Resonances in QCD - *spectroscopy efforts at JLab*

Raúl Briceño


Norfolk, VA [Home to ODU]

Jefferson Lab

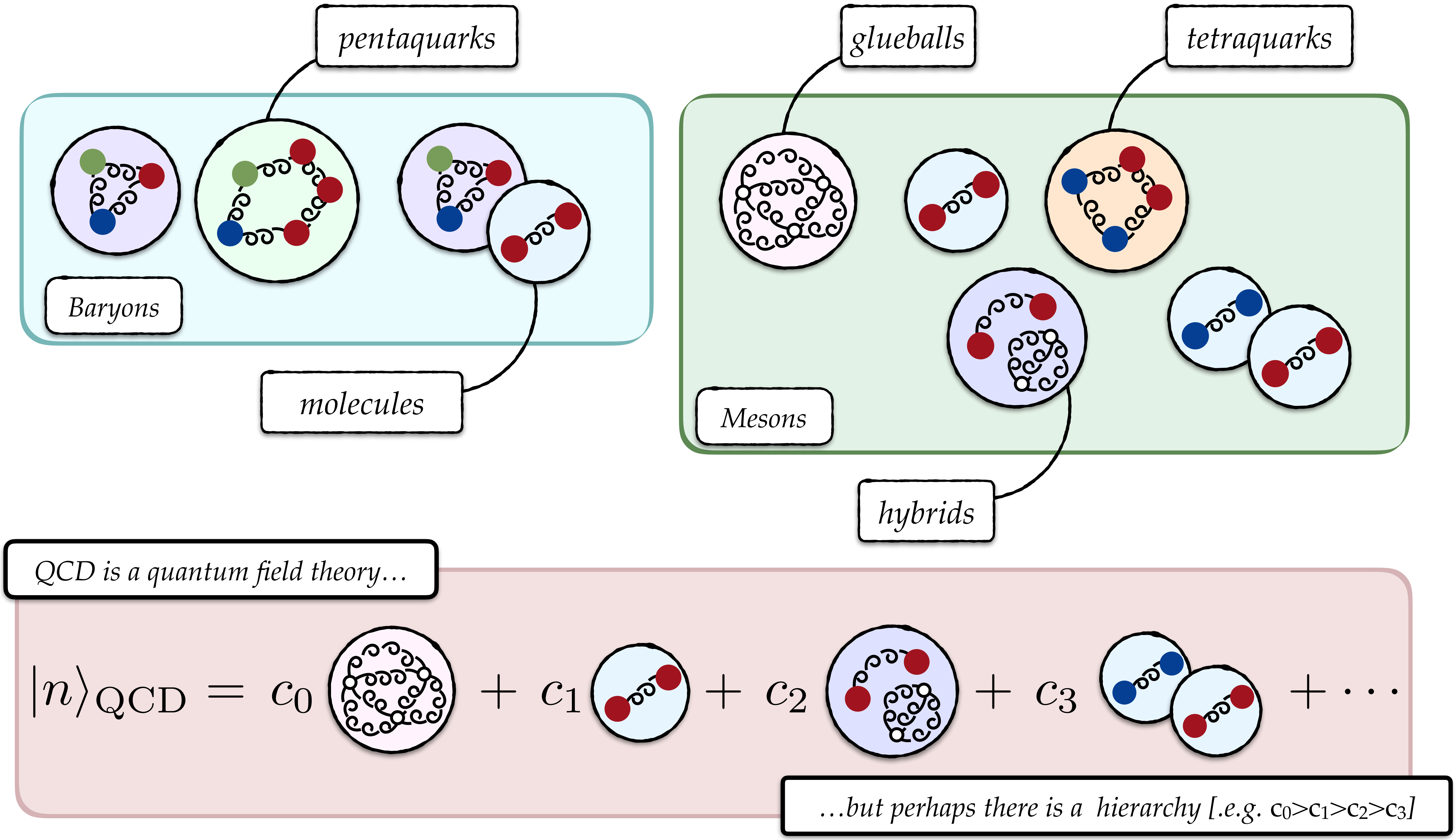
OLD DOMINION
UNIVERSITY

had spec

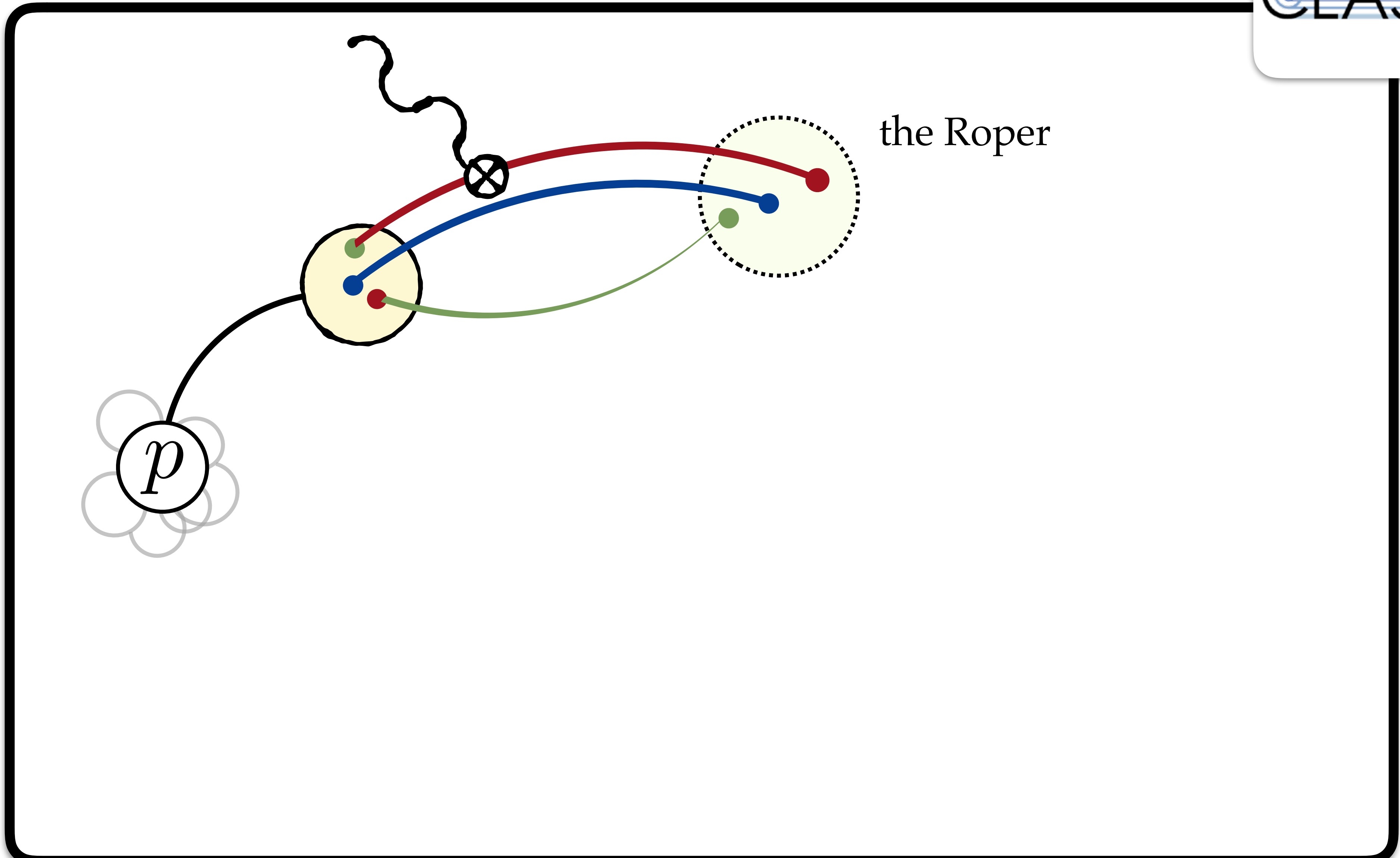
Hadrons, 2017


JLab, VA

Hadrons: QCD's rich spectrum

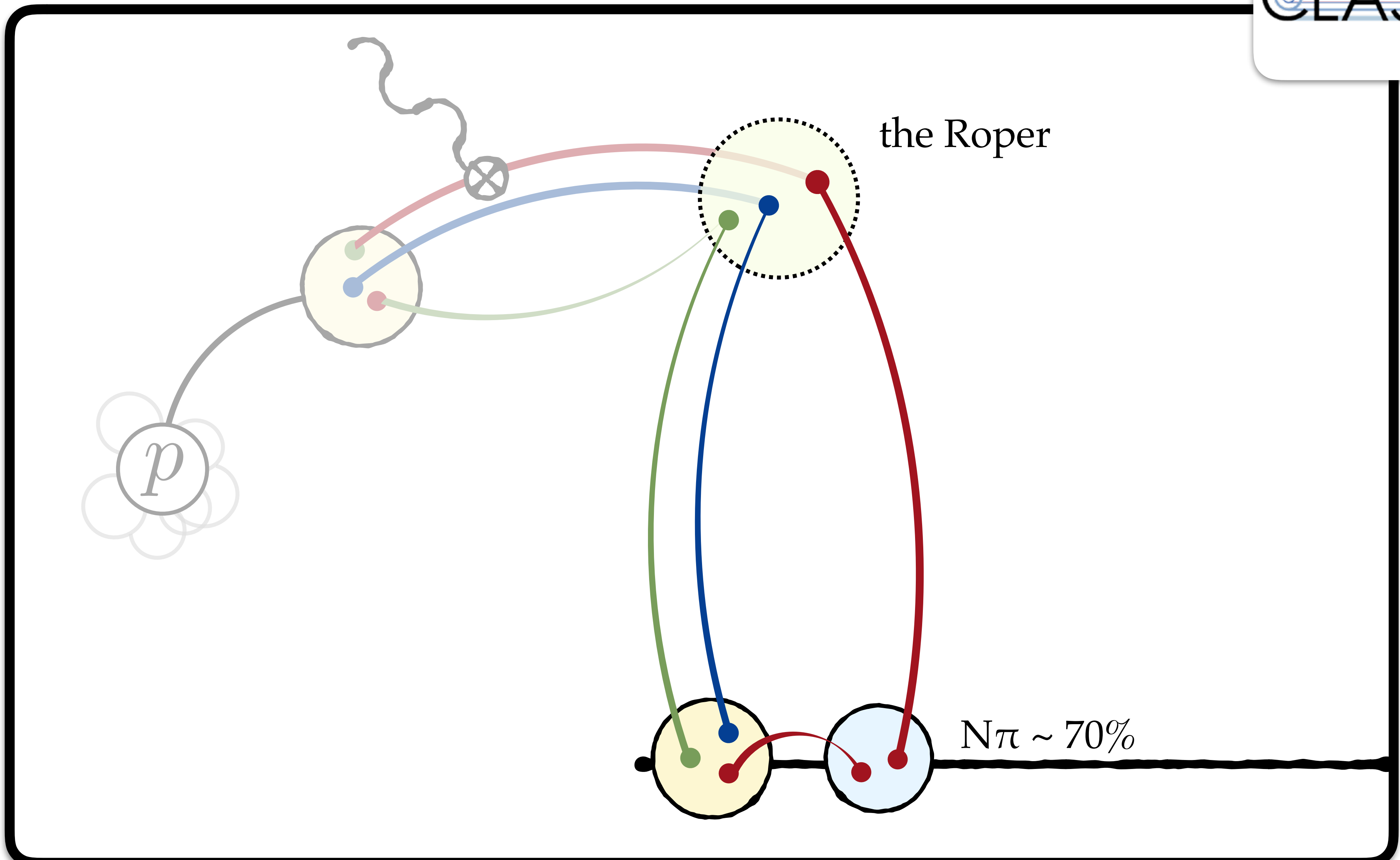


Resonances in experiment



- The vast majority of QCD states are **composite states**, which are either:
  - unstable under QCD (resonances)
  - *accidentally* stable (bound states)
  - depending on the QCD parameters, a state can *transition*

Resonances in experiment



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GlueX CLAS12 COMPASS LHCb BESIII panda

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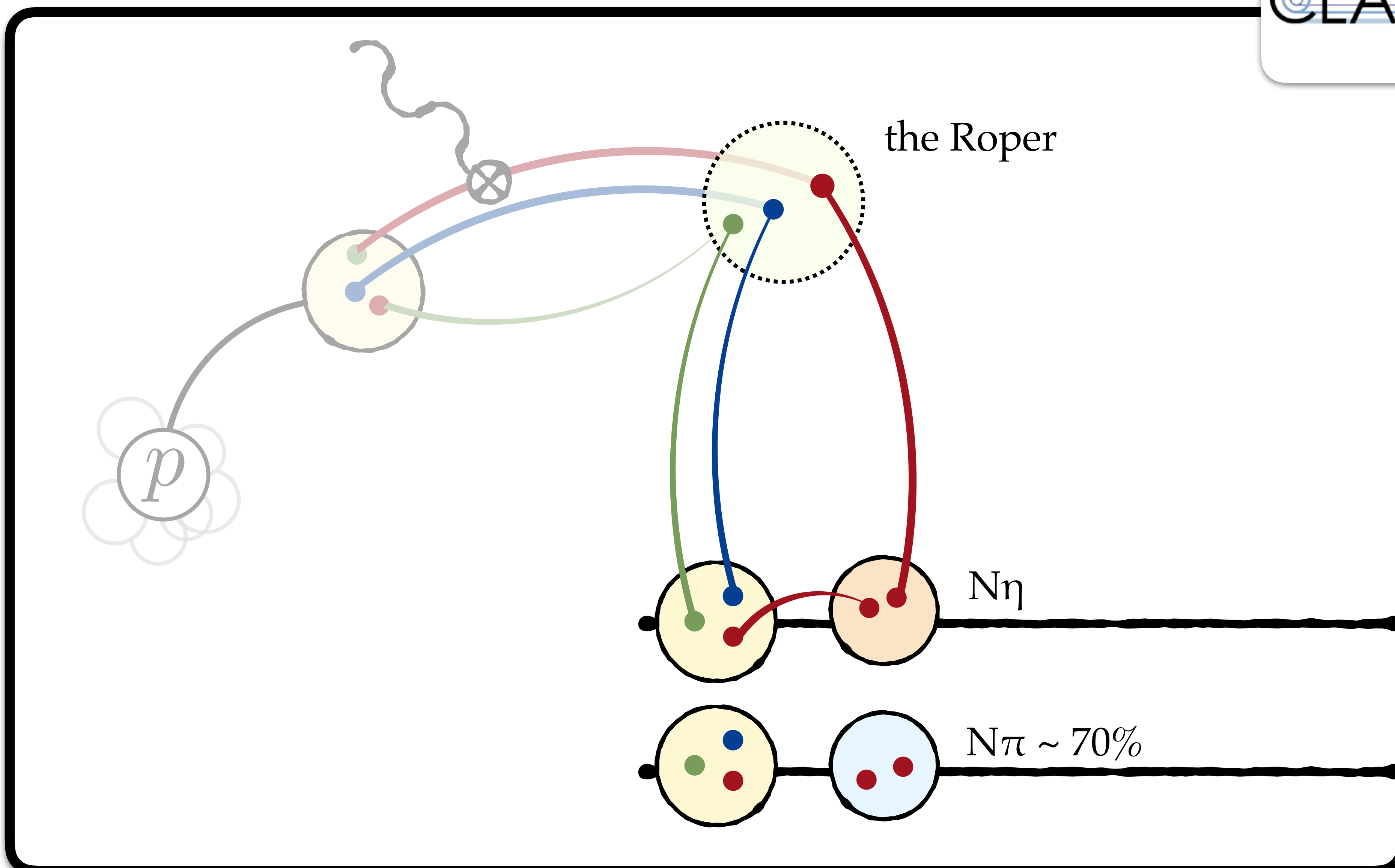

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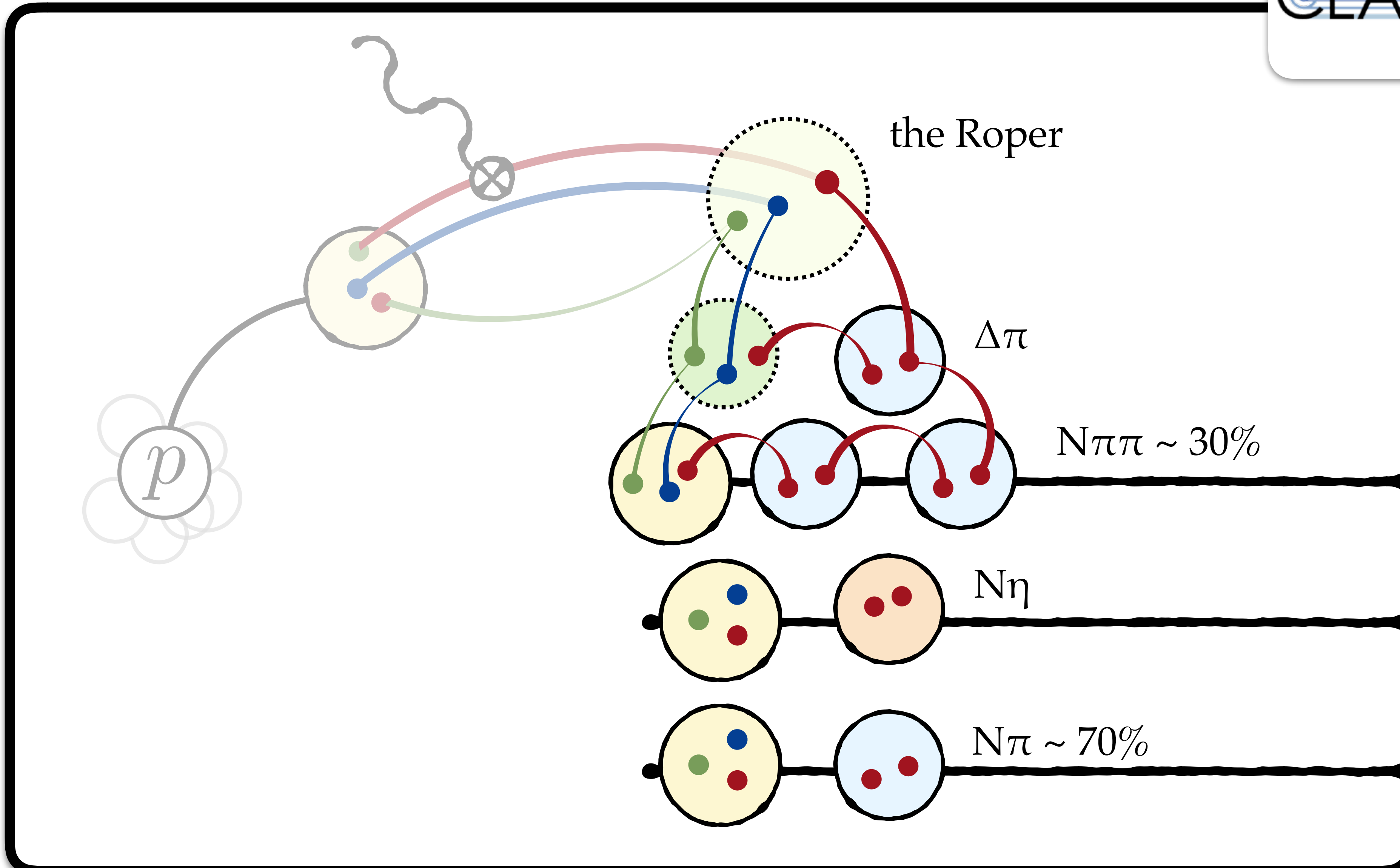

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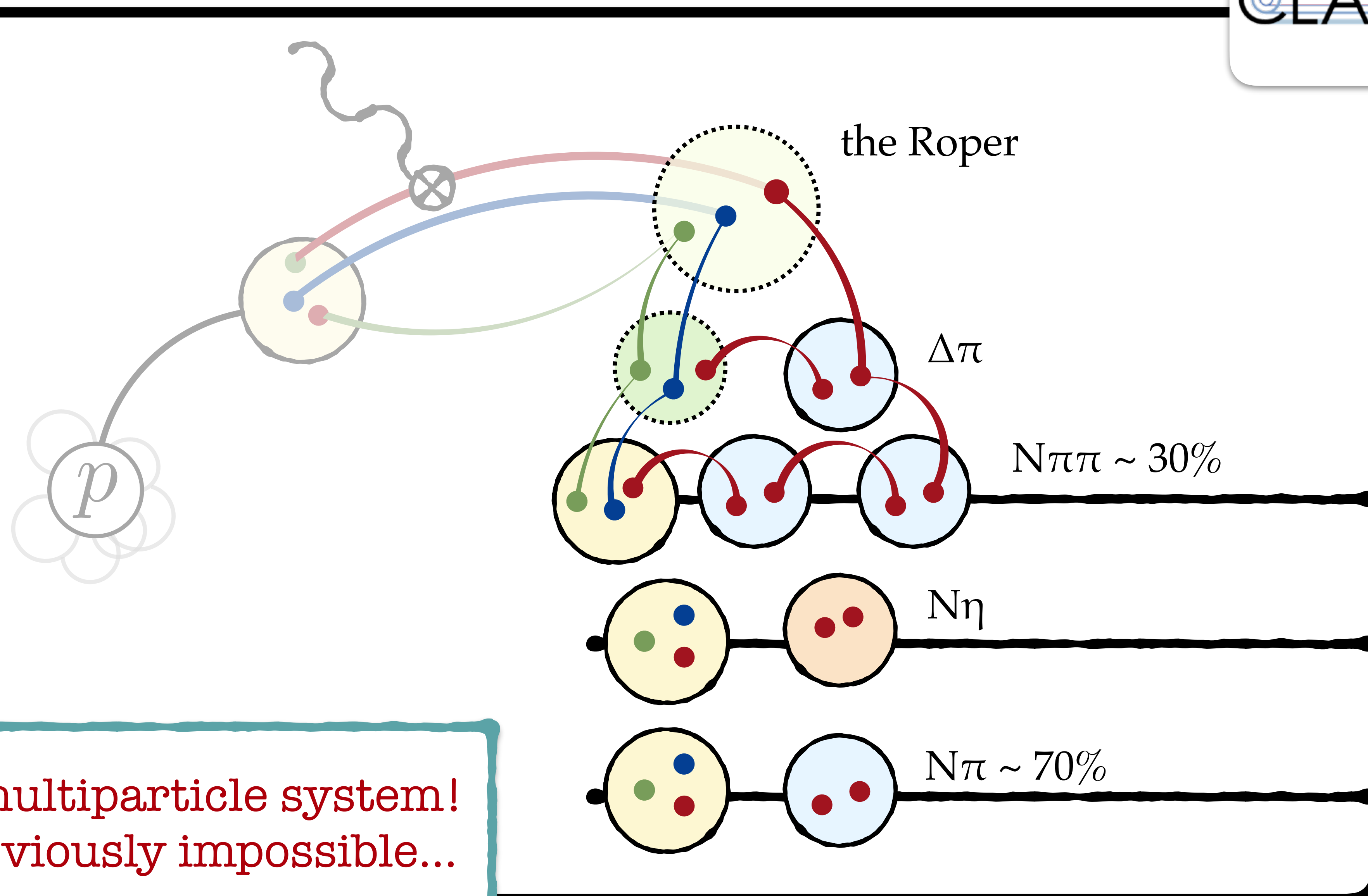


multichannel, multiparticle system!
hard, but not obviously impossible...

experimental needs

- confirmation
- production mechanism [couplings]
- identification of prominent decay channels
  - couplings to decay channels

theoretical needs

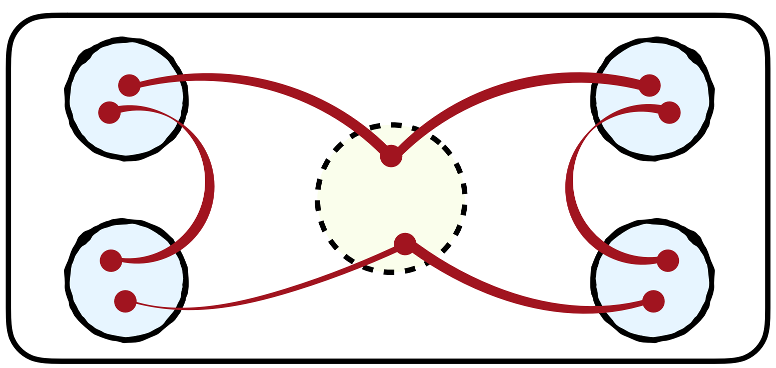
- structural understanding

Obtaining the QCD spectrum

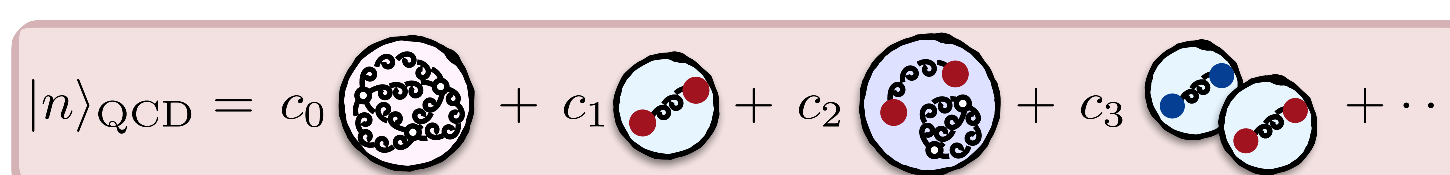
QCD → Lattice QCD

"the only game in town"

Cutting edge of the field is in the study of mesonic systems. I will focus on this, but the same lessons apply to baryons as well.



