Excited State Spectroscopy & QCD

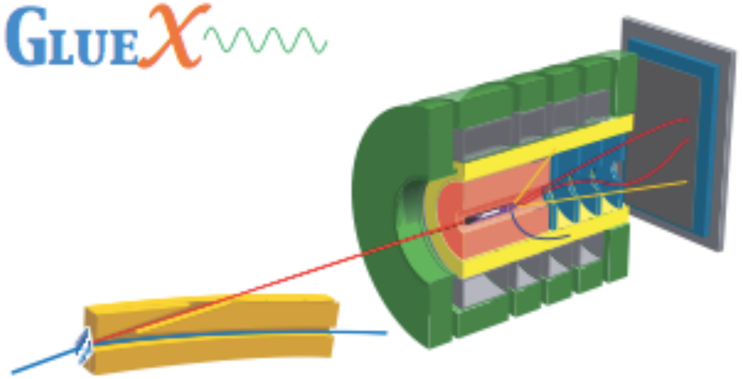
Jefferson Lab

Hadron spectroscopy

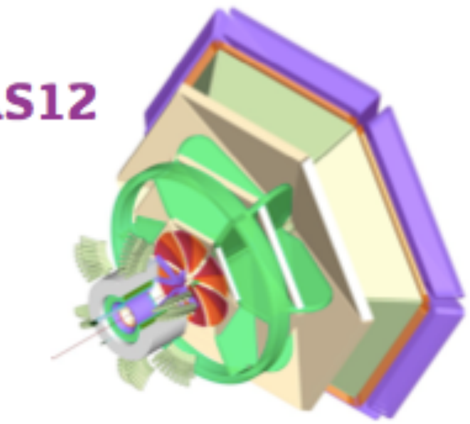
- Determination of hadron spectrum of QCD a central goal in NP
- Several experiments worldwide

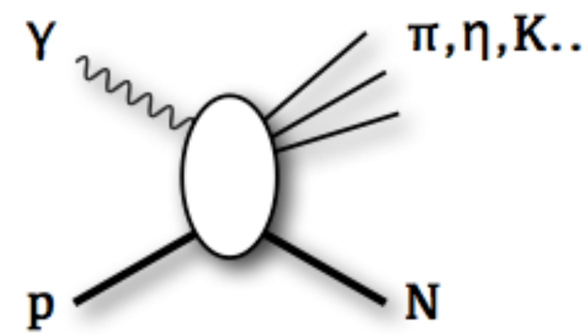
Spectrum - light meson experiments

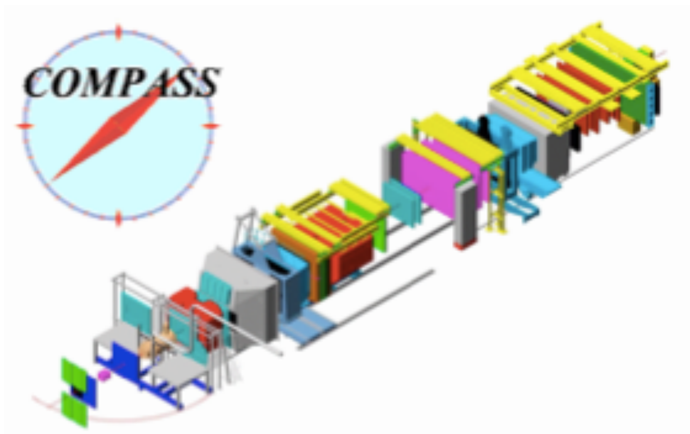
GlueX

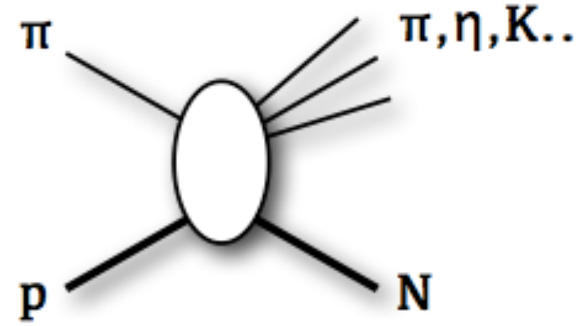


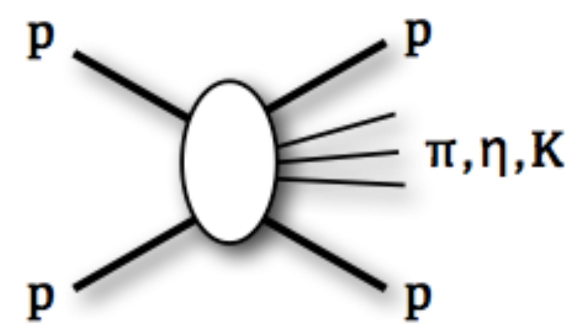
CLAS12



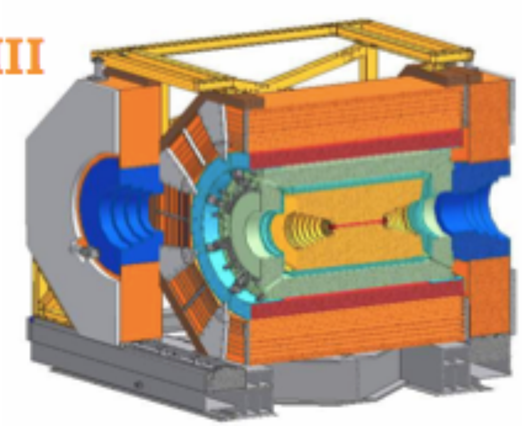


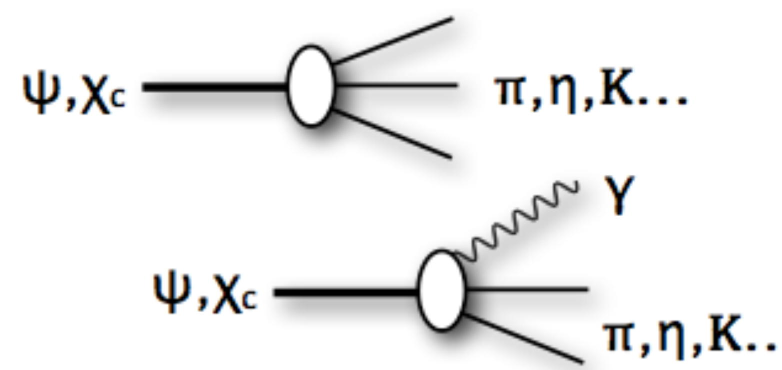






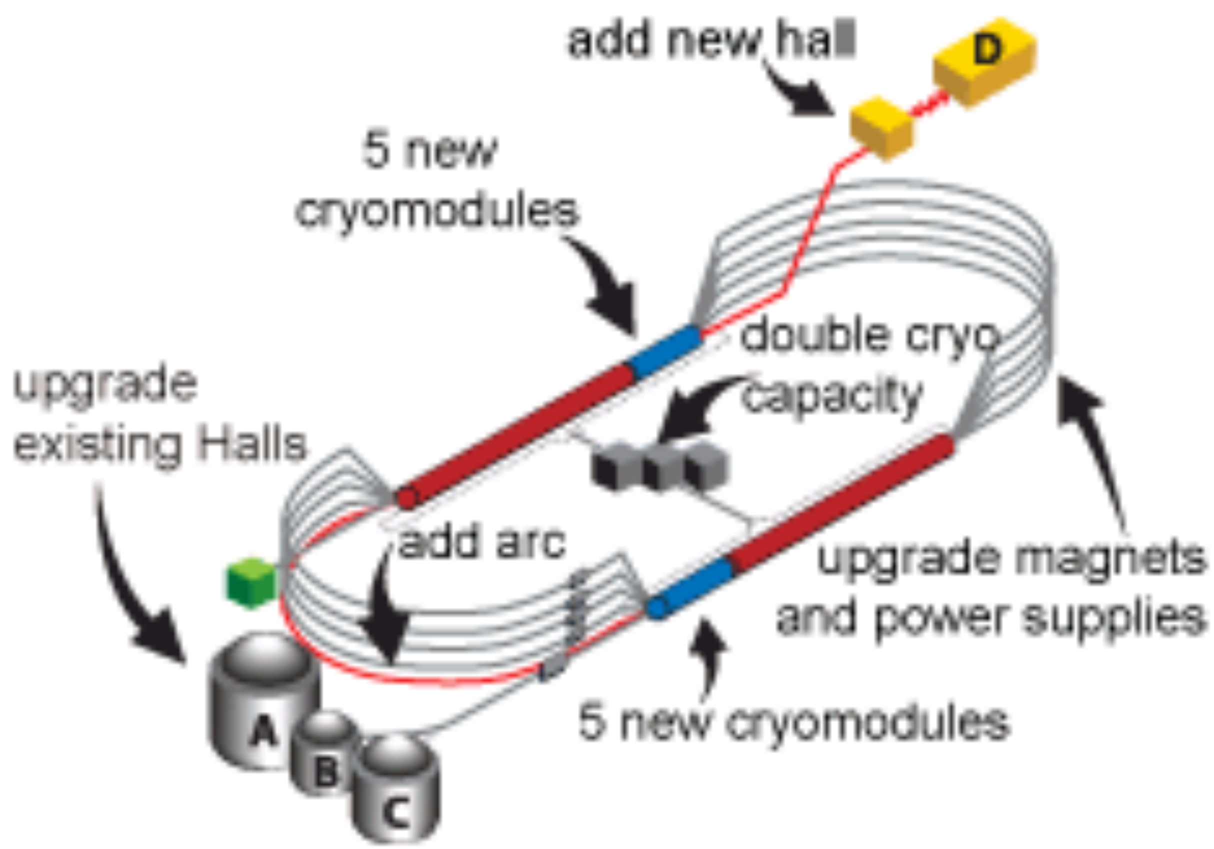
BES III





Nuclear Physics & Jefferson Lab

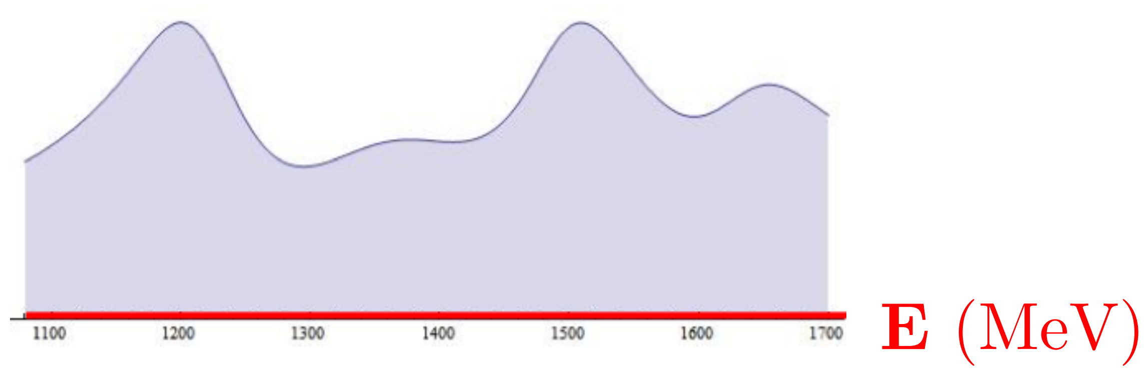
- JLab finishing a $335M upgrade

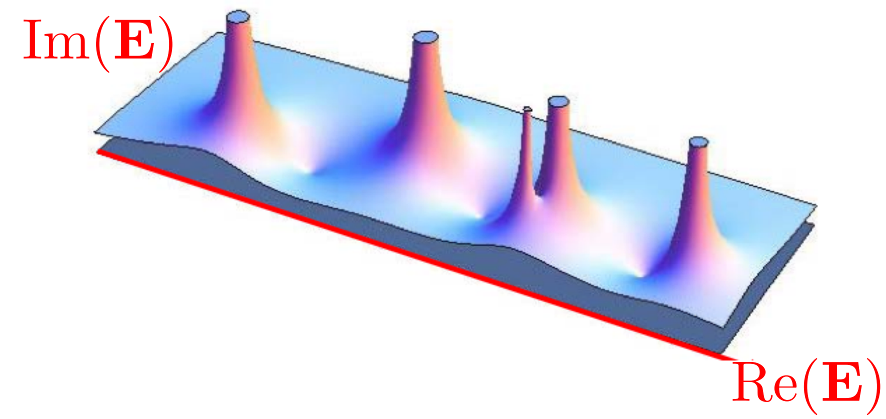


- Doubled beam energy
- Added new Hall D (GlueX)

Resonances

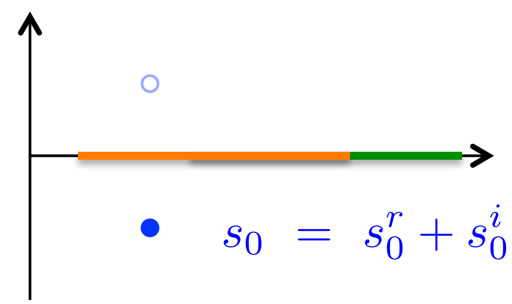
- Most hadrons are resonances
  - E.g., πN πN





  - Formally defined as a pole in a partial-wave scattering amplitude

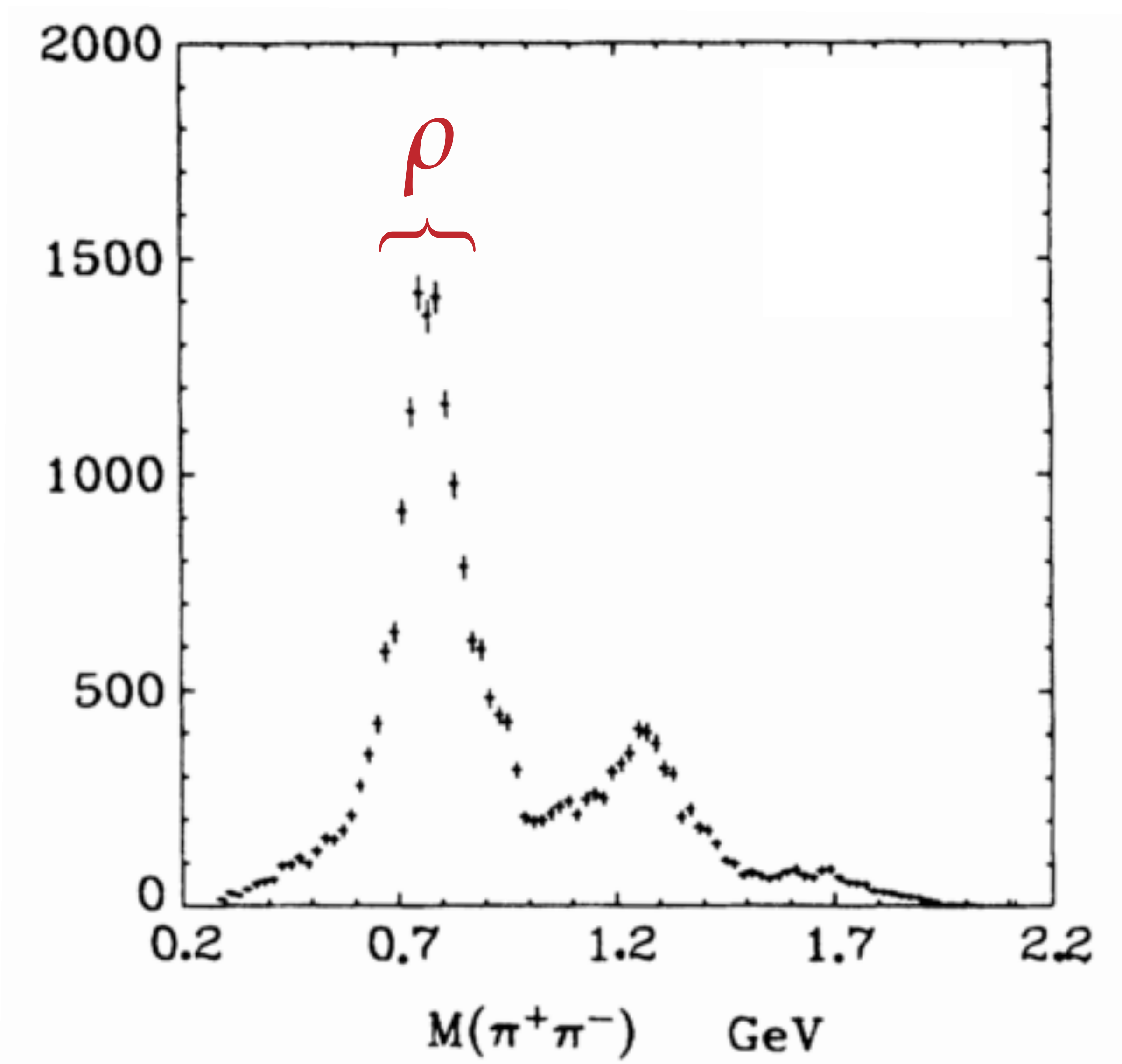
$$t_l(s) \sim \frac{R}{s_0 - s} + \ldots$$



  - Different channels should have same pole location
  - Pole structure gives decay information

- Can we predict hadron properties from first principles?

