hadron spectroscopy – theory

Jozef Dudek

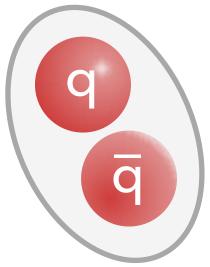
(will focus on mesons due to limited time)

William & Mary
CHARTERED 1693

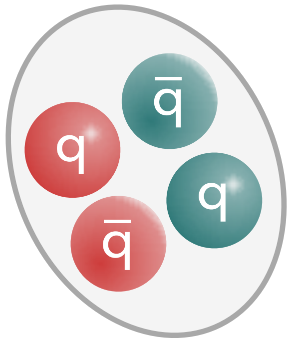
Jefferson Lab
Thomas Jefferson National Accelerator Facility

meson spectroscopy

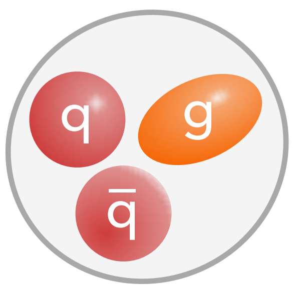
“pictures”



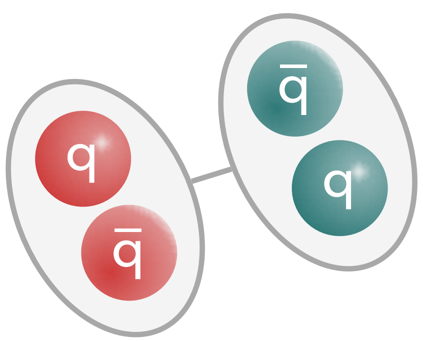
conventional meson



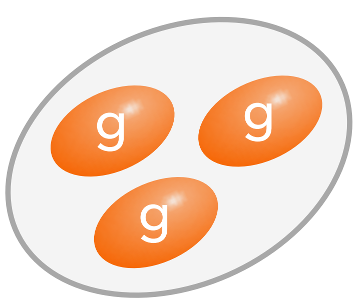
tetraquark



hybrid meson



meson-meson molecule



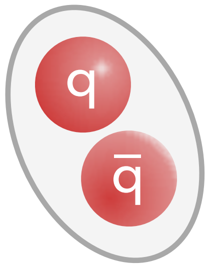
glueball

+ other suggestions …

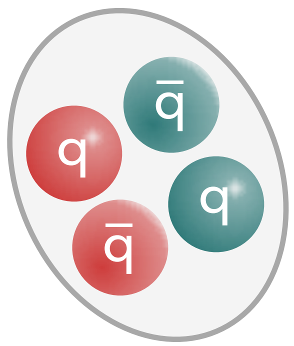
traditionally the preserve of **modeling**
– connection to QCD unclear

meson spectroscopy

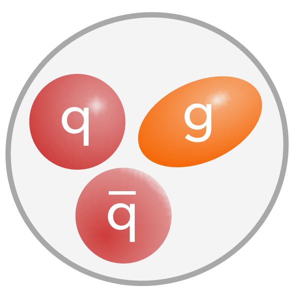
"pictures"



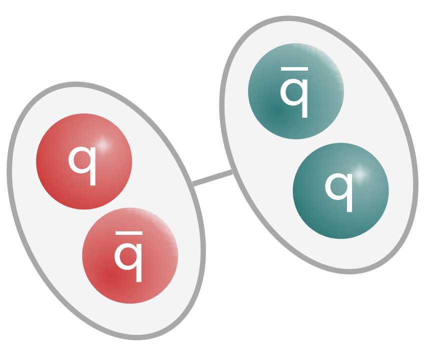
conventional meson



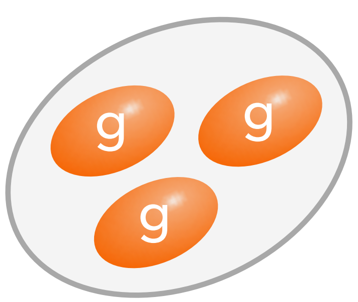
tetraquark



hybrid meson



meson-meson molecule



glueball

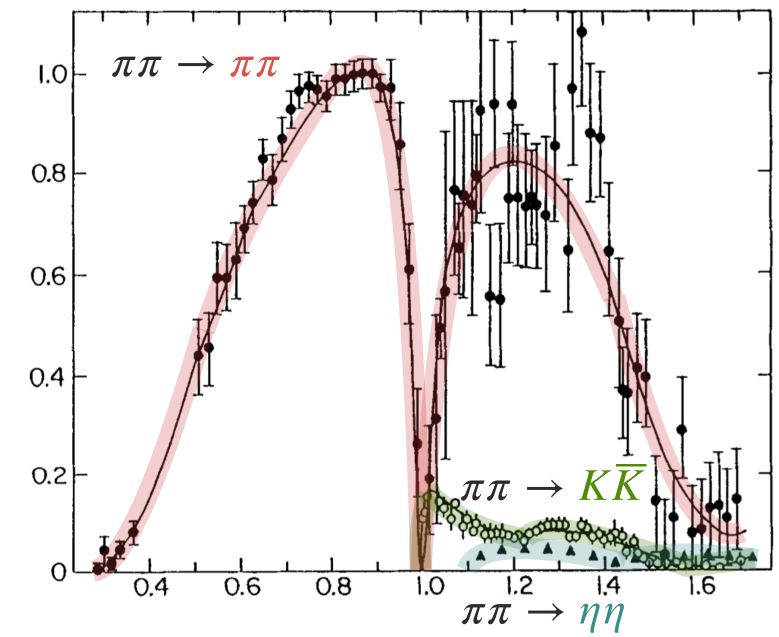
+ other suggestions …

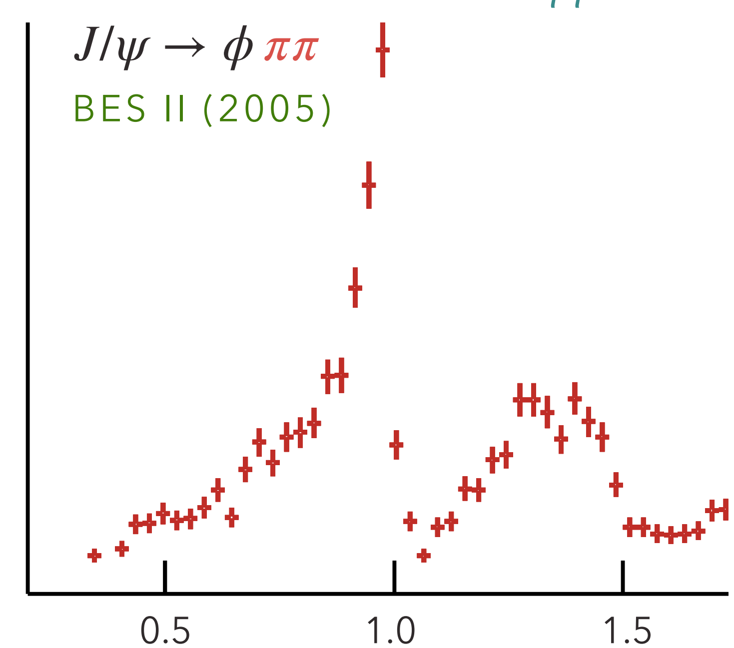
traditionally the preserve of **modeling**
– connection to QCD unclear

