lattice spectroscopy @ JLab

Raúl Briceño - http://bit.ly/rbricenoPhD

Norfolk, VA [Home to ODU]

OLD DOMINION UNIVERSITY

Jefferson Lab

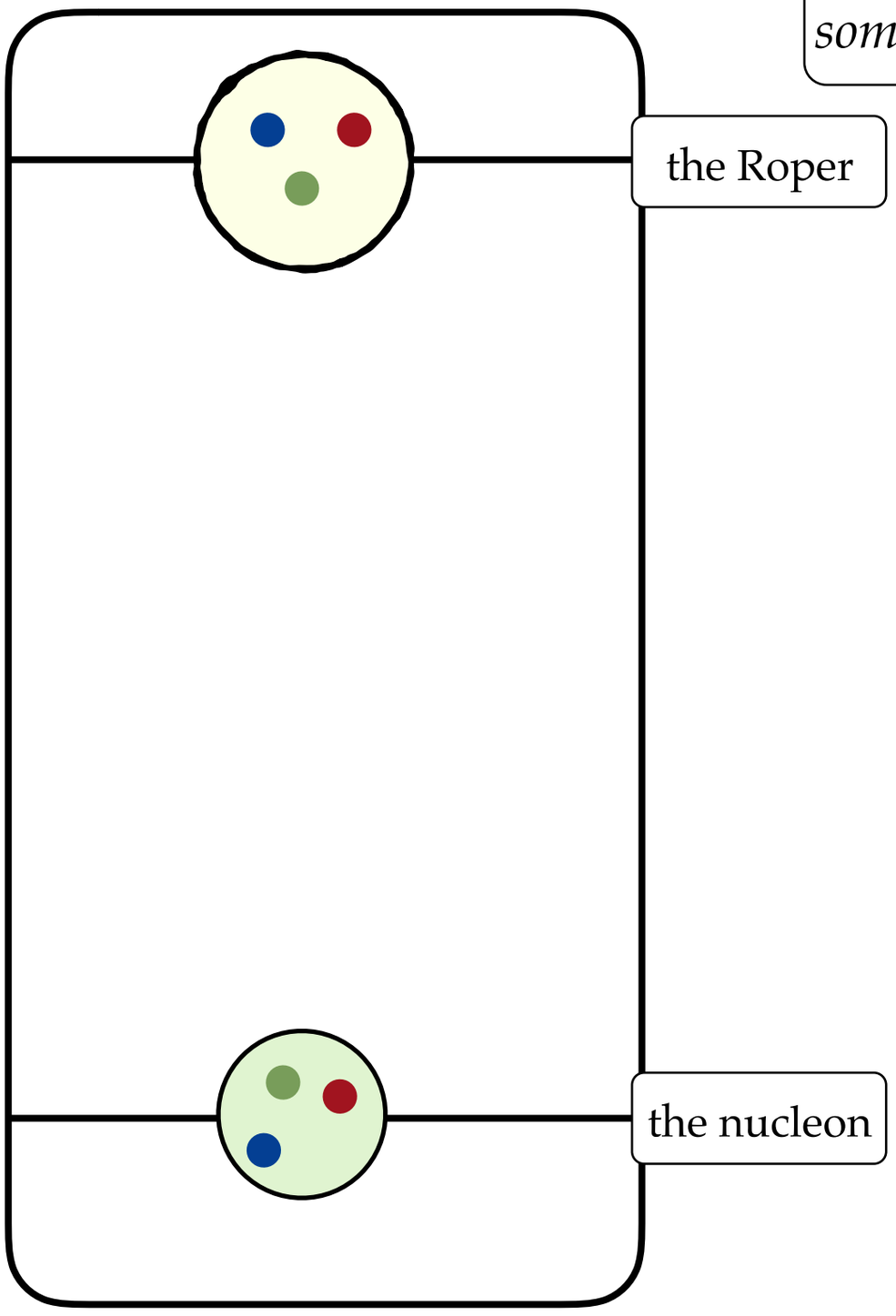
had spec

http://hadspec.org

sQCD, 2019

JLab, VA

the Roper an outstanding 50yr puzzle

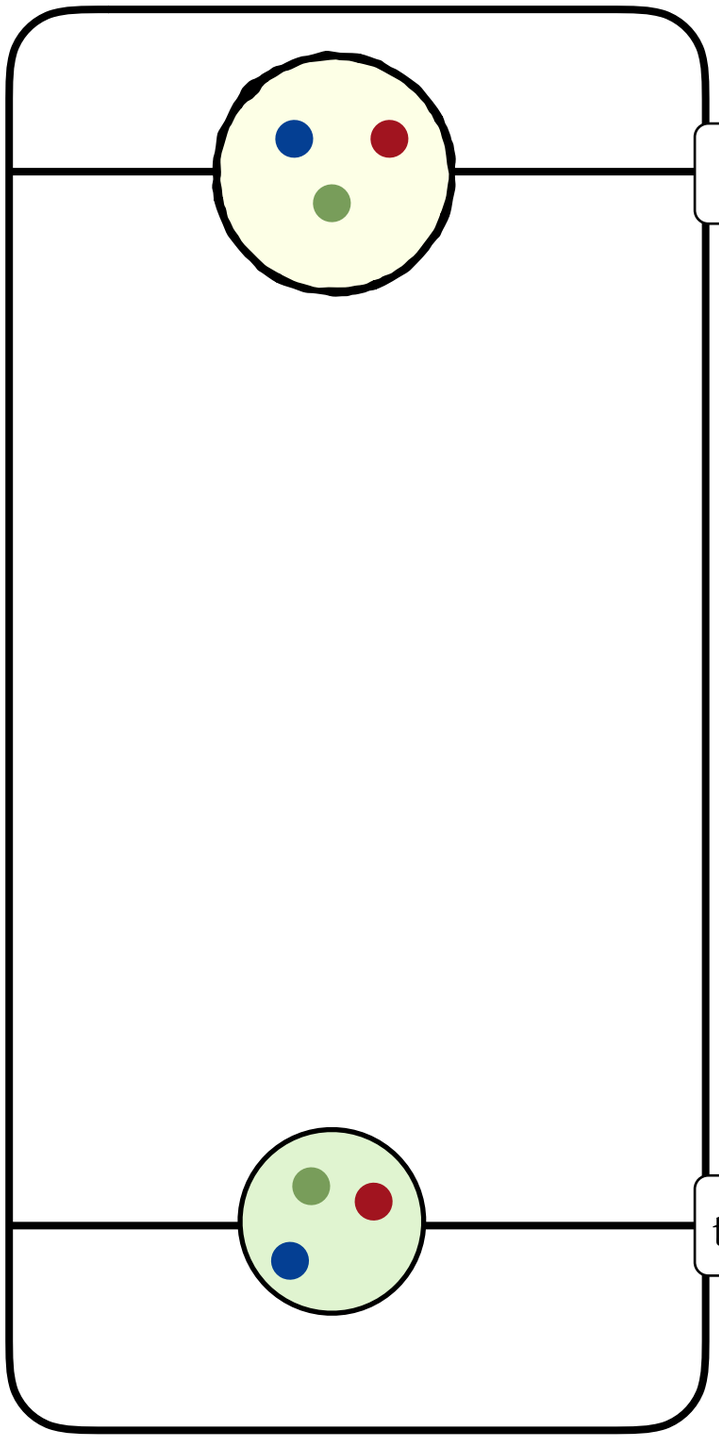


The Roper is naïvely simple…
…but understanding its nature, requires us to face some of the major theoretical challenges in QCD.

to claim understanding, we need to convincingly reproduce experimental observables

we need a standard of measure

the Roper an outstanding 50yr puzzle



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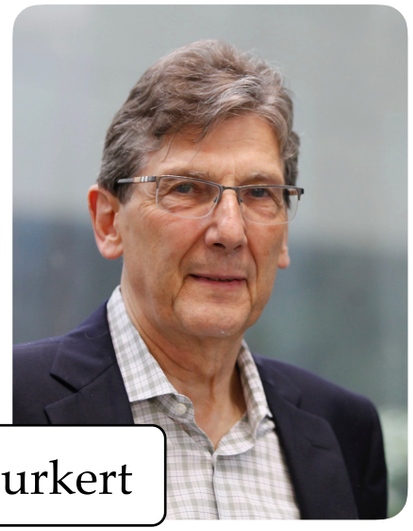


Volker Burkert

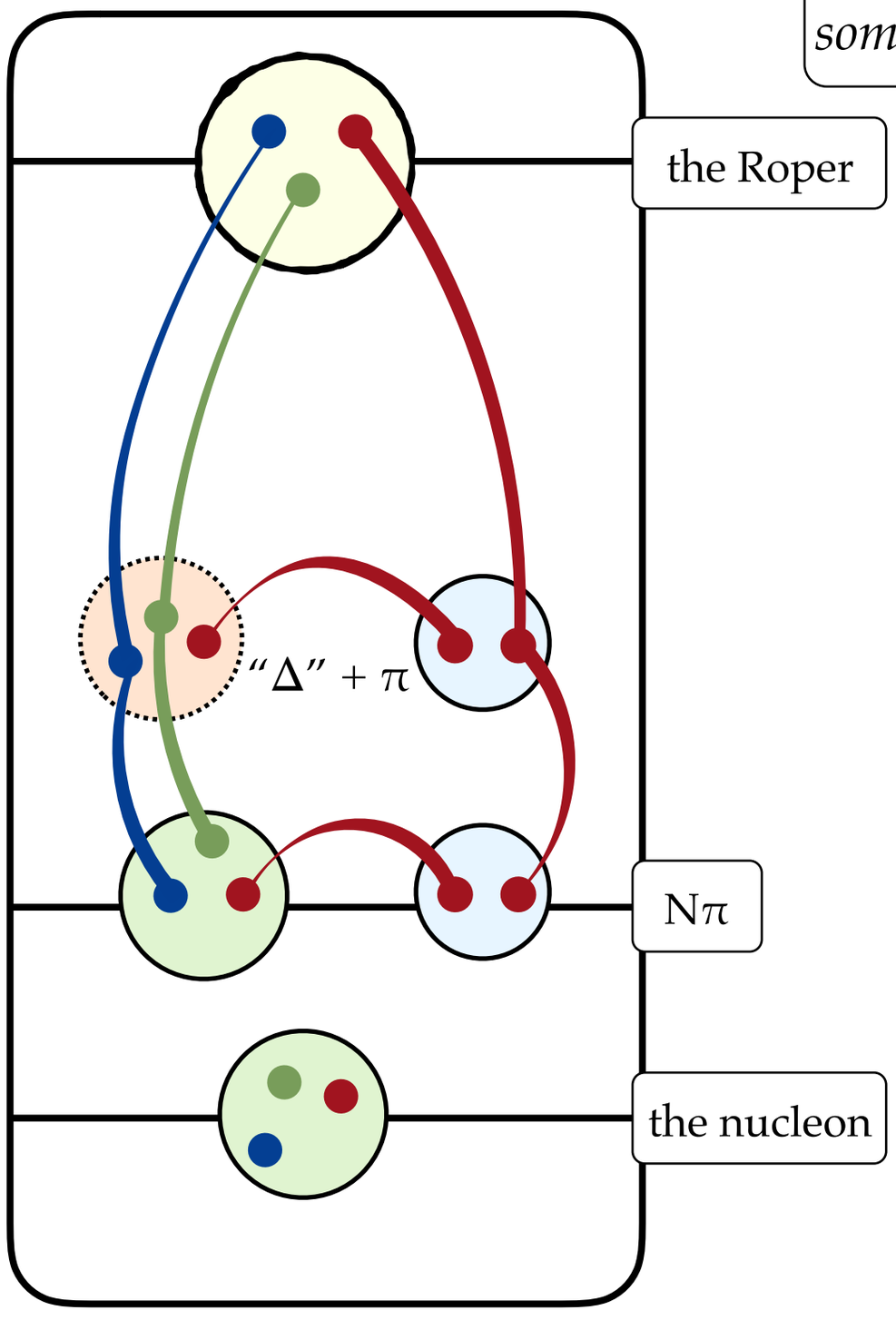
Volker Standard

*"**Accuracy** of predictions should be commensurate with experiments, i.e. O(few MeV)"*

Corollary

no theoretical study meets the "Volker standard" for the Roper!

the Roper an outstanding 50yr puzzle



The Roper is naïvely simple…
…but understanding its nature, requires us to face some of the major theoretical challenges in QCD.

What are the necessary features needed to be able to claim **accuracy**?

broad resonance

this already disqualifies most if not all theoretical studies!

the Roper an outstanding 50yr puzzle

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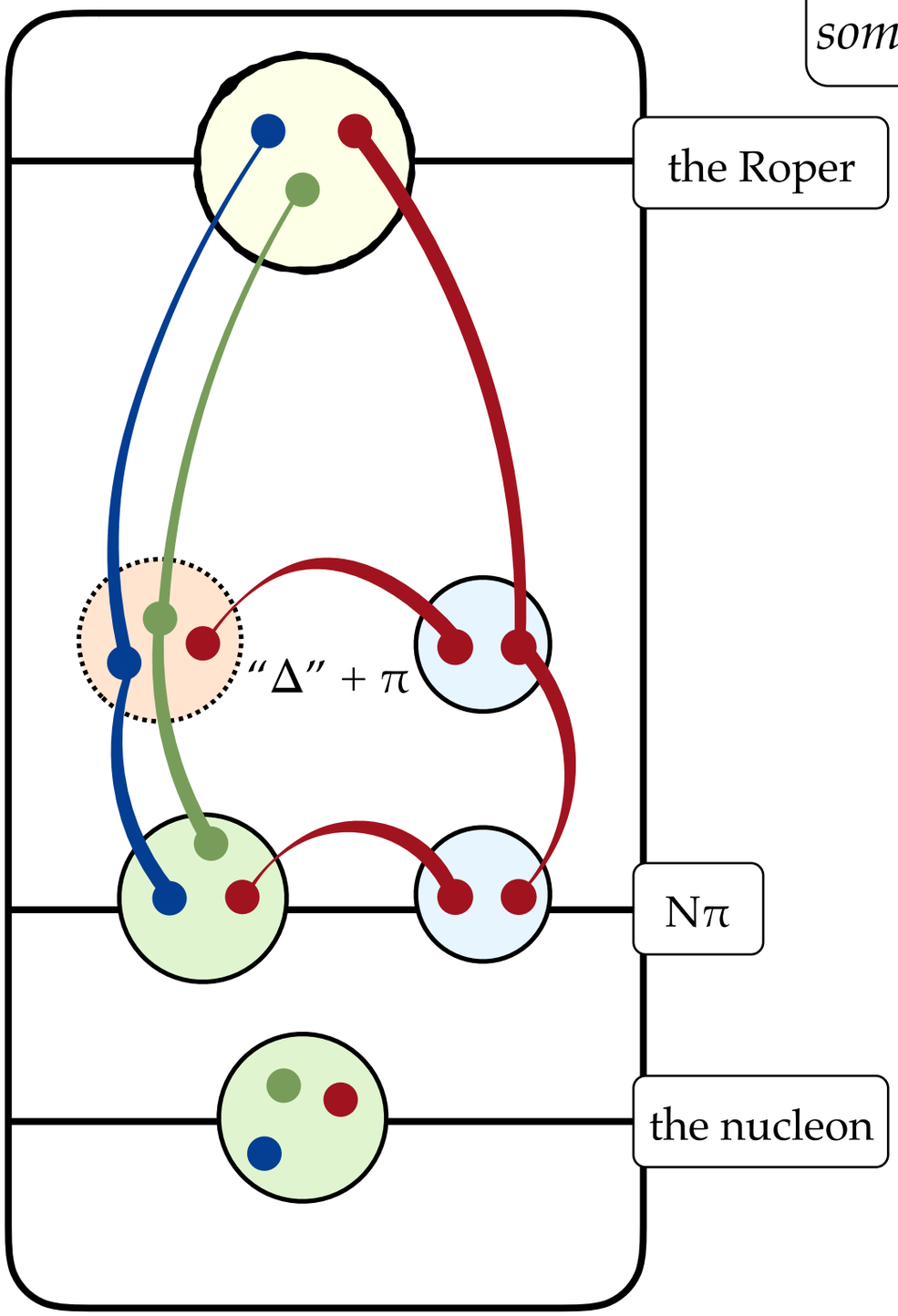

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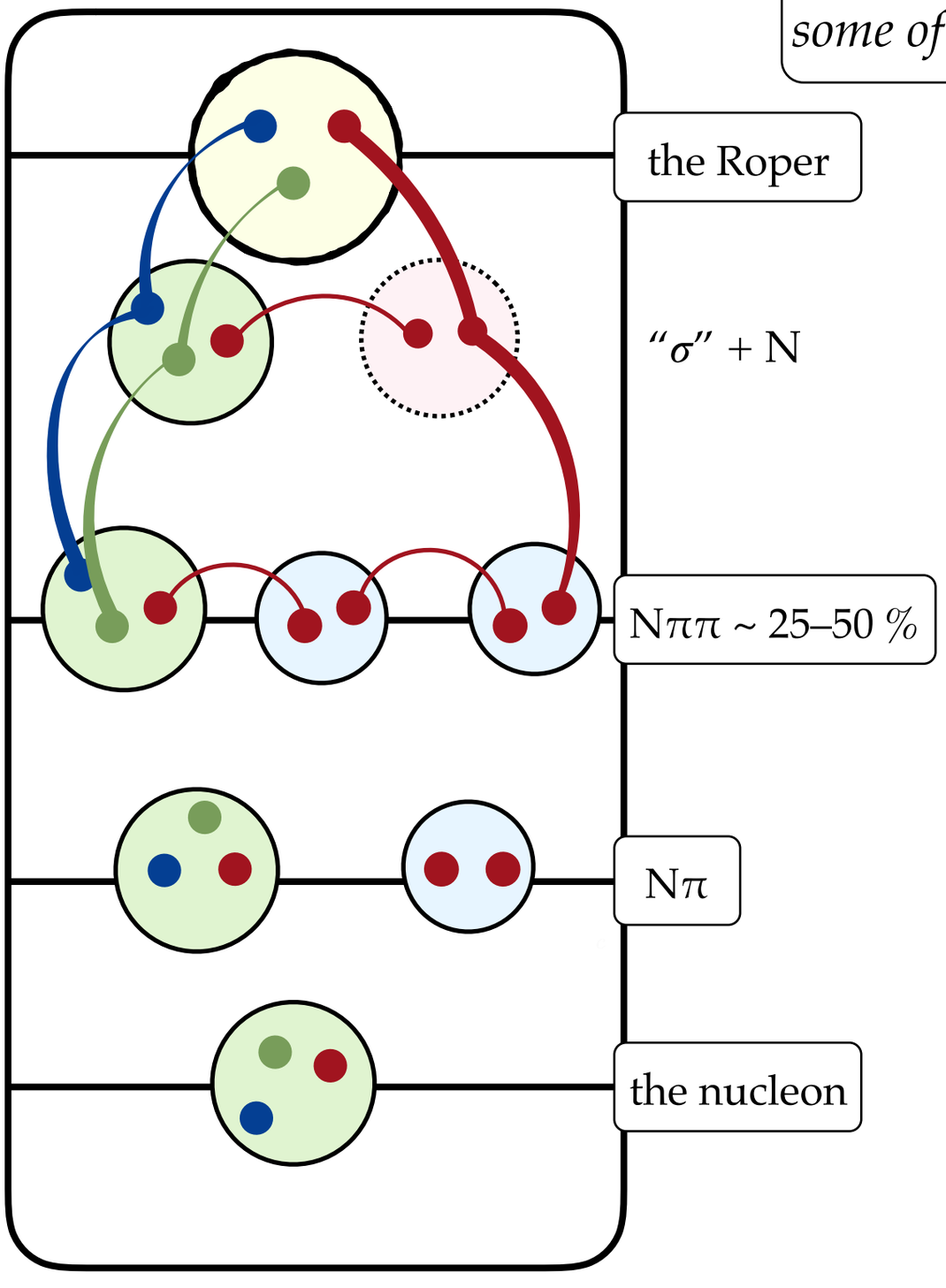

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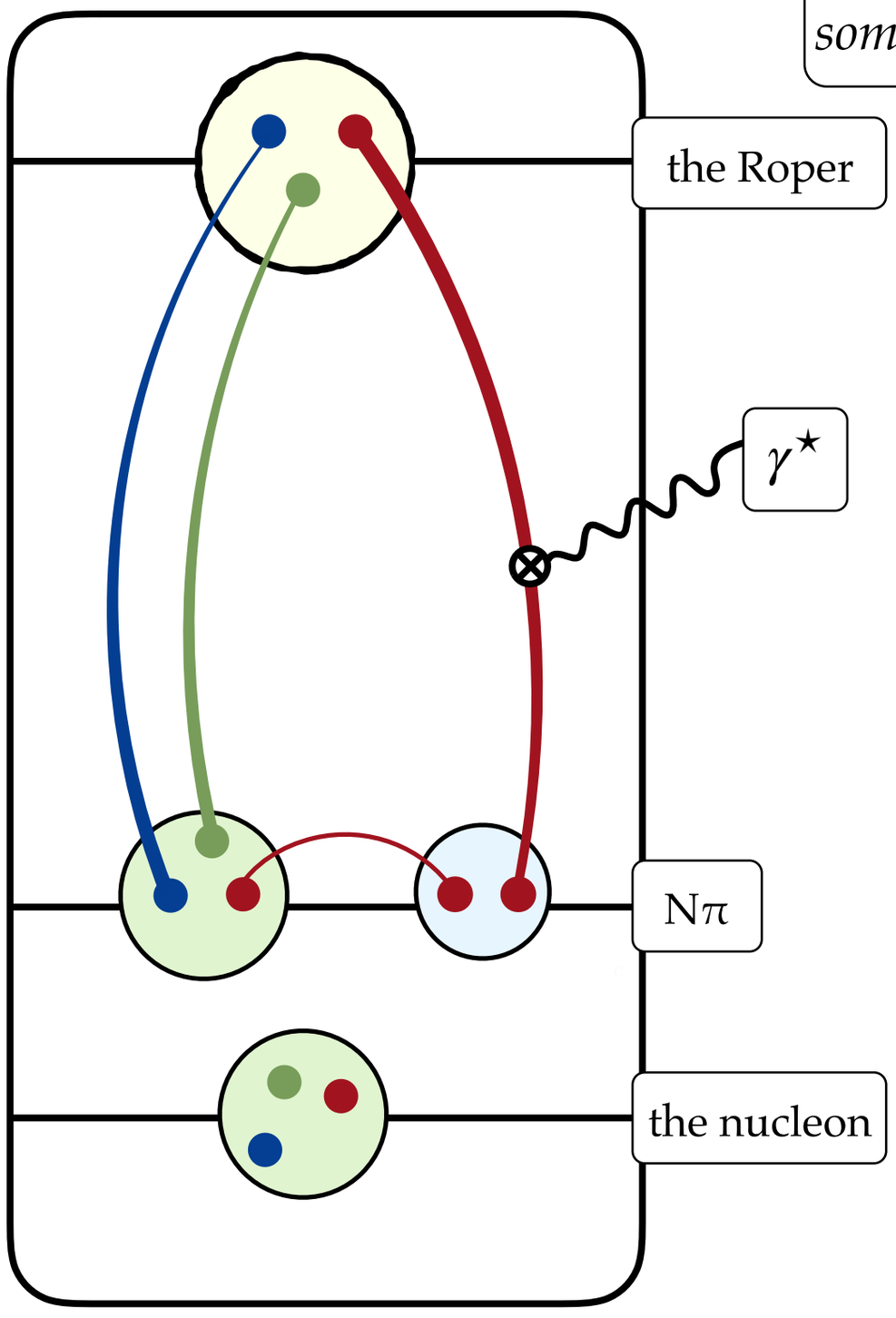