Isospin=1 ππ P-wave



expand angular dependence in *partial waves*

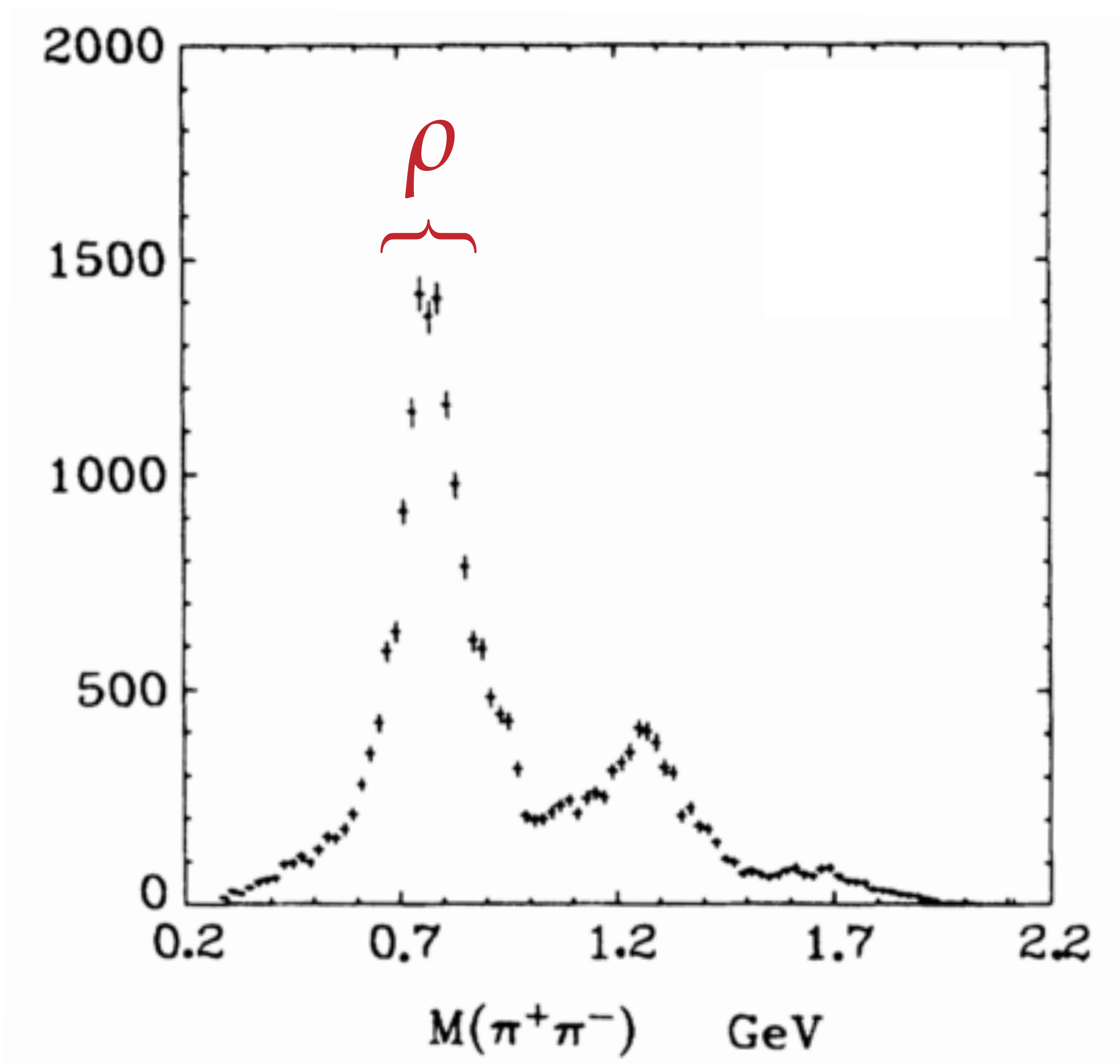
PARTIAL WAVE AMPLITUDE

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

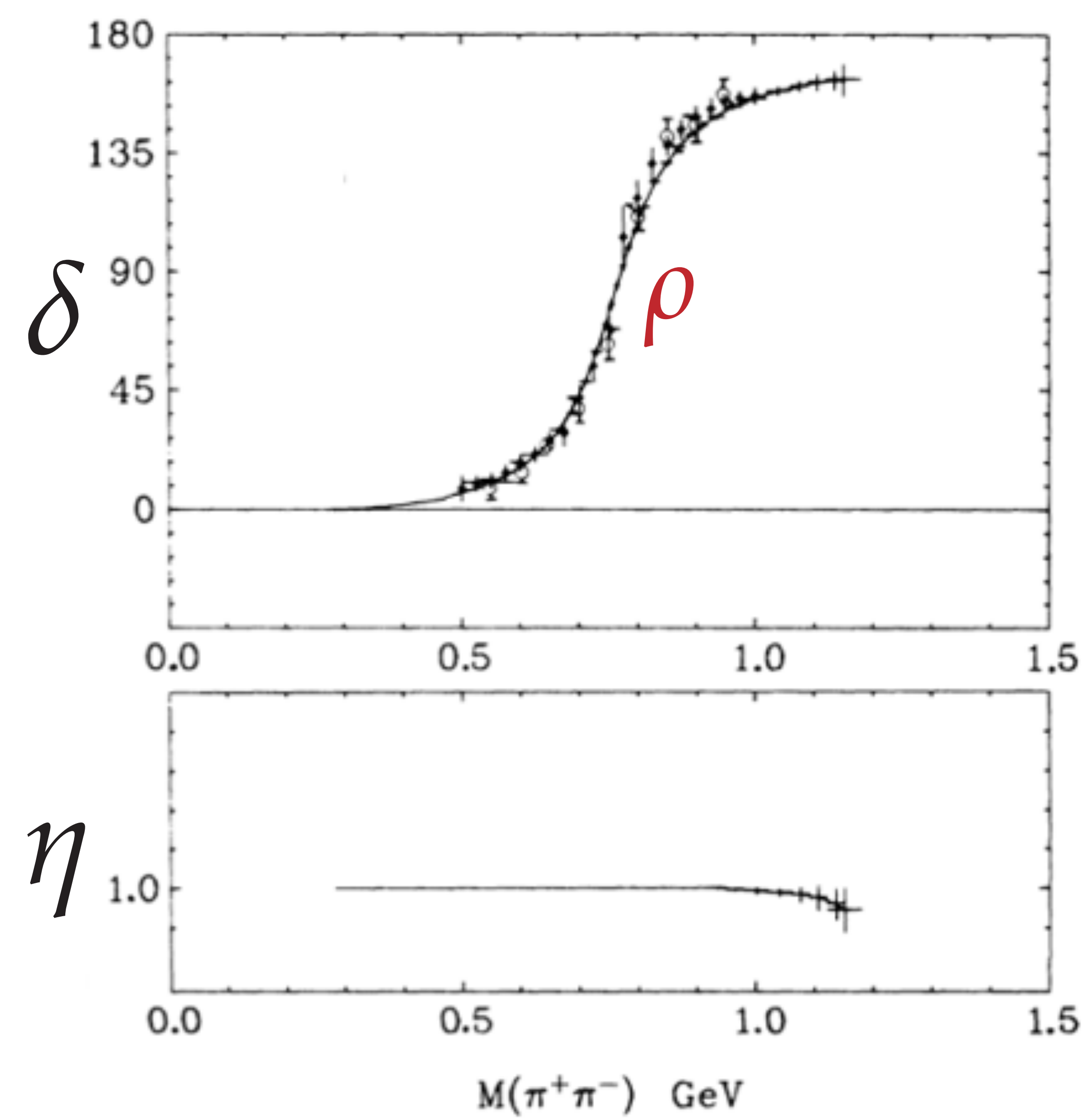
$\eta = 1$ elastic

$\eta \leq 1$ inelastic

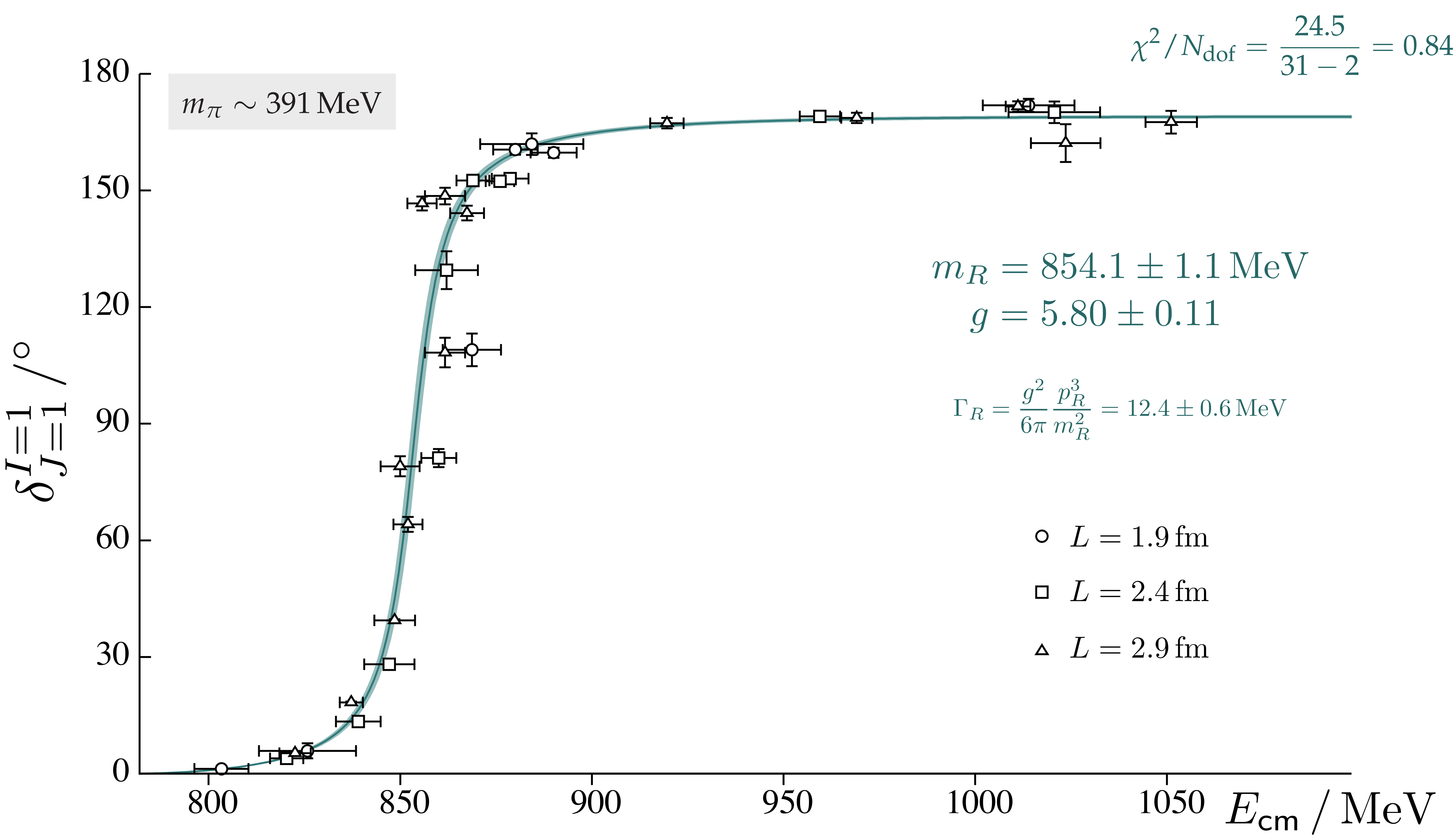
Isospin=1 ππ P-wave



RESONANT PHASE SHIFT



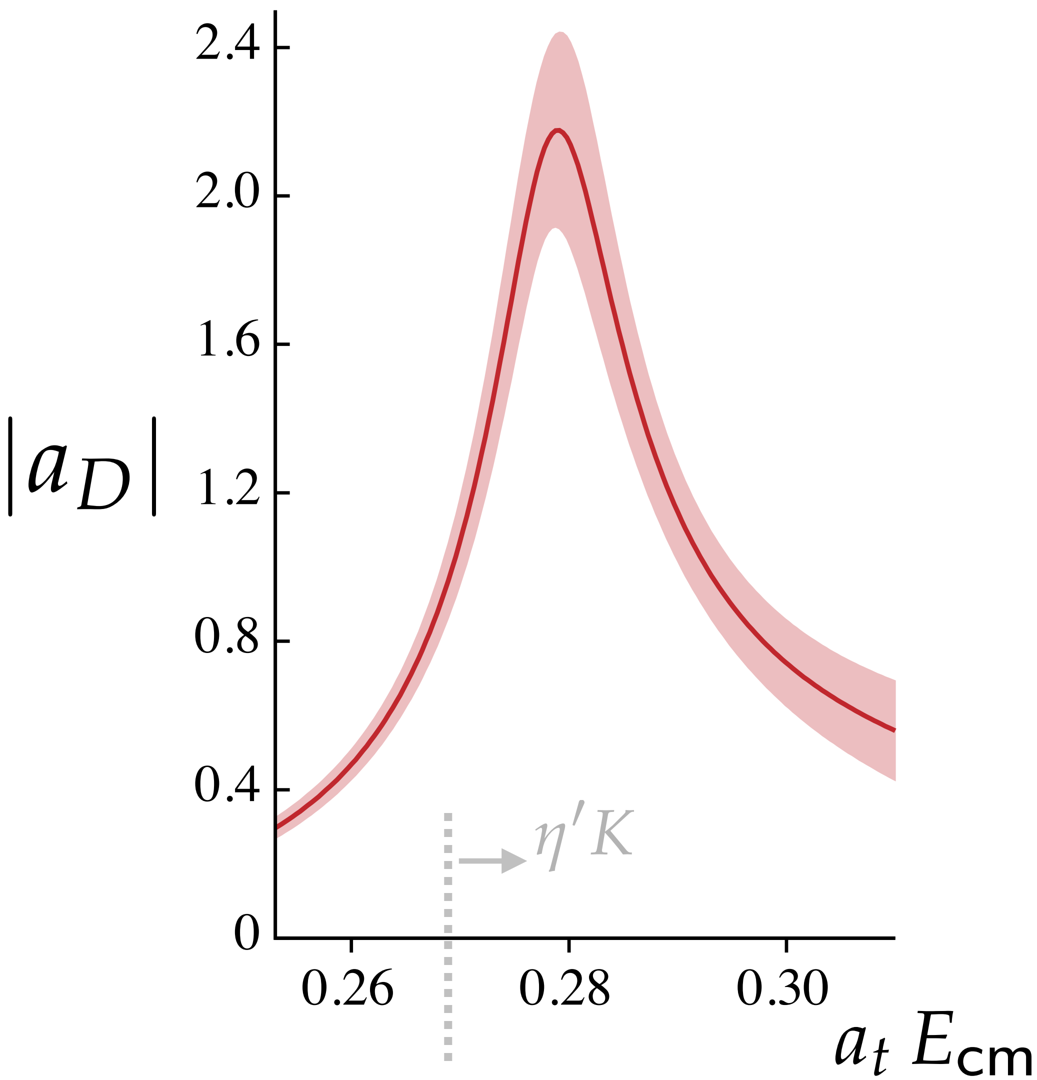
ρ resonance



$g_{\mathrm{phys.}} = 5.95(2)$ *PDG*

