QCD spectroscopy

OLD DOMINION UNIVERSITY

Jefferson Lab

RAÚL BRICEÑO

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http://bit.ly/rbricenoPhD

@RaulBriceno12

hadspec

QCD spectroscopy

Amplitude analysis

Experiments

GLUEX CLAS12 COMPASS

LHCb Belle II BESIII

panda

QCD

QCD spectroscopy

Amplitude analysis

Experiments

QCD

<u>GOAL:</u>

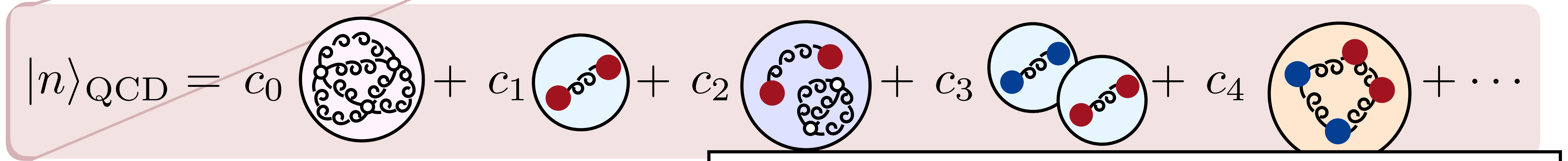
Get insights to the governing patterns and rules of QCD from emergent phenomena

Observables to test our understanding:

- Purely hadronic scattering,
- Production and decay,
- Exotic states,
- …

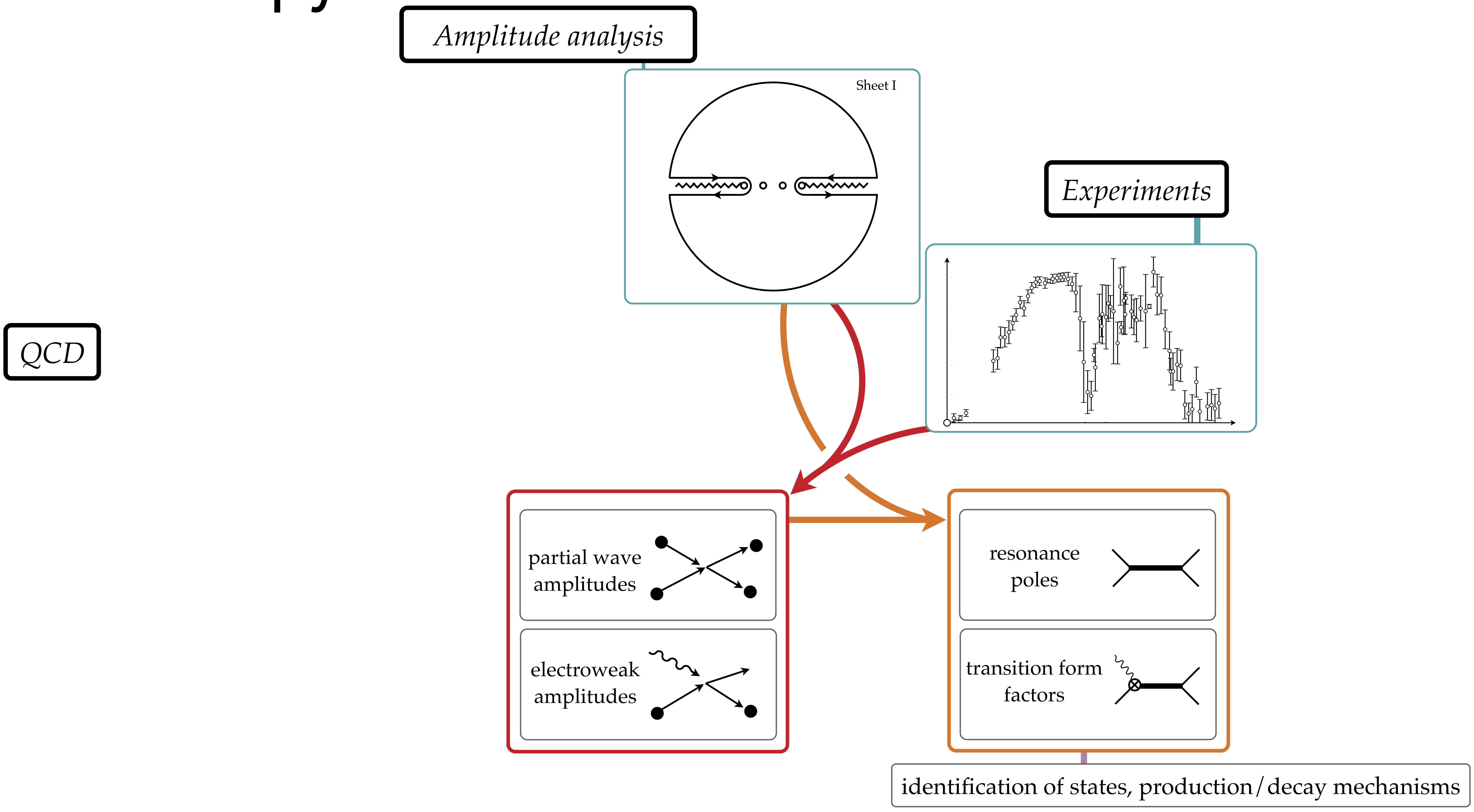
Possible outcomes:

- Source of masses,
- Role of glue,
- Structure of excited states,
- …

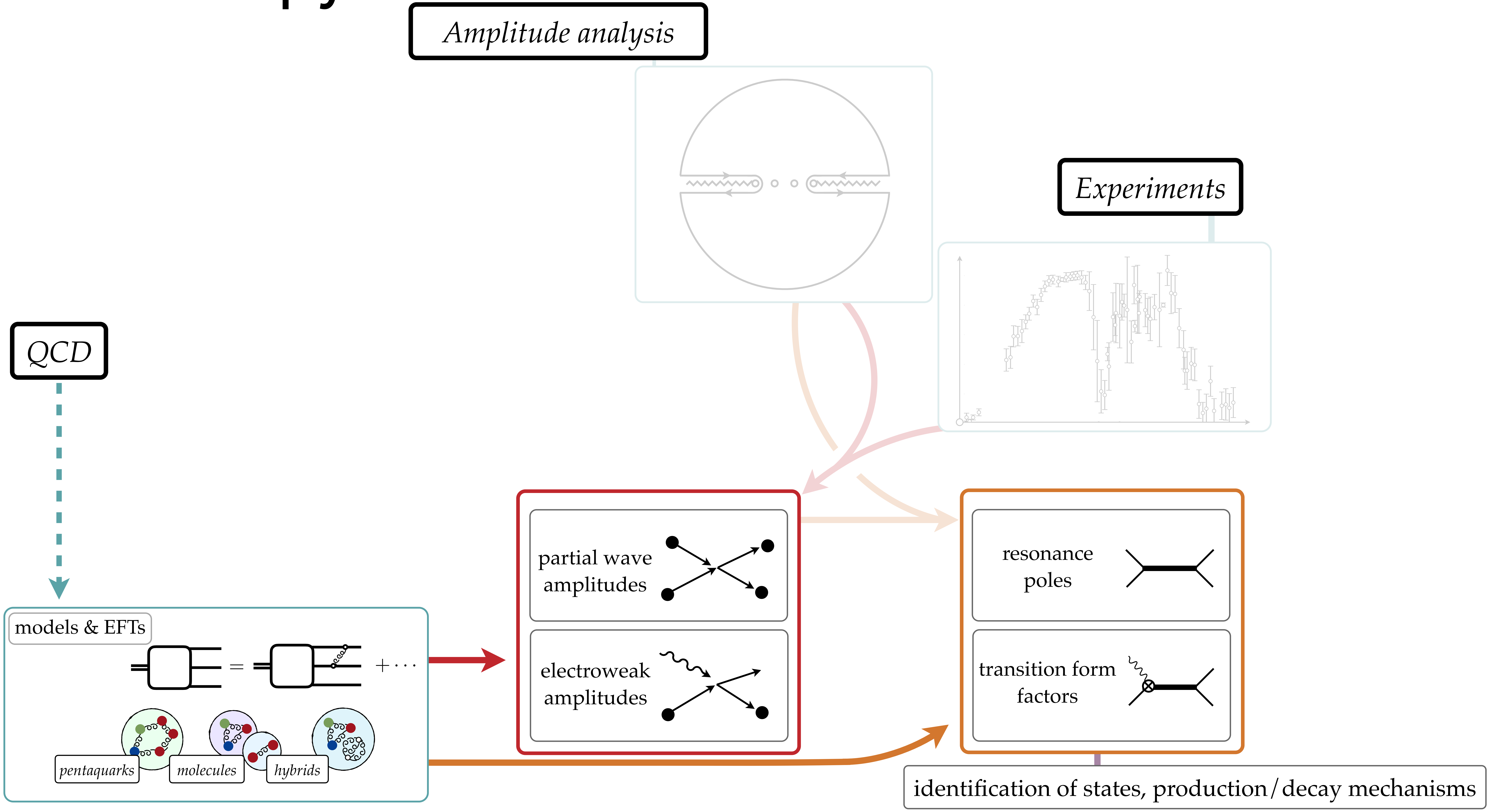


… perhaps there is a hierarchy [e.g. $c_0 > c_1 > c_2 > c_3 > c_4$]

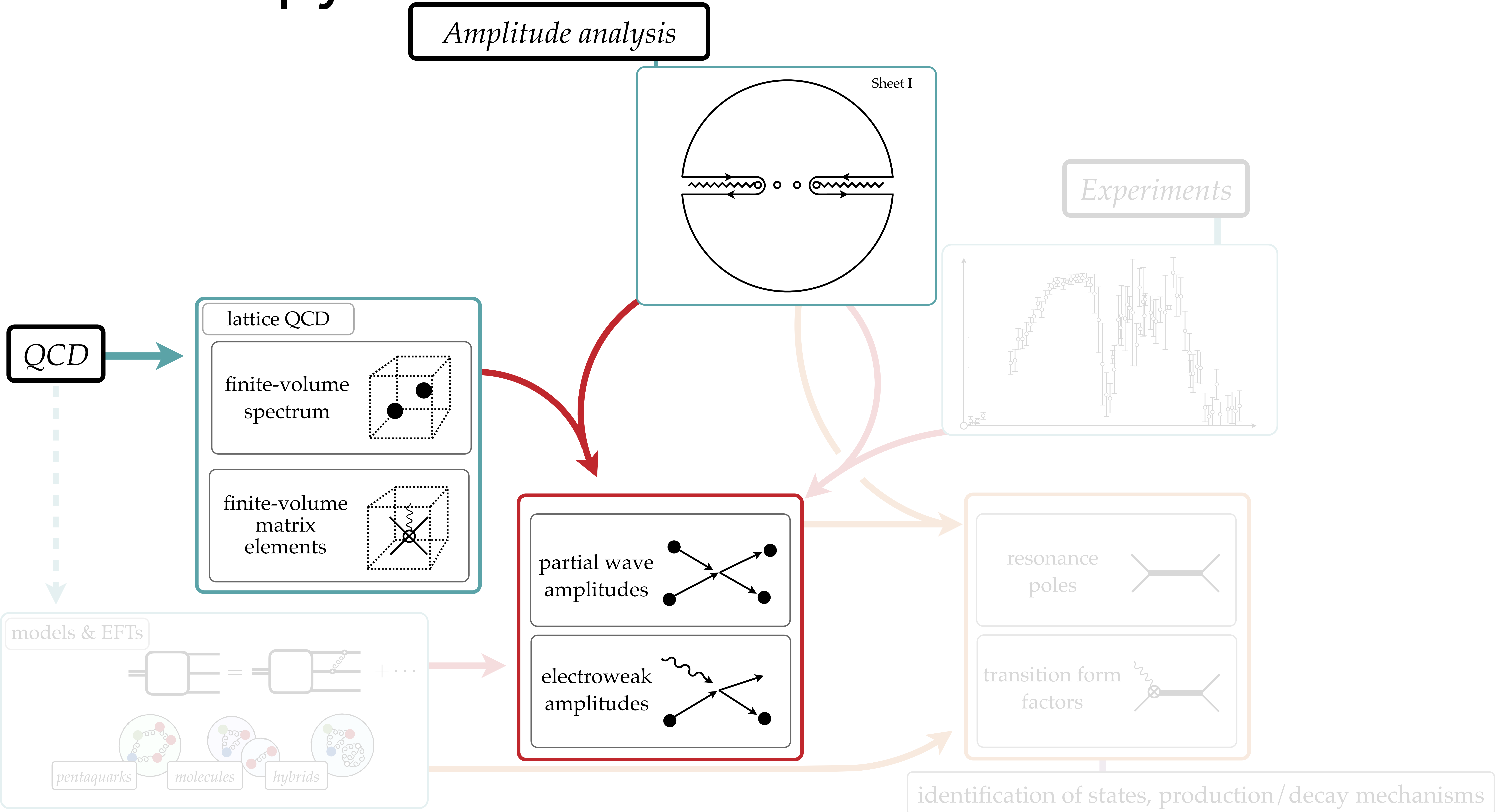
QCD spectroscopy



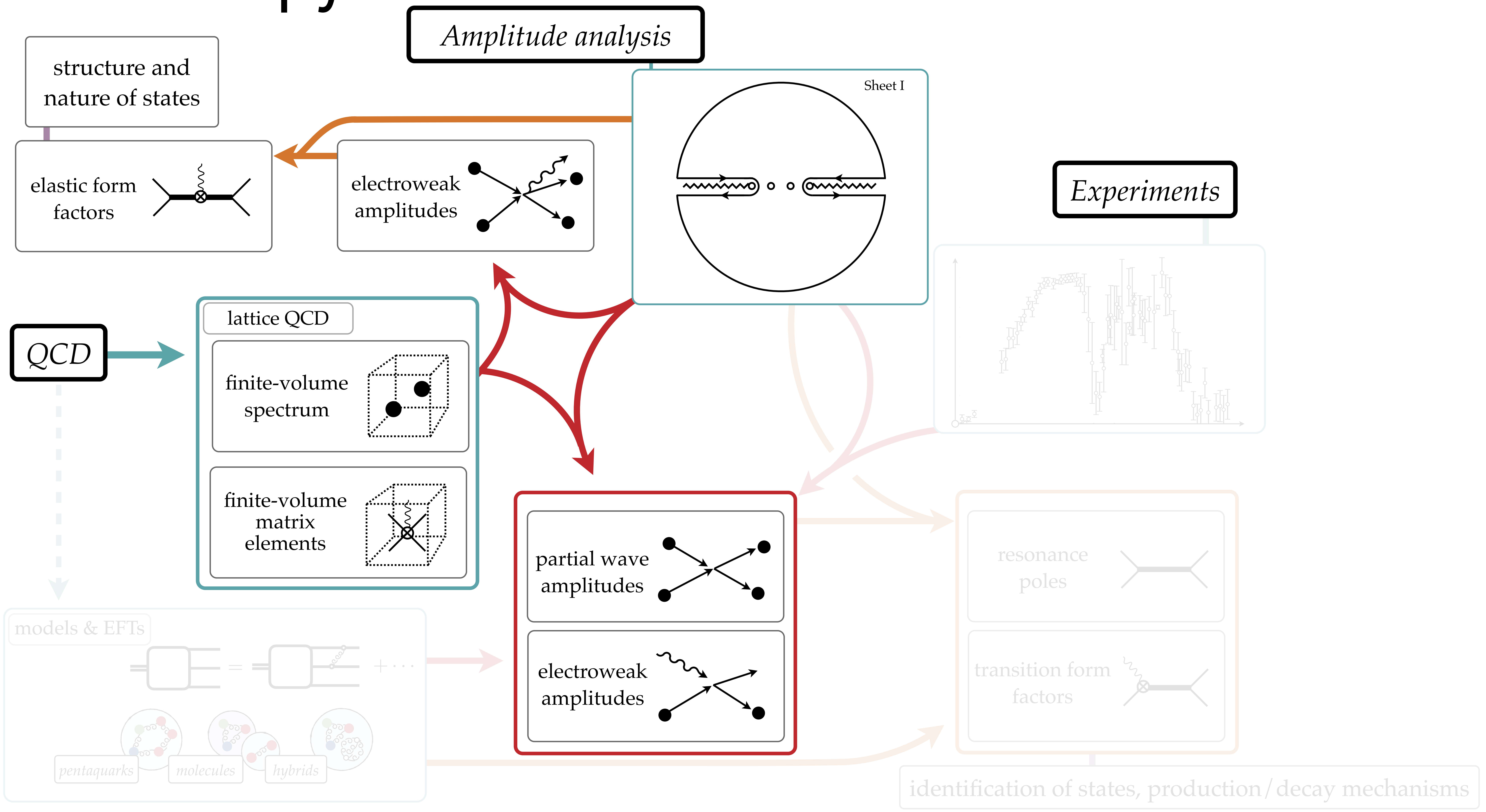
QCD spectroscopy



QCD spectroscopy



QCD spectroscopy



2+1 minimum requirements

Two "musts" for few-body systems:

- ☑ Generalized eigenvalue problem (GEVP),
  - ☑ large basis of ops,

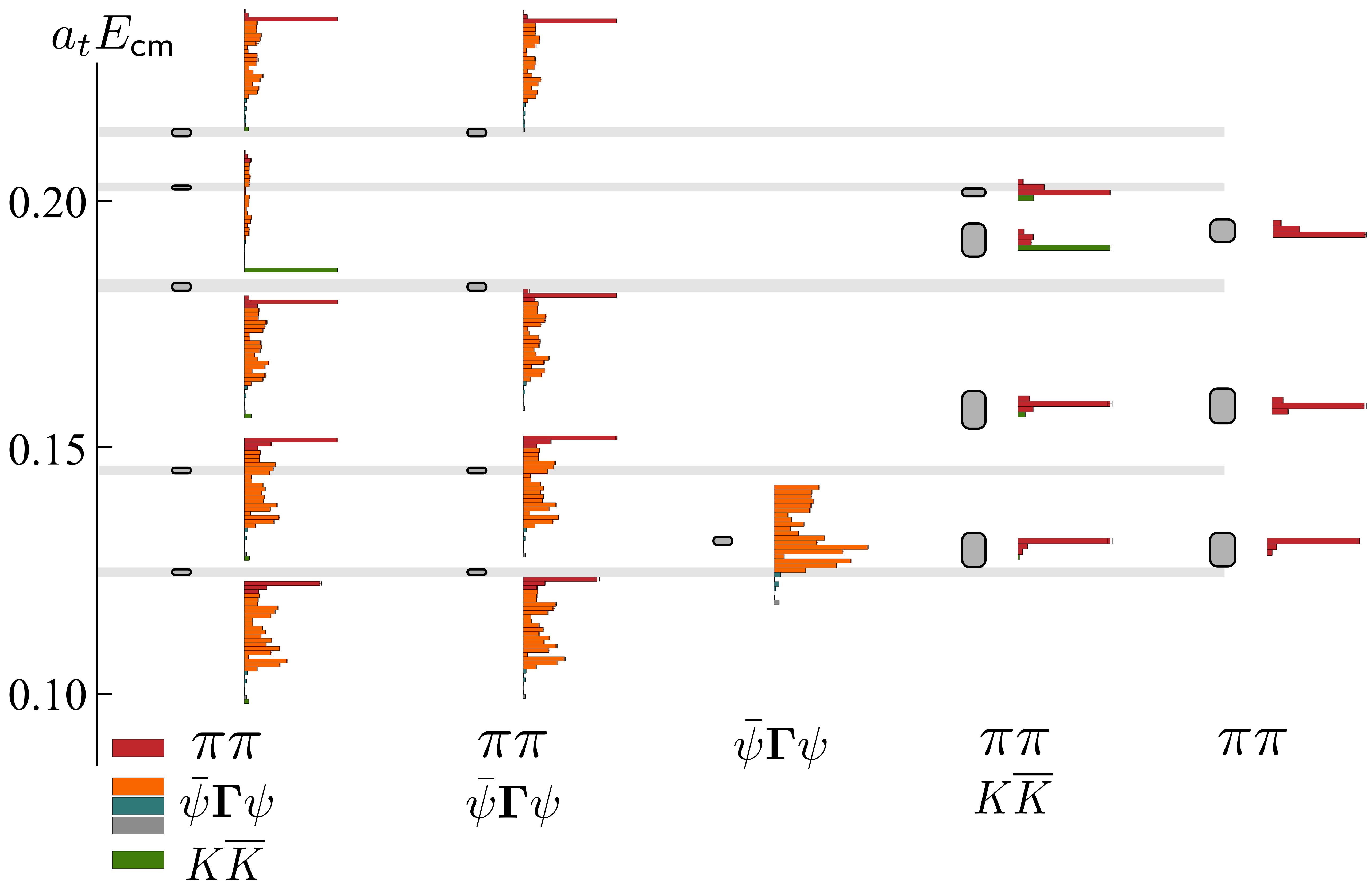
    $\mathcal{O}_b \sim \bar{q}\,\Gamma_b\, q, \pi\pi, K\overline{K}, \ldots, 3\pi, \ldots$
  - ☑ diagonalization,

    $C^{2pt.}_{ab}(t,\mathbf{P}) \equiv \langle 0|\mathcal{O}_b(t,\mathbf{P})\mathcal{O}^\dagger_a(0,\mathbf{P})|0\rangle = \sum_n Z_{b,n} Z^*_{a,n} e^{-E_n t}$
- ☑ Finite-volume formalisms.

One powerful tool to make GEVP practical:

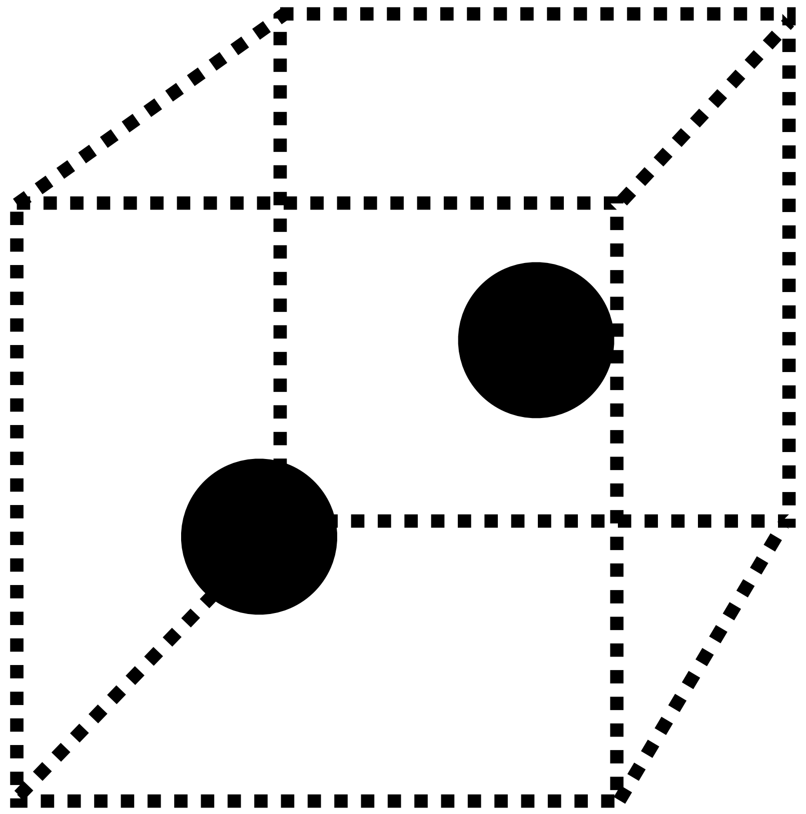
- ☑ Distillation [Peardon, *et al.* (HadSpec, 2009)].

GEVP with large basic is **necessary** but **not sufficient** to trust spectrum!



