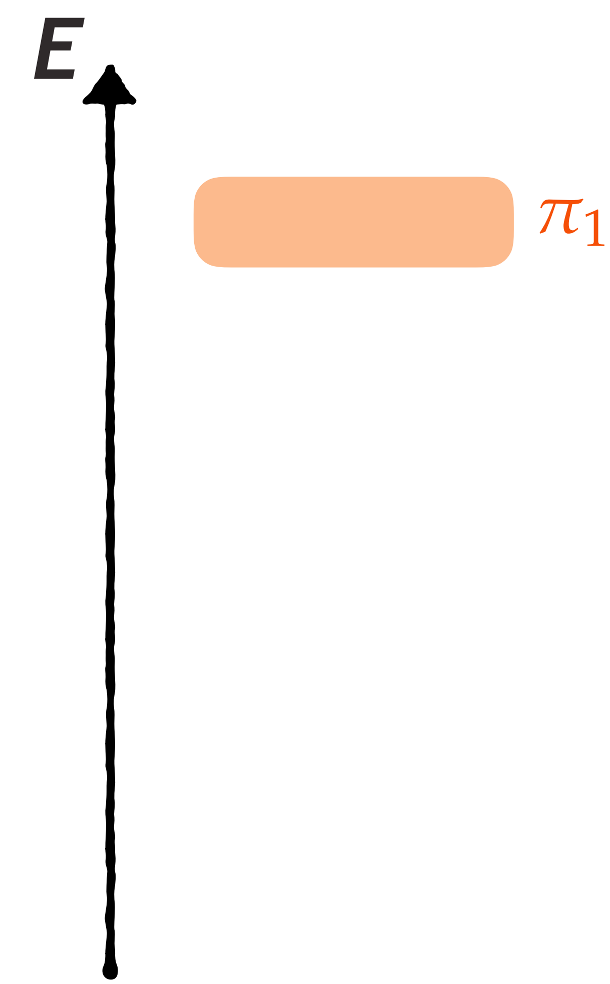
Excited State Spectroscopy & QCD

Jefferson Lab

Exotic hybrid mesons in QCD?

Goal: Predict and understand hybrid mesons from QCD

signals for a 1^{-+} resonance above 1600 MeV



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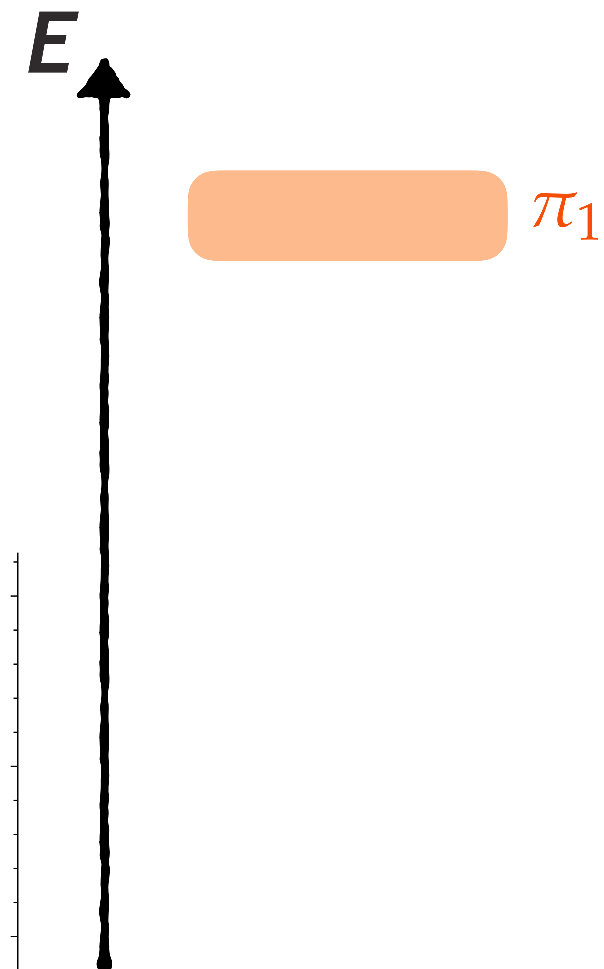
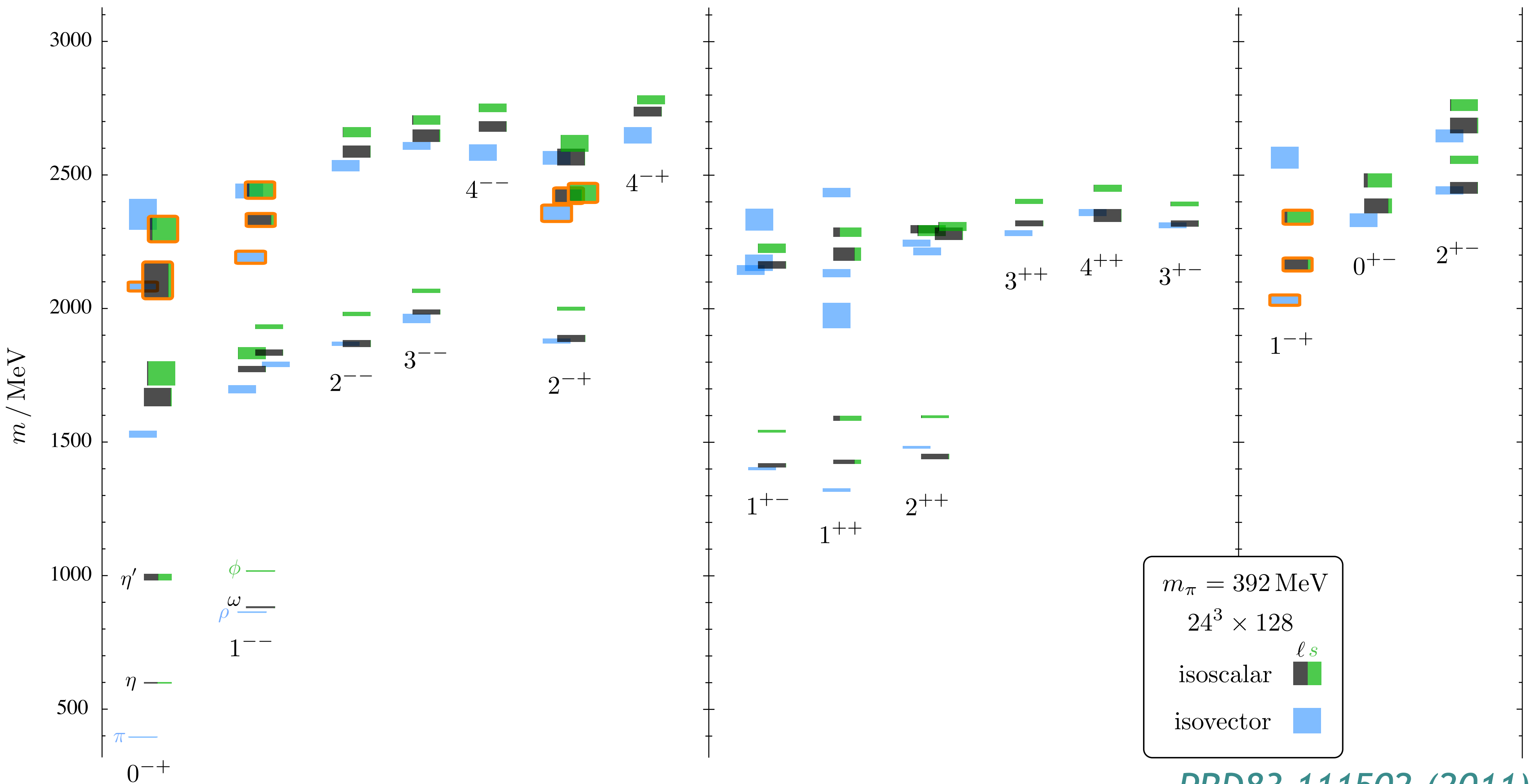


Can calculate a discrete spectrum of states using lattice QCD



PRD83 111502 (2011)
PRD88 094595 (2013)

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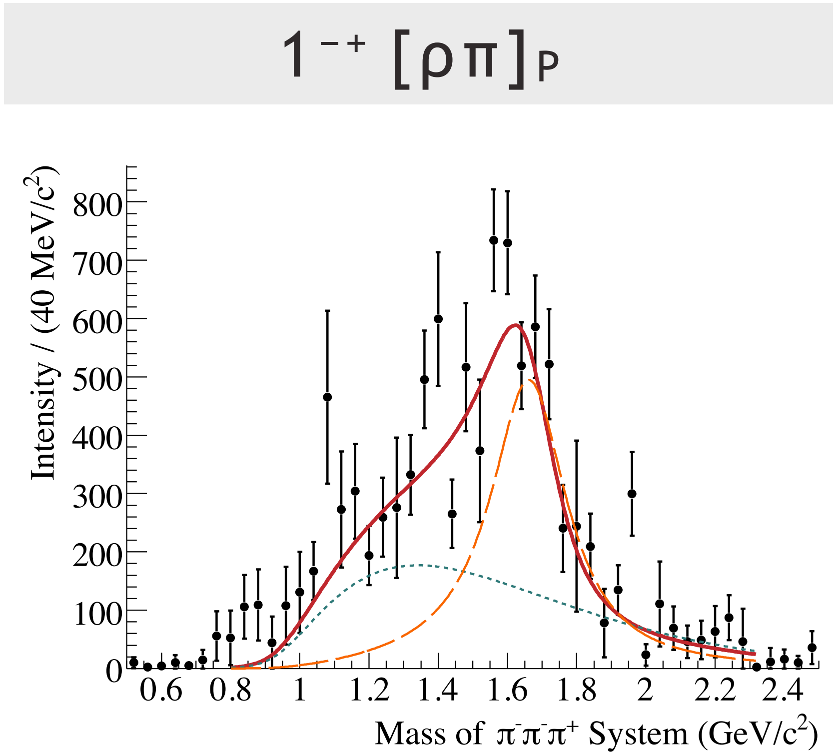
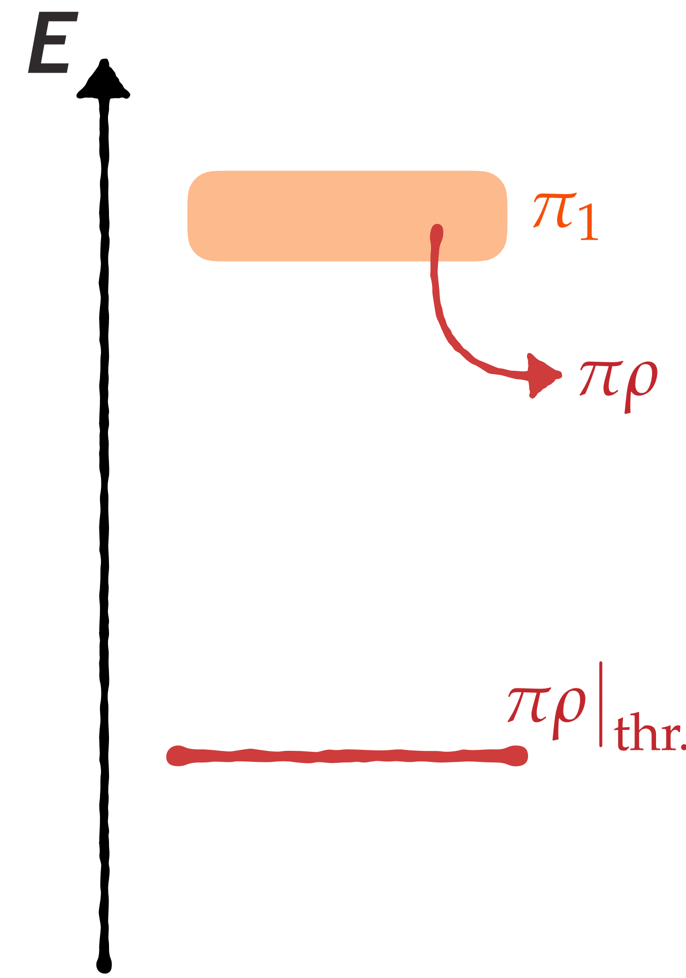
Exotic hybrid mesons in QCD?

Excited states are resonances in scattering of lighter hadrons

We should see this in LQCD



COMPASS Pb data
PRL104 241803 (2010)



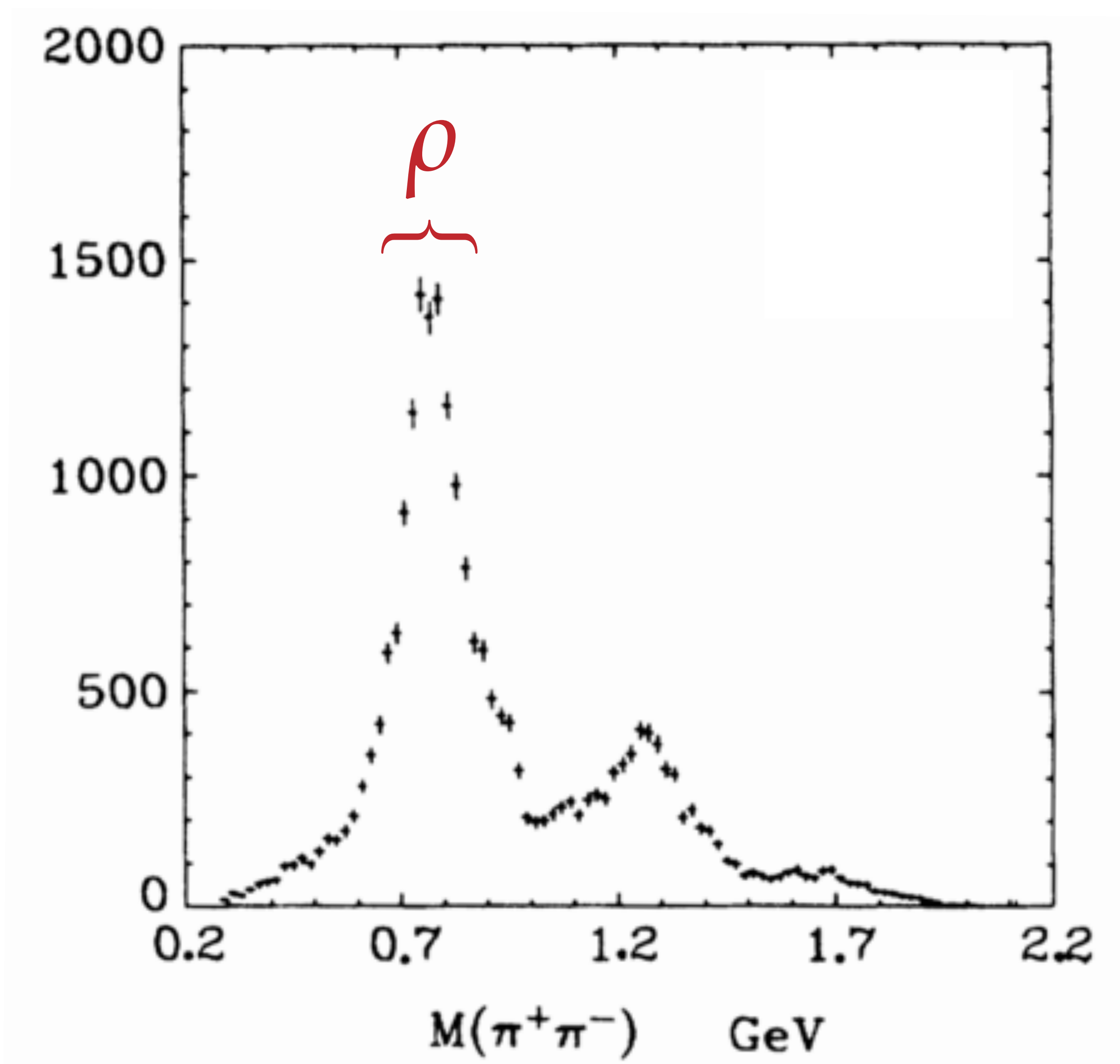
continuous distribution
of hadron states

Isospin=1 ππ P-wave

PHYSICAL REVIEW D VOLUME 7, NUMBER 5 1 MARCH 1973

ππ 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)