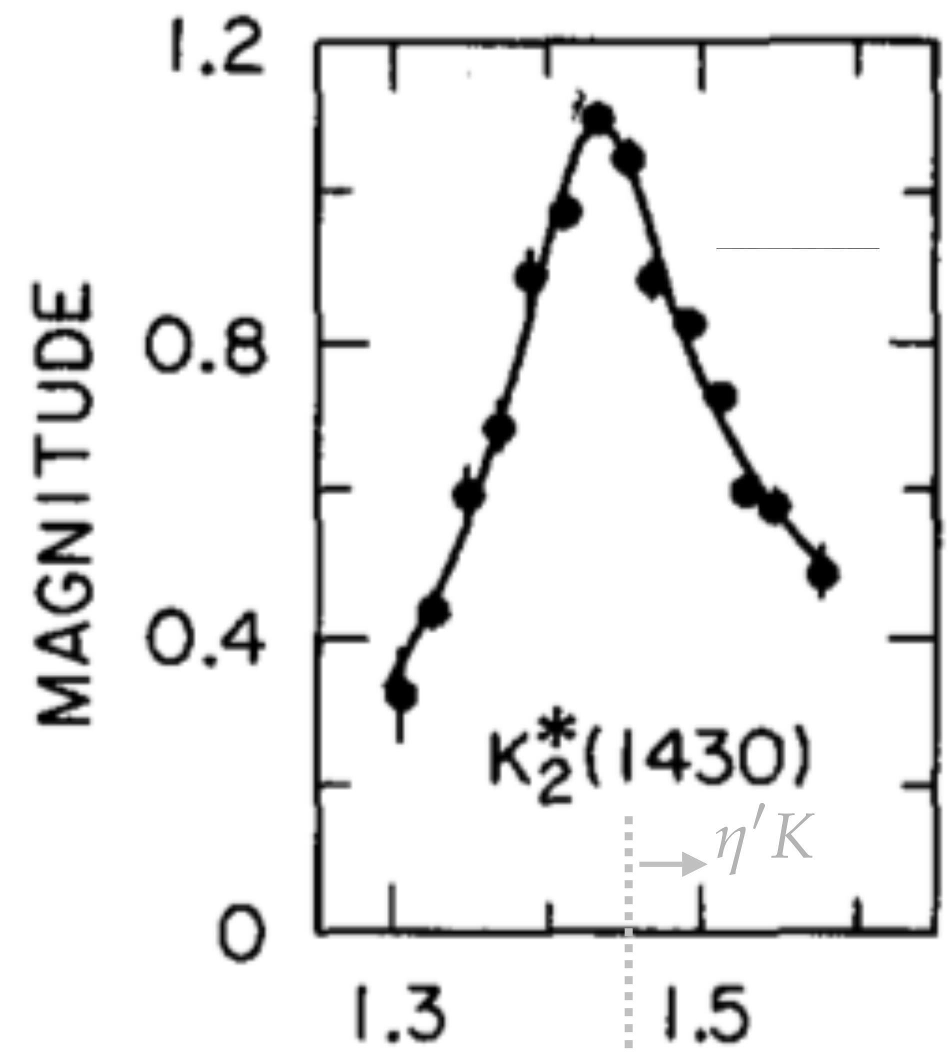
$\pi K/\eta K$ scattering amplitudes

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



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

LASS D-WAVE



LASS, NPB296 493

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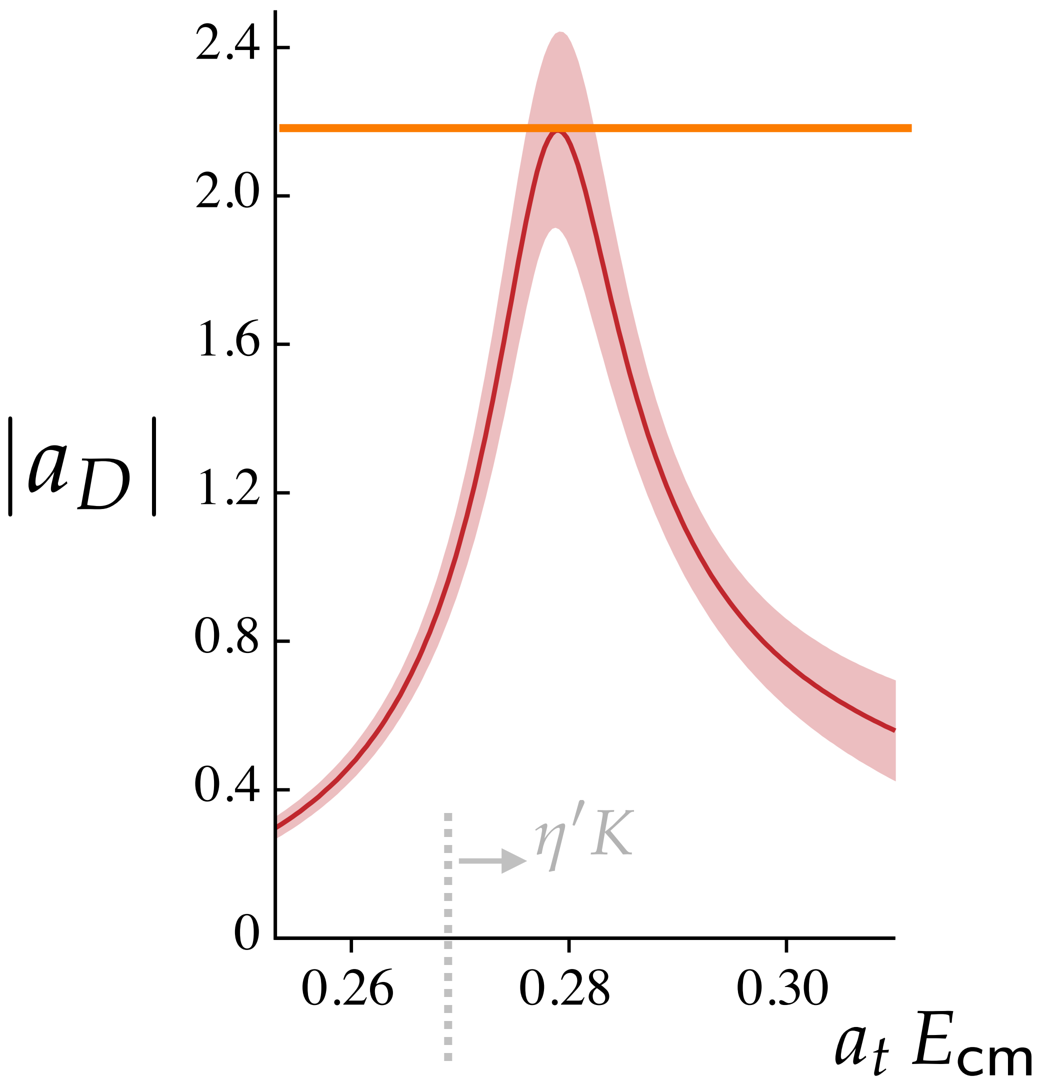

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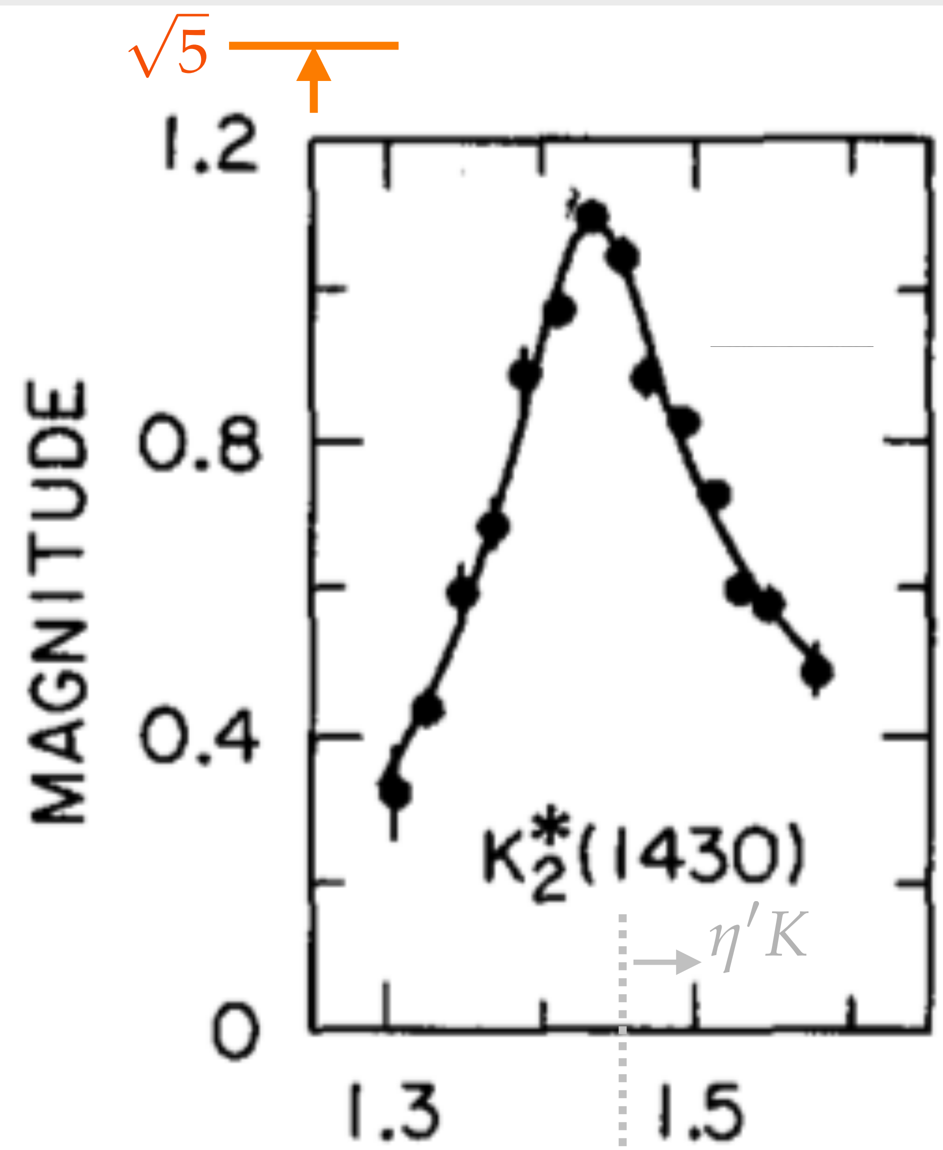
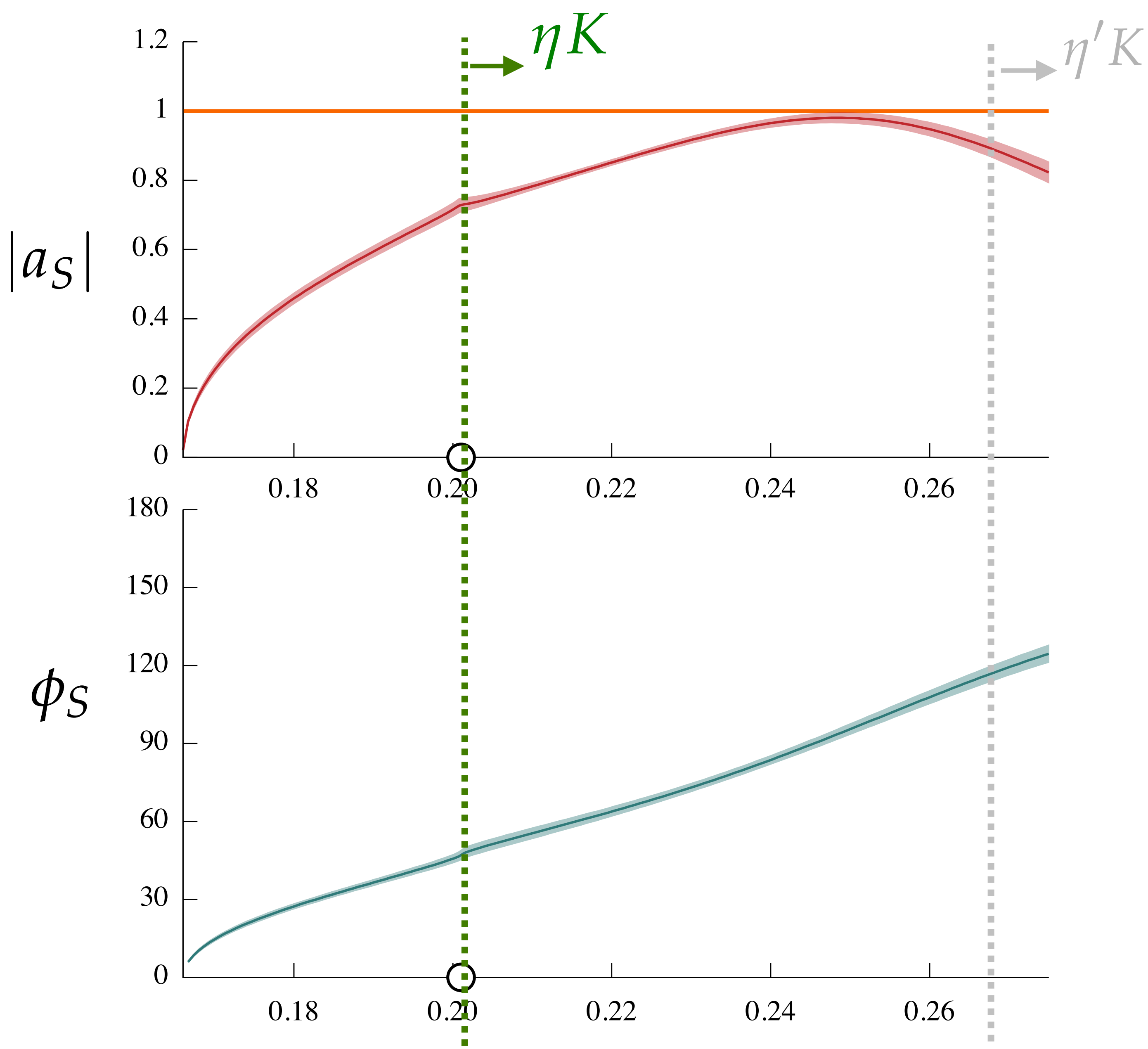