"reality"

resonances in complicated production/decay

e.g. $f_0(980)$





amplitudes in terms of scattering **stable hadrons**
– connection to QCD unclear

meson spectroscopy

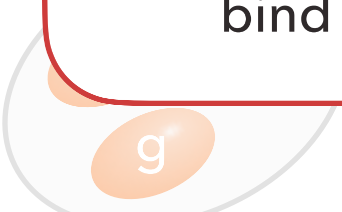
"pictures"

conventional meson

tetraquark

hybrid meson

meson-meson molecule

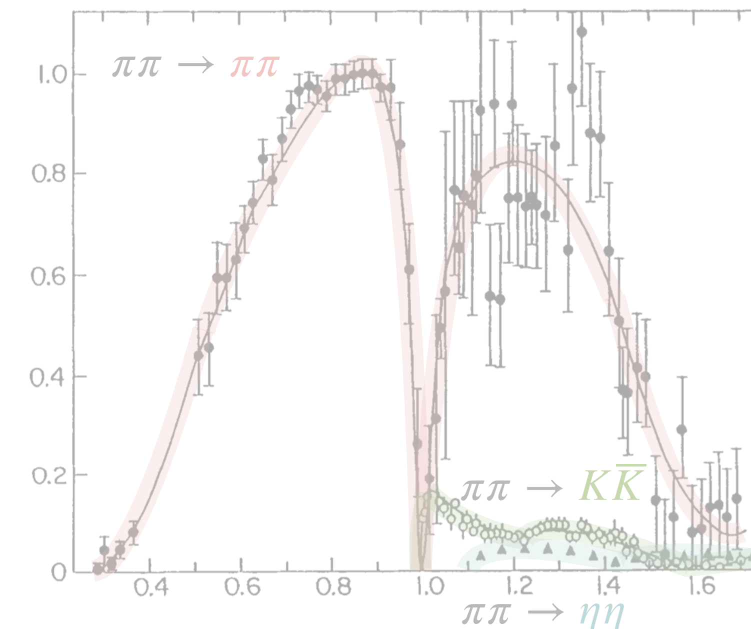


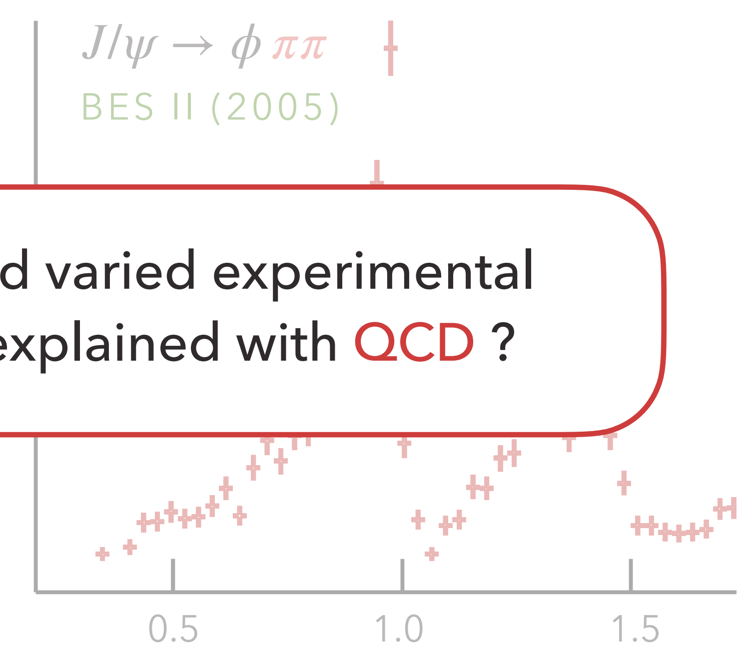
in what configurations does QCD bind quarks and gluons ?

"reality"

resonances in complicated production/decay

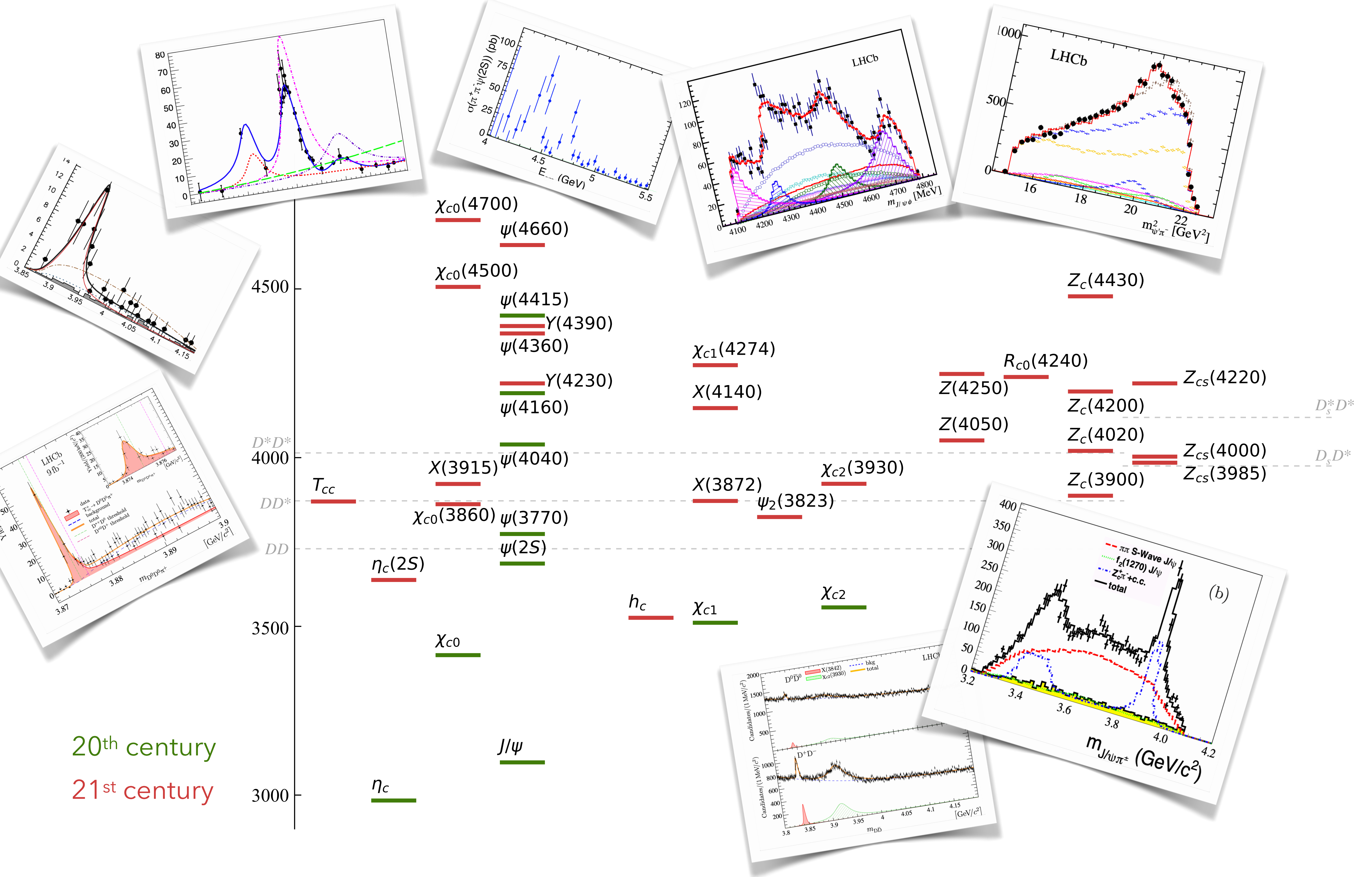
e.g. $f_0(980)$





can complex and varied experimental amplitudes be explained with QCD ?