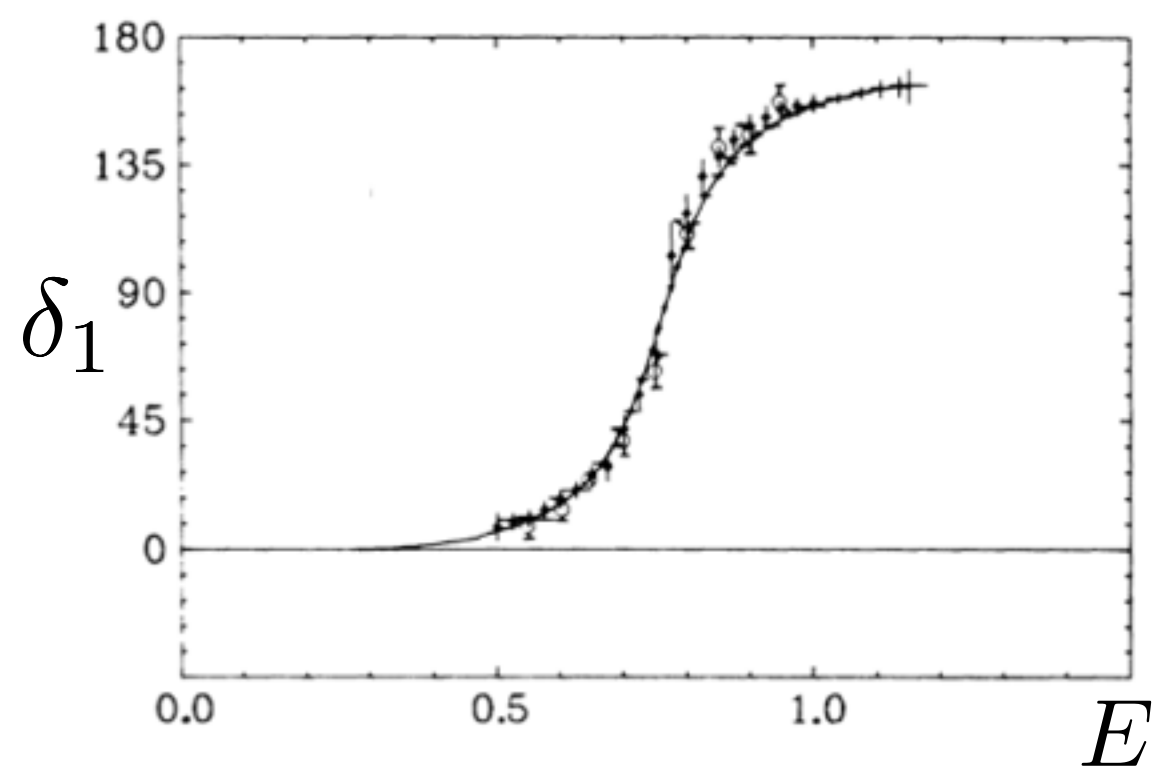


PARTIAL WAVE AMPLITUDE

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

expand angular dependence in *partial waves*

RESONANT PHASE SHIFT

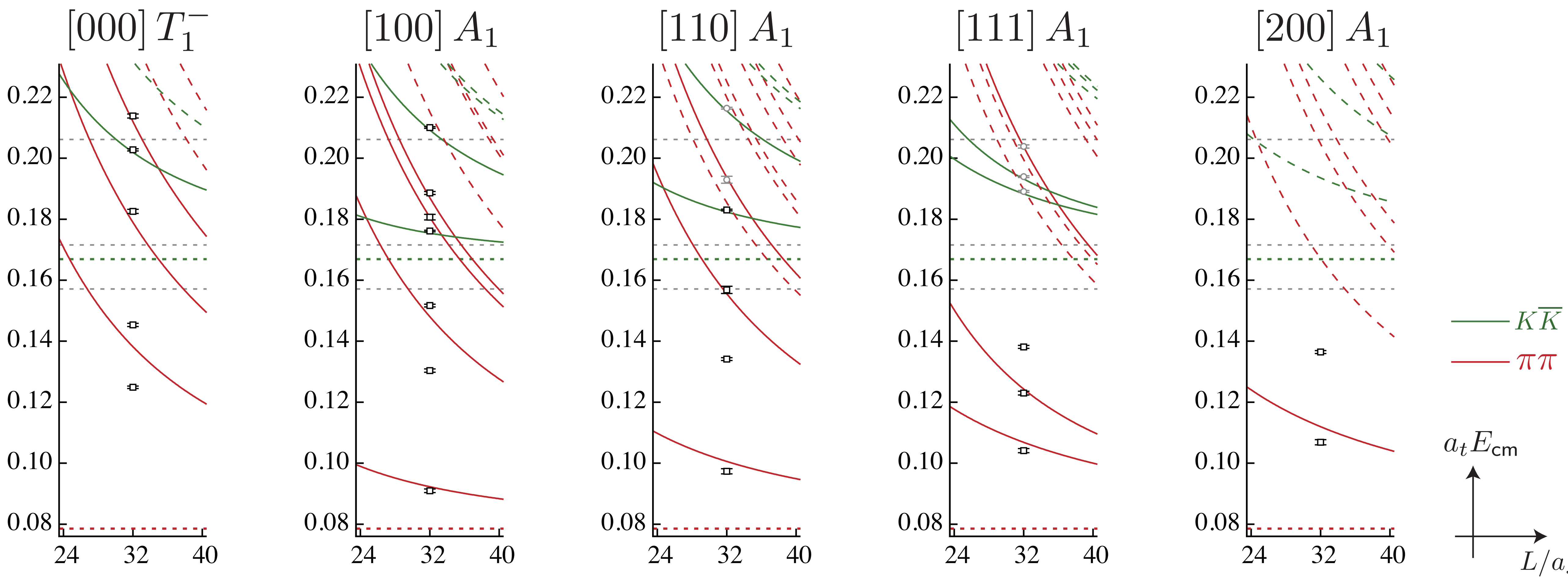


Finite-volume spectrum - moving frames

- Non-interacting thresholds and energies as a function of $\vec{k}$

$m_\pi \sim 236$ MeV

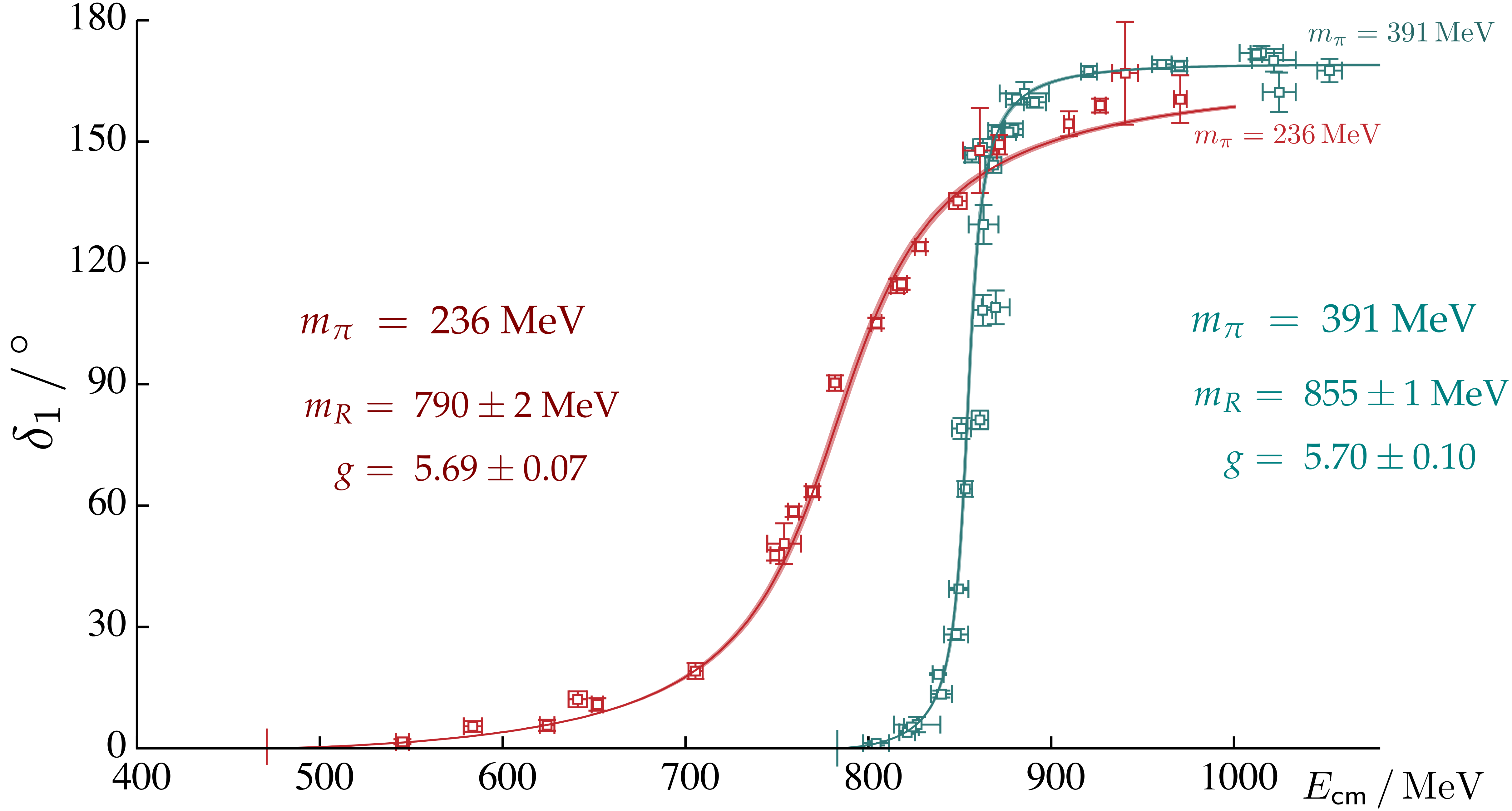
Momentum & lattice irrep labels: $[\vec{k}]\,\Lambda$



Strong volume dependence for light-pion noninteracting levels

ρ resonance at different pion masses

- BW couplings nearly constant in pion mass (will come back to this later…)

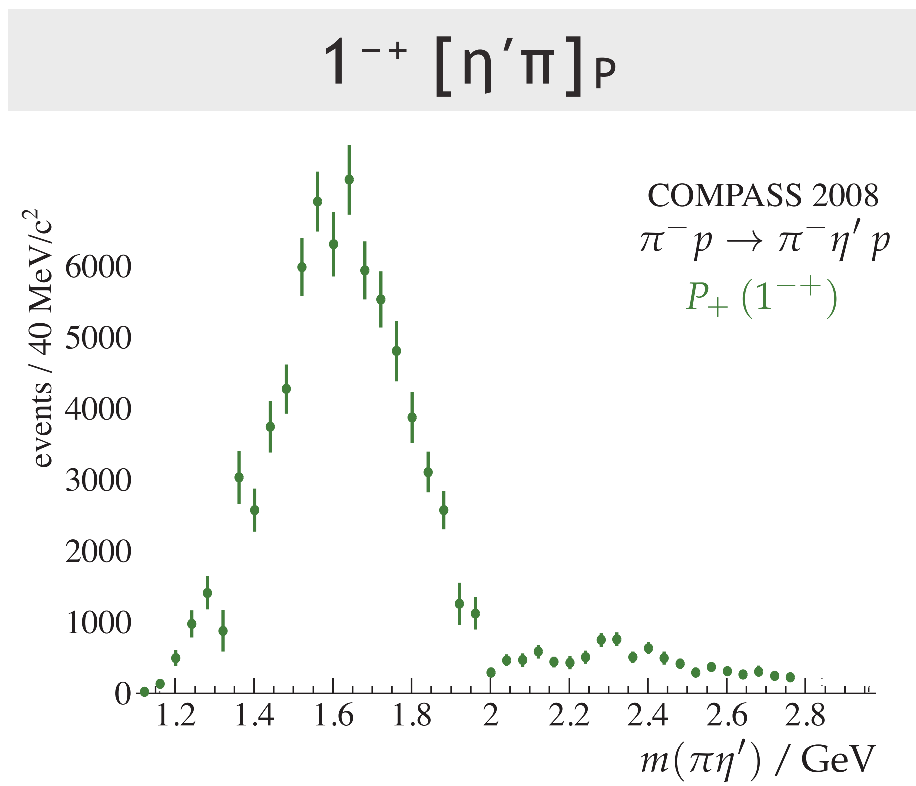


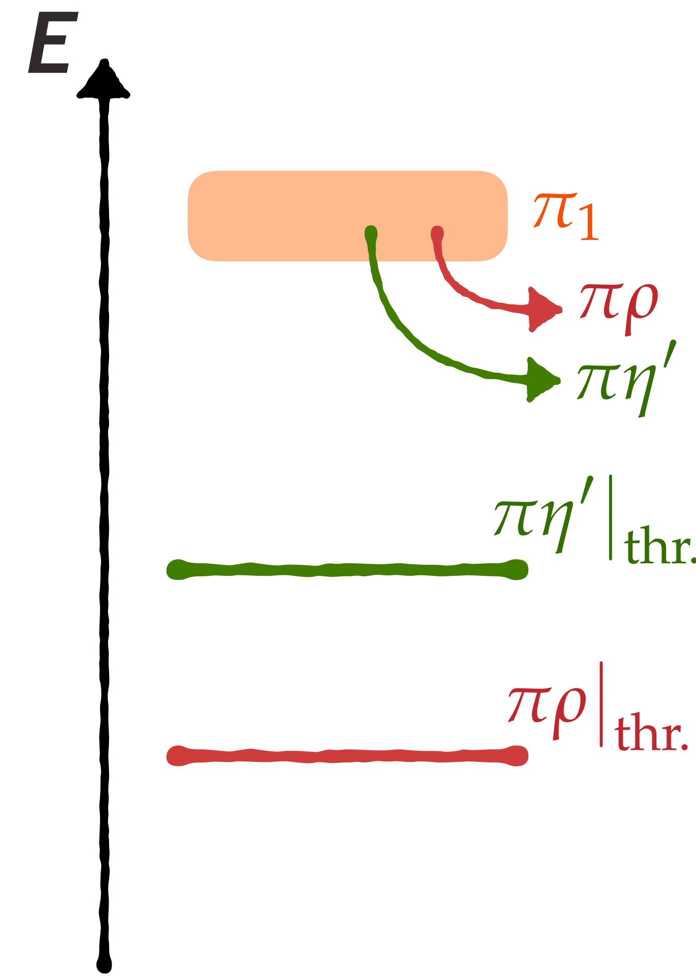
PRD 87 034505

Coupled-channel resonances in QCD

- But most excited resonances decay to more than one final state

coupled-channel resonances





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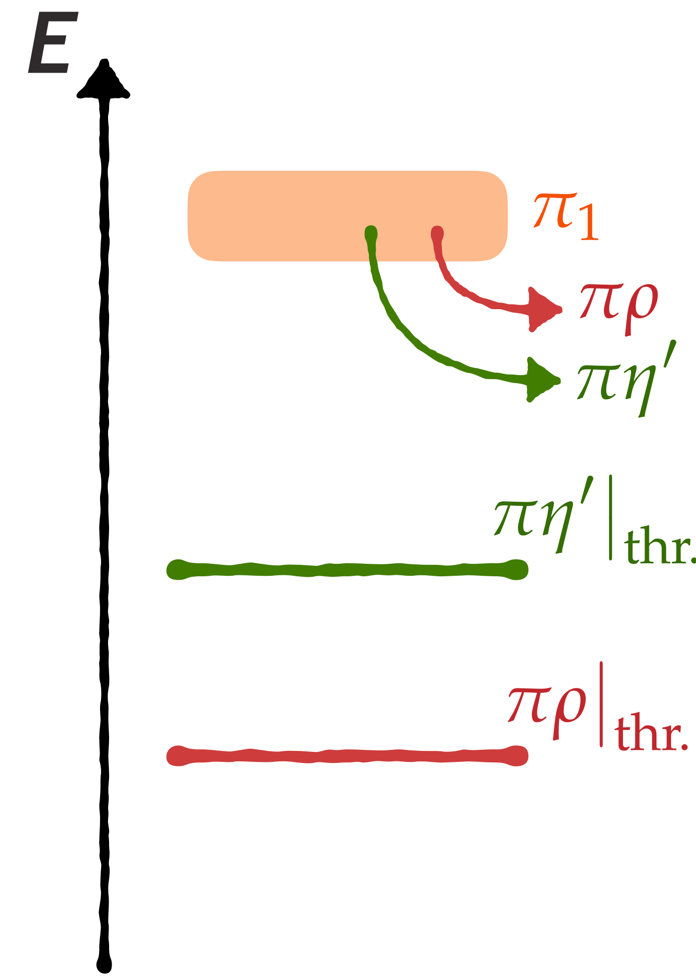
coupled-channel resonances

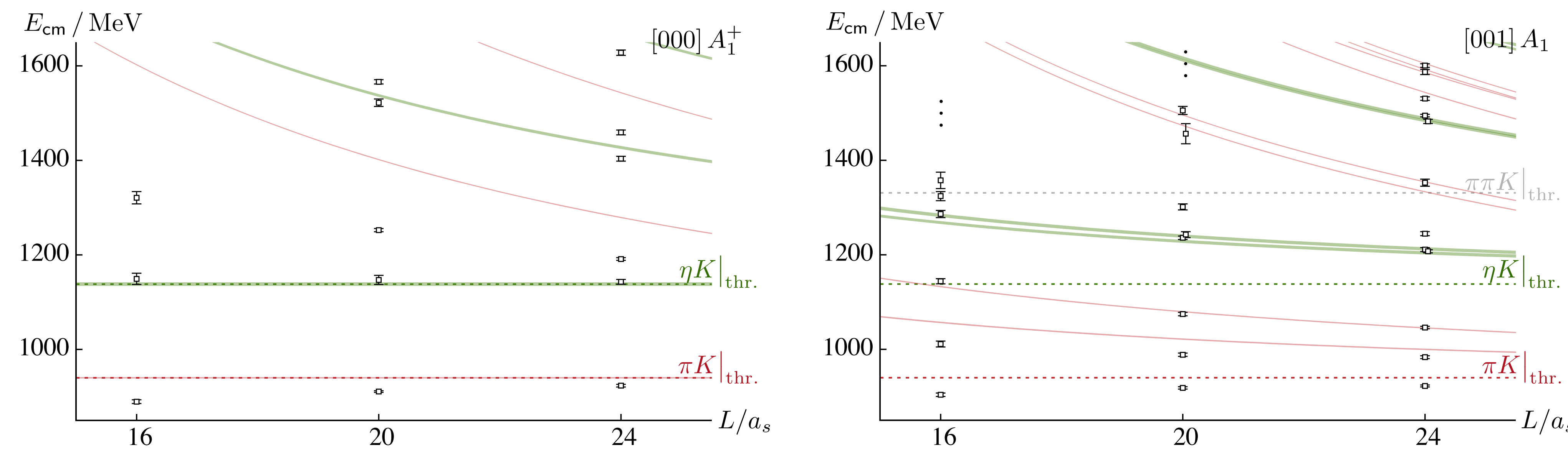


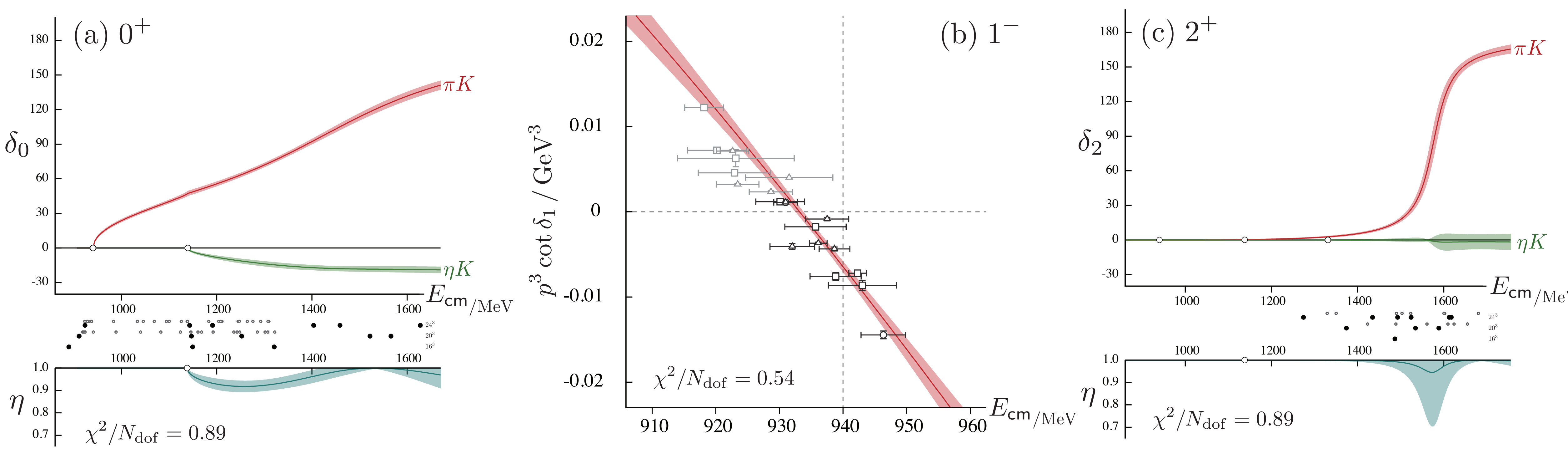
have recently seen the first determinations of coupled-channel resonances in QCD …

Coupled-channel resonances in QCD

- First case calculated explicitly: πK/ηK

PRL113 182001 (2014)
PRD91 054008 (2015)