LASS, NPB296 493

S-wave πK/ηK more complicated

S-WAVE πK→πK AMPLITUDE



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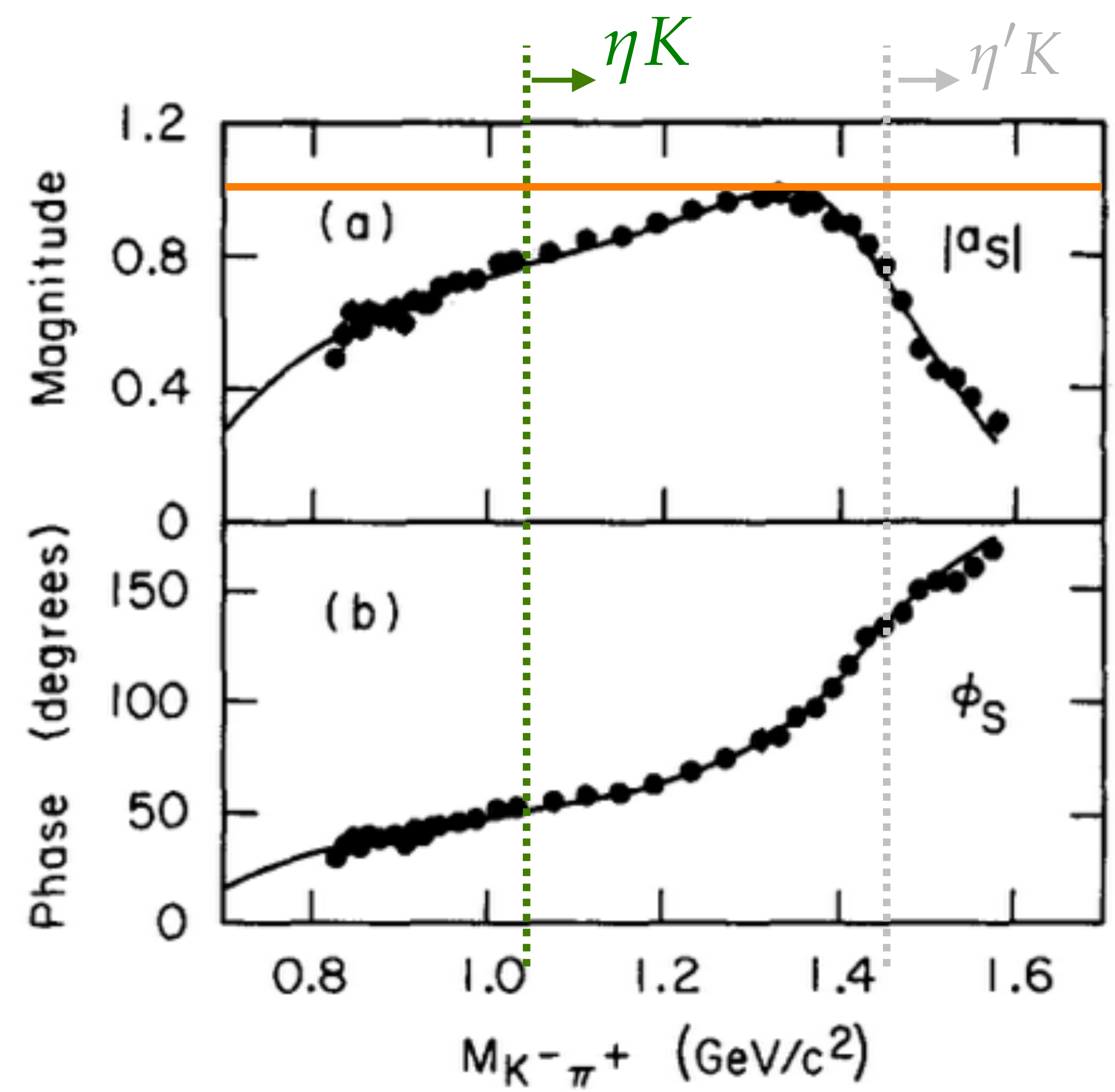
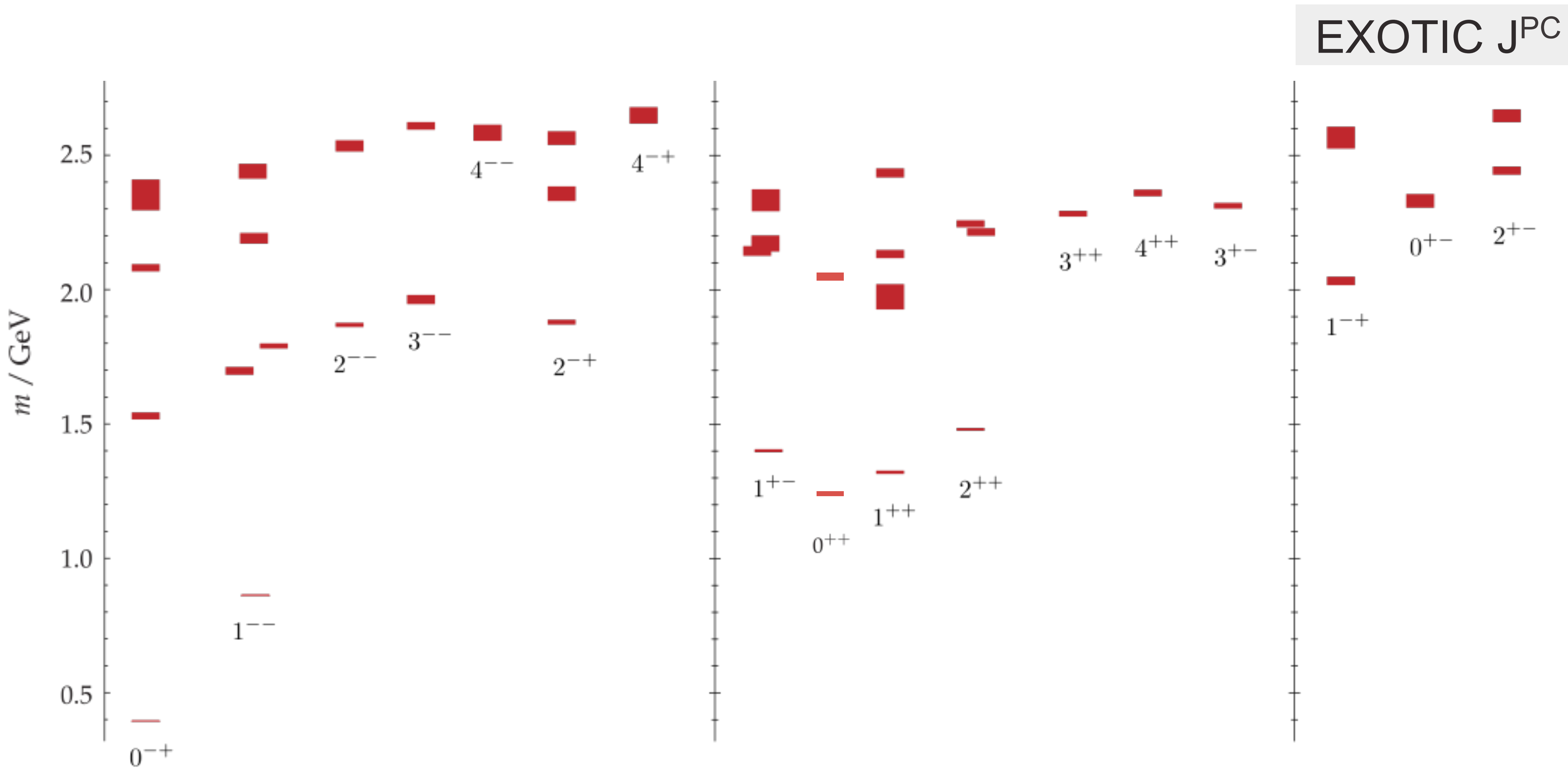
LASS S-WAVE



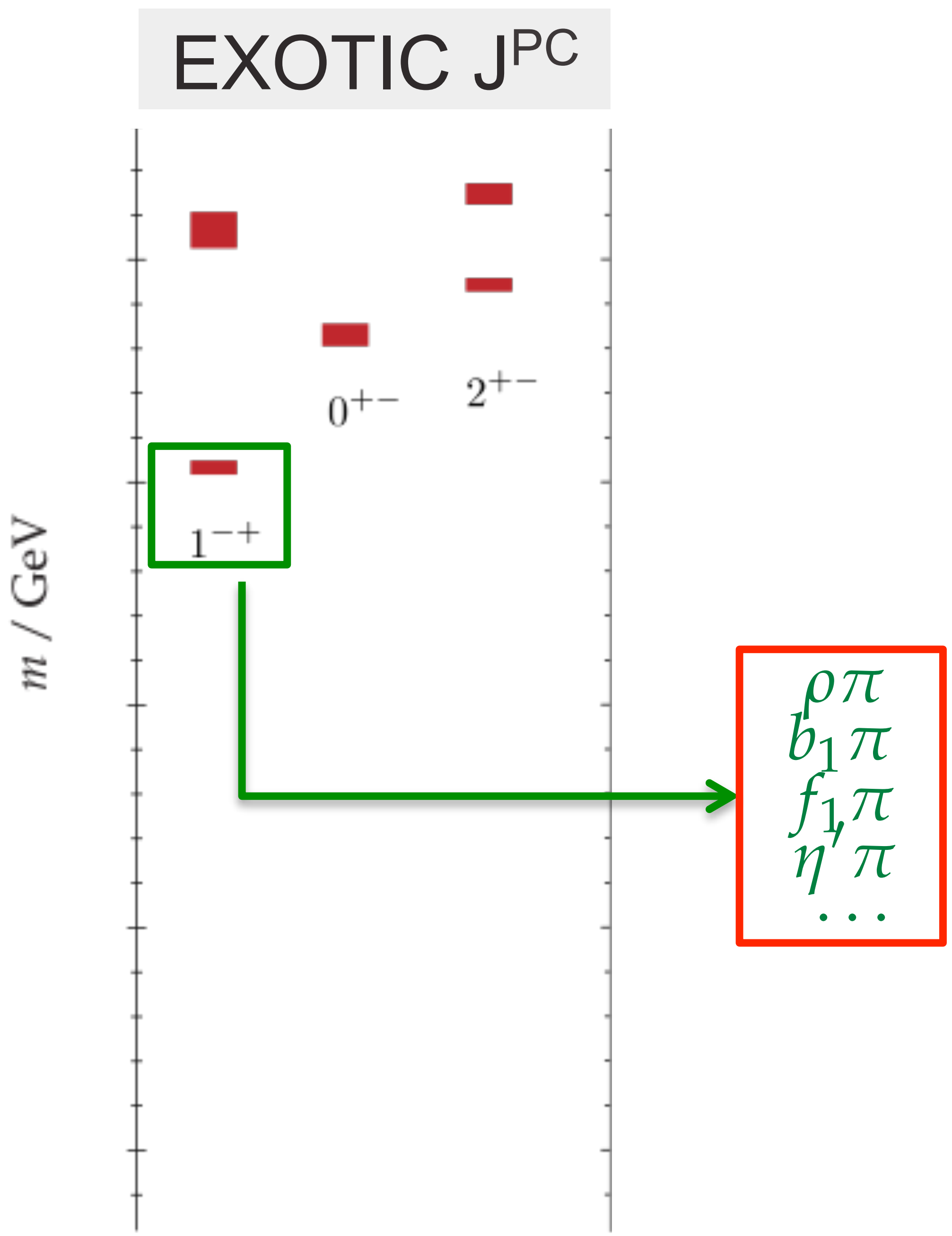
LASS, NPB296 493

Major objective

- Compute decays (branching fractions) of exotic mesons:



Major objective - exotic meson decays



- LQCD suggests existence of exotic mesons
- Expt. determination requires measurement in many decay channels
- Present LQCD calculations missing this info

- Objective is to compute them ahead of expt.
  ➡ Guide expt. analysis

JLab expt. beam has started

What pion mass?

- Getting to the physical pion mass **not the most pressing concern here**
- Need to establish feasibility of techniques for resonances

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e.g. Some of the simple low-lying resonances: $f_2(1270) \quad M > 8m_\pi$

$a_2(1320) \quad M > 9m_\pi$

the number of open channels is too large to start here

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the number of open channels is too large to start here

- Development of three-body formalism required

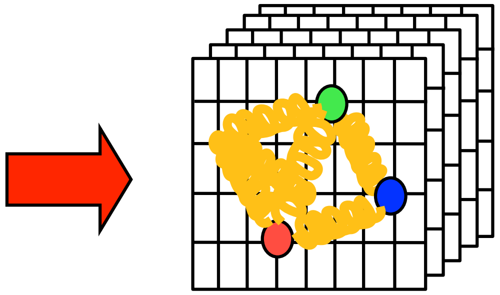
HANSEN & SHARPE - MUCH PROGRESS

LQCD workflow

LQCD workflow

Generate the configurations

- Leadership level
- 60K cores, 10’s TF-yr



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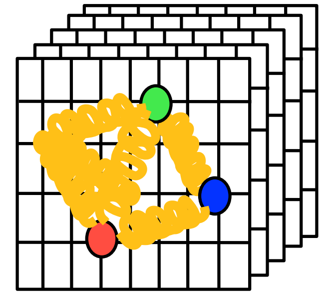
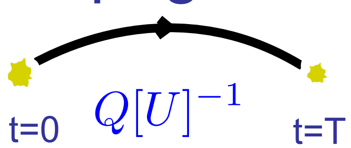


Propagators



+

Analyze
100K copies
4 Kepler GPUs

LQCD workflow

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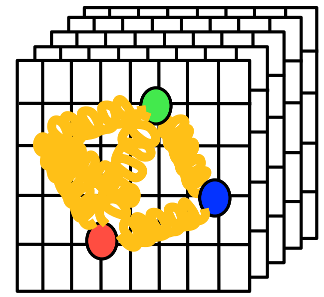

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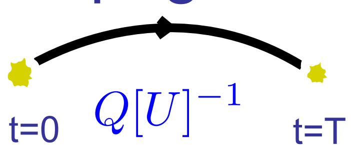

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Now also AMG!

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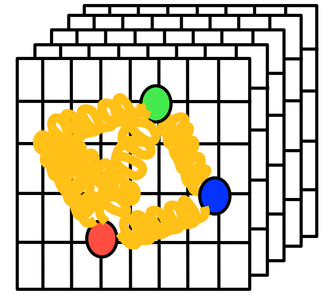

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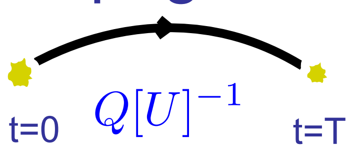
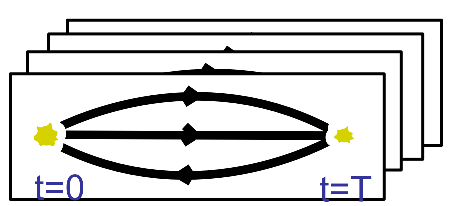


Contract
- 8 cores, CPUs

Correlators
100K – 1M copies



LQCD workflow

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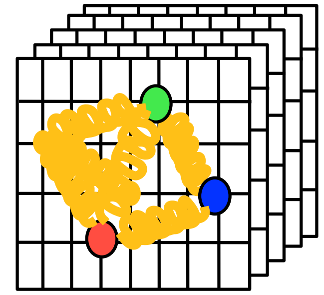

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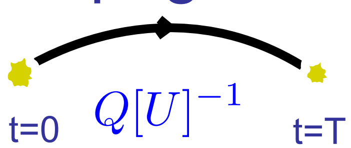

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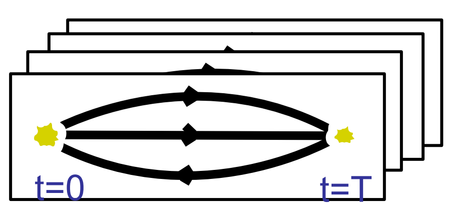

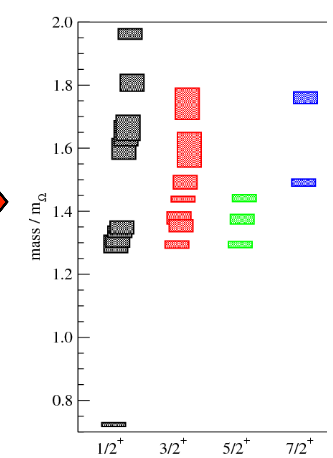

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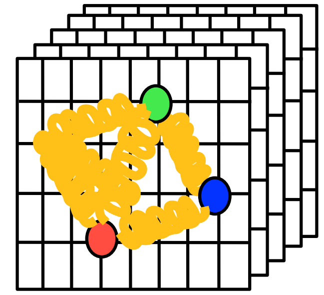
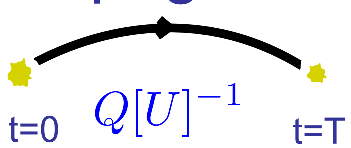


Few big jobs
Few big files

Analyze
100K copies
4 Kepler GPUs
Now also AMG!

