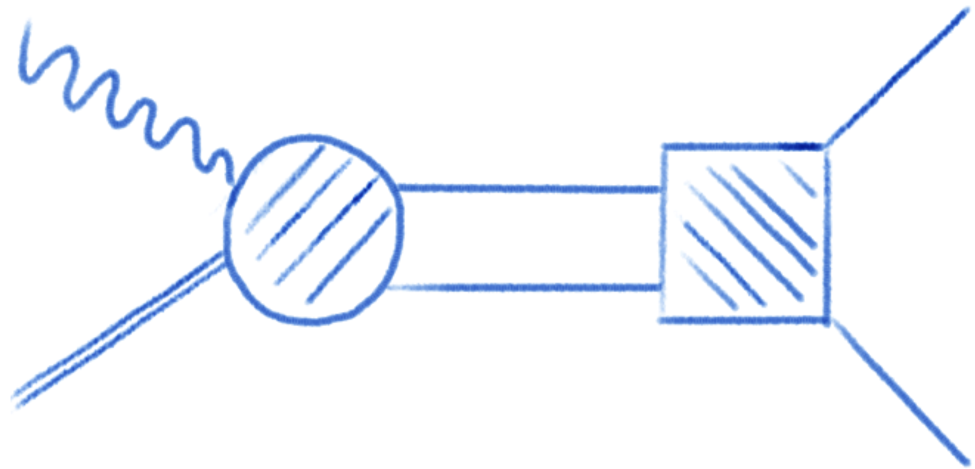
Photoproduction of Resonances on the Lattice

Luka Leskovec

PWA11/ATHOS6



2-6 September 2019

Centro Brasileiro de Pesquisas Físicas

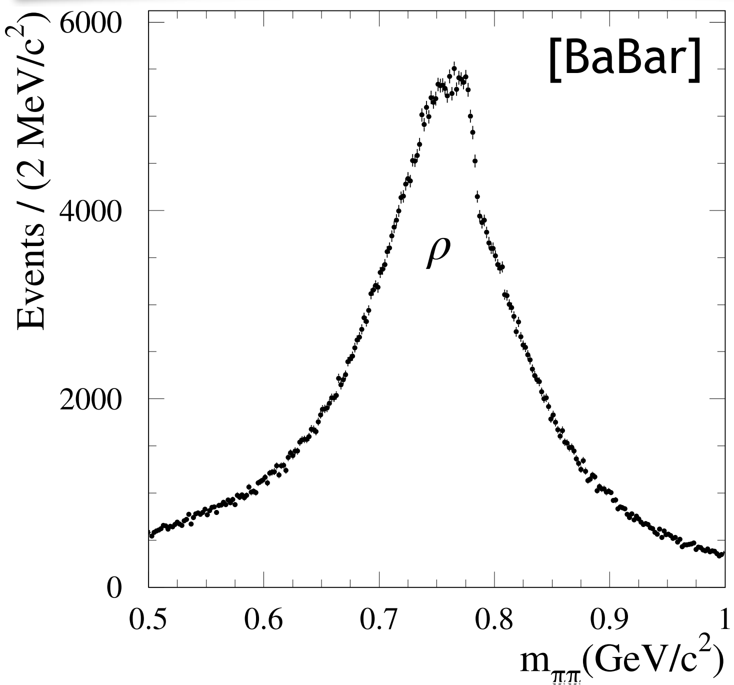
Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

Hadrons

• $\pi^{\pm}$	$1^-(0^-)$	$f_1(1510)$	$0^+(1^{++})$
• π^0	$1^-(0^{-+})$	• $f_2'(1525)$	$0^+(2^{++})$
• η	$0^+(0^{-+})$	$f_2(1565)$	$0^+(2^{++})$
• $f_0(500)$ aka σ; was $f_0(600)$	$0^+(0^{++})$	$\rho(1570)$	$1^+(1^{--})$
• $\rho(770)$	$1^+(1^{--})$	$h_1(1595)$	$0^-(1^{+-})$
• $\omega(782)$	$0^-(1^{--})$	• $\pi_1(1600)$	$1^-(1^{-+})$
• $\eta'(958)$	$0^+(0^{-+})$	• $a_1(1640)$	$1^-(1^{++})$
• $f_0(980)$	$0^+(0^{++})$	$f_2(1640)$	$0^+(2^{++})$
• $a_0(980)$	$1^-(0^{++})$	• $\eta_2(1645)$	$0^+(2^{-+})$
• $\phi(1020)$	$0^-(1^{--})$	• $\omega(1650)$	$0^-(1^{--})$
• $h_1(1170)$	$0^-(1^{+-})$	• $\omega_3(1670)$	$0^-(3^{--})$
		• $\pi_2(1670)$	$1^-(2^{-+})$



- interesting phenomena
- (un)similar to atoms
- QCD stable hadrons (π, K, η)
- QCD unstable hadrons $(\rho, \sigma, a_0, \ldots)$
- resonances are most of the hadronic spectrum

What do we know about Hadrons?

https://www.jlab.org/research/jleic/overview

- but can we learn more about unstable hadrons?

