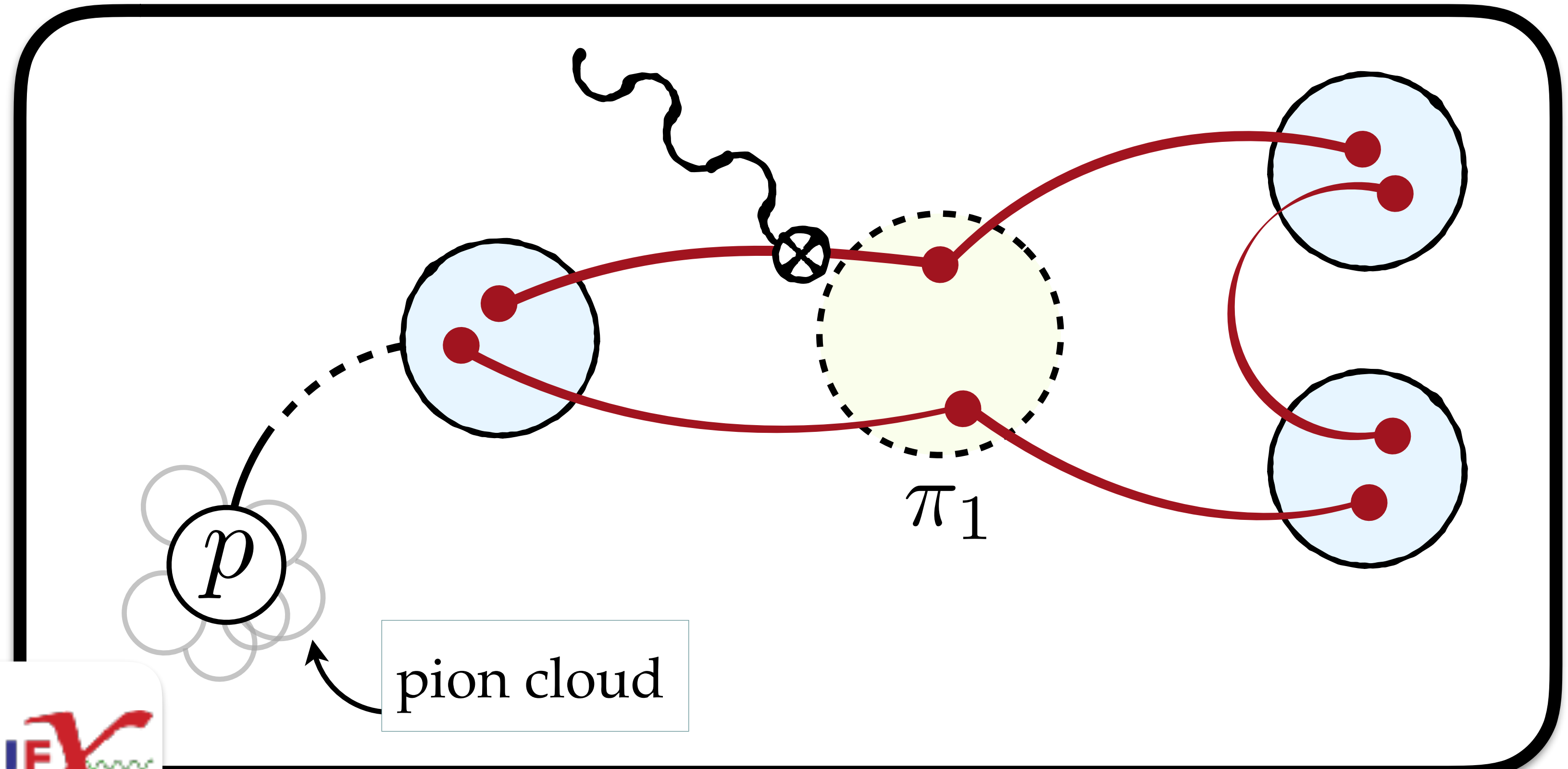
Meson resonances and their couplings

Briceño, Chakraborty, Edwards, Joó,
Richards, Winter
Dudek, *Johnson* , *Radhakrishnan*

Cheung, Moir, Thomas, *Moss*
O Hara, Peardon, *Tims*, Ryan, Wilson
Mathur

Resonances in experiments



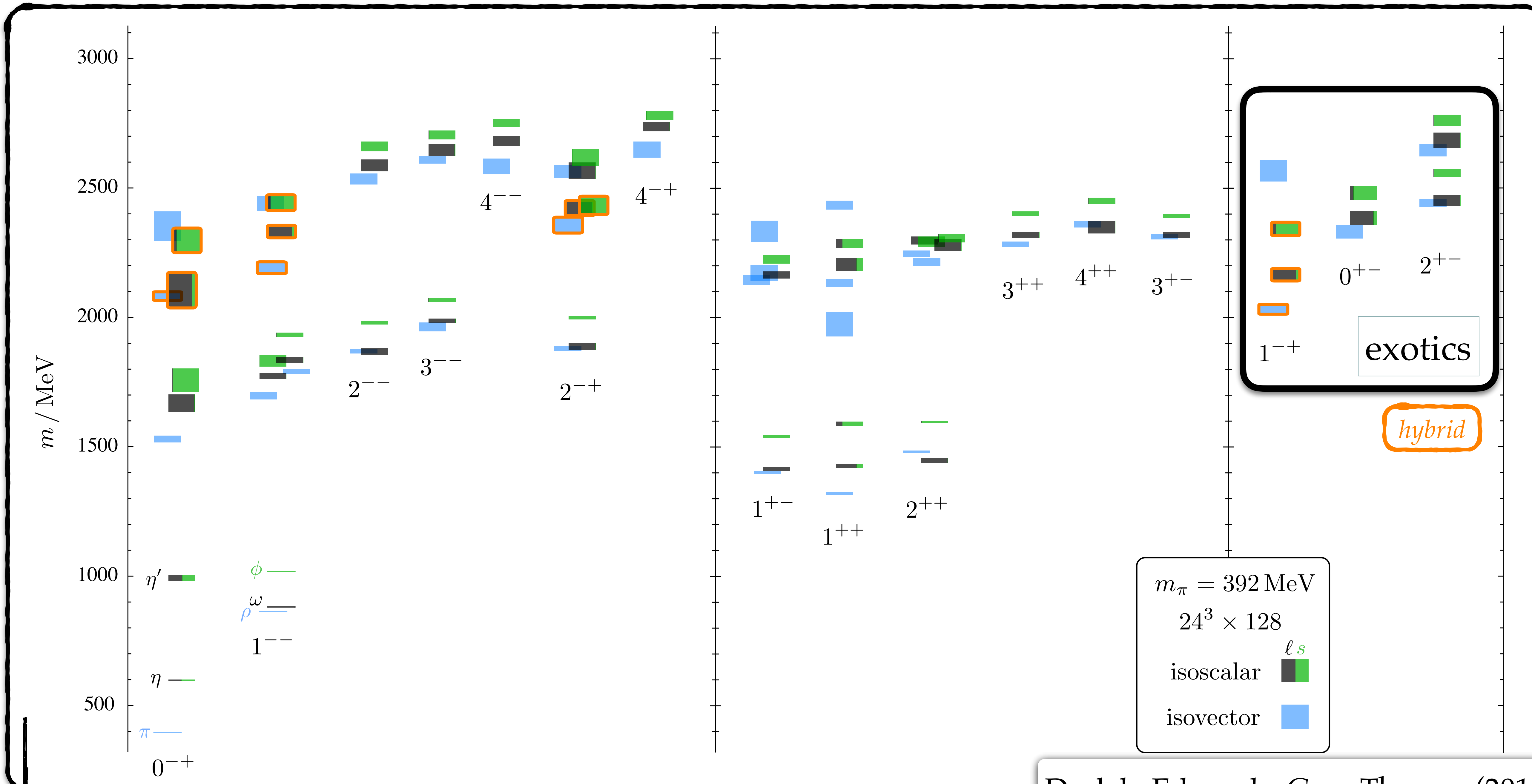
experimental demands

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

theoretical demands

- structural understanding

Inspired by lattice



Dudek, Edwards, Guo, Thomas (2013)

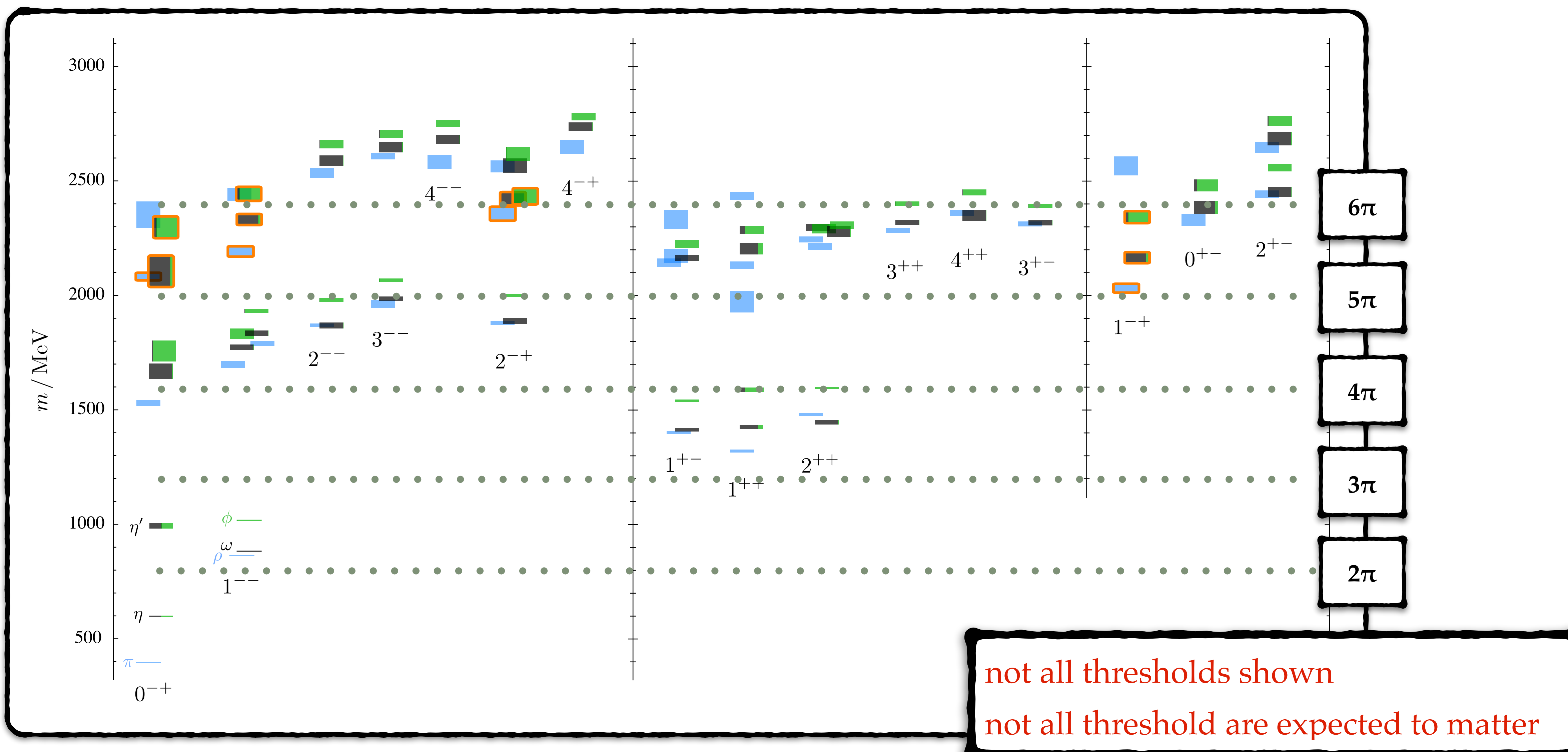
Extracted from: $C_{ab}^{2pt.}(t, \mathbf{P}) \equiv \langle 0 | \mathcal{O}_b(t, \mathbf{P}) \mathcal{O}_a^\dagger(0, \mathbf{P}) | 0 \rangle = \sum_n Z_{b,n} Z_{a,n}^* e^{-E_n t}$

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

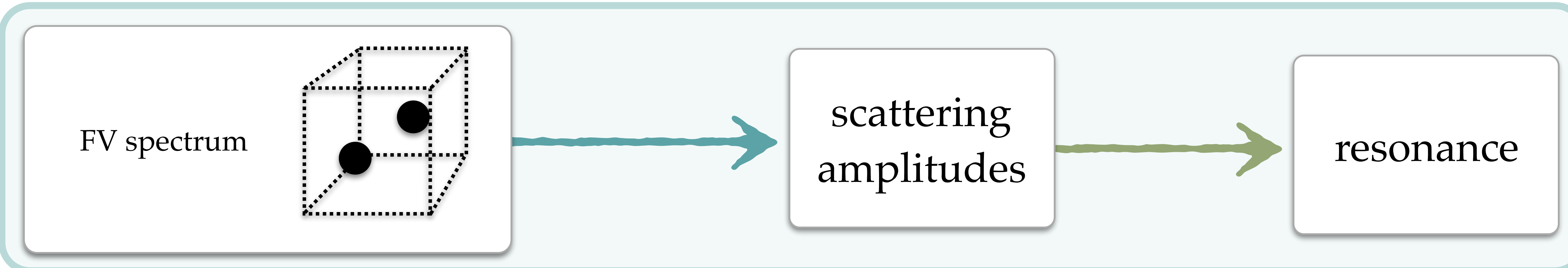
Similar calculations by hadspec have inspired baryon searches in CLAS12

Approximations

- Ops. basis did not include multi-hadron ops: $\pi\pi,\ K\overline{K}, \eta\eta, \pi\pi\pi, \ldots$
  - Incomplete spectrum
- Unstable nature of the states ignored
  - Finite volume are *not* resonances
  - Demand for formalism
- Spectrum does suggest where *some* resonance are



Spectroscopy formalism



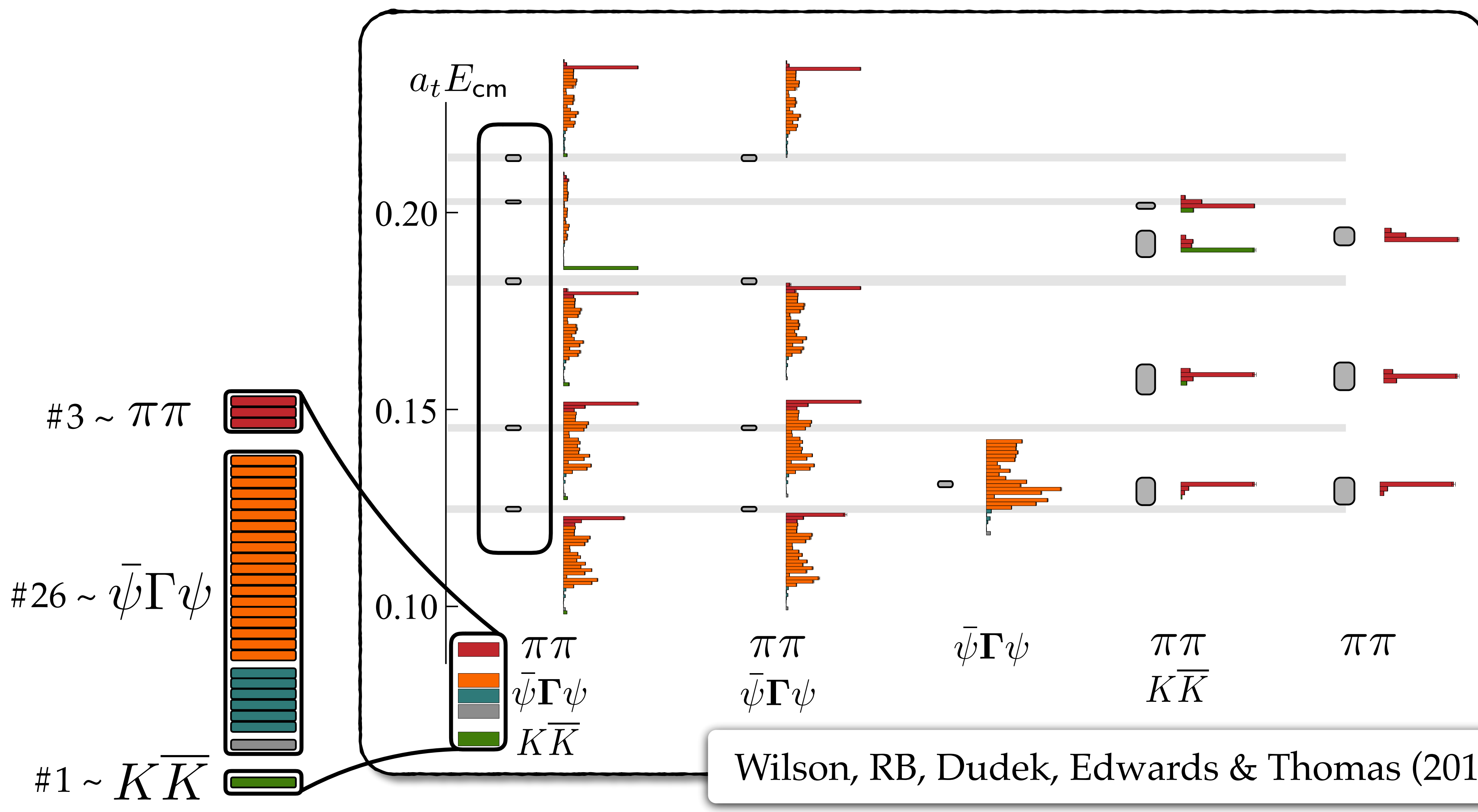
$$\det[F^{-1}(E_L, L) + \mathcal{M}(E_L)] = 0$$

