hadron spectroscopy and QCD

Jozef Dudek

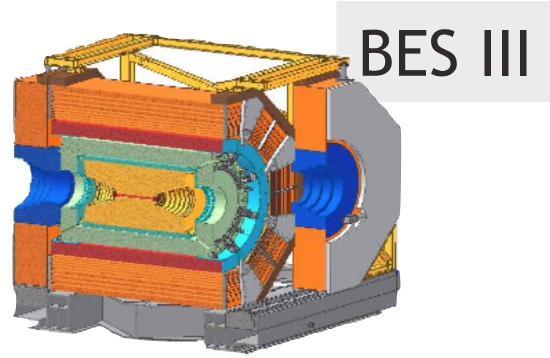
OLD DOMINION UNIVERSITY

Jefferson Lab

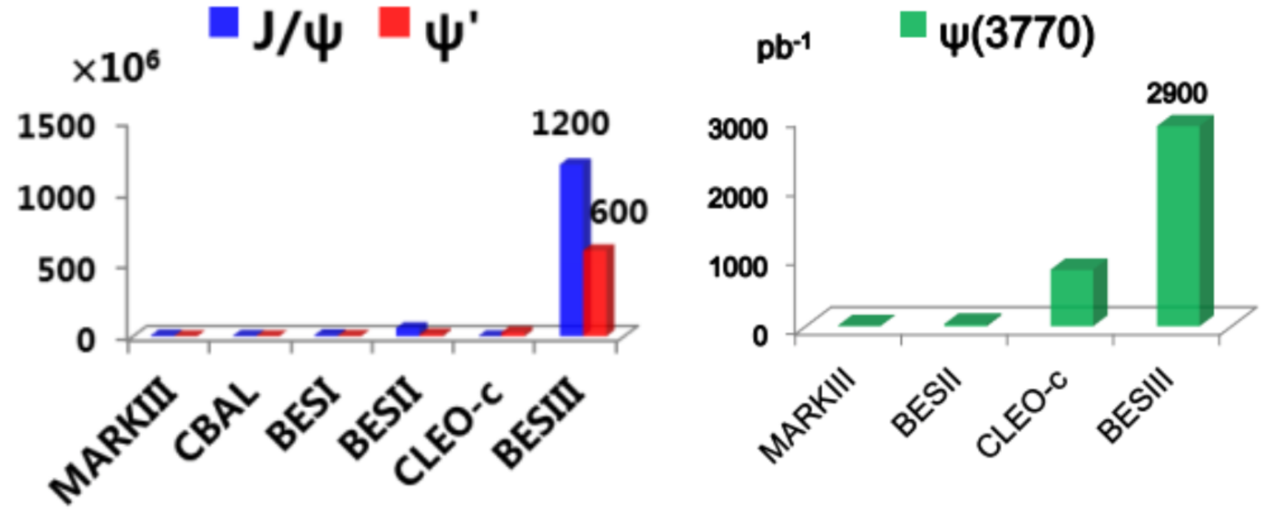
hadron spectrum collaboration

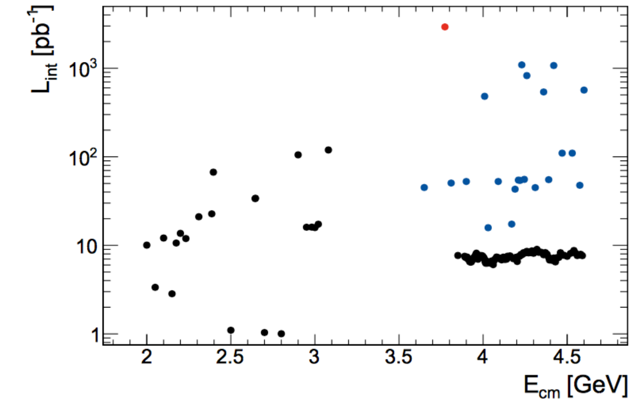
current & future experiments

high statistics
novel production

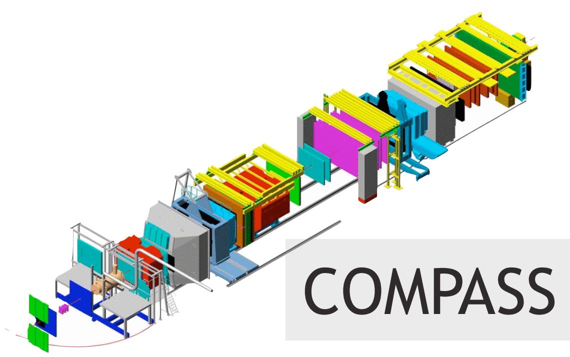


e^+e^-

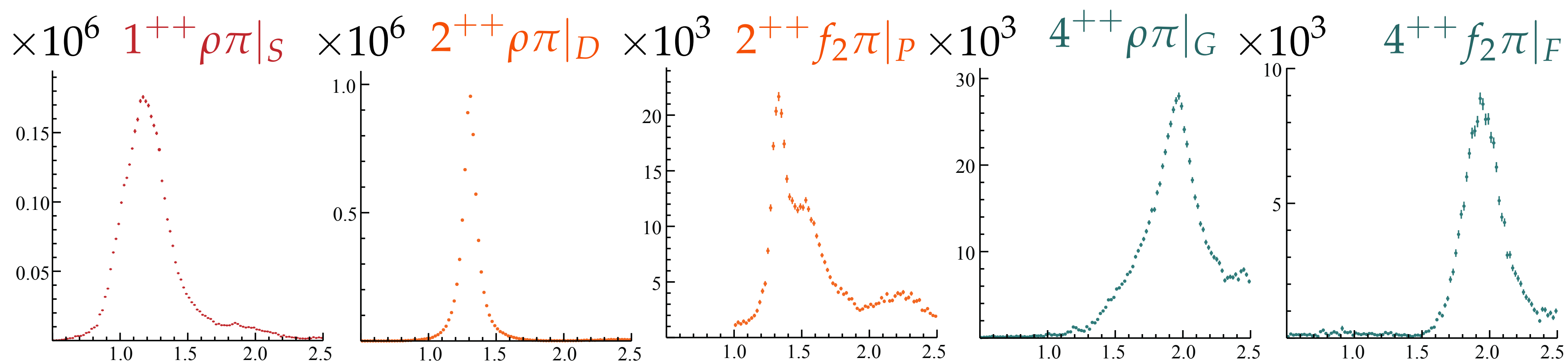


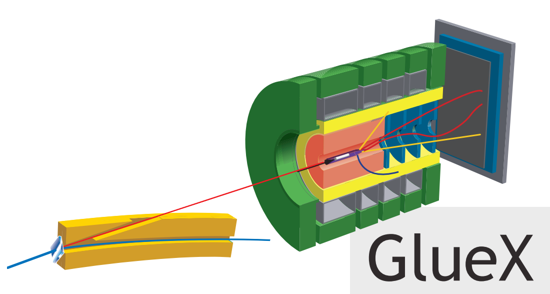


W.Gradl

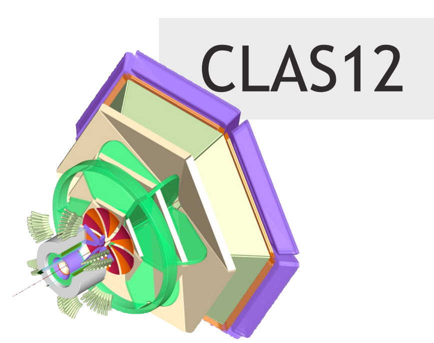


πN

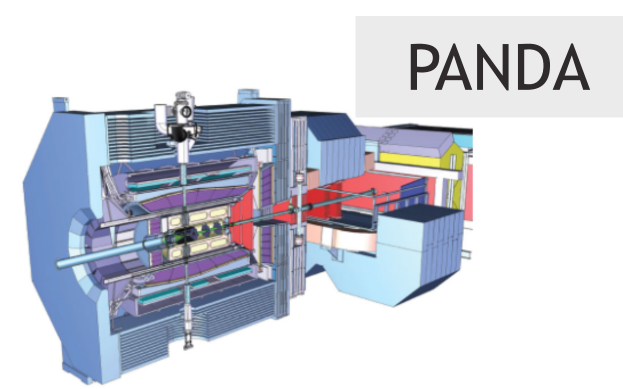




γN



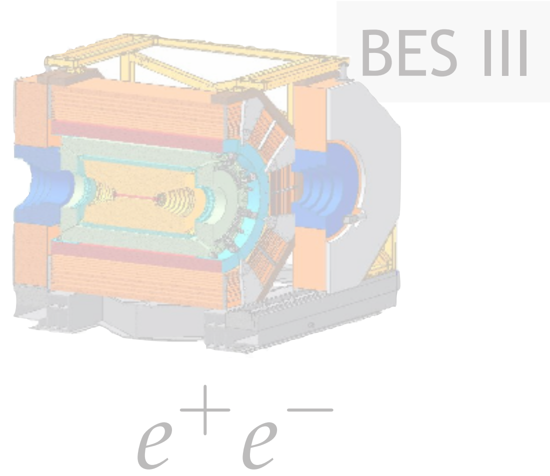
$e^- N$

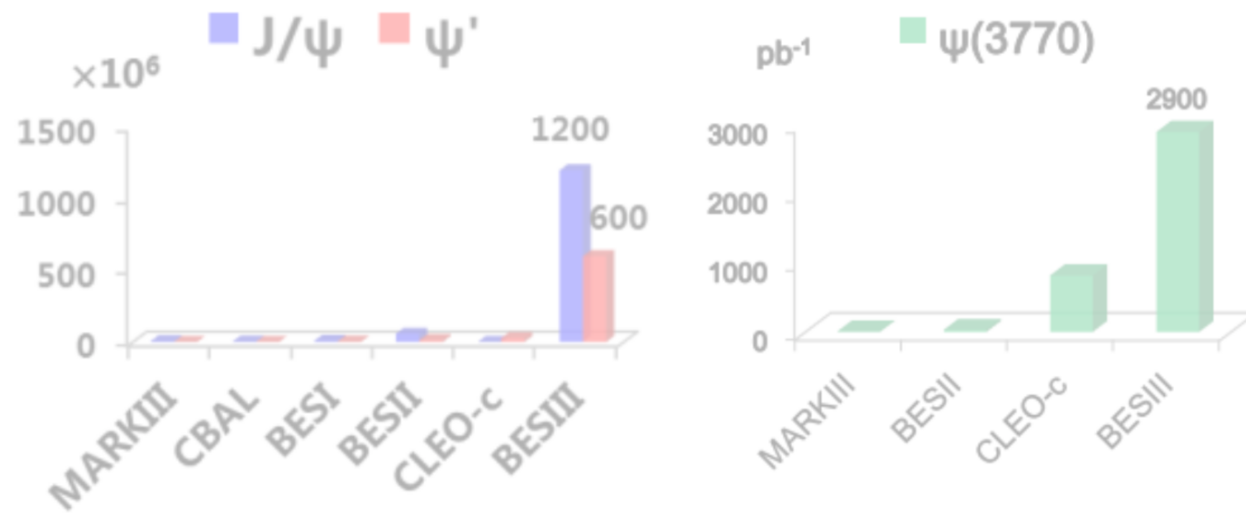


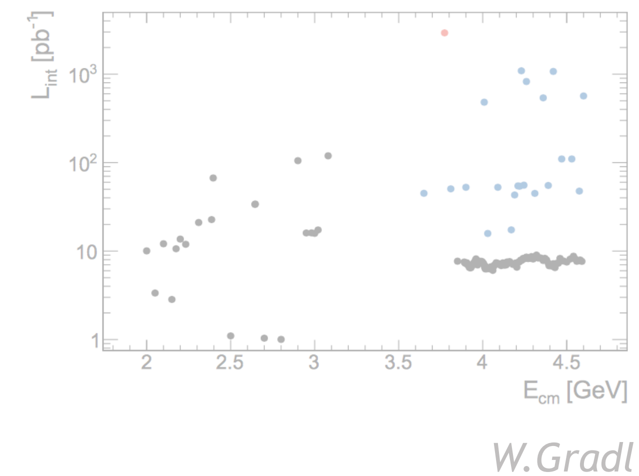
$\bar{p}p$

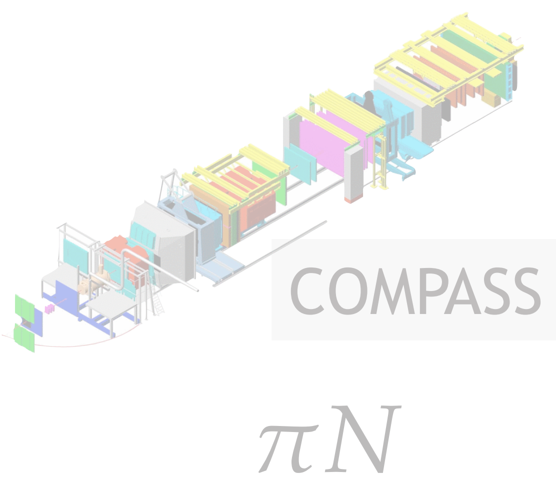
current & future experiments

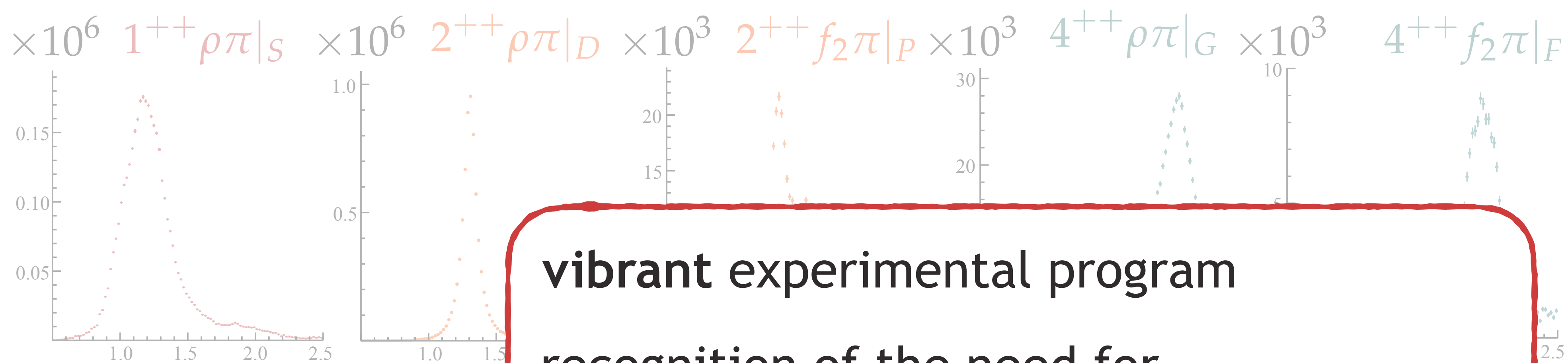
high statistics
novel production

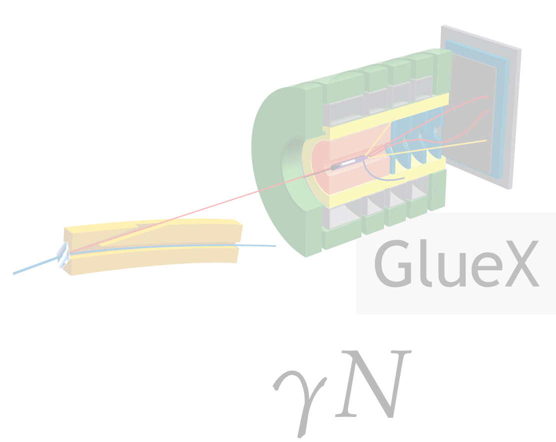


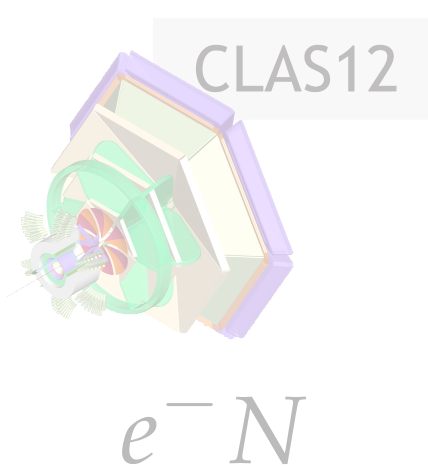












vibrant experimental program

recognition of the need for advanced analysis tools
→ JPAC & other efforts

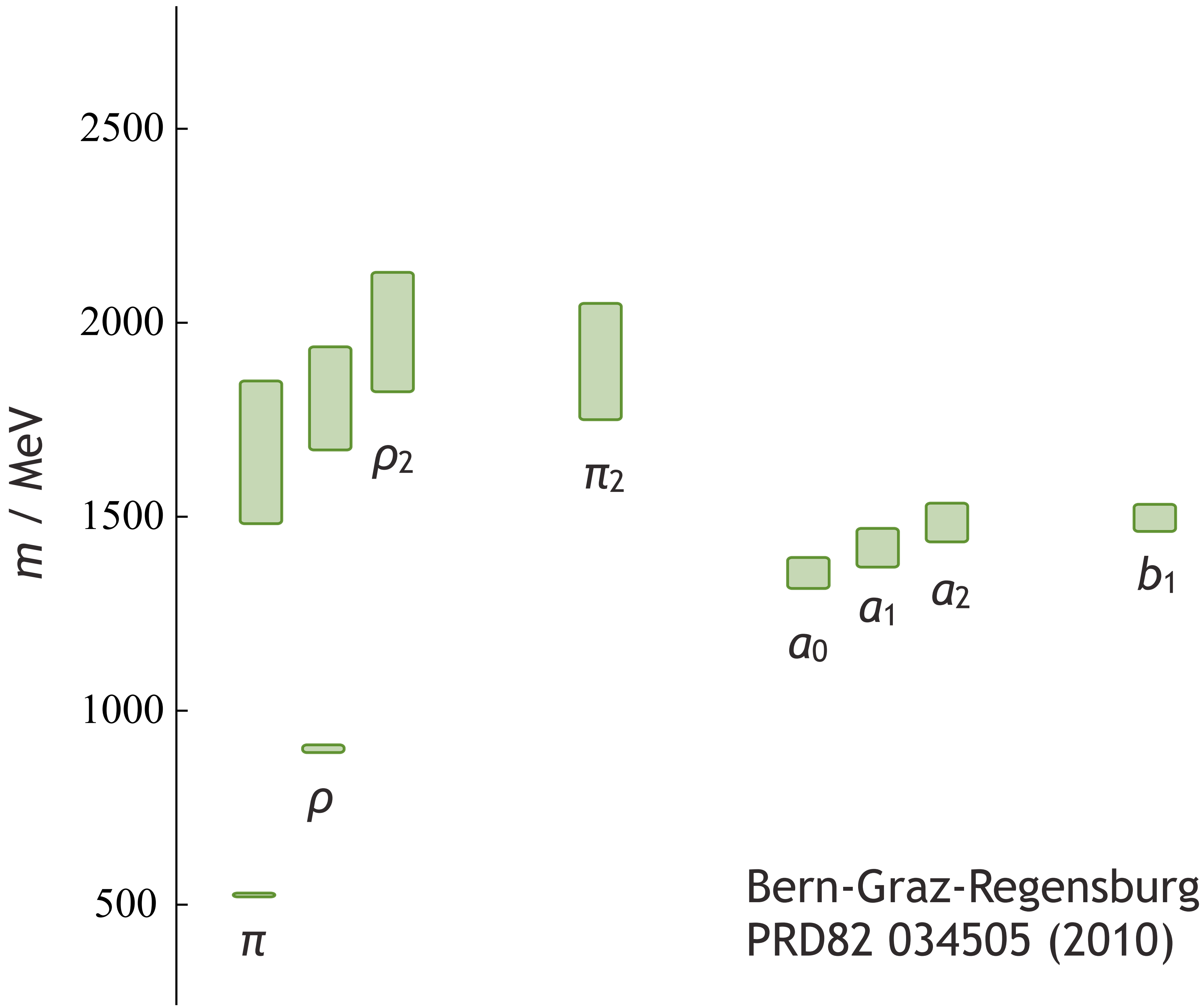
… but what about the connection to QCD ?

lattice QCD
& the **Hadron Spectrum Collaboration**

in its current form since 2009

where the field was … meson spectrum

state-of-the-art determinations of the excited meson spectrum in lattice QCD



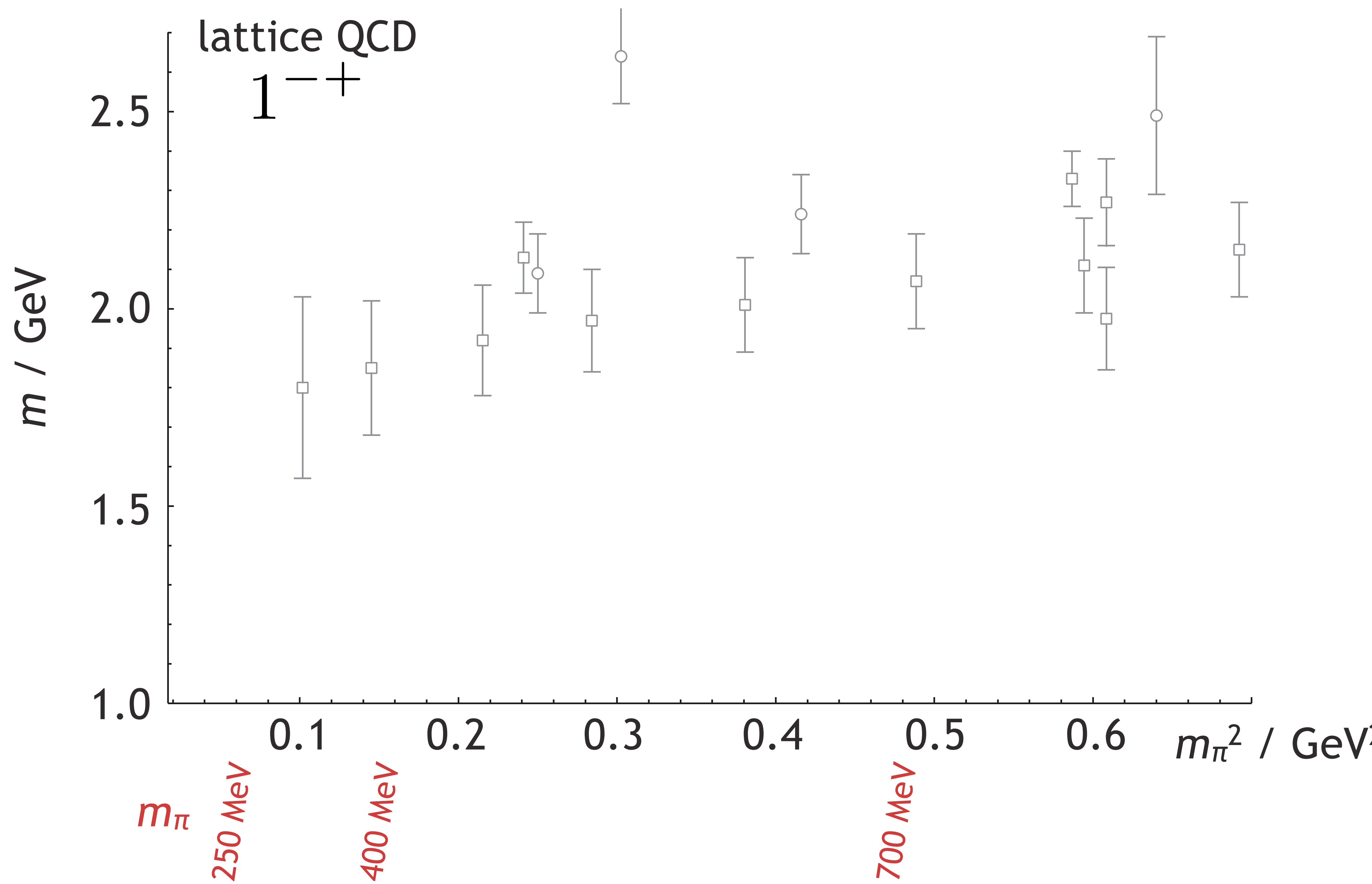
few low-spin ground-states
plus occasionally one
badly-determined excited state

Bern-Graz-Regensburg
PRD82 034505 (2010)

(*actually appeared* ***after*** *first HSC results*)

where the field was ... hybrid mesons

in 2009 flux-tube and bag models (1980s) were still state-of-the-art



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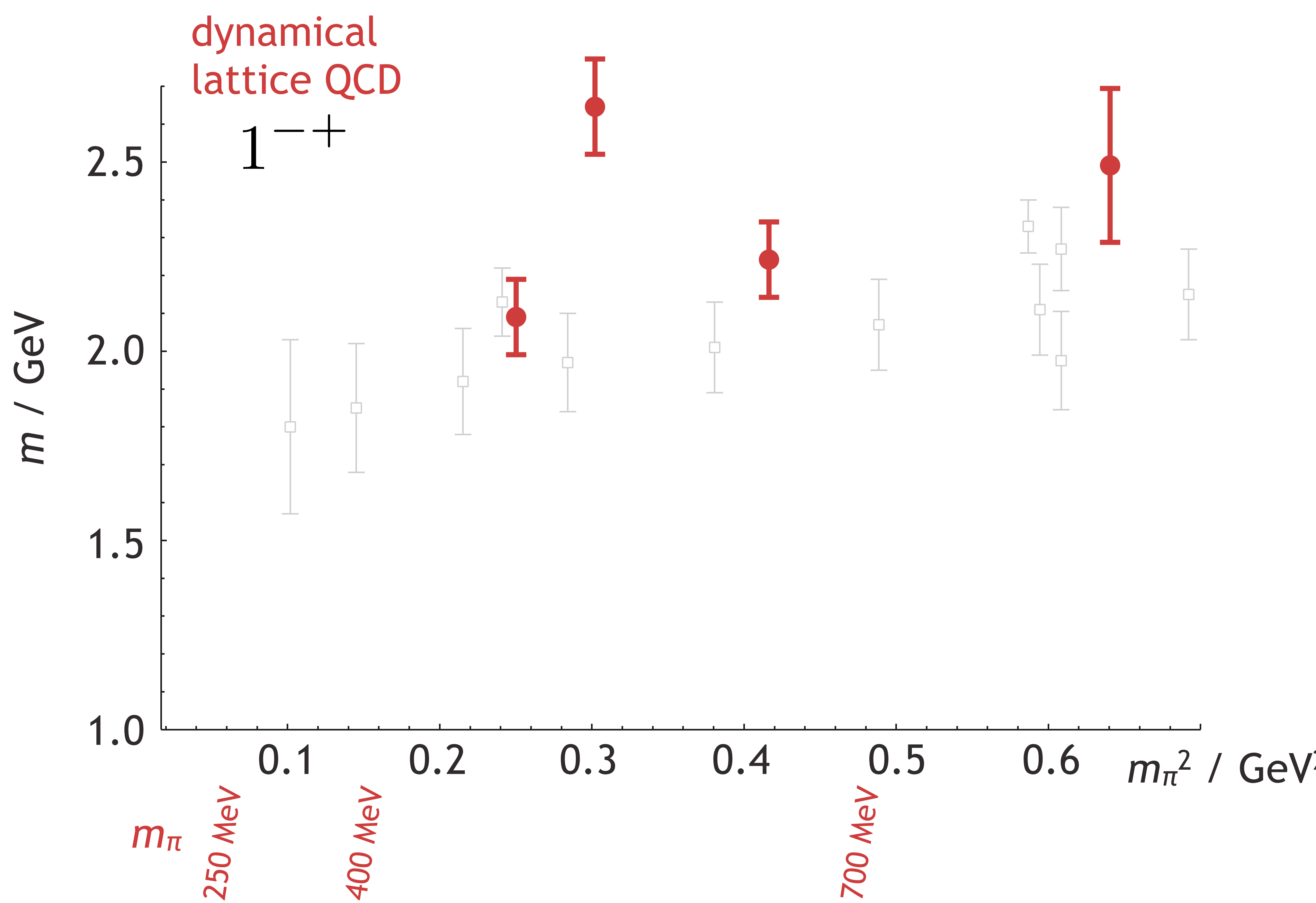


hadron spectrum collaboration

distillation

efficiently evaluate a large number of correlation functions

compute quark annihilation where needed

large basis of hadron operators

began with meson operator basis $\bar{\psi}\Gamma \overleftrightarrow{D} \ldots \overleftrightarrow{D} \psi$ (up to three derivatives)

'subduced' into the irreps of the cubic symmetry

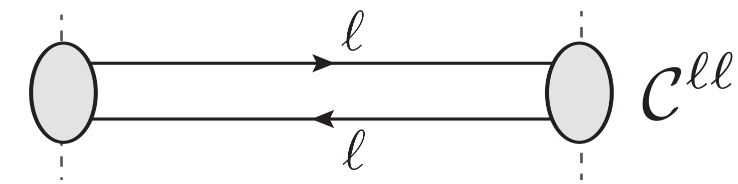
found a workaround for the breakdown of rotational symmetry

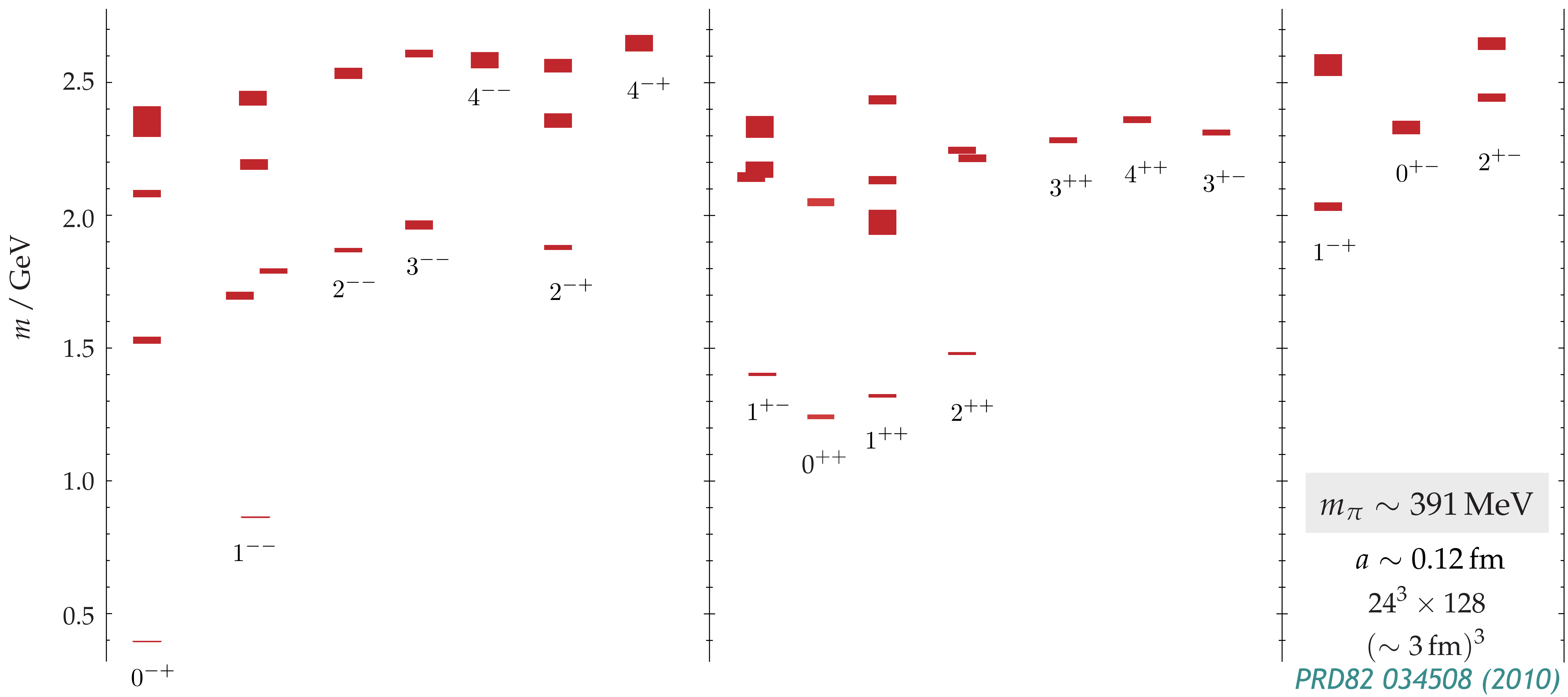
variational solution

'diagonalize' a matrix of correlation functions $C_{ij}(t) = \langle 0 | \mathcal{O}_i(t) \, \mathcal{O}_j^\dagger(0) | 0 \rangle$

extract many excited states $C(t) v^{\mathfrak{n}} = \lambda^{\mathfrak{n}}(t) \, C(t_0) v^{\mathfrak{n}}$

excited isovector meson spectrum

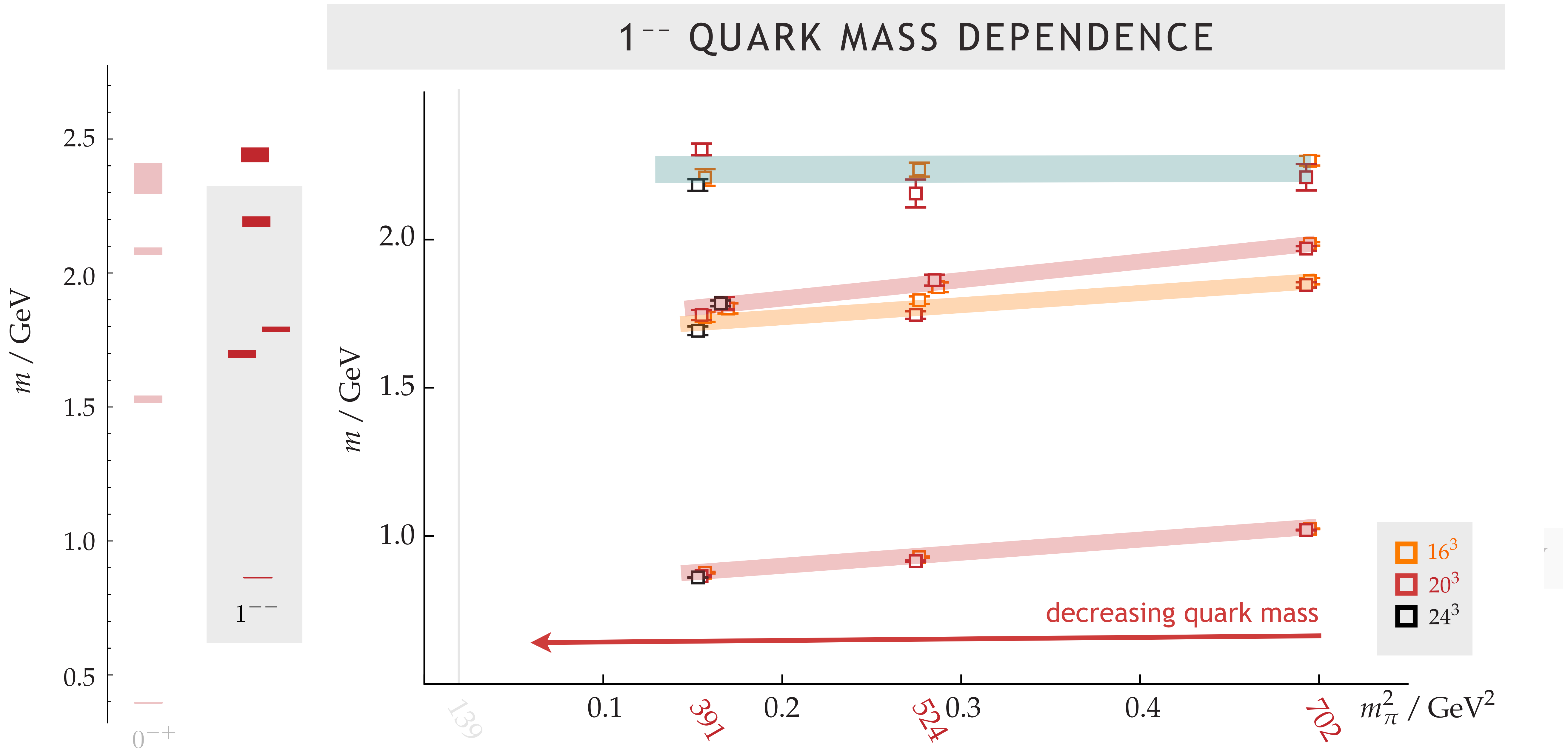




PRD82 034508 (2010)