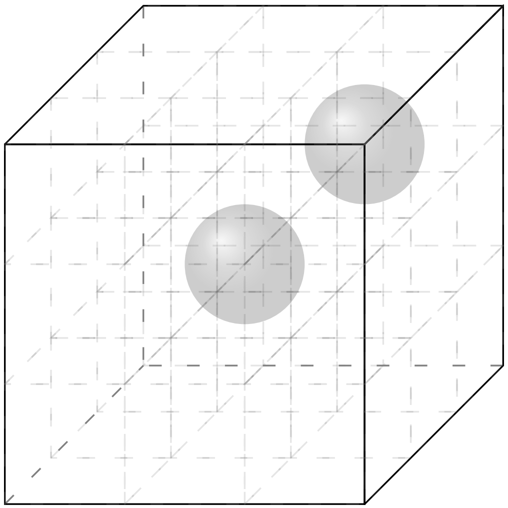
Photoproduction Amplitudes

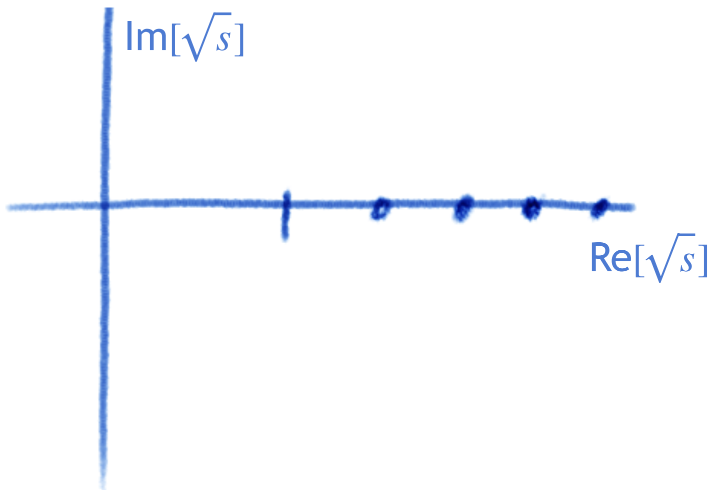
- Stable Hadrons from first principles:
  - masses
  - structure
- Unstable Hadrons from first principles:
  - resonance masses
  - strong decay widths
  - couplings to channels
  - Branching Ratios
  - scattering amplitudes

more lattice:
-> M. Döring Tue@++
-> D.Wilson Thu@17:00

Intro to Lattice QCD

- Euclidean space-time
- Monte Carlo sample the Feynman Path Integral
- $m_\pi \geq m_\pi^{phys}$
- Finite Volume Box
- $\psi(x) = \psi(x + L)$
- discrete spectrum