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]

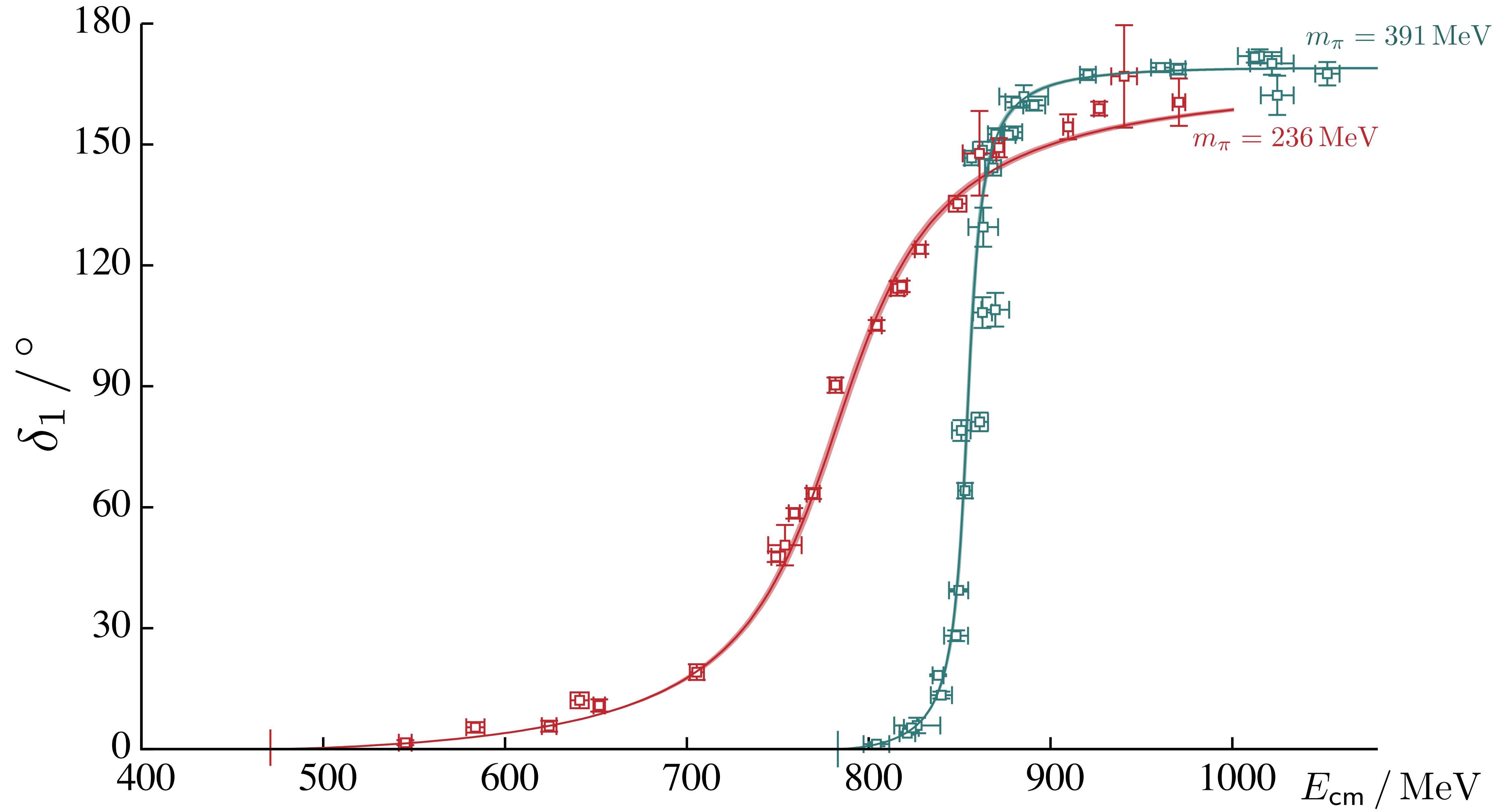
Extracting the spectrum

- Use local and multi-hadron ops
- Evaluate all Wick contraction: **distillation**
- *Variationally* optimize operators: $\Omega_n = \sum_b w_b^{(n)} \mathcal{O}_b$
- e.g., $\pi\pi$ isotriplet at rest, m_π=236 MeV



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

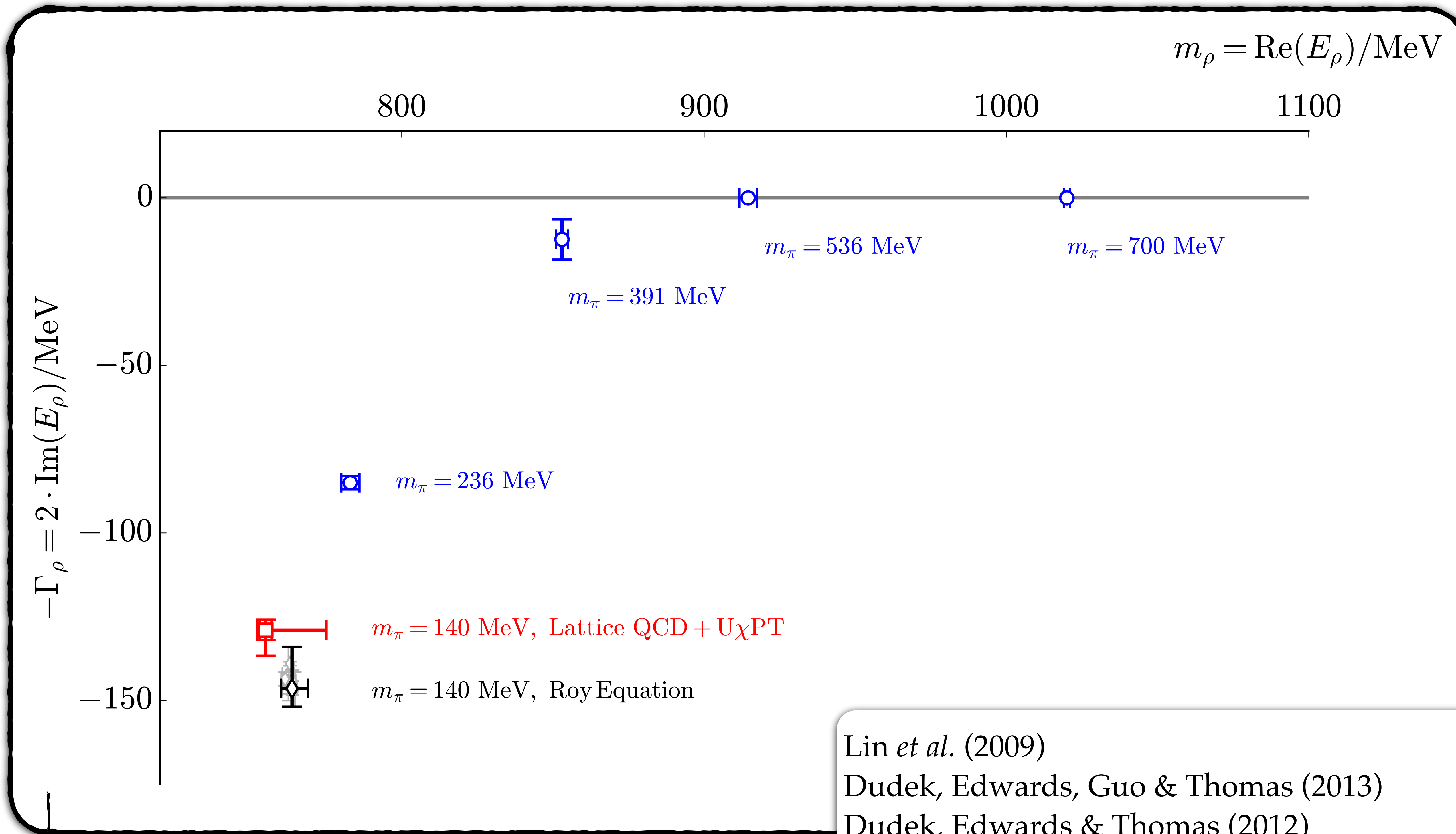
Isovector $\pi\pi$ scattering



$$\mathcal{M}_1 = \frac{16\pi E_{\mathrm{cm}}}{p \cot \delta_1 - ip}$$

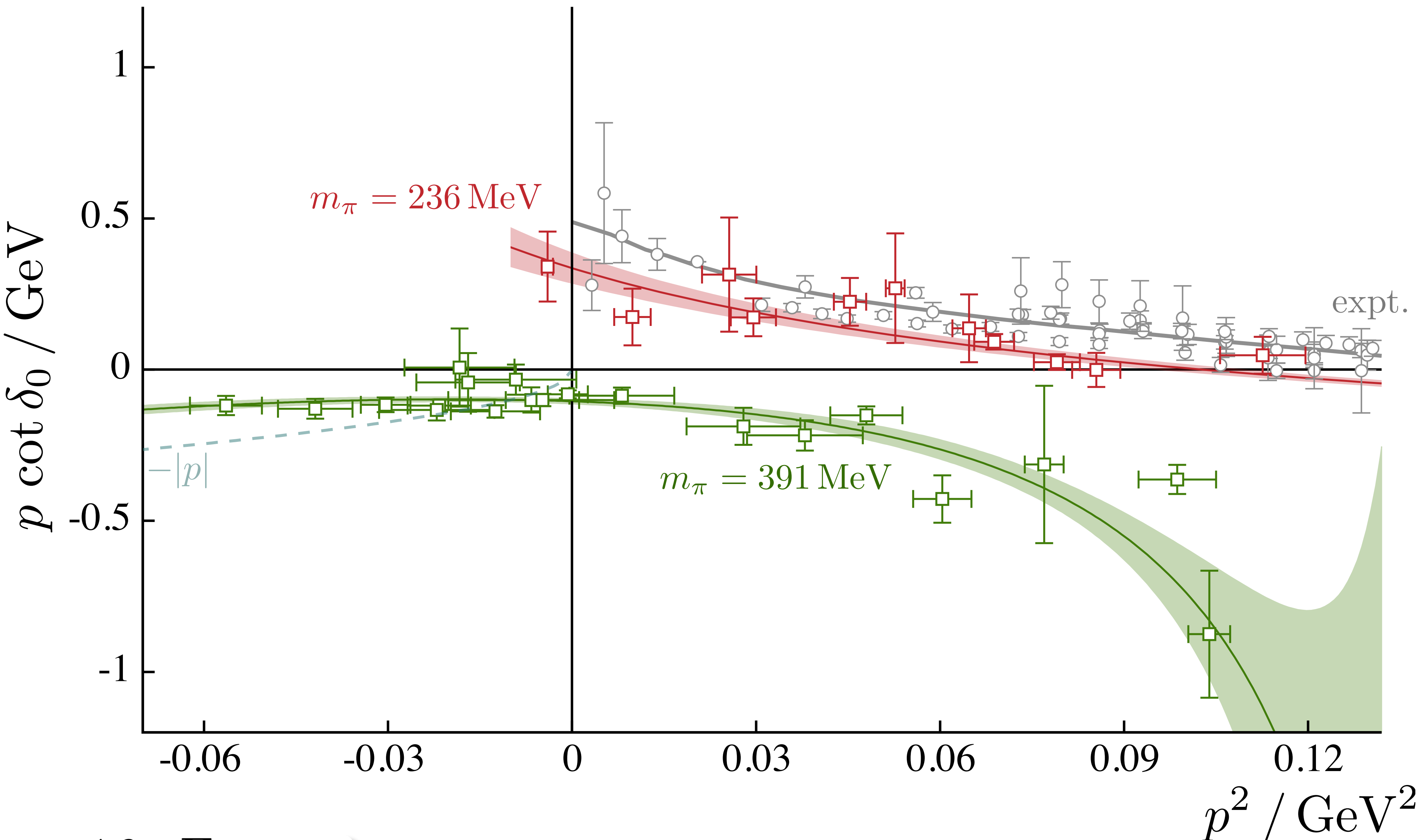
Dudek, Edwards & Thomas (2012)
Wilson, RB, Dudek, Edwards & Thomas (2015)

The ρ vs m_π



Lin *et al.* (2009)
Dudek, Edwards, Guo & Thomas (2013)
Dudek, Edwards & Thomas (2012)
Wilson, RB, Dudek, Edwards & Thomas (2015)
Bolton, RB & Wilson (2015)