+

Propagators



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Correlators
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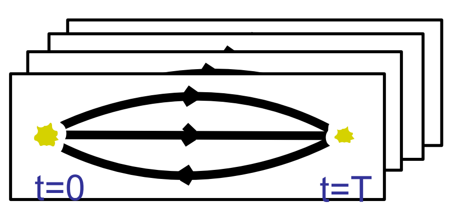

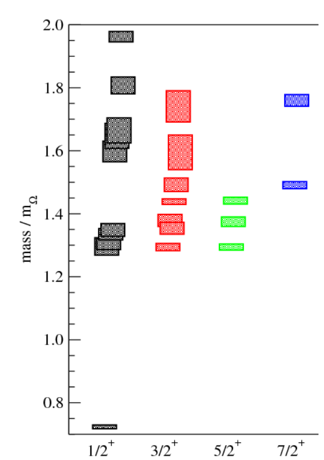

Many small jobs
Many big files

I/O movement

LQCD workflow

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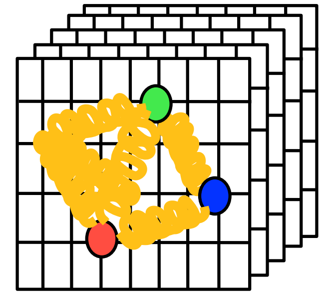
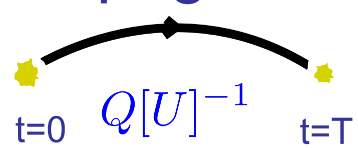


~25%

Leadership level

Propagators



+

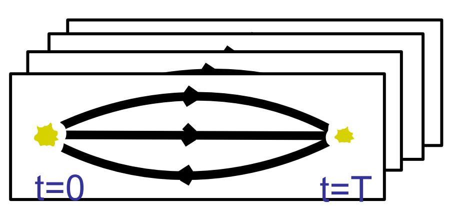
Analyze
- 100K copies
- 4 Kepler GPUs
- Now also AMG!

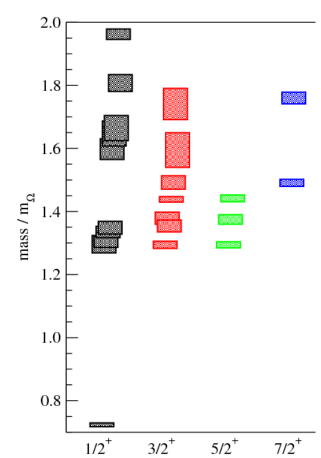
~75%

Throughput mode

Contract
- 8 cores, CPUs

Correlators
- 100K – 1M copies





> 5%

New analysis cost

Scattering in a finite cubic volume

- Expect a discrete spectrum in a finite periodic volume $\psi(x+L) = \psi(x)$

  e.g. free particle $e^{ip(x+L)} = e^{ipx}$

  quantized momentum $p = \frac{2\pi}{L} n$

- For an interacting theory $\cot \delta_\ell(E) = \mathcal{M}_\ell(E, L)$ LÜSCHER ...

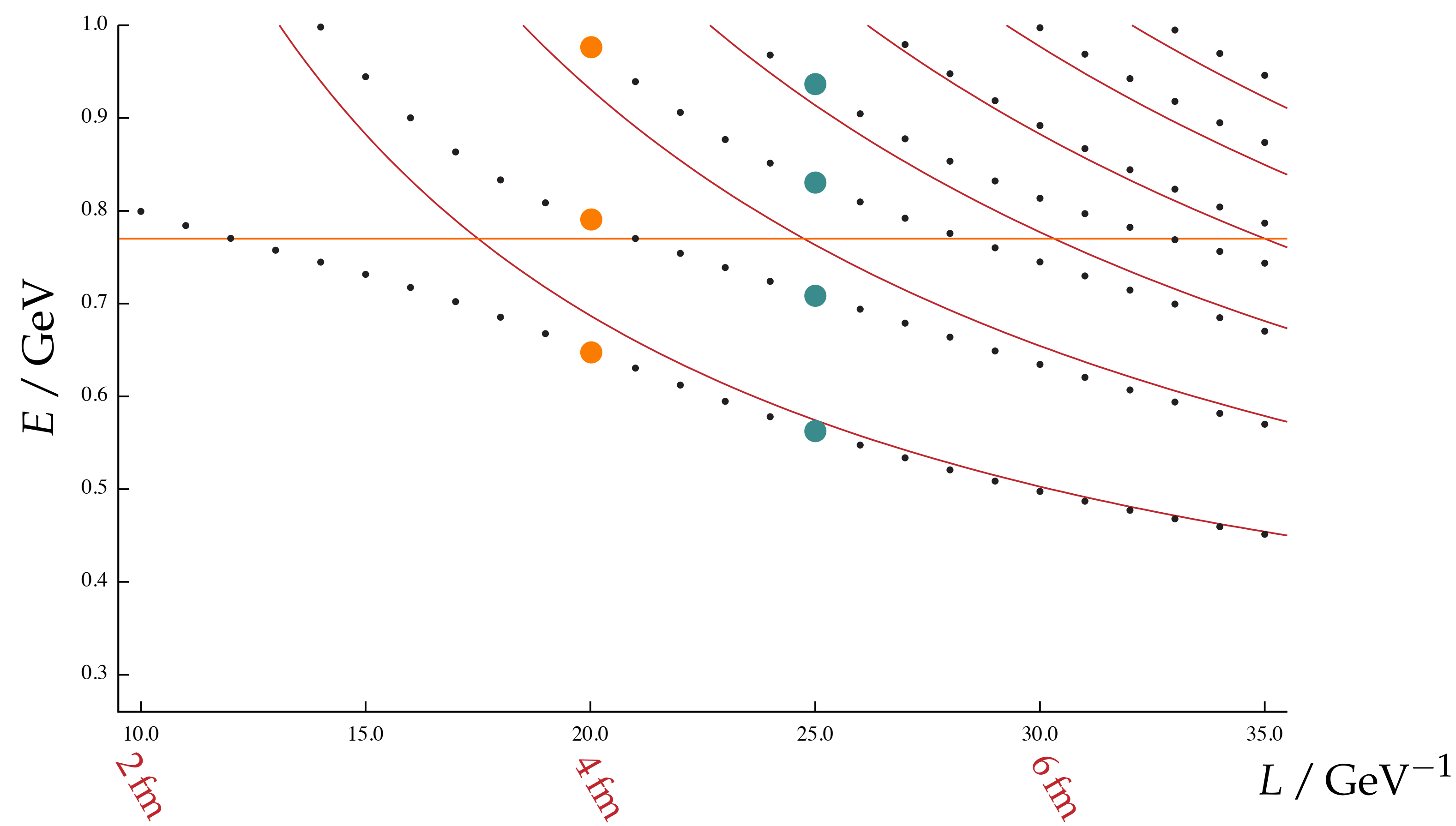
  elastic scattering phase-shift — known function

Discrete energies in a finite-volume $\longleftrightarrow$ Discrete values of the phase-shift

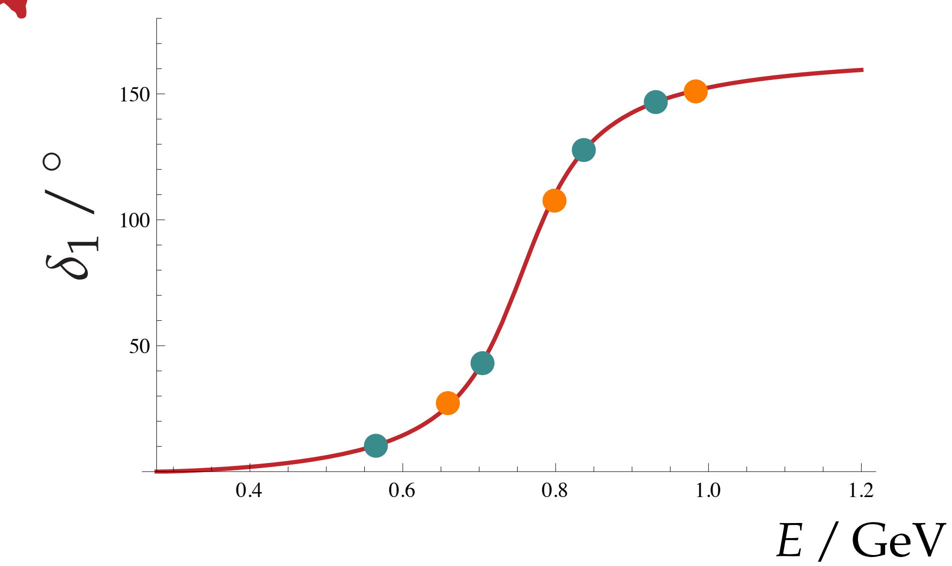
Scattering in a finite cubic volume

- Experimental $\pi\pi$ I=1 P-wave scattering amplitude

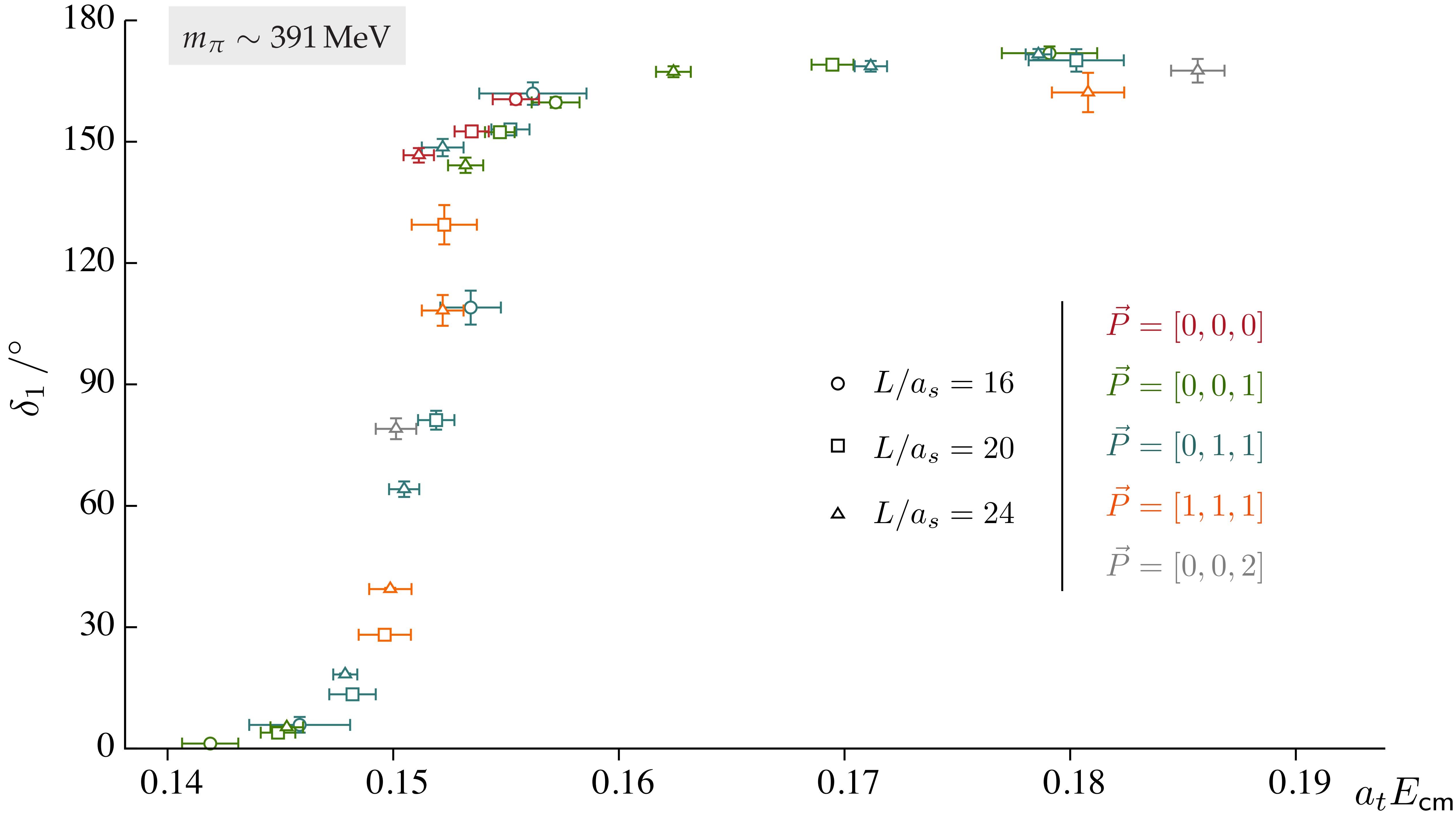
CUBIC BOX SPECTRUM



P-WAVE PHASE SHIFT



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



PRD87 034505 (2013)

