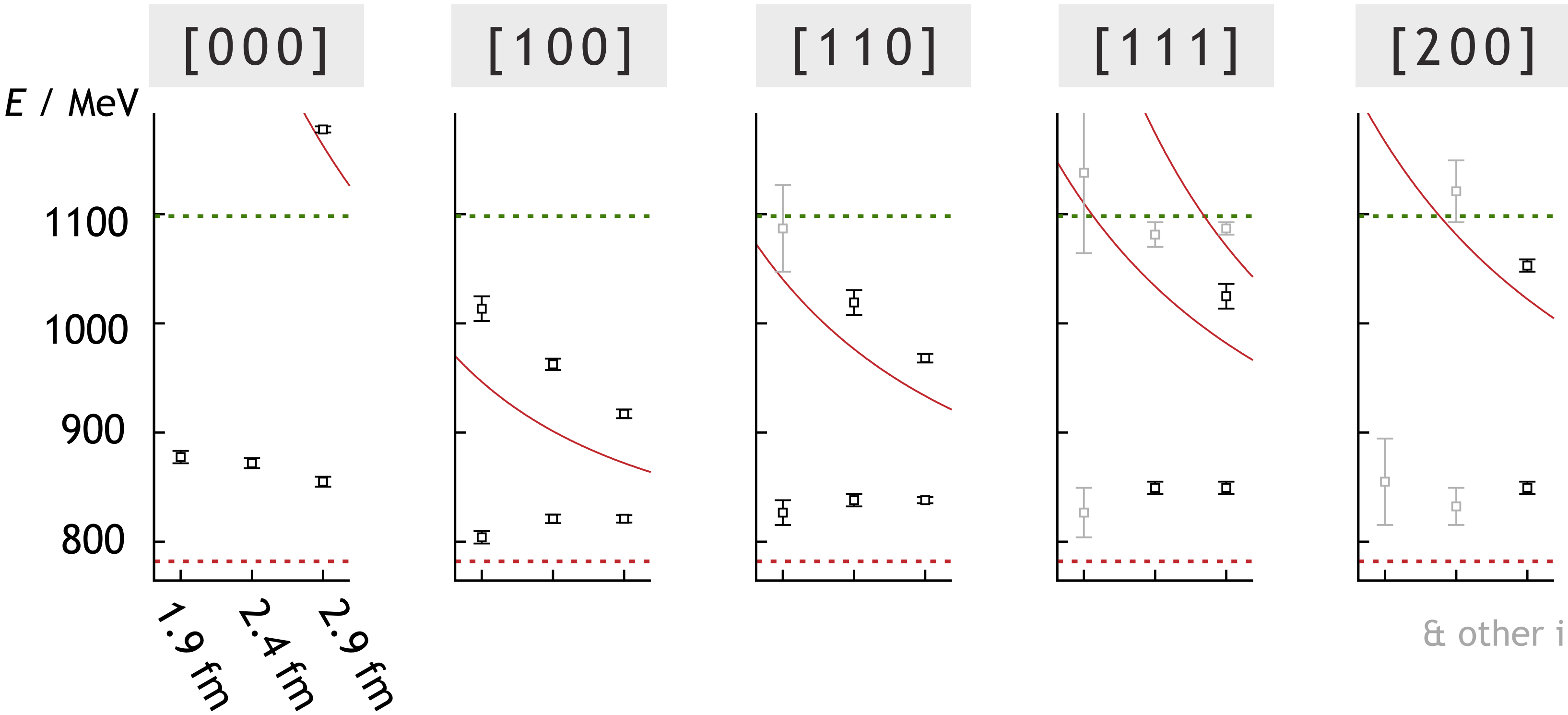
$\pi\pi$ Partial-Wave Analysis from Reactions $\pi^+p \to \pi^+\pi^-\Delta^{++}$ and $\pi^+p \to K^+K^-\Delta^{++}$ at 7.1 GeV/c†

S. D. Protopopescu,* M. Alston-Garnjost, A. Barbaro-Galtieri, S. M. Flatté,‡
J. H. Friedman,§ T. A. Lasinski, G. R. Lynch, M. S. Rabin,‖ and F. T. Solmitz
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
(Received 25 September 1972)

an elastic resonance — the ρ in $\pi\pi$ — lattice QCD

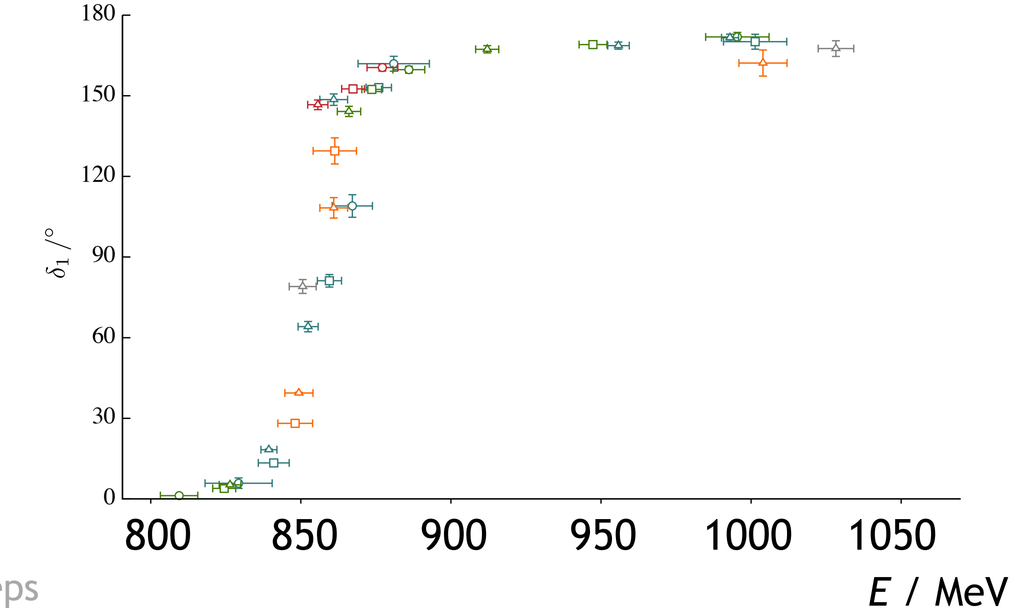
PRD87 034505 (2013)

m_π ~ 391 MeV



& other irreps

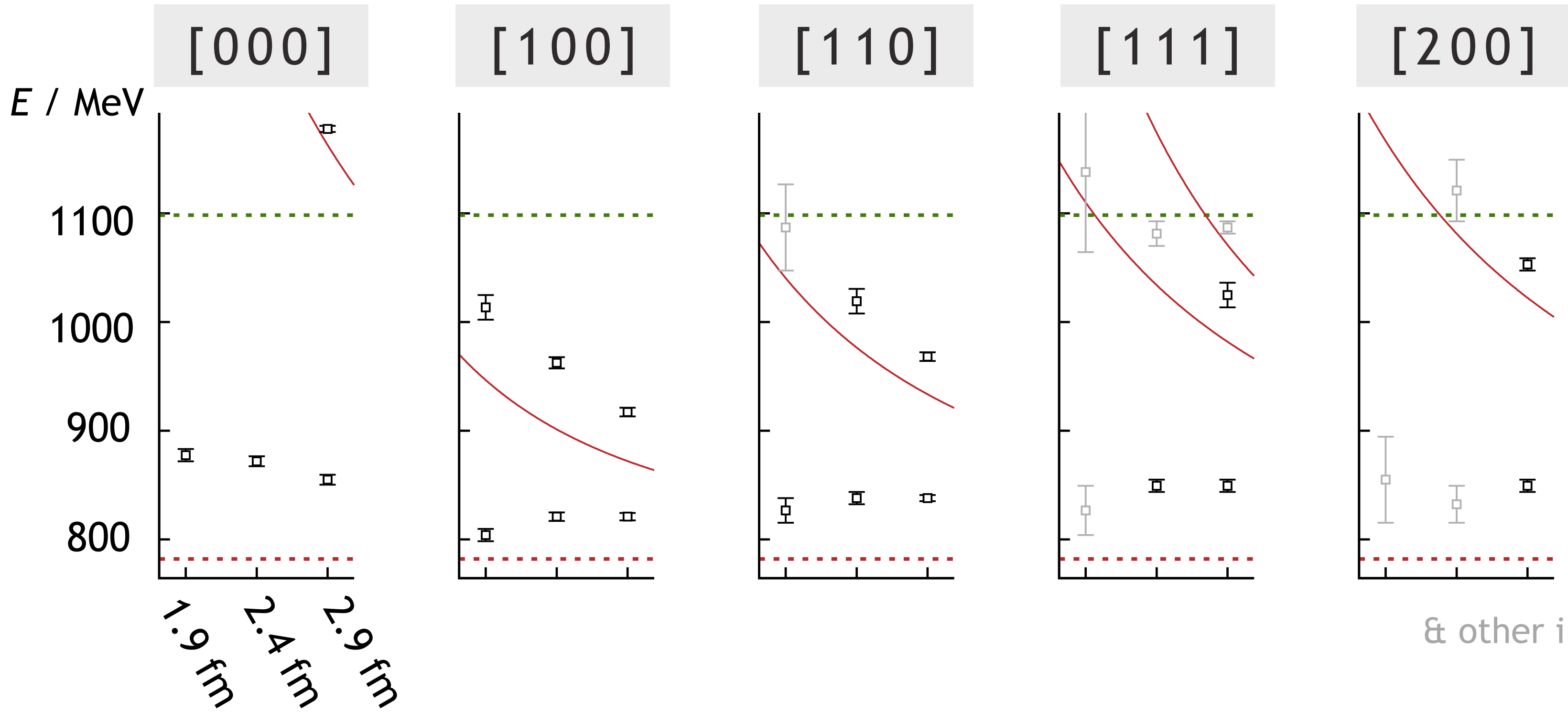
scattering phase-shift



an elastic resonance — the ρ in $\pi\pi$ — lattice QCD

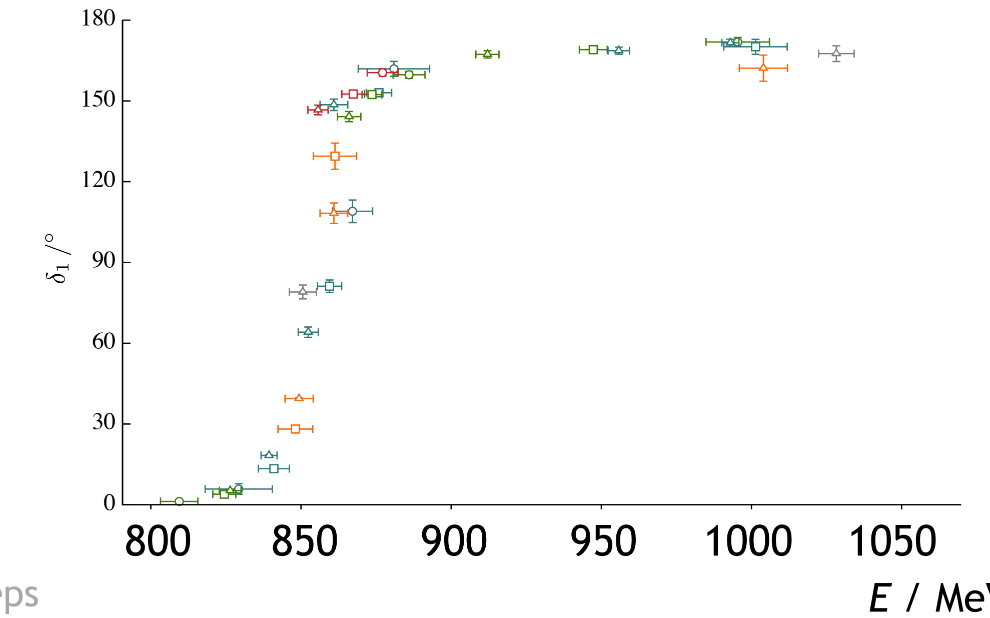
PRD87 034505 (2013)