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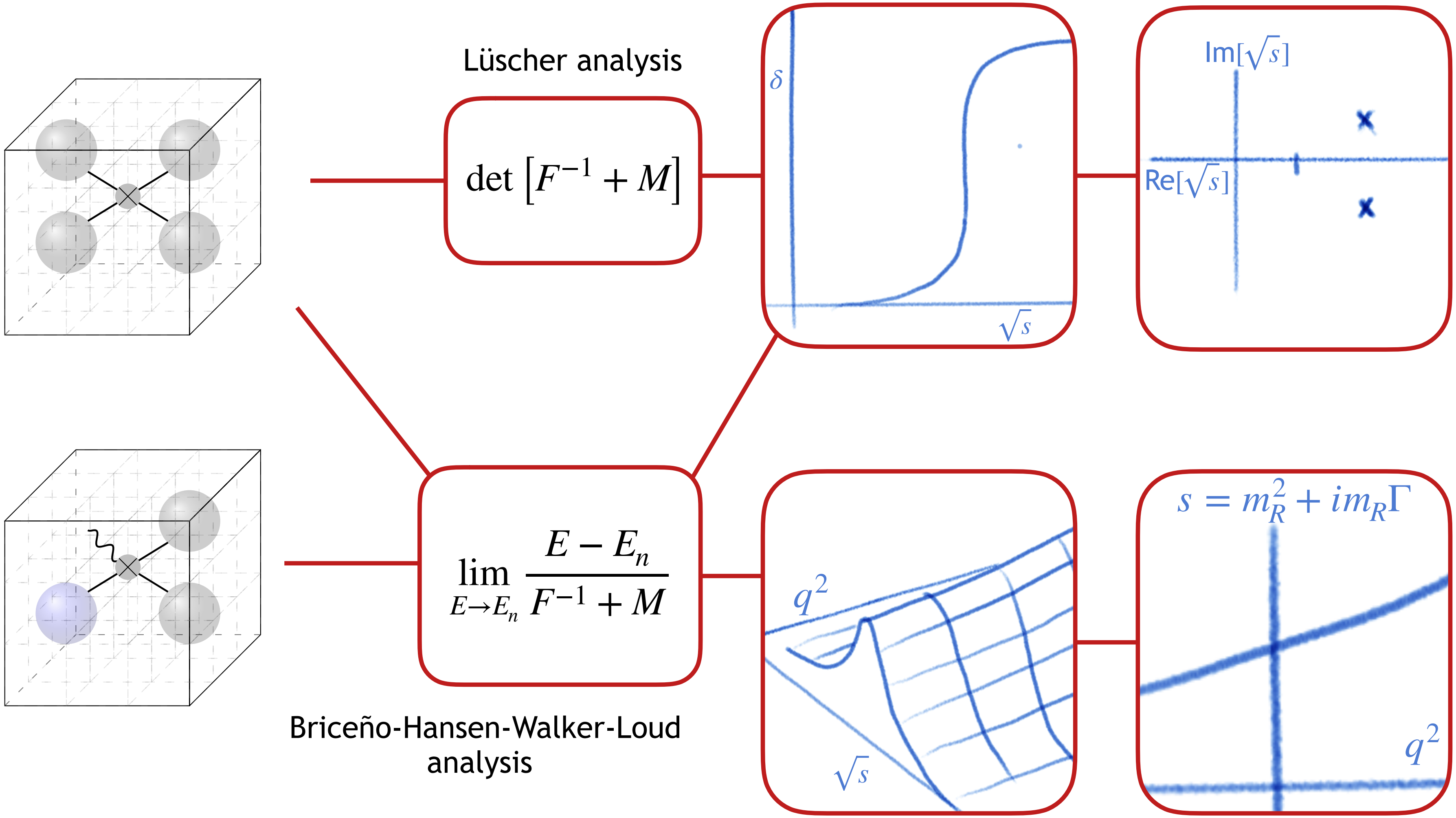
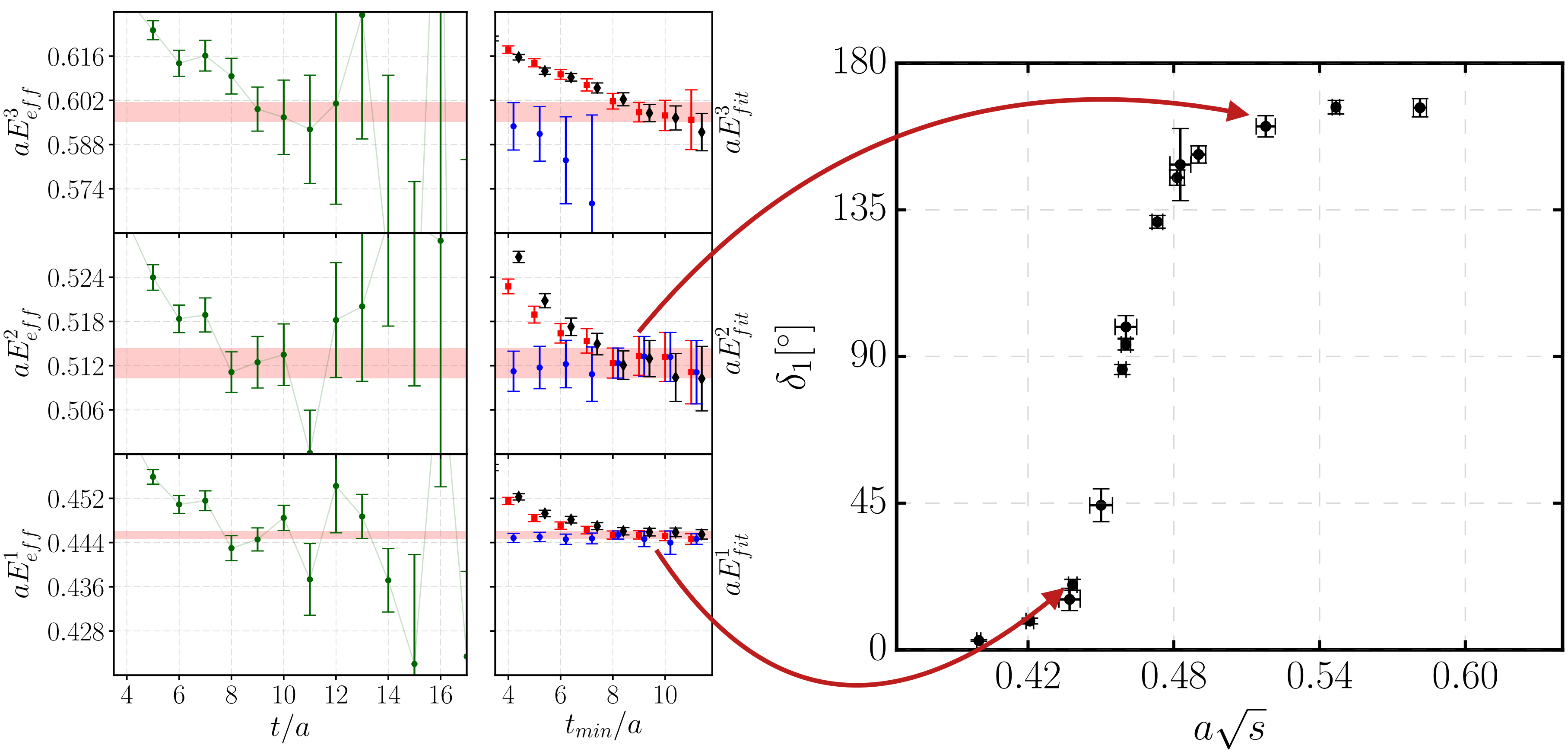
Photoproduction on the Lattice