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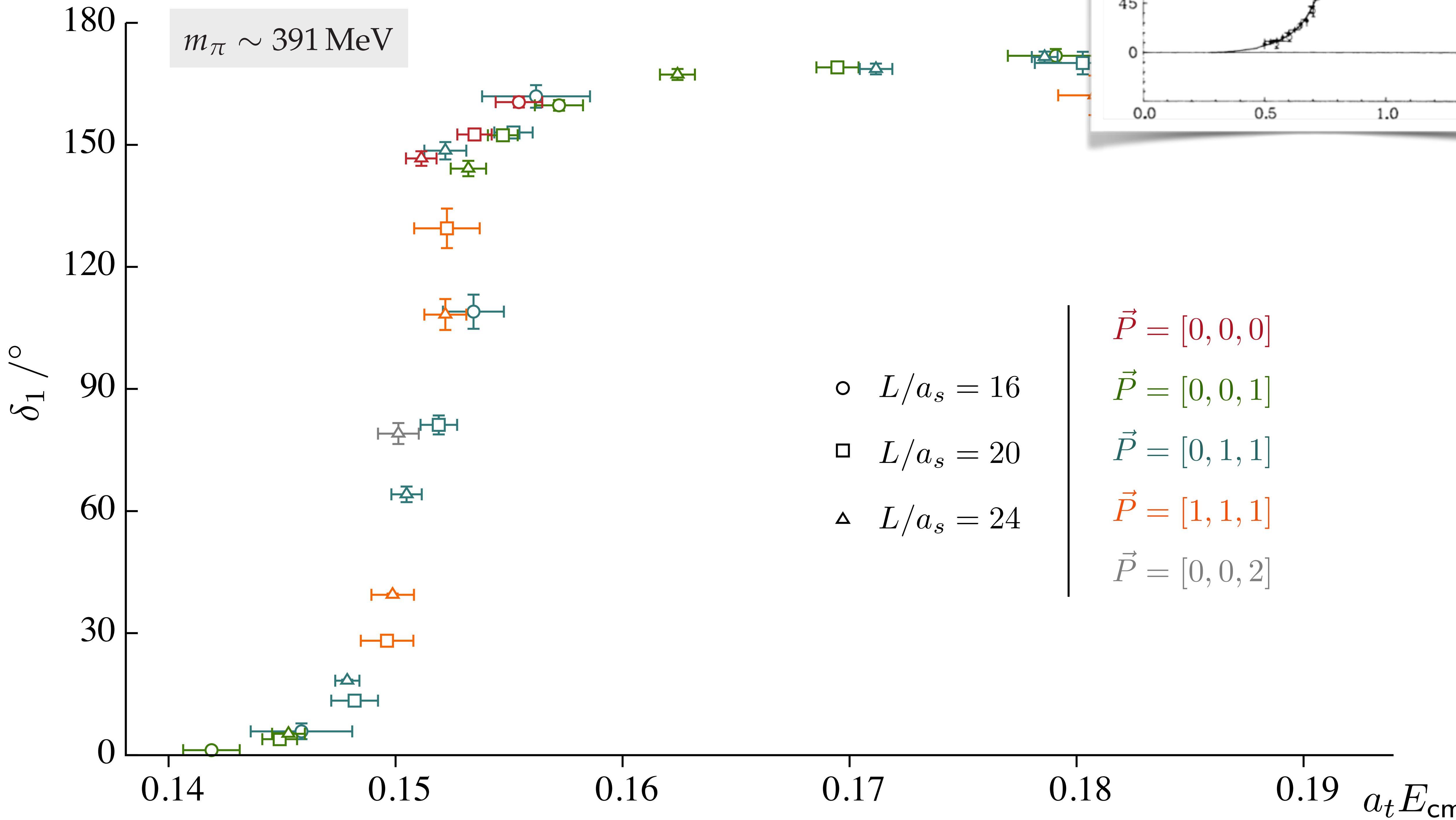
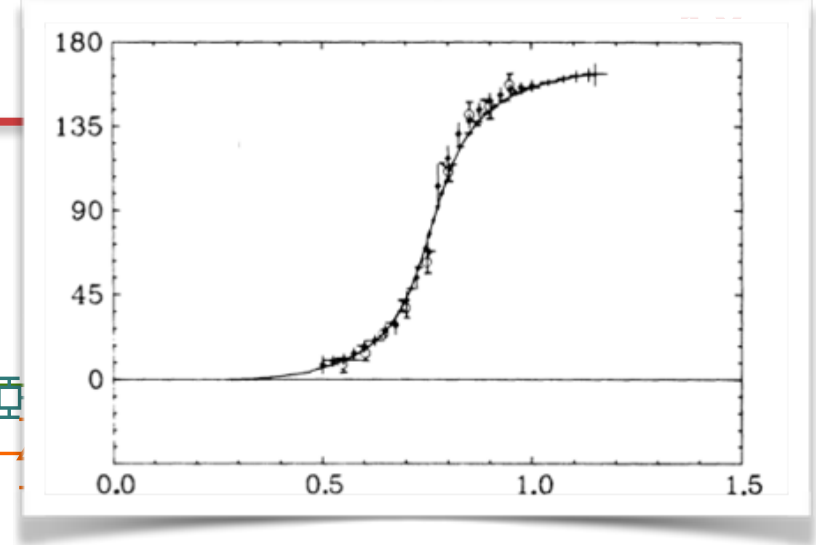
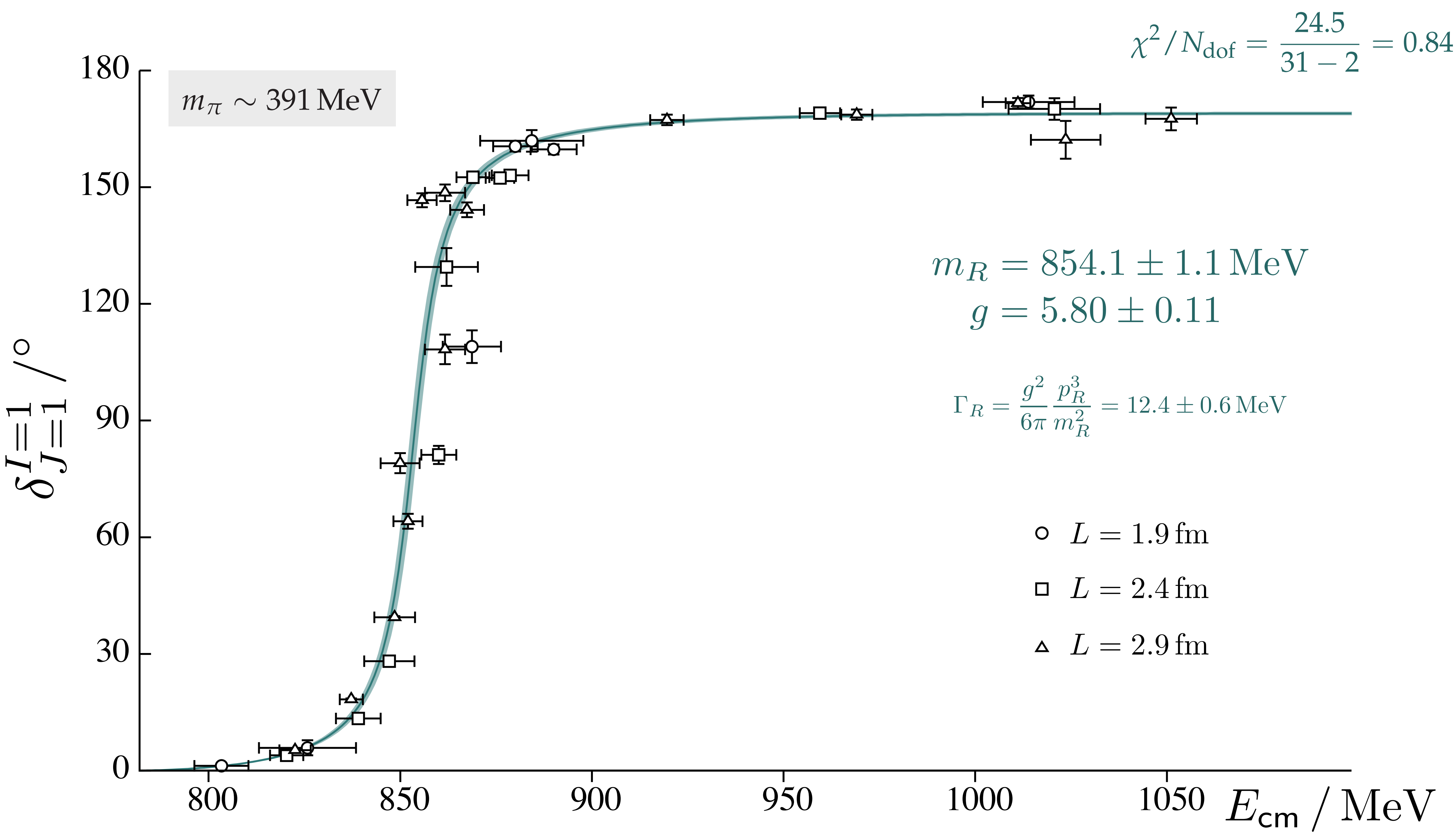




PRD87 034505 (2013)

Jefferson Lab

ρ resonance



$g_{\rm phys.} = 5.95(2)$ *PDG*

Coupled-channel scattering

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

- Finite-volume formalism recently 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

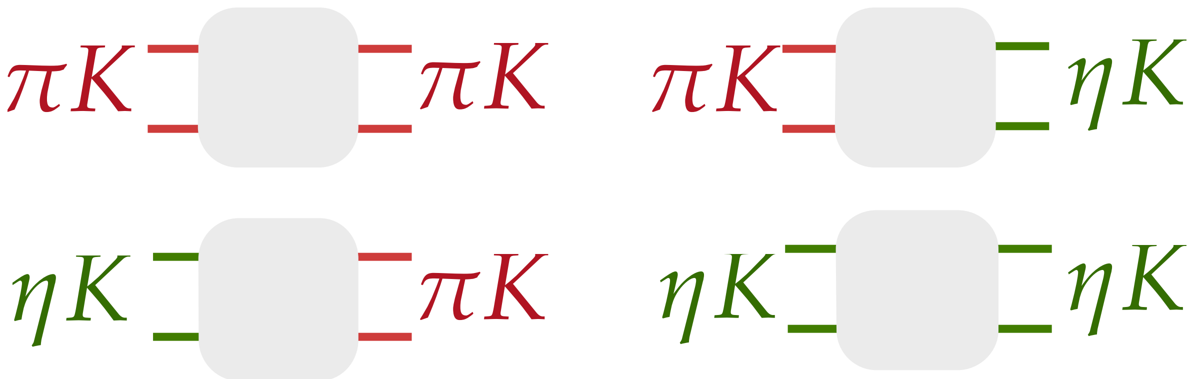
matrices in partial-wave space ...

- 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

$\pi K/\eta K$ scattering & kaon resonances

- Example of coupled-channel scattering



- Compute finite-volume spectrum

$$\bar{u}\mathbf{\Gamma}s$$

$$\sum_{\hat{k}_1,\hat{k}_2} C(\Lambda,\vec{P};\vec{k}_1,\vec{k}_2)\ \pi^\dagger(\vec{k}_1)\ K^\dagger(\vec{k}_2)$$

$$\sum_{\hat{k}_1,\hat{k}_2} C(\Lambda,\vec{P};\vec{k}_1,\vec{k}_2)\ \eta^\dagger(\vec{k}_1)\ K^\dagger(\vec{k}_2)$$

PRL 113 182001
PRD 91 054008

$\pi K/\eta K$ scattering & kaon resonances

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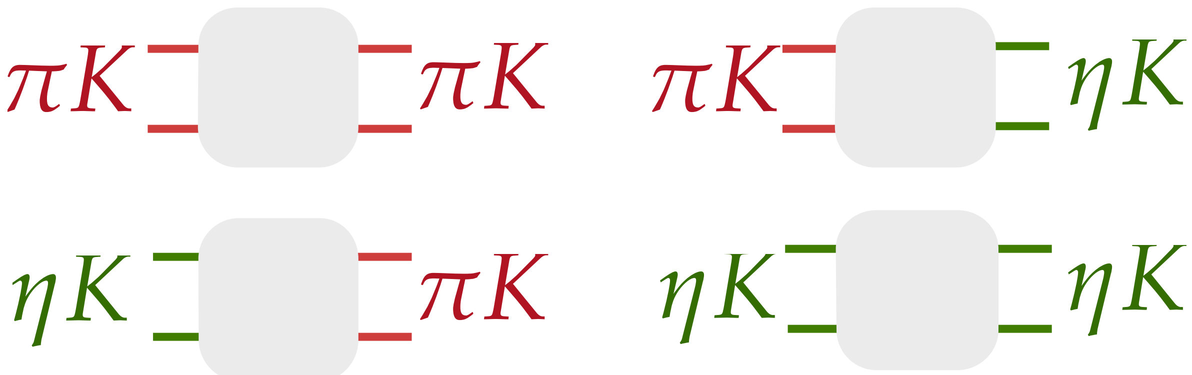

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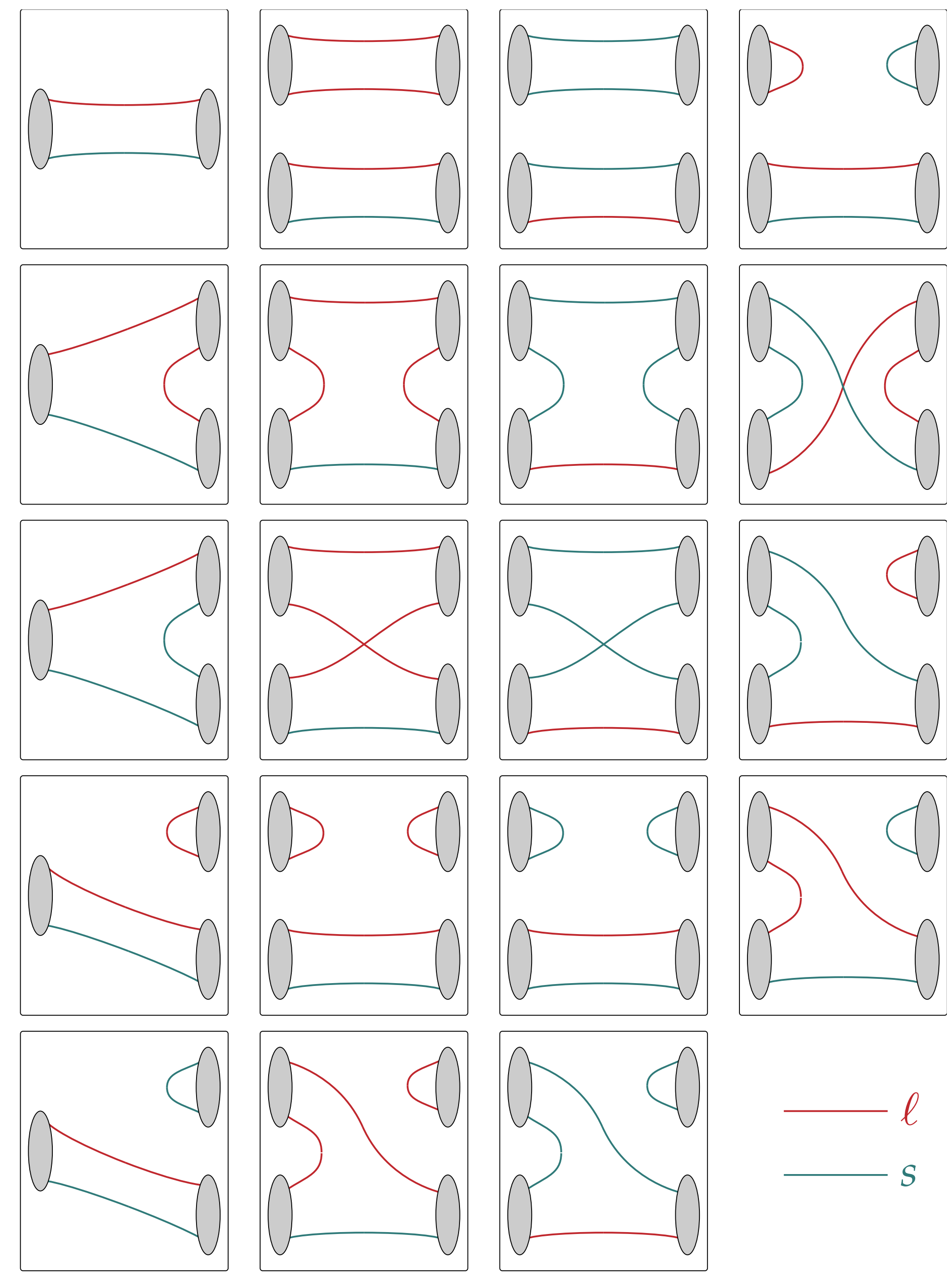
PRL 113 182001
PRD 91 054008

WICK CONTRACTIONS



$\pi K/\eta K$ scattering & kaon resonances

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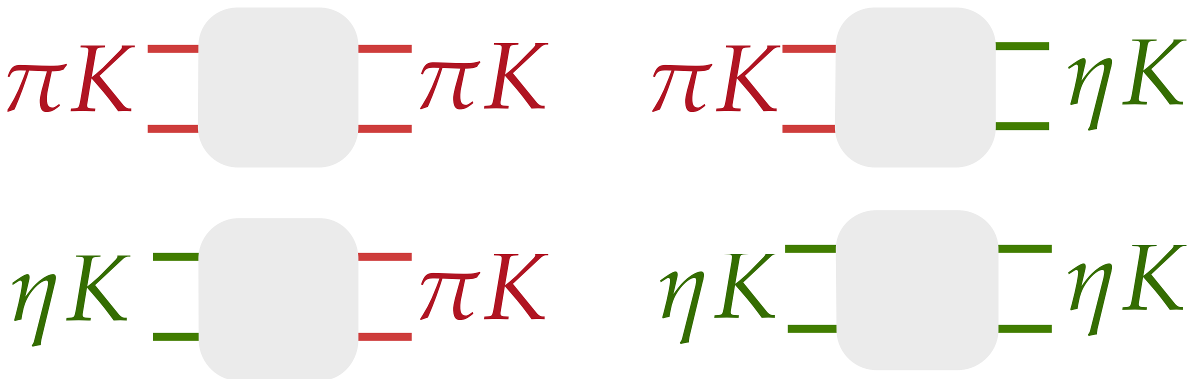