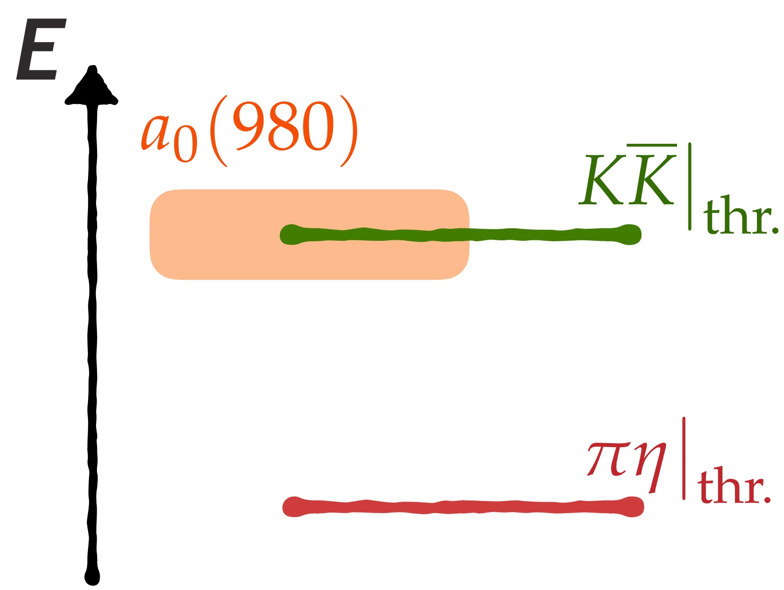


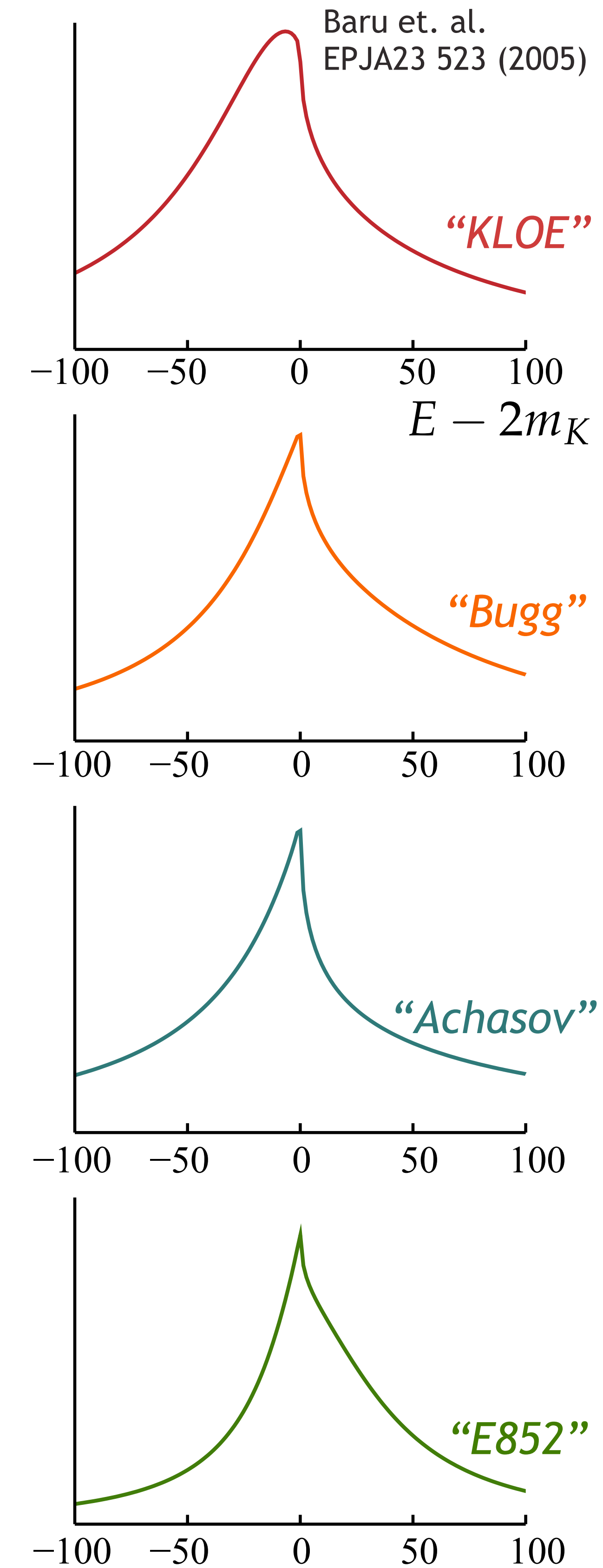


but these channels not strongly coupled …

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

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





- usually observed in 'less-simple' production processes

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

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

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

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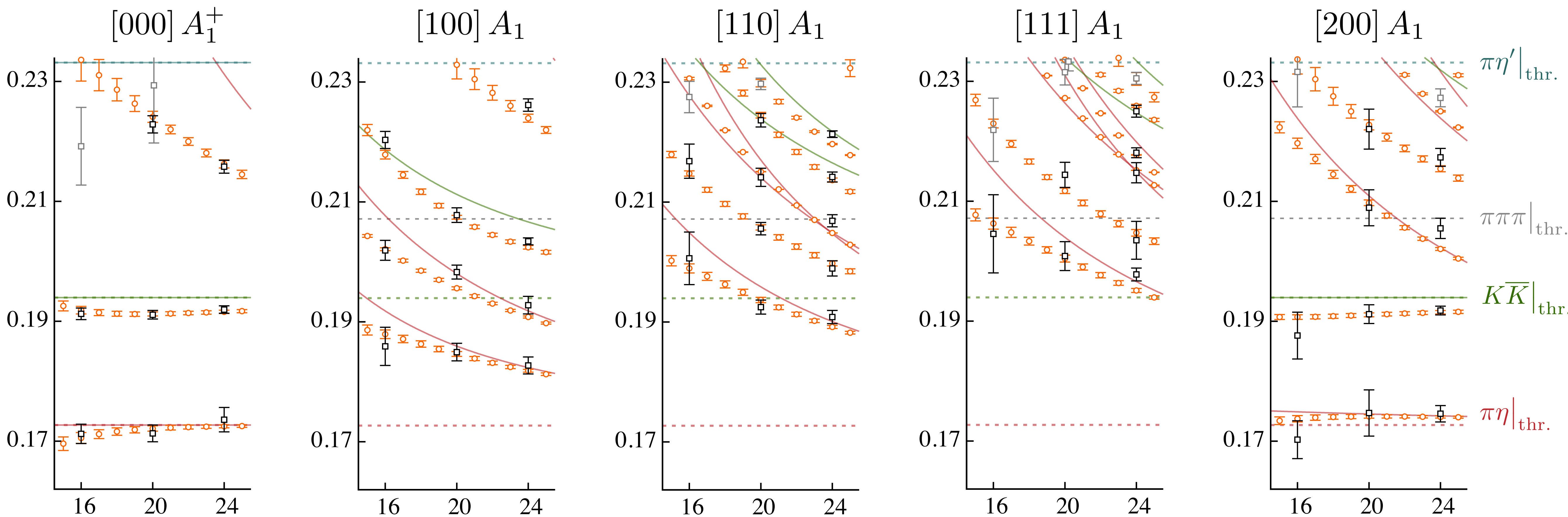
$\pi\eta/K\bar{K}$ scattering

- Spectrum as well as calculated spectrum from amplitudes

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

PRD (in press)



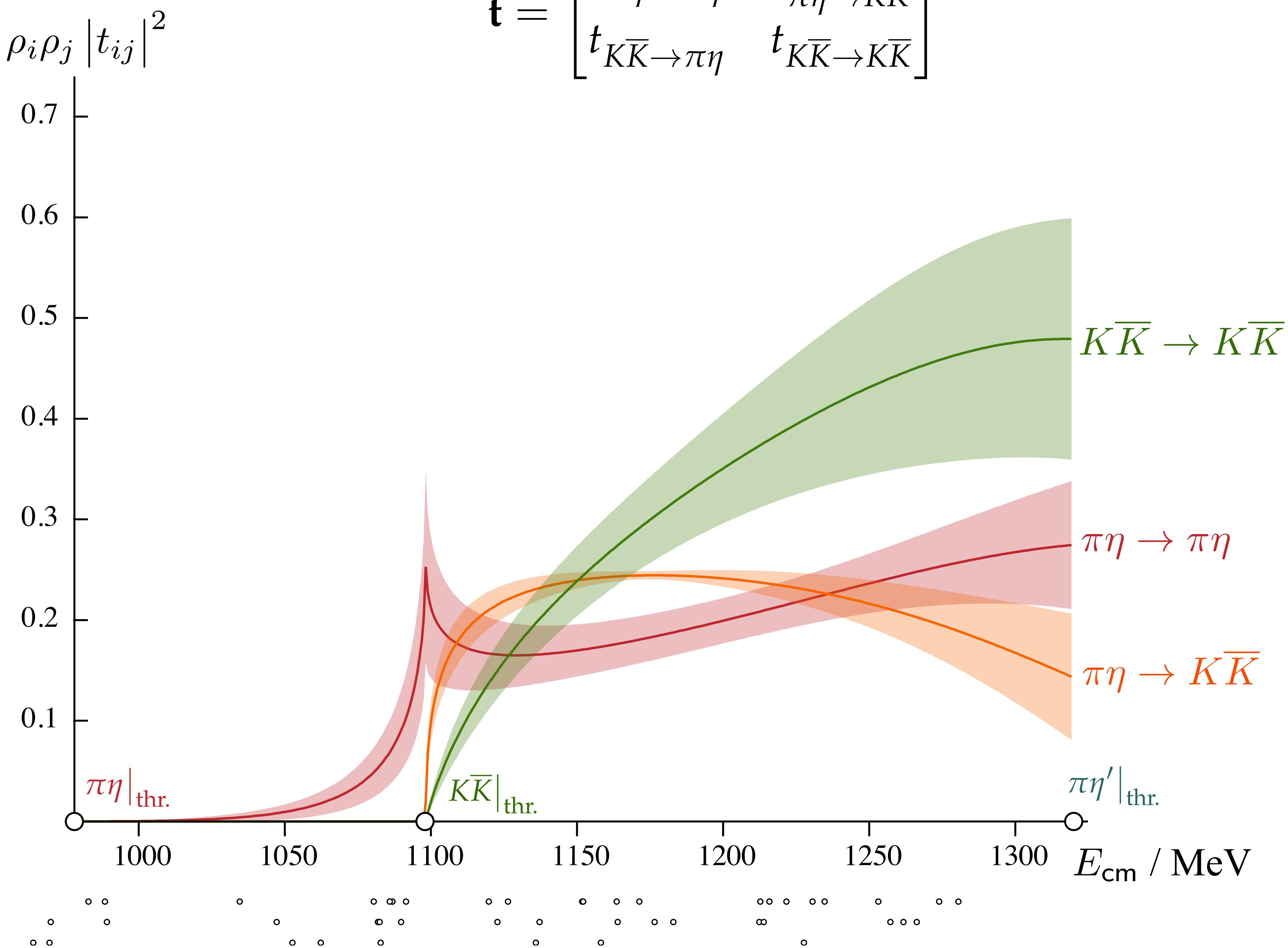
$\pi\eta/K\overline{K}$ scattering in $J^P = 0^+$

- Scattering amplitudes

$$\mathbf{t} = \begin{bmatrix} t_{\pi\eta\to\pi\eta} & t_{\pi\eta\to K\overline{K}} \\ t_{K\overline{K}\to\pi\eta} & t_{K\overline{K}\to K\overline{K}} \end{bmatrix}$$

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

PRD (in press)



$\pi\eta/K\bar{K}$ scattering in $J^P = 0^+$

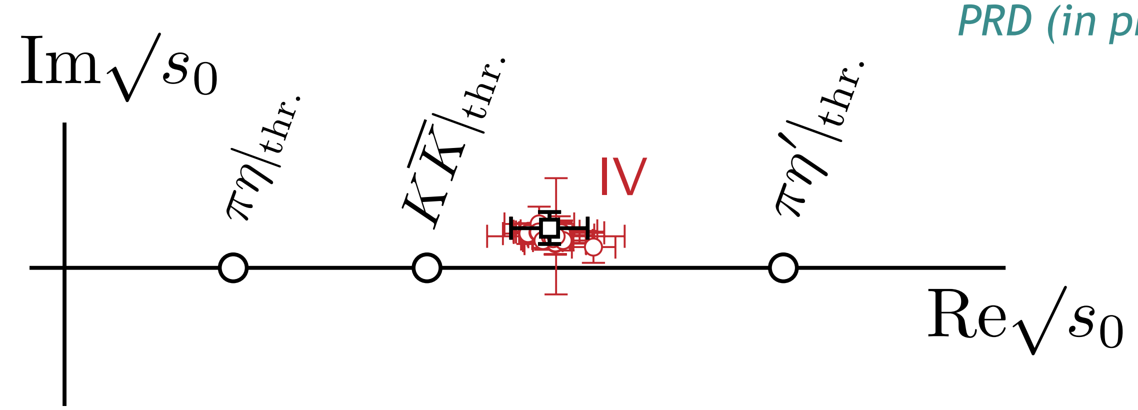
$m_\pi \sim 391\,\mathrm{MeV}$

PRD (in press)

strong cusp in $\pi\eta$ at $K\bar{K}$ threshold

rapid turn-on of $K\bar{K}$ amplitudes

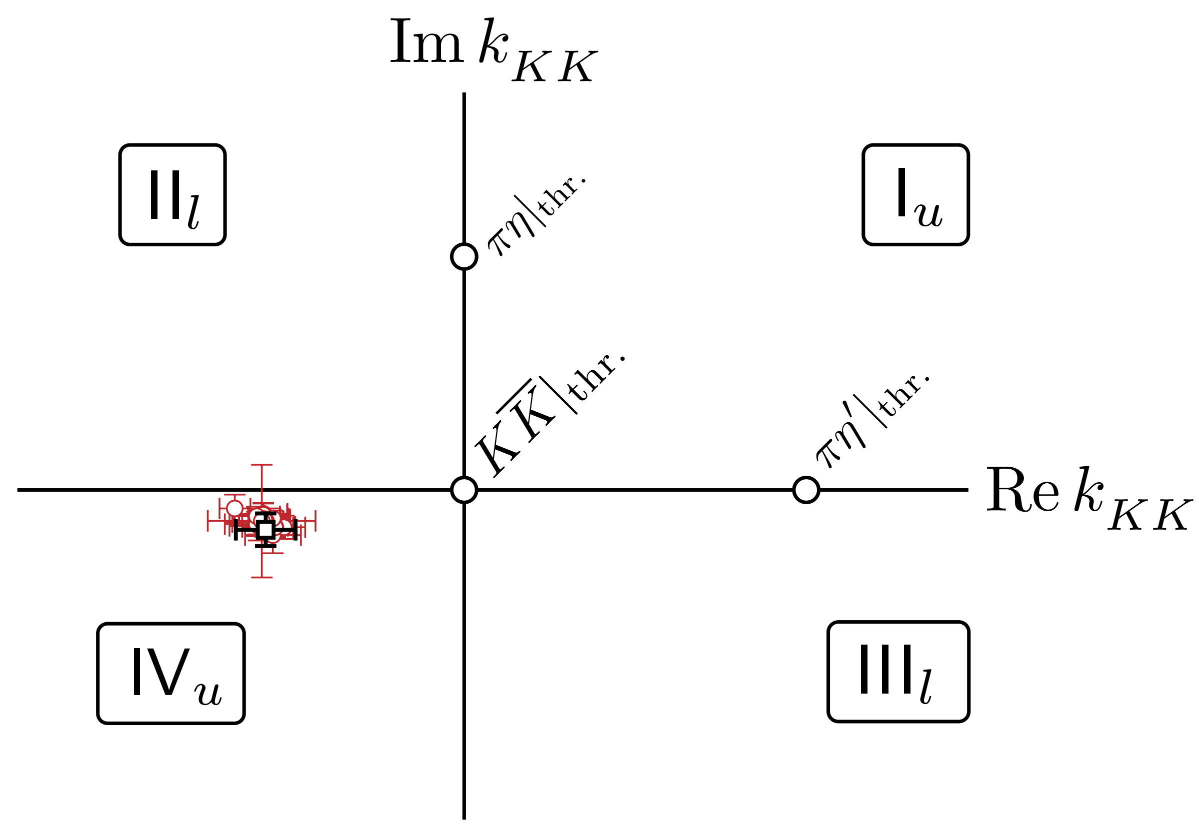
indicative of a nearby **resonance**



resonance
= a **pole** at complex $s = s_0$

$$t_{ij}(s) \sim \frac{g_i\, g_j}{s_0 - s}$$

$\mathrm{Re}[\sqrt{s_0}]$ ~ ‘mass’
$2\cdot\mathrm{Im}[\sqrt{s_0}]$ ~ ‘width’



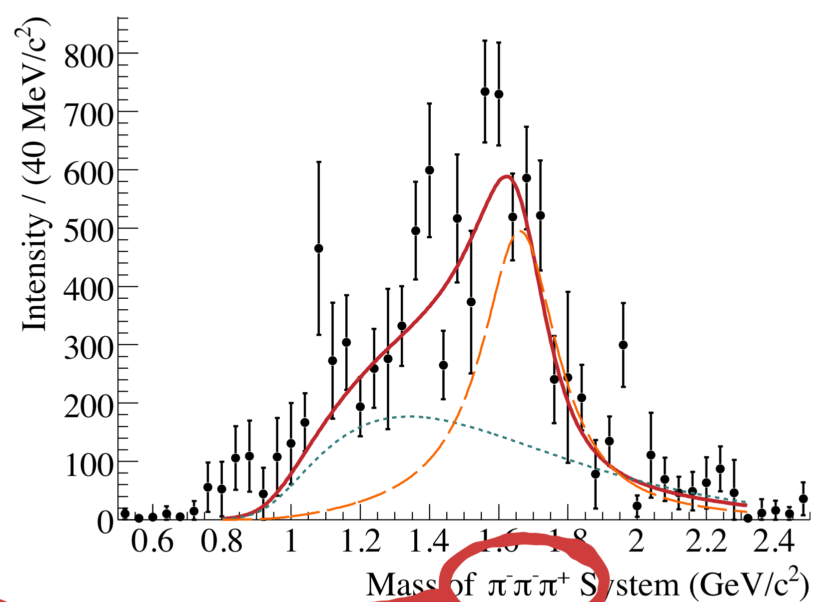
Sheet	$\mathrm{Im}k_{\pi\eta}$	$\mathrm{Im}k_{K\bar{K}}$
I	+	+
II	−	+
III	−	−
IV	+	−

a single pole on sheet IV ⇒ a **molecular interpretation** ?