"Resonances are manifested as enhancement of cross sections"



Obtaining the QCD spectrum

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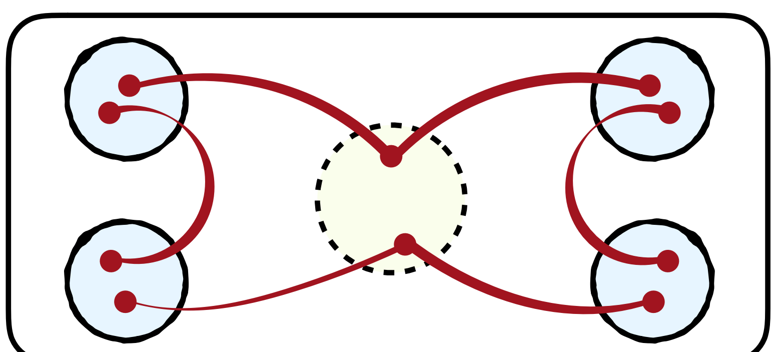
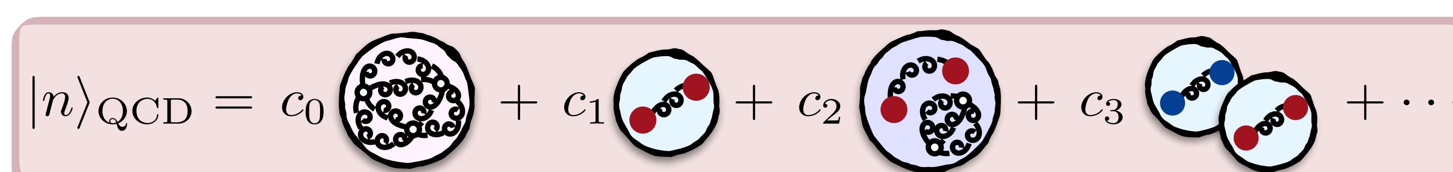


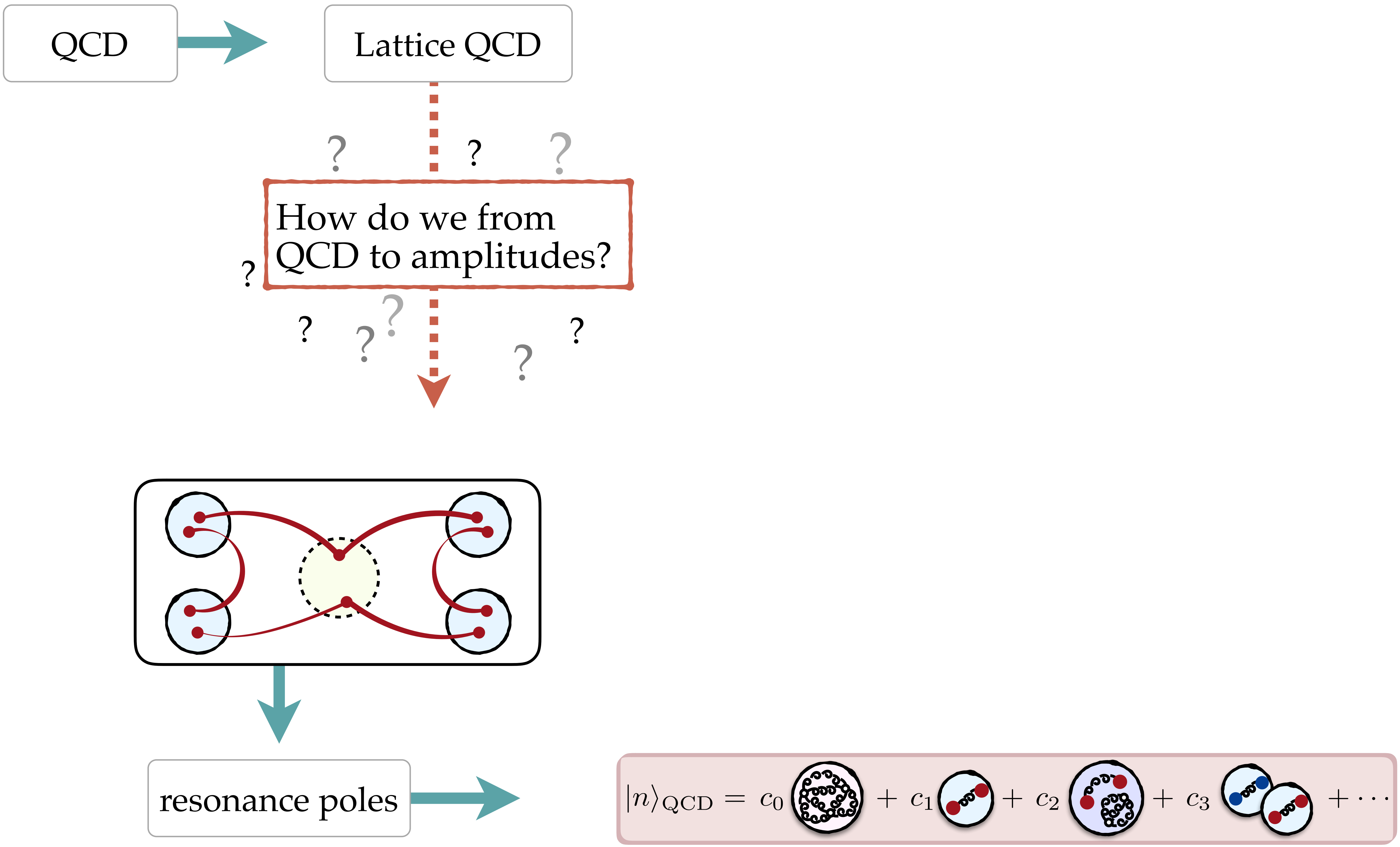
"Resonances are manifested as enhancement of cross sections"

…Complex valued poles in unphysical Riemman sheets

resonance poles →



Obtaining the QCD spectrum



Obtaining the QCD spectrum

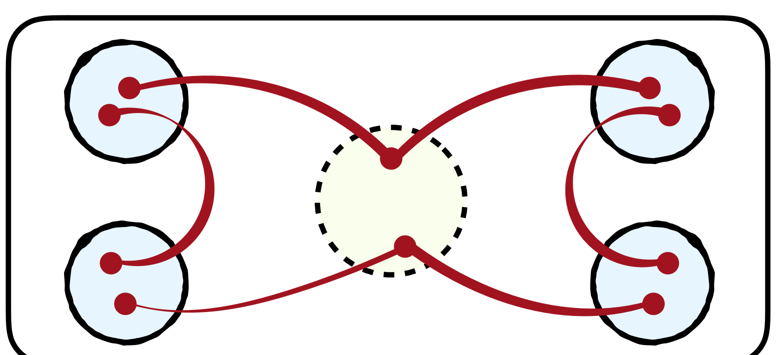
QCD → Lattice QCD

? ? ?

How do we from QCD to amplitudes?

? ? ? ? ? ?

step #1: gather a team!



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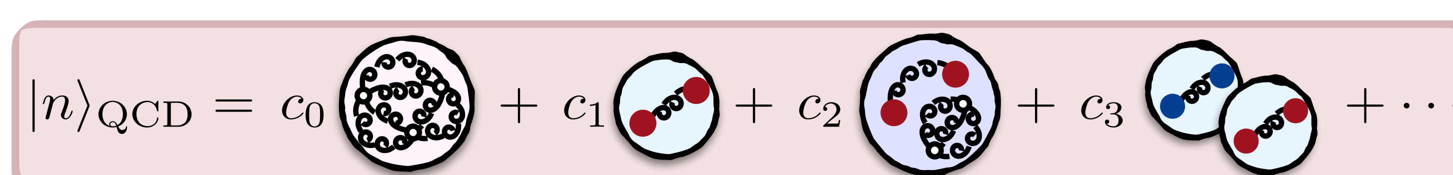


Meet the team -
LQCD *spectroscopy efforts at JLab and abroad*

more formal

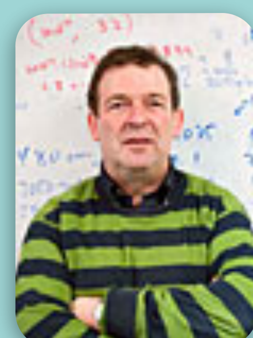

Chakraborty


Dudek


Edwards


Winter


Joó


Richards

more numerical - JLab


Wilson


Peardon


Ryan


Thomas

more numerical - Europe


Hansen


Sharpe

Students:
Johnson, Radhakrishnan, Cheung, Moss, O Hara, Tims

hadspec

OLD DOMINION UNIVERSITY

UNIVERSITY of WASHINGTON

CERN

Jefferson Lab

WILLIAM & MARY

UNIVERSITY OF CAMBRIDGE

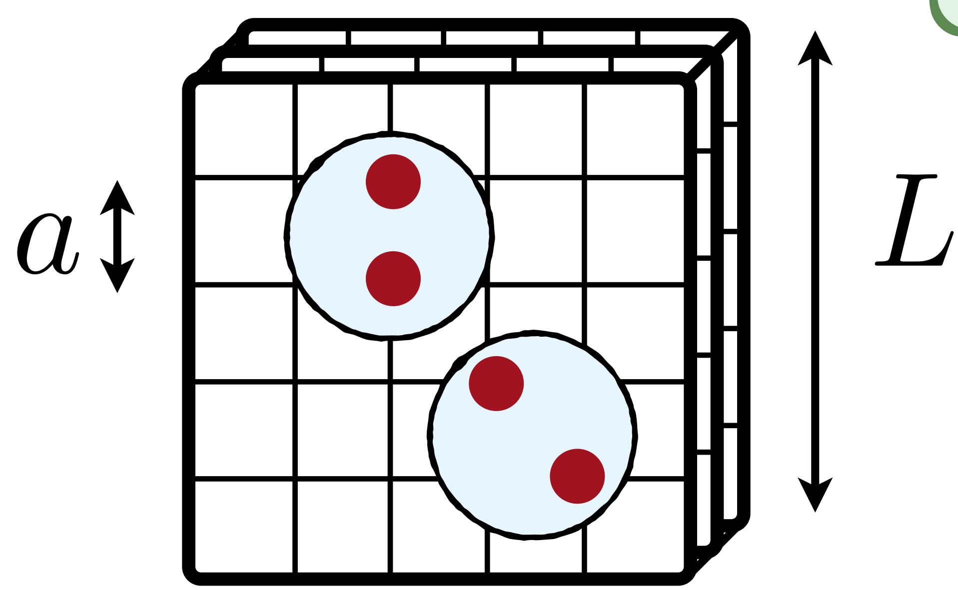
TRINITY COLLEGE DUBLIN

tifr

Lattice QCD in a nutshell

- Wick rotation [Euclidean spacetime]: $t_M \to -it_E$
- Monte Carlo sampling
- quark masses: $m_q \to m_q^{\text{phys.}}$
- lattice spacing: $a \sim 0.03 - 0.15 \text{ fm}$
- finite volume

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



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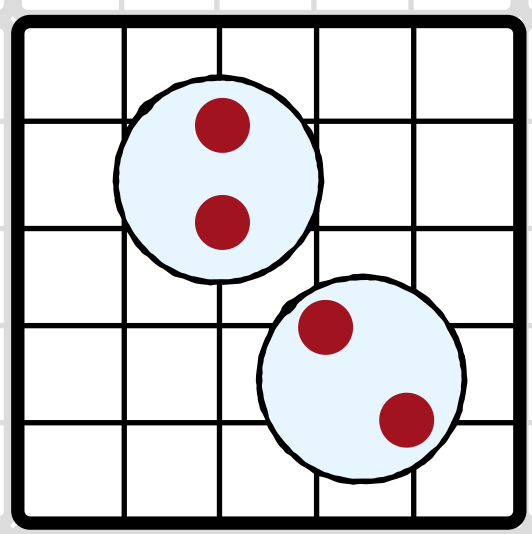

Never free!
No asymptotic states!
No scattering!

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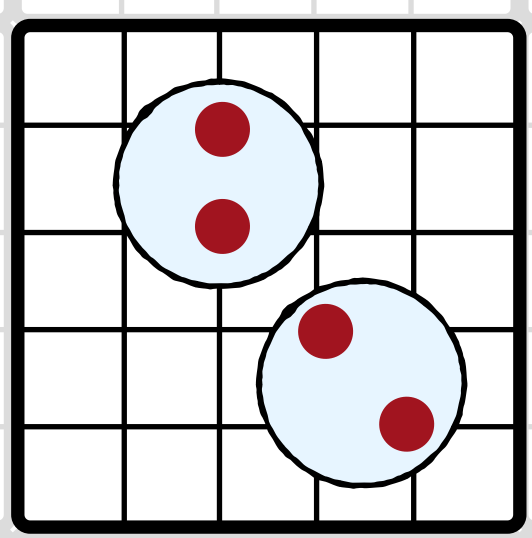

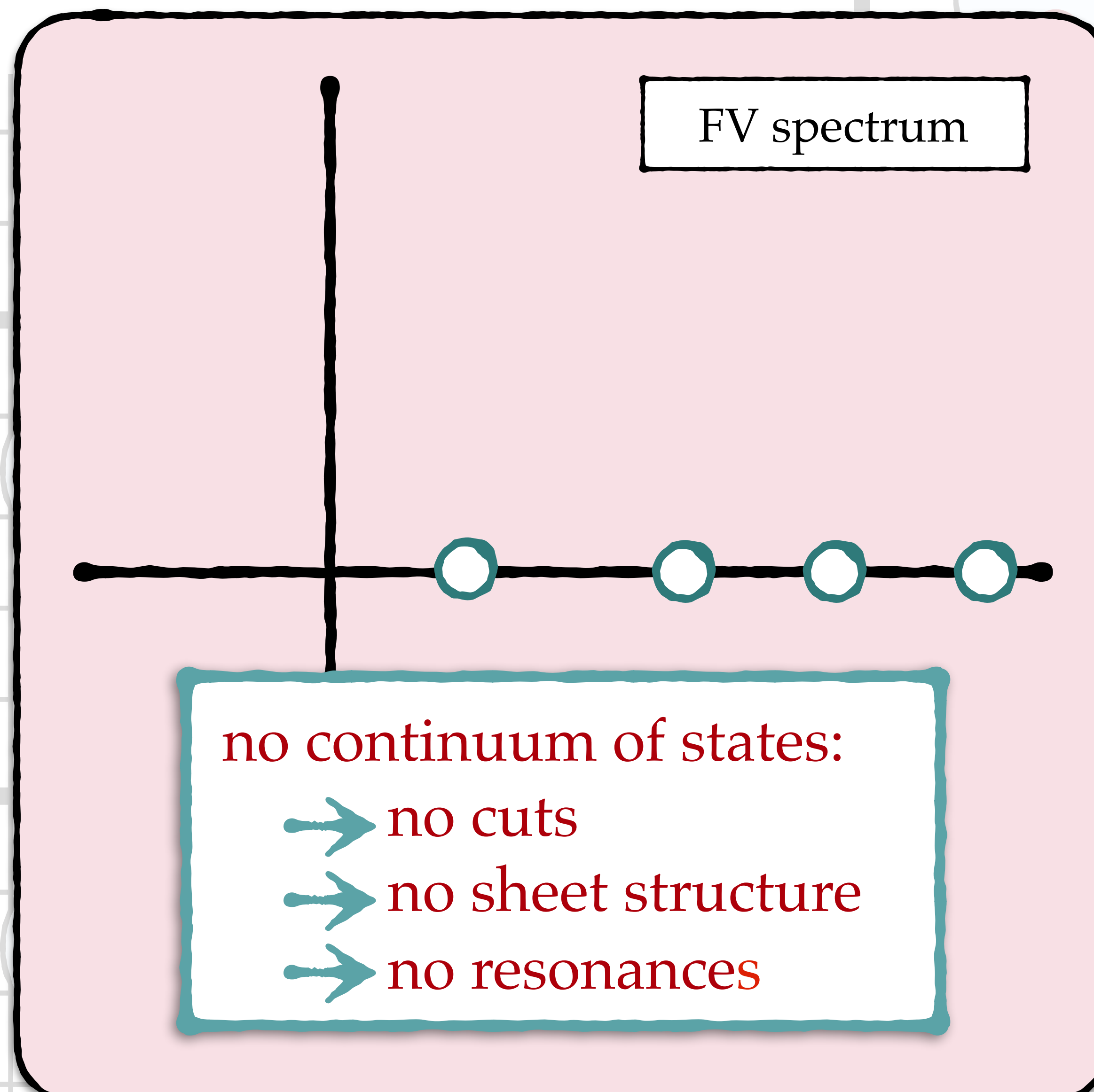

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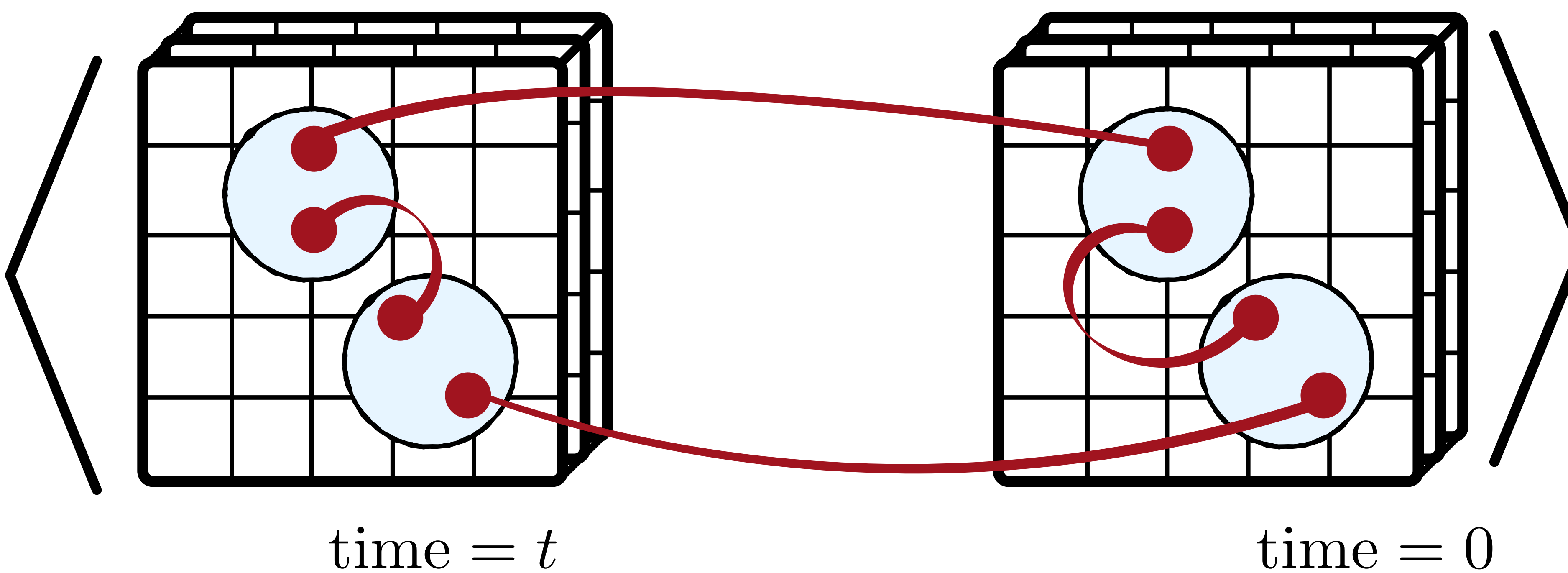
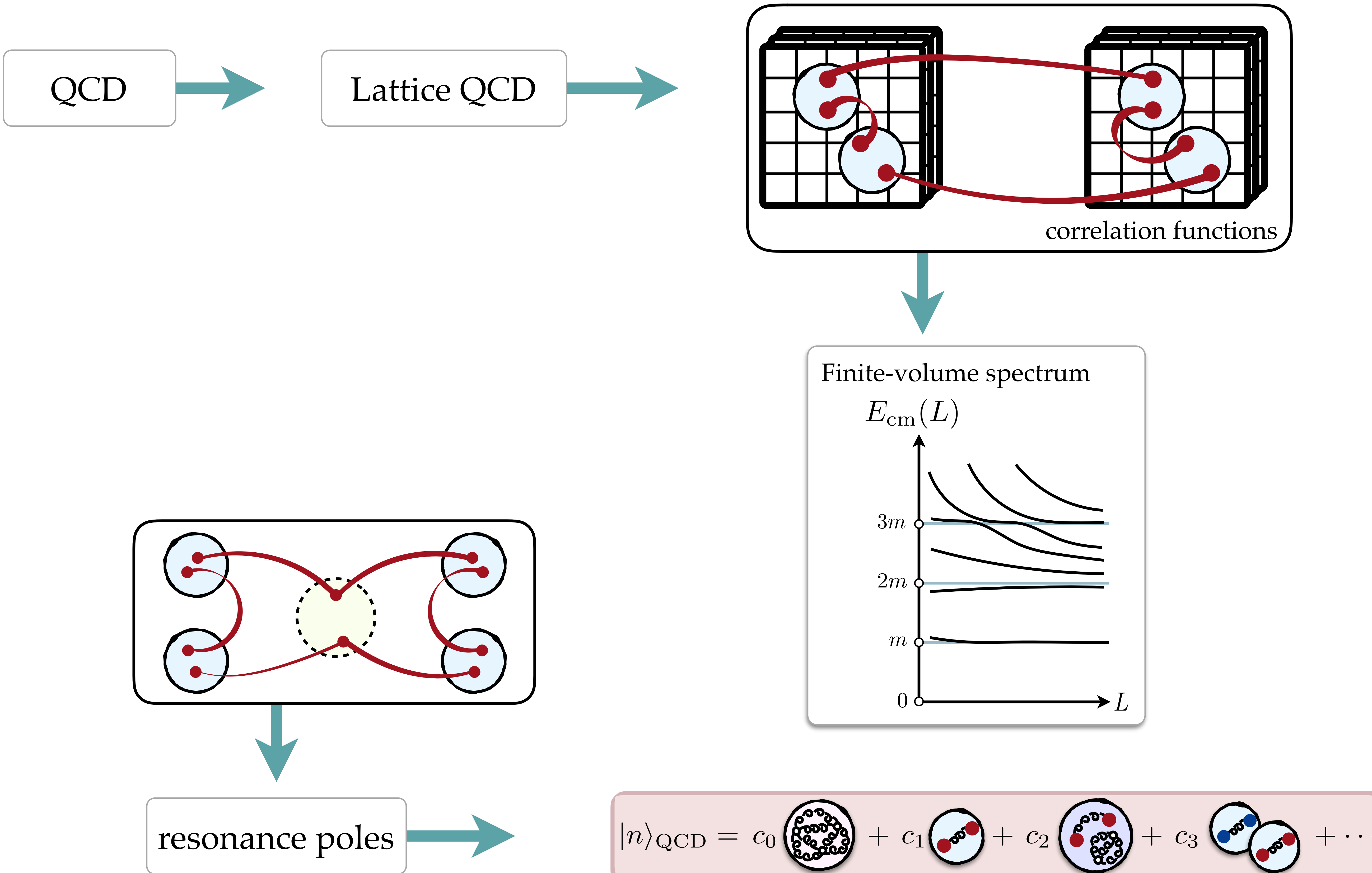
- finite volume
- Correlation functions: spectrum, matrix elements

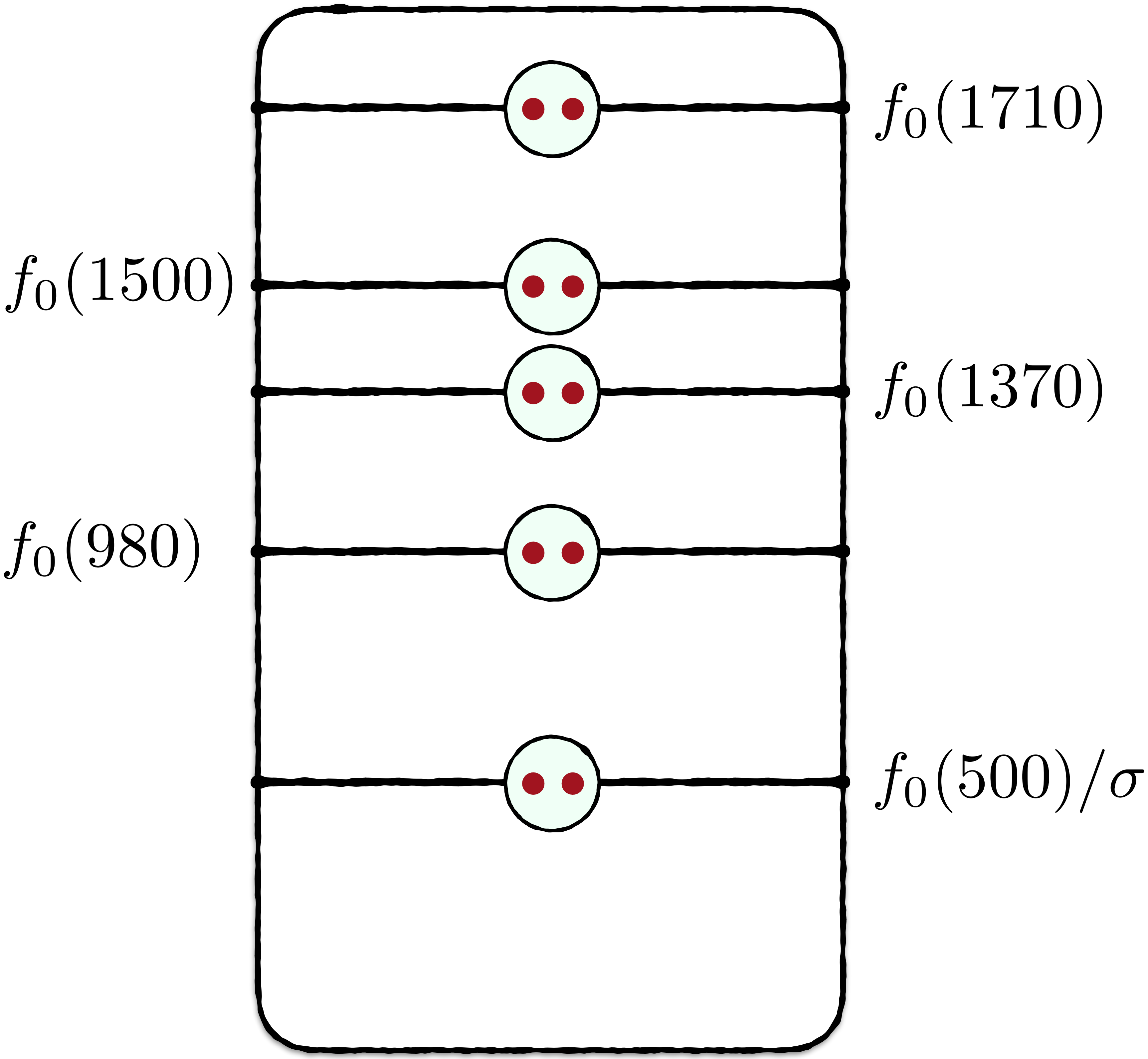
$$C_L(t, \mathbf{P}) = \Big\langle \quad \Big\rangle$$



Obtaining the QCD spectrum



The isoscalar, scalar sector



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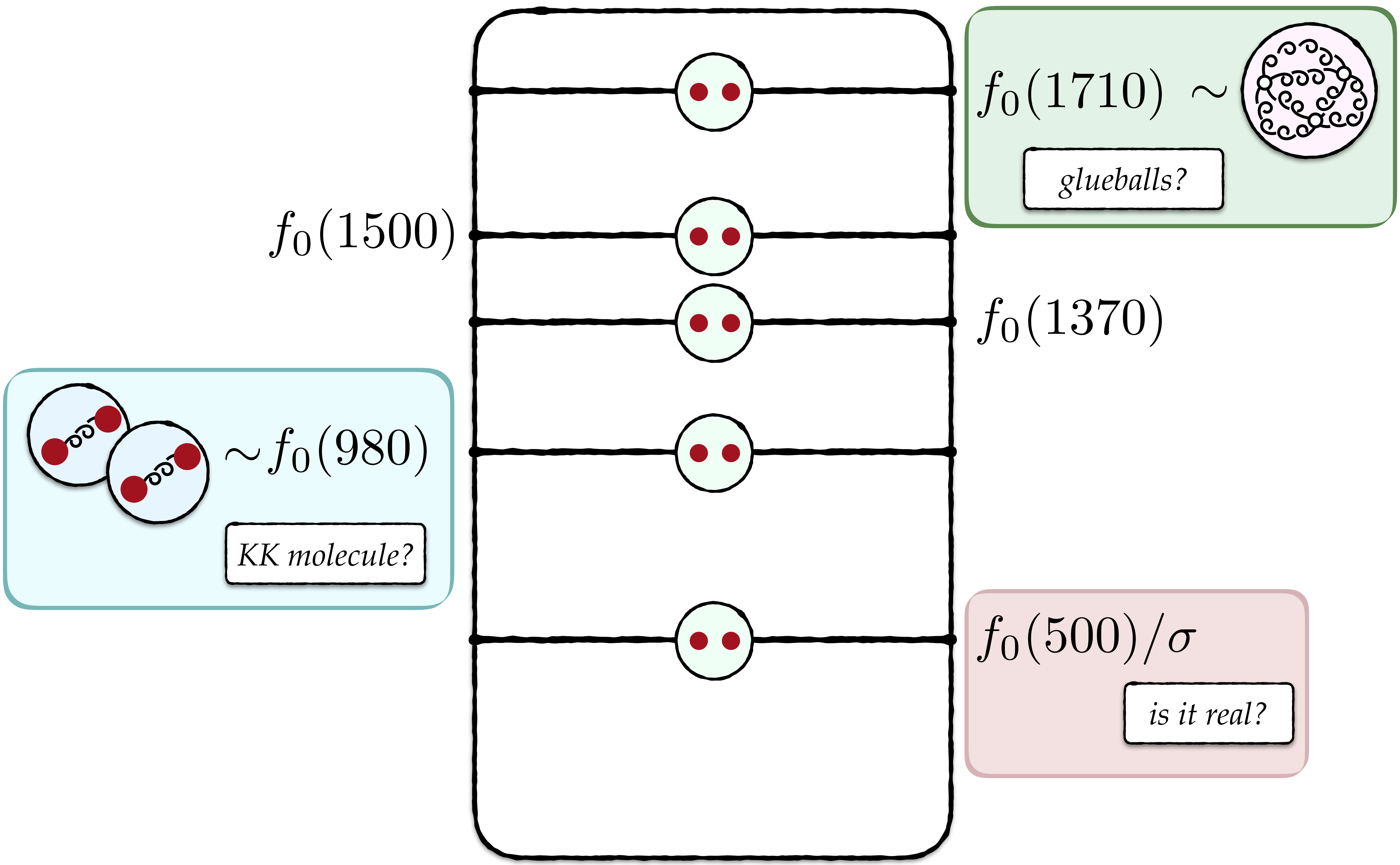