m_π ~ 391 MeV



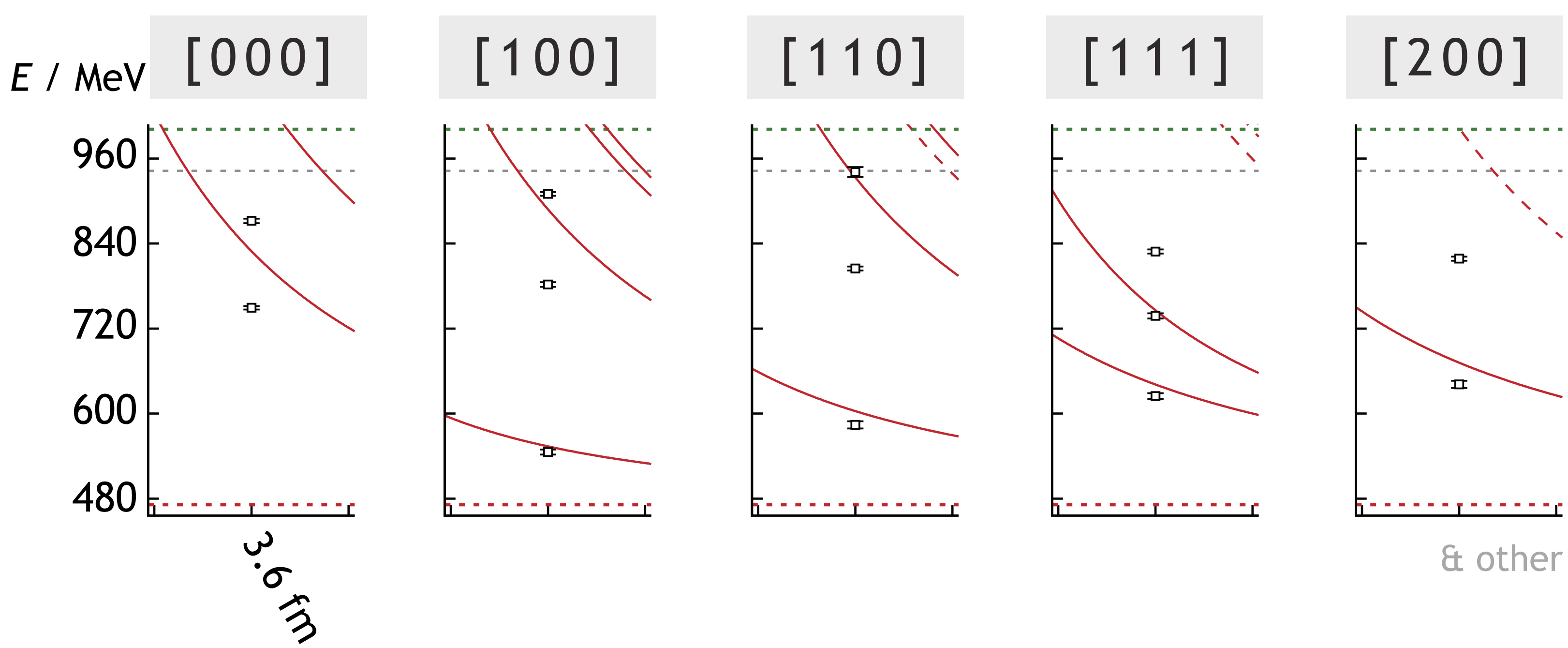
& other irreps

scattering phase-shift



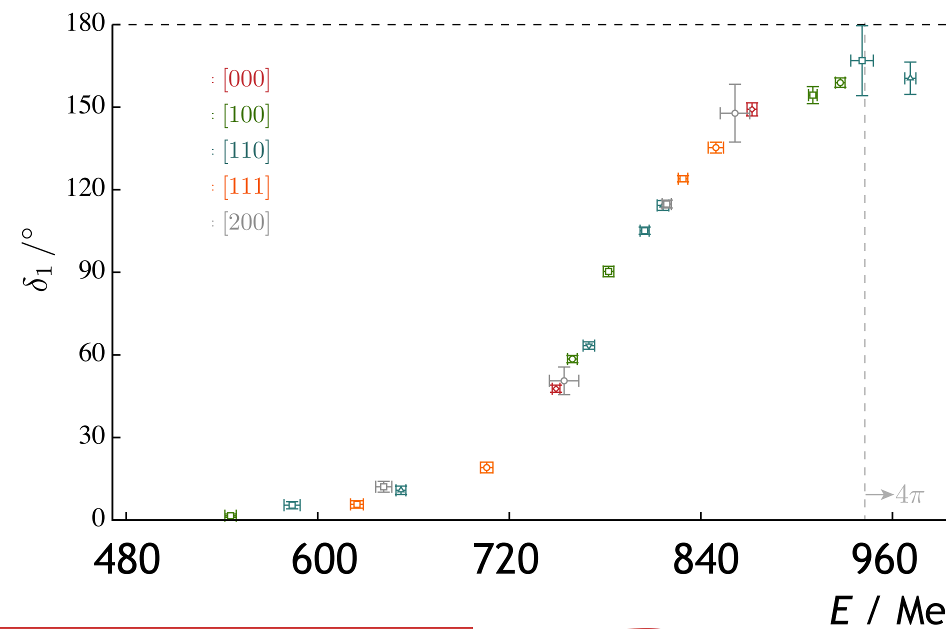
PRD92 094502 (2015)

m_π ~ 236 MeV

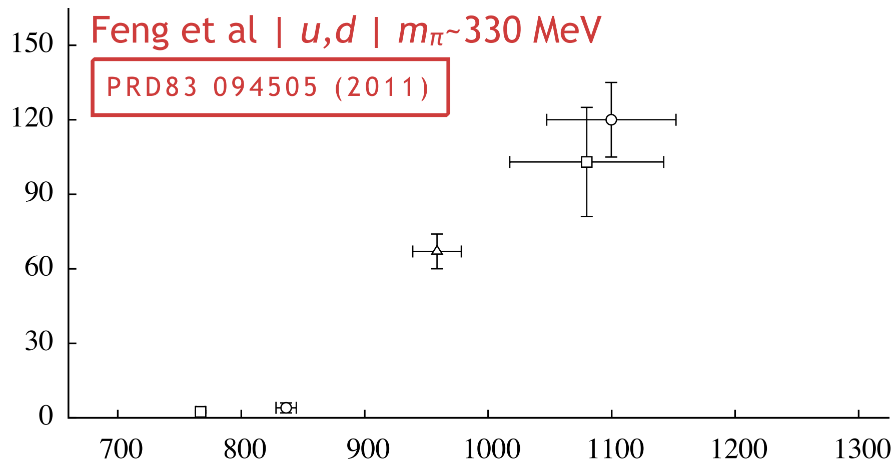


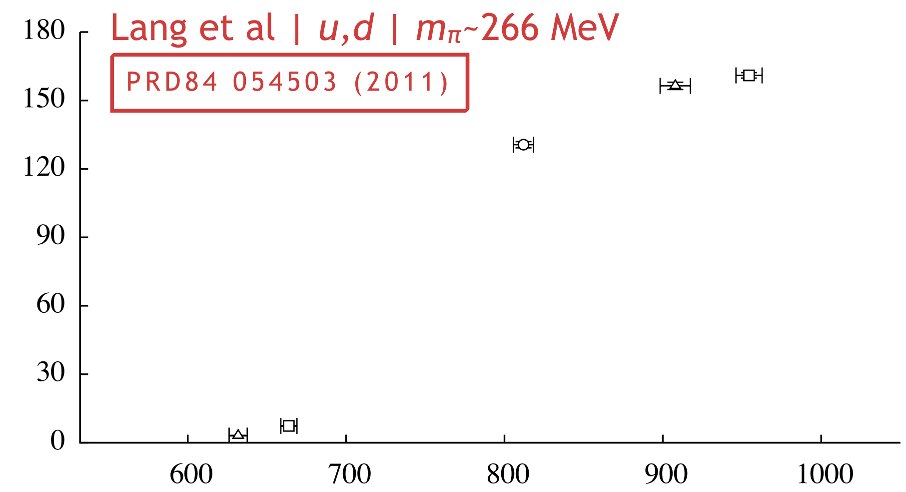
& other irreps

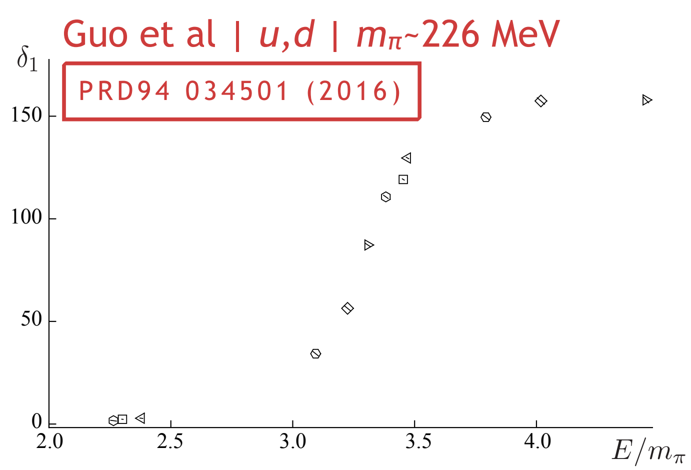
scattering phase-shift

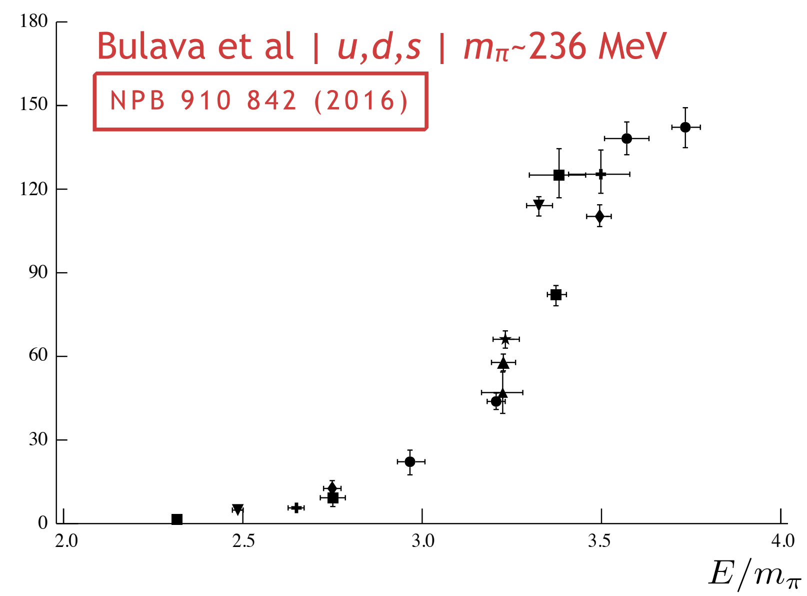


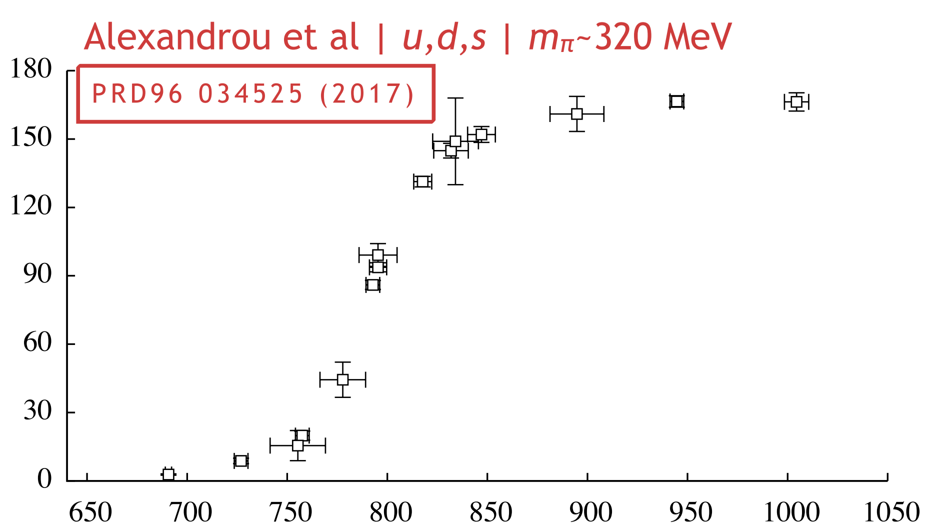
an elastic resonance — the ρ in $\pi\pi$ — lattice QCD