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strongly coupled

three-particle system

structure of resonant states

QCD spectroscopy

Amplitude analysis

Experiments

QCD

INT Program : ”Accessing and Understanding the QCD Spectrum"
August 17 - September 18, 2020

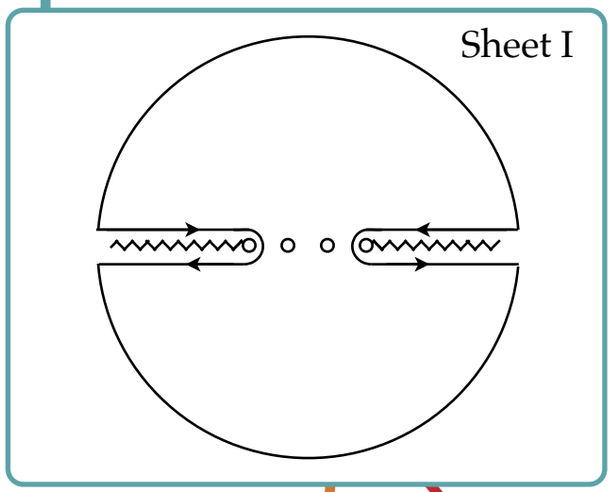
Pilloni [ECT*]

Eichmann [CFTP]

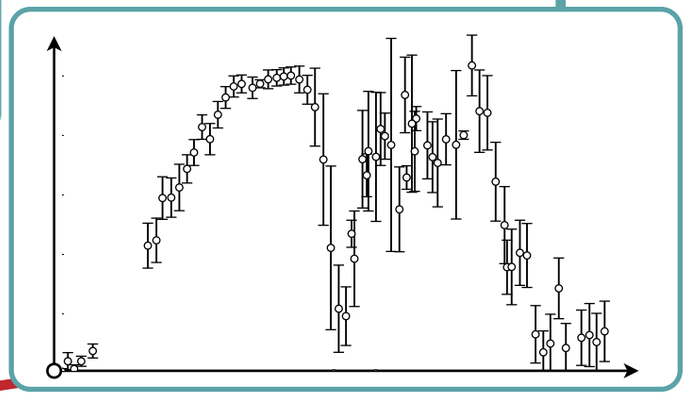
QCD spectroscopy

QCD

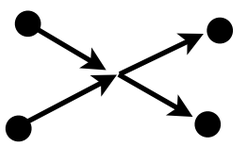
Amplitude analysis



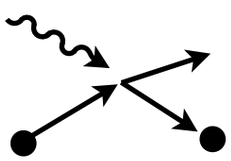
Experiments



partial wave amplitudes

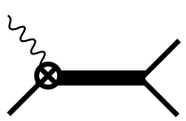


electroweak amplitudes



resonance poles

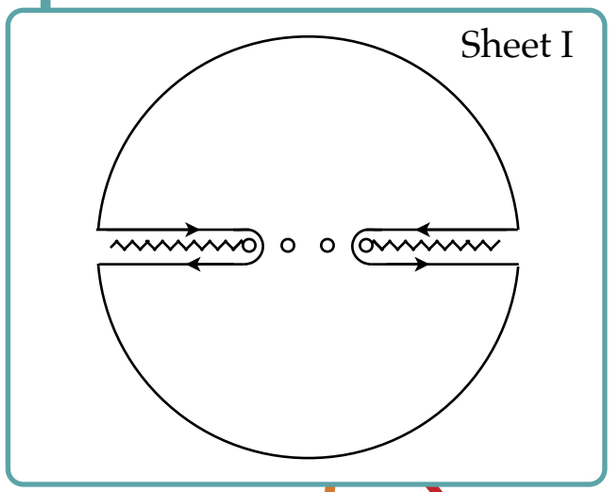
transition form factors



identification of states, production/decay mechanisms

QCD spectroscopy

Amplitude analysis



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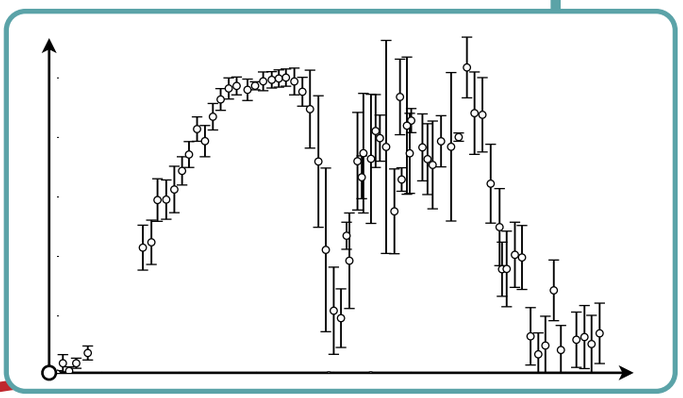
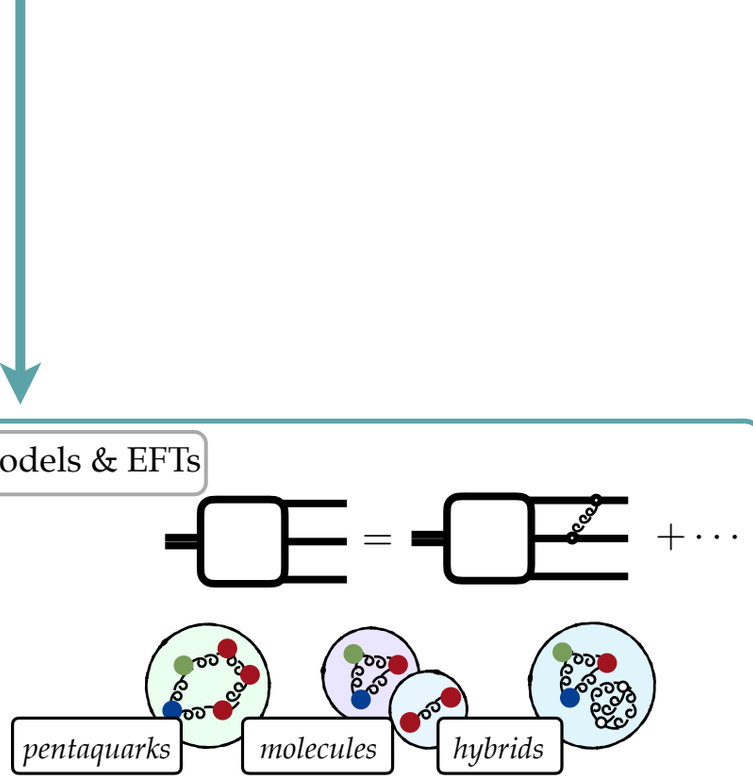


QCD

models & EFTs



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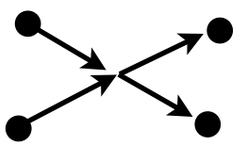

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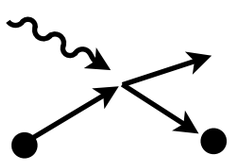

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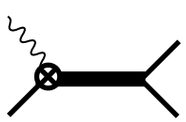

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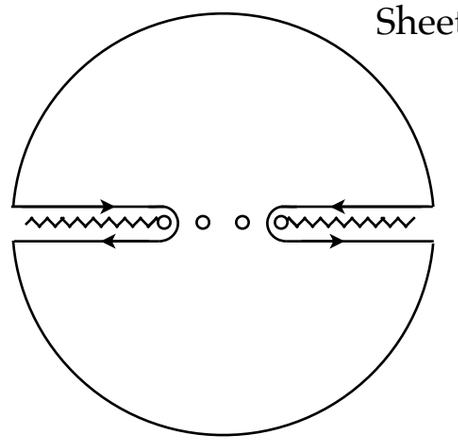
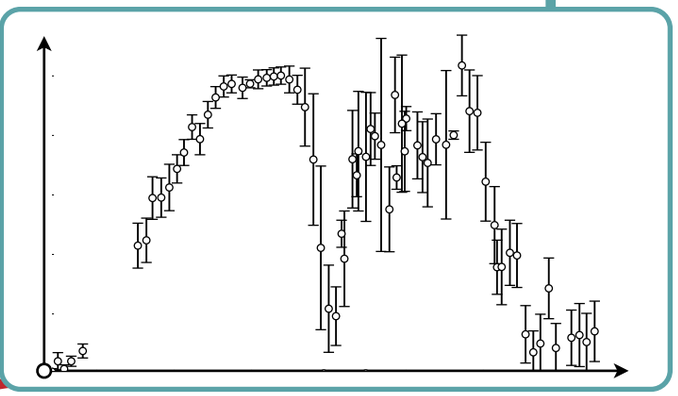
Sheet I



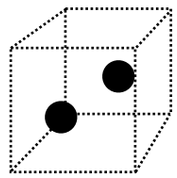
Experiments



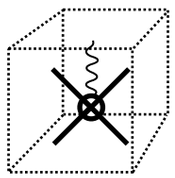
QCD

lattice QCD

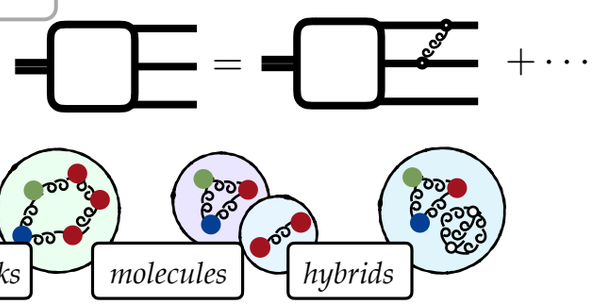
finite-volume spectrum



finite-volume matrix elements



models & EFTs



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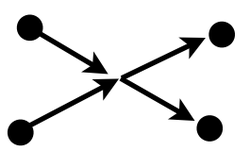

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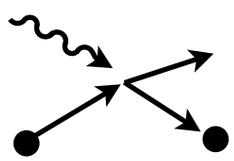
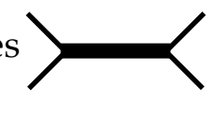
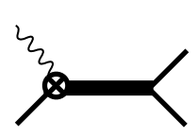


resonance poles



transition form factors



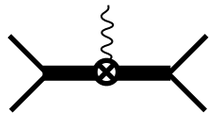
identification of states, production / decay mechanisms

QCD spectroscopy

Amplitude analysis

structure and nature of states

elastic form factors



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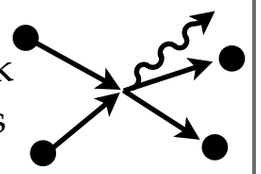

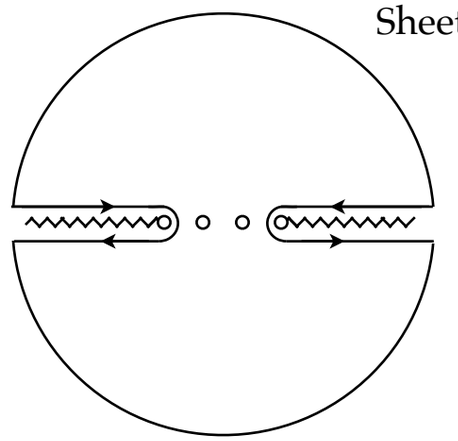

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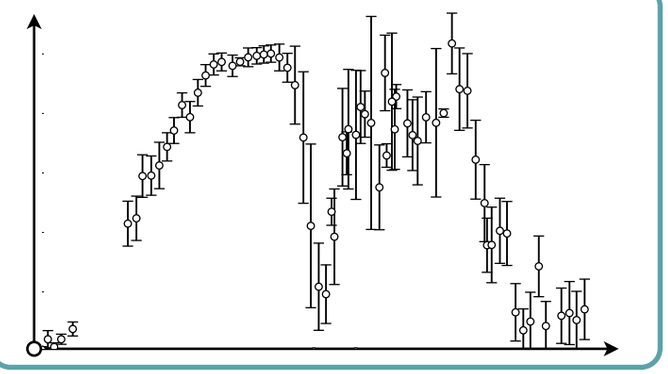

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lattice QCD

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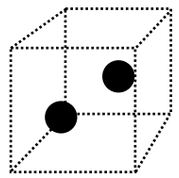
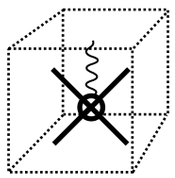


finite-volume matrix elements



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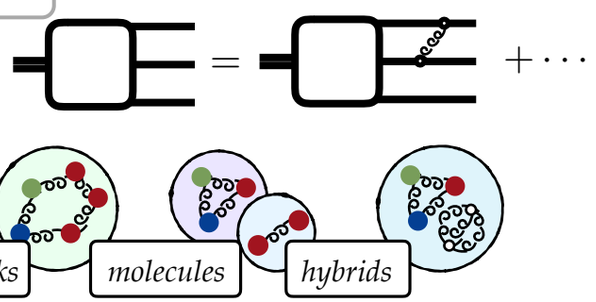
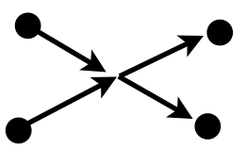


partial wave amplitudes



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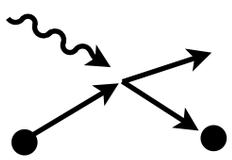

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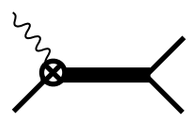
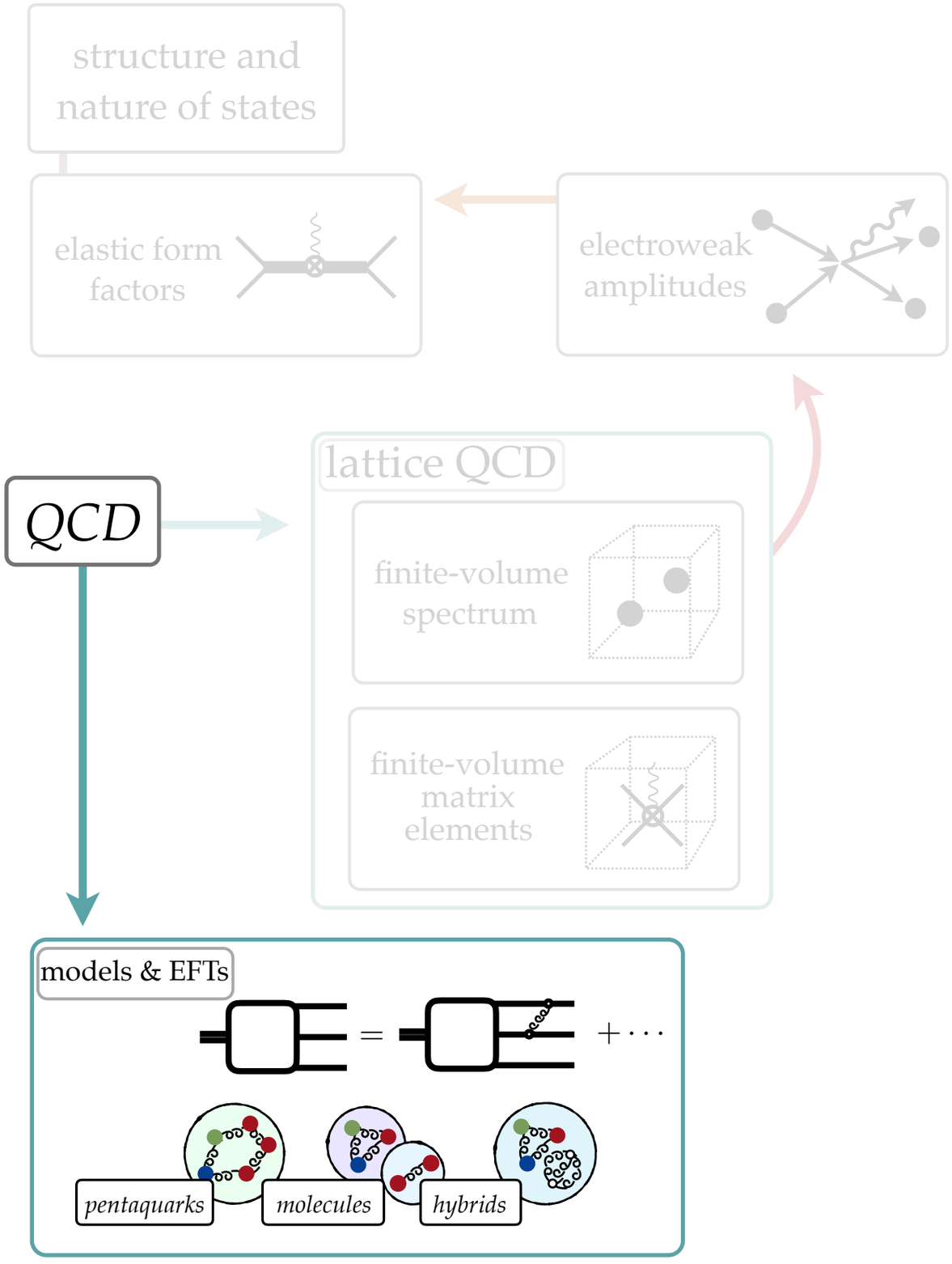
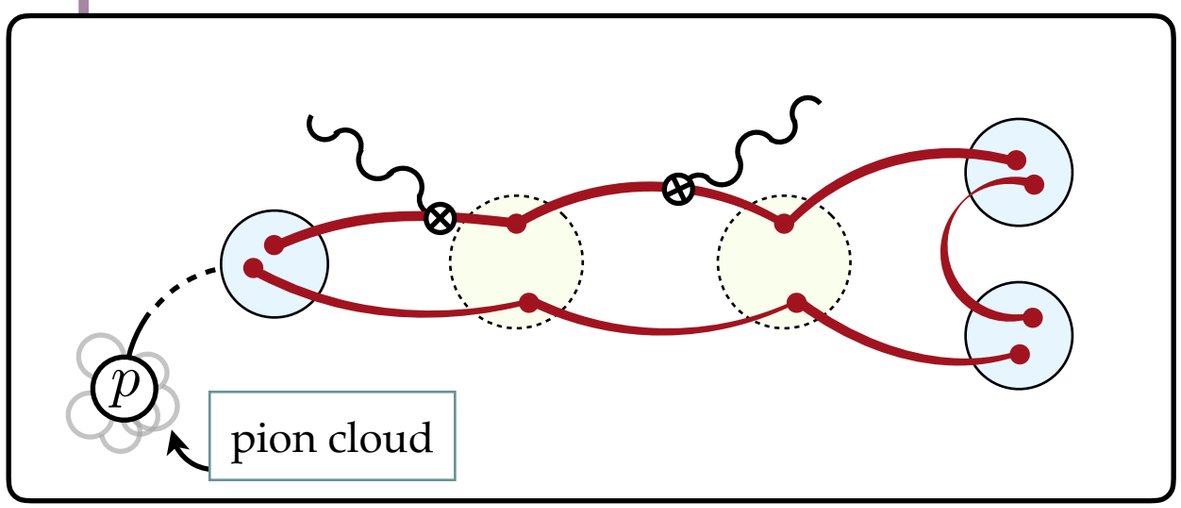


identification of states, production / decay mechanisms

QCD spectroscopy



furthermore, **most** structural information cannot be accessed directly from experiments



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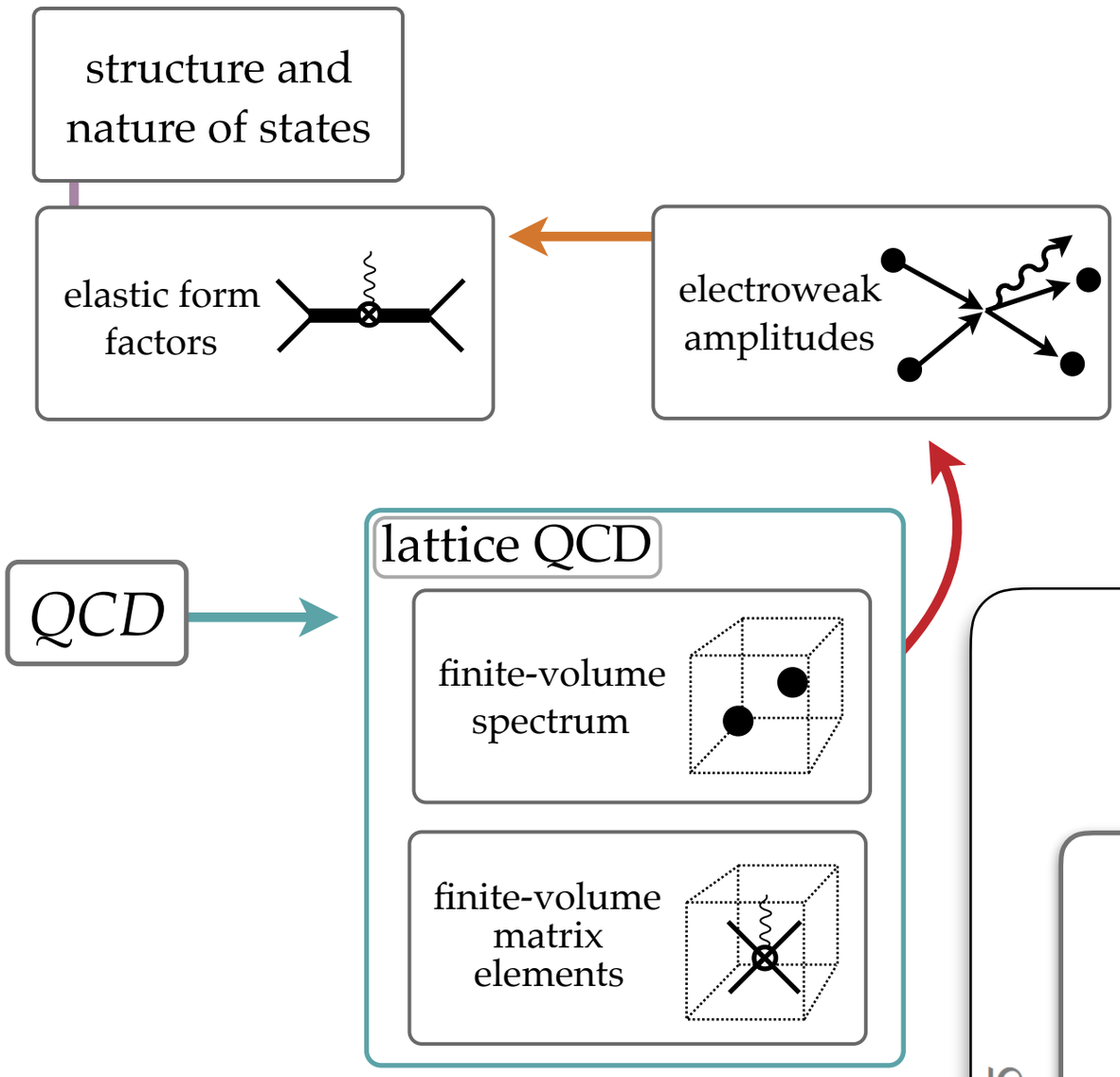

Hansen (CERN)

Baroni (USC)

Jackura (IU)

Ortega (W&M)

JLAB-THY-15-2140

Relativistic, model-independent, multichannel $2 \to 2$ transition amplitudes in a finite volume

Raúl A. Briceño[1,*] and Maxwell T. Hansen[2,†]

[1] *Thomas Jefferson National Accelerator Facility, 12000 Jefferson Avenue, Newport News, VA 23606, USA*

JLAB-THY-18-2878
CERN-TH-2018-263

Form factors of two-hadron states from a covariant finite-volume formalism

Alessandro Baroni,[1,*] Raúl A. Briceño,[2,3,†] Maxwell T. Hansen,[4,‡] and Felipe G. Ortega-Gama[2,5,§]

[1] *Department of Physics and Astronomy University of South Carolina, 712 Main Street, Columbia, South Carolina 29208, USA*
[2] *Thomas Jefferson National Accelerator Facility, 12000 Jefferson Avenue, Newport News, Virginia 23606, USA*