PRD88 094505 (2013)

excited isovector meson spectrum

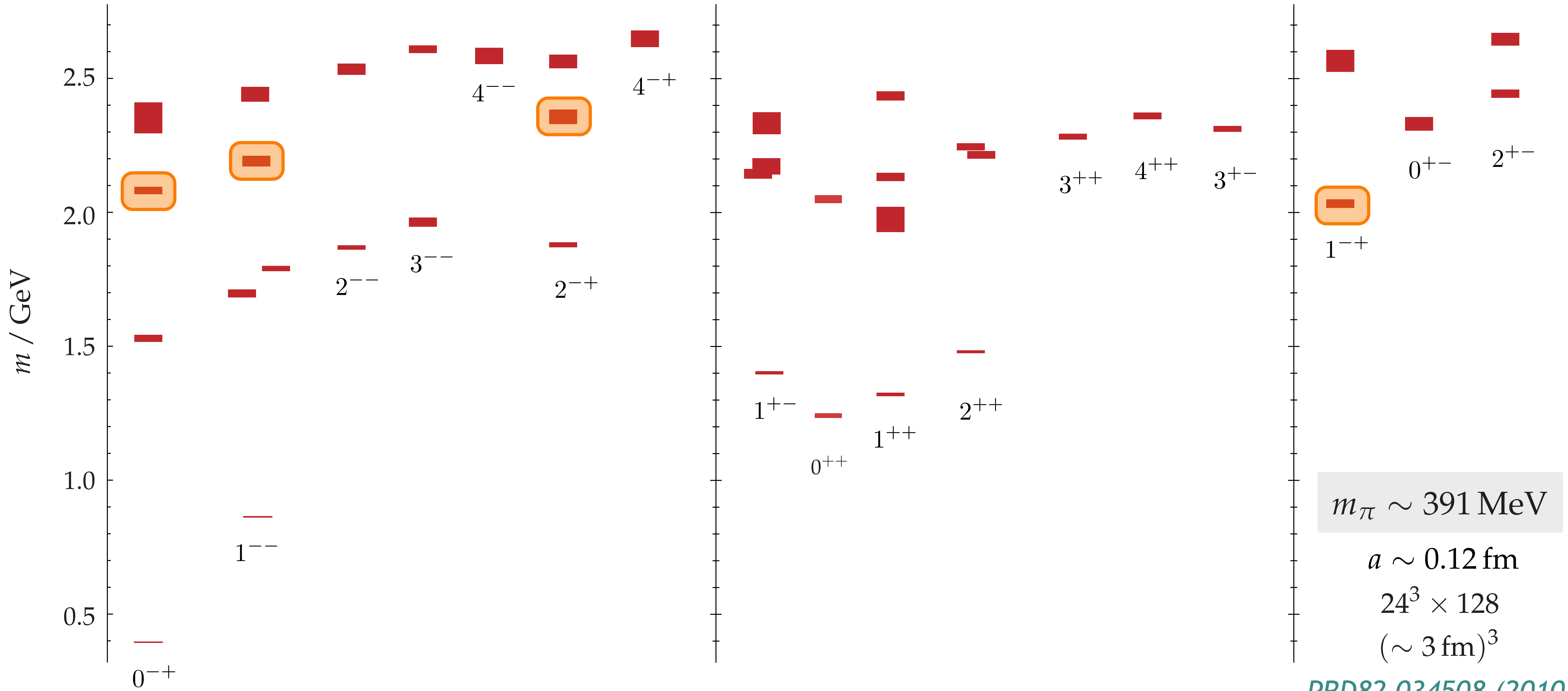


• spectrum does not change qualitatively

isovector hybrid mesons

- 'super'-multiplet of **hybrid mesons** roughly 1.3 GeV above the ρ

$(0,\mathbf{1},2)^{-+},\ 1^{--}$

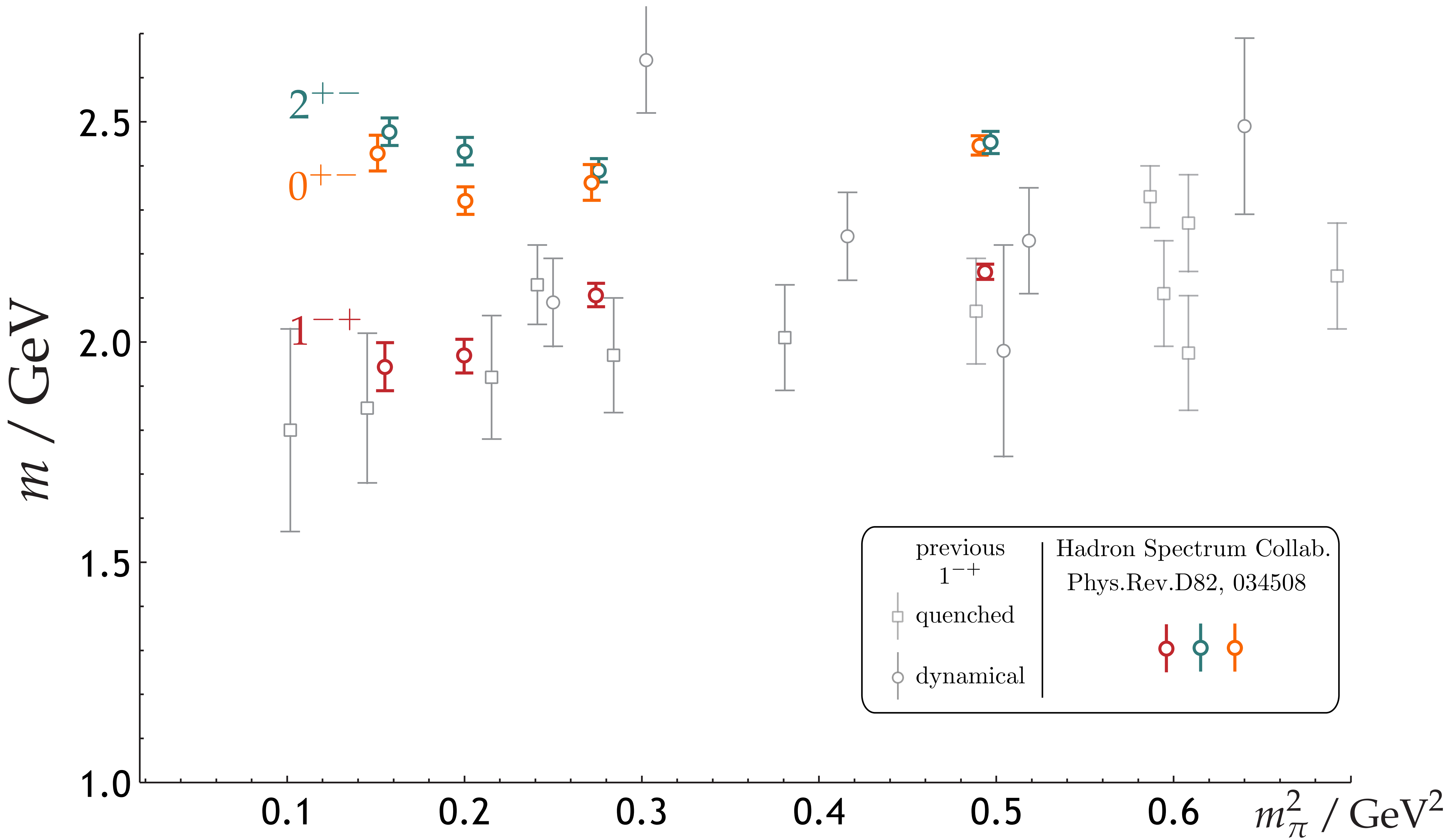


PRD82 034508 (2010)
PRD88 094595 (2013)

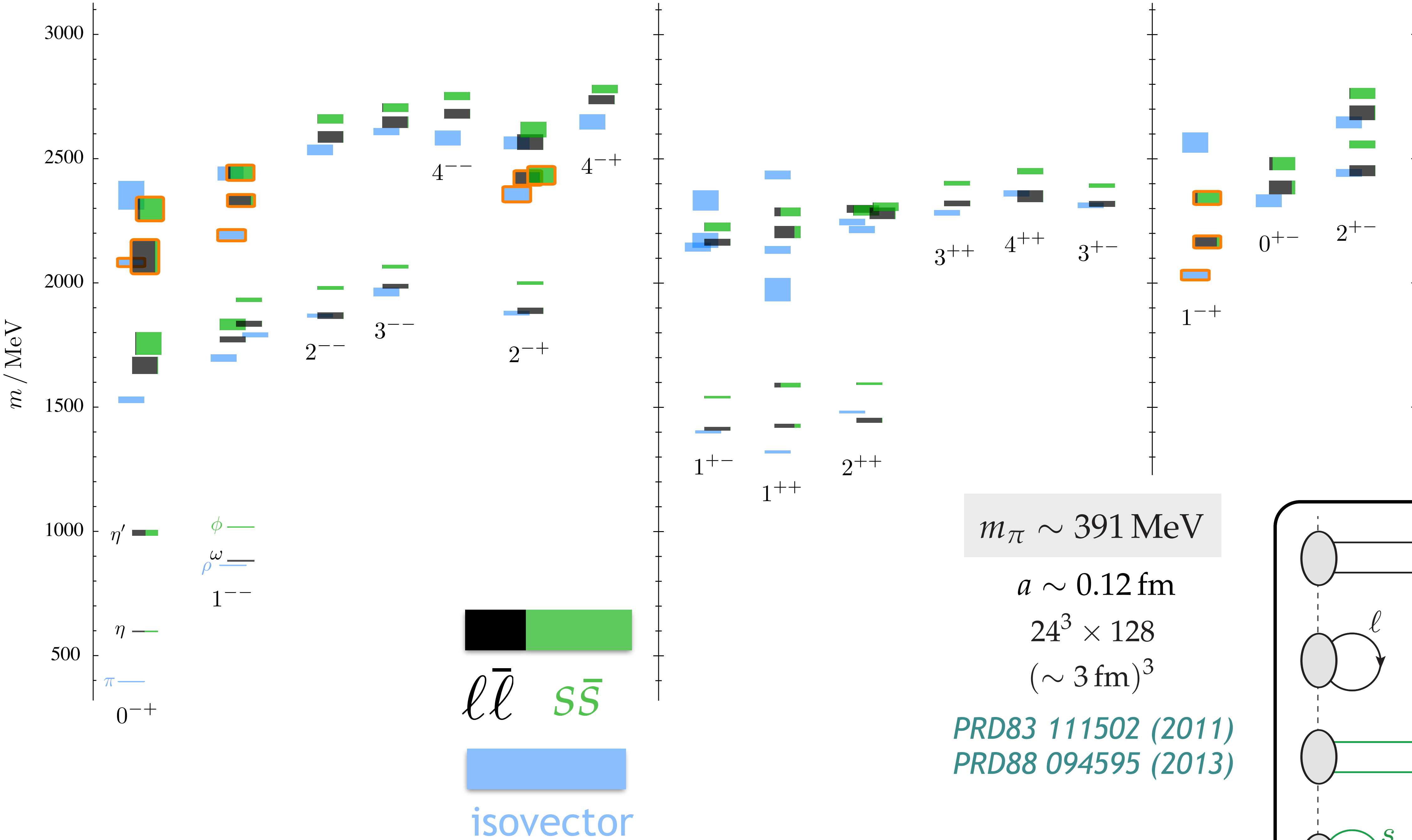
utilized overlaps with characteristic operators to identify state make-up

- these states have a dominant overlap onto $\bar{\psi}\Gamma[D,D]\psi \;\sim\; [q\bar{q}]_{8_c} \otimes B_{8_c}$

exotic hybrid quark mass dependence



isoscalar meson spectrum



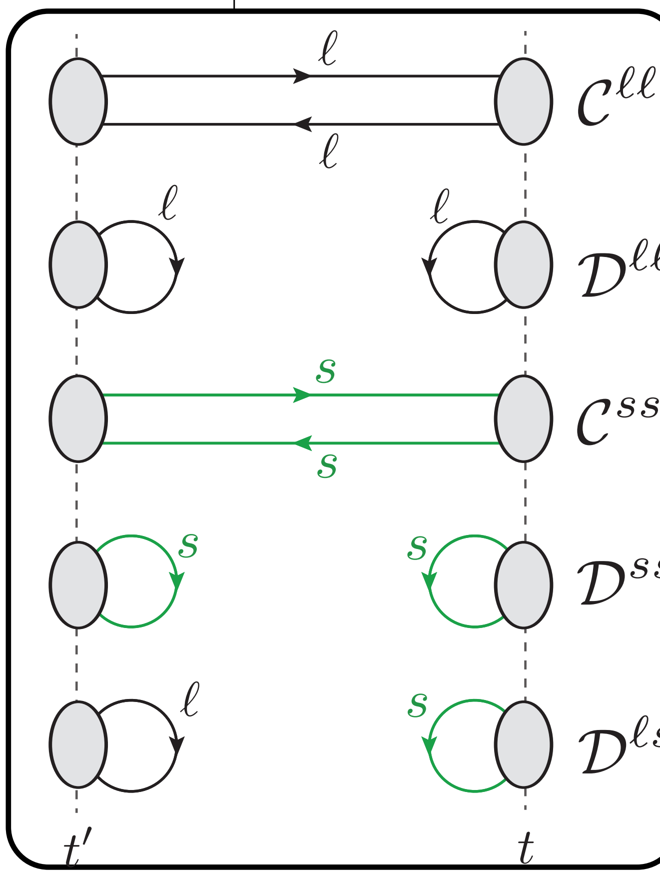
$m_\pi \sim 391\,\mathrm{MeV}$

$a \sim 0.12\,\mathrm{fm}$

$24^3 \times 128$

$(\sim 3\,\mathrm{fm})^3$

PRD83 111502 (2011)
PRD88 094595 (2013)

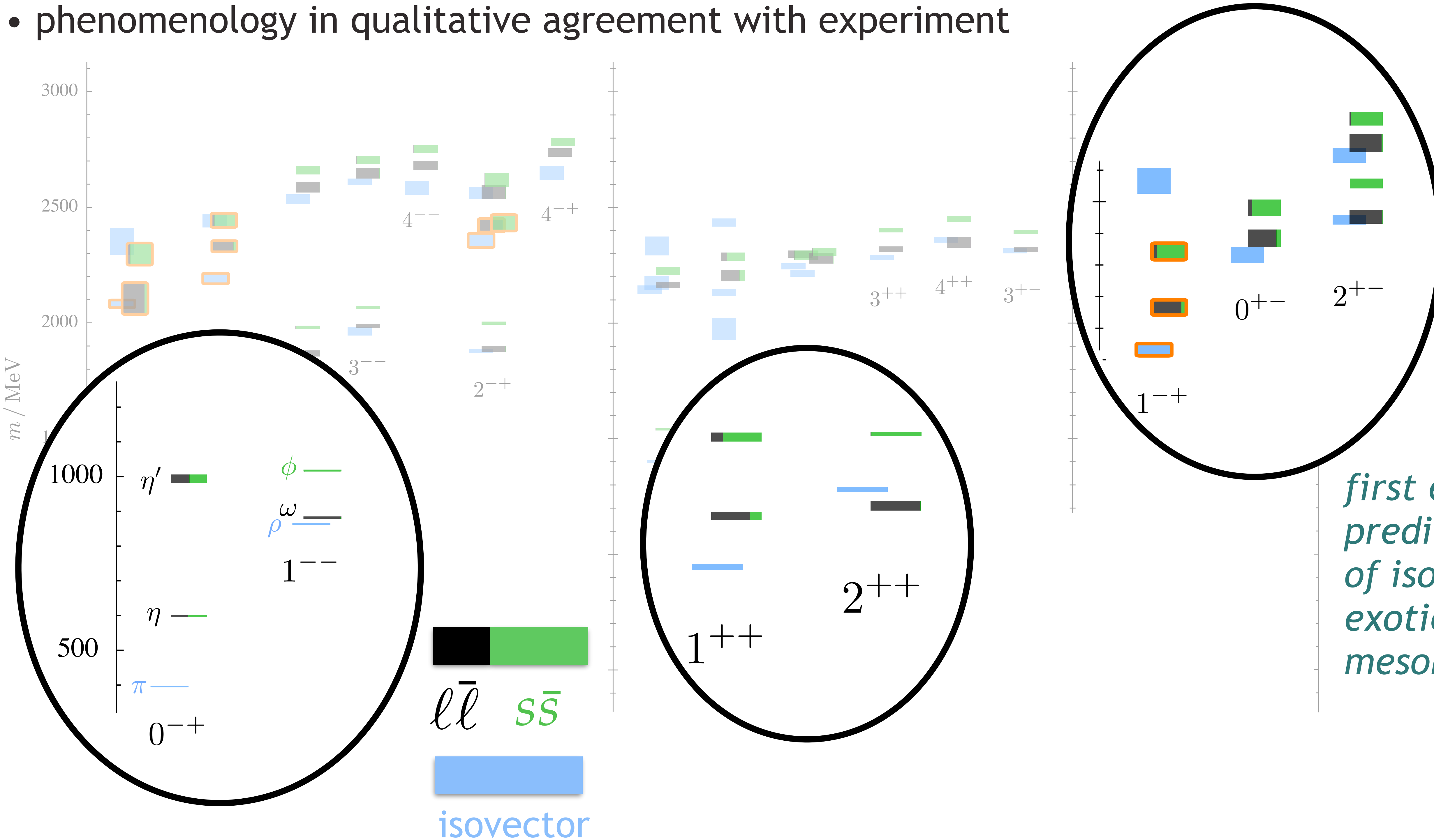


evaluated all the required annihilation diagrams

determined light-strange mixing through operator overlaps

isoscalar meson spectrum

- phenomenology in qualitative agreement with experiment



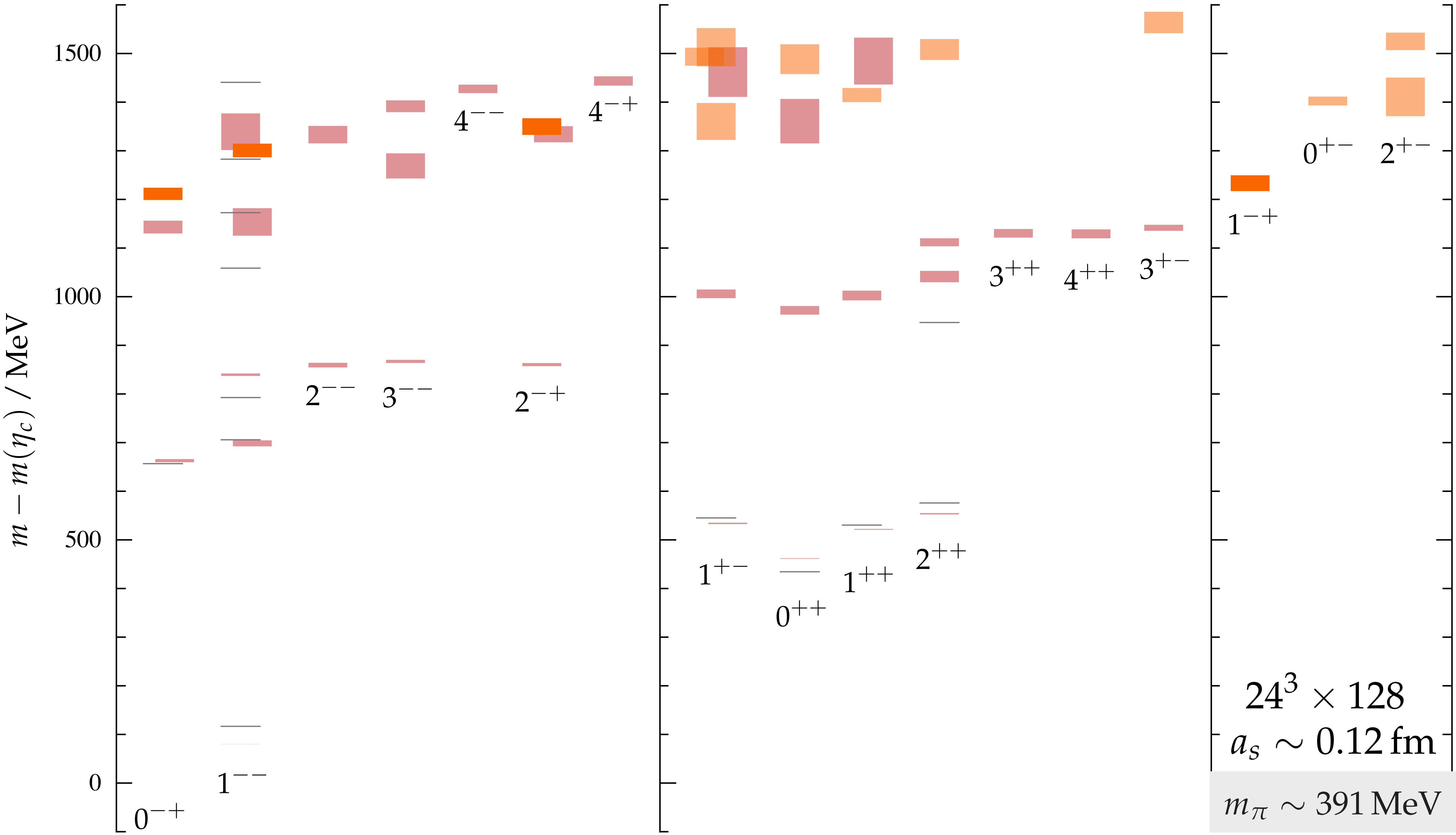
first ever prediction of isoscalar exotic J^{PC} mesons

rest of the lattice community still struggling with η,η' alone

charmonium

- two 'super'-multiplets of hybrid mesons

this work lead by our Dublin collaborators



JHEP 1207 126 (2012)

chromo-magnetic gluonic excitation

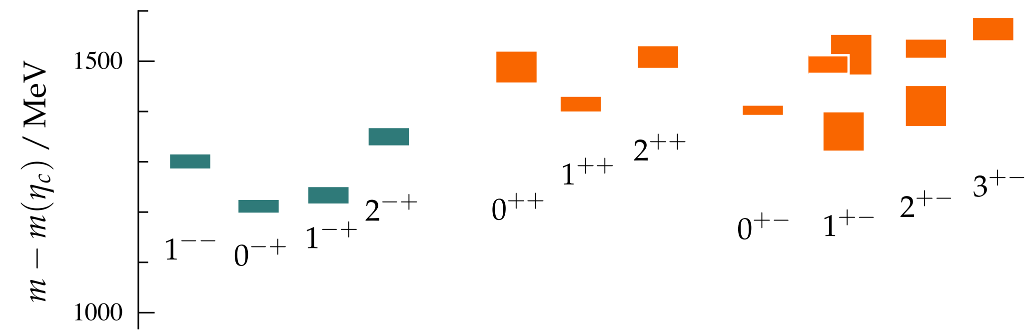
- lightest set of hybrid mesons appear to contain a *1*$^{+-}$ gluonic excitation

quarks in an *S*-wave

$$\left[q\bar{q}_{\mathbf{8_c}} \left[{}^1S_0 \right] G^\star_{\mathbf{8_c}} \left[B \right] \right]_{\mathbf{1_c}} \to 1^{--}_{\text{hyb.}}$$

$$\left[q\bar{q}_{\mathbf{8_c}} \left[{}^3S_1 \right] G^\star_{\mathbf{8_c}} \left[B \right] \right]_{\mathbf{1_c}} \to (0,1,2)^{-+}_{\text{hyb.}}$$

CHARMONIUM HYBRIDS



- some models have similar systematics
  - bag model also has *1*$^{+-}$ lowest in energy
  - *1*$^{+-}$ in a Coulomb-gauge approach

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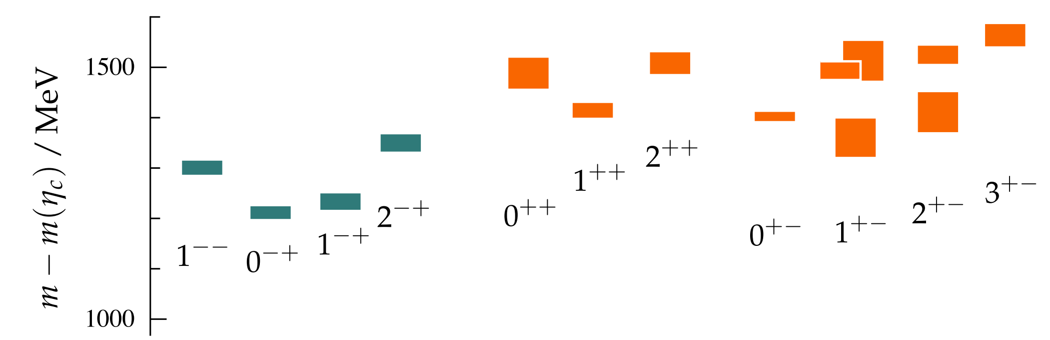
quarks in a *P*-wave

$$\left[q\bar{q}_{\mathbf{8_c}} \left[{}^1P_1 \right] G^\star_{\mathbf{8_c}} \left[B \right] \right]_{\mathbf{1_c}} \to (0,1,2)^{++}_{\text{hyb.}}$$

$$\left[q\bar{q}_{\mathbf{8_c}} \left[{}^3P_{0,1,2} \right] G^\star_{\mathbf{8_c}} \left[B \right] \right]_{\mathbf{1_c}} \to (0,1^3,2^2,3)^{+-}_{\text{hyb.}}$$

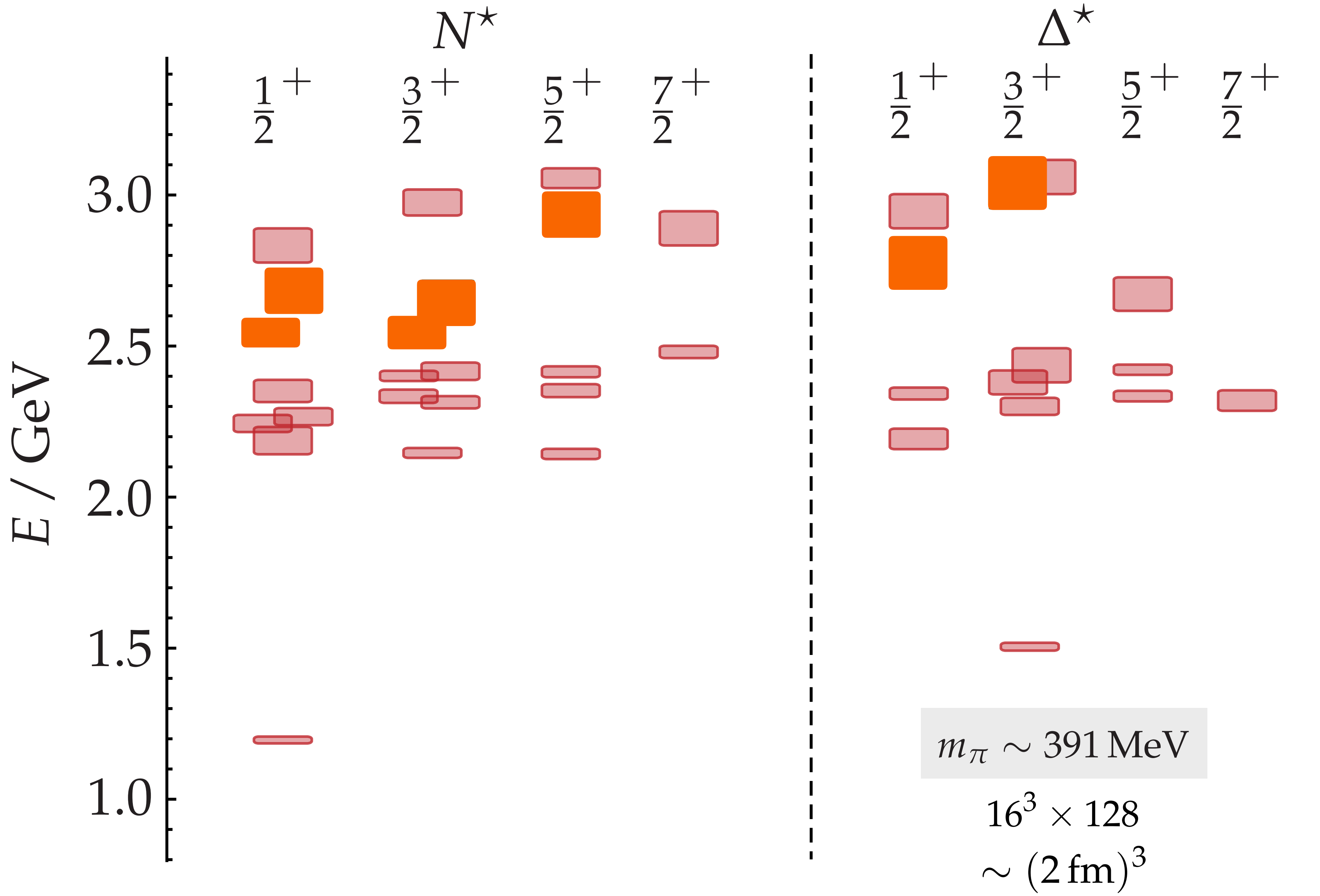
CHARMONIUM HYBRIDS



- some models have similar systematics
  - bag model also has *1*$^{+-}$ lowest in energy
  - *1*$^{+-}$ in a Coulomb-gauge approach

excited baryons

- a ‘super’-multiplet of **hybrid baryons**



spectrum from large basis of baryon operators

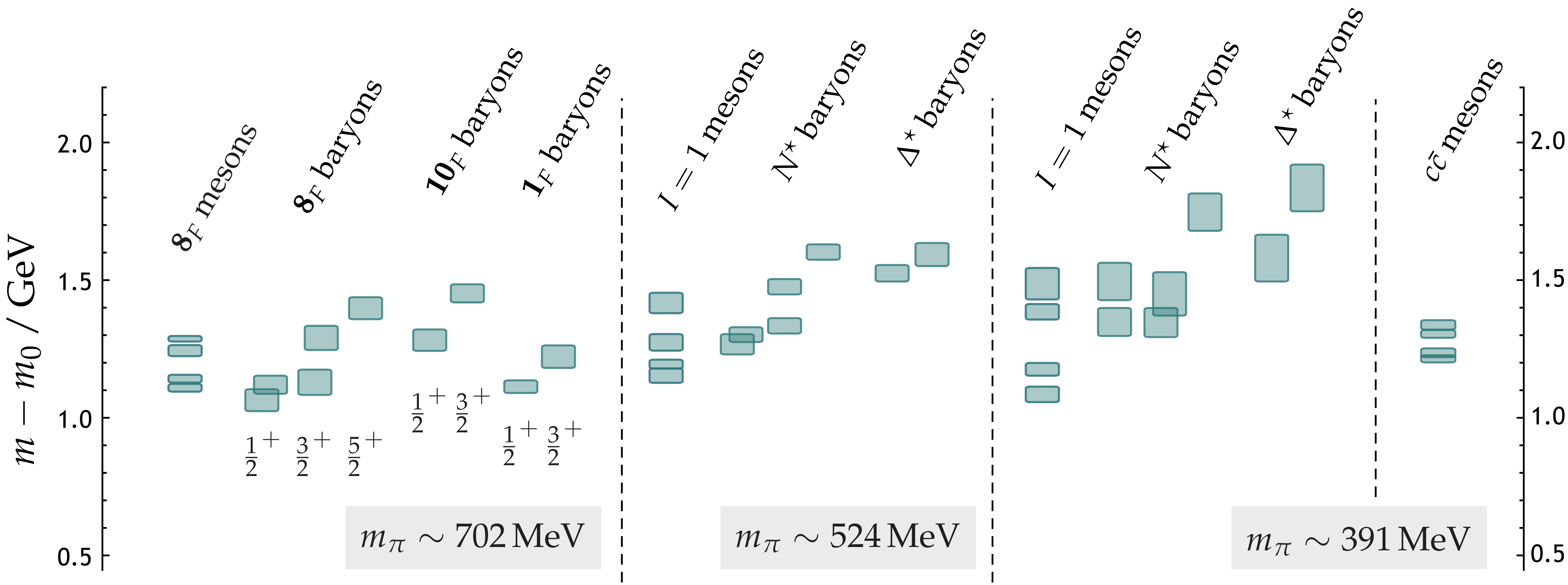
$$\epsilon_{abc}\left(D^{n_1}\tfrac{1}{2}(1\pm\gamma_0)\psi\right)^a\left(D^{n_2}\tfrac{1}{2}(1\pm\gamma_0)\psi\right)^b\left(D^{n_3}\tfrac{1}{2}(1\pm\gamma_0)\psi\right)^c$$

PRD84 074508 (2011)
PRD85 054016 (2012)

chromo-magnetic excitation

- subtract the 'quark mass' contribution

$$m_0^{\text{mes}} = m_\rho$$
$$m_0^{\text{bar}} = m_N$$
$$m_0^{c\bar{c}} = m_{\eta_c}$$

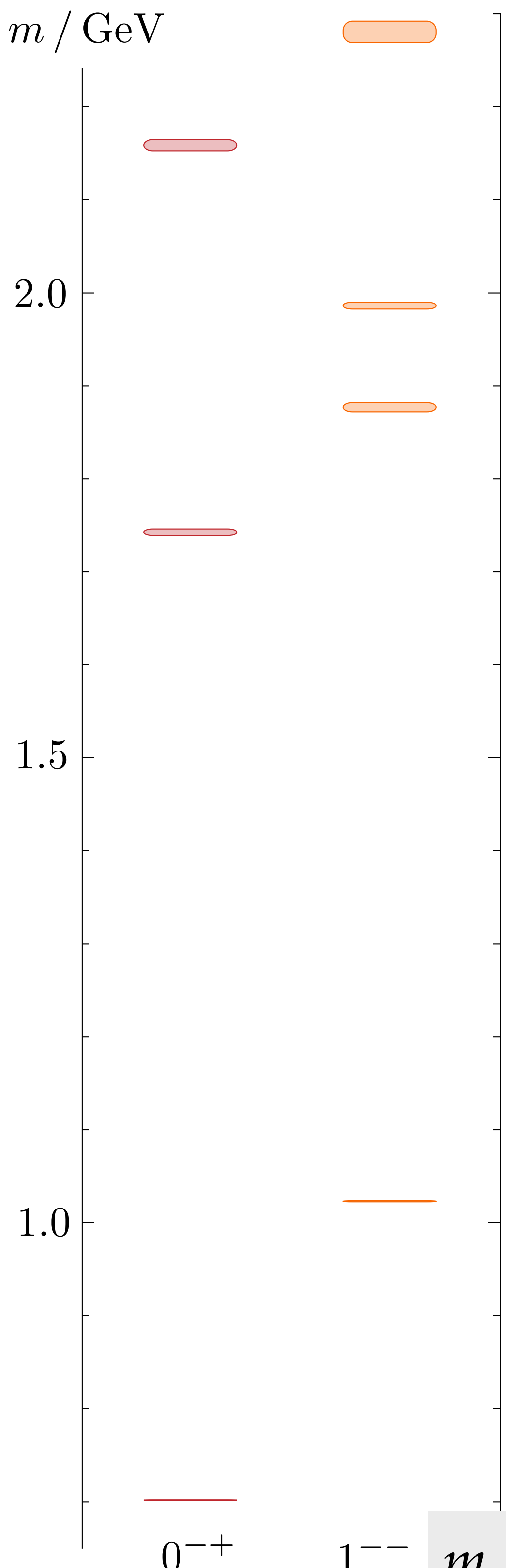


SU(3)F point

common energy scale of chromomagnetic gluonic excitation $\sim 1.3\,\text{GeV}$

lowest gluonic excitation in QCD now determined ?

what other properties ?

