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decays of an exotic 1^{-+} hybrid meson in QCD

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hadspec
hadron spectrum collaboration
hadspec.org

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hybrid mesons

one hypothesis to go beyond the $q\bar{q}$ picture of mesons

— add an **excitation of the gluonic field** $q\bar{q}G$

— can give rise to J^{PC} not allowed for $q\bar{q}$

e.g. $0^{+-}, 1^{-+}, 2^{+-} \ldots$

long history of study within QCD-motivated models

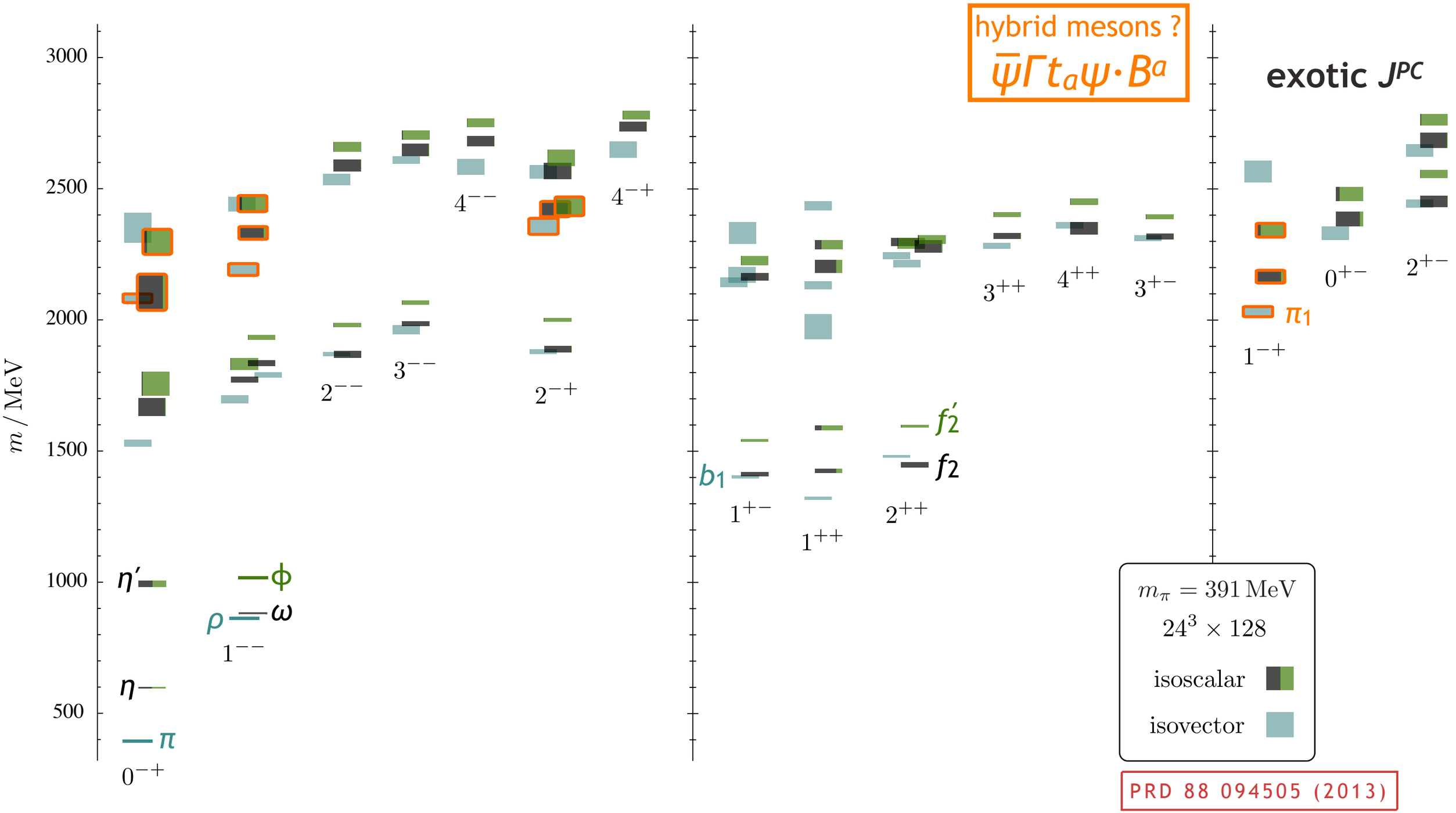
— constituent gluon
— bag model
— flux-tube model

⋮

all have exotic J^{PC} mesons,
but spectra differ

more recently studied in (incomplete) **lattice QCD calculations …**

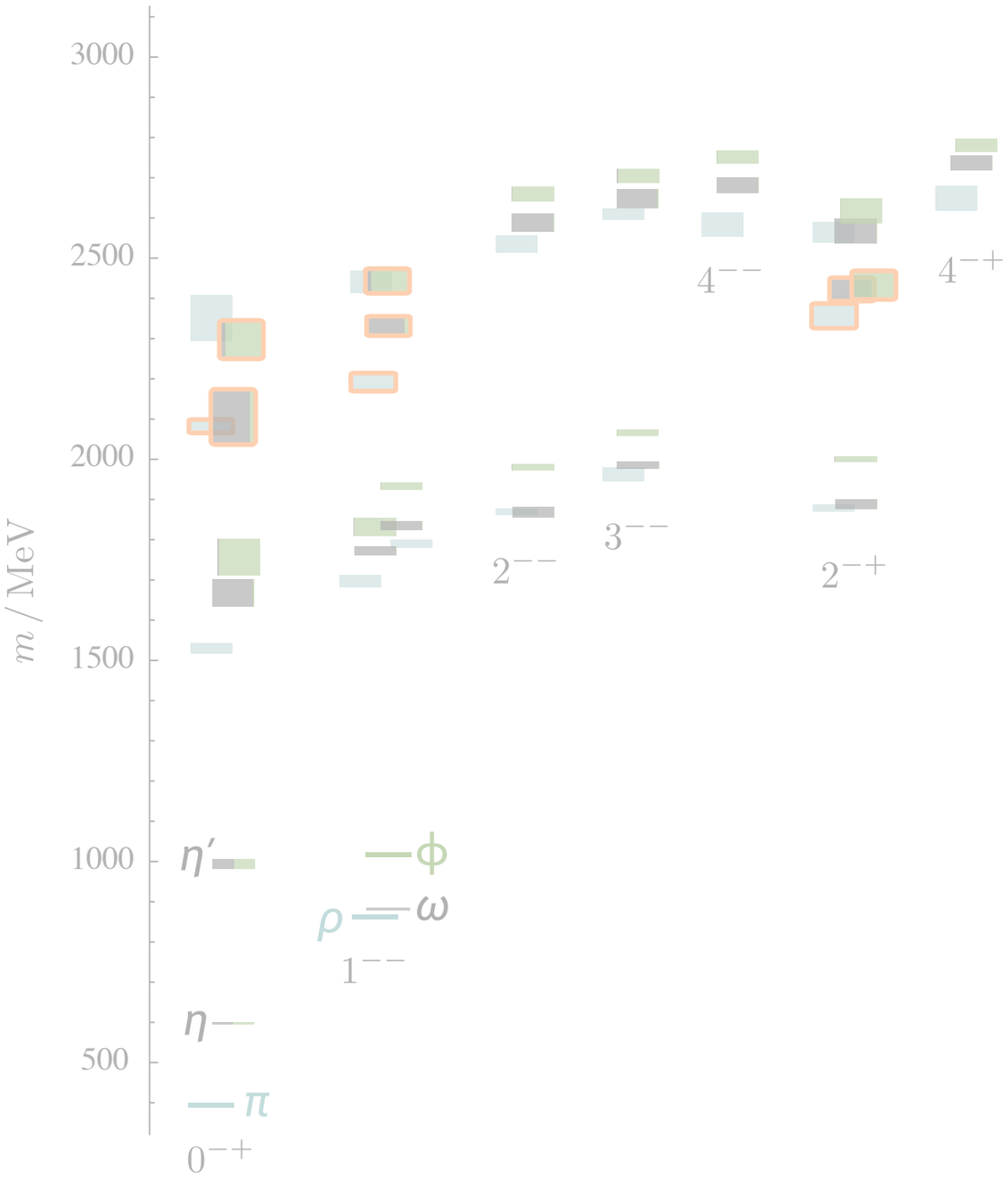
(incomplete) lattice QCD spectrum of mesons