renewed motivation – the XYZ explosion



theory technology

nonperturbative
numerical approach

respecting fundamental constraints:
unitarity, causality, crossing …

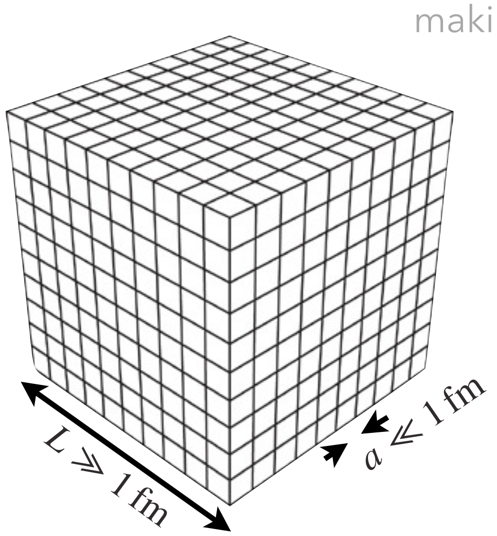
lattice QCD


$\mathscr{L}_{\text{QCD}}$
lattice QCD
amplitude analysis
experimental data

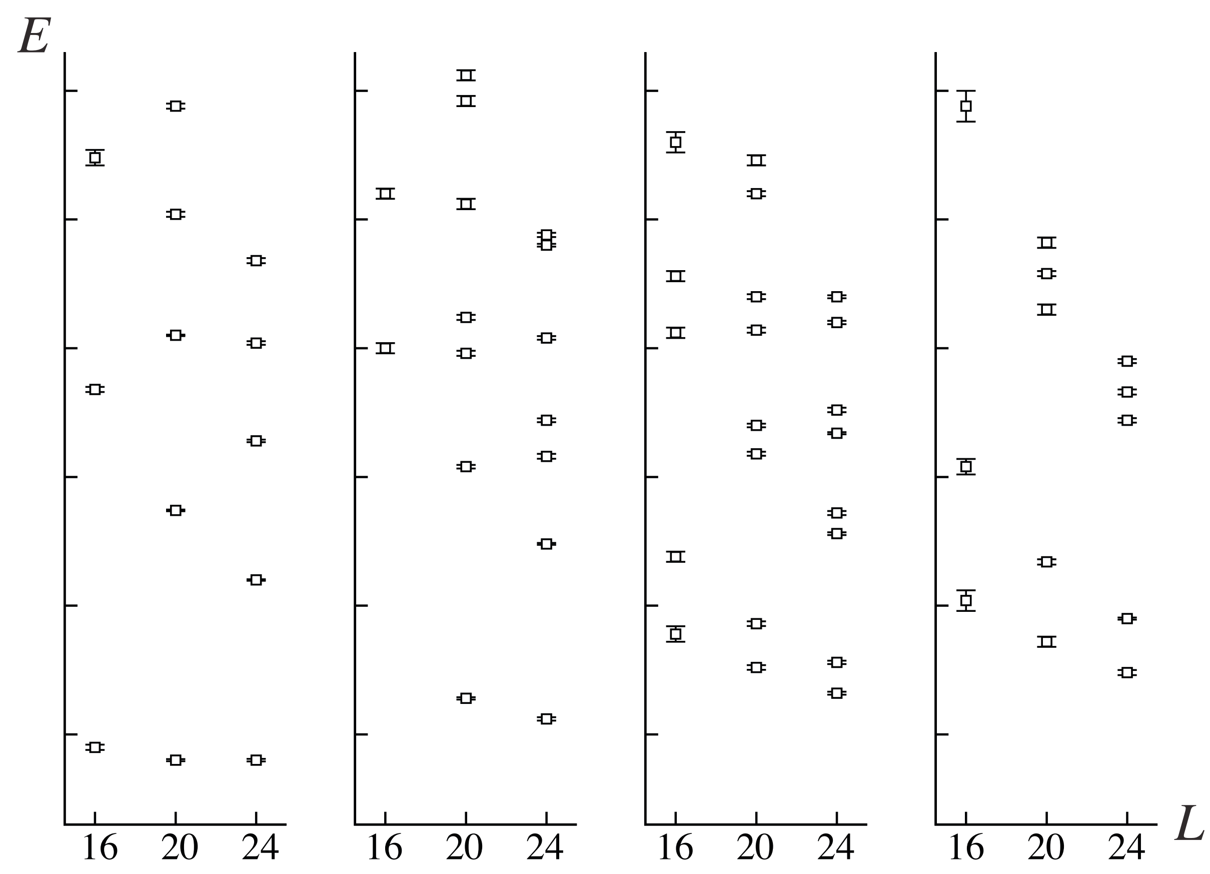
respecting fundamental constraints:
unitarity, causality, crossing …

discretize in a finite space-time

making only controlled approximations



extract discrete spectra from computed correlation functions



volume dependence maps to scattering amplitudes

lattice QCD – scattering amplitudes in finite–volume

rigorous relation between
discrete spectrum in a finite-volume, $E_n(L)$
and coupled-channel scattering amplitudes, $\mathbf{t}(E)$

$E_n(L)$ are discrete solutions of

$$0 = \det\left[\,\mathbf{t}(E) + \mathbf{F}(E,L)\,\right]$$

known functions

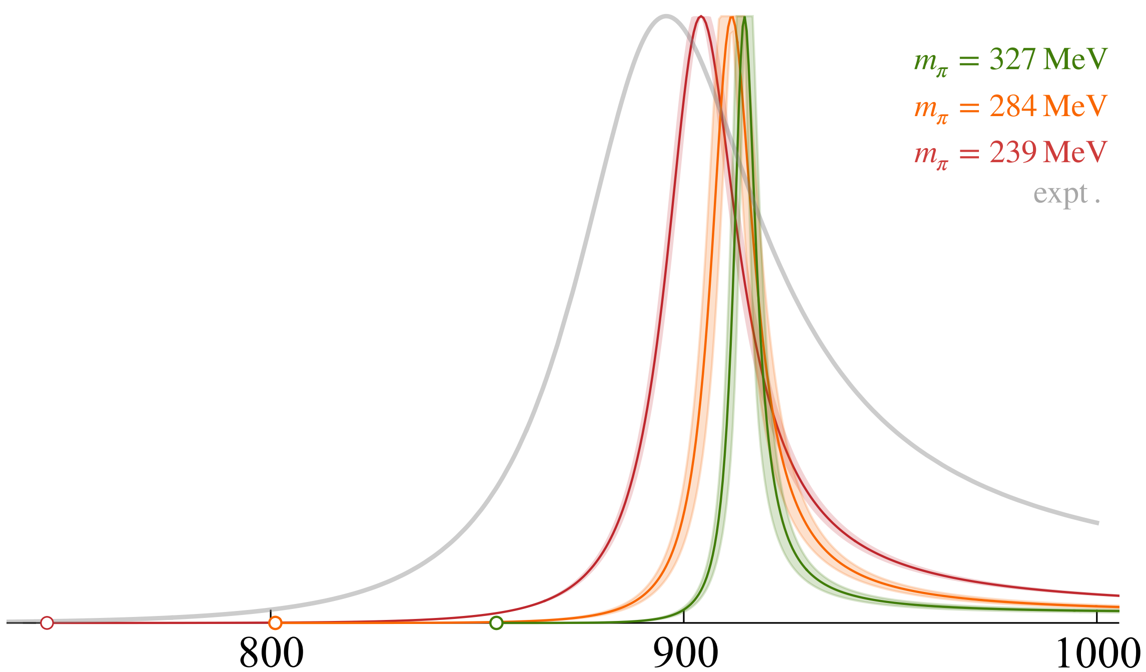
Lüscher & many others

lattice QCD – scattering amplitudes in finite–volume

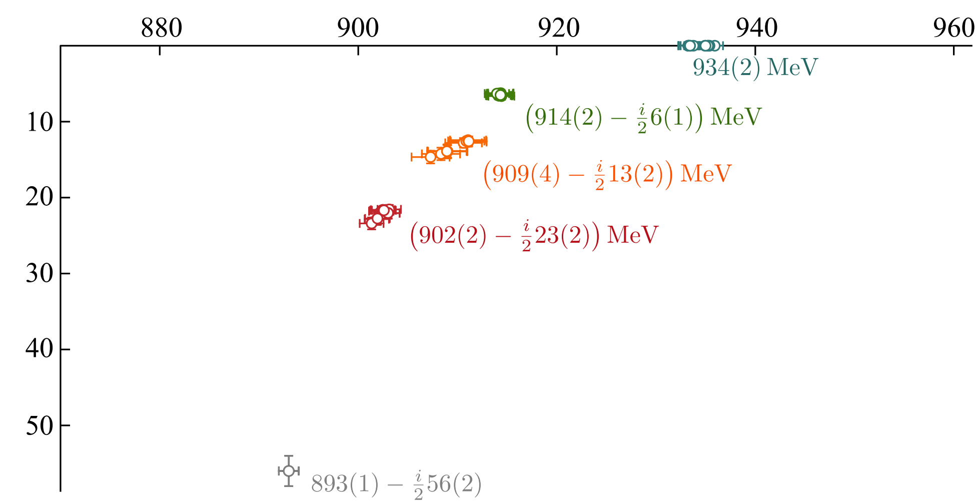
rigorous relation between
discrete spectrum in a finite-volume, $E_n(L)$
and coupled-channel scattering amplitudes, $\mathbf{t}(E)$

$$0 = \det\left[\, \mathbf{t}(E) + \mathbf{F}(E,L) \,\right]$$

e.g. $\pi K \to \pi K \quad J^P = 1^-$ elastic scattering PRL 123 042002 (2019)