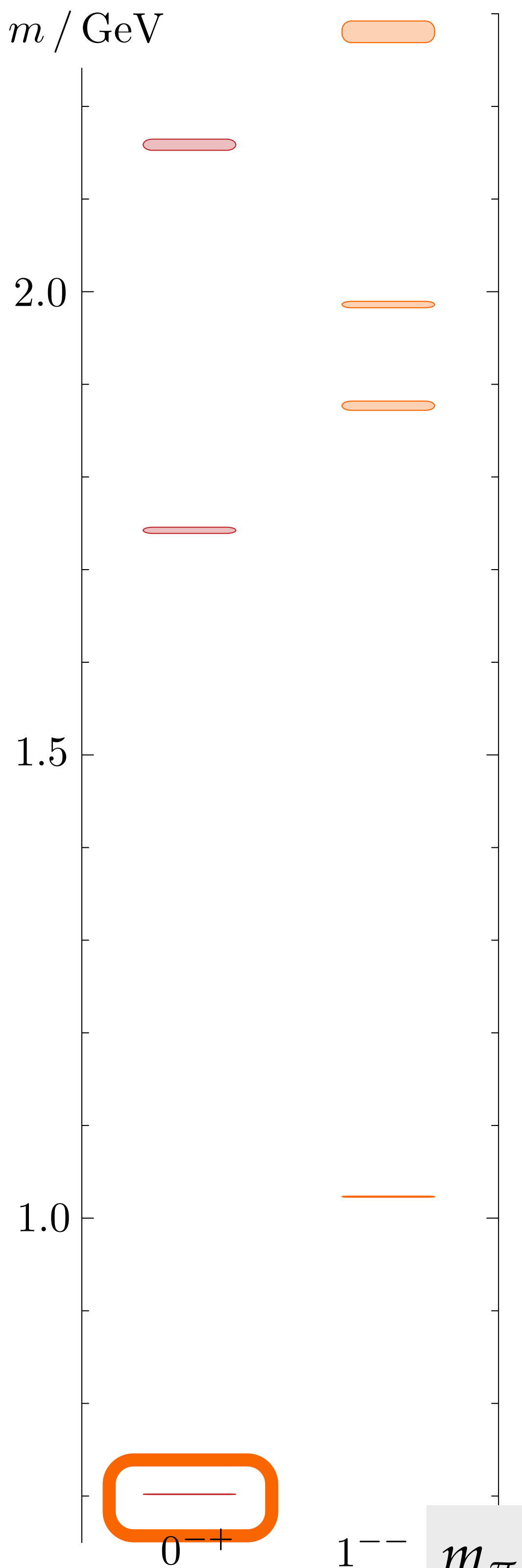


$m_\pi \sim 700\,\mathrm{MeV}$

with this technology, can you obtain any other info about excited state mesons ?

interactions with external currents ?

excited-state radiative transitions



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

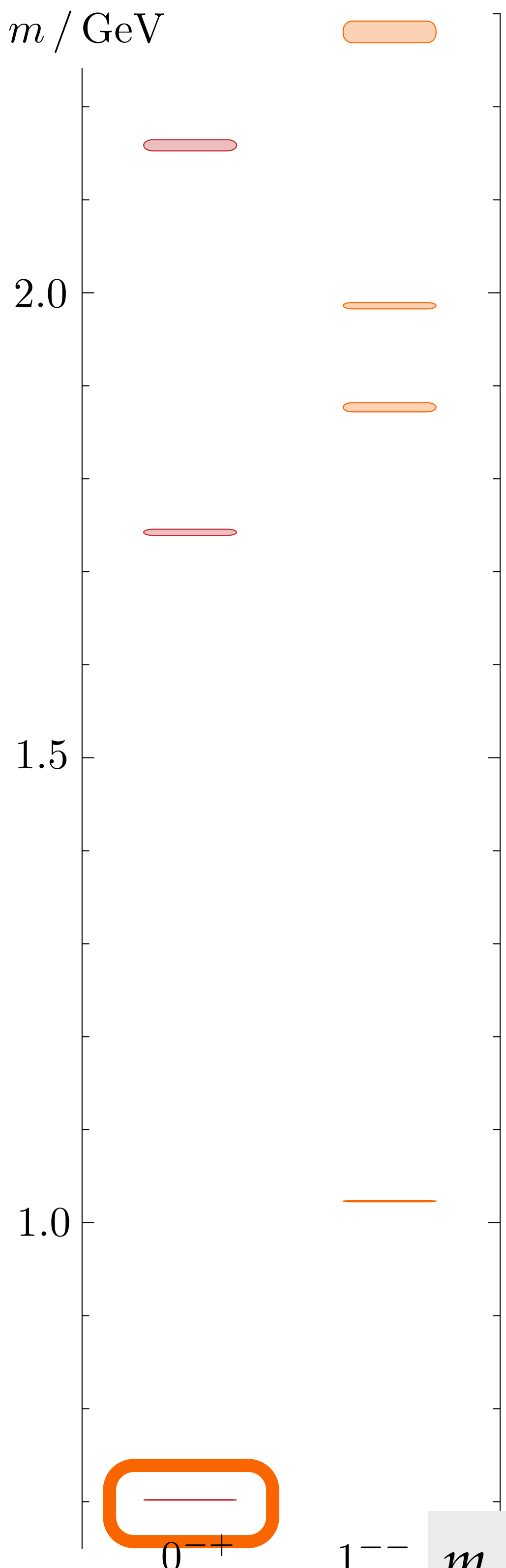
PRD91 114501 (2015)

three-point correlation functions

$$\langle 0 | \Omega_\pi(t_f)\, j^\mu(t)\, \Omega_\pi^\dagger(0) | 0 \rangle$$

this work lead by graduate student Christian Shultz

excited-state radiative transitions



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PRD91 114501 (2015)

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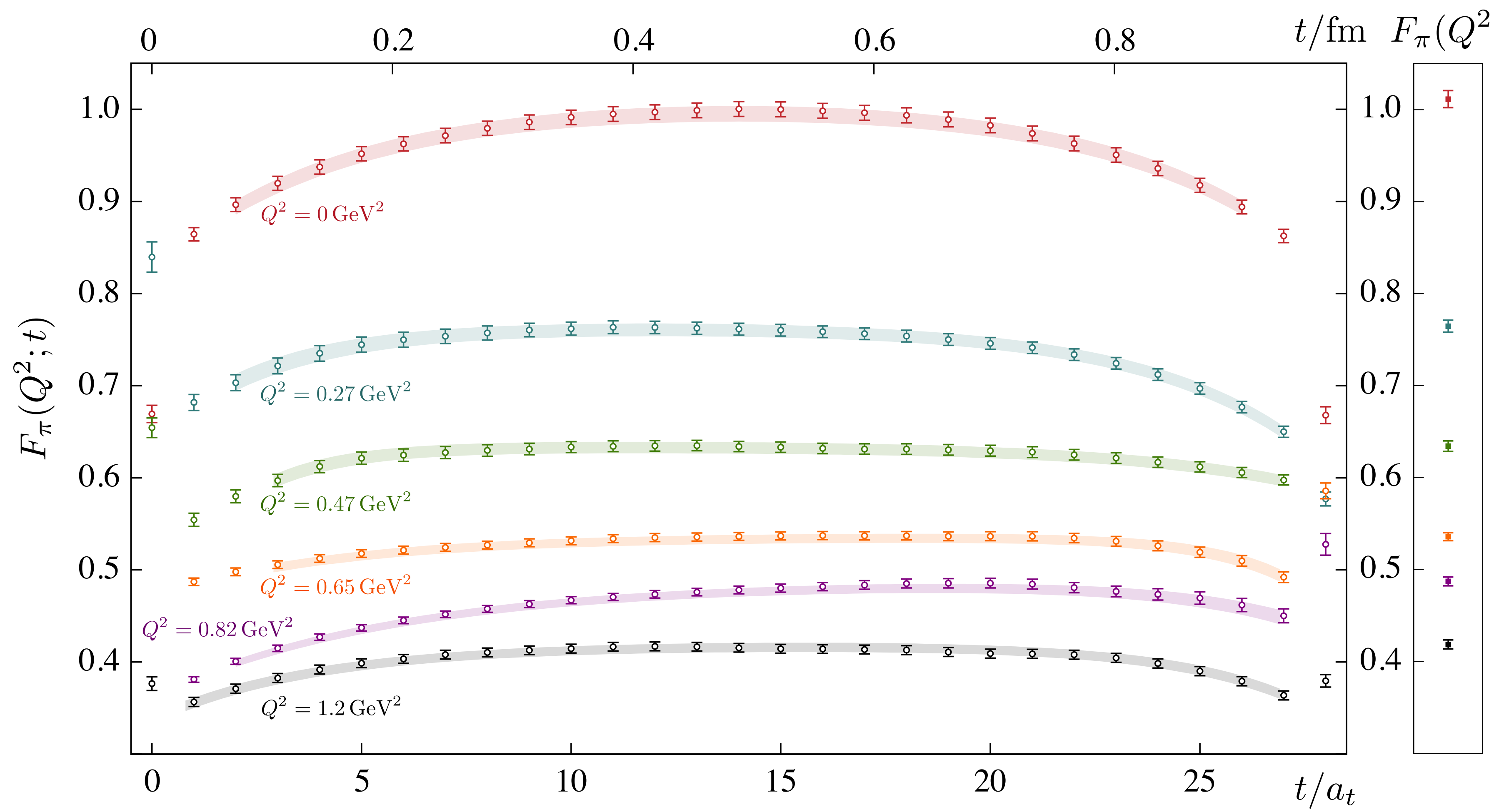
range of $\vec{p}_i$, $\vec{p}_f$



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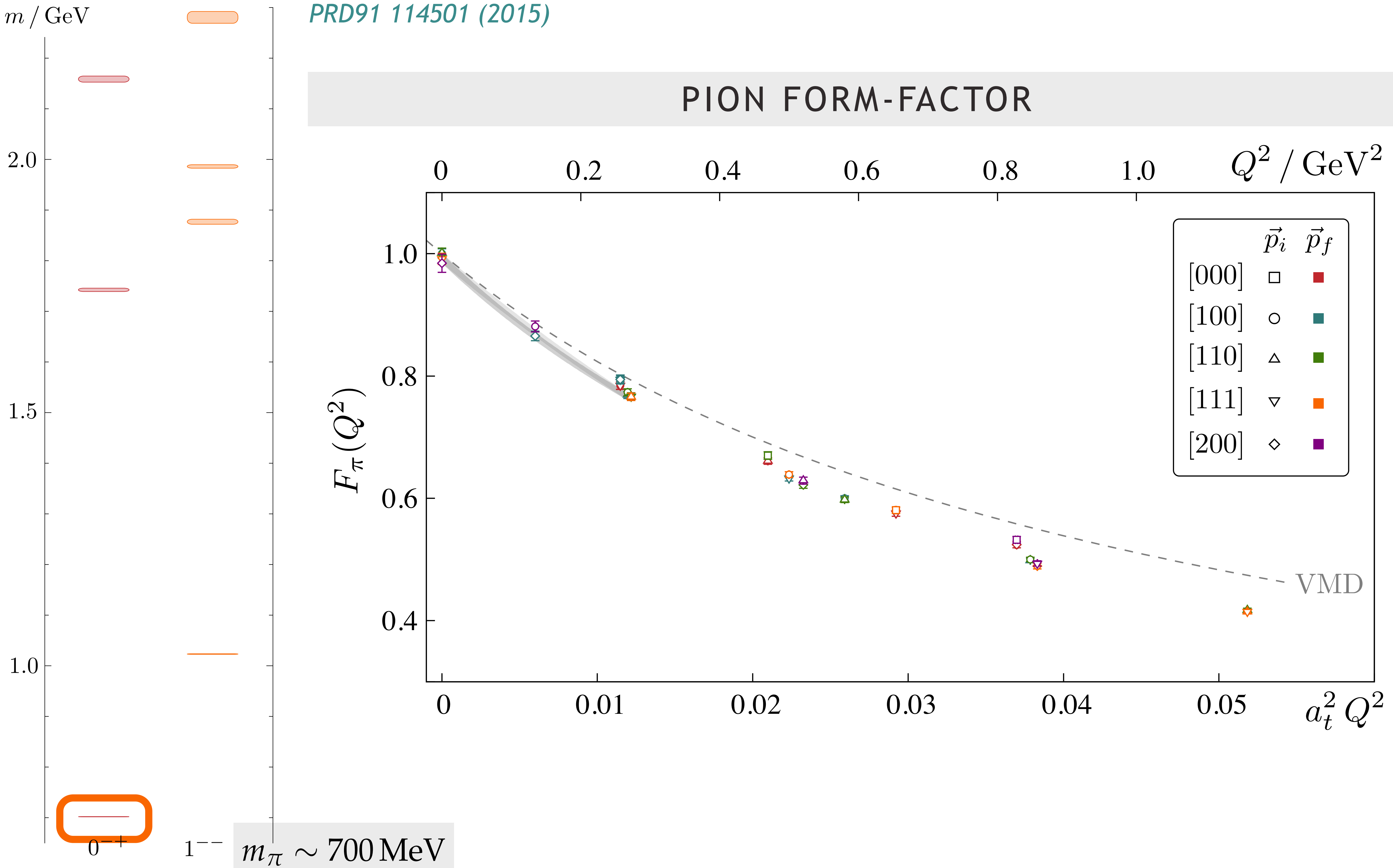

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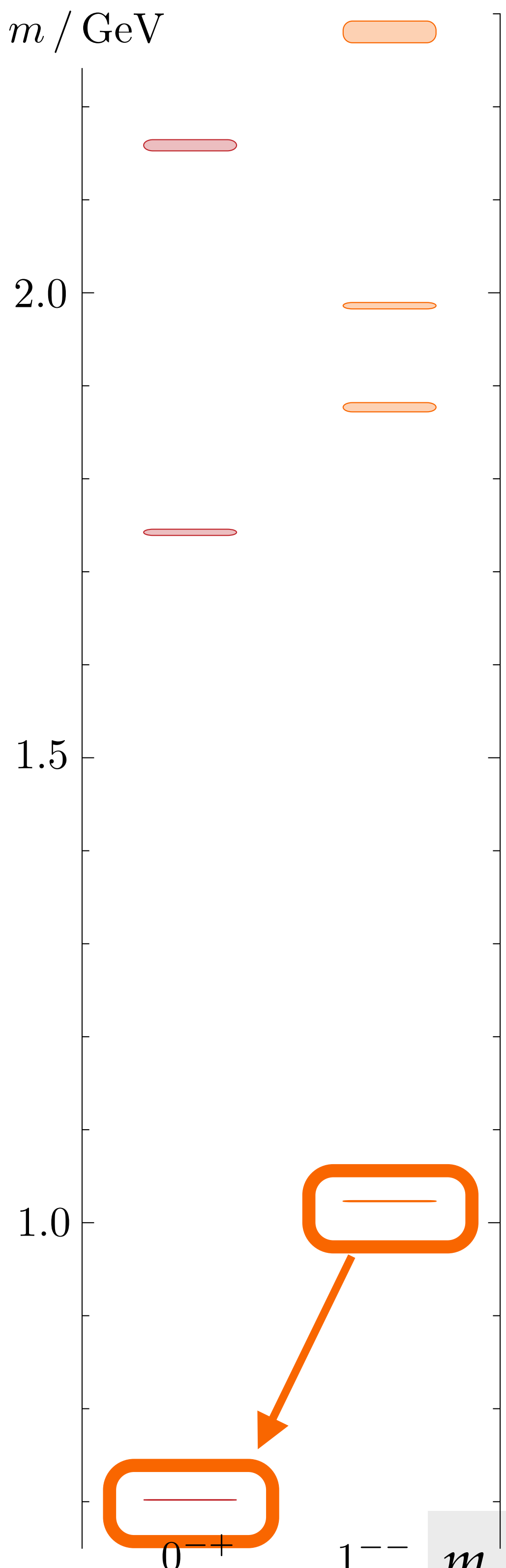

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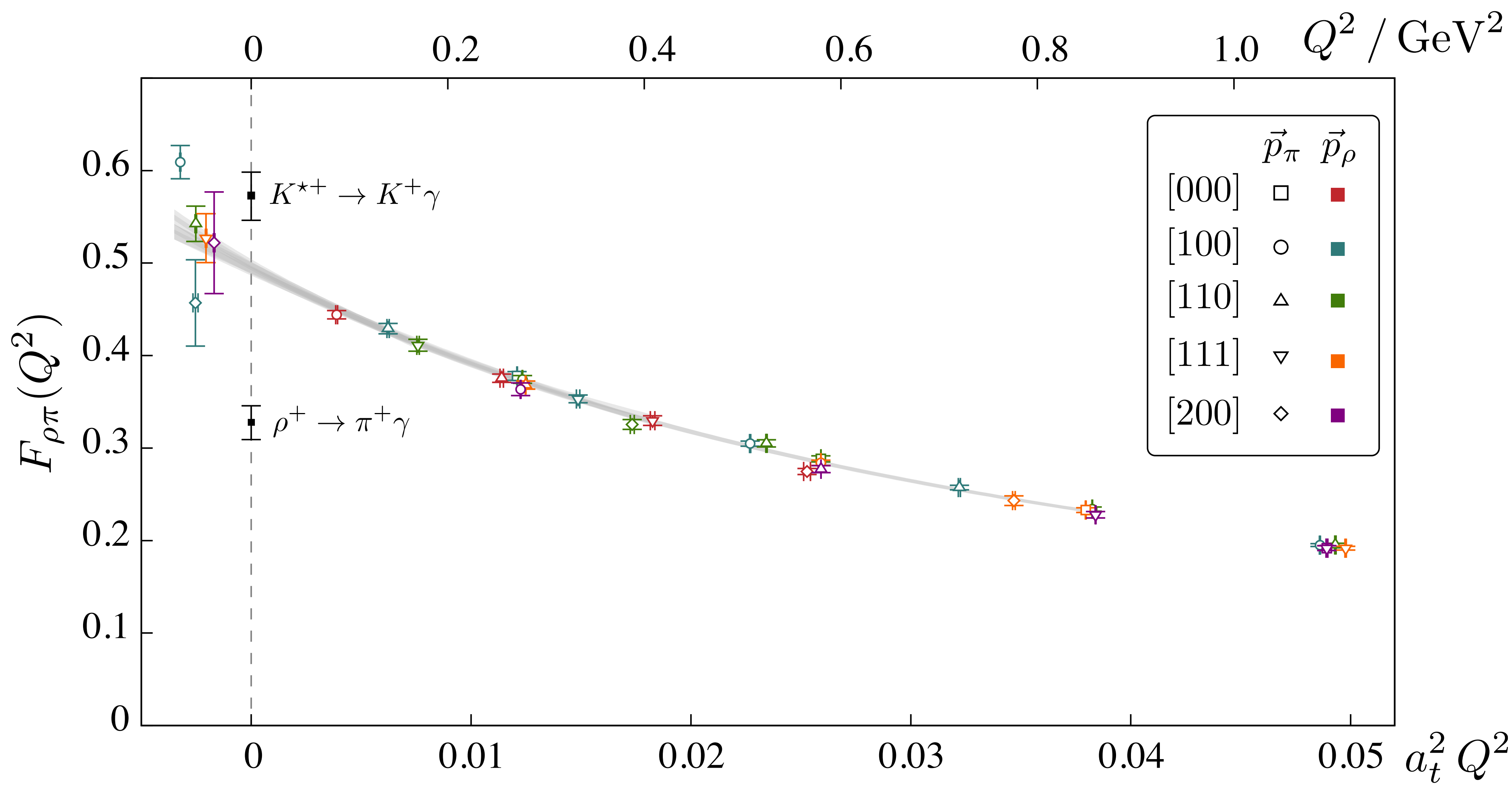
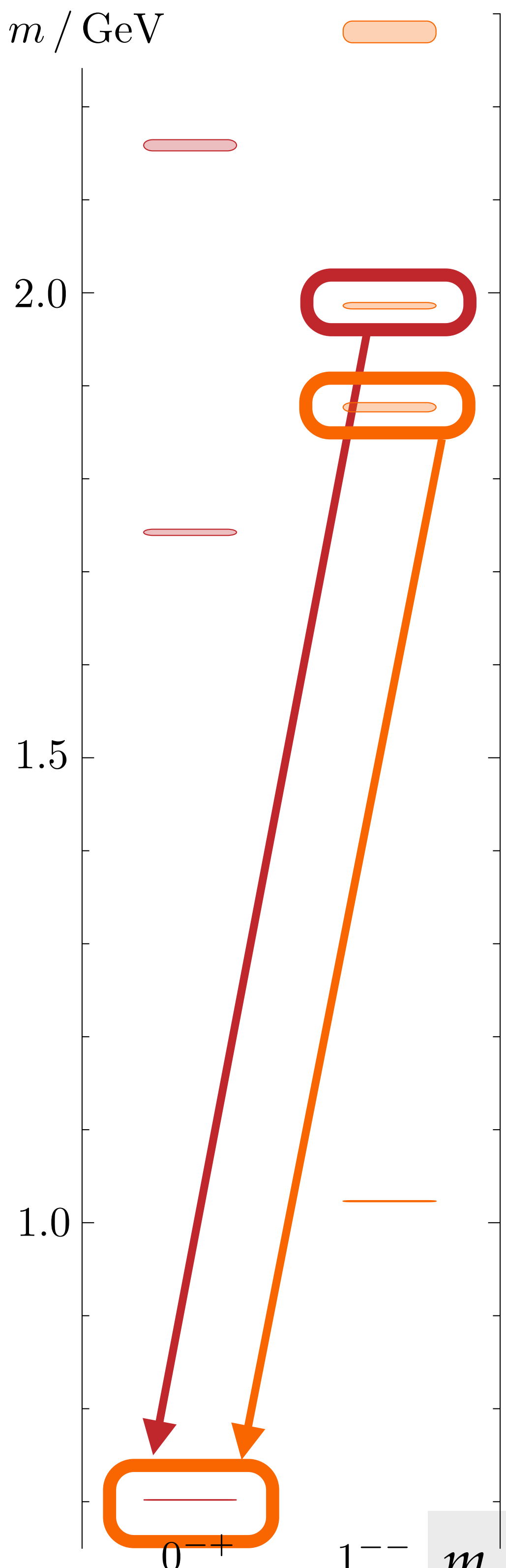
PRD91 114501 (2015)

$\rho \to \pi$ TRANSITION FORM-FACTOR



excited-state radiative transitions



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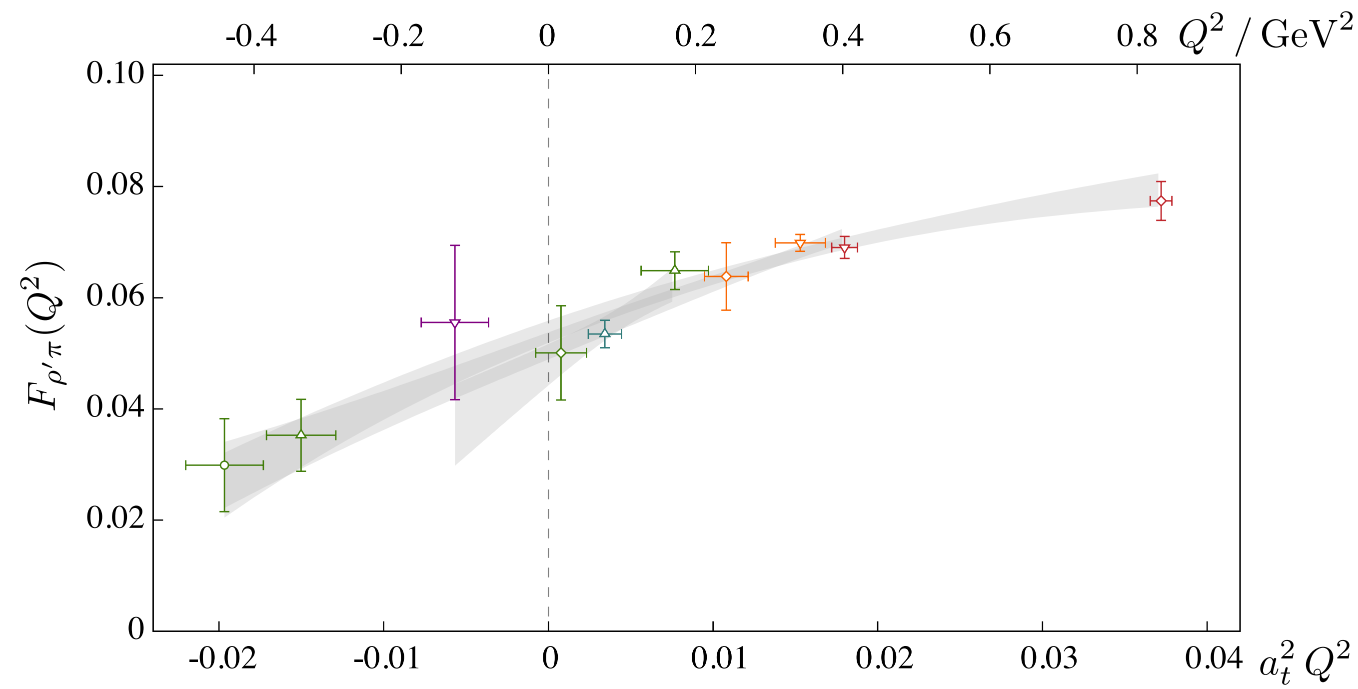
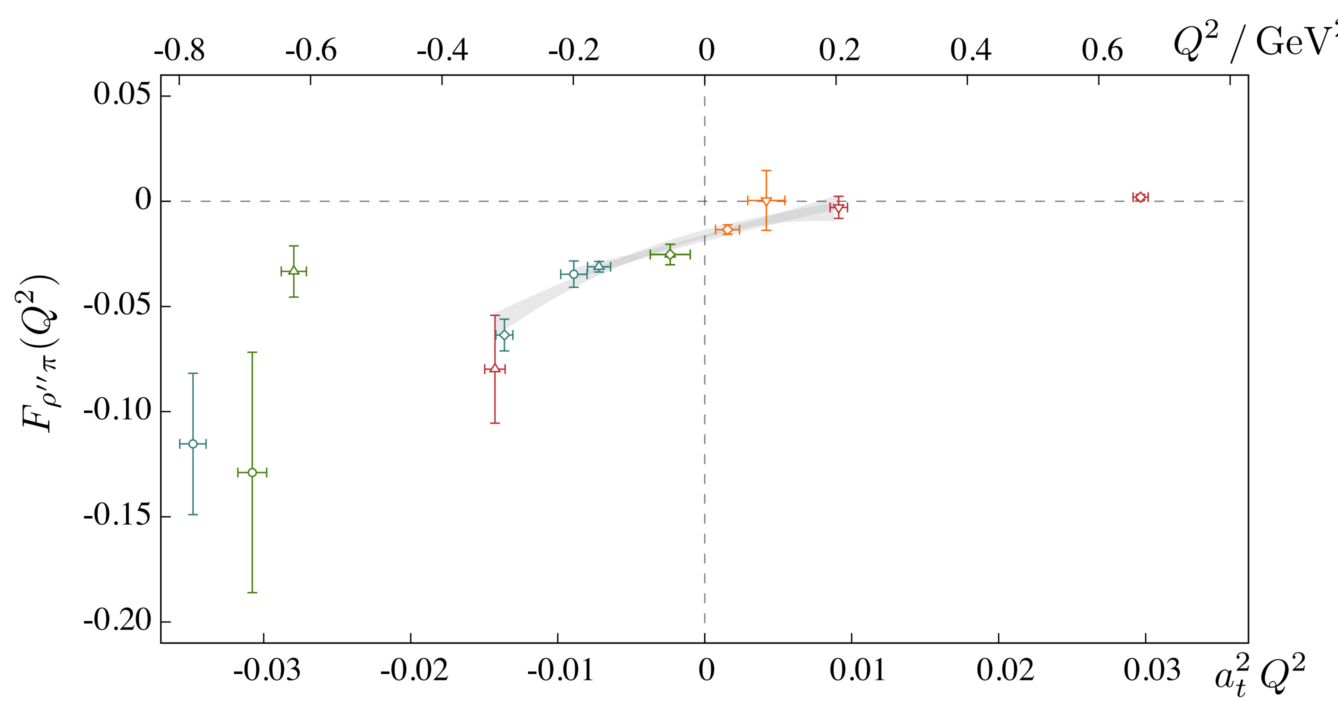
PRD91 114501 (2015)

$\rho' \rightarrow \pi$ TRANSITION FORM-FACTOR



$\rho'' \rightarrow \pi$ TRANSITION FORM-FACTOR



excited spectra summary of progress

using operators $\bar{\psi}\Gamma\overleftrightarrow{D}\ldots\overleftrightarrow{D}\psi$ and $\epsilon_{abc}\Big(D^{n_1}\tfrac{1}{2}(1\pm\gamma_0)\psi\Big)^a\Big(D^{n_2}\tfrac{1}{2}(1\pm\gamma_0)\psi\Big)^b\Big(D^{n_3}\tfrac{1}{2}(1\pm\gamma_0)\psi\Big)^c$

- obtained unprecedented, and mainly still unmatched, detailed excited state spectra
- isolated the spectrum of hybrid mesons and baryons, both exotic and non-exotic
- inferred the probable nature of the lightest gluonic excitation
- demonstrated the possibility of extracting current transitions between excited states

(2009 - 2013)

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(2009 - 2013)

but this comes close to exhausting what can usefully be learned
from using just these operators

we learn a lot from these results, but need to move to methods
that can reproduce the true physics of excited states

resonances !