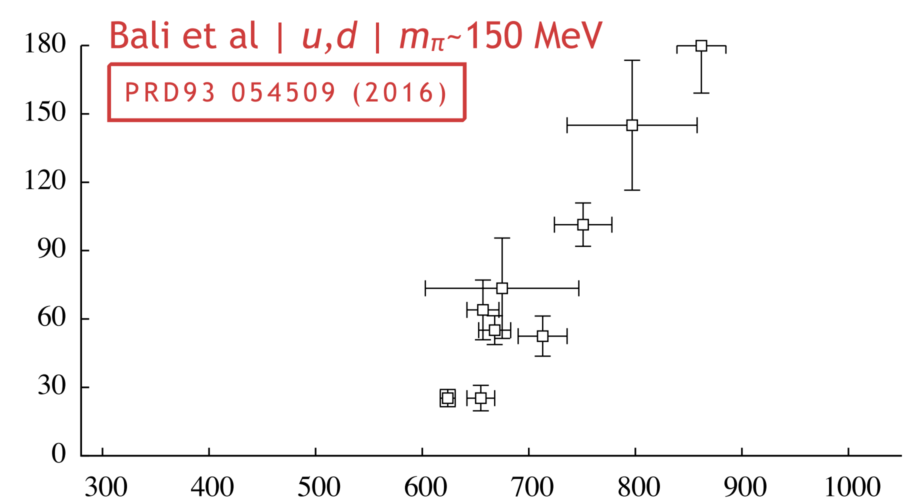












coupled-channel resonances

most resonances decay into more than one final state

e.g. two-channel scattering described by a ***t***-matrix $\mathbf{t}(E) = \begin{pmatrix} t_{11}(E) & t_{12}(E) \\ t_{21}(E) & t_{22}(E) \end{pmatrix}$

finite-volume spectrum as a function of scattering becomes more complicated

coupled-channel spectrum

solutions $E_n(L)$ of

$$\det\left[\mathbf{t}^{-1}(E) - \widetilde{\boldsymbol{\mathcal{M}}}(E,L)\right] = 0$$

matrix of known kinematic functions

no longer a one-to-one mapping from energy to scattering …

… can parameterize the energy dependence of the scattering ***t***-matrix

first lattice QCD calculations of coupled meson-meson scattering have appeared in the last four years …

$a_0(980)$ in $\pi\eta$

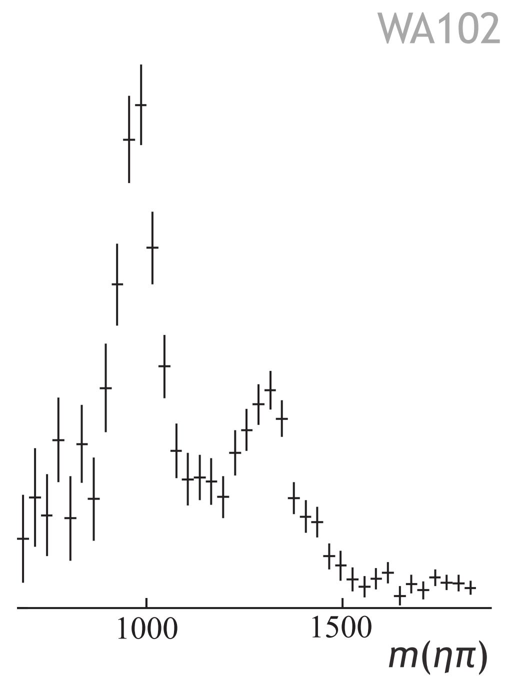
a narrow resonance seen in the $\pi\eta$ final state

$a_0(980)$ [j] $I^G(J^{PC}) = 1^-(0^{++})$

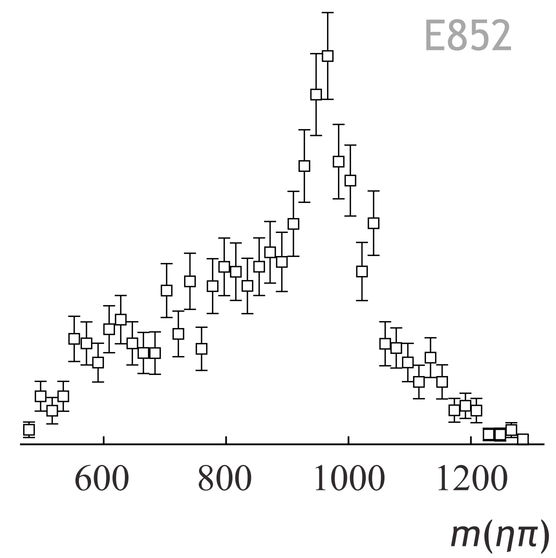
Mass $m = 980 \pm 20$ MeV
Full width $\Gamma = 50$ to 100 MeV

e.g.

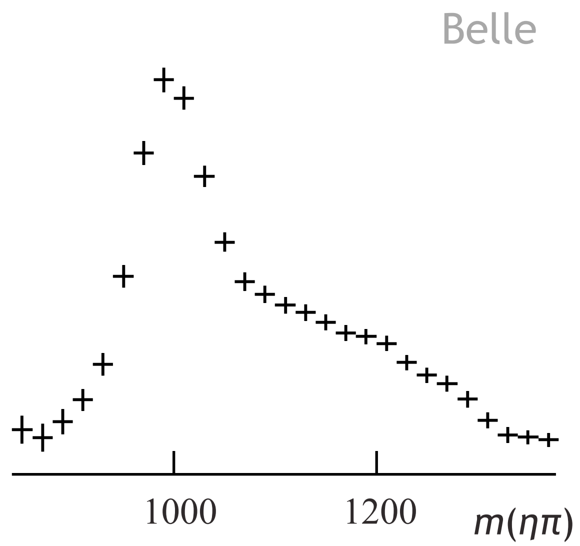
$pp \to p\,\eta\pi^0\,p$



$\pi^- p \to \eta\pi^+\pi^-\,n$



$\gamma\gamma \to \eta\pi^0$

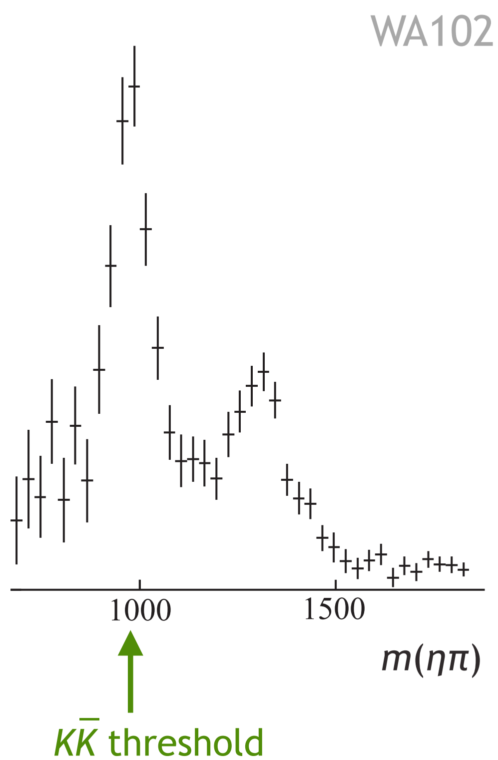


a narrow resonance seen in the $\pi\eta$ final state

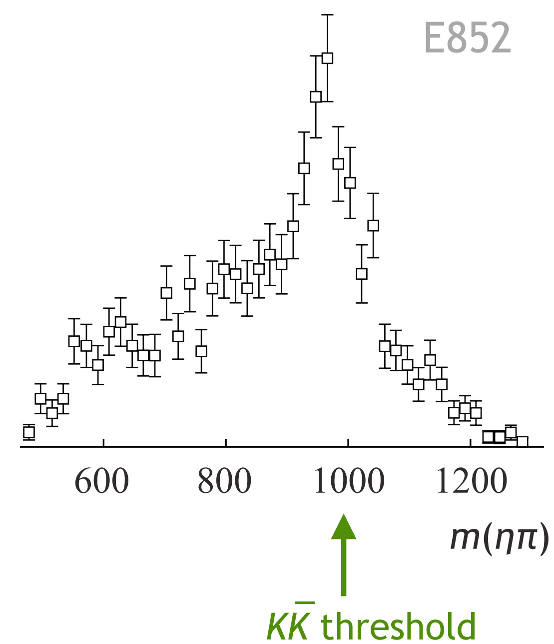
right at the $K\bar{K}$ threshold

e.g.