JLAB-T
CERN-

Consistency checks for two-body finite-volume matrix elements: I. Conserved currents and bound states

Raúl A. Briceño,[1,2,*] Maxwell T. Hansen,[3,†] and Andrew W. Jackura[1,2,‡]

[1] *Thomas Jefferson National Accelerator Facility, 12000 Jefferson Avenue, Newport News, VA 23606, U*
[2] *Department of Physics, Old Dominion University, Norfolk, Virginia 23529, USA*
[3] *Theoretical Physics Department, CERN, 1211 Geneva 23, Switzerland*

(Dated: September 24, 2019)

Recently, a framework has been developed to study form factors of two-hadron states probed by an external current. The method is based on relating finite-volume matrix elements, computed using numerical lattice QCD, to the corresponding infinite-volume observables. As the formalism is complicated, it is important to provide non-trivial checks on the final results and also to explore

Scattering observables from lattice QCD

- Wick rotation [Euclidean spacetime]: $t_M \to -it_E$
- Monte Carlo sampling
- quark masses: $m_q \to m_q^{\text{phys.}}$
- lattice spacing
- finite volume

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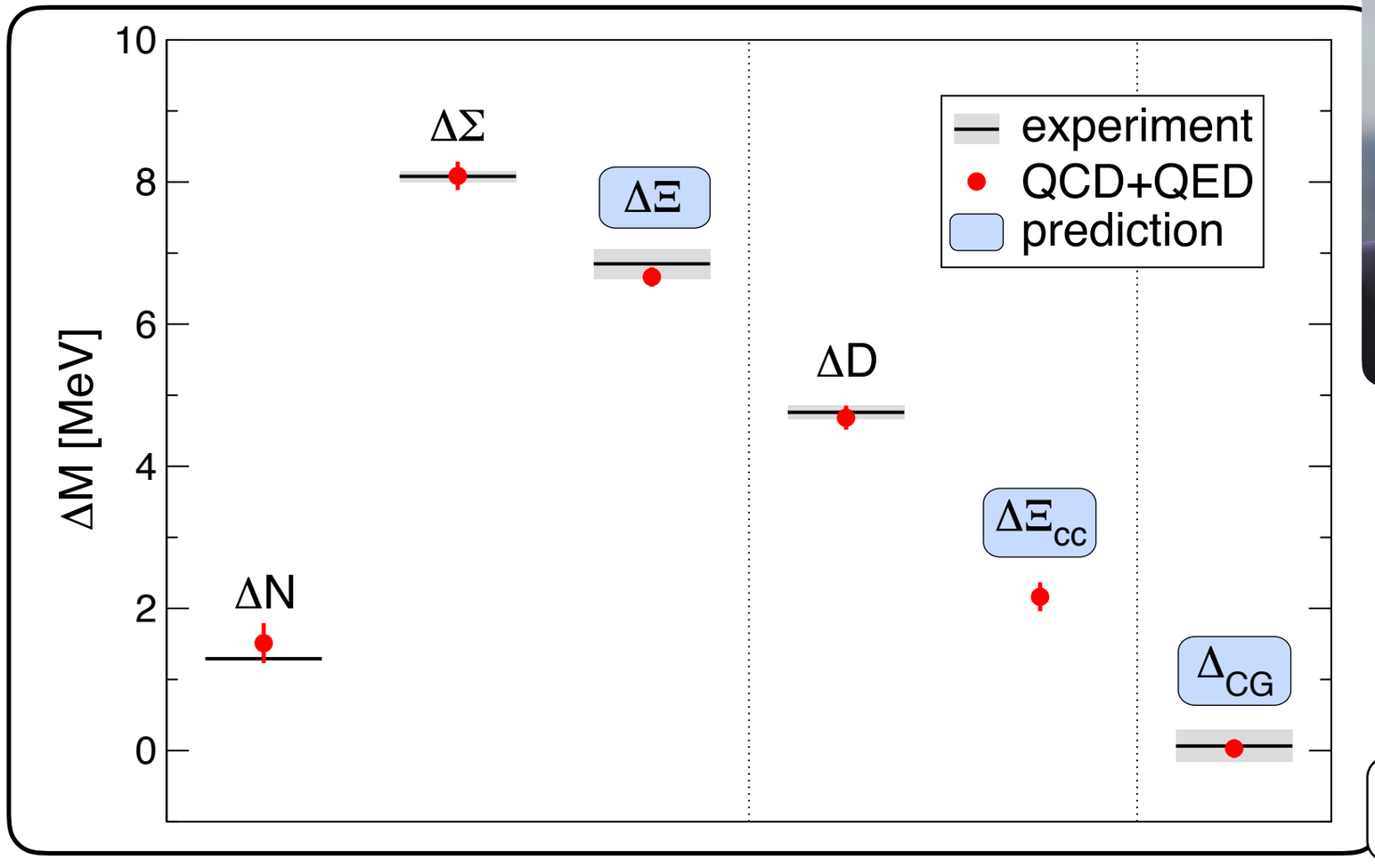

satisfies the Volker Standard

BMW Collaboration (2015)

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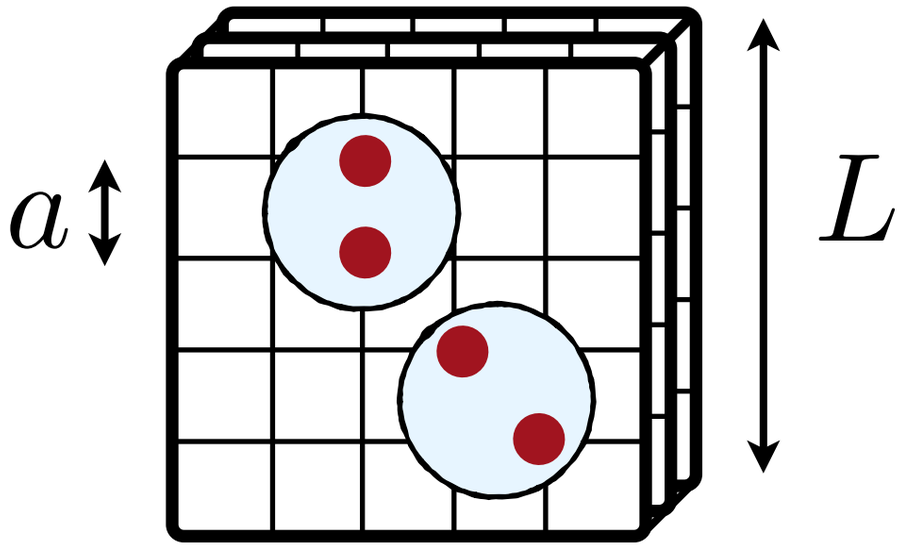

$$D_\mu = \Big(\qquad \Big) \Big\updownarrow (L/a)^3 \times (T/a)$$

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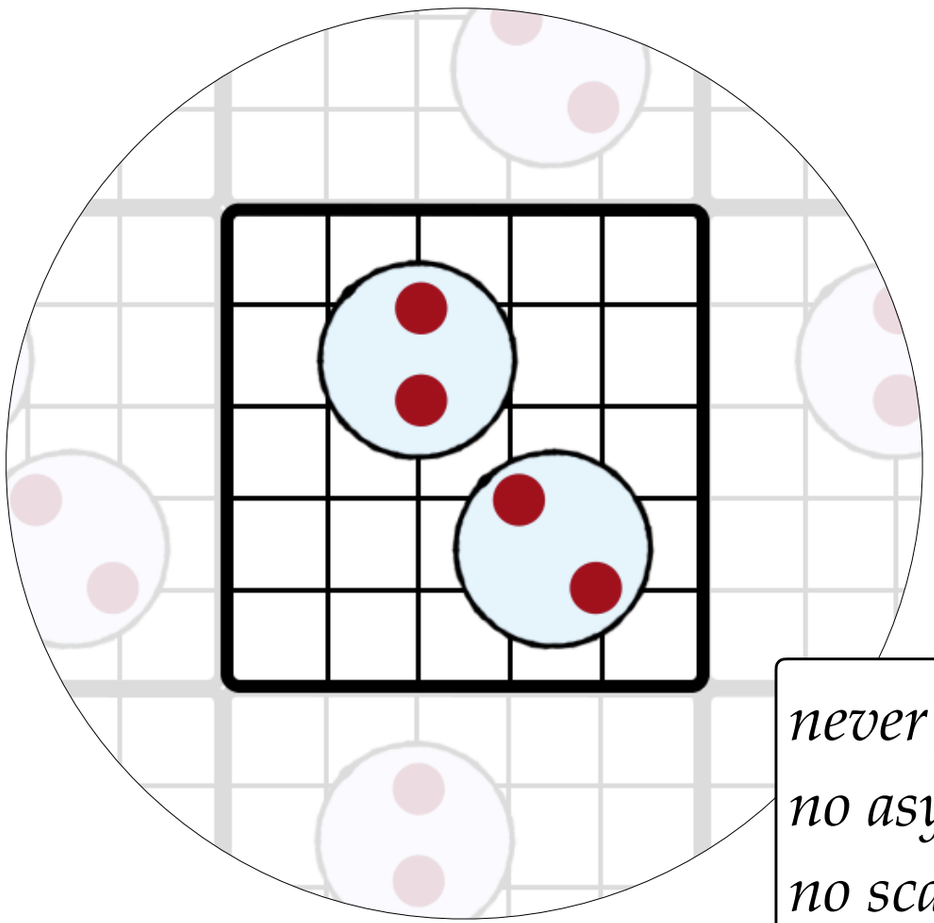
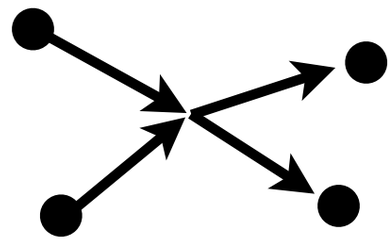


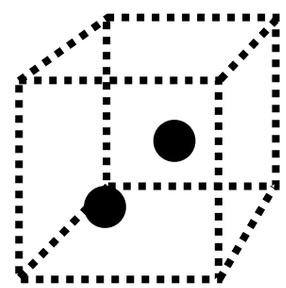
never free
no asymptotic staes
no scattering

partial wave amplitudes

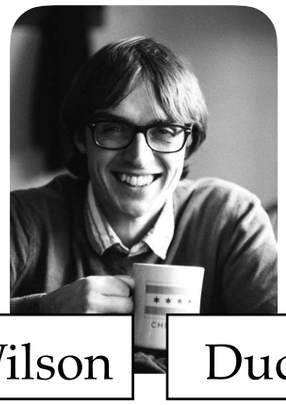


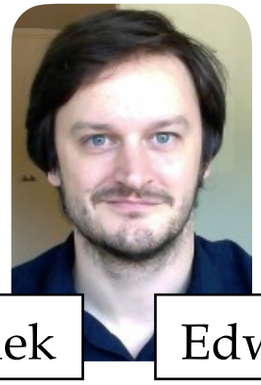
all-orders mapping

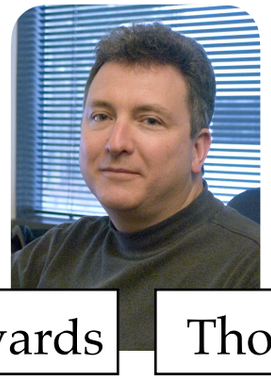
spectrum



the light sector


Wilson


Dudek


Edwards


Thomas


Woss

had spec

PRL 118, 022002 (2017) PHYSICAL REVIEW LETTERS week ending 13 JANUARY 2017

Isoscalar $\pi\pi$ Scattering and the σ Meson Resonance from QCD

Raul A. Briceño,[1,*] Jozef J. Dudek,[1,2,†] Robert G. Edwards,[1,‡] and David J. Wilson[3,§]

JLAB-THY-17-2534

Isoscalar $\pi\pi, K\overline{K}, \eta\eta$ scattering and the σ, f_0, f_2 mesons from QCD

Raul A. Briceño,[1,2,*] Jozef J. Dudek,[1,3,†] Robert G. Edwards,[1,‡] and David J. Wilson[4,§]
(for the Hadron Spectrum Collaboration)

PHYSICAL REVIEW LETTERS 123, 042002 (2019)

Quark-Mass Dependence of Elastic πK Scattering from QCD

David J. Wilson,[1,*] Raúl A. Briceño,[2,3,†] Jozef J. Dudek,[2,4,‡] Robert G. Edwards,[2,§] and Christopher E. Thomas[5,‖]

PHYSICAL REVIEW D 100, 054506 (2019)

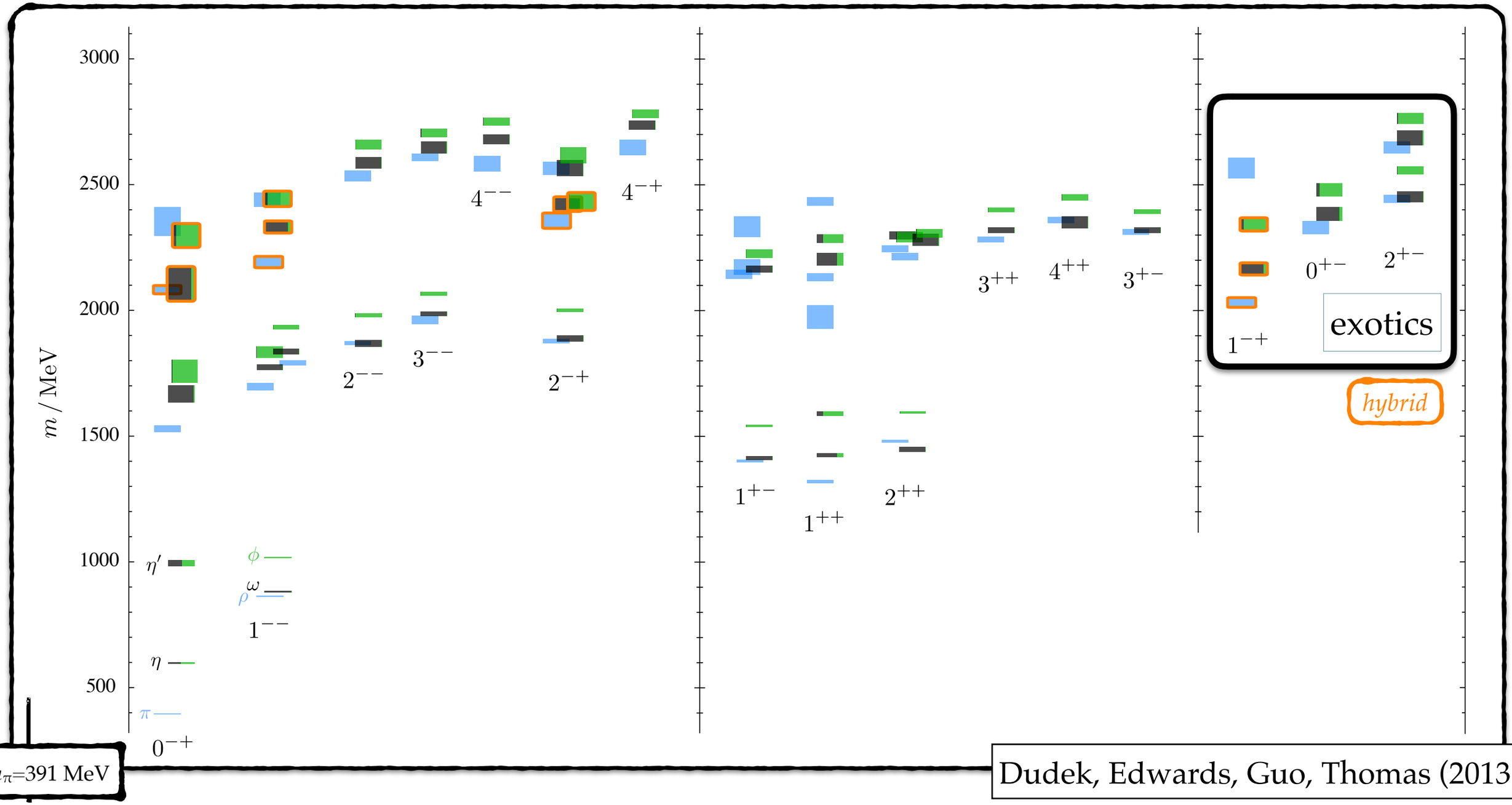
b_1 resonance in coupled $\pi\omega$, $\pi\phi$ scattering from lattice QCD

Antoni J. Woss,[1,*] Christopher E. Thomas,[1,†] Jozef J. Dudek,[2,3,‡] Robert G. Edwards,[2,‡] and David J. Wilson[4,‖]

Interesting but "old-school spectroscopy"

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

…using distillation and a large number [10-30] of local ops, $\mathcal{O}_b \sim \bar{q}\,\Gamma_b\,q$



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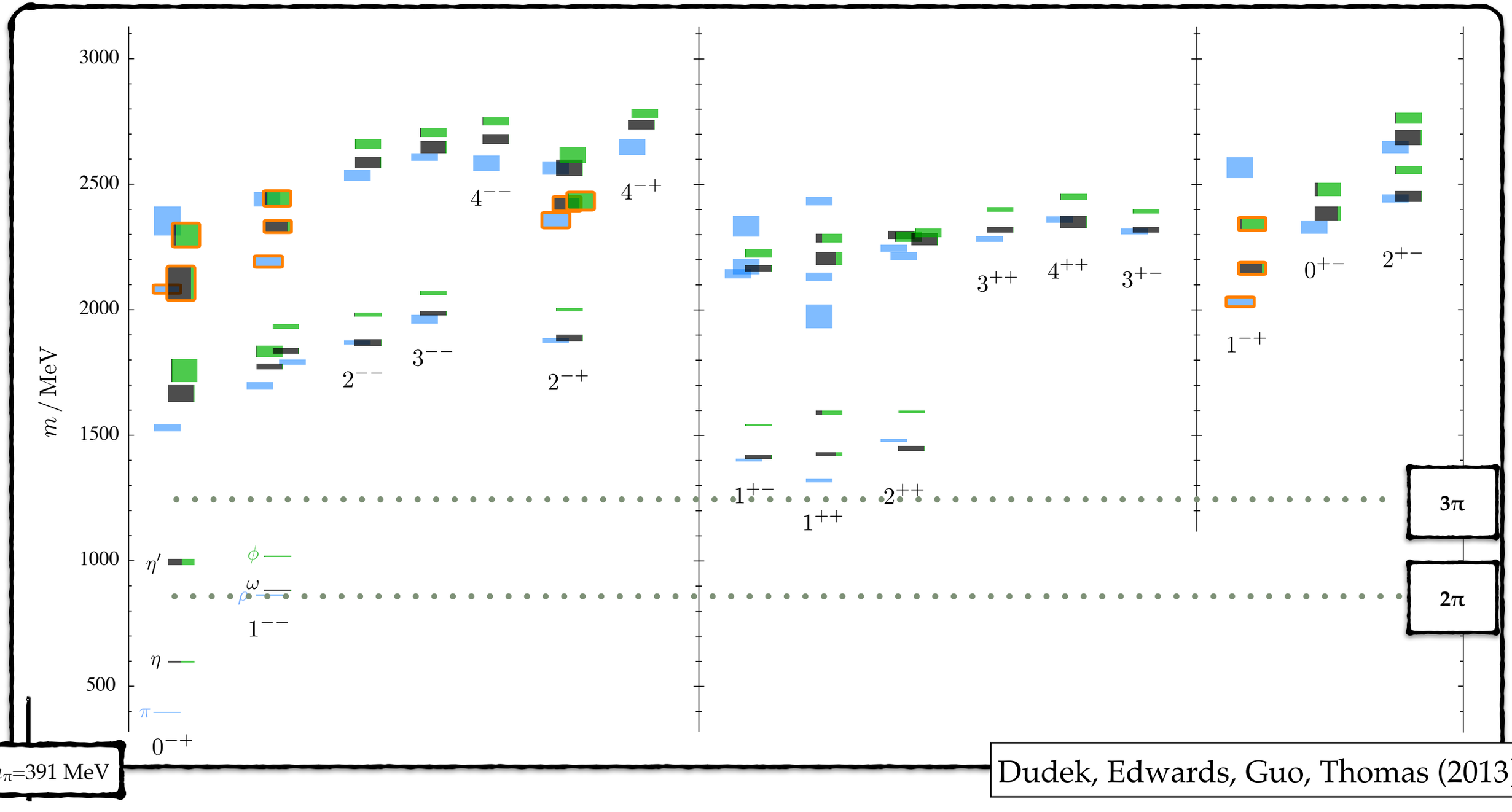
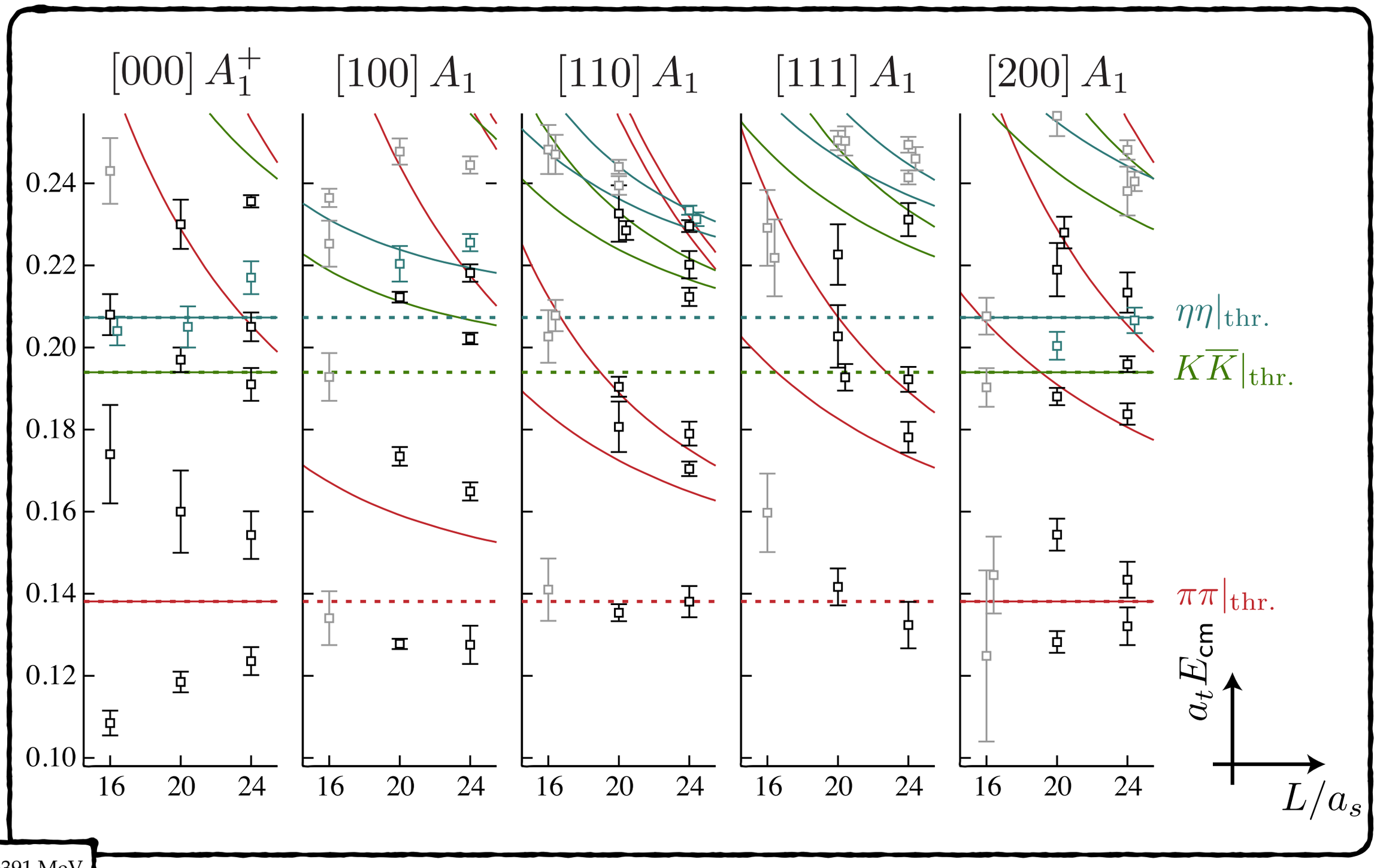