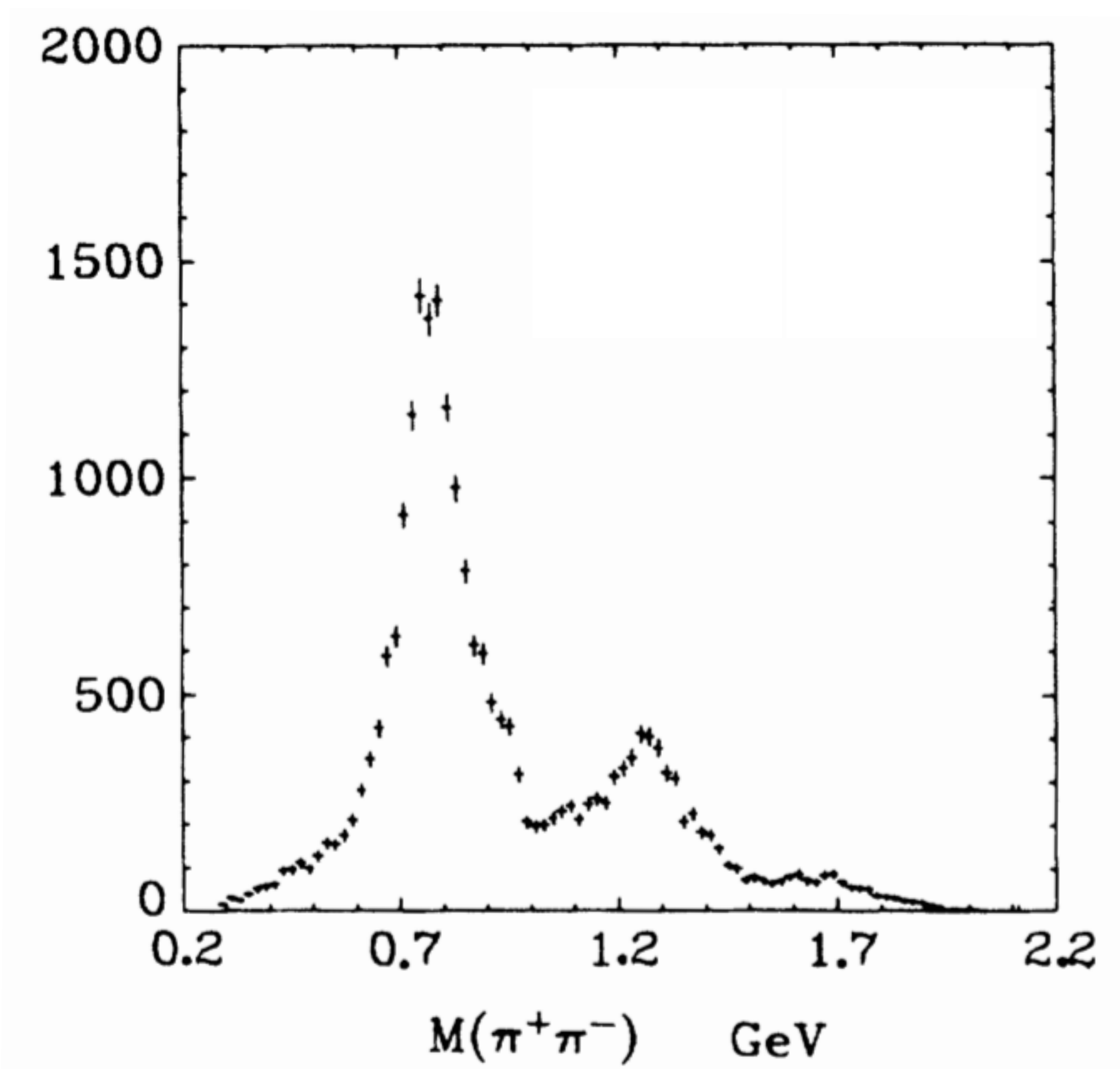
excited hadrons are resonances

even the simplest excited hadrons are not really states of a definite single mass

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)



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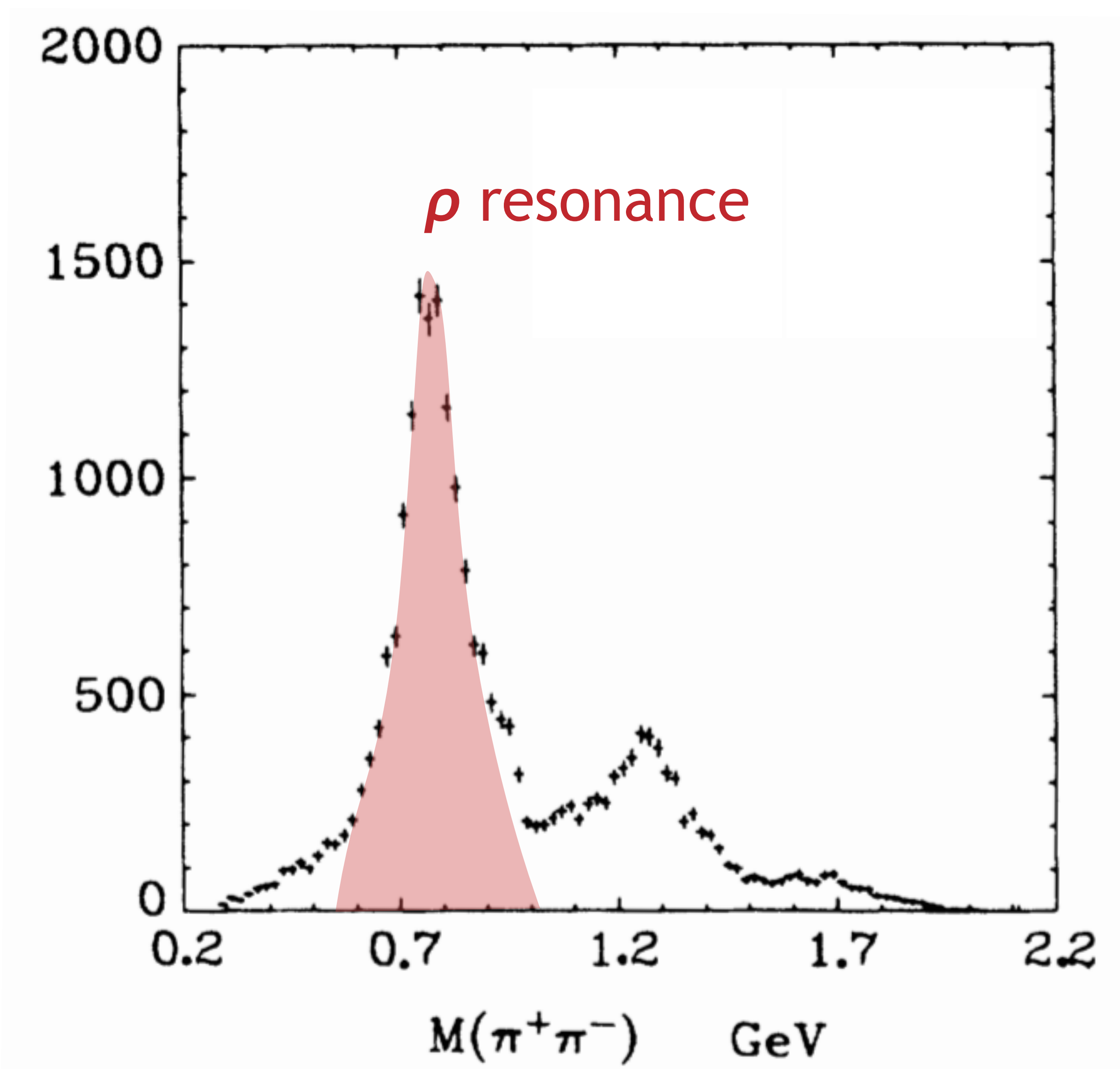
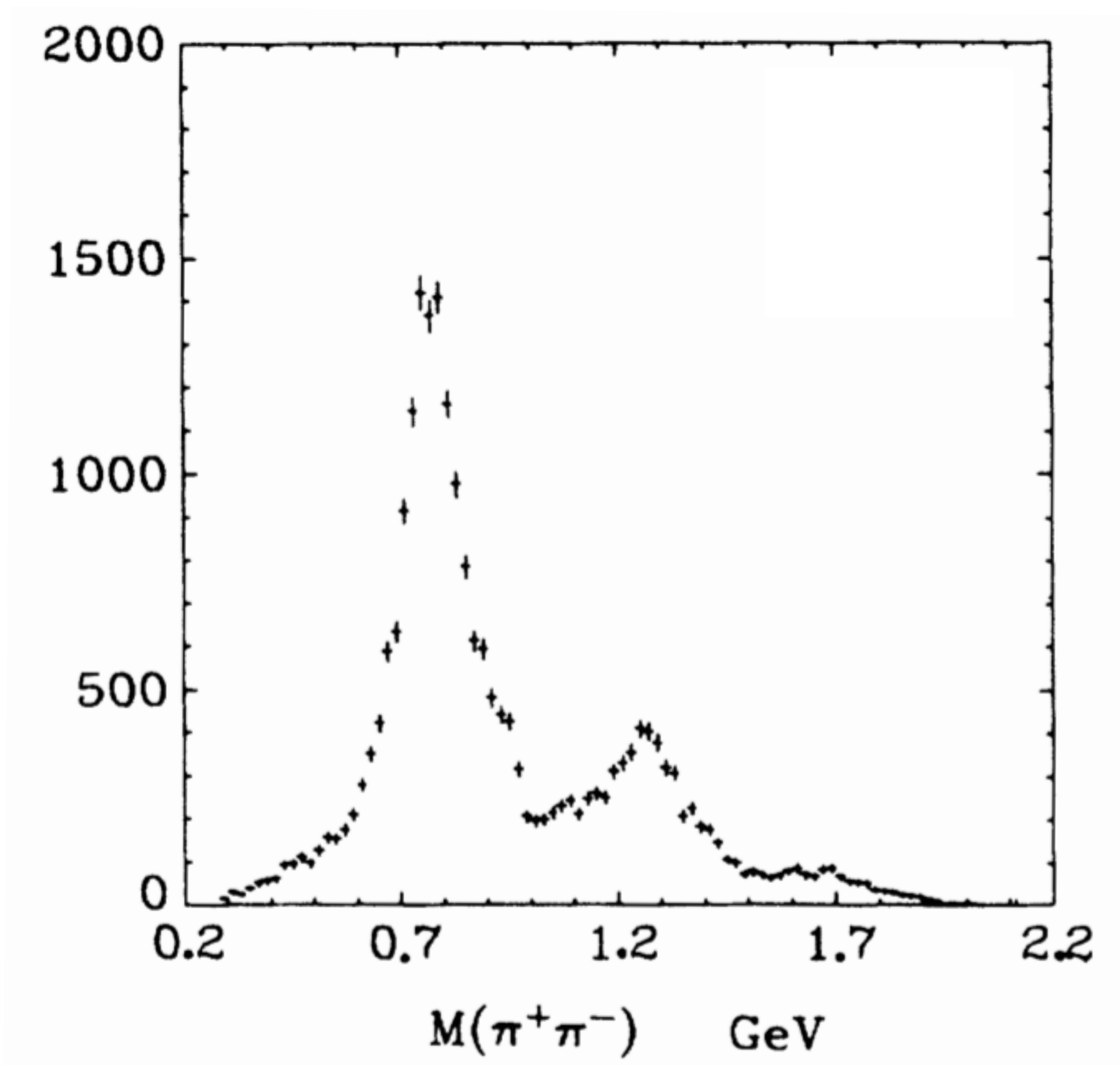


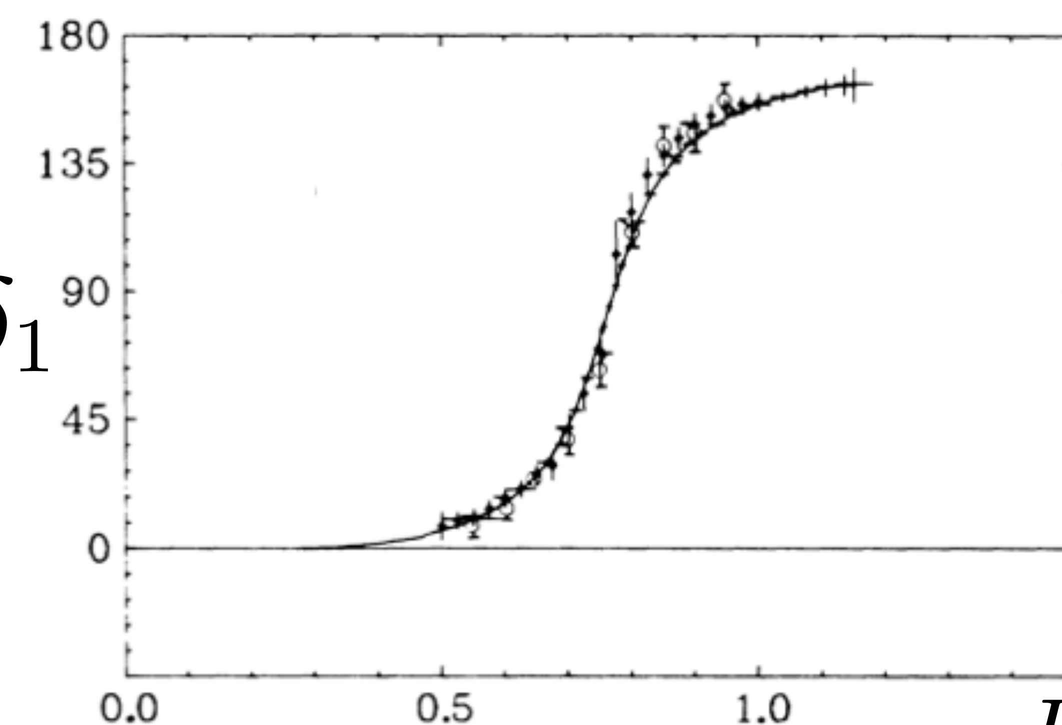
excited hadrons are resonances

PARTIAL WAVE AMPLITUDE

$$f_\ell(E) = \frac{1}{2i}\left(e^{2i\,\delta_\ell(E)} - 1\right)$$



RESONANT PHASE SHIFT

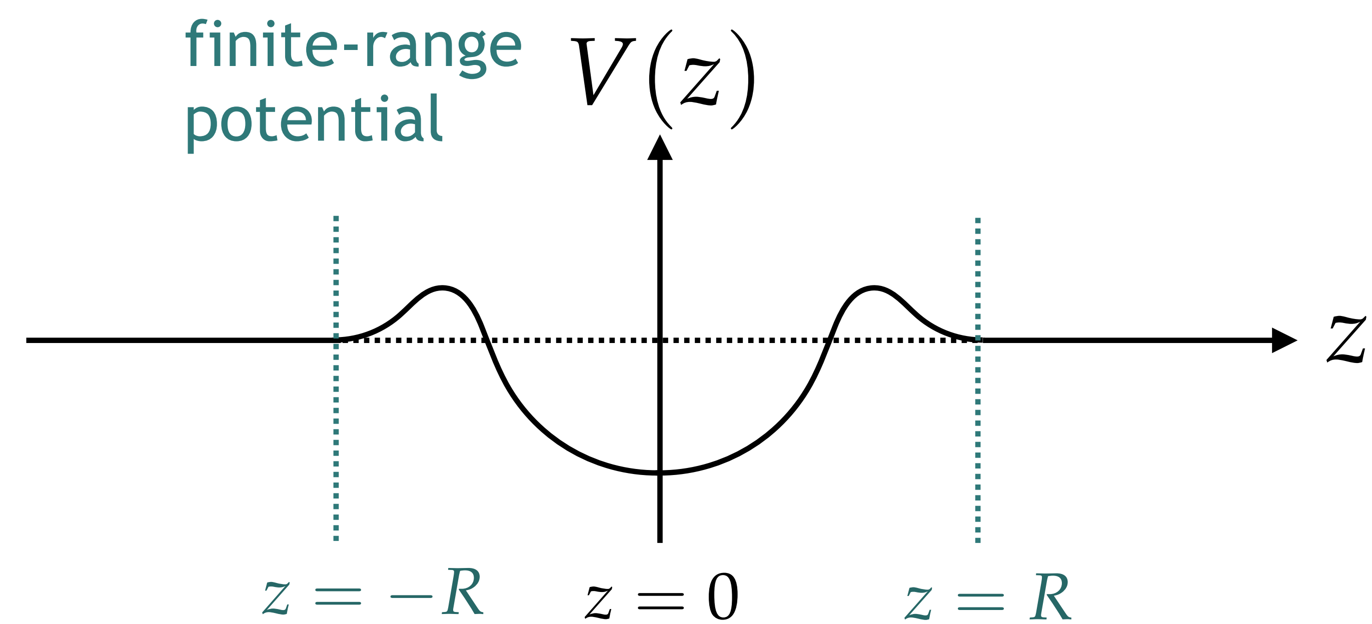


δ_1 E

but how can scattering amplitudes be accessed in lattice QCD ?

one-dim quantum mechanics

- consider scattering of two identical bosons



outside the well

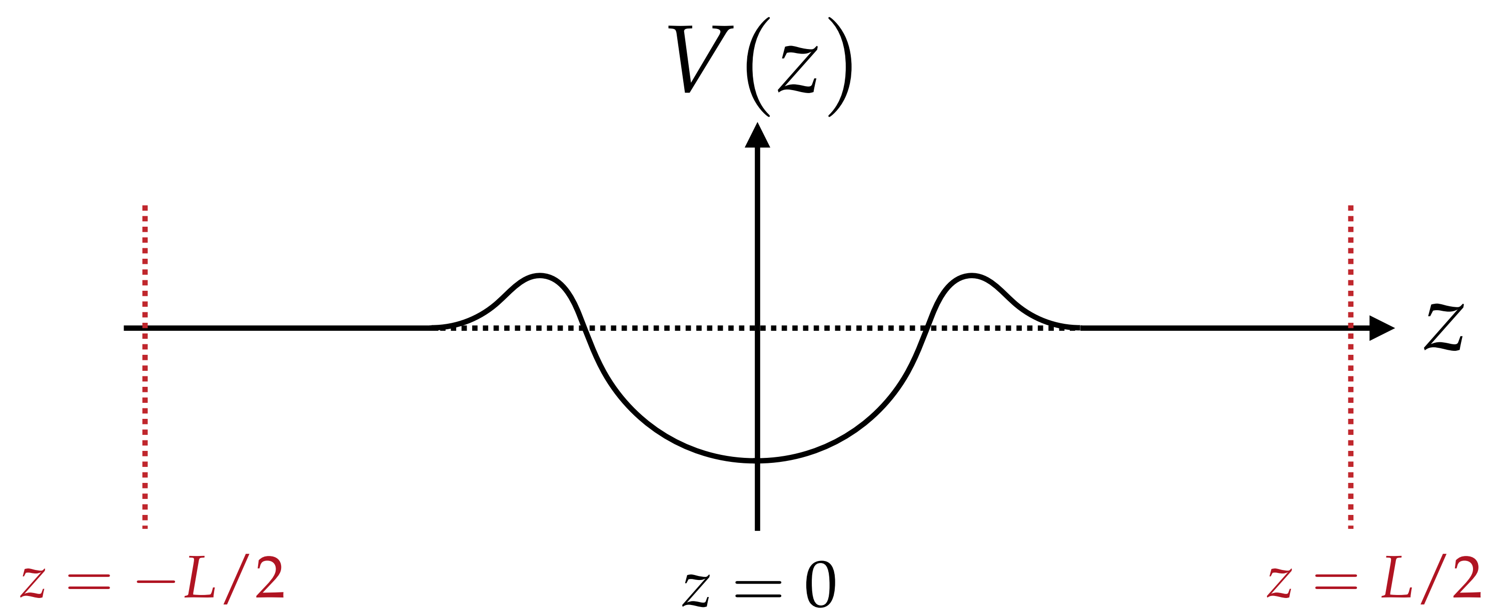
$$\psi(|z| > R) \sim \cos\left(p|z| + \delta(p)\right)$$

scattering phase-shift

continuous momentum ⇒ continuous spectrum of energy eigenstates

‘scattering’ in a finite-volume

- consider scattering of two identical bosons



outside the well

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

- apply periodic boundary conditions

$$\left.\begin{aligned} \psi(-L/2) &= \psi(L/2) \\ \frac{d\psi}{dz}(-L/2) &= \frac{d\psi}{dz}(L/2) \end{aligned}\right\} \frac{pL}{2} + \delta(p) = n\pi$$

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

discrete energy spectrum

3+1 dim field theory in a cubic volume

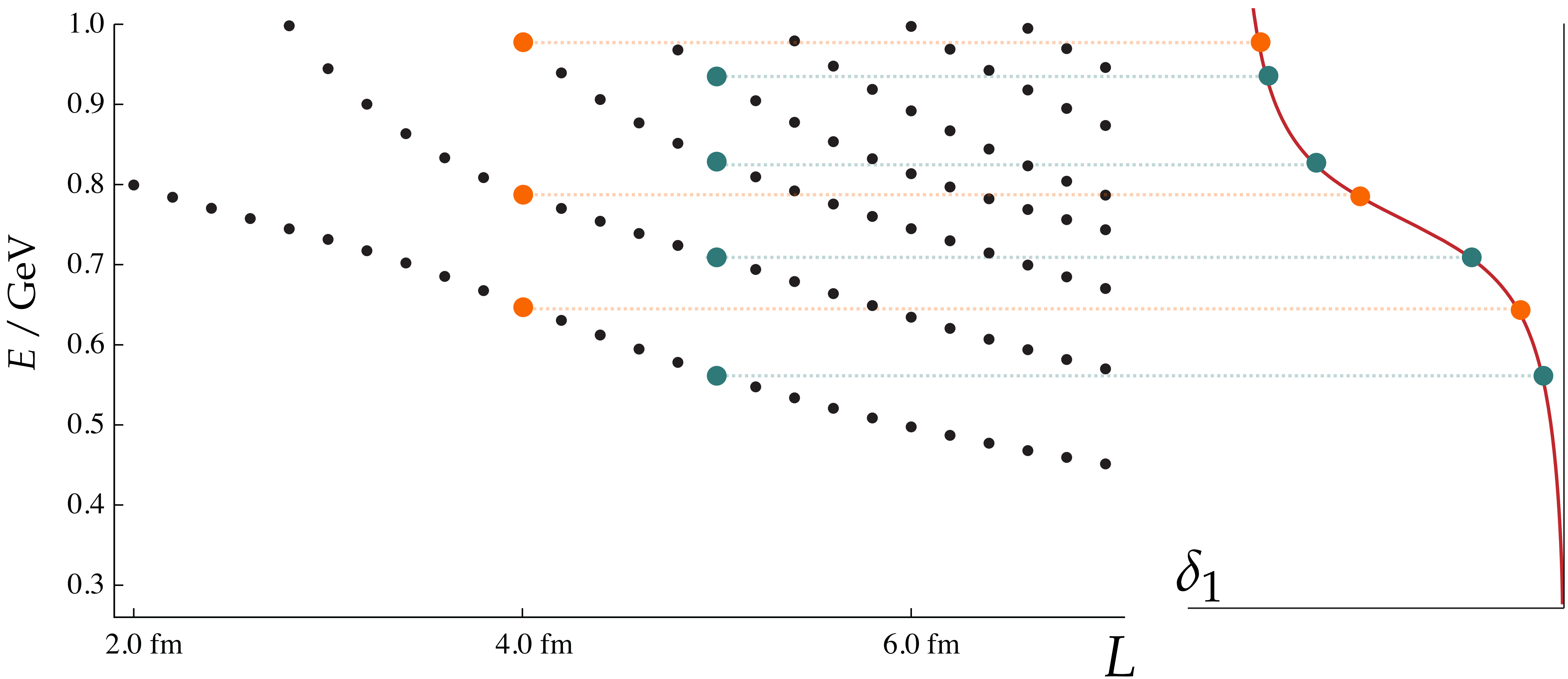
Lüscher:

$$\cot \delta_\ell(E) = \mathcal{M}_\ell(E, L)$$

known functions

[modulo some subtleties regarding ℓ-mixing]

L×L×L BOX SPECTRUM | PHASE SHIFT

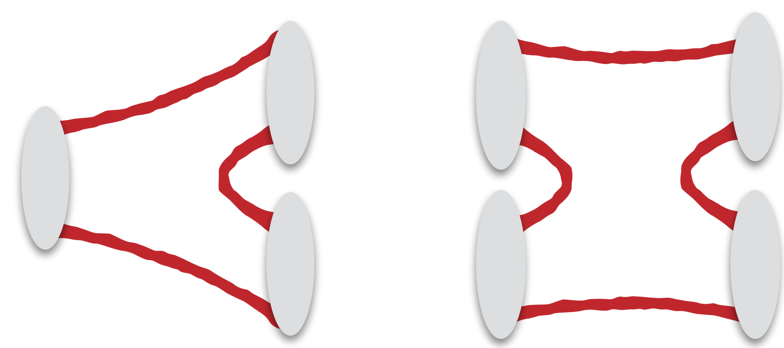


what operator basis is required ?

supplement large $\bar{\psi}\Gamma\overleftrightarrow{D}\dots\overleftrightarrow{D}\psi$ basis with meson-meson-like operators

e.g. $\mathcal{O}_{\pi\pi}^{|\vec{p}|} = \sum_{\hat{p}} C(\hat{p})\,\mathcal{O}_\pi(\vec{p})\,\mathcal{O}_\pi(-\vec{p})$ where $\mathcal{O}_\pi(\vec{p}) = \sum_{\vec{x}} e^{i\vec{p}\cdot\vec{x}}\,\bar{\psi}\mathbf{\Gamma}\psi(\vec{x})$

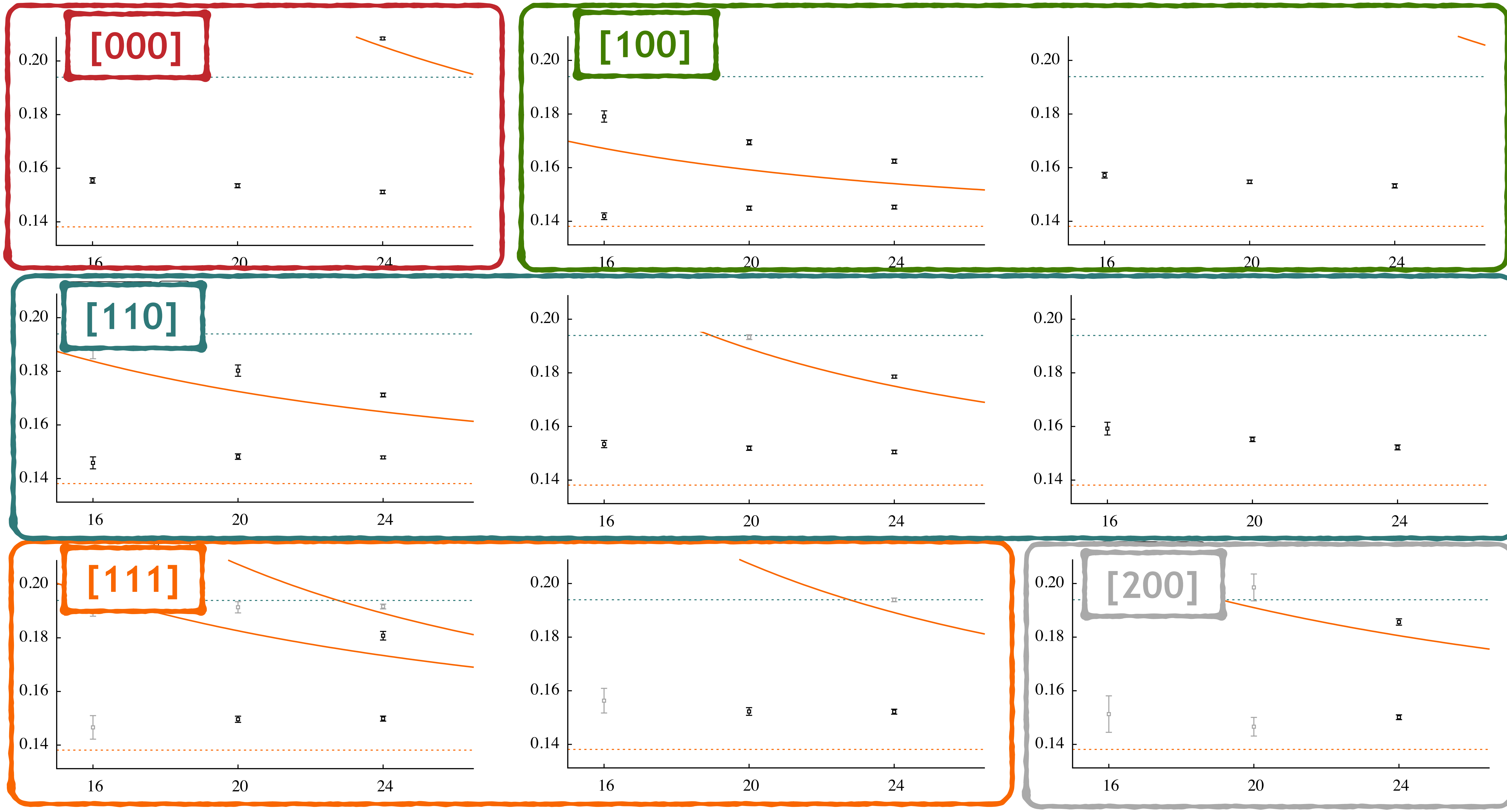
now need to evaluate diagrams like



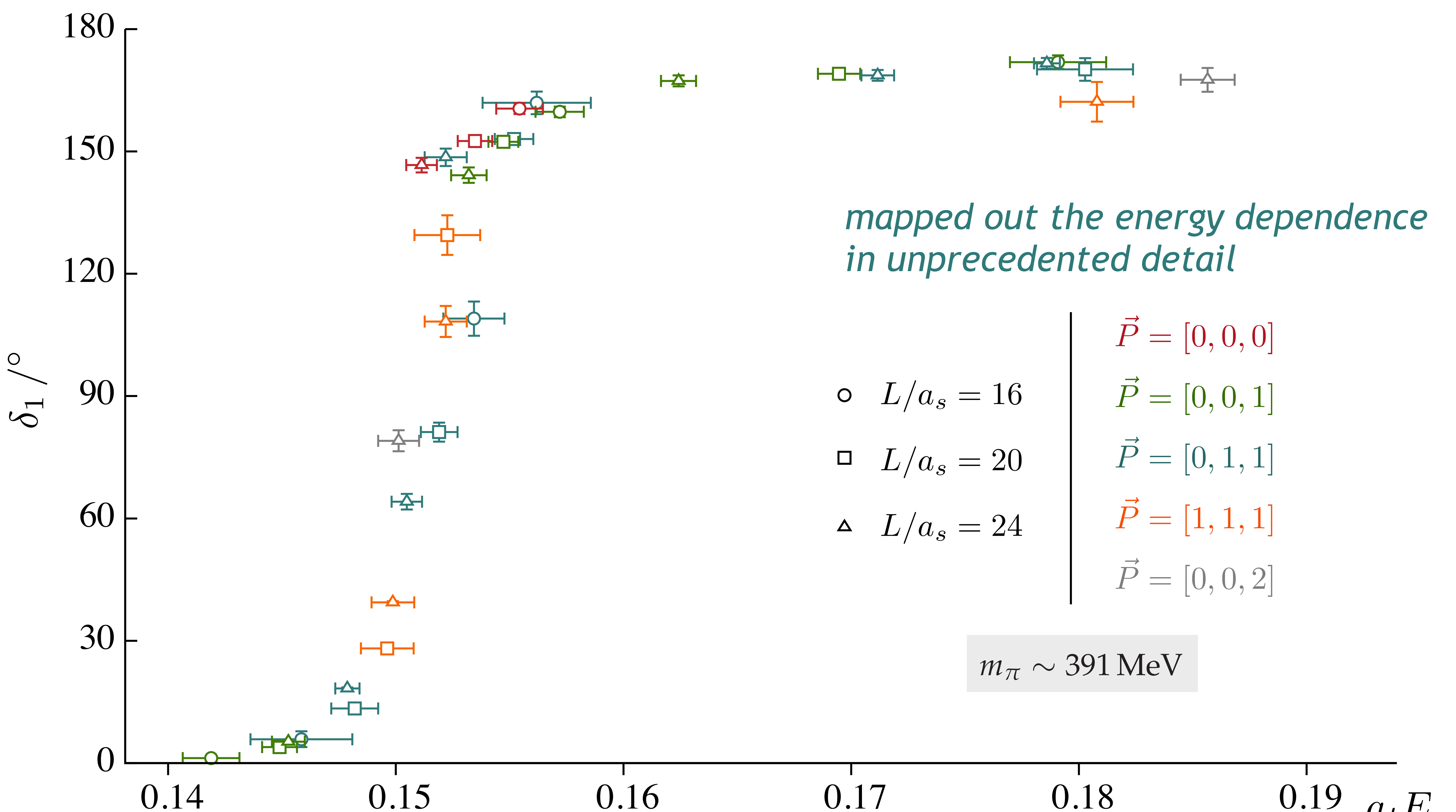
distillation can handle the annihilation lines

spectra in moving frames

$m_\pi \sim 391\,\mathrm{MeV}$

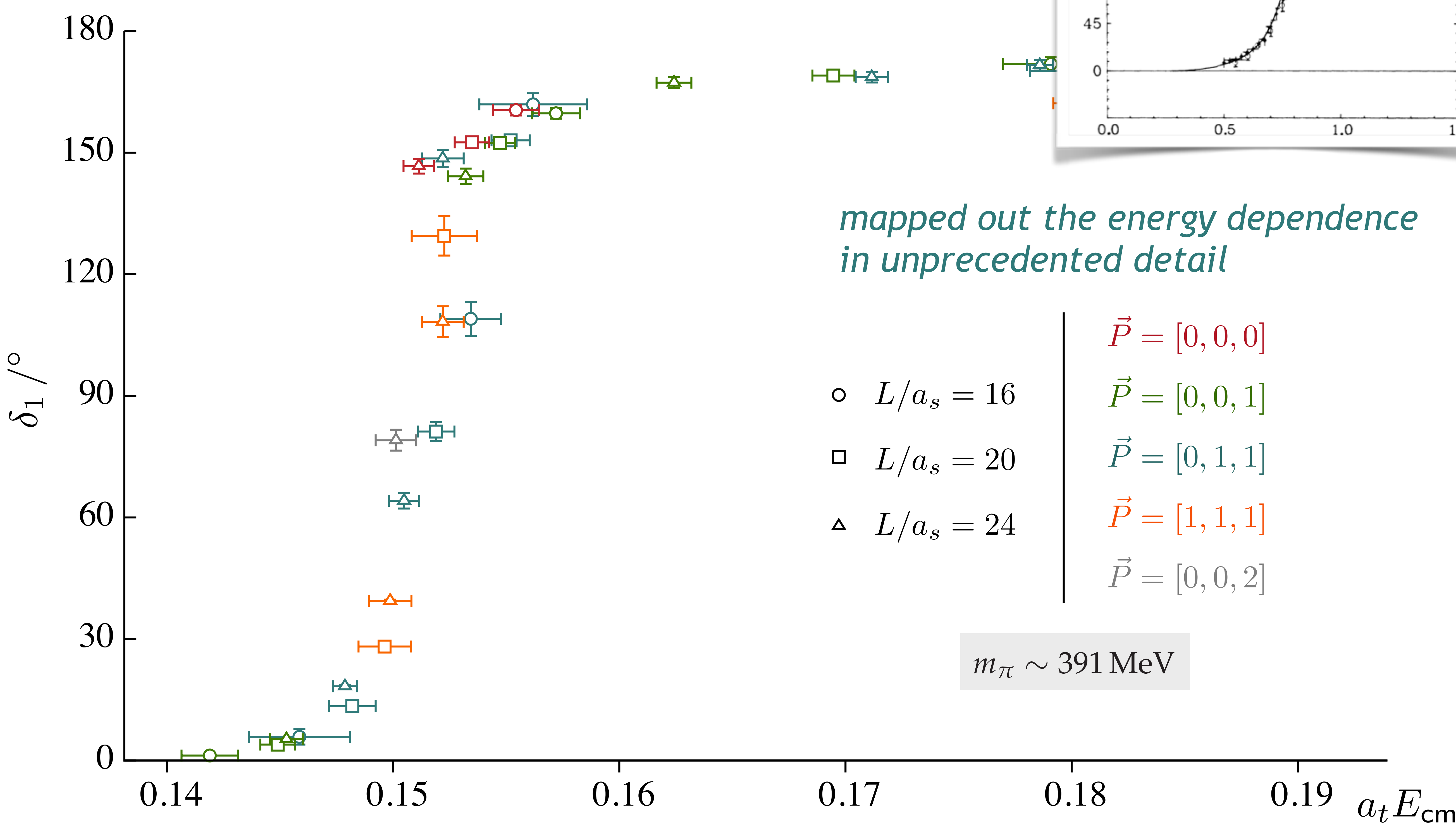


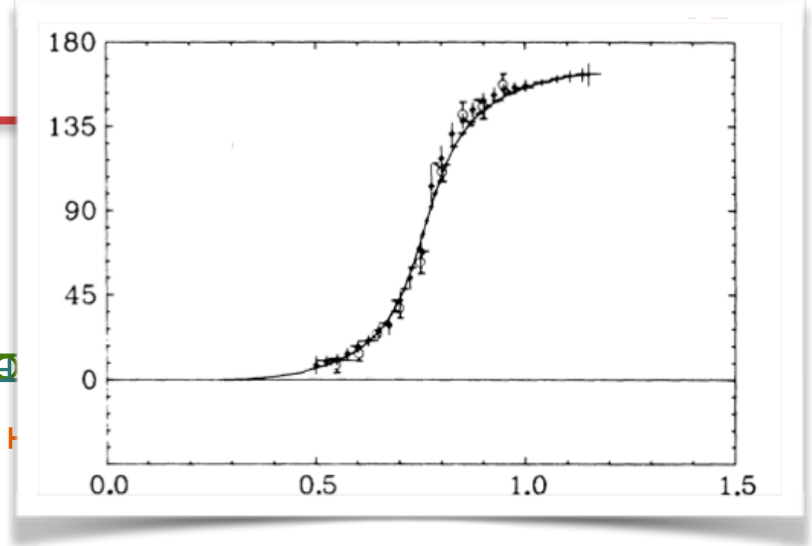
ππ *P*-wave phase-shift



PRD87 034505 (2013)