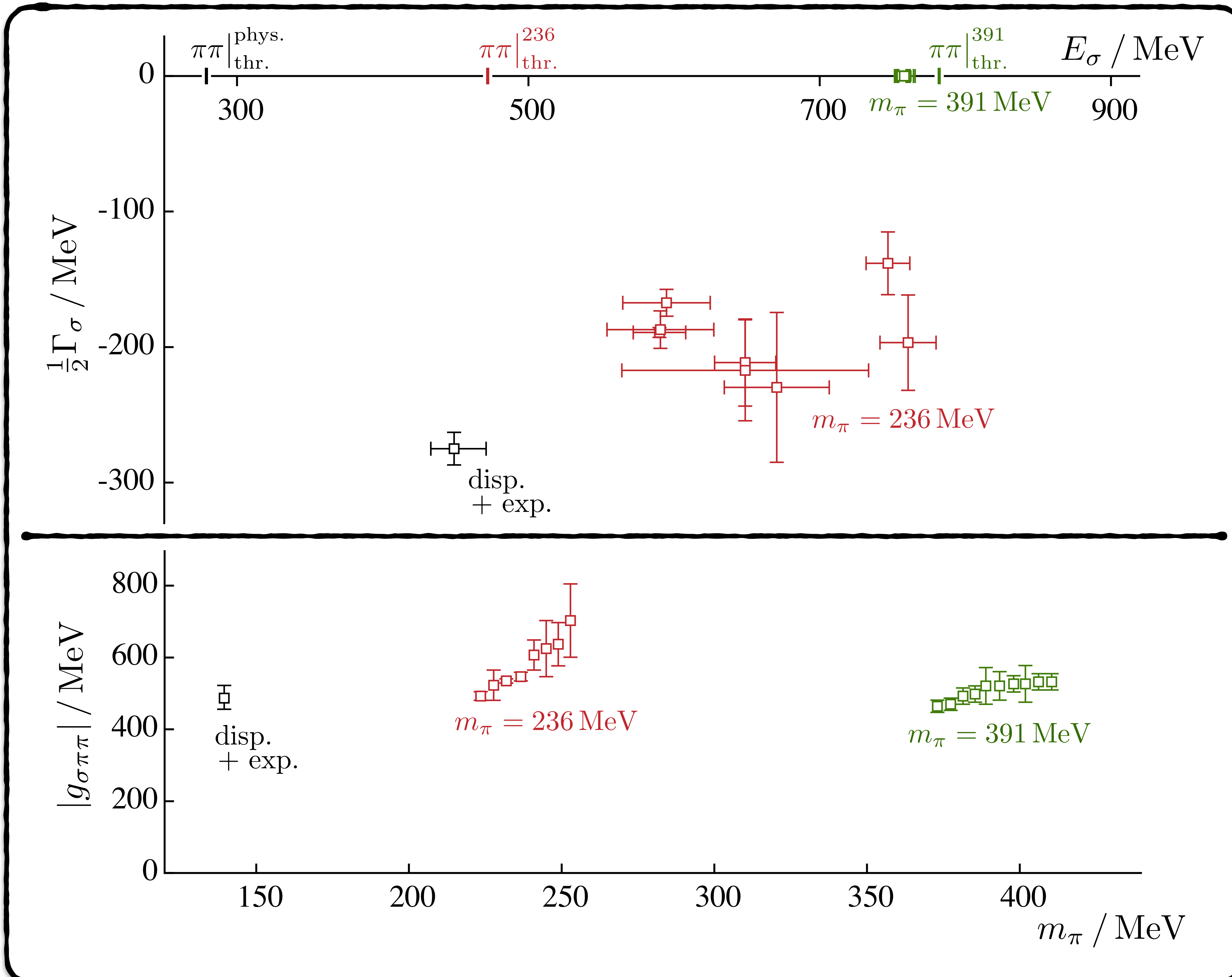
Isoscalar $\pi\pi$ scattering



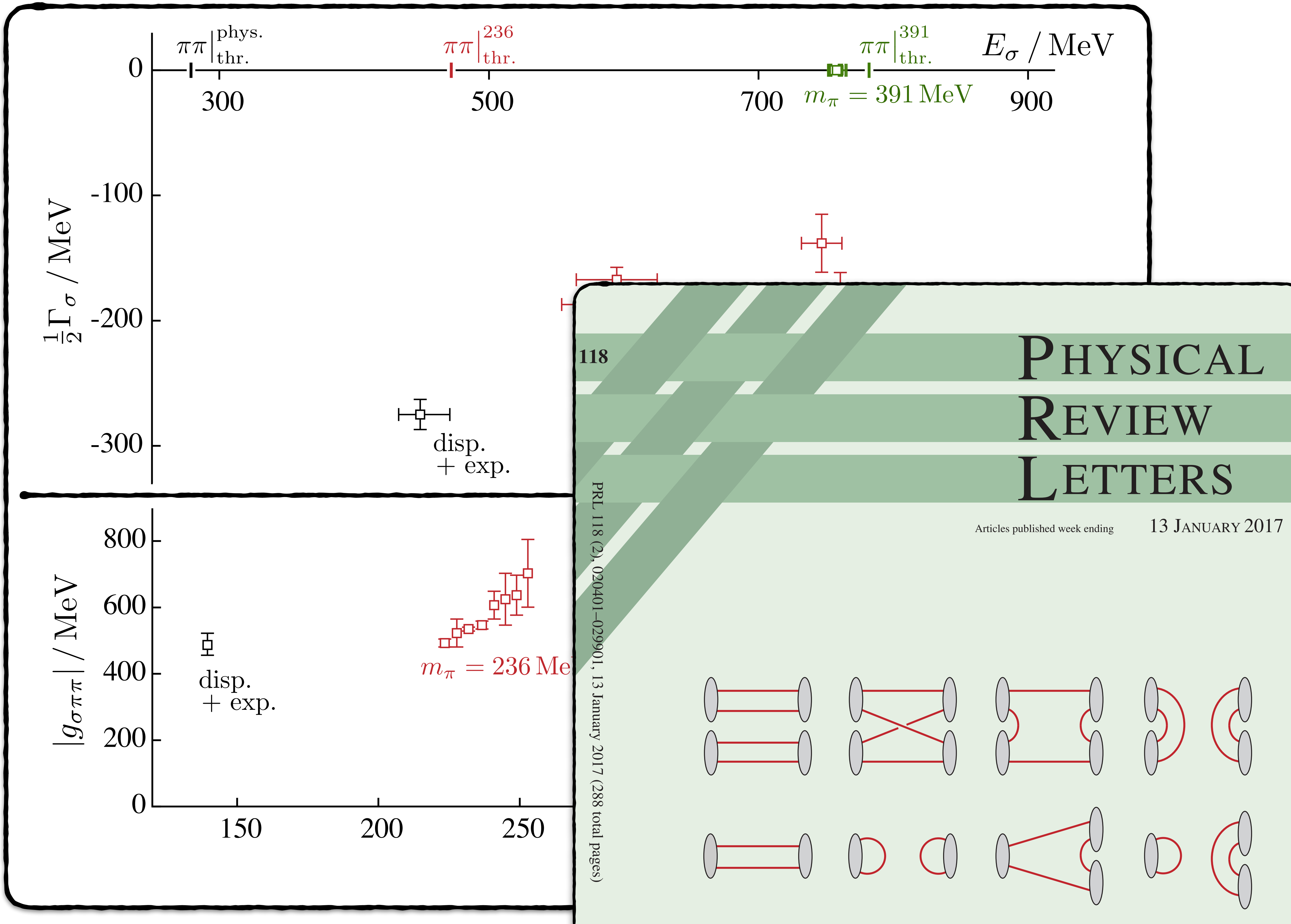
$$\mathcal{M}_0 = \frac{16\pi E_{\mathrm{cm}}}{p\cot\delta_0 - ip}$$

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

The σ / f$_0$(500) vs m$_\pi$



The σ / $f_0(500)$ vs m_π

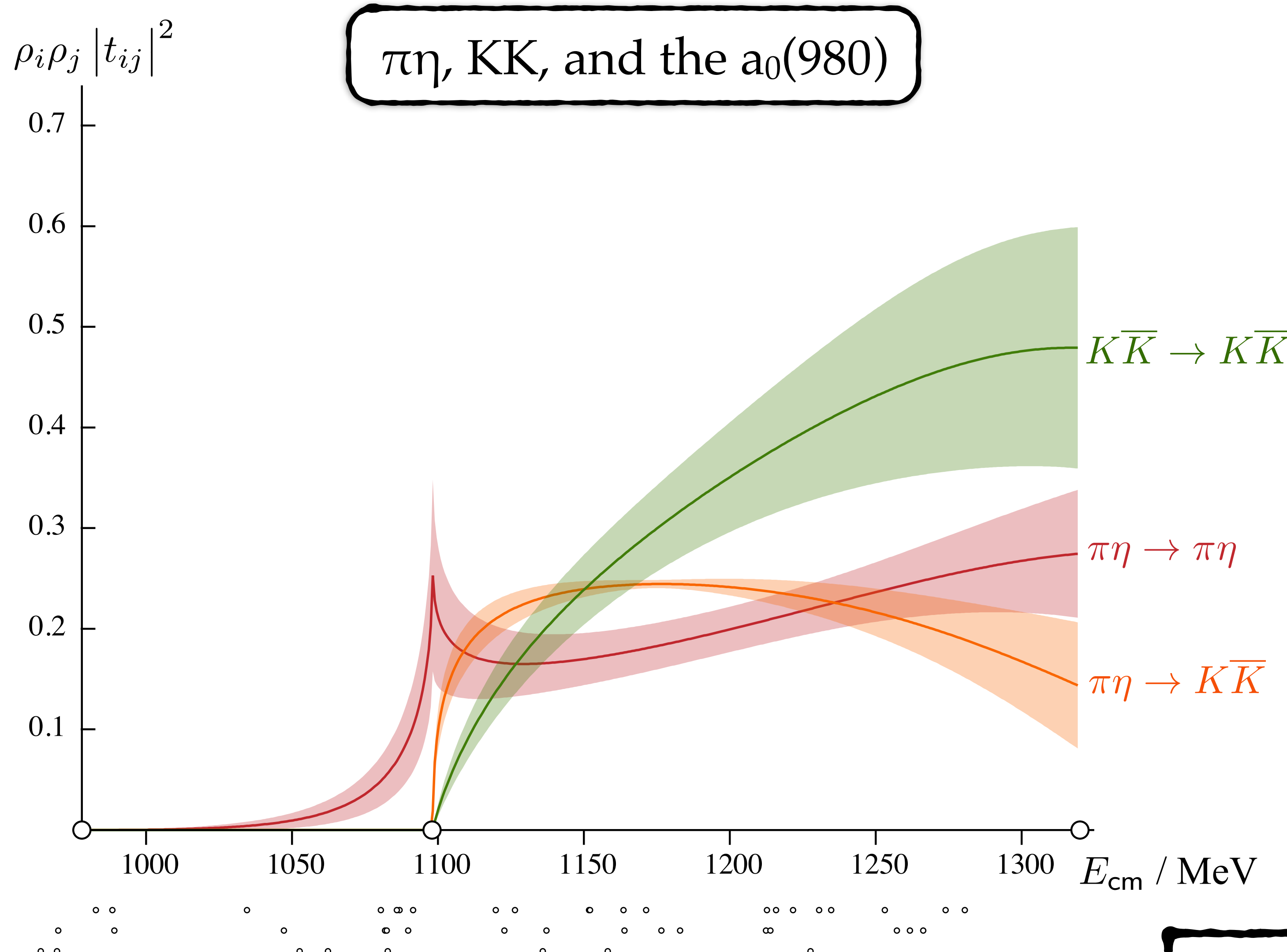


Coupled-channels systems

Four systems consider so far, all by hadspec

Kπ, Kη:	Dudek, Edwards, Thomas, Wilson - PRL (2015)
	Wilson, Dudek, Edwards, Thomas - PRD (2015)
ππ, KK:	Wilson, RB, Dudek, Edwards - PRD (2015)
πη, KK:	Dudek, Edwards, Wilson - PRD (2016)
Dπ , Dη, D_sK:	Moir, Peardon, Ryan, Thomas, Wilson - JHEP (2016)

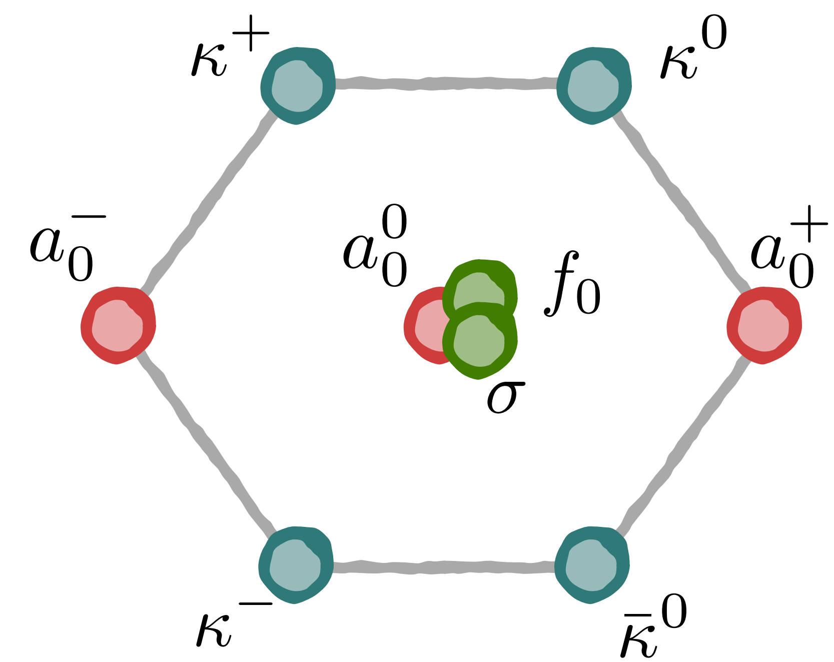
πη, KK, and the $a_0(980)$



m_π=391 MeV

Physics Plan for 2017/2018
Part 1 - meson-meson scattering

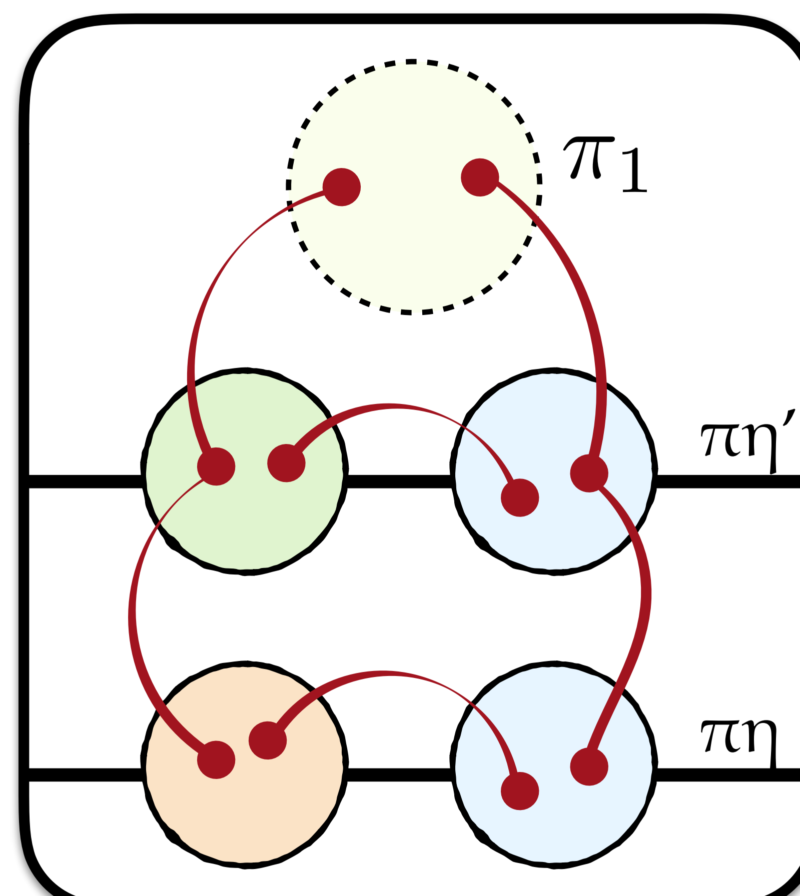
- Isoscalars at higher energies:
  - $\pi\pi$, KK, $\eta\eta$
  - $f_0(980)$, $f_2(1270)$,…
  - First complete study of the scalar nonet



- Continuation to lighter quark masses
  - m_π=236, 275, 325 MeV

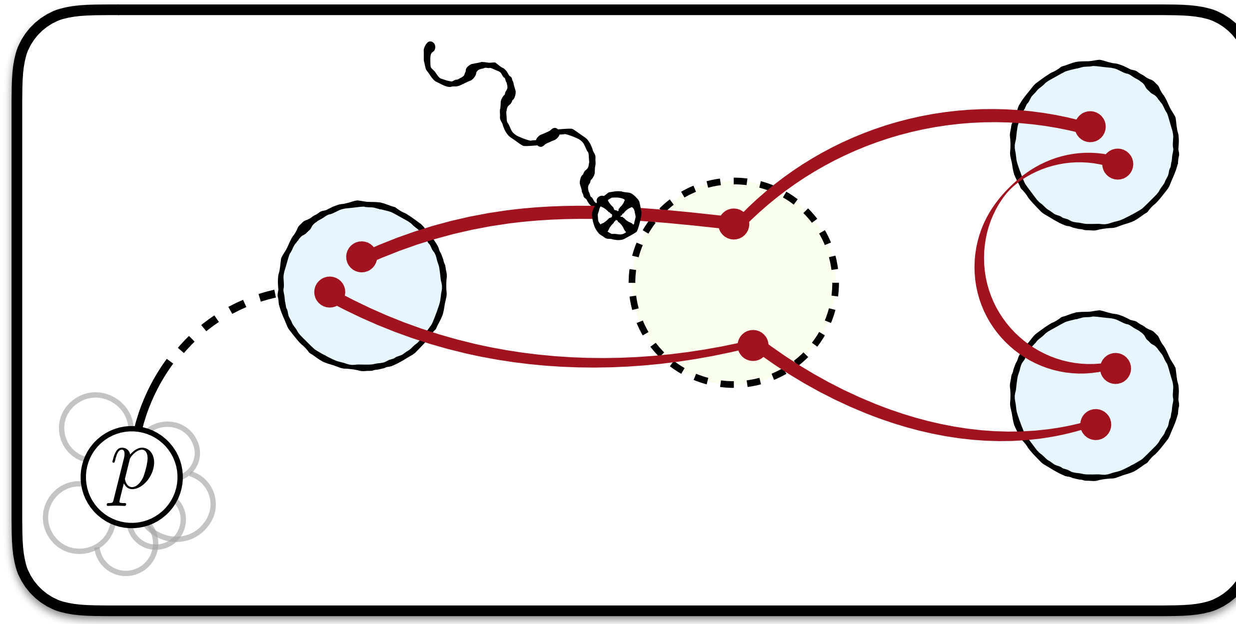
- Quark-mass dependence of couplings

- First exotic resonance: π_1, $J^{PC}=1^{-+}$
  - m_π= 700 MeV
  - ρ and b_1 are stable
  - only two-body decays: $\pi\eta$, $\pi\eta'$, $\rho\pi$, $b_1\pi$