Lüscher analysis

$|\vec{P}| = \frac{2\pi}{L}$, $\Lambda = A_2$, basis: O_{1234}



[Briceño, Dudek, Young 2018]

The ρ resonance mass and decay width

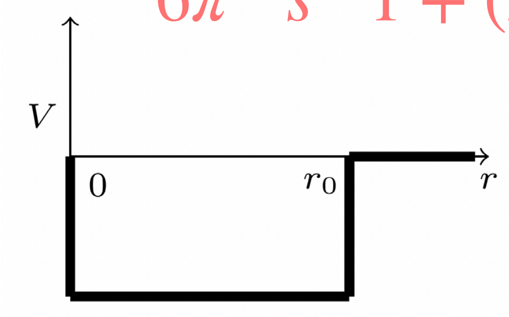
$$\mathcal{M}_i = \frac{16\pi}{k}\frac{s\Gamma_i}{m_R^2 - s - i\sqrt{s}\Gamma_i}$$

- i = BW I:

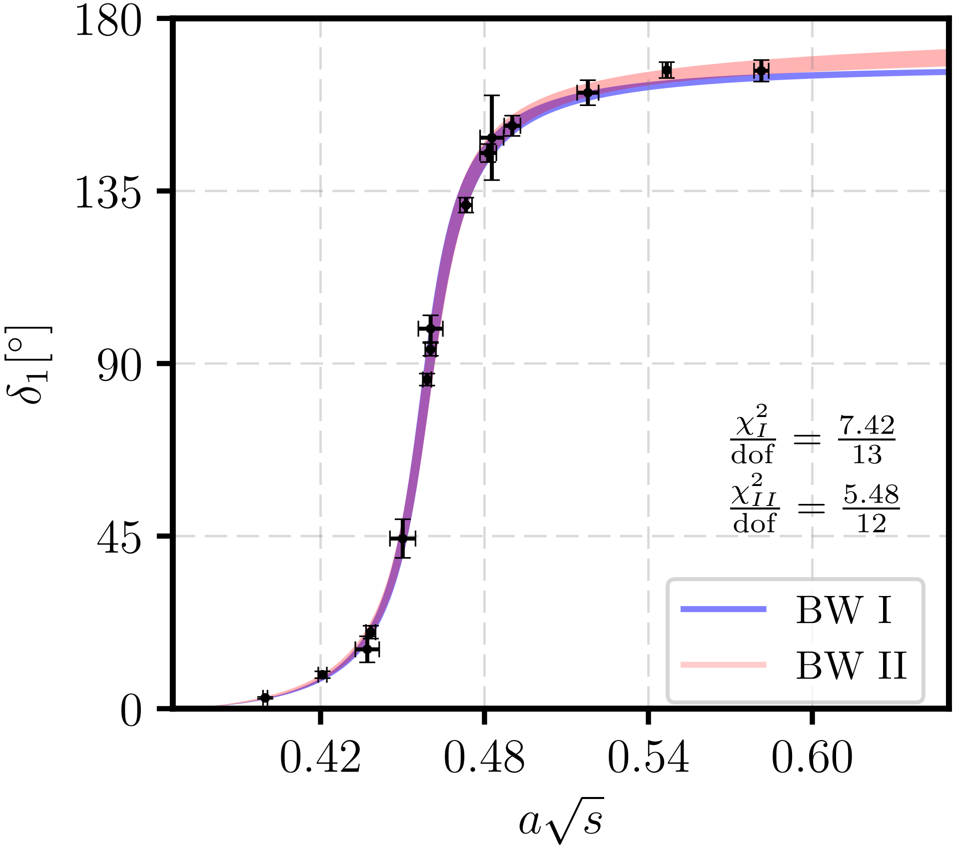
$$\Gamma_I = \frac{g_{\rho\pi\pi}^2}{6\pi}\frac{k^3}{s}$$

- i = BW II:

$$\Gamma_{II} = \frac{g_{\rho\pi\pi}^2}{6\pi}\frac{k^3}{s}\frac{1+(k_R r_0)^2}{1+(kr_0)^2}$$



[Feng et al., Lang et al., Aoki et al., Pelissier et al., HadSpec, HadSpec, RQCD, Bulava et al., Guo et al., Fu et al., Bulava et al., ETMC, …]



[Alexandrou et al. 2017]

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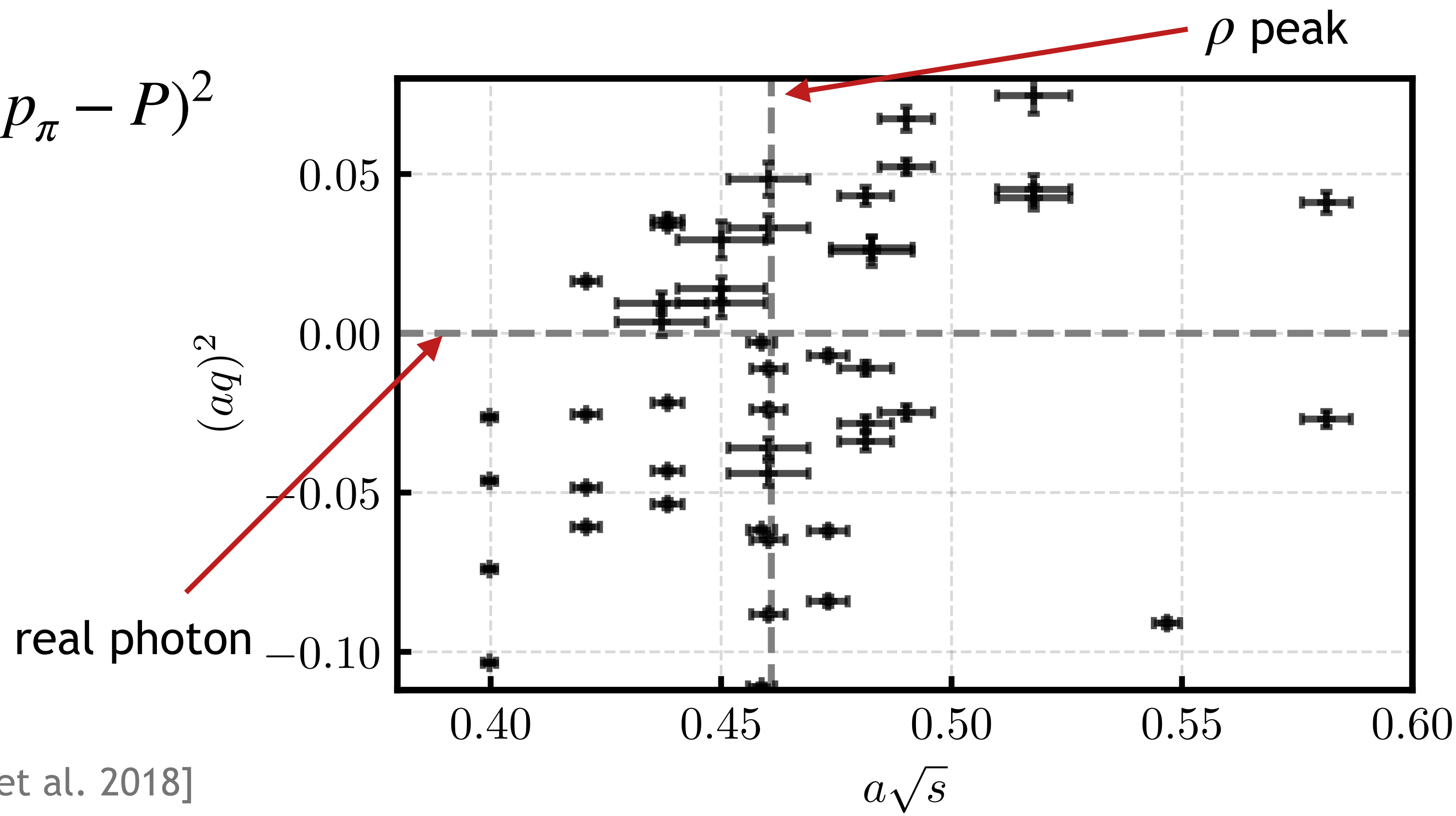
About $\pi\gamma^* \to \pi\pi$

