Resonance properties via lattice QCD

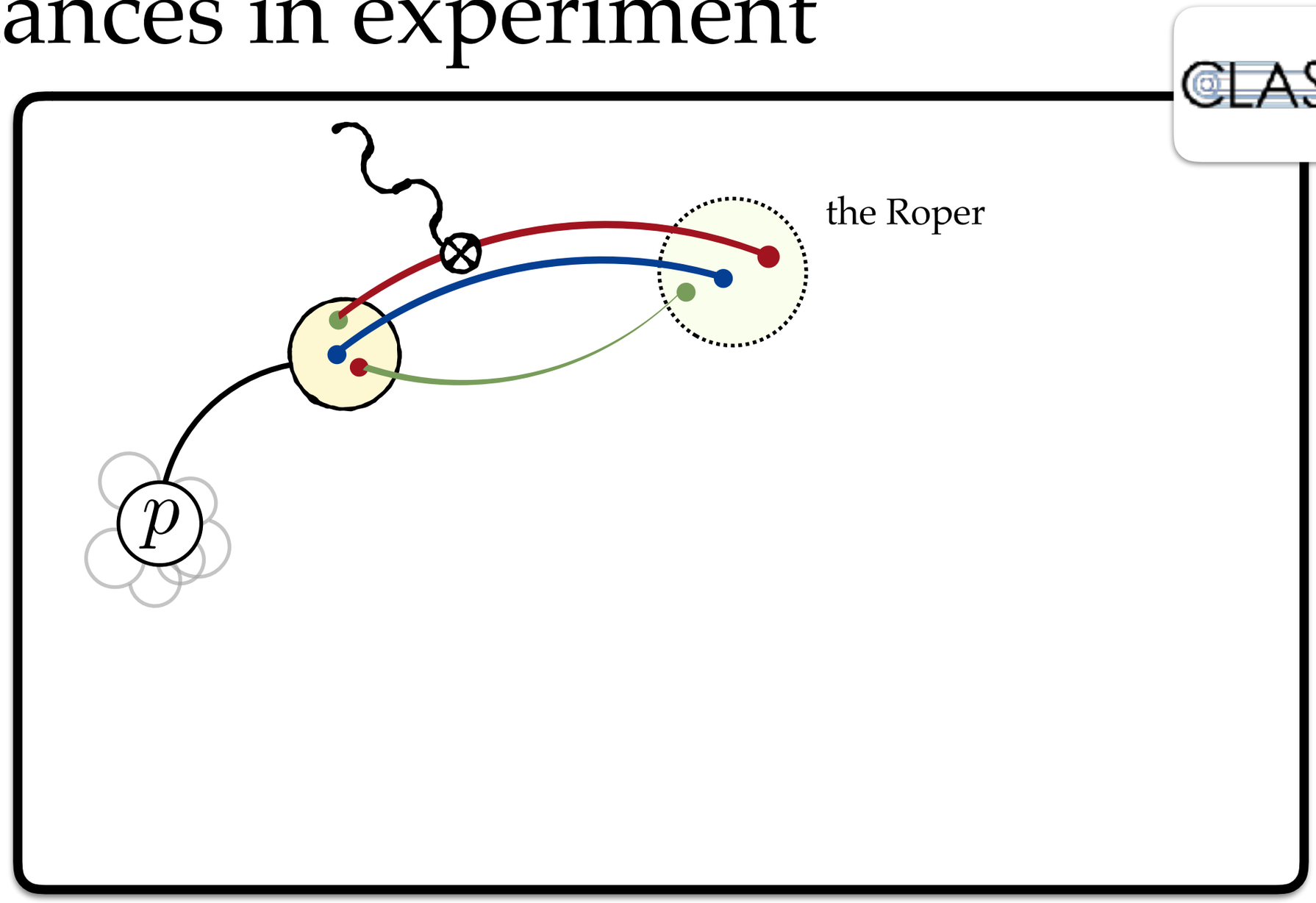
Raúl Briceño

hadspec

Jefferson Lab

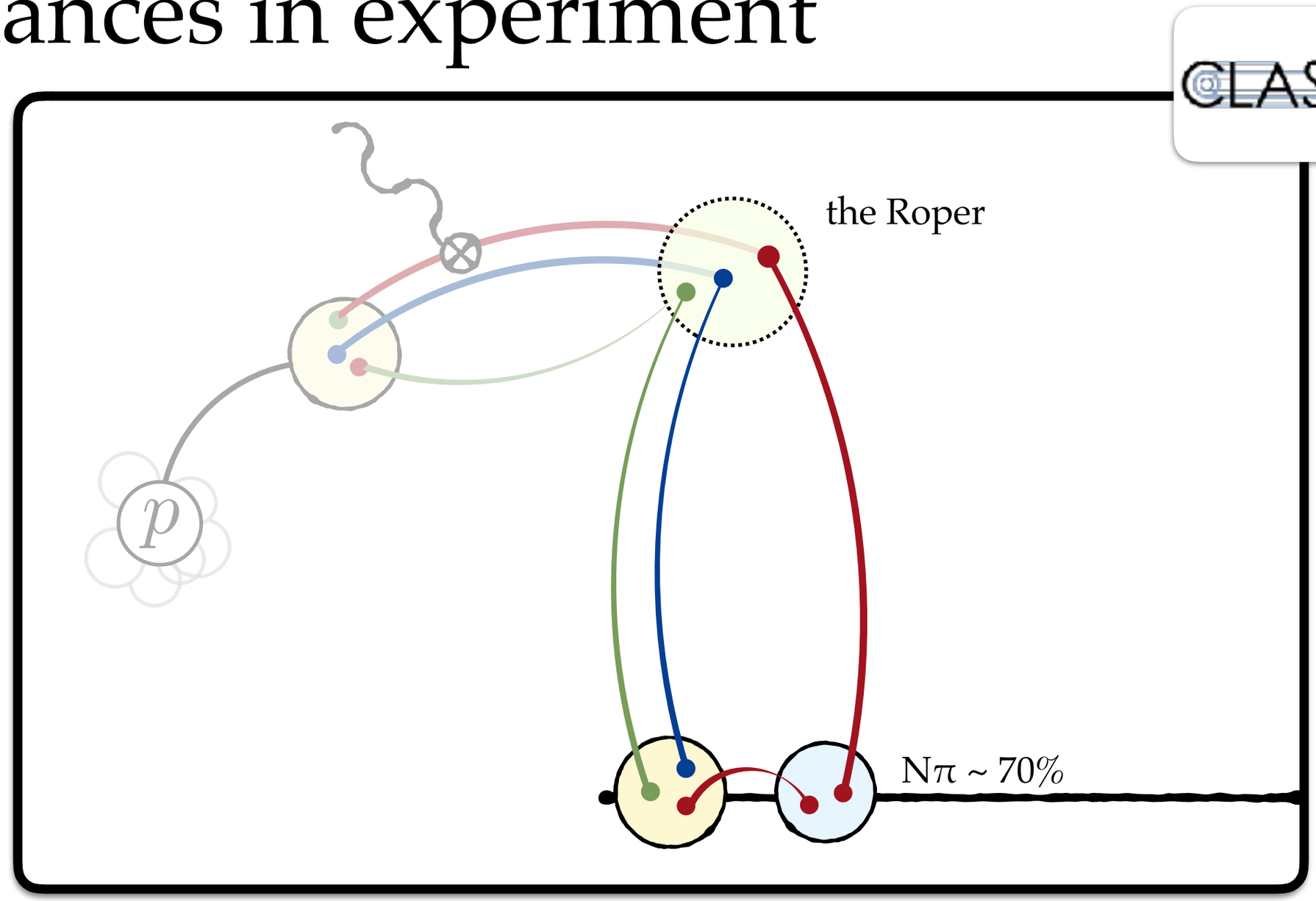
OLD DOMINION UNIVERSITY

Resonances in experiment



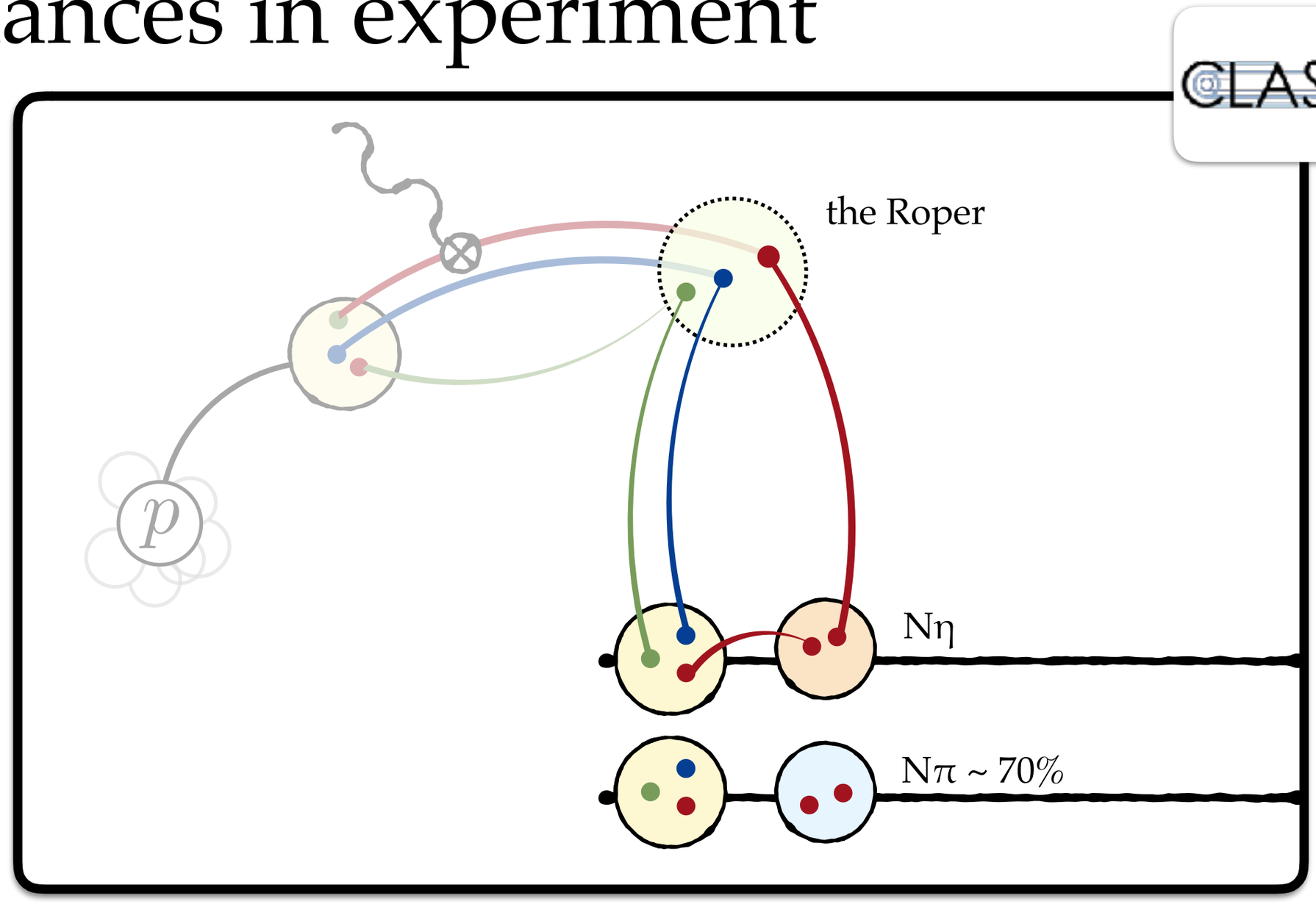
- The vast majority of QCD states are **composite states**, which are either:
  - unstable under QCD (resonances)
  - *accidentally* stable (bound states)
  - depending on the QCD parameters, a state can *transition*

Resonances in experiment



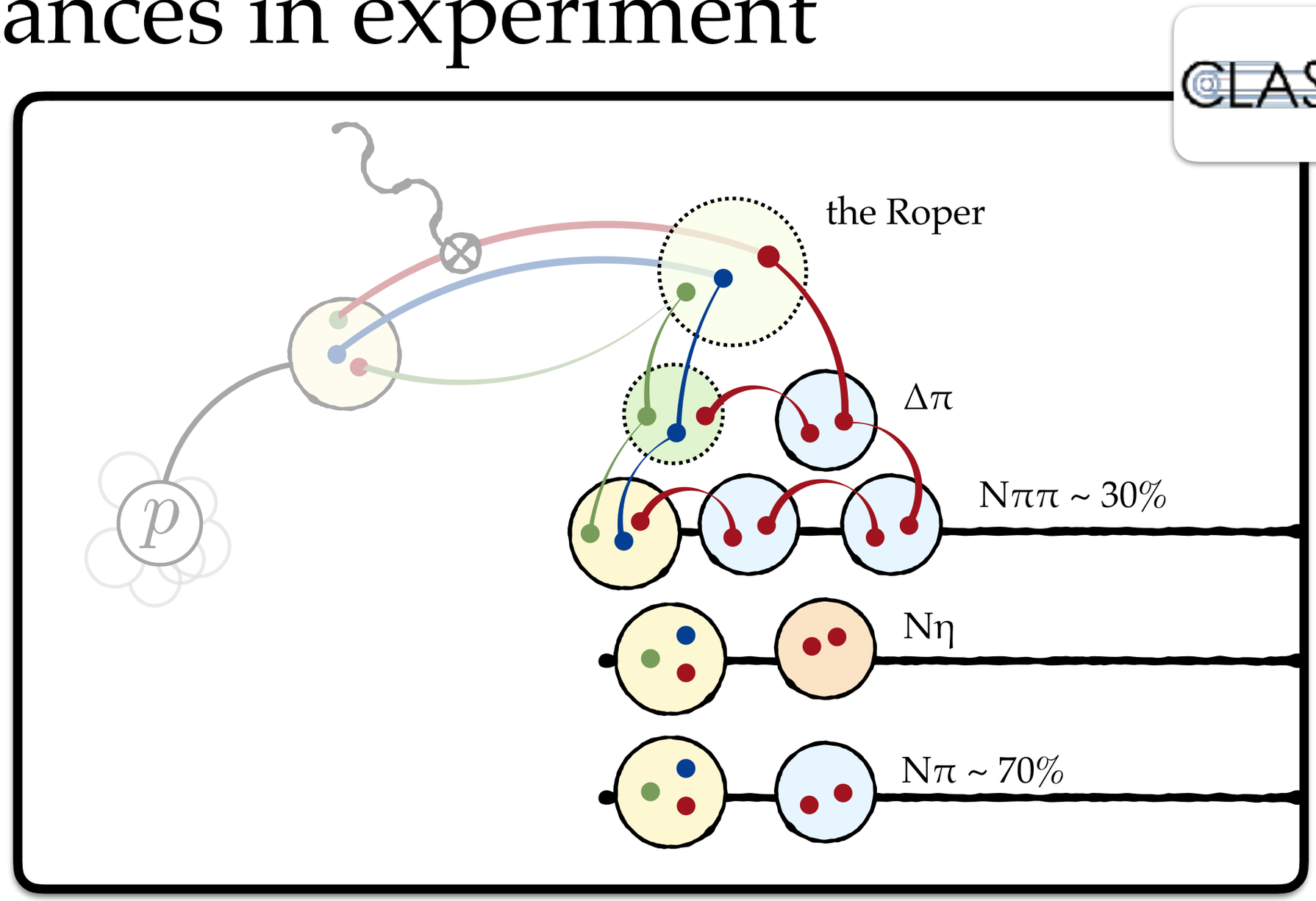
- The vast majority of QCD states are **composite states**, which are either:
  - unstable under QCD (resonances)
  - *accidentally* stable (bound states)
  - depending on the QCD parameters, a state can *transition*

Resonances in experiment



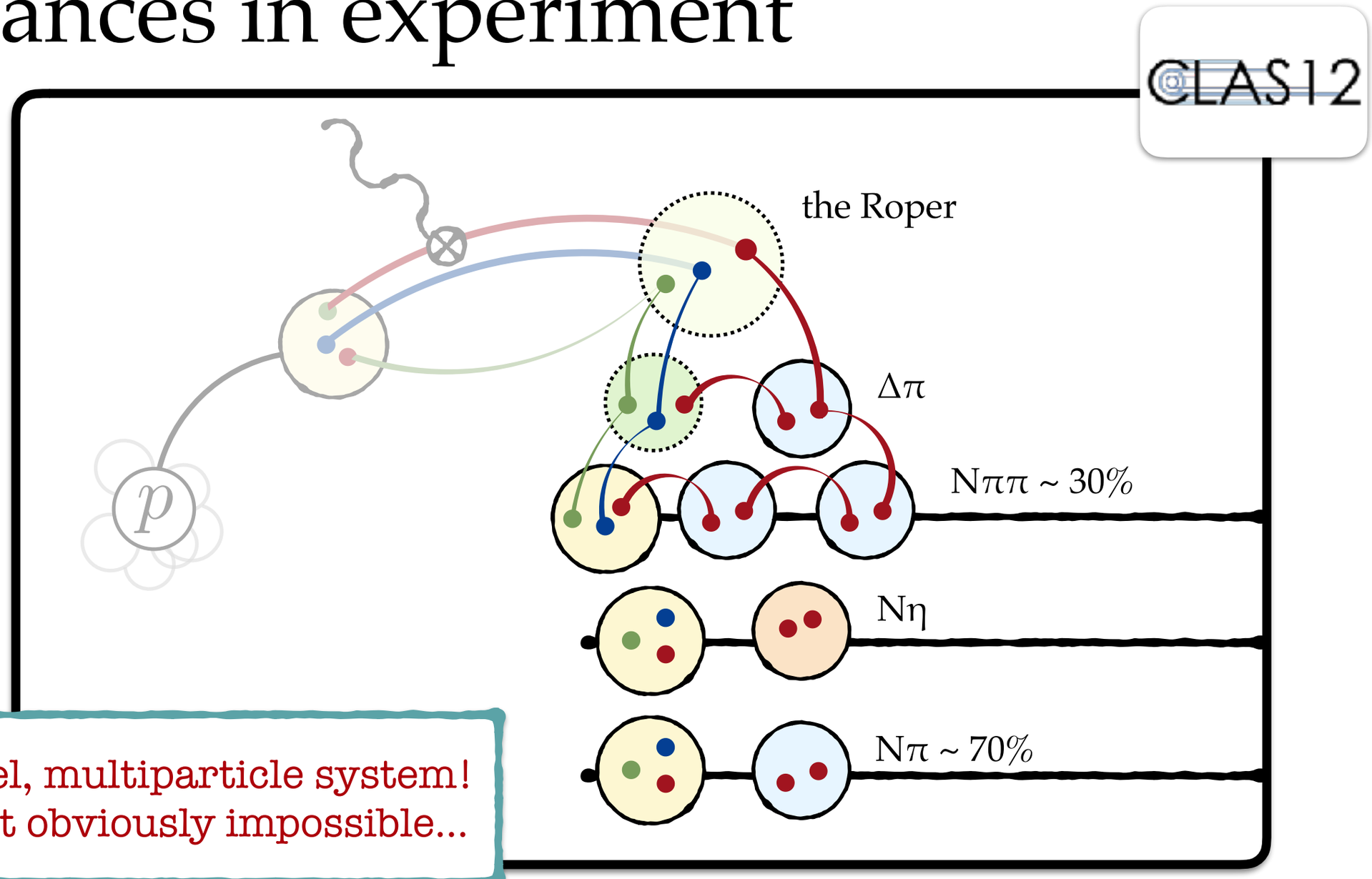
- The vast majority of QCD states are **composite states**, which are either:
  - unstable under QCD (resonances)
  - *accidentally* stable (bound states)
  - depending on the QCD parameters, a state can *transition*