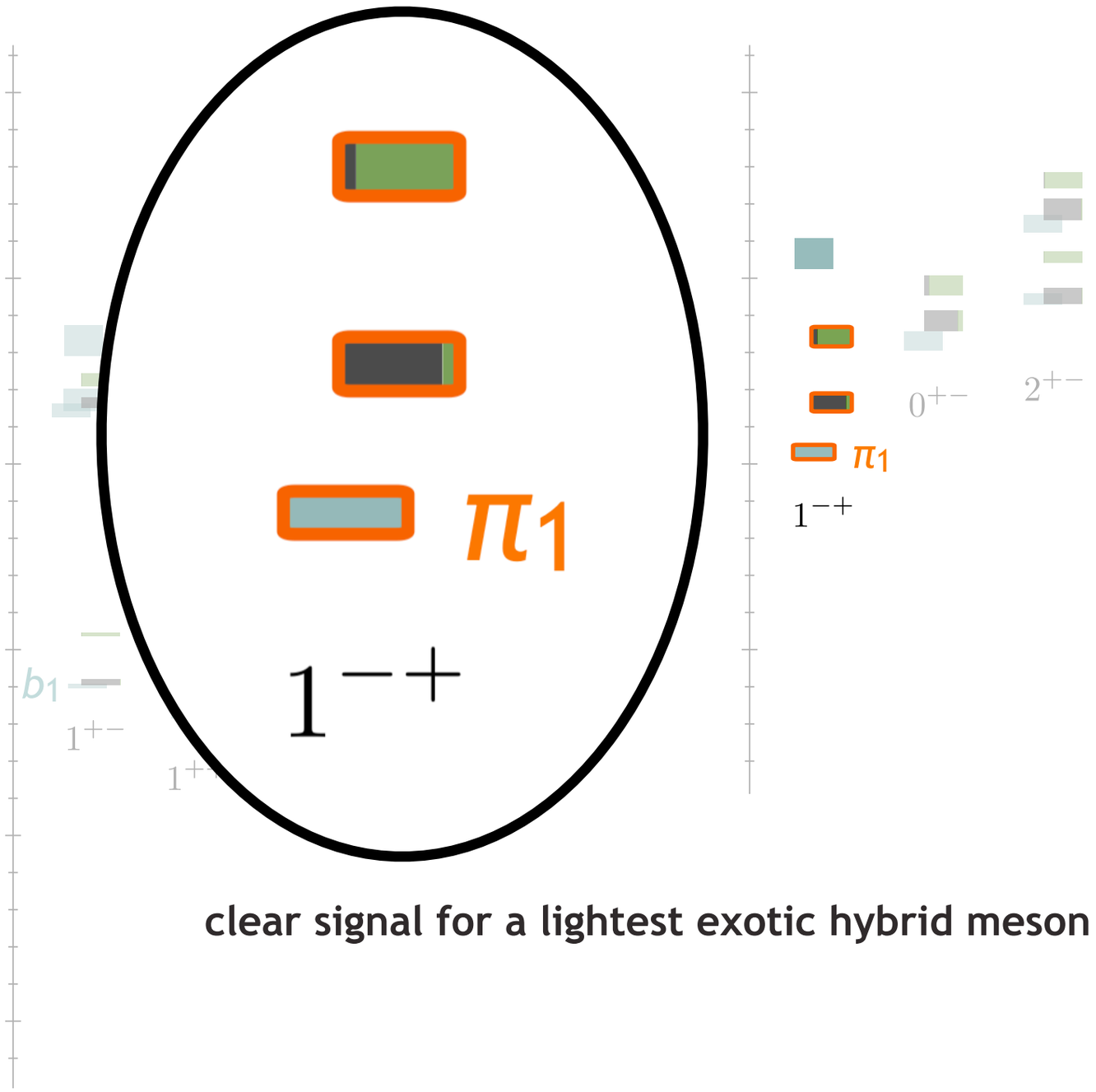


PRD 88 094505 (2013)

lightest hybrid meson supermultiplet ? $(0, 1, 2)^{-+},\ 1^{--}$

(incomplete) lattice QCD spectrum of mesons





clear signal for a lightest exotic hybrid meson

experimental situation

a recent **JPAC** analysis of **COMPASS** data on $\pi p \to \pi\eta\, p$, $\pi p \to \pi\eta'\, p$

Determination of the Pole Position of the Lightest Hybrid Meson Candidate

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(Joint Physics Analysis Center)

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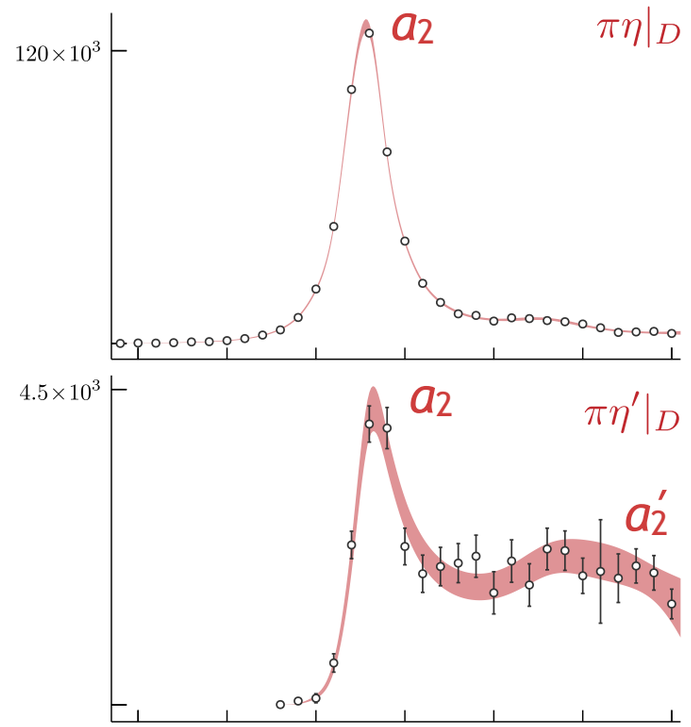
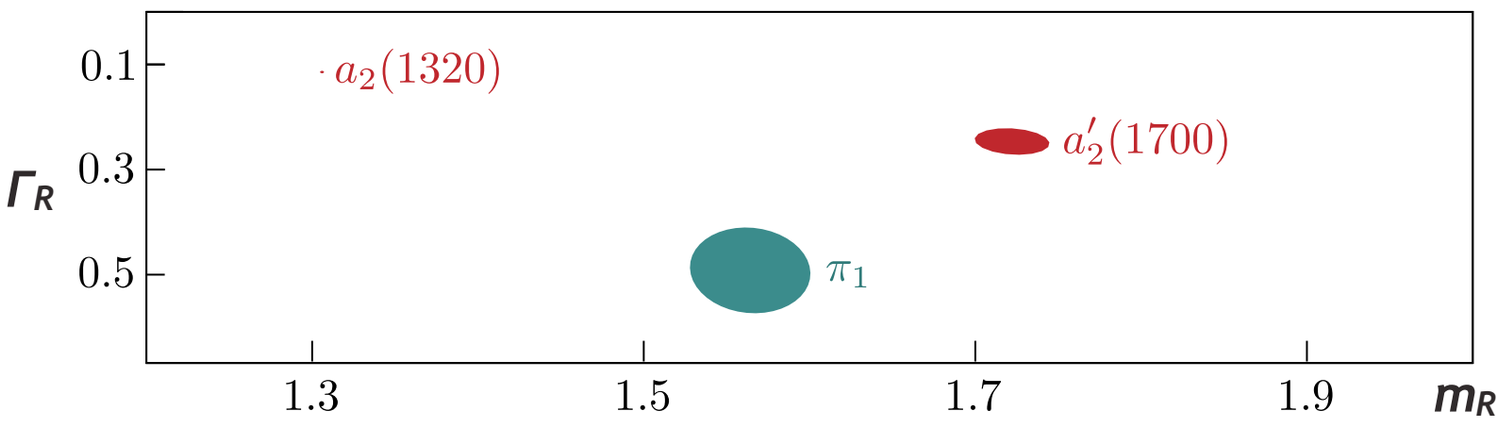


pole singularity of a π_1 resonance



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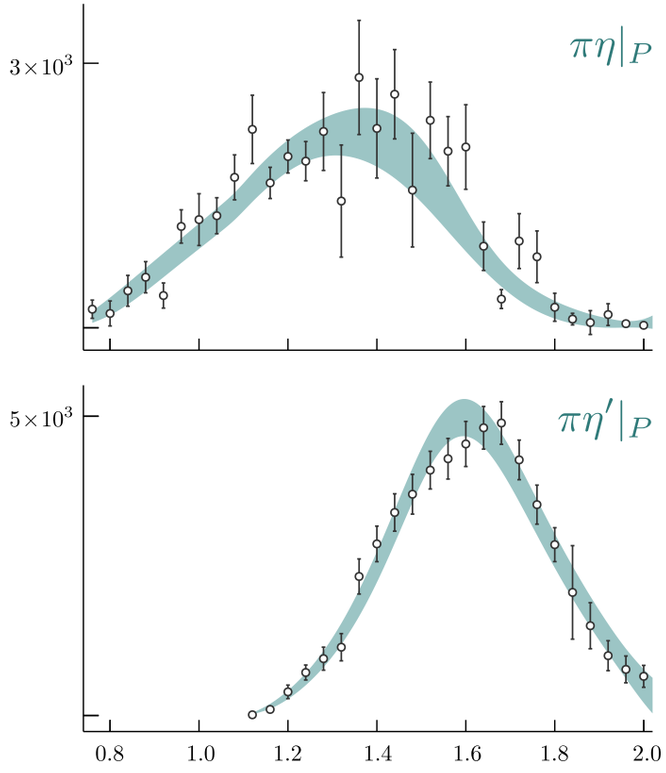


m_R=1564(89) MeV, Γ_R=492(115) MeV

a rather broad resonance

a resonance in QCD ?