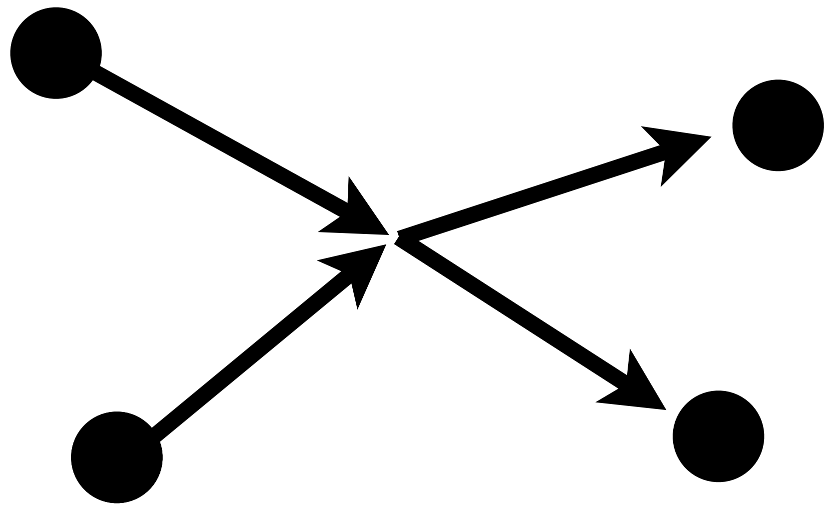
Wilson, RB, Dudek, Edwards, & Thomas (2015)

Two-hadron systems

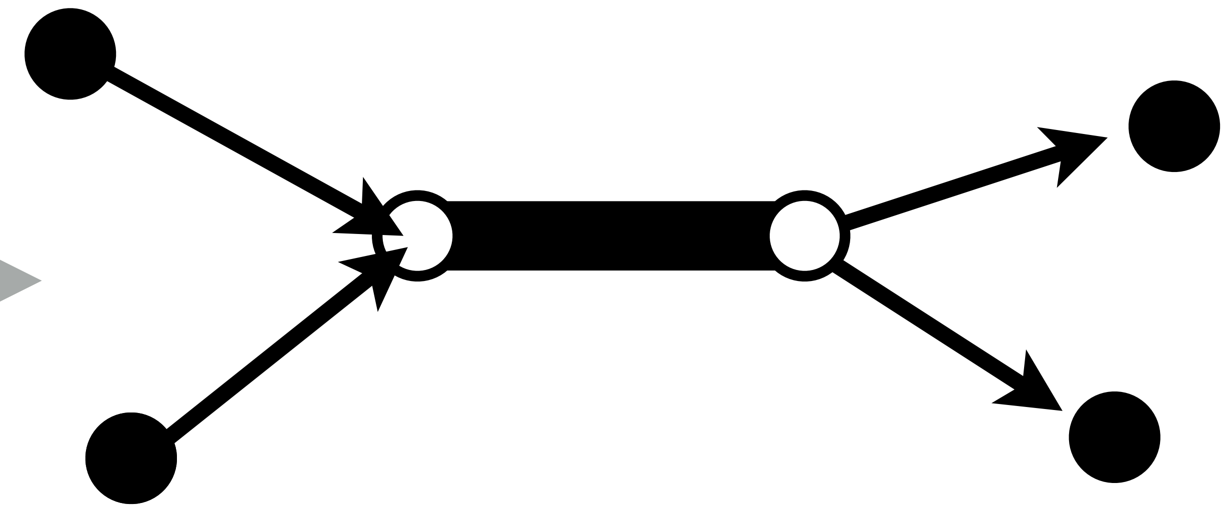


finite-volume
spectroscopy

Lüscher (1986, 1991)
Rummukainen & Gottlieb (1995)
Kim, Sachrajda, & Sharpe (2005)
Christ, Kim & Yamazaki (2005)
Feng, Li, & Liu (2004)
Hansen & Sharpe (2021)
RB & Davoudi (2012)
RB (2014)

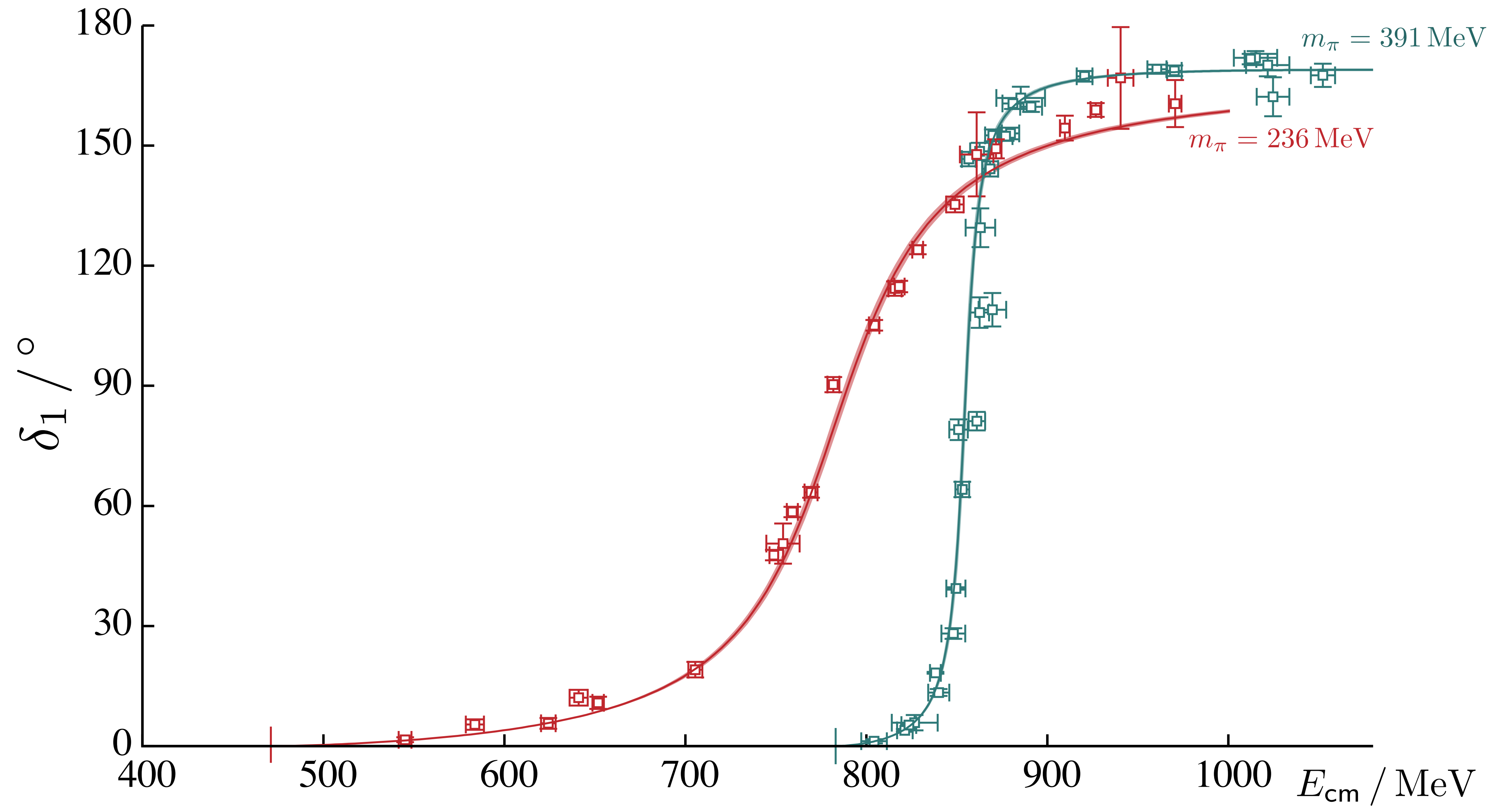


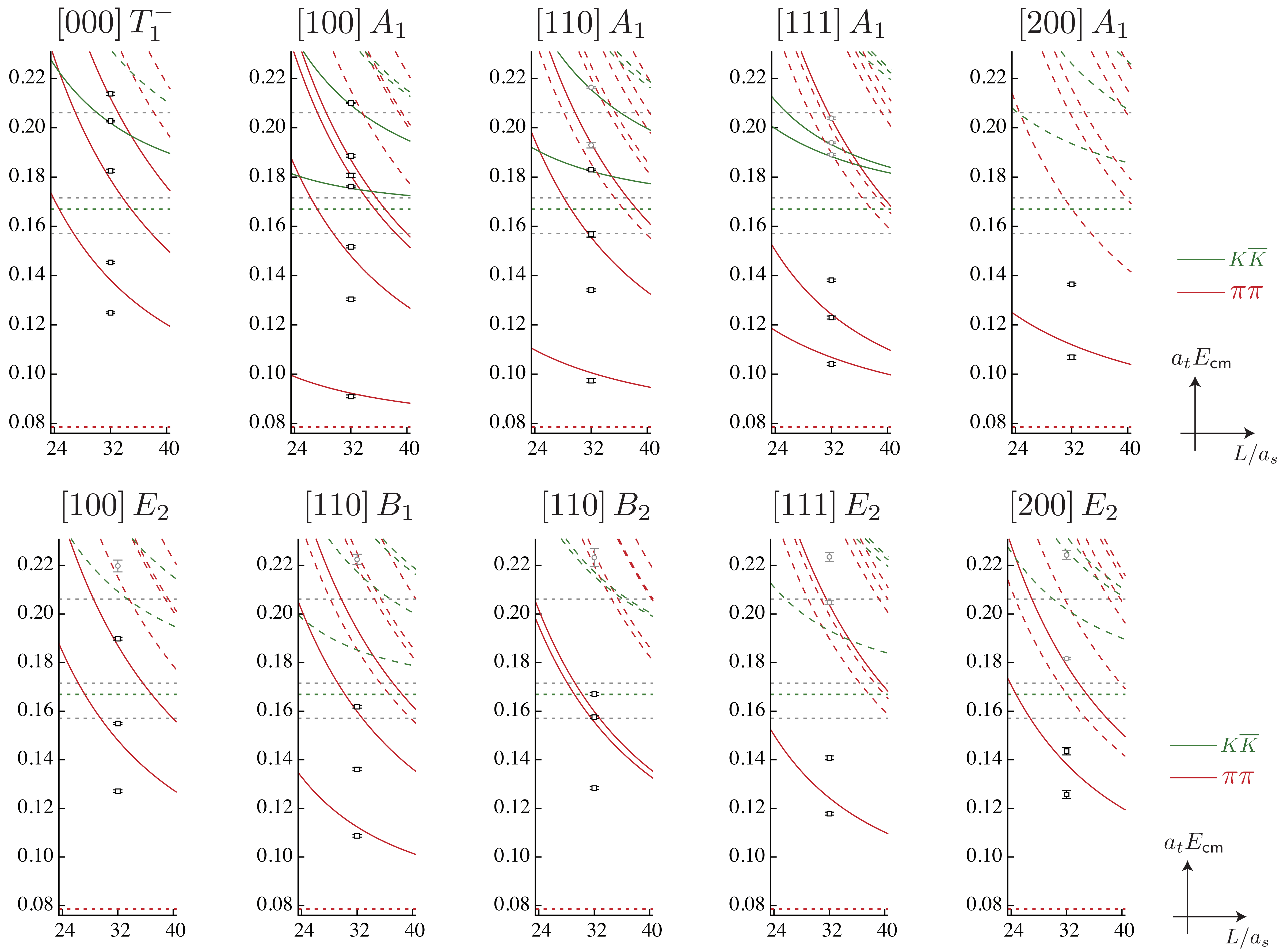
infinite-volume
scattering amplitudes



bound state and
resonance poles

$\pi\pi$ scattering
(I=1 channel)

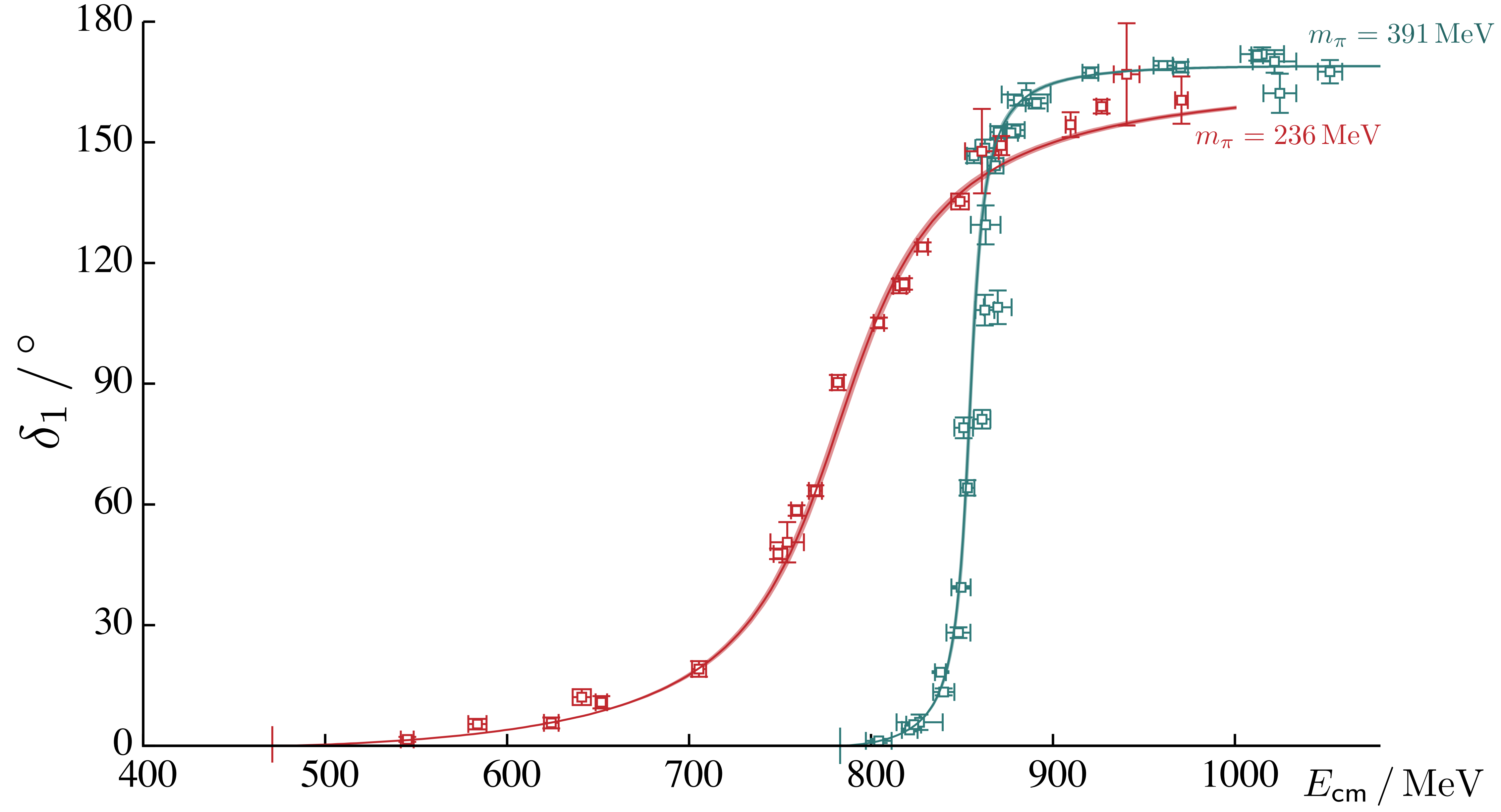




$$\mathcal{M} \sim \frac{1}{p \cot \delta - ip}$$

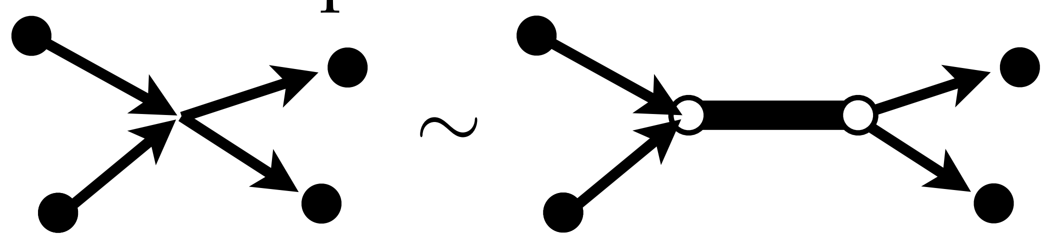
Dudek, Edwards, & Thomas (2012)
Wilson, RB, Dudek, Edwards, & Thomas (2015)

$\pi\pi$ scattering
(I=1 channel)



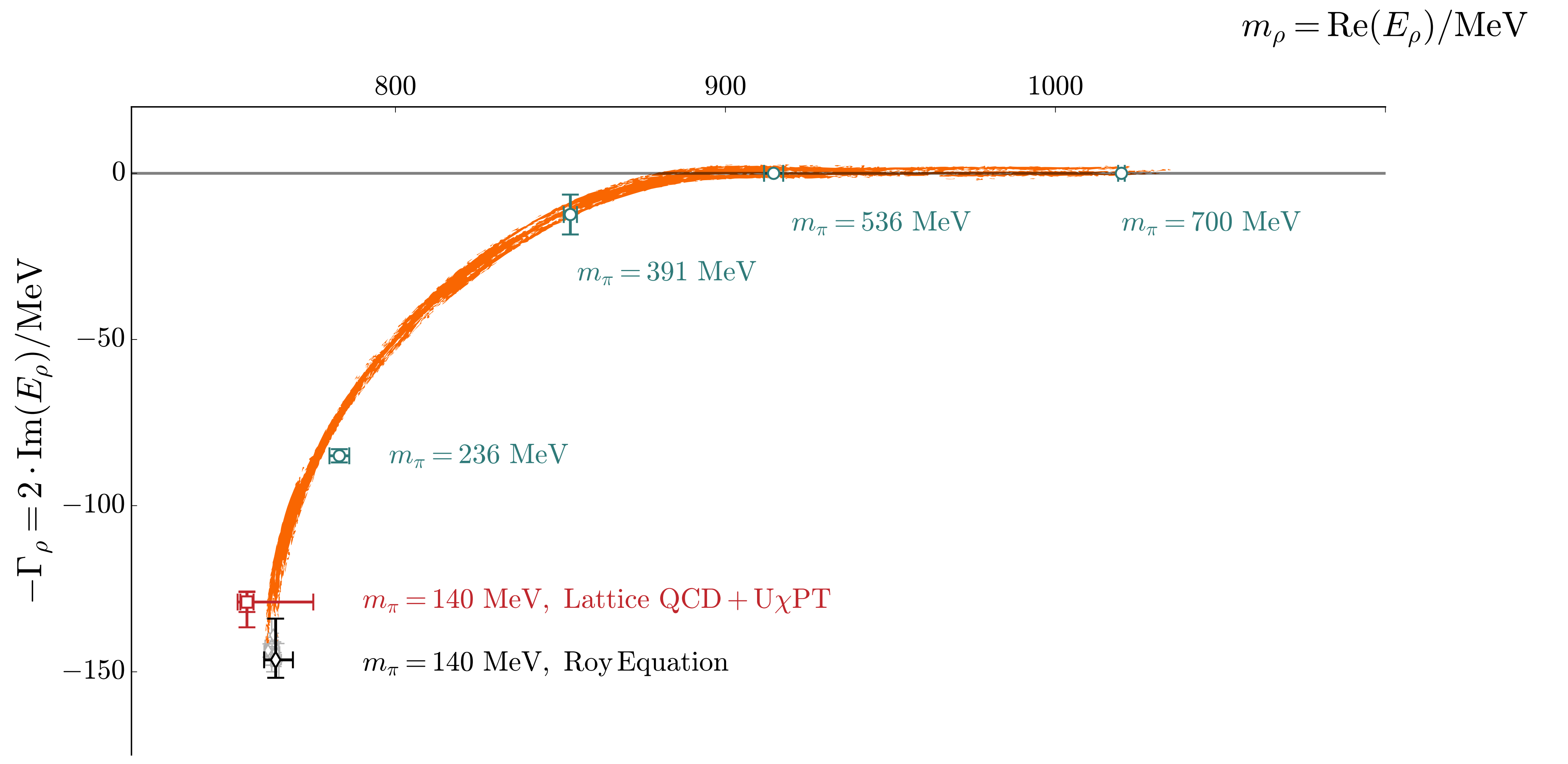
$$\mathcal{M} \sim \frac{1}{p \cot \delta - ip}$$

resonance pole



$$\sim \frac{1}{s - s_0}$$

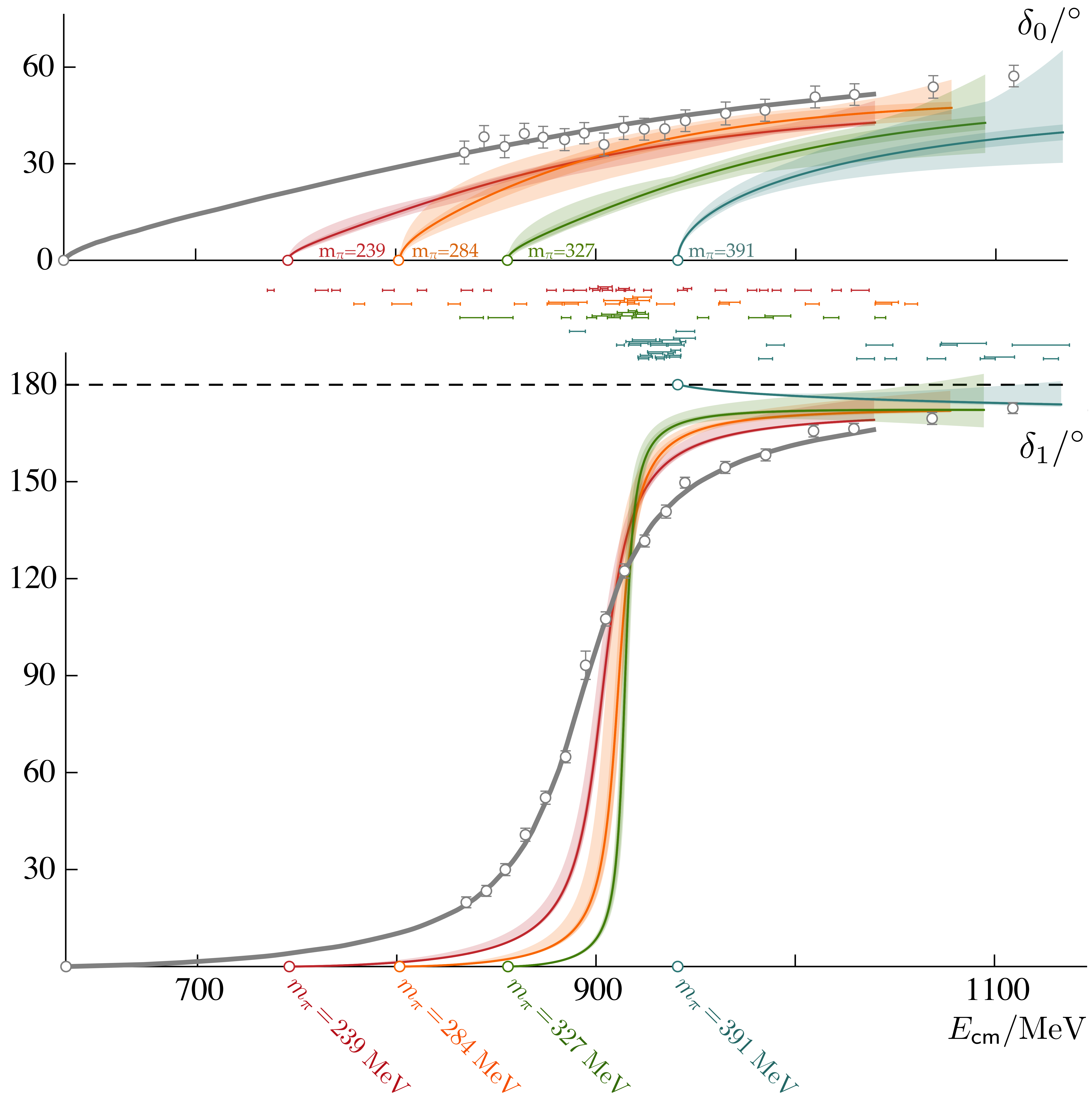
$$s_0 = (m_R - i\Gamma_R/2)^2$$



Dudek, Edwards, & Thomas (2012)

Wilson, RB, Dudek, Edwards, & Thomas (2015)

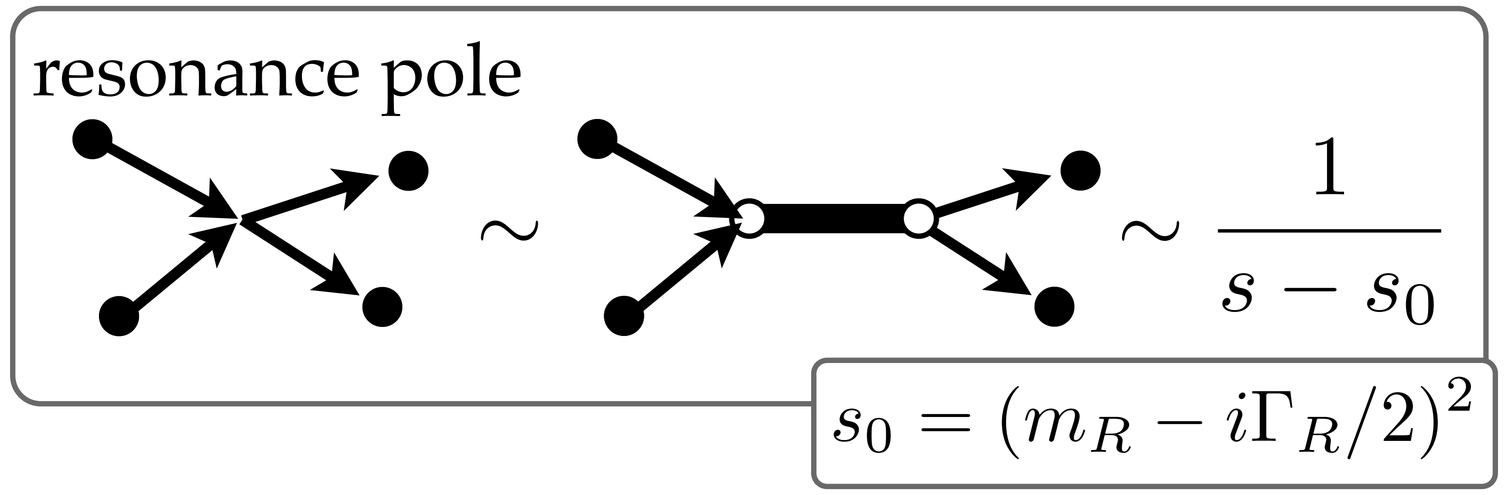
πK scattering
(I=1/2 channel)