Resonances in experiment



- 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



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

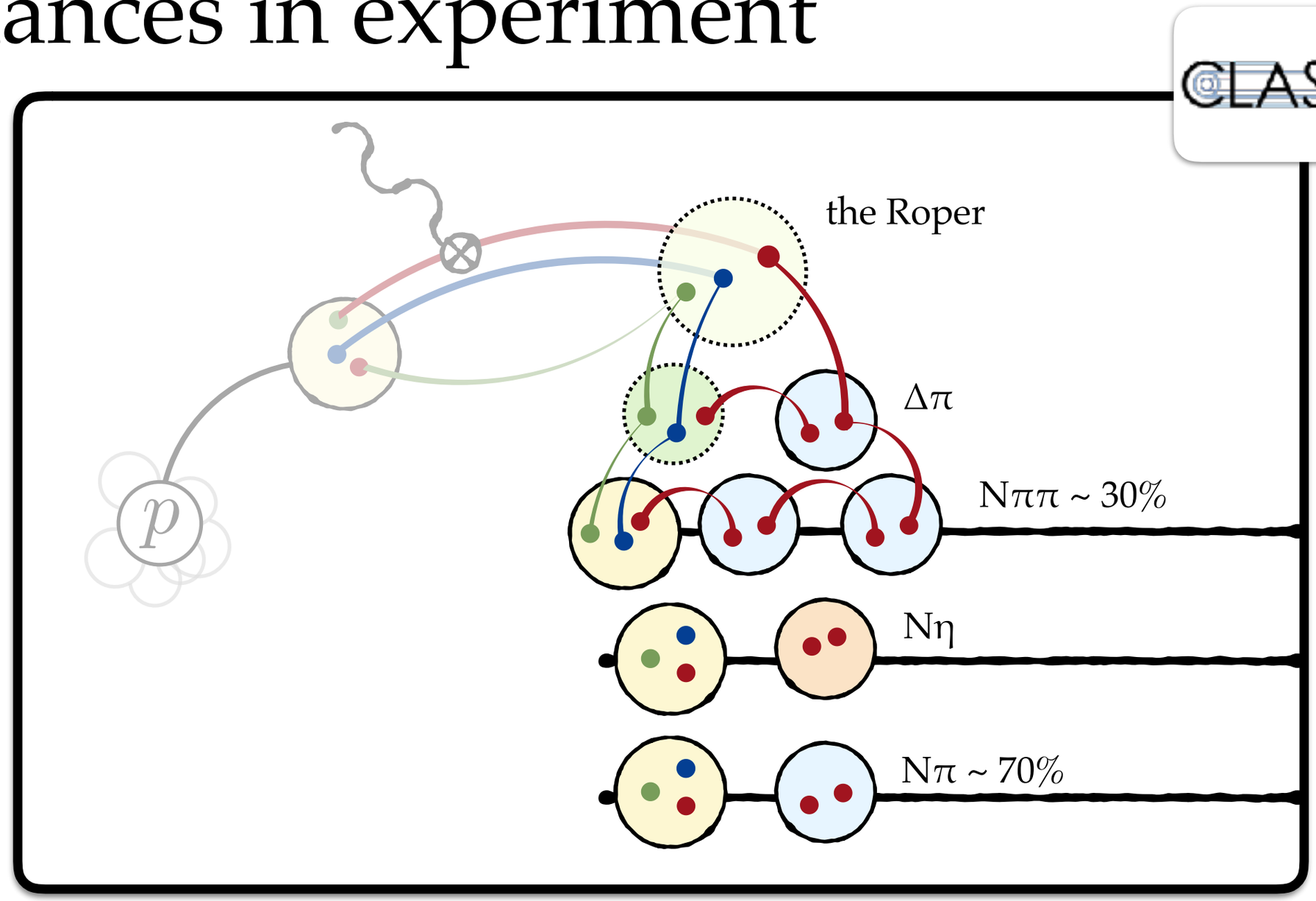
experimental needs

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

theoretical needs

- structural understanding

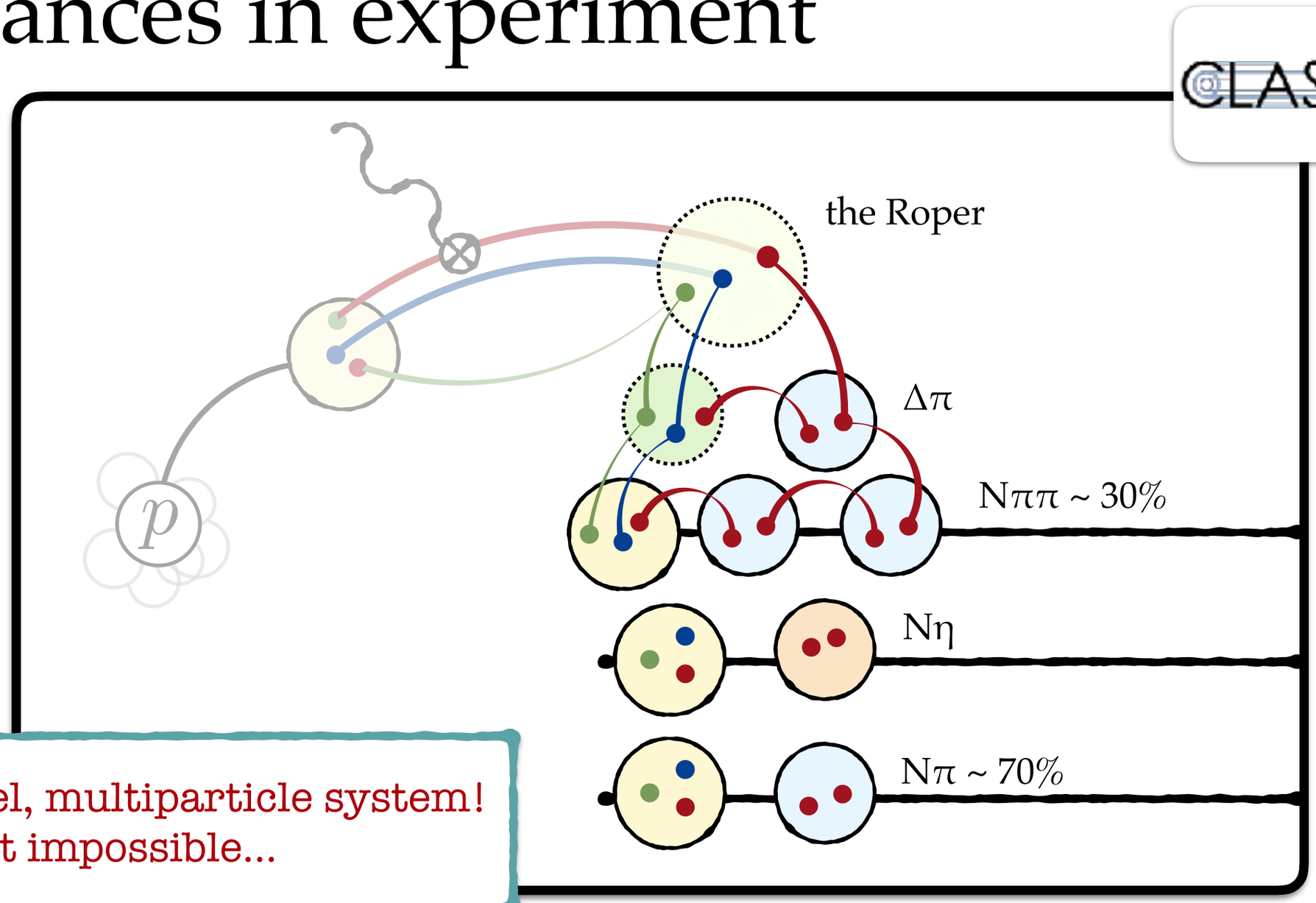
Resonances in experiment



$$|n\rangle_{\mathrm{QCD}} = c_0 + c_1 + c_2 + c_3 + \cdots$$

theoretical needs — structural understanding

Resonances in experiment

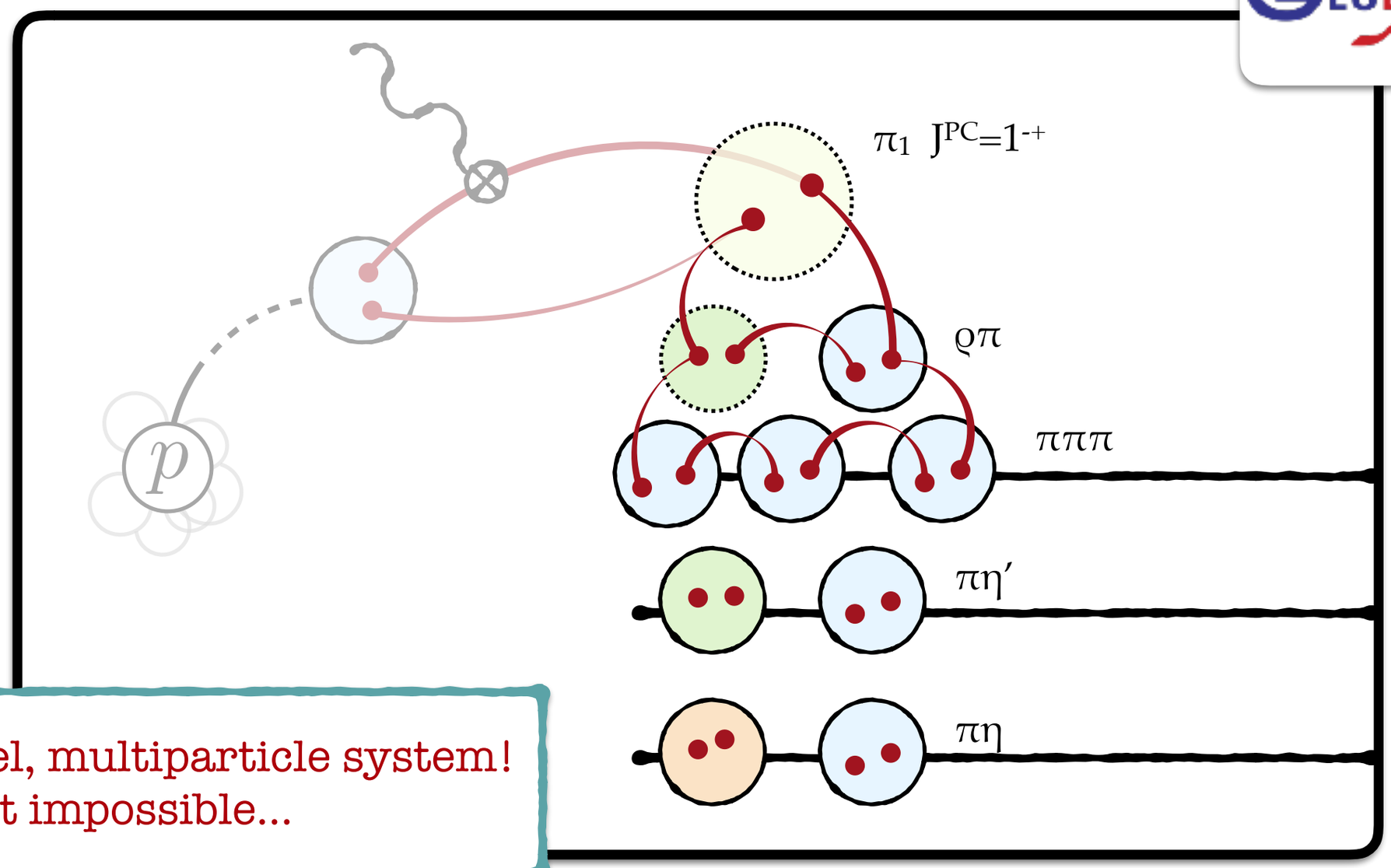


multichannel, multiparticle system!
hard, but not impossible...

demand for lattice:

- Stable states generated *"exactly"*
- Resonant/non-resonant amplitudes are generated *"exactly"*
- QED/weak can be introduced perturb. or non-perturb.

Resonances in experiment



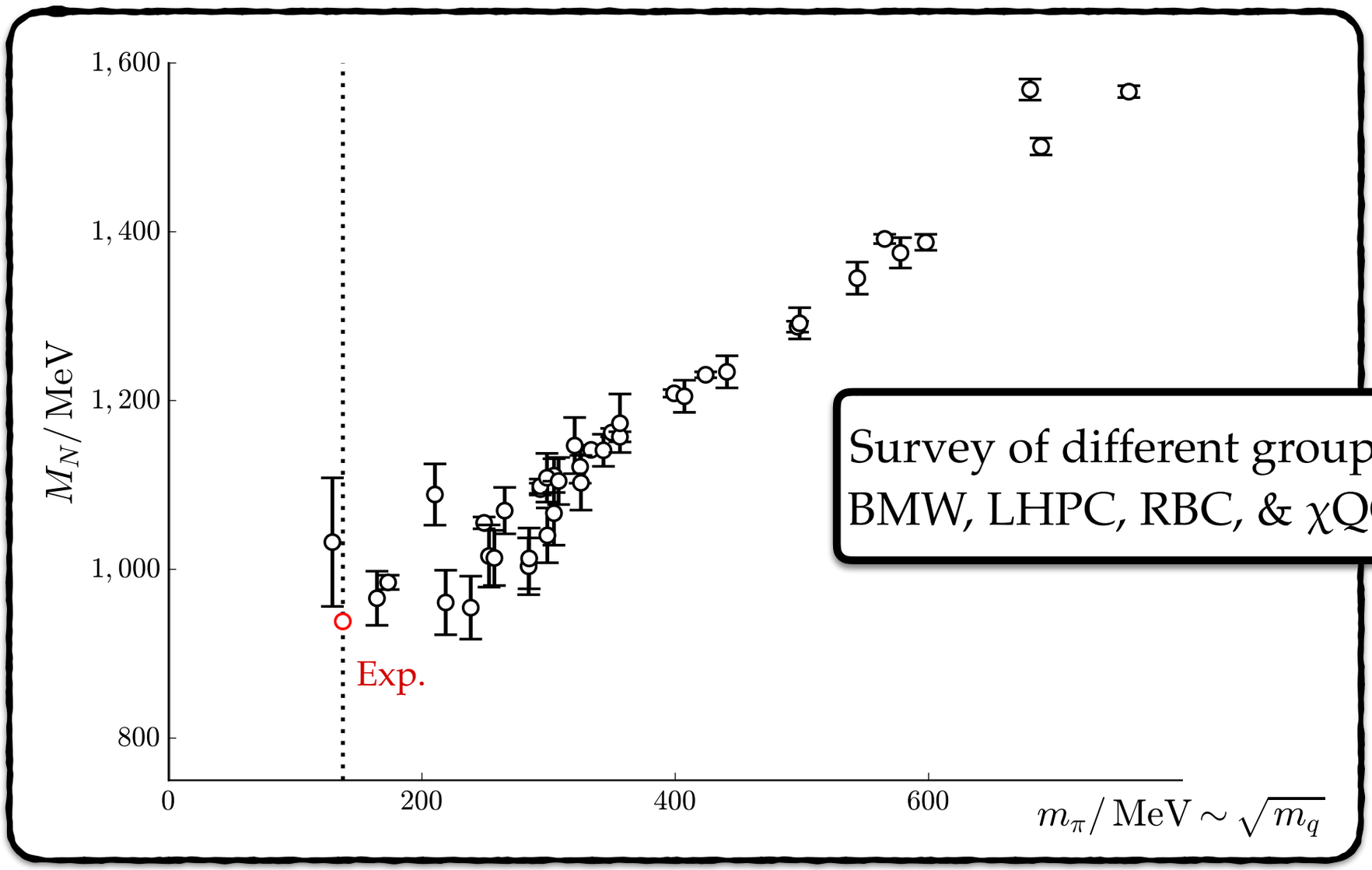
multichannel, multiparticle system!
hard, but not impossible...

demand for lattice:

- Stable states generated *"exactly"*
- Resonant/non-resonant amplitudes are generated *"exactly"*
- QED/weak can be introduced perturb. or non-perturb.

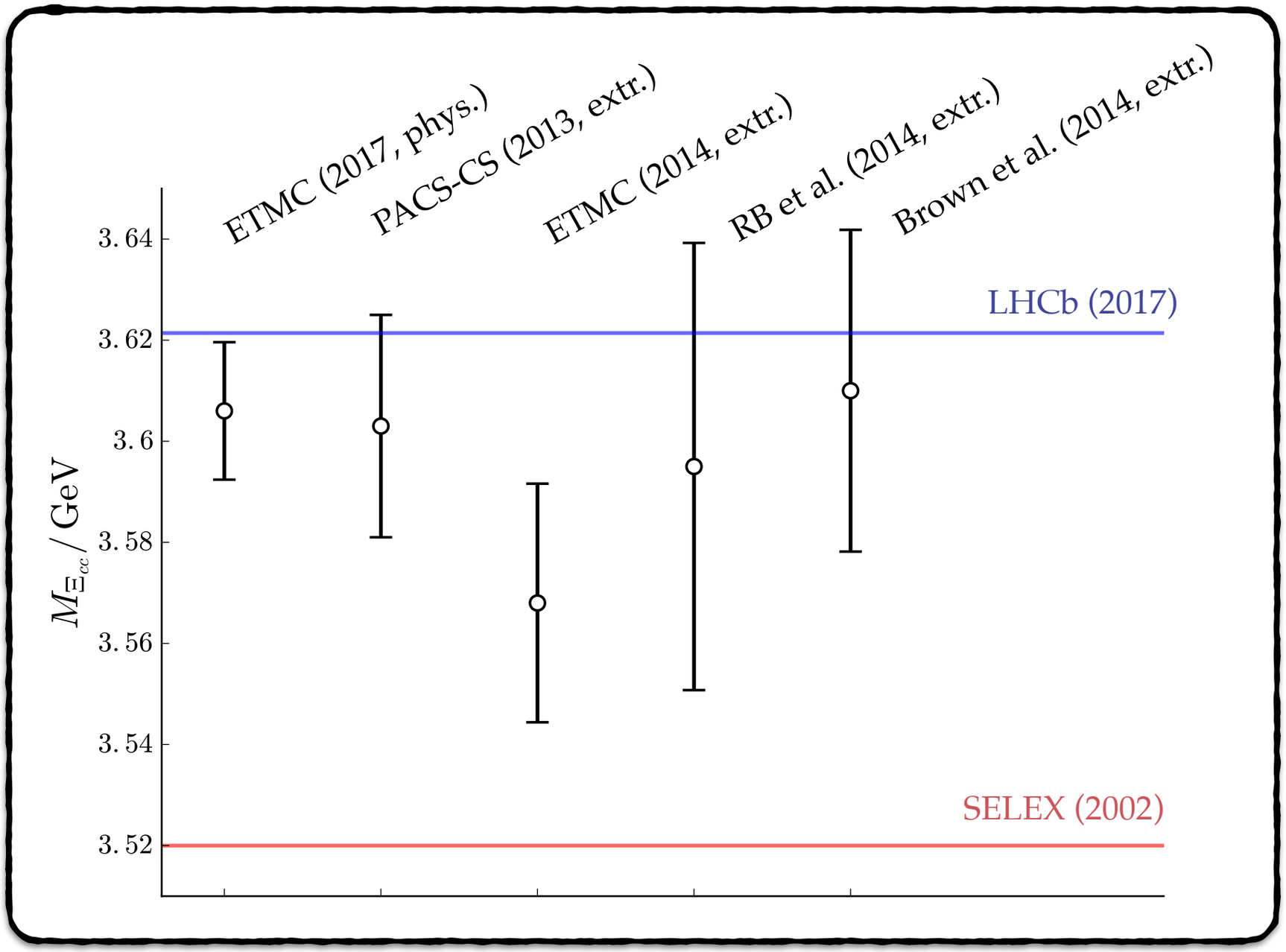
Status of the field

- *Simple* properties of QCD stable states [non-composite states]
  - physical or lighter quark masses [down to m_π~120 MeV] ✓
  - non-degenerate light-quark masses: N_f=1+1+1+1 ✓
  - dynamical QED ✓



Status of the field

- *Simple* properties of QCD stable states [non-composite states]
  - physical or lighter quark masses [down to m_π~120 MeV] ✓
  - non-degenerate light-quark masses: N_f=1+1+1+1 ✓
  - dynamical QED ✓



Status of the field

- *Simple* properties of QCD stable states [non-composite states]
  - physical or lighter quark masses [down to m_π~120 MeV] ✓
  - non-degenerate light-quark masses: N_f=1+1+1+1 ✓
  - dynamical QED ✓
- One of the frontiers of lattice QCD: multi-particle physics
  - scattering/reactions
  - composite states
    - bound states
    - hadronic resonances
    - electrocouplings

Formal development:
- under way
- more needed

Benchmark calculations:
- unphysical quark masses
- exploratory
- proof of principle
- …

Lattice QCD efforts in N*

Unfortunately, there is no plenaries reviewing the field

Plenary reviewing Adelaide efforts - Jia-Jun Wu

A young, vibrant, and diverse community:

Today:

Bulava (CP³-Origins): “Precise scattering calculations”

Hansen (Mainz/CERN): “Total transition rates”

Shanahan (W&M/JLab): “Gluonic structure”