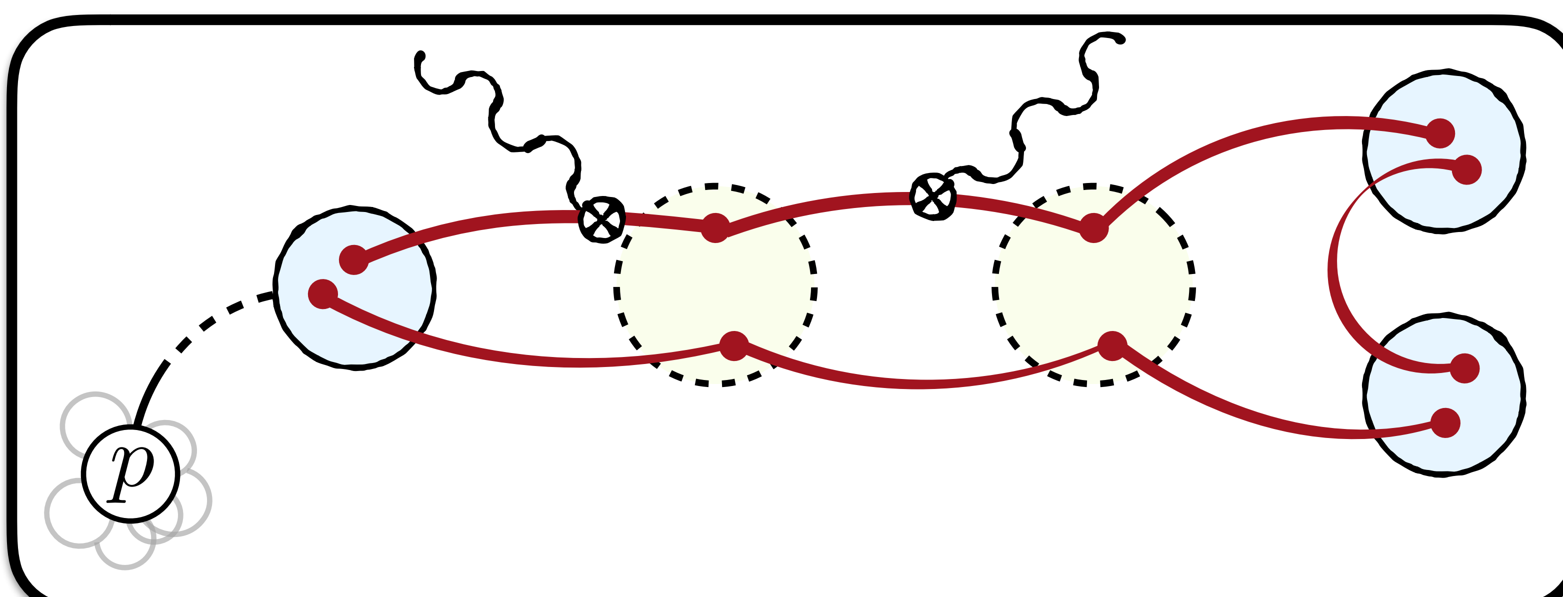


Resonant electroweak processes

- Production/decay mechanisms:



- Resonance form factors
  - *experimentally challenging or impossible*
  - information about structure
    - Shape, size, composition,…



Optimized three-point functions

Vanilla 3pt. functions:

$$C^{3pt.}_{i\to f\mathcal{J}} = \langle 0|\mathcal{O}_f(\delta t)\mathcal{J}(t)\mathcal{O}_i^\dagger(0)|0\rangle_L = \sum_{n,n'} Z_{n,f}Z^*_{n',i}e^{-(\delta t-t)E_n}e^{-tE_{n'}}\langle n|\mathcal{J}|n'\rangle_L$$

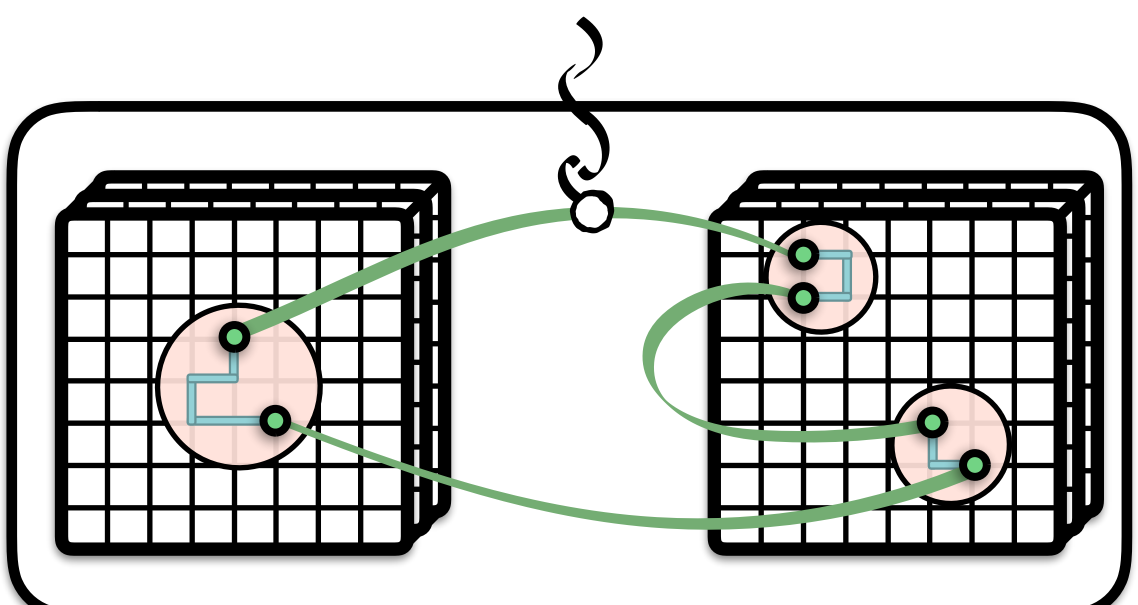
Instead, use optimized ops: $\Omega_n = \sum_b w_b^{(n)}\mathcal{O}_b$

to obtain: $C^{3pt.}_{i\to f\mathcal{J}} = \langle 0|\Omega_{f,n_f}(\delta t)\mathcal{J}(t)\Omega^\dagger_{i,n_i}(0)|0\rangle_L = e^{-(\delta t-t)E_{n_f}}e^{-tE_{n_i}}\langle n_f|\mathcal{J}|n_i\rangle_L + \cdots$

Benefits:

- excited state contamination is suppressed
- access excited state matrix elements

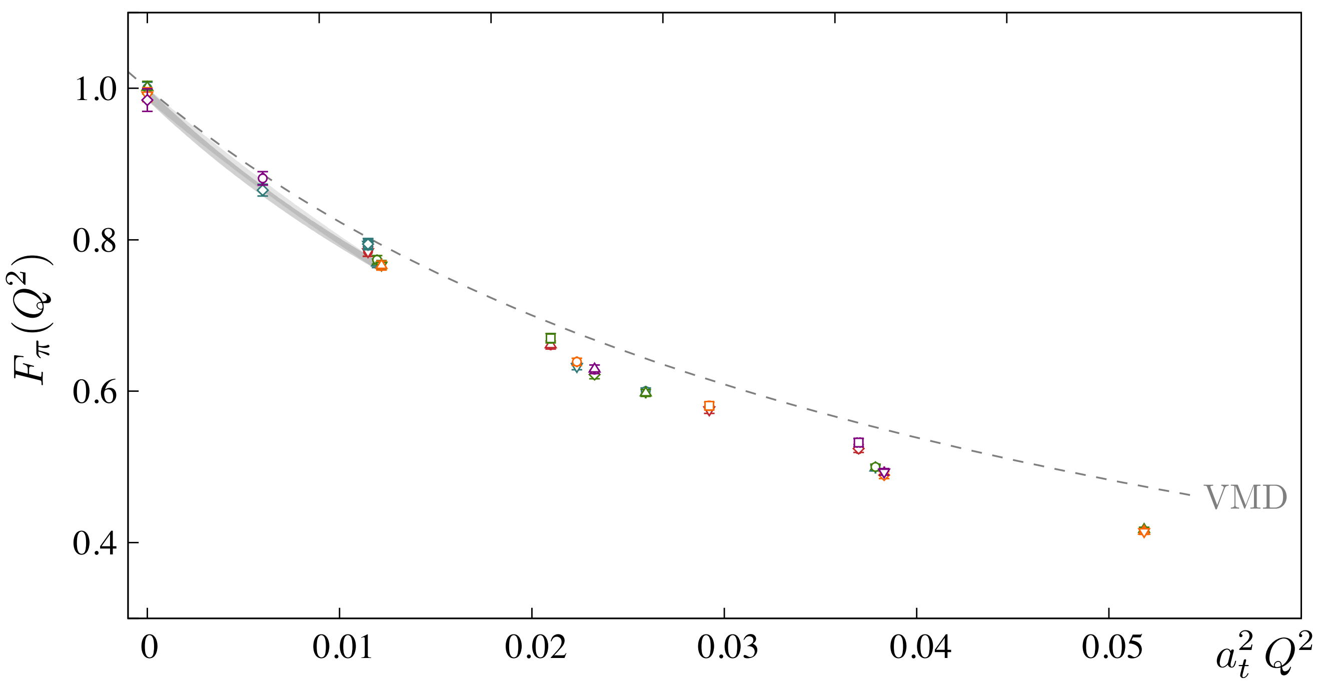
Crucial for few-body/resonance physics

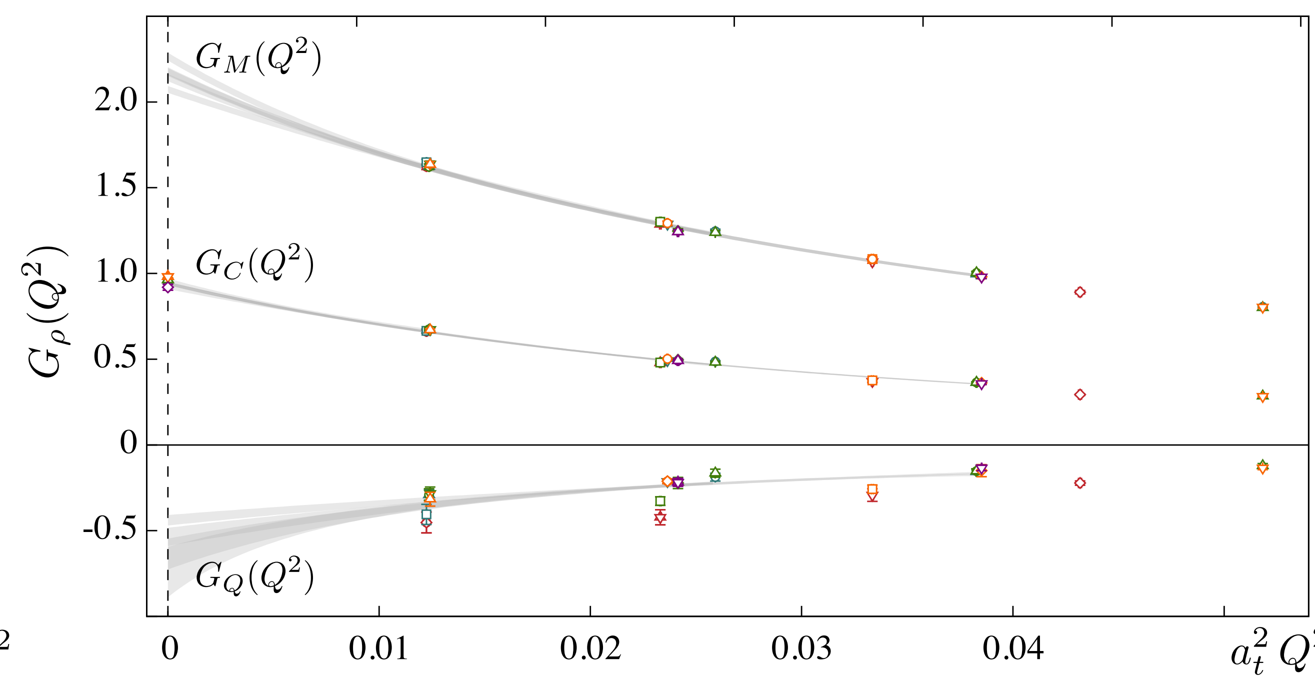


Form factors

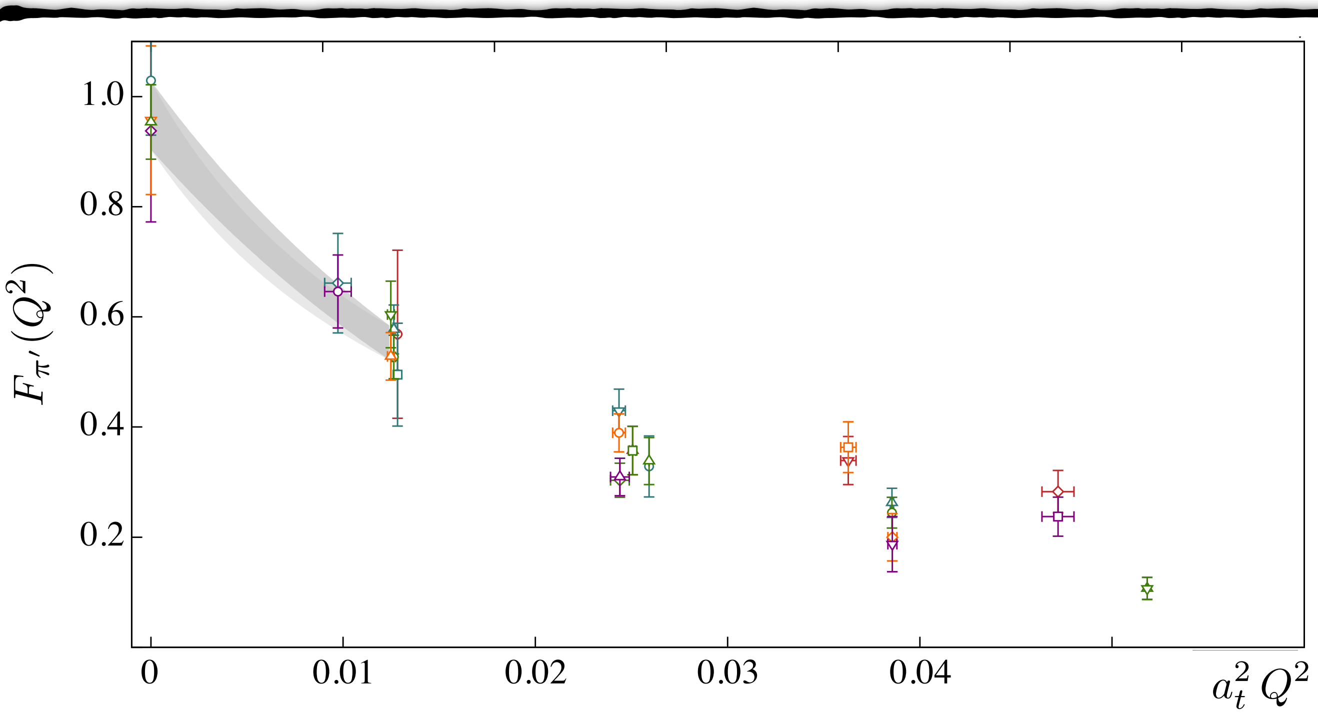
@ m_π= 700 MeV (*everything is stable!*)