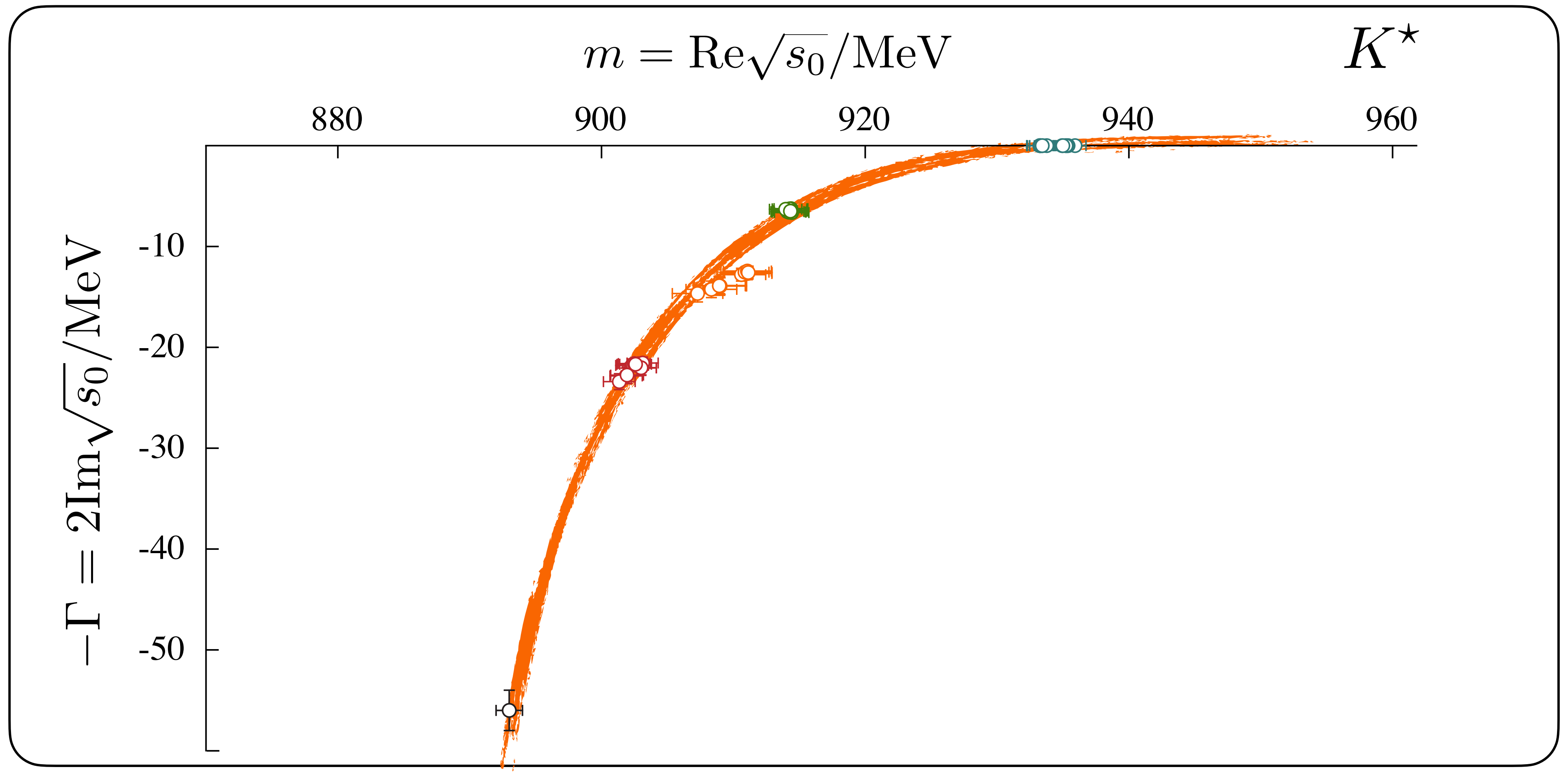


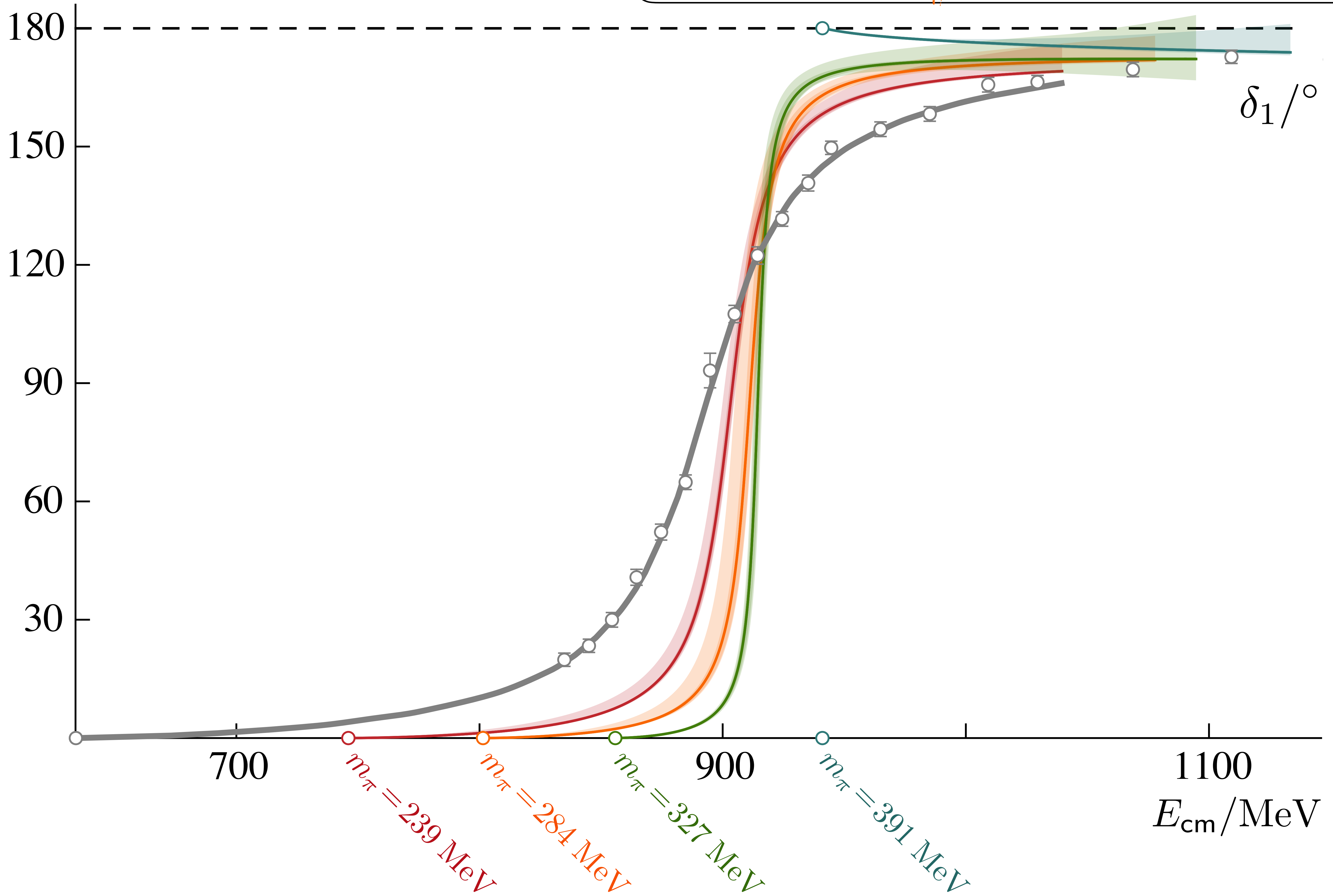
$$\mathcal{M} \sim \frac{1}{p\cot\delta - ip}$$

Dudek, Edwards, Thomas, & Wilson (2014)
Wilson, RB, Dudek, Edwards, & Thomas (2019)

πK scattering
(I=1/2 channel)





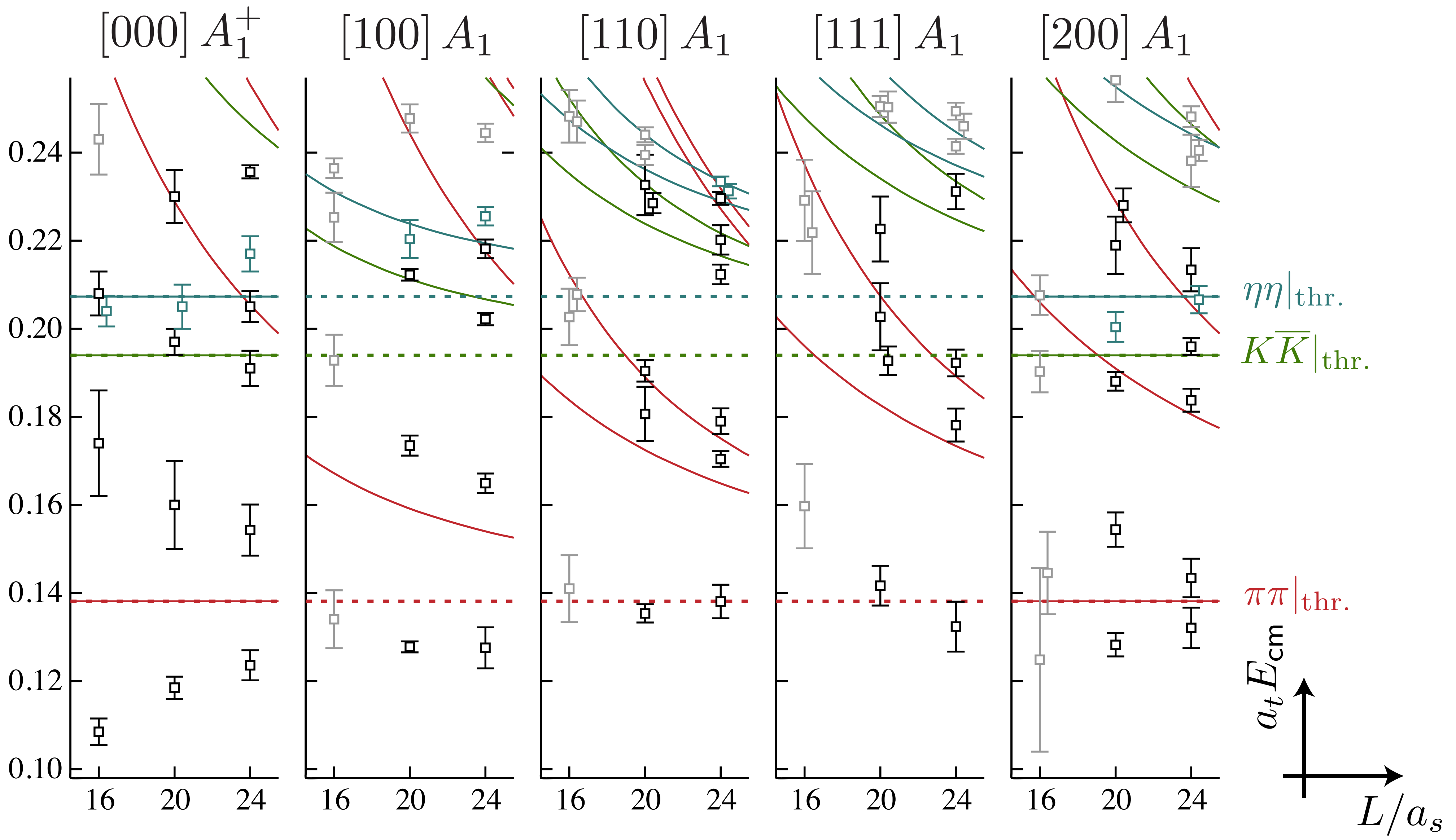


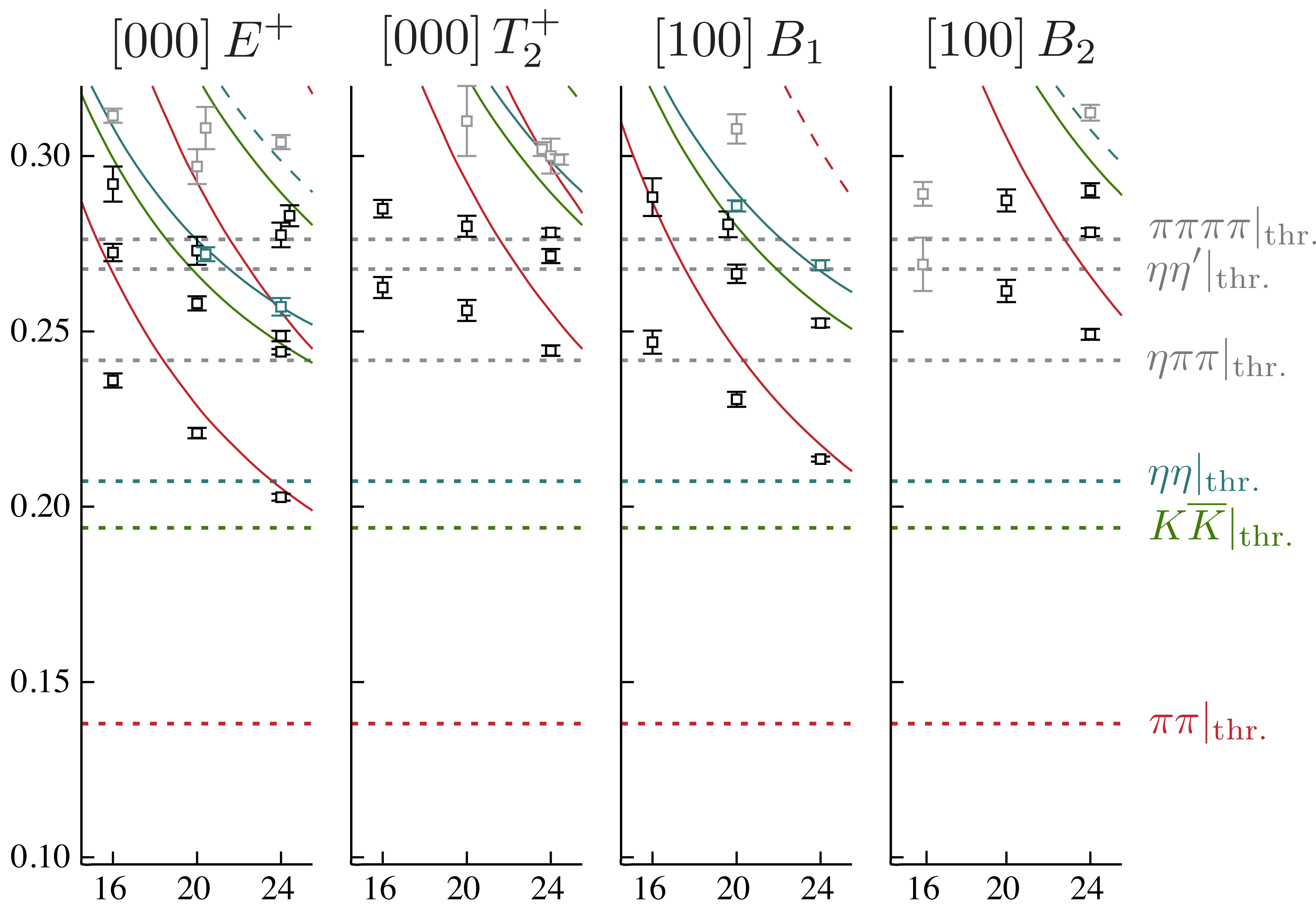
$$\mathcal{M} \sim \frac{1}{p\cot\delta - ip}$$

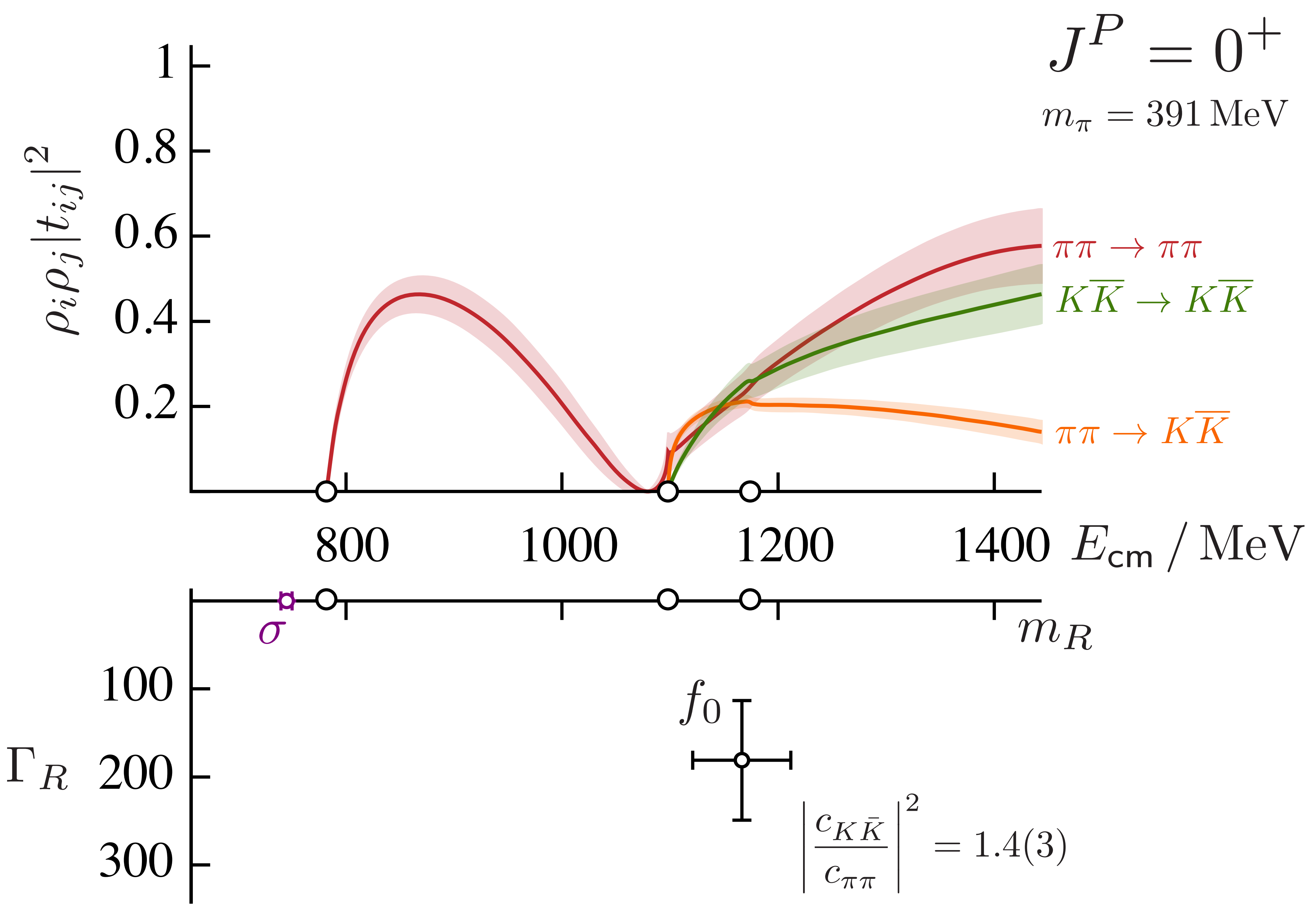
Dudek, Edwards, Thomas, & Wilson (2014)

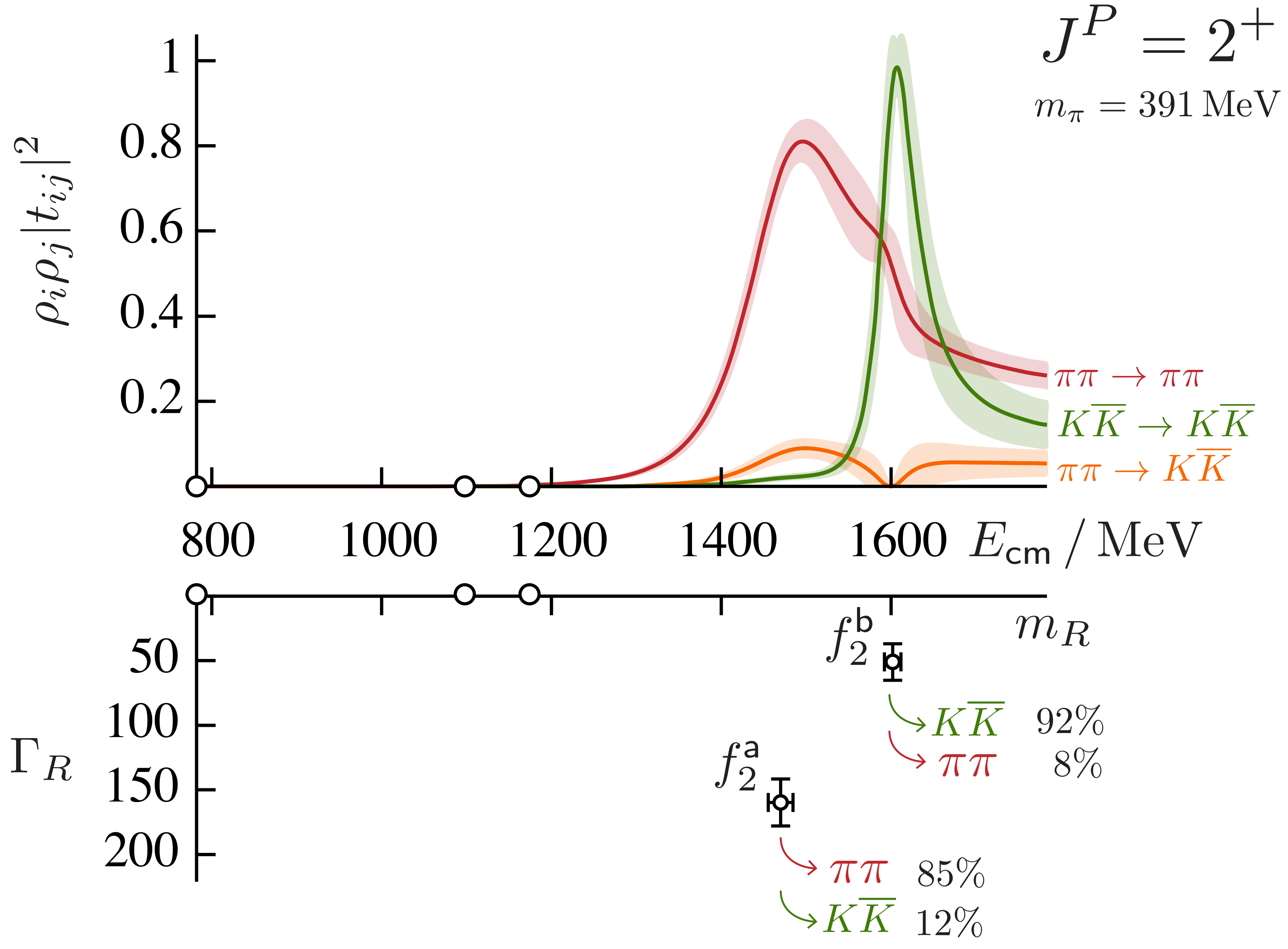
Wilson, RB, Dudek, Edwards, & Thomas (2019)

$\pi\pi$-KK
(I=0 channel)