Dudek, Edwards, Guo, Thomas (2013)

Isoscalar spectra: S-wave dominant

- Spectrum including a large basis: $\{\pi\pi, K\overline{K}, \eta\eta, \ell\bar{\ell}, s\bar{s}\}$



m_π=391 MeV

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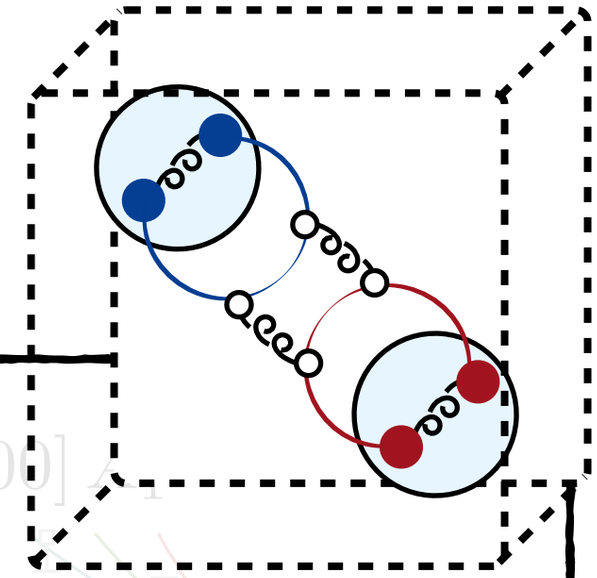
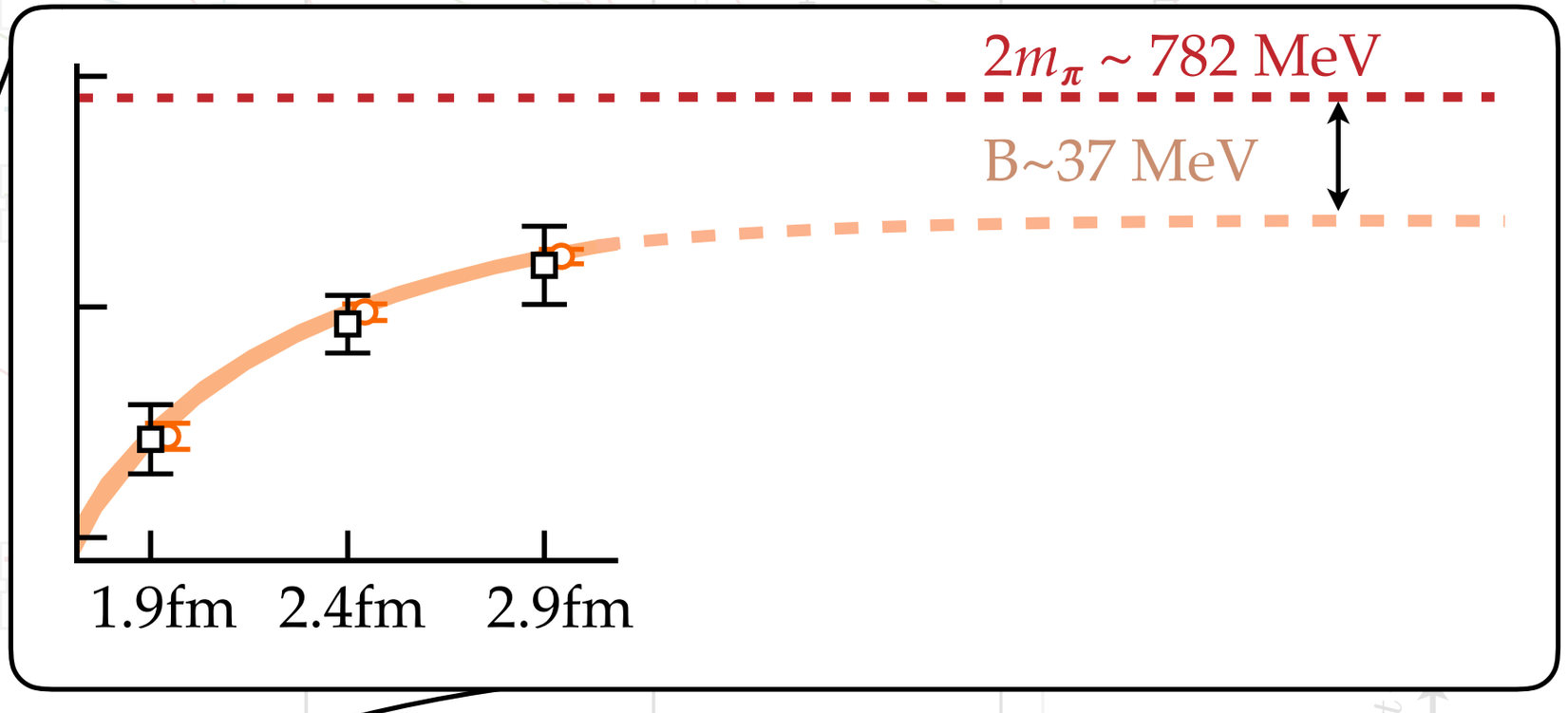
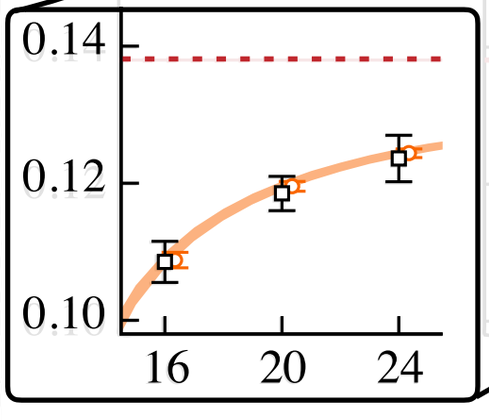


$2-3fm$





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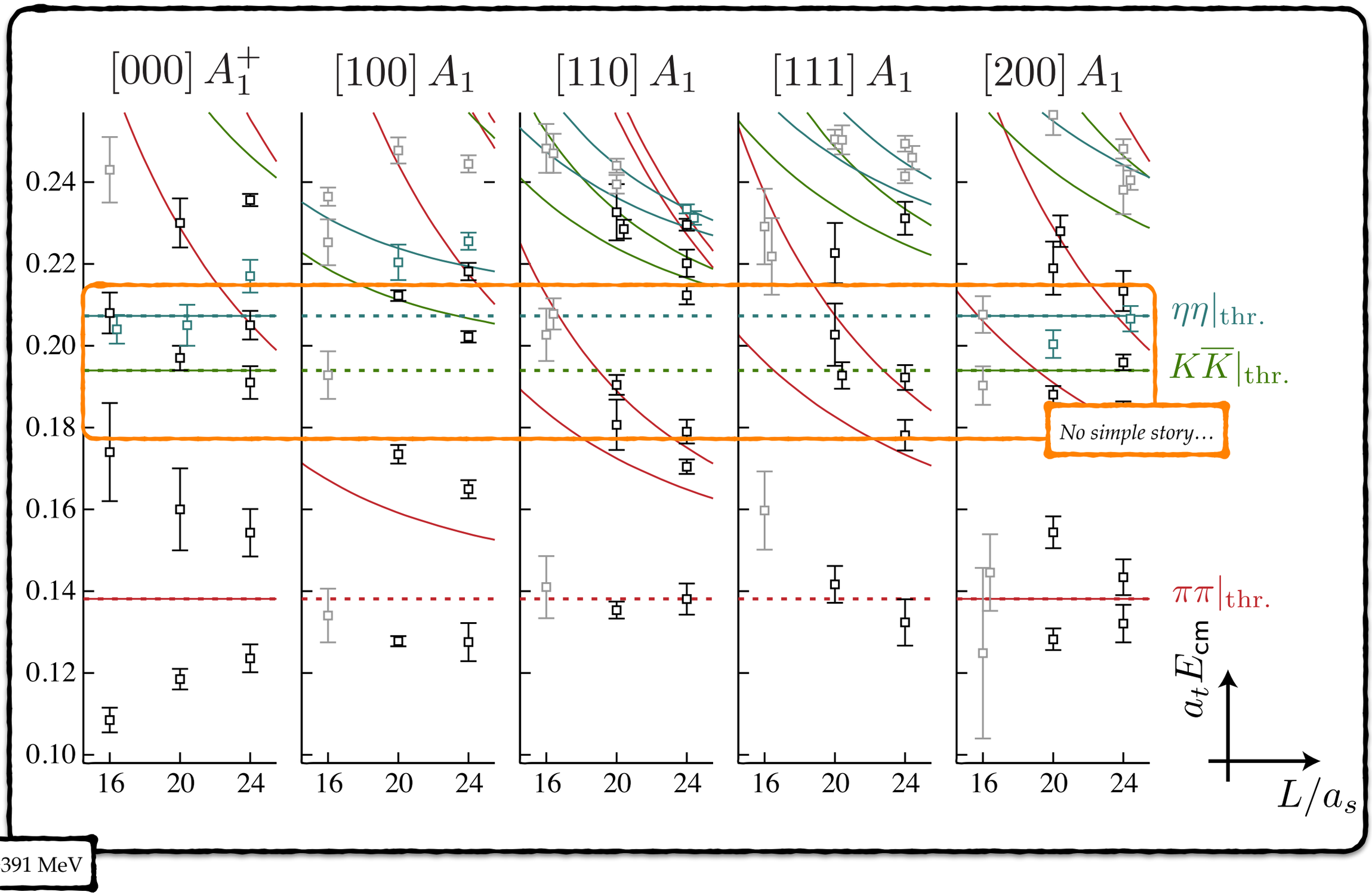

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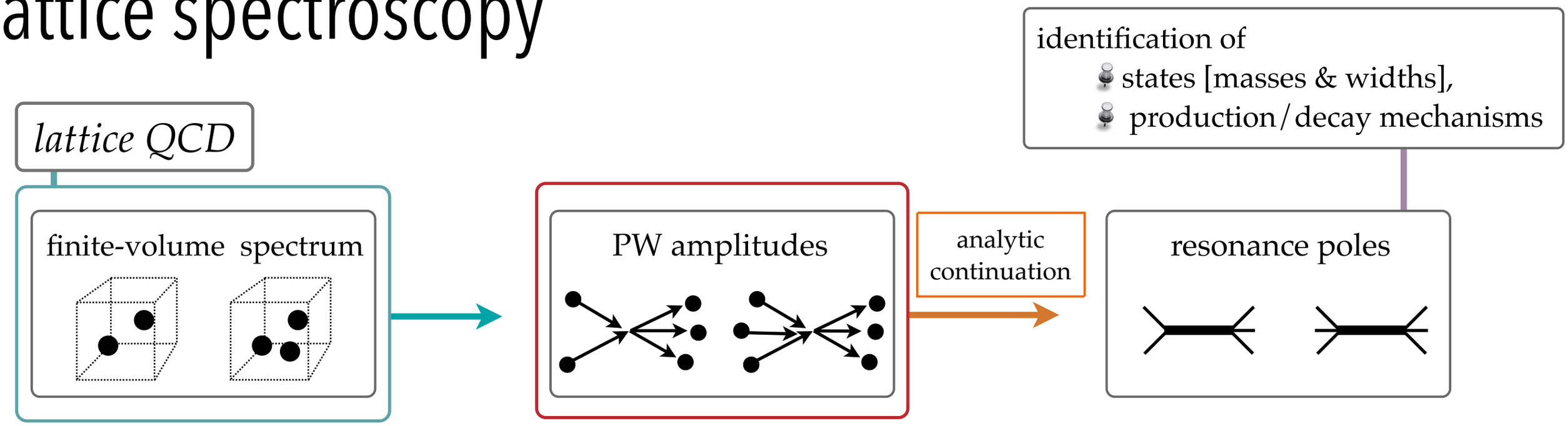
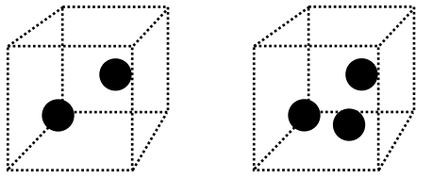
lattice spectroscopy



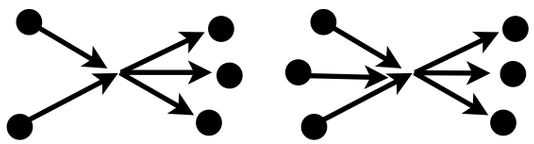
lattice spectroscopy

lattice QCD

finite-volume spectrum



PW amplitudes



analytic continuation

identification of
- states [masses & widths],
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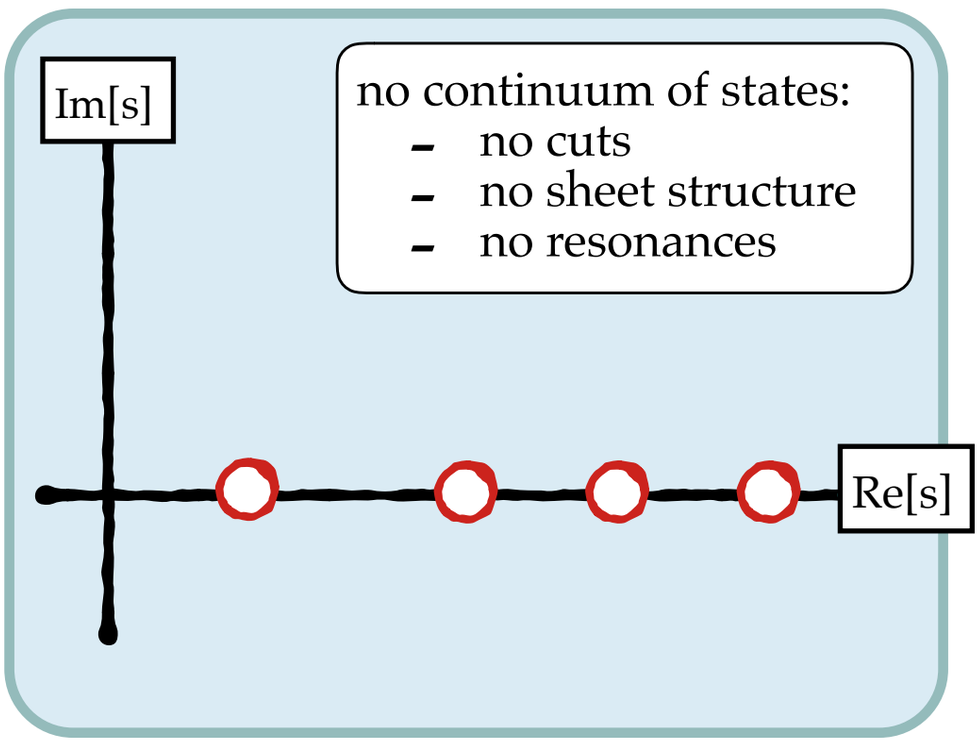
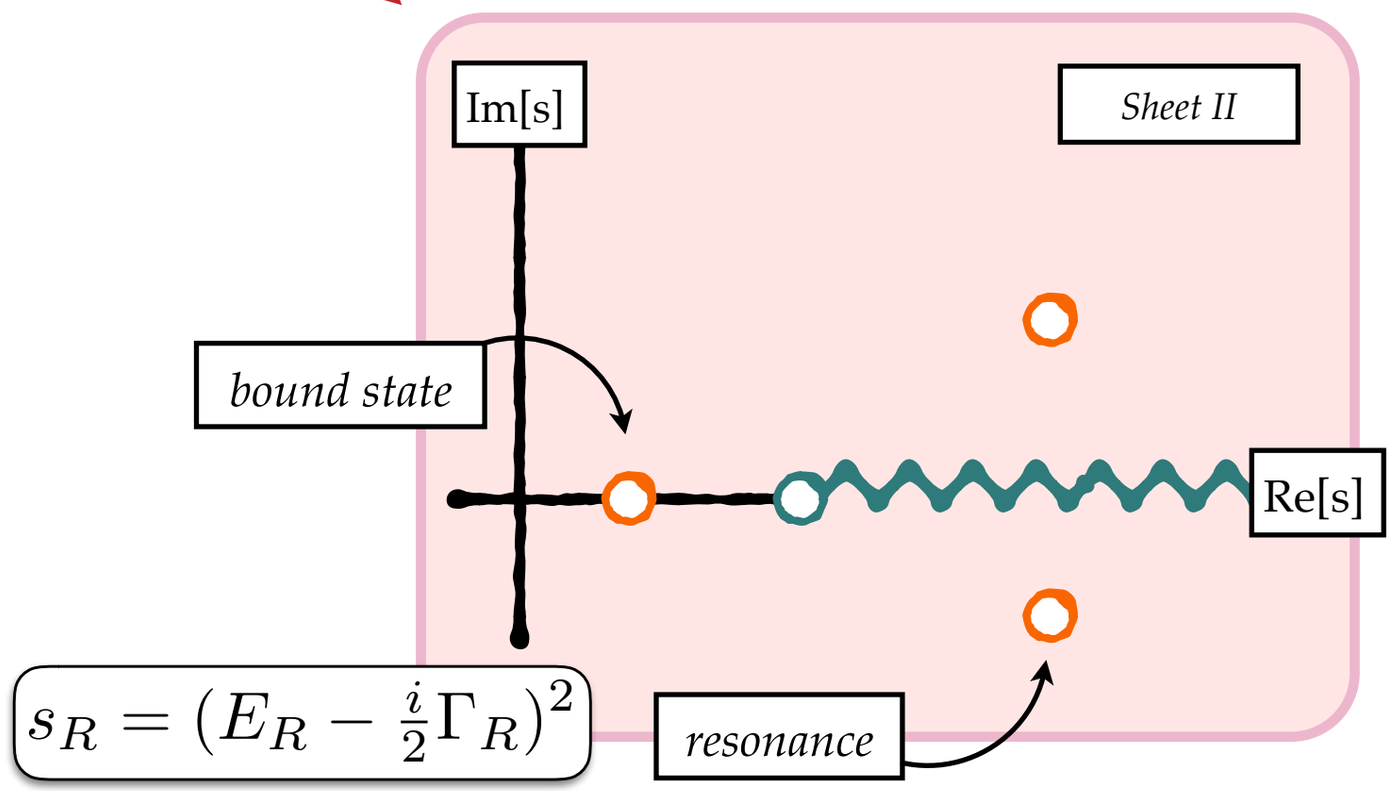
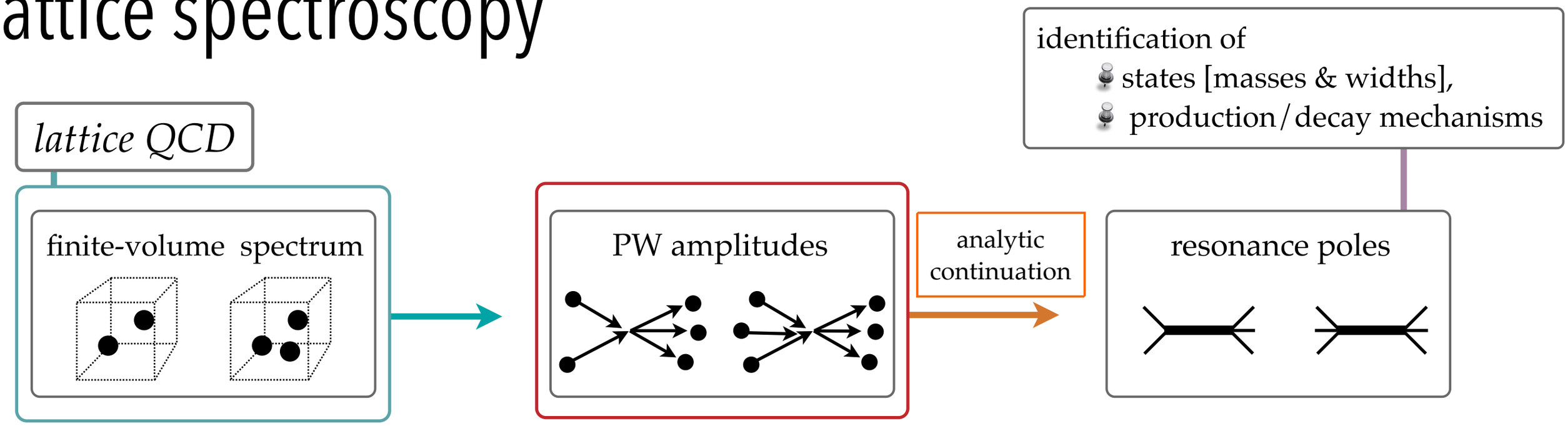
resonance poles





$$s_R = (E_R - \tfrac{i}{2}\Gamma_R)^2$$

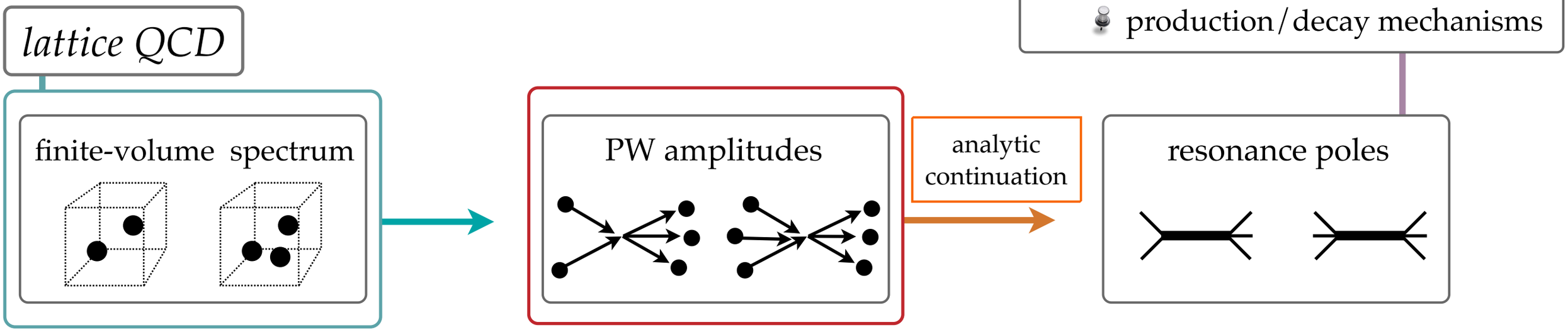
lattice spectroscopy



two-particle
spectrum satisfies: $\det[F^{-1}(P,L) + \mathcal{M}(P)] = 0$

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

lattice spectroscopy



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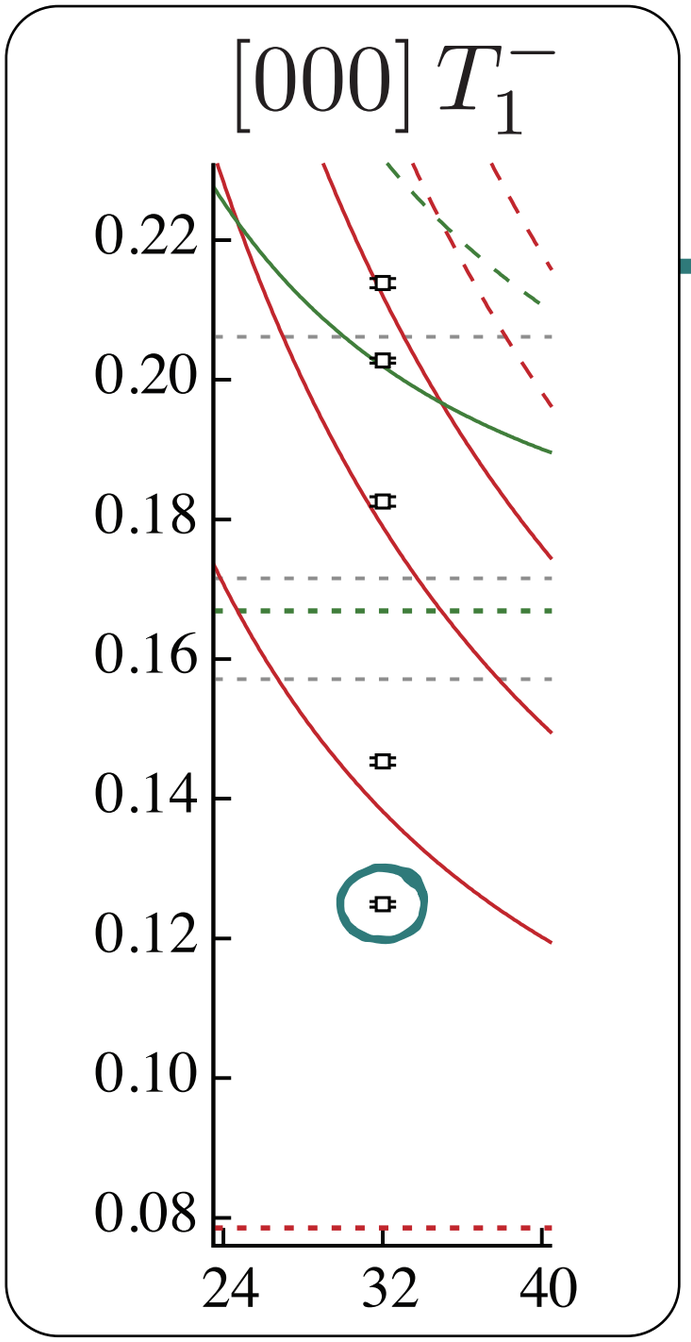
single channel: "easy"