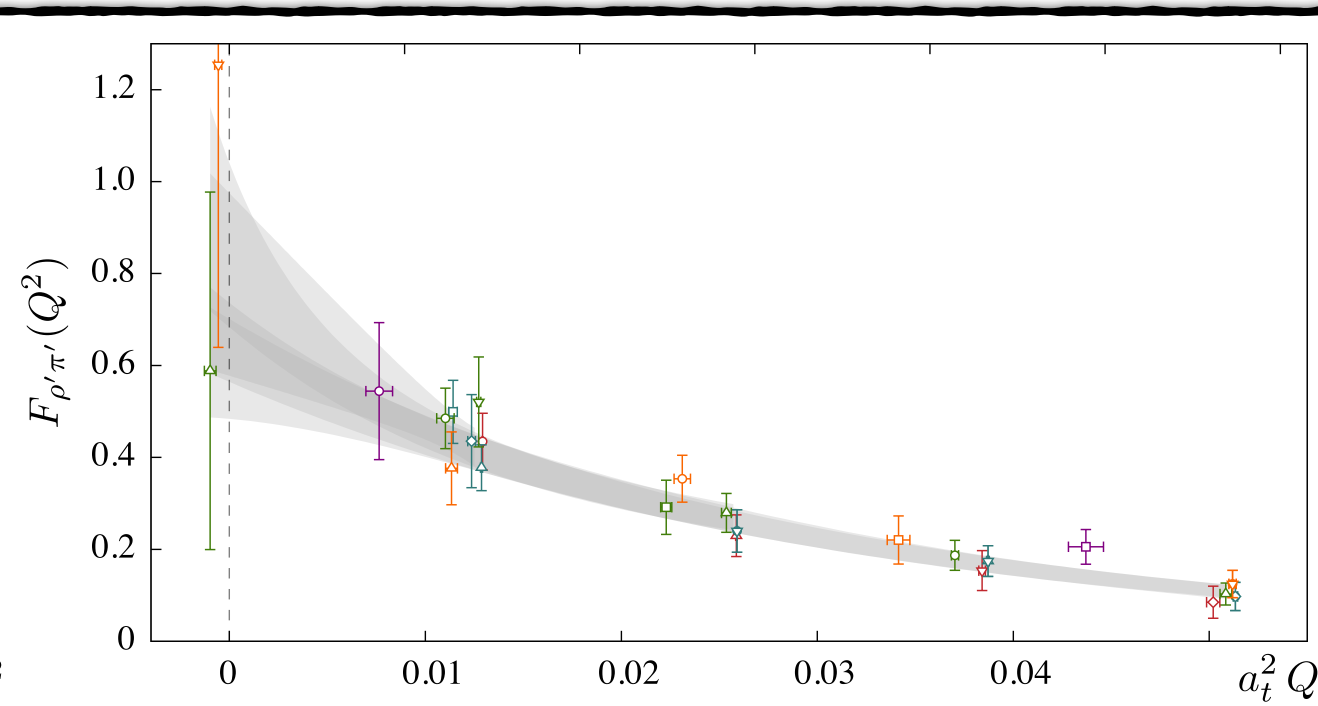
Ground states…





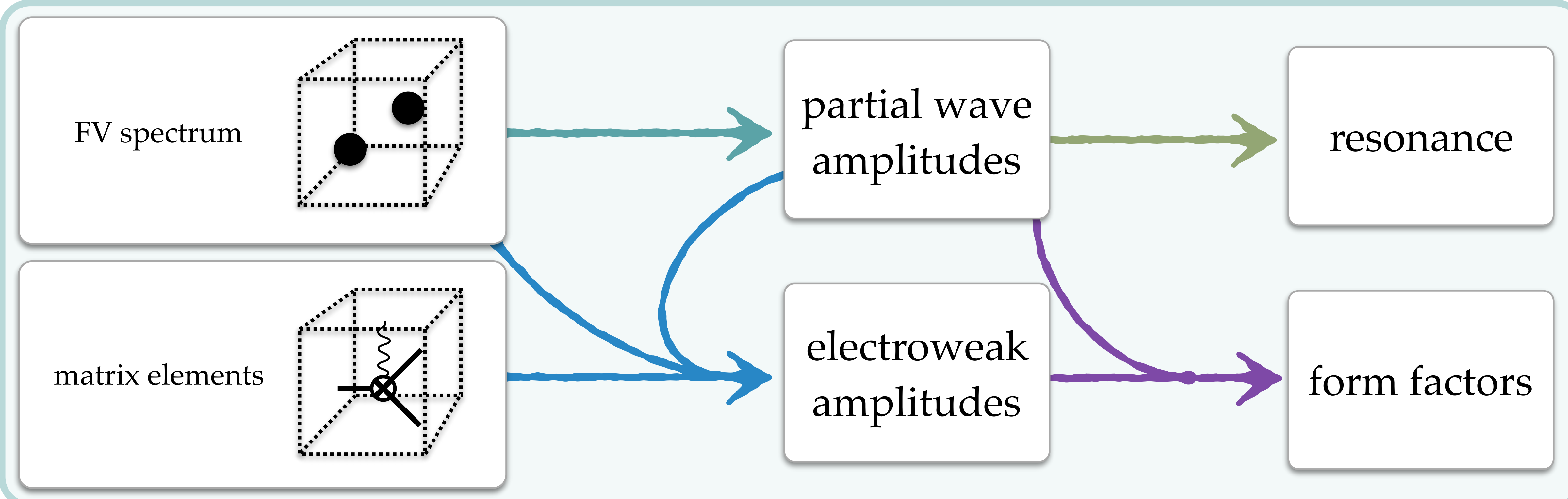
Excited states…





Shultz, Dudek, Edwards - PRD (2015)

1-to-2 formalism

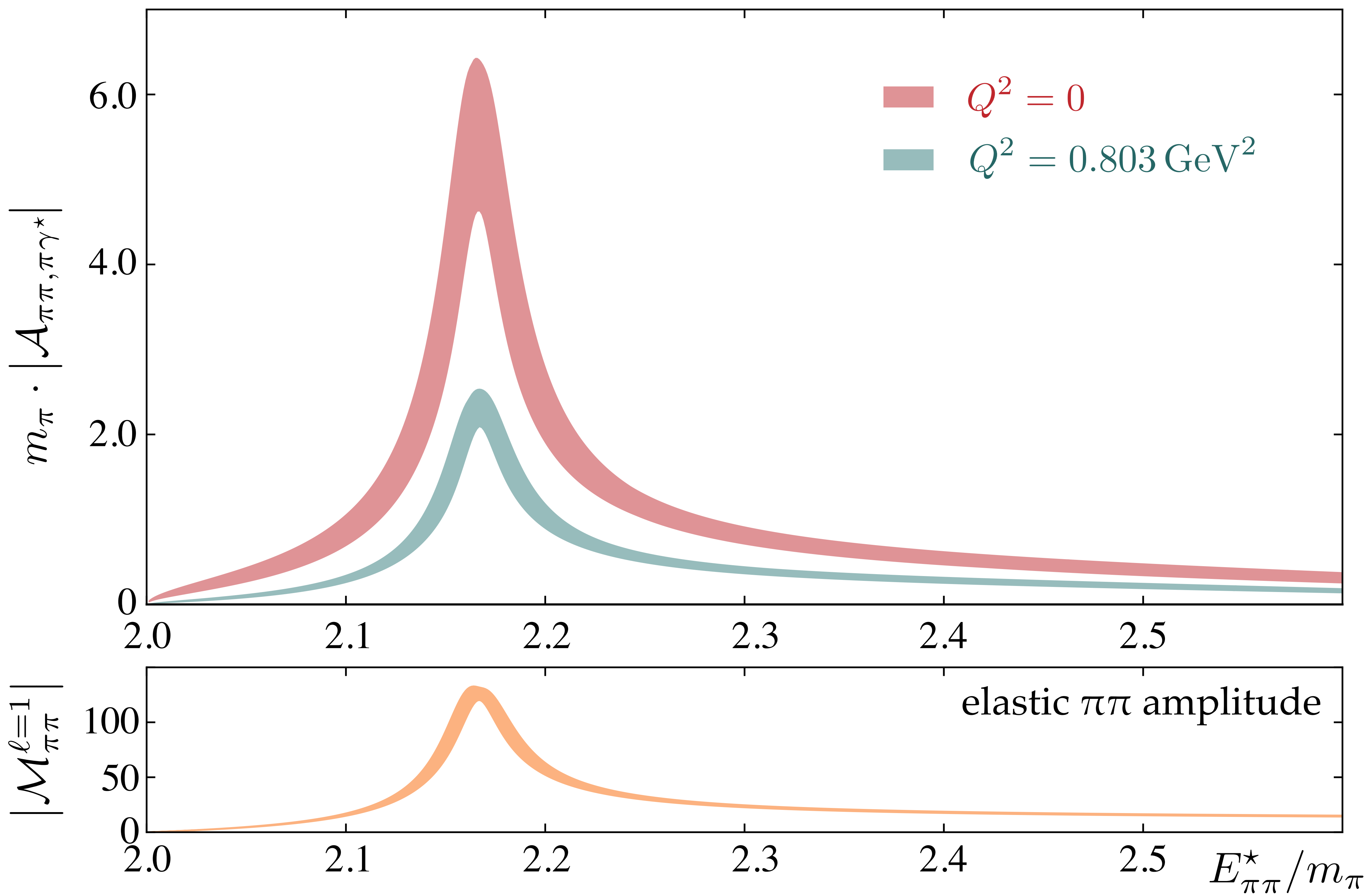


$$\left|\langle \mathbf{2}|\mathcal{J}|\mathbf{1}\rangle_L\right| = \sqrt{\mathcal{A}\,\mathcal{R}\,\mathcal{A}}$$

$\langle \mathbf{2}|\mathcal{J}|\mathbf{1}\rangle_L = \text{FV matrix element}$
$\mathcal{R} = \text{known function}$
$\mathcal{A} = \text{electroweak amp.}$

- Lellouch & Lüscher (2000) [K-to-$\pi\pi$ at rest]
- Kim, Sachrajda, & Sharpe / Christ, Kim & Yamazaki (2005) [moving K-to-$\pi\pi$]
- …
- Hansen & Sharpe (2012) [D-to-$\pi\pi$ / KK]
- RB, Hansen Walker-Lou / RB & Hansen (2014-2015) [general 1-to-2 result]

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

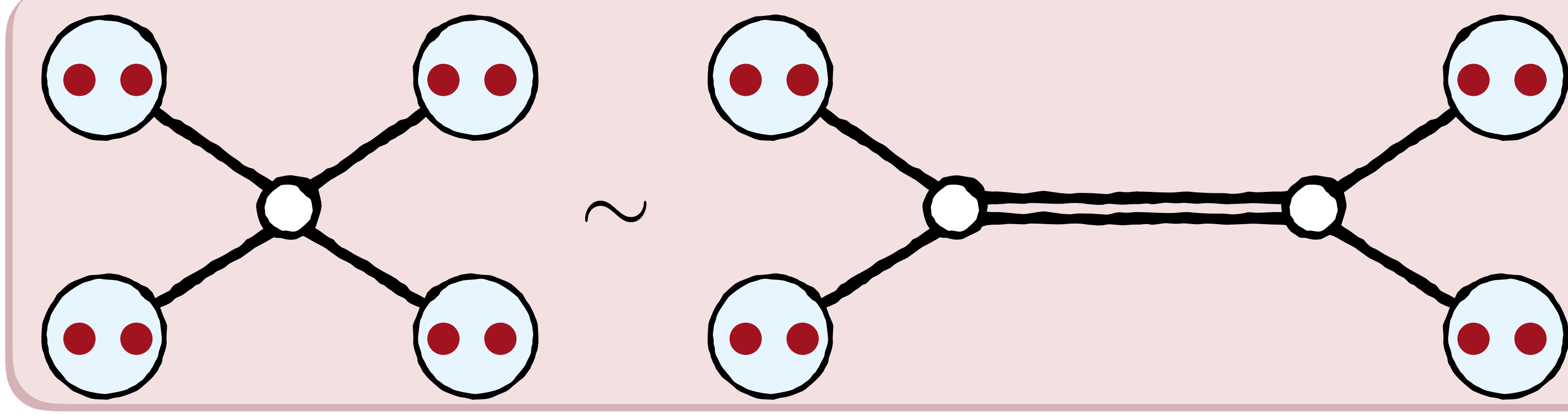


m_π=391 MeV

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

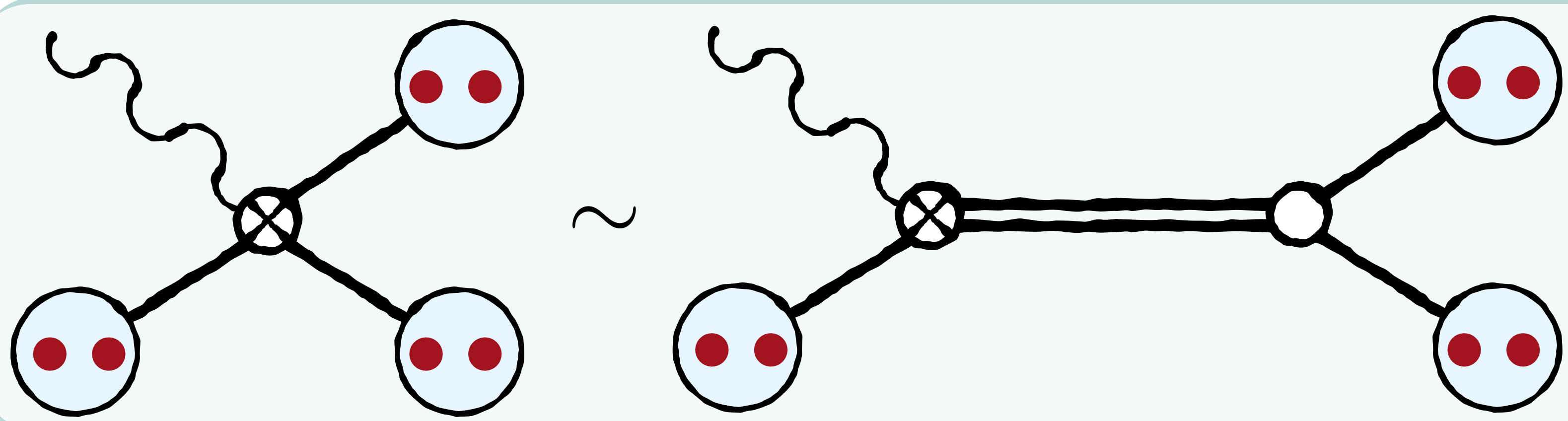
Explanation

- *$\pi\pi$-to-$\pi\pi$ amplitude:*



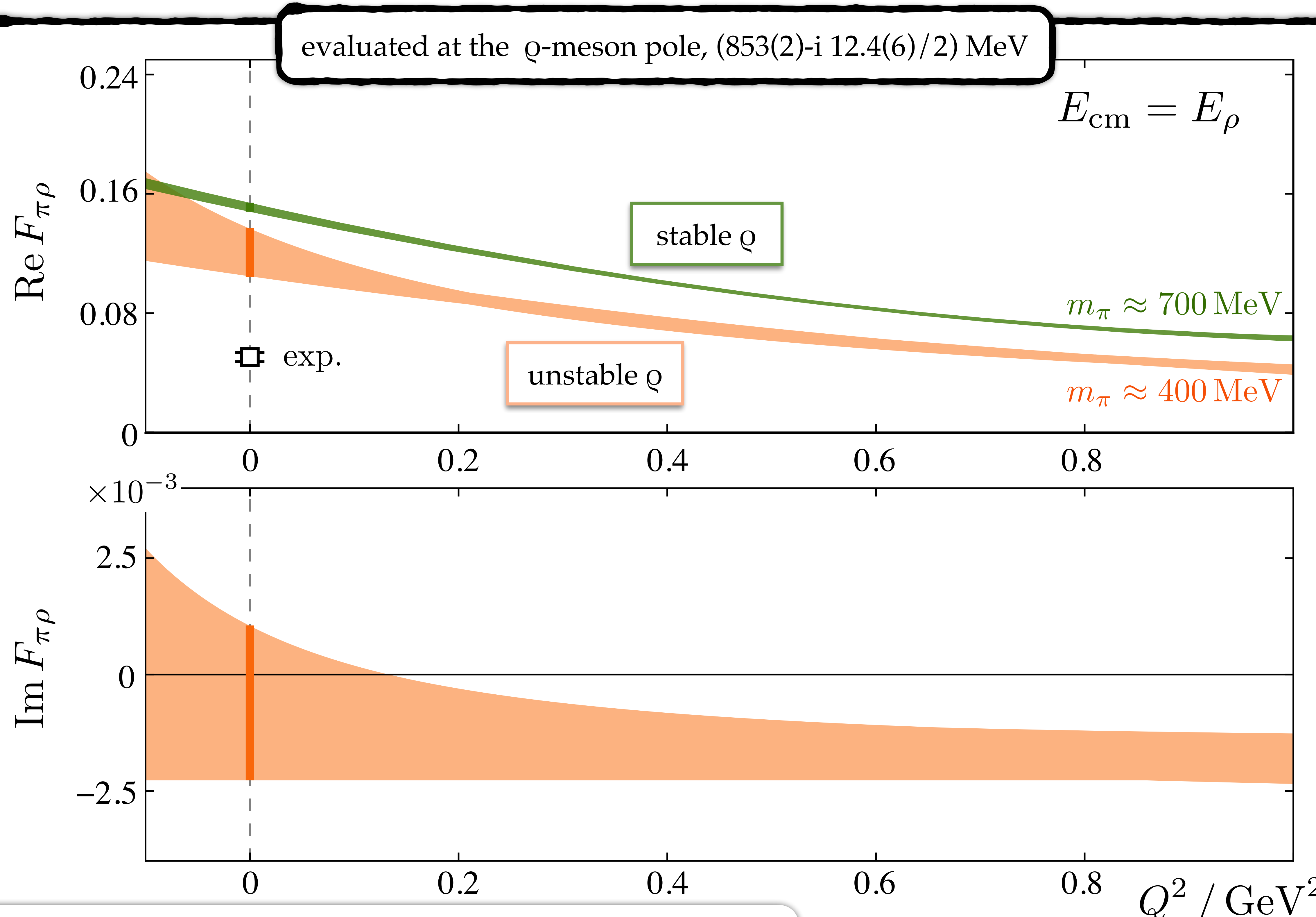
$$\sim \frac{i|g_{\rho,\pi\pi}|^2}{s - s_0}$$