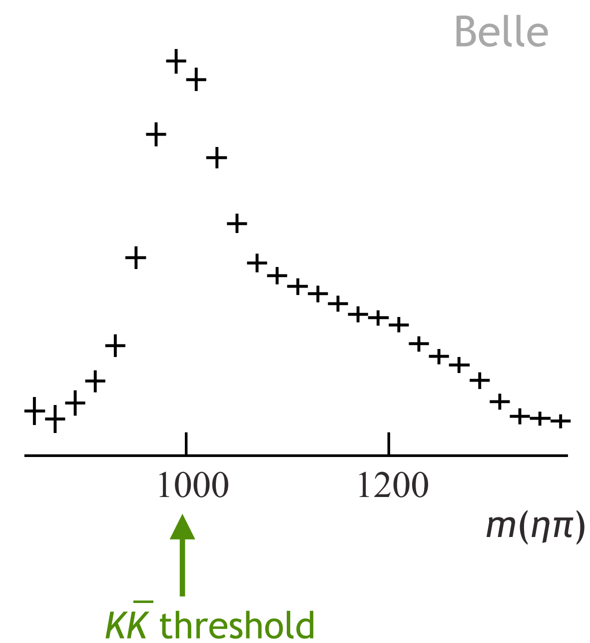
$pp \to p\, \eta\pi^0\, p$



$\pi^- p \to \eta\pi^+\pi^-\, n$



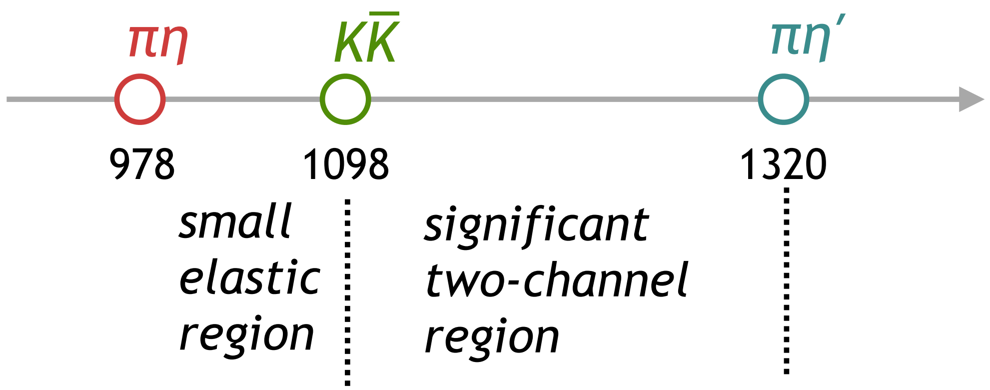
$\gamma\gamma \to \eta\pi^0$

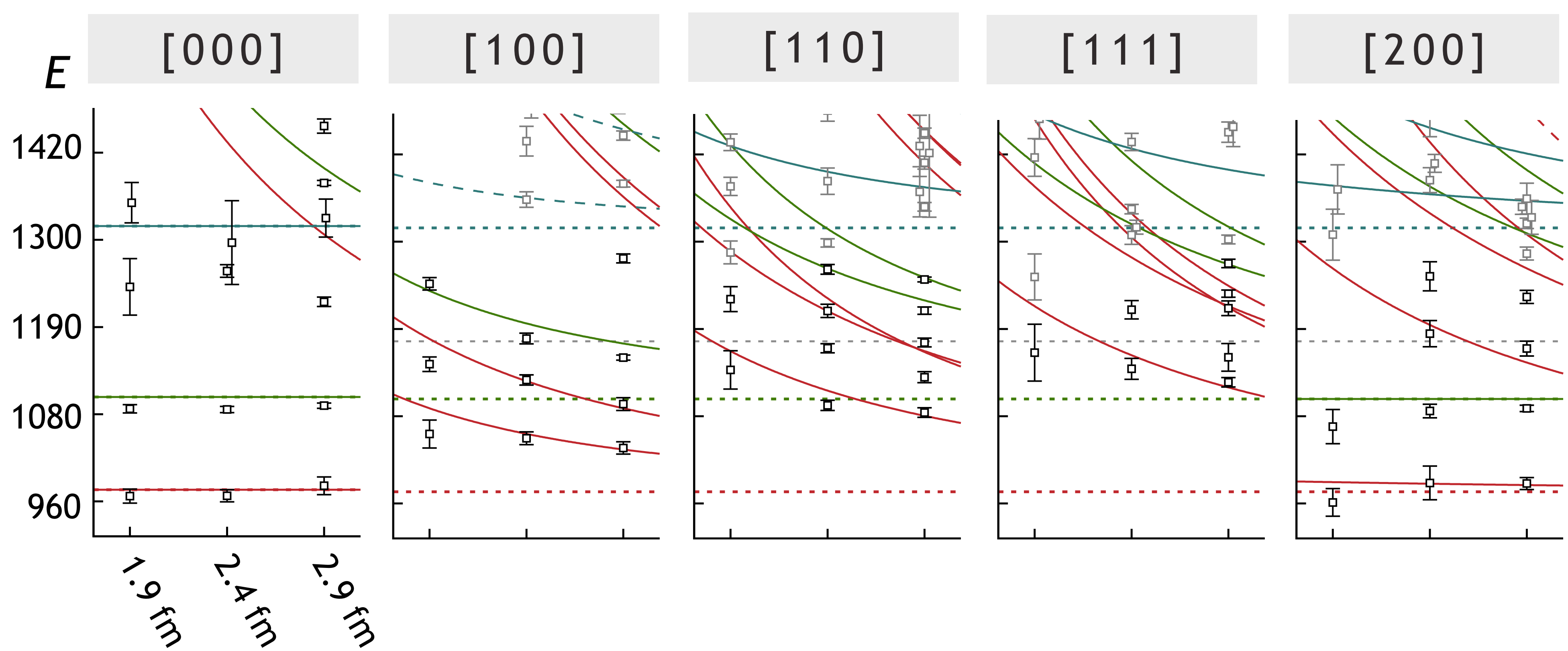


will need a coupled $\pi\eta$, $K\bar{K}$ approach …

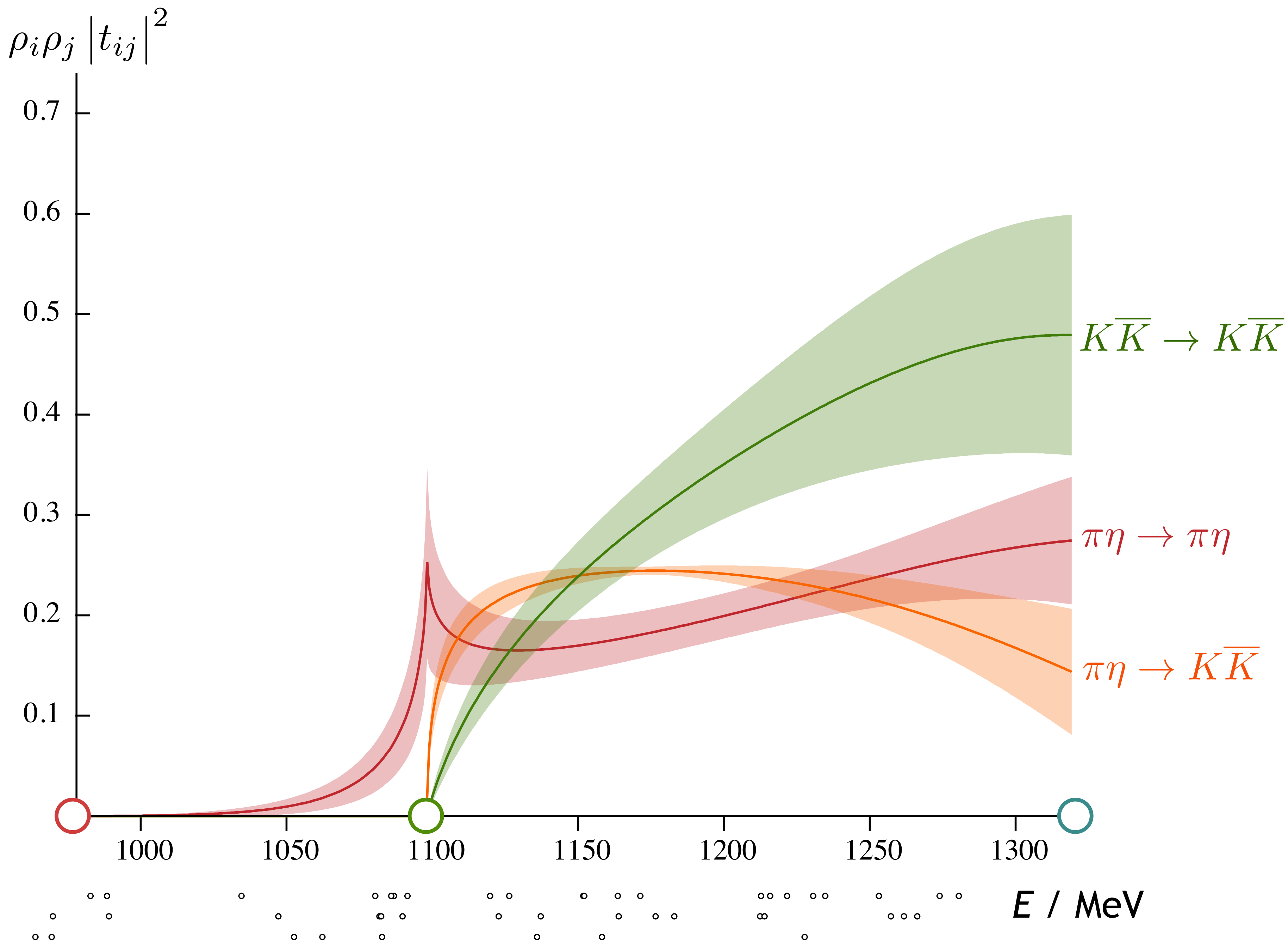
first calculation — unphysically heavy u,d quarks

m_π ~ 391 MeV
m_K ~ 549 MeV
m_η ~ 587 MeV

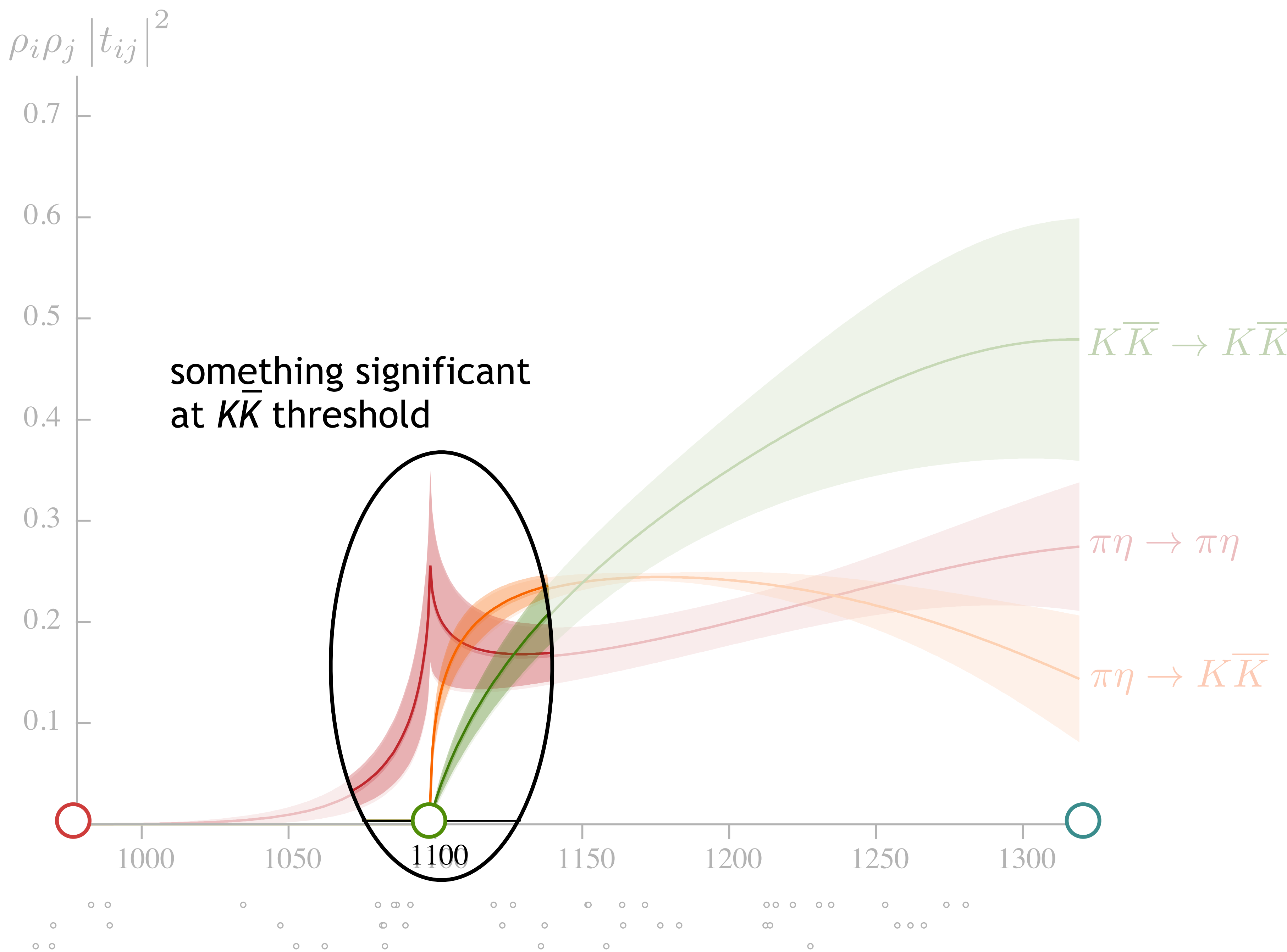




πη/KK̄ coupled-channel scattering amplitudes



πη/K$\bar{K}$ coupled-channel scattering amplitudes



is there a resonance causing this ?