ππ *P*-wave phase-shift



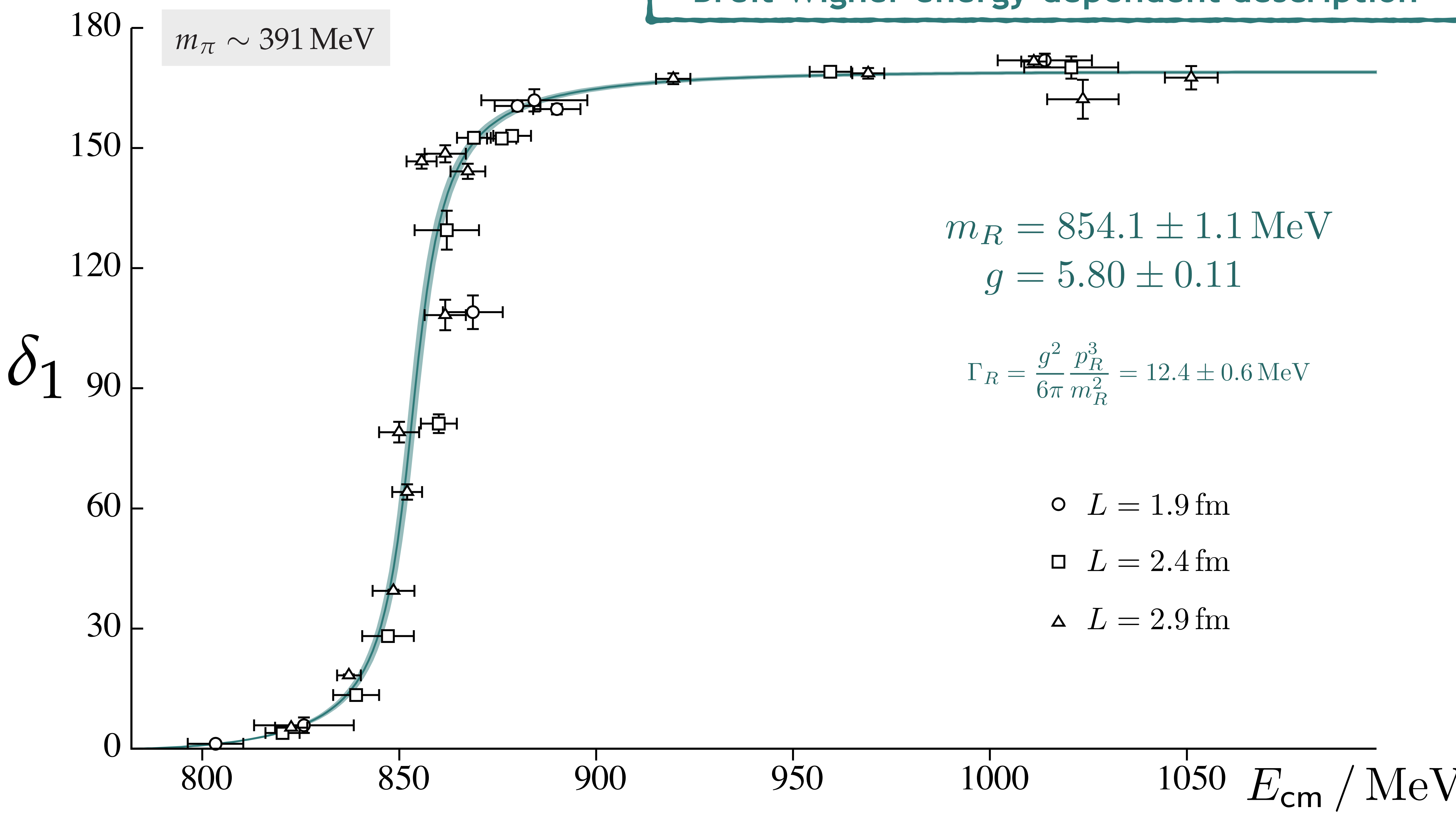


mapped out the energy dependence in unprecedented detail

PRD87 034505 (2013)

$\pi\pi$ *P*-wave phase-shift

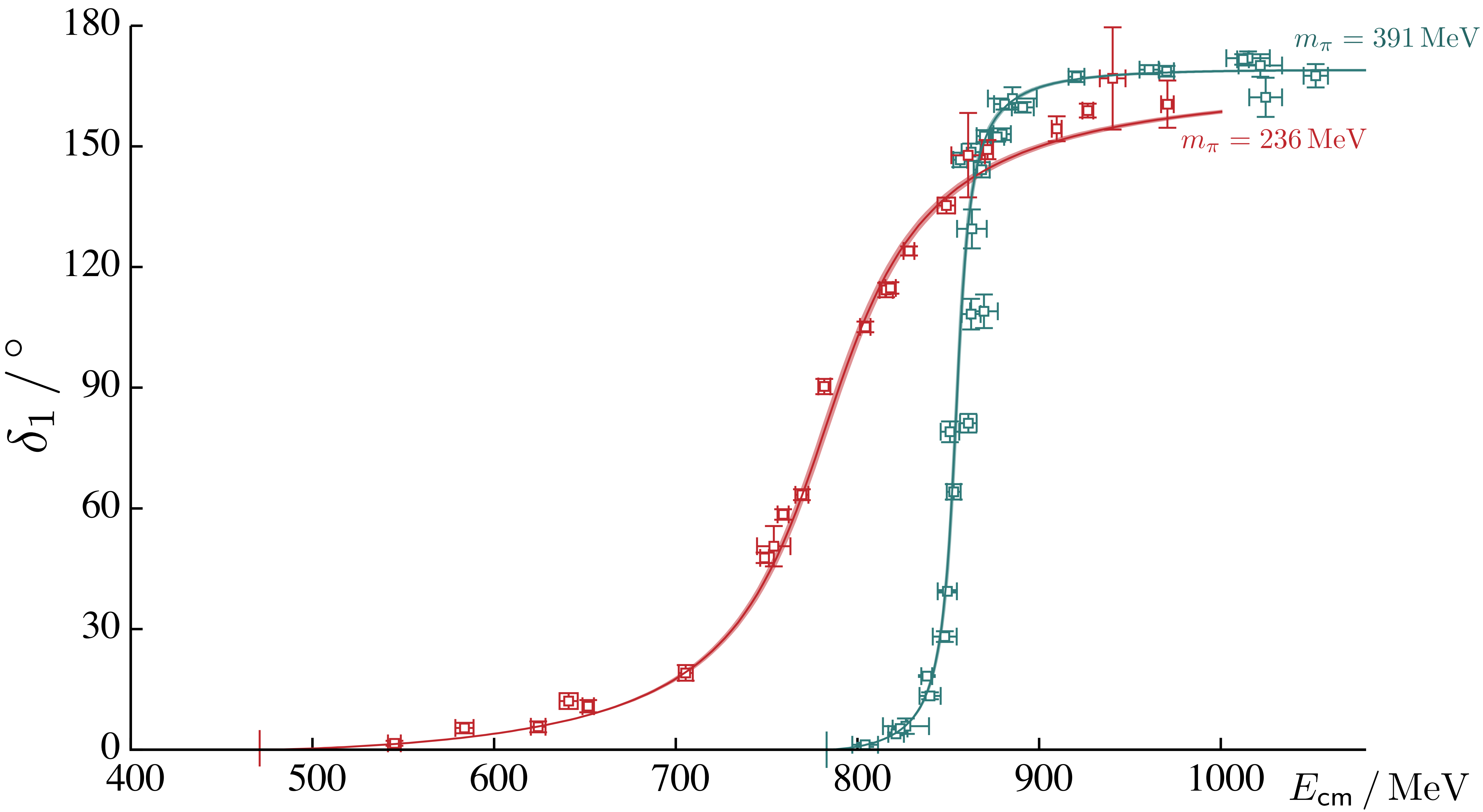
Breit-Wigner energy-dependent description



PRD87 034505 (2013)

$\pi\pi$ *P*-wave phase-shift

- reducing the pion mass moves mass, width in the right direction ...



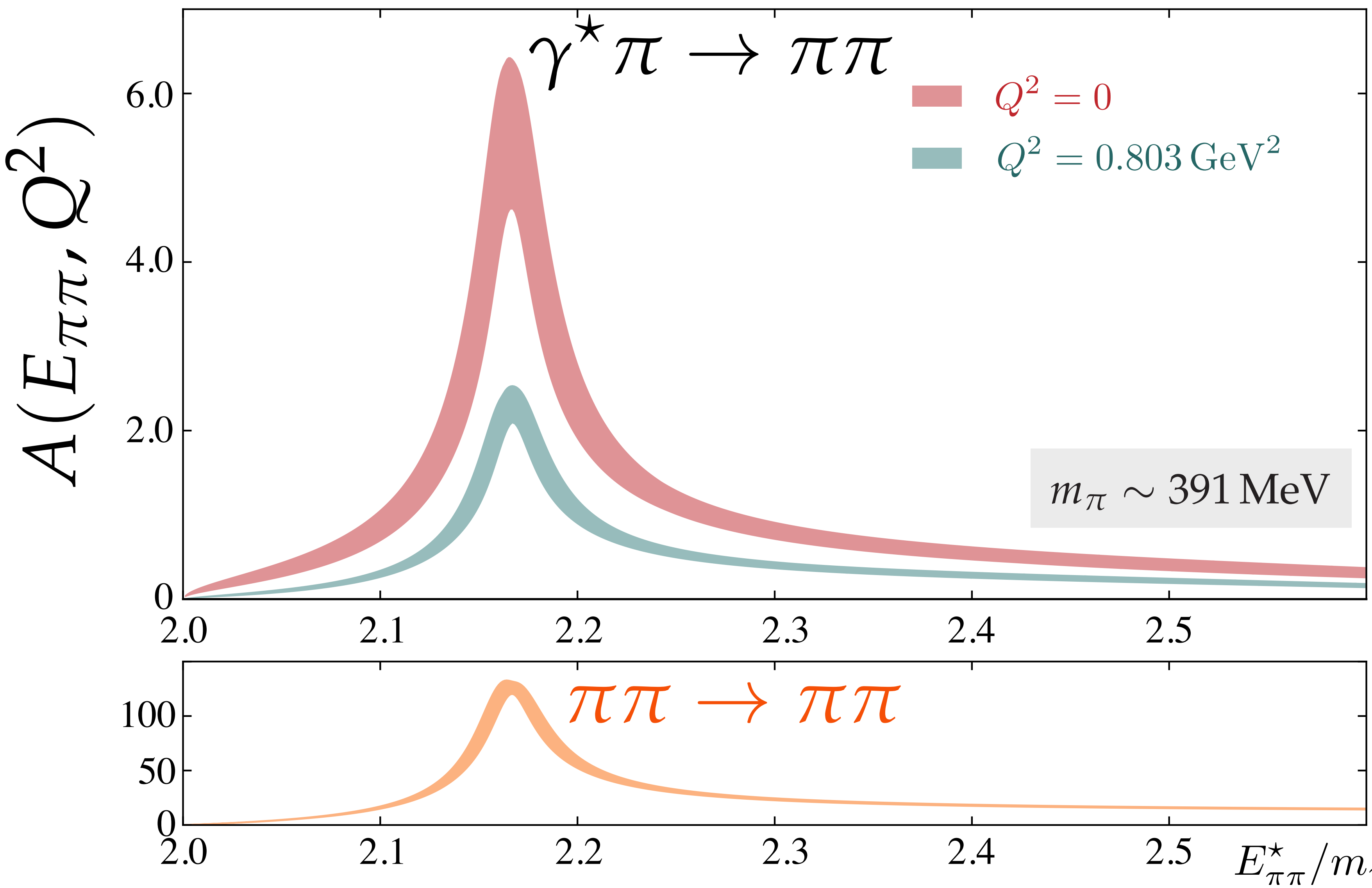
PRD87 034505 (2013)
PRD92 094502 (2015)

coupling to external currents

- e.g. GlueX/CLAS12 use photons to excite resonances - can this be studied ?
- finite-volume formalism applied to three-point functions

coupling to external currents

- e.g. GlueX/CLAS12 use photons to excite resonances - can this be studied ?
- finite-volume formalism applied to three-point functions
- first explicit application has appeared $\gamma^\star \pi \to \rho \to \pi\pi$ PRL 115 242001 (2015)

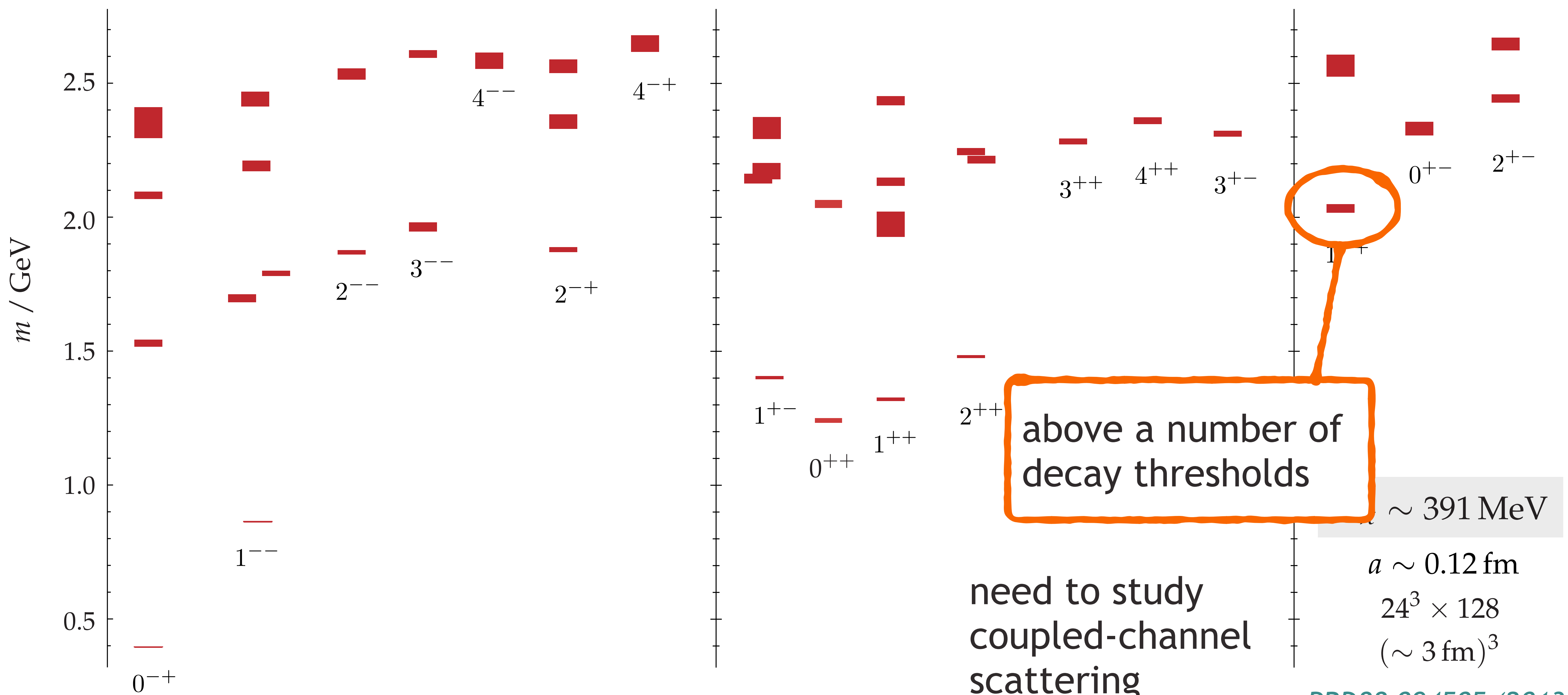


Raul Briceño

excited isovector meson spectrum

- what about decays of higher excited states ?

e.g. the exotic hybrid mesons



need to study coupled-channel scattering

PRD88 094505 (2013)

coupled-channel meson-meson scattering

- more challenging analysis problem

  e.g. in a **two-channel** process, **three** unknowns specify the *S*-matrix at each energy

our solution: parameterize the energy dependence of the *S*-matrix and describe the finite-volume spectra by varying parameters

coupled-channel meson-meson scattering

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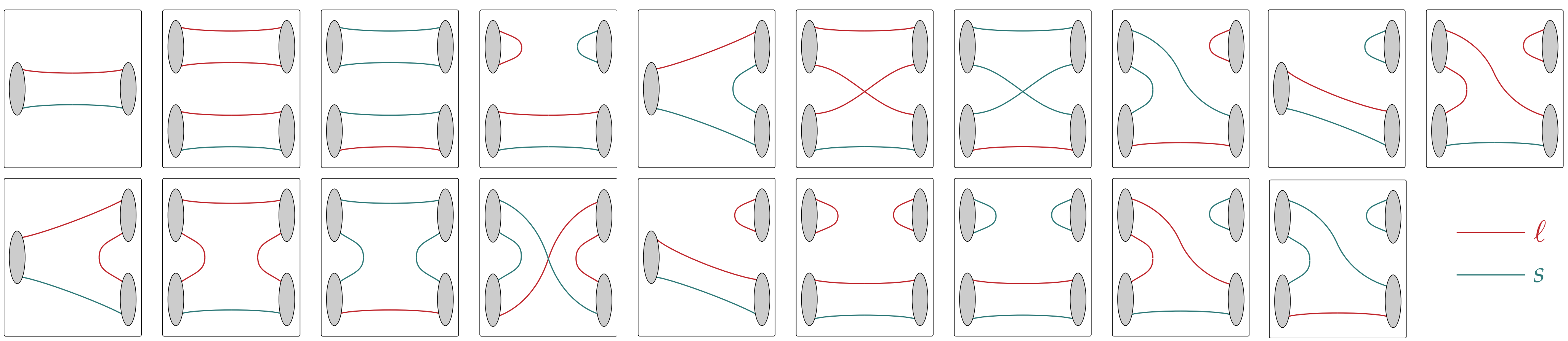
  e.g. in a **two-channel** process, **three** unknowns specify the *S*-matrix at each energy

our solution: parameterize the energy dependence of the *S*-matrix and describe the finite-volume spectra by varying parameters

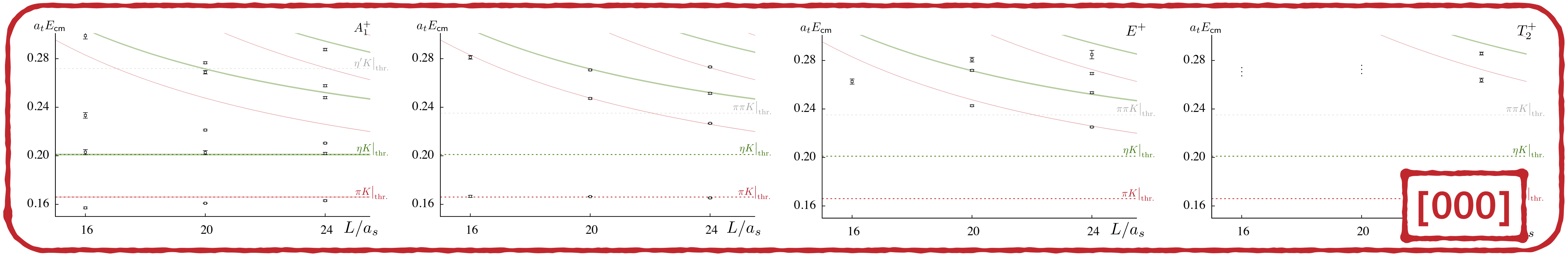
- first attempt, coupled-channel ***πK***/***ηK*** scattering

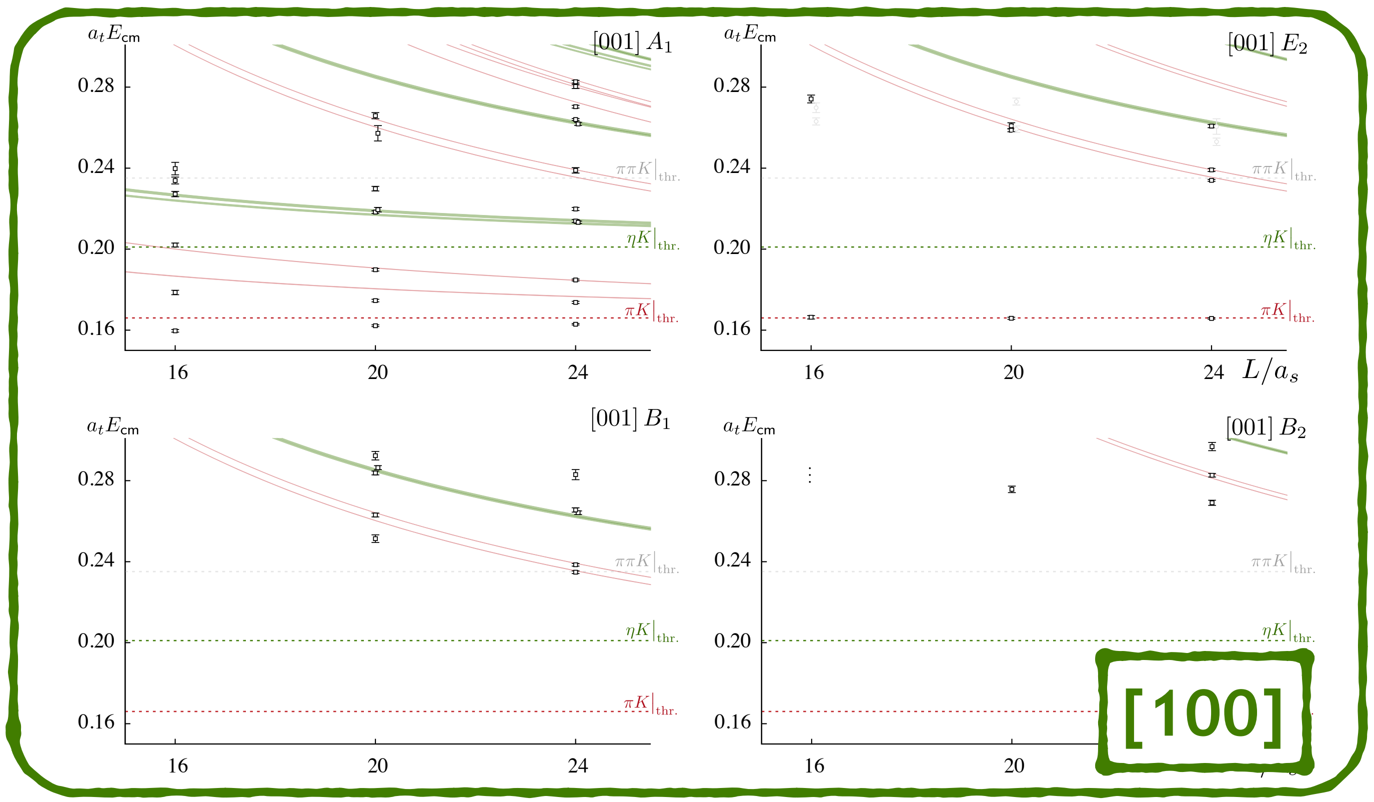
- need to compute the finite-volume spectra … lots of Wick contractions …

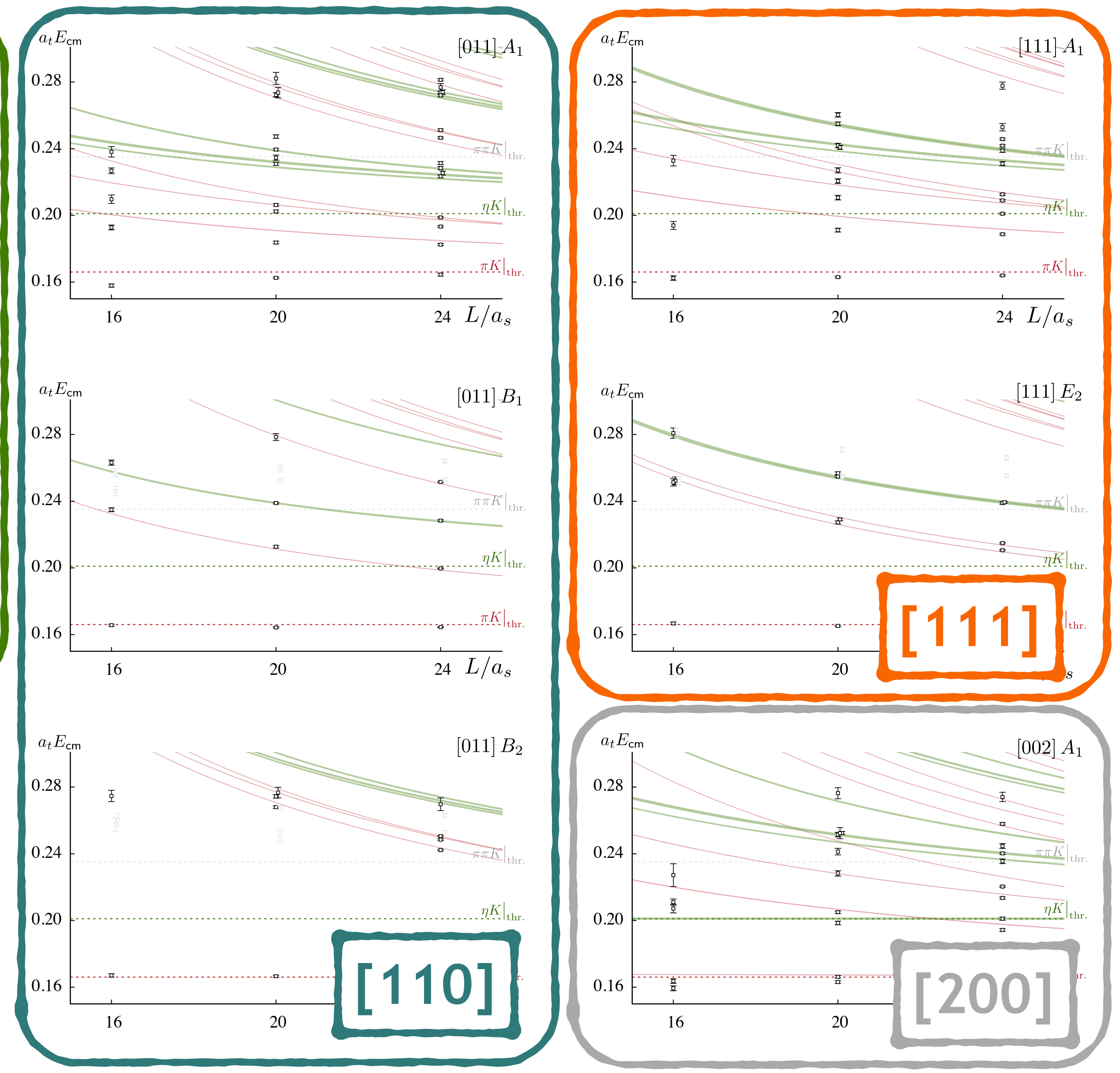


πK/ηK lattice QCD spectra

$m_\pi \sim 391\,\mathrm{MeV}$







> 100 levels in the usable energy region

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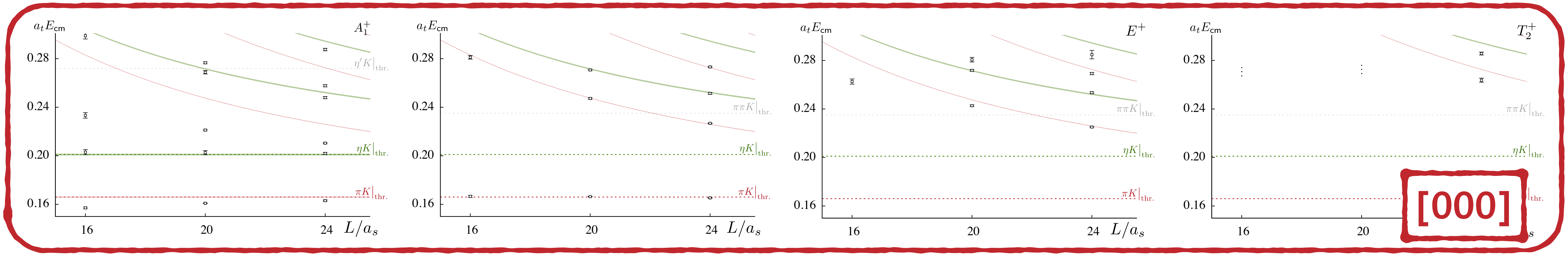