Lattice QCD efforts in N*

Unfortunately, there is no plenaries reviewing the field

Plenary reviewing Adelaide efforts - Jia-Jun Wu

A young, vibrant, and diverse community:

Today:

Bulava (CP³-Origins)

Hansen (Mainz/CERN)

Shanahan (W&M/JLab)

Tuesday:

Wilson (Marie Curie/Royal fellow/Trinity): “Mesonic resonances”

Davoudi (Maryland): “Light nuclei”

Leskovec (Arizona): “The Roper”

Lattice QCD efforts in N*

Unfortunately, there is no plenaries reviewing the field

Plenary reviewing Adelaide efforts - Jia-Jun Wu

A young, vibrant, and diverse community:

= non-permanent

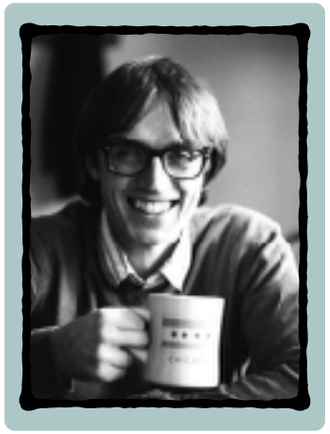
Today:

Bulava (CP³-Origins)

Hansen (Mainz/CERN)

Shanahan (W&M/JLab)

Tuesday:



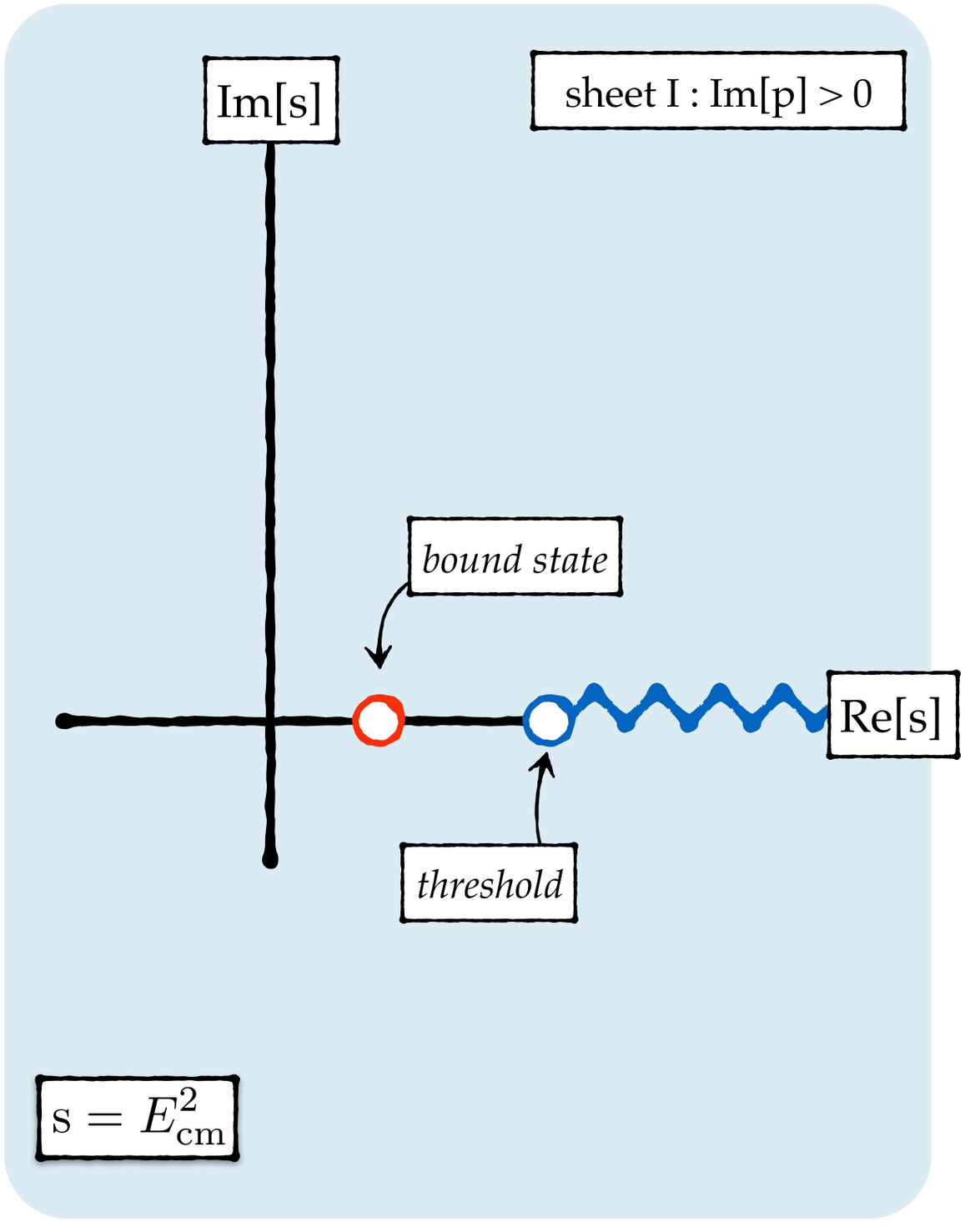
Wilson (Marie Curie, Trinity)

Davoudi (Maryland)

Leskovec (Arizona)

Wednesday: **Giannis Koutsou**, “Nucleon and Delta structure“

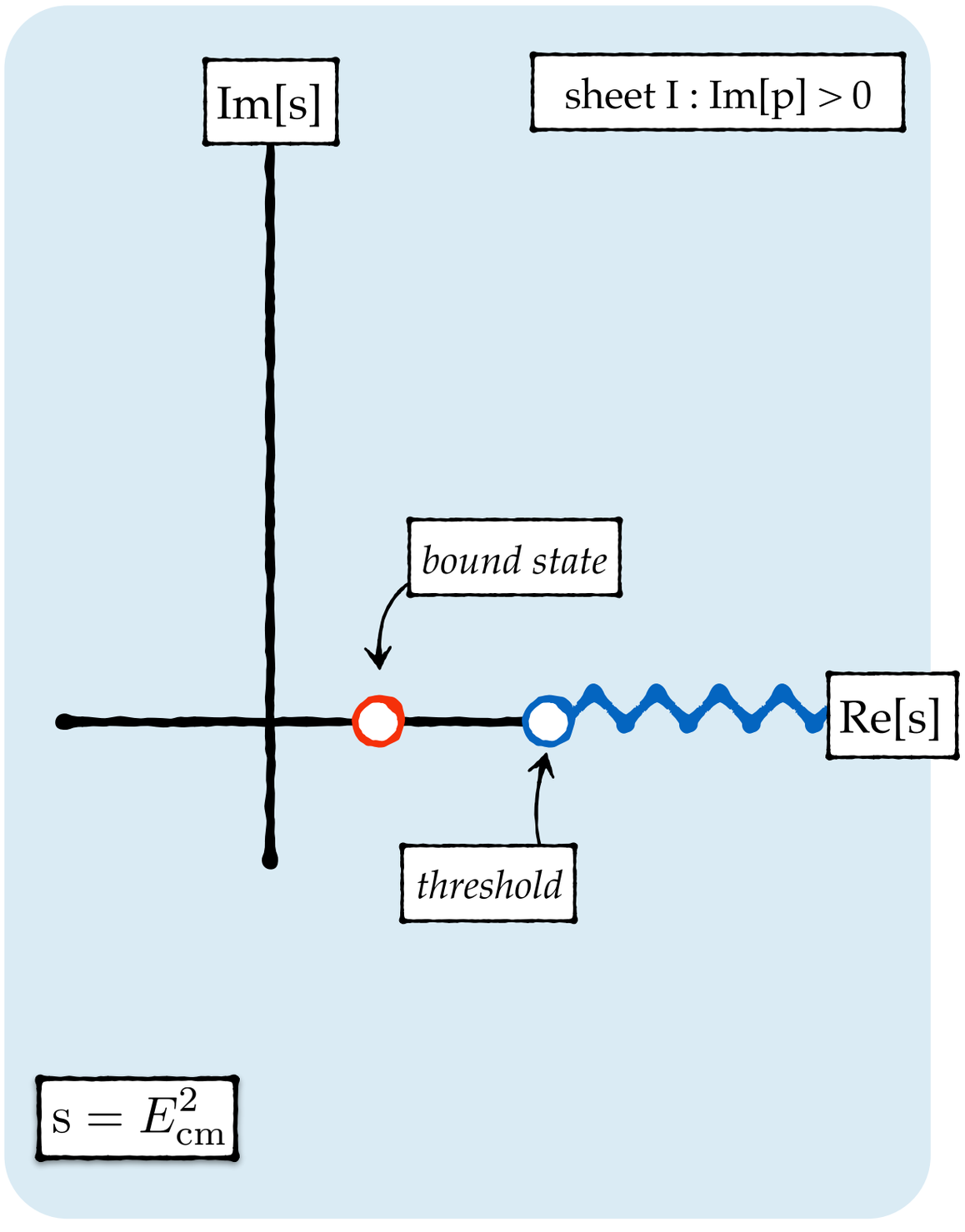
Definition of resonances

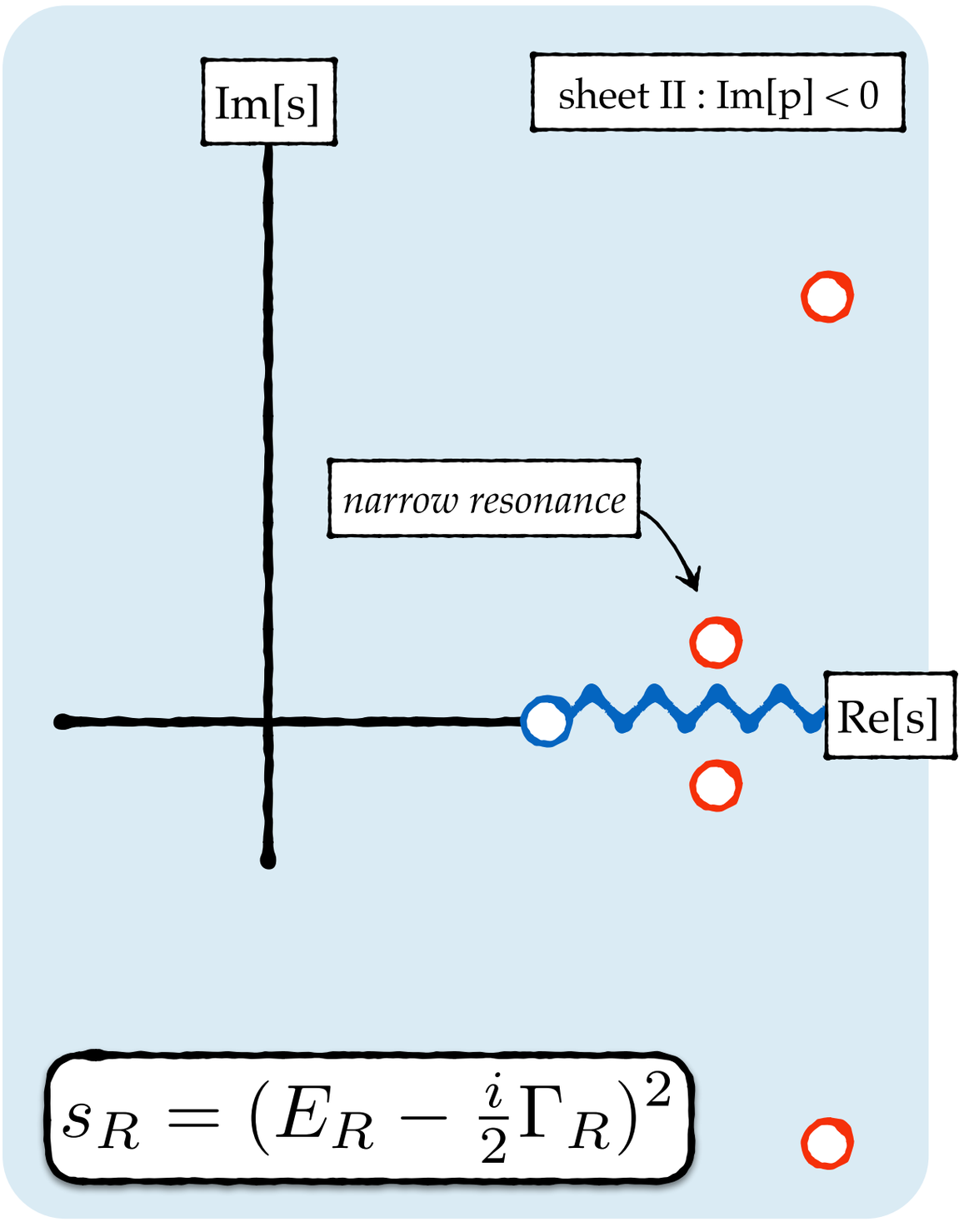


unitarity: $\mathcal{M} \sim \dfrac{1}{p \cot \delta - ip}$

square-root singularity
at threshold: $p = \sqrt{s/4 - m^2}$

Definition of resonances

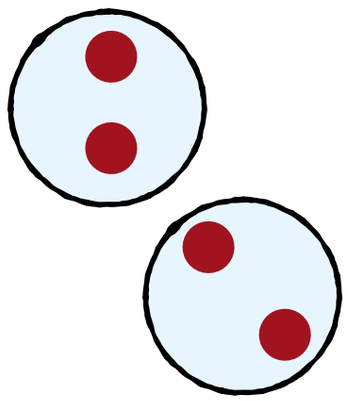




Intro to Lattice QCD

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

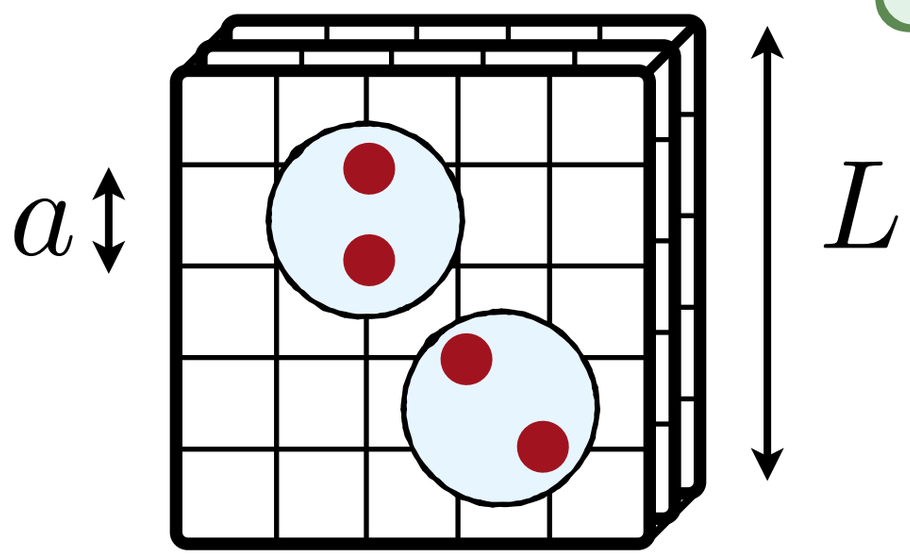
Advantage over experiment!



Intro to Lattice QCD

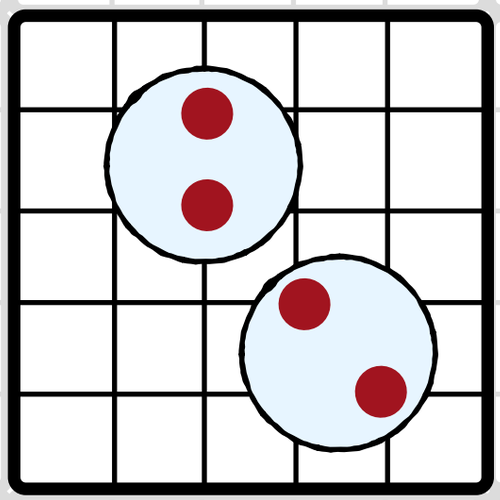
- Wick rotation [Euclidean spacetime]: $t_M \to -it_E$
- Monte Carlo sampling
- quark masses: $m_q \to m_q^{\text{phys.}}$
- lattice spacing: $a \sim 0.03 - 0.15$ fm
- finite volume

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



Intro to Lattice QCD

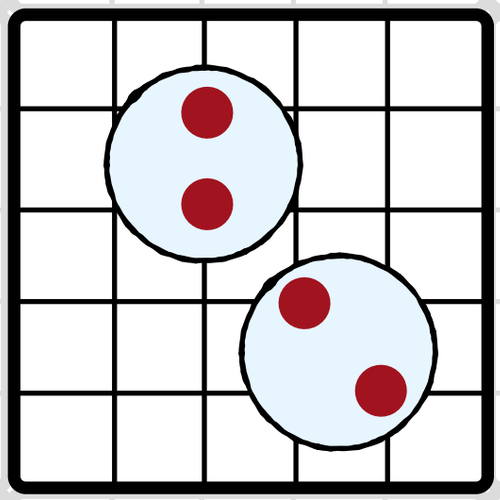
- Wick rotation [Euclidean spacetime]: $t_M \to -it_E$
- Monte Carlo sampling
- quark masses: $m_q \to m_q^{\text{phys.}}$
- lattice spacing: $a \sim 0.03 - 0.15$ fm
- finite volume

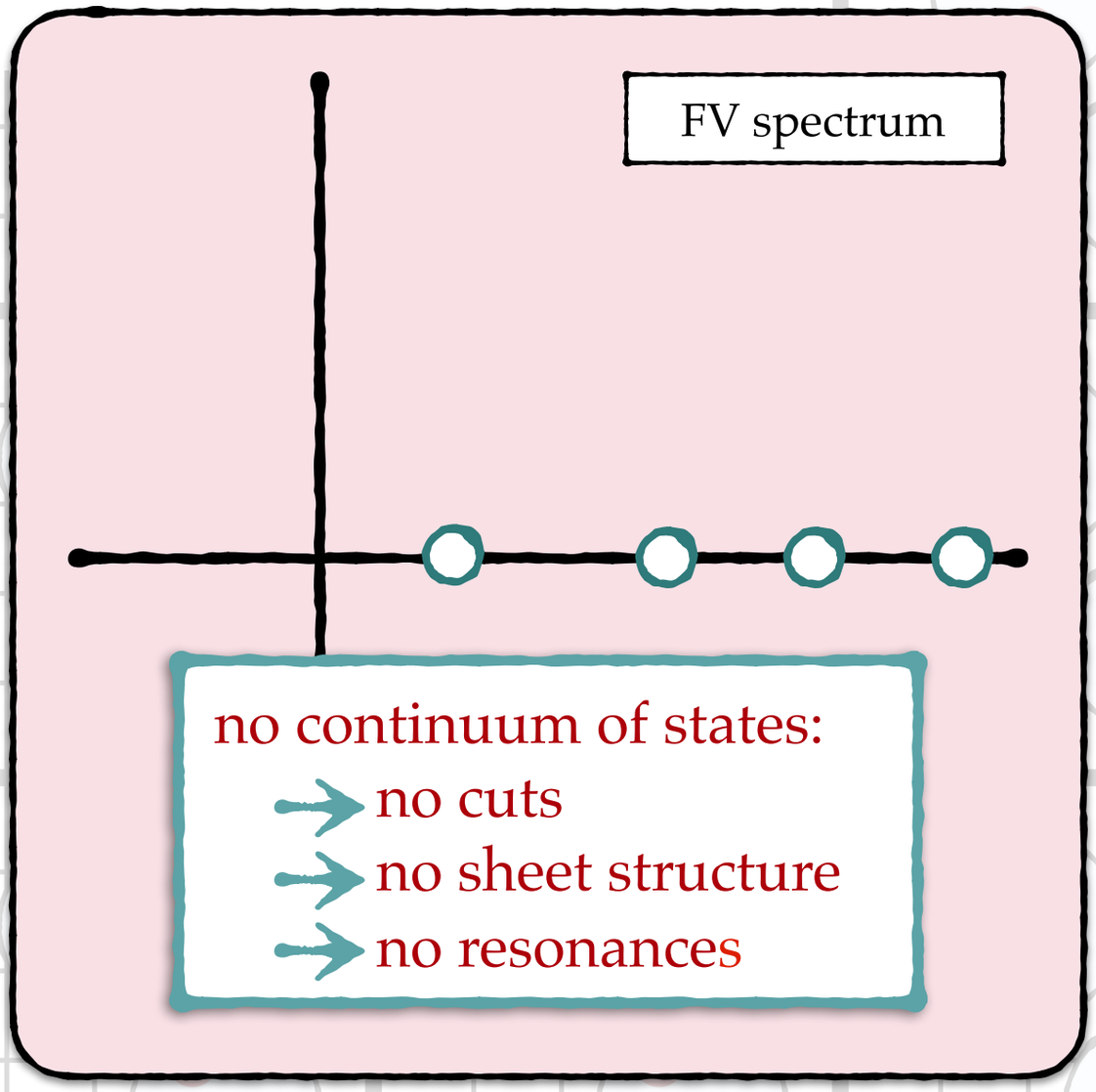


Never free!
No asymptotic states!
No scattering!