$\pi\eta/K\bar{K}$ scattering — the a_0 resonance

a **resonance** can be rigorously defined to be a **pole singularity** at a **complex energy**

$$t_{ij}(E) \sim \frac{c_i\, c_j}{E_0^2 - E^2}$$

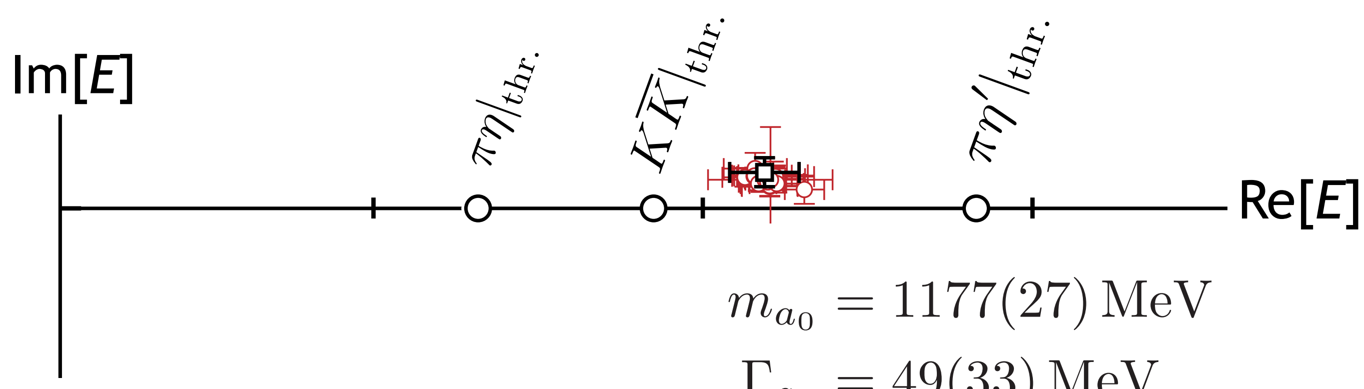
with pole position $E_0 = m_R \pm i\frac{1}{2}\Gamma_R$

a **resonance** can be rigorously defined to be a **pole singularity** at a **complex energy**

$$t_{ij}(E) \sim \frac{c_i\, c_j}{E_0^2 - E^2}$$

with pole position $E_0 = m_R \pm i\frac{1}{2}\Gamma_R$

pole position



$$m_{a_0} = 1177(27)\,\mathrm{MeV}$$
$$\Gamma_{a_0} = 49(33)\,\mathrm{MeV}$$

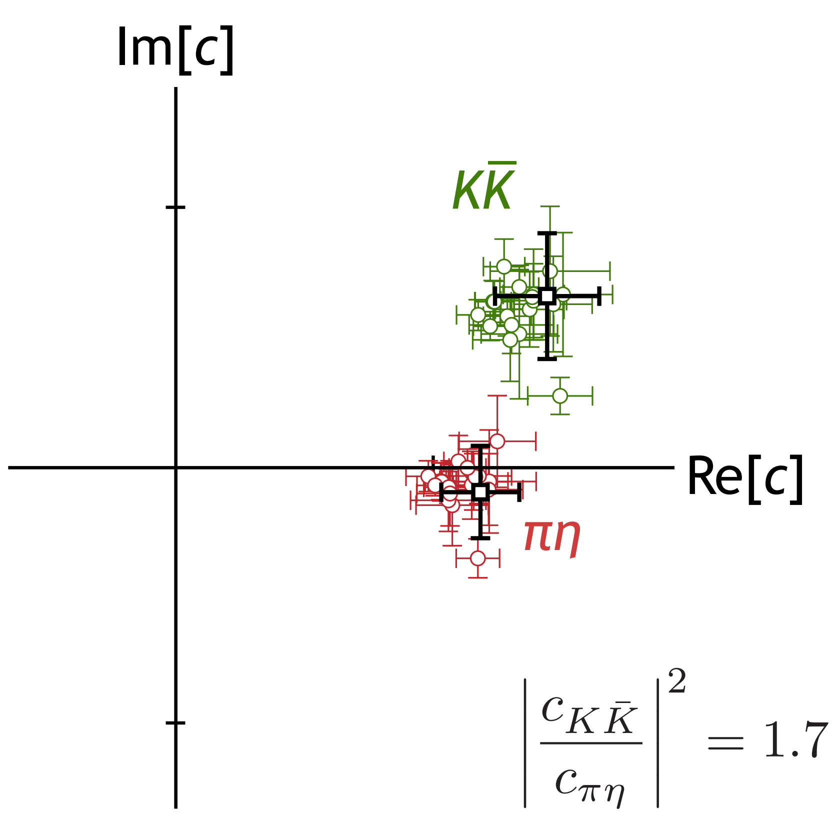
$\pi\eta / K\bar{K}$ scattering — the a_0 resonance

a **resonance** can be rigorously defined to be a **pole singularity** at a **complex energy**

$$t_{ij}(E) \sim \frac{c_i\, c_j}{E_0^2 - E^2}$$

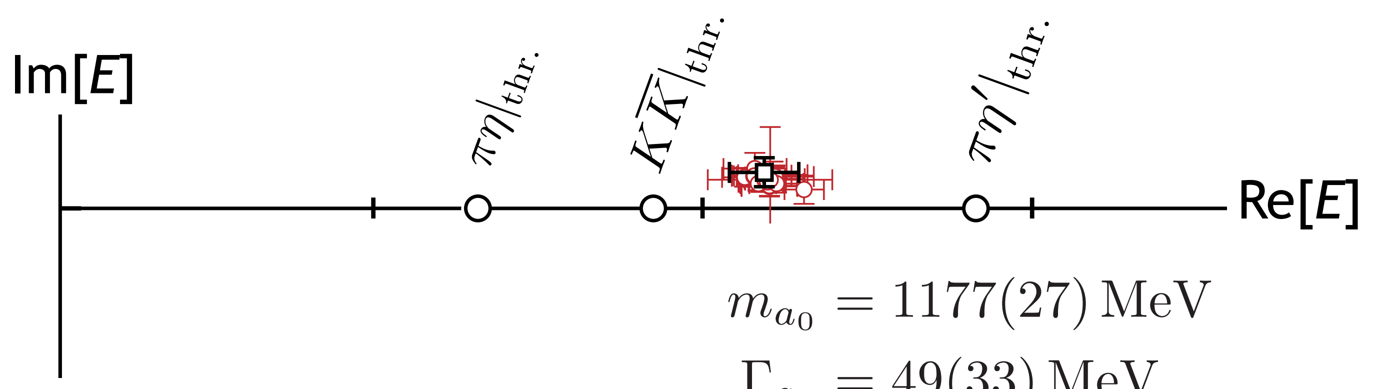
with pole position $\quad E_0 = m_R \pm i\tfrac{1}{2}\Gamma_R$