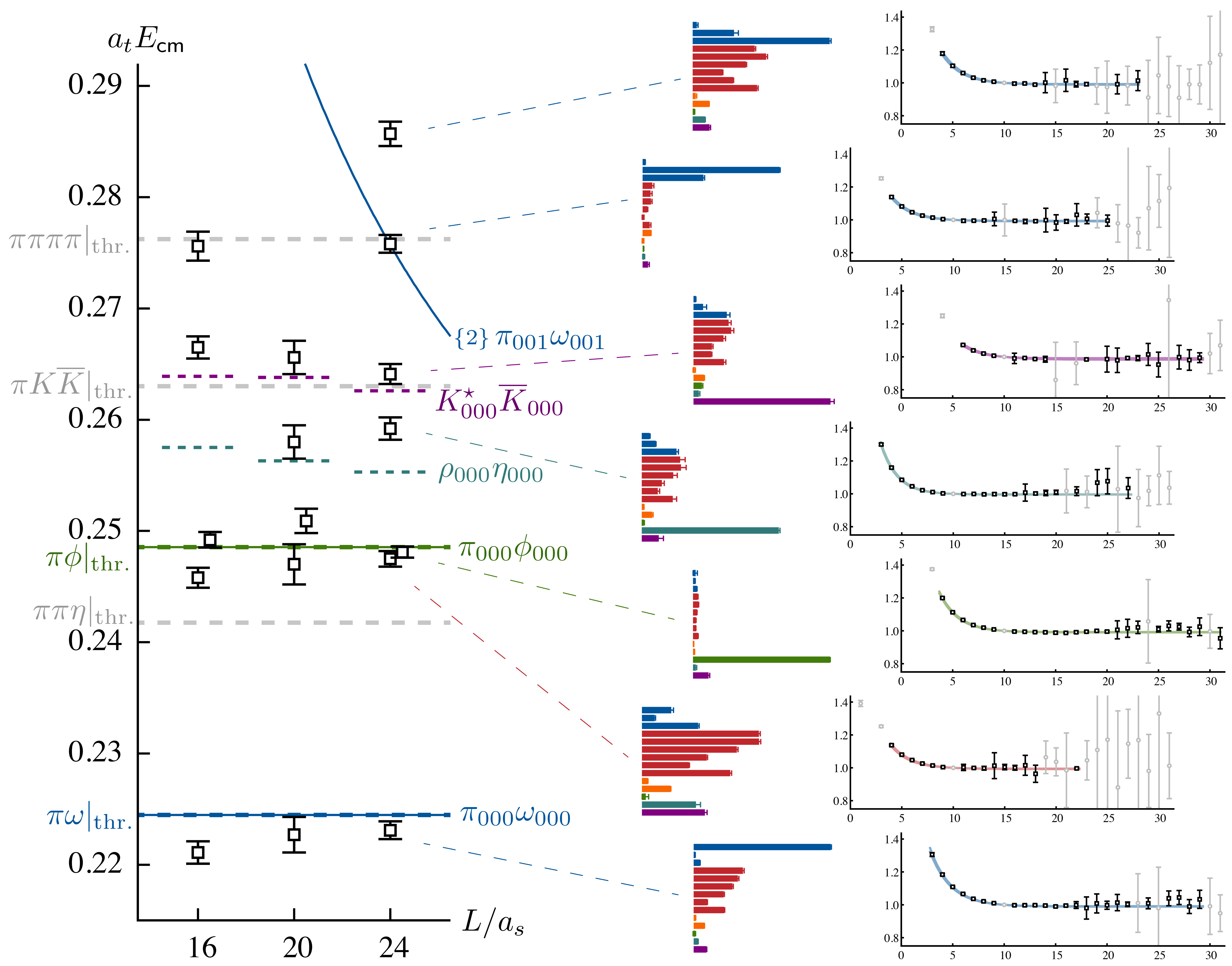
$m_\pi \sim 390$ MeV

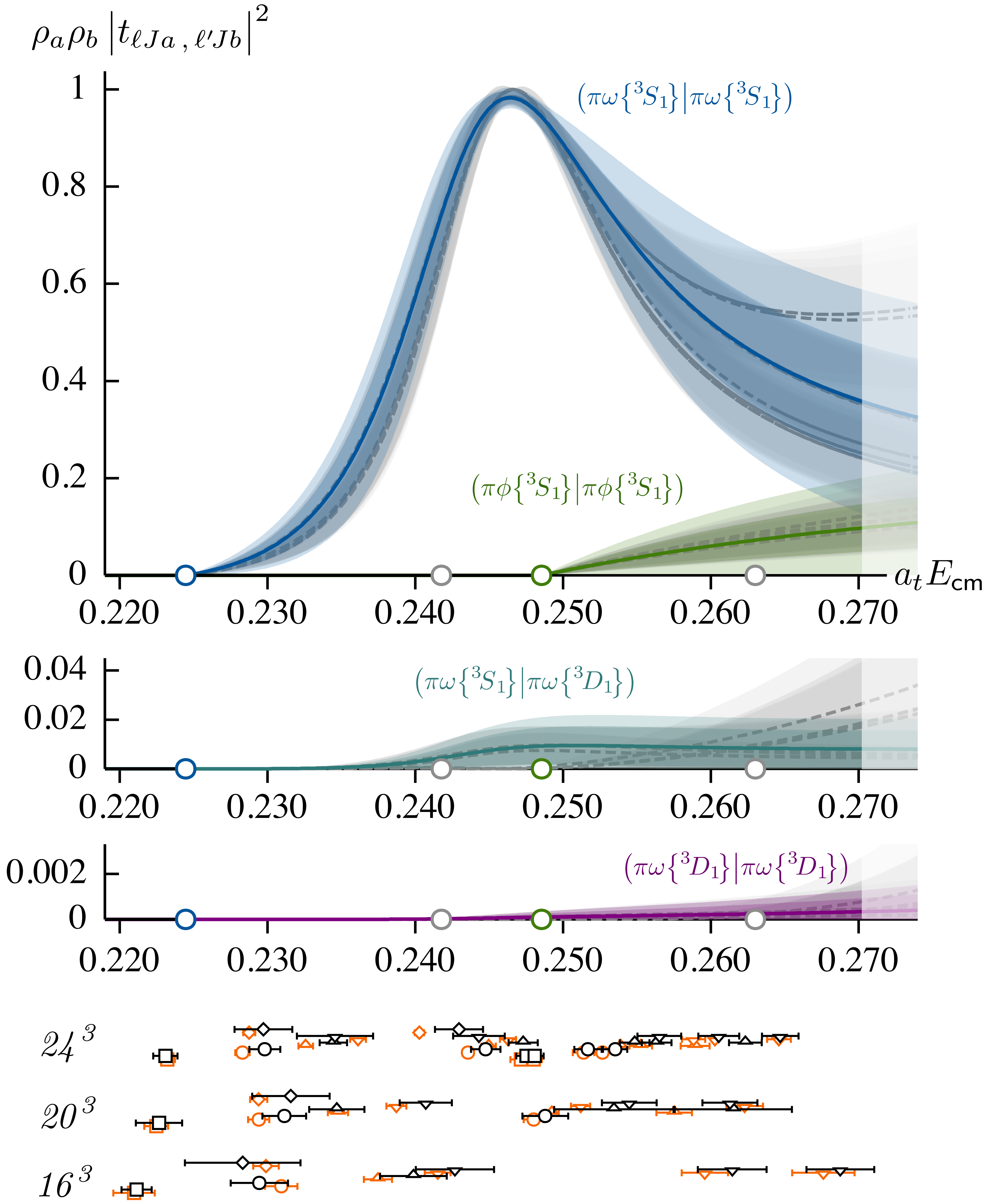
RB, Dudek, Edwards, & Wilson (2016)

RB, Dudek, Edwards, & Wilson (2017)

$\pi\omega, \pi\phi, \ldots \Leftrightarrow b_1$

$(I^G = 1^+, J^{PC} = 1^{+-})$



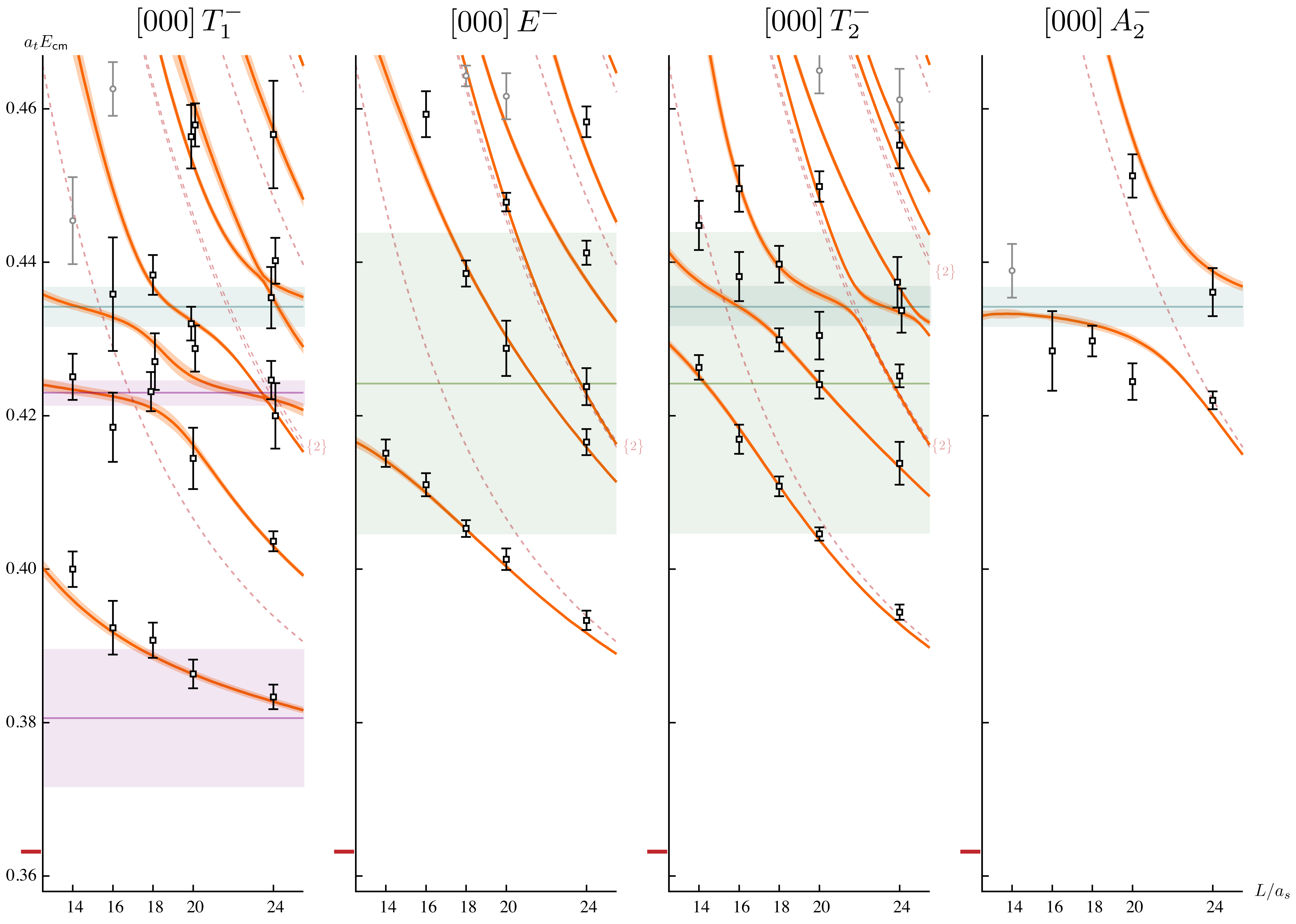


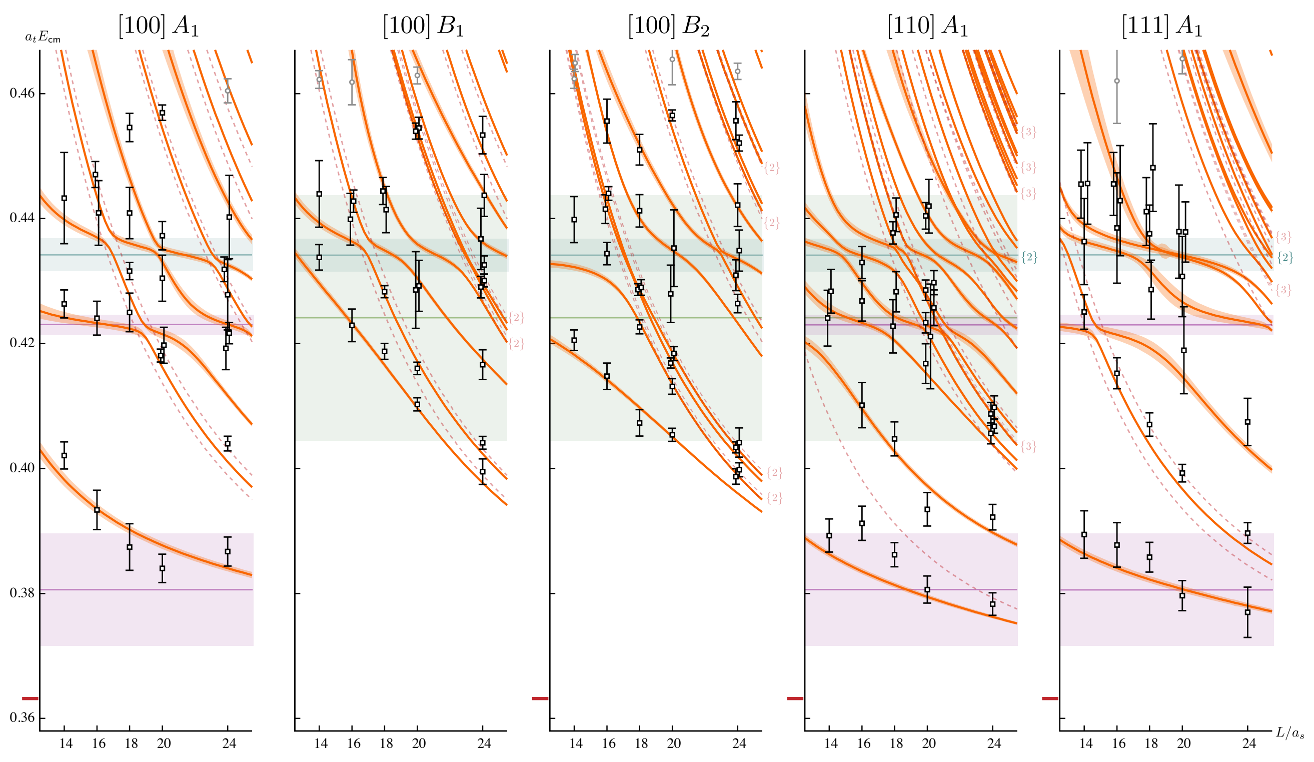
$m_\pi \sim 390\,\mathrm{MeV}$

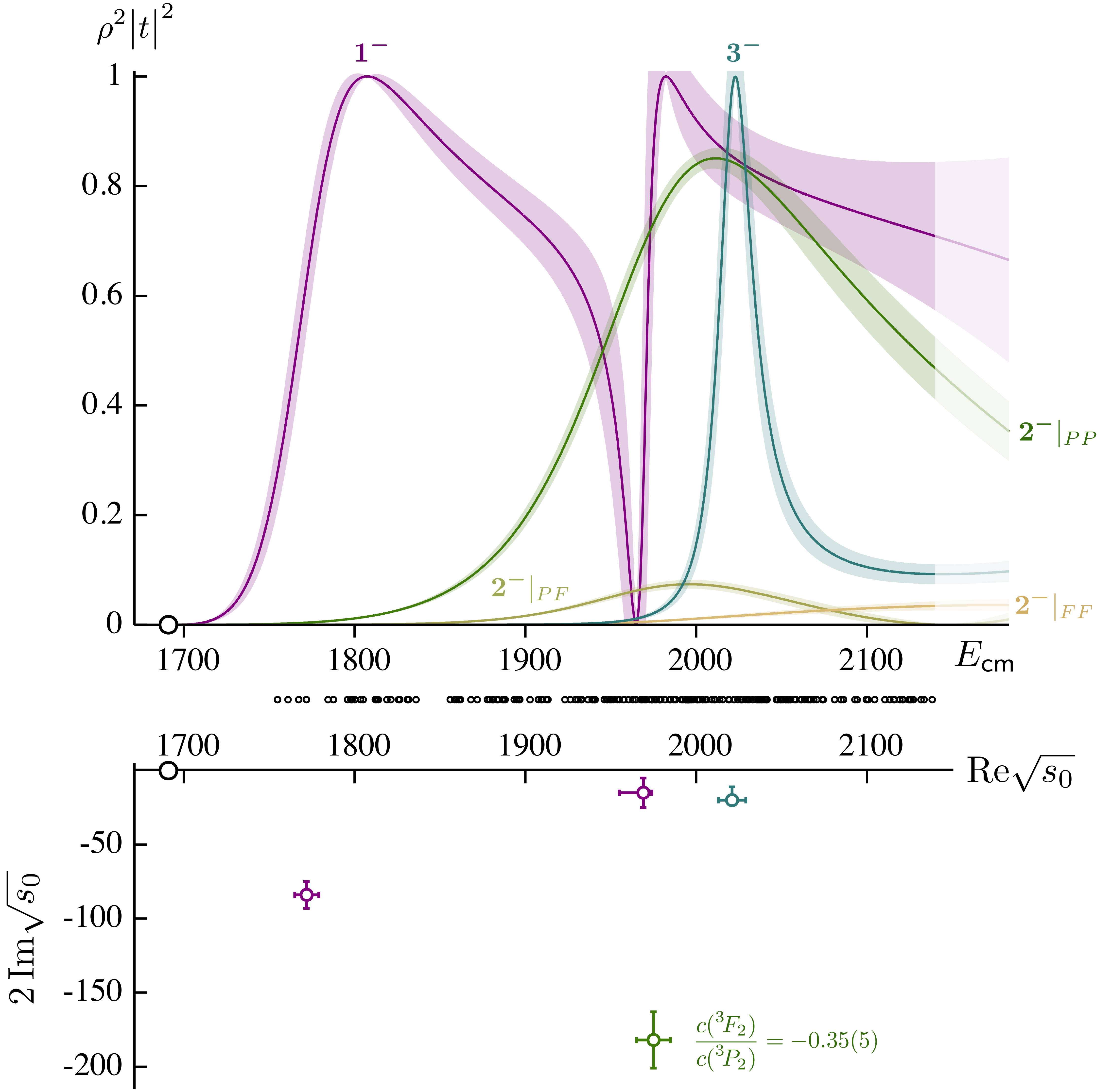
Woss, Dudek, Edwards, Thomas, & Wilson (2020)

$\pi\rho, KK^*, \eta\omega, \ldots \Leftrightarrow \omega^*, \rho^*$

$(J^{PC} = 1^{--}, 2^{--}, 3^{--})$ 192 energy levels…world record!



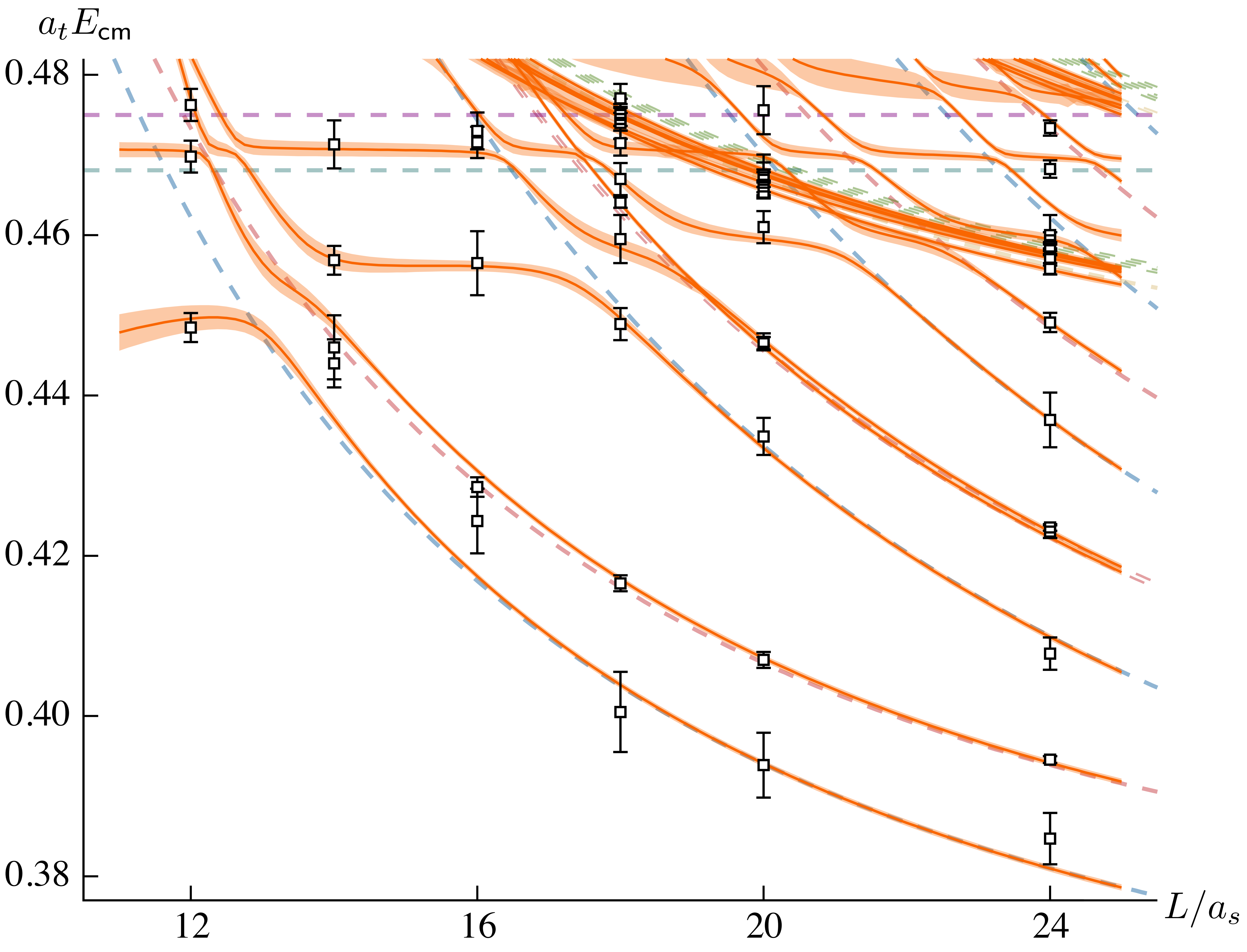


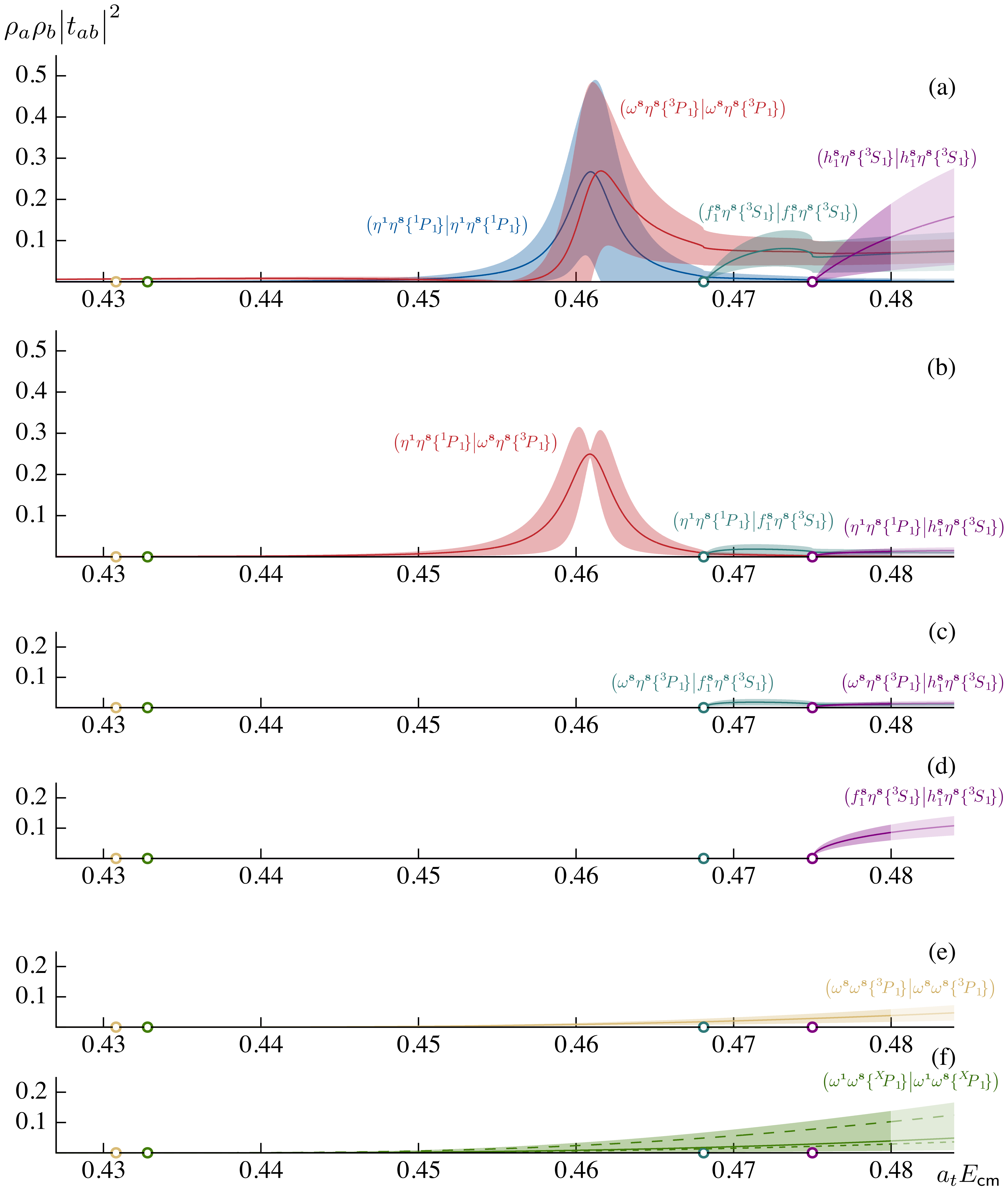


Johnson & Dudek (2020)