Intro to Lattice QCD

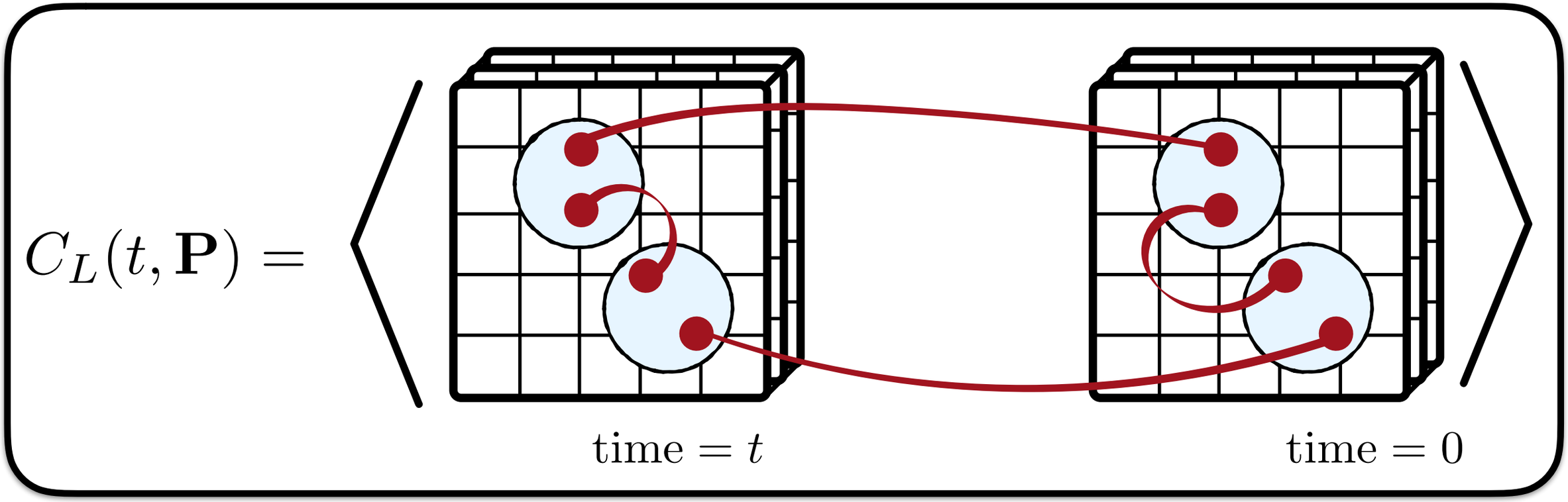
- Wick rotation [Euclidean spacetime]: $t_M \to -it_E$
- Monte Carlo sampling
- quark masses: $m_q \to m_q^{\text{phys.}}$
- lattice spacing: $a \sim 0.03 - 0.15$ fm
- finite volume





Intro to Lattice QCD

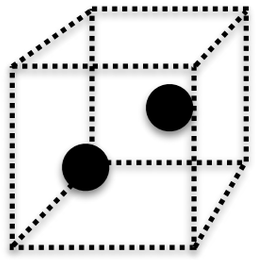
- Wick rotation [Euclidean spacetime]: $t_M \to -it_E$
- Monte Carlo sampling
- quark masses: $m_q \to m_q^{\text{phys.}}$
- lattice spacing: $a \sim 0.03 - 0.15$ fm
- finite volume
- Correlation functions: spectrum, matrix elements



Scattering amplitudes

Lattice QCD

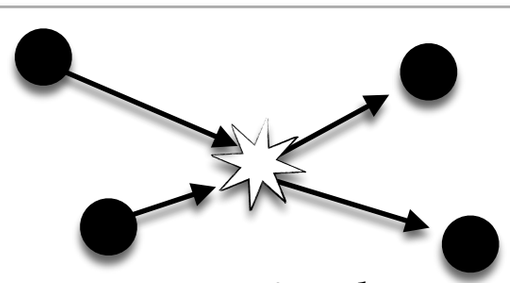
FV spectrum



partial wave amplitudes

resonance

Experiment

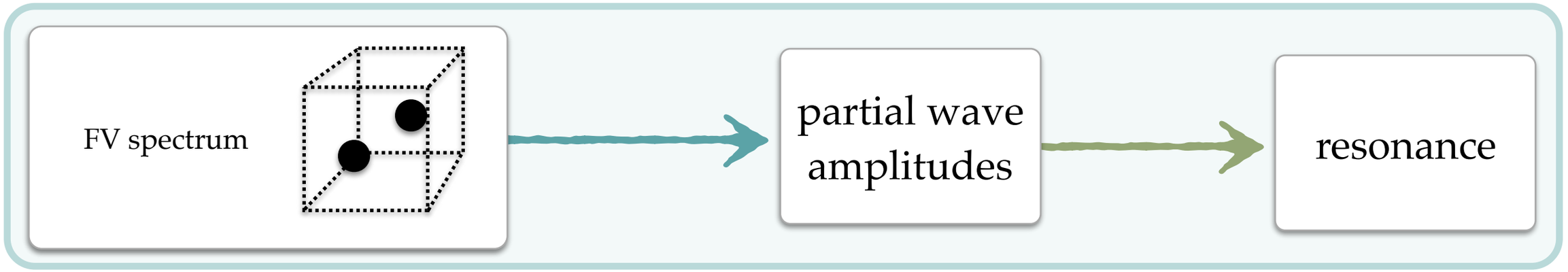


amplitude analysis

partial wave amplitudes

resonance

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.

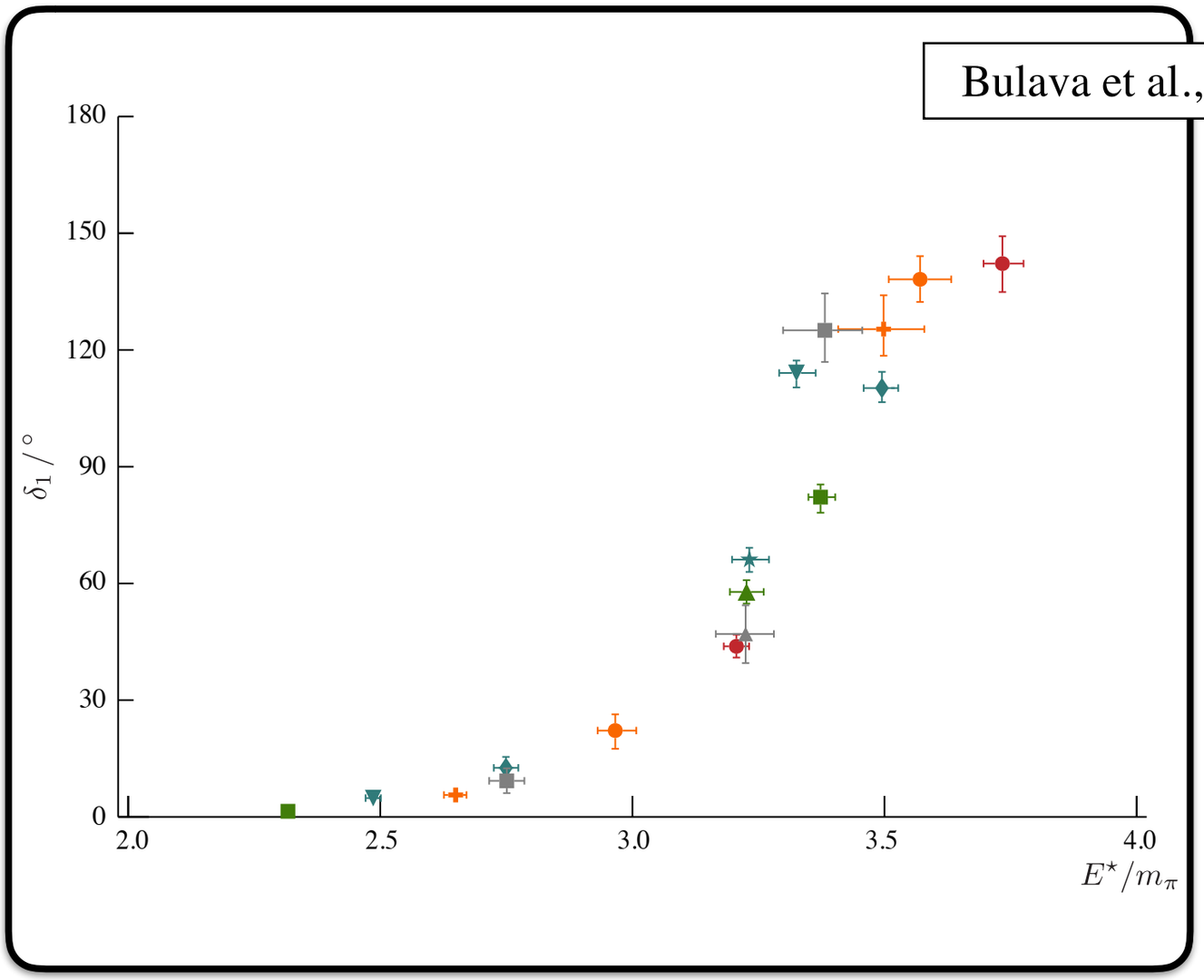
not an extrapolation!

- 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]

Hansen (Mainz/CERN)

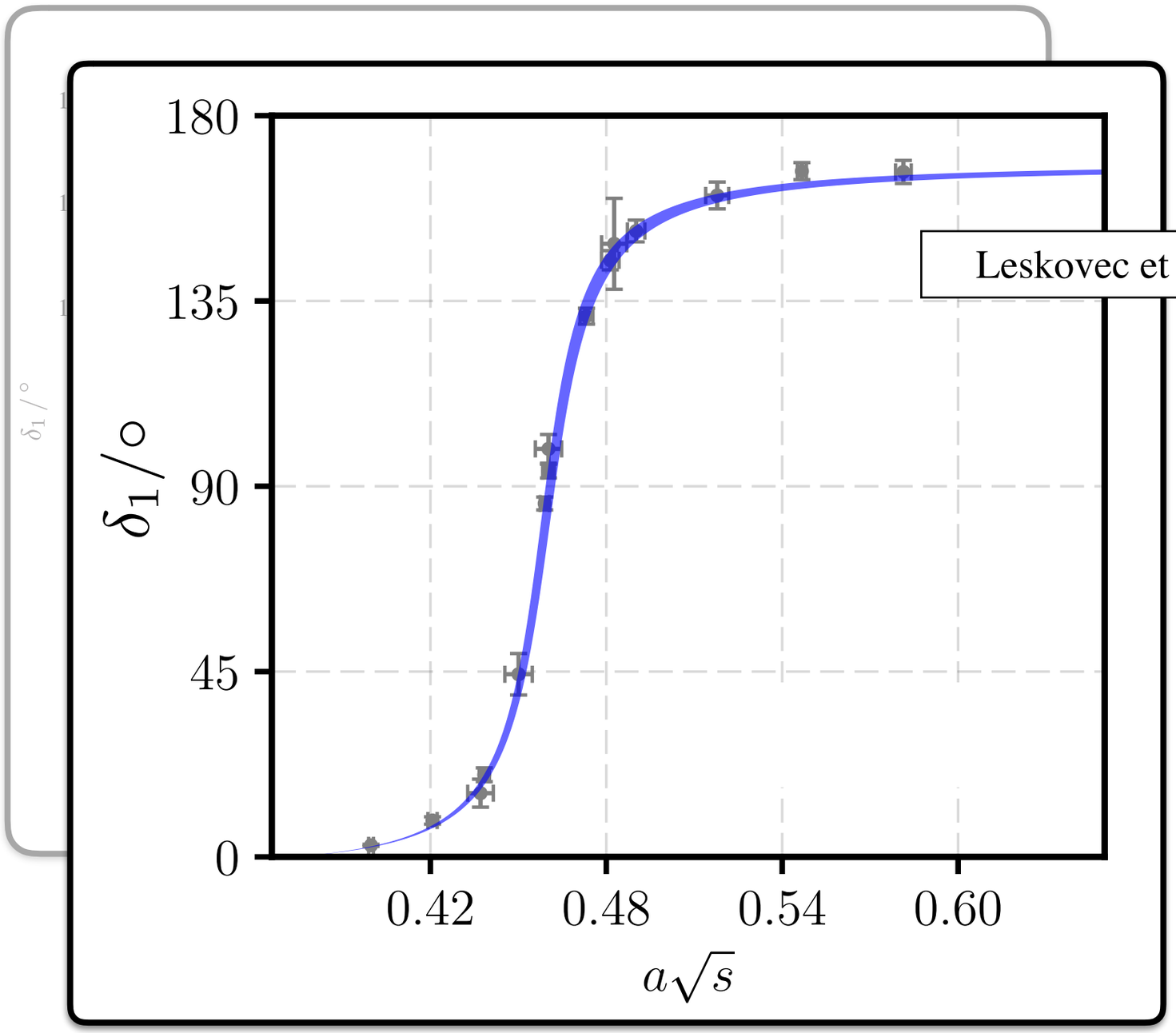
Davoudi (Maryland)

Isovector $\pi\pi$ scattering



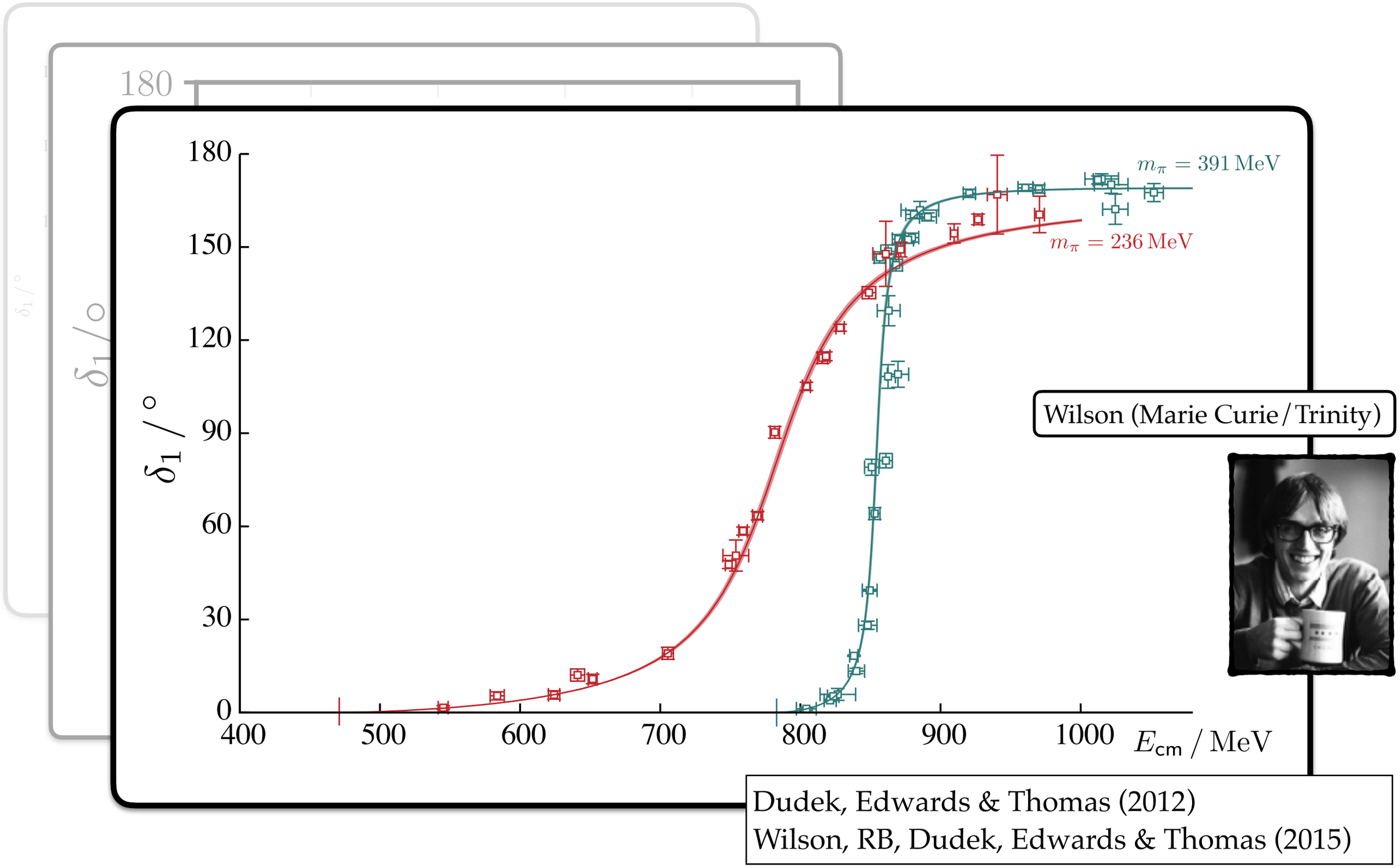
Bulava (CP³-Origins)

Isovector $\pi\pi$ scattering



Leskovec (Arizona)

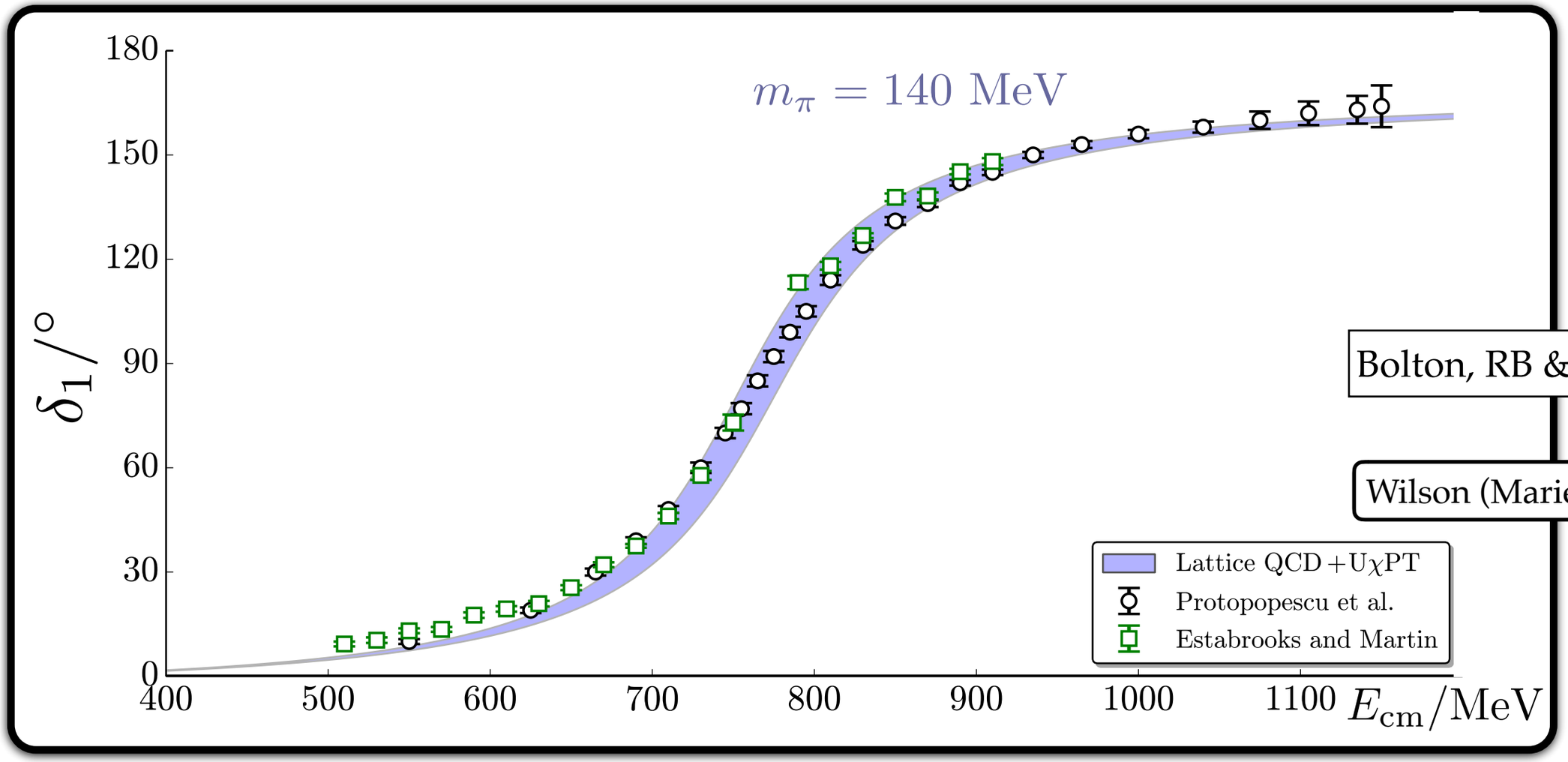
Isovector $\pi\pi$ scattering



Wilson (Marie Curie / Trinity)