resonance couplings



$$\left|\frac{c_{K\bar{K}}}{c_{\pi\eta}}\right|^2 = 1.7(6)$$

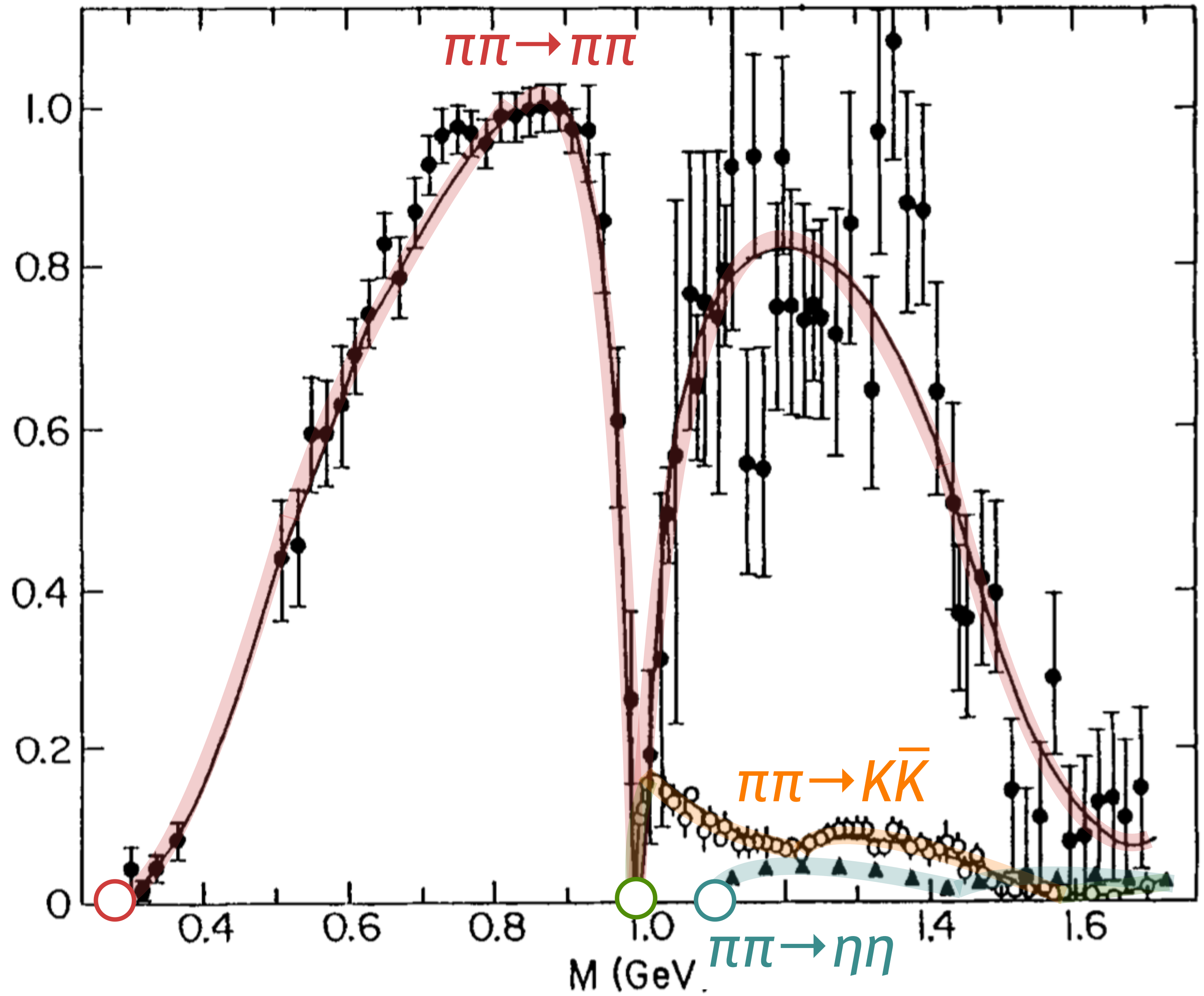
pole position



$$m_{a_0} = 1177(27)\,\text{MeV}$$
$$\Gamma_{a_0} = 49(33)\,\text{MeV}$$

$\pi\pi$, $K\bar{K}$, $\eta\eta$ scattering

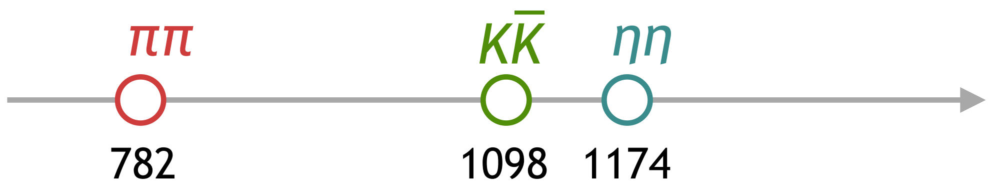
experimental amplitudes



combination of broad σ resonance and narrow $f_0(980)$ at $K\bar{K}$ threshold

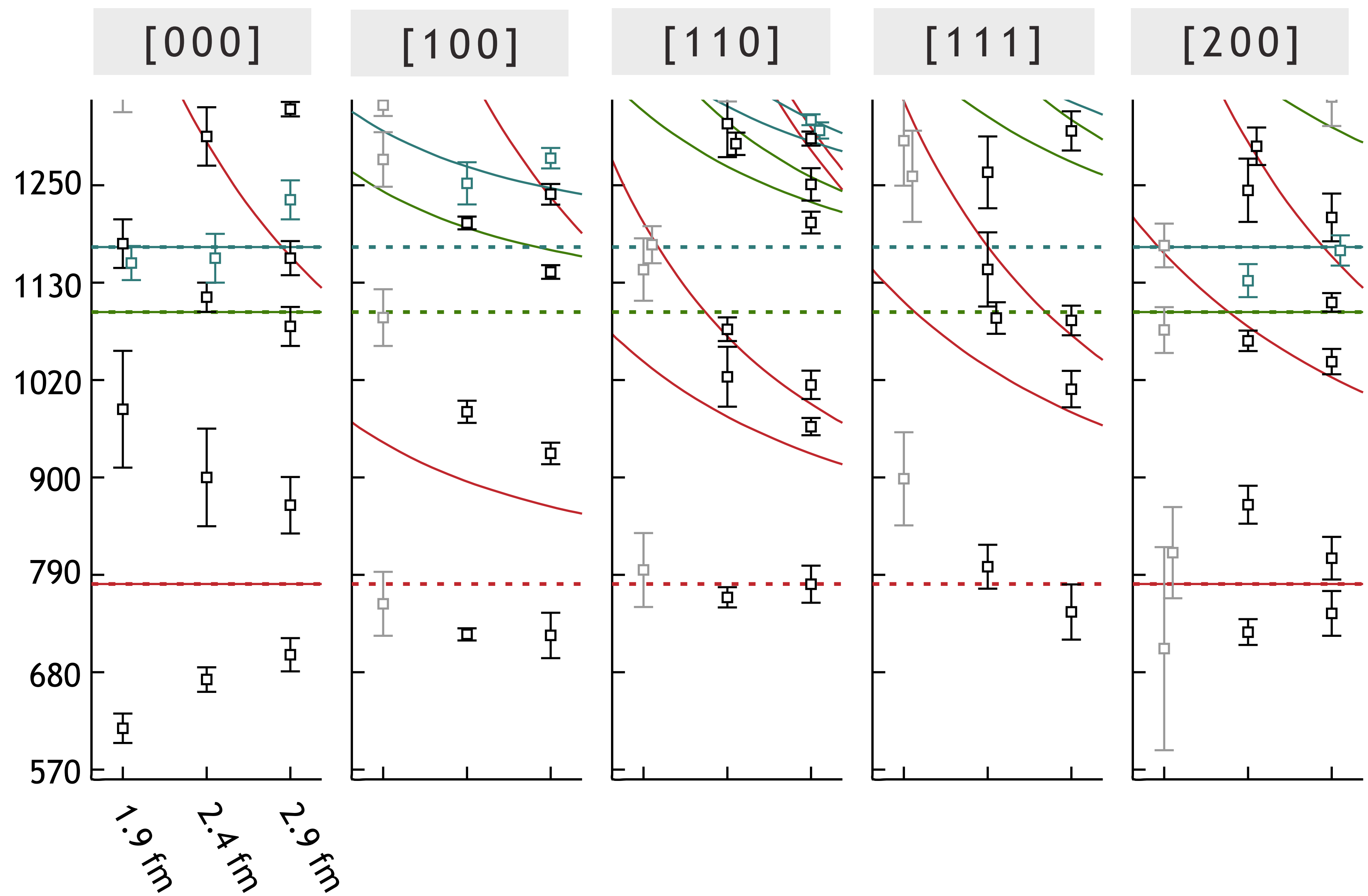
$\pi\pi$, $K\bar{K}$, $\eta\eta$ scattering in lattice QCD