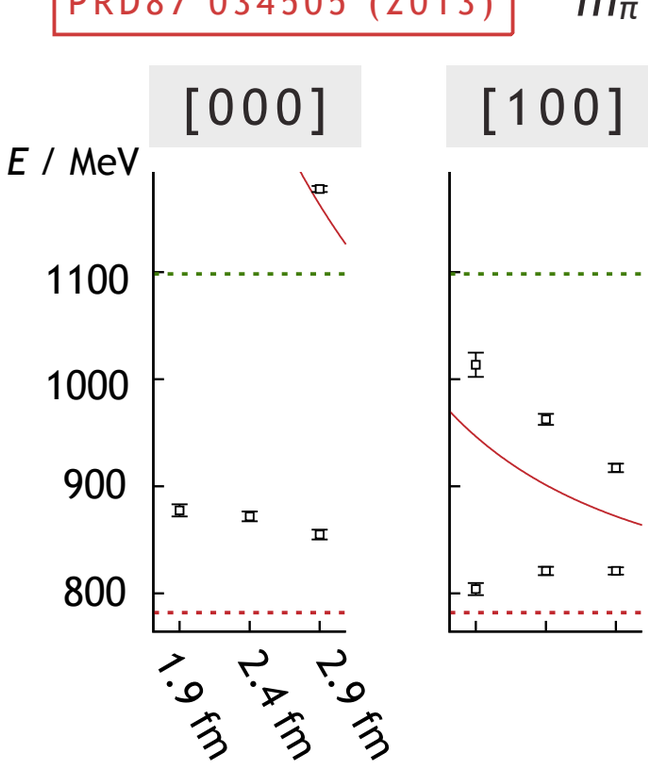
how would an unstable resonance appear in lattice QCD ?

the lattice has a **finite-volume** ⇒ spectrum is **discrete**

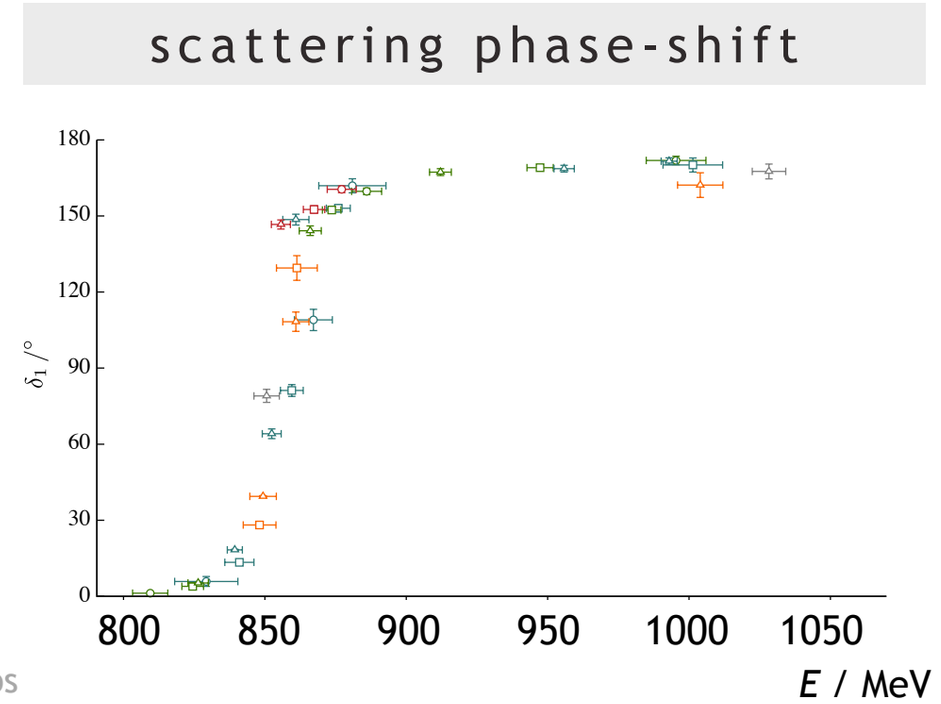
but the mapping **discrete-spectrum** ⟷ **scattering matrix** is known