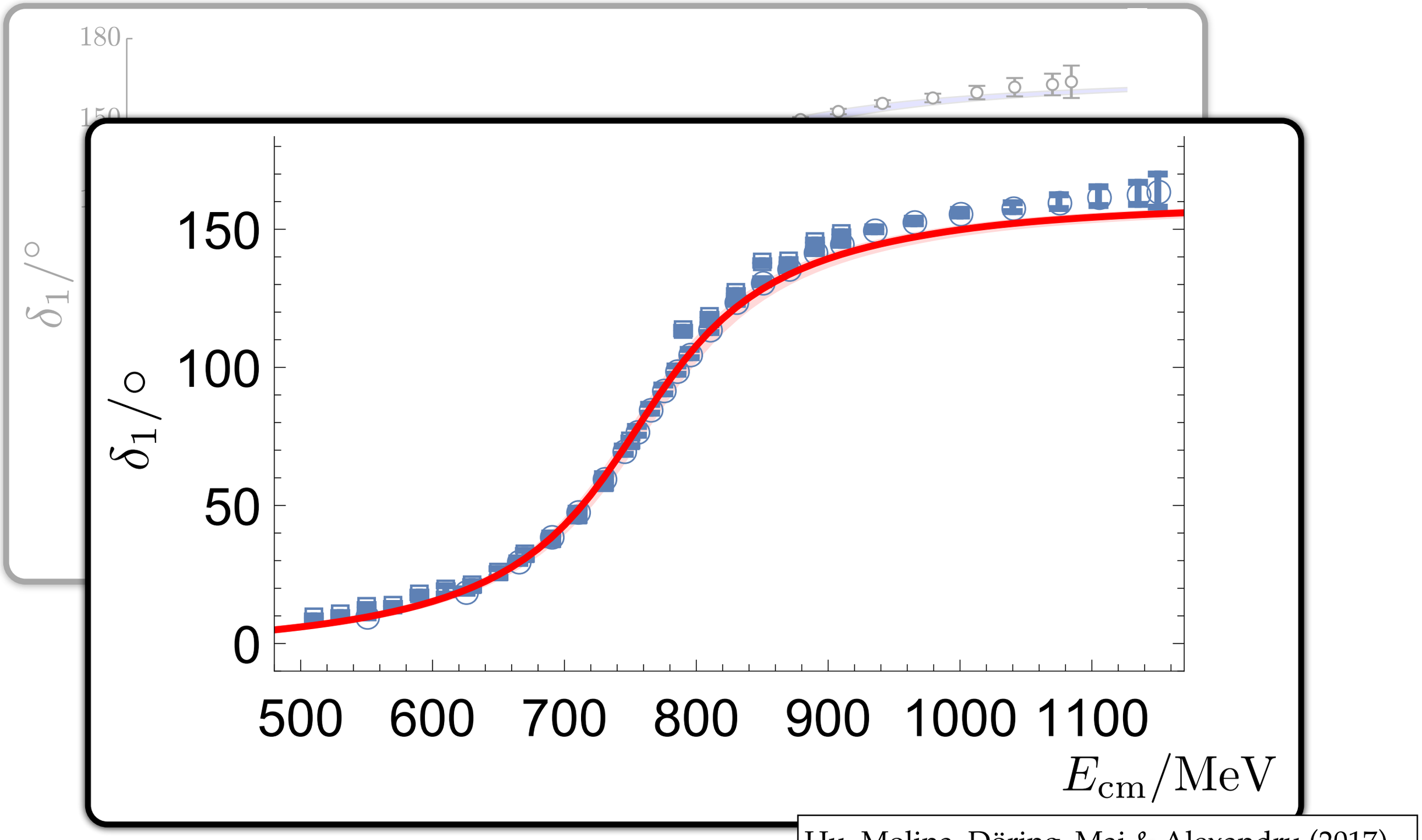
Dudek, Edwards & Thomas (2012)
Wilson, RB, Dudek, Edwards & Thomas (2015)

Comparison with experiment



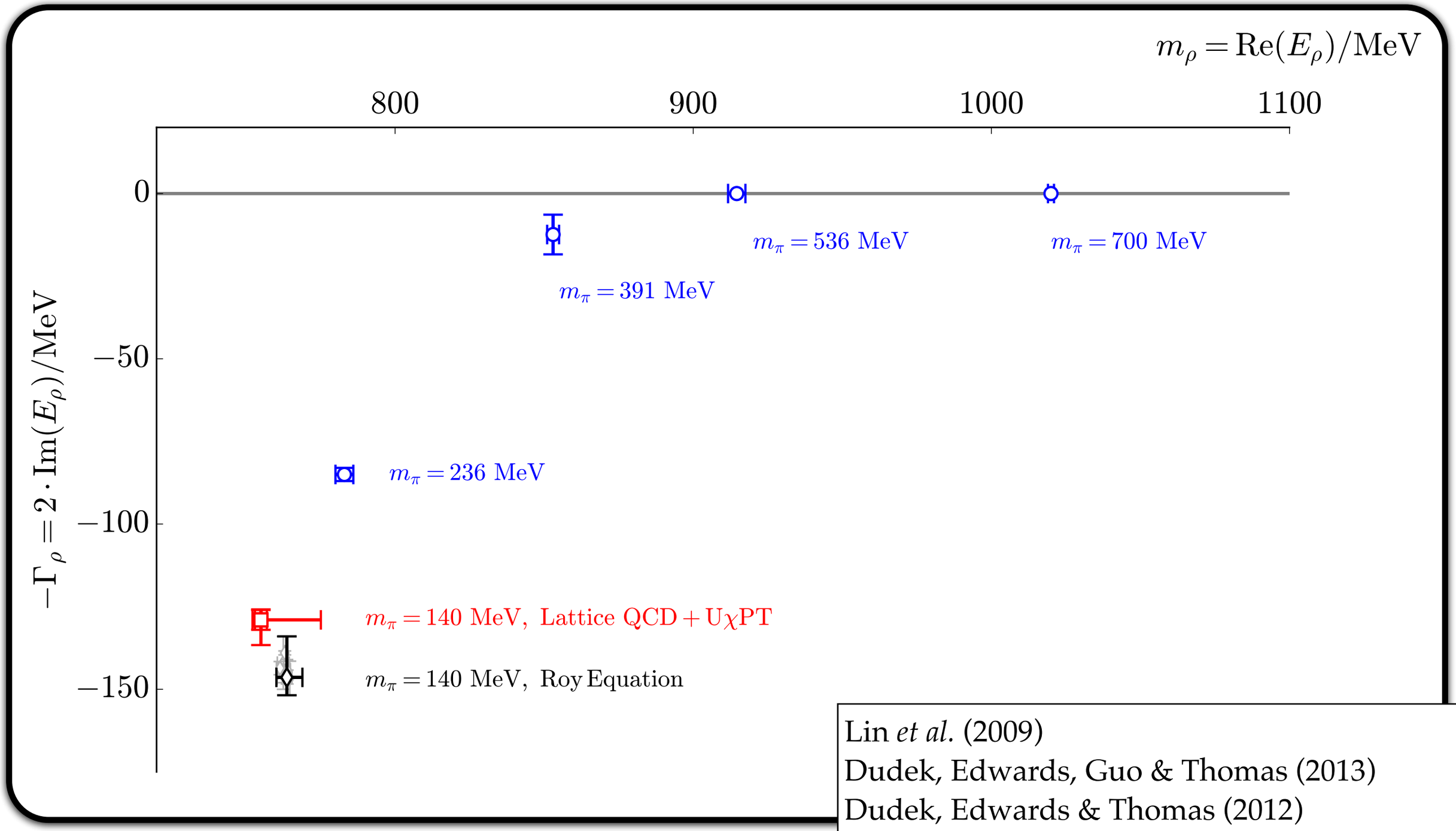
- *U*χ*PT* in a nut-shell:
  - enforce unitarity exactly: $\mathcal{M}^{-1}_{U\chi PT} \equiv \mathrm{Re}\left(\mathcal{M}^{-1}_{\chi PT}\right) - i\rho$
  - *treat dynamics perturbatively:* $\mathrm{Re}\left(\mathcal{M}^{-1}_{\chi PT}\right) = \mathrm{Re}\left(\dfrac{1}{\mathcal{M}_2 + \mathcal{M}_4 + \cdots}\right) \approx \dfrac{1}{\mathcal{M}_2} - \dfrac{\mathrm{Re}(\mathcal{M}_4)}{\mathcal{M}_2^2}$

Comparison with experiment



Hu, Molina, Döring, Mai & Alexandru (2017)

The ϱ vs m_π

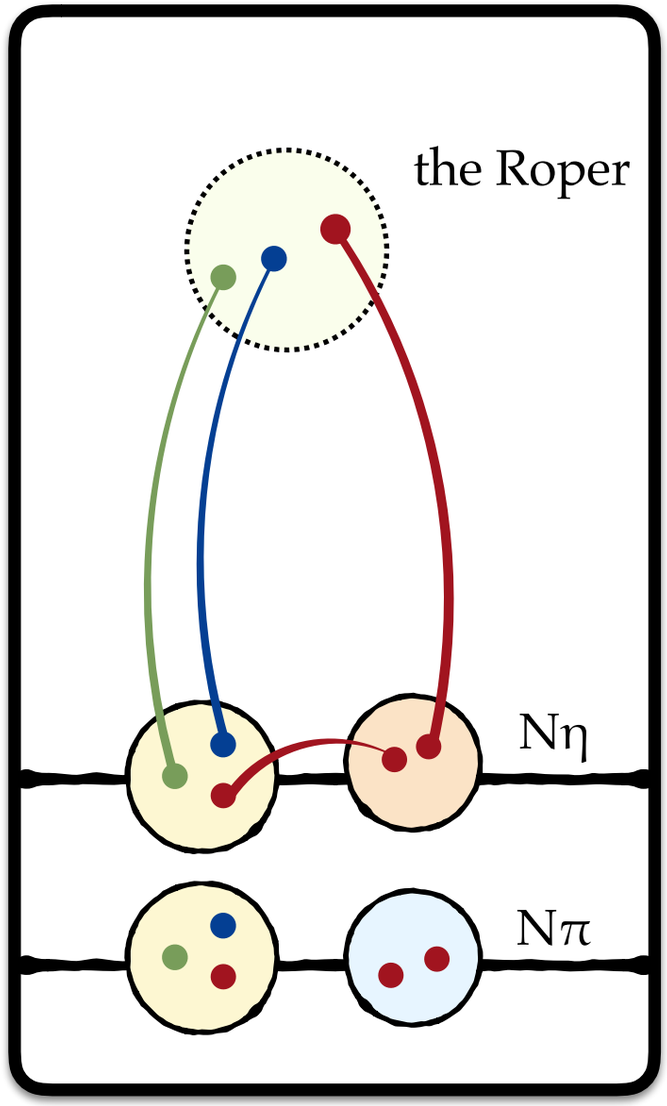


Lin *et al.* (2009)
Dudek, Edwards, Guo & Thomas (2013)
Dudek, Edwards & Thomas (2012)
Wilson, RB, Dudek, Edwards & Thomas (2015)
Bolton, RB & Wilson (2015)

Multi-channel systems - the bleeding edge!

Hansen (Mainz/CERN)

Davoudi (Maryland)

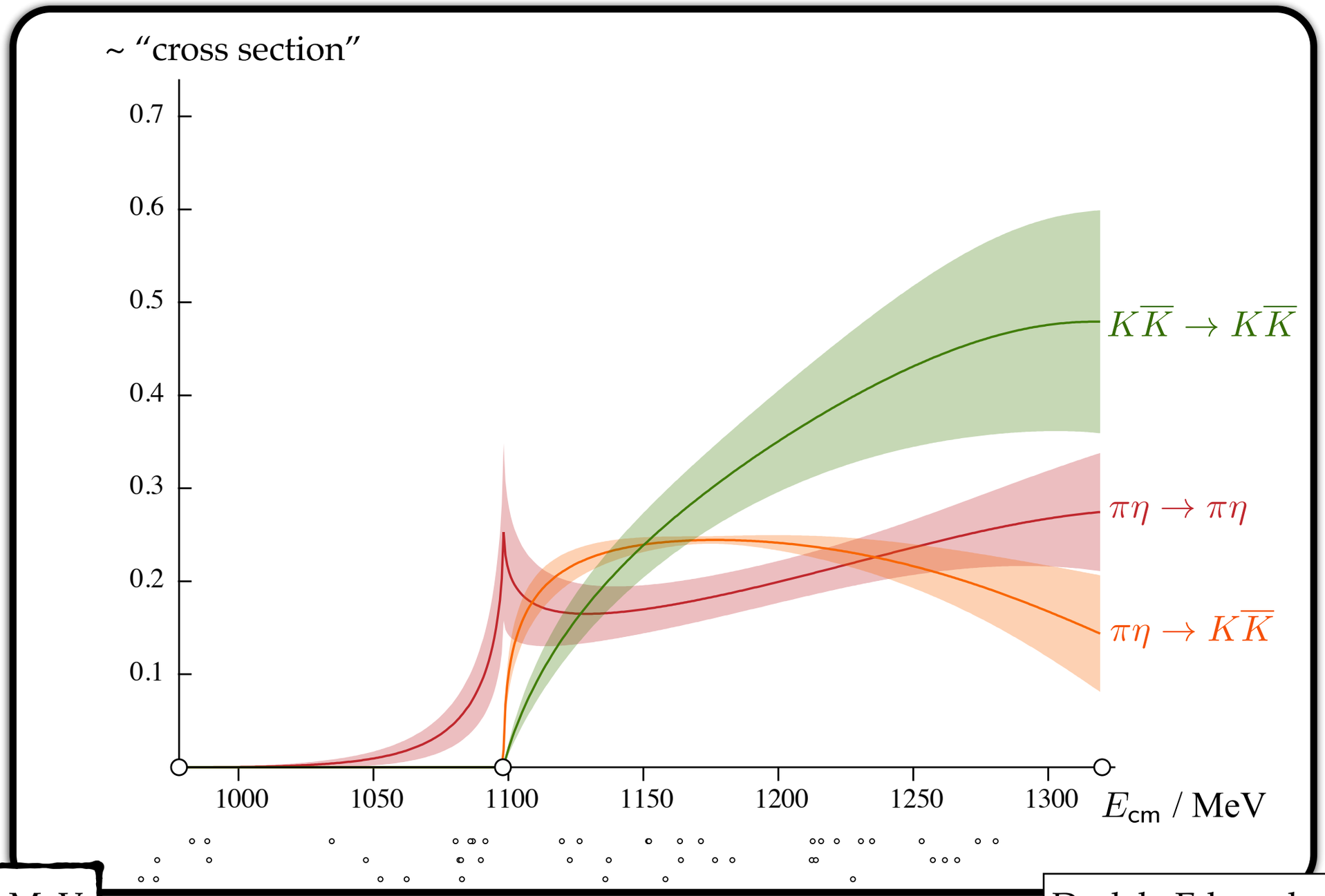


- Feng, Li, & Liu (2004) [inelastic scalar bosons]
- **Hansen** & Sharpe / RB & **Davoudi** (2012) [moving inelastic scalar bosons]
- RB (2014) [general 2-body result]

Multi-channel systems - the bleeding edge!

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

Wilson (Marie Curie / Trinity)



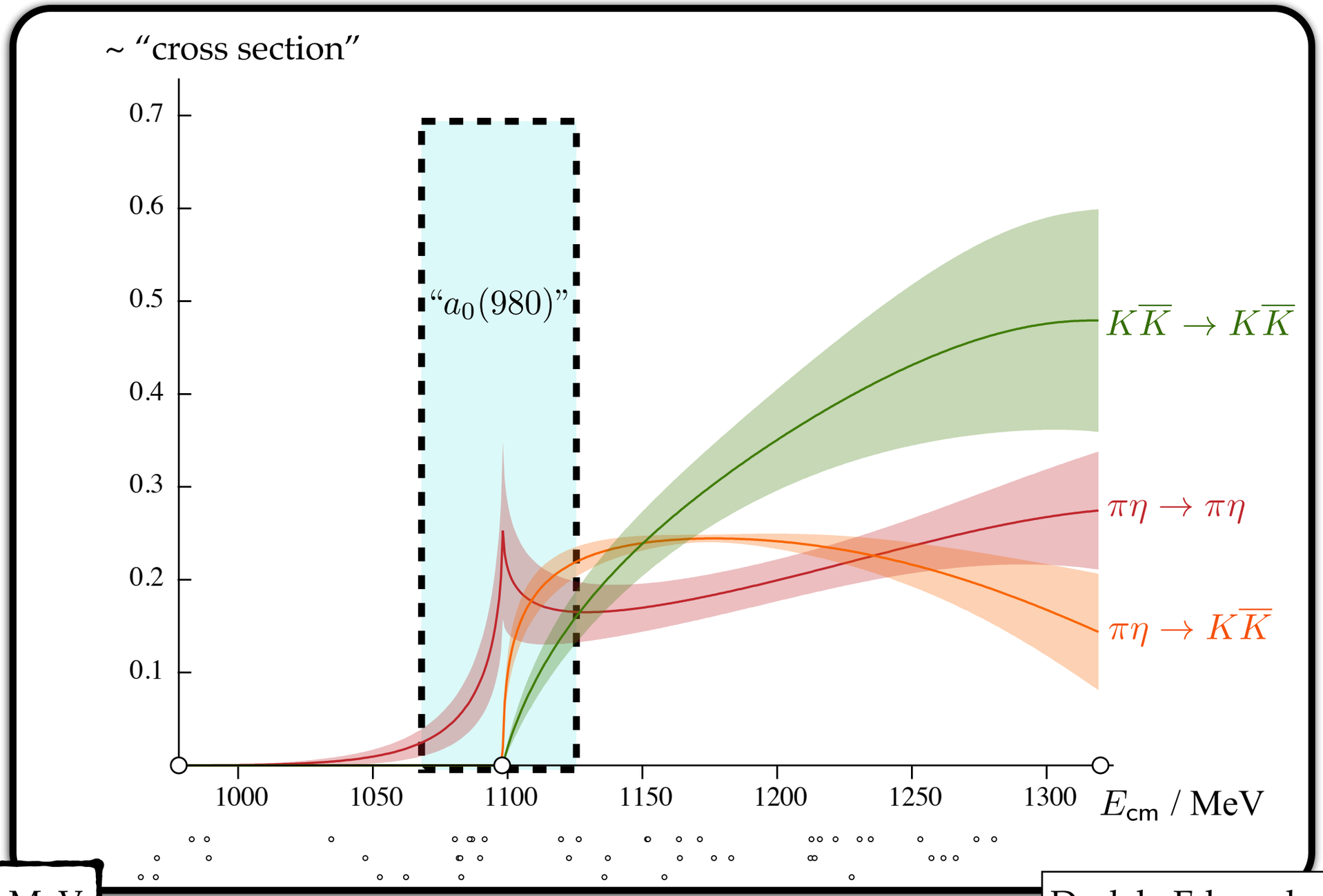
m_π=391 MeV

Dudek, Edwards & Wilson (2016)

Multi-channel systems - the bleeding edge!