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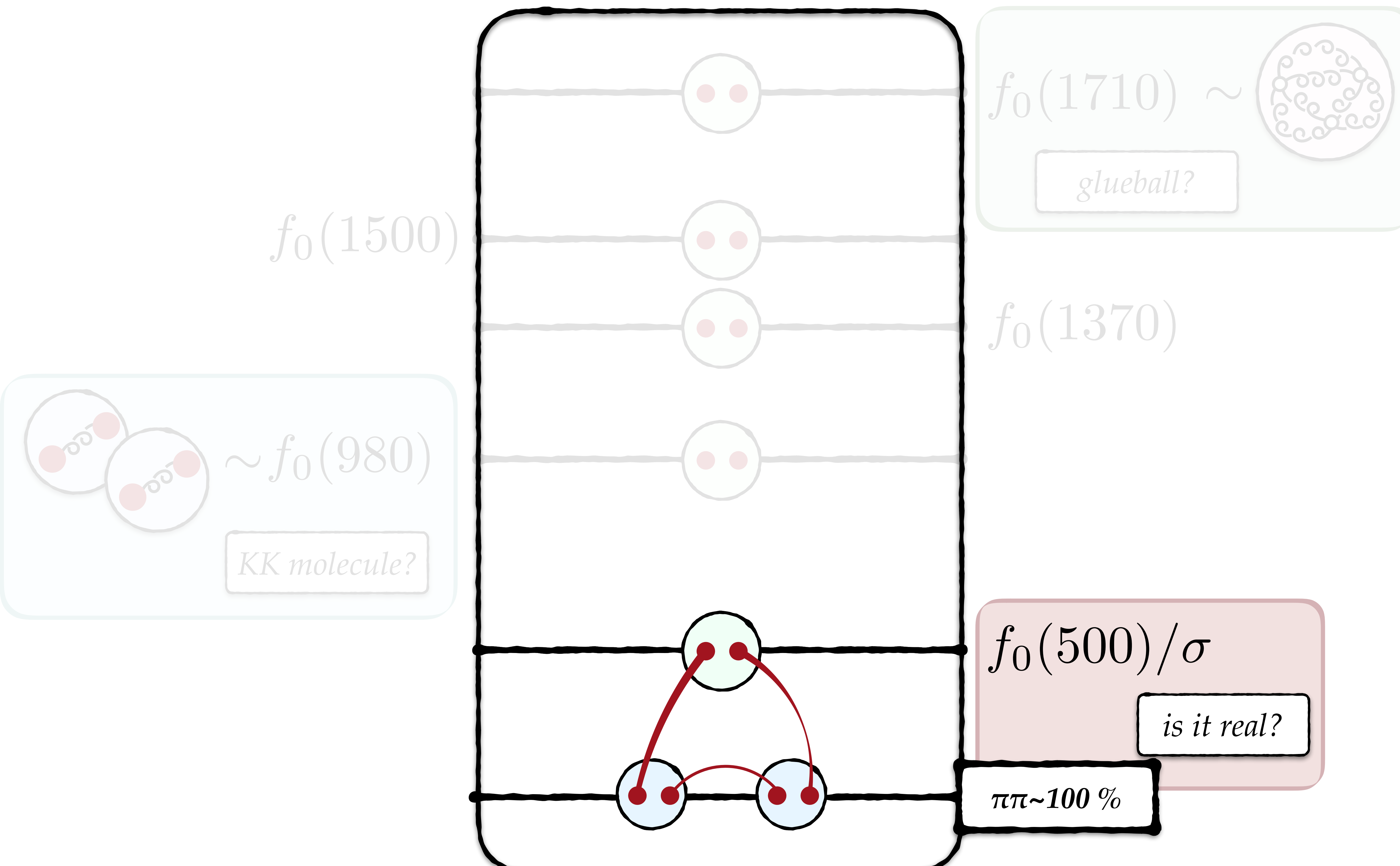

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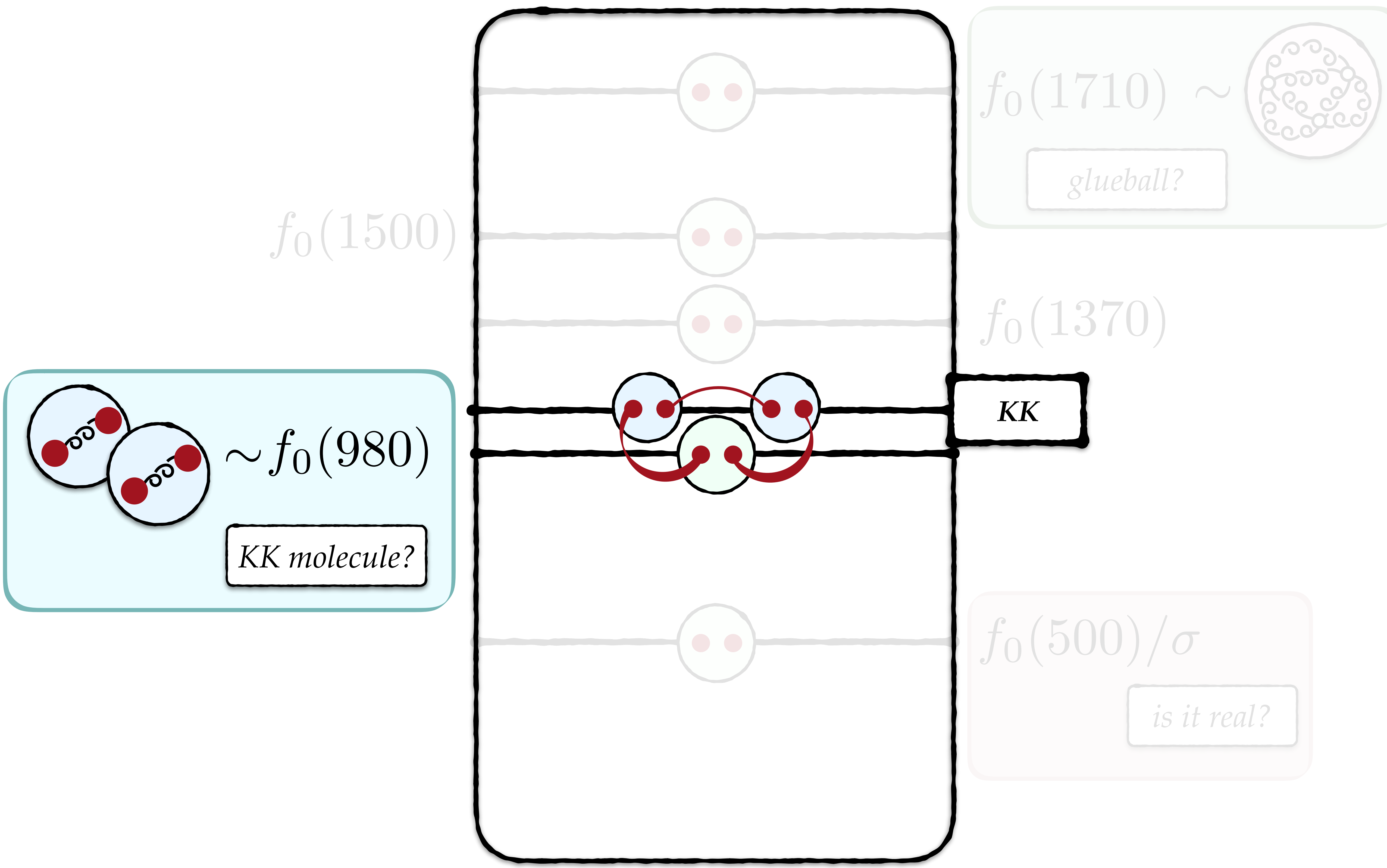

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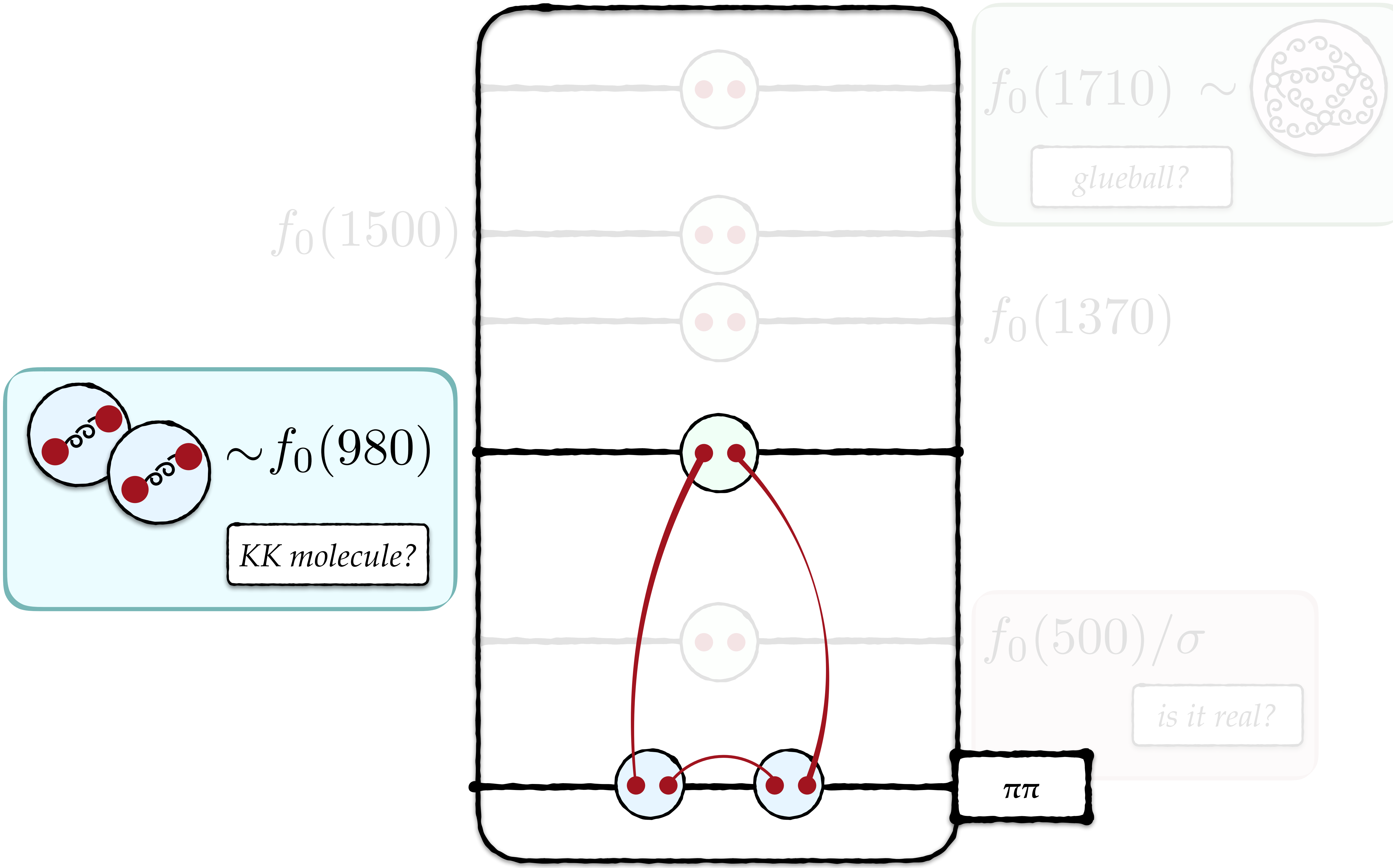
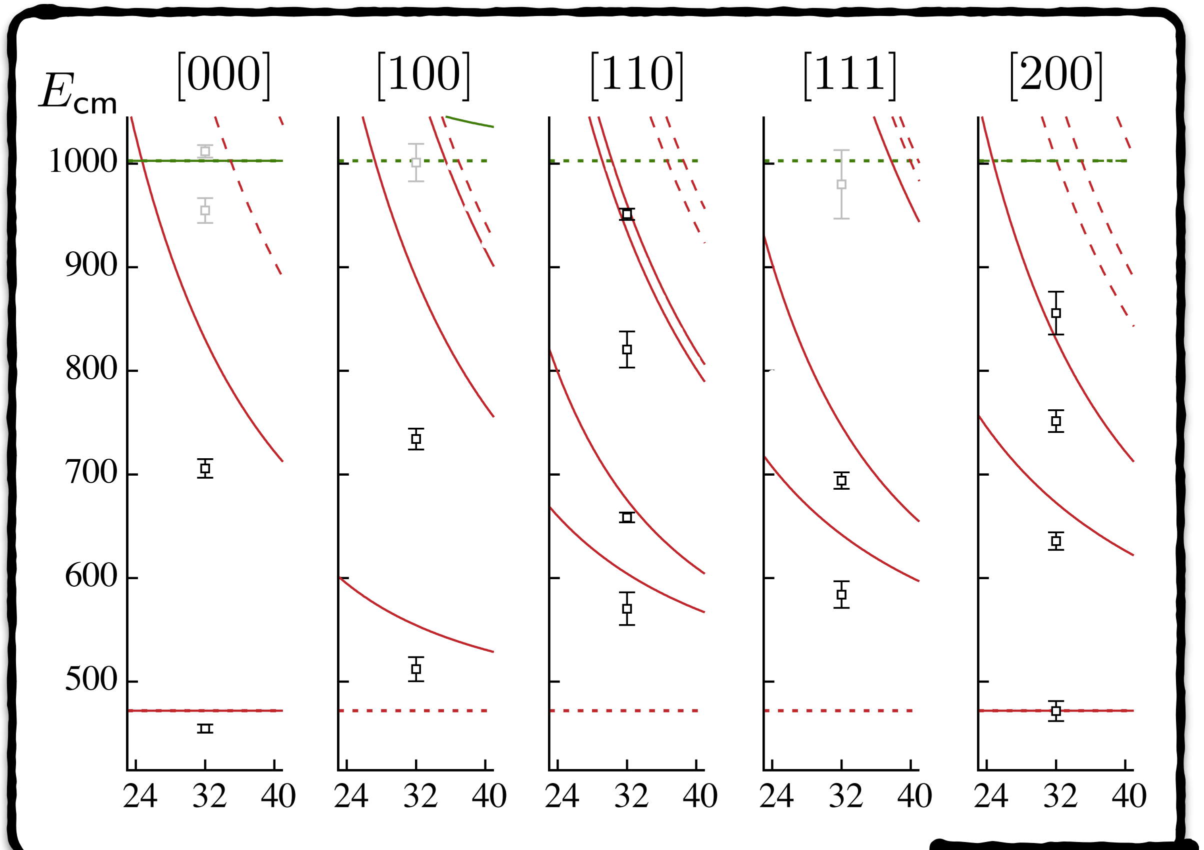


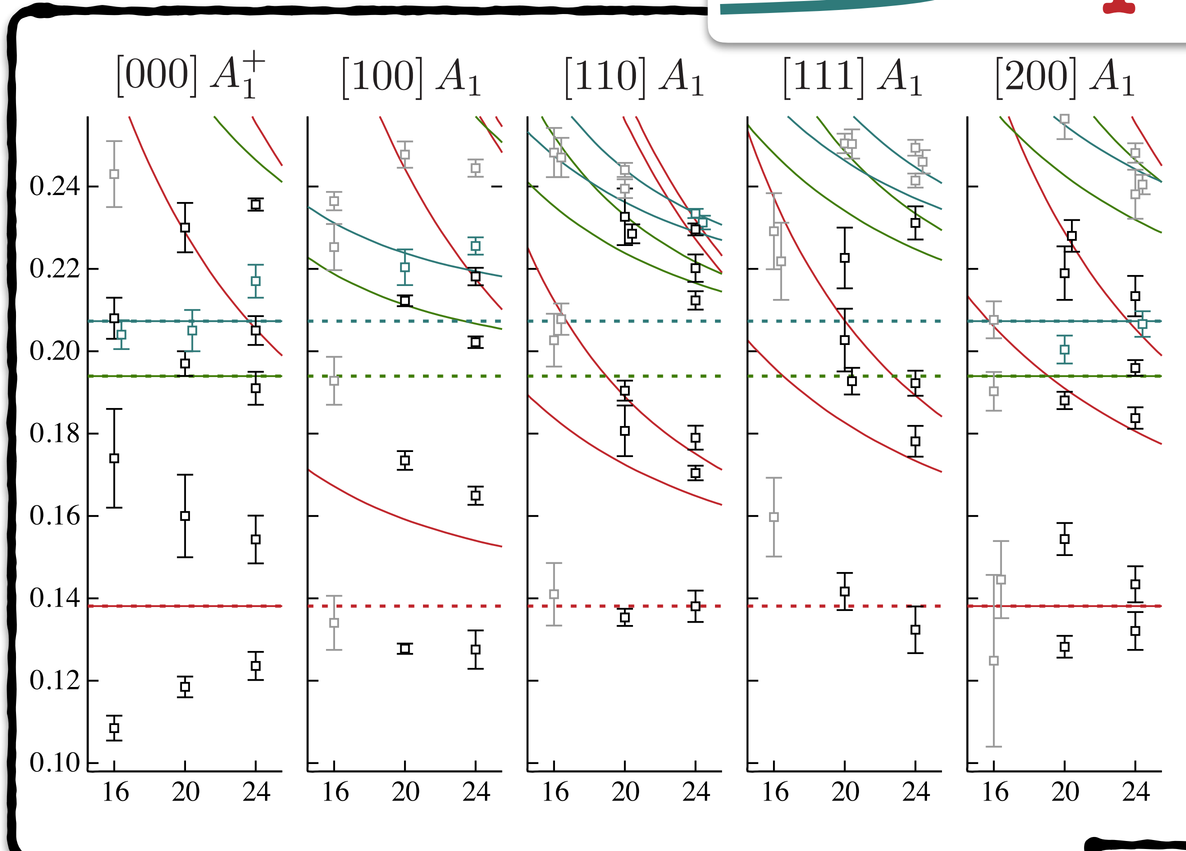
Extracting the spectrum

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

- *Use local and multi-hadron ops ~ 20-30 ops*
- Evaluate all Wick contraction: **distillation** [Peardon, *et al.* (2009)]
- *Variationally* optimize operators [Michael (1985), Lüscher & Wolff (1990)]
- extract ~ 30 - 100 energy levels



m_π=236 MeV

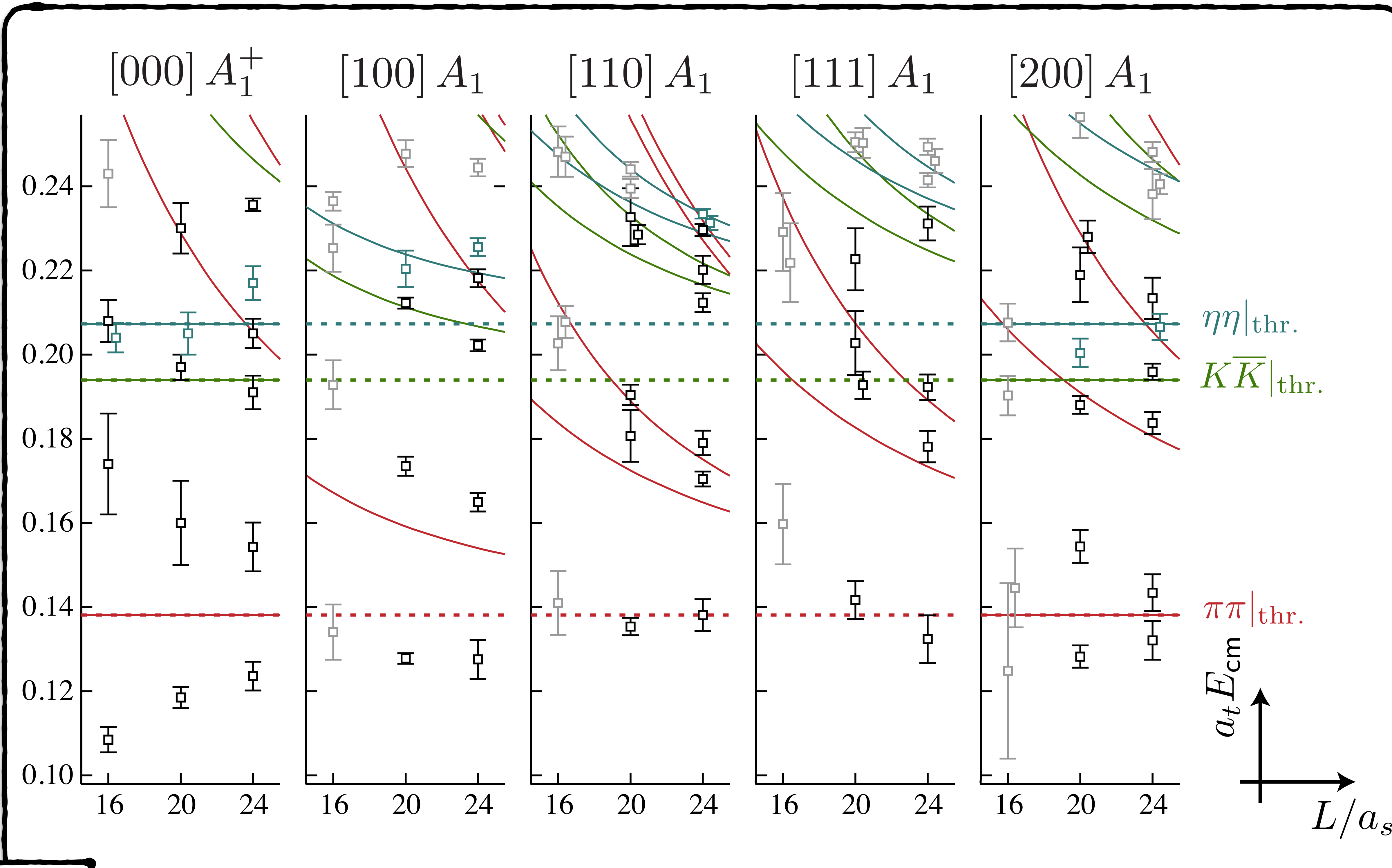


m_π=391 MeV

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

Isoscalar spectra: S-wave dominant

- Multi-meson ops. are crucial
- Spectrum including a larger basis: $\{\pi\pi, K\overline{K}, \eta\eta, \ell\bar{\ell}, s\bar{s}\}$



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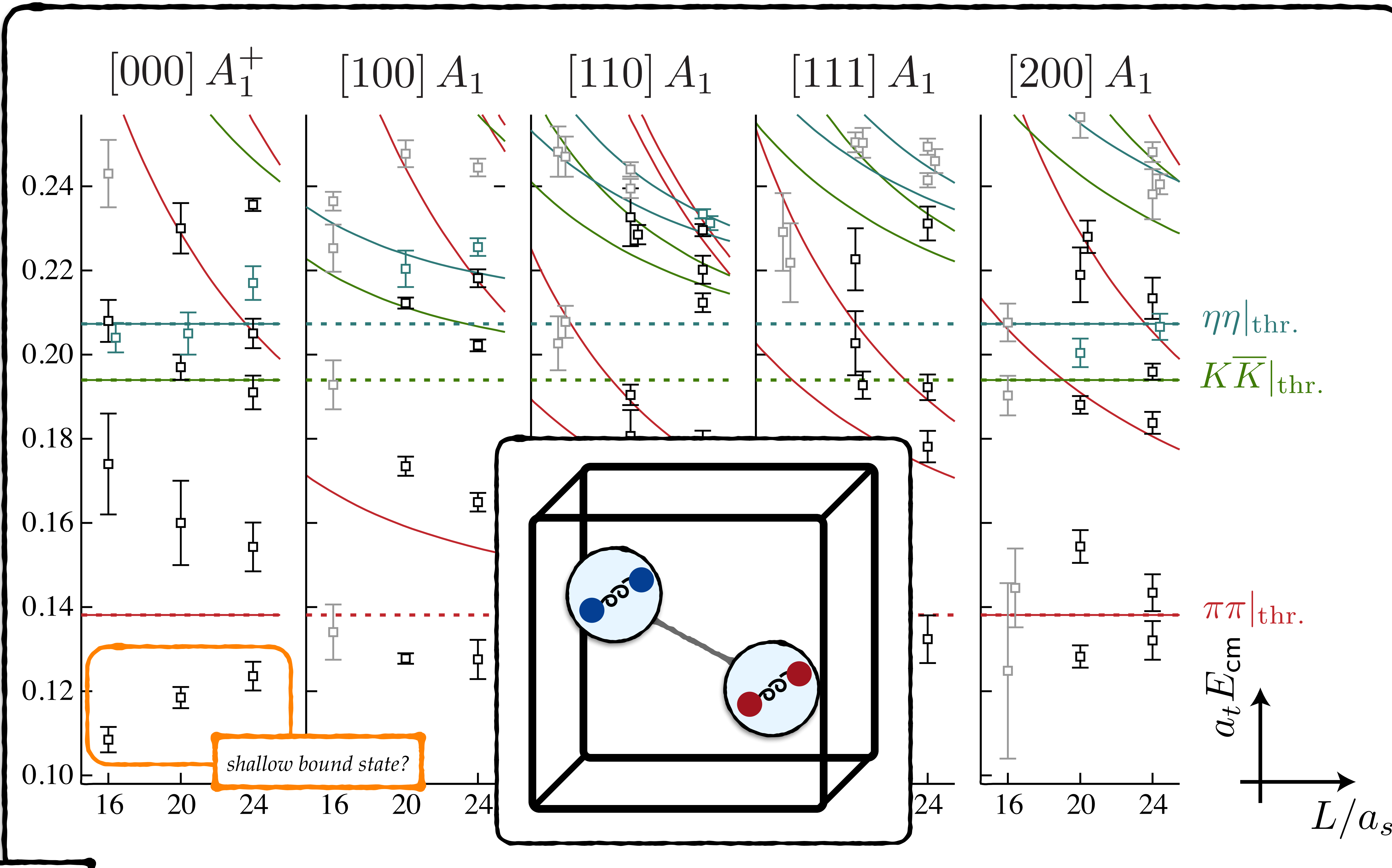

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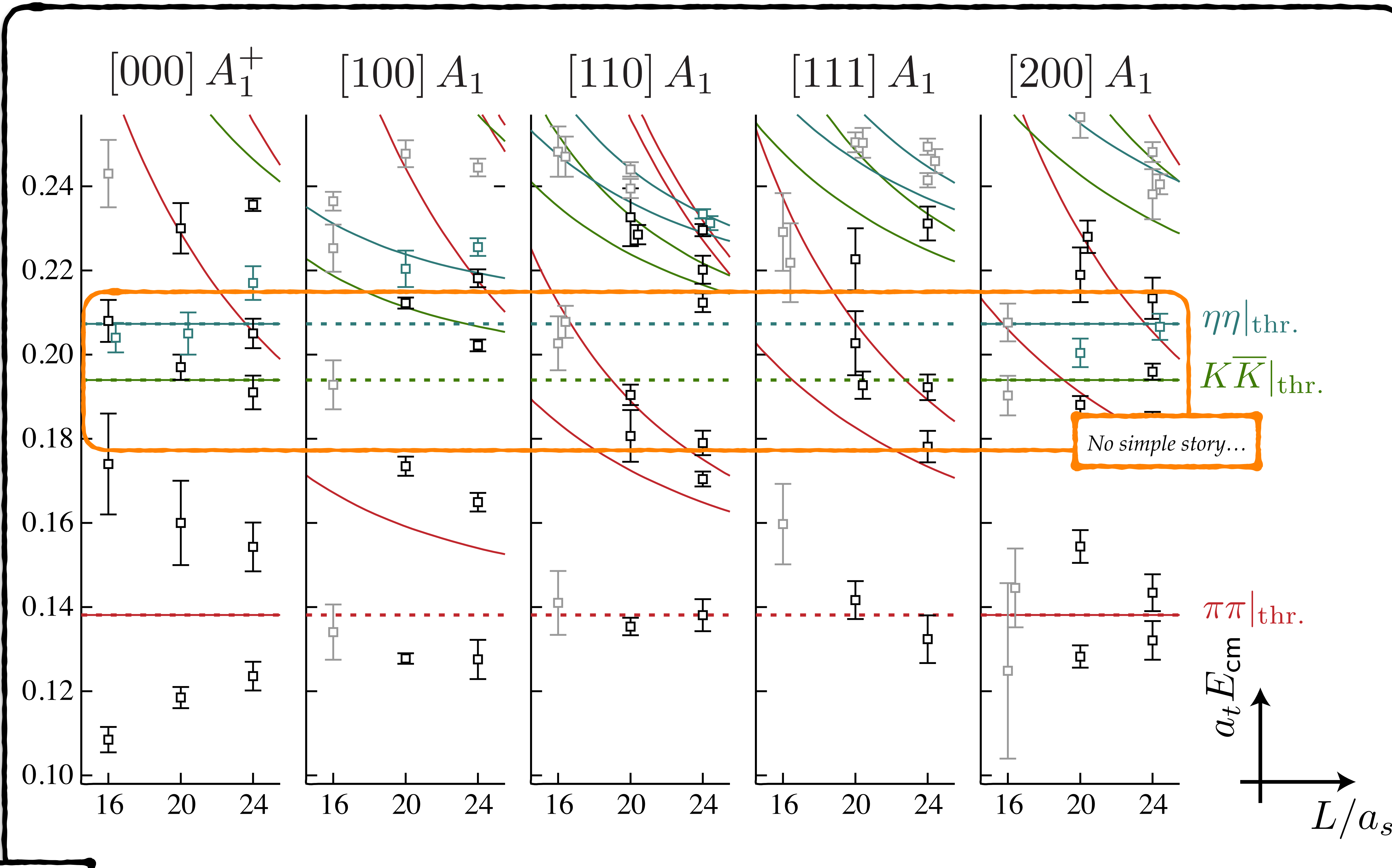