$$\langle \pi\pi; P, m \,|\, J^\mu(0) \,|\, \pi \rangle = \frac{2i\mathscr{V}_{\pi\gamma\to\pi\pi}(q^2, s)}{m_\pi} \epsilon^{\nu\mu\alpha\beta} \varepsilon_\nu(P, m)(p_\pi)_\alpha (P)_\beta$$

$$q^2 = (p_\pi - P)^2$$



[Alexandrou et al. 2018]

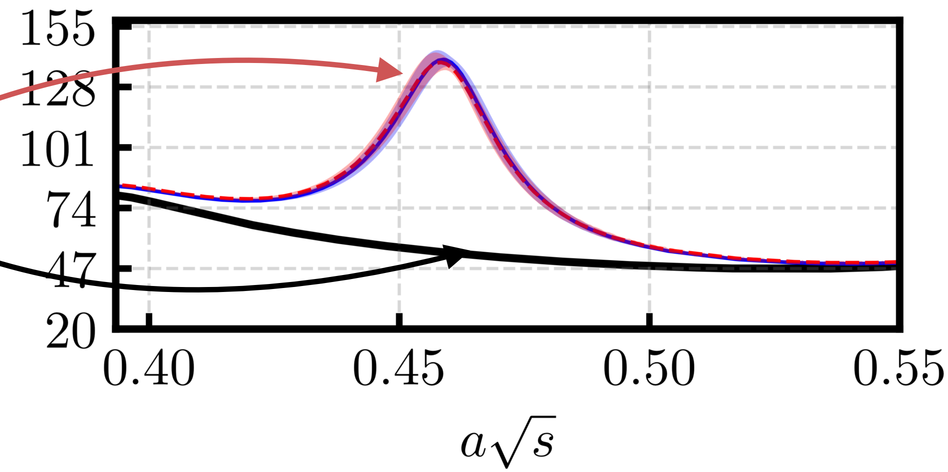
Briceno-Hansen-Walker-Loud analysis

$$\mathscr{V}^{FV}_{\pi\gamma\to\pi\pi}(q^2, s) = \sqrt{R\,\mathscr{V}^{IV}_{\pi\gamma\to\pi\pi}(q^2, s)\,R}$$