Many-body decays of resonances in QCD

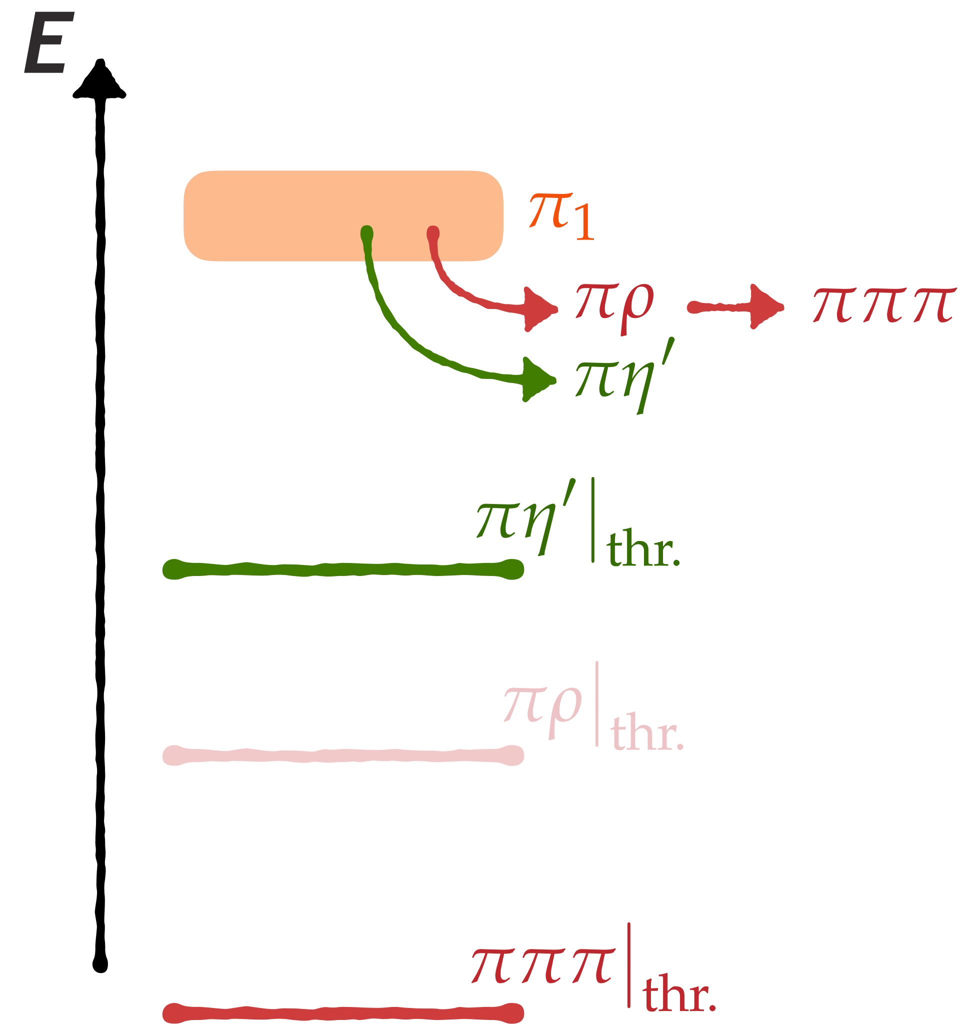
- Actually the true final-states can include more than two stable hadrons

$1^{-+}\,[\rho\pi]_P$



$\pi\pi\pi$

COMPASS Pb data
PRL104 241803 (2010)



This is the cutting edge of formalism …

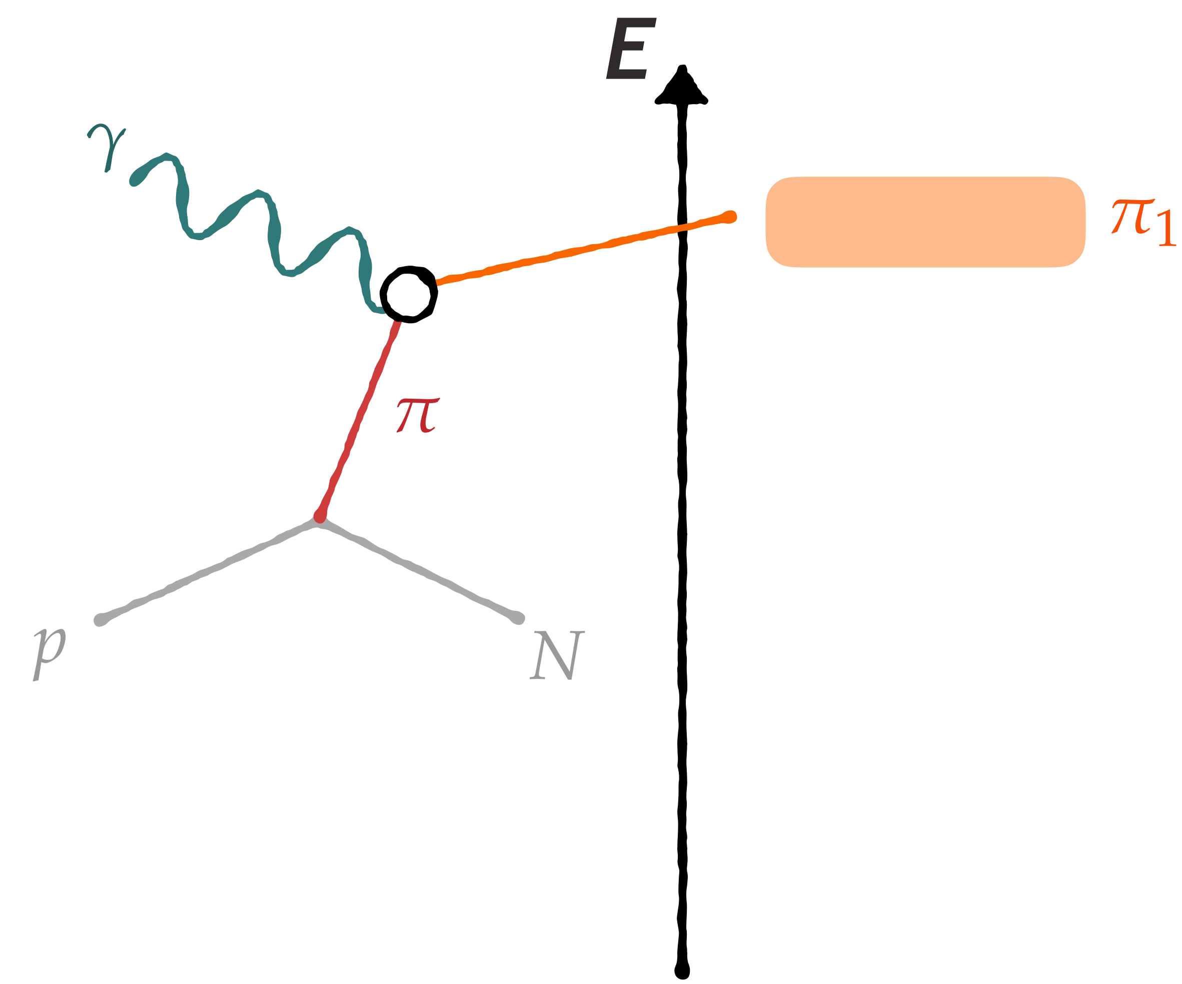
Briceno, Hansen, Sharpe …

A focus of our project

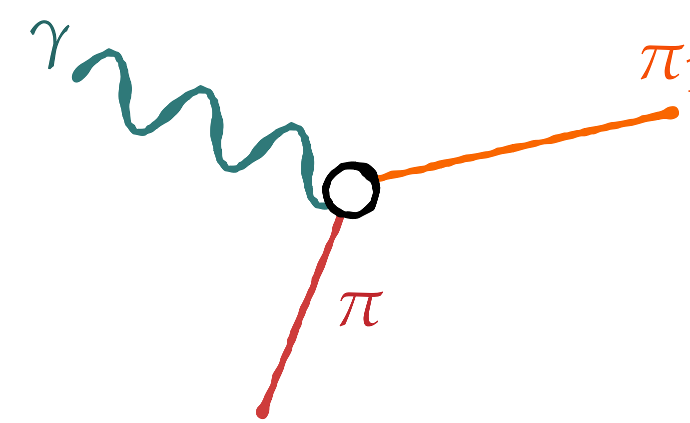
Resonances and currents

- What about production mechanisms ?

  e.g. photoproduction in **GlueX/CLAS12** ?

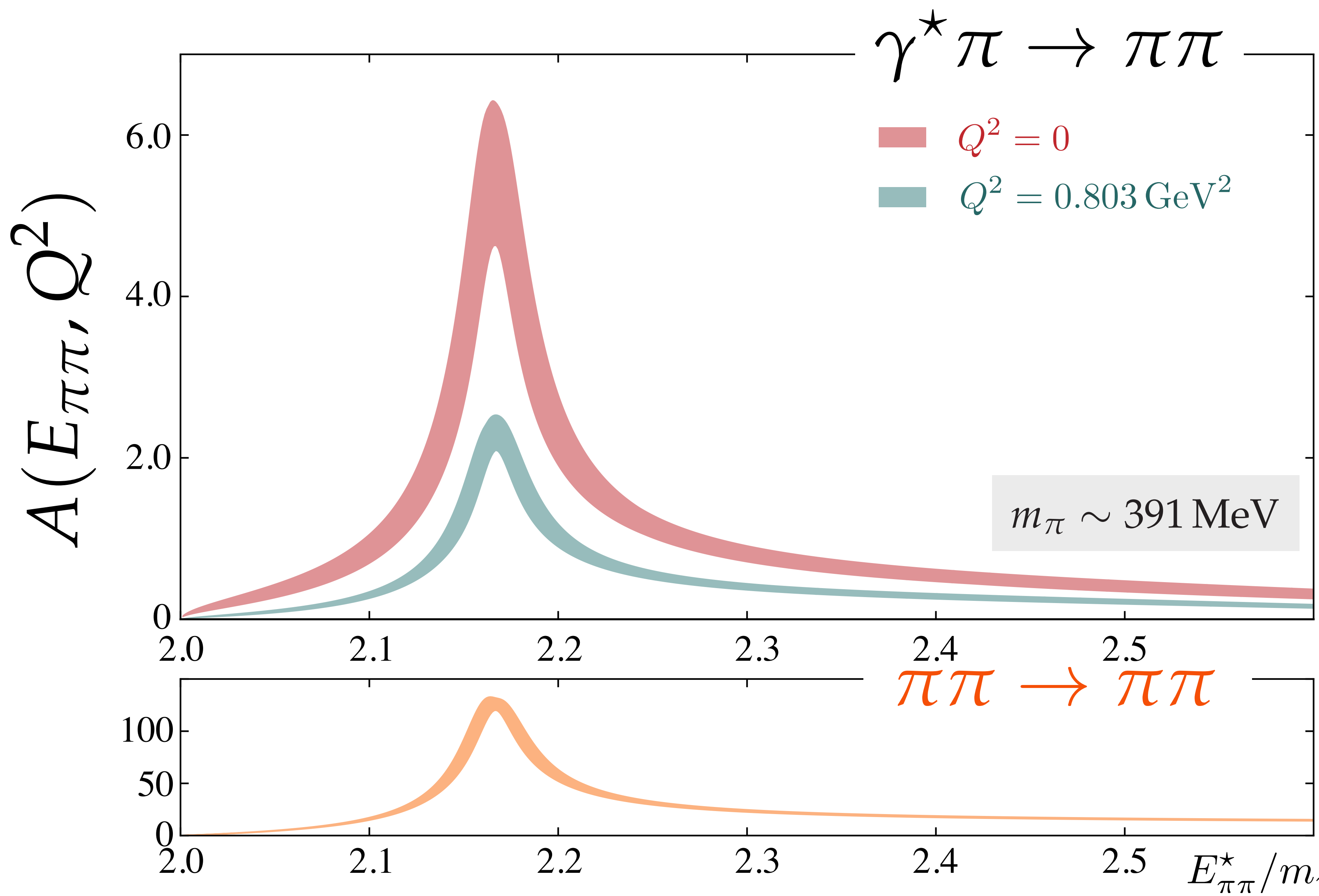


Need tools to study coupling of resonances to 'external' currents …



Resonances and currents : e.g. $\gamma\pi\rightarrow\pi\pi$

- First such calculation (of a simpler case) has recently appeared



PRL 115 242001 (2015)
arXiv: 1604.03530

Involvement with experimental program

Physics Opportunities with the 12 GeV Upgrade at Jefferson Lab

Jozef Dudek, Rolf Ent, Rouven Essig, Krishna Kumar, Curtis Meyer, Robert McKeown, Zein Eddine Meziani, Gerald A. Miller, Michael Pennington, David Richards, Larry Weinstein, Glenn Young

12 GeV science case

A study of decays to strange final states with GlueX in Hall D using components of the BaBar DIRC

(A proposal to the 42nd Jefferson Lab Program Advisory Committee)

M. Dugger,[1] B. Ritchie,[1] I. Senderovich,[1] E. Anassontzis,[2] P. Ioannou,[2] C. Kourkoumeli,[2] G. Vasileiadis,[2] G. Voulgaris,[2] N. Jarvis,[3] W. Levine,[3] P. Mattione,[3] W. McGinley,[3] C. A. Meyer,[3] R. Schumacher,[3] M. Staib,[3] F. Klein,[4] D. Sober,[4] N. Sparks,[4] N. Walford,[4] D. Doughty,[5] A. Barnes,[6] R. Jones,[6] J. McIntyre,[6] F. Mokaya,[6] B. Pratt,[6] W. Boeglin,[7] L. Guo,[7] E. Pooser,[7] J. Reinhold,[7] H. Al Ghoul,[8] V. Crede,[8] P. Eugenio,[8] A. Ostrovidov,[8] A. Tsaris,[8] D. Ireland,[9] K. Livingston,[9] D. Bennett,[10] J. Bennett,[10] J. Frye,[10] M. Lara,[10] J. Leckey,[10] R. Mitchell,[10] K. Moriya,[10] M. R. Shepherd,[10] O. Chernyshov,[11] A. Dolgolenko,[11] A. Gerasimov,[11] V. Goryachev,[11] I. Larin,[11] V. Matveev,[11] V. Tarasov,[11] F. Barbosa,[12] E. Chudakov,[12] M. Dalton,[12] A. Deur,[12] J. Dudek,[12] H. Egiyan,[12] S. Furletov,[12] M. Ito,[12] D. Mack,[12] D. Lawrence,[12] M. McCaughan,[12] M. Pennington,[12] L. Pentchev,[12] Y. Qiang,[12] E. Smith,[12] A. Somov,[12] S. Taylor,[12] T. Whitlatch,[12] B. Zihlmann,[12]

Second phase of GlueX program with BaBar DIRC-s (approved)

Studies of Nucleon Resonance Structure in Exclusive Meson Electroproduction

I. G. Aznauryan,[1,2] A. Bashir,[3] V. M. Braun,[4] S. J. Brodsky,[5,6] V. D. Burkert,[2] L. Chang,[7,8] Ch. Chen,[7,9,10] B. El-Bennich,[11,12] I. C. Cloët,[7,13] P. L. Cole,[14] R. G. Edwards,[2] G. V. Fedotov,[15,16] M. M. Giannini,[17,18] R. W. Gothe,[15] F. Gross,[2,19] Huey-Wen Lin,[20] P. Kroll,[21,4] T.-S. H. Lee,[7] W. Melnitchouk,[2] V. I. Mokeev,[2,16] M. T. Peña,[22,23] G. Ramalho,[22] C. D. Roberts,[7,10] E. Santopinto,[18] G. F. de Teramond,[24] K. Tsushima,[13,25] and D. J. Wilson[7,26]

JLab CLAS12 expt (approved)

Exclusive $N^* \to KY$ Studies with CLAS12

Daniel S. Carman *(contact person, spokesperson)*, Victor Mokeev *(spokesperson)*, Harut Avakian, Volker Burkert, Eugene Pasyuk
Jefferson Laboratory, Newport News, VA 23606, USA

Robert G. Edwards, Michael R. Pennington, David G. Richards, Adam Szczepaniak[†]
Theory Center, Jefferson Laboratory, Newport News, VA 23606, USA
([†] Joint with Indiana University, Bloomington, IN 47405)

Hybrid baryons
CLAS12 expt (approved)

Searching for the Rules that Govern Hadron Construction

J. Dudek, R. Mitchell, M. Shepherd

Expt/Theory Review for Nature (in press)

Looking towards the future

Computational Nuclear Physics Meeting
SURA Headquarters, Washington DC, July 14-15, 2014

REPORT

Prepared by the Computational Nuclear Physics Meeting Writing Committee
A. Burrows, J. Carlson, W. Detmold, R. Edwards, R. Furnstahl, F. Karsch, W. Nazarewicz, P. Petreczky, D. Richards, W. Hicks, M.J. Savage.

Town Hall report providing input for 2015 NSAC Long Range Plan

NSAC Long Range Plan appeared in 2015

Strong endorsement of LQCD spectroscopy program (page 13)

The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

Underscoring this huge progress, LQCD plays an essential role in guiding experimental work. GlueX at JLab, one of the flagship experiments of the 12-GeV Upgrade, is designed to search for exotic particles where the glue is in an energetically excited state. Initial LQCD calculations motivated the experiment and guided its design. Recent LQCD results confirm the mass range of the predicted particles. And in the future, LQCD calculations of hadron dynamics will play a critical role in the analysis of the data.

Hadron Spectrum Collaboration

JEFFERSON LAB

Jozef Dudek
Robert Edwards
Balint Joo
David Richards
Raul Briceno

TRINITY, DUBLIN

Michael Peardon
Sinead Ryan
Cian O Hara
Vanessa Koch
Barry Thornton
David Tims

CAMBRIDGE

Christopher Thomas
Graham Moir
David Wilson
Gavin Cheung
Antoni Woss

MESON SPECTRUM

***PRL**103 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)	$D,\ D_s$

HADRON SCATTERING

PRD83 071504 (2011)	$\pi\pi\ I=2$
PRD86 034031 (2012)	$\pi\pi\ I=2$
PRD87 034505 (2013)	$\pi\pi\ I=1,\ \rho$
***PRL**113 182001 (2014)*	$\pi K, \eta K : K^\star$
PRD91 054008 (2015)	$\pi K, \eta K : K^\star$
PRD92 094502 (2015)	$\pi\pi, K\bar{K} : \rho$
PRD (to appear)	$\pi\eta, K\bar{K} : a_0$

BARYON SPECTRUM

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

MATRIX ELEMENTS

PRD91 114501 (2015)	$M' \to \gamma M$
PRD90 014511 (2014)	$f_{\pi^\star}$
***PRL**115 242001 (2015)*	$\gamma^\star\pi \to \pi\pi$

LATTICE TECH.

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

Summary

- LQCD spectroscopy program maturing. First phase:
  - With only “single-hadron” operators obtain sketch of hadron spectrum
  - Suggests rich spectrum of mesons & baryons - exotic & non-exotic hybrids
  - ➡ Direct impact on expt. program -> instigated new expt. proposals

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- *Goal is to compute resonance information - decays & branching fractions*
  - Including multi-hadron operators leads to richer spectrum
  - Demonstrated viability of finite-volume methods
  - S-matrix formalism increasingly important - extended collabs. with JPAC, …

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  - Including multi-hadron operators leads to richer spectrum
  - Demonstrated viability of finite-volume methods
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- Near term:
  - Use multiple volumes over range of pion masses -> poles & couplings
  - ➡ Knowledge of even size of branching fractions useful for expt. analysis

- Long term:
  - Switch to isotropic lattices at physical limit
  - Envision merging spectroscopy and structure projects
    - ➡ Understanding role of gluonic structures

Four-particle effects

We don't know the equation that describes 2π-4π spectrum, but we know it will have the form:

$$\det\left[\begin{pmatrix} F_{2\pi} & \\ & F_{4\pi} \end{pmatrix}^{-1} + \begin{pmatrix} \mathcal{M}_{2\pi,2\pi} & \mathcal{M}_{2\pi,4\pi} \\ \mathcal{M}_{4\pi,2\pi} & \mathcal{M}_{4\pi,4\pi} \end{pmatrix}\right] = 0$$

$F_a(L, E_{L,n})$: finite volume function, (don't know it for 4π)

$\mathcal{M}_{a,b}(E_{L,n})$: scattering amplitude coupling ath and bth channel

$E_{L,n}$: energy level for the nth state, which satisfies the equation above

---

If $\mathcal{M}_{2\pi,4\pi} \sim \mathcal{O}(\epsilon)$

$$\det\left[F_{2\pi}^{-1} + \mathcal{M}_{2\pi,2\pi}\right] \times \det\left[F_{4\pi}^{-1} + \mathcal{M}_{4\pi,4\pi}\right] + \mathcal{O}(\epsilon) = 0$$

Two spectra that do not talk to each other.