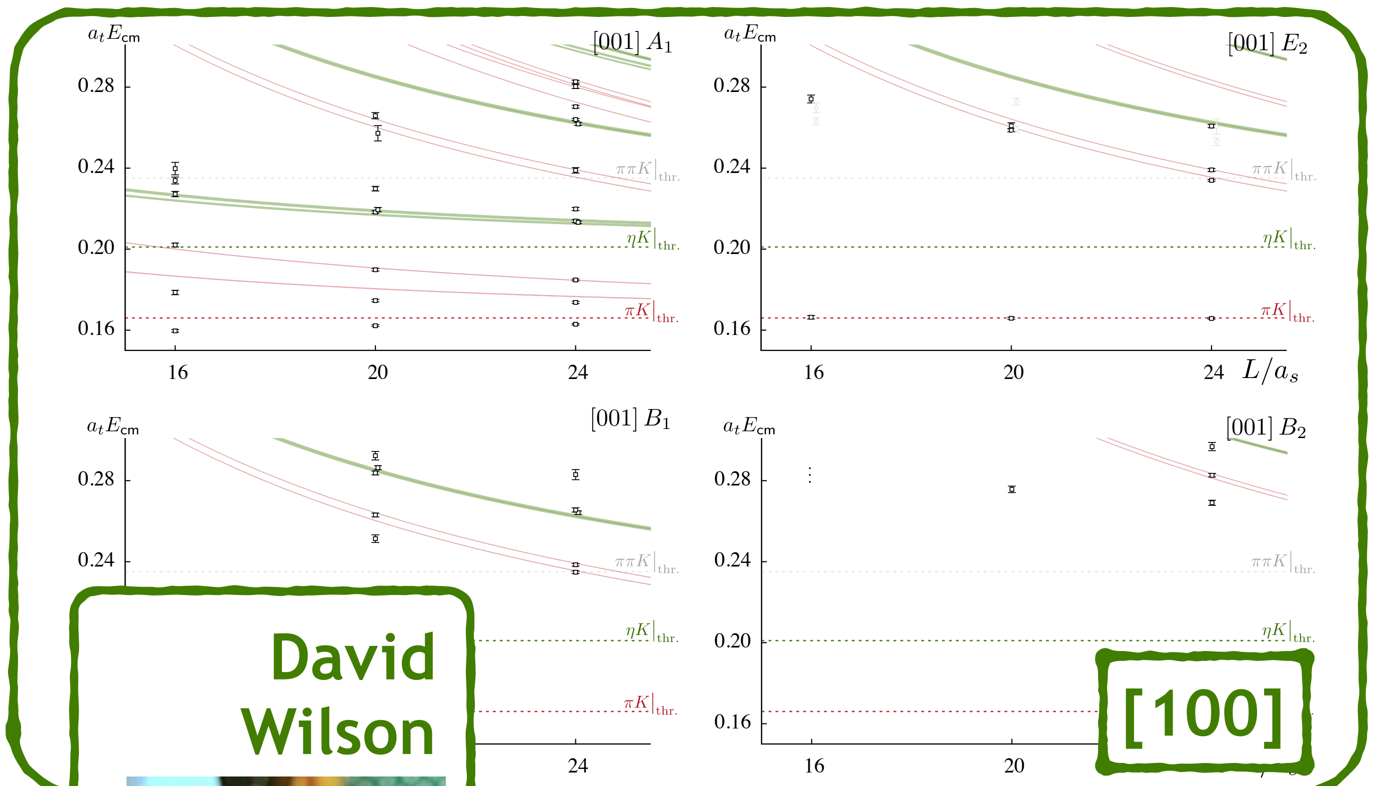

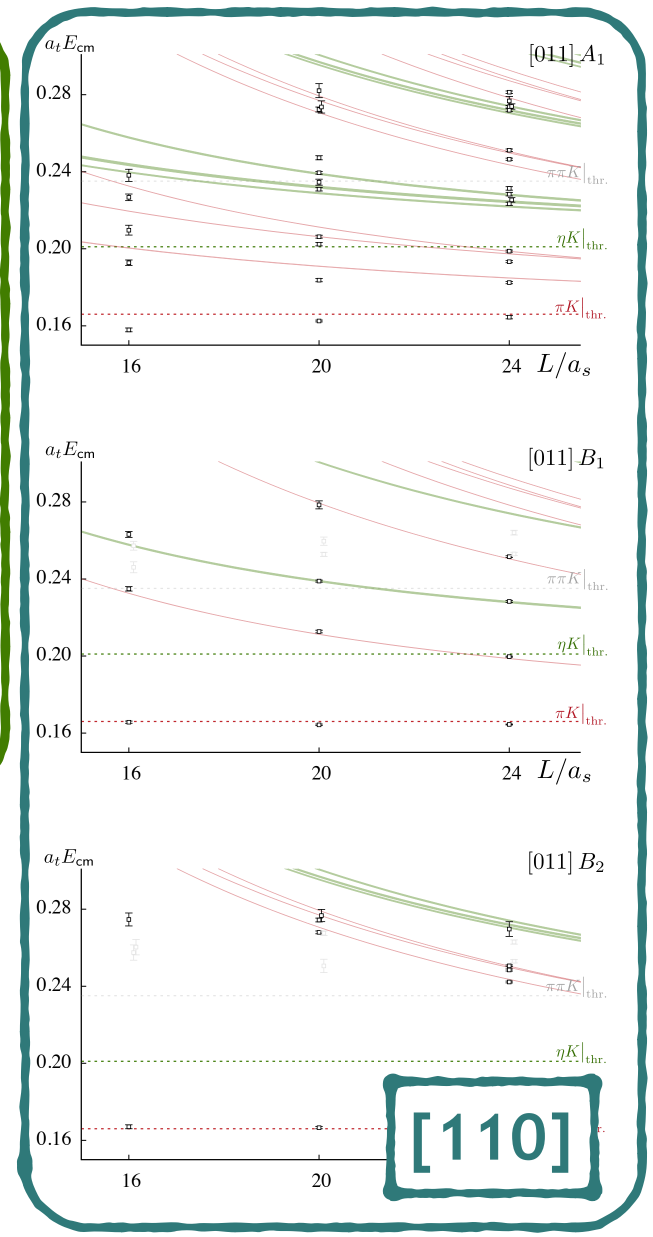

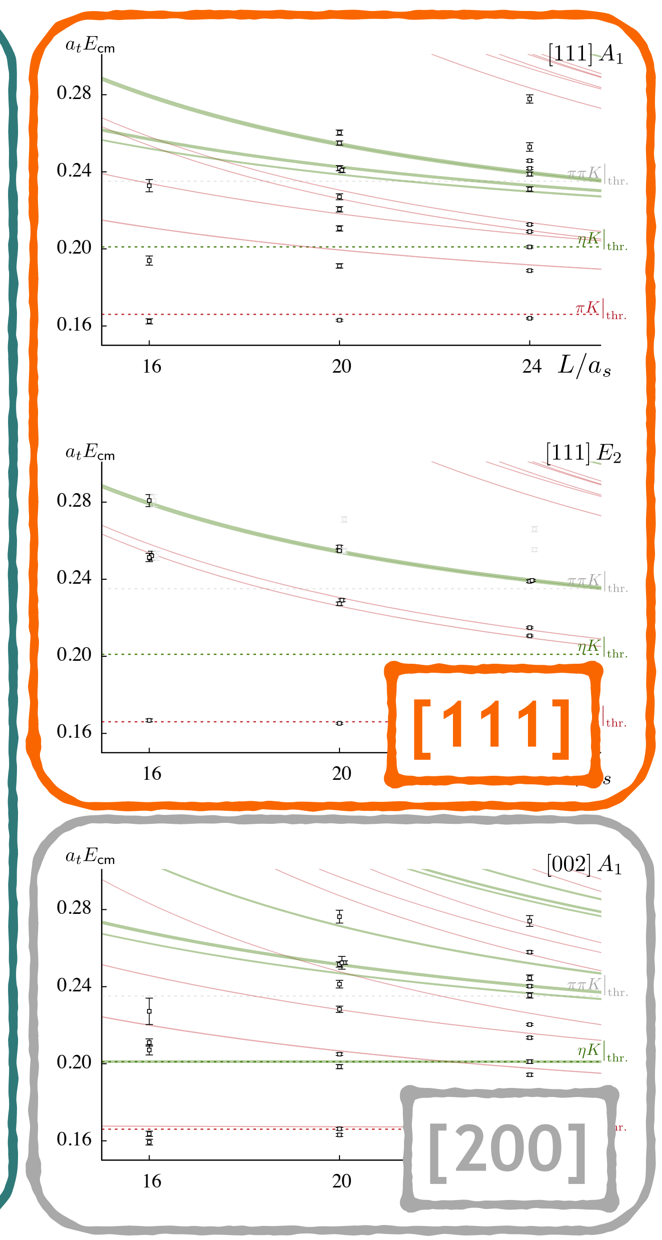

David Wilson

> 100 levels in the usable energy region

$\pi K/\eta K$ lattice QCD spectra

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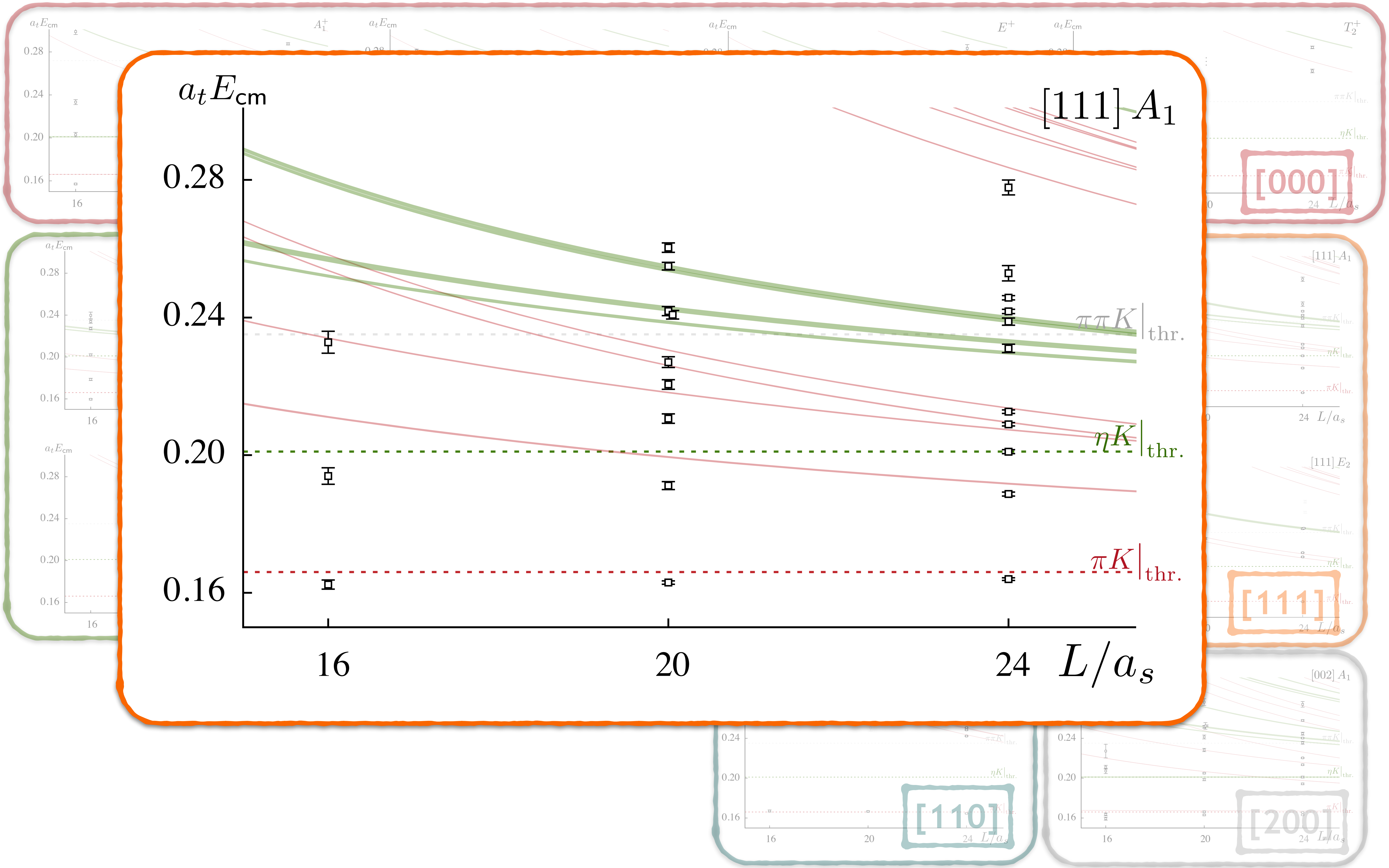
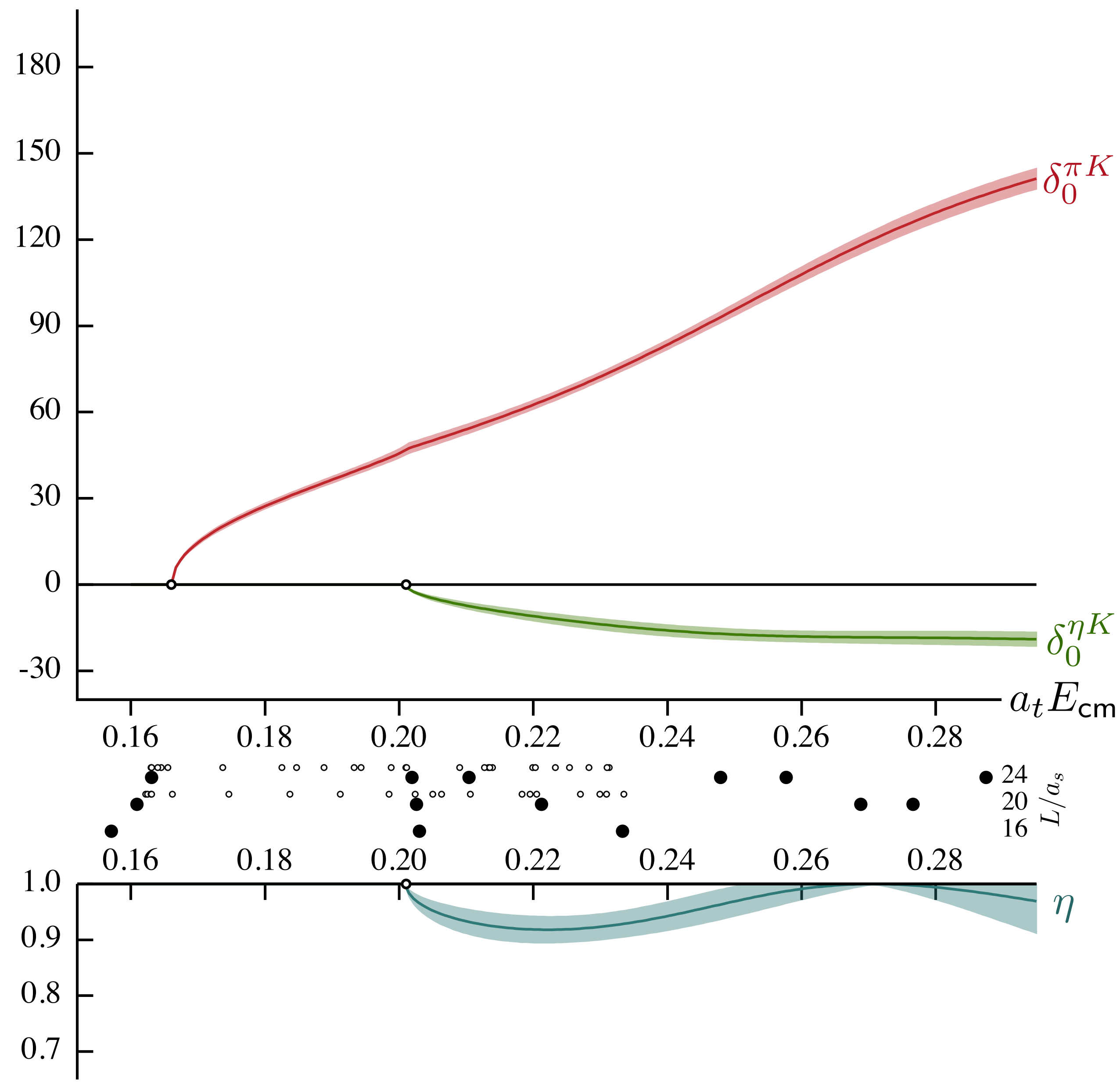


$\pi K/\eta K$ coupled-channel scattering

- describe all the finite-volume spectra

$$\chi^2/N_{\mathrm{dof}} = \frac{49.1}{61-6} = 0.89$$

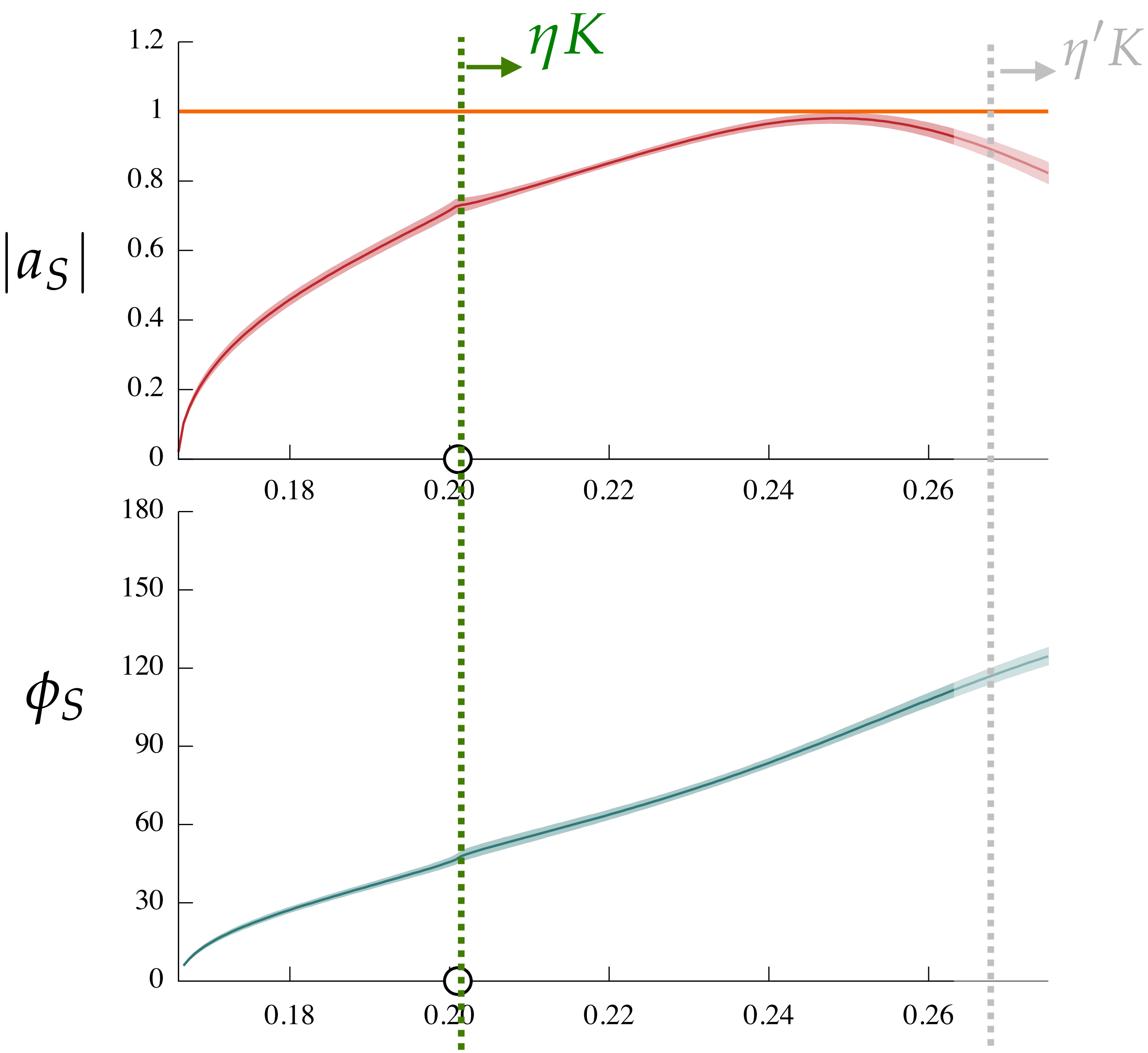
S-WAVE $\pi K/\eta K$ SCATTERING



PRL 113 182001
PRD 91 054008

versus experimental scattering

S-WAVE $\pi K \to \pi K$ AMPLITUDE



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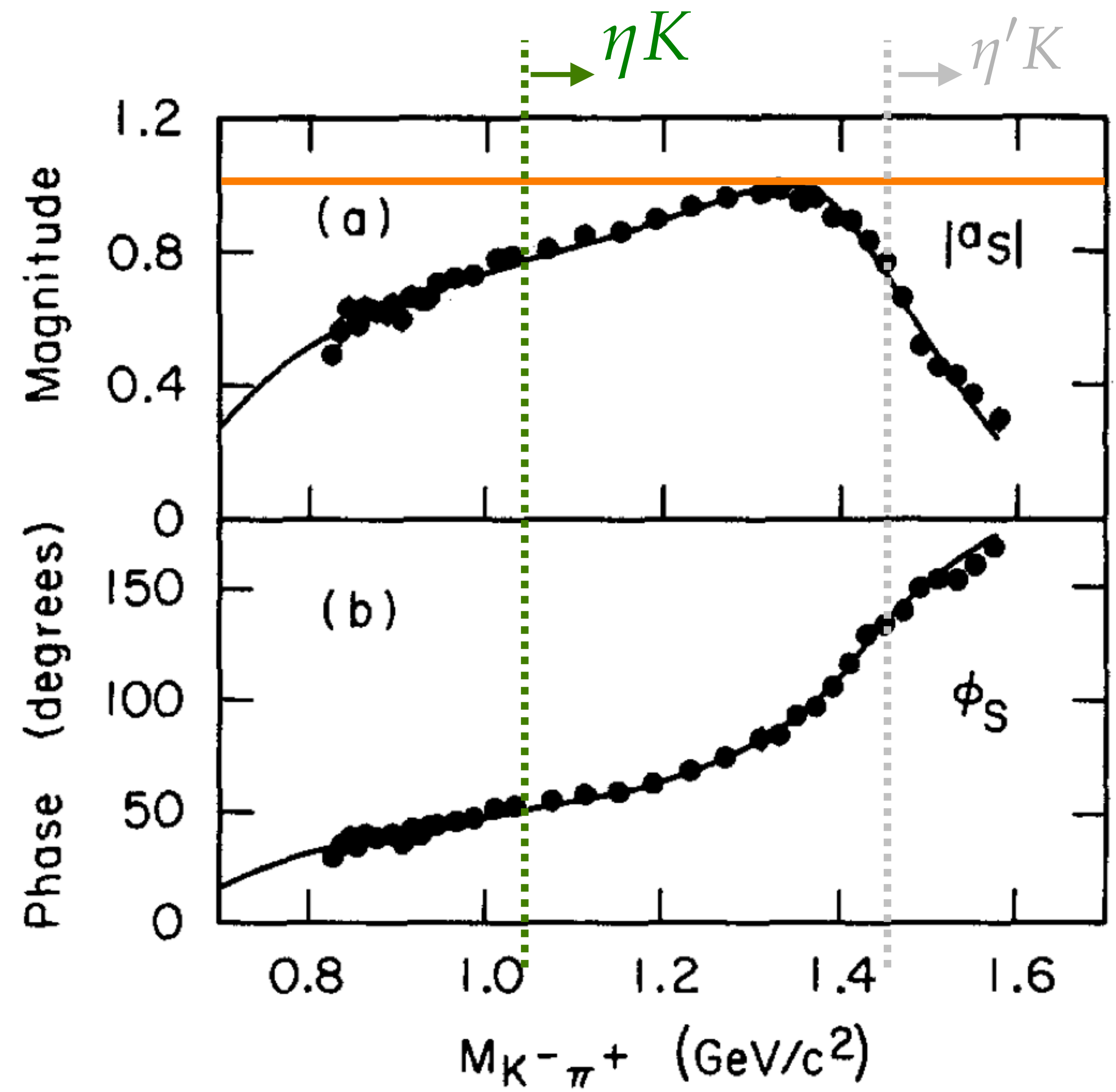
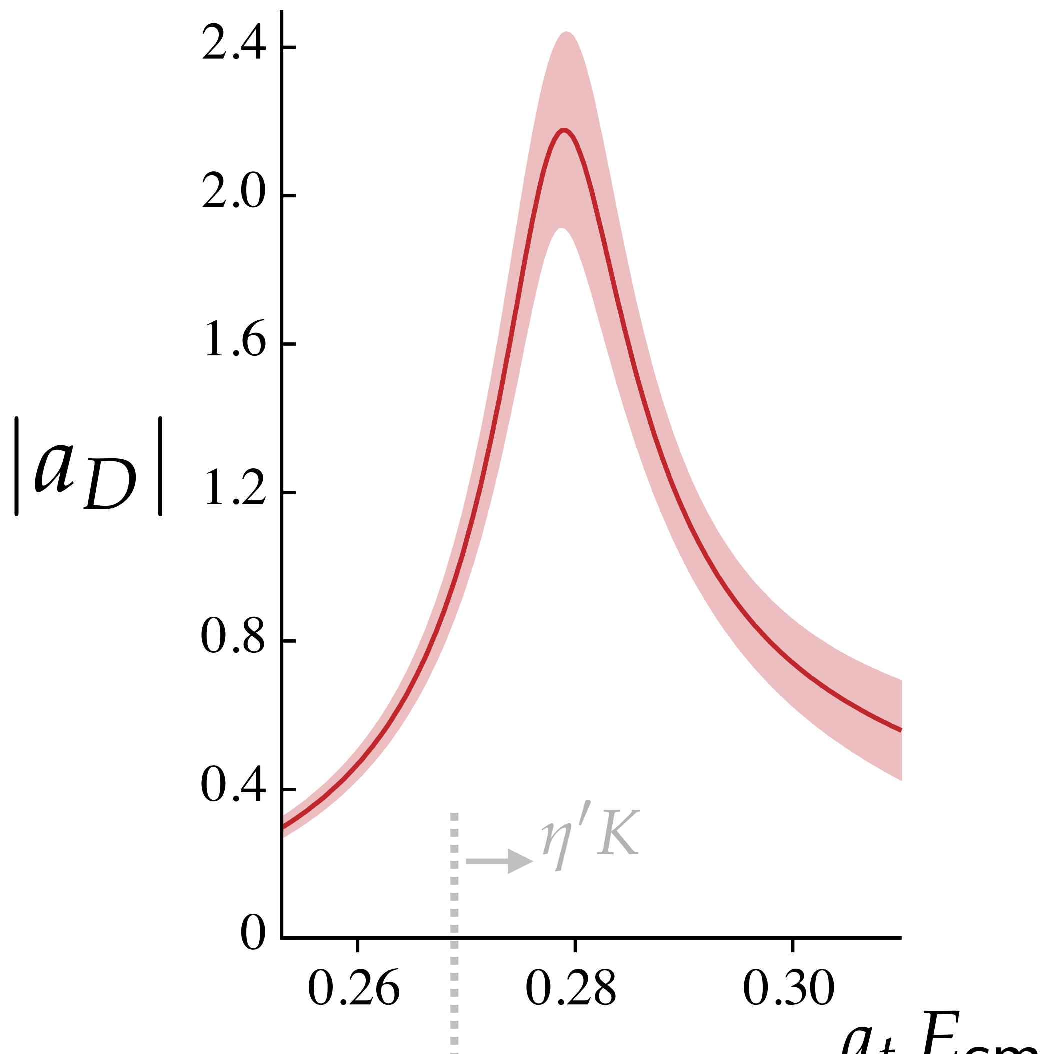
LASS S-WAVE



LASS, NPB296 493

versus experimental scattering

D-WAVE $\pi K \rightarrow \pi K$ AMPLITUDE



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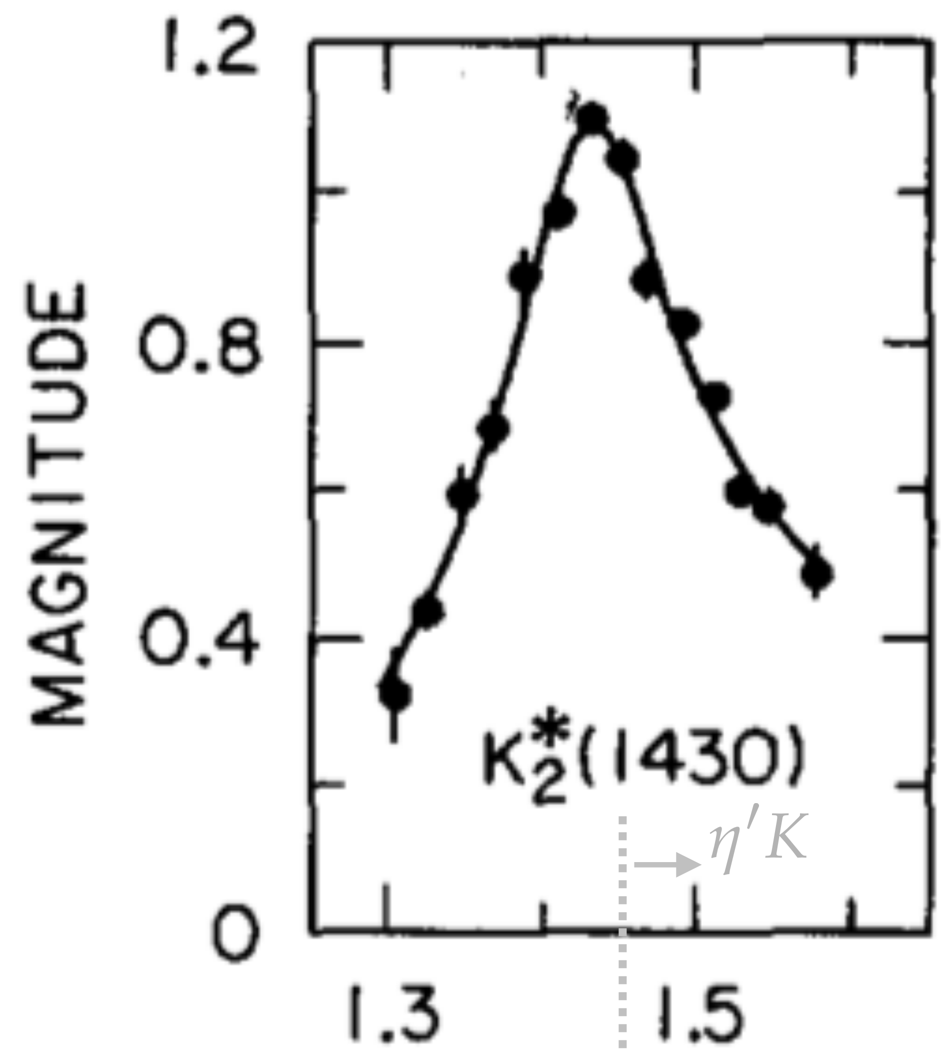
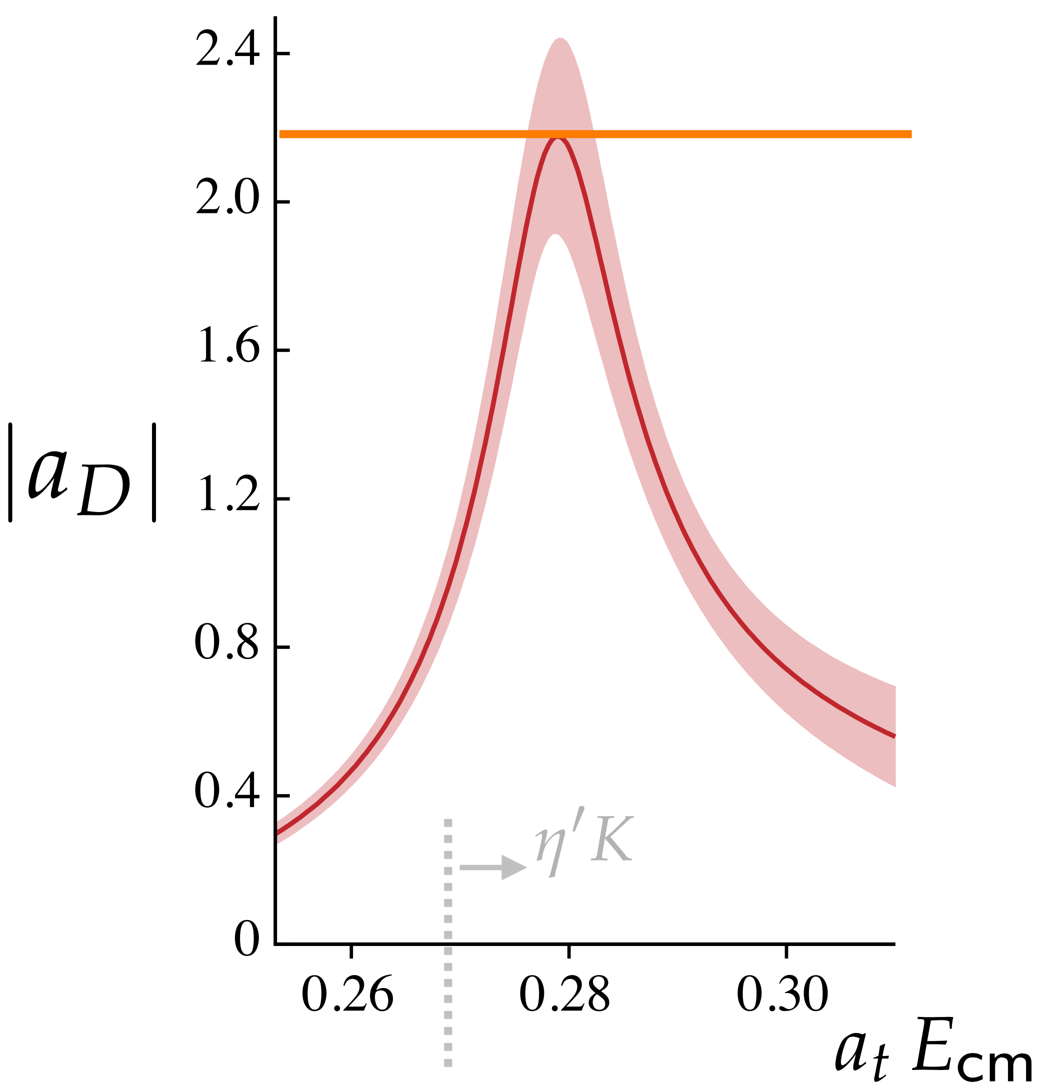
LASS D-WAVE



LASS, NPB296 493

D-WAVE $\pi K \to \pi K$ AMPLITUDE



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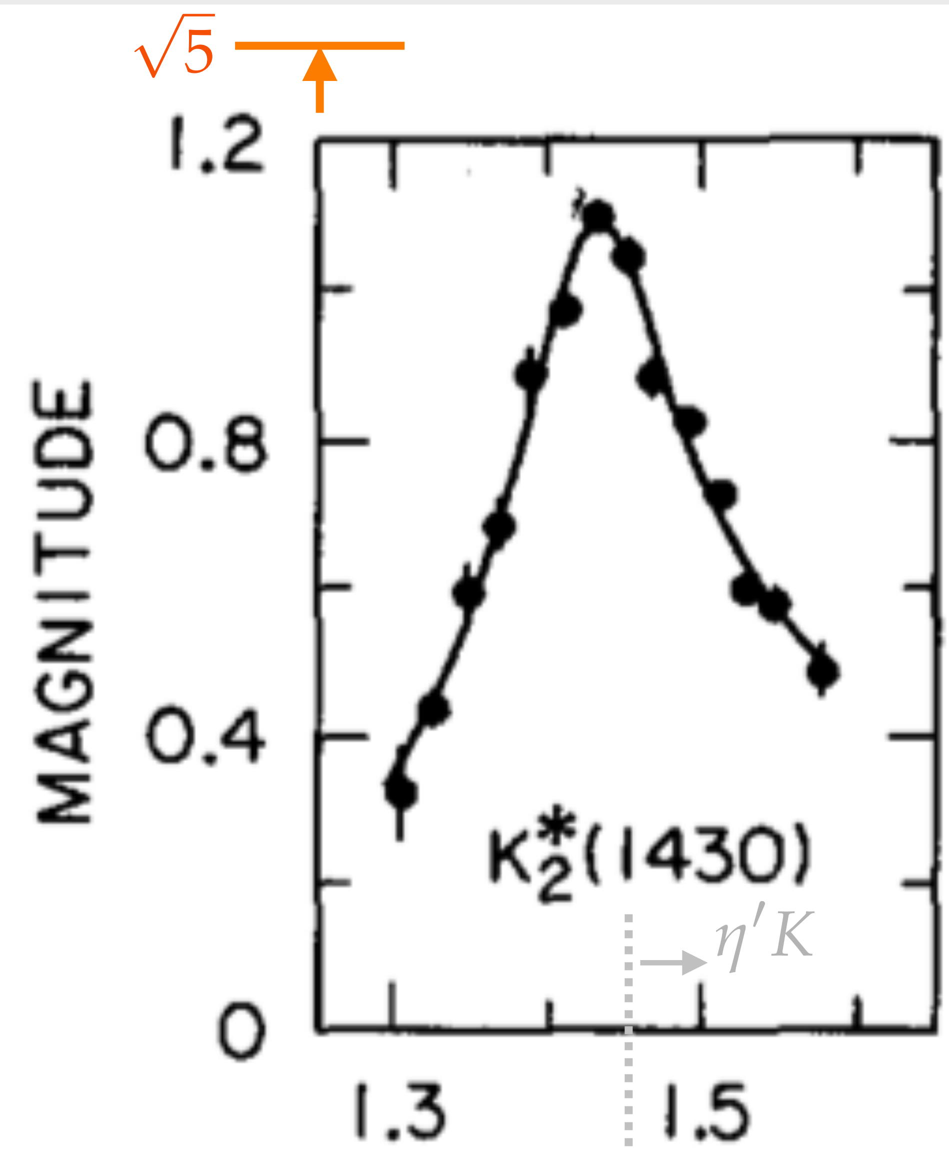
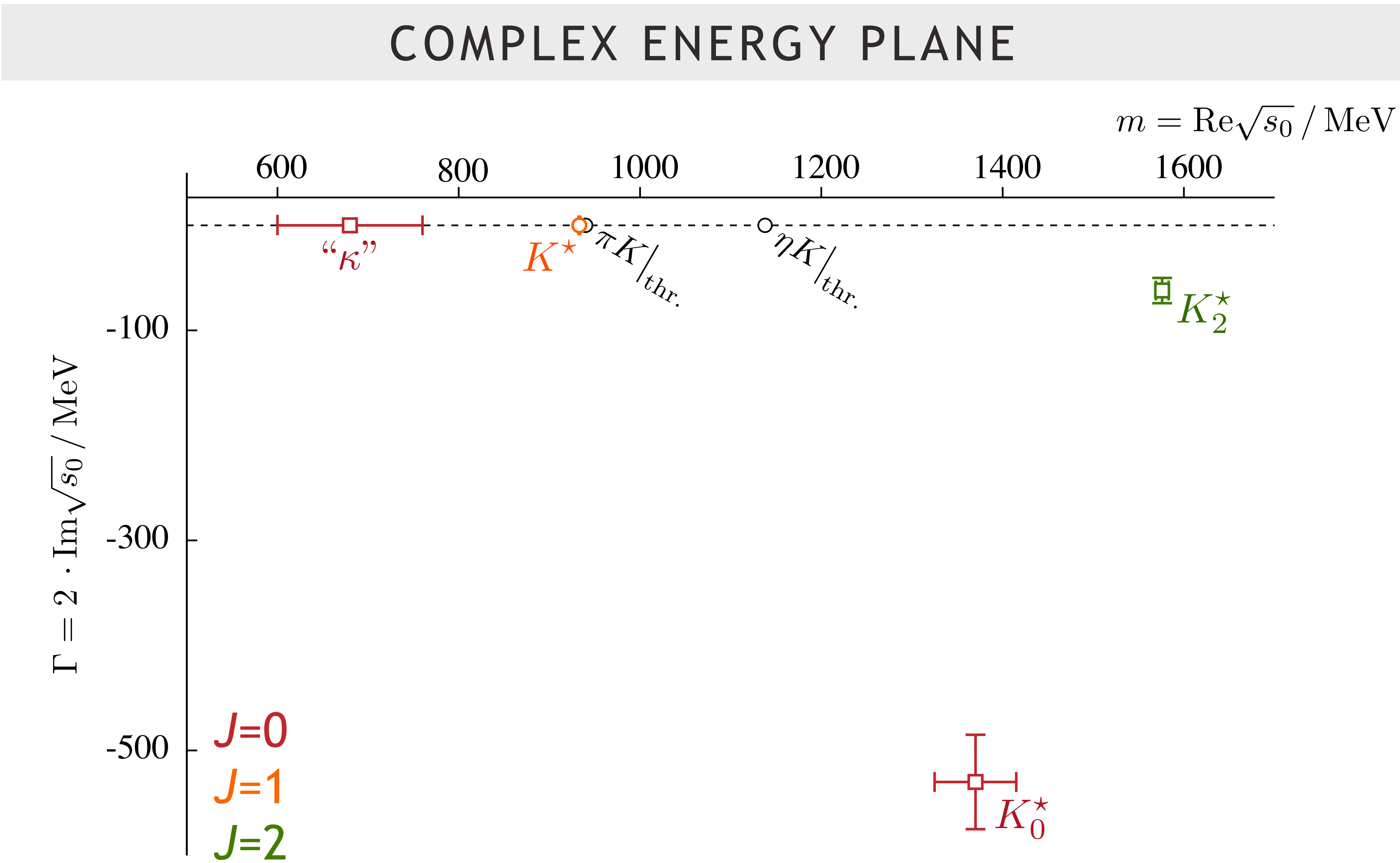


LASS, NPB296 493

singularity content - *K** resonances

- ***S*-matrix poles** as least model-dependent characterization of resonances



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PRL 113 182001
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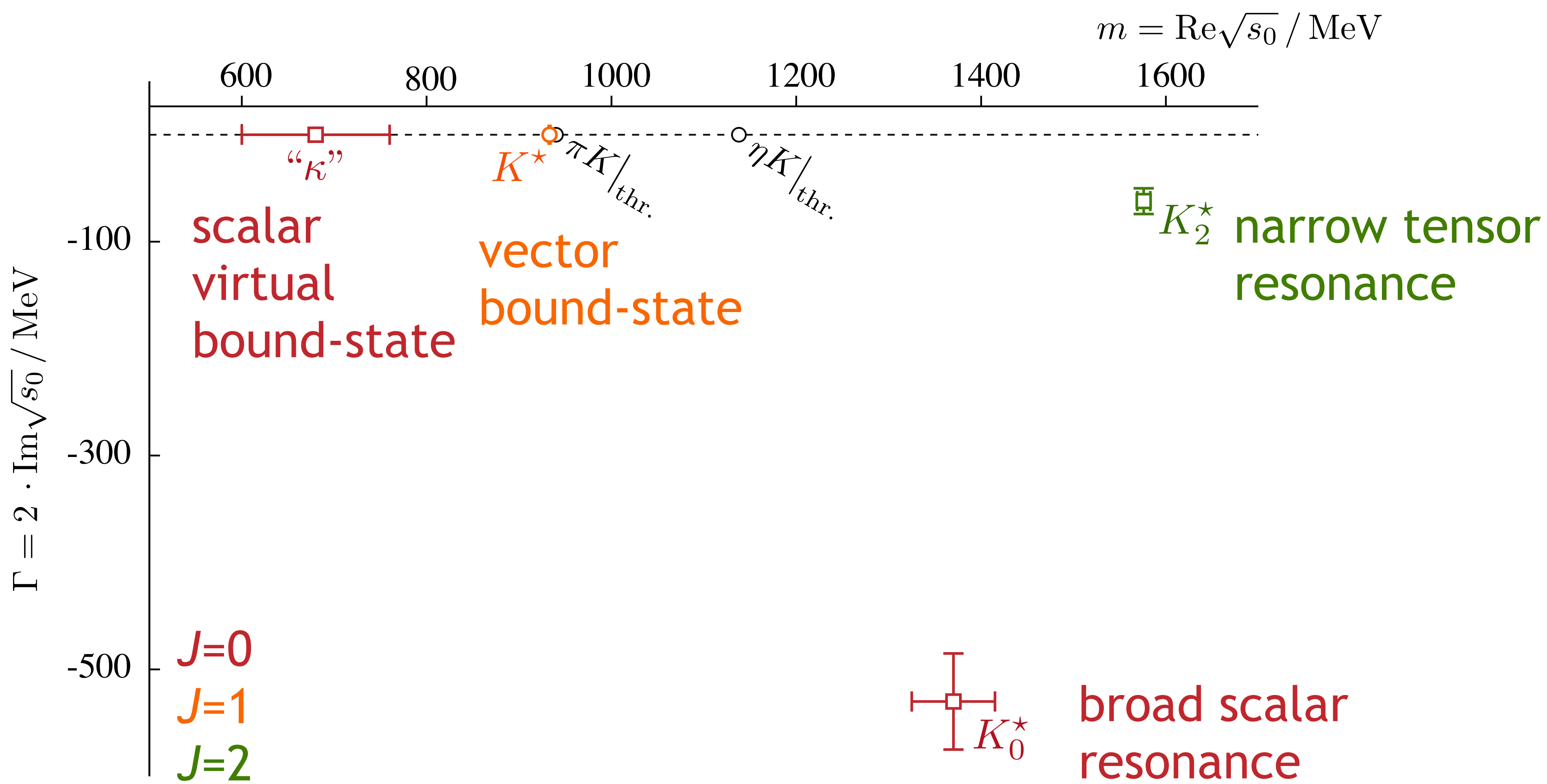
COMPLEX ENERGY PLANE