ππ I=1 $J^P=1^-$

PRD87 034505 (2013) m_π ~ 391 MeV

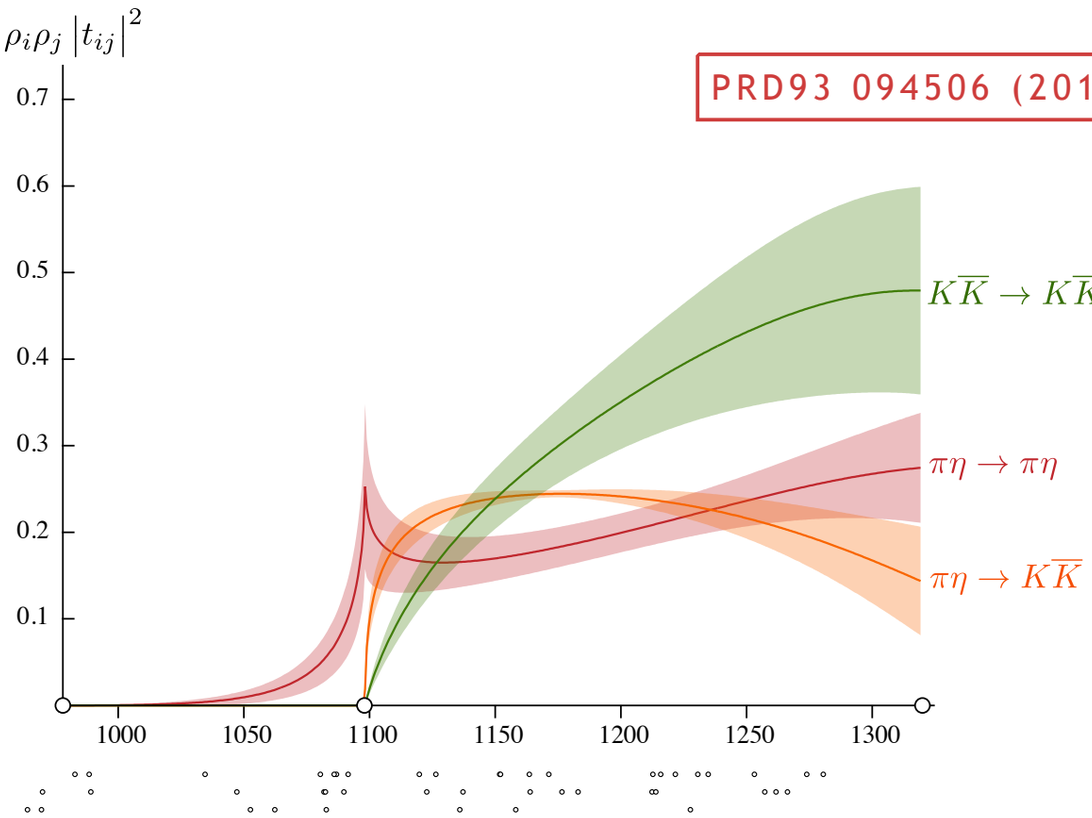


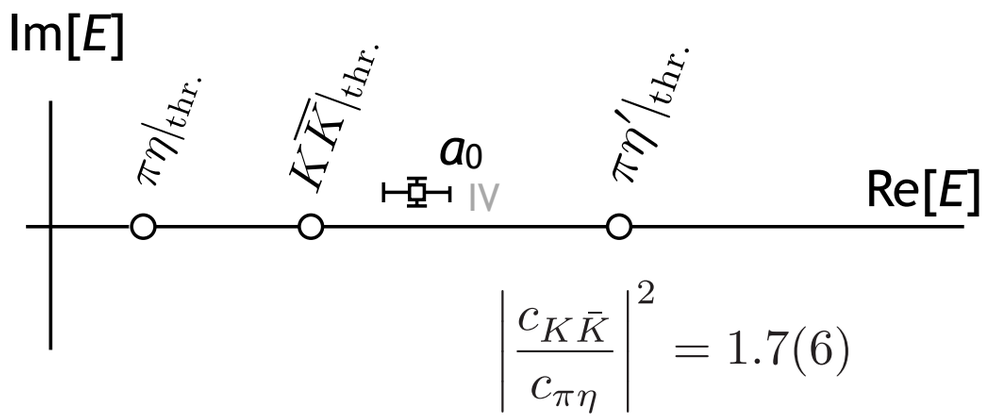
& other irreps



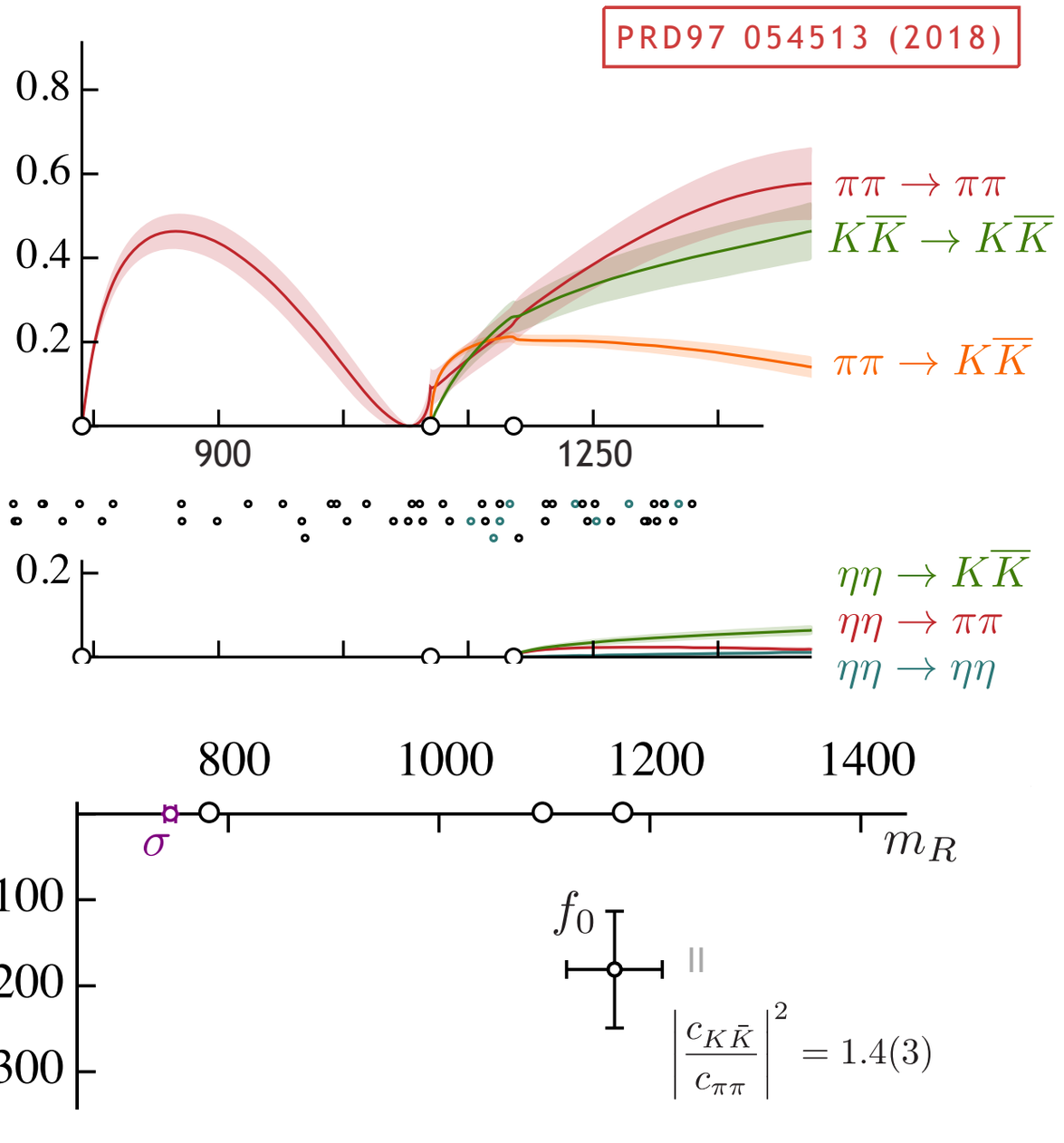
coupled-channel resonances

isospin=1 πη, K$\bar{K}$



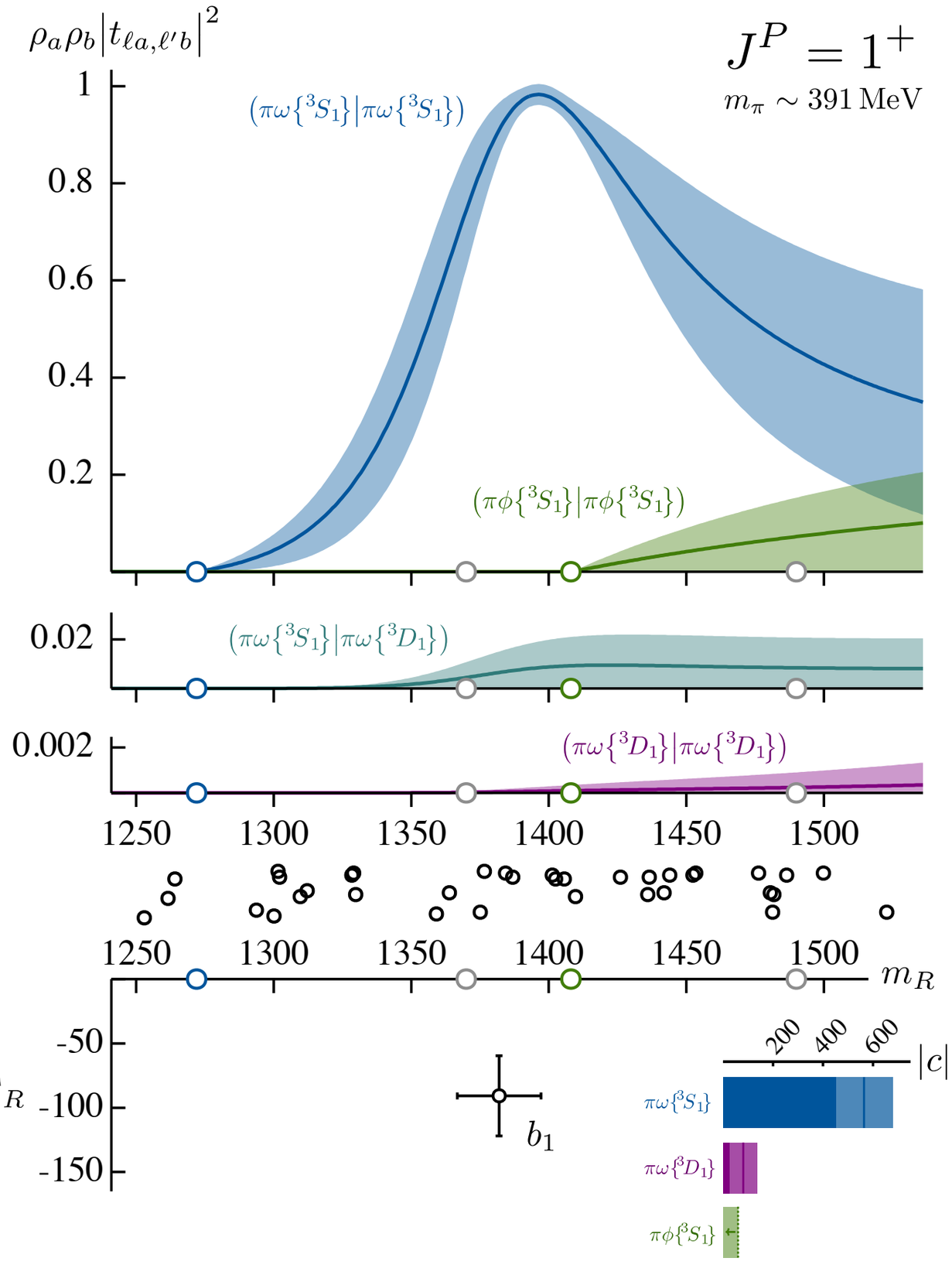


isospin=0 ππ, K$\bar{K}$, ηη



resonances decaying to hadrons with spin — $b_1 \to \omega\pi$

PRD100 054506 (2019)