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



$$\sim \frac{iF_{\pi\rho}\; g_{\rho,\pi\pi}}{s - s_0}$$

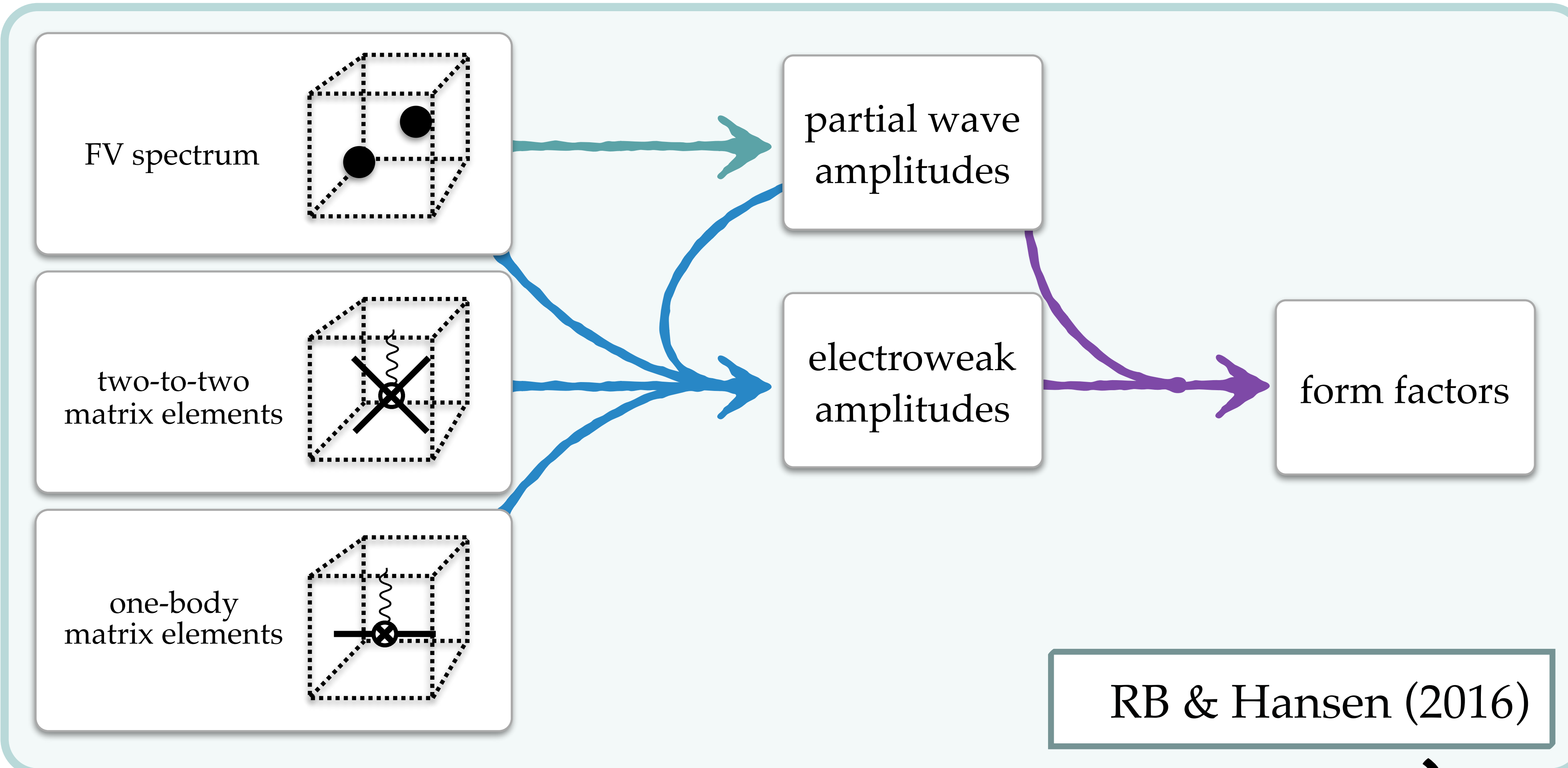
π-to-ρ form factor



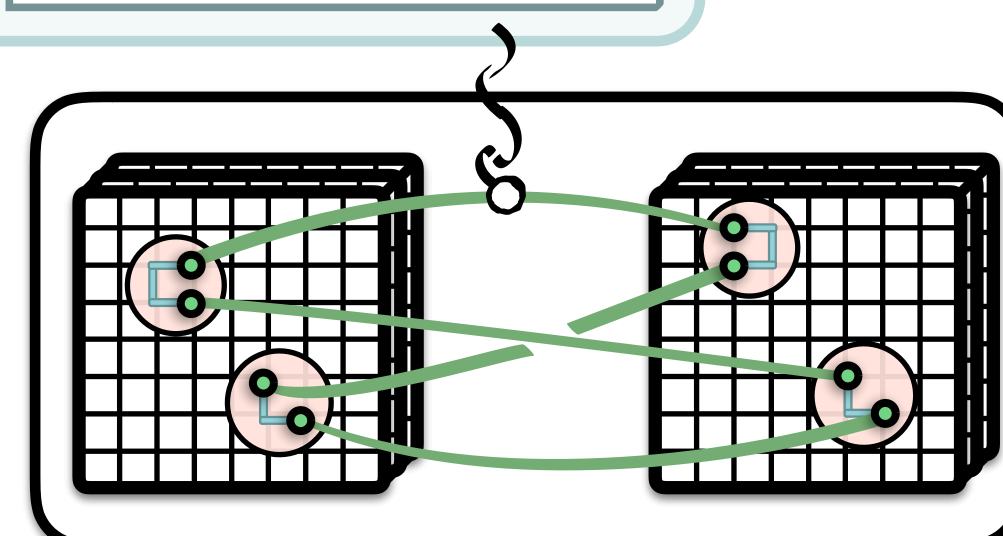
Shultz, Dudek, & Edwards (2014)
RB, Dudek, Edwards, Shultz, Thomas & Wilson - PRL (2015)

Elastic form factors of composite states

- Formalism in place:



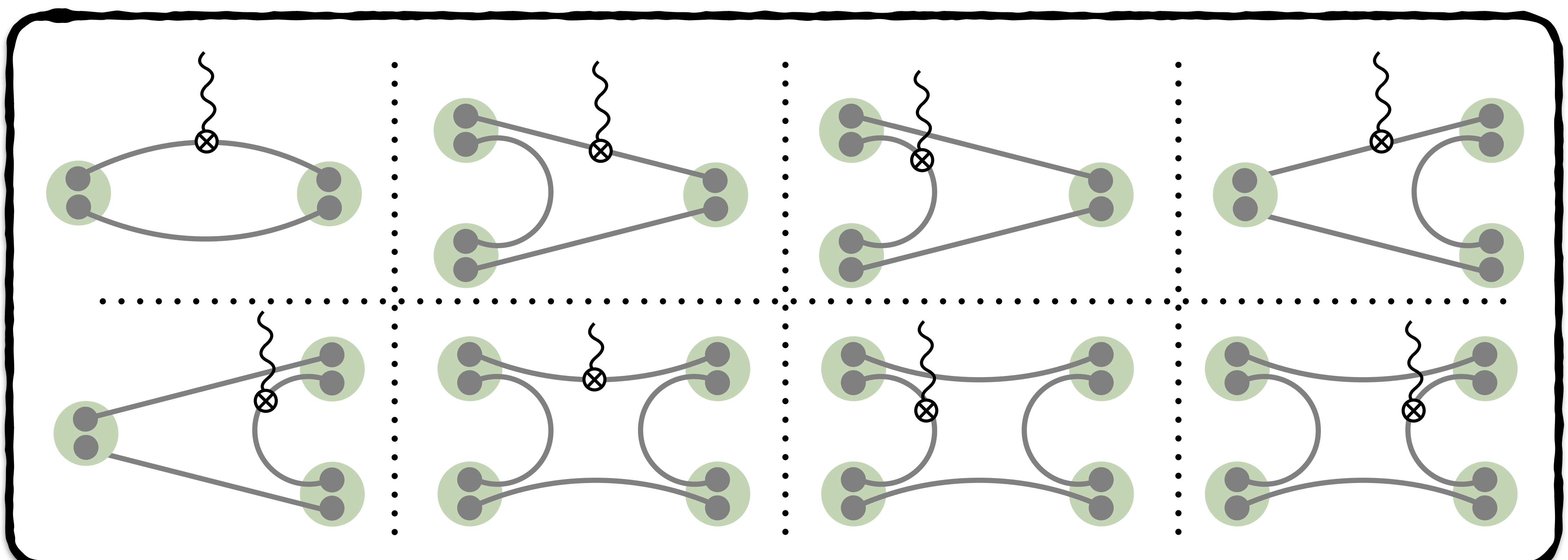
- necessary for:
  - scattering states
  - bound states
  - resonances
- untested!



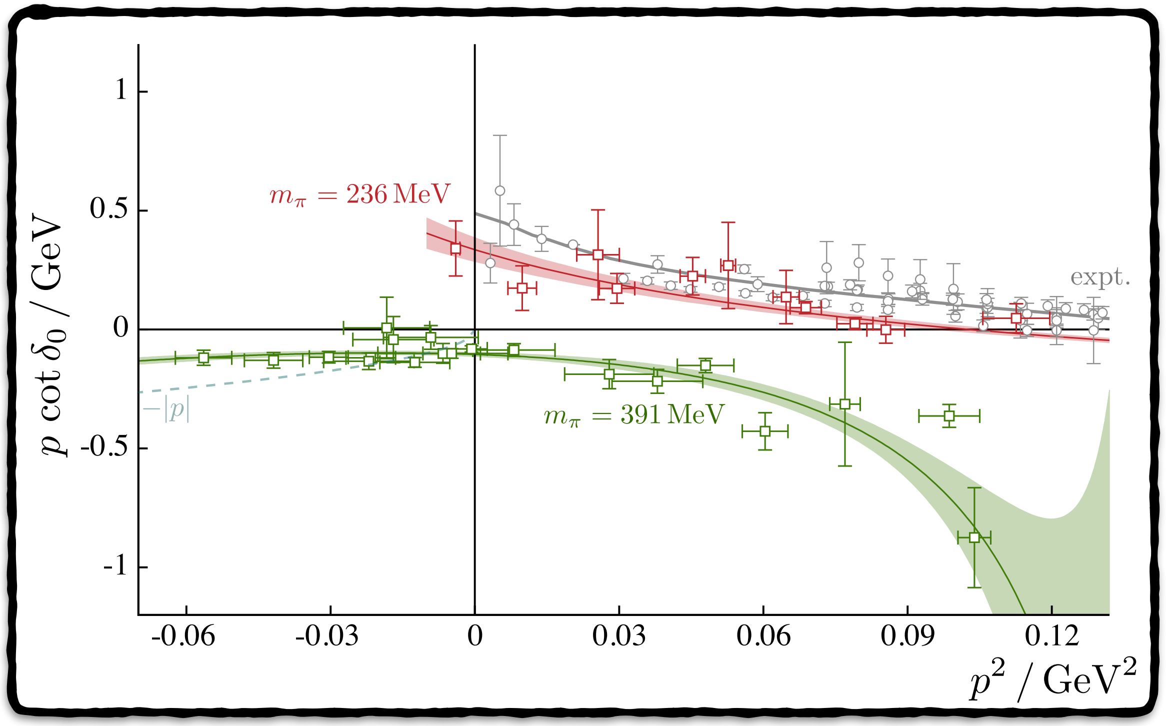
Physics Plan for 2017 / 2018
Part 2 - matrix elements

- Quark-mass dependence of $\pi\gamma^*$-to-$\pi\pi$ amplitude
  - m_π=236, 275, 325 MeV
  - Test chiral anomaly

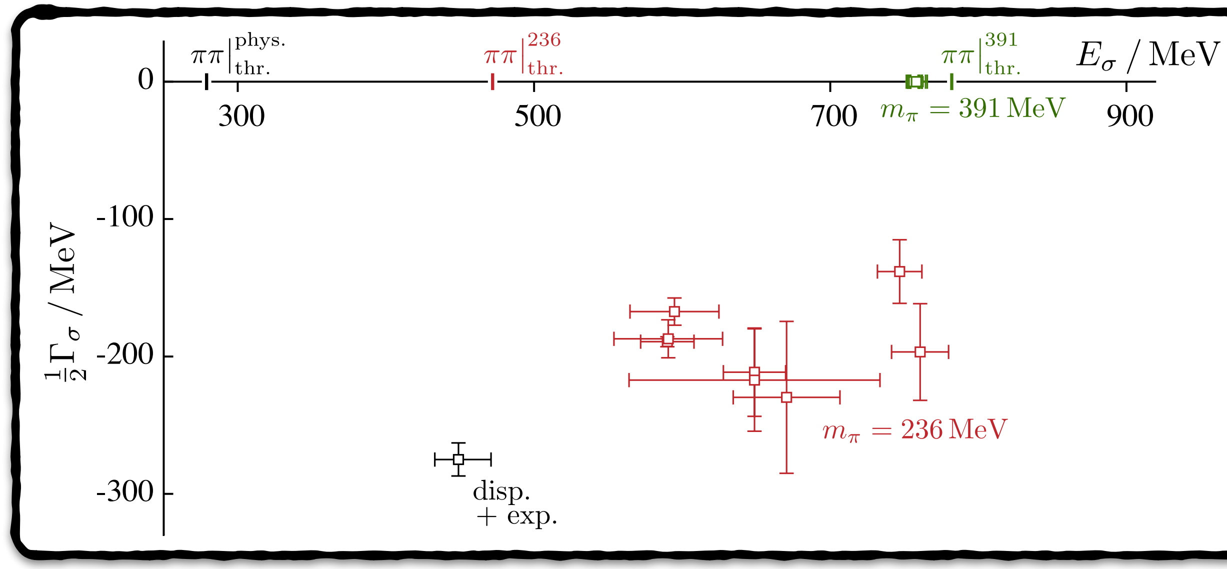
- First calculation of a form factor of a composite state
  - $\pi\pi\gamma^*$-to-$\pi\pi$
  - elastic ϱ form factors
  - m_π=236 MeV