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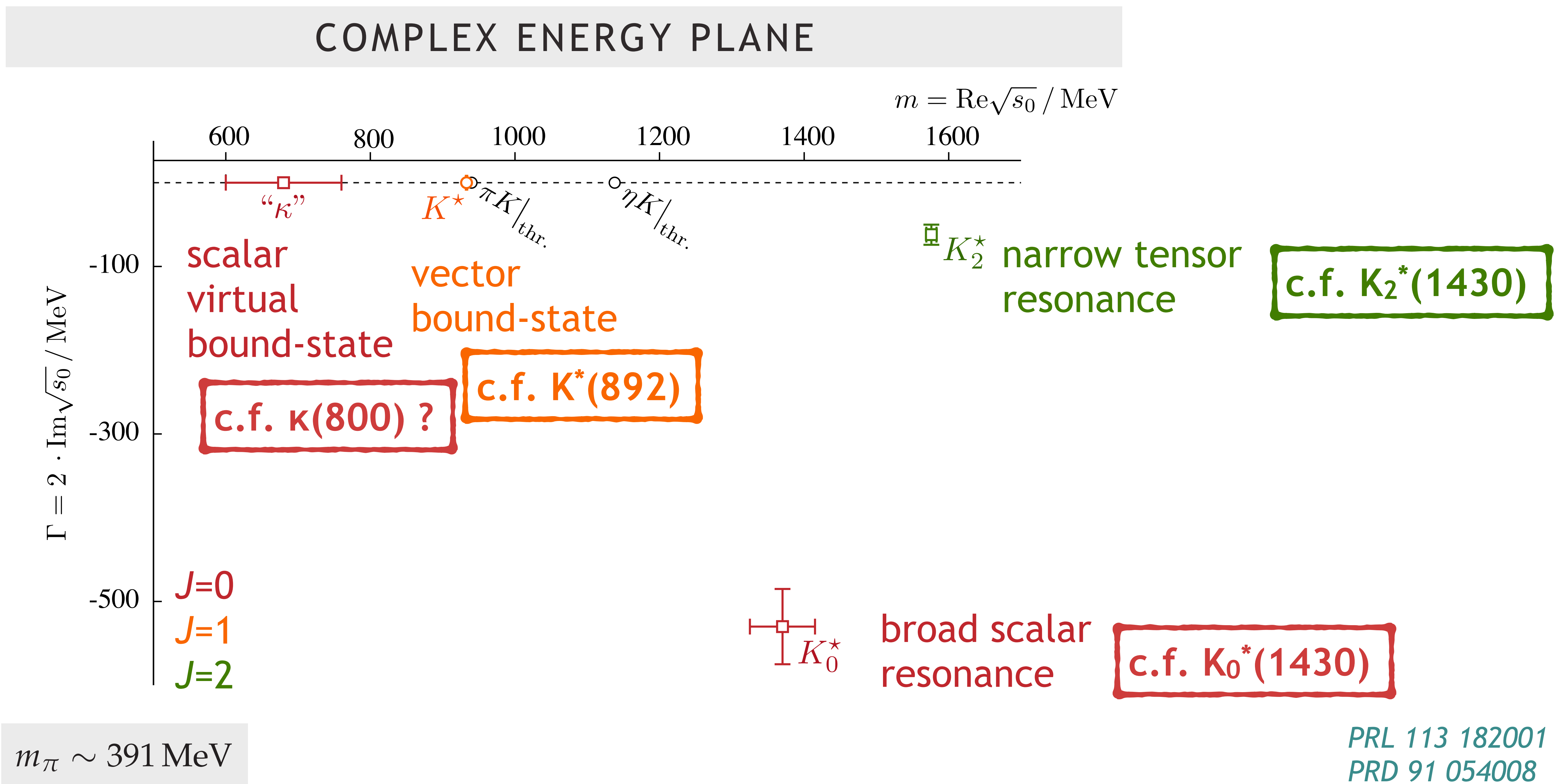

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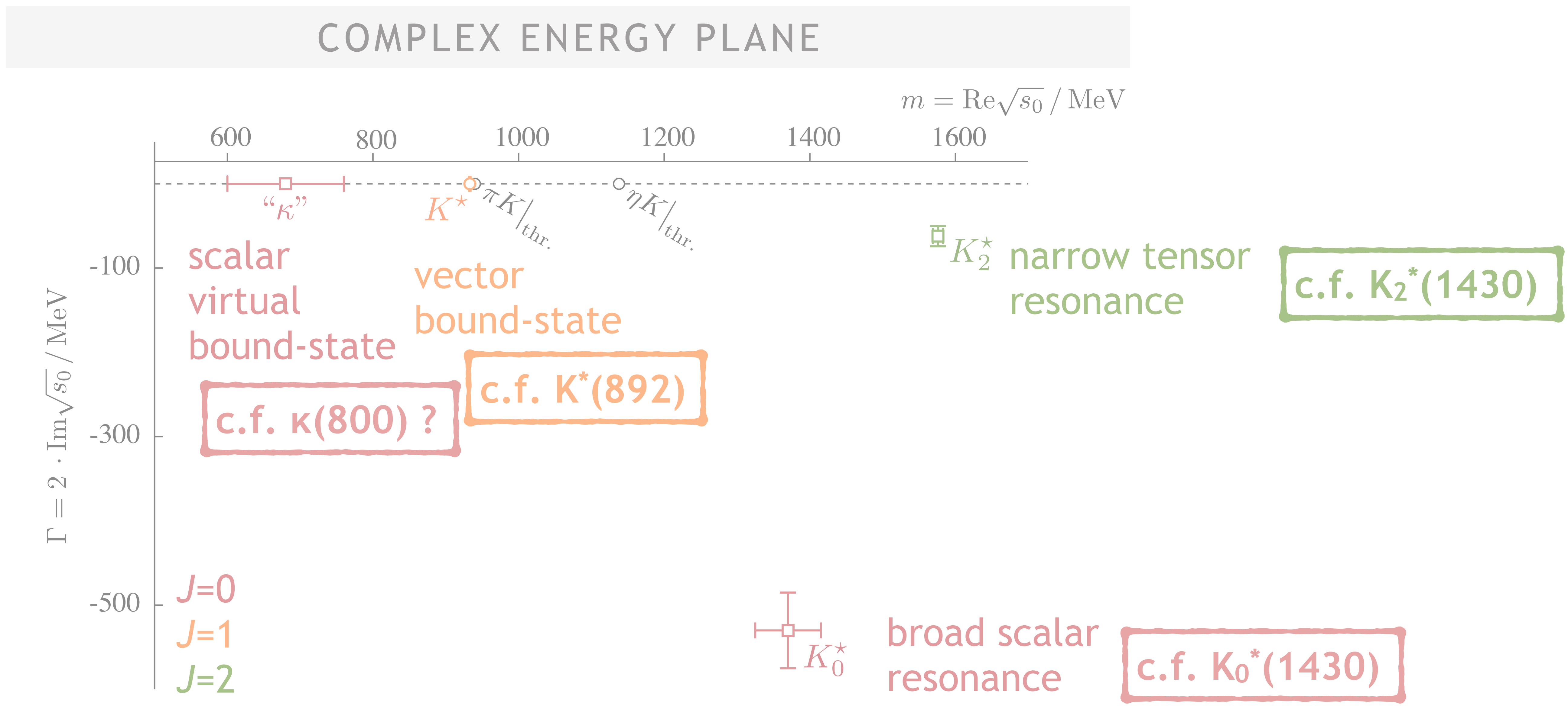


$m_\pi \sim 391$ MeV

PRL 113 182001
PRD 91 054008

… but no strong channel-coupling here …

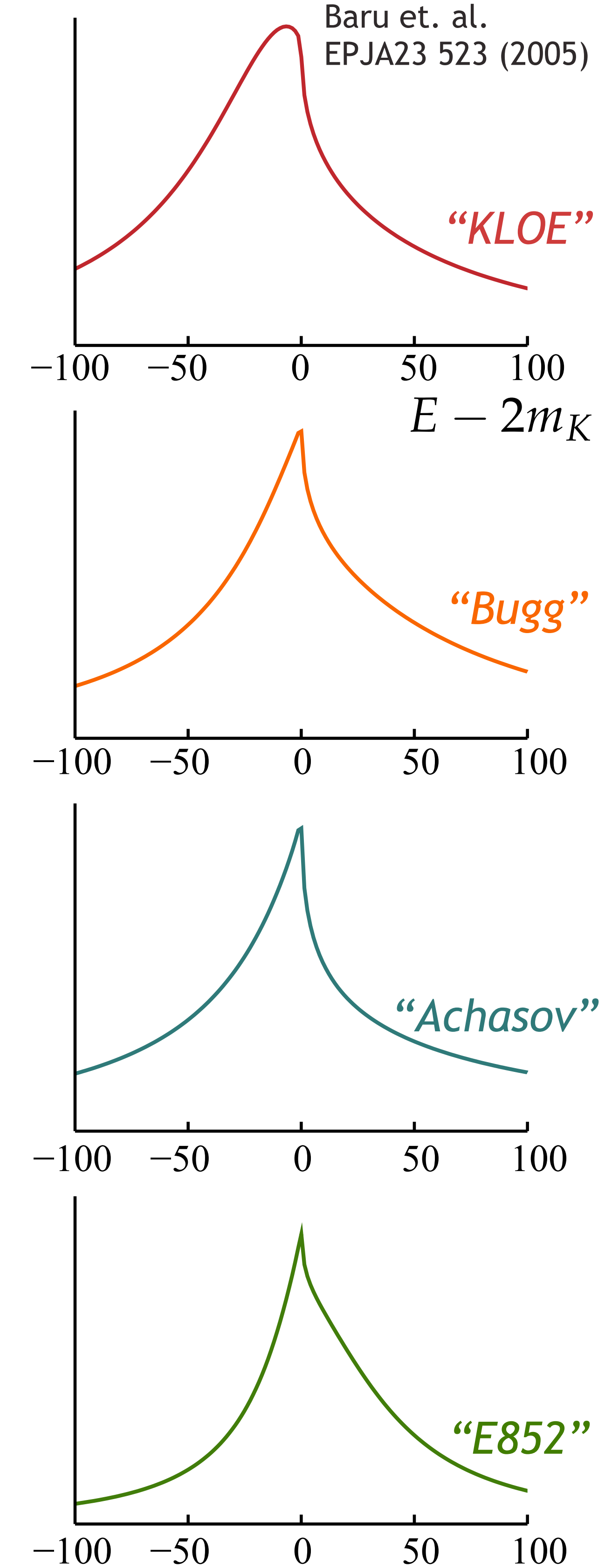
$\pi\eta/K\bar{K}$ scattering and the $a_0(980)$

- sharp experimental enhancement at $K\bar{K}$ threshold
- usually in ‘less-simple’ production processes

  e.g. $p\bar{p}\to\pi\pi\eta$

  $\phi\to\gamma\pi\eta$

- amplitude models typically give $\frac{g^2(K\bar{K})}{g^2(\pi\eta)} \sim 1$



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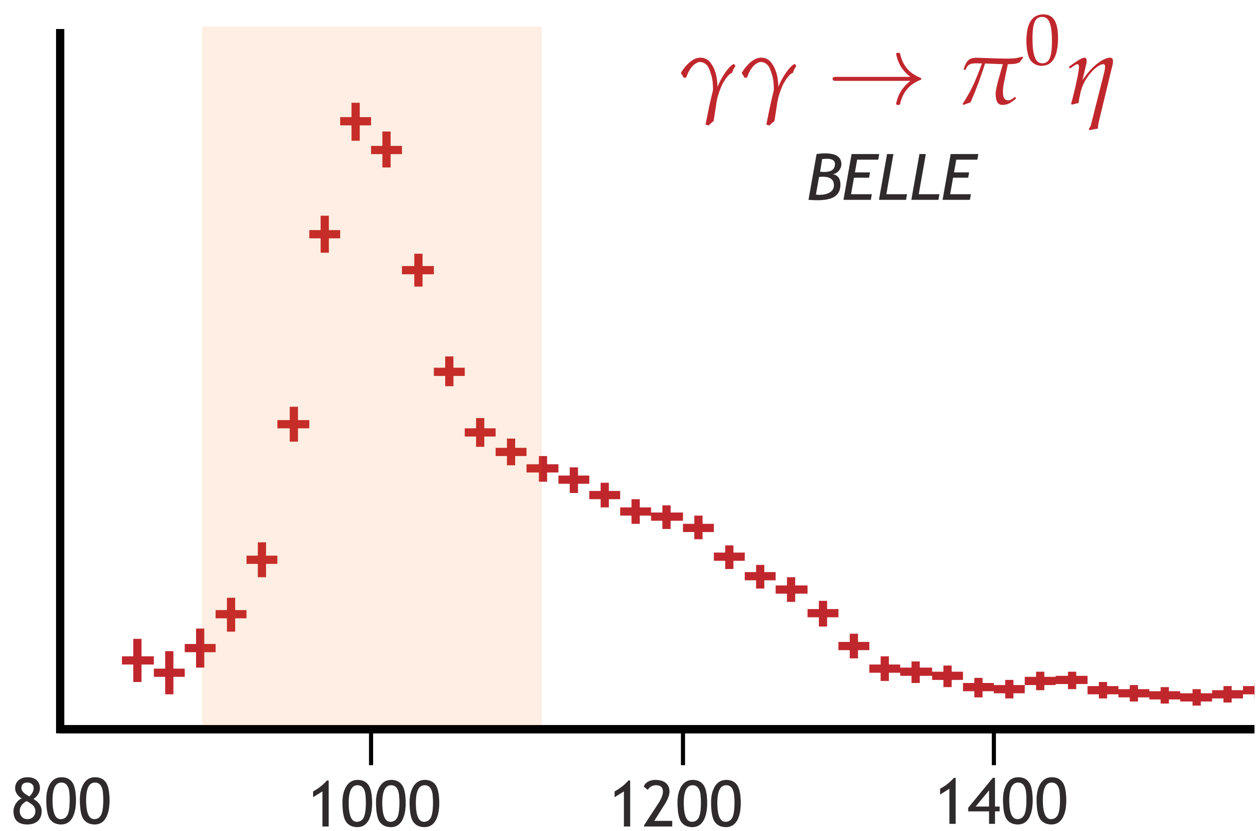

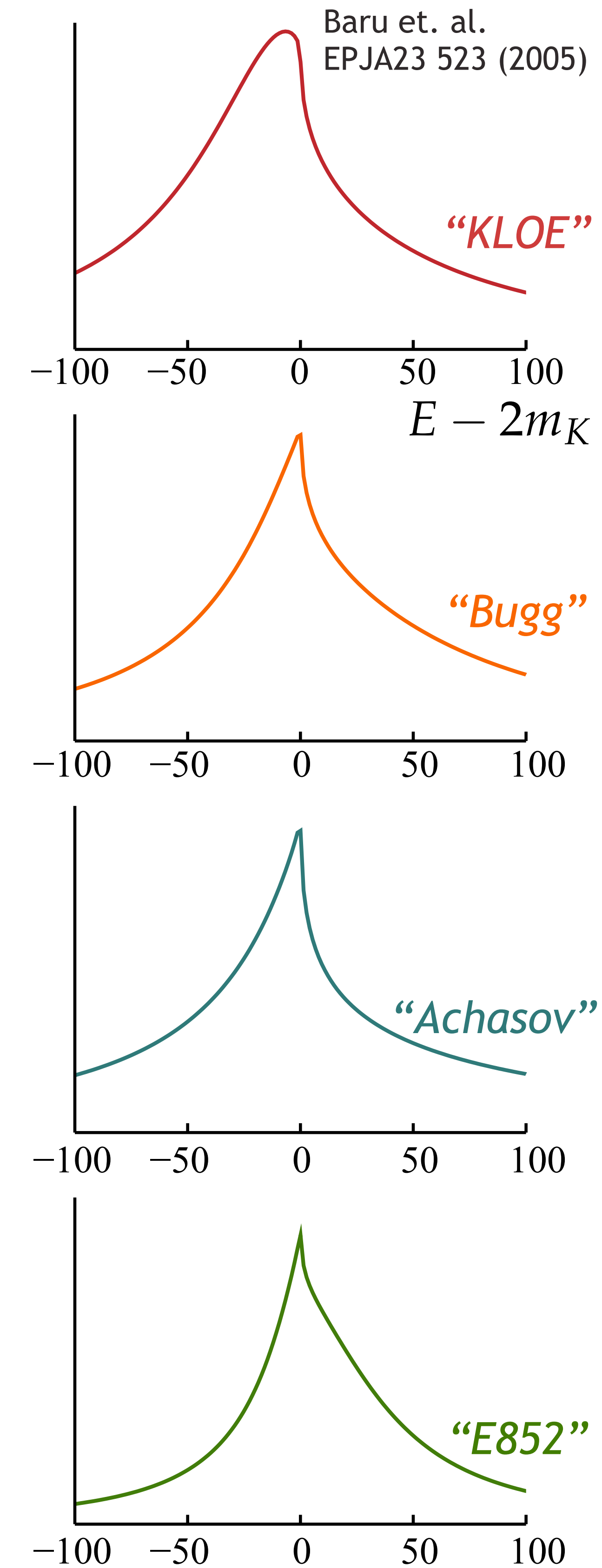

$\pi\eta/K\bar{K}$ scattering and the $a_0(980)$

- sharp experimental enhancement at $K\bar{K}$ threshold

  has a 'partner' resonance, $f_0(980)$, in $\pi\pi$ at $K\bar{K}$ threshold

- often argued that these states don't fit into the $q\bar{q}$ picture

  hidden strange tetraquarks ?

  $K\bar{K}$ molecules ?

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Progress of Theoretical Physics Supplement No. 168, 2007

Can Experiment Distinguish Tetraquark Scalars, Molecules and $\bar{q}q$ Mesons?

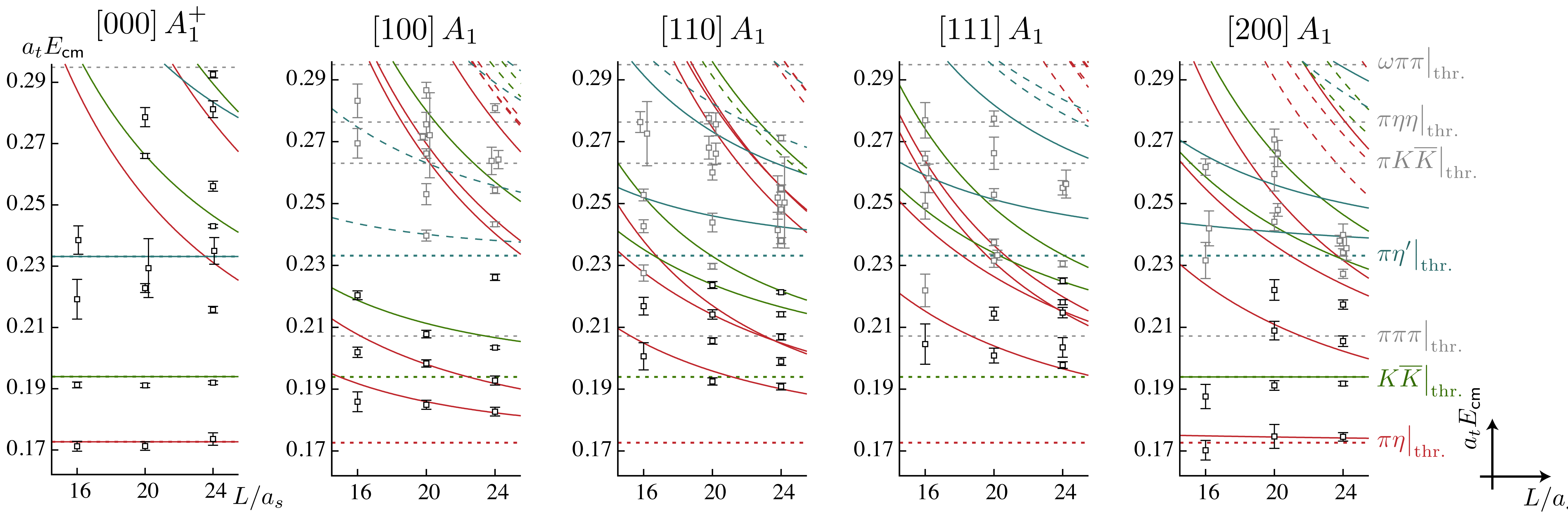
Michael PENNINGTON*)

Institute for Particle Physics Phenomenology, Durham University, Durham DH1 3LE, UK

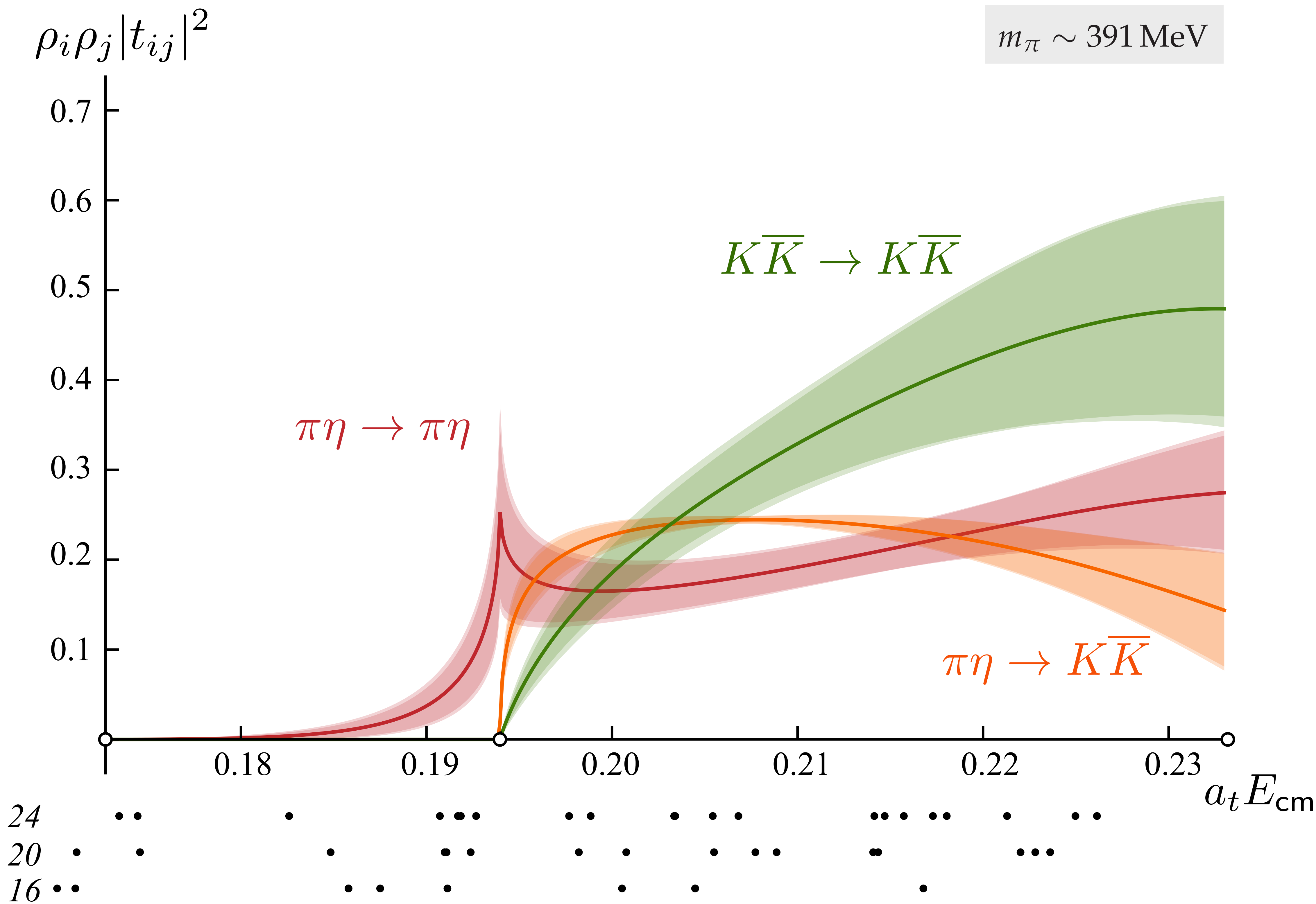
... and can theory ?

$\pi\eta/K\overline{K}/\pi\eta'$ lattice QCD spectra

- used a basis of $\pi\eta/K\overline{K}/\pi\eta'$ like operators and $\bar{\psi}\Gamma\overleftrightarrow{D}\ldots\overleftrightarrow{D}\psi$



$\pi\eta/K\bar{K}$ scattering amplitudes



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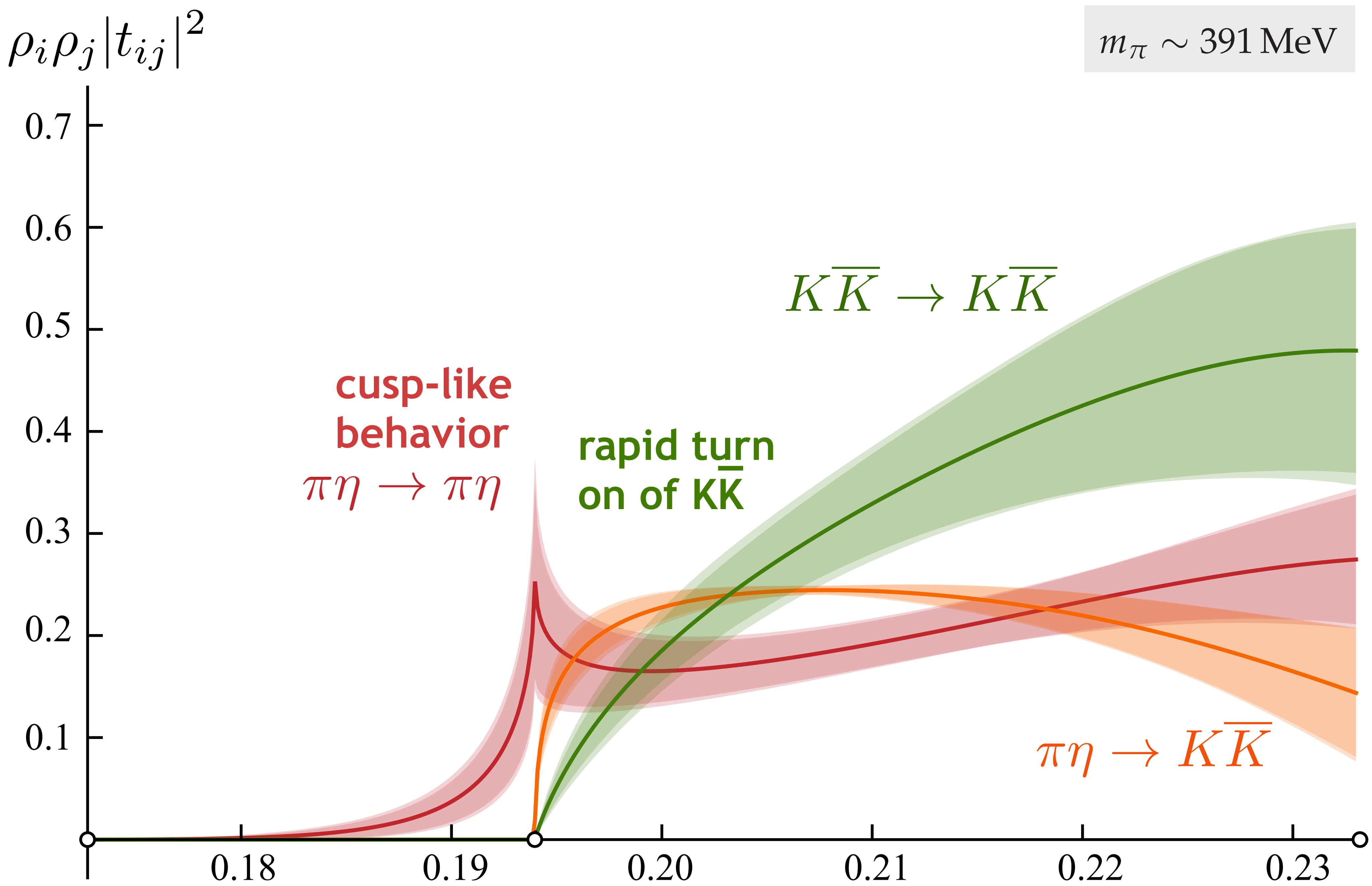
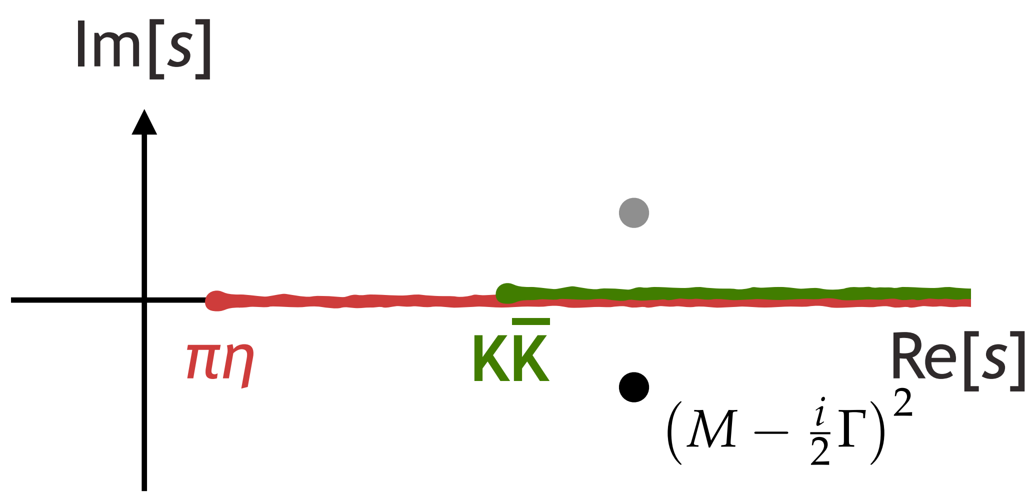
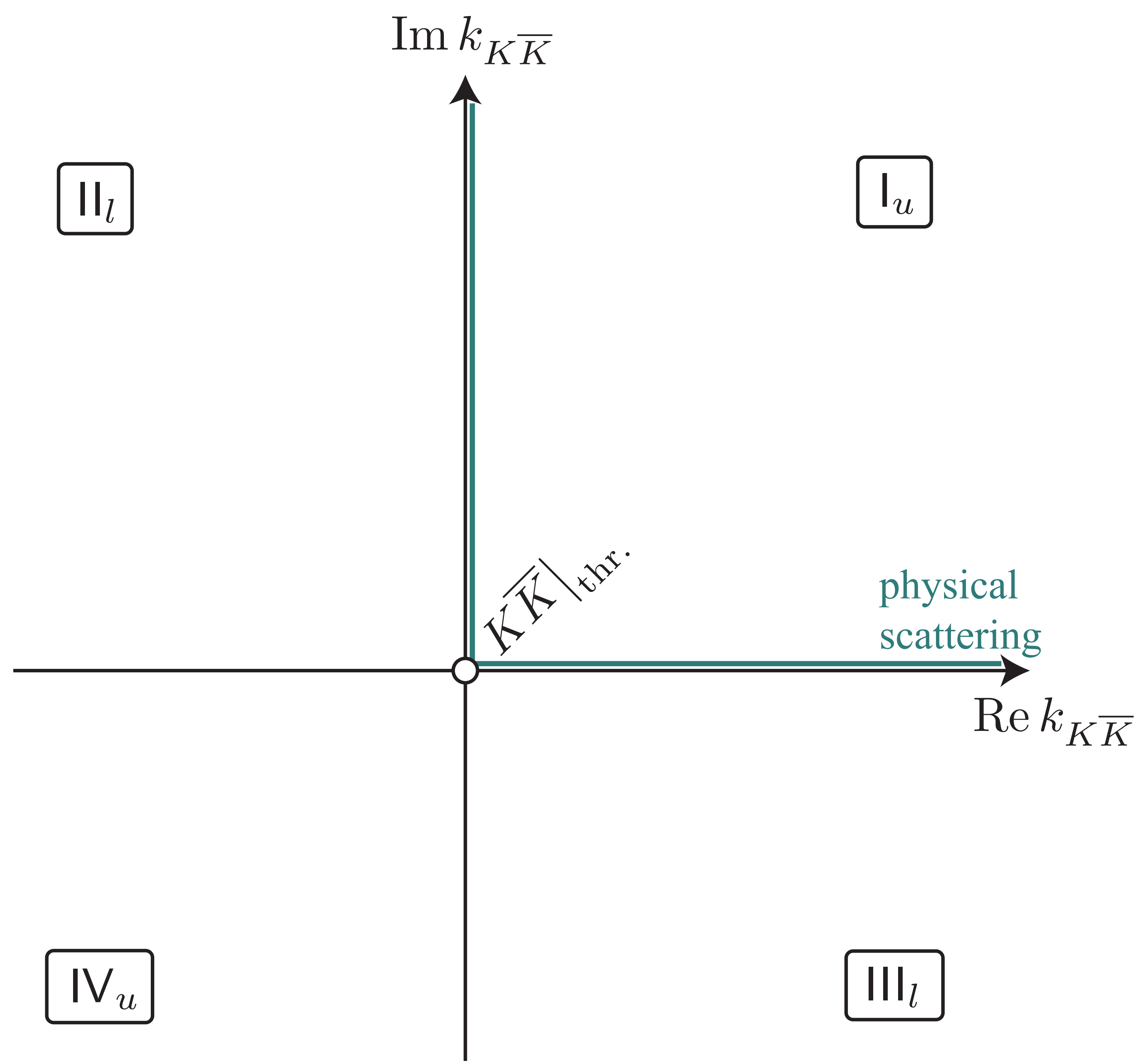