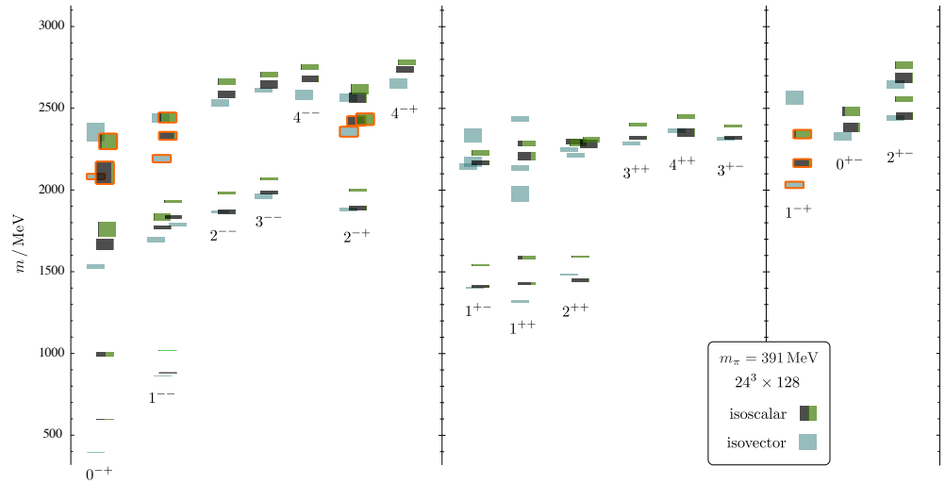
ω is stable at m_π~391 MeV

several successful calculations with m_π~391 MeV

but a π_1 resonance potentially has a very large set of decay modes …

m_u=m_d=m_s SU(3)$_F$ point

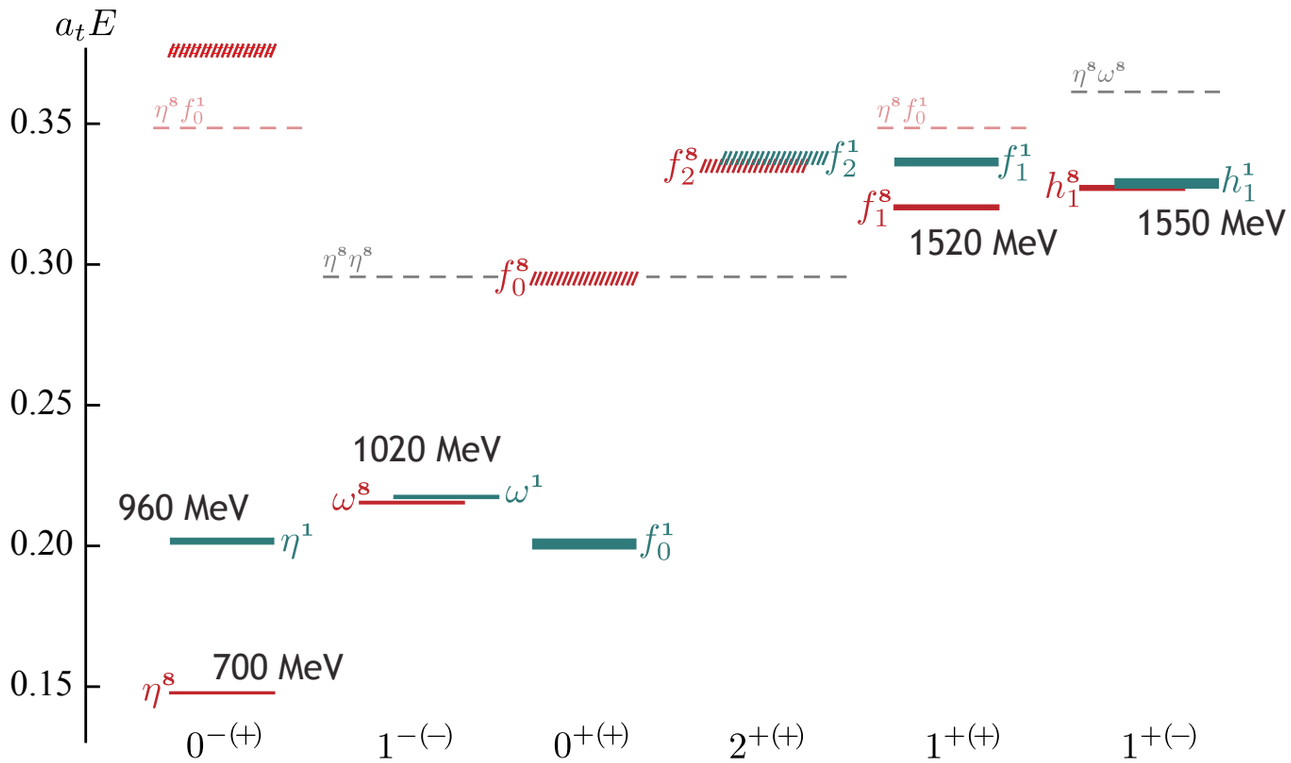
increase the light quark mass to the strange quark mass …



(incomplete) **lattice spectrum calculation** PRD 88 094505 (2013)

m_u=m_d=m_s SU(3)$_F$ point

several stable mesons:



please forgive the obscure lattice units, will convert at the end …

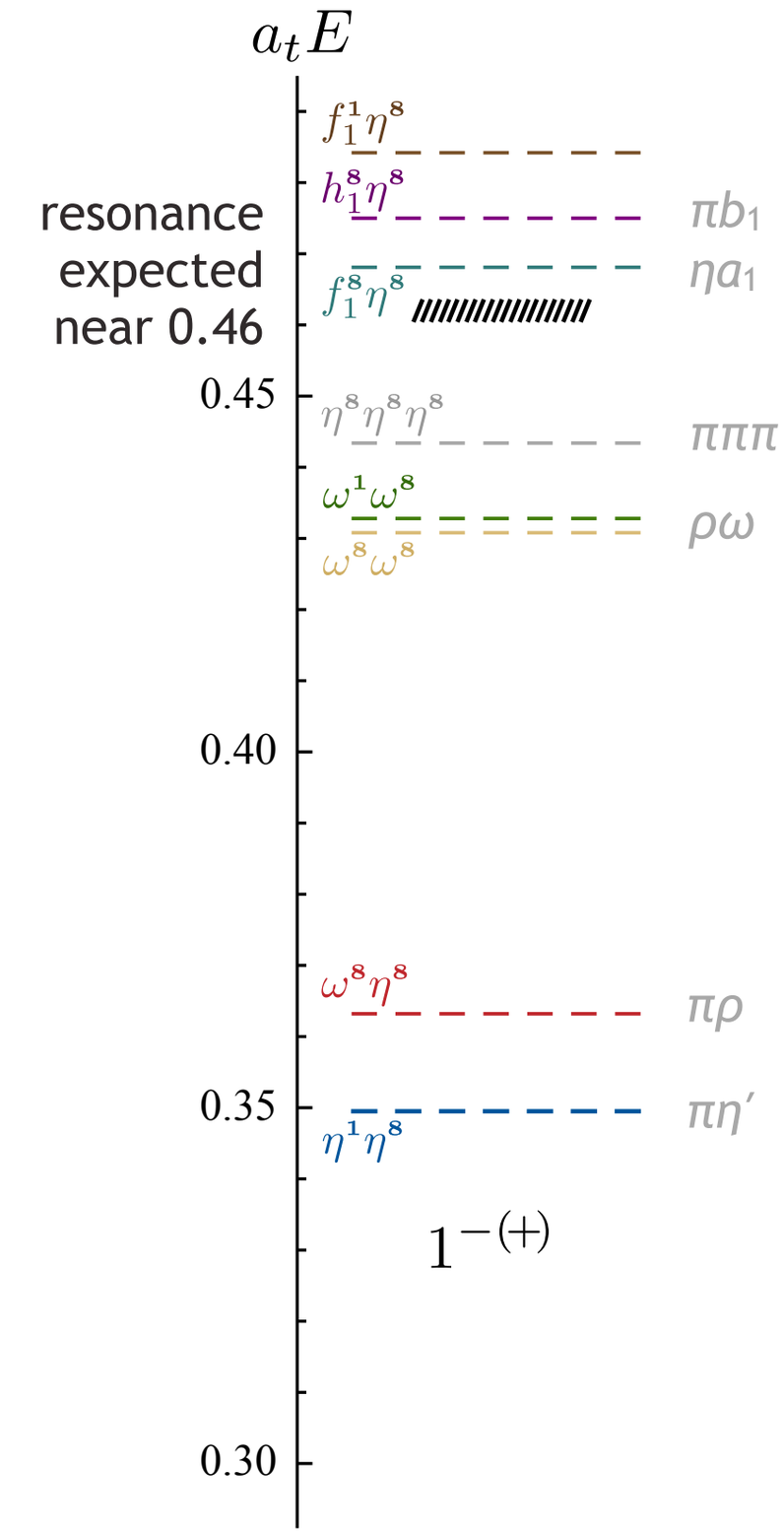
$\eta^8 \rightsquigarrow \pi, K, \eta$

$\eta^1 \rightsquigarrow \eta'$

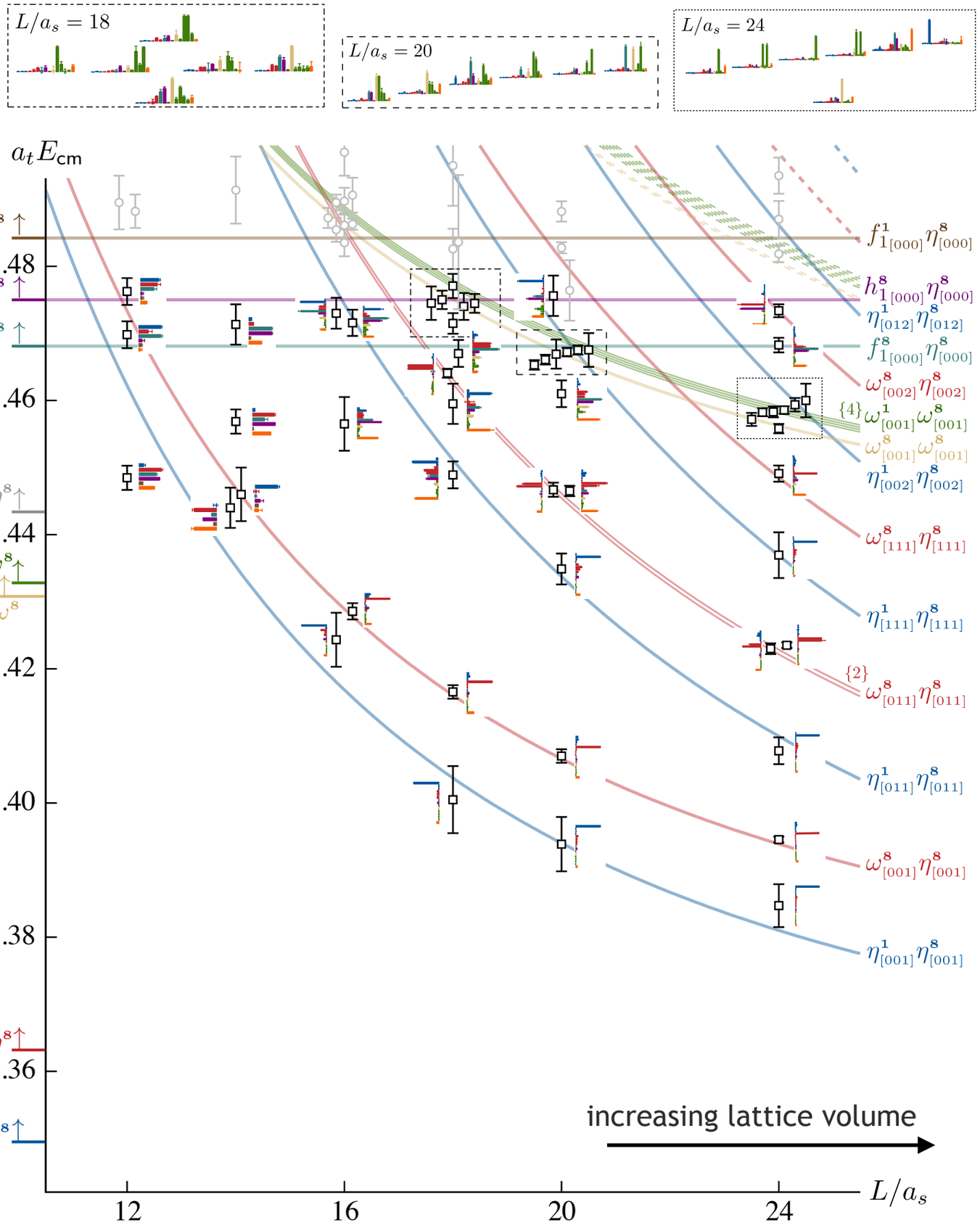
$\omega^8, \omega^1 \rightsquigarrow \rho, K^*, (\omega, \varphi)$

$h_1^8, h_1^1 \rightsquigarrow b_1, K_1, (h_1, h_1')$

$f_1^8, f_1^1 \rightsquigarrow a_1, K_1, (f_1, f_1')$

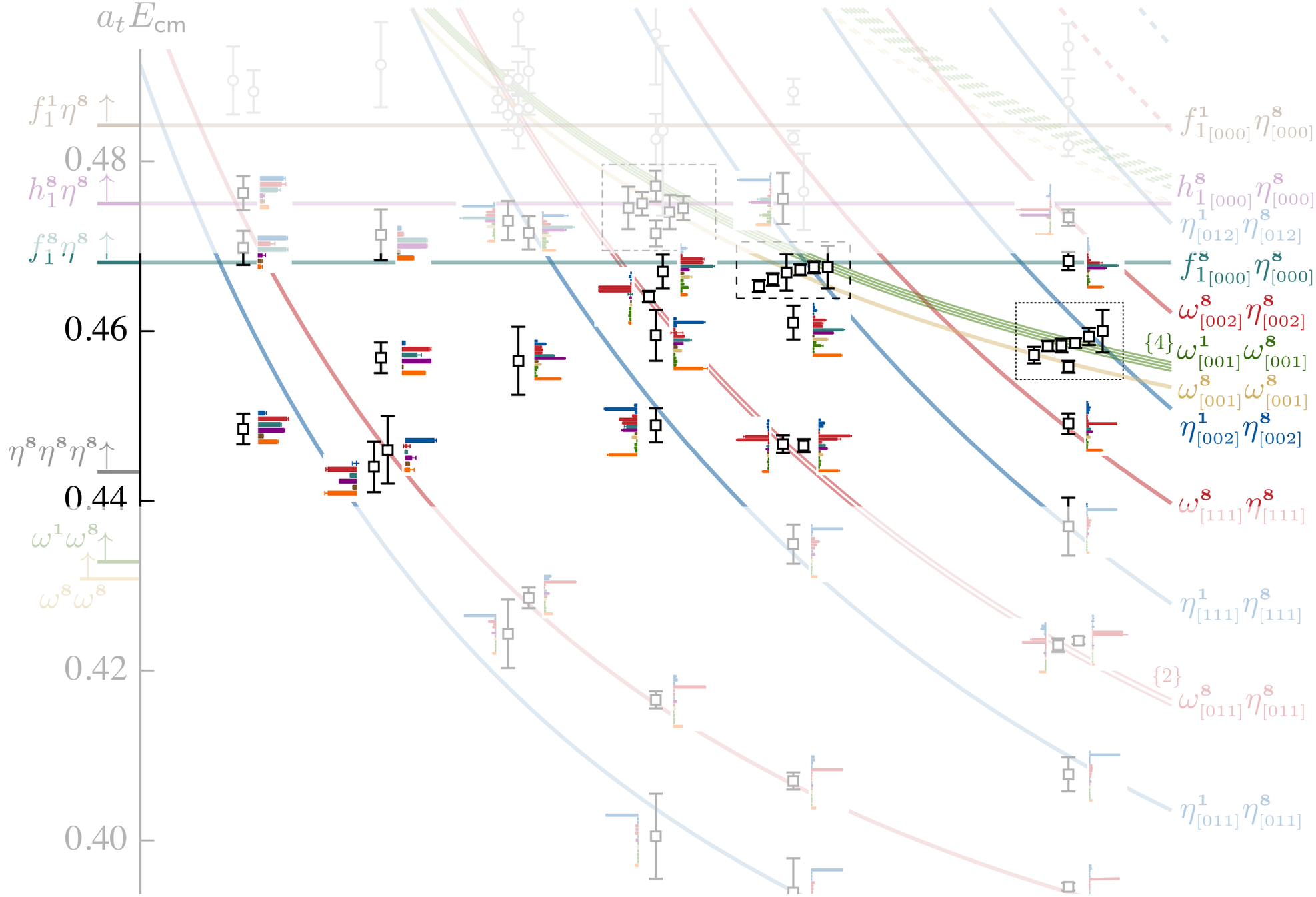


lattice QCD spectrum computed in 6 volumes (rest frame)