K^* resonance pole position



evolution of the K^* resonance as a function of varying light quark mass

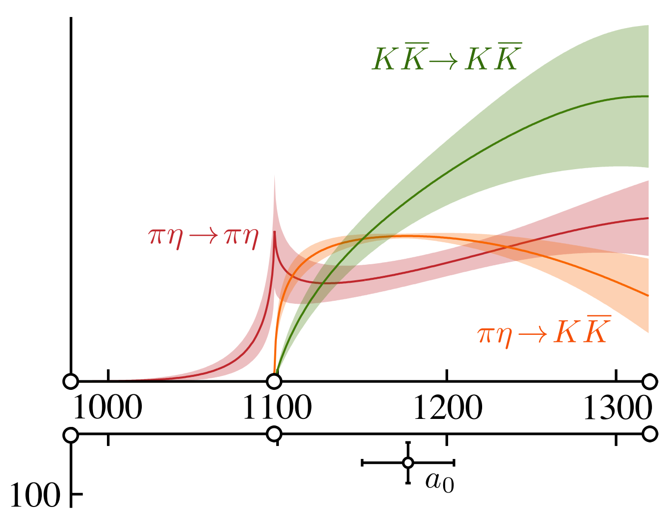
lattice QCD – scattering amplitudes in finite–volume

rigorous relation between
discrete spectrum in a finite-volume, $E_n(L)$
and **coupled-channel** scattering amplitudes, $\mathbf{t}(E)$

$$0 = \det\left[\,\mathbf{t}(E) + \mathbf{F}(E,L)\,\right]$$

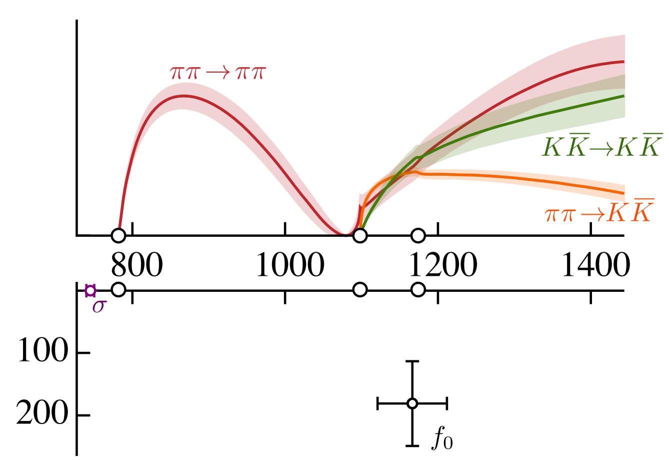
parameterize **coupled-channel** $\mathbf{t}(E)$ and describe lattice spectra

$J^P = 0^+\ I^G = 1^-\ (\eta\pi, K\bar{K})$

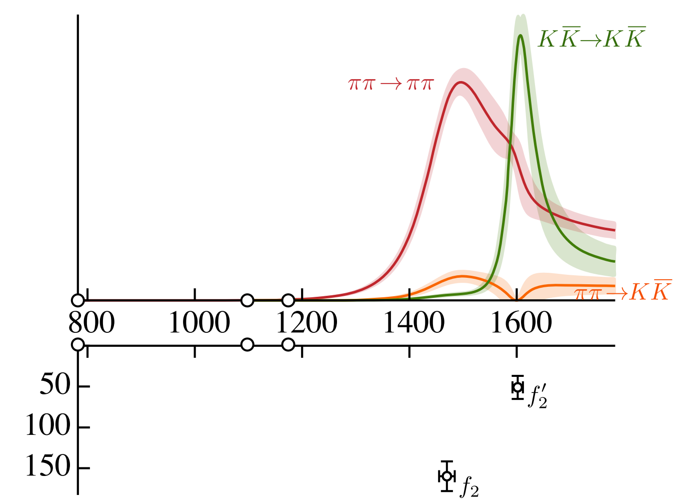


PRD 93 094506 (2016)

$J^P = 0^+\ I^G = 0^+\ (\pi\pi, K\bar{K}, \eta\eta)$

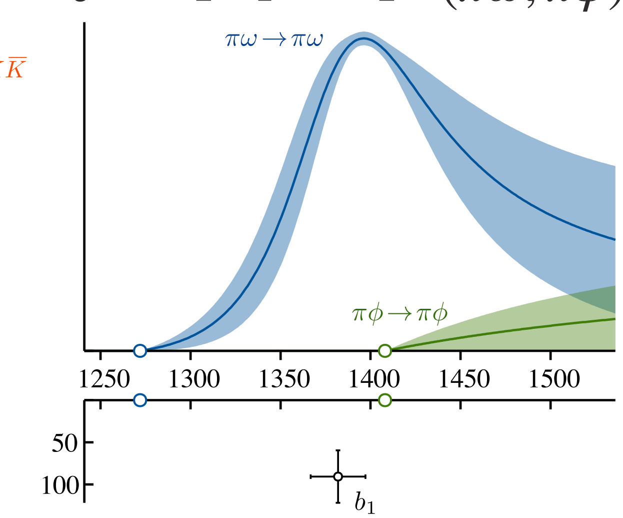


$J^P = 2^+\ I^G = 0^+\ (\pi\pi, K\bar{K}, \eta\eta)$



PRD 97 054513 (2018)

$J^P = 1^+\ I^G = 1^-\ (\pi\omega, \pi\phi)$



PRD 100 054506 (2019)

...

amplitude analysis

amplitude analysis

$\mathscr{L}_{\text{QCD}}$ → lattice QCD

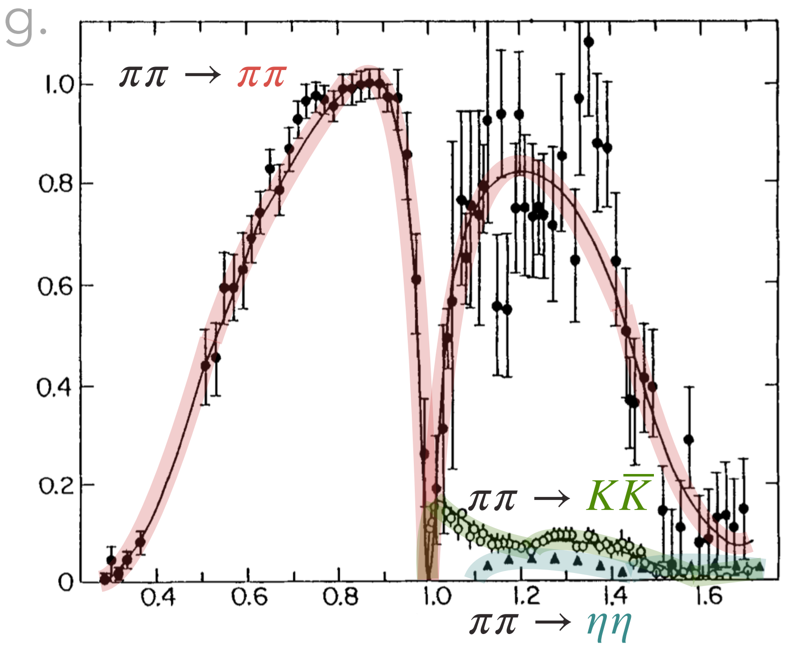
amplitude analysis ← experimental data

hadron scattering amplitudes

should satisfy generally true constraints: unitarity, analyticity/causality, crossing symmetry …

build relevant constraints into amplitudes used in analysis

e.g.