Same argument applies for charmonium systems:

$$(E_{L,n} - E_{J/\Psi}) \times \det\left[F_{Nbody} + \mathcal{M}_{Nbody}\right] + \mathcal{O}(\epsilon) = 0$$

Four-particle effects

Two-point correlation functions:

$$C_{ab}^{2pt.}(t,\mathbf{P}) \equiv \langle 0|\mathcal{O}_b(t,\mathbf{P})\mathcal{O}_a^\dagger(0,-\mathbf{P})|0\rangle = \sum_n Z_{b,n} Z_{a,n}^\dagger e^{-E_n t}$$

Assume only a basis of two-particle operators is used, and $\mathcal{M}_{2\pi,4\pi} \sim \mathcal{O}(\epsilon)$

If the n^th state satisfies

$$\det\left[F_{4\pi}^{-1} + \mathcal{M}_{4\pi,4\pi}\right] + \mathcal{O}(\epsilon) = 0$$

The overlap with the n^th would be vanishingly small

$$|Z_{2\pi,n}|^2 = |\langle 0|(2\pi)|n, E_{L,n}\rangle|^2 \sim |\mathcal{M}_{2\pi,4\pi}|^2 \sim \mathcal{O}(\epsilon^2)$$

following arguments presented in
Briceño, Hanse & Walker-Loud (2014)

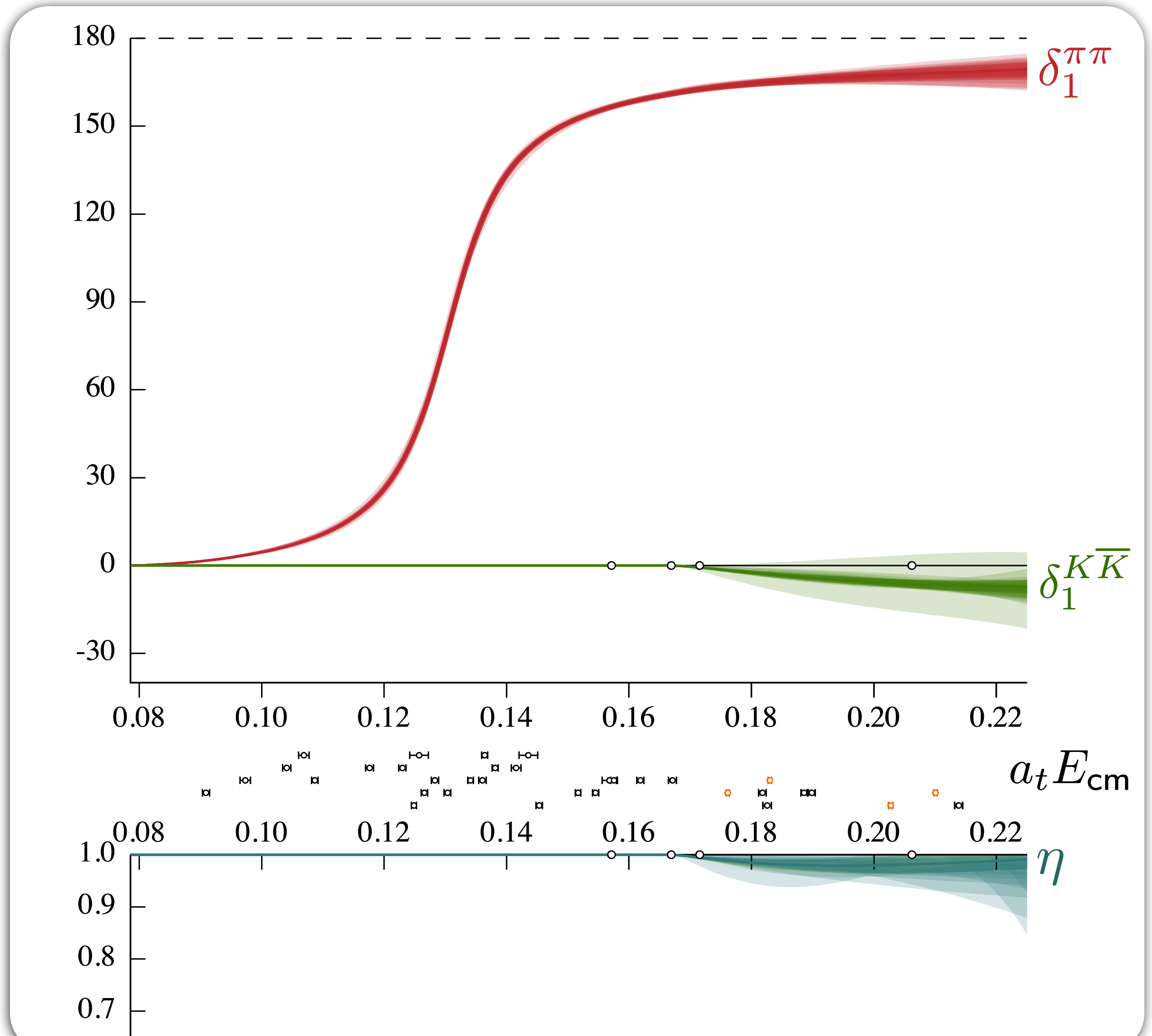
Again, it is this same principle which allows for the study of charmonia on the lattice, despite the fact that any number of light multi-meson states can go on-shell.

Consistency check

If this form were not true:

$$\det\left[\begin{pmatrix} F_{\pi\pi} & \\ & F_{K\overline{K}} \end{pmatrix}^{-1} + \begin{pmatrix} \mathcal{M}_{\pi\pi,\pi\pi} & \mathcal{M}_{\pi\pi,K\overline{K}} \\ \mathcal{M}_{\pi\pi,K\overline{K}} & \mathcal{M}_{K\overline{K},K\overline{K}} \end{pmatrix}\right] \times \det\left[F_{4\pi}^{-1} + \mathcal{M}_{4\pi,4\pi}\right] + \mathcal{O}(\epsilon) = 0$$

and/or the overlap argument were not true, the two-body coupled-channel formalism would not describe the spectrum properly above the 4π threshold



...but it does...

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Coupled-channel scattering

He, JHEP 0507 011
Hansen, PRD86 016007
Briceno, PRD88 094507
Guo, PRD88 014051

- Finite-volume formalism derived (multiple methods)

$$\det\left[\left(\left[t^{(\ell)}(E)\right]^{-1}_{ij} + i\rho_i(E)\,\delta_{ij}\right) - \delta_{ij}\,\mathcal{M}_\ell\big(p_i(E)L\big)\right] = 0$$

scattering matrix

phase space

known functions

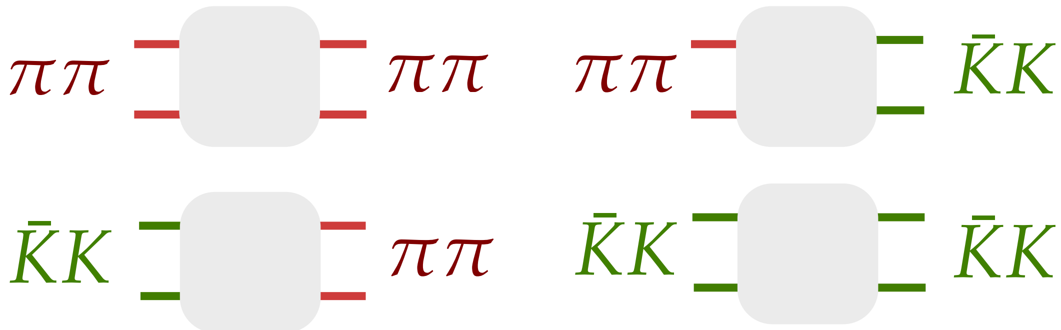
matrices in partial-wave space ...

- However, this is **one equation** for **multiple unknowns** (per energy level) $\frac{1}{2}N(N+1)$ for *N* channels
  - parameterize the energy dependence of *t*
  - try to describe a spectrum globally

"Energy-dependent" analysis

ρ resonance as a coupled channel system

- Parameterize the t-matrix in a unitarity conserving way



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

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

  - Vary the parameters, solving

$$\det\left[\left([t^{(\ell)}(E)]_{ij}^{-1} + i\rho_i(E)\,\delta_{ij}\right) - \delta_{ij}\,\mathcal{M}_\ell(E,L)\right] = 0$$

for the spectrum in each irreducible representation & momentum

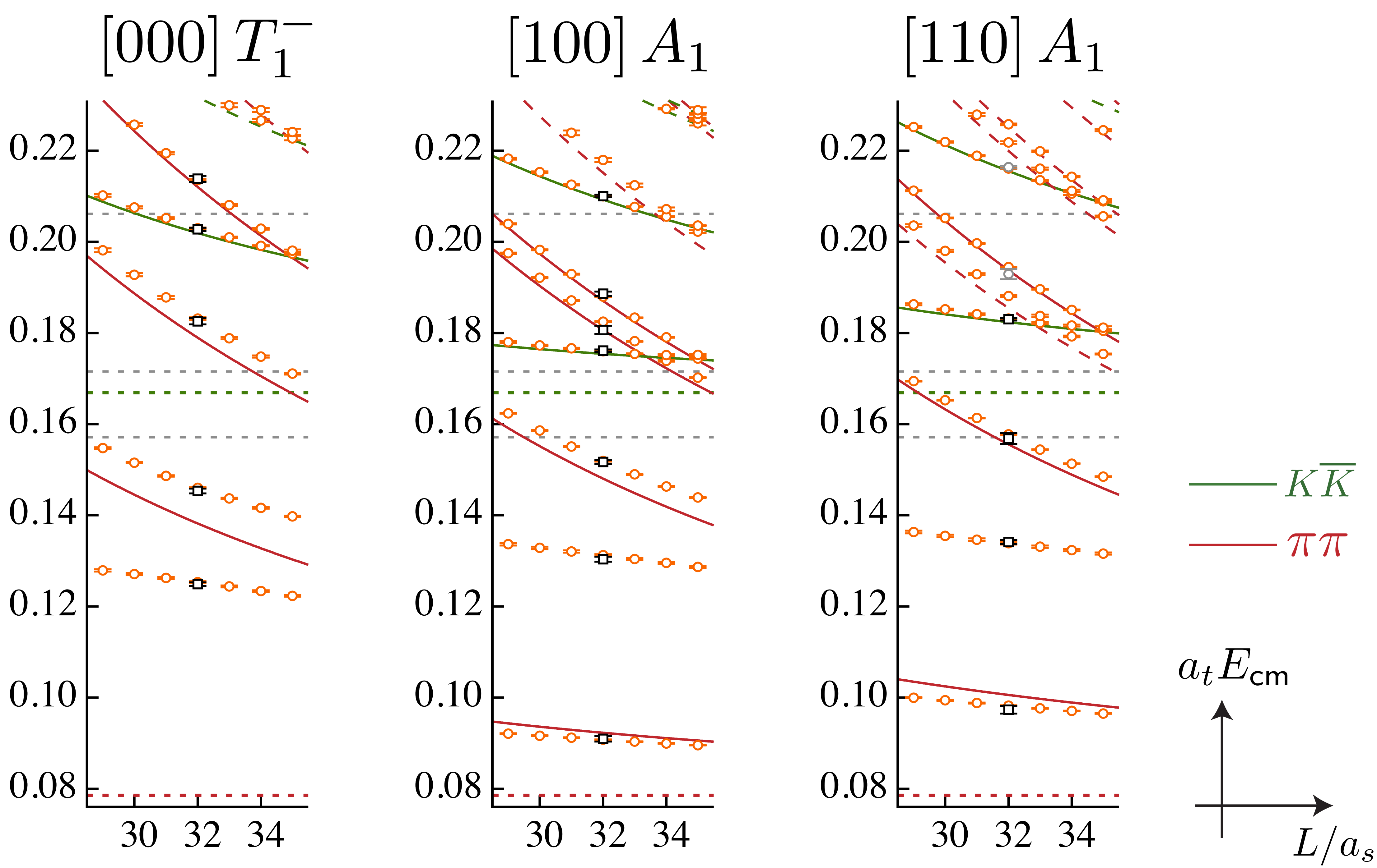
Want pole mass and couplings of t-matrix

Jefferson Lab

$\pi\pi/KK$ scattering

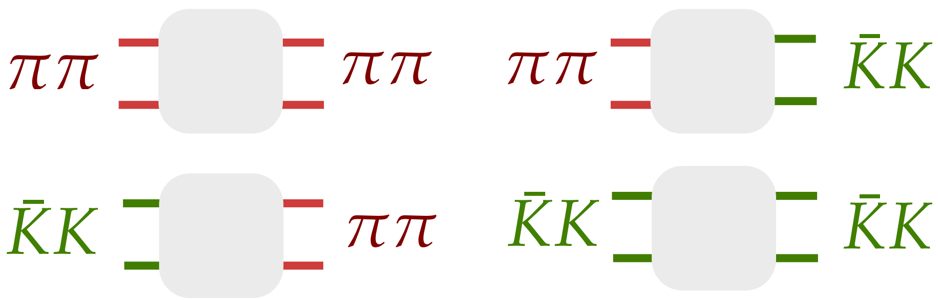
- Data points (black) compared to parameterization (gold)