$\pi\eta, \pi\rho, \ldots \Leftrightarrow \pi_1$

($J^{PC} = 1^{-+}$, *first exotic resonant amplitude // 8 channels!*)

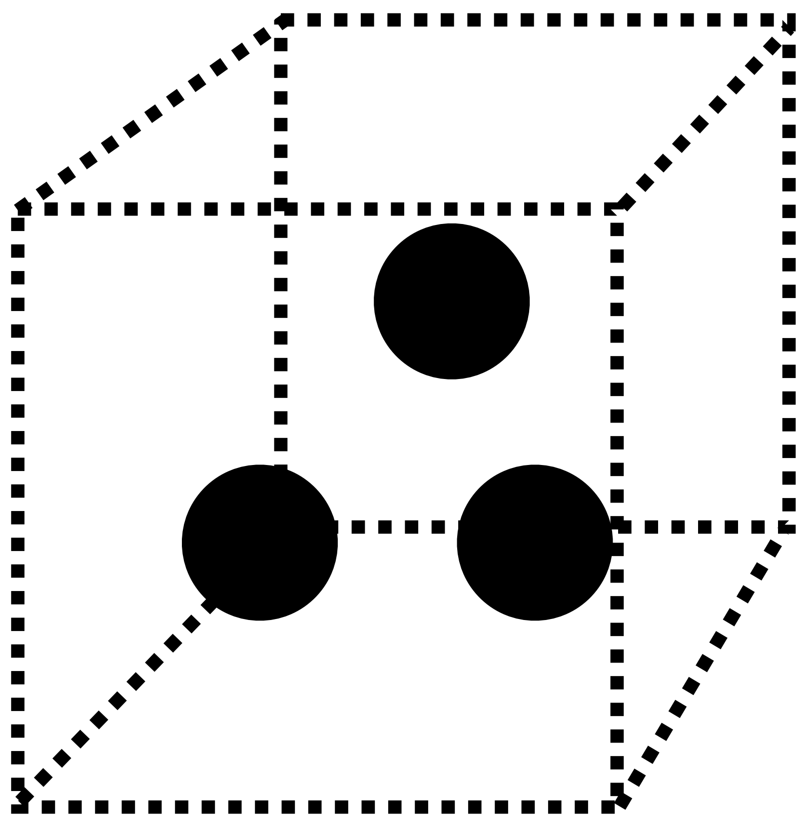




$m_\pi \sim 700\,\mathrm{MeV}$

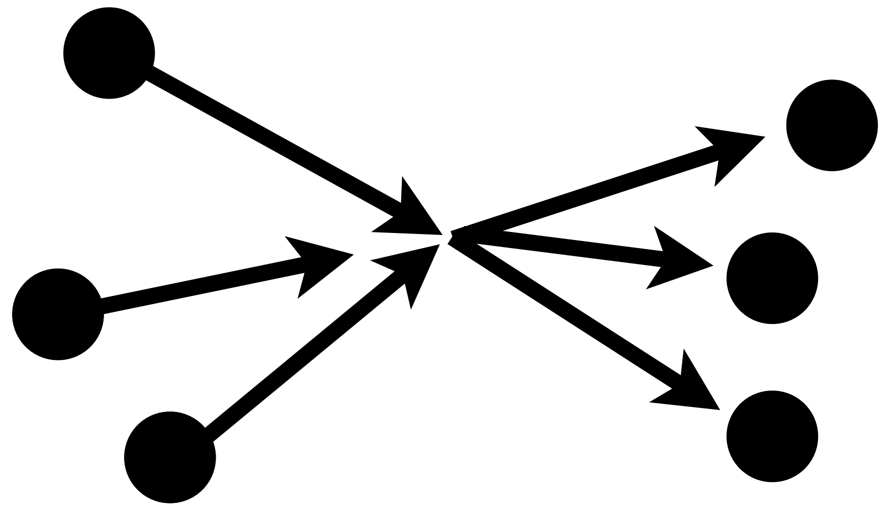
Woss, Dudek, Edwards, Thomas, & Wilson (2020)

Three-hadron systems

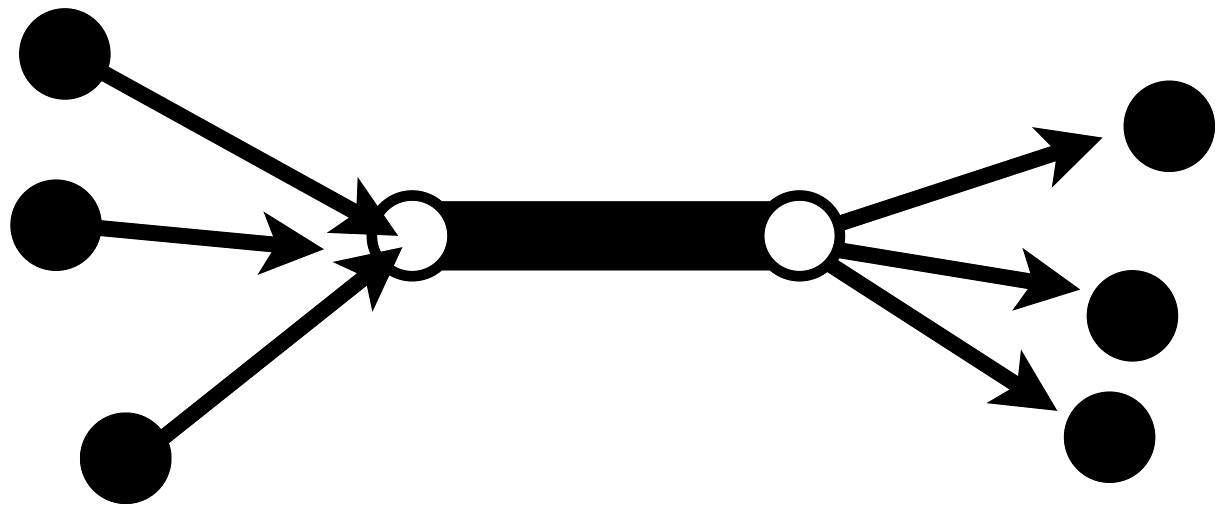


finite-volume
spectroscopy

Hansen & Sharpe ('14, '15)
Mai & Döring ('17)
RB, Hansen & Sharpe ('18)
Hansen, Romero-Lopez & Sharpe ('20)
Blanton & Sharpe ('20)
Jackura et al. ('20)



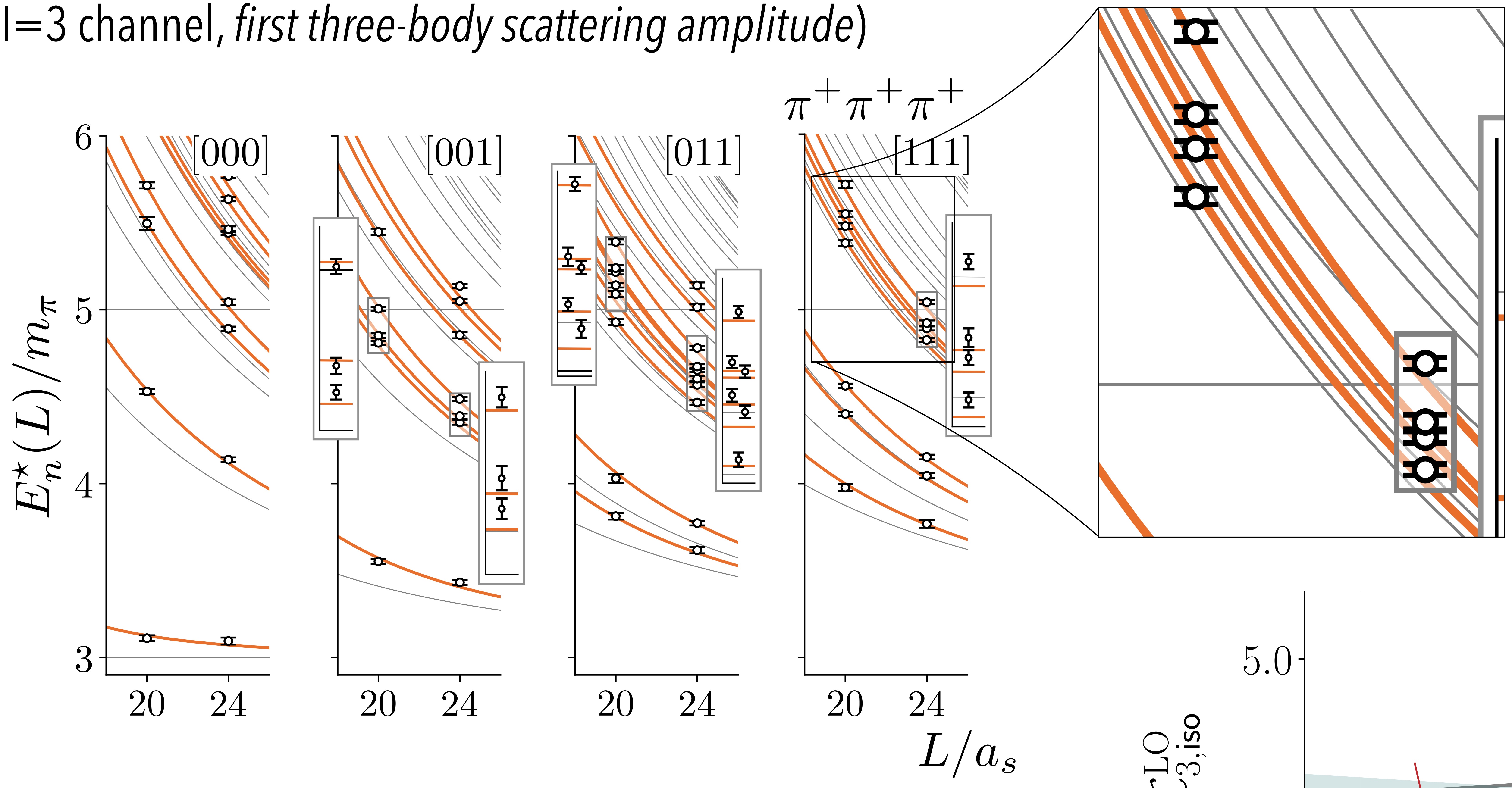
infinite-volume
scattering amplitudes

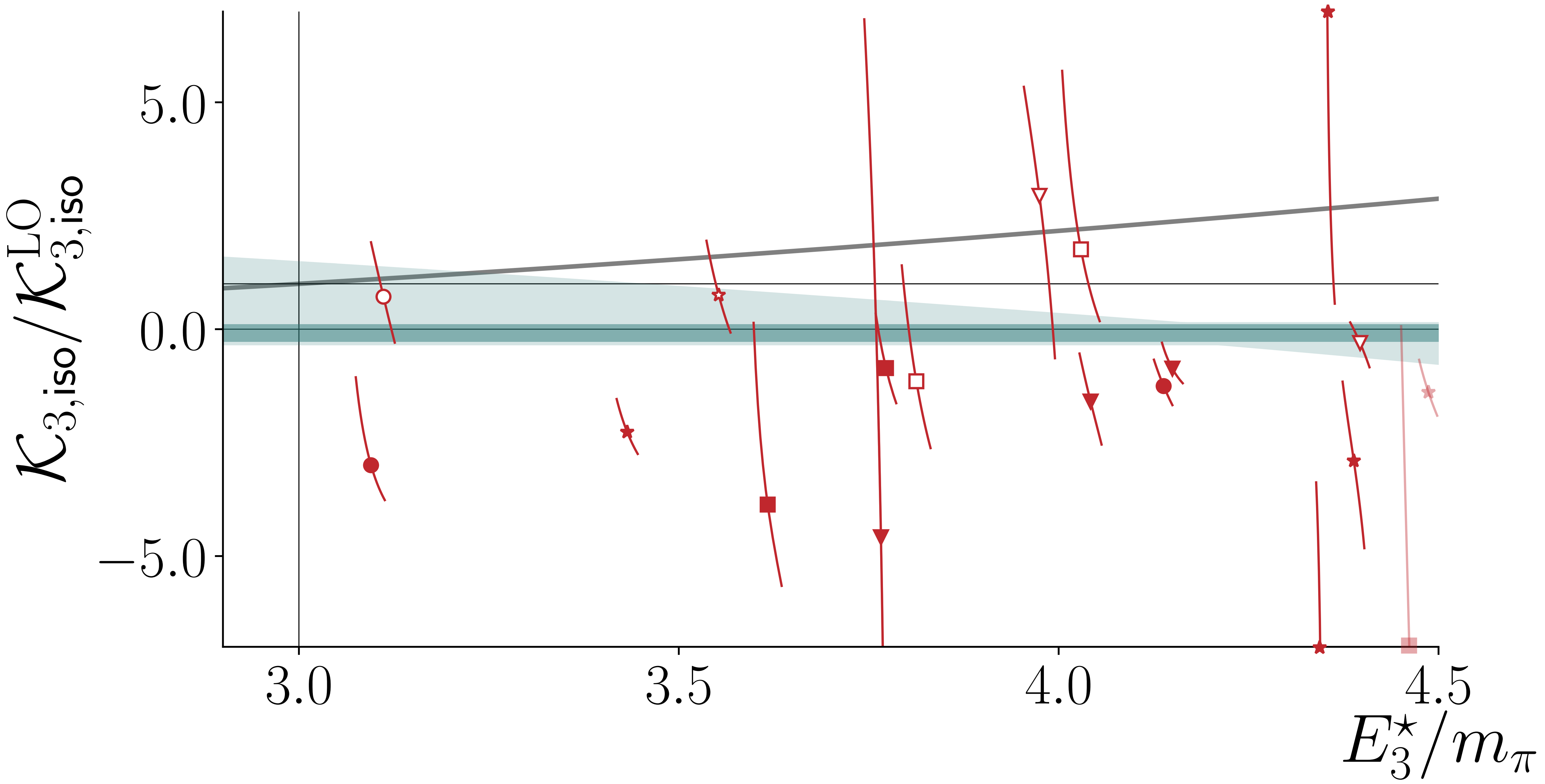


bound state and
resonance poles

$\pi\pi\pi$

(I=3 channel, *first three-body scattering amplitude*)



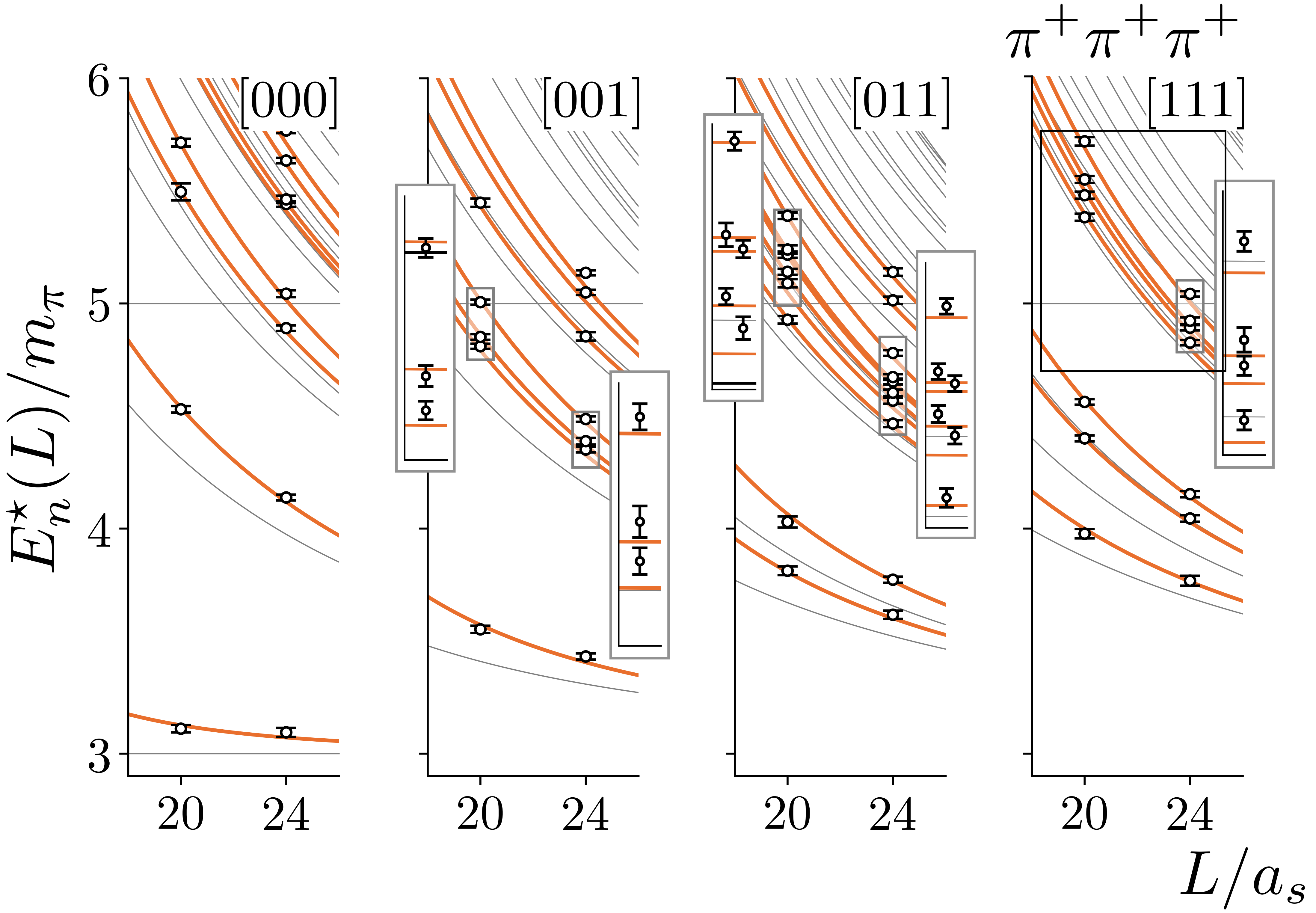


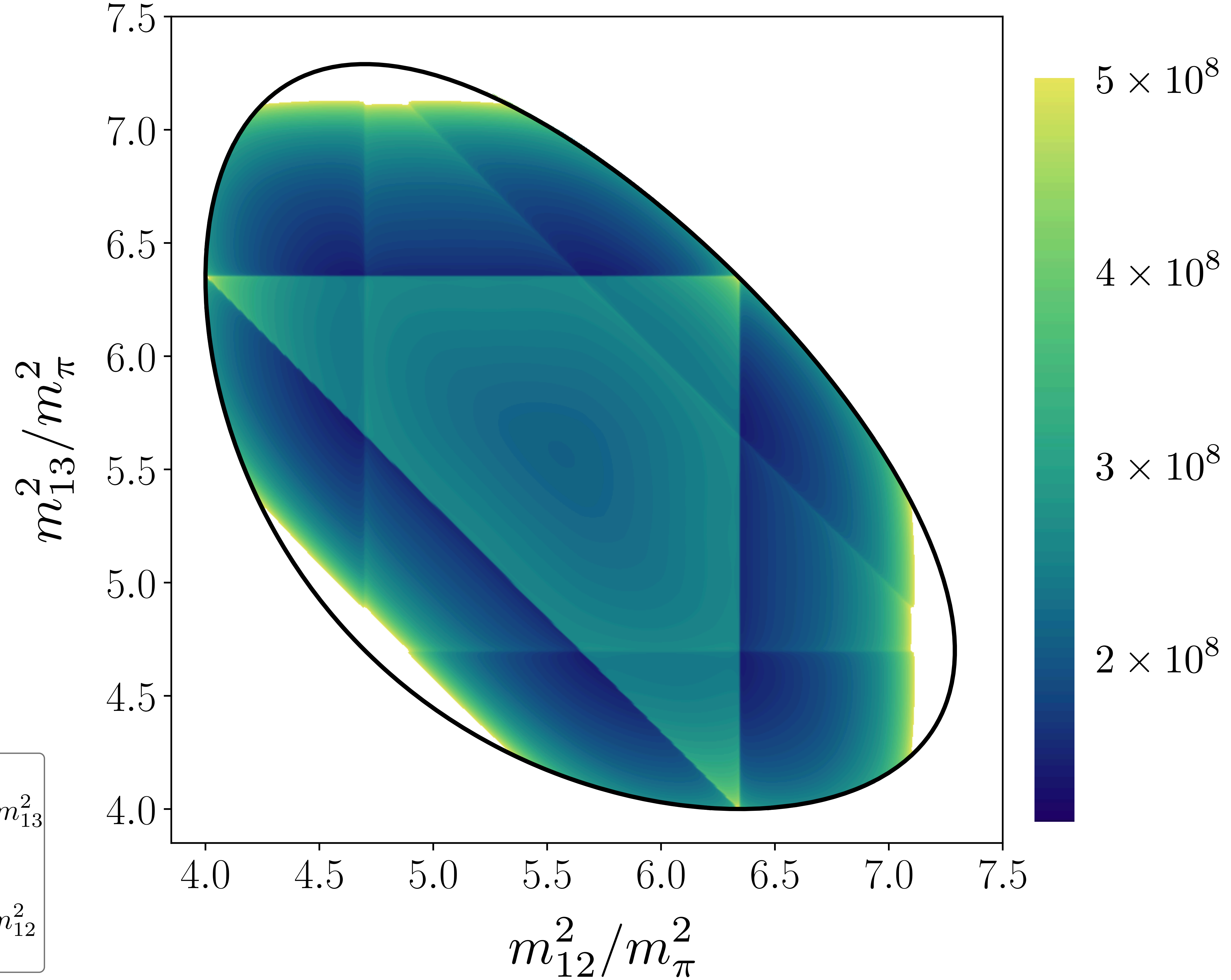
$m_\pi \sim 390\,\text{MeV}$

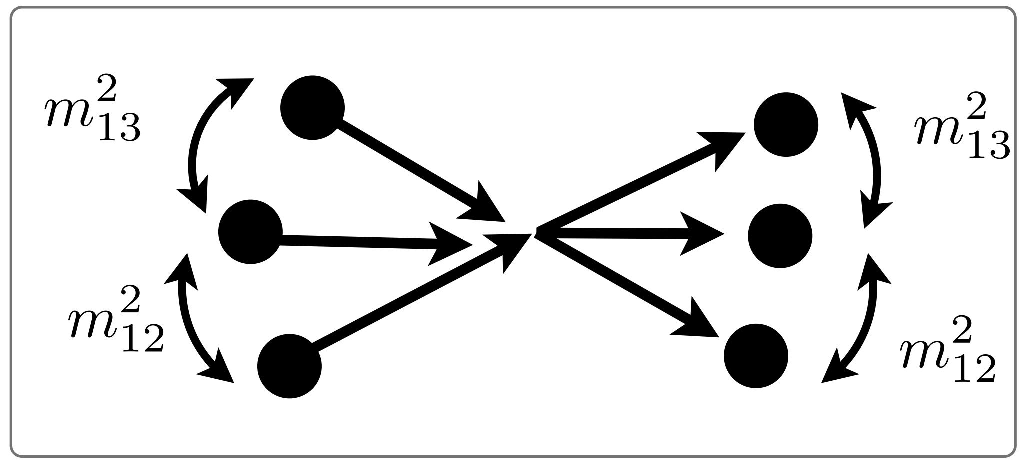
Hansen, RB, Edwards, Thomas, & Wilson (2020)

$\pi\pi\pi$

(I=3 channel, *first three-body scattering amplitude*)