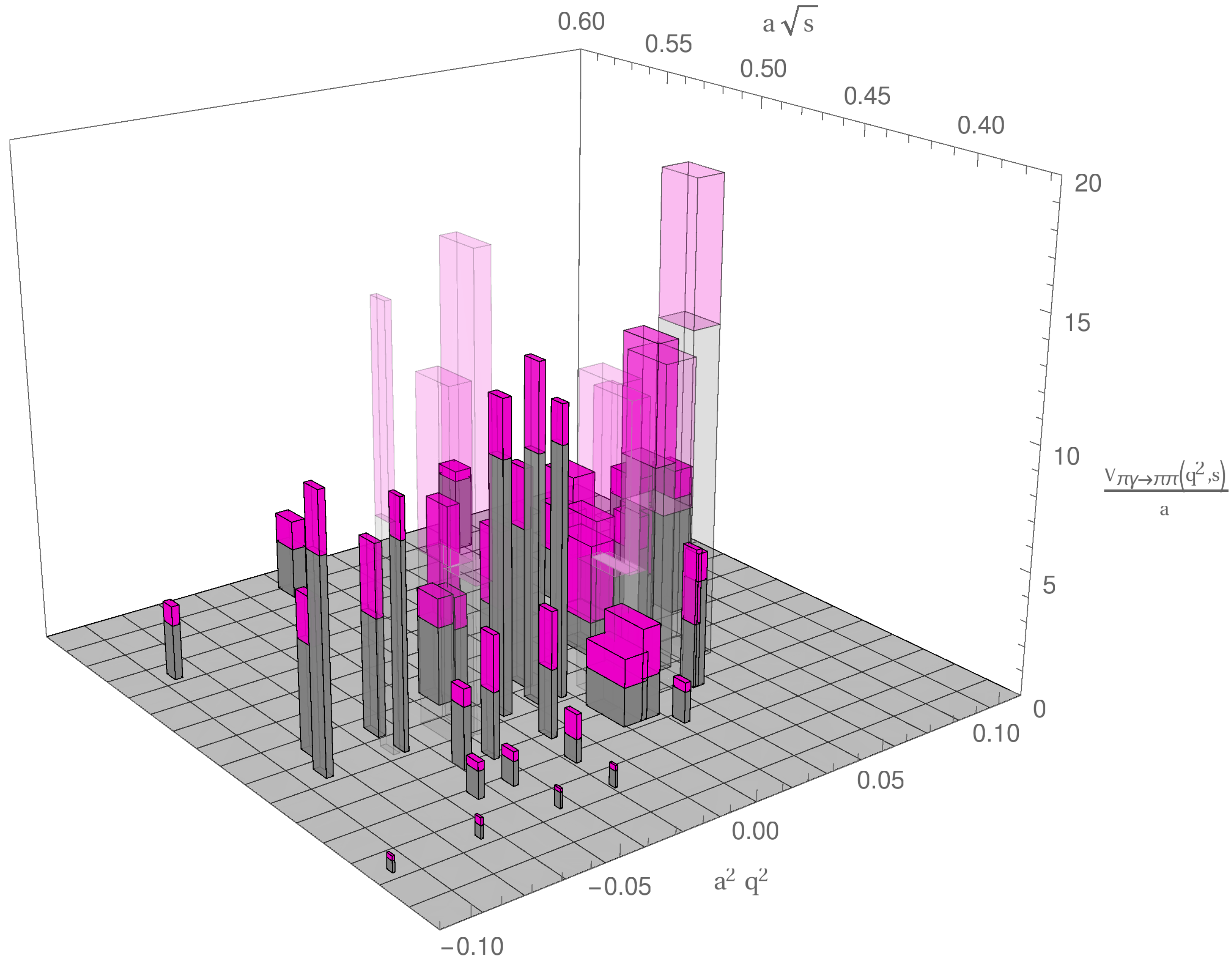
[Lellouch, Lüscher 2000, …,
Briceño, Hansen, Walker-Loud 2015]

$$R = \lim_{E\to E_n} \frac{E - E_n}{F^{-1} + M}$$

- caveats:
  - FV quantum numbers
  - only example (!)
  - F^{-1} contribution
  - $F^{-1} + M_i$
    - i = BW I
    - i = BW II



Briceno-Hansen-Walker-Loud analysis



Fitting $\mathscr{V}^{IV}_{\pi\gamma\to\pi\pi}(q^2, s)$

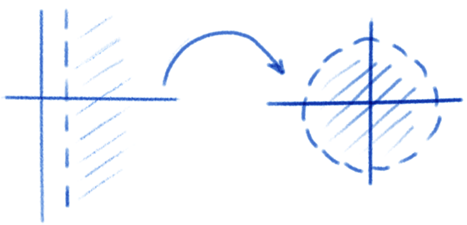
- Watson's theorem

$$\mathscr{V}^{IV}_{\pi\gamma\to\pi\pi,i}(q^2, s) = \sqrt{\frac{16\pi}{k\Gamma_i}}\,\frac{F(q^2, s)}{cot\delta_i - i}$$

$$F(q^2, s) = \frac{\sum_{n,m} A_{nm} z^n \mathscr{S}^m}{1 - \frac{q^2}{m_P^2}}$$