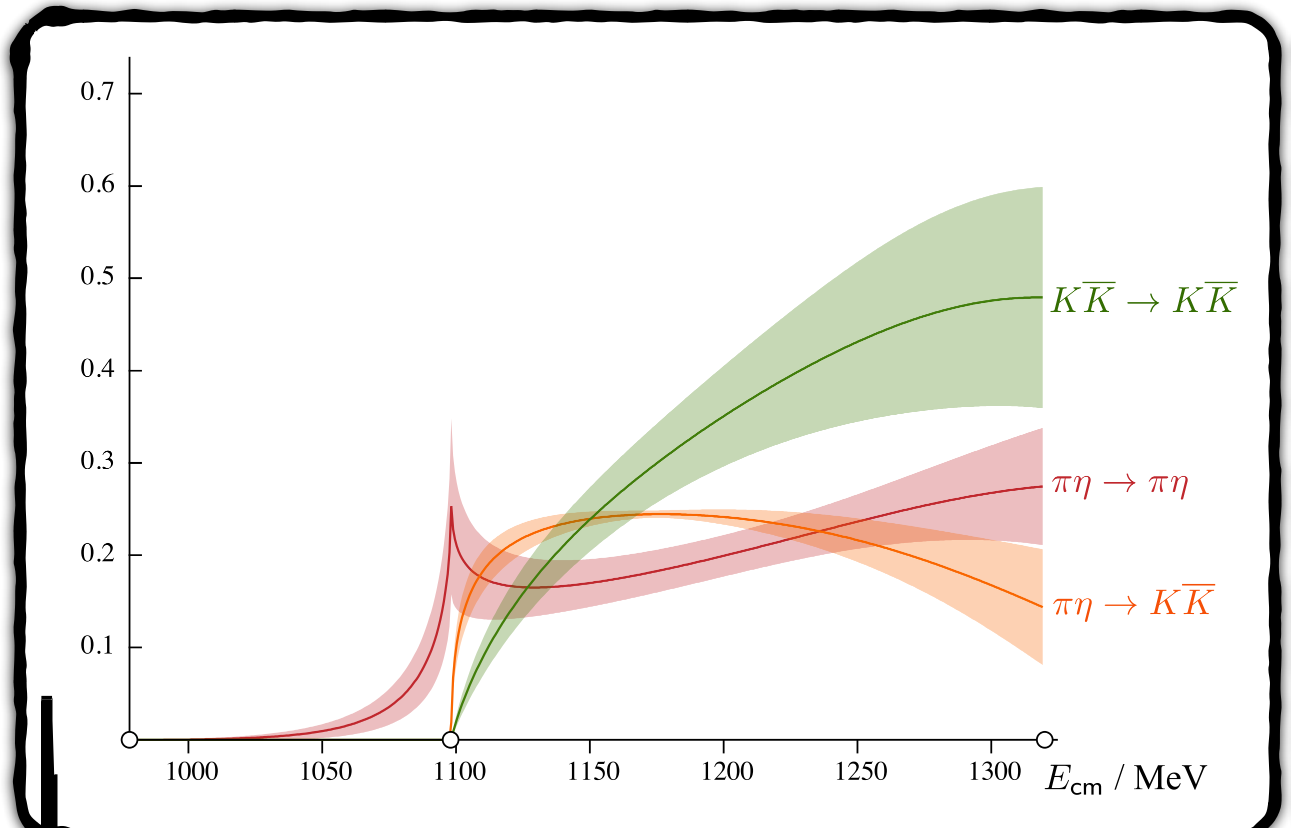
hadspec



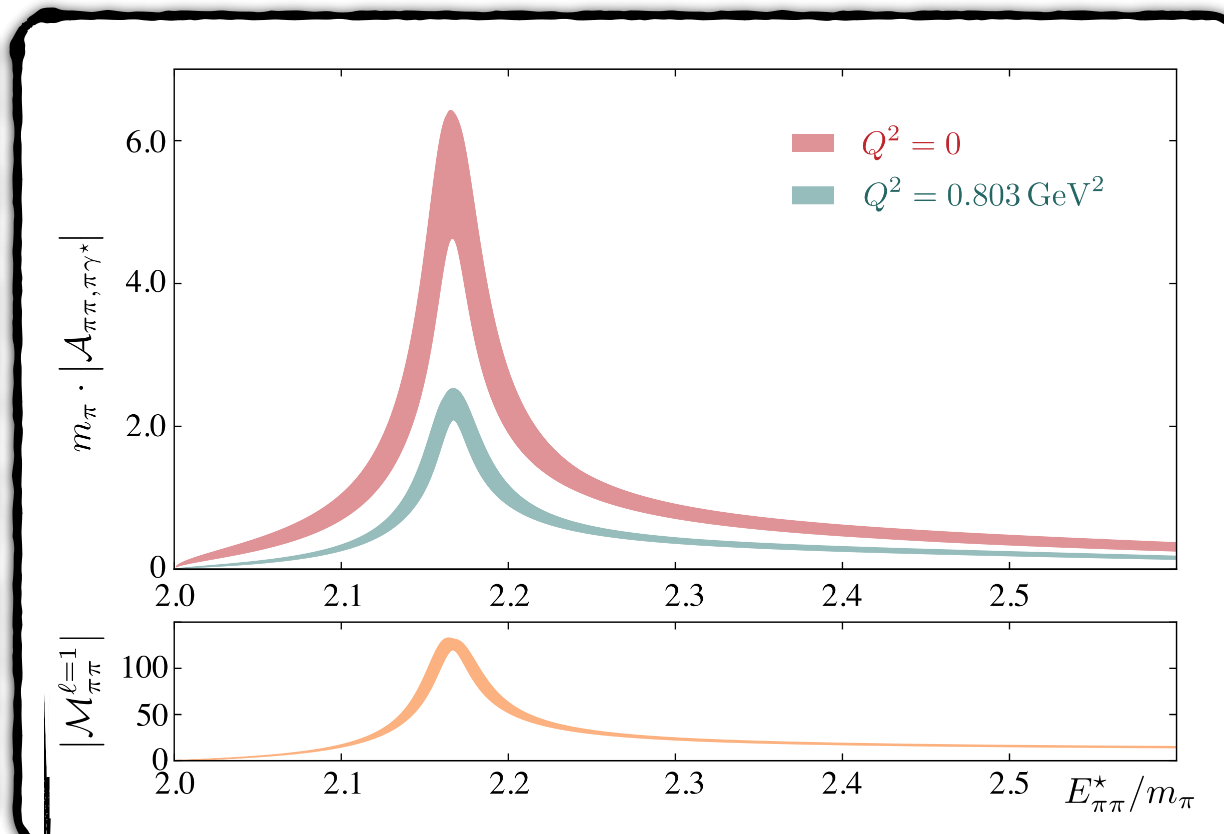
$p \cot \delta_0$ / GeV
p^2 / GeV^2
$m_\pi = 236$ MeV
$m_\pi = 391$ MeV
expt.
$-|p|$
1
0.5
0
-0.5
-1
-0.06
-0.03
0
0.03
0.06
0.09
0.12



$\frac{1}{2}\Gamma_\sigma$ / MeV
E_σ / MeV
$\pi\pi|^{\mathrm{phys.}}_{\mathrm{thr.}}$
$\pi\pi|^{236}_{\mathrm{thr.}}$
$\pi\pi|^{391}_{\mathrm{thr.}}$
$m_\pi = 391$ MeV
$m_\pi = 236$ MeV
disp.
+ exp.
0
-100
-200
-300
300
500
700
900



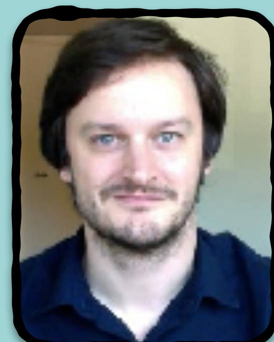
$K\overline{K} \to K\overline{K}$
$\pi\eta \to \pi\eta$
$\pi\eta \to K\overline{K}$
E_{cm} / MeV
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1000
1050
1100
1150
1200
1250
1300



$Q^2 = 0$
$Q^2 = 0.803\,\mathrm{GeV}^2$
$m_\pi \cdot |\mathcal{A}_{\pi\pi,\pi\gamma^\star}|$
$|\mathcal{M}^{\ell=1}_{\pi\pi}|$
$E^\star_{\pi\pi}/m_\pi$
6.0
4.0
2.0
0
100
50
2.0
2.1
2.2
2.3
2.4
2.5

hadspec

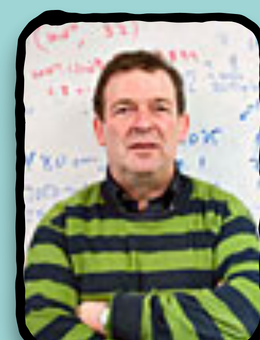

Chakraborty


Dudek


Edwards


Winter


Joó


Richards


Wilson


Moir


Peardon


Ryan


Thomas


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

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

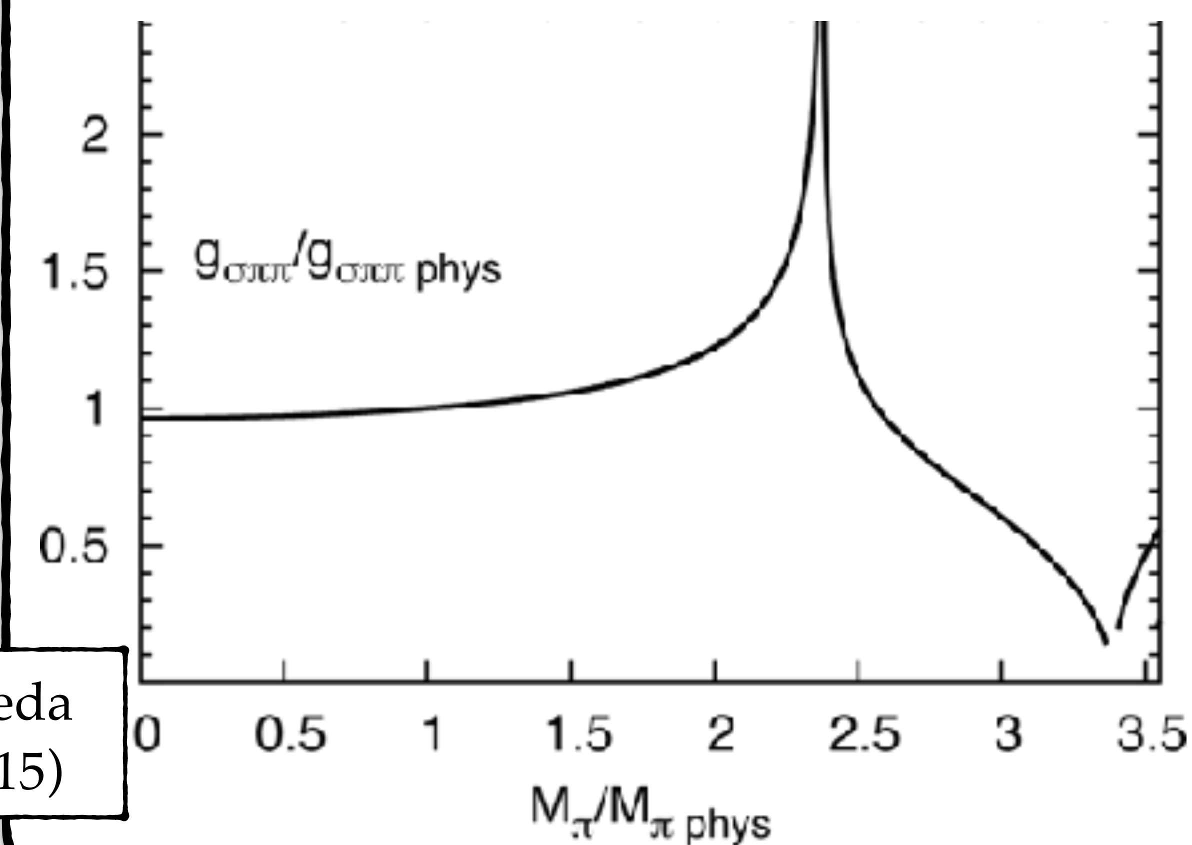
PRD85 014507 (2012)
PRD80 054506 (2009)
PRD79 034502 (2009)

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

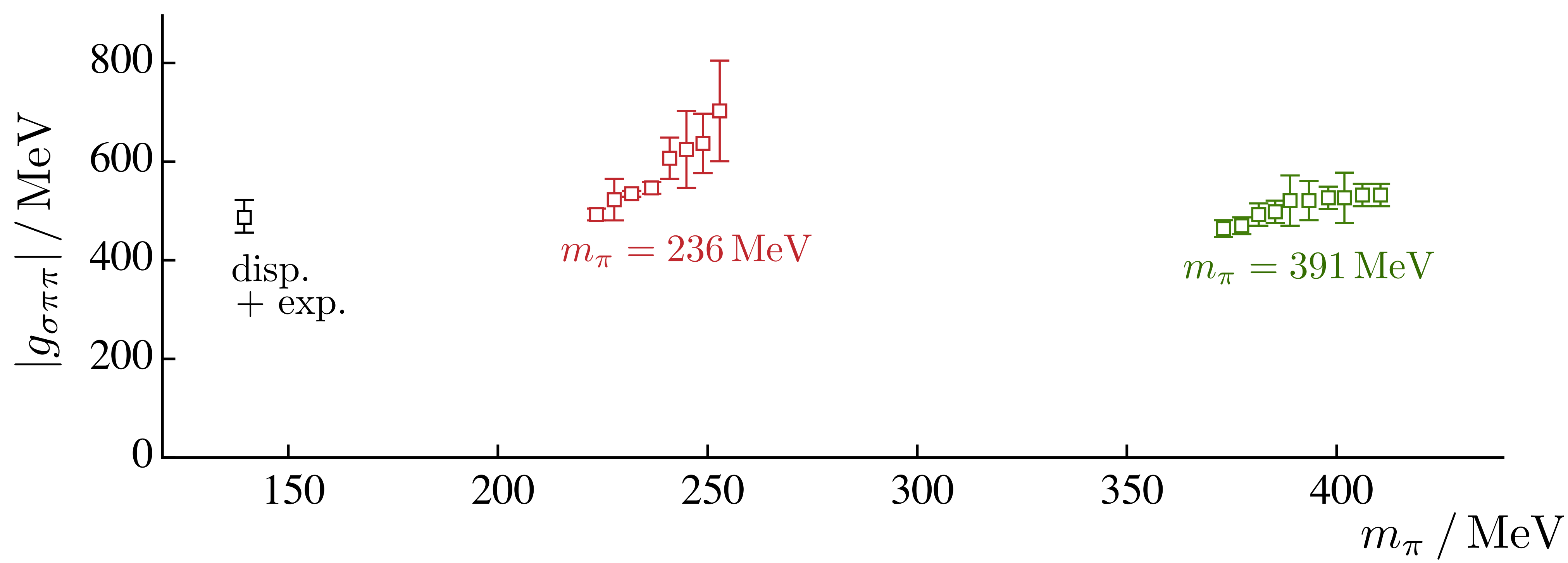
Formalism

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

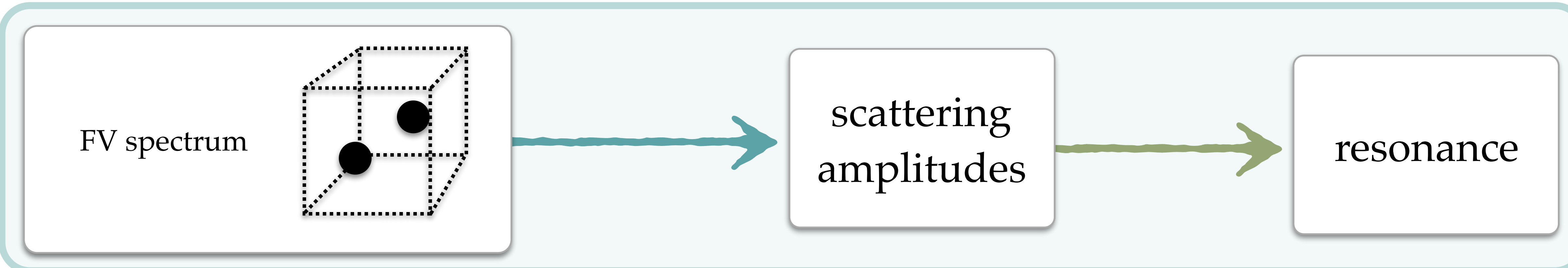
The σ / $f_0(500)$ vs m_π



UχPT - Nebreda & Peláez (2015)