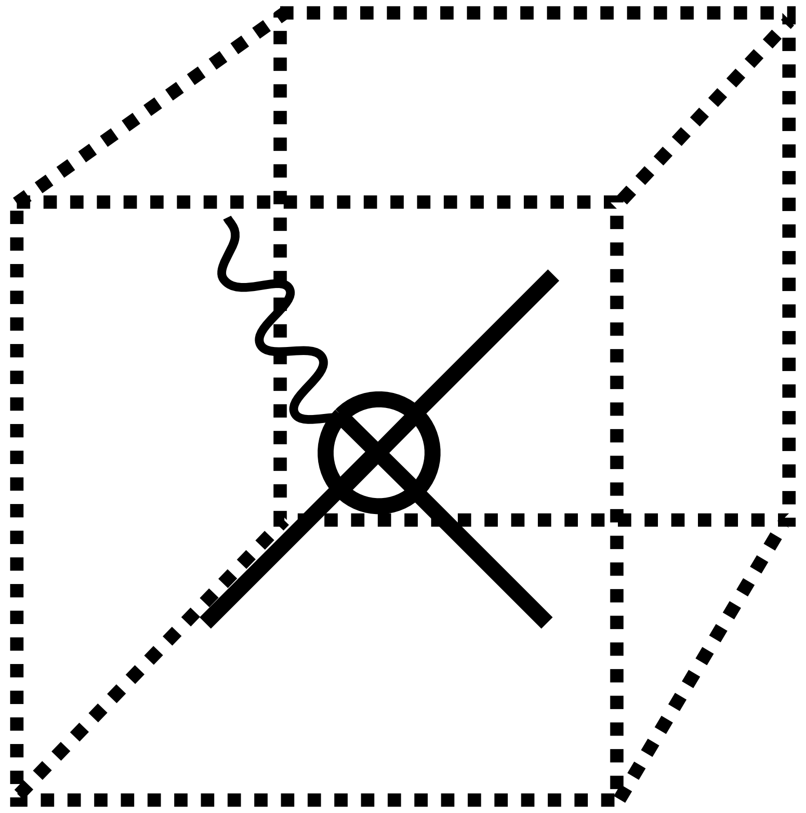




$m_\pi \sim 390\,\mathrm{MeV}$

Hansen, RB, Edwards, Thomas, & Wilson (2020)

Transition amplitudes



finite-volume
spectroscopy

Lellouch & Lüscher (2000)

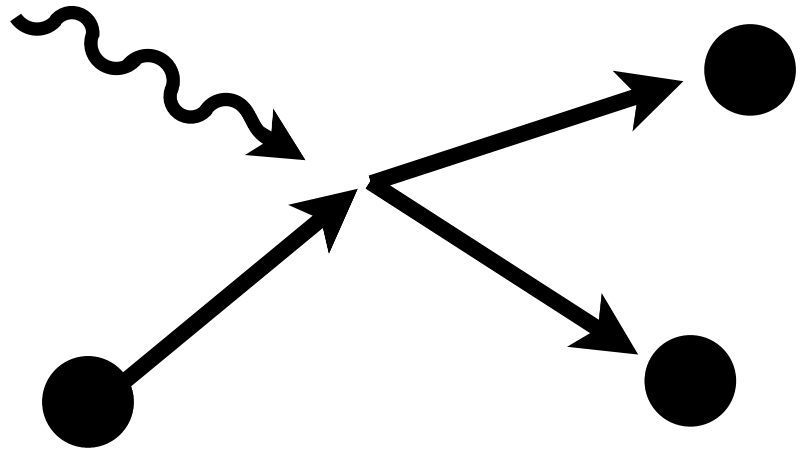
Kim, Sachrajda, & Sharpe (2005)

Christ, Kim & Yamazaki (2005)

Hansen & Sharpe (2012)

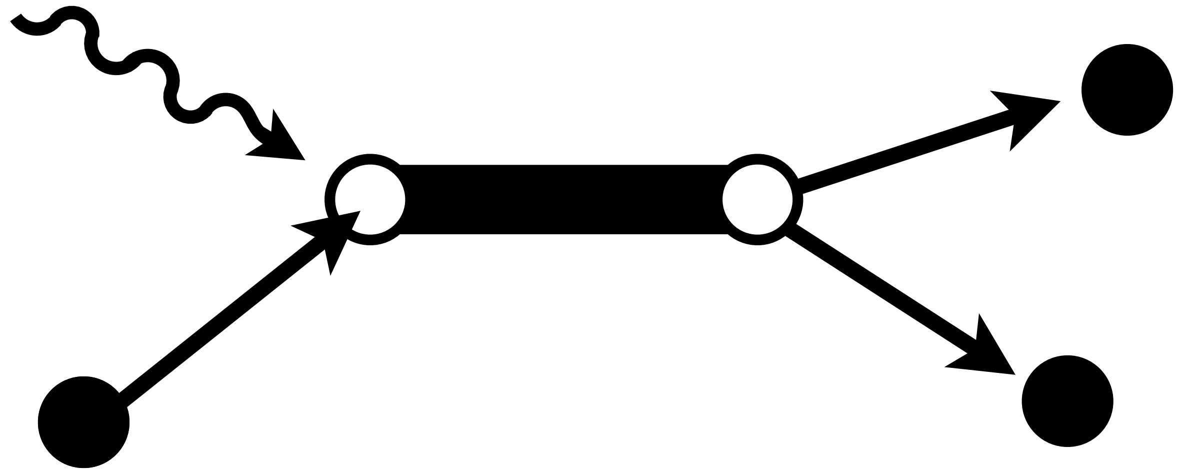
RB, Hansen Walker-Loud (2014)

RB & Hansen (2015)



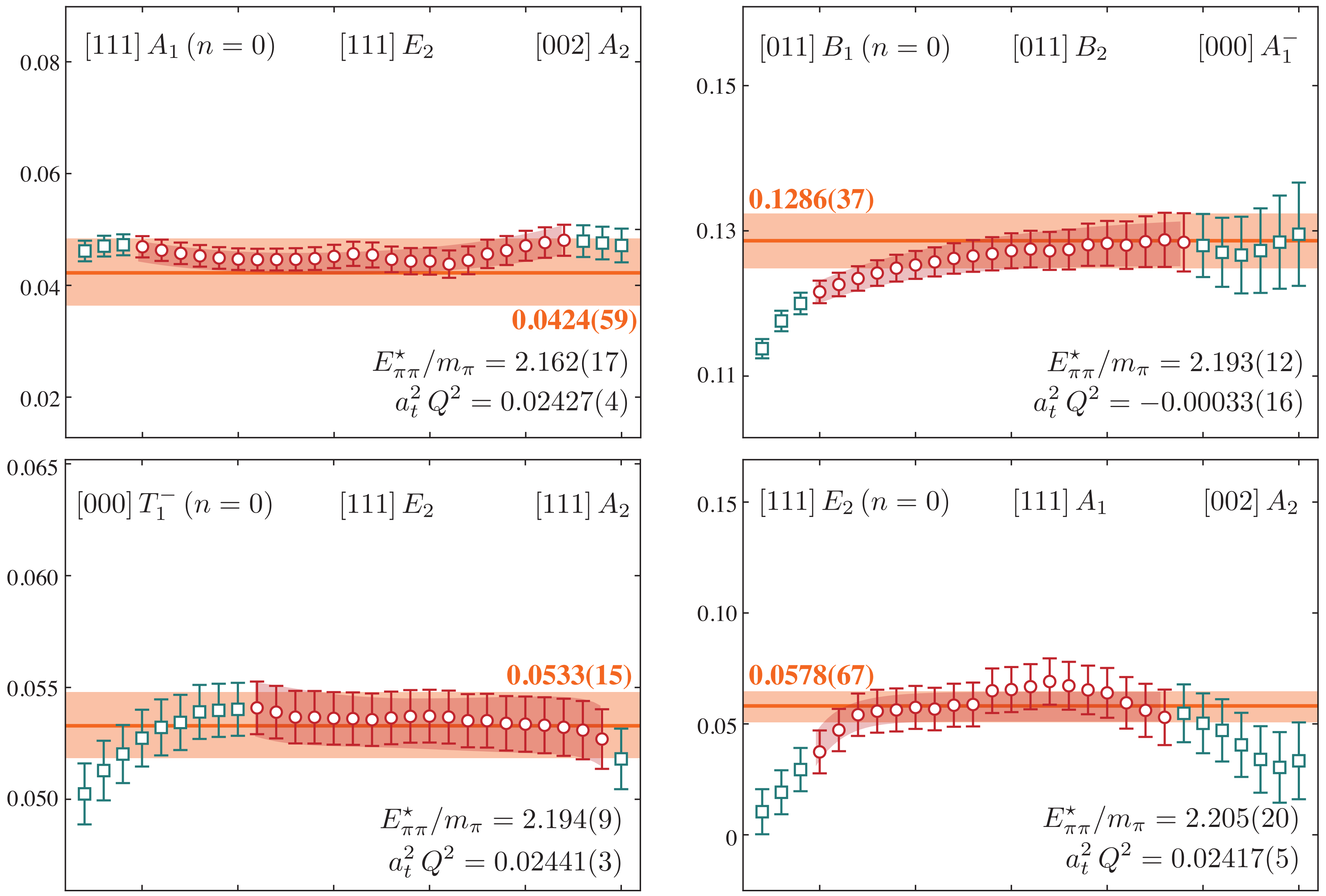
infinite-volume
scattering amplitudes

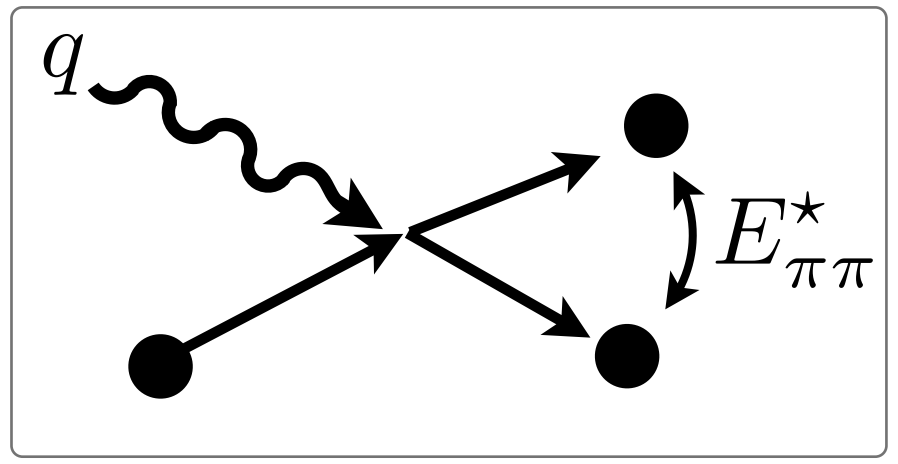
RB, Jackura, Ortega-Gama,
Sherman ('21)

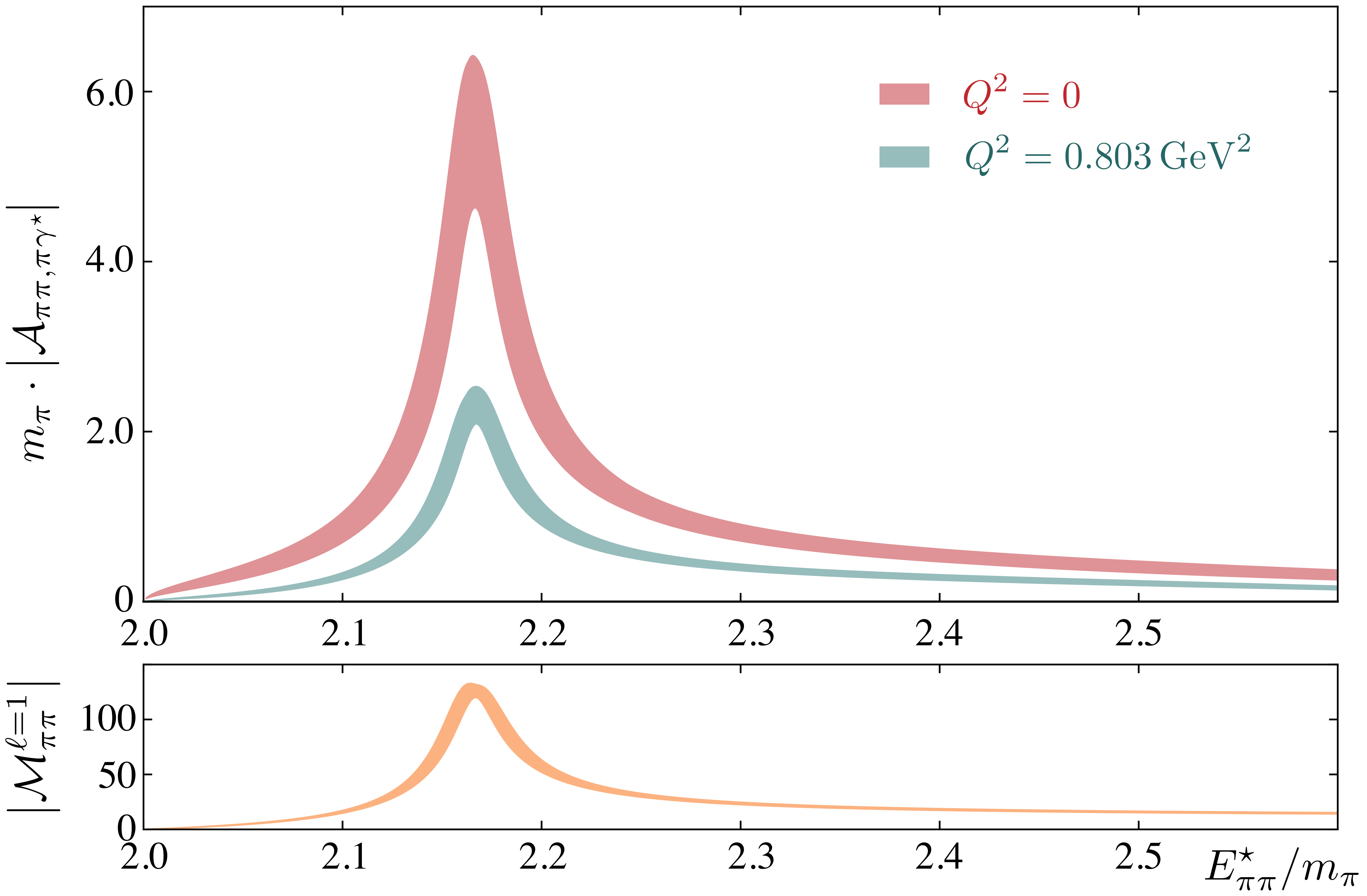


bound state and
resonance poles

$\pi\gamma \Rightarrow \pi\pi$



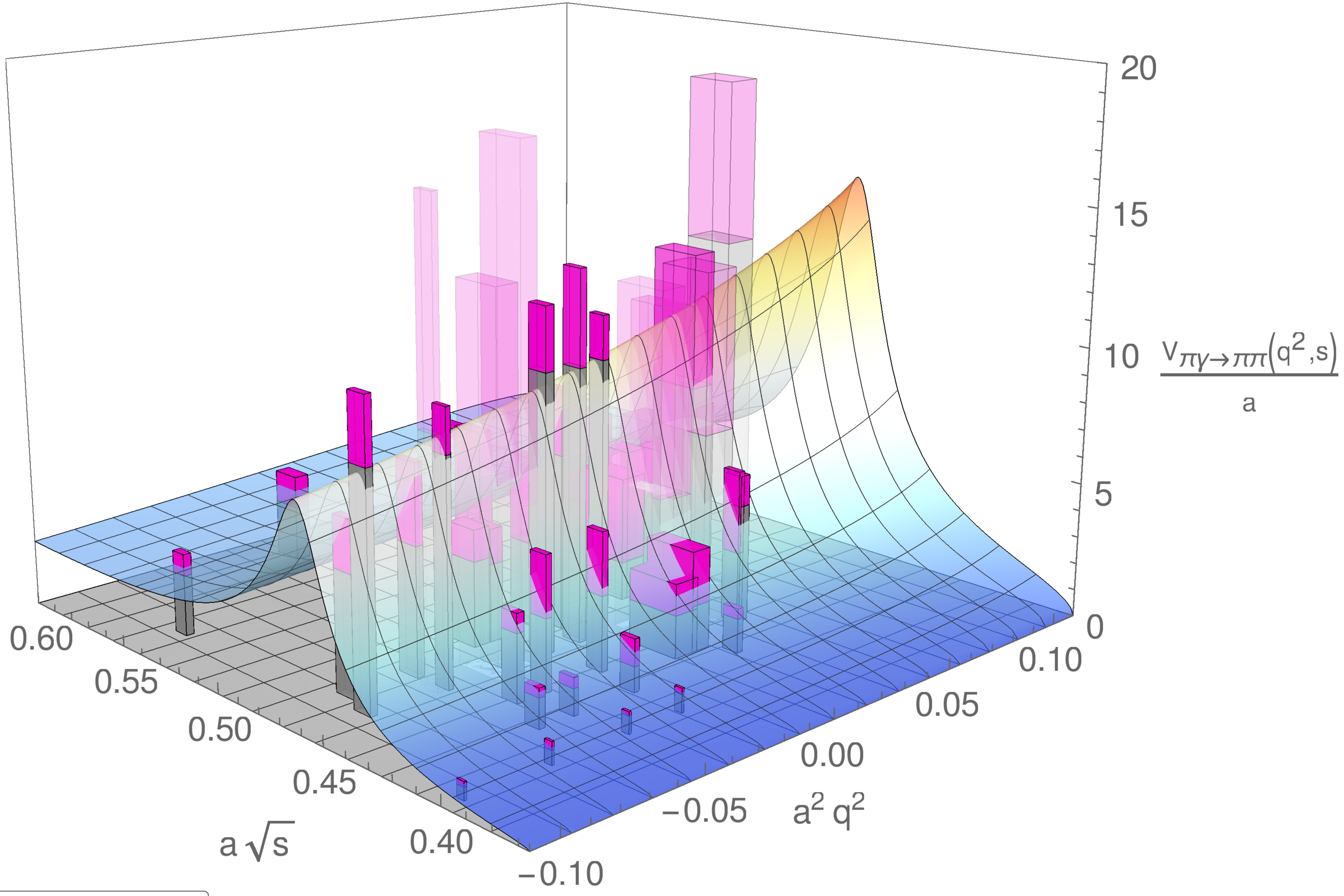


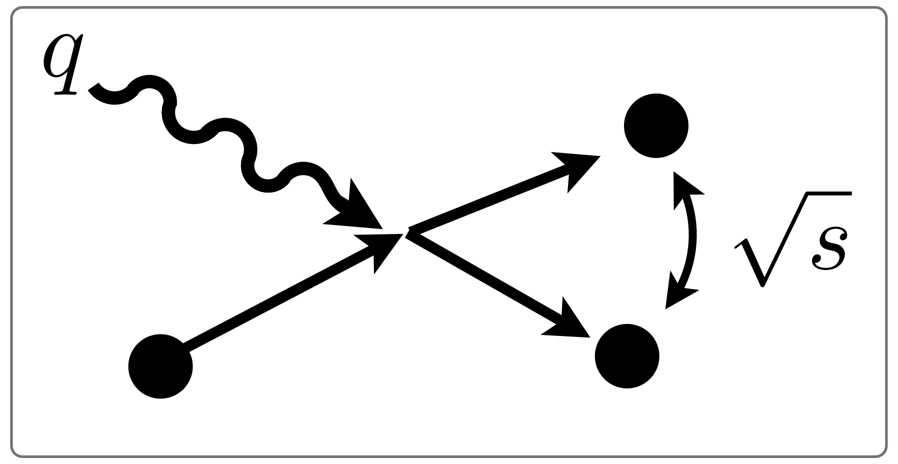


$m_\pi \sim 390\,\mathrm{MeV}$

RB, Dudek, Edwards, Shultz, & Thomas (2015)

$\pi\gamma \Rightarrow \pi\pi$

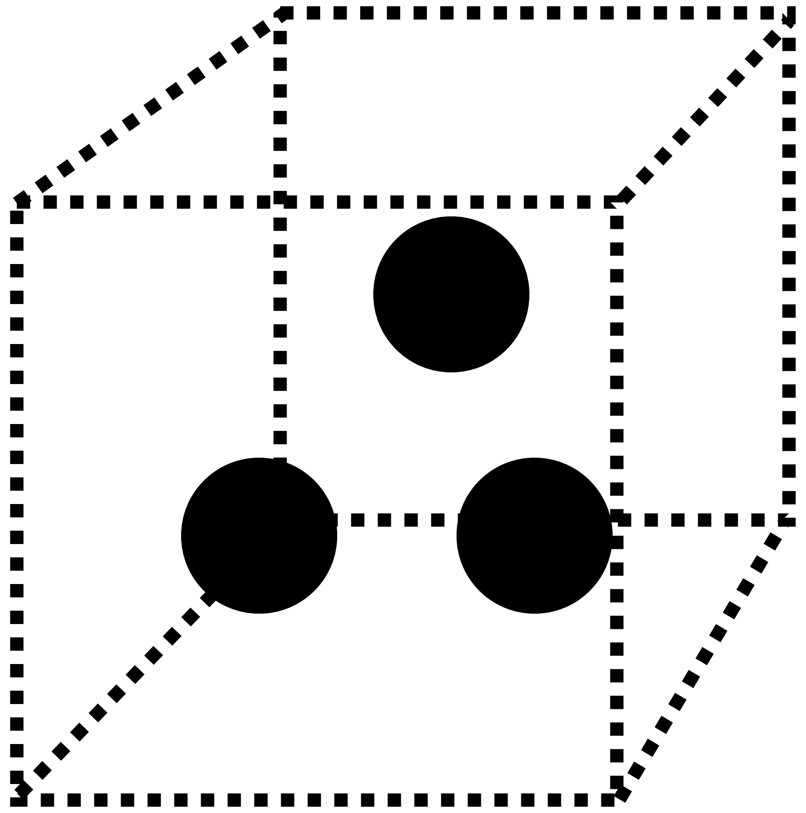


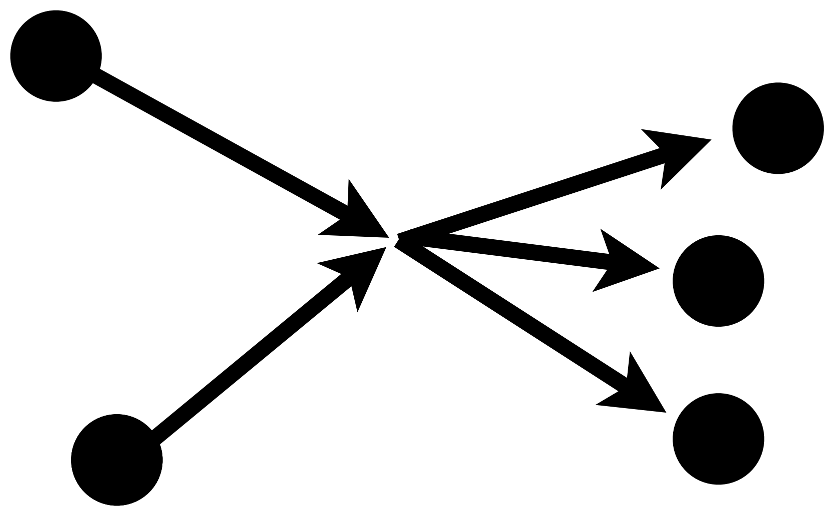


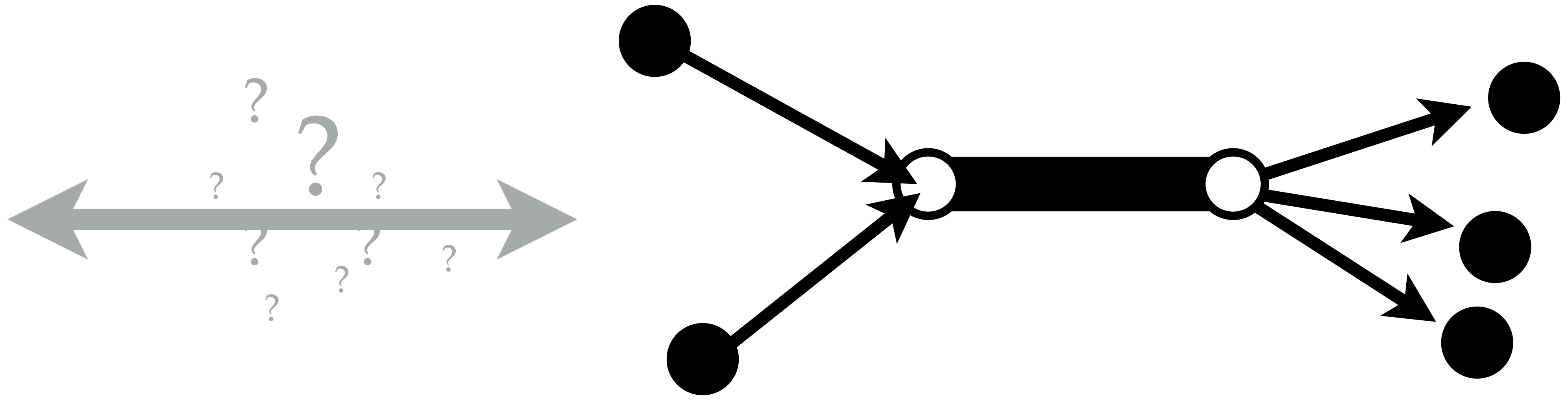
$m_\pi \sim 320\,\mathrm{MeV}$

Alexandrou, Leskovec, Meinel, Negele,
Paul, Petschlies, Pochinsky, Rendon, Syritsyn(2018)