m_π ~ 391 MeV
m_K ~ 549 MeV
m_η ~ 587 MeV



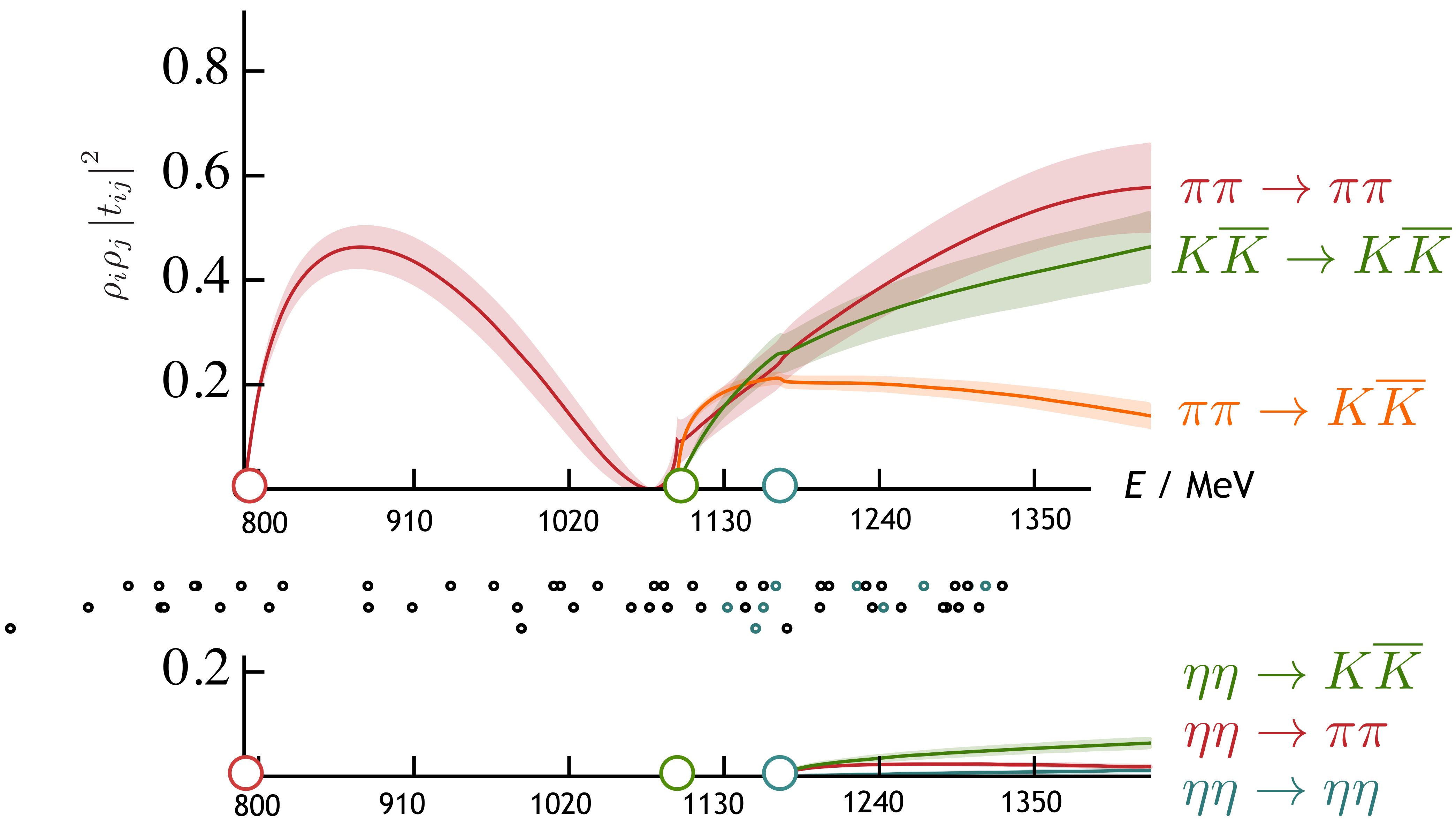
considerable elastic region

three-channel almost immediate



m_π ~ 391 MeV
m_K ~ 549 MeV
m_η ~ 587 MeV

ππ/KK̄/ηη coupled-channel scattering amplitudes

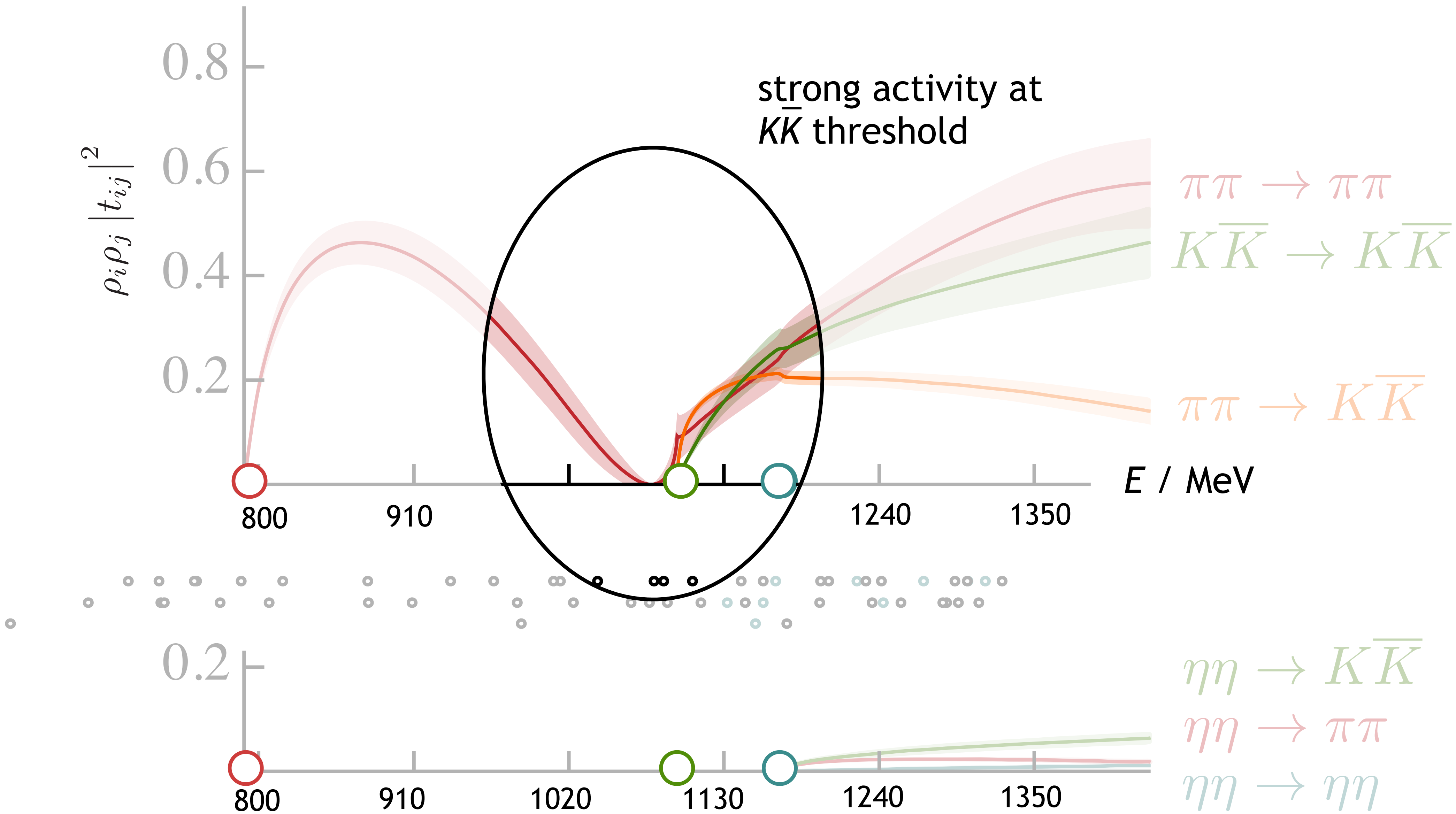


nothing much happening in $\eta\eta$

$\pi\pi$, $K\bar{K}$, $\eta\eta$ scattering in lattice QCD

m_π ~ 391 MeV
m_K ~ 549 MeV
m_η ~ 587 MeV

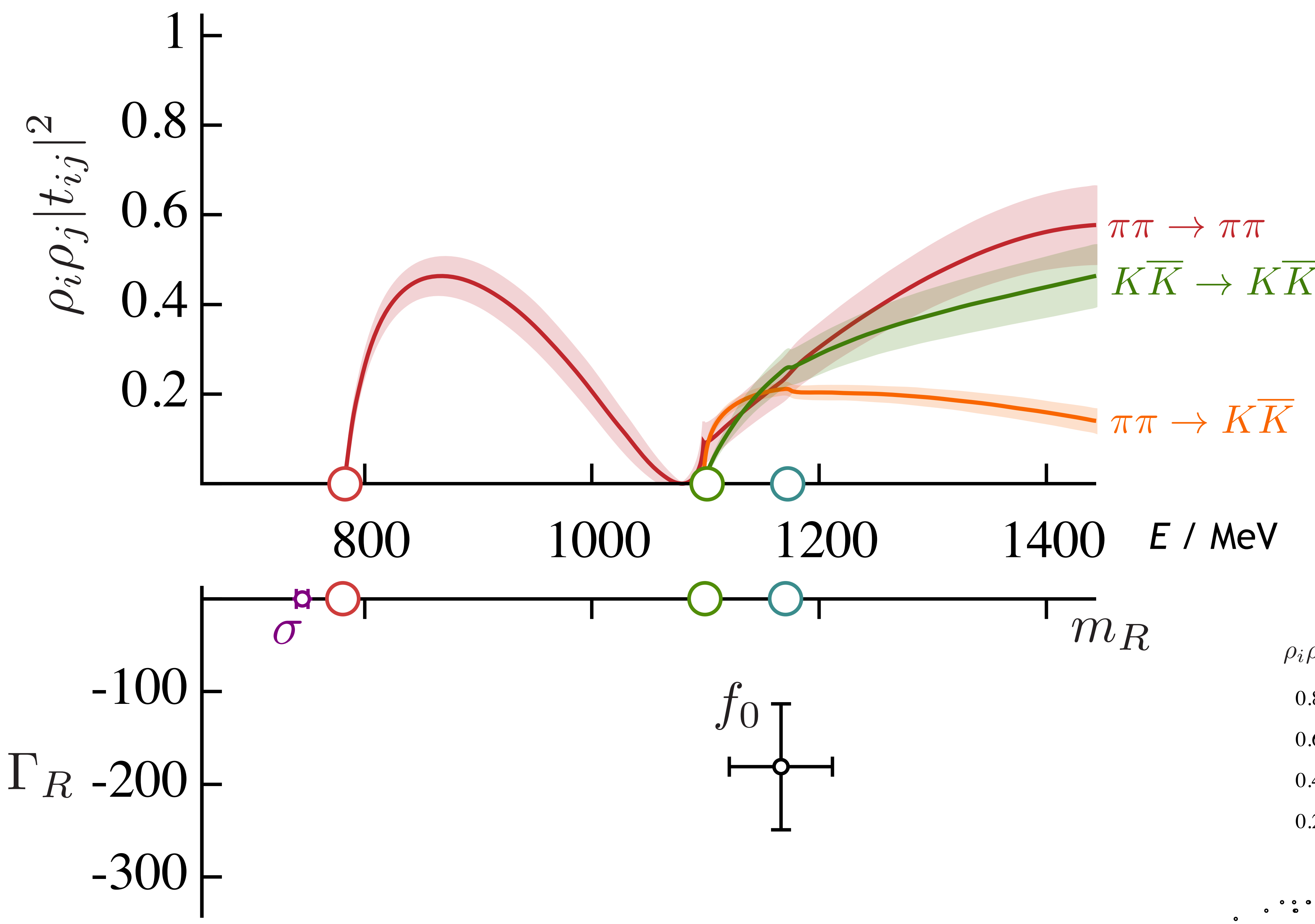
$\pi\pi / K\bar{K} / \eta\eta$ coupled-channel scattering amplitudes

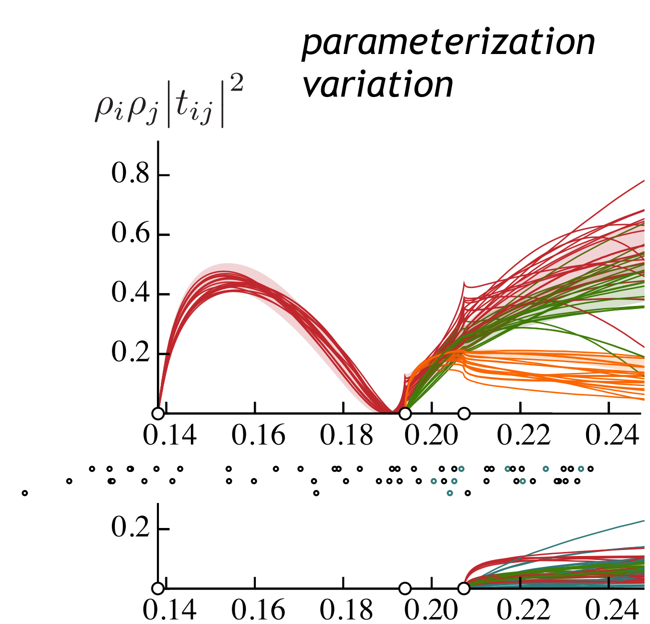


$\pi\pi$, $K\bar{K}$, $\eta\eta$ scattering in lattice QCD

m_π ~ 391 MeV
m_K ~ 549 MeV
m_η ~ 587 MeV

ππ/KK̄/ηη coupled-channel scattering amplitudes

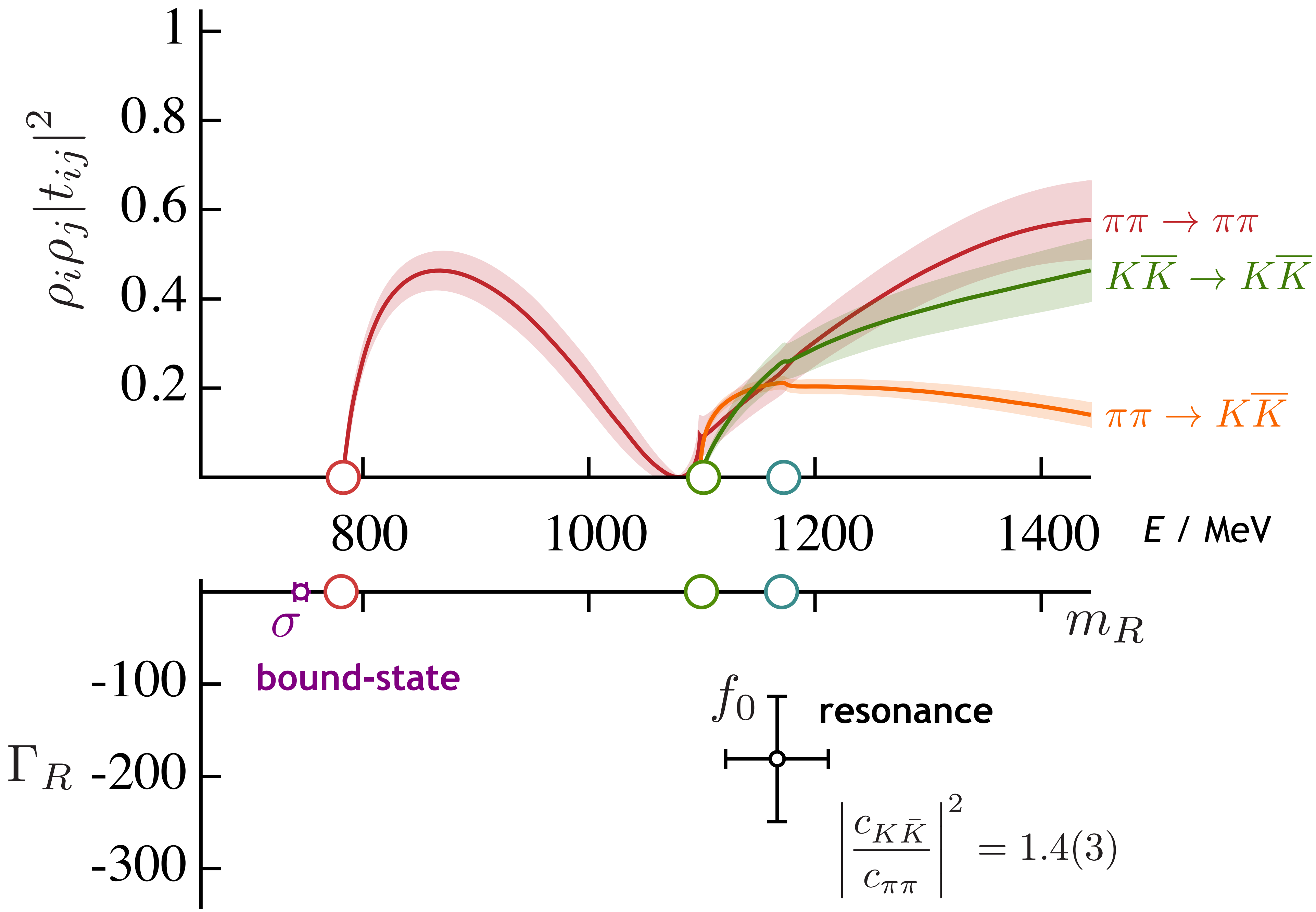




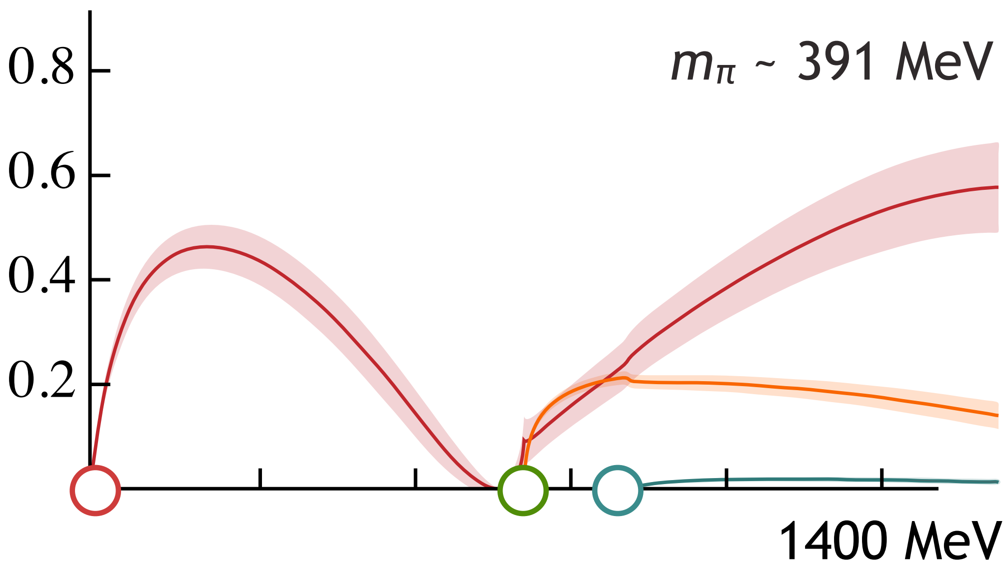
$\pi\pi$, $K\bar{K}$, $\eta\eta$ scattering in lattice QCD

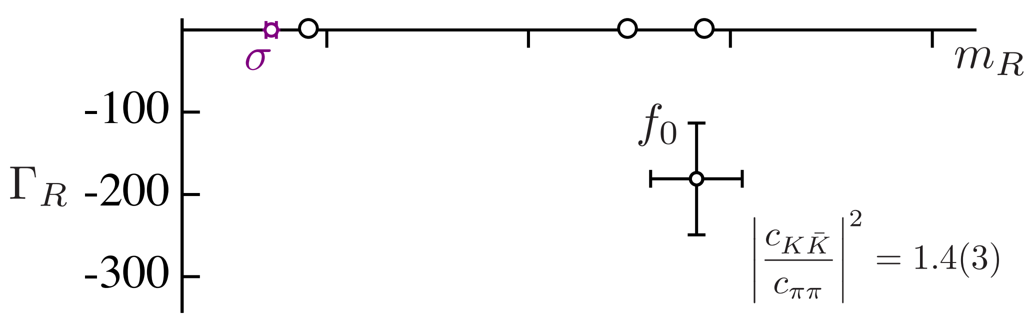
m_π ~ 391 MeV
m_K ~ 549 MeV
m_η ~ 587 MeV