just summing Breit-Wigners will lead to incorrect results

needs coupled-channels, unitarity, correct threshold behavior

hadron scattering amplitudes

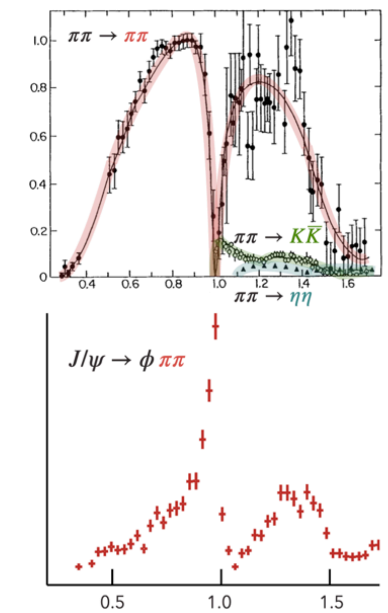
should satisfy generally true constraints: unitarity, analyticity/causality, crossing symmetry …

build relevant constraints into amplitudes used in analysis

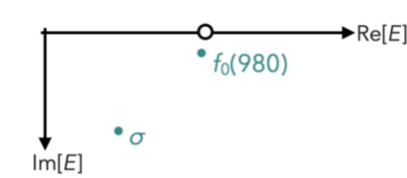
enhancements determined by singularities in the complex energy plane

rigorous determination of resonances as pole singularities

must have same location
in every process



same poles σ, $f_0(980)$
different couplings

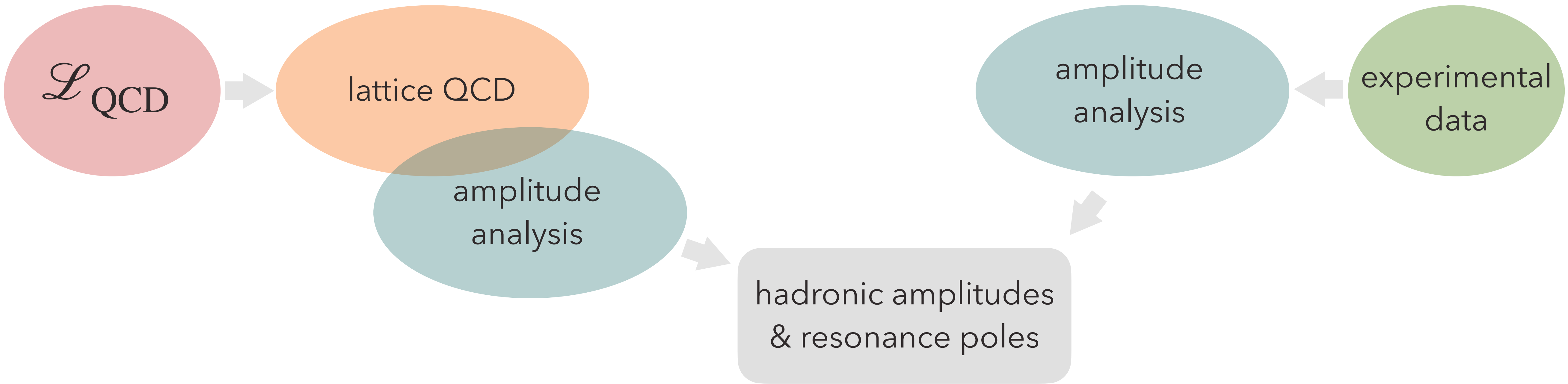


kinematical singularities, e.g. triangles in three-body

are process dependent

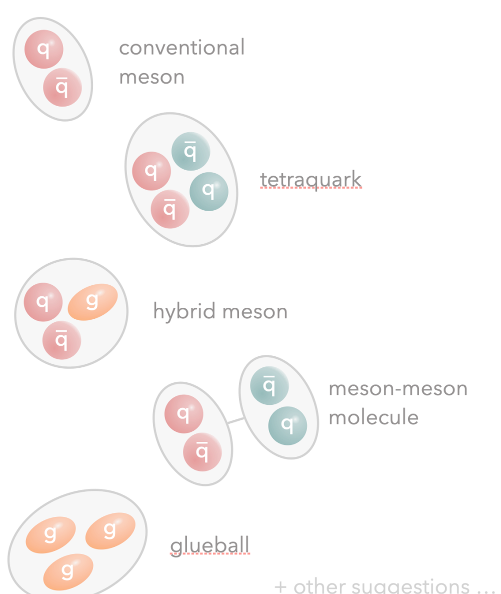
(may explain some XYZ inconsistencies)

modern hadron spectroscopy theory



robust connection made between real experiment & QCD

can "picture" assignments be made robust within QCD ?



there are ideas in this direction …

an example: the lightest exotic hybrid meson

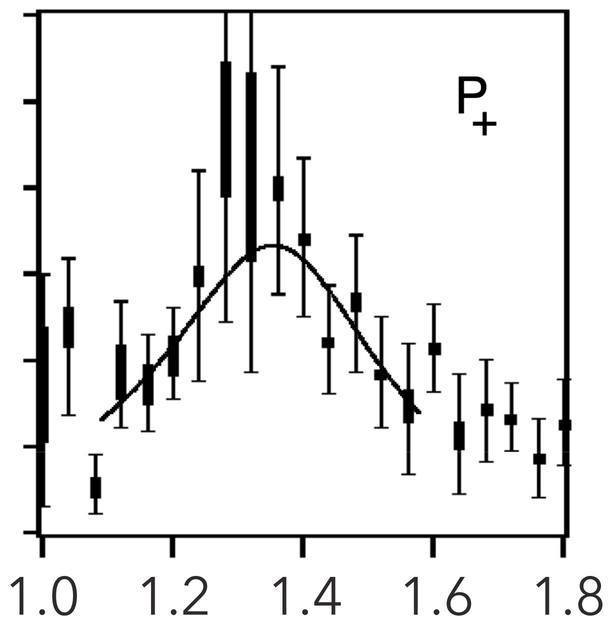
until recently, a confused situation:

$\boxed{\pi_1(1400)}$ $I^G(J^{PC}) = 1^-(1^{-+})$

Mass $m = 1354 \pm 25$ MeV
Full width $\Gamma = 330 \pm 35$ MeV

BNL e852 (1997)

$\pi^- p \to \eta\pi^- p$

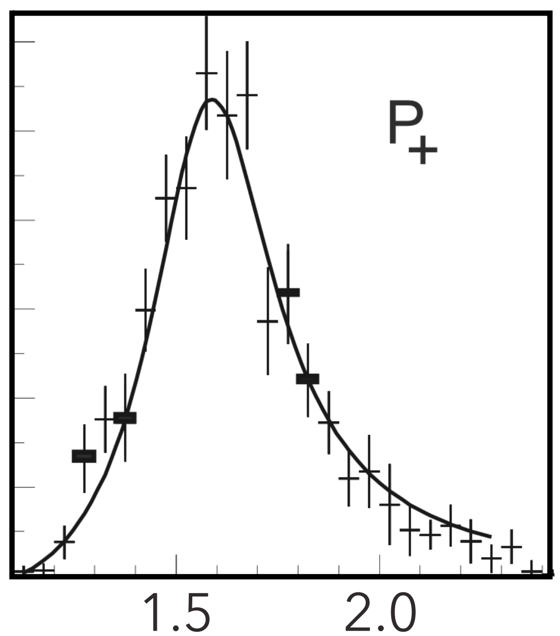


$\boxed{\pi_1(1600)}$ $I^G(J^{PC}) = 1^-(1^{-+})$

Mass $m = 1661^{+15}_{-11}$ MeV
Full width $\Gamma = 240 \pm 50$ MeV

BNL e852 (2001)