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PRL 113 182001
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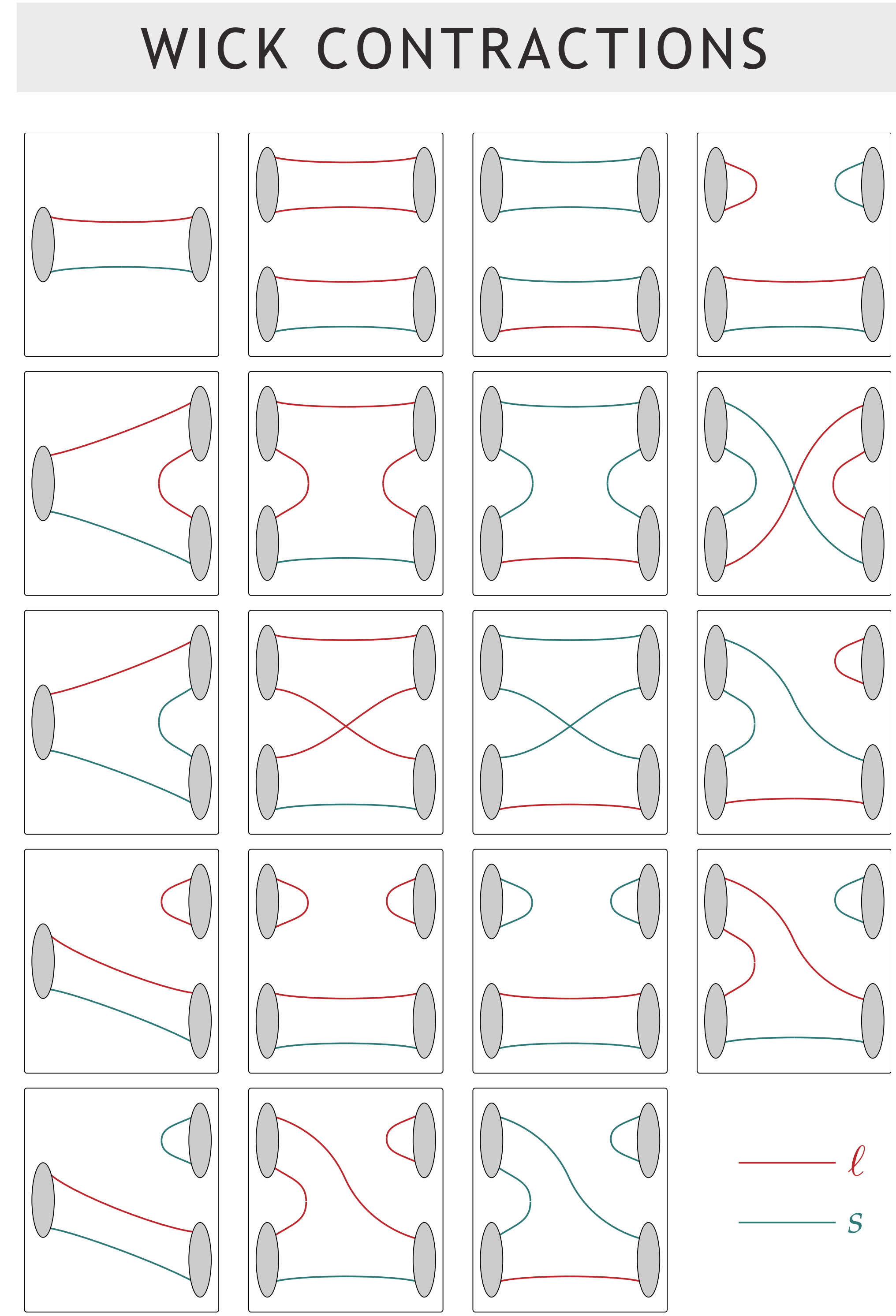
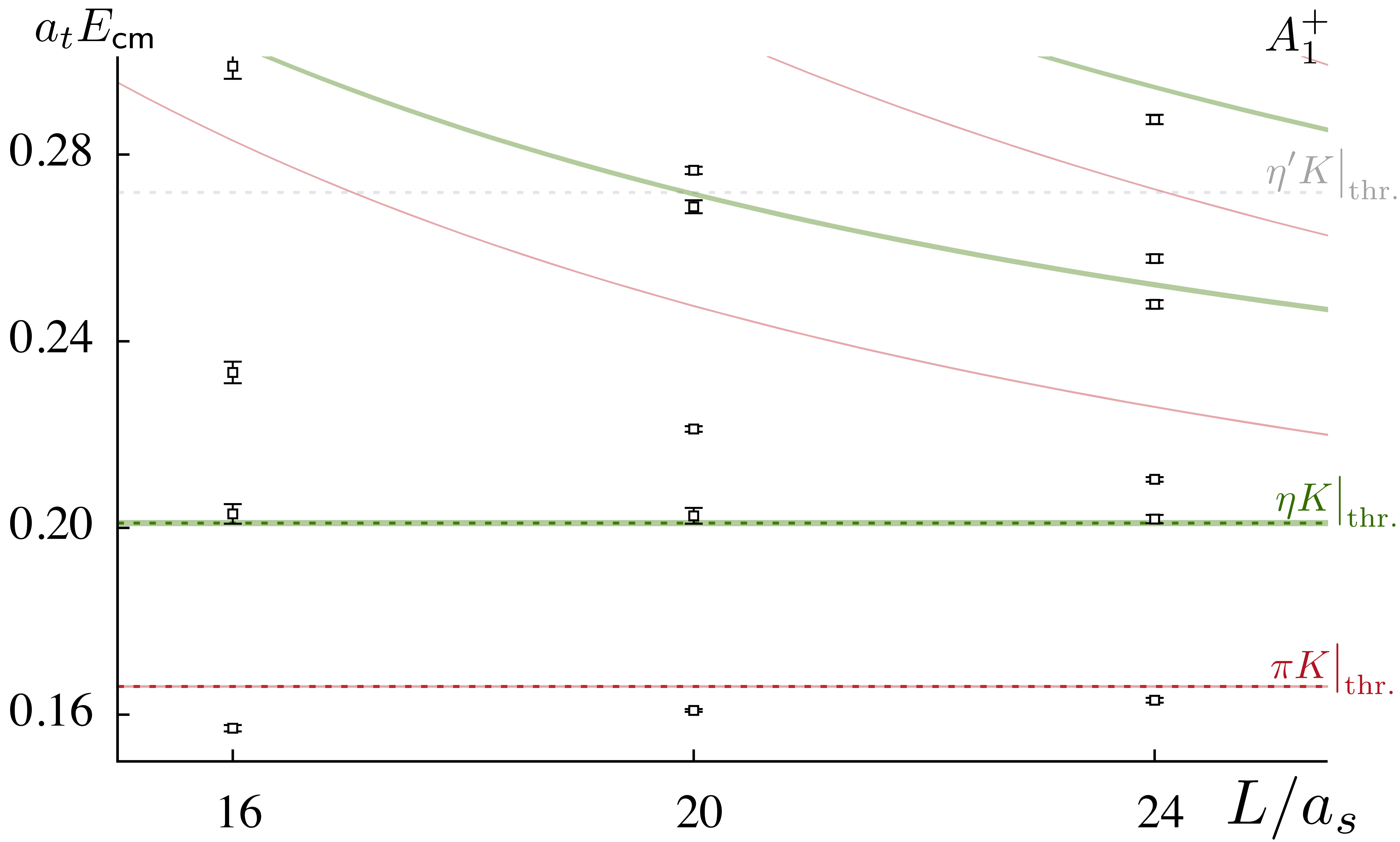
Large combinatoric factors – contractions expensive



$\pi K/\eta K$ scattering & kaon resonances

- Rest frame "S-wave" spectrum

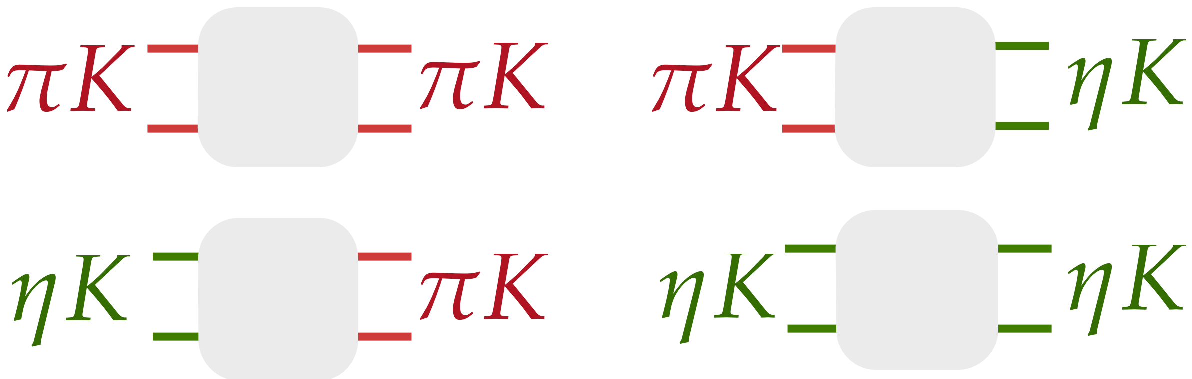
$m_\pi \sim 391\,\mathrm{MeV}$



Jefferson Lab

$\pi K/\eta K$ scattering & kaon resonances

- Parameterize the t-matrix in a unitarity conserving way



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

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

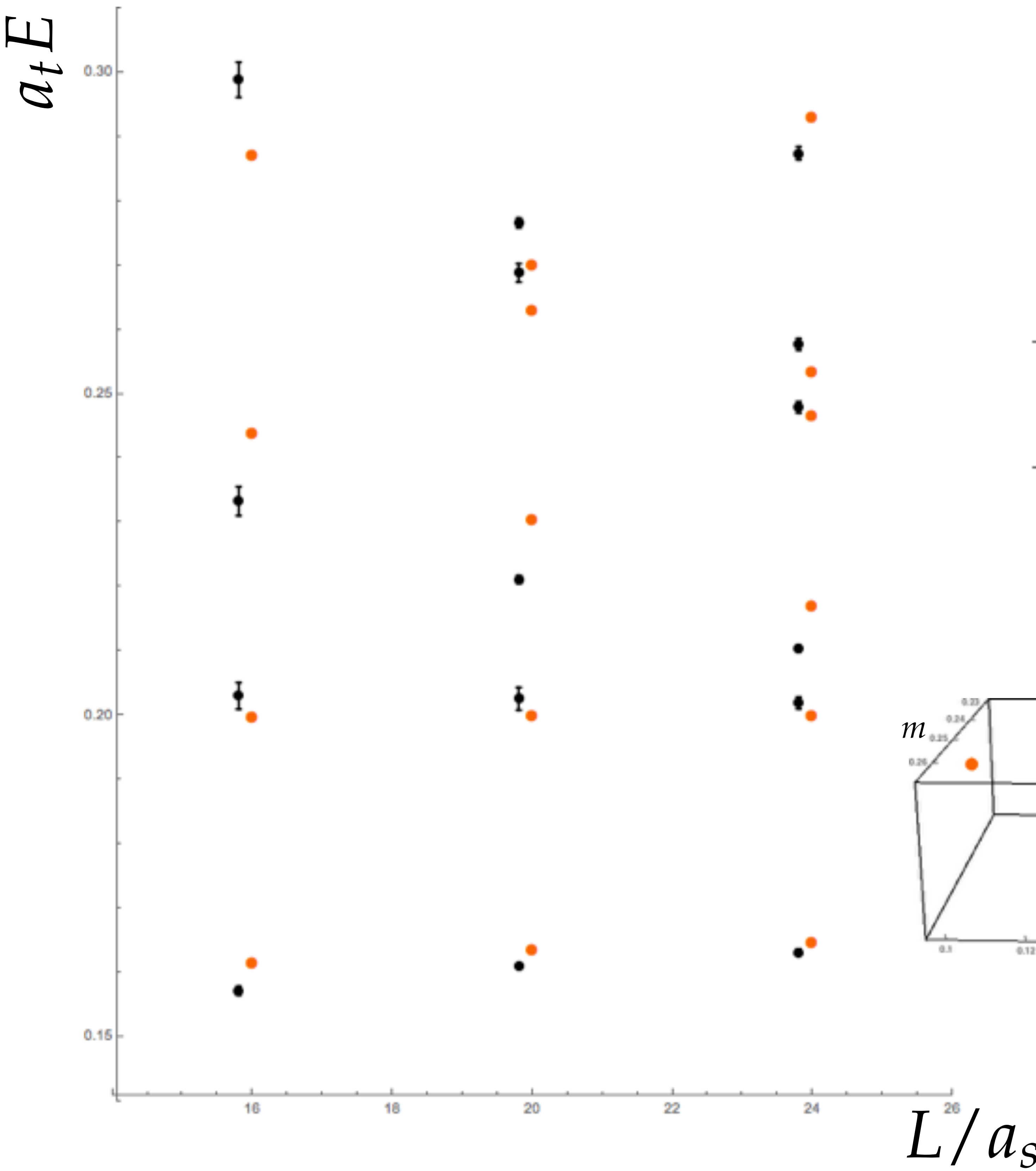
  - vary the parameters, solving

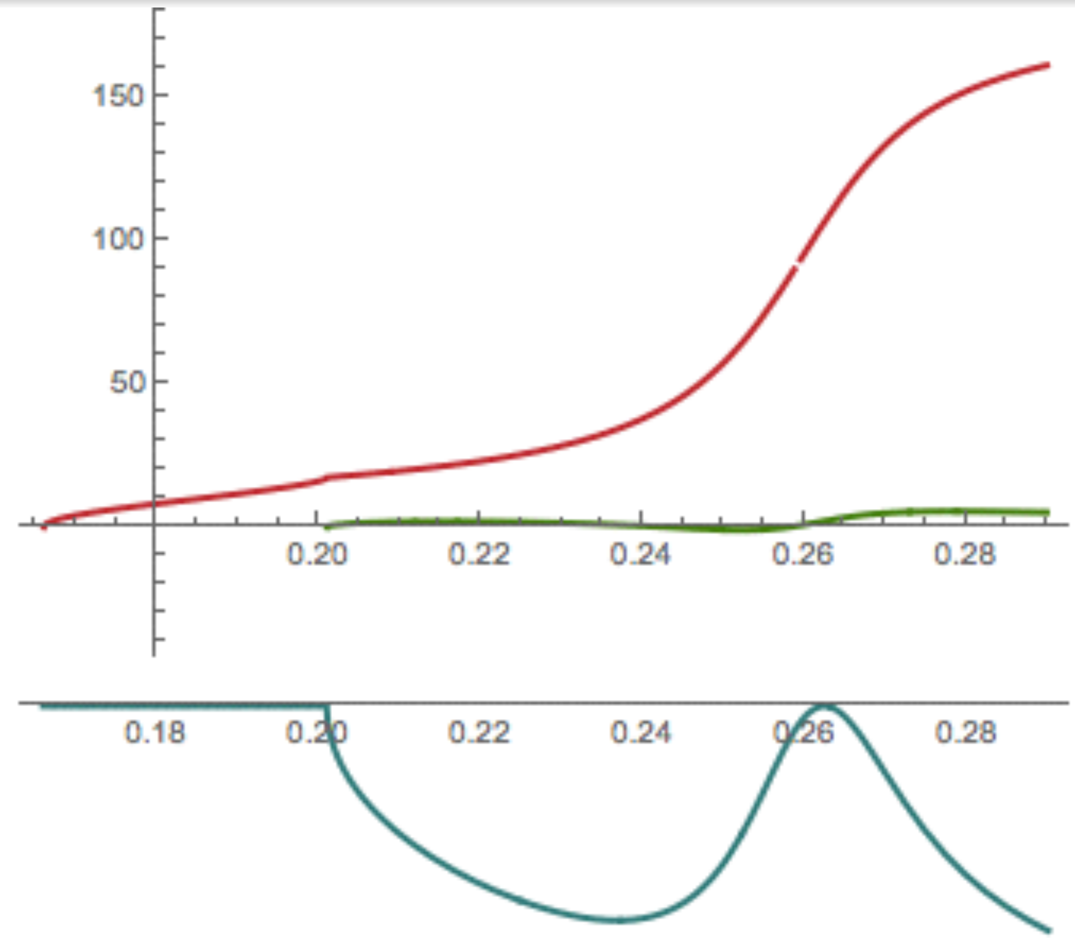
$$\det\left[\left([t^{(\ell)}(E)]_{ij}^{-1} + i\rho_i(E)\,\delta_{ij}\right) - \delta_{ij}\,\mathcal{M}_\ell(E,L)\right] = 0$$

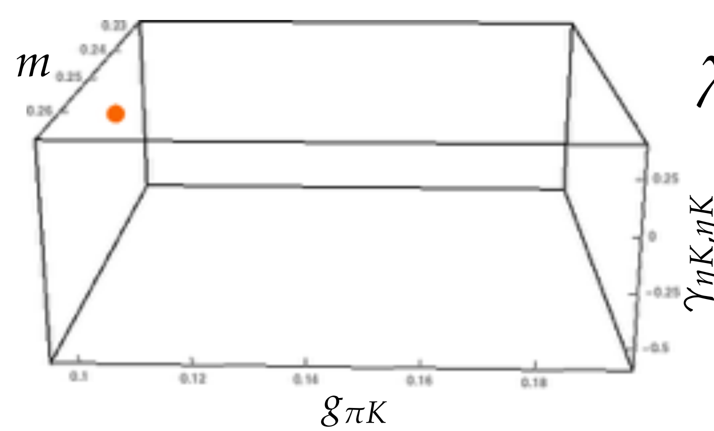
for the spectrum in each irreducible representation & momentum