53 energy levels to constrain ‘eight’ channel scattering

LQCD spectrum computed in 6 volumes

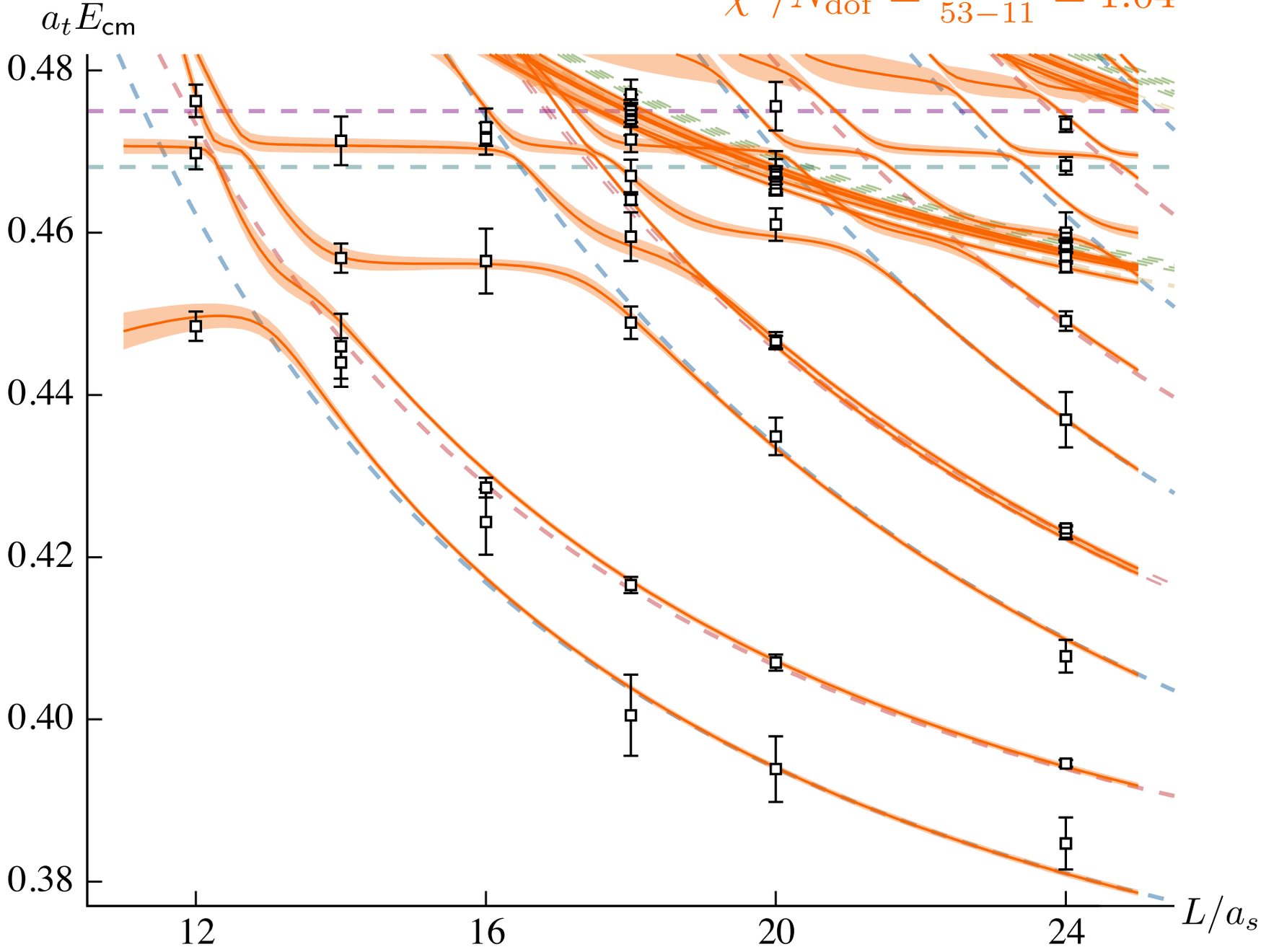


states have overlap with $\bar{\psi}\Gamma t_a \psi \cdot B^a$

an ‘eight’ channel scattering amplitude

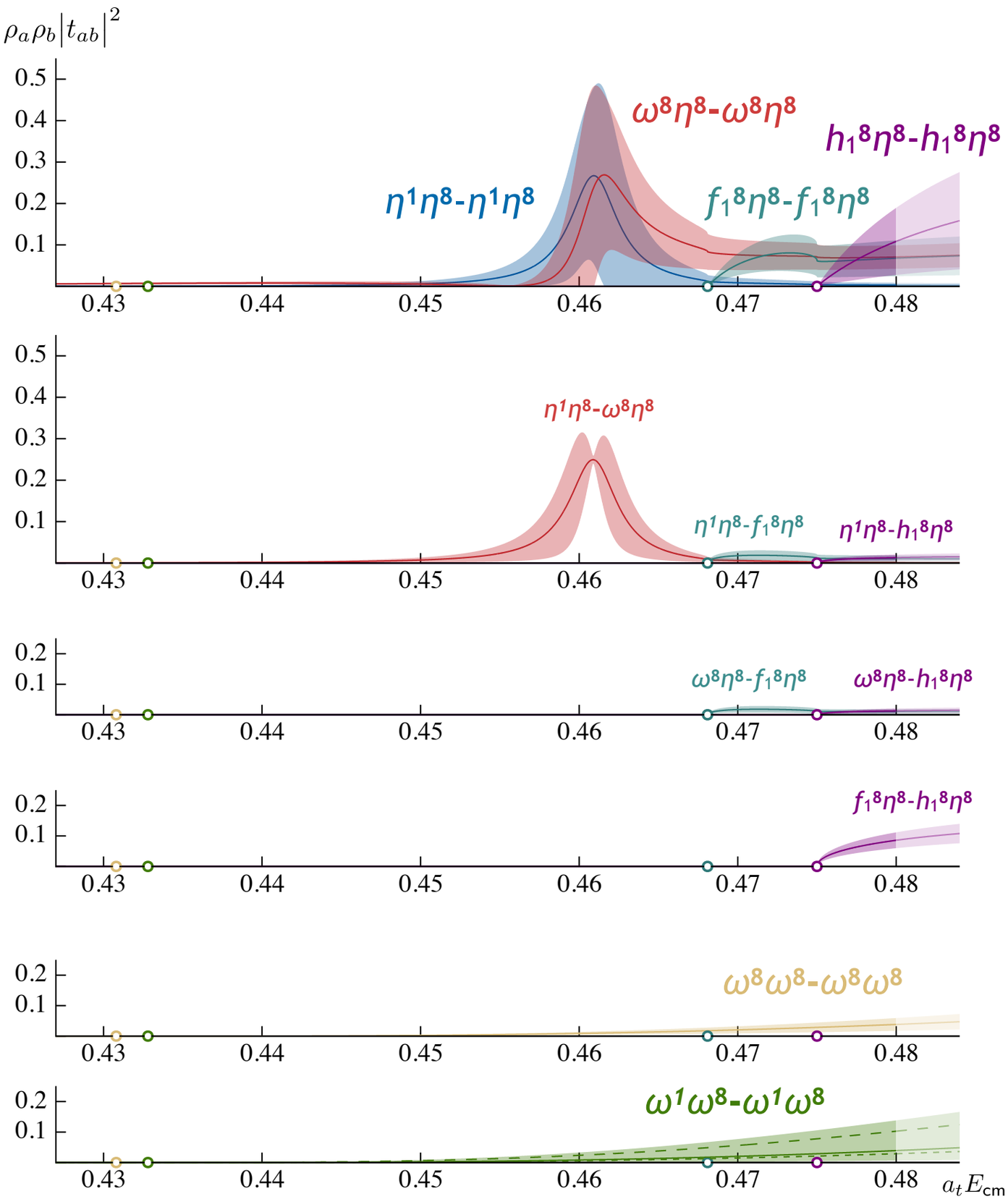
describe scattering by a unitarity-preserving *K*-matrix featuring a pole
(11 free parameters)