$\pi\pi$ Spectrum - (I=1 channel)



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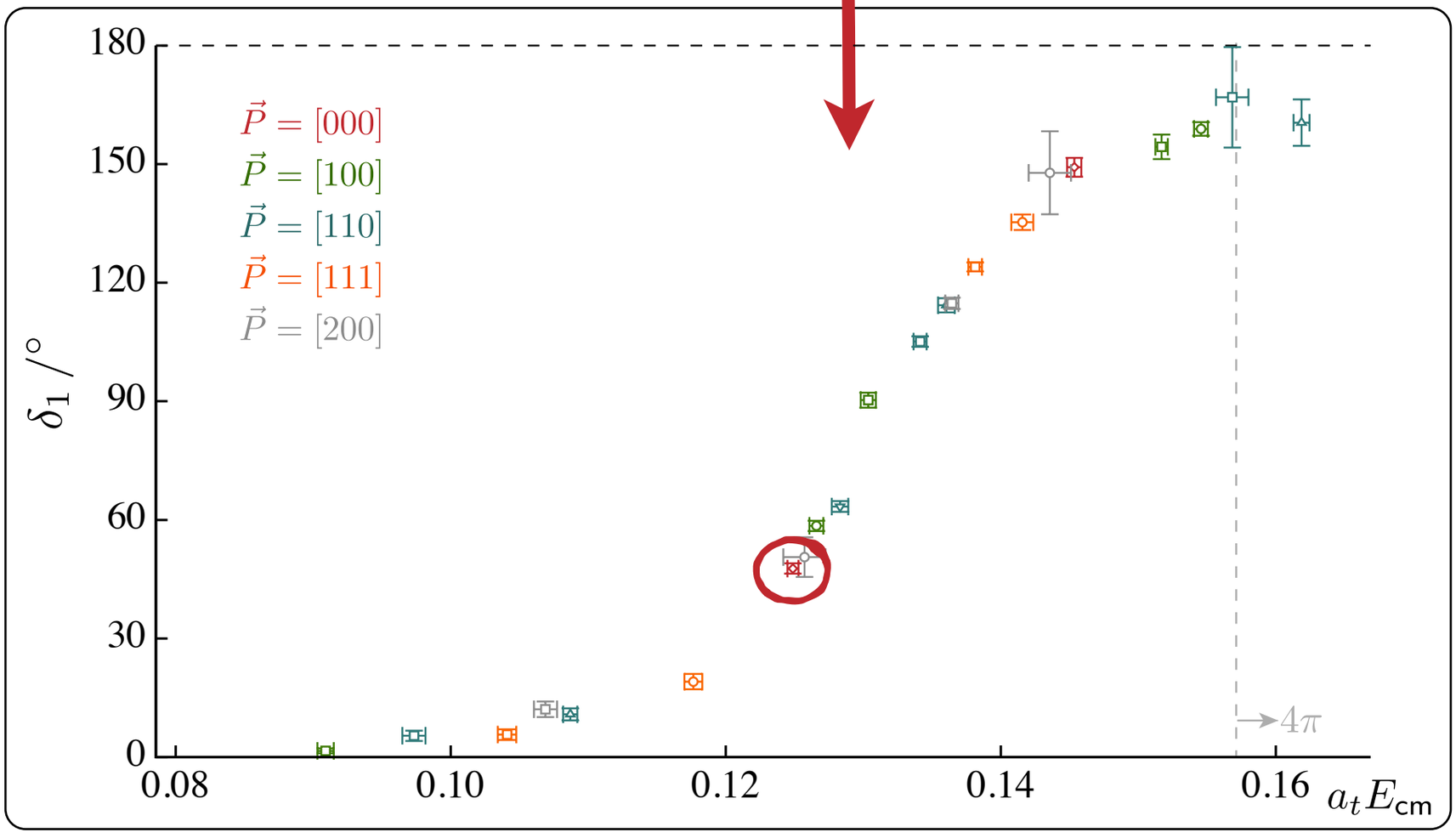
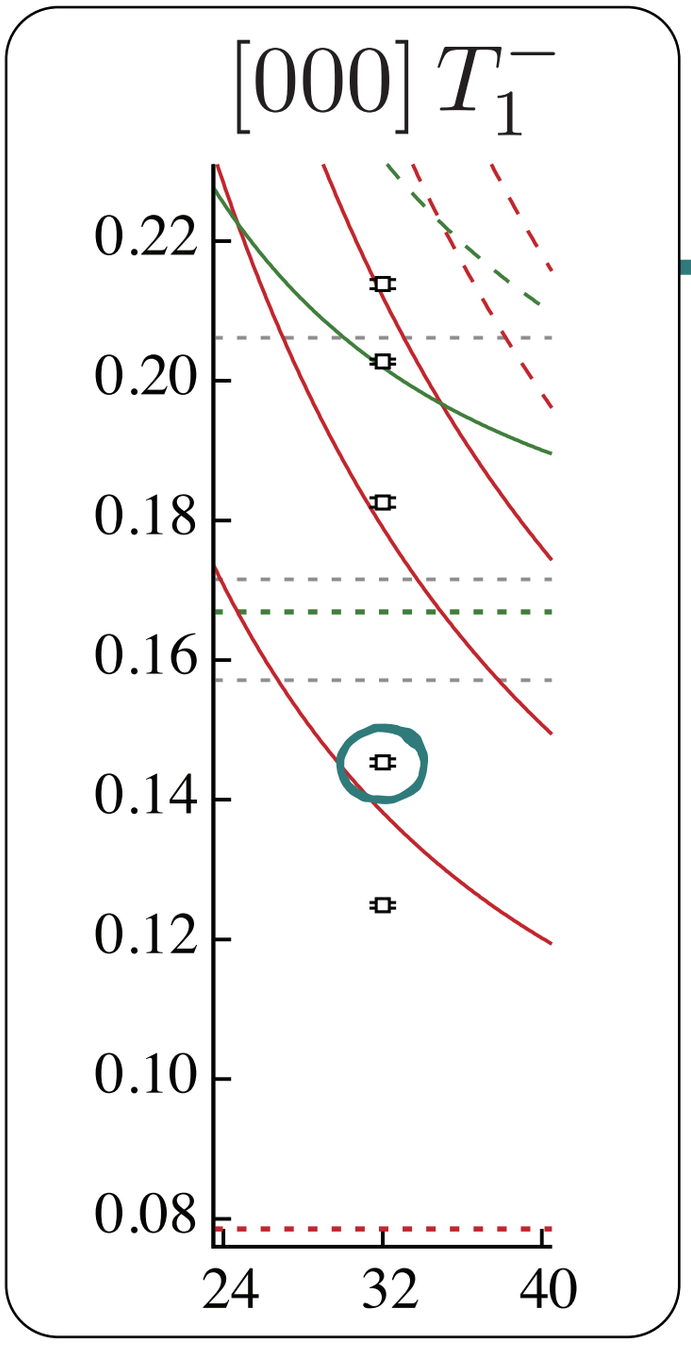


$$\mathcal{M} \propto \frac{1}{\cot\delta_1 - i}$$

$m_\pi \sim 240$ MeV

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

$\pi\pi$ Spectrum - (I=1 channel)



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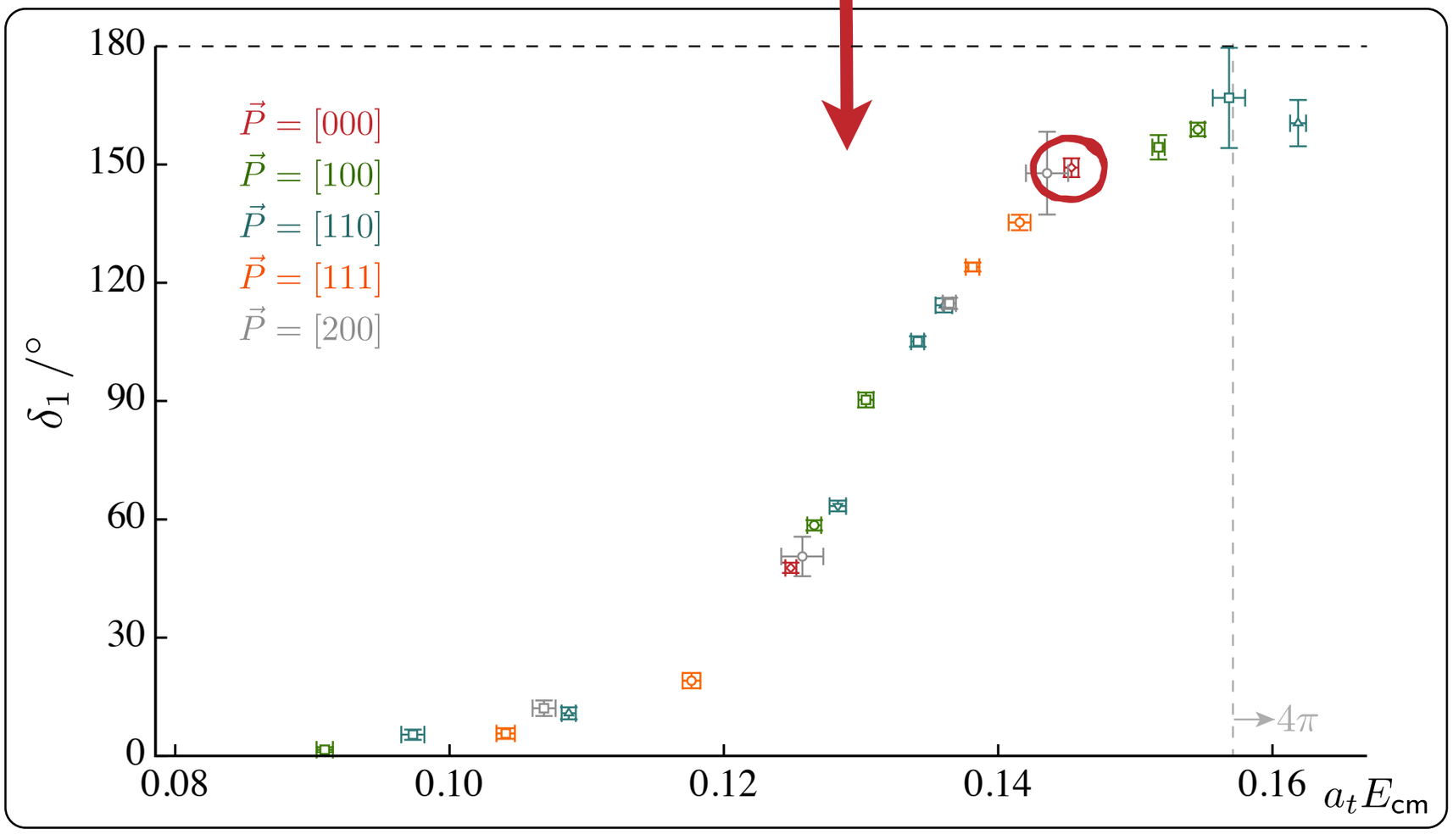

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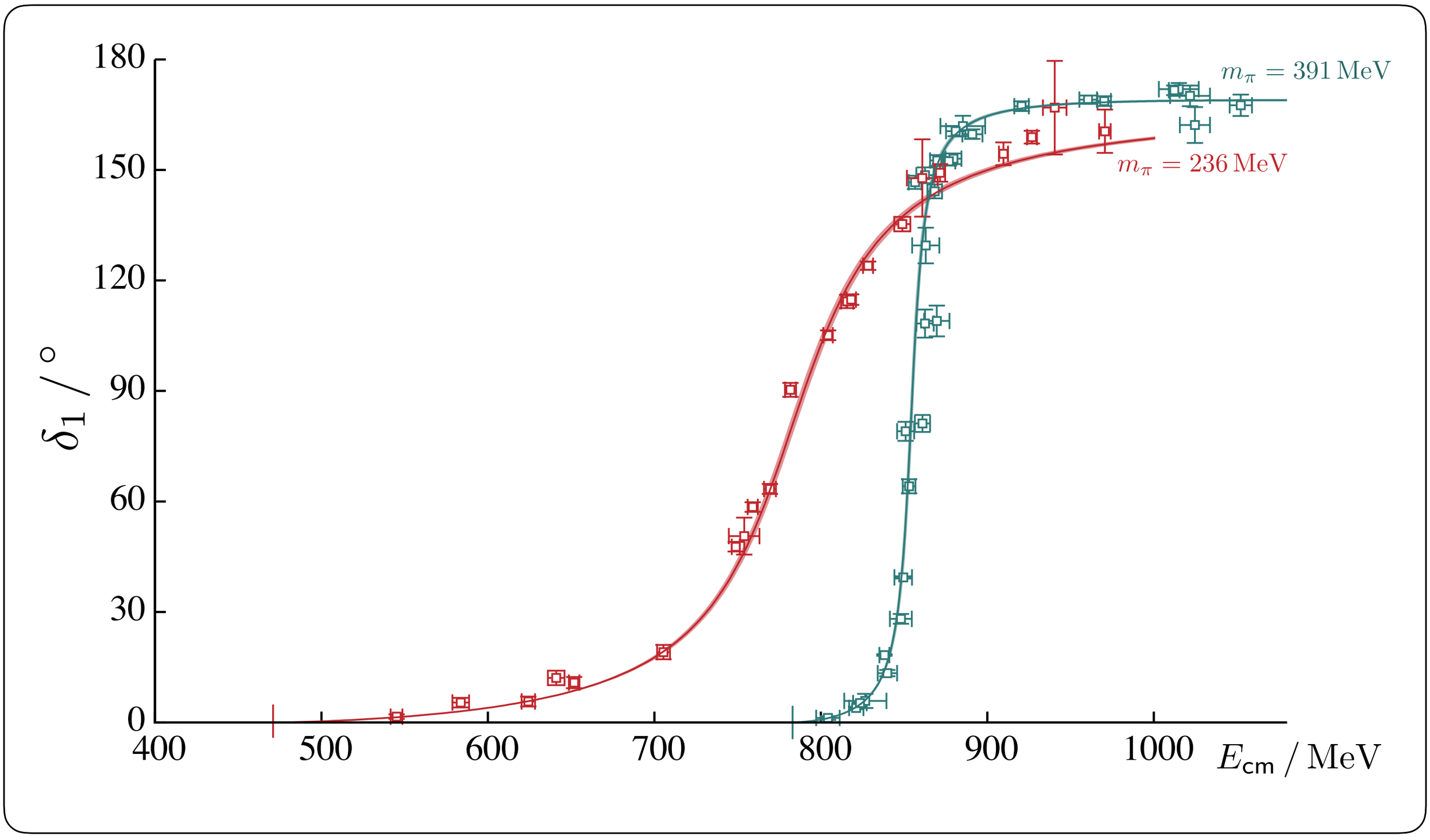
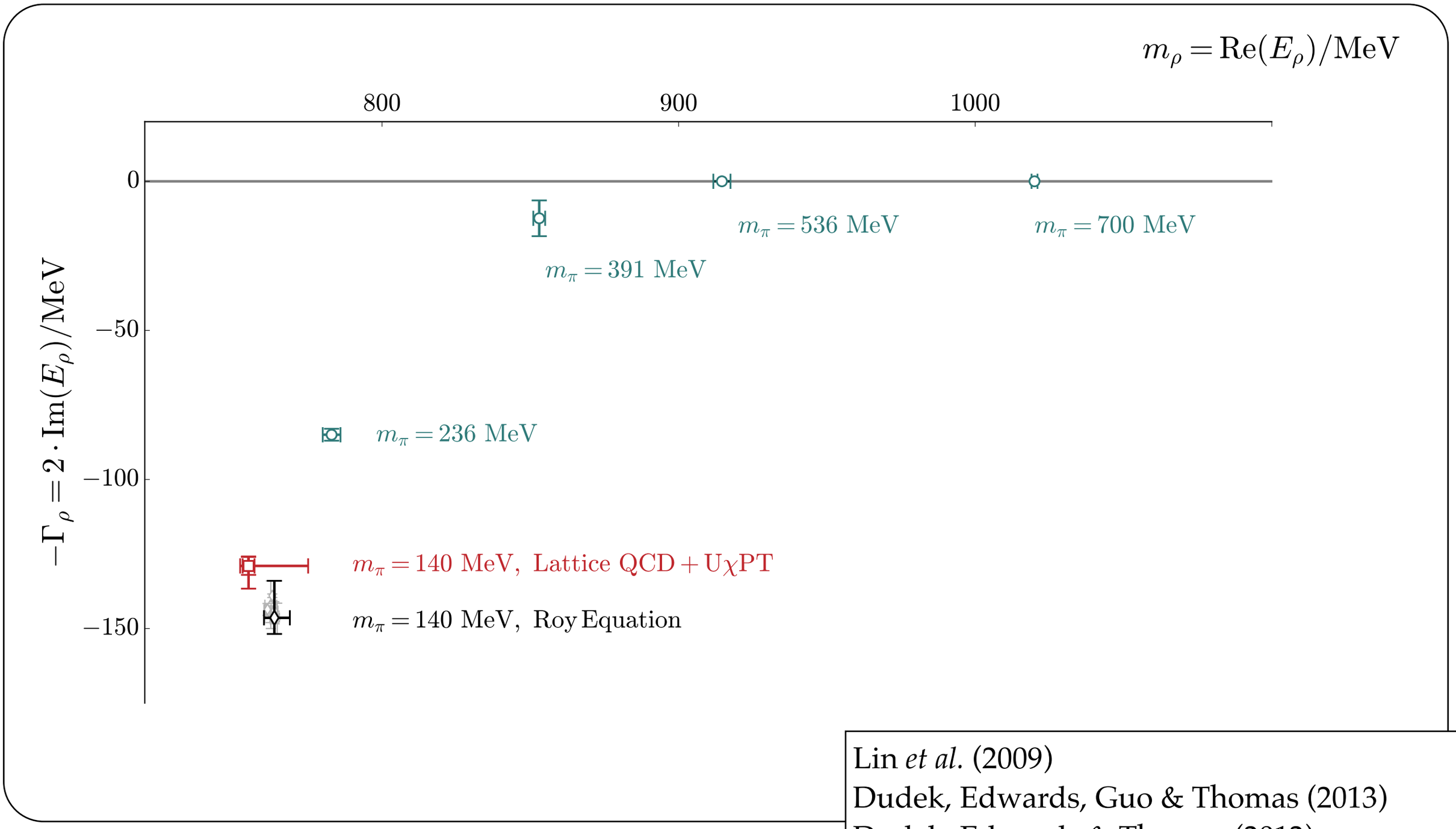
$\pi\pi$ scattering - (I=1 channel)



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

The ρ *vs* m_π



Lin *et al.* (2009)
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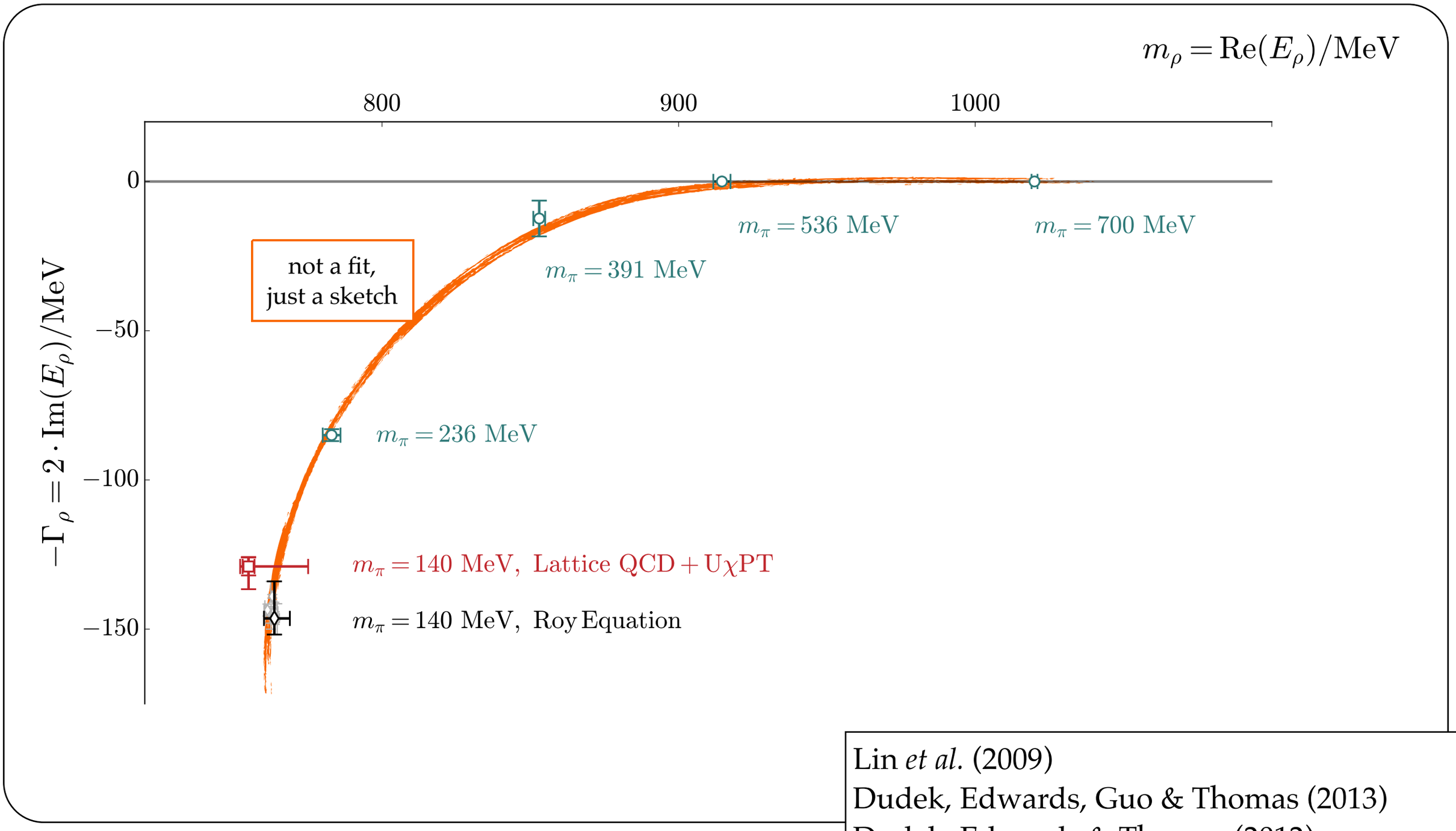