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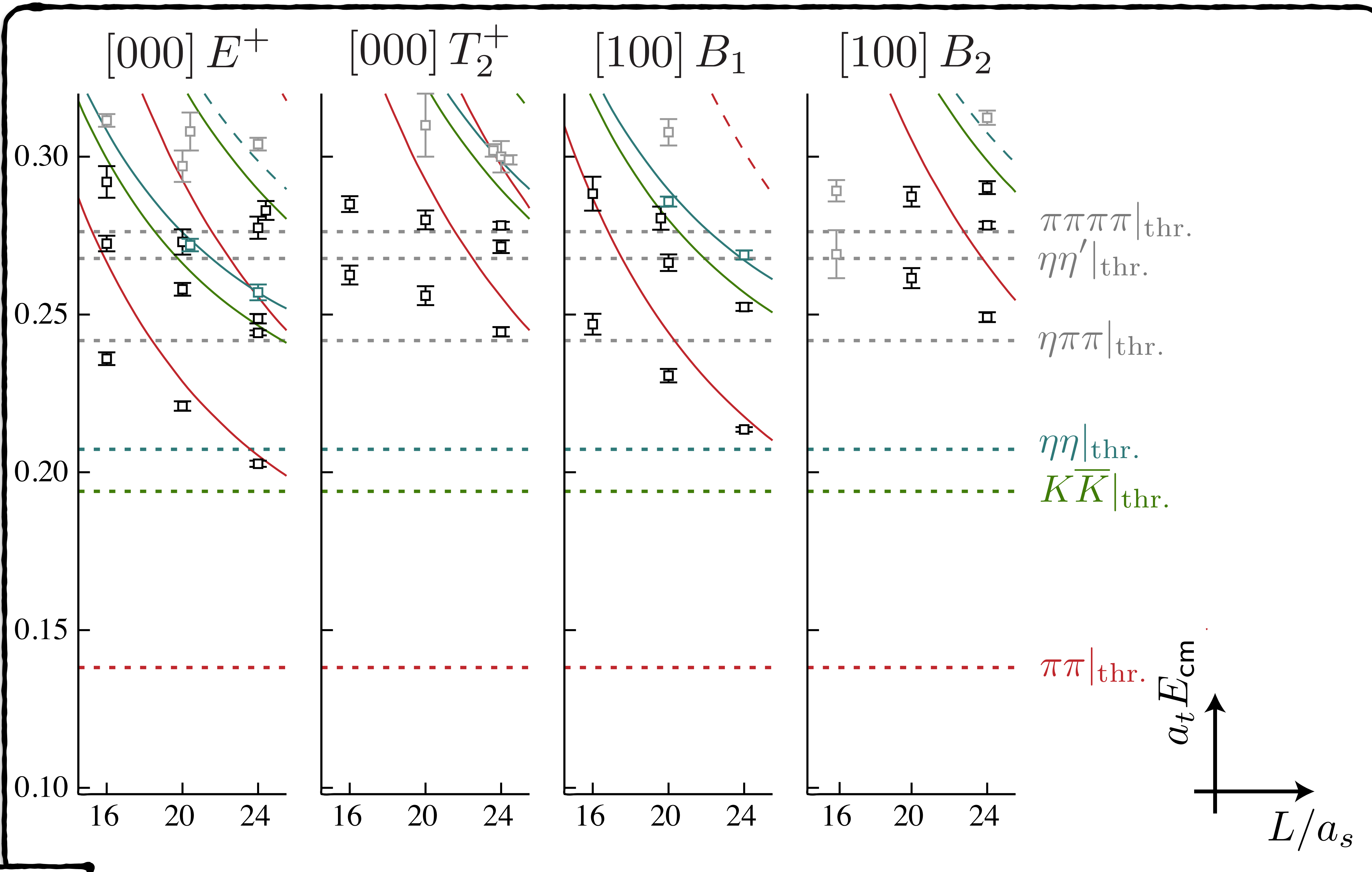

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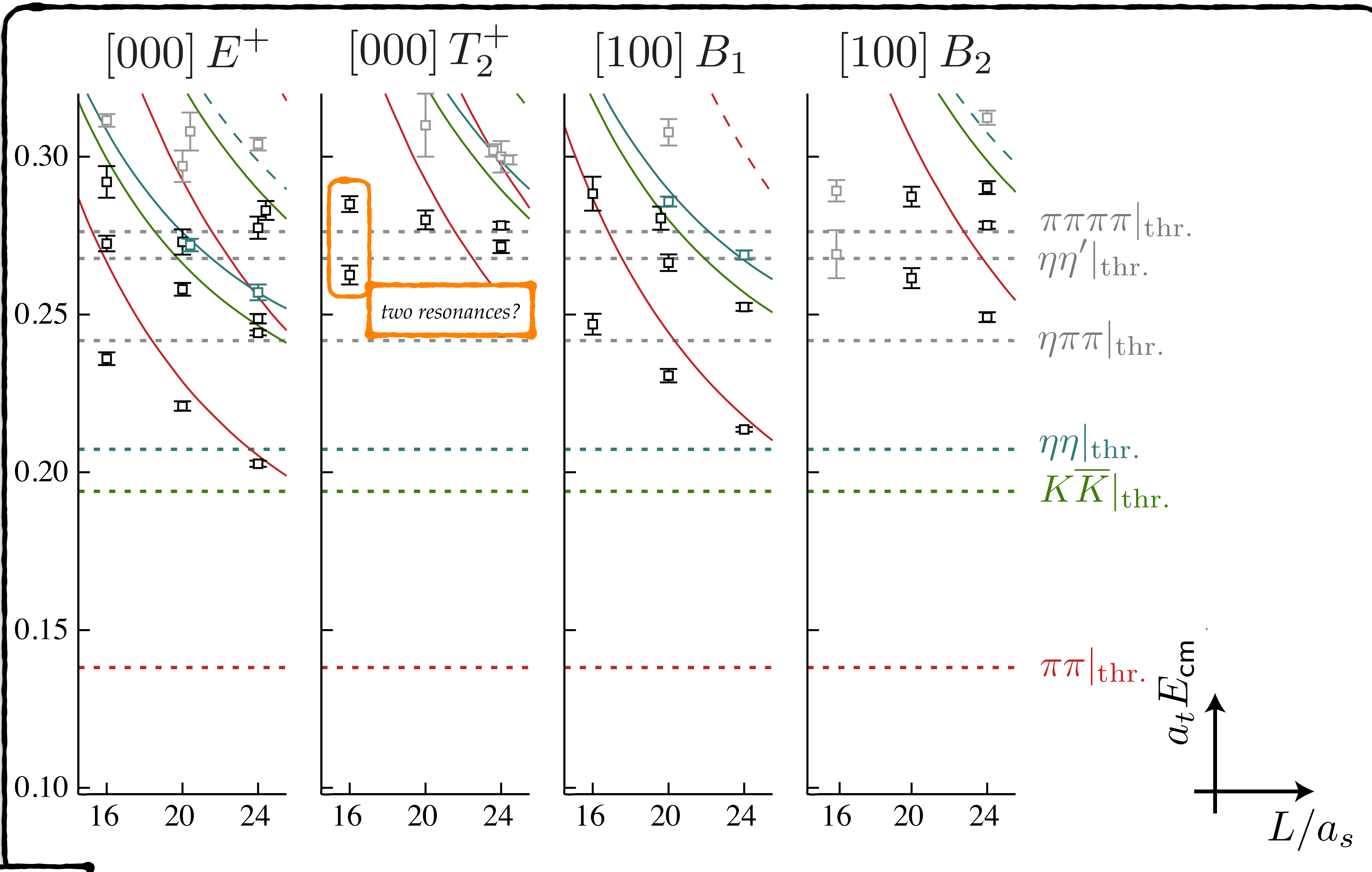

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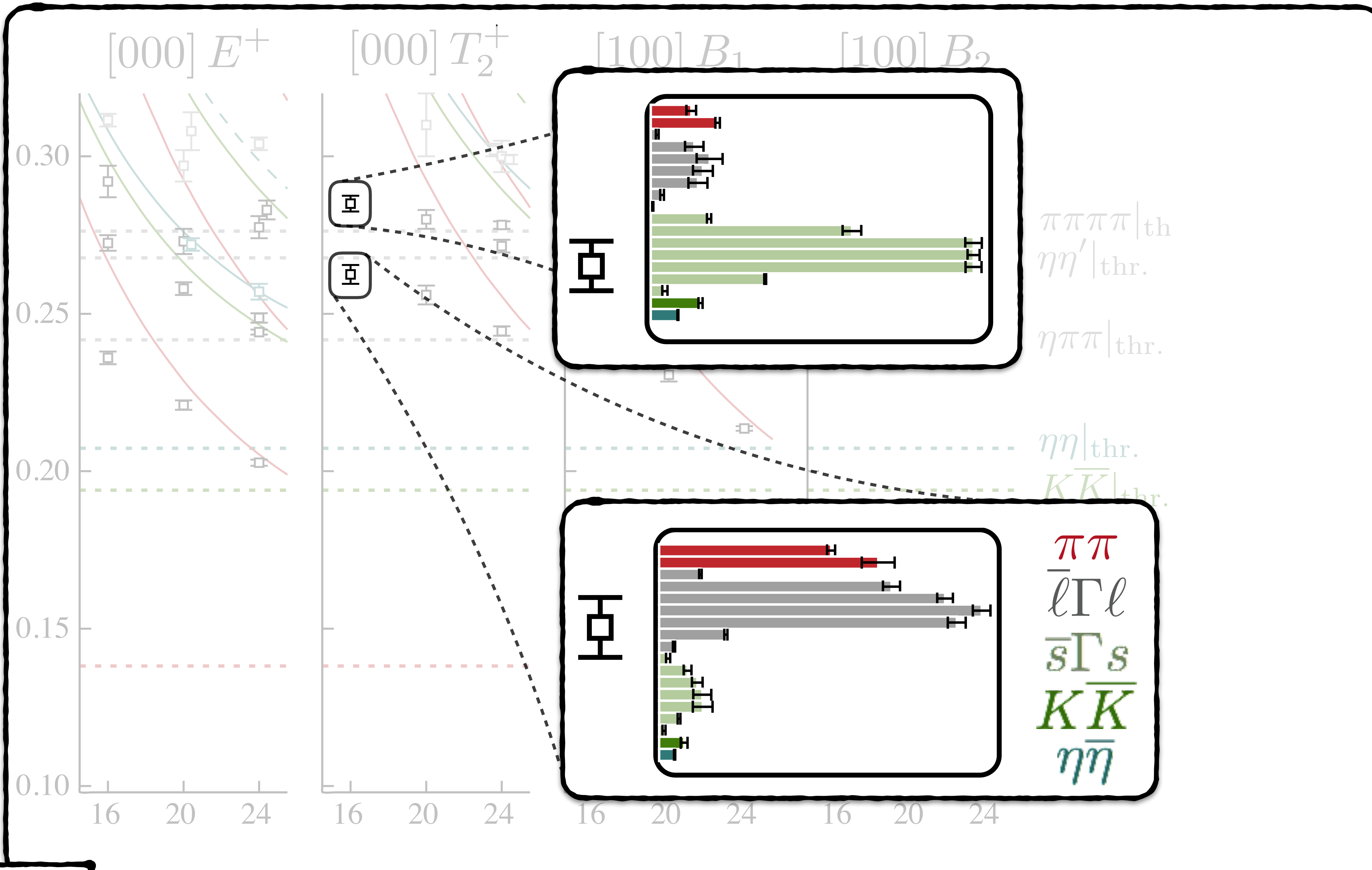

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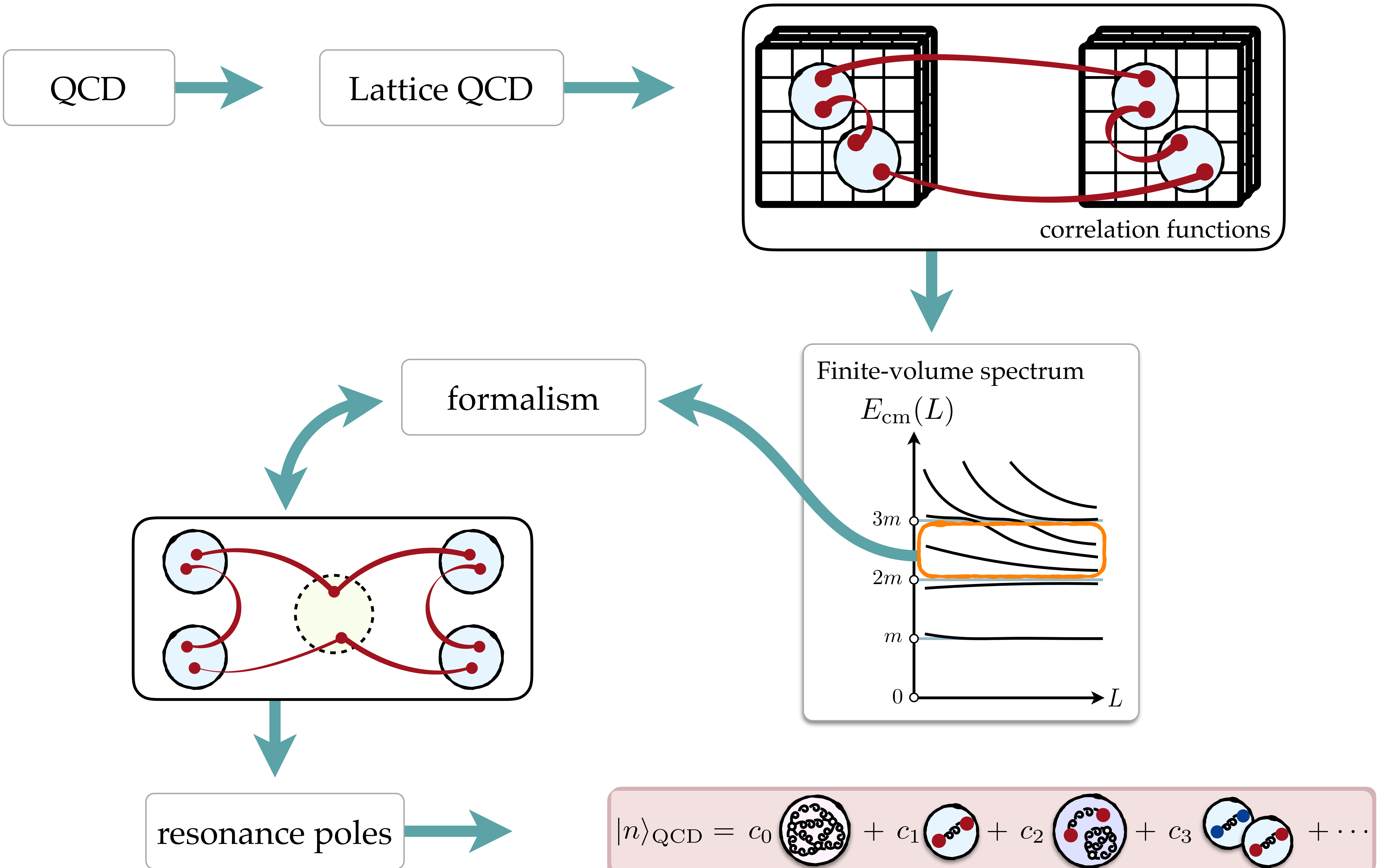
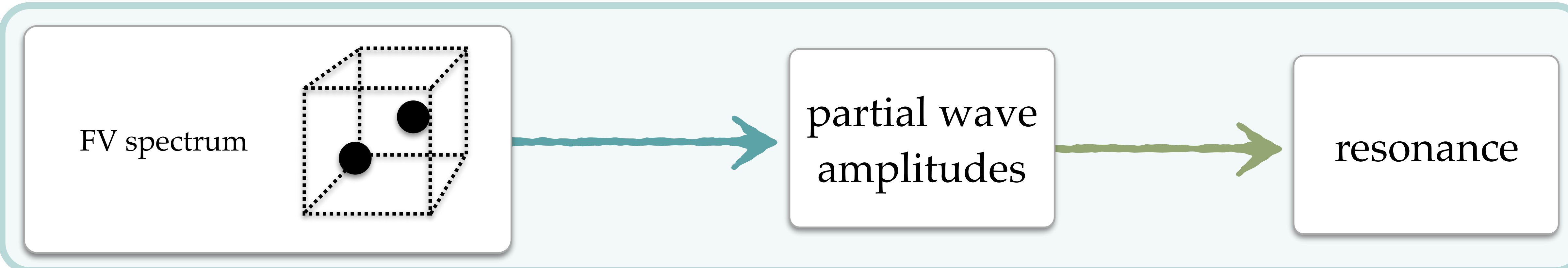


Scattering amplitudes

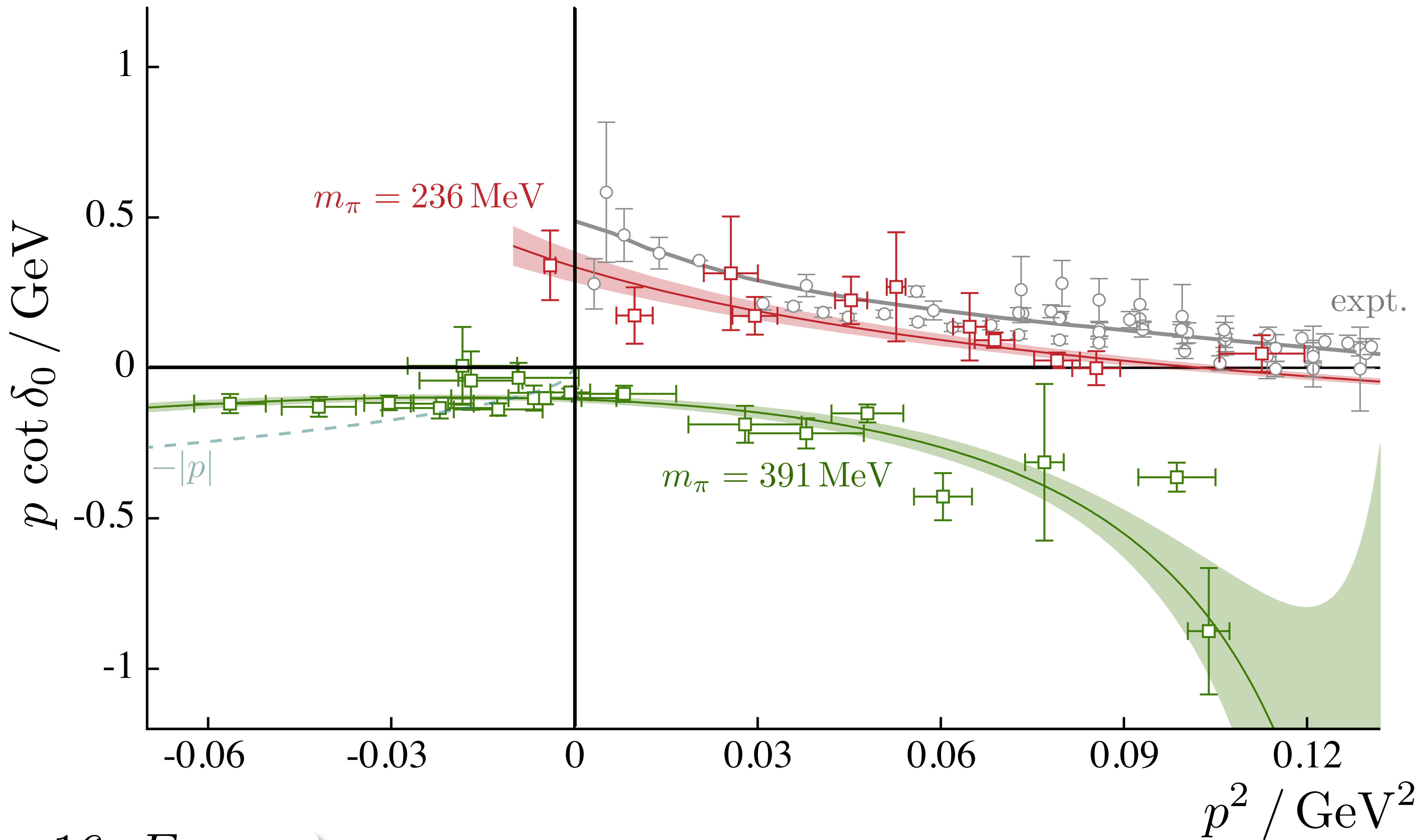


$$\det[F^{-1}(E_L, L) + \mathcal{M}(E_L)] = 0$$

E_L = finite volume spec.
L = finite volume
F = known function
$\mathcal{M}$ = scattering amp.

- Lüscher (1986, 1991) [elastic scalar bosons]
- Rummukainen & Gottlieb (1995) [moving elastic scalar bosons]
- Kim, Sachrajda, & Sharpe/Christ, Kim & Yamazaki (2005) [QFT derivation]
- Feng, Li, & Liu (2004) [inelastic scalar bosons]
- Hansen & Sharpe / RB & Davoudi (2012) [moving inelastic scalar bosons]
- RB (2014) [general 2-body result]

Isoscalar $\pi\pi$ scattering: elastic region



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

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

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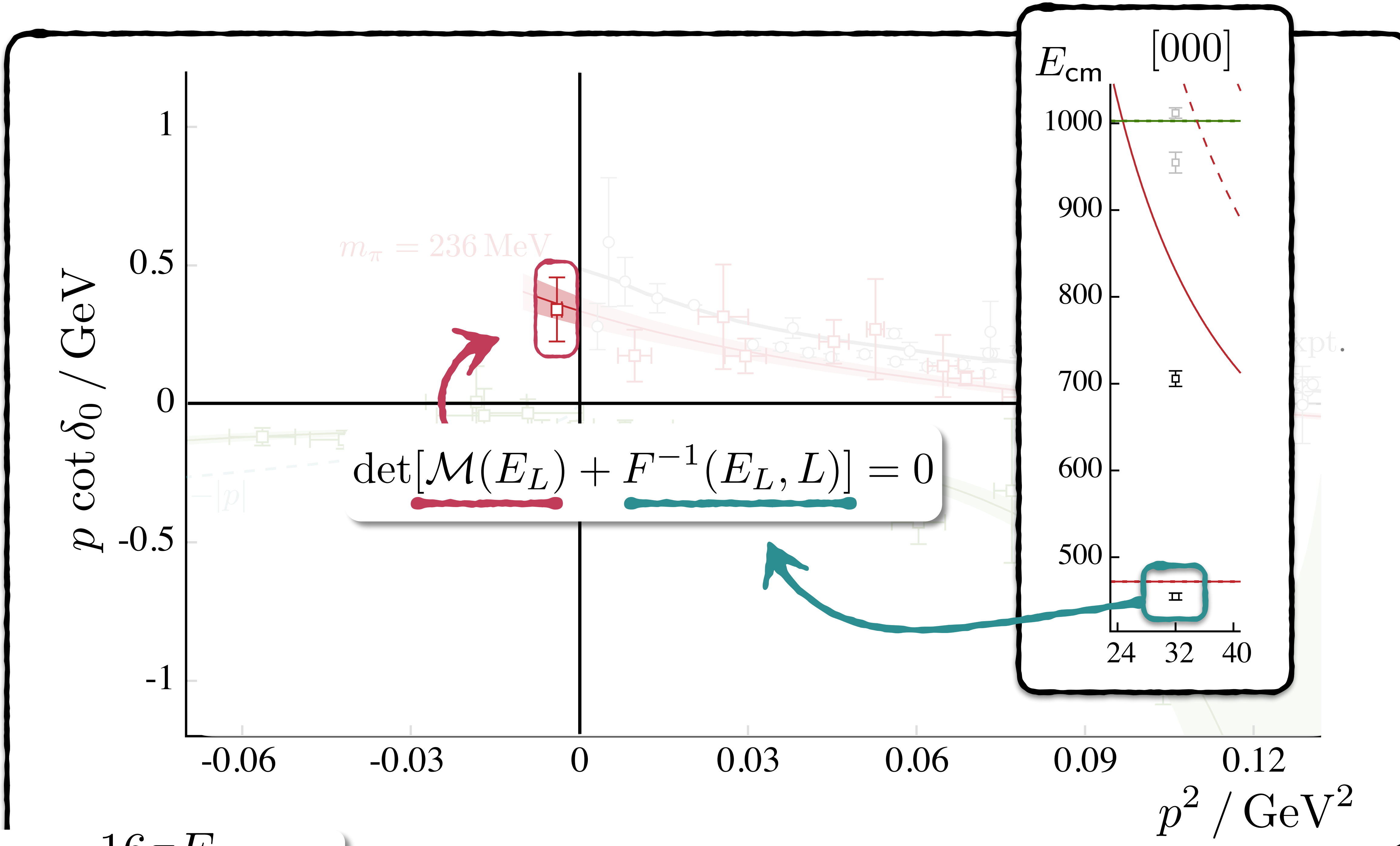

$$\det[\mathcal{M}(E_L) + F^{-1}(E_L, L)] = 0$$

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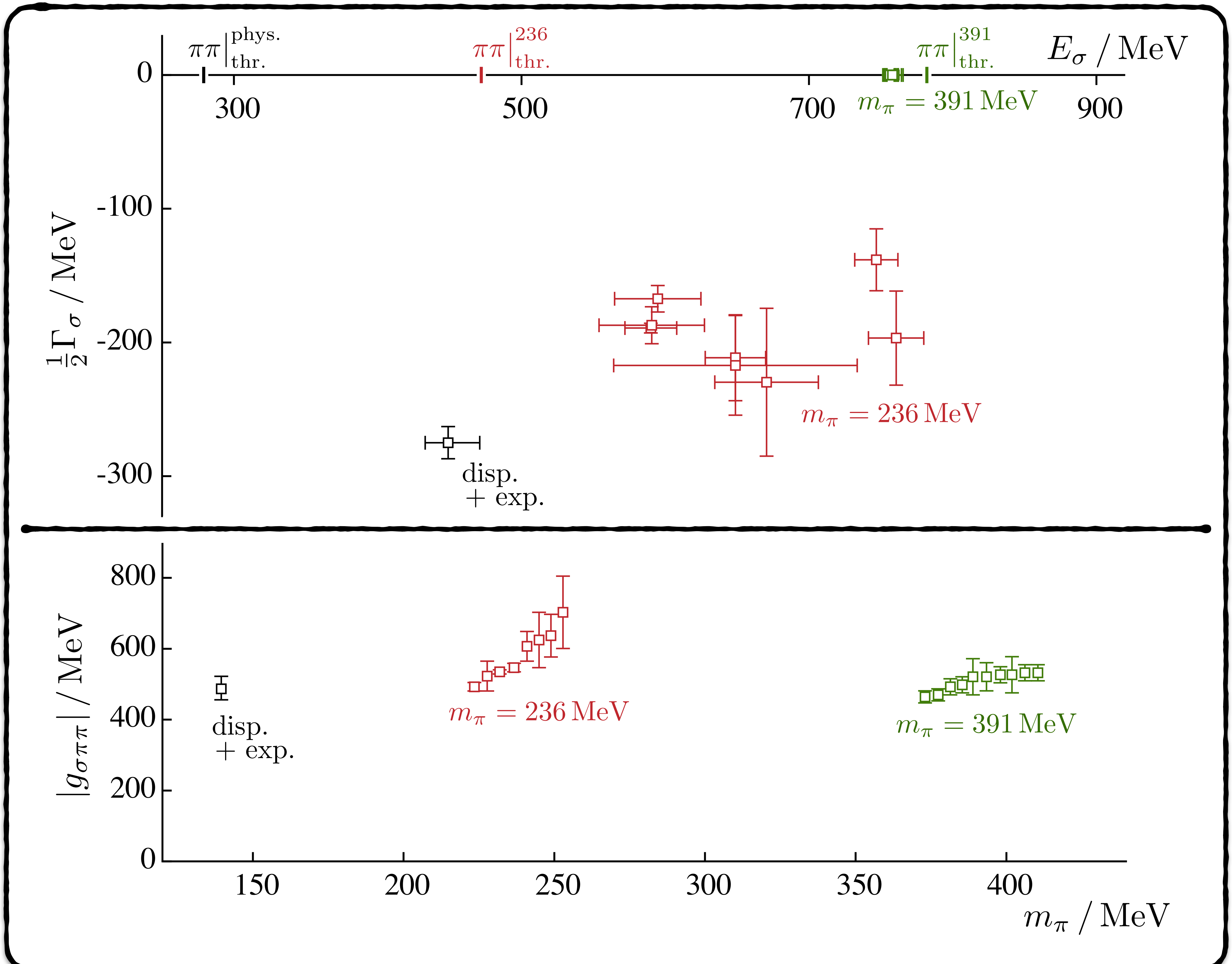
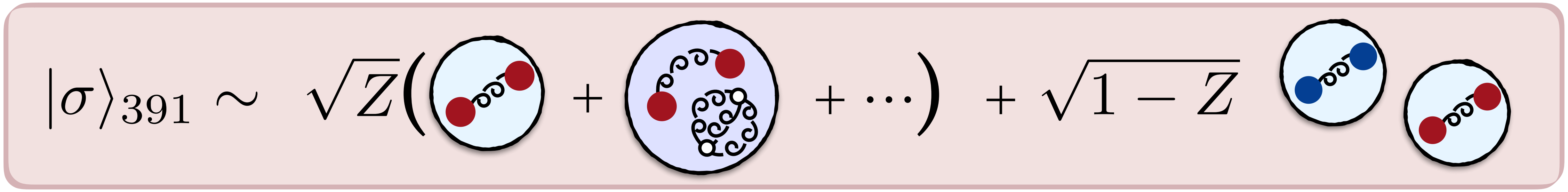
RB, Dudek, Edwards, Wilson - PRL (2017)