$$\chi^2/N_{\mathrm{dof}} = \frac{43.6}{53-11} = 1.04$$

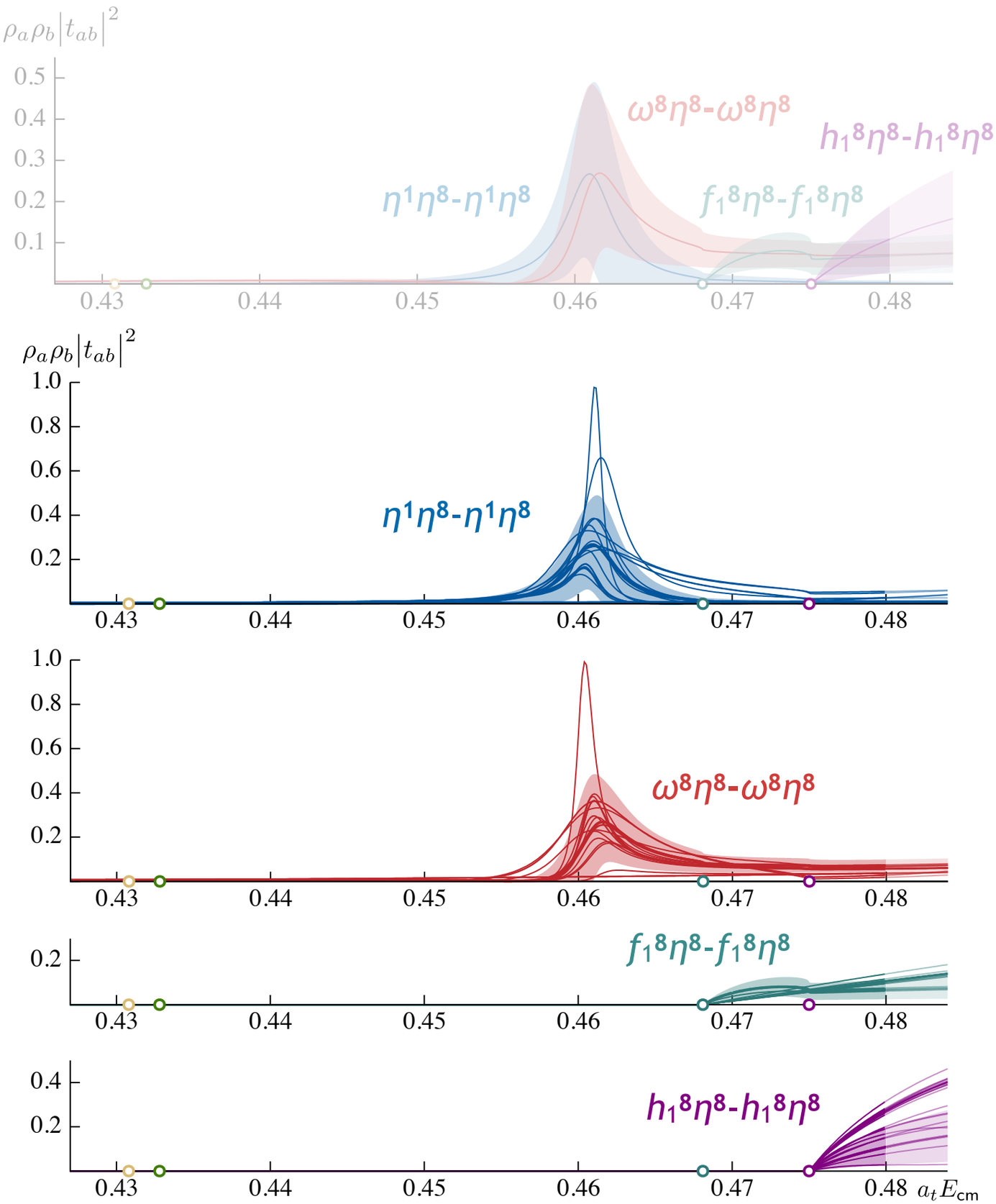


a good description of the spectrum …

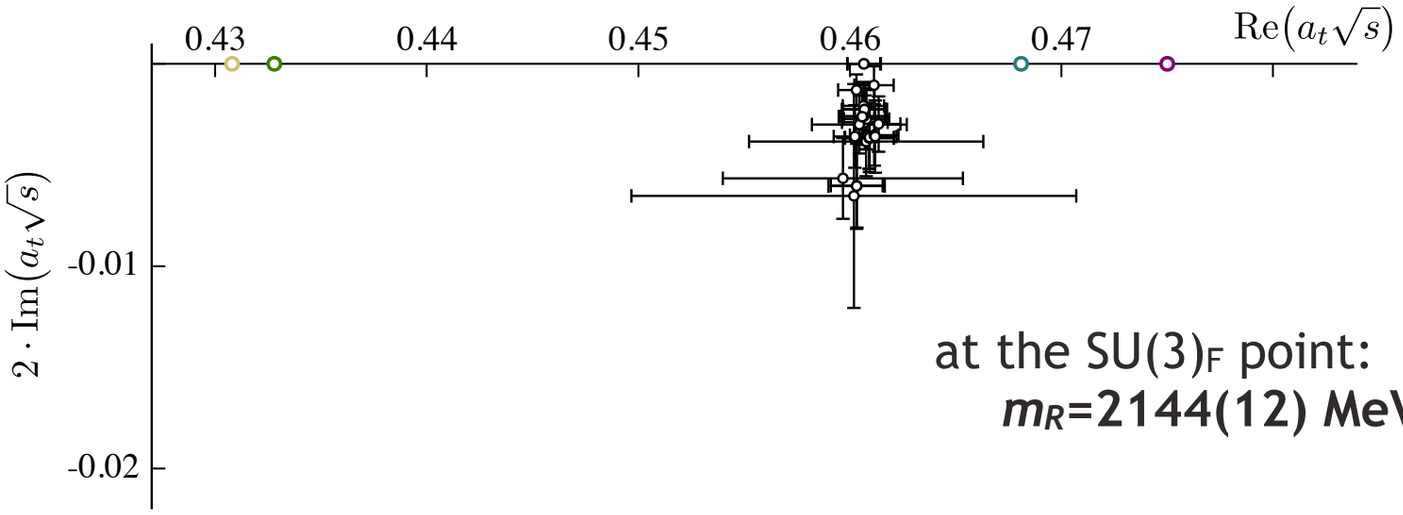
an ‘eight’ channel scattering amplitude



‘eight’ channel scattering amplitudes - varying parameterization



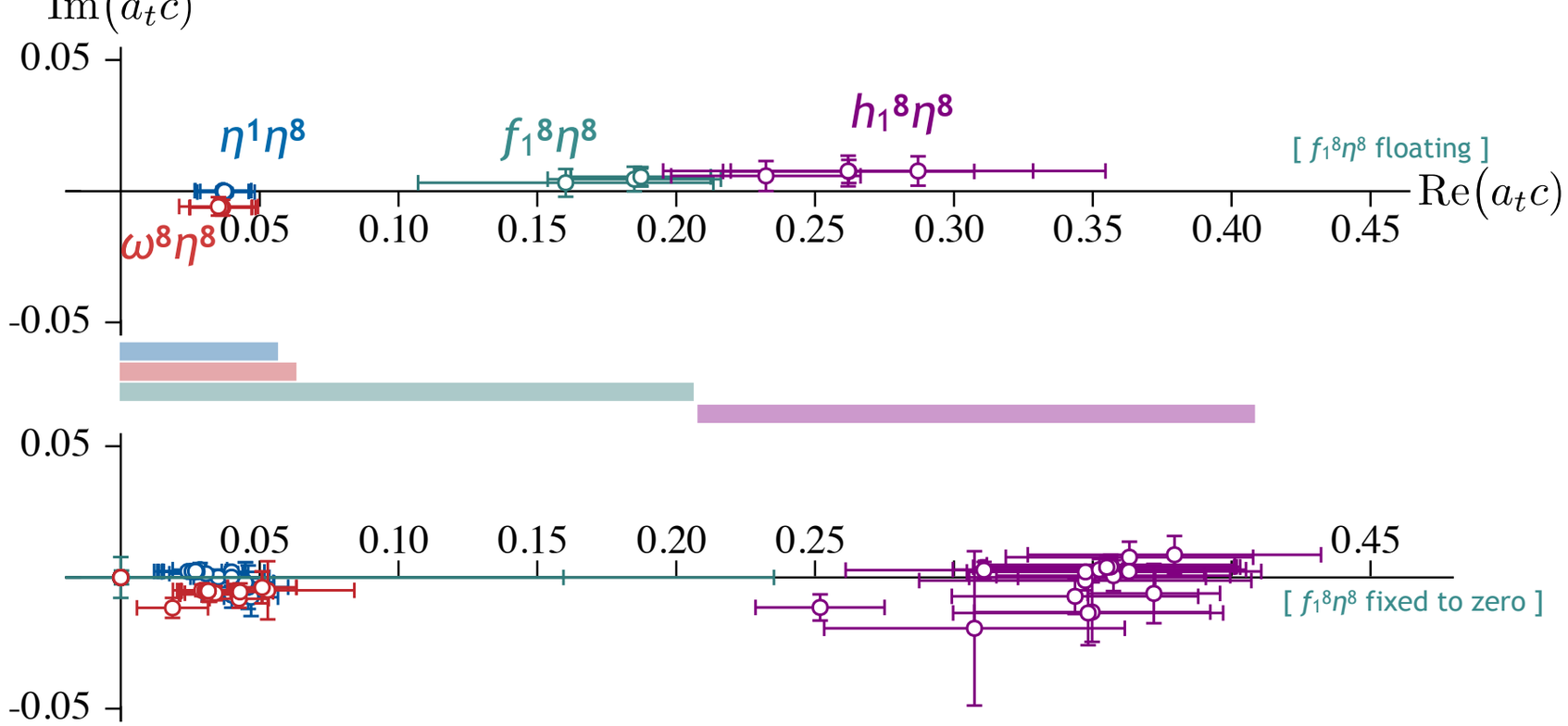
octet 1^{-+} resonance pole & couplings



$$t_{ab}(s) \sim \frac{c_a c_b}{s_0 - s}$$

$$\sqrt{s_0} = m_R - i\tfrac{1}{2}\Gamma_R$$

at the $SU(3)_F$ point:
m_R=2144(12) MeV, Γ_R=21(21) MeV (a narrow resonance)



resonance below $h_1{}^8\eta^8$ threshold, but with a large coupling

crude extrapolation to physical point

core assumption: couplings scale only with the relevant barrier factor k^{ℓ}

use PDG masses & COMPASS/JPAC π_1 mass

generates for a π_1 at 1564 MeV:

Γ_{TOT} ~ **140-600 MeV**

$\Gamma(\pi\eta) \lesssim 1$ MeV

$\Gamma(\pi\eta') \lesssim 20$ MeV

$\Gamma(\pi\rho) \lesssim 12$ MeV

$\Gamma(\pi b_1)$ ~ 140-530 MeV

JPAC/COMPASS candidate:

Γ_{TOT} ~ **492(115) MeV**

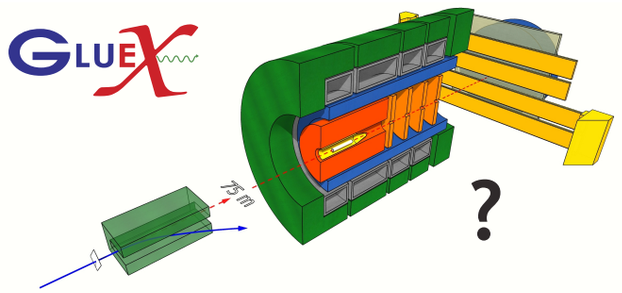
Kopf et al analysis:

Γ_{TOT} ~ **388(10) MeV**

$\Gamma(\pi\eta') / \Gamma(\pi\eta)$ ~ 6.5(1)

if correct, suggests prior observations in $\pi\eta$, $\pi\eta'$, $\pi\rho$ are in heavily suppressed decay channels

$\pi b_1 \rightarrow \pi\pi\omega \rightarrow \pi\pi\pi\pi\pi$



summary

first ever calculation of an **exotic hybrid meson** as a **resonance** in QCD

simplified scattering system using exact $SU(3)_F$ and m_π~700 MeV

flavor octet 1^{-+} state appears as a narrow resonance

crude extrapolation to physical kinematics
suggests a **potentially broad resonance**

what about other exotic J^{PC} ?

can we build a phenomenology of hybrid decays starting from QCD ?

challenge of **reducing quark mass** really the challenge of **including three-meson decays**

much progress in this direction
as you saw in Max Hansen's talk