$m_\pi \sim 236$ MeV

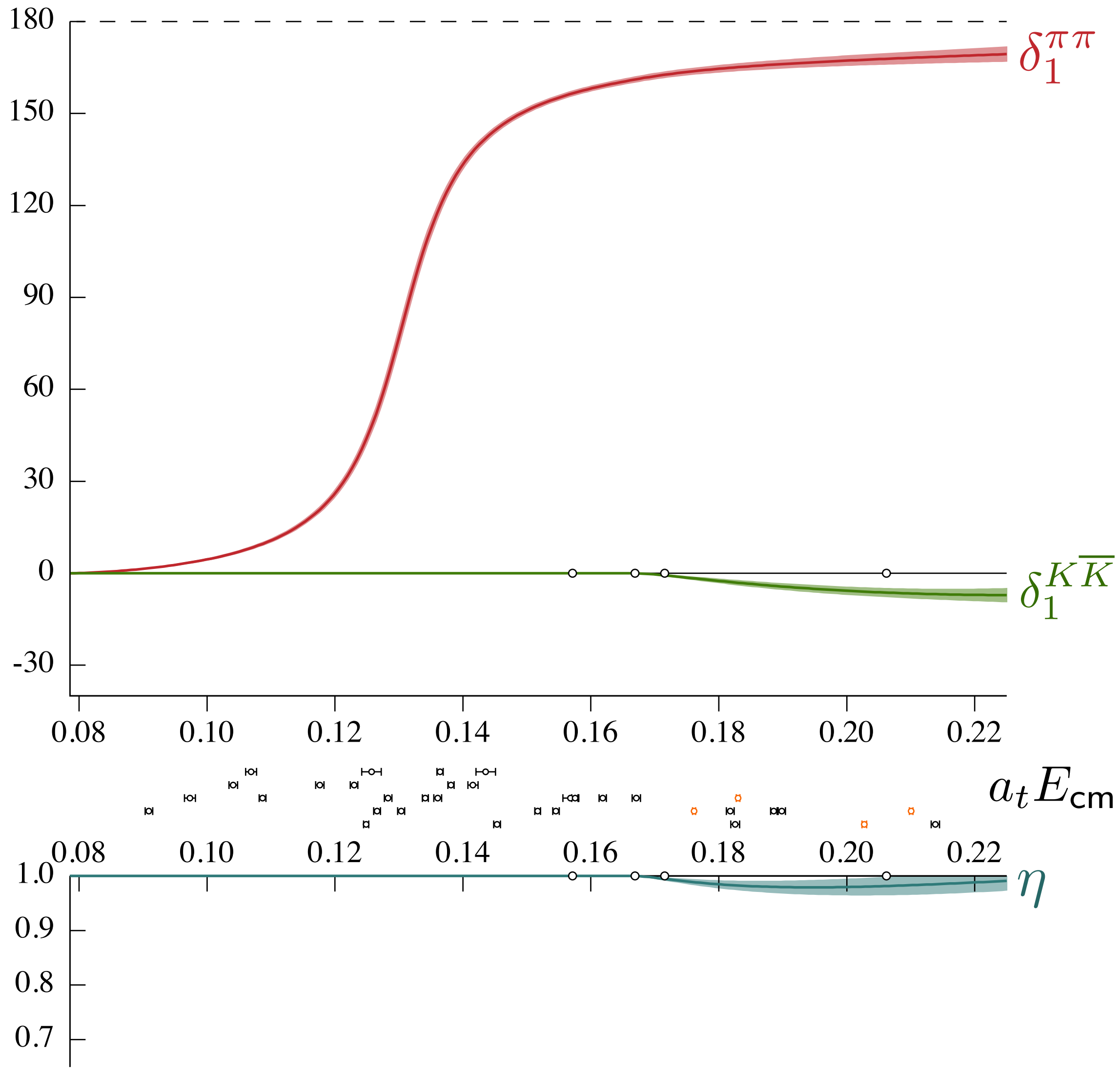


Jefferson Lab

ρ resonance as a coupled channel system

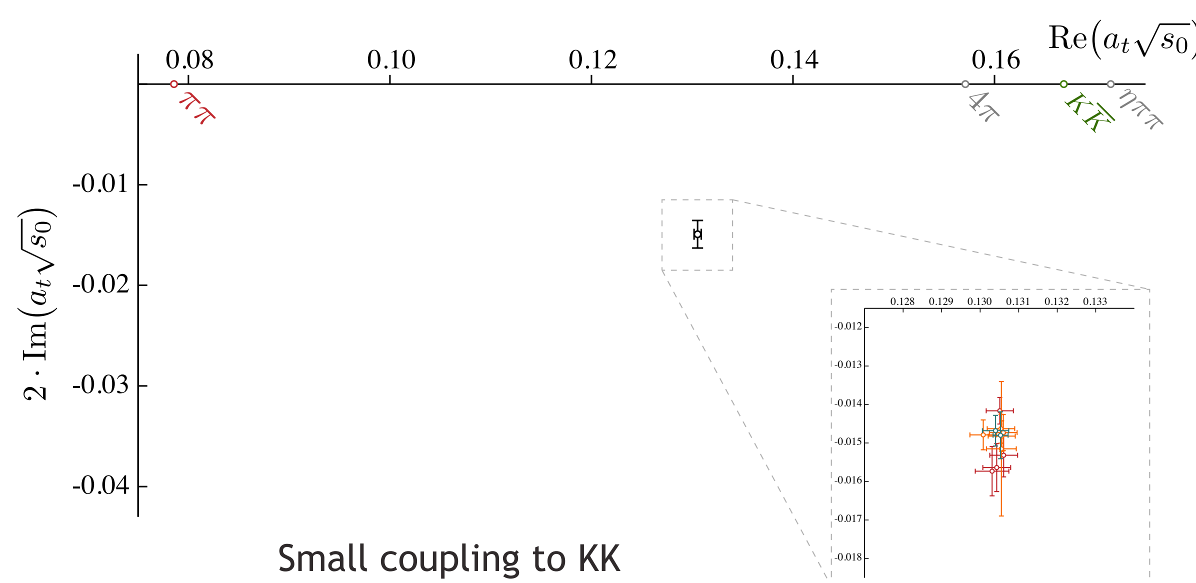


Phase shifts & inelasticity



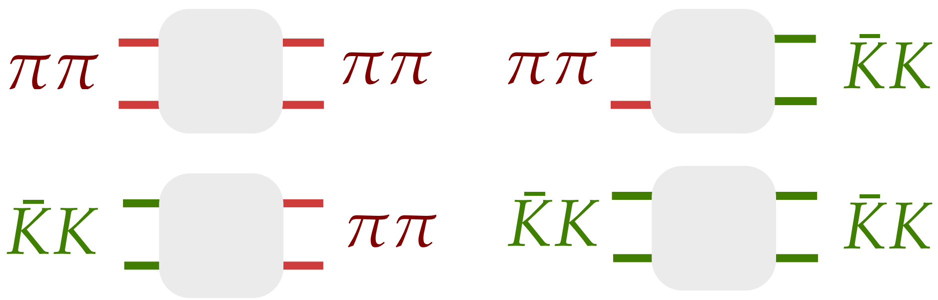
$m_\pi \sim 236$ MeV

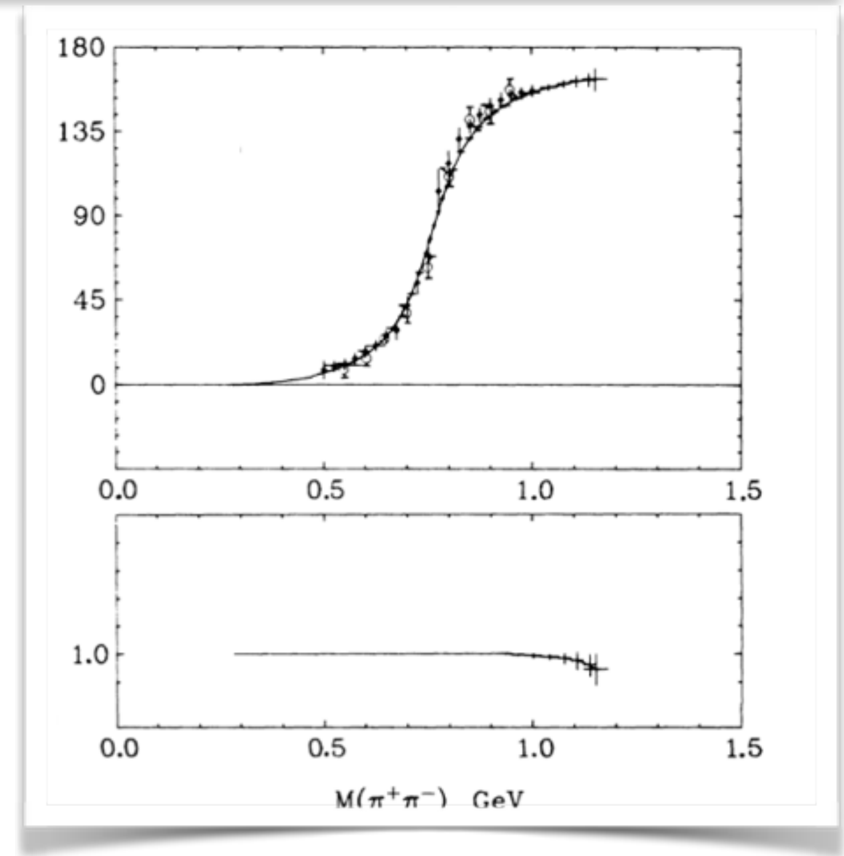
t-matrix pole location



Small coupling to KK

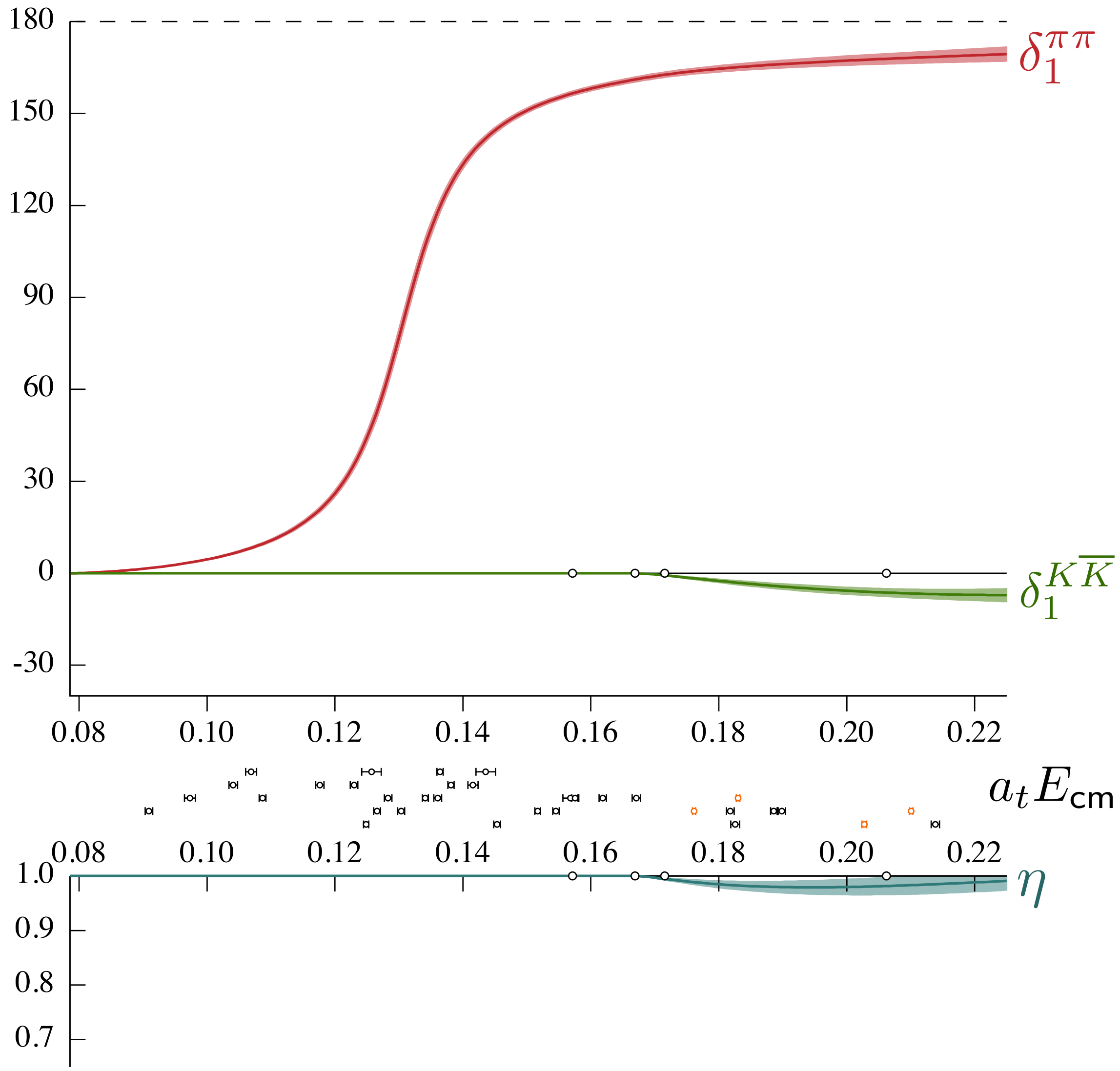
ρ resonance as a coupled channel system



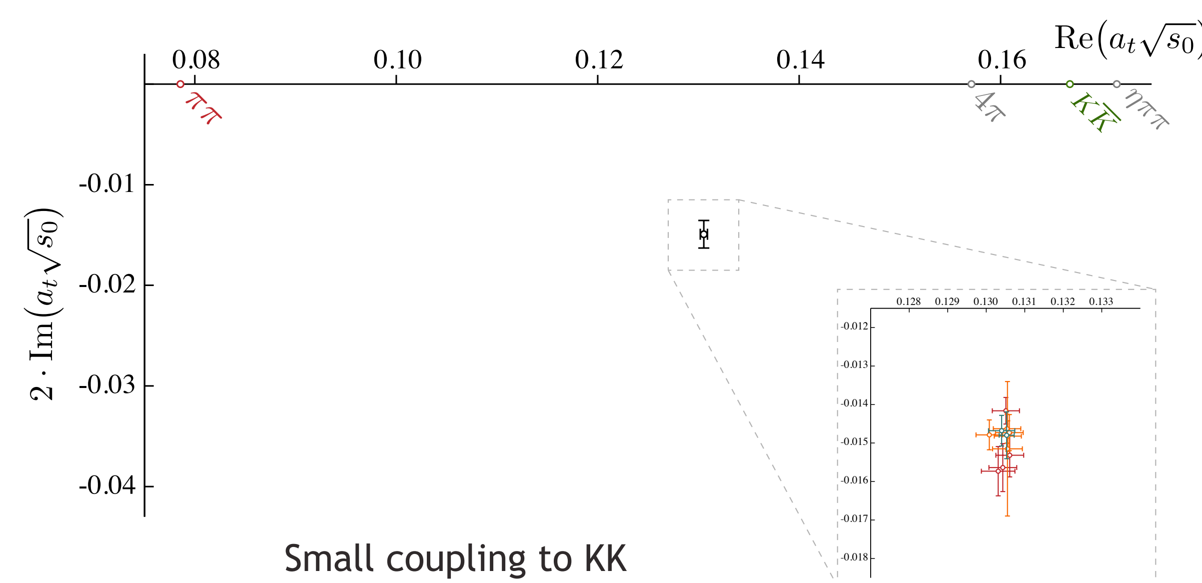


$m_\pi \sim 236$ MeV

Phase shifts & inelasticity



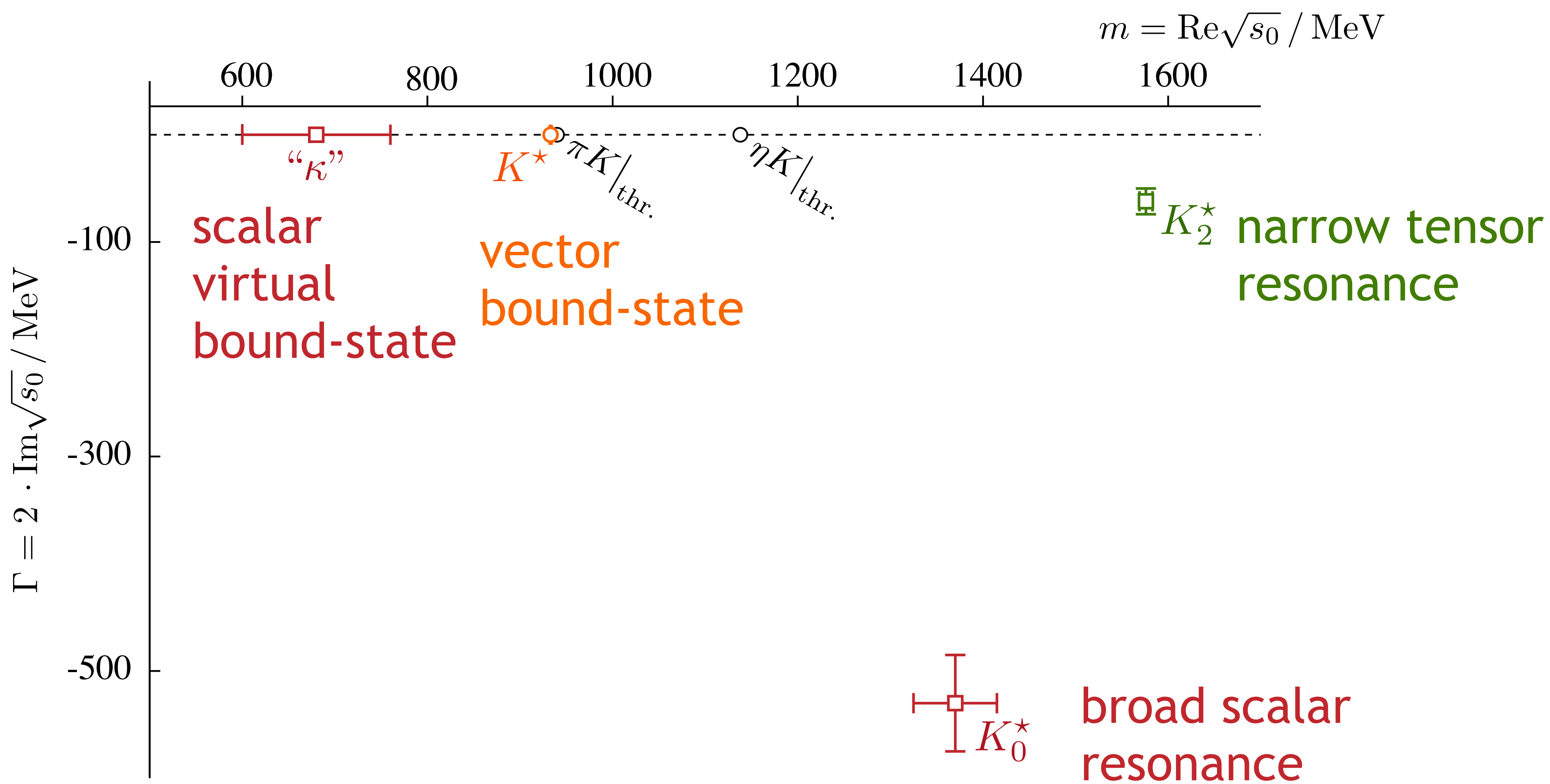
t-matrix pole location



Small coupling to KK

$\pi K/\eta K$ scattering: singularity content

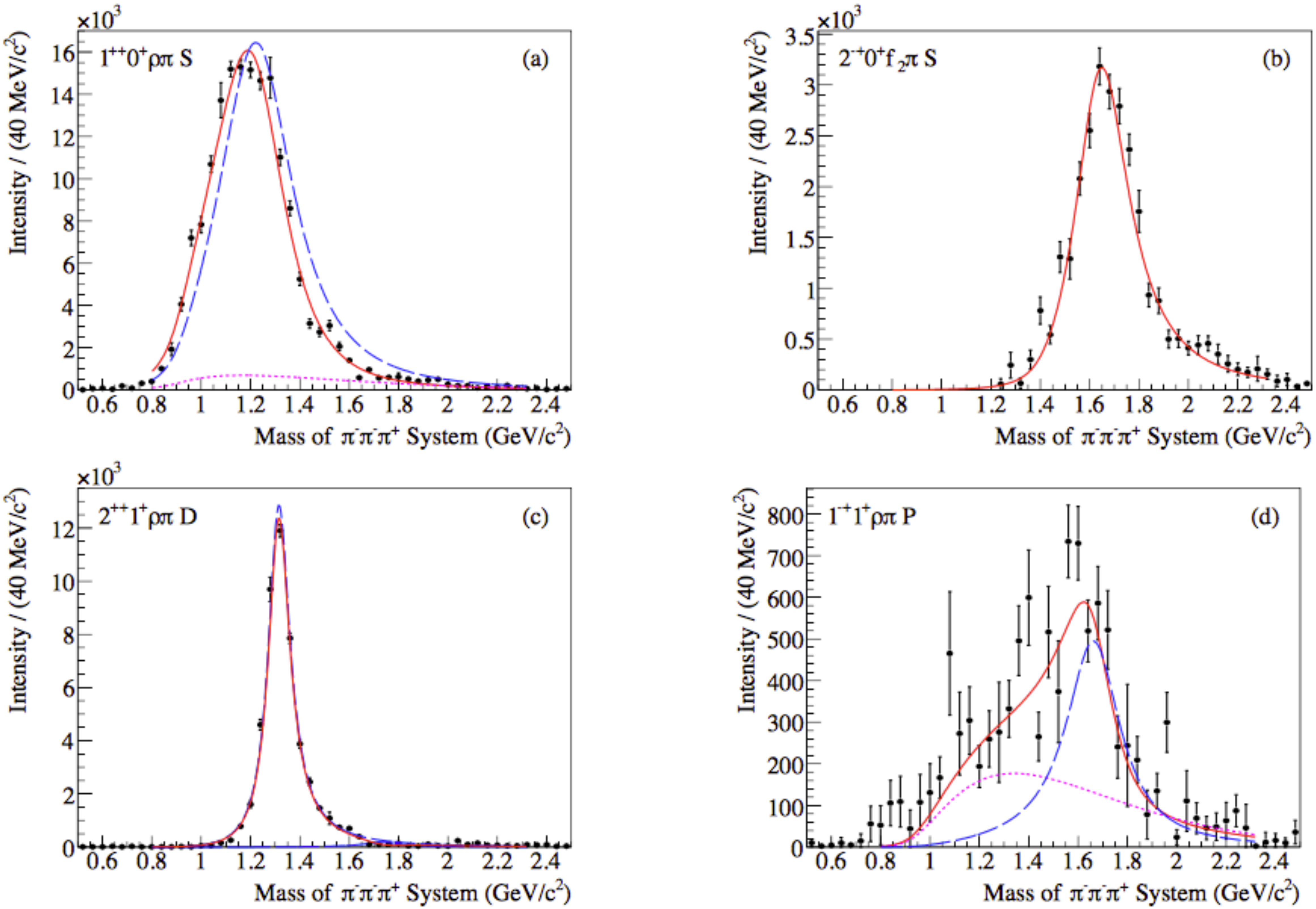
- ***t*-matrix poles** as least model-dependent characterization of resonances