$\pi^- p \to \eta'\pi^- p$



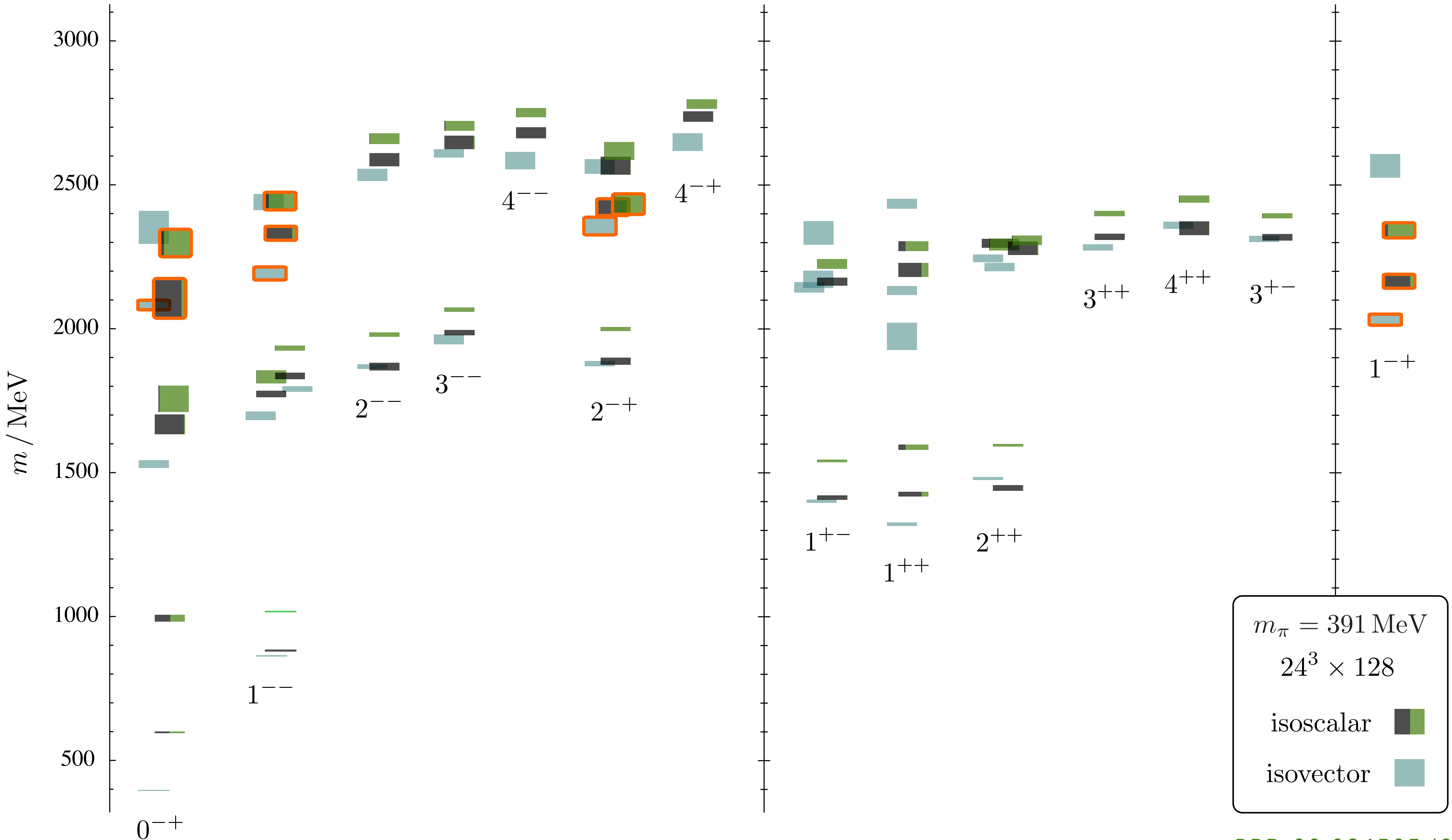
also seen in $\pi\rho$

two light states, where models predict only one ?

but models could be wrong ...

the lightest exotic hybrid meson – lattice QCD

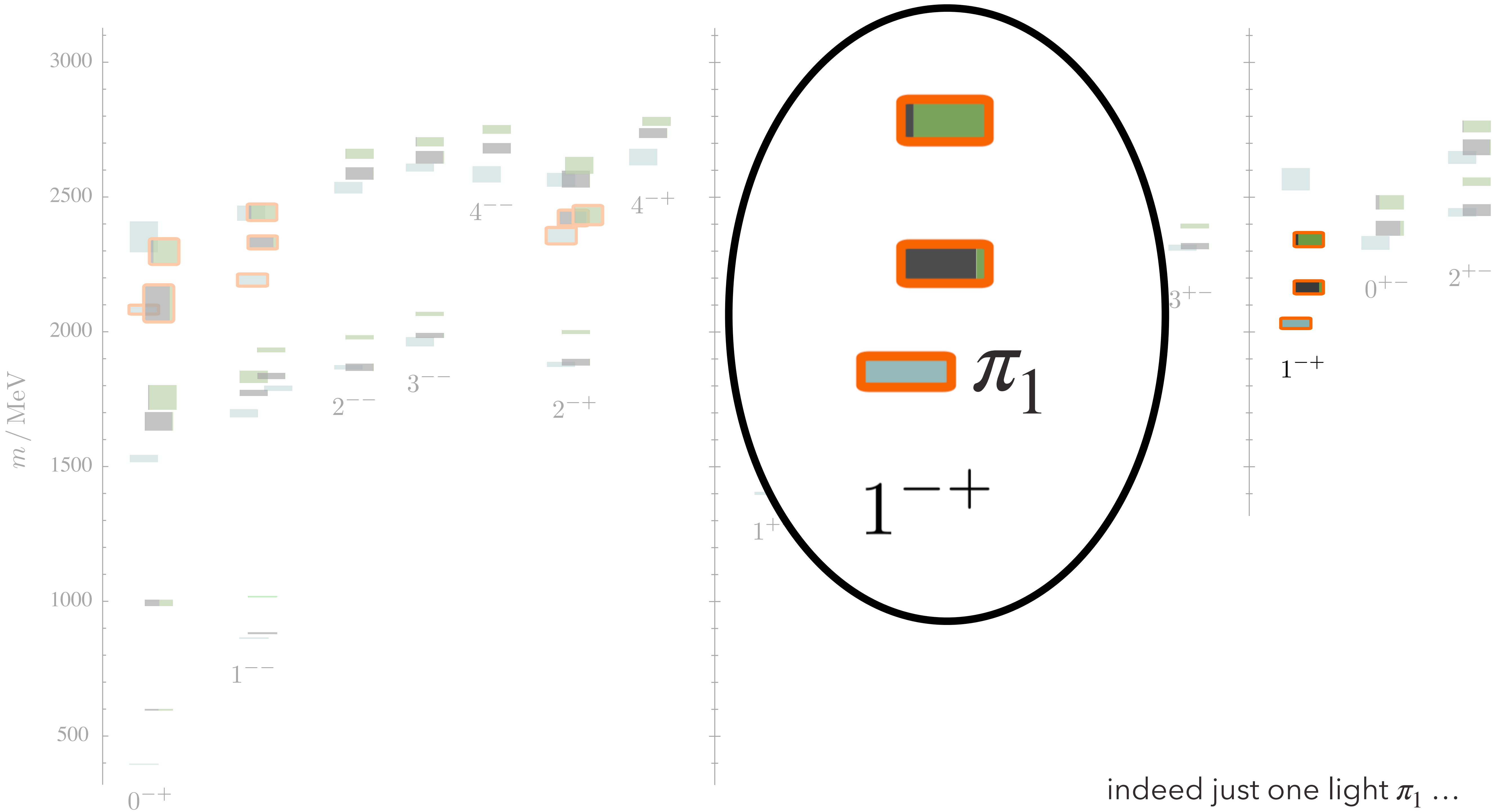
in 2013 *hadspec* calculates the "stable" light meson spectrum