The $\sigma / f_0(500)$ vs m_π



Weinberg compositeness criterion for the σ

- For the heavier ensemble, the σ is a bound state, so we can apply Weinberg's criterion

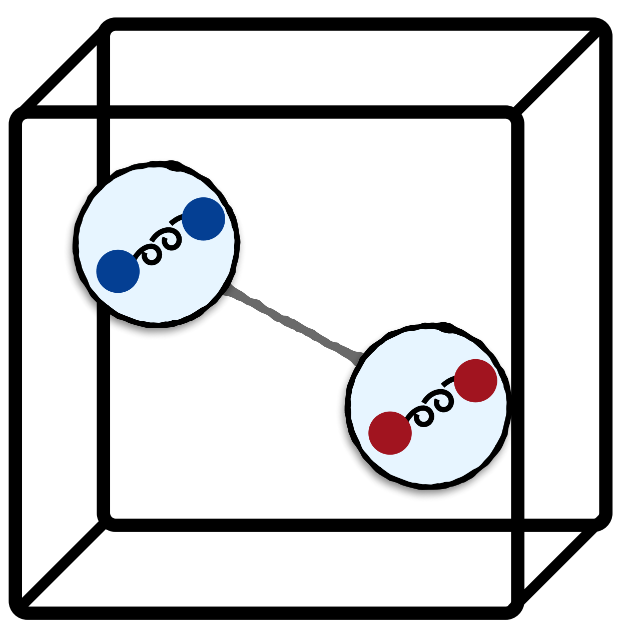


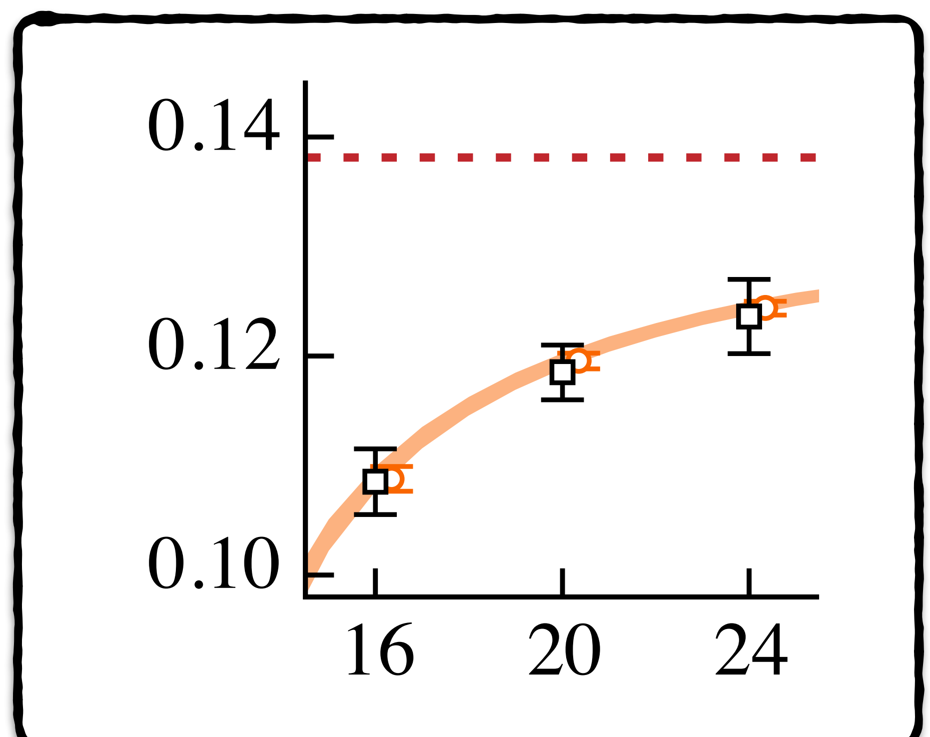
- Can relate Z to scattering information

$$a = -2\frac{1-Z}{2-Z}\frac{1}{\sqrt{m_\pi B_\sigma}}, \qquad r = -\frac{Z}{1-Z}\frac{1}{\sqrt{m_\pi B_\sigma}}$$

- To obtain: $Z \sim 0.3(1)$

- Consistent with the large FV effects





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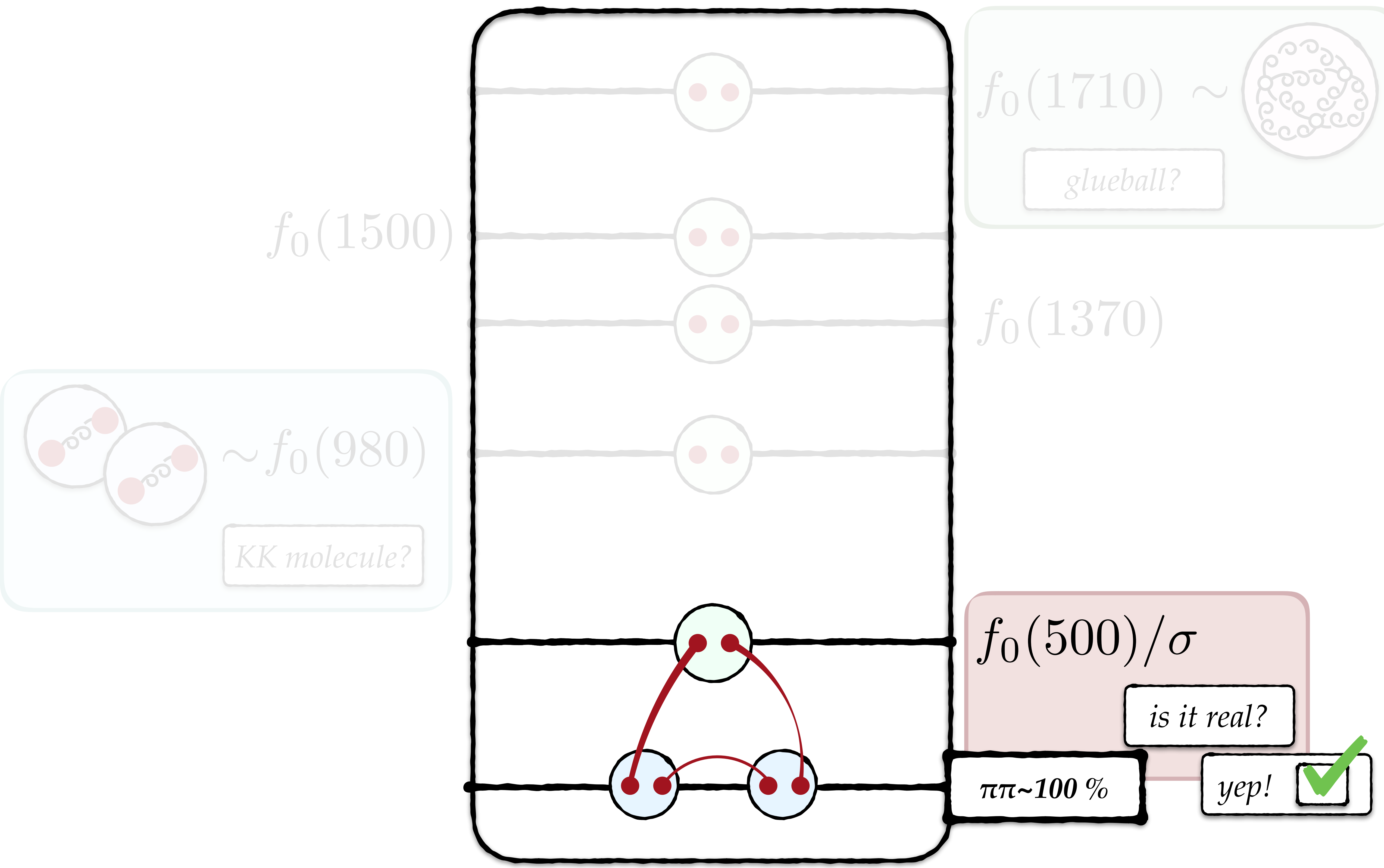
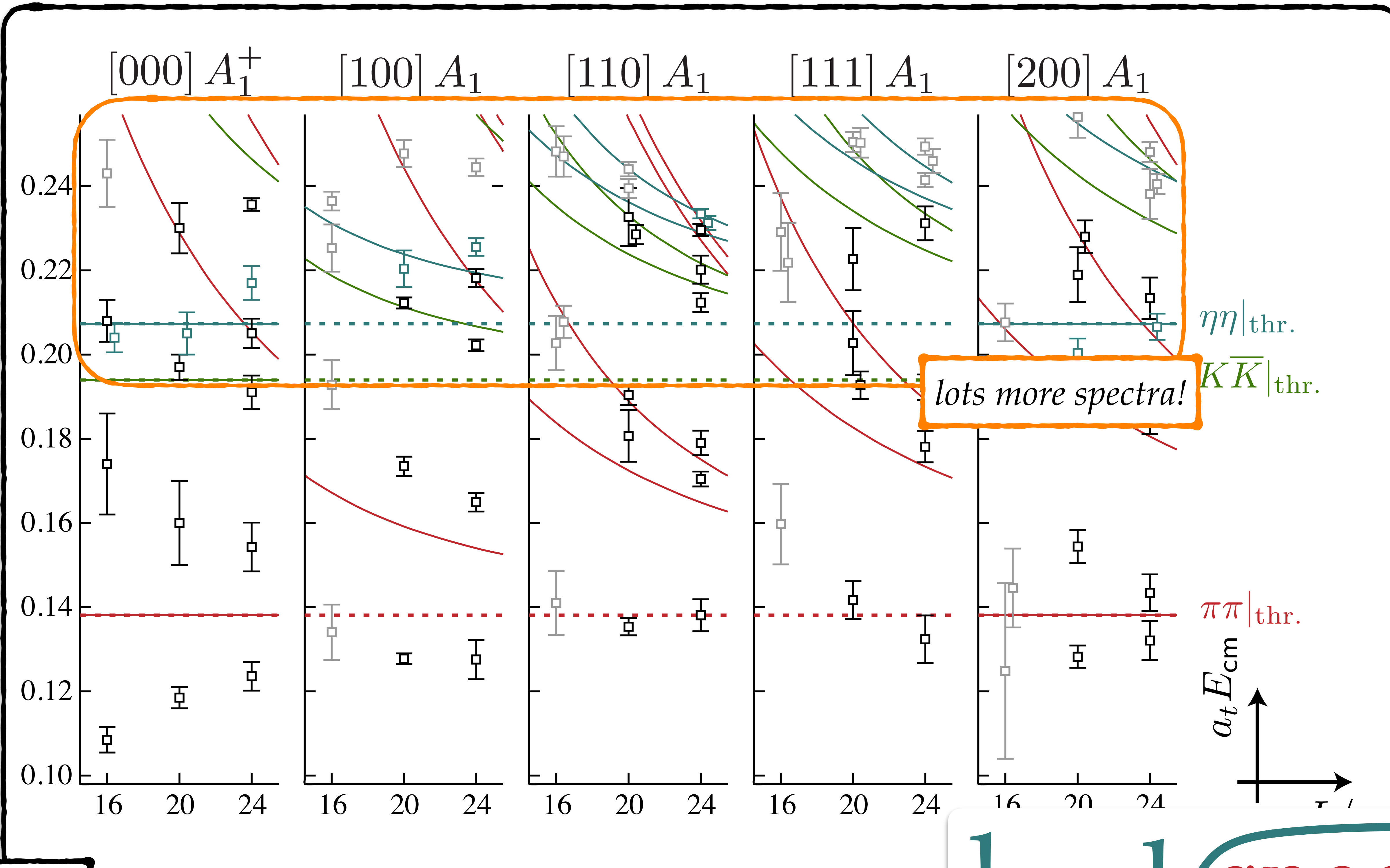


Multi-channel systems - the cutting edge!



m_π=391 MeV

hadspec

Multi-channel systems - the cutting edge!

- the *necessary* formalism for doing coupled-channel scattering of scalar systems was set in place in 2012

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 - PRL (2017)
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)

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Dπ, Dη, D_sK:	Moir, Peardon, Ryan, Thomas, Wilson - JHEP (2016)
$\pi\pi$, KK [isovector]:	Wilson, RB, Dudek, Edwards, Thomas - PRD (2015)

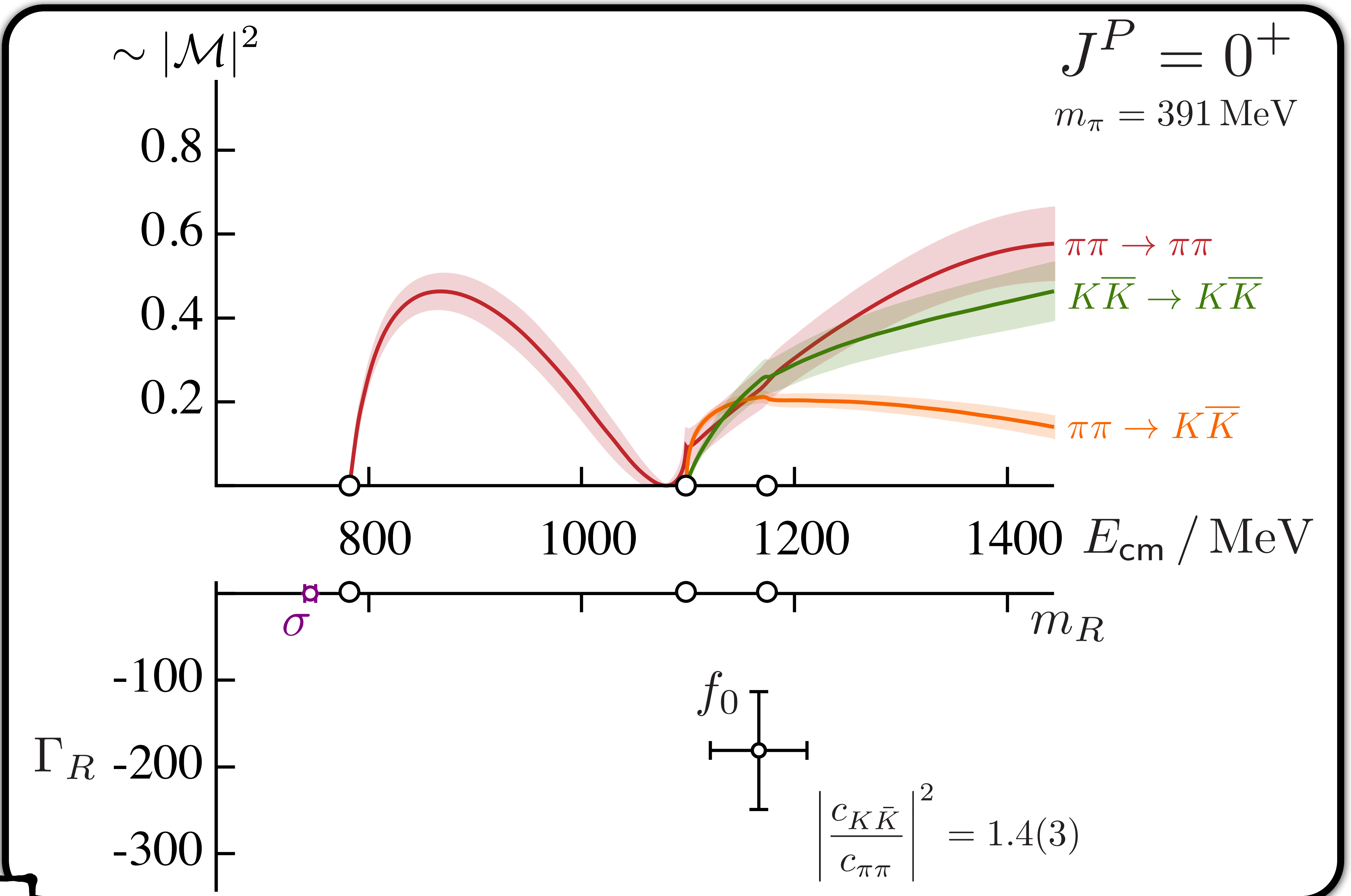
…the other common denominator…

Wilson (Royal fellow / Trinity)

hadspec

Multi-channel systems - the cutting edge!

- *Coupled channels:* e.g., S-wave $\pi\pi$, $K\overline{K}$



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RB, Dudek, Edwards & Wilson (2017)

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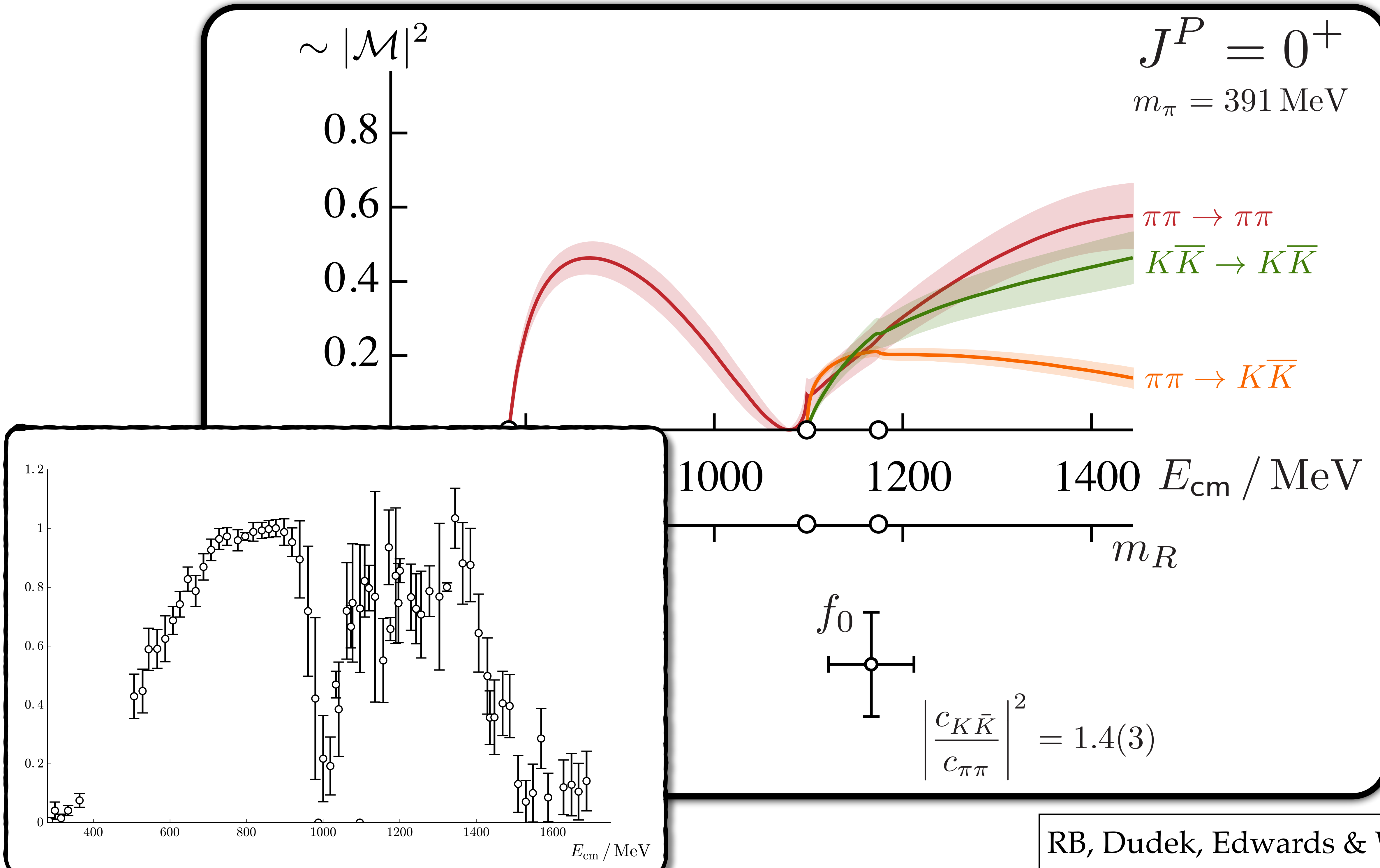

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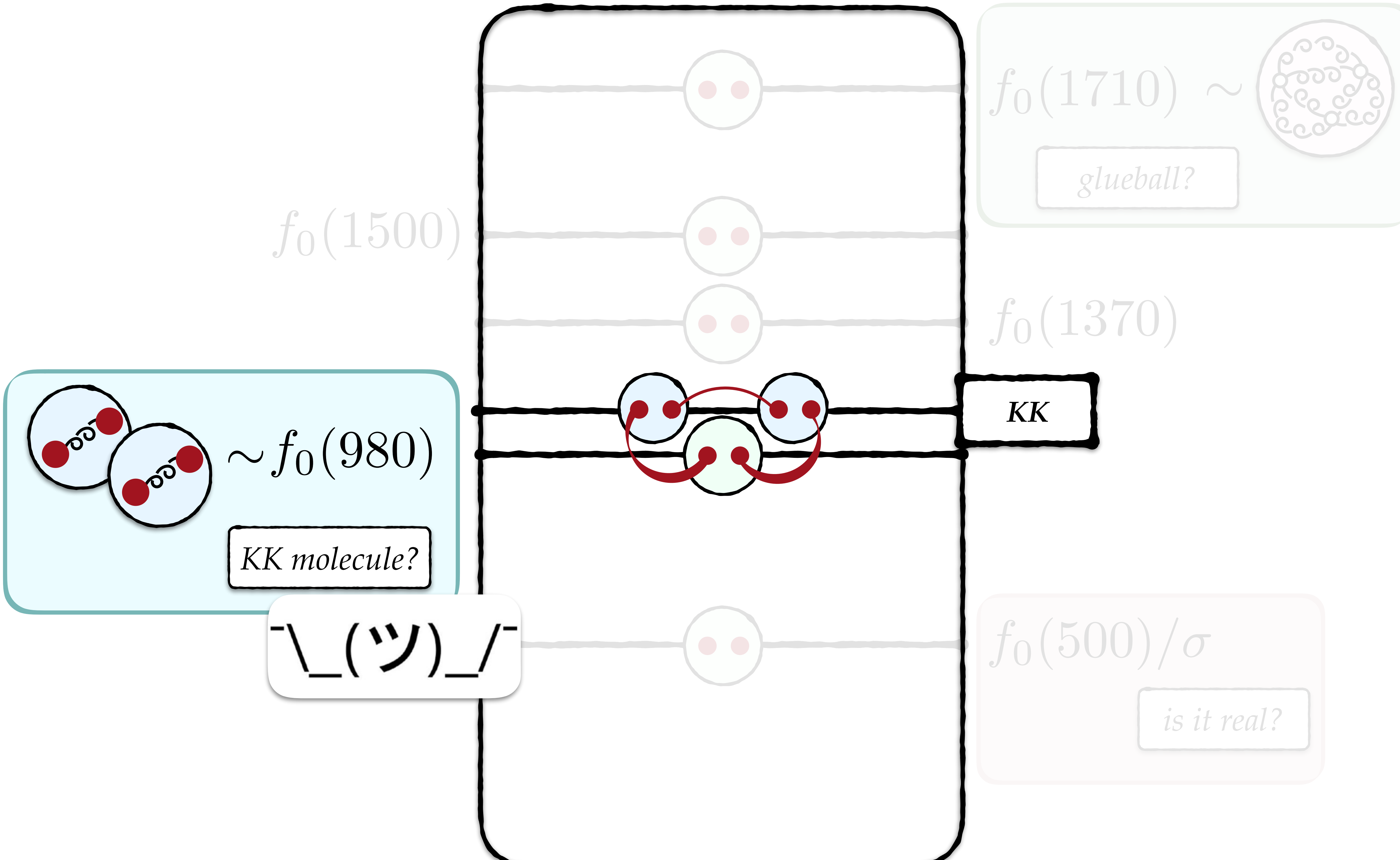