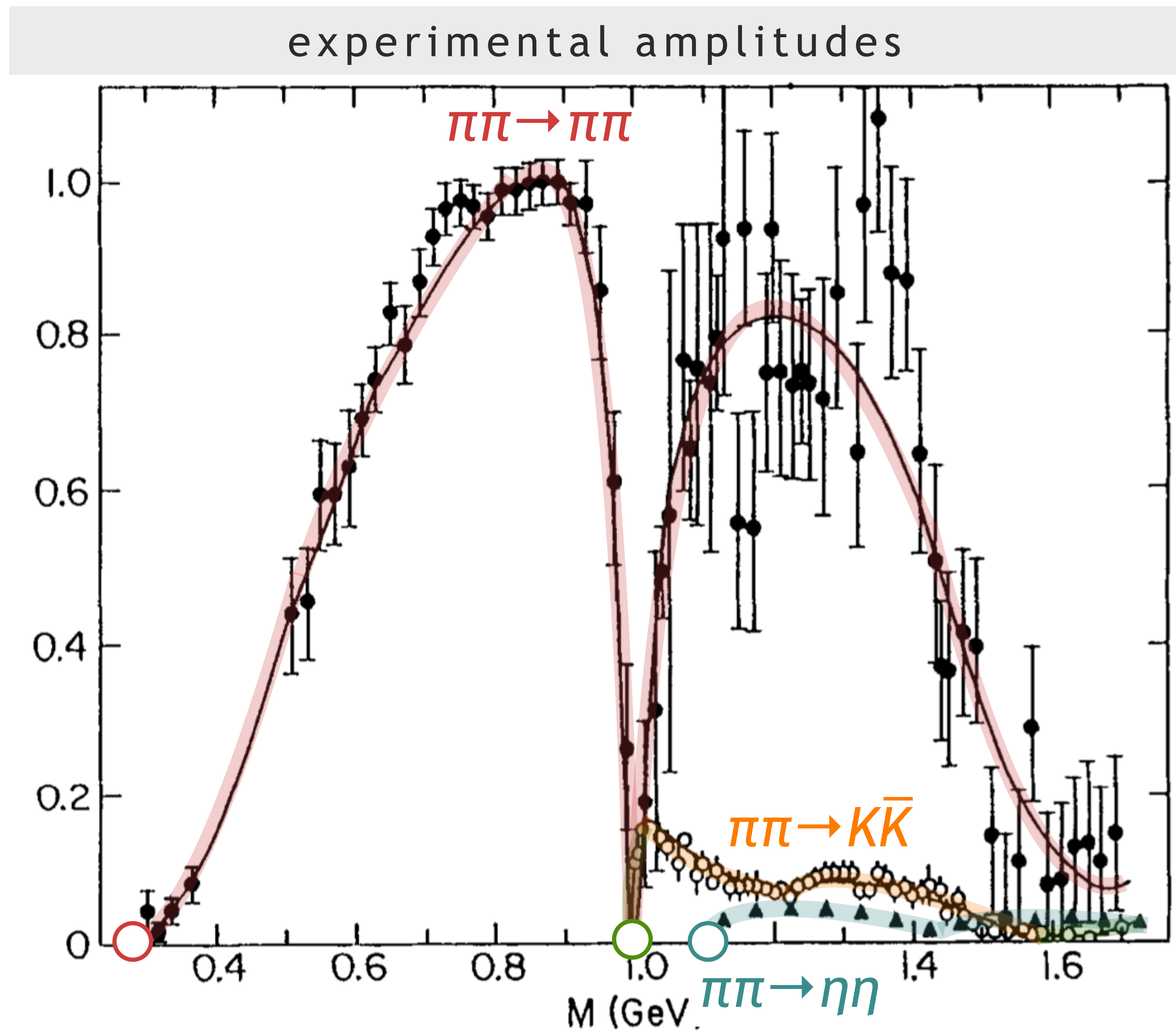
$\pi\pi/K\bar{K}/\eta\eta$ coupled-channel scattering amplitudes



$\pi\pi$, $K\bar{K}$, $\eta\eta$ scattering







$f_0(500)$ or σ [g]
was $f_0(600)$

$I^G(J^{PC}) = 0^+(0^{++})$

Mass $m = (400\text{–}550)$ MeV
Full width $\Gamma = (400\text{–}700)$ MeV

$f_0(980)$ [j]

$I^G(J^{PC}) = 0^+(0^{++})$

Mass $m = 990 \pm 20$ MeV
Full width $\Gamma = 10$ to 100 MeV

coupled-channel resonances — status

have demonstrated presence of coupled-channel resonances in (lattice) QCD

at unphysical quark masses initially

can determine pole positions (mass, width) and couplings to decay channels

would like to know if there're simple ways to 'understand' them

e.g. big differences between **scalar**, **vector**, **tensor** mesons

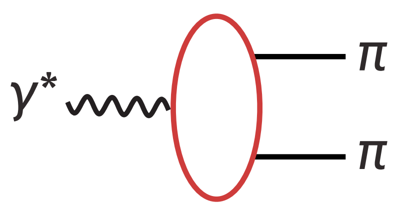
long-standing ideas of $q\bar{q}$ versus $qq\overline{qq}$ versus **meson-meson molecules**

one possible approach to this

— consider their couplings to external currents ...

coupling resonances to currents

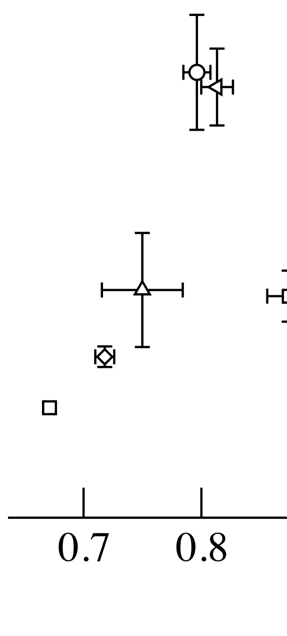
$\gamma^* \rightarrow \pi\pi$



$F_\pi(E_{\pi\pi})$

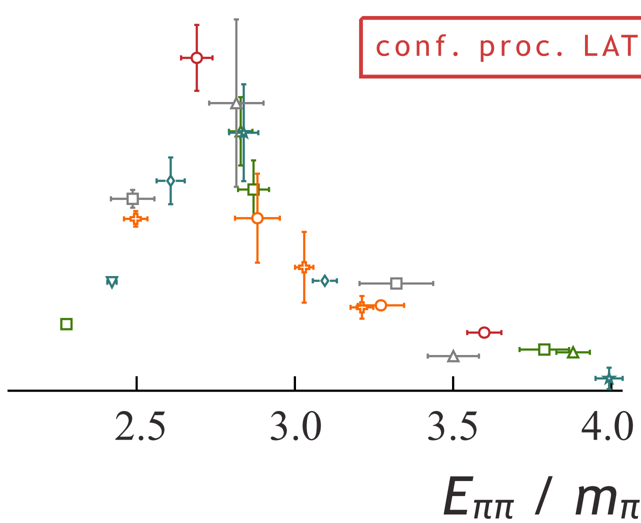
Feng et al | *u,d,s* | m_π~290 MeV

PRD97 054513 (2018)

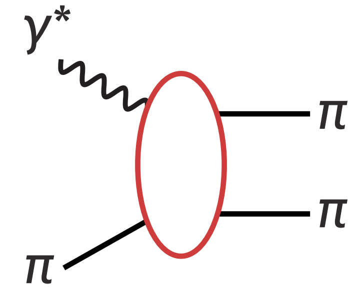


Bulava et al | *u,d,s* | m_π~280 MeV

conf. proc. LAT '15



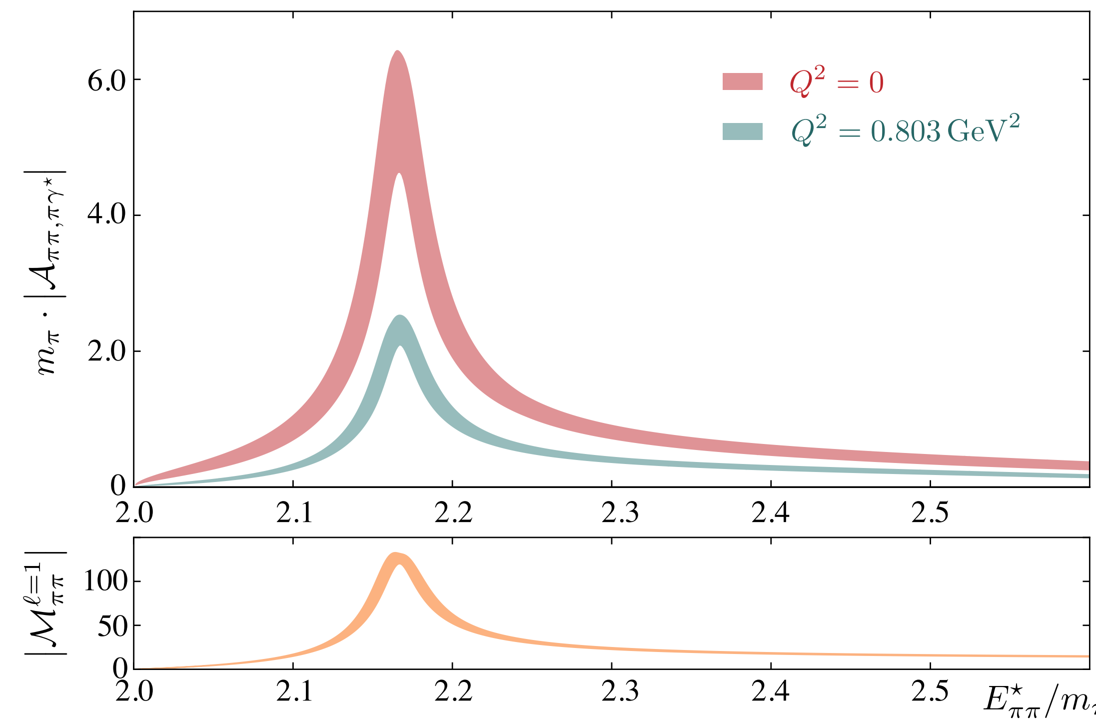
$\gamma^* \pi \rightarrow \pi\pi$

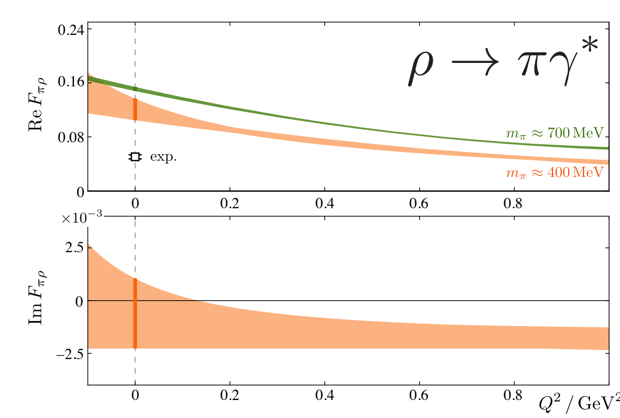


$\mathcal{A}(E_{\pi\pi}, Q^2)$

Briceno et al | *u,d,s* | m_π~391 MeV

PRL115 242001 (2015)





opportunities, challenges

addressing the new observations in charmonium (XYZ)

— challenging, often lie above several thresholds ⇒ multiple coupled channels

predicting resonant properties of hybrid hadrons

— preferred decay modes, couplings to photons (relevant to GlueX, see next talk)

(finally) understanding the scalar mesons ?

— studying their behaviour with changing quark mass, evaluating their form-factors …

⋮

a big current challenge is the importance of **three-body final states**

— lack of a complete finite-volume formalism so far

thank you

recent pedagogic review

REVIEWS OF MODERN PHYSICS, VOLUME 90, APRIL–JUNE 2018

Scattering processes and resonances from lattice QCD

Raúl A. Briceño[*]

Thomas Jefferson National Accelerator Facility,
12000 Jefferson Avenue, Newport News, Virginia 23606, USA
and Department of Physics, Old Dominion University, Norfolk, Virginia 23529, USA

Jozef J. Dudek[†]

Thomas Jefferson National Accelerator Facility,
12000 Jefferson Avenue, Newport News, Virginia 23606, USA
and Department of Physics, College of William and Mary, Williamsburg, Virginia 23187, USA

Ross D. Young[‡]

Special Research Center for the Subatomic Structure of Matter (CSSM),
Department of Physics, University of Adelaide, Adelaide 5005, Australia

(published 18 April 2018)

The vast majority of hadrons observed in nature are not stable under the strong interaction; rather they are resonances whose existence is deduced from enhancements in the energy dependence of scattering amplitudes. The study of hadron resonances offers a window into the workings of quantum chromodynamics (QCD) in the low-energy nonperturbative region, and in addition many probes of the limits of the electroweak sector of the standard model consider processes which feature hadron resonances. From a theoretical standpoint, this is a challenging field: the same dynamics that binds quarks and gluons into hadron resonances also controls their decay into lighter hadrons, so a complete approach to QCD is required. Presently, lattice QCD is the only available tool that provides the required nonperturbative evaluation of hadron observables. This article reviews progress in the study of few-hadron reactions in which resonances and bound states appear using lattice QCD techniques. The leading approach is described that takes advantage of the periodic finite spatial volume used in lattice QCD calculations to extract scattering amplitudes from the discrete spectrum of QCD eigenstates in a box. An explanation is given of how from explicit lattice QCD calculations one can rigorously garner information about a variety of resonance properties, including their masses, widths, decay couplings, and form factors. The challenges which currently limit the field are discussed along with the steps being taken to resolve them.

DOI: 10.1103/RevModPhys.90.025001