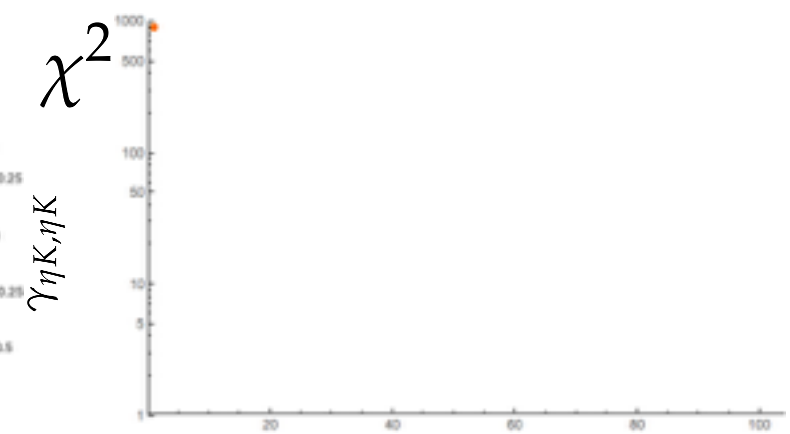
Want pole mass and couplings of t-matrix

$\pi K/\eta K$ scattering



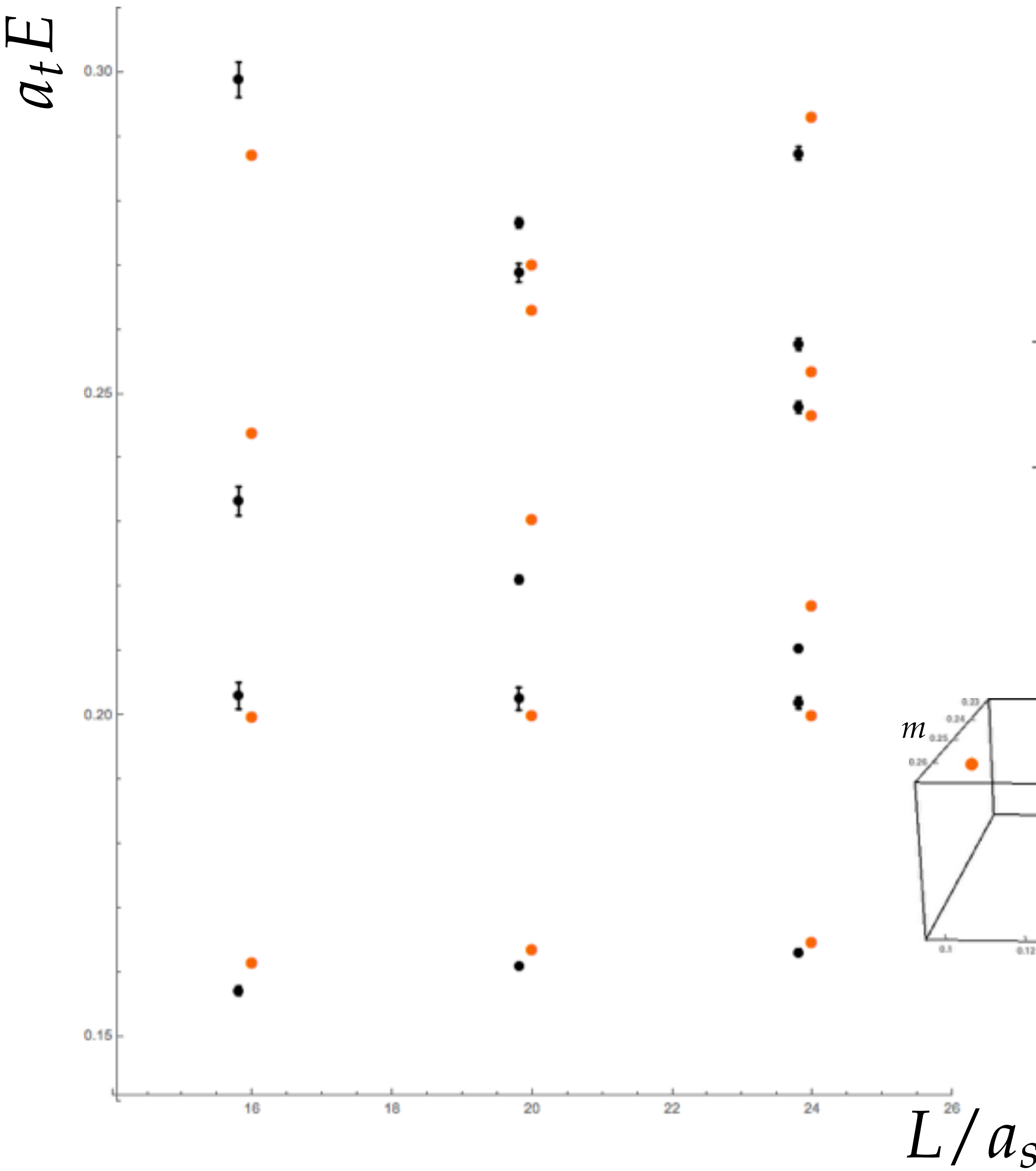


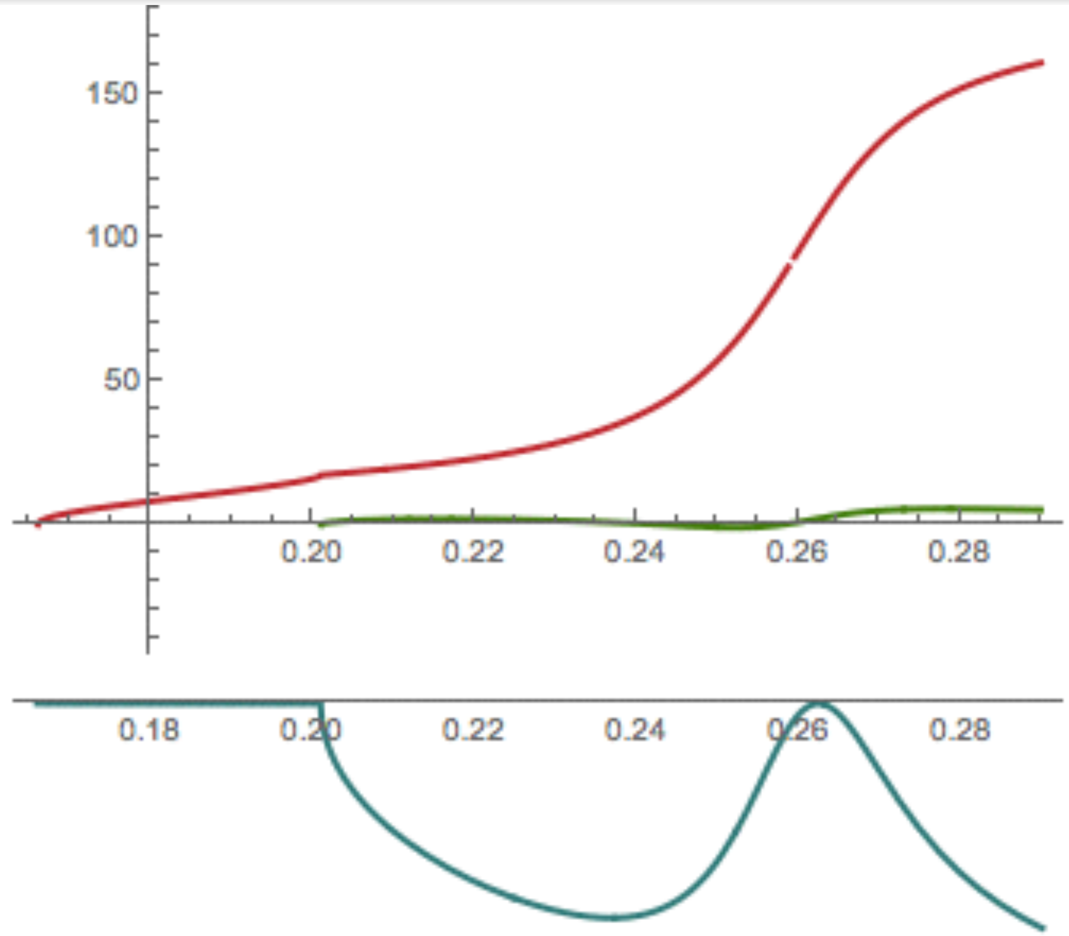


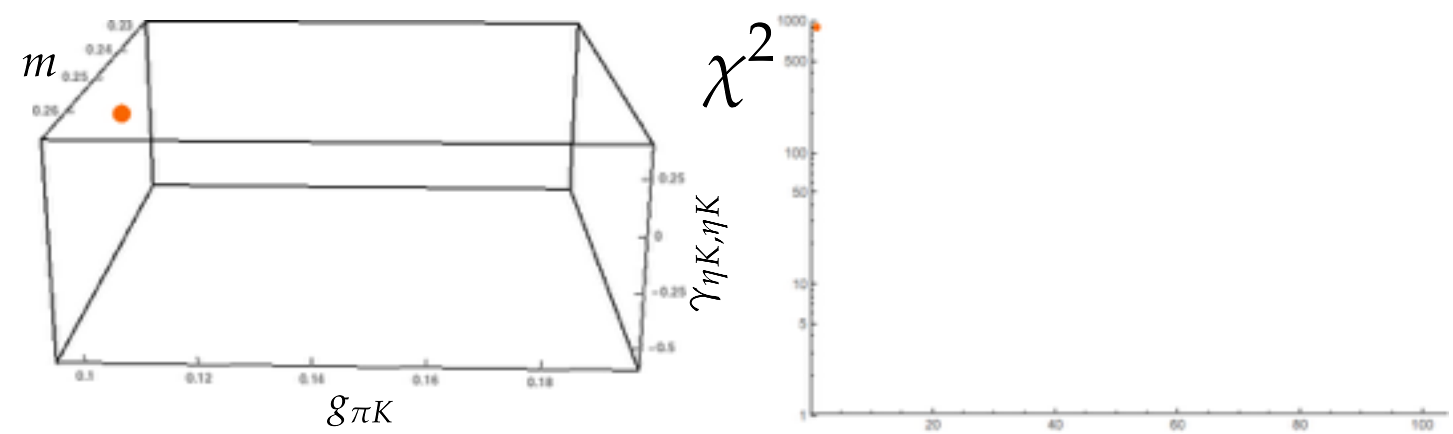


Jefferson Lab

$\pi K/\eta K$ scattering

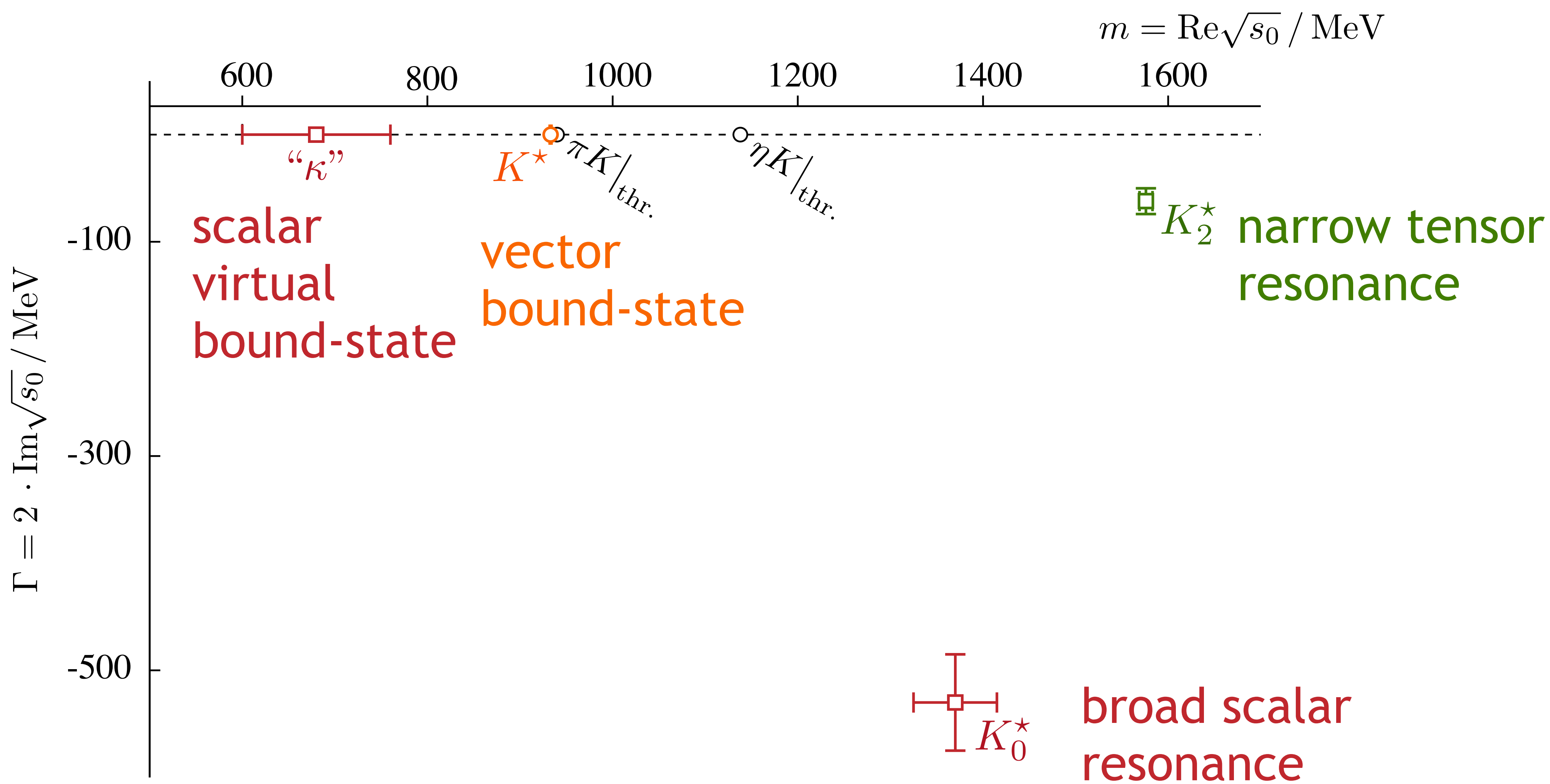






Singularity content

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



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

PRL 113 182001
PRD 91 054008

Impact on experiment

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

Approved expt: second phase of GlueX program

PR12-13-003

An initial study of mesons and baryons containing strange quarks with GlueX

(A proposal to the 40th Jefferson Lab Program Advisory Committee)

A. AlekSejevs,[1] S. Barkanova,[1] M. Dugger,[2] B. Ritchie,[2] I. Senderovich,[2] E. Anassontzis,[3] P. Ioannou,[3] C. Kourkoumeli,[3] G. Voulgaris,[3] N. Jarvis,[4] W. Levine,[4] P. Mattione,[4] W. McGinley,[4] C. A. Meyer,[4,*]

⋮

The primary motivation of the GlueX experiment is to search for and ultimately study the pattern of gluonic excitations in the meson spectrum produced in γp collisions. Recent lattice QCD calculations predict a rich spectrum of hybrid mesons that have both exotic and non-exotic J^{PC}, corresponding to $q\bar{q}$ states ($q = u$, d, or s) coupled with a gluonic field. A thorough study of the

Impact on experiment

Science case for JLab CLAS12 expt

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]

NSAC report prominently featuring exotic meson spectroscopy project

Report to the
Nuclear Science Advisory Committee
Implementing the 2007 Long Range Plan
January 31, 2013

New NSAC report in writing now…

Hadron Spectrum Collaboration

JEFFERSON LAB

Jozef Dudek
Robert Edwards
Balint Joo
David Richards
Frank Winter

TRINITY COLLEGE, DUBLIN

Mike Peardon
Sinead Ryan

TATA, MUMBAI

Nilmani Mathur

CAMBRIDGE UNIVERSITY

Christopher Thomas

U. OF MARYLAND

Steve Wallace

& postdocs, students

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)	$(N,\Delta)_{\mathrm{hyb}}$
PRD87 054506 (2013)	$(N\ldots\Xi)^\star$
PRD90 074504 (2014)	$\Omega^\star_{ccc}$
arXiv:1502.01845	$\Xi^\star_{cc}$

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)	$\pi K, \eta K$

"TECHNOLOGY"

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

MATRIX ELEMENTS

arXiv:1501.07457	$M' \to \gamma M$
PRD90 014511 (2014)	$f_{\pi^\star}$

Summary

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- First phase:
  - Unphysical pion masses
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  - See evidence of exotic and non-exotic mesons - suggests *hybrids*
  - ➡ Has had direct impact on JLab expt. program

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  - ➡ Knowledge of even size of branching fractions useful for expt. analysis

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- Switch to isotropic lattices at physical limit