PRD 88 094505 (2013)

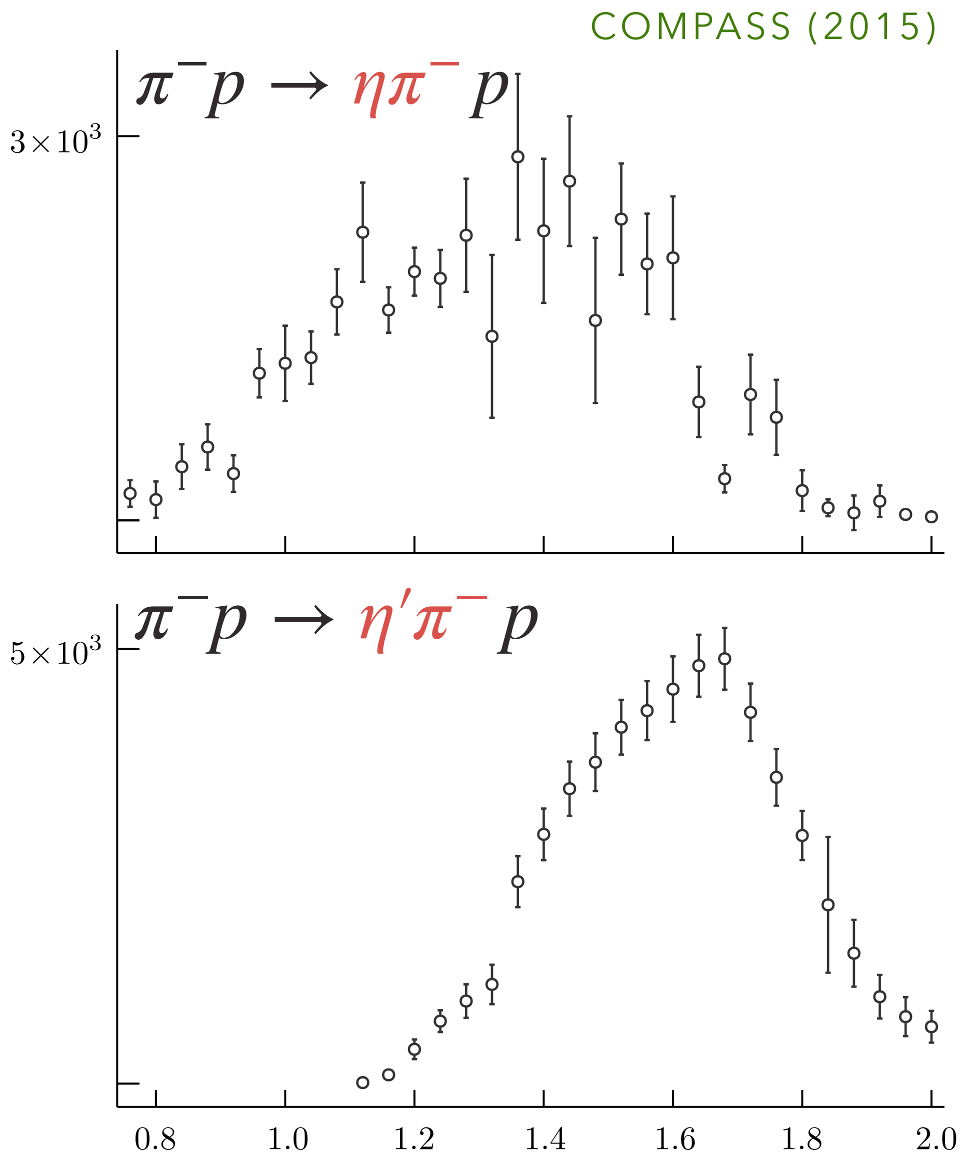
(matrix element overlaps with chromomagnetic operators)

the lightest exotic hybrid meson – lattice QCD



indeed just one light π_1 …

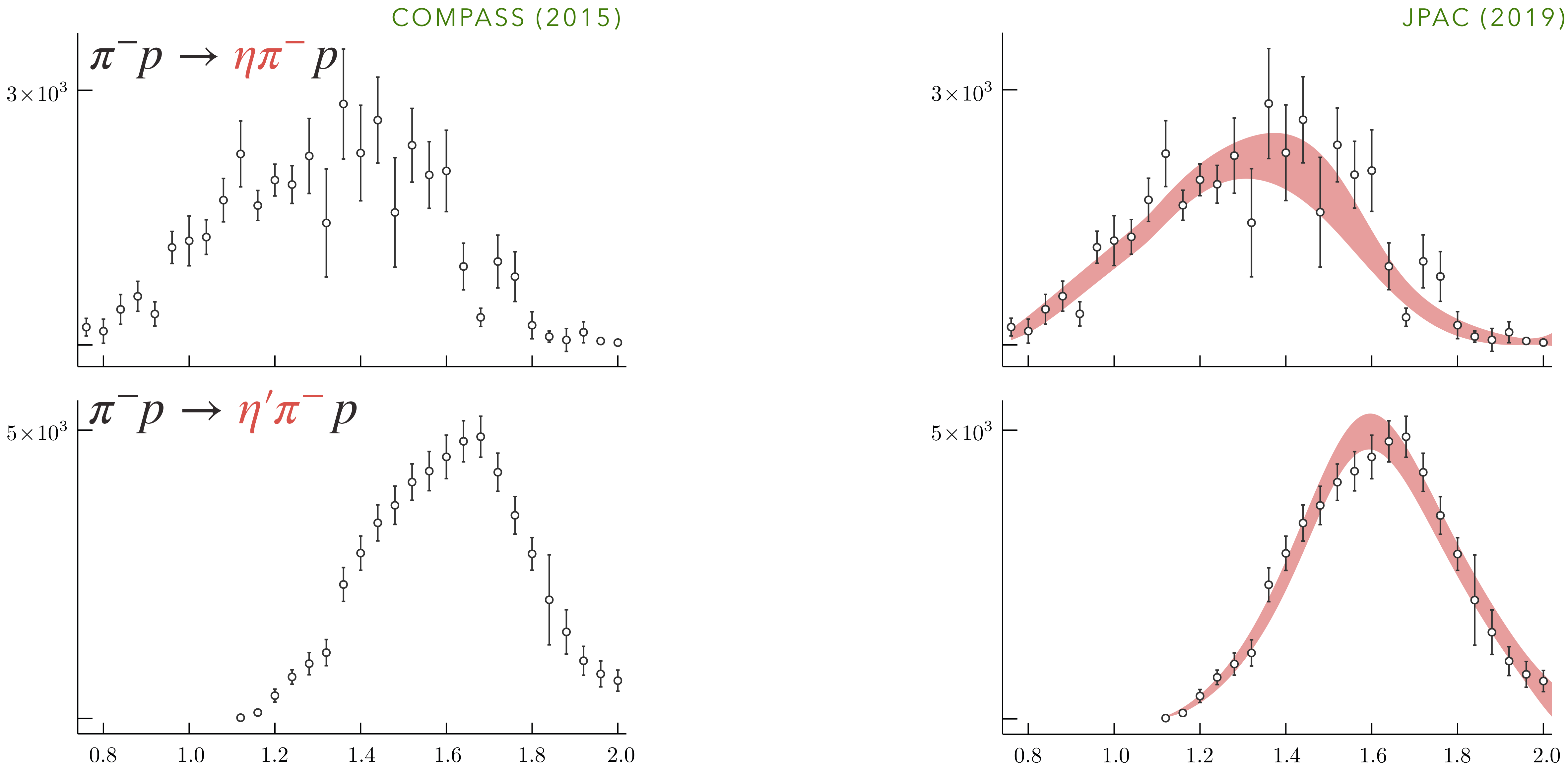
the lightest exotic hybrid meson – constrained amplitude analysis



compatible with structures seen at BNL

the lightest exotic hybrid meson – constrained amplitude analysis

in 2019 *JPAC* analyses COMPASS data with **unitary coupled-channel amplitudes**



amplitudes have only **one pole singularity**

$$m = 1564(89)\,\mathrm{MeV}$$
$$\Gamma = 492(115)\,\mathrm{MeV}$$

a broad resonance …

the lightest exotic hybrid meson – lattice QCD resonance ?