Future of spectroscopy







Hansen & Sharpe ('14, '15)

Mai & Döring ('17)

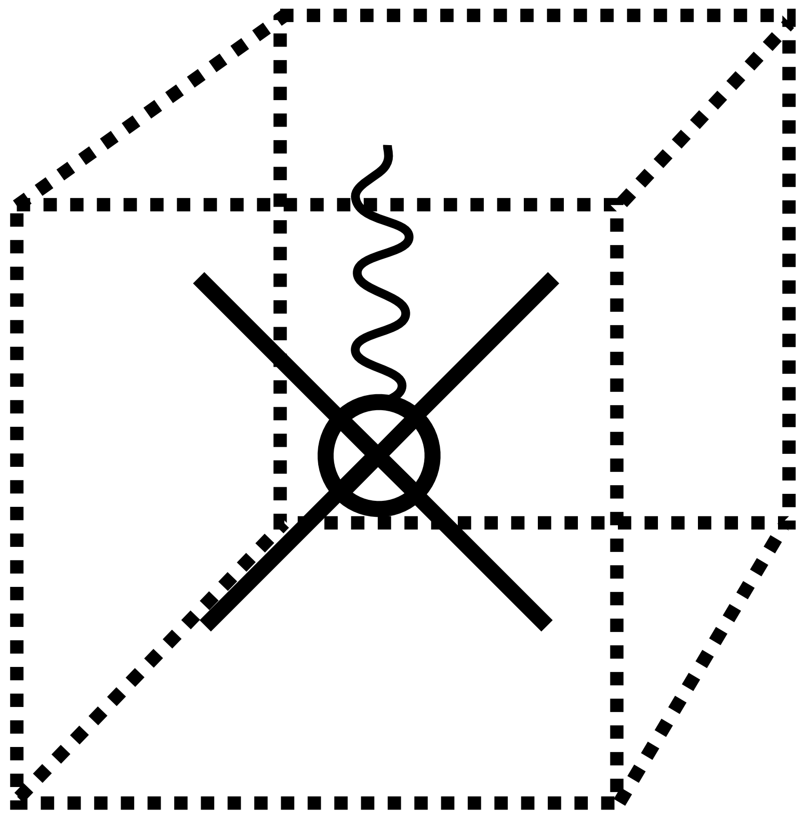
RB, Hansen & Sharpe ('18)

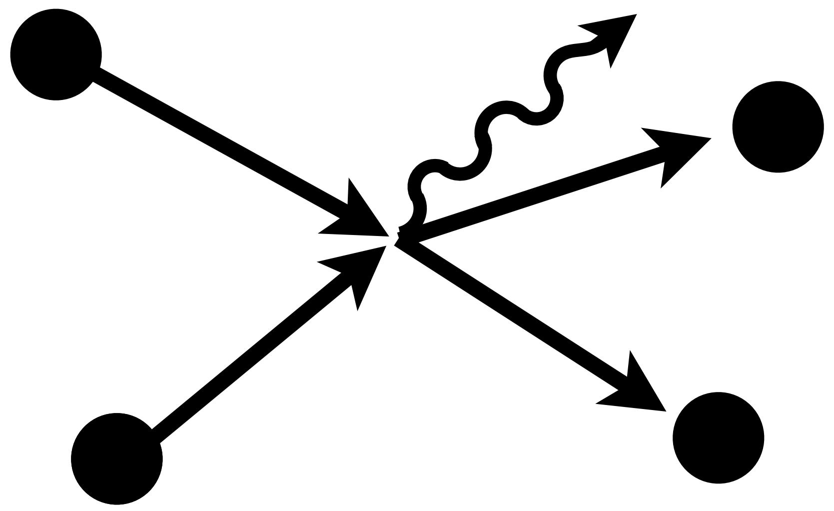
Hansen, Romero-Lopez & Sharpe ('20)

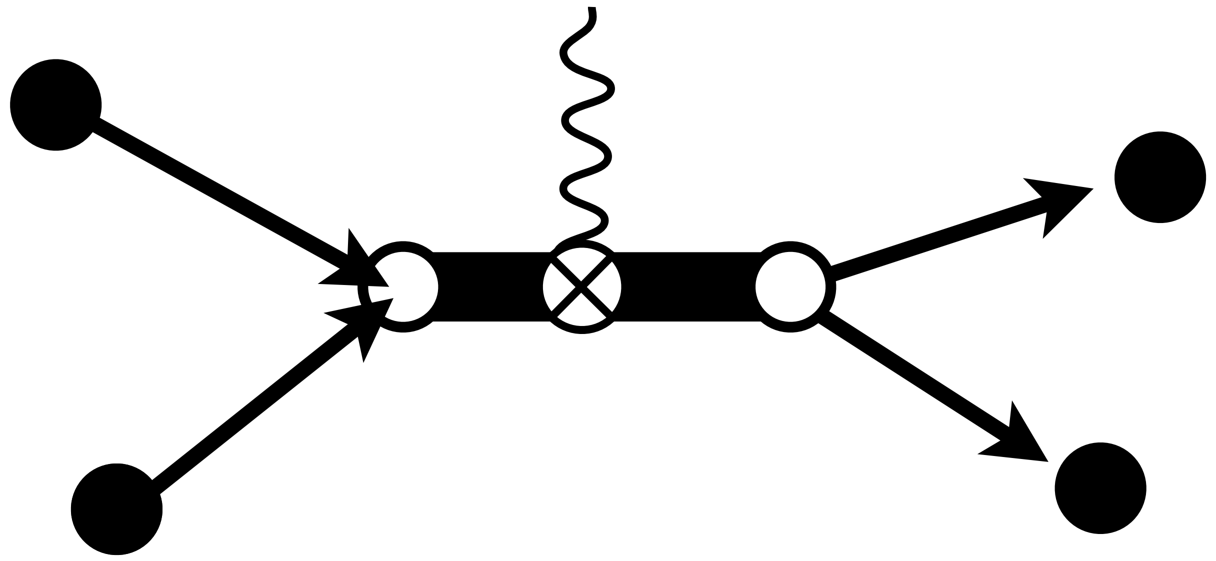
Blanton & Sharpe ('20)

Jackura et al. ('20)

Future of structure







RB & Hansen ('15)

Baroni, RB, Jackura, Hansen & Ortega-Gama ('18)

RB, Jackura, Ortega-Gama, Sherman ('21)

HadSpec

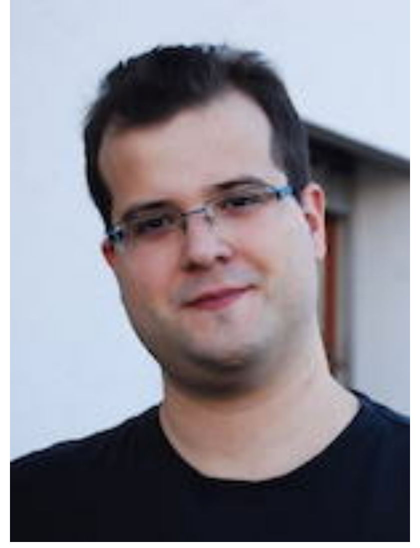
Jefferson Lab


Edwards


Chen


Winter

Old Dominion University / Jefferson Lab


Leskovec


Jackura

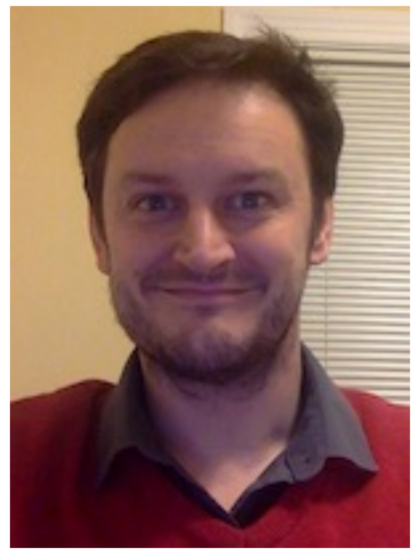
DAMTP, University of Cambridge


Wilson


Thomas


Chakraborty

William and Mary / Jefferson Lab


Dudek


Rodas

Oak Ridge National Lab


Joó

Edinburgh


Hansen

Trinity College, Dublin


Ryan


Peardon

Tata Institute, Mumbai


Mathur

Meson Spectrum

JHEP05 021 (2013)
PRD88 094505 (2013)
JHEP07 126 (2011)
PRD83 111502 (2011)
PRD82 034508 (2010)
PRL103 262001 (2009)

Baryon Spectrum

PRD91 094502 (2015)
PRD90 074504 (2014)
PRD87 054506 (2013)
PRD85 054016 (2012)
PRD84 074508 (2011)

Scattering

arXiv: 2102.04973
PRL 126 (2021)
JHEP 02 (2021)
JHEP 02 (2021)
PRD 103 (2021)
PRD 103 (2021)
PRD 100 (2019)
PRL 123 (2019)
JHEP 07 (2018)
JHEP 11 (2017)
PRD 97 (2018)

PRL118 022002 (2017)
JHEP011 1610 (2016)
PRD93 094506 (2016)
PRD92 094502 (2015)
PRD91 054008 (2015)
PRL113 182001 (2014)
PRD87 034505 (2013)
PRD86 034031 (2012)
PRD83 071504 (2011)

Electroweak

PRD93 114508 (2016)
PRL115 242001 (2015)
PRD91 114501 (2015)
PRD90 014511 (2014)

Techniques

PRD85 014507 (2012)
PRD80 054506 (2009)
PRD79 034502 (2009)
PRD 101 (2020)

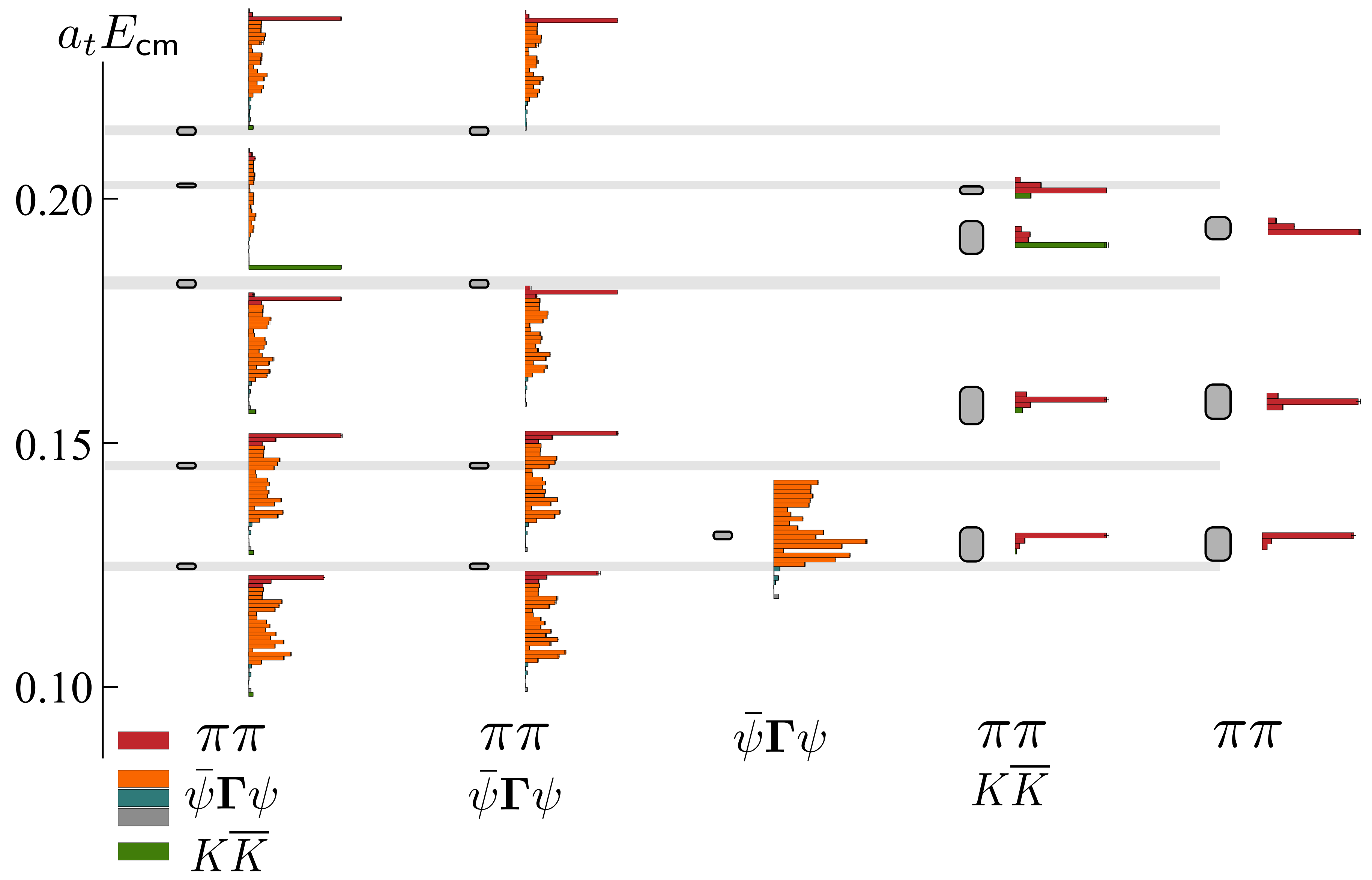
Formalism

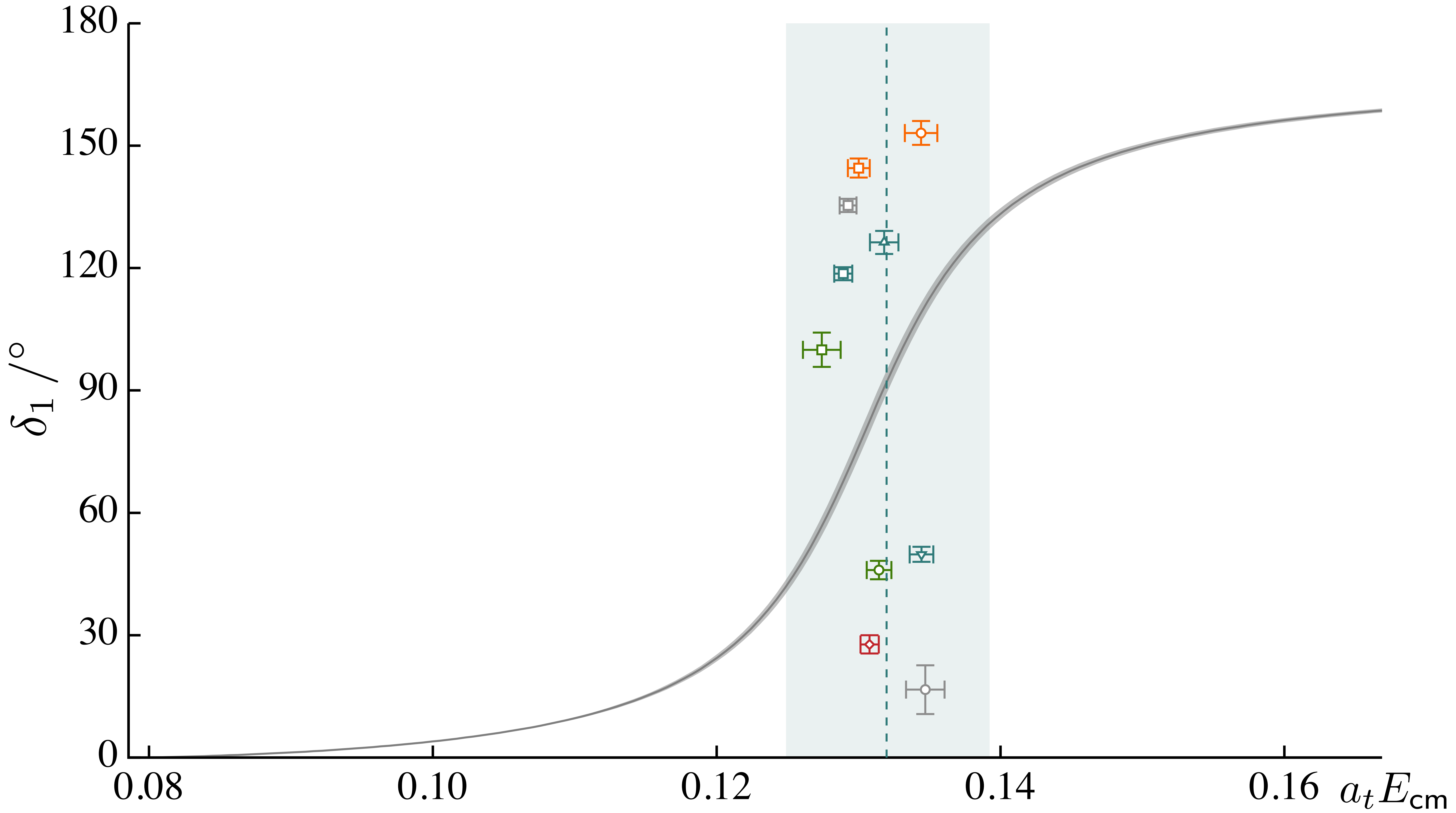
JHEP 04 (2021)
JHEP 07 (2020)
PRD 101 (2020)
PRD 101 (2020)
PRD 100 (2019)
JHEP 10 (2019)
PRD 100 (2019)
PRD 100 (2019)
PRD 99 (2019)
PRD 98 (2018)

PRD95 074510 (2017)
PRD94 013008 (2016)
PRD92 074509 (2015)
PRD91 034501 (2015)
PRD89 074507 (2014)

Backup slides

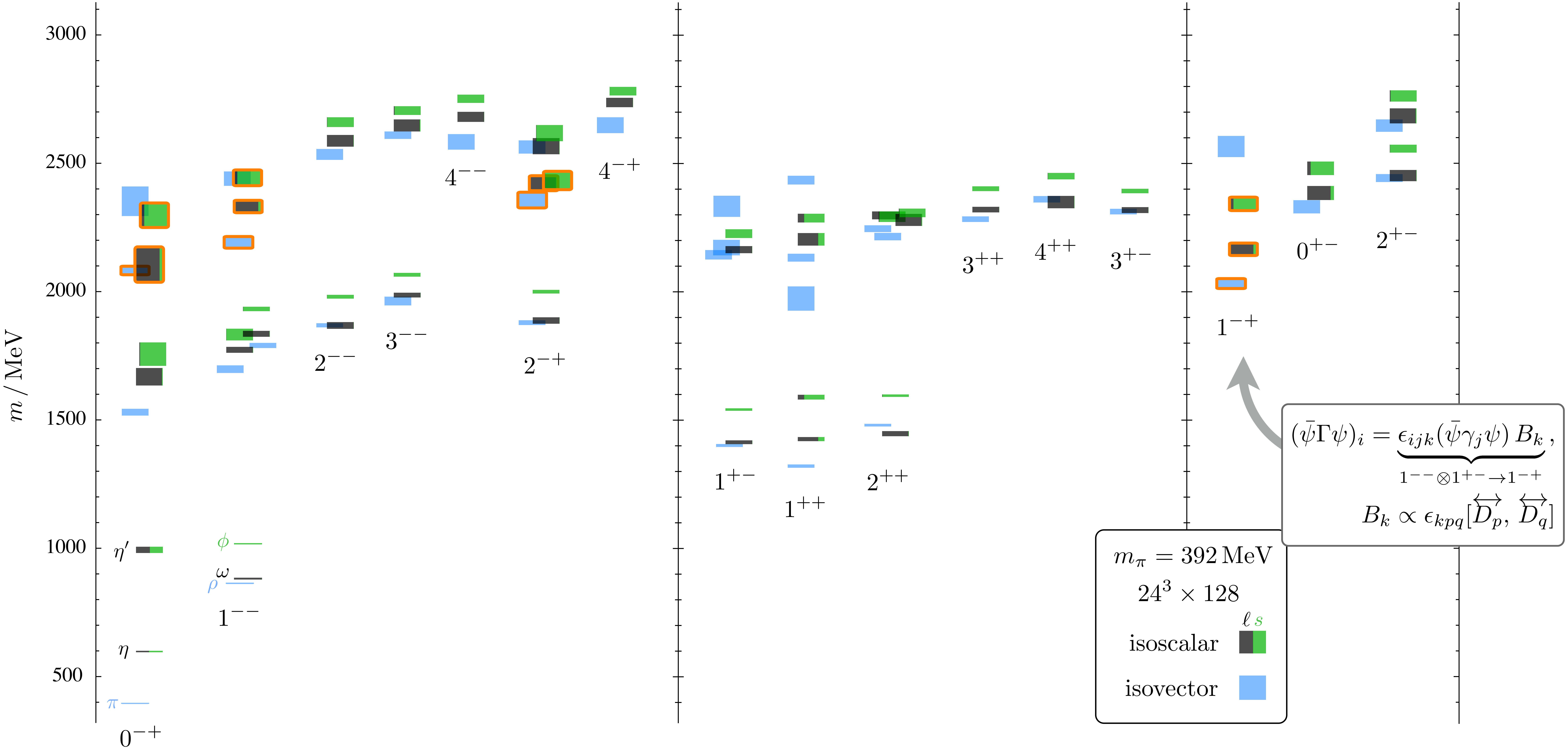
GEVP necessary but not sufficient





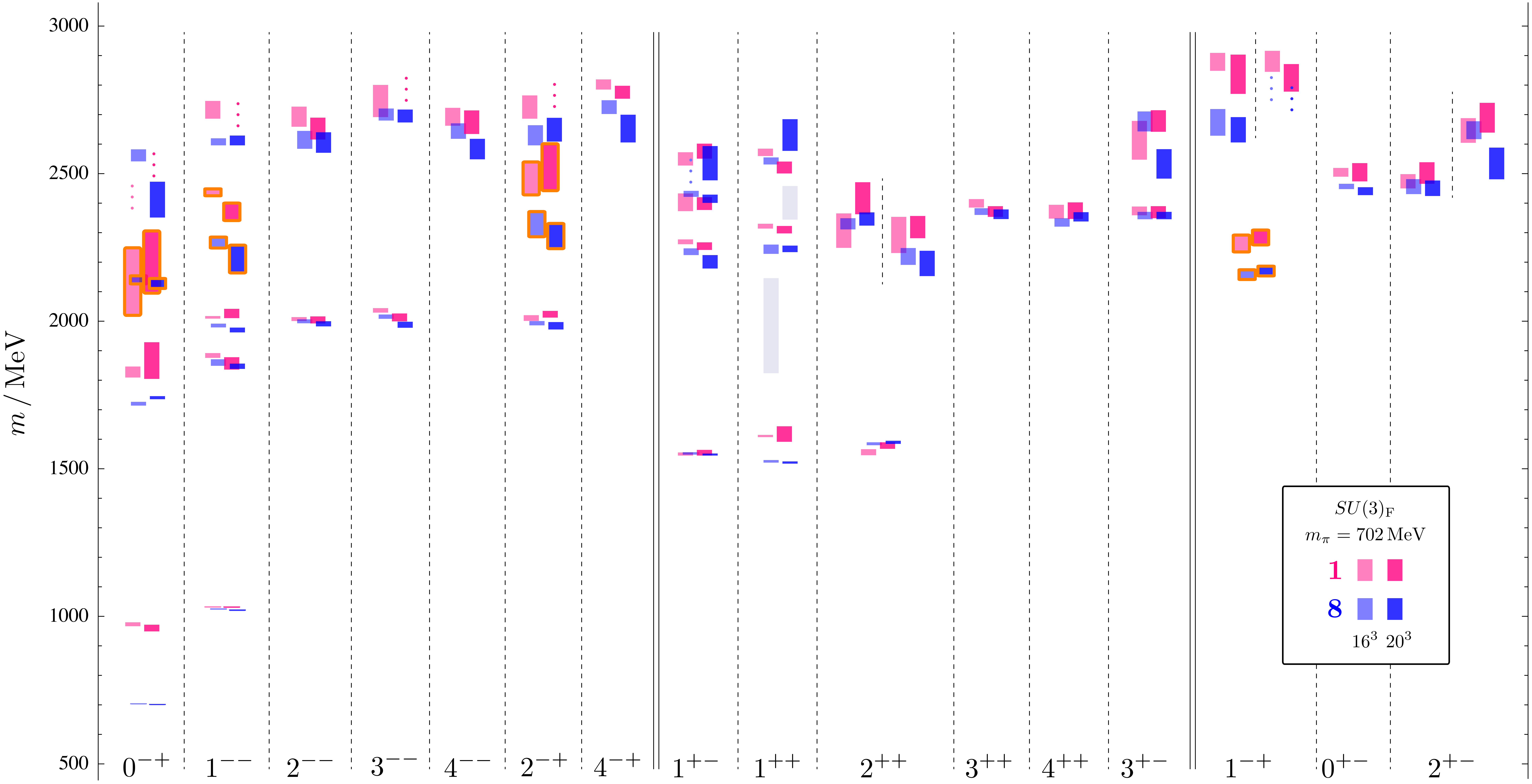
Wilson, RB, Dudek, Edwards, & Thomas (2015)