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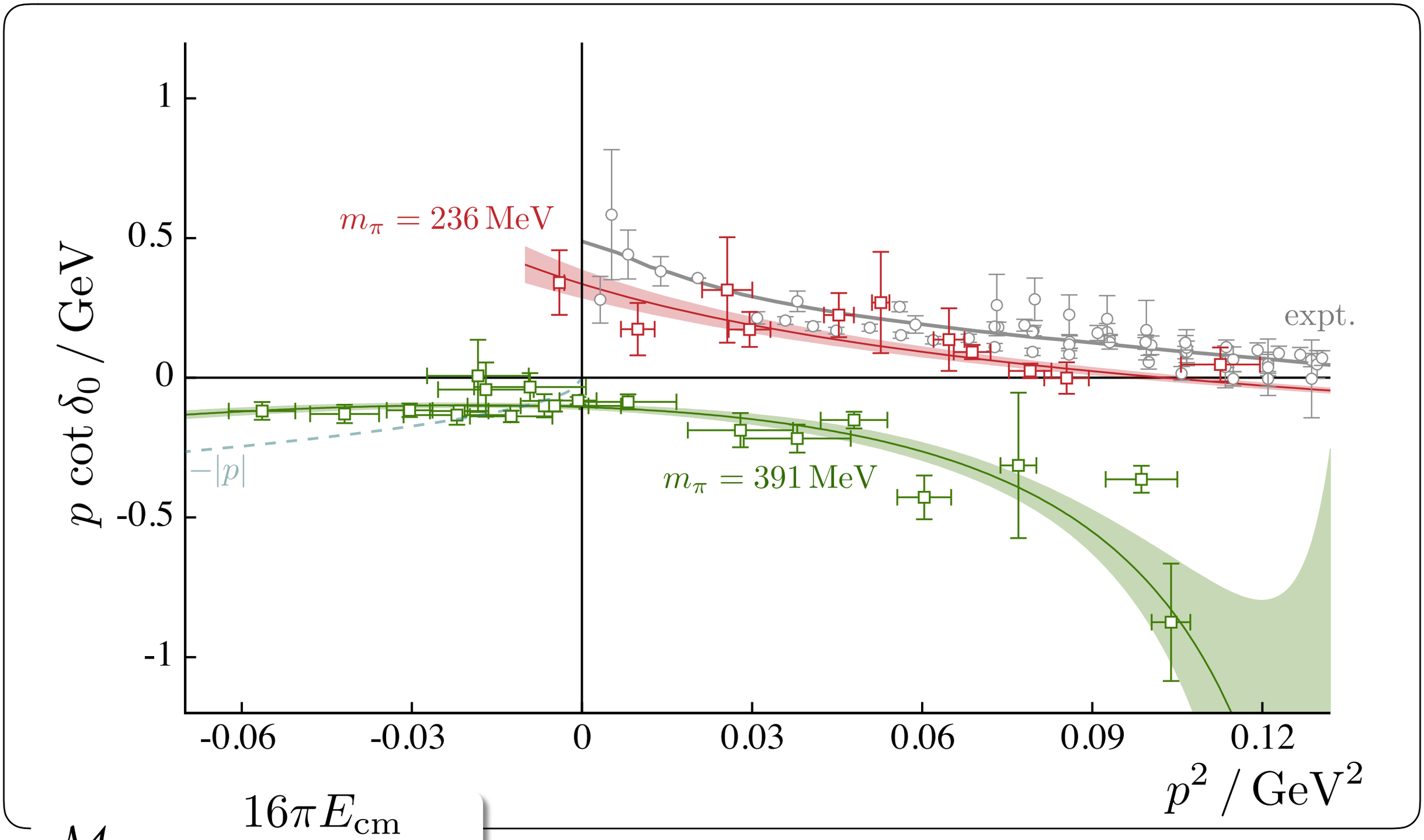
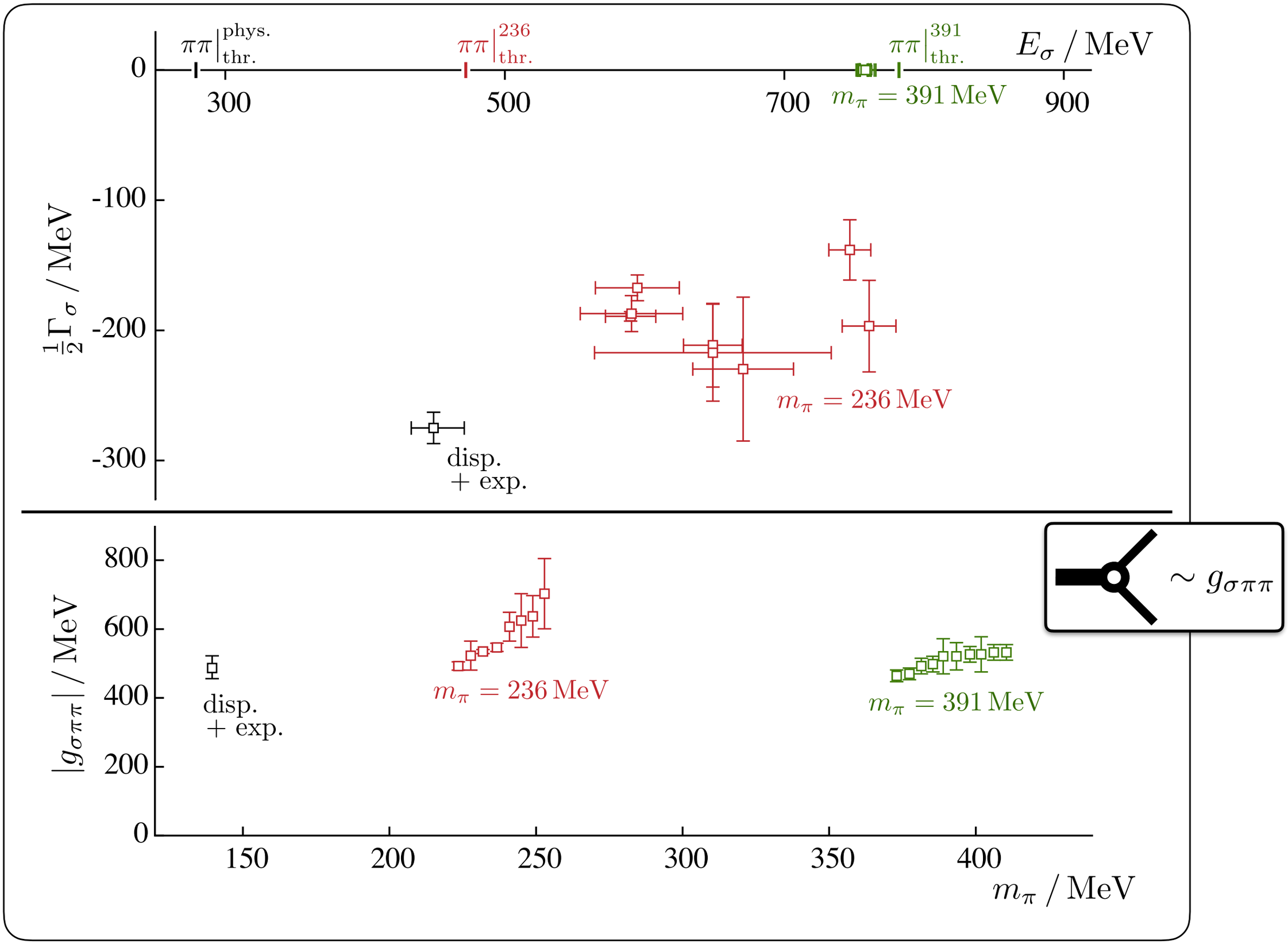
$\pi\pi$ scattering - (I=0 channel)



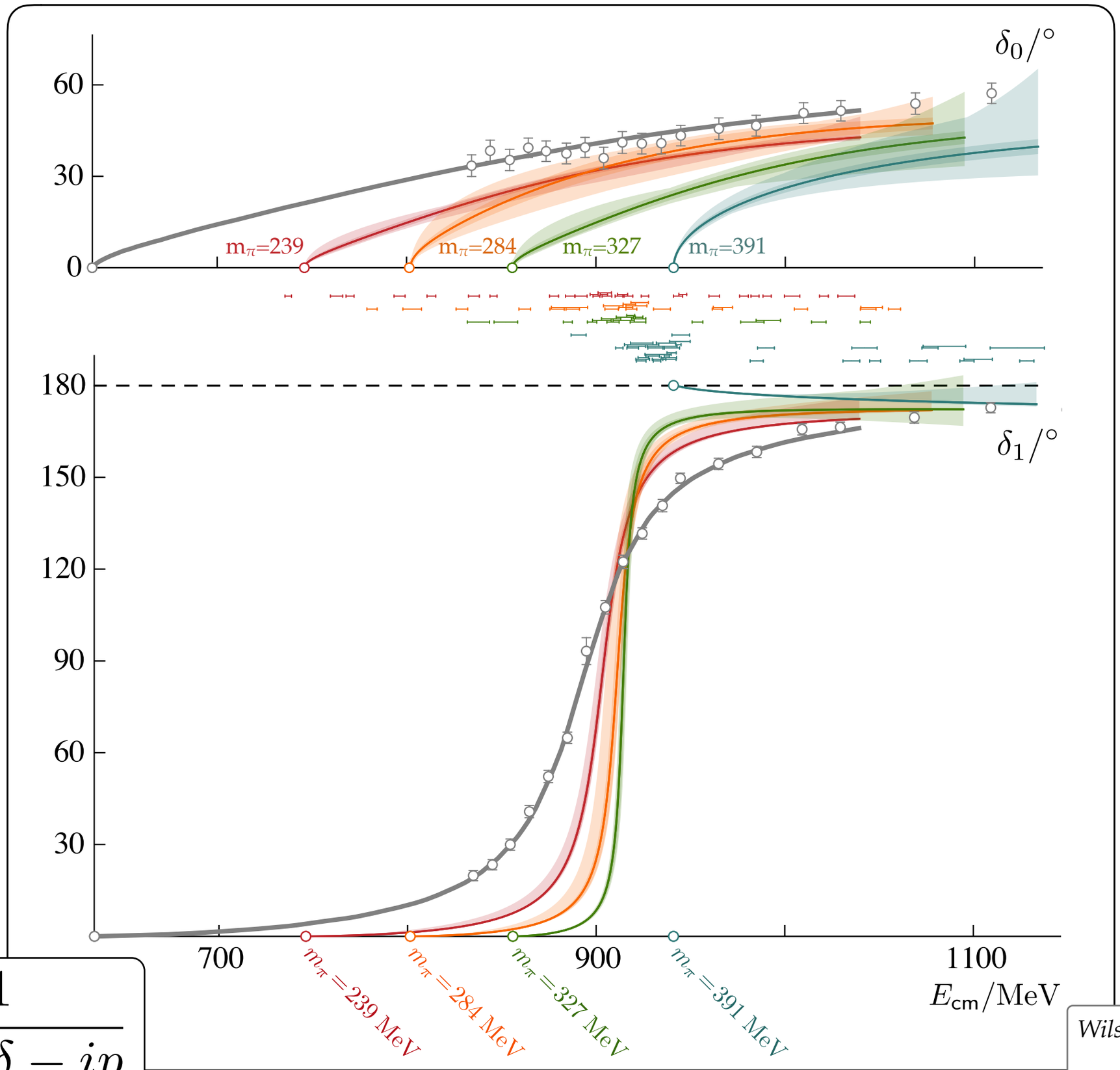
$$\mathcal{M}_0 = \frac{16\pi E_{\mathrm{cm}}}{p\cot\delta_0 - ip}$$

RB, Dudek, Edwards, Wilson - PRL (2017)

The σ *vs* m_π


$\pi\pi|^{\text{phys.}}_{\text{thr.}}$
$\pi\pi|^{236}_{\text{thr.}}$
$\pi\pi|^{391}_{\text{thr.}}$
E_σ / MeV
0
300
500
700
900
$m_\pi = 391$ MeV
-100
-200
-300
$\frac{1}{2}\Gamma_\sigma$ / MeV
$m_\pi = 236$ MeV
disp.
+ exp.
$\sim g_{\sigma\pi\pi}$
800
600
400
200
0
$|g_{\sigma\pi\pi}|$ / MeV
disp.
+ exp.
$m_\pi = 236$ MeV
$m_\pi = 391$ MeV
150
200
250
300
350
400
m_π / MeV

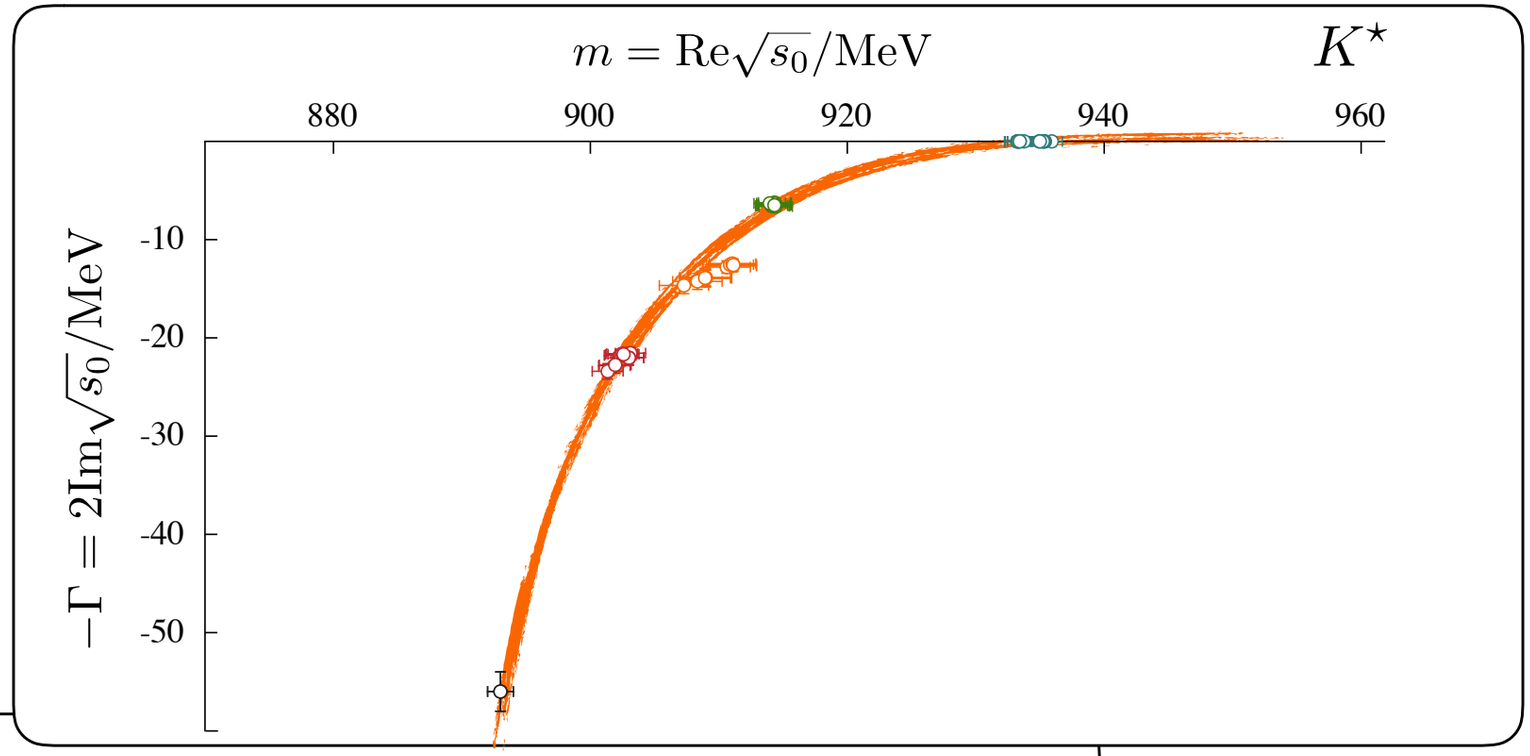
πK scattering - (I=1/2 channel)

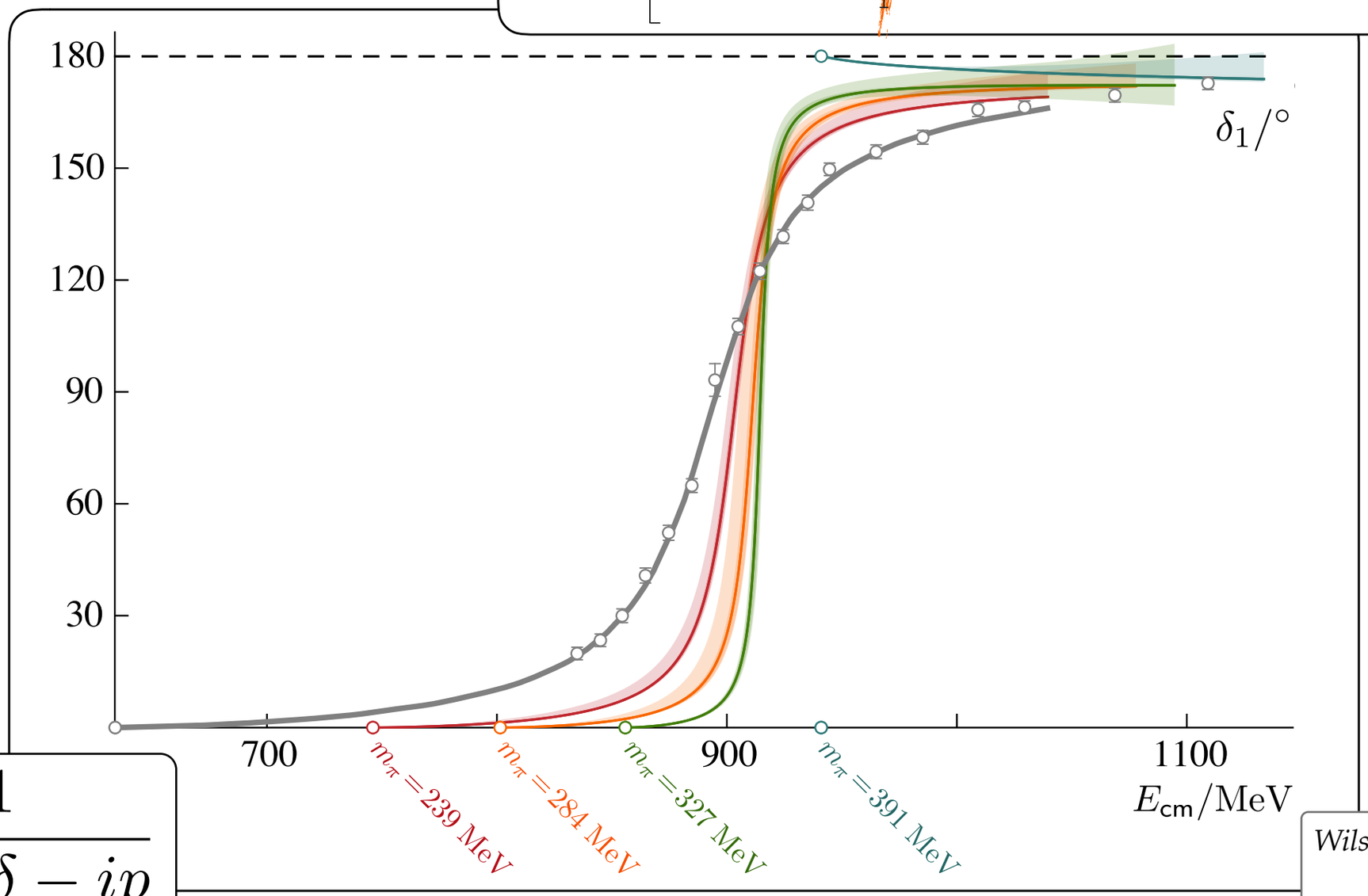


$$\mathcal{M} \sim \frac{1}{p\cot\delta - ip}$$

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

πK scattering - (I=1/2 channel)





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

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

multi-channel systems - the cutting edge!

- the *necessary* formalism for doing coupled-channel scattering of

  Feng, Li, & Liu (2004) [inelastic scalar bosons]
  Hansen & Sharpe / RB & Davoudi (2012) [moving inelastic scalar bosons]
  RB (2014) [general 2-body result]

- to date, the ***Hadron Spectrum*** **collaboration** is the only one to have extracted coupled-channel scattering amplitude information from QCD

$\pi\pi$, KK, $\eta\eta$ [isoscalar]:	RB, Dudek, Edwards, Wilson - PRL (2017)
	RB, Dudek, Edwards, Wilson - PRD (2018)
Kπ, Kη:	Dudek, Edwards, Thomas, Wilson - PRL (2015)
	Wilson, Dudek, Edwards, Thomas - PRD (2015)
$\pi\eta$, KK:	Dudek, Edwards, Wilson - PRD (2016)
Dπ, Dη, D_sK:	Moir, Peardon, Ryan, Thomas, Wilson - JHEP (2016)
$\pi\pi$, KK [isovector]:	Wilson, RB, Dudek, Edwards, Thomas - PRD (2015)

had spec

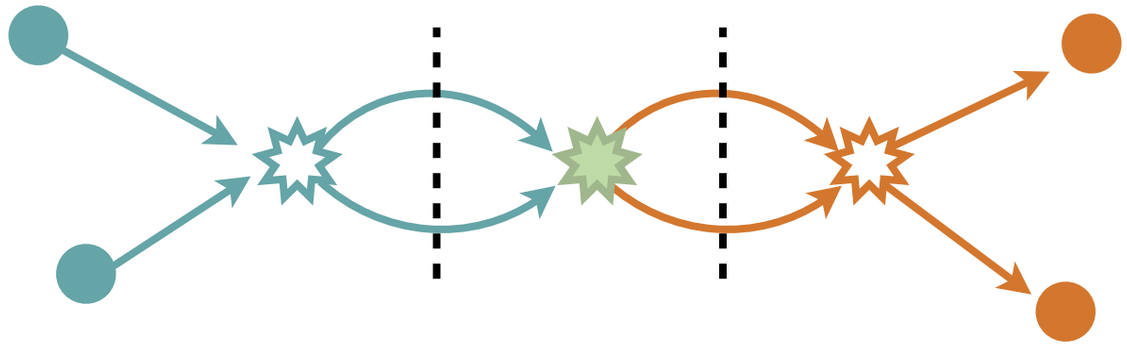
multi-channel systems - the cutting edge!

- Above $2m_K$, there is not a one-to-one correspondence

$$\det \begin{bmatrix} F_{\pi\pi}^{-1} + \mathcal{M}_{\pi\pi,\pi\pi} & \mathcal{M}_{\pi\pi,K\overline{K}} \\ \mathcal{M}_{\pi\pi,K\overline{K}} & F_{K\overline{K}}^{-1} + \mathcal{M}_{K\overline{K},K\overline{K}} \end{bmatrix} = 0$$

Feng, Li, & Liu (2004),
Hansen & Sharpe / RB & Davoudi (2012)

infinite volume:
- coupled, scattering amplitude
- branch cuts



finite volume:
- power-law finite-volume effects

multi-channel systems - the cutting edge!