in 2021 *hadspec* computes π_1 as an unstable resonance

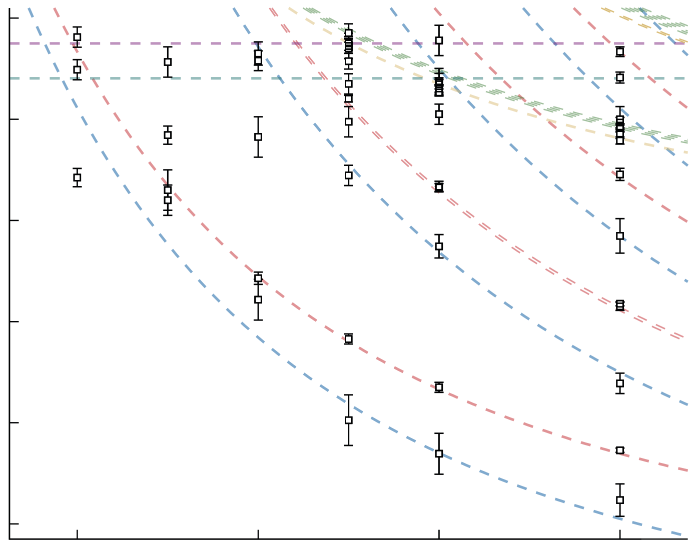
(not as tightly constrained as other cases shown earlier)

SU(3)$_F$ point

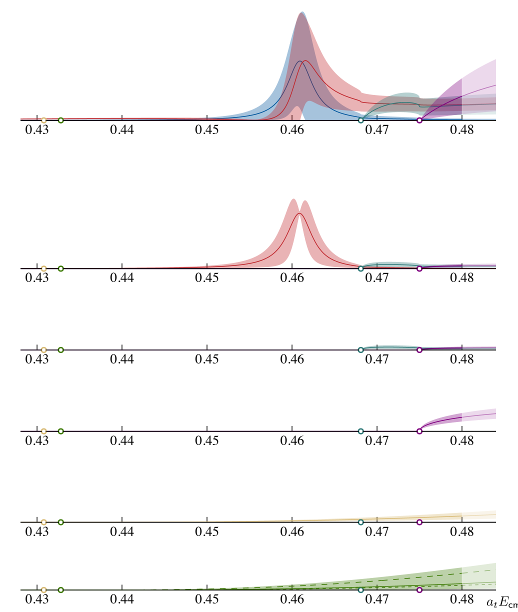
$m_u = m_d = m_s^{\mathrm{phys}}$

$m_\pi \sim 700\,\mathrm{MeV}$

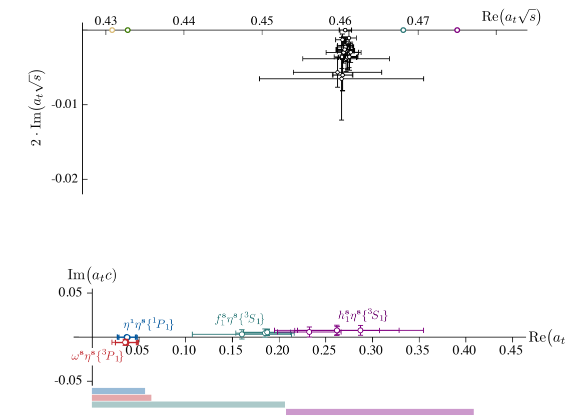
spectrum in six lattice volumes



amplitudes in eight channels



decay couplings of
one resonance pole



narrow resonance at
this heavy quark mass

extrapolated to
physical quark mass

for a $\pi_1(1564)$

$\Gamma \sim 140 - 600\,\mathrm{MeV}$

$\Gamma(\pi\eta) \lesssim 1\,\mathrm{MeV}$

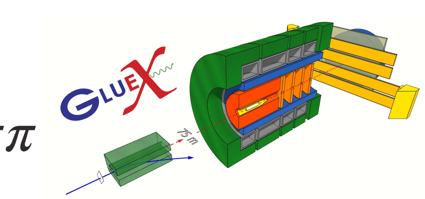
$\Gamma(\pi\eta') \lesssim 12\,\mathrm{MeV}$

$\Gamma(\pi\rho) \lesssim 20\,\mathrm{MeV}$

$\Gamma(\pi b_1) \sim 139 - 529\,\mathrm{MeV}$

compatible with being a broad resonance

suggests dominant decay into $\pi b_1 \to \pi\pi\omega \to \pi\pi\pi\pi\pi$



US efforts in hadron spectroscopy theory

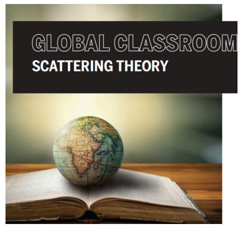
lattice QCD collaborations
e.g. *hadspec*
www.hadspec.org

hardware & software development grants — SciDAC Scientific Discovery through Advanced Computing, ECP Exascale Computing Project …
LQCD@SciDAC-5

computing time awards — U.S. Department of Energy INCITE Leadership Computing, USQCD …
capability — capacity

amplitude analysis collaborations
e.g. *JPAC*
cgl.soic.indiana.edu/jpac

workforce development



online course


in-person summer schools

relationships with experiments — GlueX, clas, COMPASS, BESIII, LHCb
"nucl" — "hep"

broad collaborative efforts
proposed *DoE topical collaboration* to co-ordinate, also with modeling, EFTs

the big picture for spectroscopy

novel & high statistics data

new tools & computational advances in lattice QCD

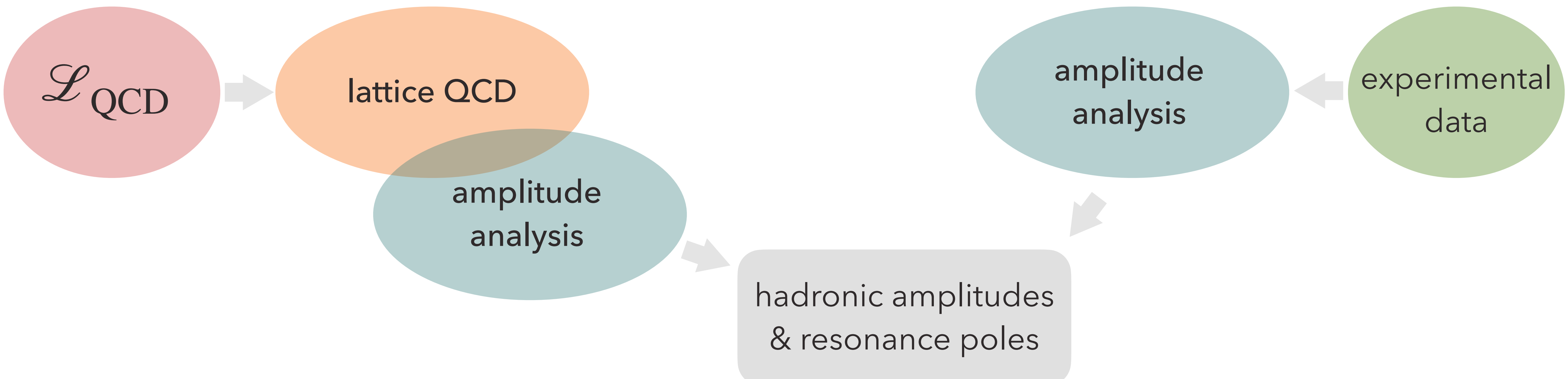
new structures

excited hadrons

reliable description requires **robust amplitudes**

faithfully, **as resonances**

tools are common to light quark and heavy quark systems



hadron spectroscopy has evolved into a rigorous probe of the emergent properties of strongly-coupled QCD