Light mesons without multi-particle ops



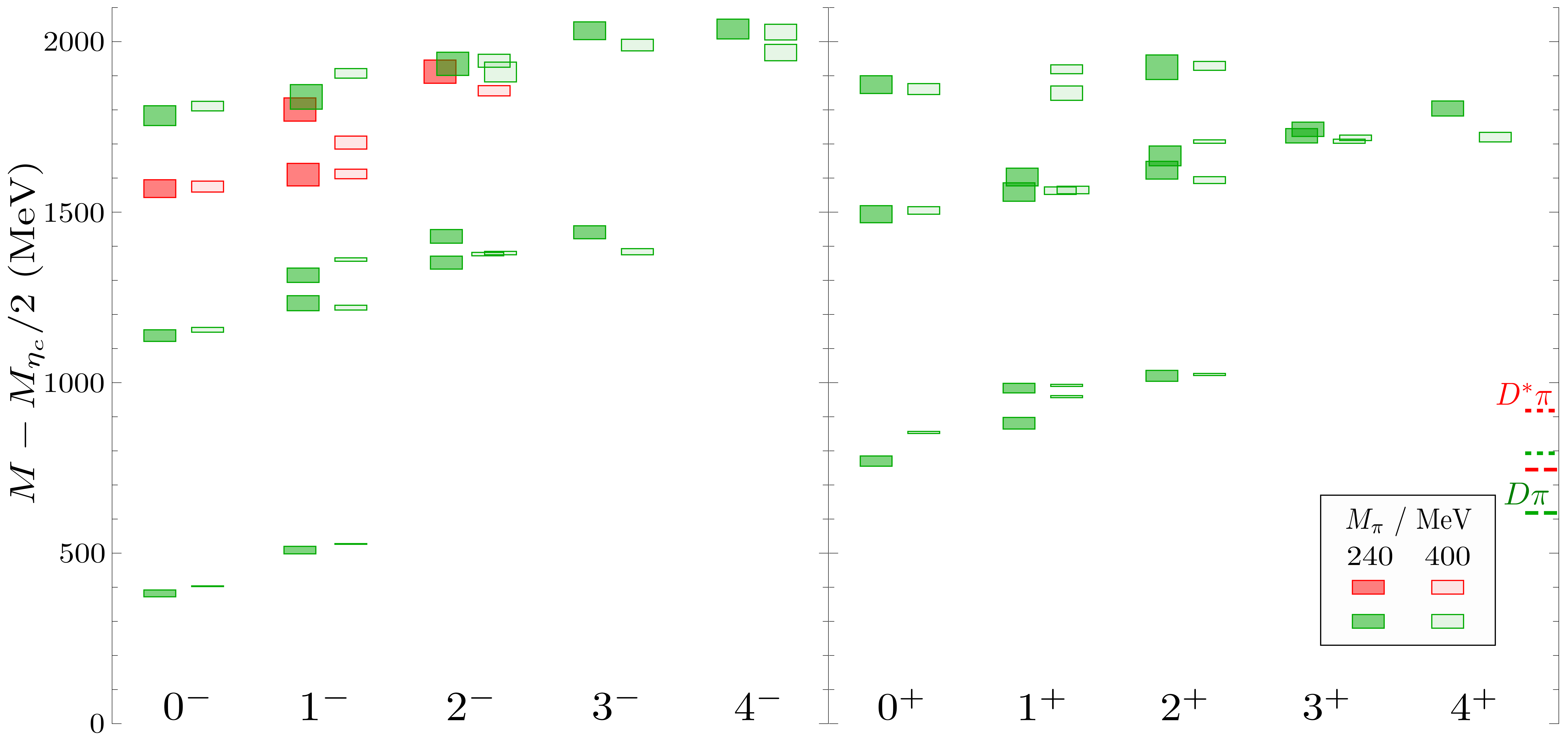
Dudek, Edwards, Guo, Thomas (2013)

Light mesons without multi-particle ops



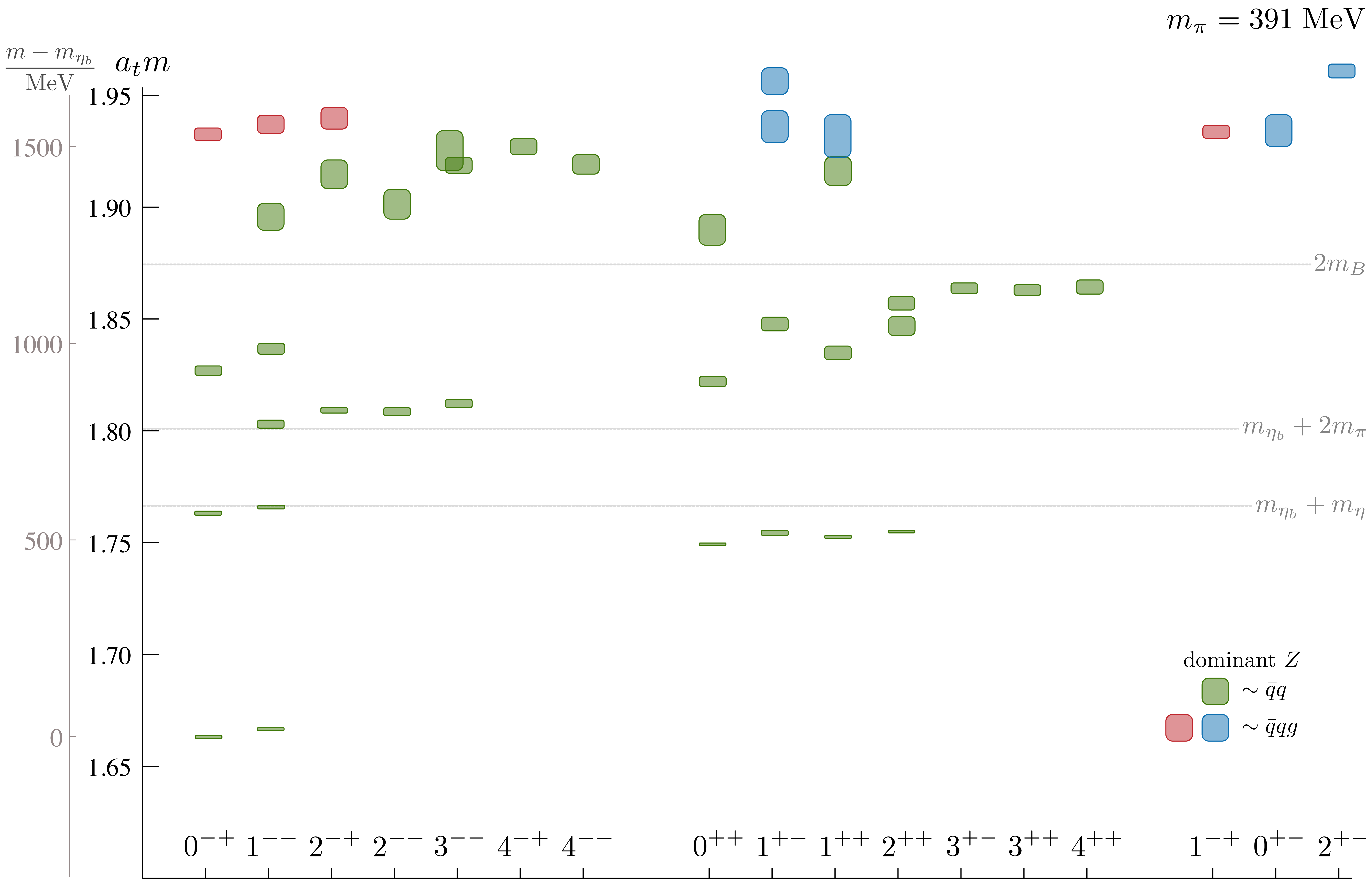
Dudek, Edwards, Guo, Thomas (2013)

Charmonium without multi-particle ops



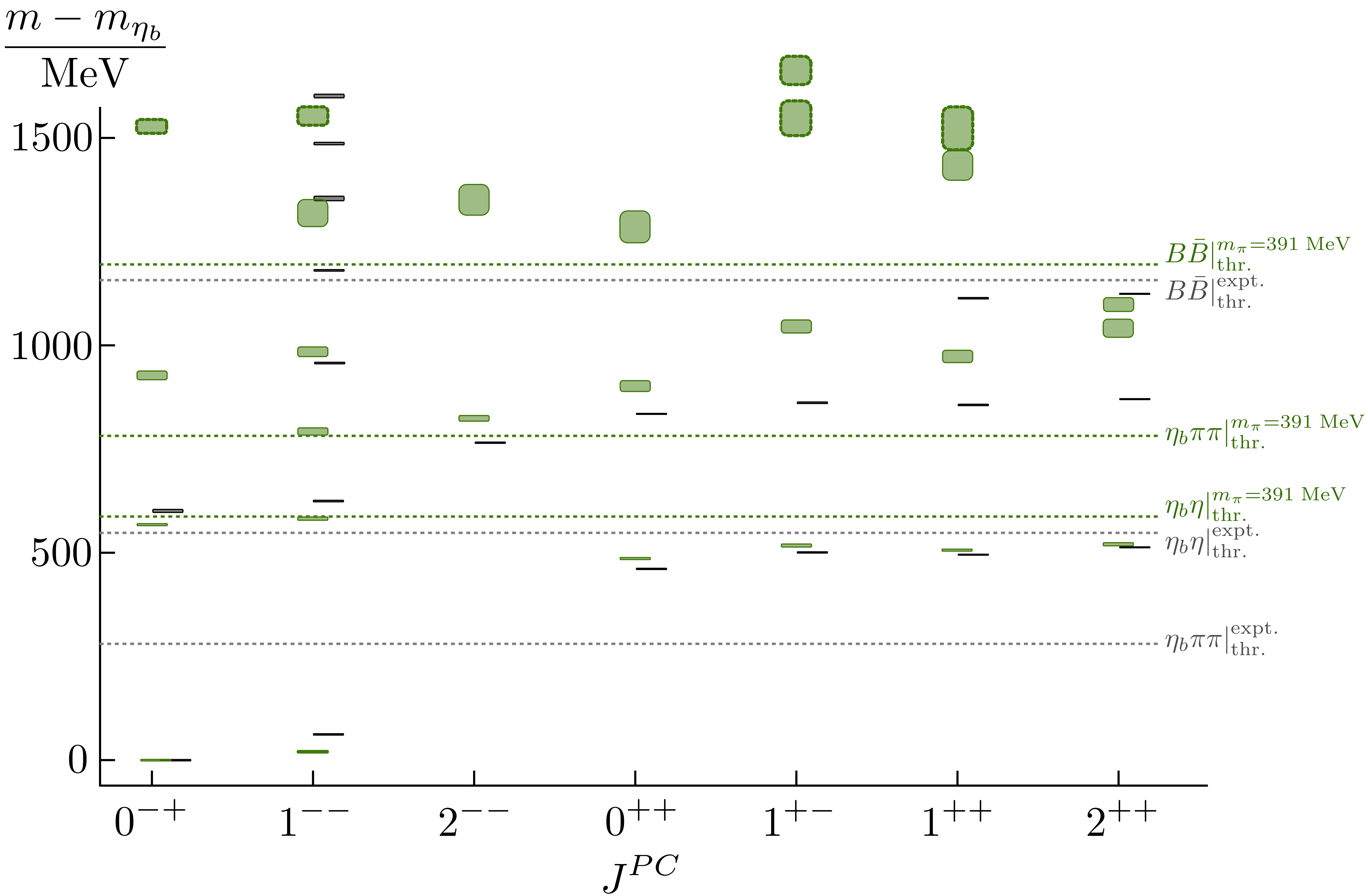
Cheung, O'Hara, Moir, Peardon, Ryan, Thomas, Tims (2016)

Bottomonium without multi-particle ops



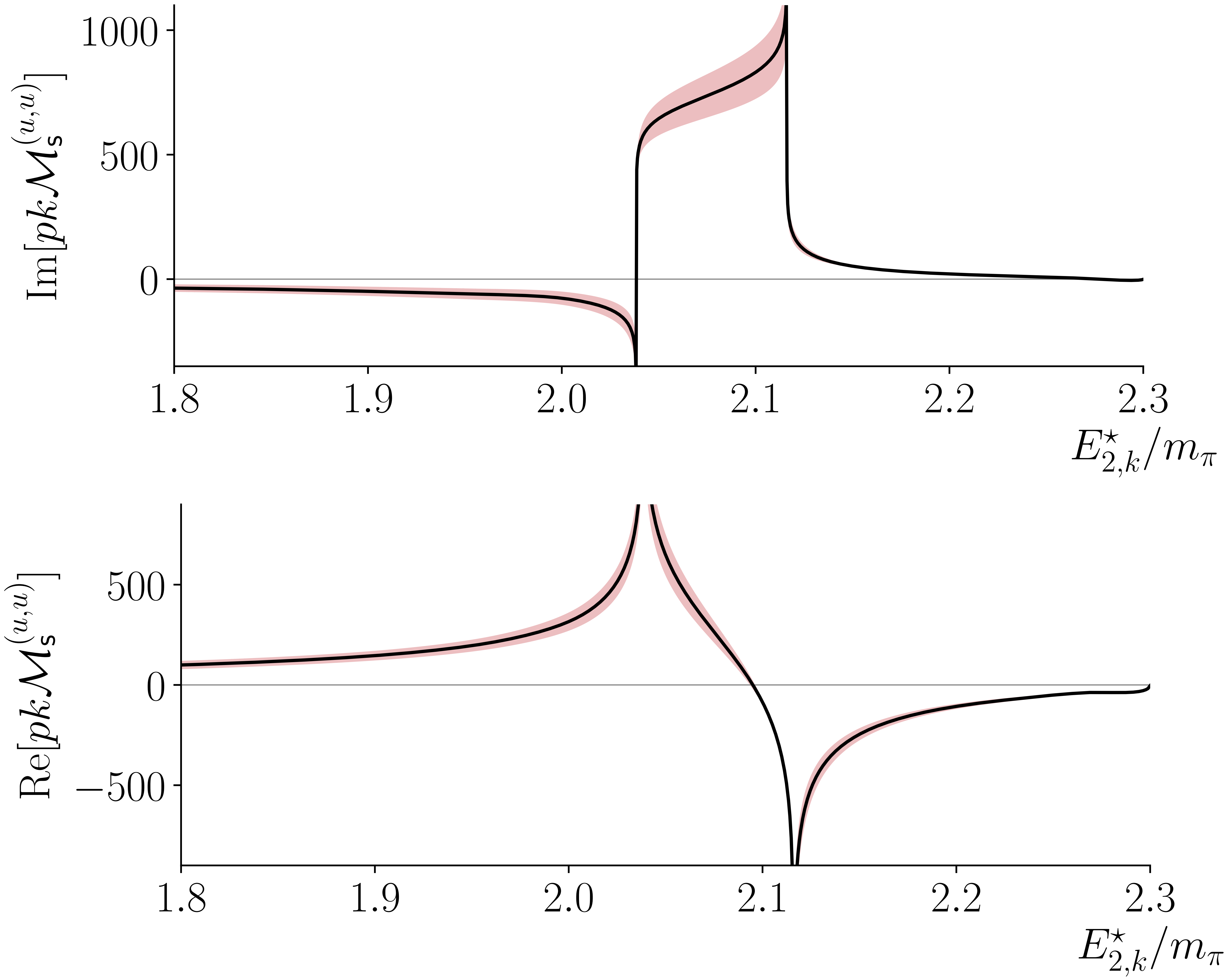
Ryan and Wilson (2020)

Bottomonium without multi-particle ops



Ryan and Wilson (2020)

three-body scattering



$m_\pi \sim 390\,\mathrm{MeV}$

Hansen, RB, Edwards, Thomas, & Wilson (2020)

$$\mathcal{D}_{\mathsf{s}}^{(u,u)}(p,k) = -\mathcal{M}_2(E^\star_{2,p})G_{\mathsf{s}}(p,k,\epsilon)\mathcal{M}_2(E^\star_{2,k}) - \mathcal{M}_2(E^\star_{2,p})\int_0^{k_{\mathsf{max}}} \frac{k'^2\,dk'}{(2\pi)^2\omega_{k'}}\,G_{\mathsf{s}}(p,k',\epsilon)\mathcal{D}_{\mathsf{s}}^{(u,u)}(k',k),$$

Pheno π_1

Slide by Jozef Dudek

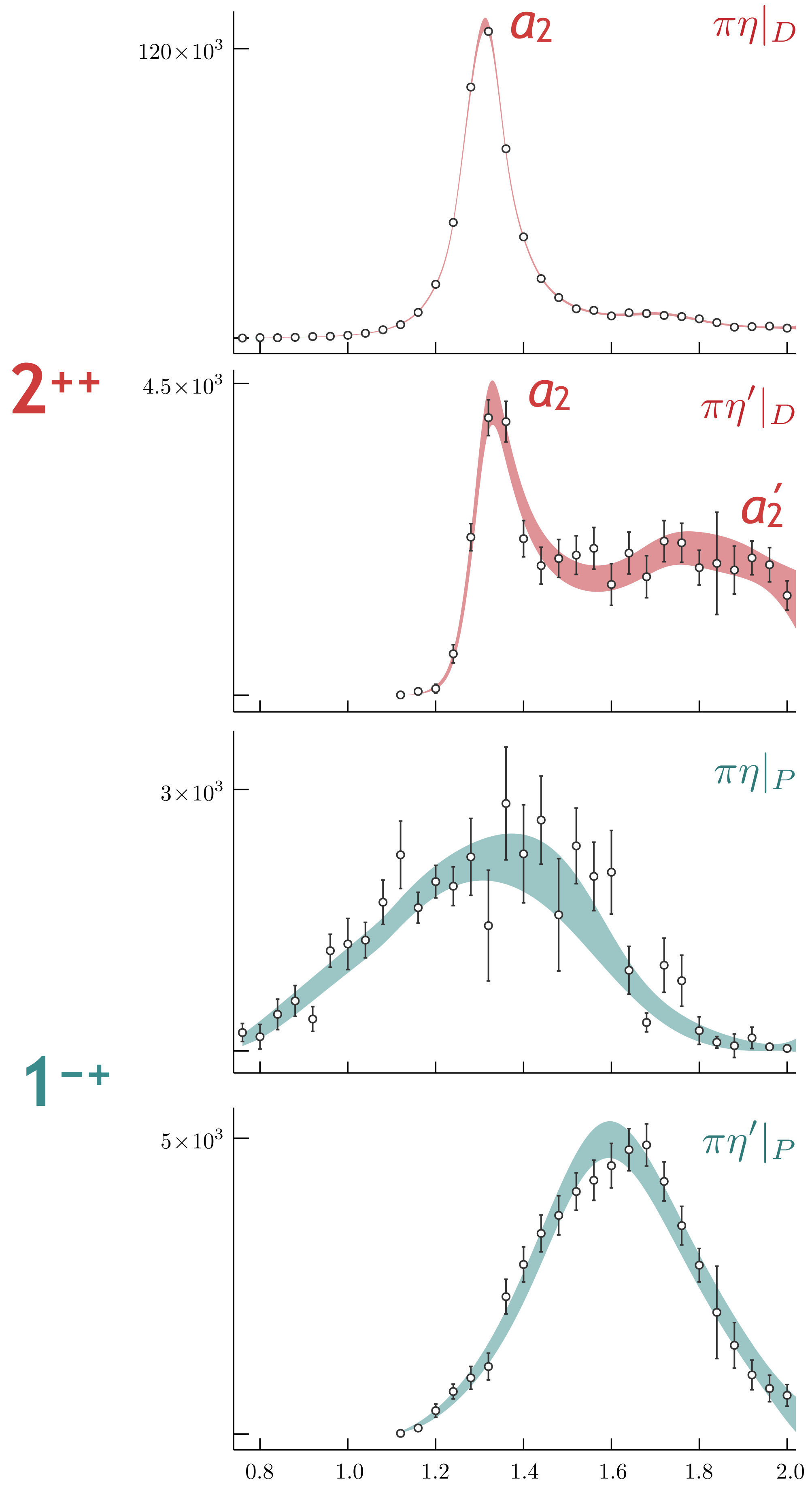
experimental situation

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

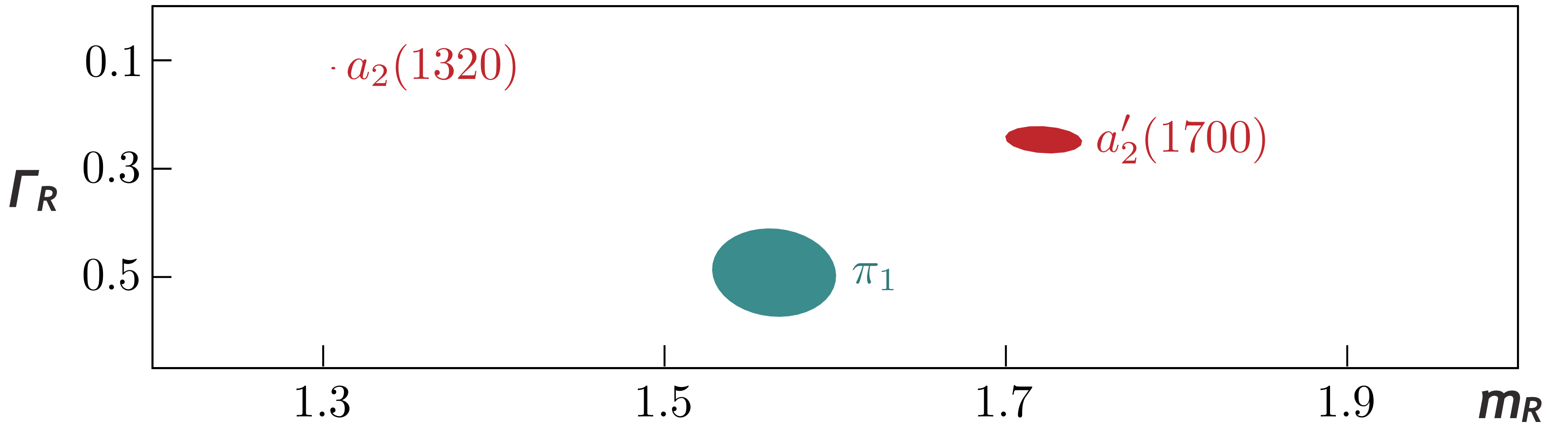
Determination of the Pole Position of the Lightest Hybrid Meson Candidate

A. Rodas,[1,*] A. Pilloni,[2,3,†] M. Albaladejo,[2,4] C. Fernández-Ramírez,[5] A. Jackura,[6,7] V. Mathieu,[2] M. Mikhasenko,[8] J. Nys,[9] V. Pauk,[10] B. Ketzer,[8] and A. P. Szczepaniak[2,6,7]

(Joint Physics Analysis Center)



pole singularity of a π_1 resonance



m_R=1564(89) MeV, Γ_R=492(115) MeV

a rather broad resonance

Pheno π_1

Slide by Jozef Dudek

crude extrapolation to physical point

core assumption: couplings scale only with the relevant barrier factor $\boldsymbol{k^{\ell}}$

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

$\boldsymbol{\Gamma(\pi b_1)}$ ~ **140-530 MeV**

JPAC/COMPASS candidate:

Γ_{TOT} ~ **492(115) MeV**

Kopf et al analysis:

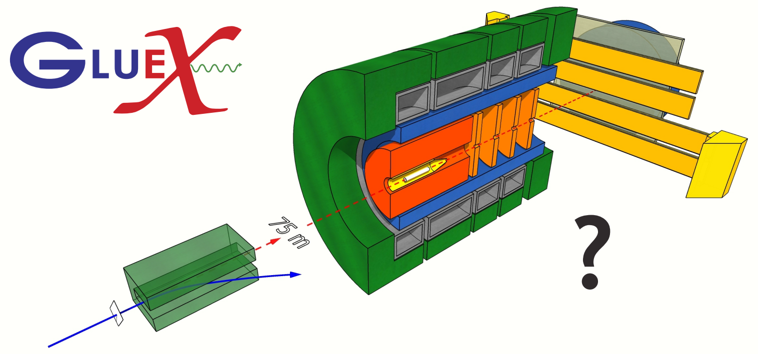
Γ_{TOT} ~ **388(10) MeV**

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

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

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

GlueX



Lattice π_1 *poles and couplings*