- Above $2m_K$, there is not a one-to-one correspondence

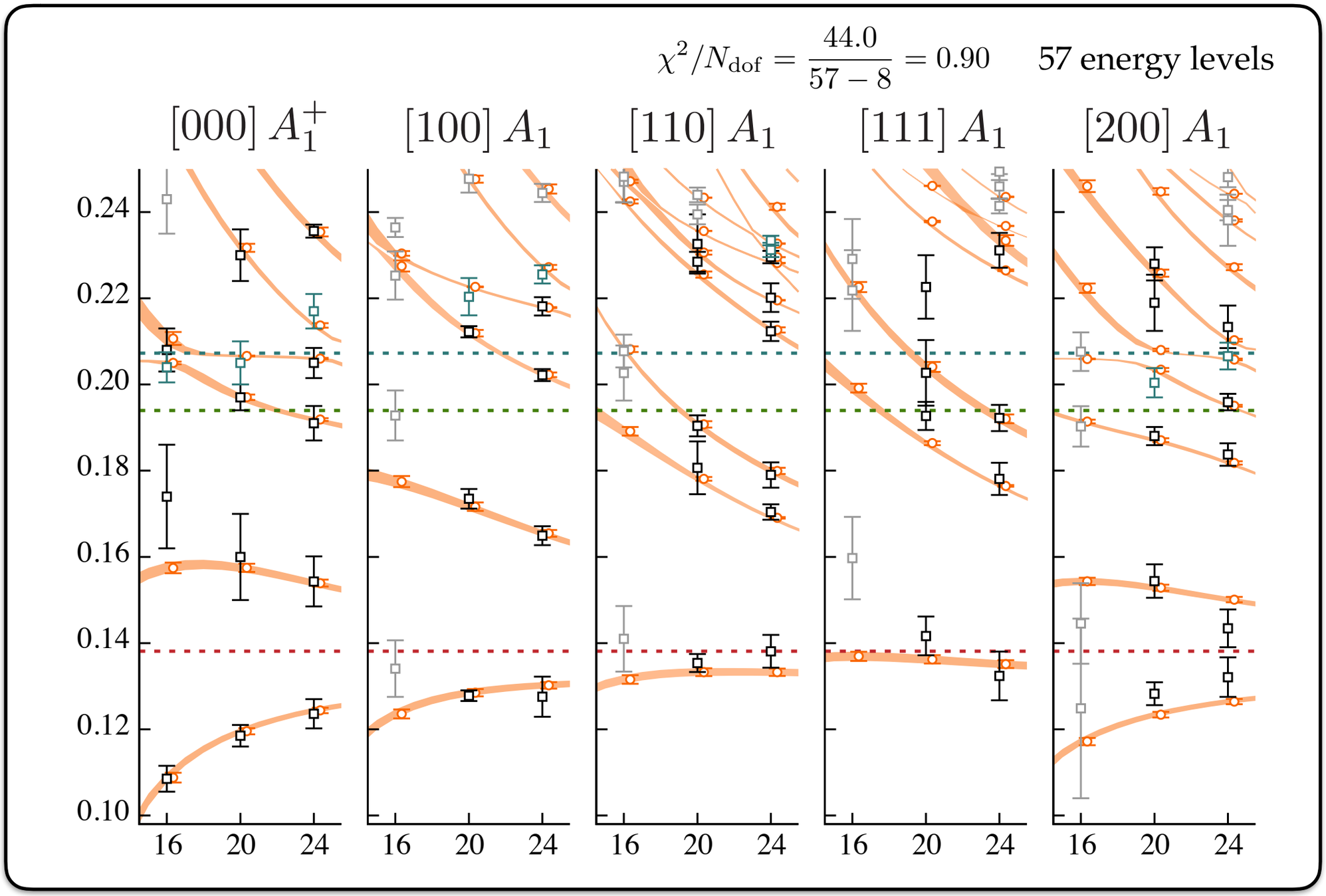
$$\det \begin{bmatrix} F^{-1}_{\pi\pi} + \mathcal{M}_{\pi\pi,\pi\pi} & \mathcal{M}_{\pi\pi,K\overline{K}} \\ \mathcal{M}_{\pi\pi,K\overline{K}} & F^{-1}_{K\overline{K}} + \mathcal{M}_{K\overline{K},K\overline{K}} \end{bmatrix} = 0$$

Feng, Li, & Liu (2004),
Hansen & Sharpe / RB & Davoudi (2012)

- In general, must constrain *(1/2) [N^2 + N]* functions of energy
- Need that many energy levels at the same energy
- Alternatively, parametrize scattering amplitude and do a global fit

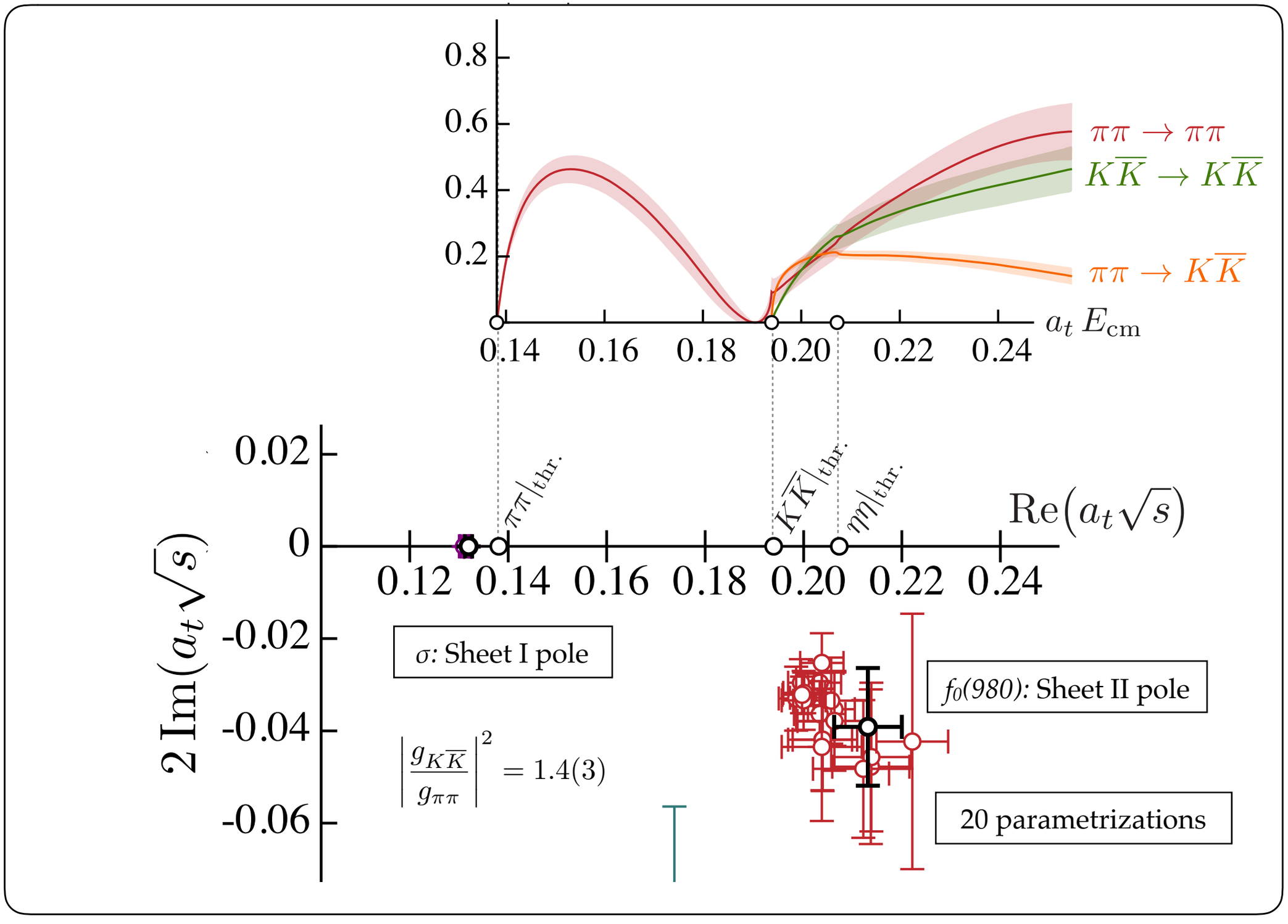
coupled-channels analysis

- S-wave above $2m_\pi$, $2m_K$, *and* $2m_\eta$
- Ansatz $\mathbf{K}^{-1}(s) = \begin{pmatrix} a+bs & c+ds & e \\ c+ds & f & g \\ e & g & h \end{pmatrix}$



scalar $\pi\pi$-$K\overline{K}$

- Near poles: $\mathcal{M} \sim \dfrac{g^2}{s_0 - s}$



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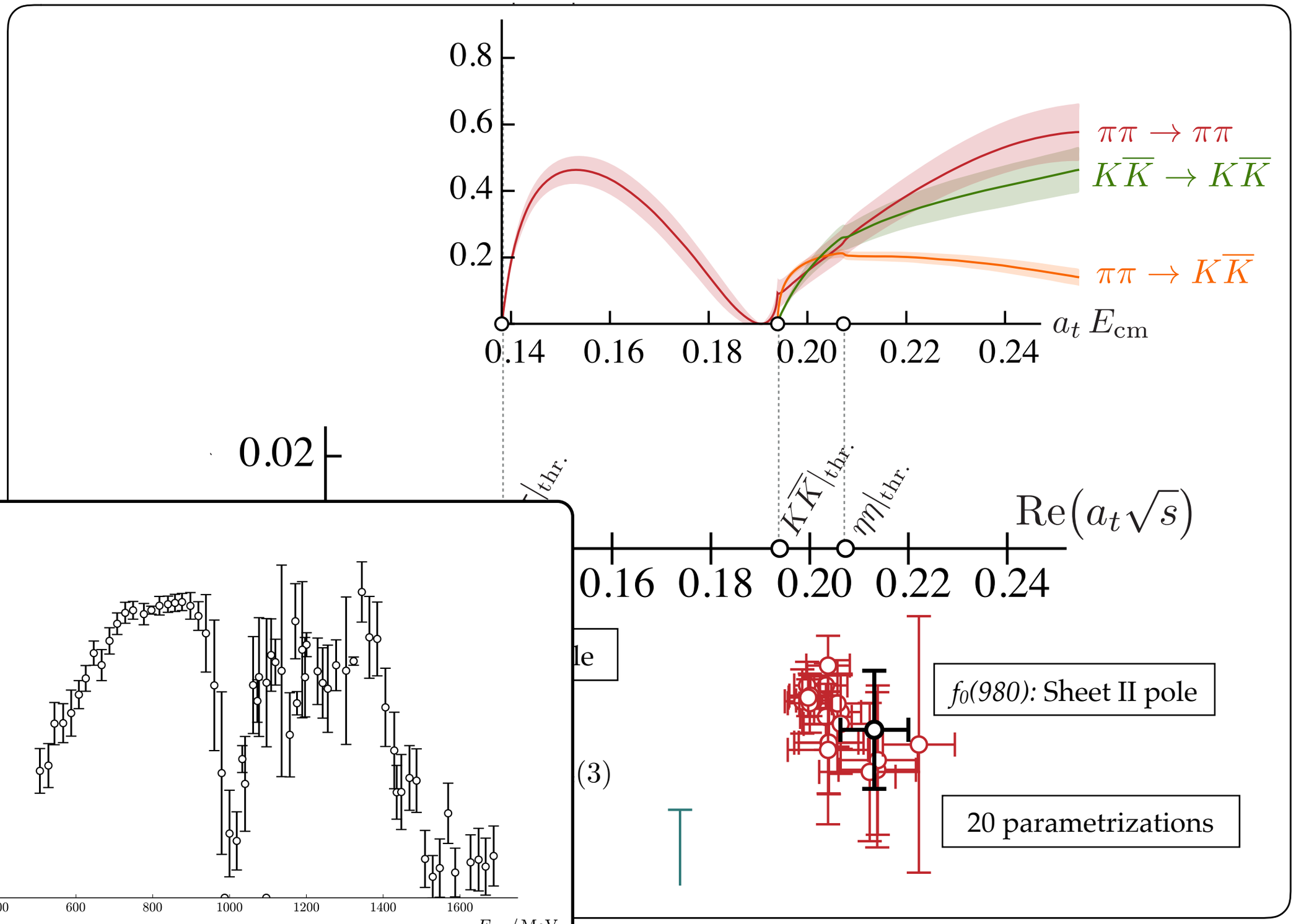
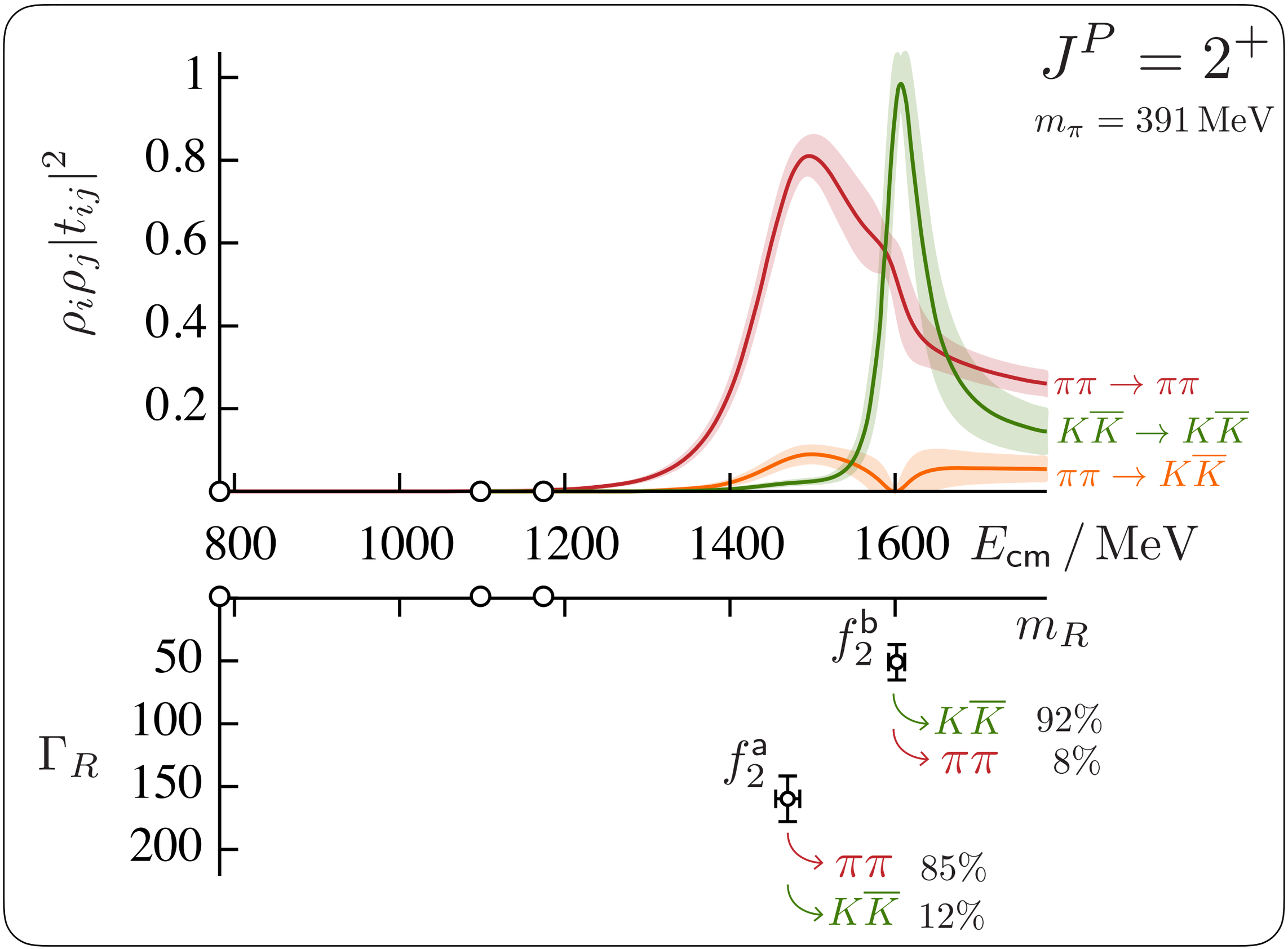
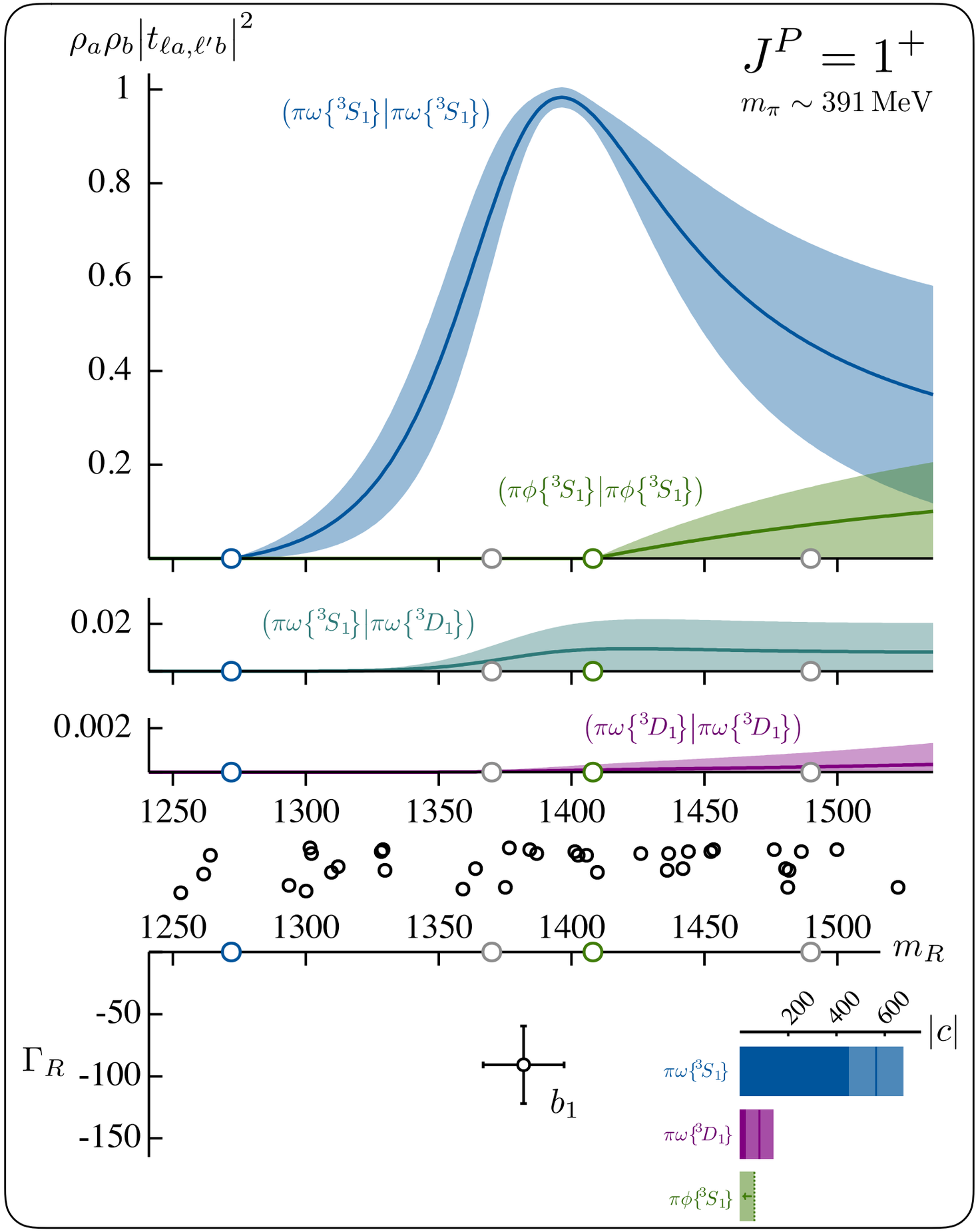


tensor $\pi\pi$-$K\overline{K}$



$\pi\omega$-$\pi\phi$ and the b_1



lattice spectroscopy

identification of
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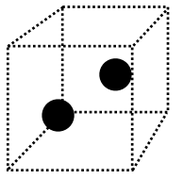
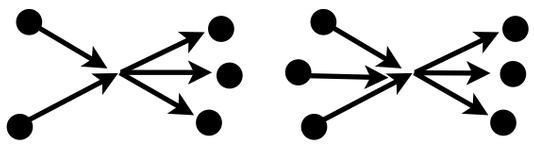
lattice QCD

finite-volume spectrum

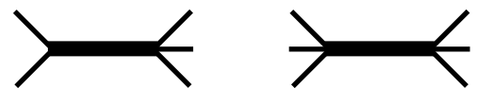


PW amplitudes

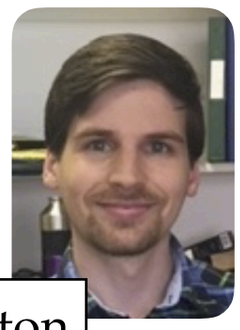


analytic continuation

resonance poles



inside the box



Blanton

Sharpe

Romero-López

Hansen

outside the box

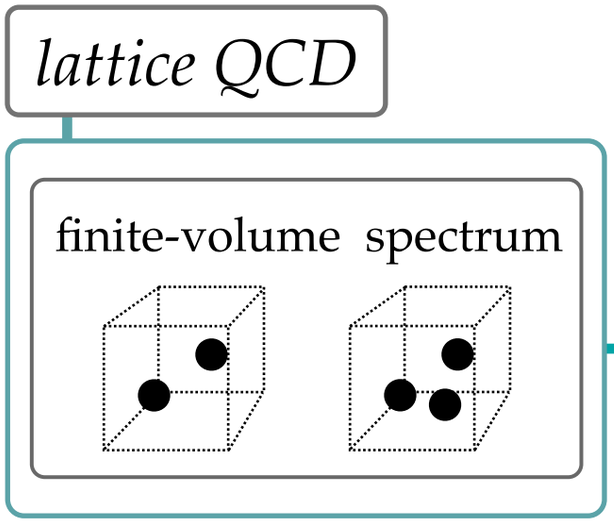
Szczepaniak

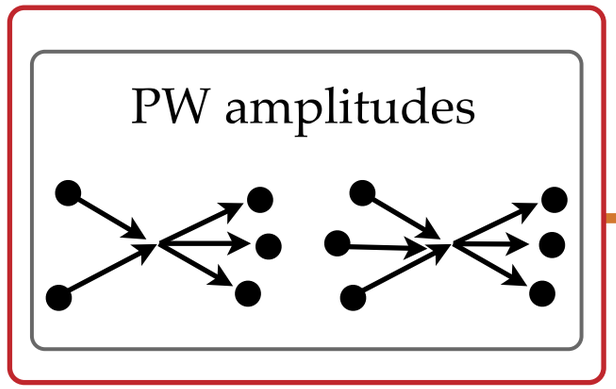
three-particle spectrum satisfies:

$$\det[F_3^{-1} + \mathcal{K}_{\mathrm{df},3}] = 0$$

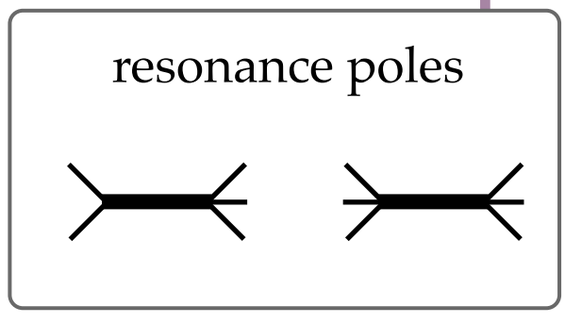
- Hansen & Sharpe (2014, 2015)
- RB, Hansen & Sharpe (2017, 2018)
- Romero-López, Sharpe, Blanton, RB, & Hansen (2019)
- RB, Hansen, Sharpe, & Szczepaniak (2019)