Spectroscopy formalism

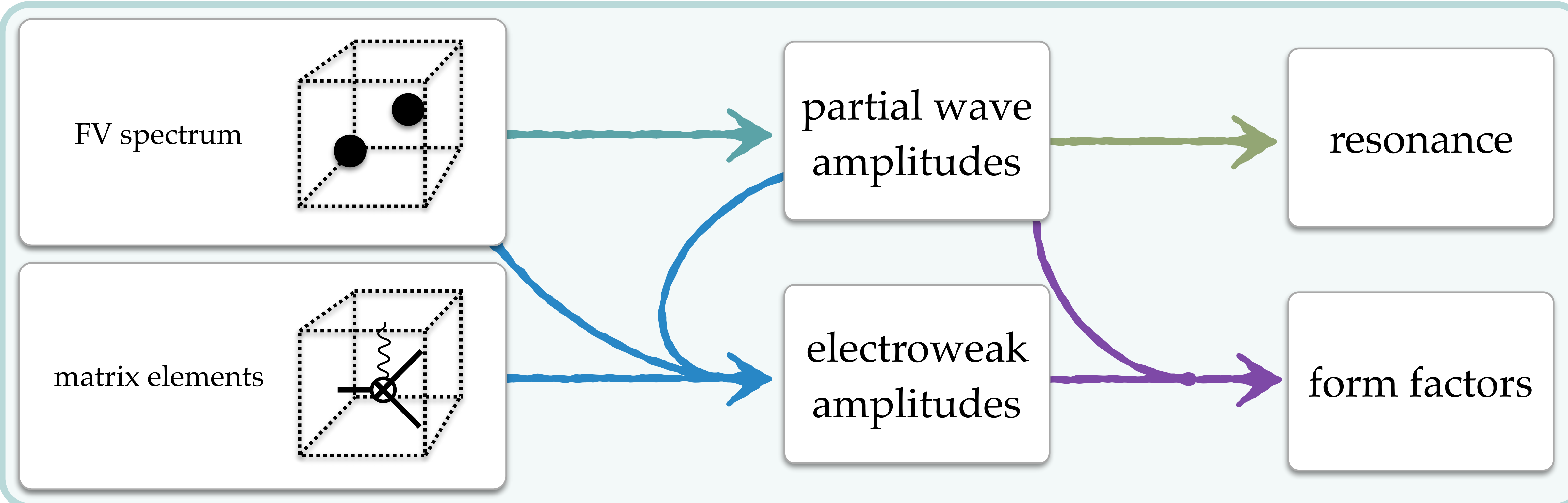


$$\det[F^{-1}(E_L, L) + \mathcal{M}(E_L)] = 0$$

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]

1-to-2 formalism



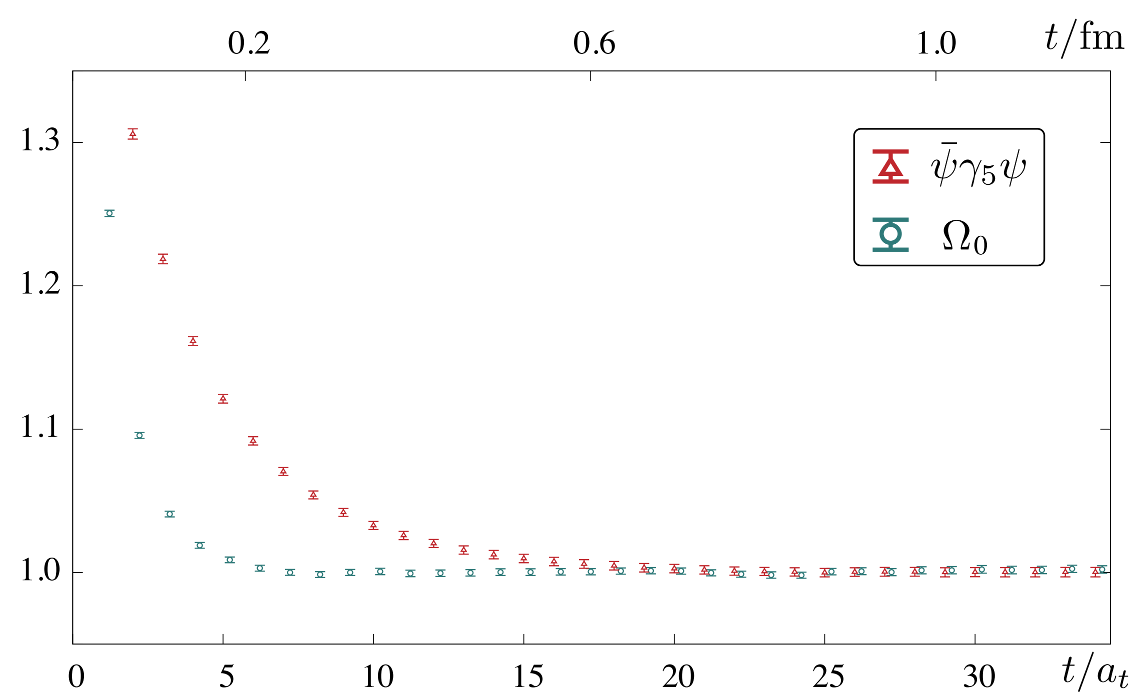
$$\left|\langle \mathbf{2}|\mathcal{J}|\mathbf{1}\rangle_L\right| = \sqrt{\mathcal{A}\,\mathcal{R}\,\mathcal{A}}$$

$\langle \mathbf{2}|\mathcal{J}|\mathbf{1}\rangle_L =$ FV matrix element
$\mathcal{R} =$ known function
$\mathcal{A} =$ electroweak amp.

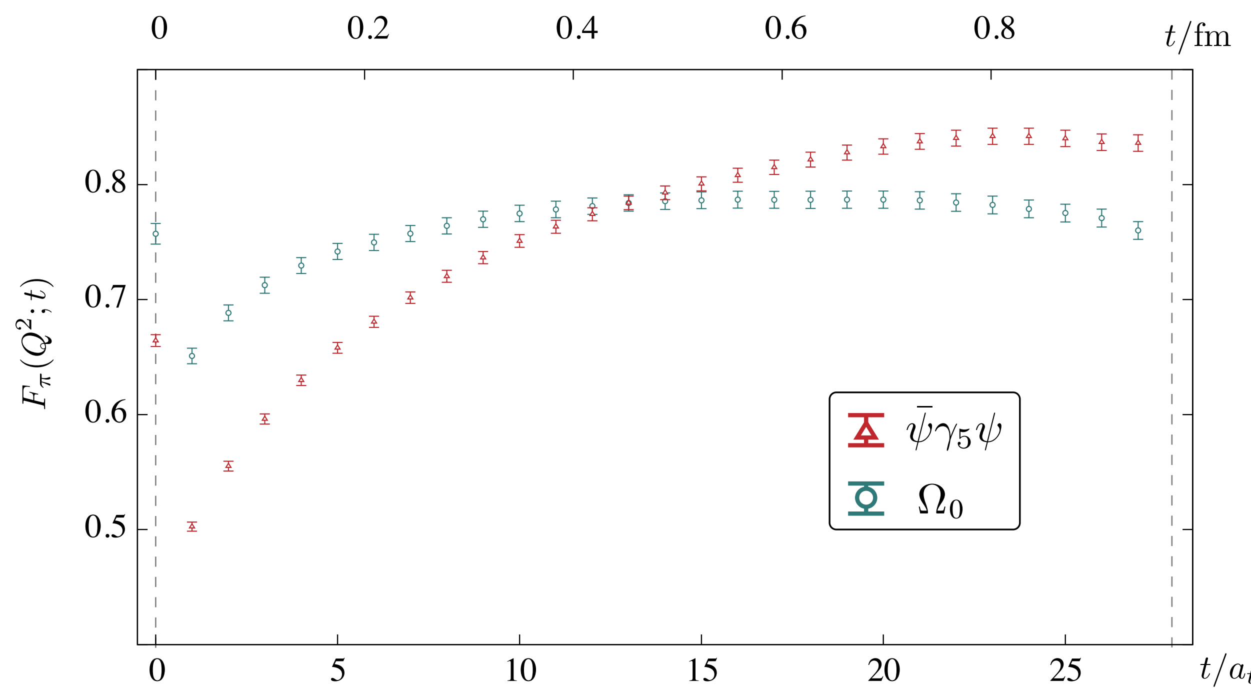
- Lellouch & Lüscher (2000) [K-to-$\pi\pi$ at rest]
- Kim, Sachrajda, & Sharpe / Christ, Kim & Yamazaki (2005) [moving K-to-$\pi\pi$]
- …
- RB, Hansen Walker-Lou / RB & Hansen (2014-2015) [general 1-to-2 result]

Optimized operators

π at rest

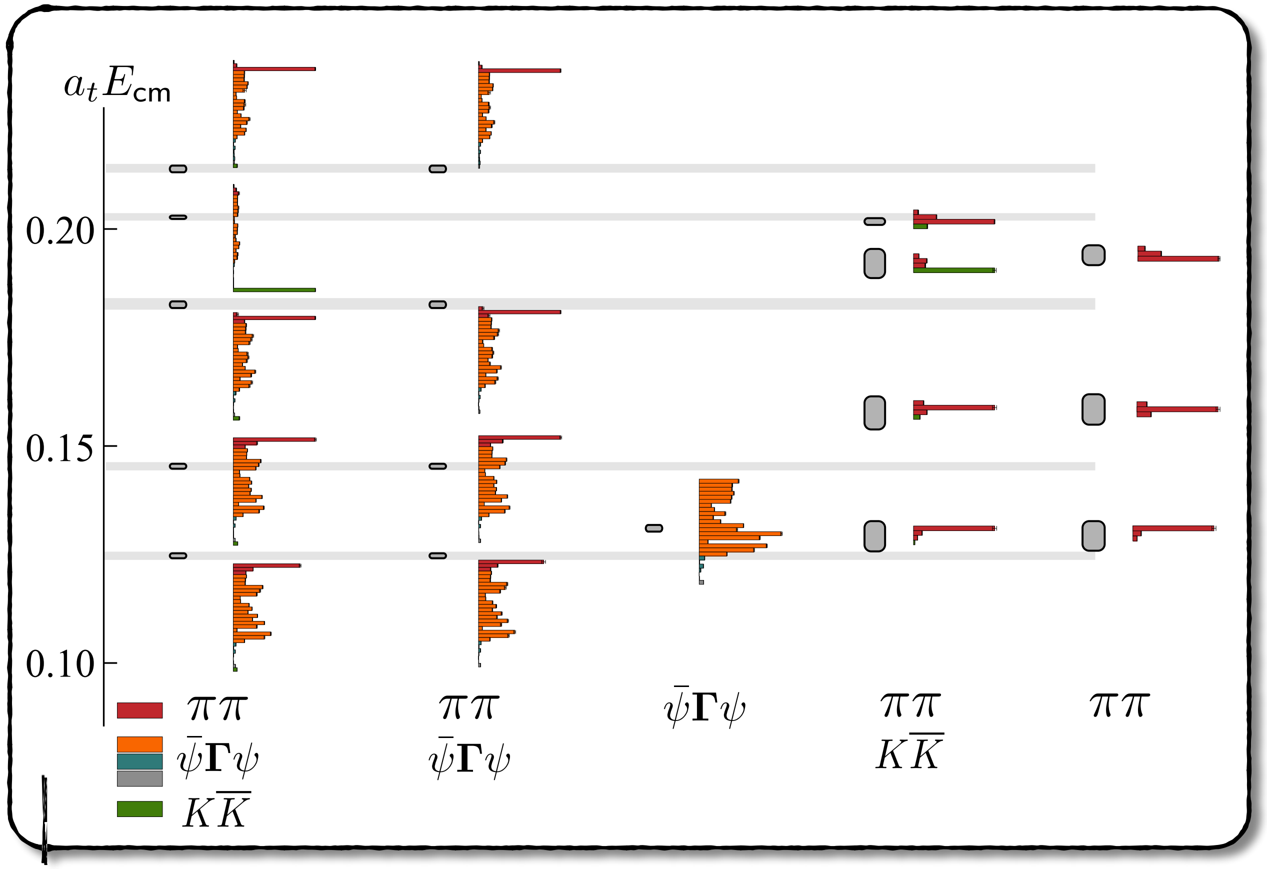


$p_i = 000, \;\; p_f = 100$

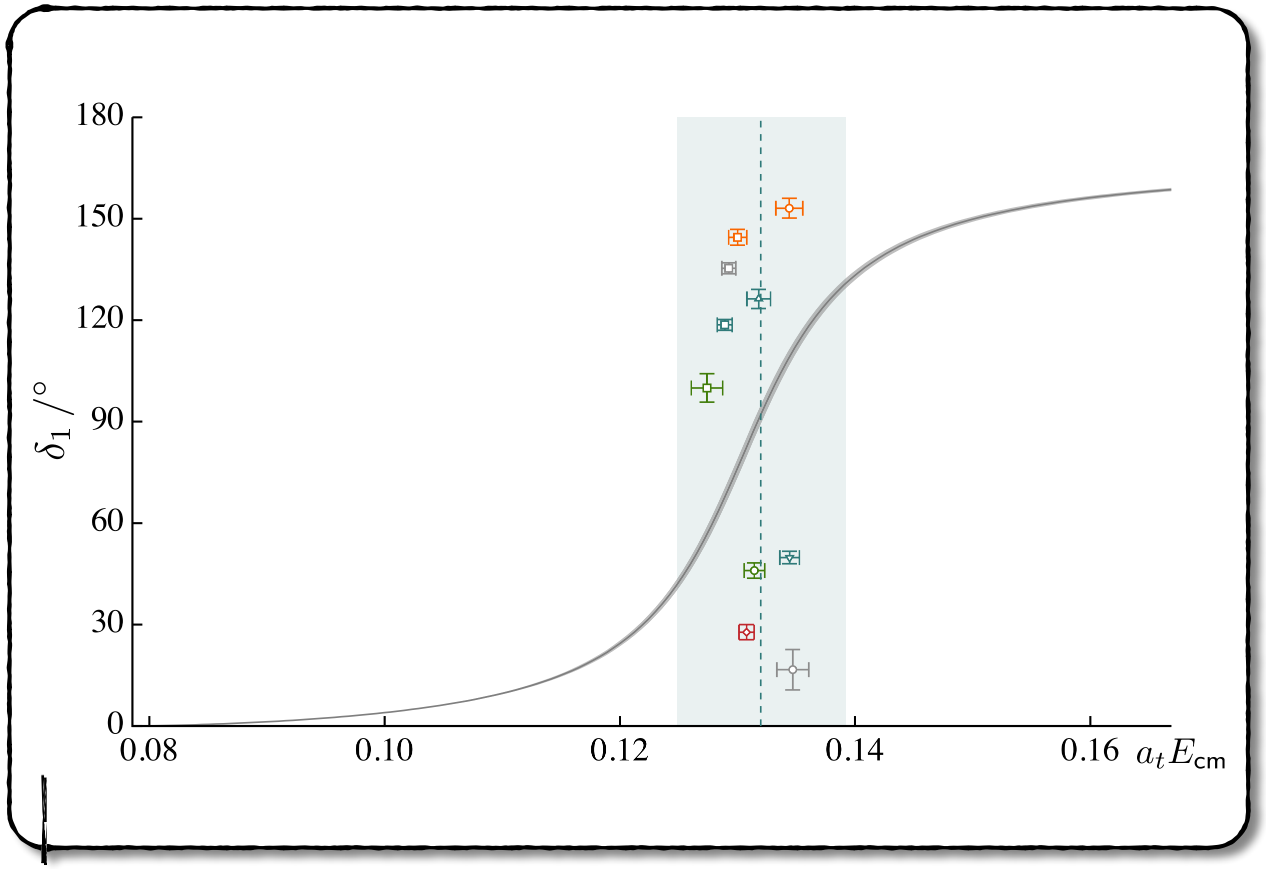


Shultz, Dudek, Edwards - PRD (2015)

Locals ops



$a_t E_{\mathsf{cm}}$
0.20
0.15
0.10
$\pi\pi$
$\bar{\psi}\boldsymbol{\Gamma}\psi$
$K\overline{K}$
$\pi\pi$
$\bar{\psi}\boldsymbol{\Gamma}\psi$
$\bar{\psi}\boldsymbol{\Gamma}\psi$
$\pi\pi$
$K\overline{K}$
$\pi\pi$



$\delta_1 /°$
180
150
120
90
60
30
0
0.08
0.10
0.12
0.14
0.16
$a_t E_{\mathsf{cm}}$