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

Wilson (Marie Curie / Trinity)



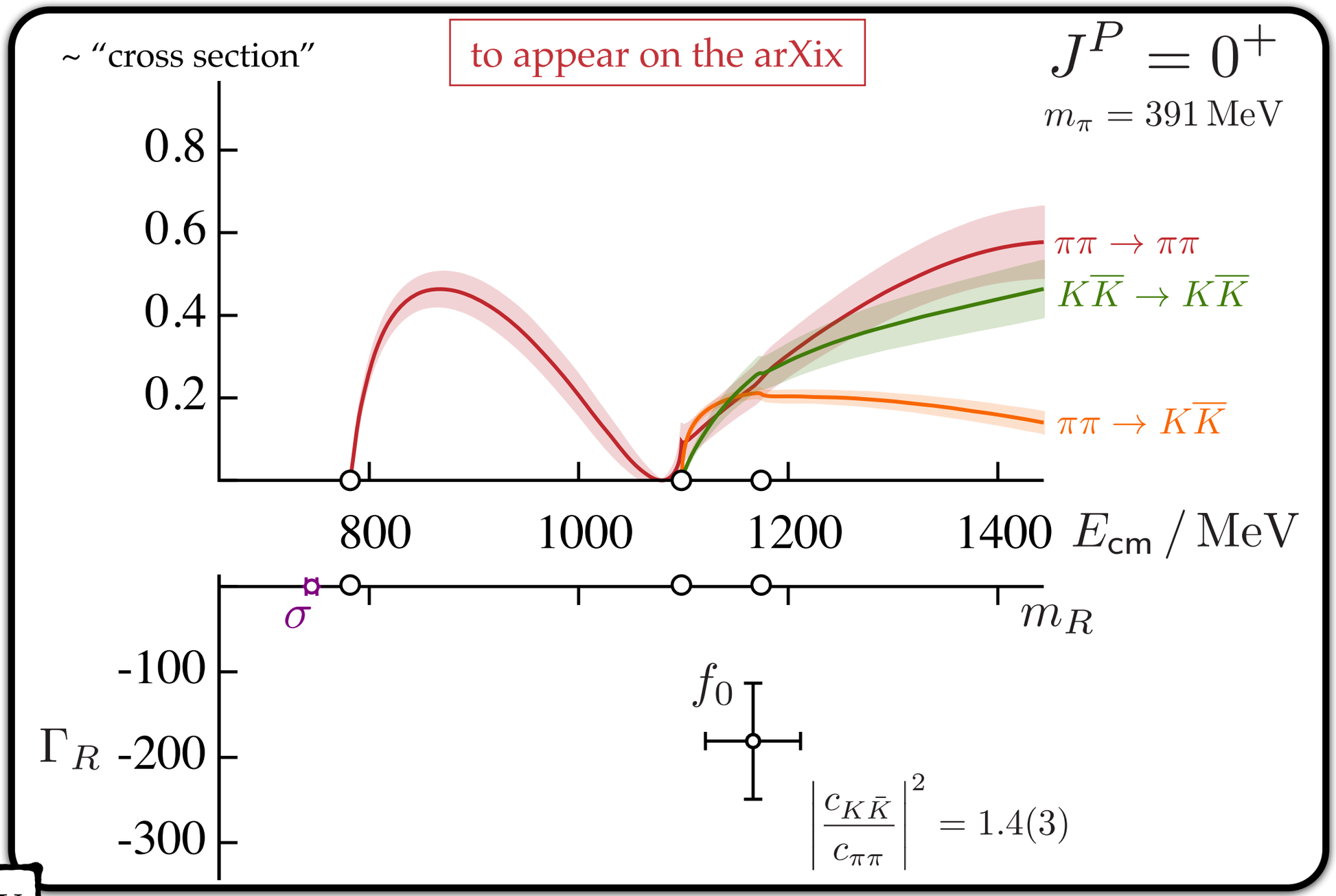
m_π=391 MeV

Dudek, Edwards & Wilson (2016)

Multi-channel systems - the bleeding edge!

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

Wilson (Marie Curie / Trinity)



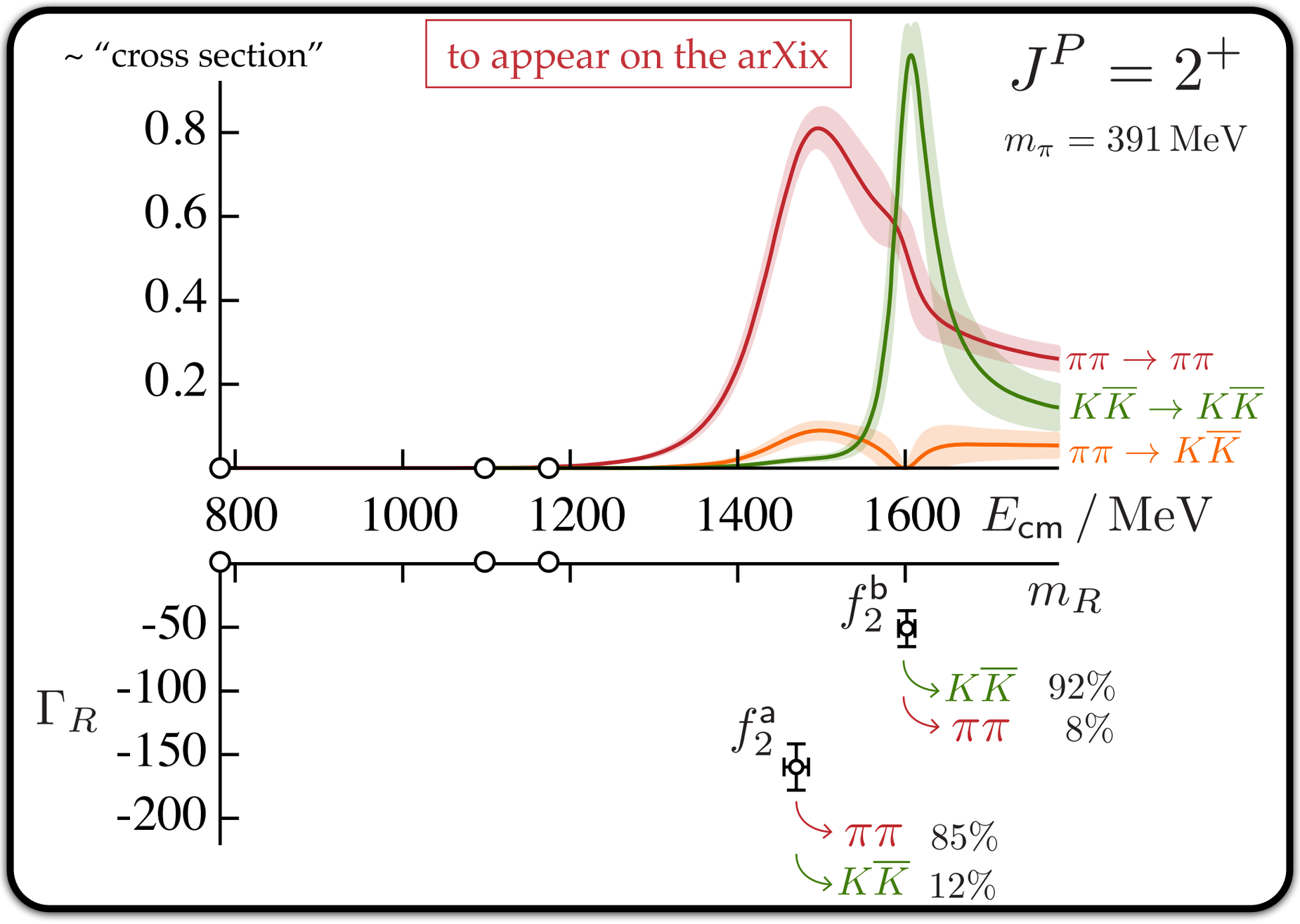
m_π=391 MeV

RB, Dudek, Edwards & Wilson (2017)

Multi-channel systems - the bleeding edge!

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

Wilson (Marie Curie / Trinity)

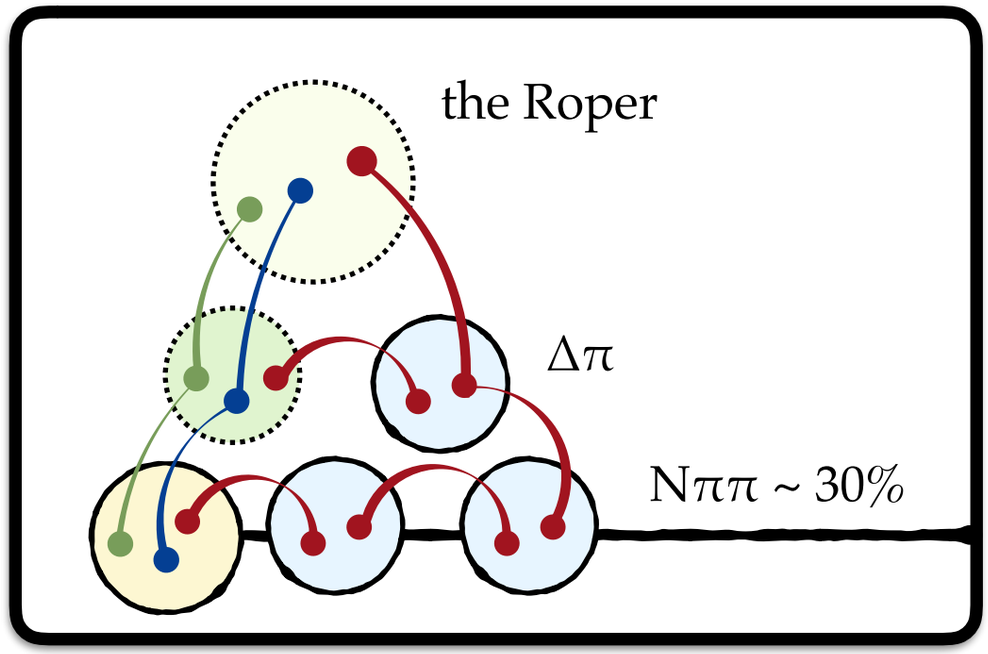


RB, Dudek, Edwards & Wilson (2017)

The future spectroscopy

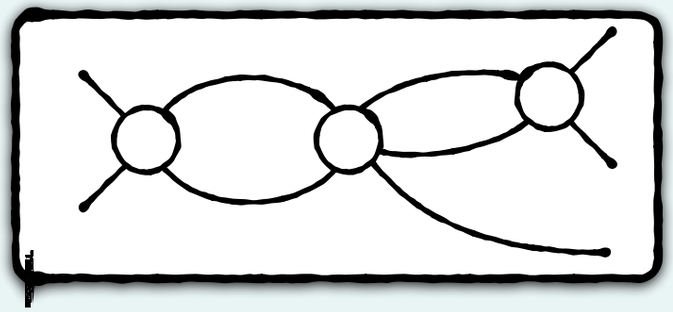
three-body scattering

- Experimentally challenging!
- Theoretically less so….under way!
- Needed for:
  - resonance [e.g., the Roper]
  - 3N-force



$$\det\left[1+\begin{pmatrix} F_2 & 0 \\ 0 & F_3 \end{pmatrix}\begin{pmatrix} \mathcal{K}_2 & \mathcal{K}_{23} \\ \mathcal{K}_{32} & \mathcal{K}_{\mathrm{df},3} \end{pmatrix}\right]=0$$

RB, Hansen & Sharpe (2016)

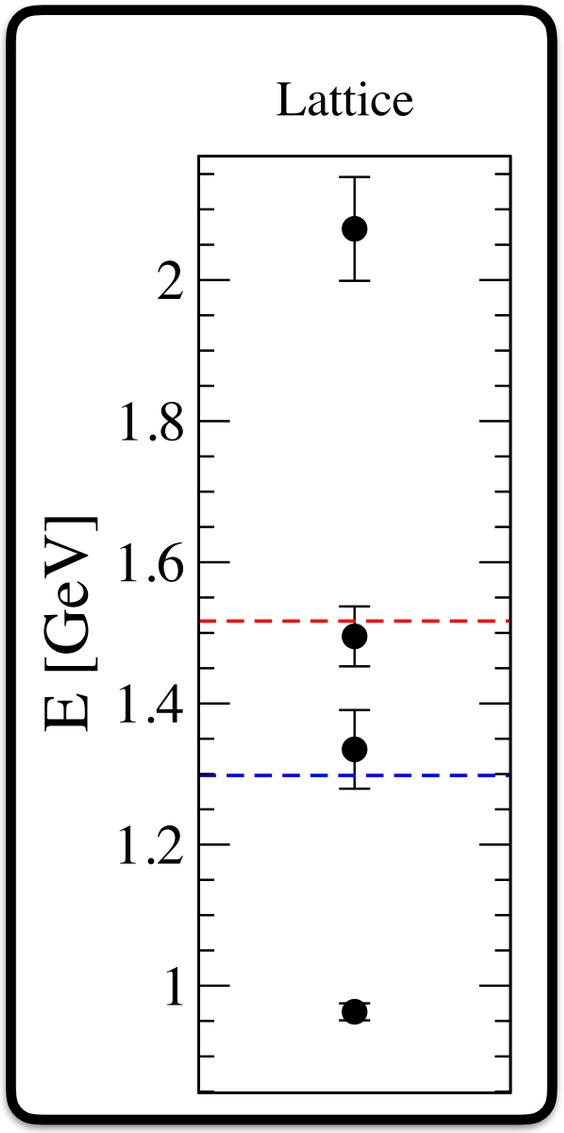


- Polejaeva & Rusetsky (2012) [spectrum depends on S-matrix]
- RB & **Davoudi** (2013) [1+shallow bound states]
- **Hansen** & Sharpe (2014-15) [relativistic $\pi\pi\pi$]
- Polejaeva & Rusetsky (2012) [spectrum depends on S-matrix]
- RB, **Hansen** & Sharpe (2016) [relativistic coupled, 2-,and 3-mesons]

Hansen (Mainz/CERN)

Davoudi (Maryland)

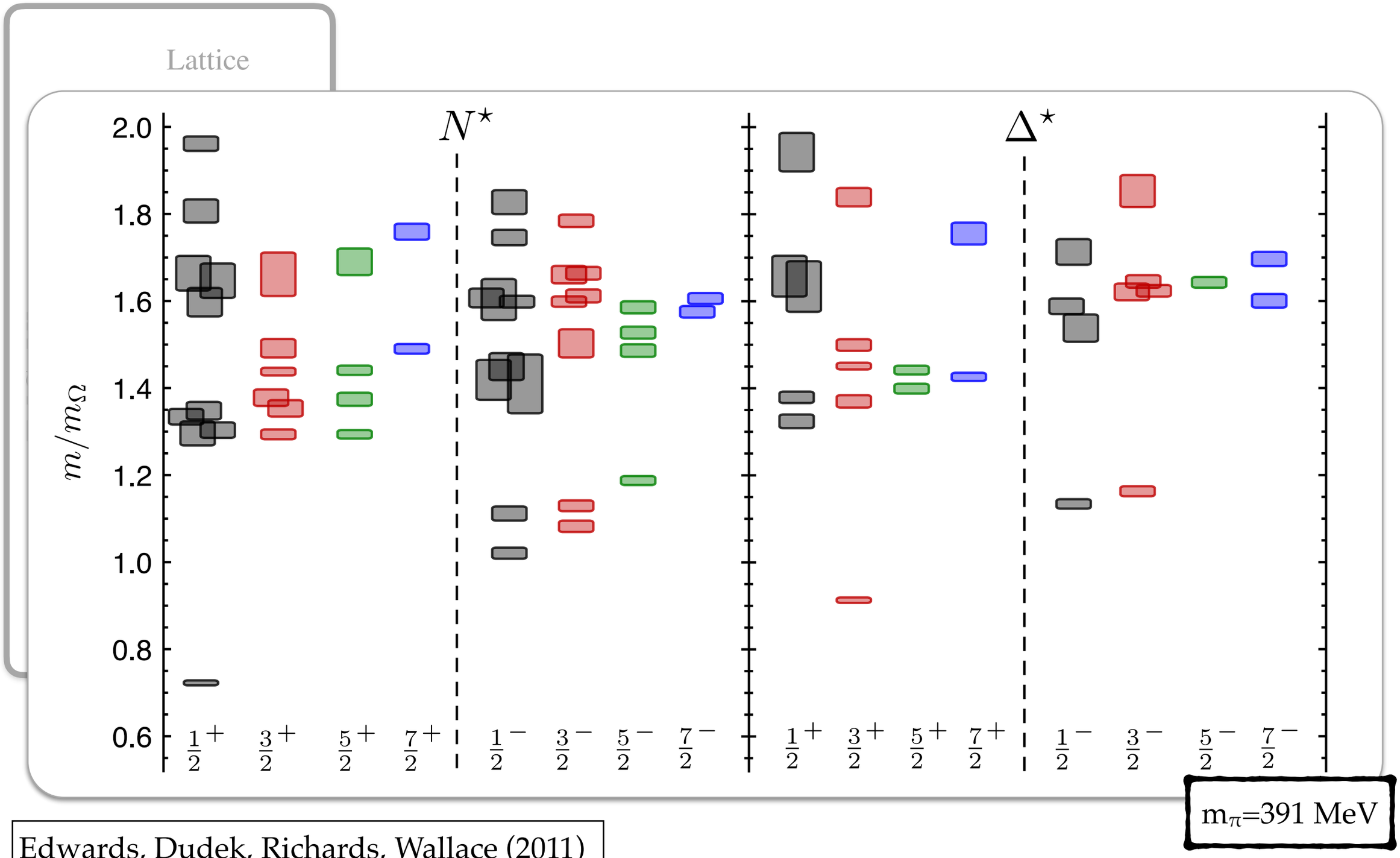
Towards the Roper



Lang, Leskovec, Padmanath,& Prelovsek(2017)

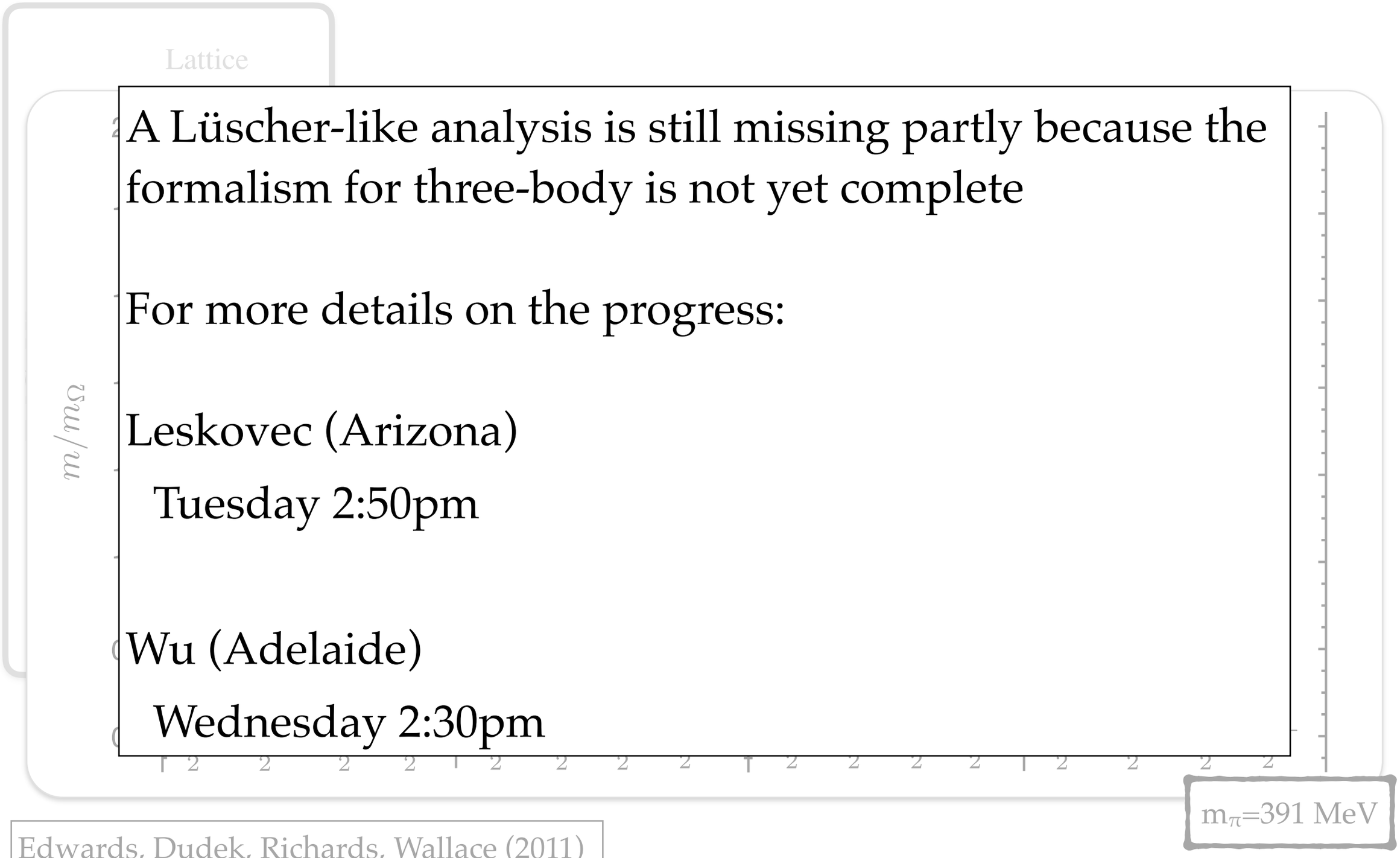
Leskovec (Arizona)