lattice spectroscopy





analytic continuation



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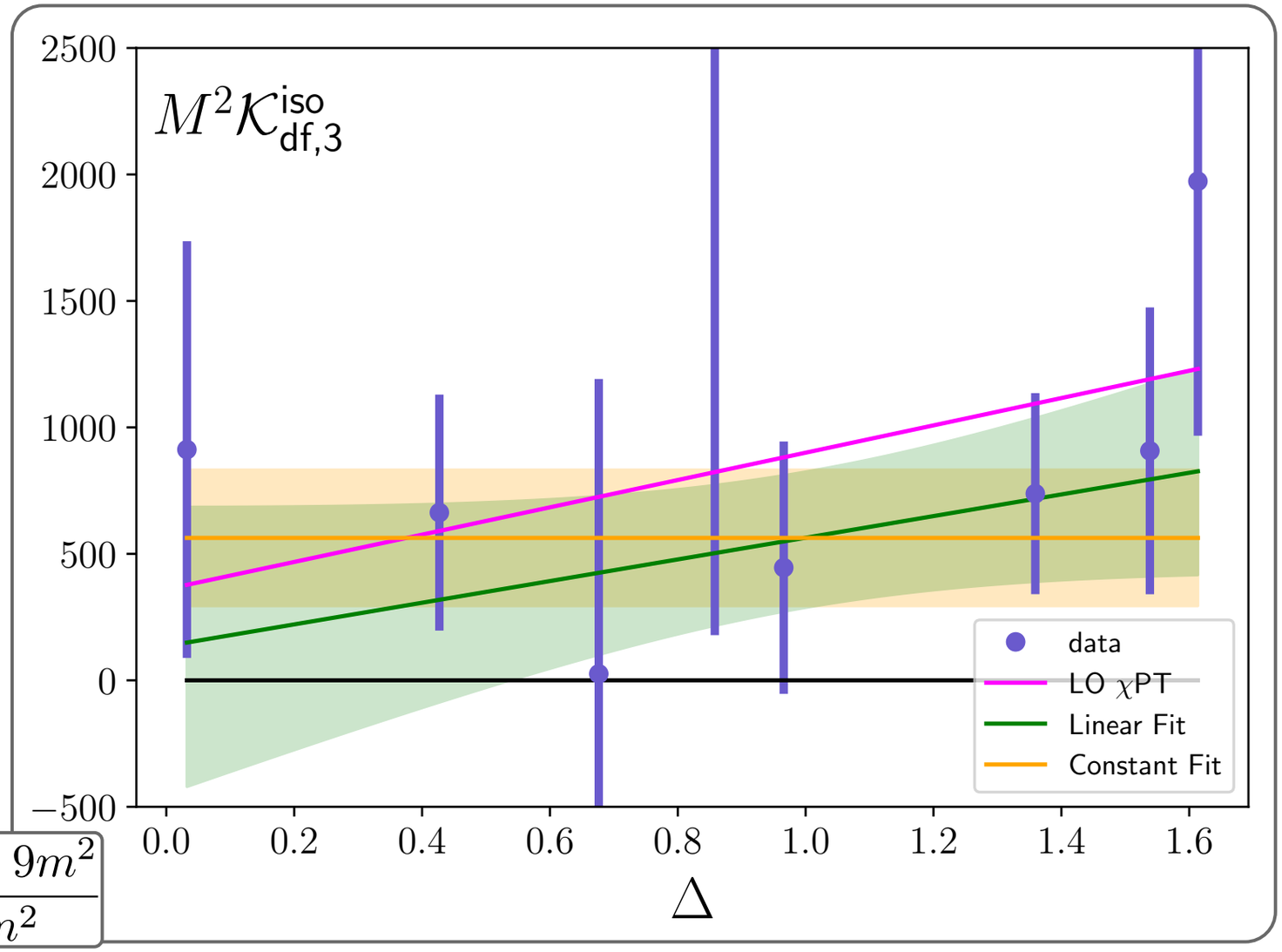
Hörz and Hanlon (2019)

Romero-López, Blaton, & Sharpe (2019)



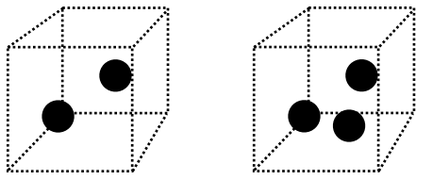
$$\Delta = \frac{E^2 - 9m^2}{9m^2}$$

lattice spectroscopy

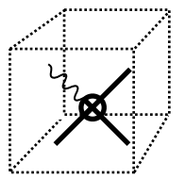
identification of
- states [masses & widths],
- production/decay mechanisms

lattice QCD

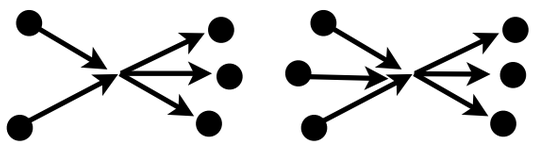
finite-volume spectrum



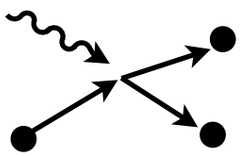
0/1-to-2 FV matrix elements



PW amplitudes



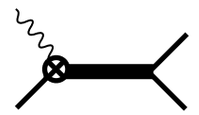
electroweak amplitudes



analytic continuation

resonance poles

transition form factors



- Lellouch & Lüscher (2000)
- Kim, Sachrajda, & Sharpe
- Christ, Kim & Yamazaki (2005)
- …
- Hansen & Sharpe (2012)
- RB, Hansen Walker-Loud (2014)
- RB & Hansen (2015)

$$\left|\langle \mathbf{2}|\mathcal{J}|\mathbf{1}\rangle_L\right| = \sqrt{\mathcal{A}\,\mathcal{R}\,\mathcal{A}}$$

Lellouch-Lüscher matrix:

$$\mathcal{R}(E_n,\mathbf{P}) \equiv \lim_{E\to E_n}\left[\frac{(E-E_n)}{F^{-1}(P,L)+\mathcal{M}(P)}\right]$$

lattice spectroscopy

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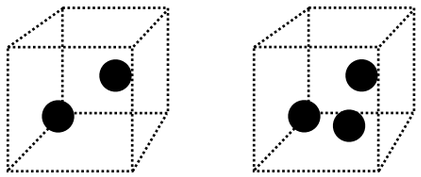
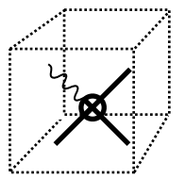
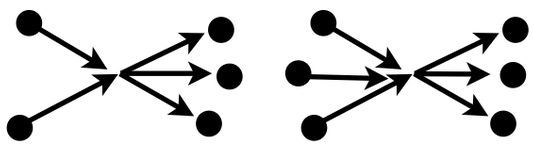
finite-volume spectrum



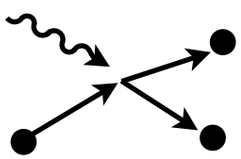
0/1-to-2 FV matrix elements



PW amplitudes

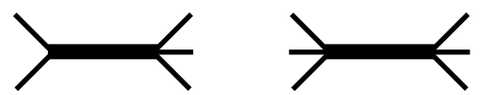


electroweak amplitudes

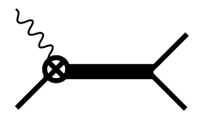


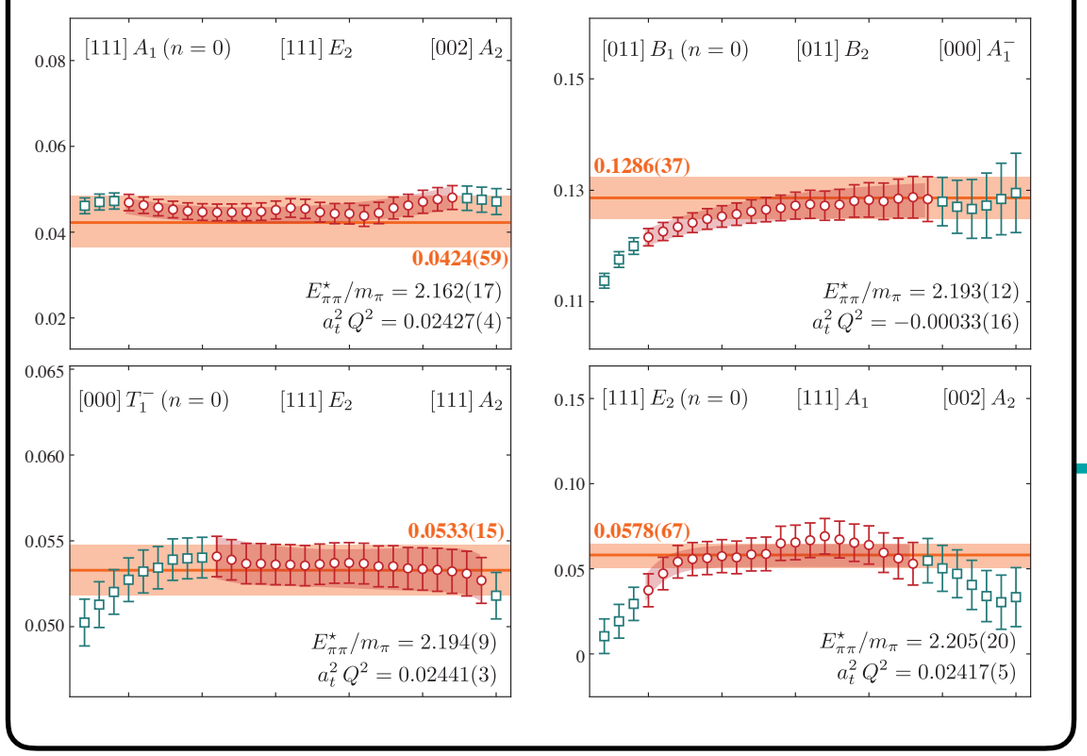
analytic continuation

resonance poles

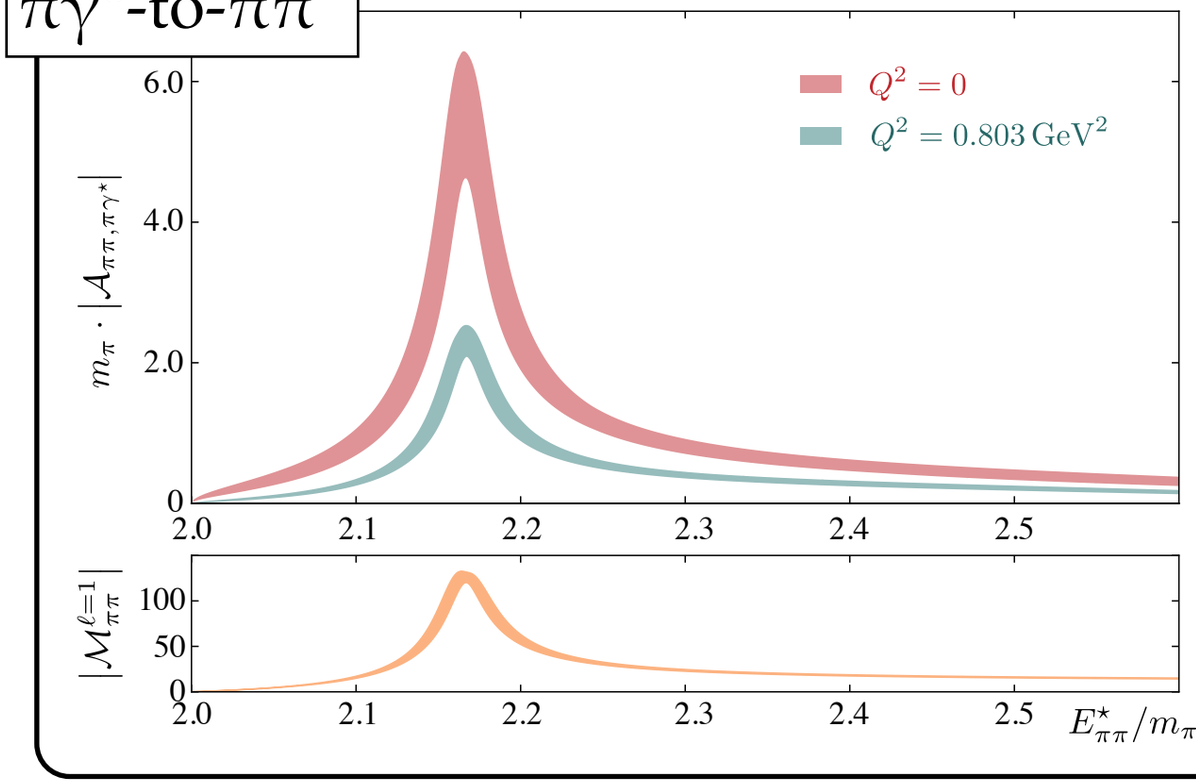


transition form factors





$\pi\gamma^*$-to-$\pi\pi$



lattice spectroscopy

identification of
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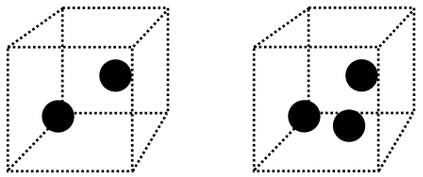
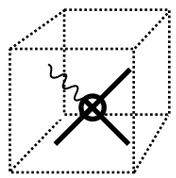
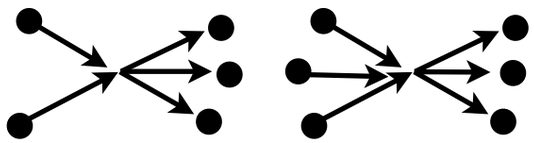
finite-volume spectrum



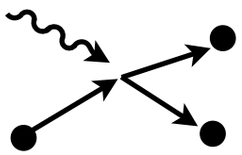
0/1-to-2 FV matrix elements



PW amplitudes



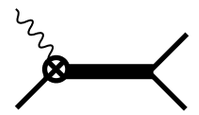
electroweak amplitudes



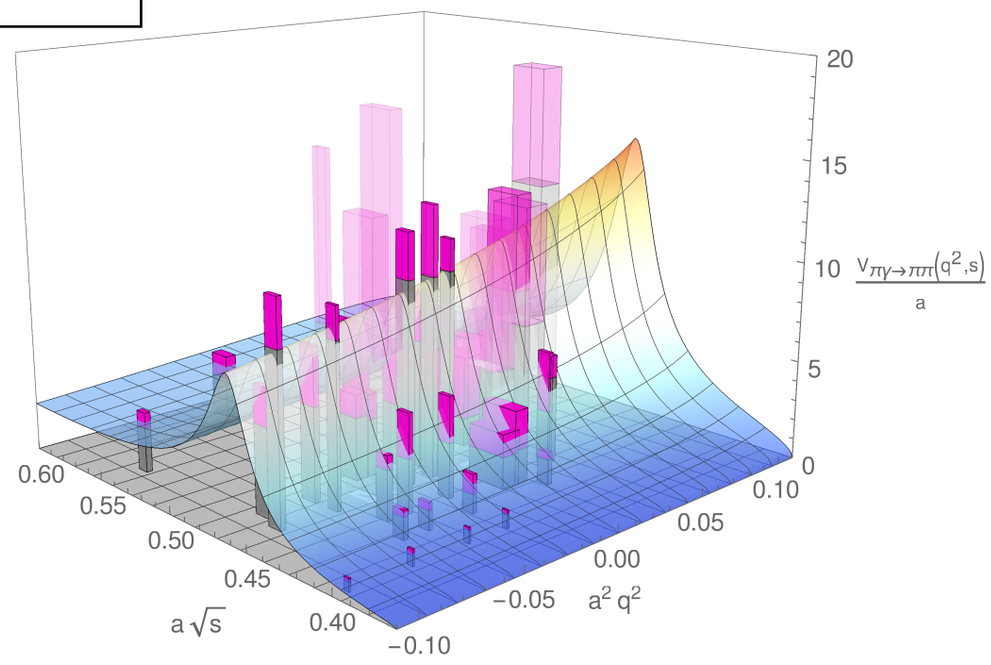
analytic continuation

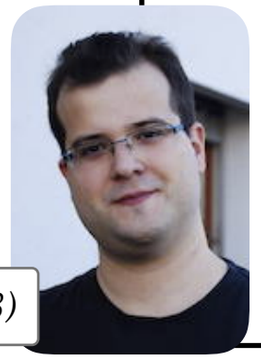
resonance poles

transition form factors



$\pi\gamma^*$-to-$\pi\pi$





Leskovec, Meivel, et al. (2018)

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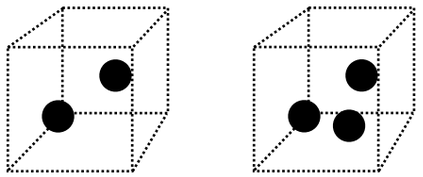
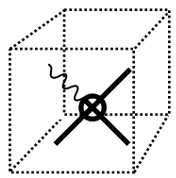
lattice QCD

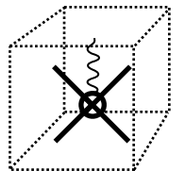
finite-volume spectrum



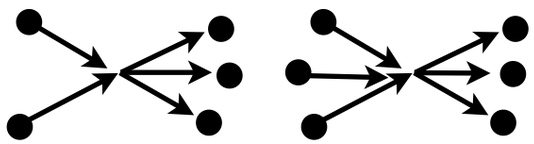
0/1-to-2 FV matrix elements



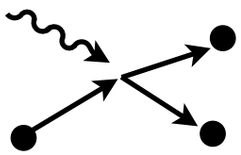
2-to-2 FV matrix elements



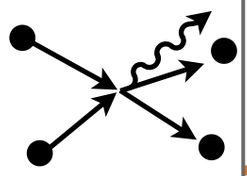
PW amplitudes



electroweak amplitudes



electroweak amplitudes

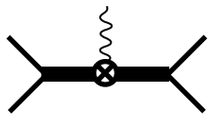


analytic continuation

resonance poles

transition form factors

elastic form factors



structure and nature of states

- RB & Hansen (2015)
- Baroni, RB, Hansen, Ortega (2018)

Baroni

Hansen

Ortega

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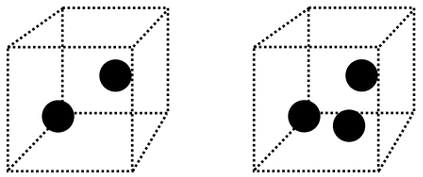

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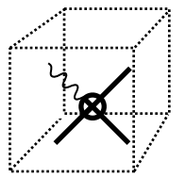
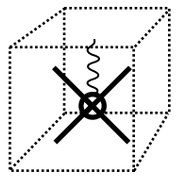
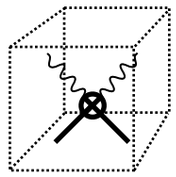


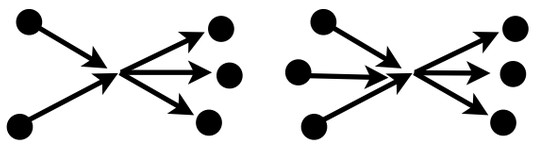
2-to-2 FV matrix elements



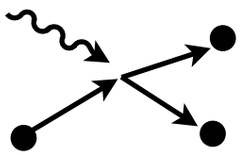
0/1-to-0/1 with two currents



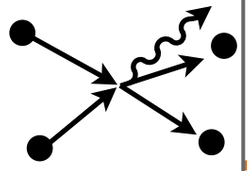
PW amplitudes



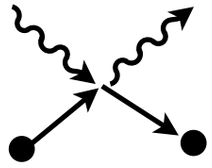
electroweak amplitudes



electroweak amplitudes



electroweak amplitudes



analytic continuation

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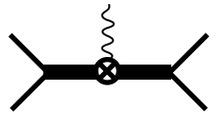


- Christ, Feng, Martinelli, & Sachrajda (2017)
- Baroni, RB, Davoudi, Hansen, Schindler (to appear)

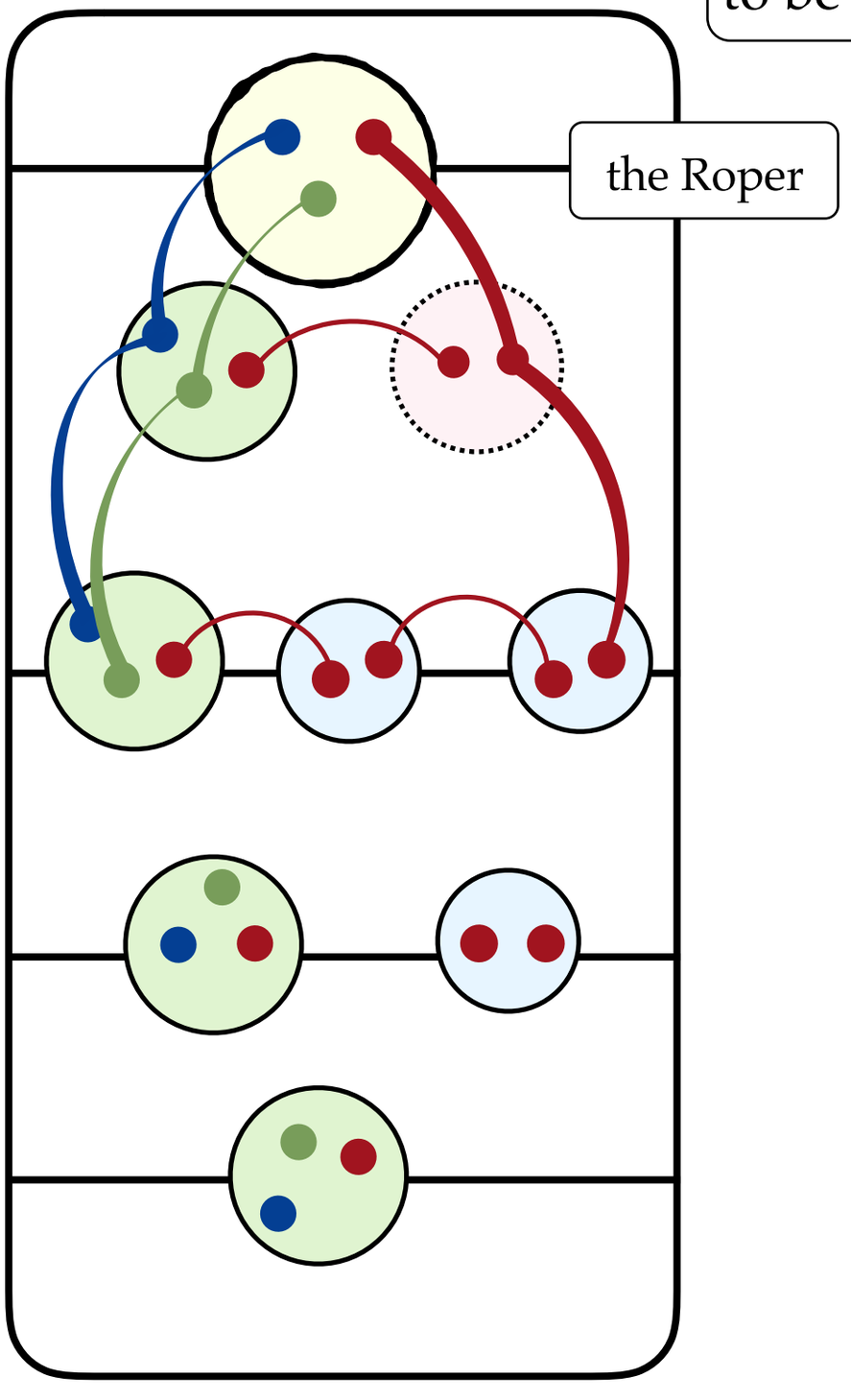
Baroni

Hansen

Schindler

Davoudi

the Roper an outstanding 50yr puzzle



What are the necessary features needed to be able to claim **accuracy**?

exploratory study

formalism

broad resonance

non-trivial spin structure

strongly coupled

three-particle system

structure of resonant states