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

PRL 113 182001
PRD 91 054008

COMPASS

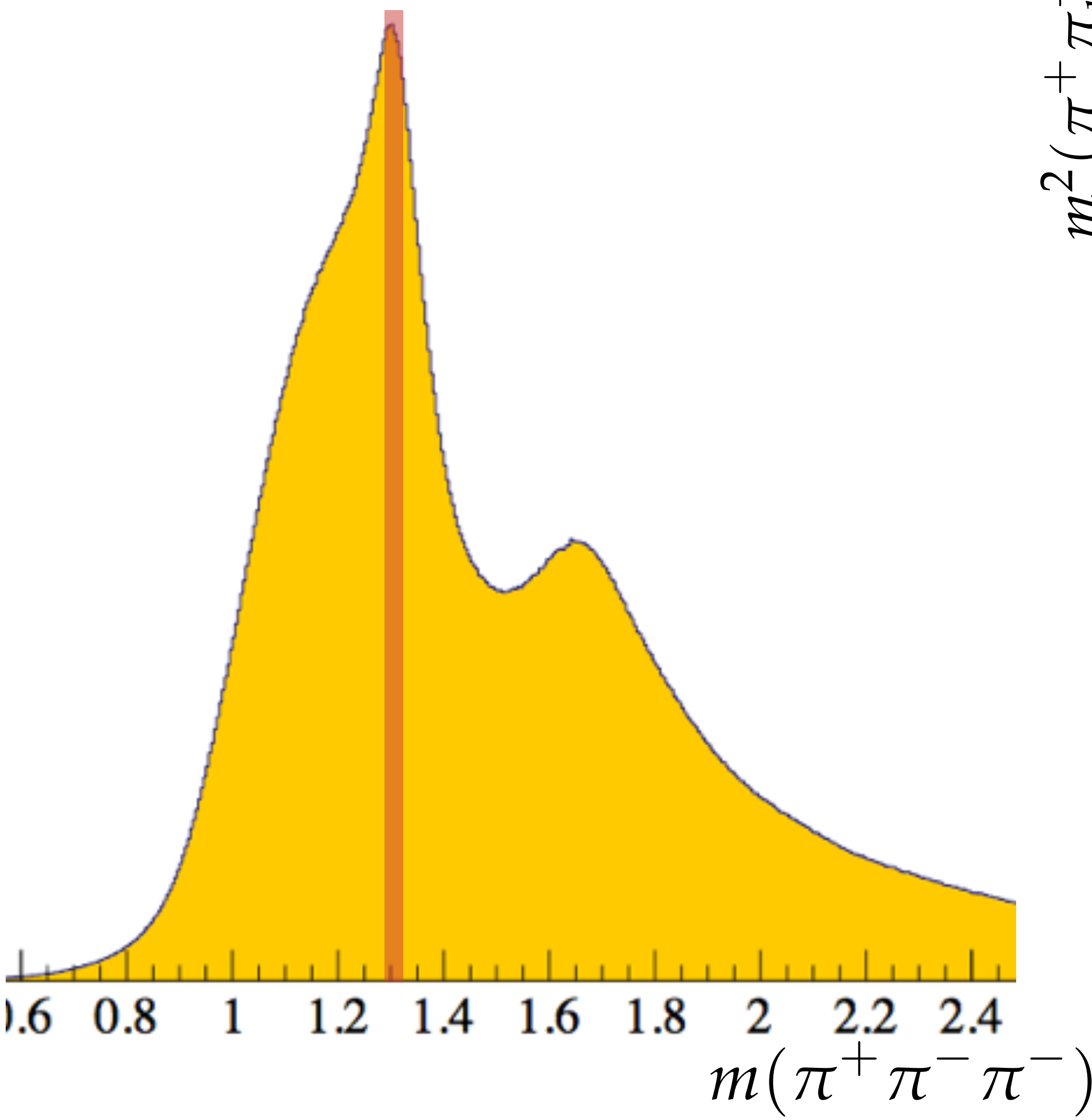


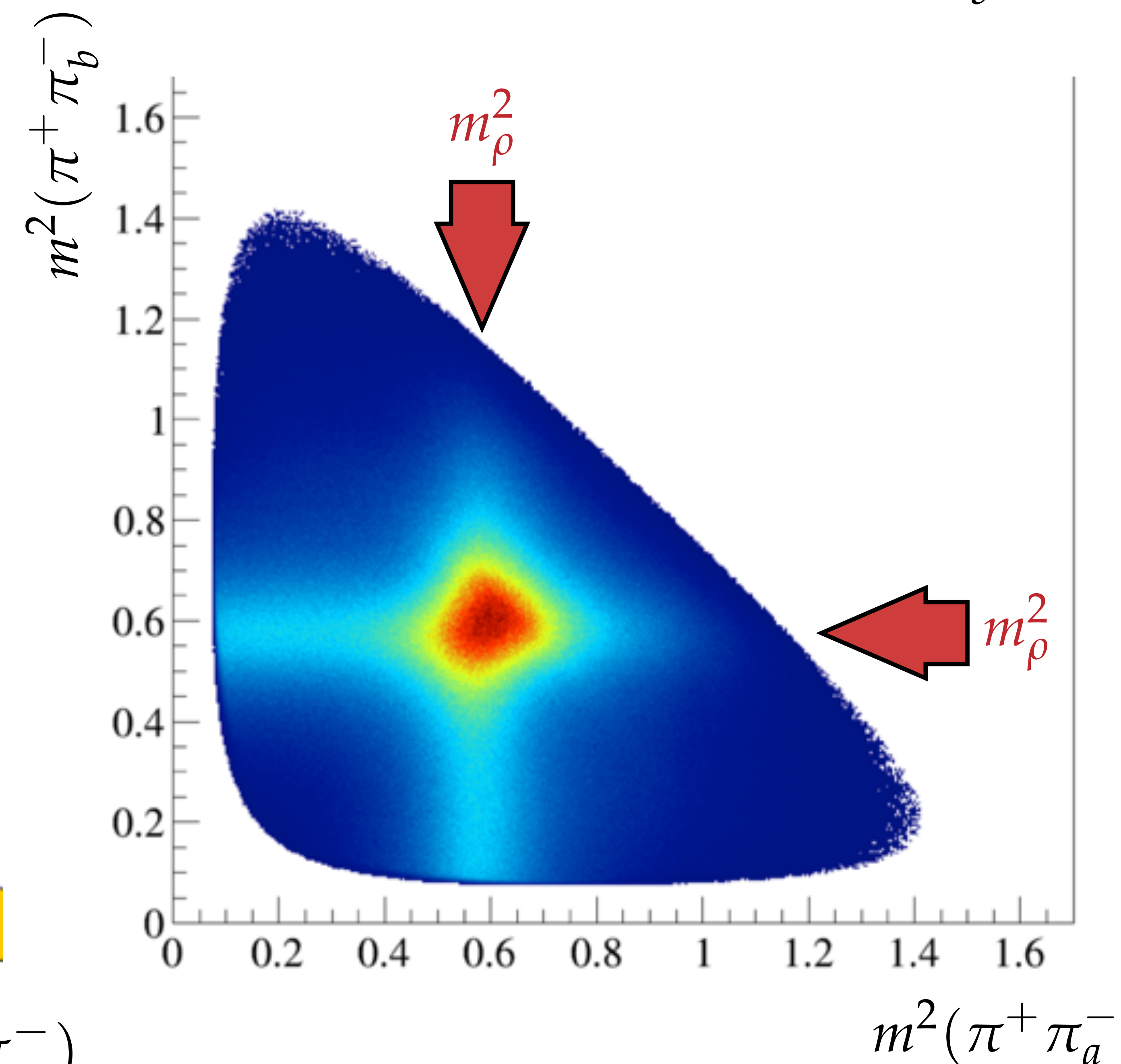
Exotic

multihadron decays / isobars

- high statistics data from COMPASS

$$\pi^- p \to \pi^+ \pi_a^- \pi_b^- p$$





multihadron decays / isobars

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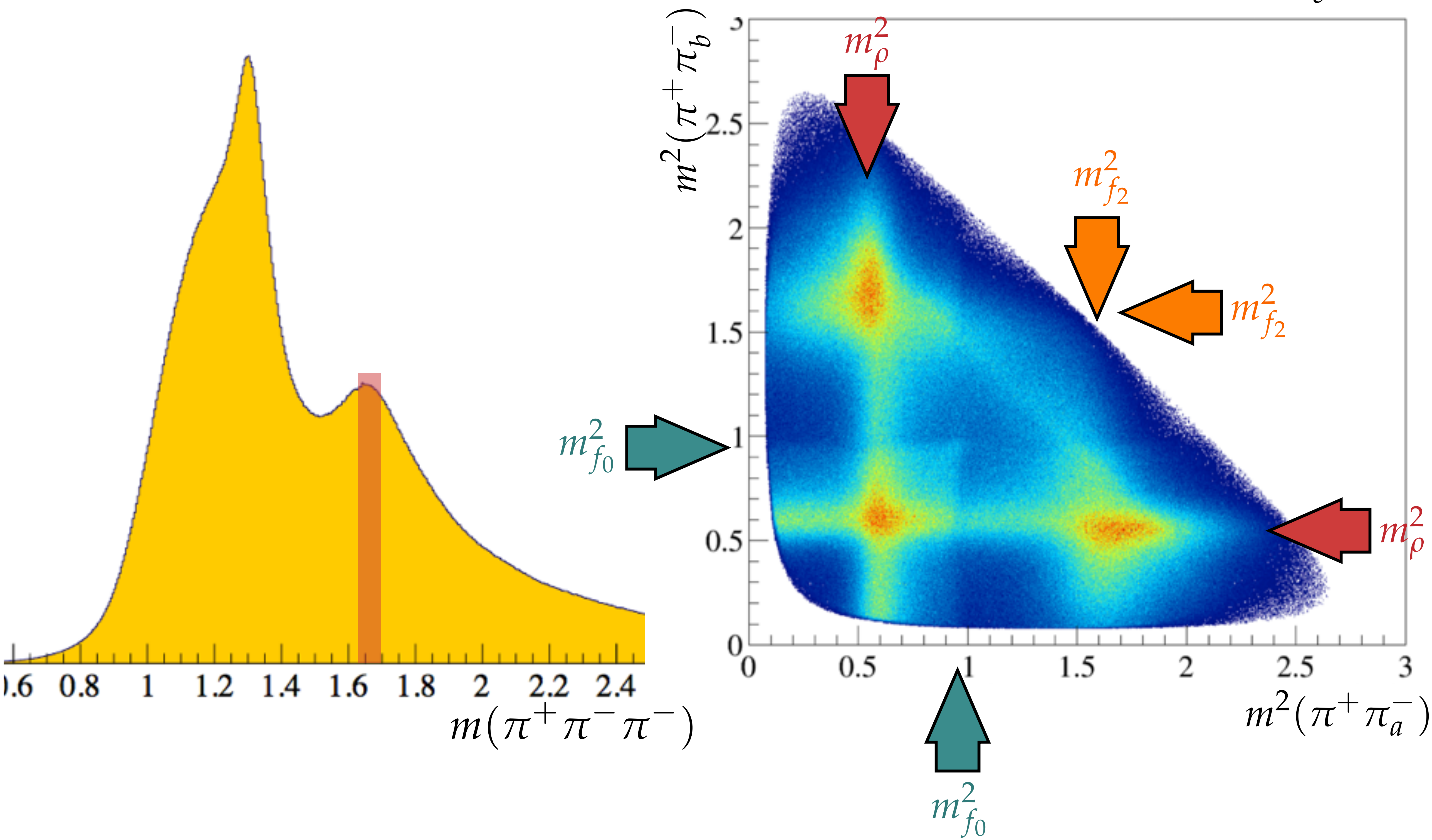
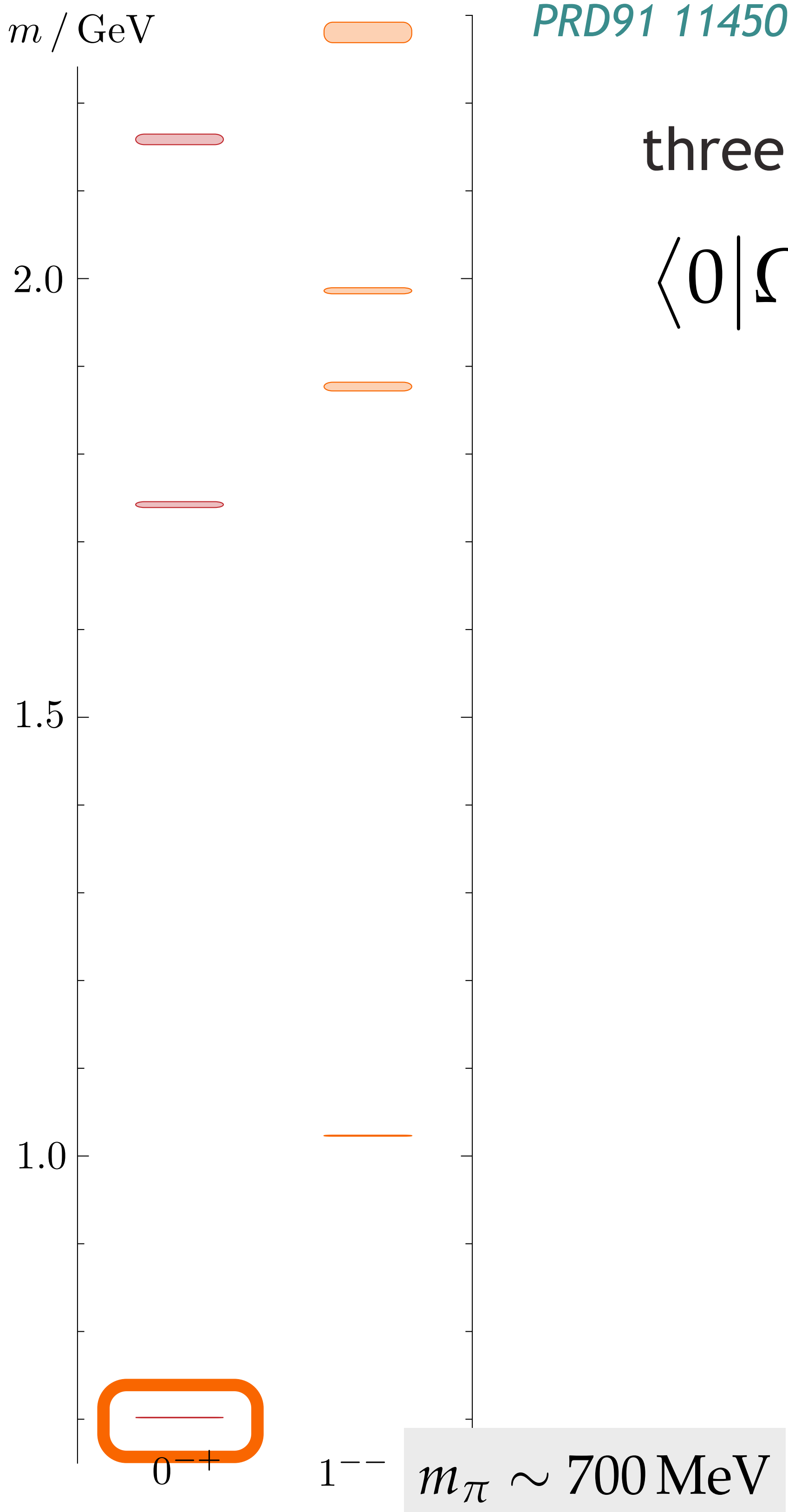


Excited-state radiative transitions



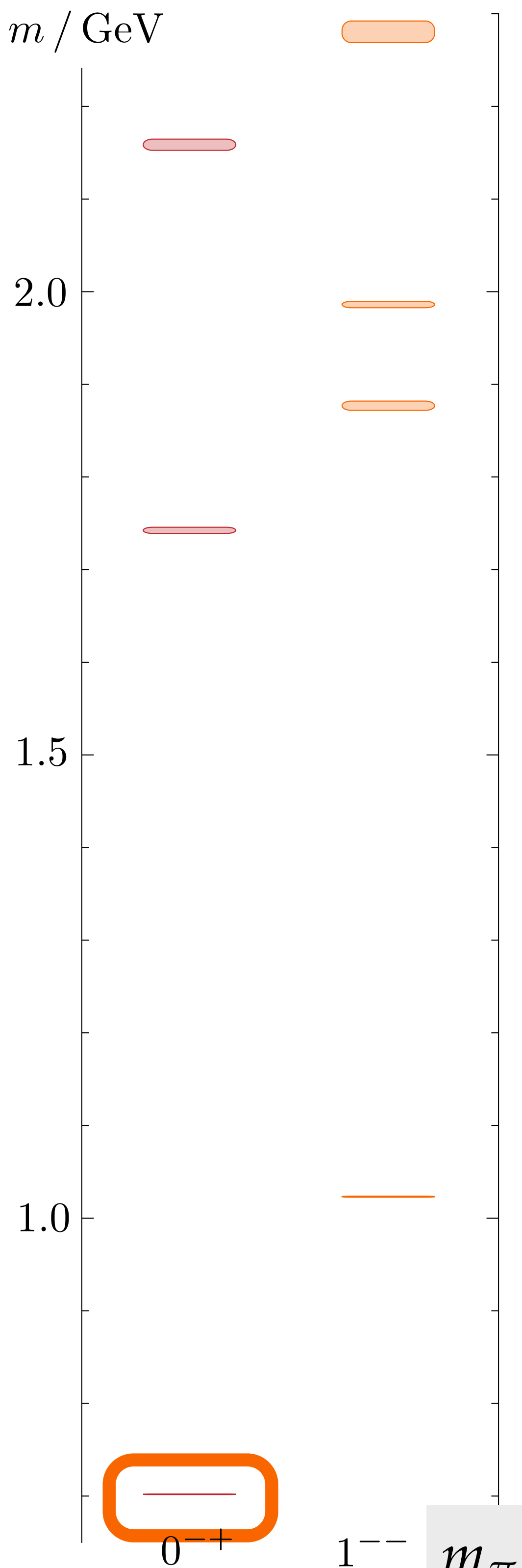
PRD91 114501 (2015)

three-point correlation functions

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

work of Christian Shultz, ODU

Excited-state radiative transitions

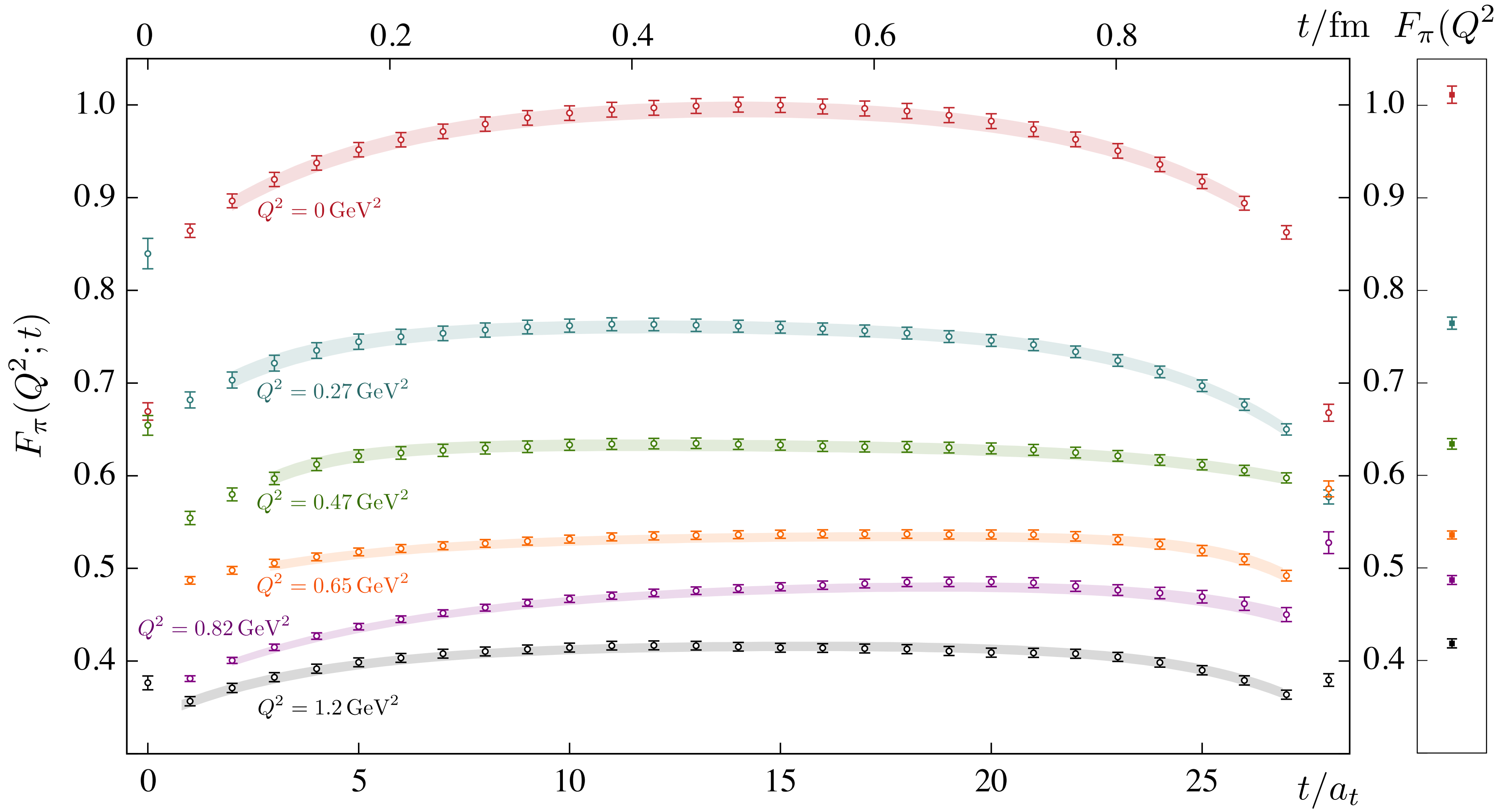


PRD91 114501 (2015)