Towards the Roper



Edwards, Dudek, Richards, Wallace (2011)

Towards the Roper



A Lüscher-like analysis is still missing partly because the formalism for three-body is not yet complete

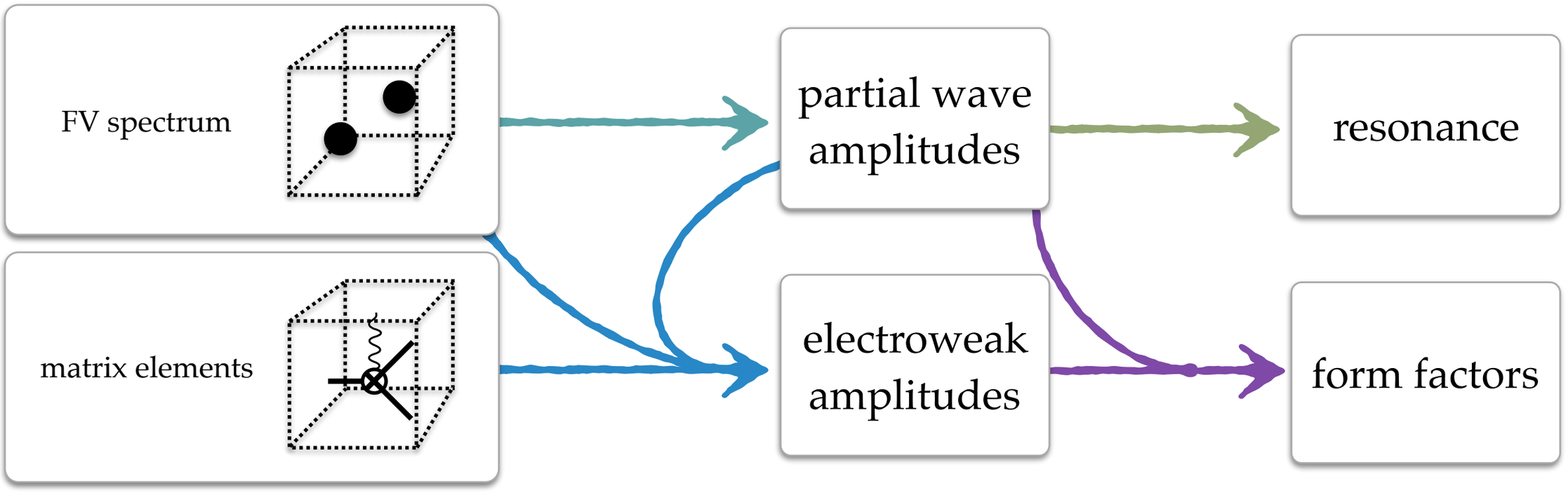
For more details on the progress:

Leskovec (Arizona)
Tuesday 2:50pm

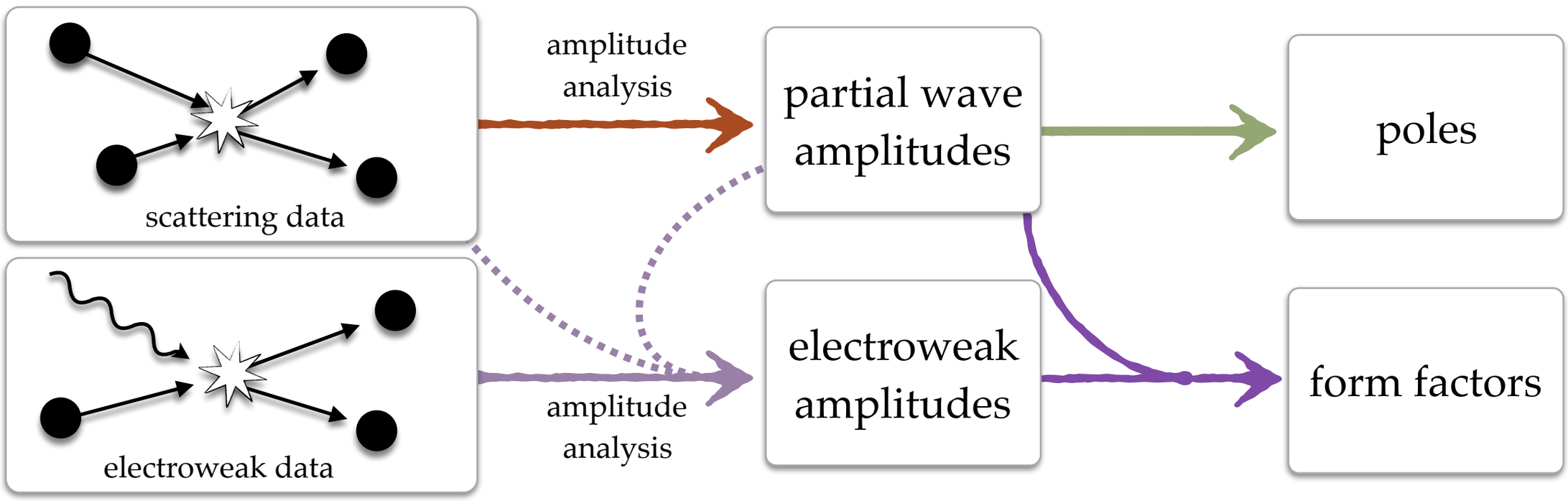
Wu (Adelaide)
Wednesday 2:30pm

Edwards, Dudek, Richards, Wallace (2011)

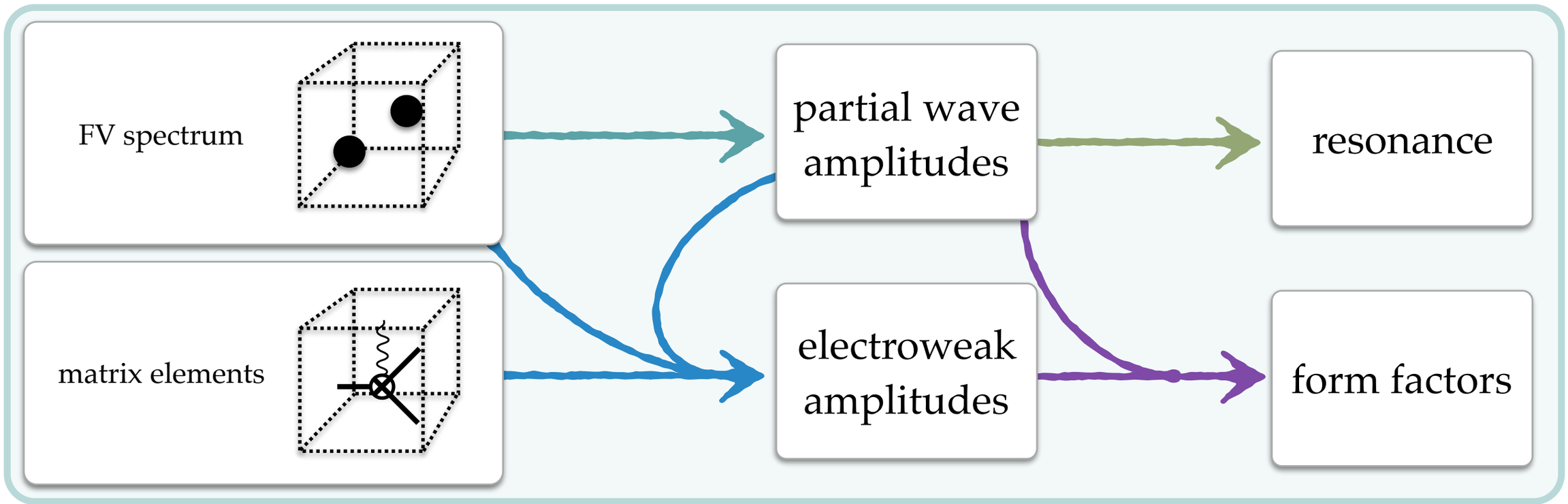
Electroproduction amplitudes



Experiment



Electroproduction amplitudes

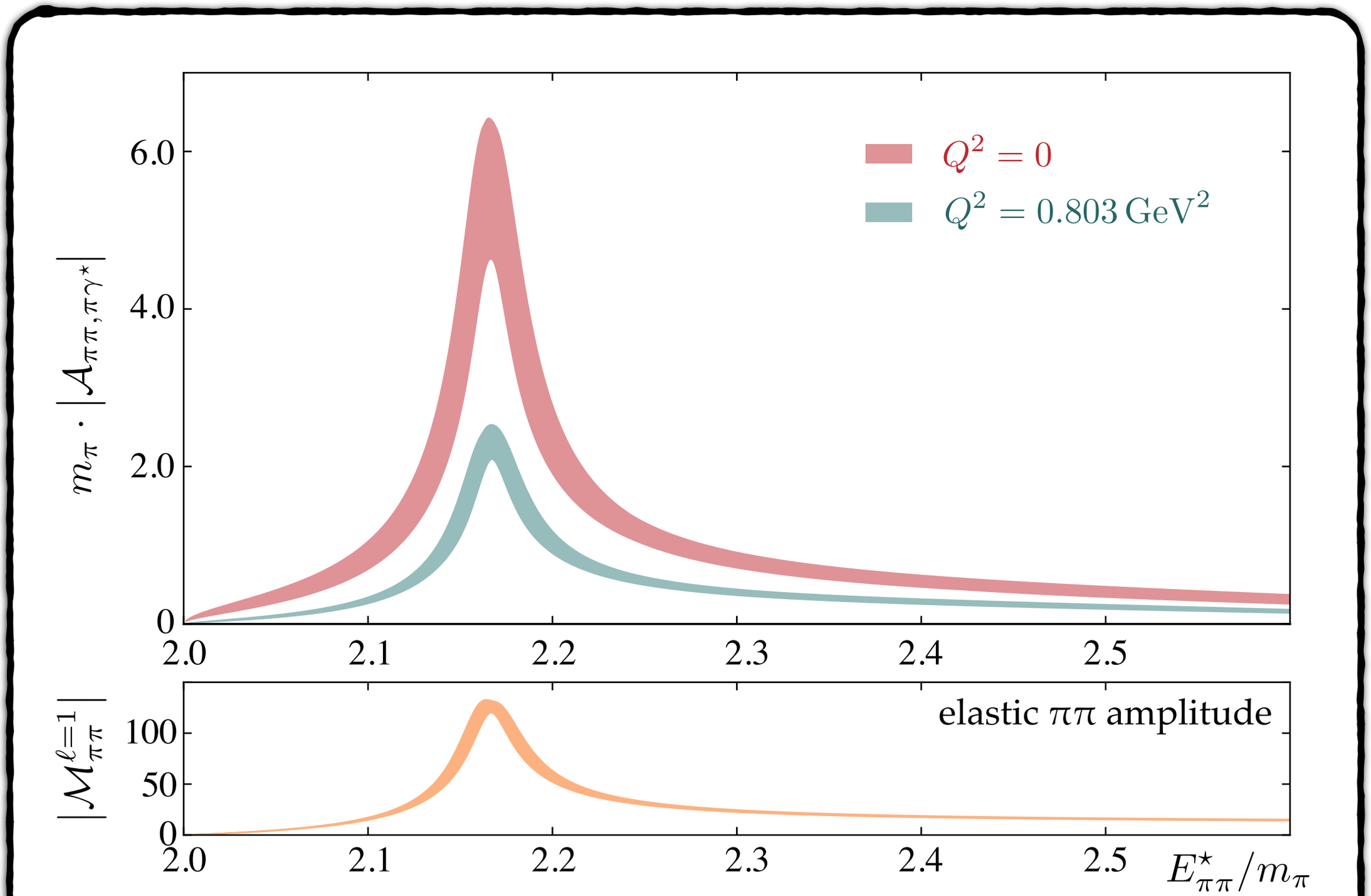


$$\left|\langle \mathbf{2}\left|\mathcal{J}\right|\mathbf{1}\rangle_L\right| = \sqrt{\mathcal{A}\,\mathcal{R}\,\mathcal{A}}$$

$\langle \mathbf{2}\left|\mathcal{J}\right|\mathbf{1}\rangle_L$ = 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-$\pi\pi$]
- Meyer (2011) [bound state radiative decay B-to-γ^*mm]
- Agadjanov, V. Bernard, Meissner, Rusetsky (2013) [N-to-Δ]
- **Hansen** & Sharpe (2012) [D-to-$\pi\pi$/KK]
- RB, **Hansen** Walker-Loud /RB & **Hansen** (2014-2015) [general 1-to-2 result]

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

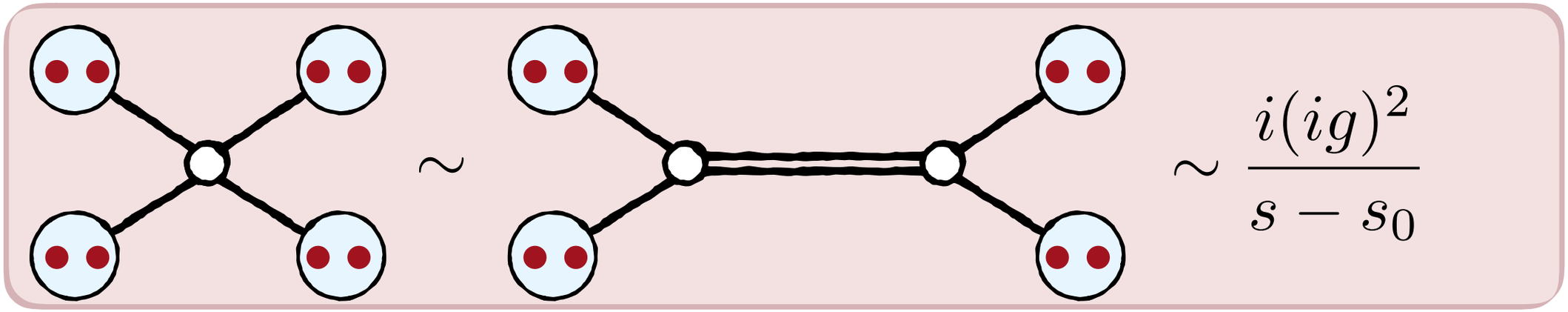


m_π=391 MeV

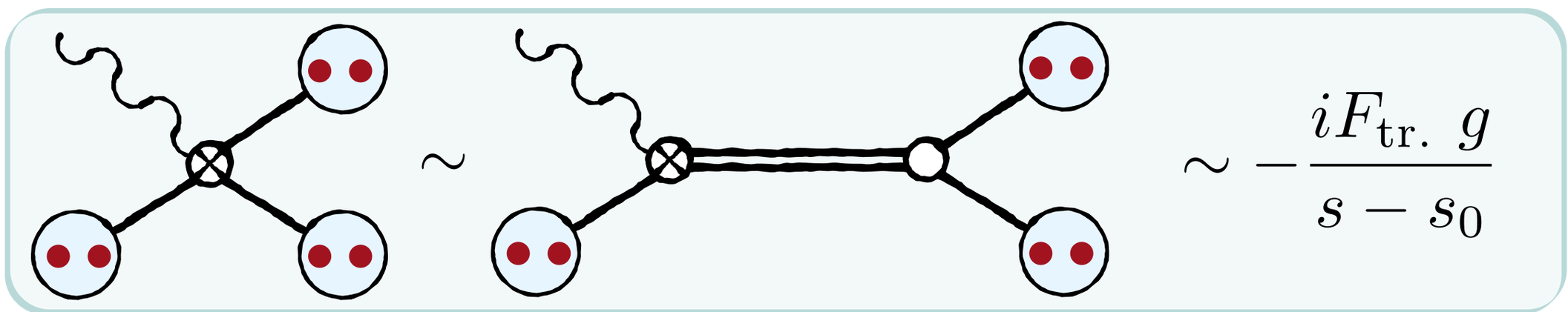
RB, Dudek, Edwards, Thomas, Shultz, Wilson - PRL (2015)