- such a strong effect at threshold likely indicates a nearby singularity

pole singularities in two-channels

- unitarity implies four Riemann sheets in this case

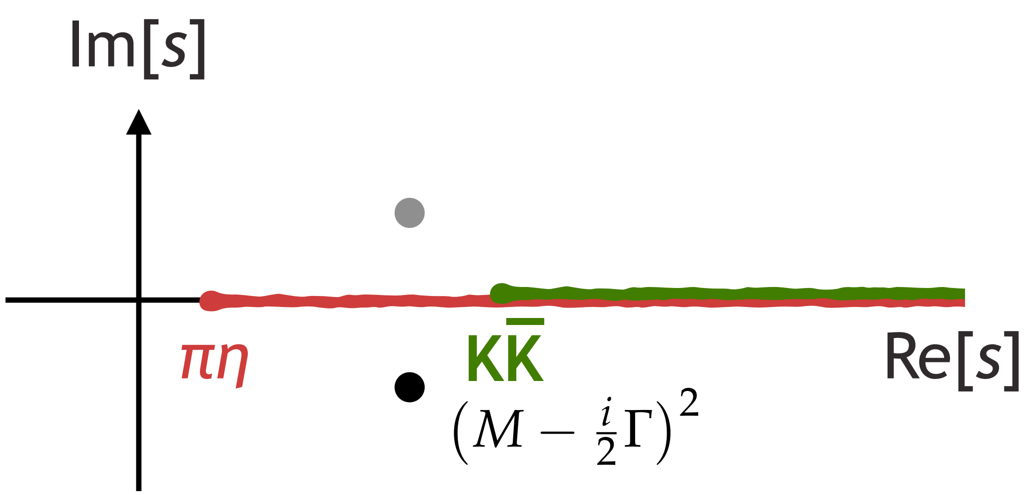


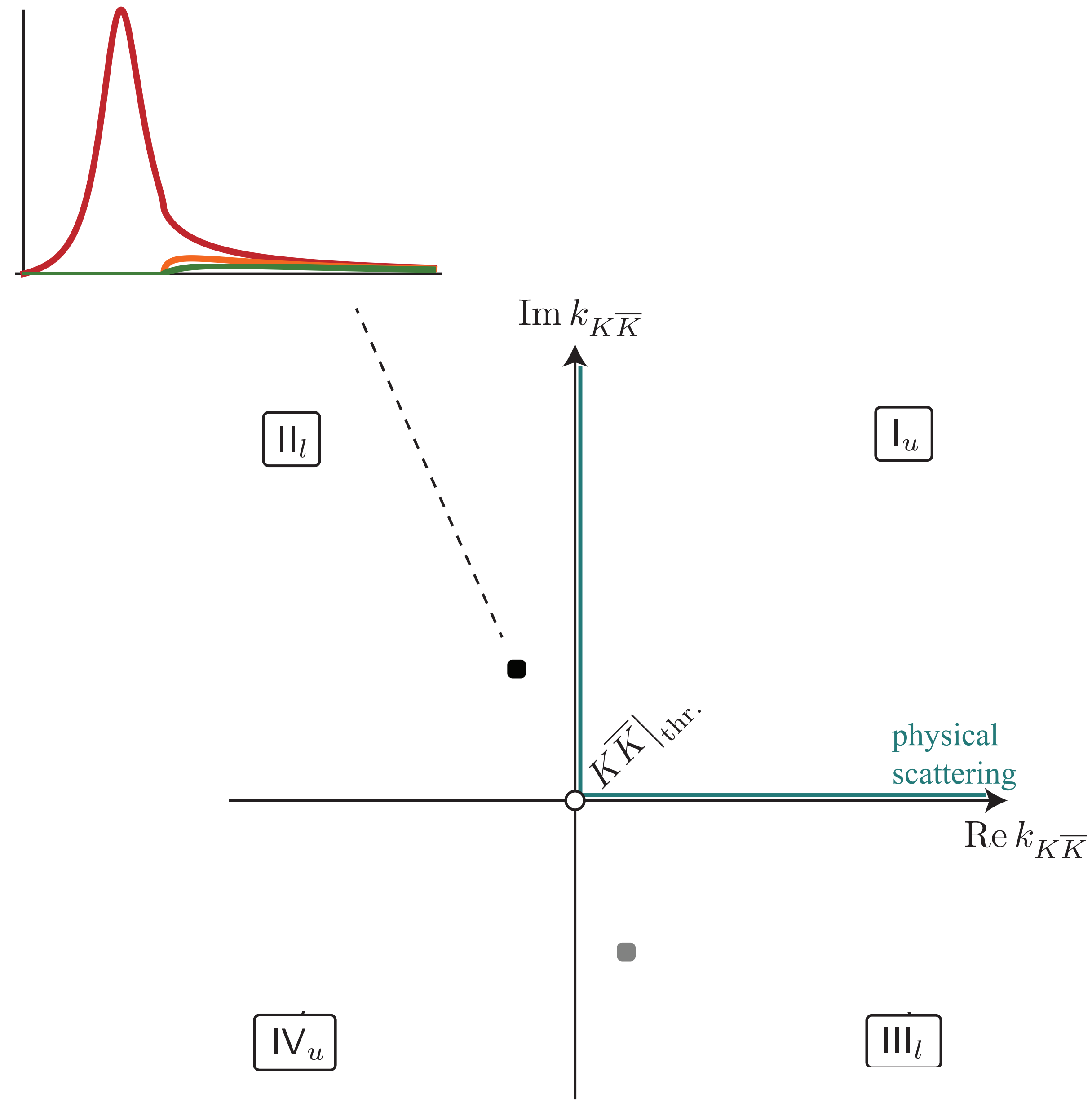


'BW-like' resonance below $K\bar{K}$ threshold

'Flatté form'

$$t_{ij}(s) = \frac{g_i g_j}{m^2 - s - i g_1^2 \rho_1(s) - i g_2^2 \rho_2(s)}$$





‘BW-like’ resonance above $K\bar{K}$ threshold

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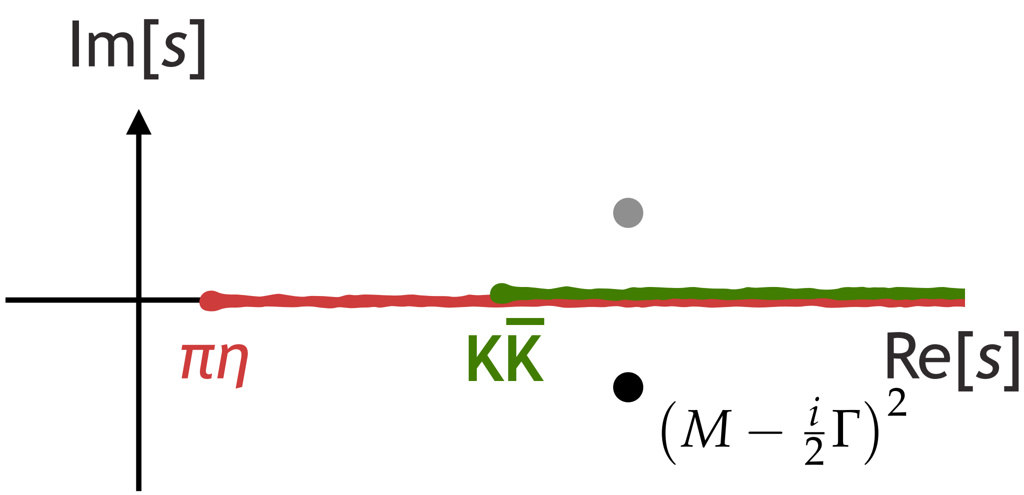
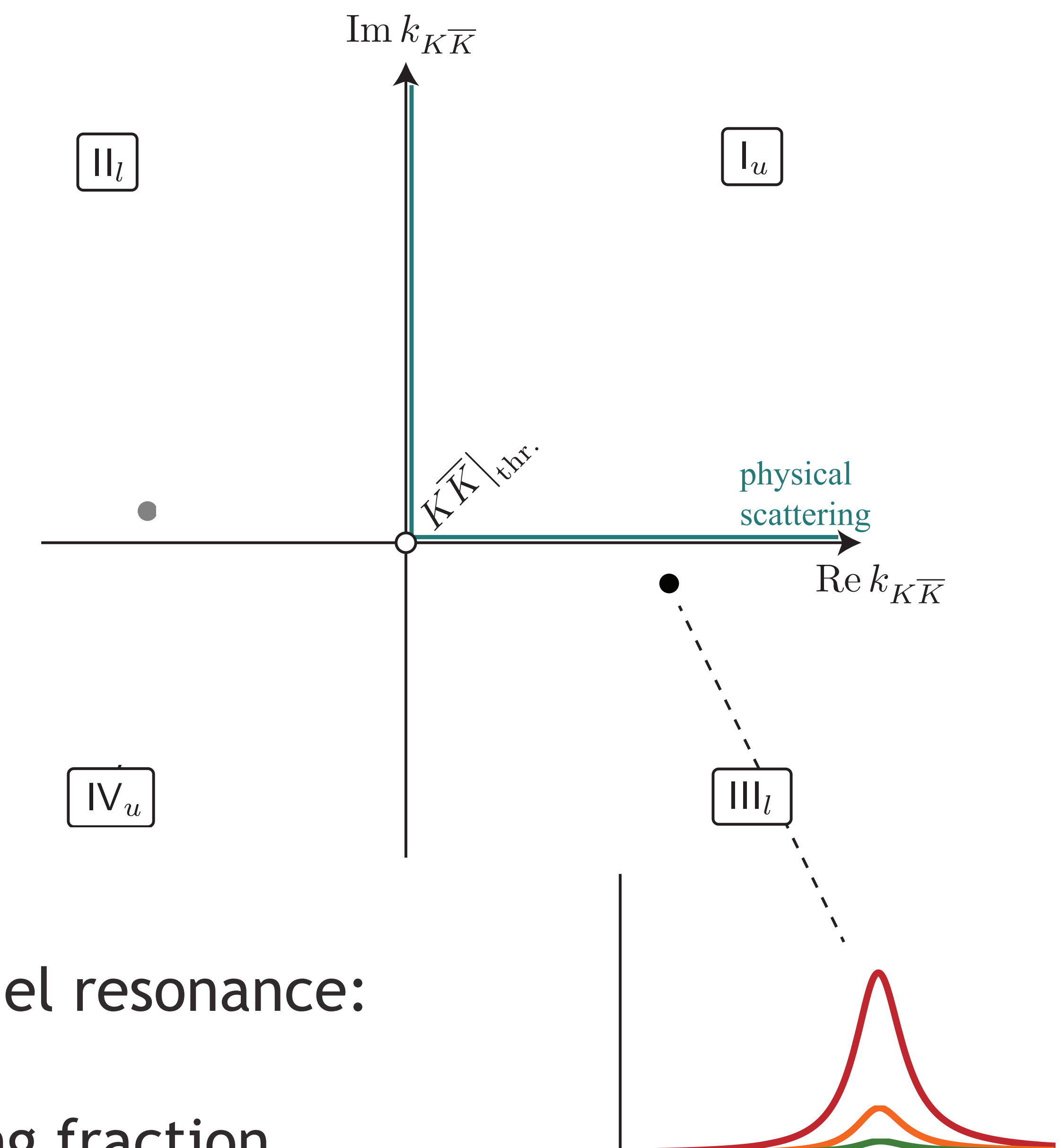
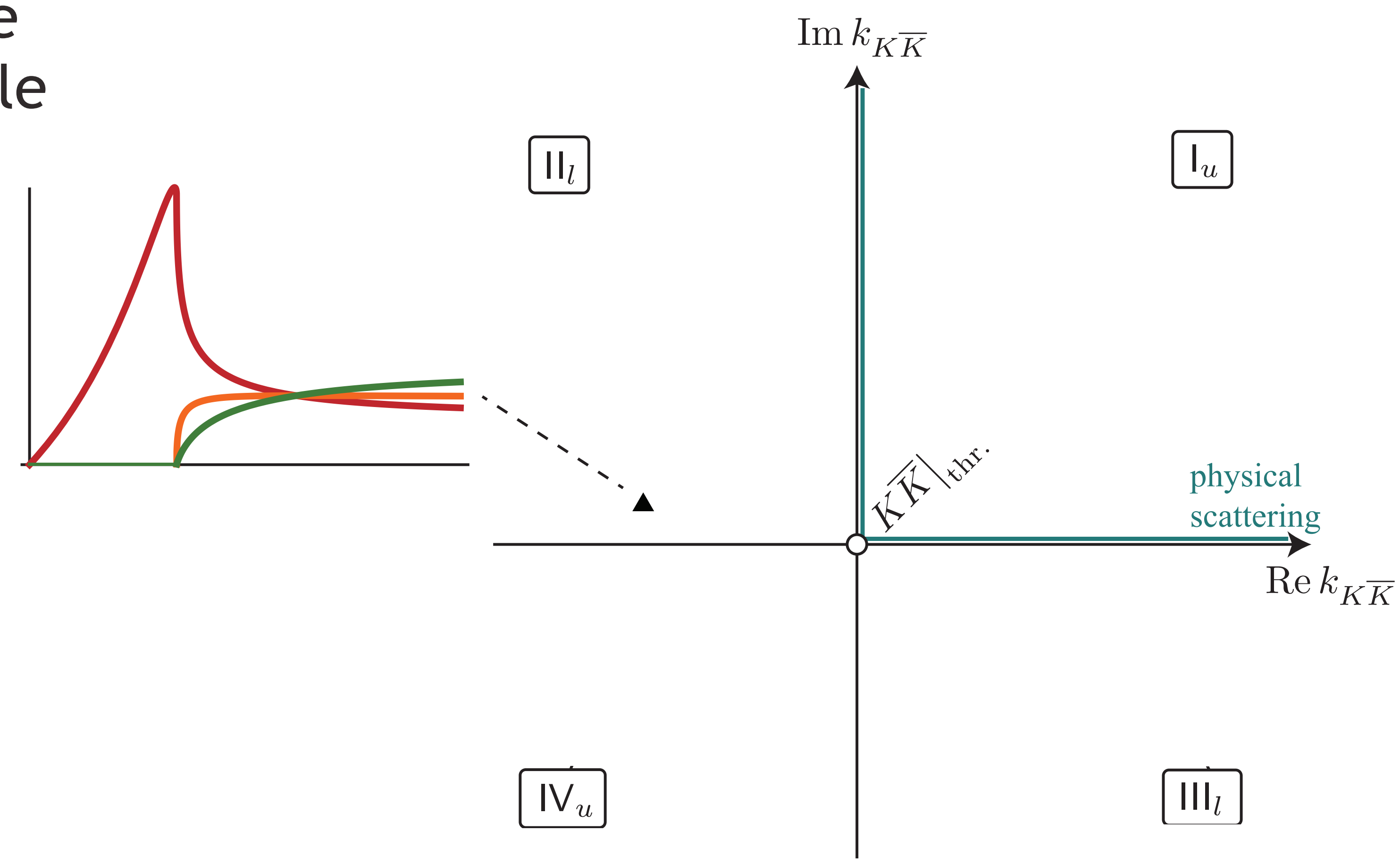




our canonical view of a multichannel resonance:
“a bump in each channel”
relative height of bump → branching fraction

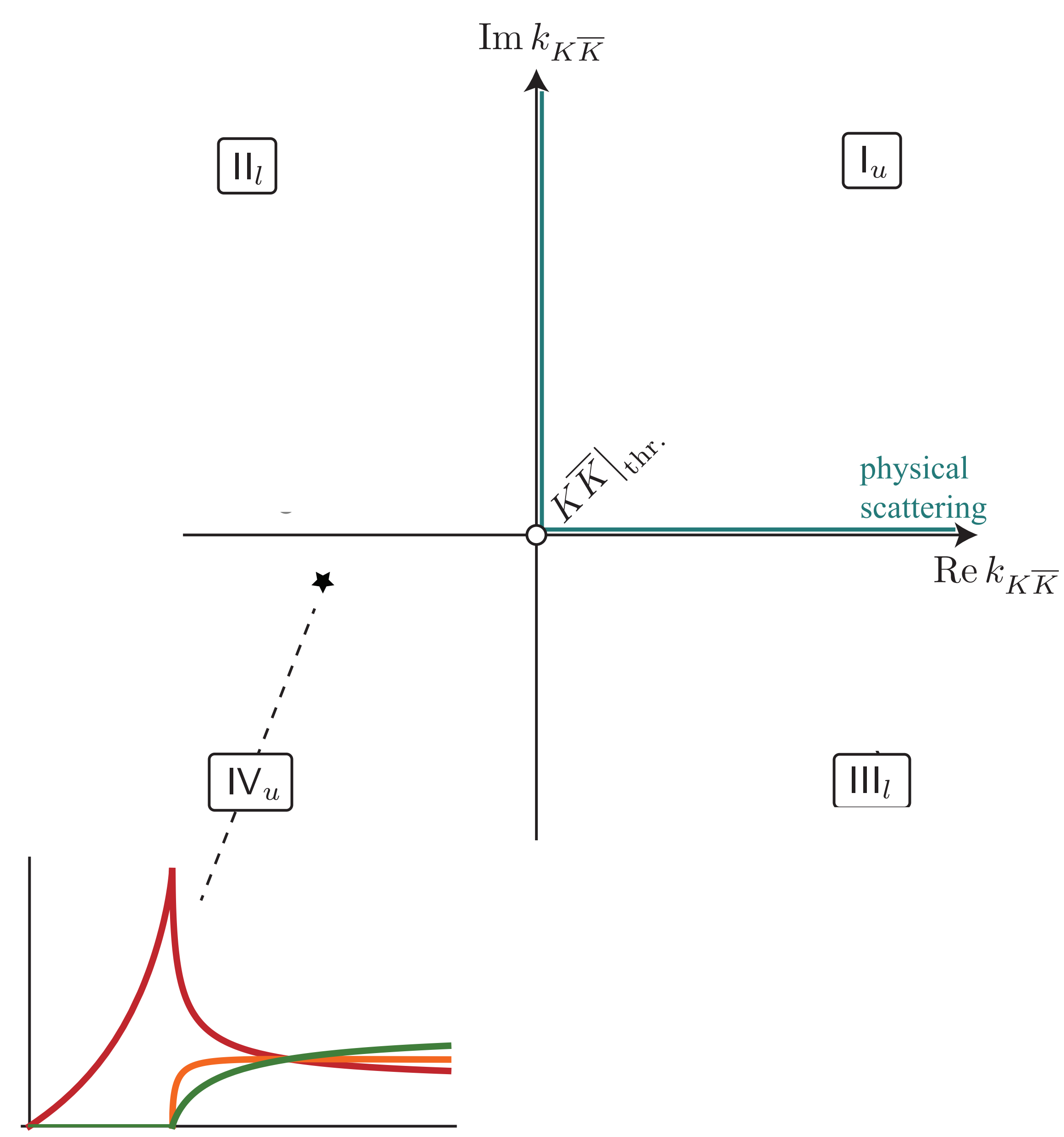
single-pole resonance on sheet II

nothing forbids an amplitude with only a single nearby pole

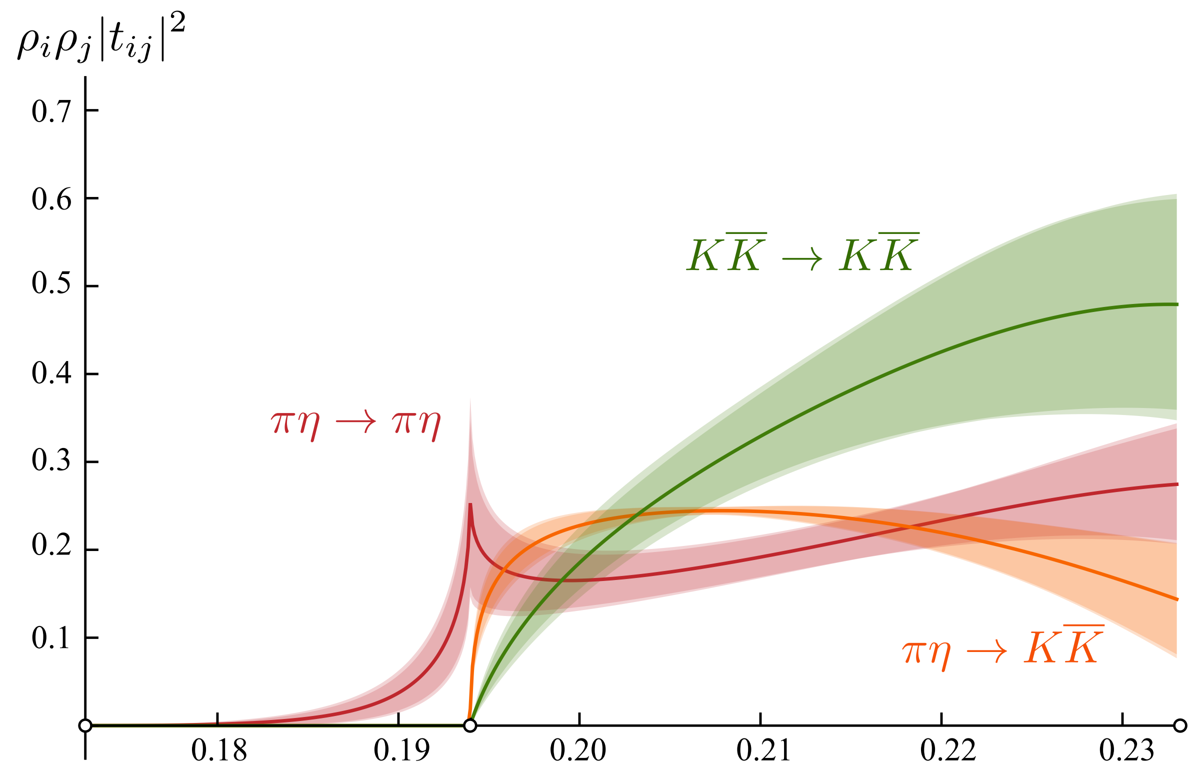


fits to experimental data tend to exhibit this structure

single-pole resonance on sheet IV



amplitude from lattice spectrum

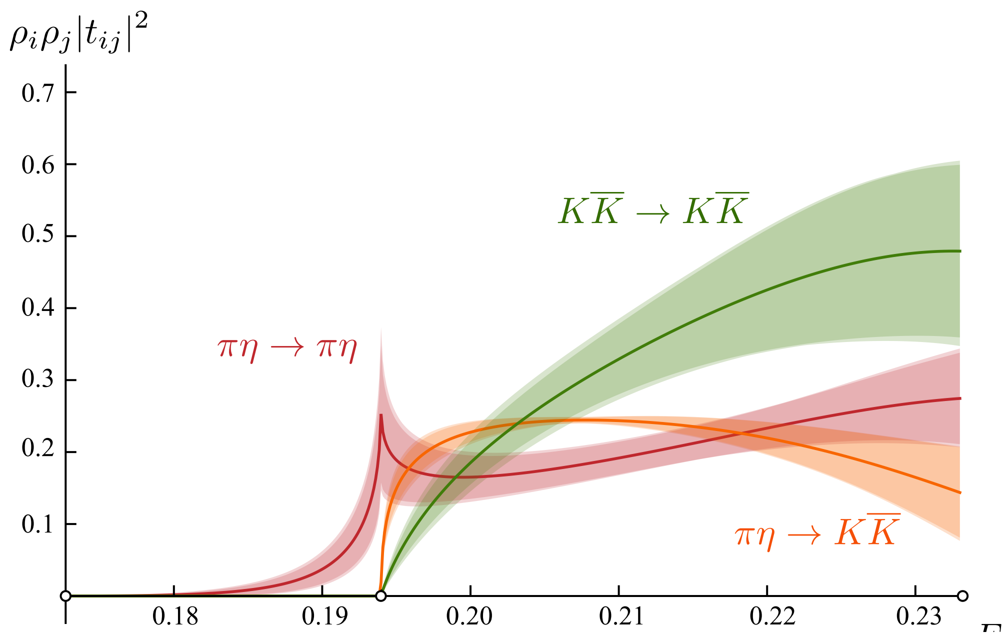


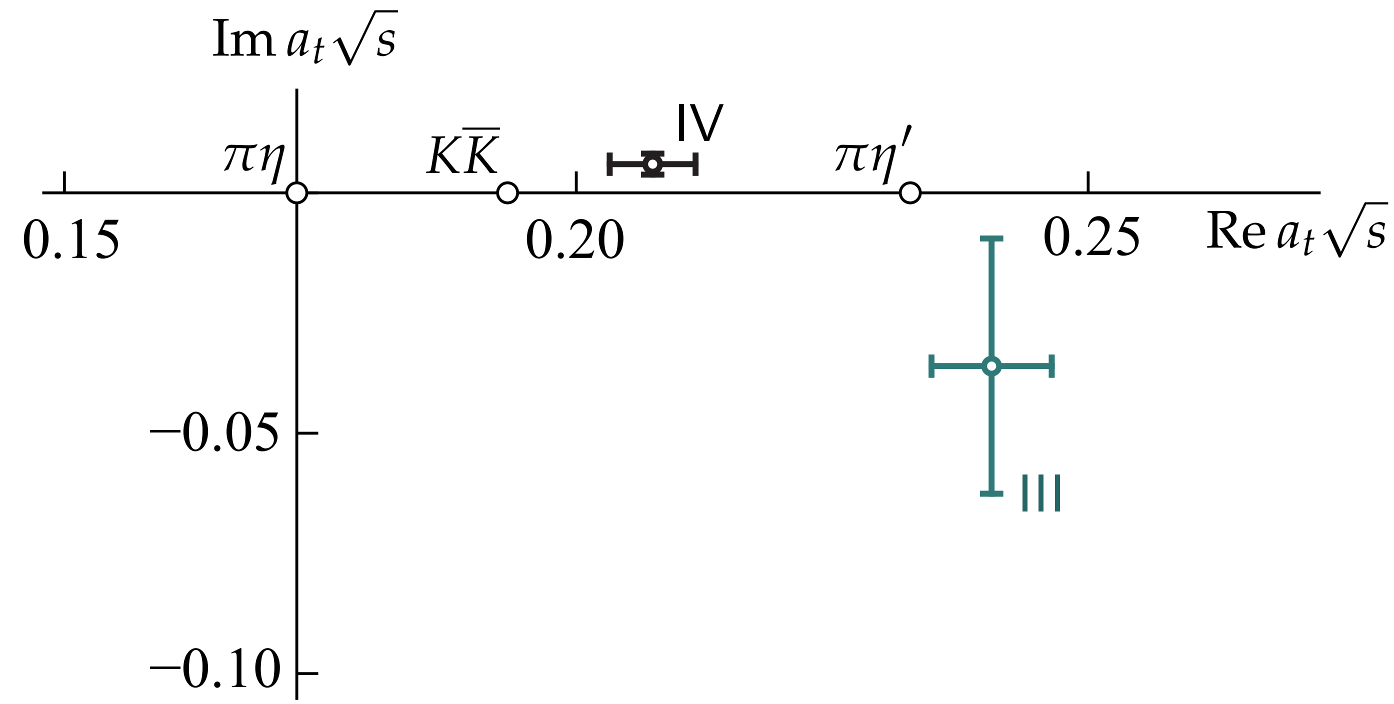
this fit from a *K*-matrix parameterization

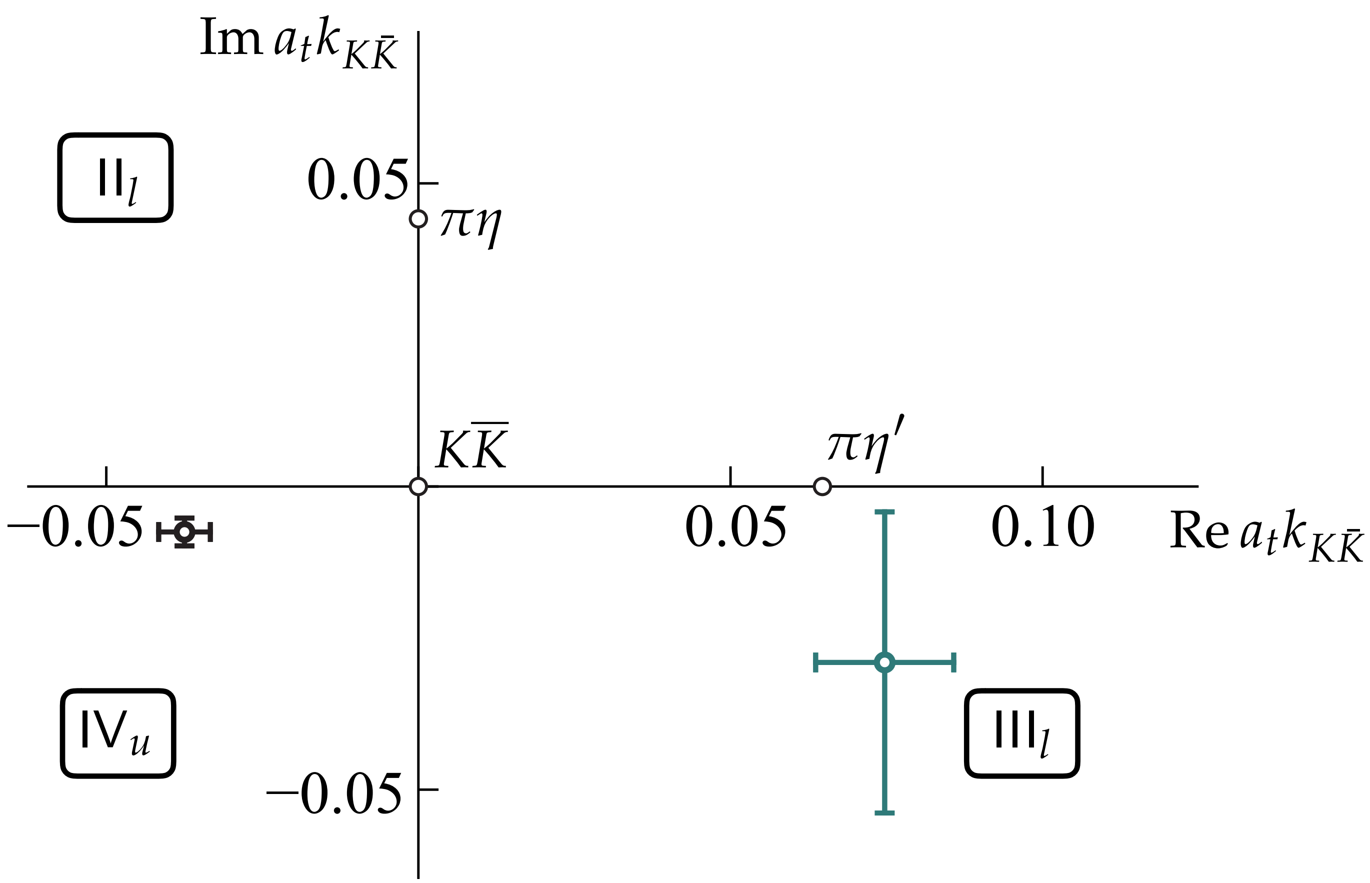
$$t_{ij}^{-1}(E) = K_{ij}^{-1}(E) + \delta_{ij}\, I_i(E)$$

$$K_{ij}(E) = \frac{g_i\, g_j}{m^2 - E^2} + \gamma_{ij}$$

singularity structure







bit esoteric isn’t it … ?

pole distributions and molecular states ?

Pole counting and resonance classification

D. Morgan
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, UK

Received 14 January 1992

'confined' state coupled to decay continuum → Breit-Wigner like (two poles)

molecular state from long-range potential → one pole

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other molecule diagnostics ?

couple to an external current e.g. $\phi \to \gamma(\pi\eta, K\bar{K})$

or $(\pi\eta, KK) \to \gamma(\pi\eta, K\bar{K})$ or other currents …

and extract form-factors from the residue of the pole

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examples of the interesting convergence of lattice QCD, S-matrix ideas, and phenomenology

highlights

- application of lattice methods has **reinvigorated theoretical hadron spectroscopy**

  → have a tool for **phenomenology directly connected to QCD**

  → put ideas of **gluonic excitations** / **hybrid hadrons** on a firmer footing

  → **finite-volume methods** give access to **scattering amplitudes**

  → can now really calculate the physical observables

- the **Hadron Spectrum Collaboration** is the world-leader in these efforts

  → nobody else is doing 'spectrum' calculations of this scope

(near) future

scattering

scalar mesons at lower m_π

axial and other
mesons in e.g. $\pi\rho$, $\pi\omega$

hybrid meson decays at heavier quark masses

simple baryon resonances

more photon transitions

three-body scattering

⋮

phenomenology

tetraquark operator basis

molecules ? pole distributions ? form-factors ?

⋮

and haven't mentioned charmonium sector …
XYZ's …

timeline

2009	dynamical anisotropic lattices, distillation
2010	highly excited isovector meson spectrum
2011	highly excited isoscalar meson spectrum highly excited baryon spectrum phenomenology of hybrid mesons
2012	hybrid baryon spectrum $\pi\pi$ scattering, isospin=2 highly excited charmonium spectrum
2013	$\pi\pi$ scattering, isospin=1, ρ resonance coupled-channel formalism
2014	coupled-channel $\pi K, \eta K$ scattering
2015	excited meson radiative transitions $\gamma\pi \to \pi\pi$ and the $\rho \to \pi\gamma$ transition
2016	(to appear) coupled-channel $\pi\eta, K\bar{K}$ scattering

hadron spectrum collaboration

JEFFERSON LAB

Jozef Dudek
Robert Edwards
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David Richards

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Christopher Thomas

U. OF MARYLAND

Steve Wallace

MESON SPECTRUM

PRL103 262001 (2009)	$I=1$
PRD82 034508 (2010)	$I=1,\ K^\star$
PRD83 111502 (2011)	$I=0$
JHEP07 126 (2011)	$c\bar{c}$
PRD88 094505 (2013)	$I=0$
JHEP05 021 (2013)	$D,\ D_s$

BARYON SPECTRUM

PRD84 074508 (2011)	$(N,\Delta)^\star$
PRD85 054016 (2012)	$(N,\Delta)_{\text{hyb}}$
PRD87 054506 (2013)	$(N\ldots\Xi)^\star$
PRD90 074504 (2014)	$\Omega^\star_{ccc}$
PRD91 094502 (2015)	$\Xi^\star_{cc}$

"TECHNOLOGY"

PRD79 034502 (2009)	lattices
PRD80 054506 (2009)	distillation
PRD85 014507 (2012)	$\vec{p}>0$

HADRON SCATTERING

PRD83 071504 (2011)	$\pi\pi\ I=2$
PRD86 034031 (2012)	$\pi\pi\ I=2$
PRD87 034505 (2013)	$\pi\pi\ I=1,\ \rho$
PRL113 182001 (2014)	$\pi K, \eta K$
PRD91 054008 (2015)	$\pi K, \eta K$
PRD92 094502 (2015)	$\pi\pi, K\bar{K}$

MATRIX ELEMENTS

PRD91 114501 (2015)	$M' \to \gamma M$
PRD90 014511 (2014)	$f_{\pi^\star}$
PRL115 242001 (2015)	$\gamma^\star\pi \to \pi\pi$