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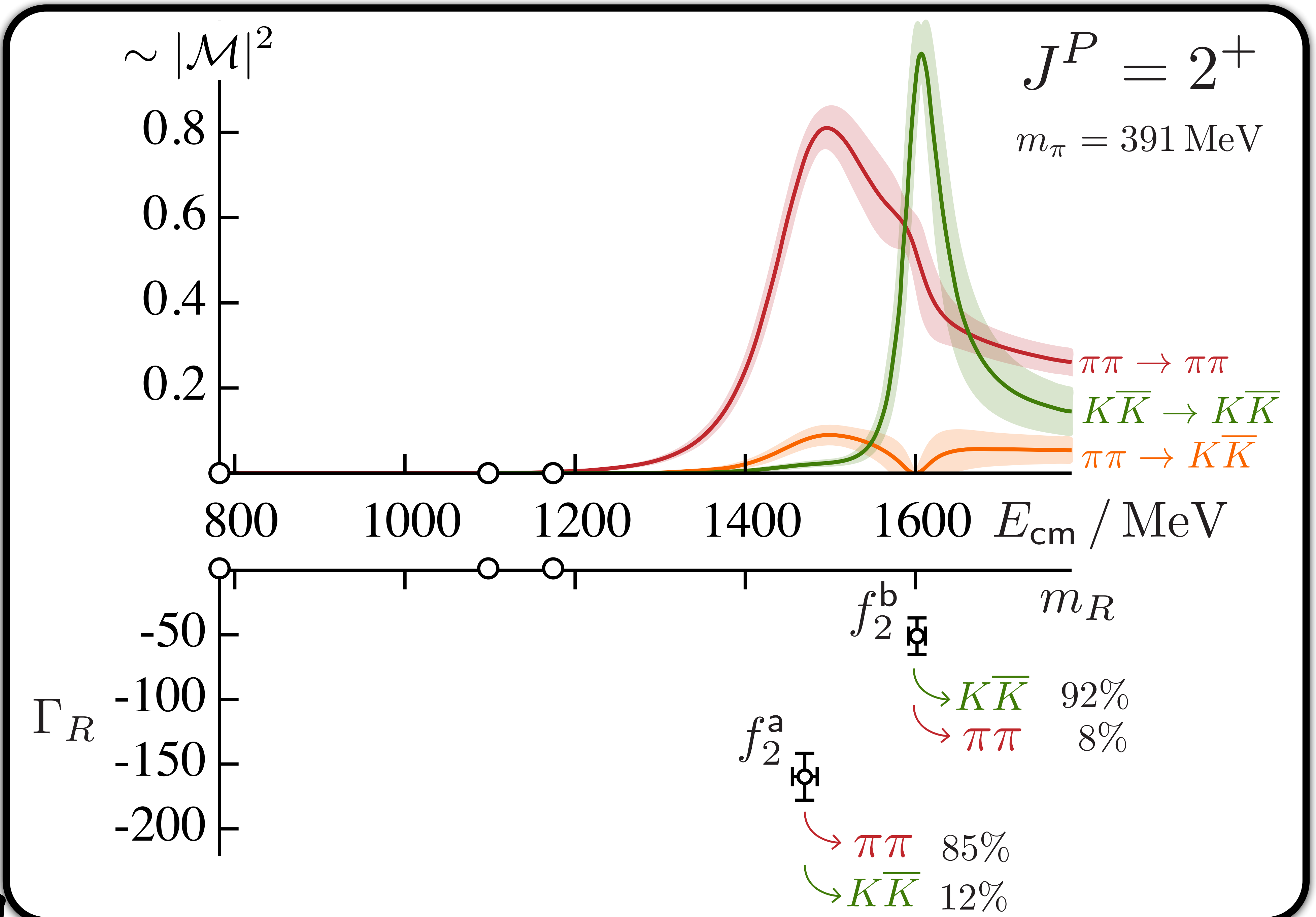

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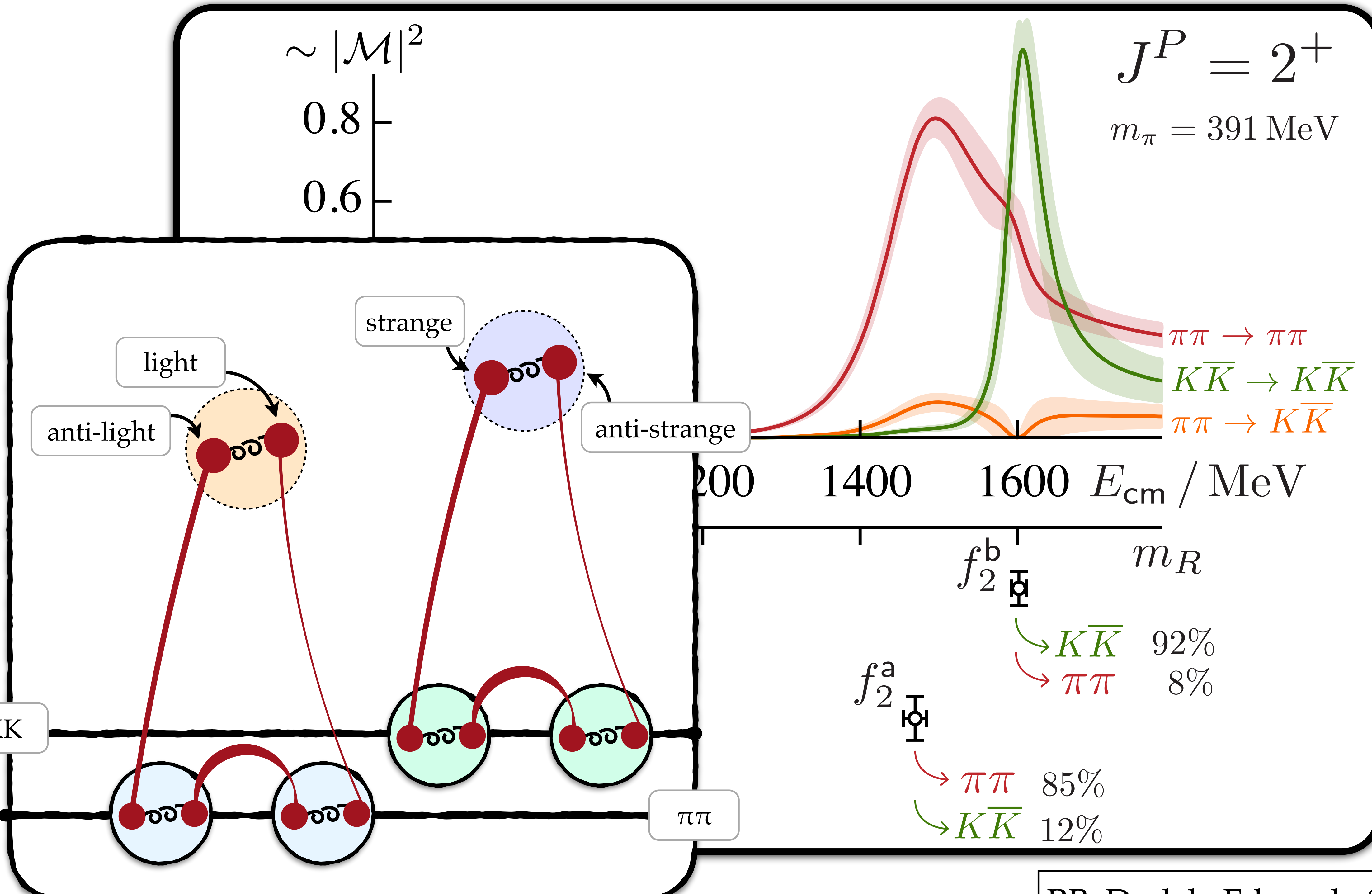
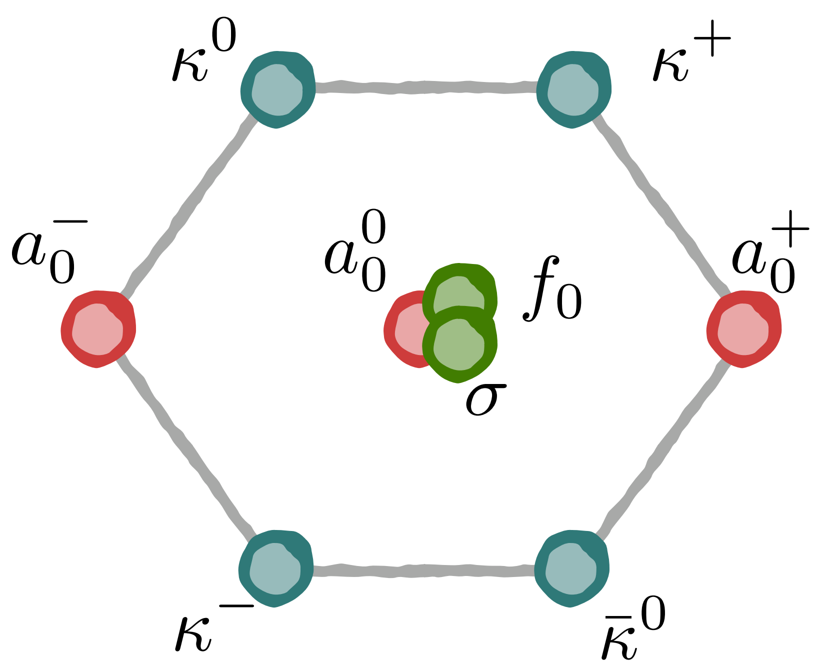
- *Coupled channels:* e.g., D-wave $\pi\pi$, $K\overline{K}$

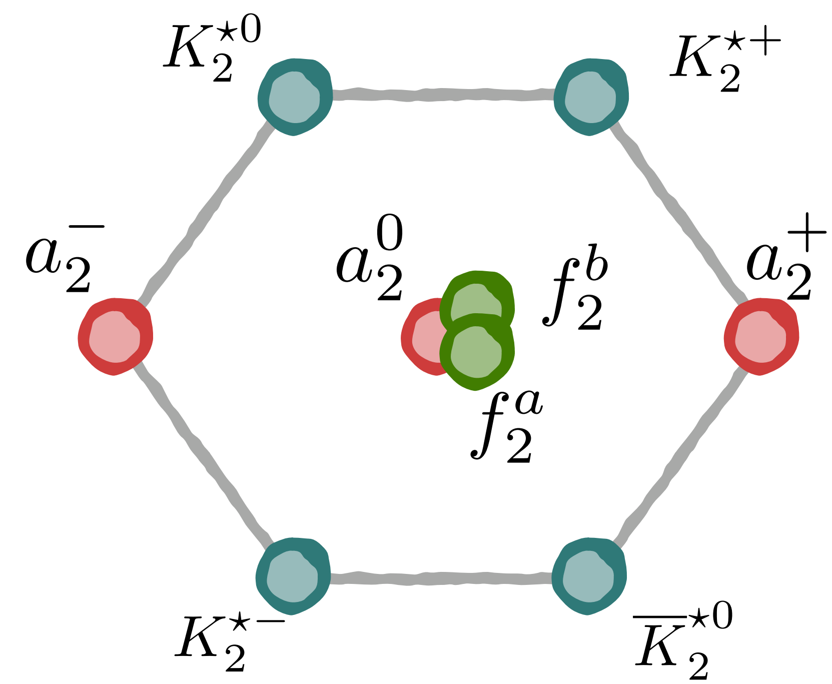


RB, Dudek, Edwards & Wilson (2017)

Tensor and scalar nonets

- First complete determination of the scalar and tensor nonets from LQCD :

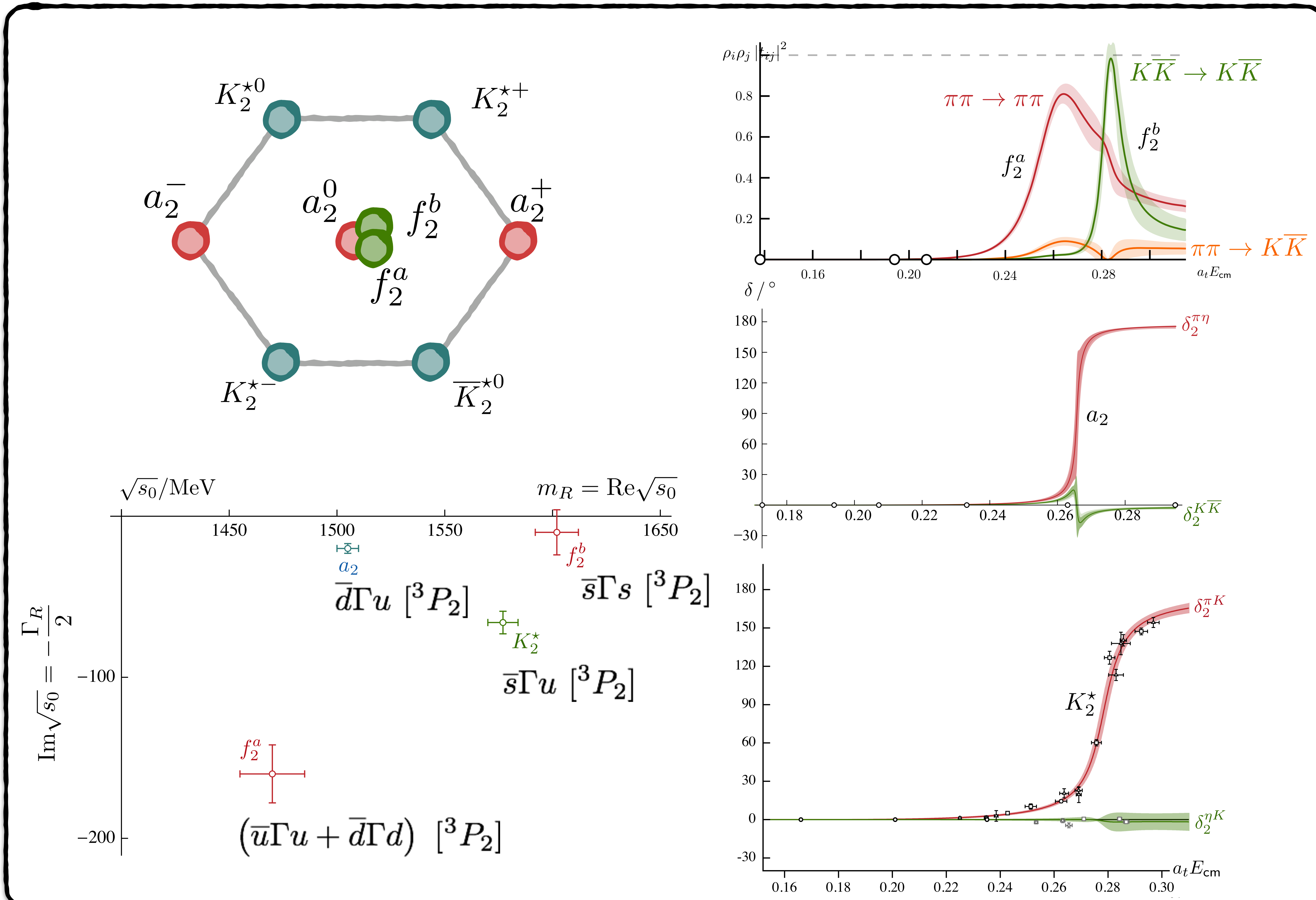




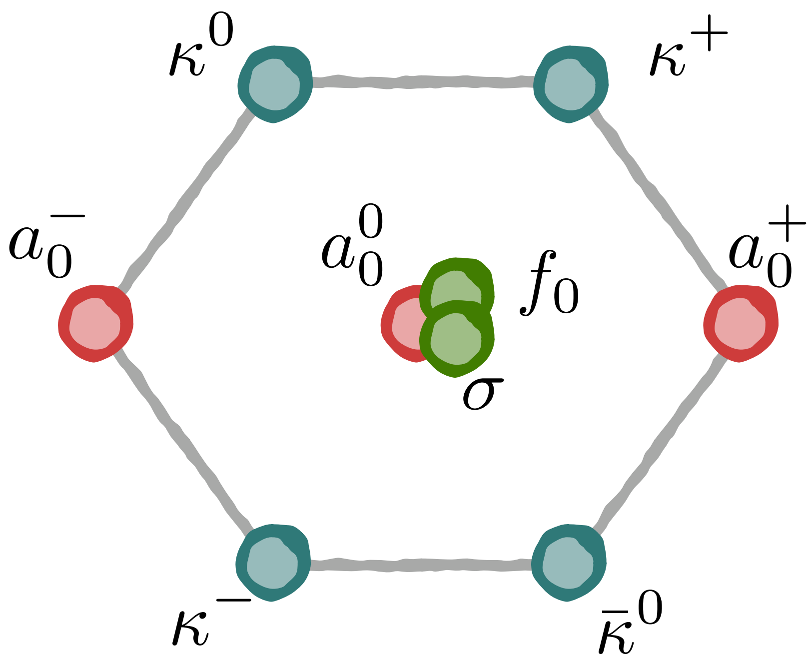
ππ, KK, ηη:	RB, Dudek, Edwards - PRL (2017)
	RB, Dudek, Edwards - arXiv (2017)
Kπ, Kη:	Dudek, Edwards, Thomas, Wilson - PRL (2015)
	Wilson, Dudek, Edwards, Thomas - PRD (2015)
πη, KK:	Dudek, Edwards, Wilson - PRD (2016)