Explanation

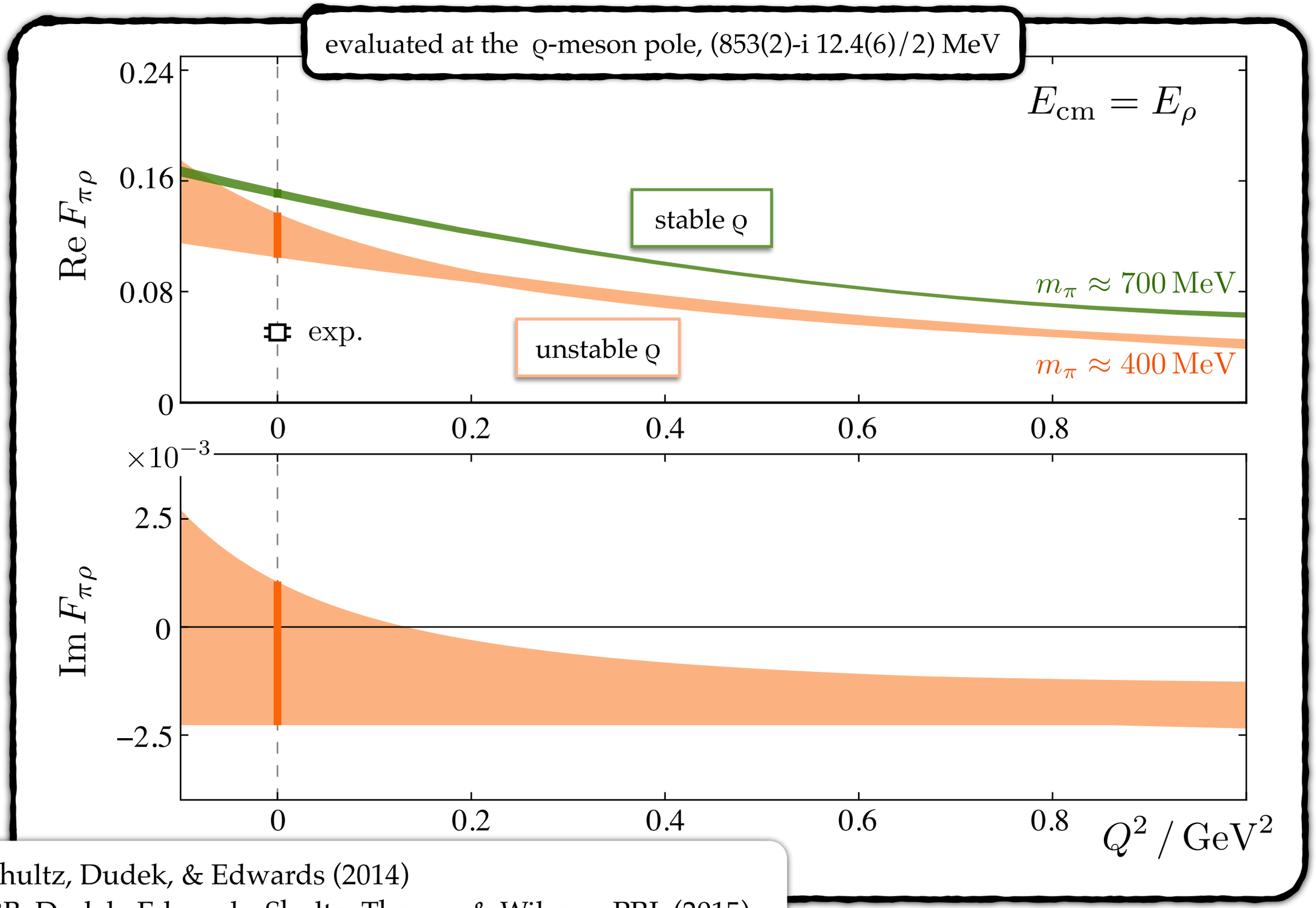
- *$\pi\pi$-to-$\pi\pi$ amplitude:*



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



π-*to*-ρ form factor



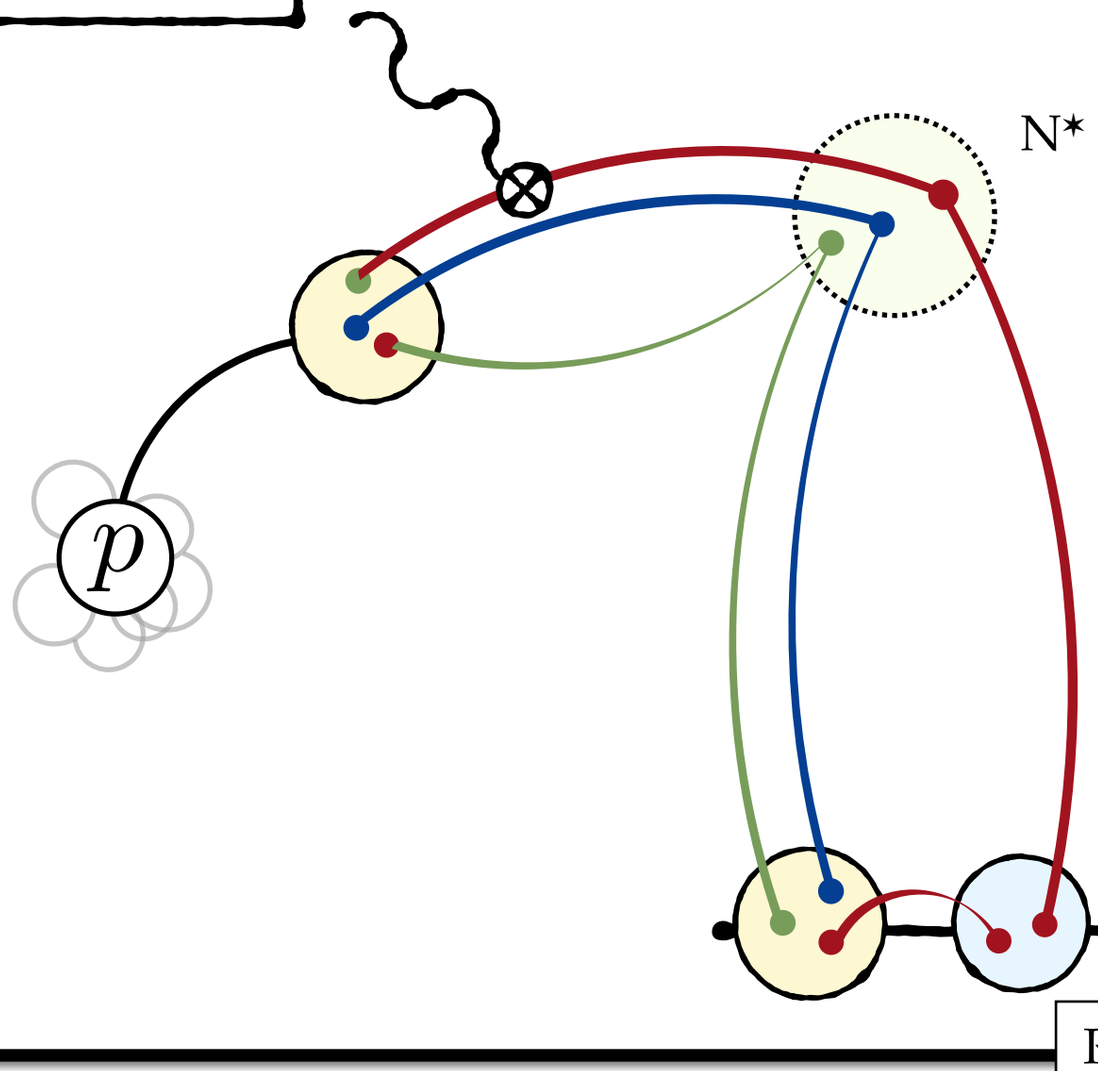
Shultz, Dudek, & Edwards (2014)
RB, Dudek, Edwards, Shultz, Thomas & Wilson - PRL (2015)

π-to-ρ form factor

evaluated at the ϱ-meson pole, (853(2)-i 12.4(6)/2) MeV

Hansen (Mainz/CERN)

Formalism set in place for…



RB & Hansen (2015)

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

The future of "structure"

matrix elements of few-body systems

- *matrix elements of resonant or bound states*

Hansen (Mainz/CERN)

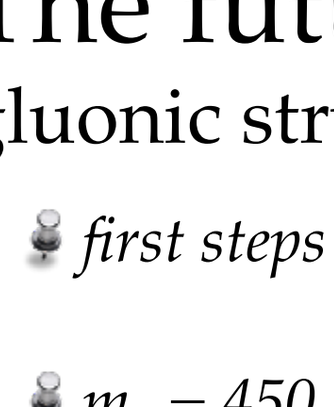
- RB, & Davoudi (2012) [pp-fusion (pp-to-npve)]
- Bernard, Lage, Meissner, & Rusetsky (2012) [S-wave, elastic, 2-body system]
- RB & Hansen (2016) [generic result for two-meson systems]

The future of "structure"

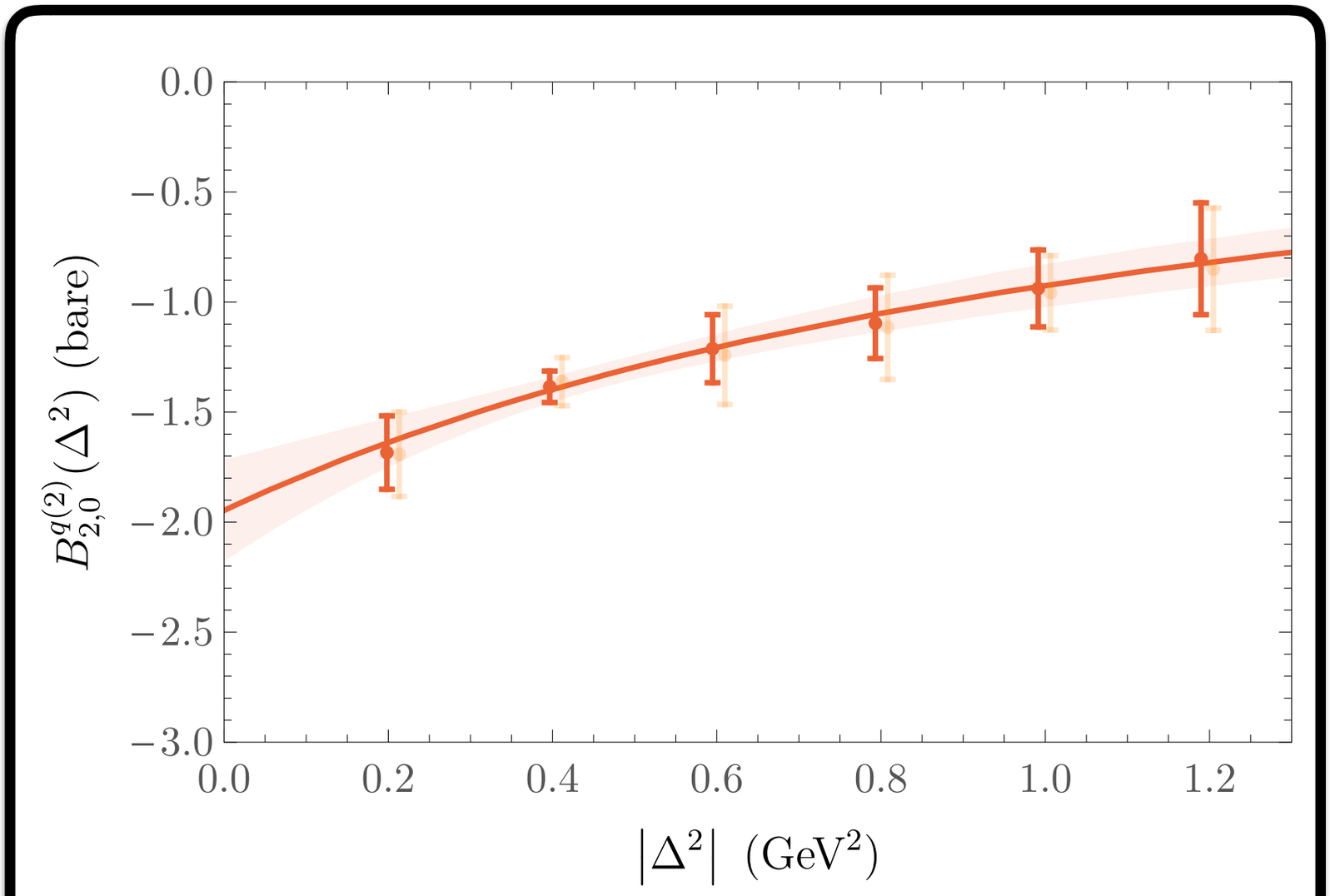
gluonic structure of resonances

- *first steps to studies of spin-independent gluonic-form factors of the ϕ*

- *$m_\pi = 450$ MeV, ϕ is stable*



Shanahan (W&M/JLab)



$$|n\rangle_{\mathrm{QCD}} = c_0 \; + \; c_1 \; + \; c_2 \; + \; c_3 \; + \cdots$$

A review / introduction

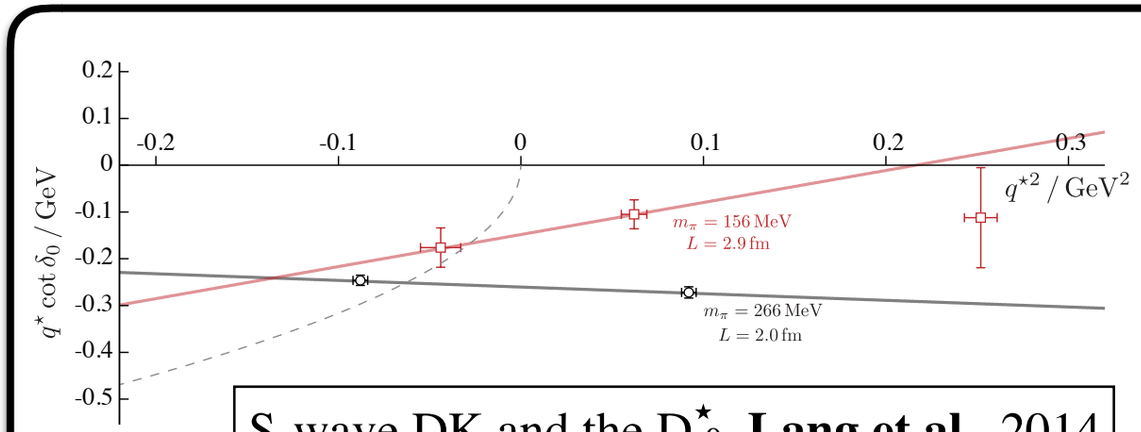
Scattering processes and resonances from lattice QCD

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

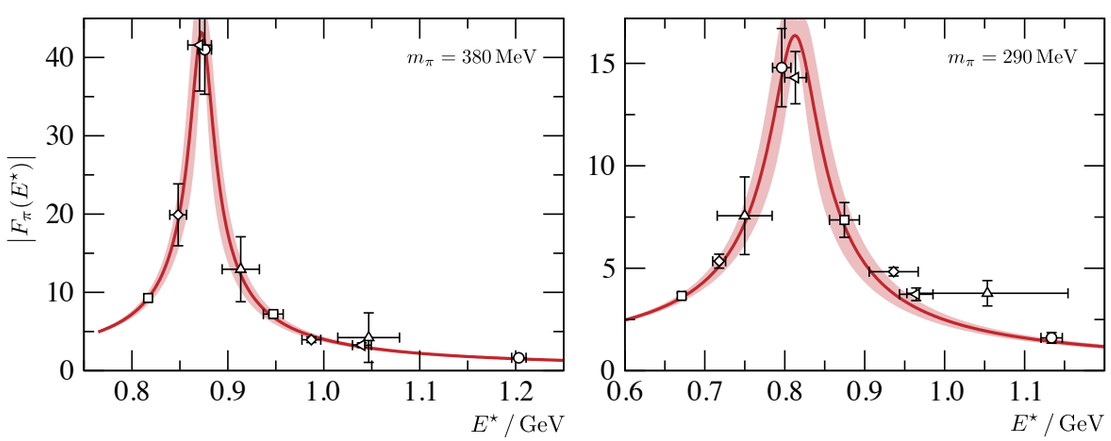
[1] *Thomas Jefferson National Accelerator Facility, 12000 Jefferson Avenue, Newport News, Virginia 23606, USA*

[2] *Department of Physics, College of William and Mary, Williamsburg, Virginia 23187, USA*

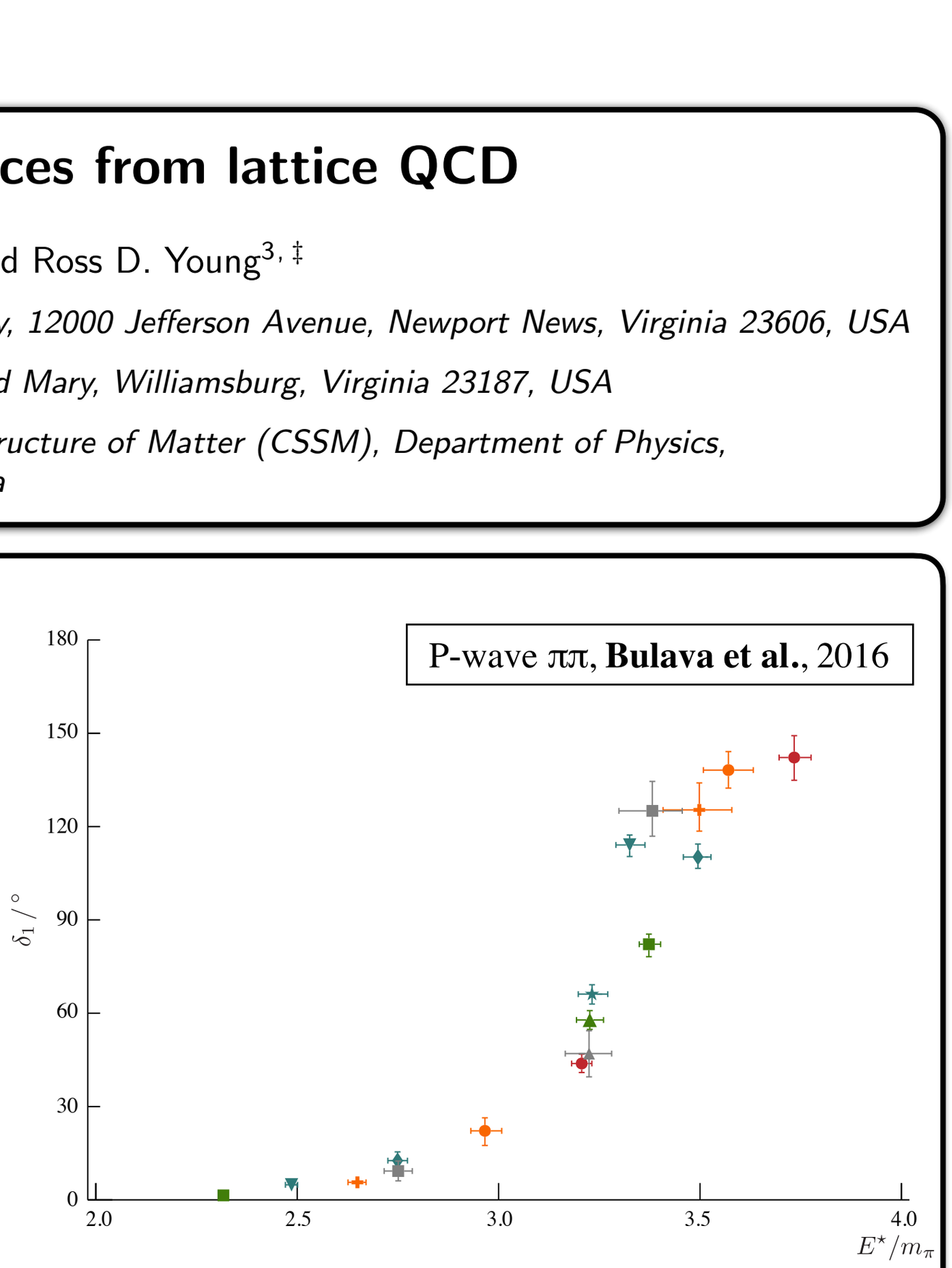
[3] *Special Research Center for the Subatomic Structure of Matter (CSSM), Department of Physics, University of Adelaide, Adelaide 5005, Australia*



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

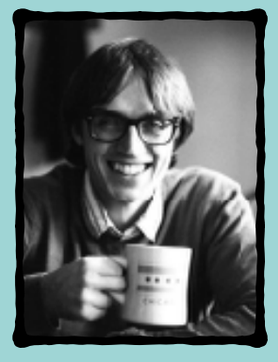
Multi-Hadron Systems from Lattice QCD

INT workshop: Seattle, WA

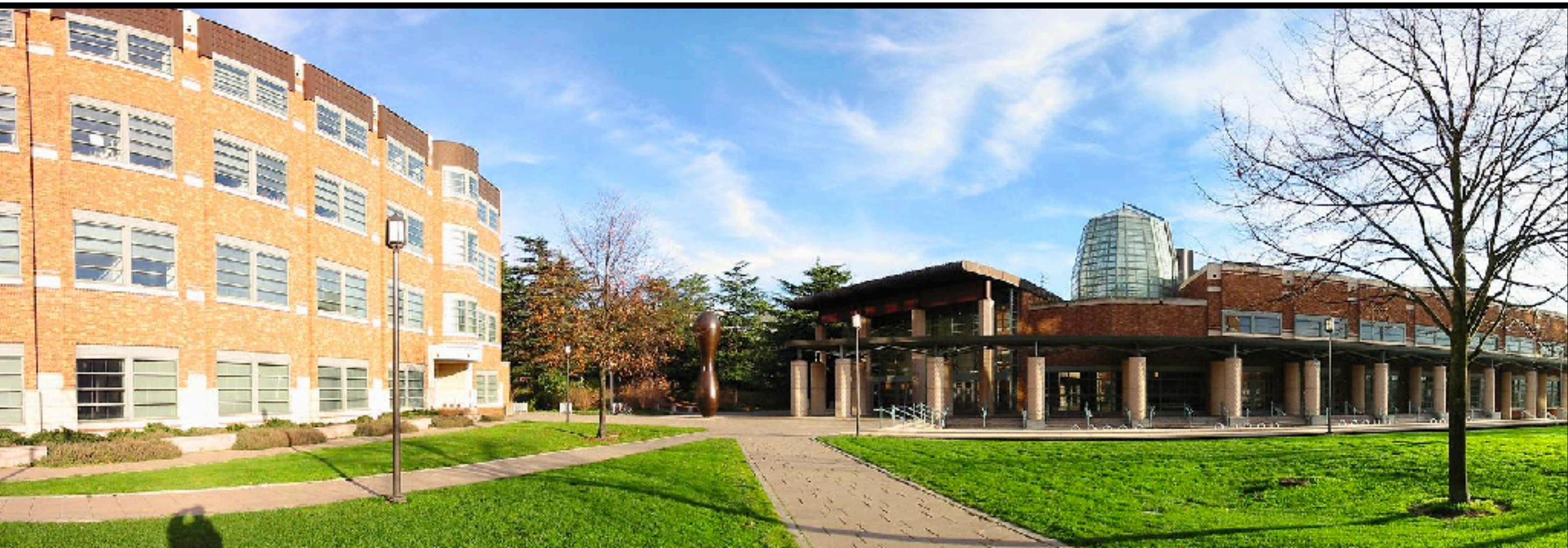
early 2018 (TBD)

Hansen

Sharpe



Wilson



Lattice QCD efforts in N*

Unfortunately, there is no plenaries reviewing the field

Plenary reviewing Adelaide efforts - Jia-Jun Wu

A young, vibrant, and diverse community:

Today:

Bulava (CP³-Origins)

Hansen (Mainz/CERN)

Shanahan (W&M/JLab)

Tuesday:

Wilson (Royal fellow, Trinity)

Davoudi (Maryland)

Leskovec (Arizona)

Wednesday: **Giannis Koutsou**, “Nucleon and Delta structure“