three-point correlation functions

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

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

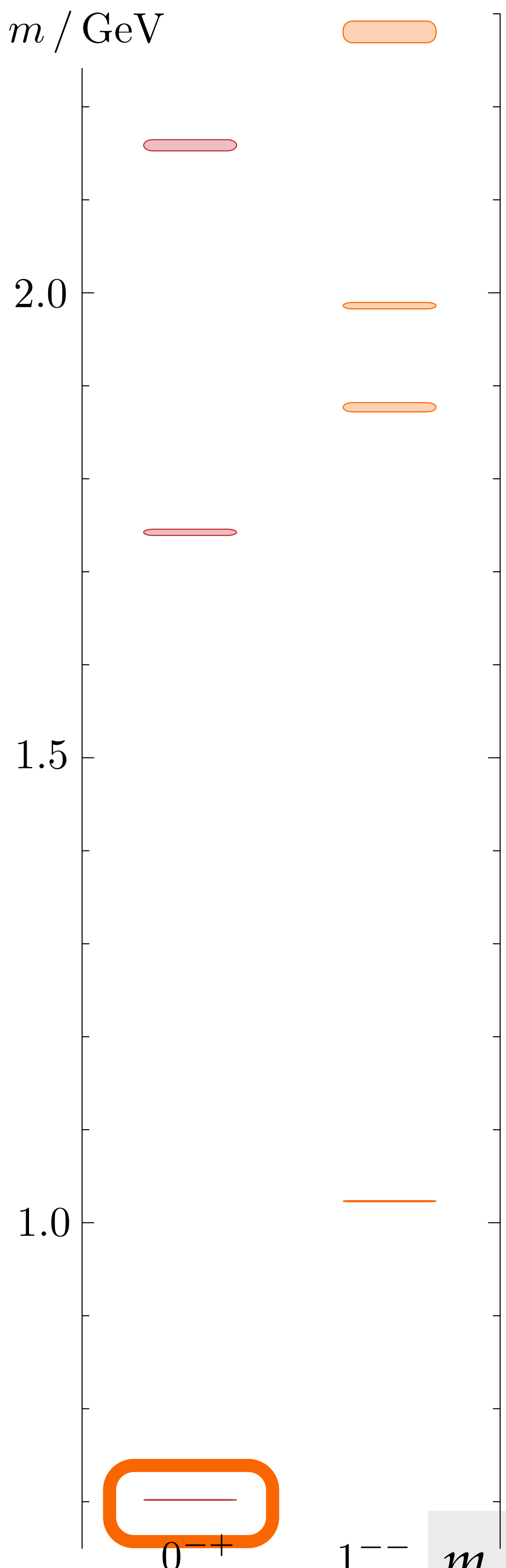


$m_\pi \sim 700\,\mathrm{MeV}$

work of Christian Shultz, ODU

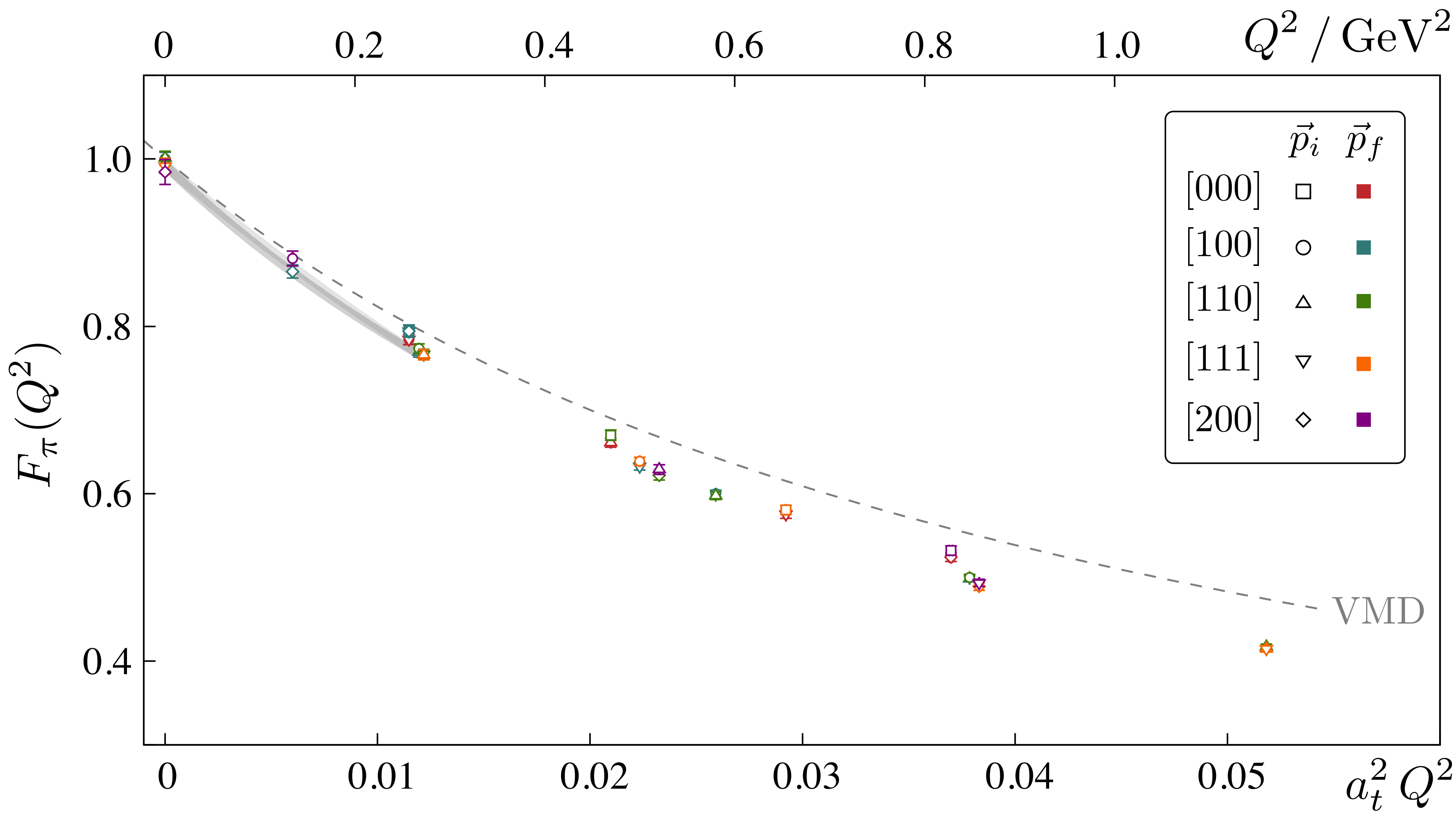
Excited-state radiative transitions

PRD91 114501 (2015)



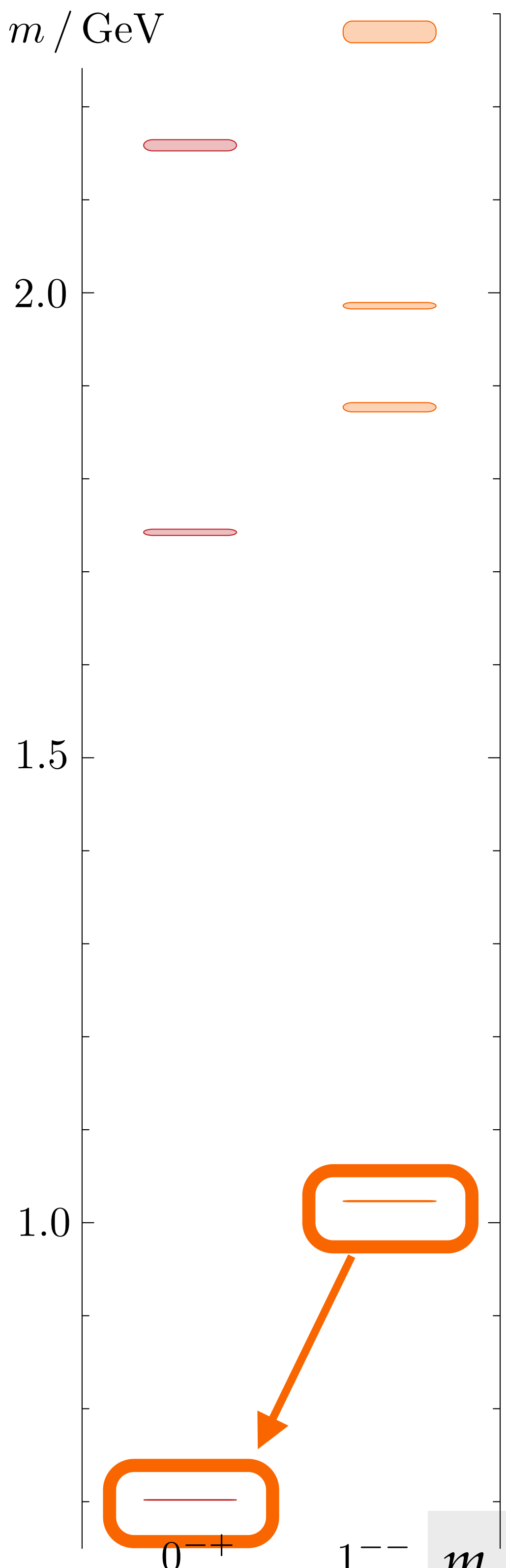
$m_\pi \sim 700\,\mathrm{MeV}$

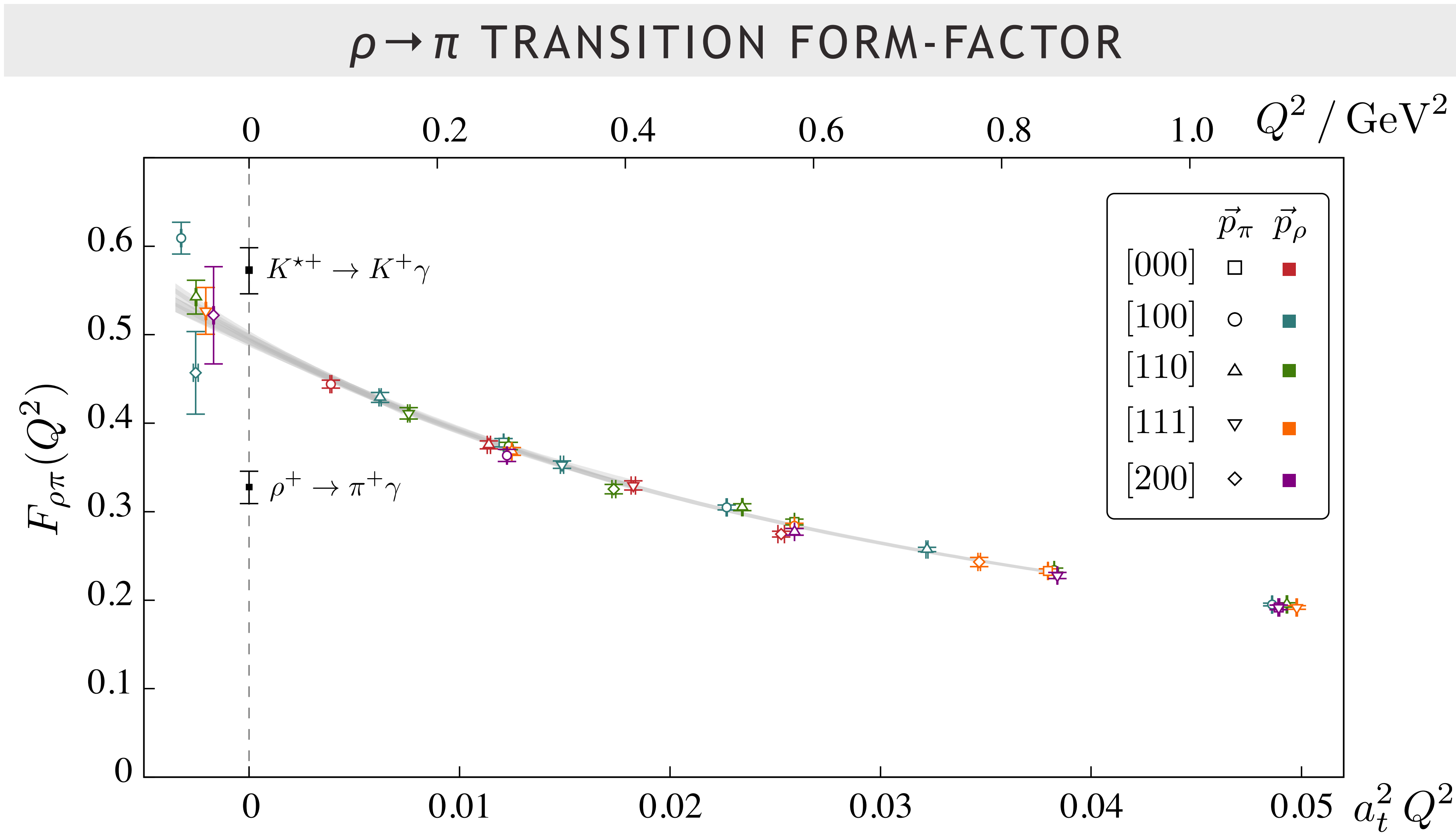
PION FORM-FACTOR



Excited-state radiative transitions

PRD91 114501 (2015)

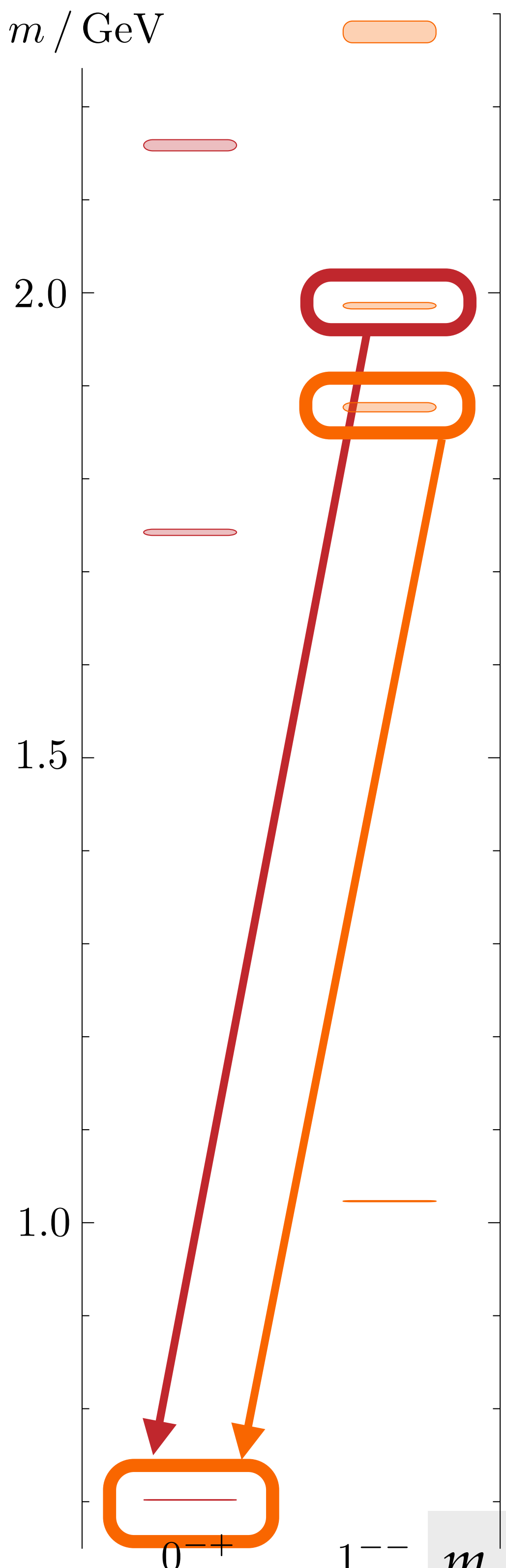




$m_\pi \sim 700\,\mathrm{MeV}$

Jefferson Lab

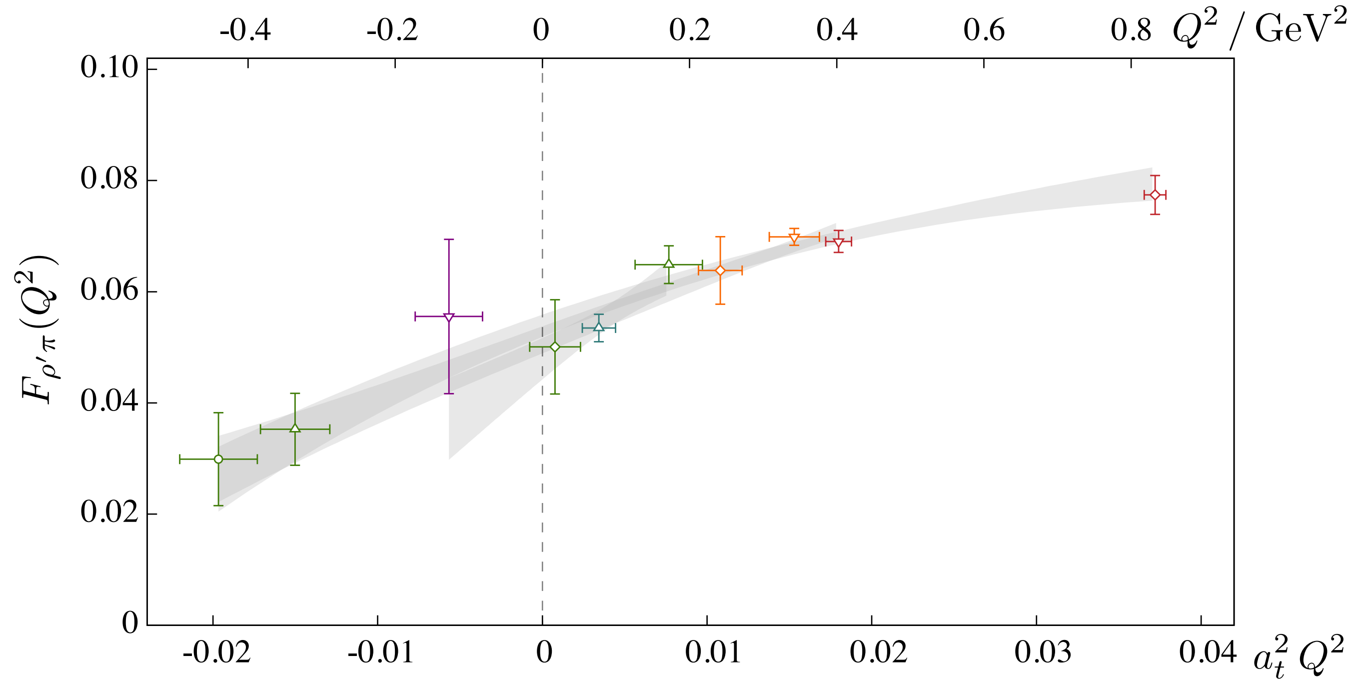
Excited-state radiative transitions



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

PRD91 114501 (2015)

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



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