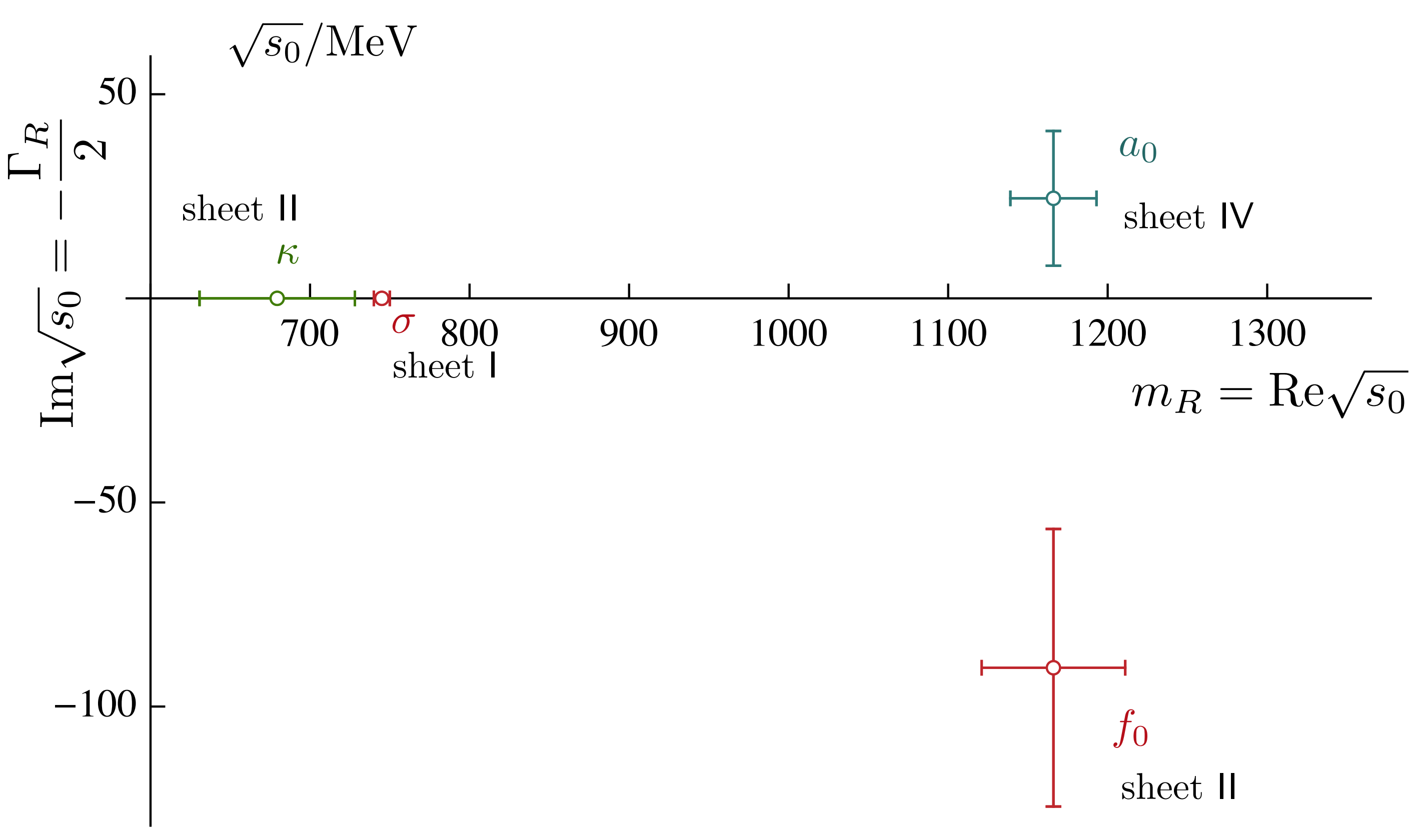
had/spec

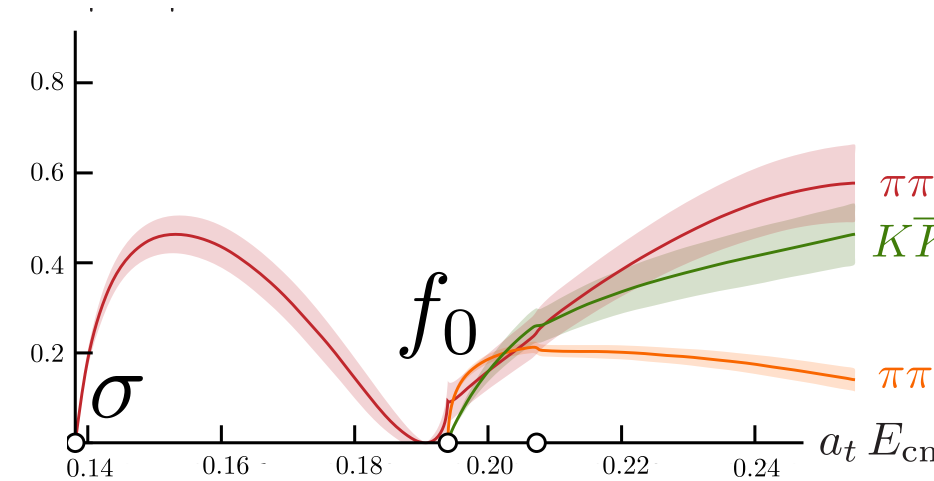
Tensor nonet

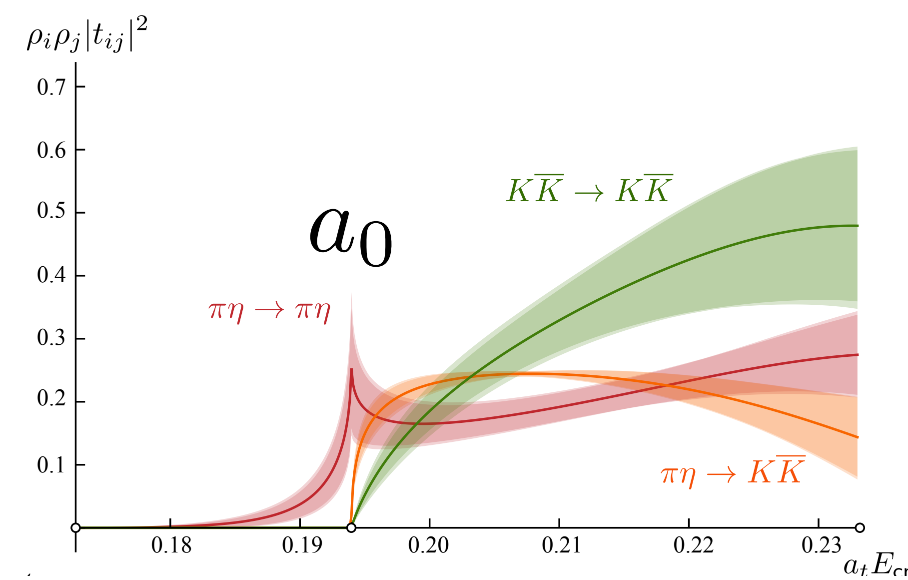


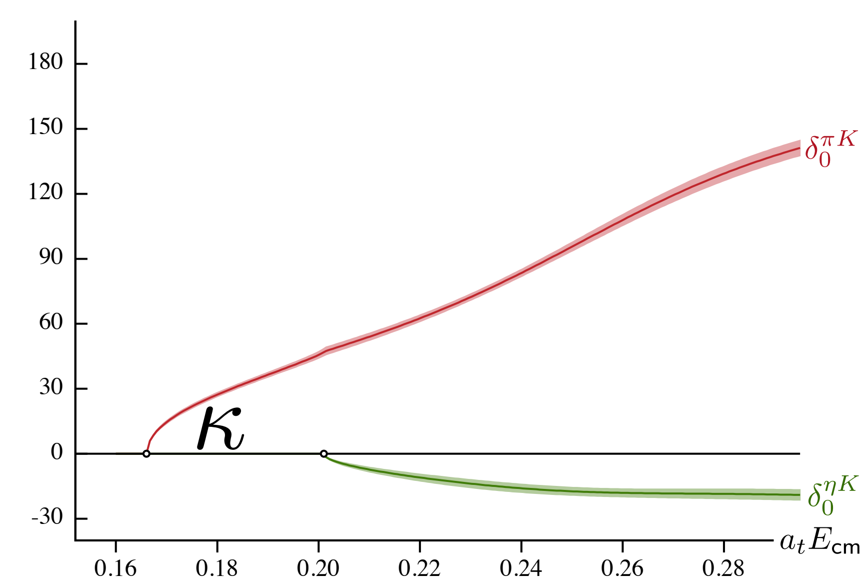
Scalar nonet





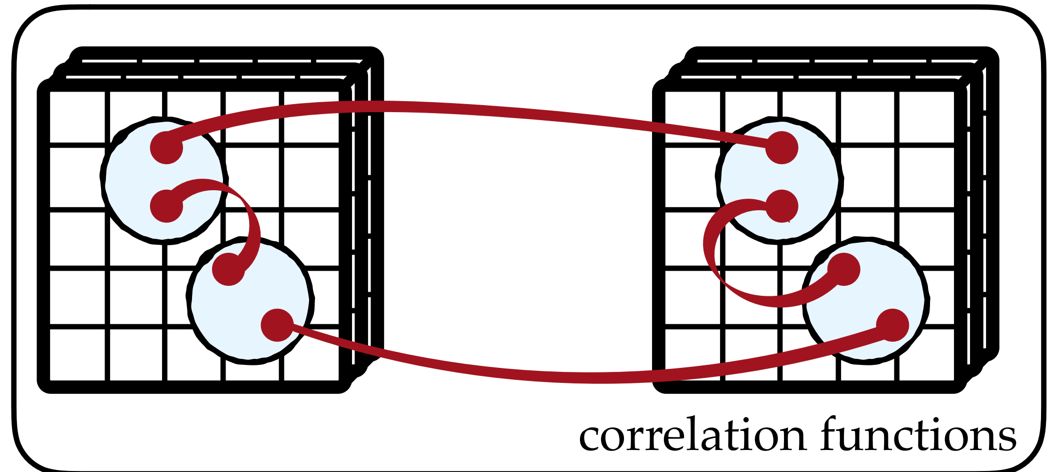


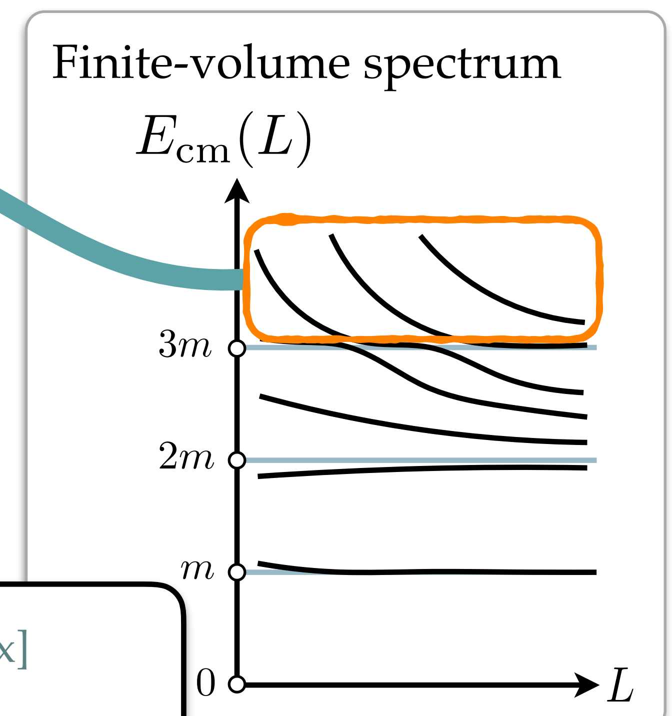


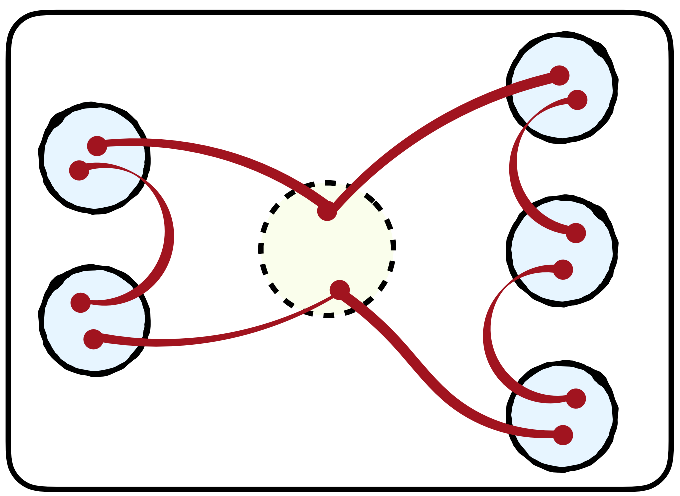


Obtaining the QCD spectrum

QCD → Lattice QCD →





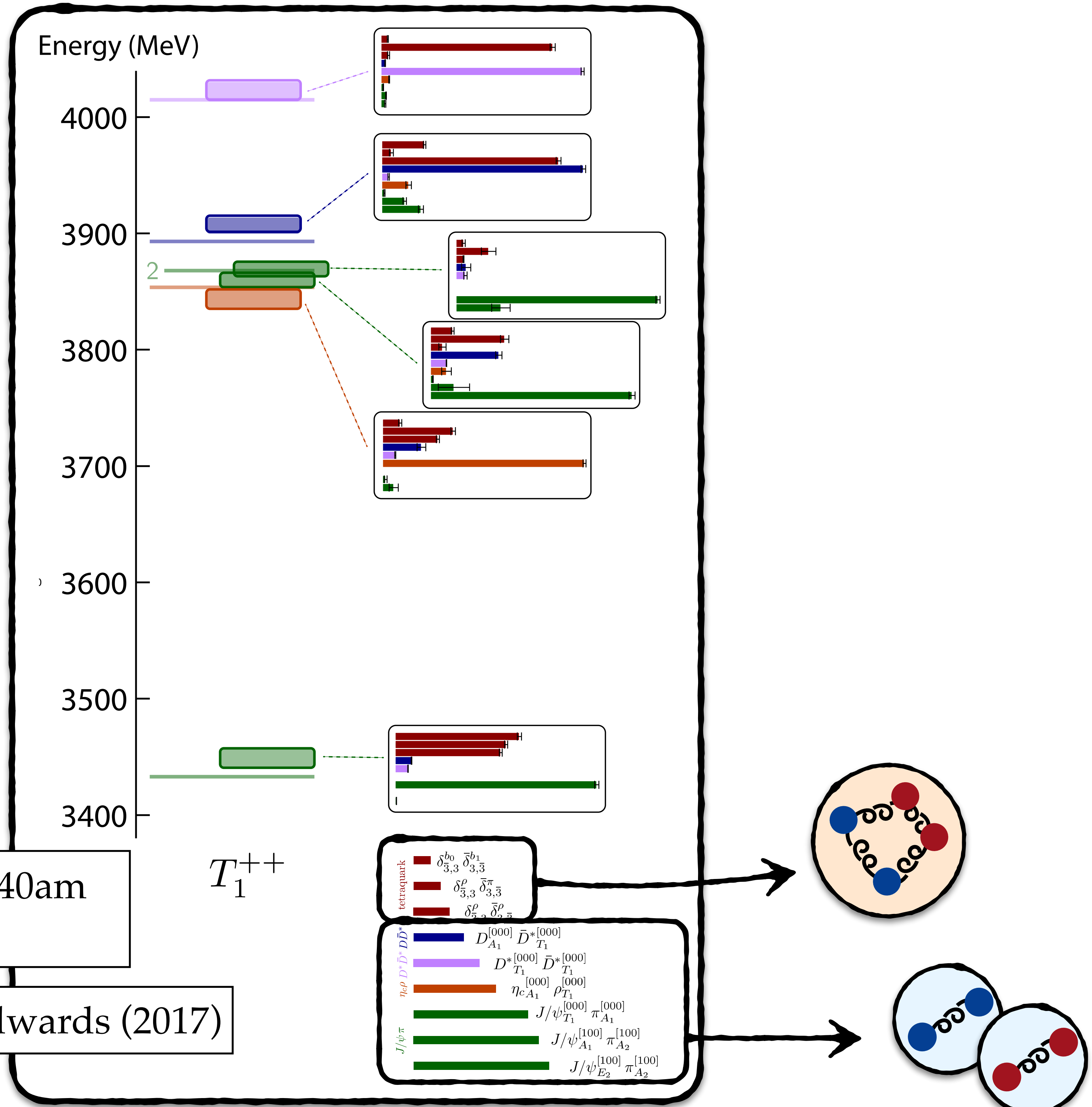


- Polejaeva & Rusetsky (2012) [spectrum depends on S-matrix]
- RB & Davoudi (2013) [1+shallow bound states]
- Hansen & Sharpe (2014-15) [relativistic $\pi\pi\pi$]
- Hammer, Pang, Rusetsky (2017) [NR EFT parameterization]
- Mai & Doring (2017) [NR numerical explorations]
- RB, Hansen & Sharpe (2016) [relativistic coupled, 2-,and 3-mesons]

Remaining questions:

Operator basis:

- tetraquarks, pentaquarks…
- 3 particles or more
- glueballs,
- …



go to G. Cheung's talk Wed. 11:40am
for recent developments

Cheung , Thomas, Dudek & Edwards (2017)

Remaining questions:

Operator basis:

- tetraquarks, pentaquarks…
- 3 particles or more
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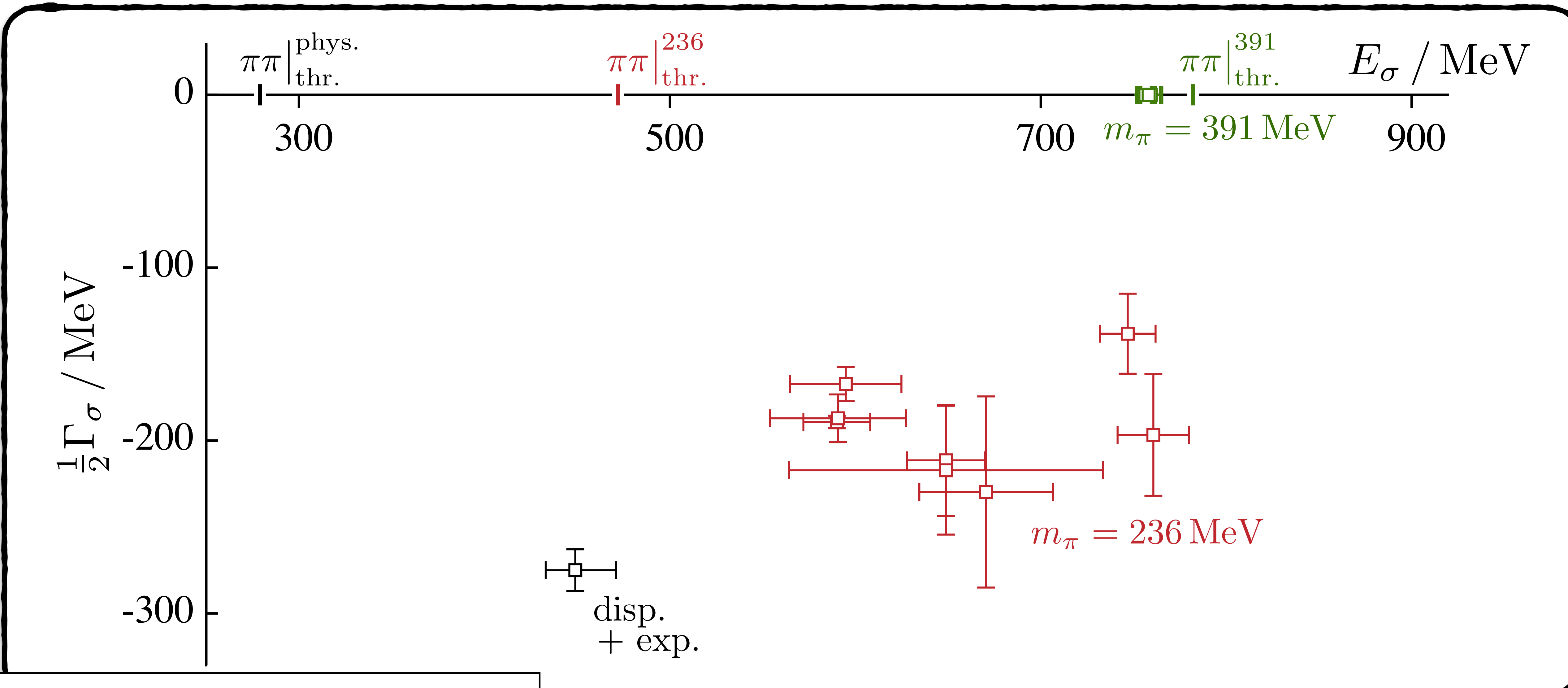
- …

Amplitude analysis:

- 3 particles or more
- dispersive techniques



RB, Dudek, Edwards & Wilson (2016)

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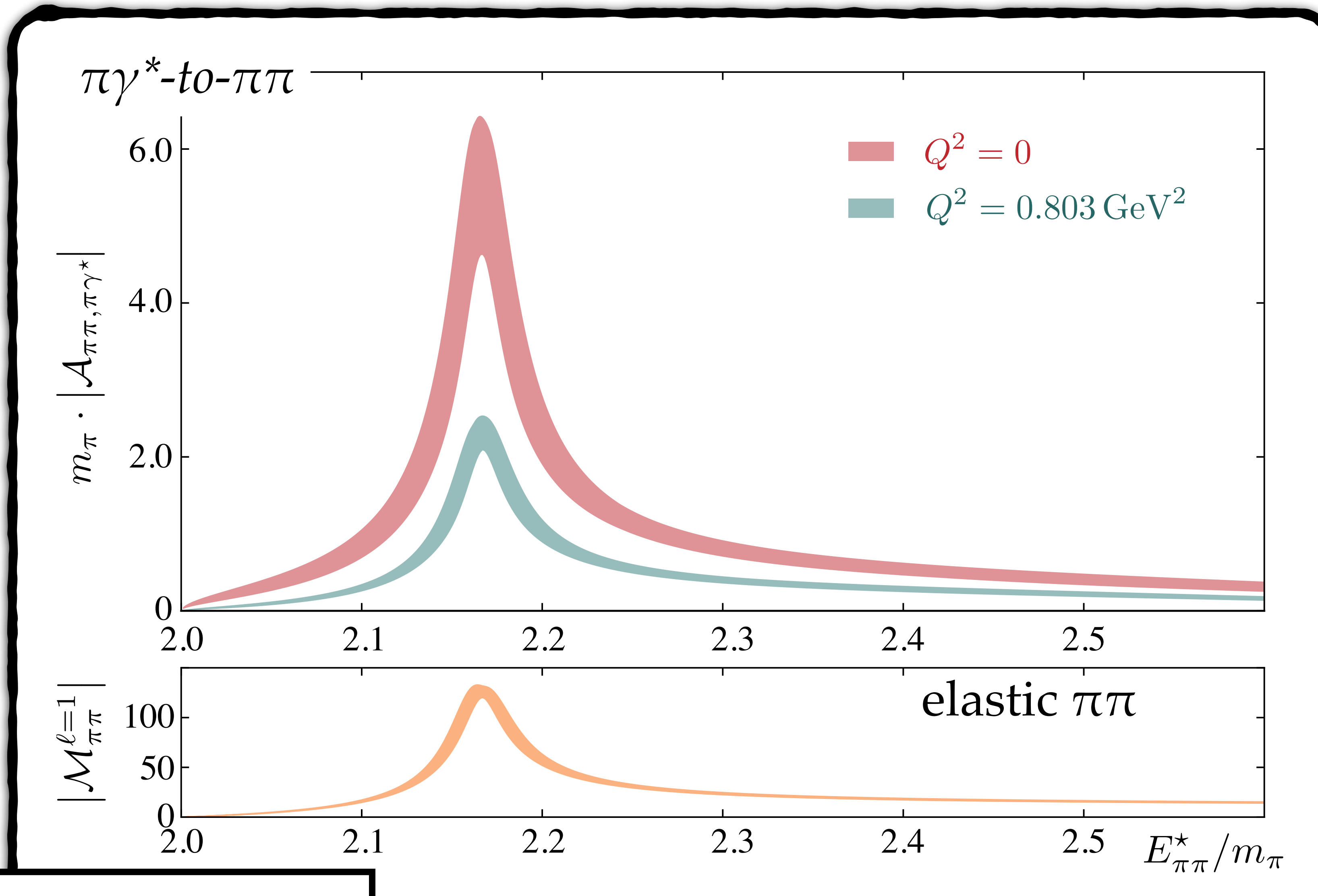
Coupling to QED currents:

- transition processes



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

Remaining questions:

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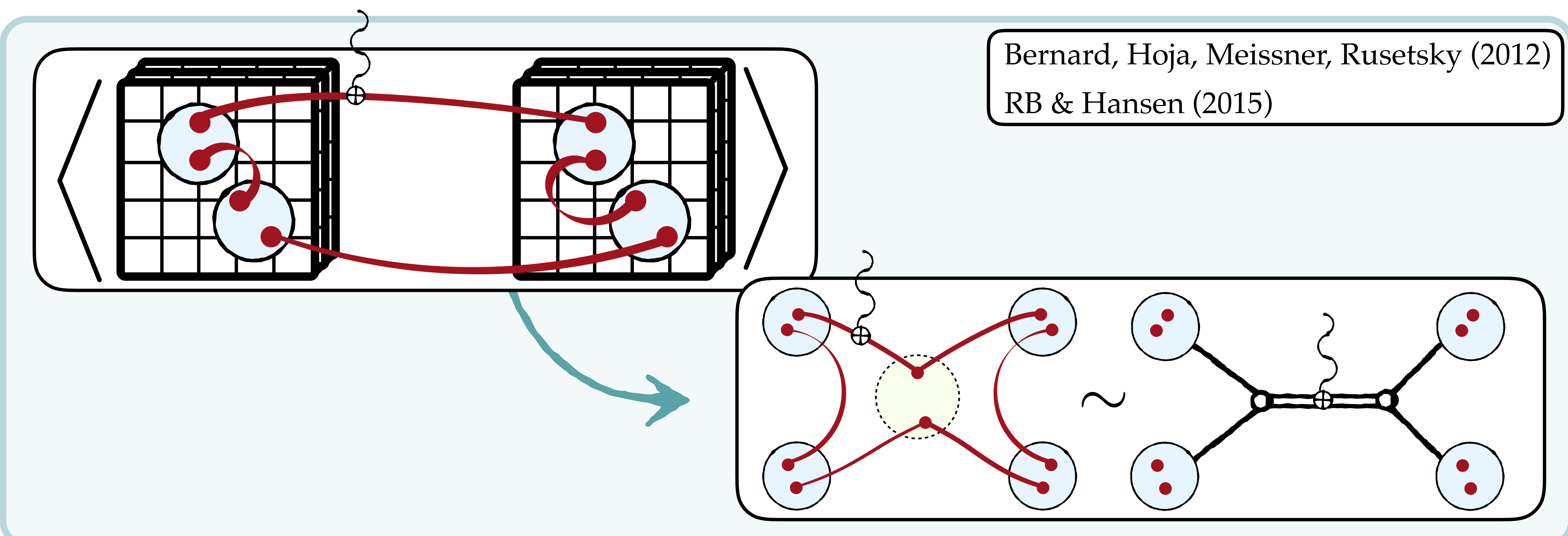
- 3 particles or more
- dispersive techniques

Coupling to QED currents:

- transition processes
- elastic processes (the future)



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- …

Amplitude analysis:

- 3 particles or more
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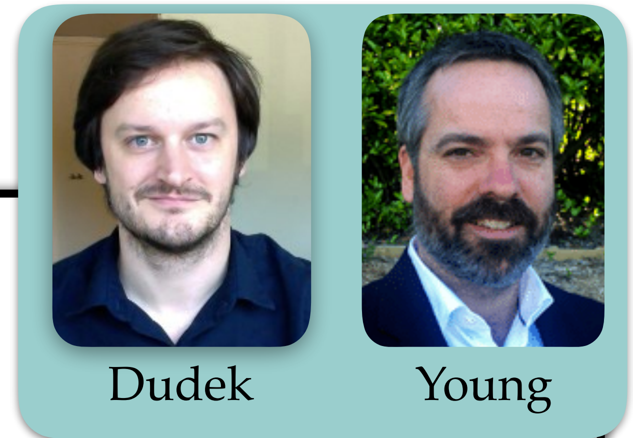
Coupling to QED currents:

- transition processes
- elastic processes (the future)

Baryons:

- no published Lüscher analysis to date
- three-body is crucial for many channels

A review / introduction



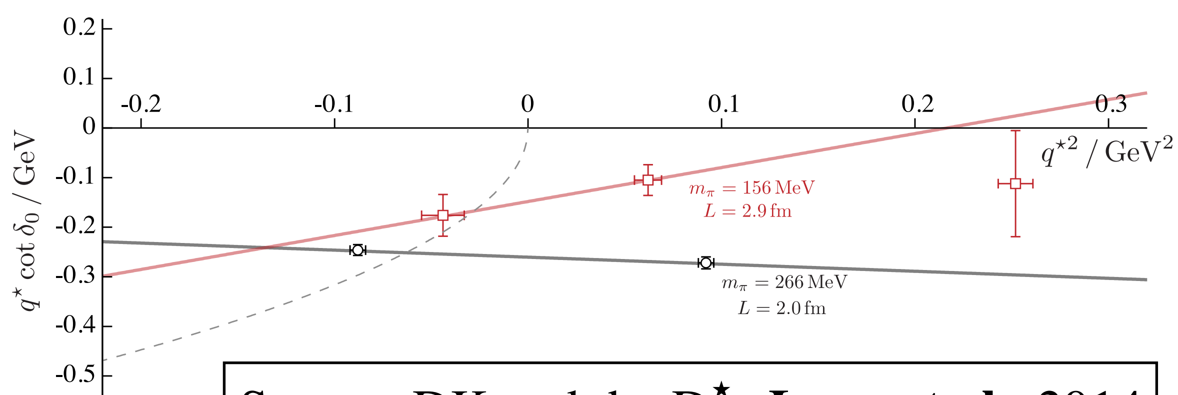
Scattering processes and resonances from lattice QCD

Raúl … Briceño,[1,*] Jozef J. Dudek,[1,2,†] and Ross D. Young[3,‡]

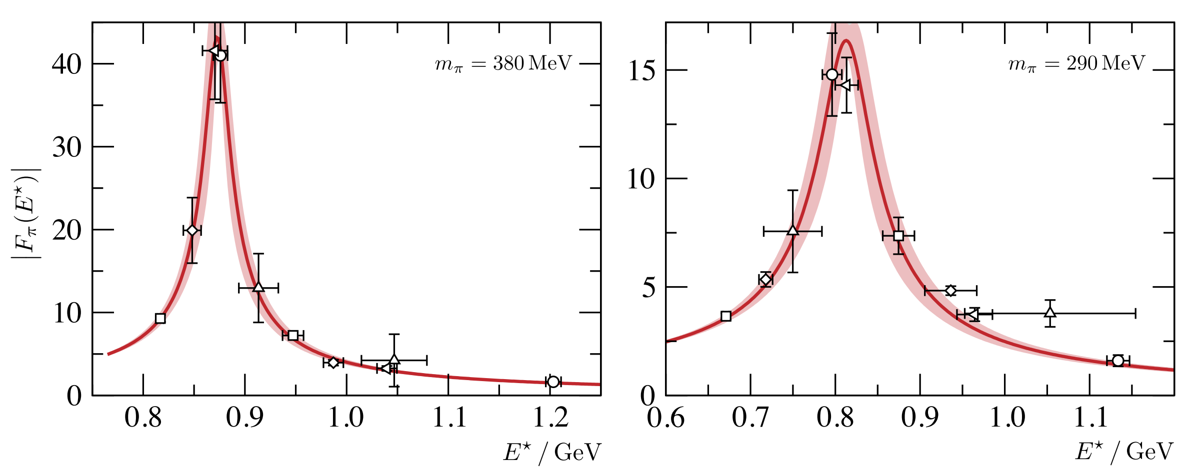
[1] *Thc… Jefferson National Accelerator Facility, 12000 Jefferson Avenue, Newport News, Virginia 23606, USA*

[2] *Dep… ent of Physics, College of William and Mary, Williamsburg, Virginia 23187, USA*

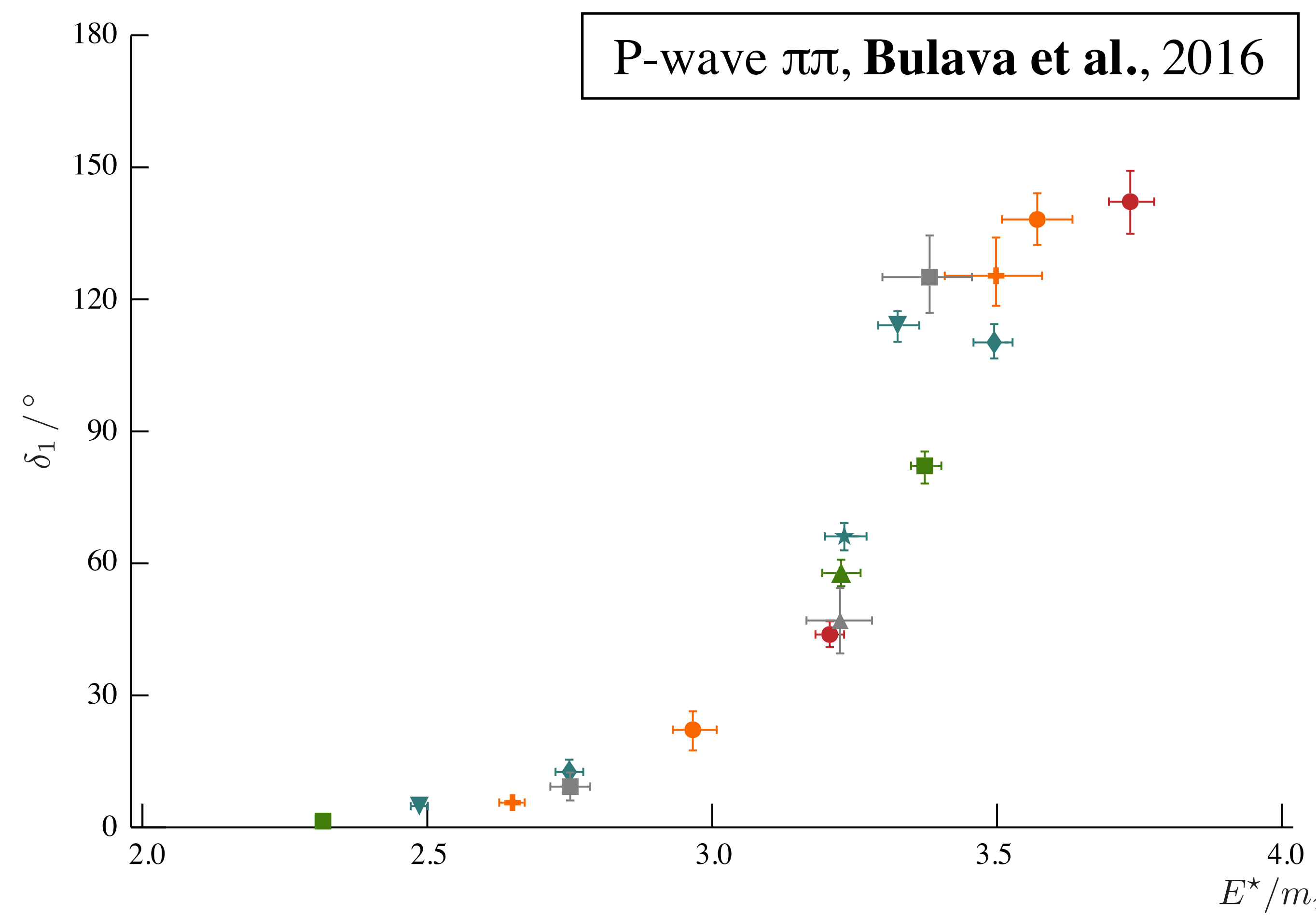
[3] *Spe… Research Center for the Subatomic Structure of Matter (CSSM), Department of Physics, Univ… of Adelaide, Adelaide 5005, Australia*



S-wave DK and the $D_{s0}^\star$, **Lang et al.**, 2014



γ*-to-ππ, **Feng et al.**, 2015



P-wave ππ, **Bulava et al.**, 2016

The team and some references

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:1708.06667
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

arXiv:1709.01417
PRD85 014507 (2012)
PRD80 054506 (2009)
PRD79 034502 (2009)

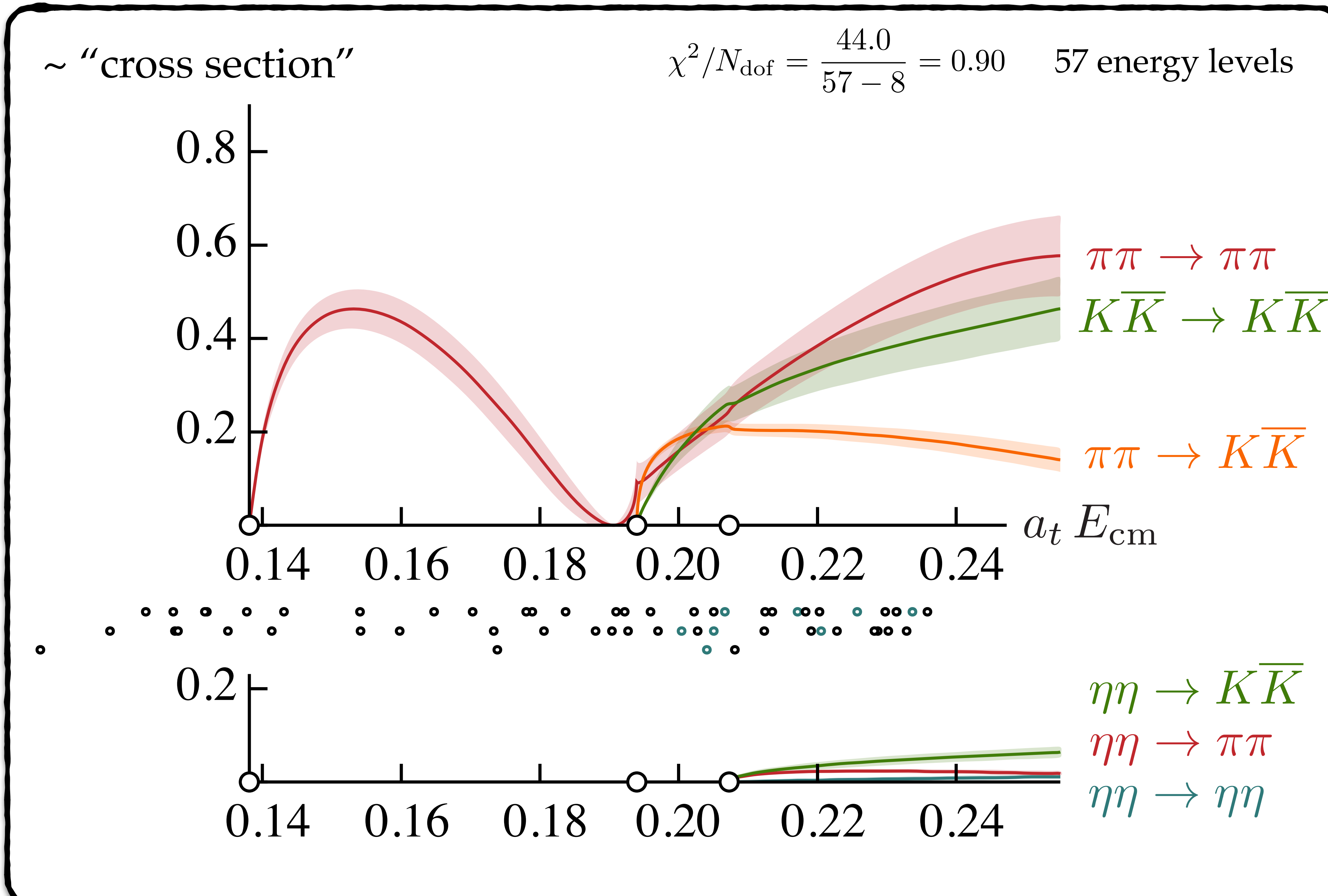
Students:
Johnson, Radhakrishnan, Cheung, Moss, O Hara, Tims

Formalism

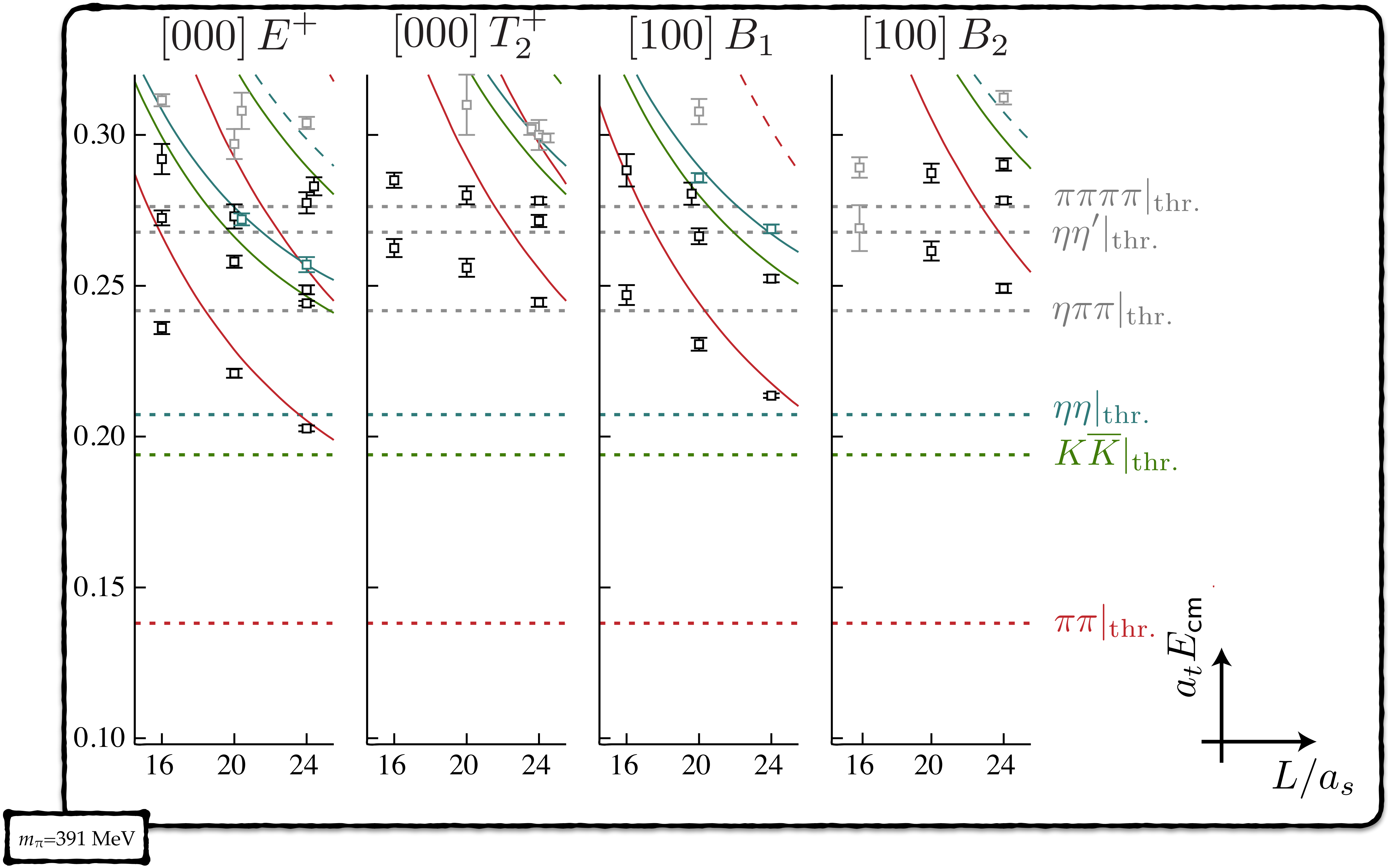
PRD95 074510 (2017)
PRD94 013008 (2016)
PRD92 074509 (2015)
PRD91 034501 (2015)
PRD89 074507 (2014)

Coupled-channels analysis

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



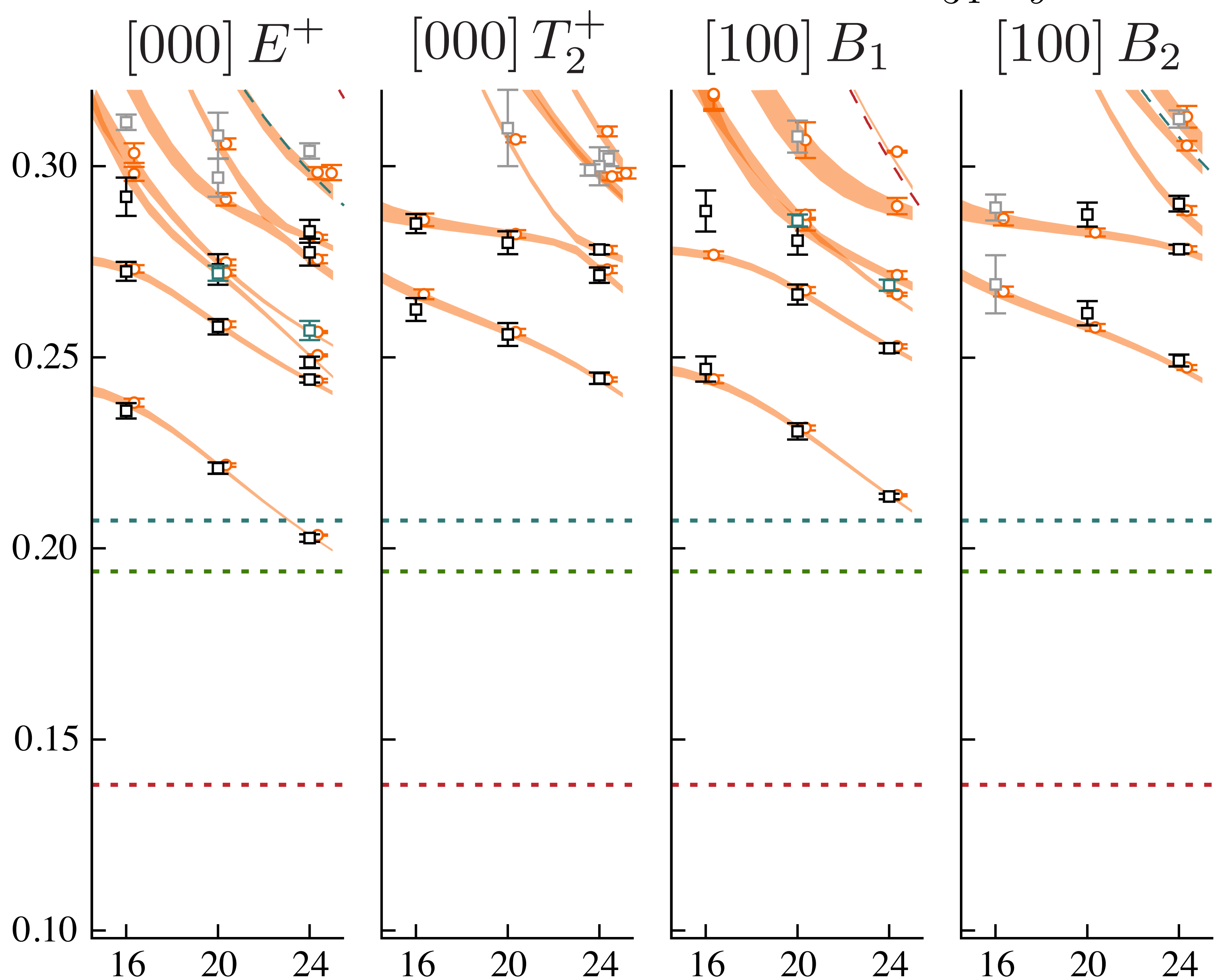
Isoscalar spectra: D-wave dominant



Coupled-channels analysis

- D-wave above $2m_\pi$, $2m_K$, and $2m_\eta$
- Ansatz $K_{ij}(s) = \frac{g_i^{(1)} g_j^{(1)}}{m_1^2 - s} + \frac{g_i^{(2)} g_j^{(2)}}{m_2^2 - s} + \gamma_{ij}$ $\quad \gamma_{\eta\eta} \neq 0$, $\gamma_{ij} = 0$ otherwise

Spectrum $\quad \chi^2/N_{\text{dof}} = \frac{28.9}{34-9} = 1.15 \quad$ 34 energy levels



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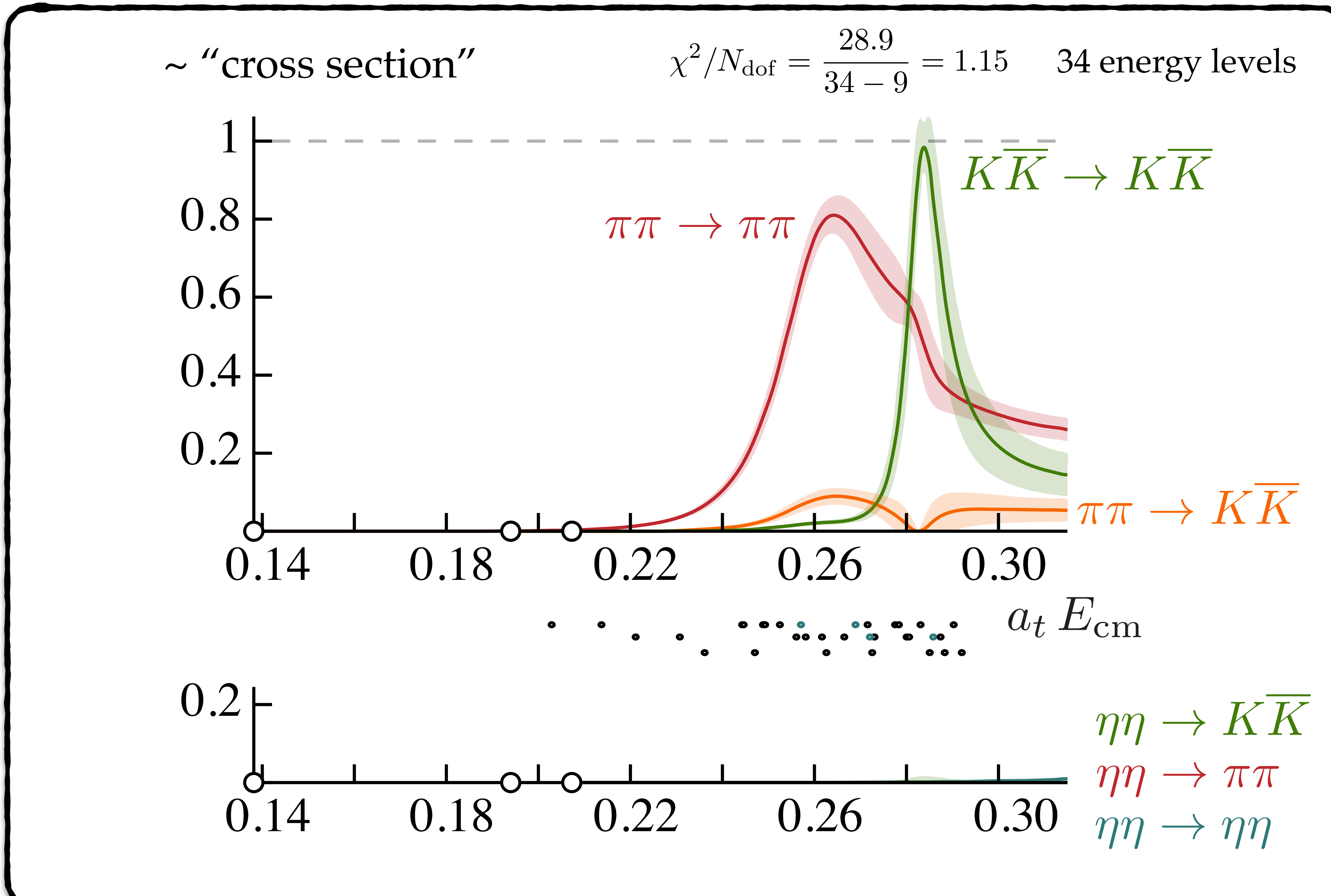
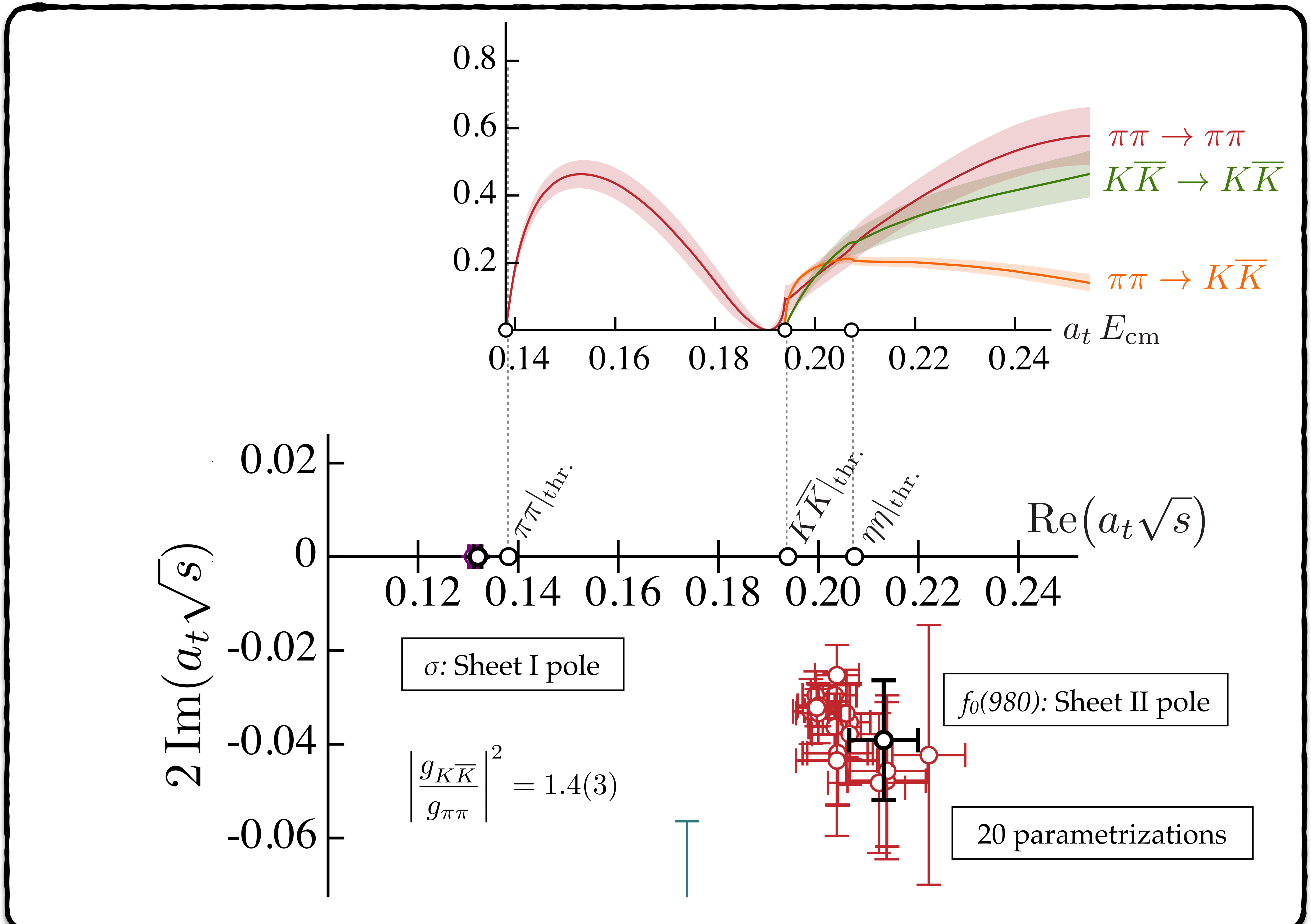
- Ansatz $$K_{ij}(s) = \frac{g_i^{(1)} g_j^{(1)}}{m_1^2 - s} + \frac{g_i^{(2)} g_j^{(2)}}{m_2^2 - s} + \gamma_{ij}$$ $\gamma_{\eta\eta} \neq 0$; $\gamma_{ij} = 0$ otherwise



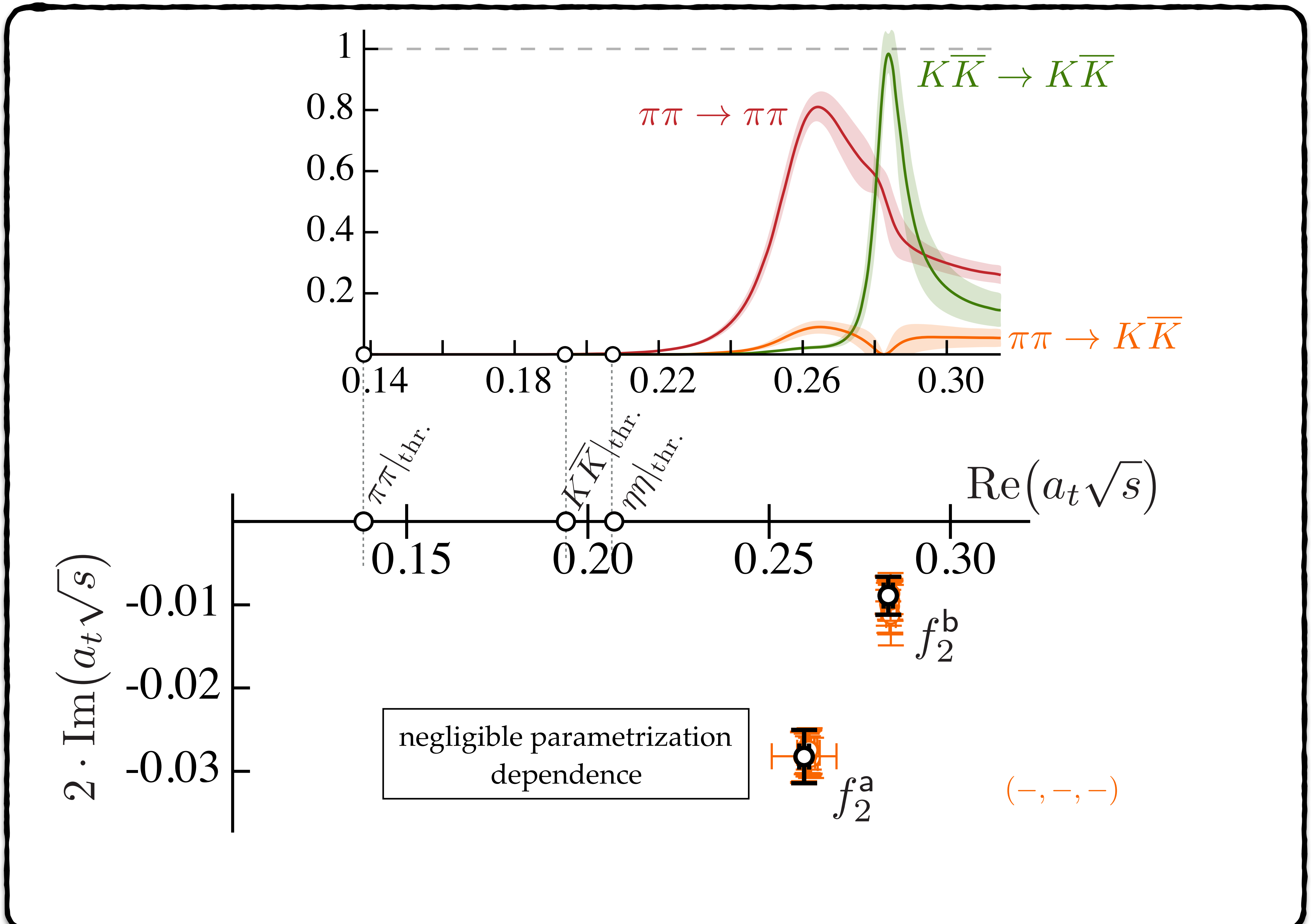
Scalar poles: σ and *f₀(980)*

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



Tensor poles: the f_2's

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



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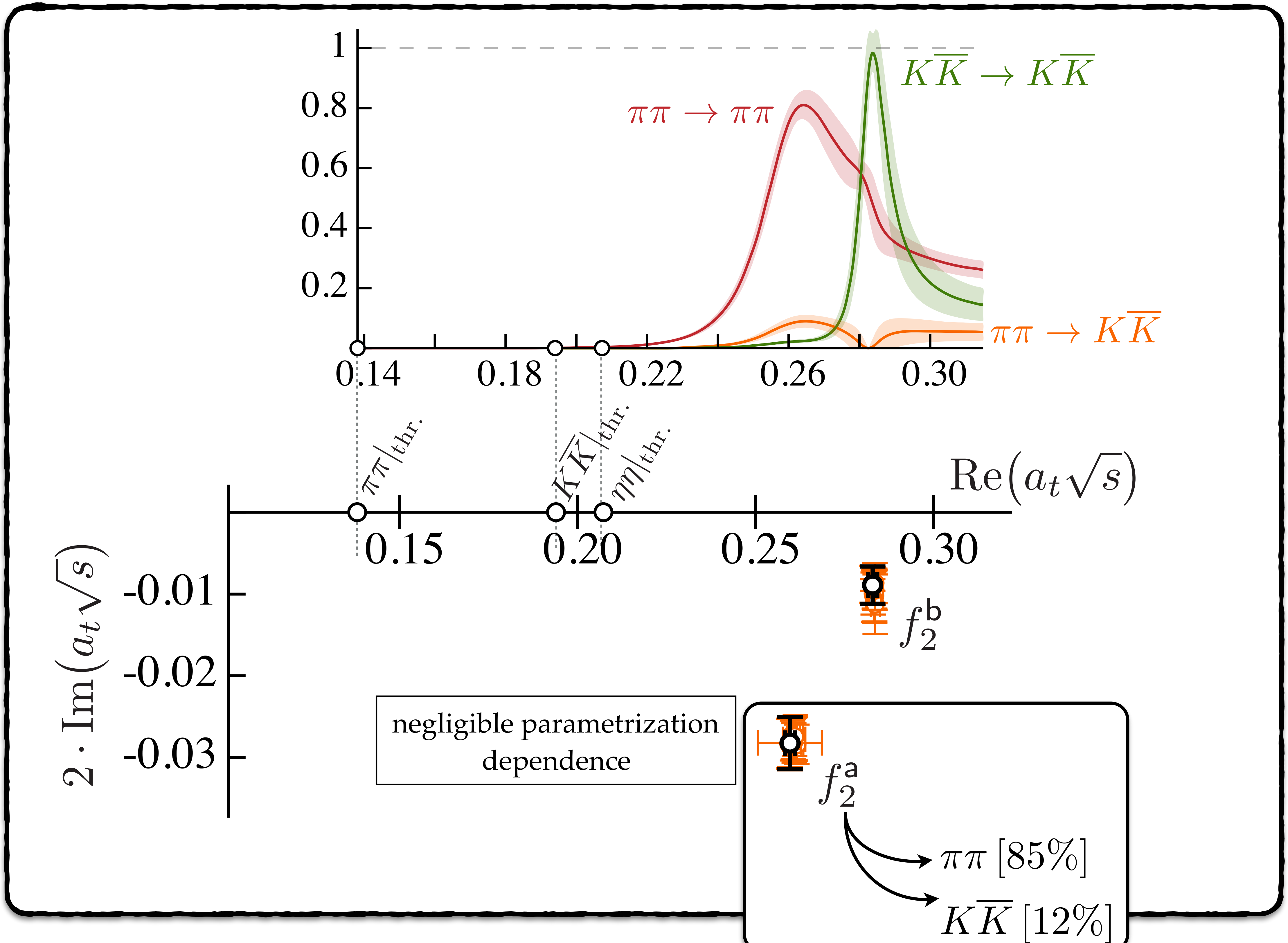

Tensor poles: the f_2's

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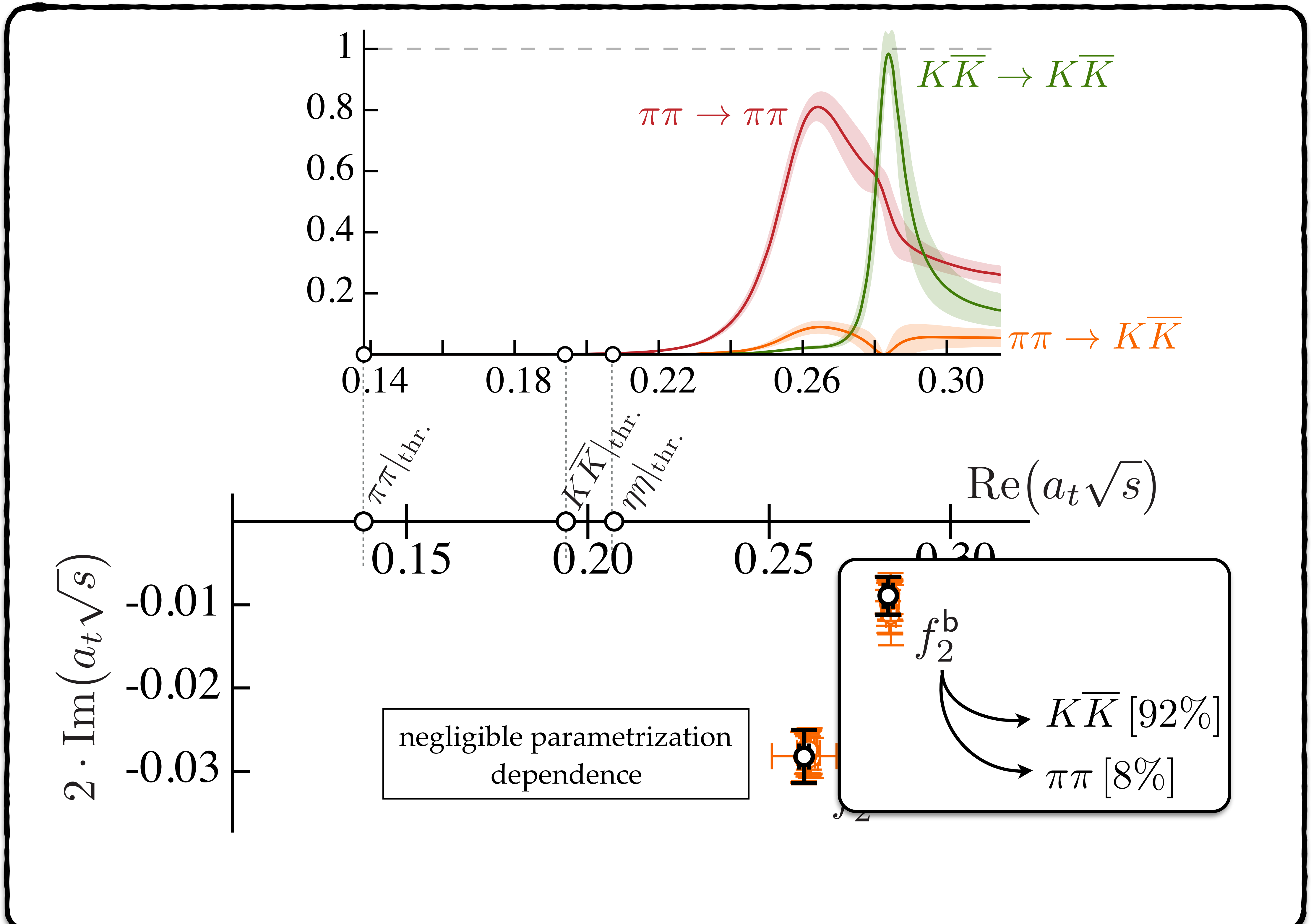

Complex momentum plane