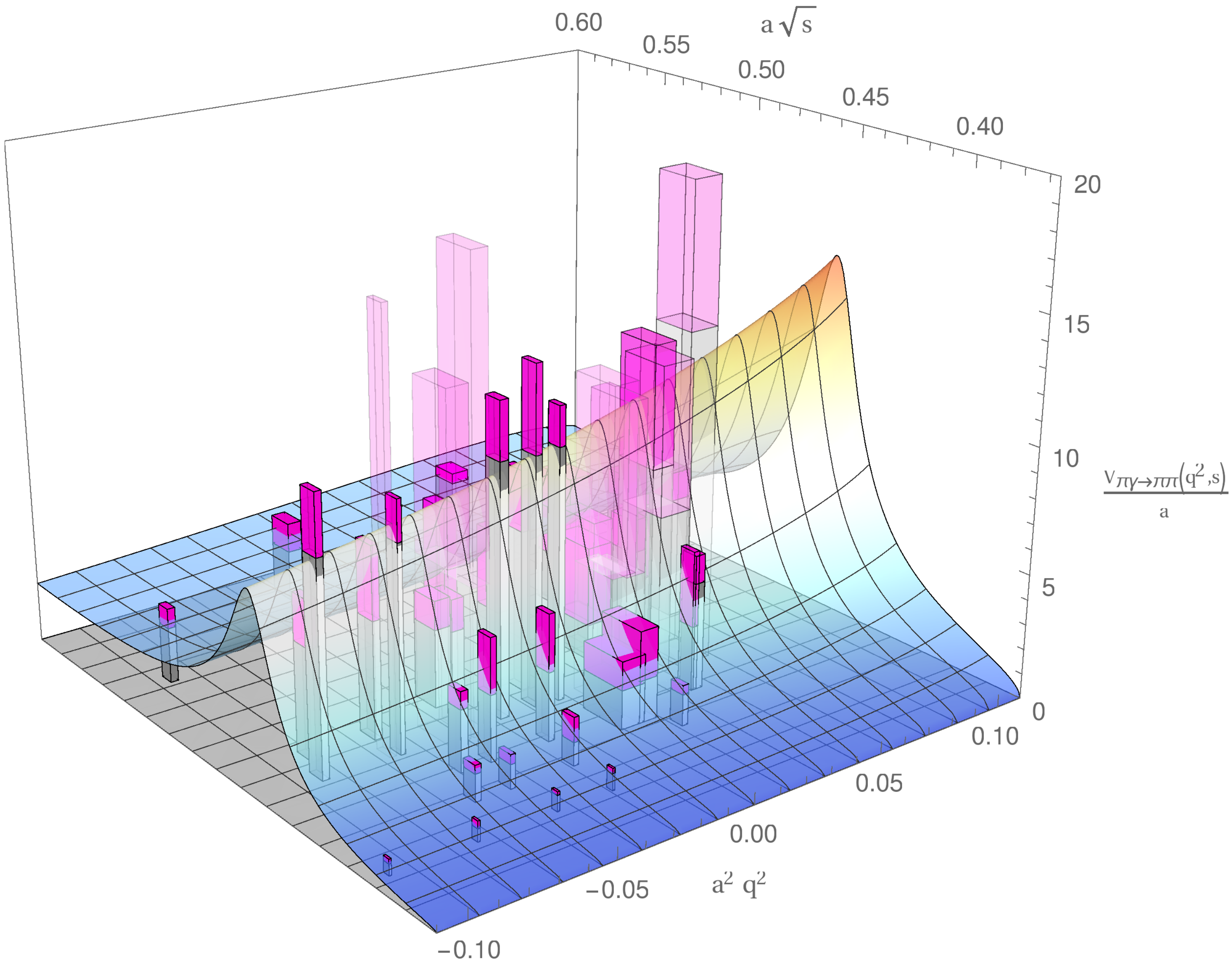
- expand F in:
  - $\mathscr{S} = \frac{s - m_R^2}{m_R^2}$
  - $z = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+}}{\sqrt{t_+ - q^2} + \sqrt{t_+}}$
  - $t_+ = (2m_\pi)^2$

[Boyd et al. 1994, Bourelly et al. 2008]



- systematic truncations:
  - F1: $n + m \leq K$
  - F2: $n \leq N, m \leq K - n$
  - F3: $n \leq N, m \leq M$
- analytic structure
  - needed
  - not sensitive

$\mathscr{V}^{IV}_{\pi\gamma\to\pi\pi}(q^2, s)$ 3-D view



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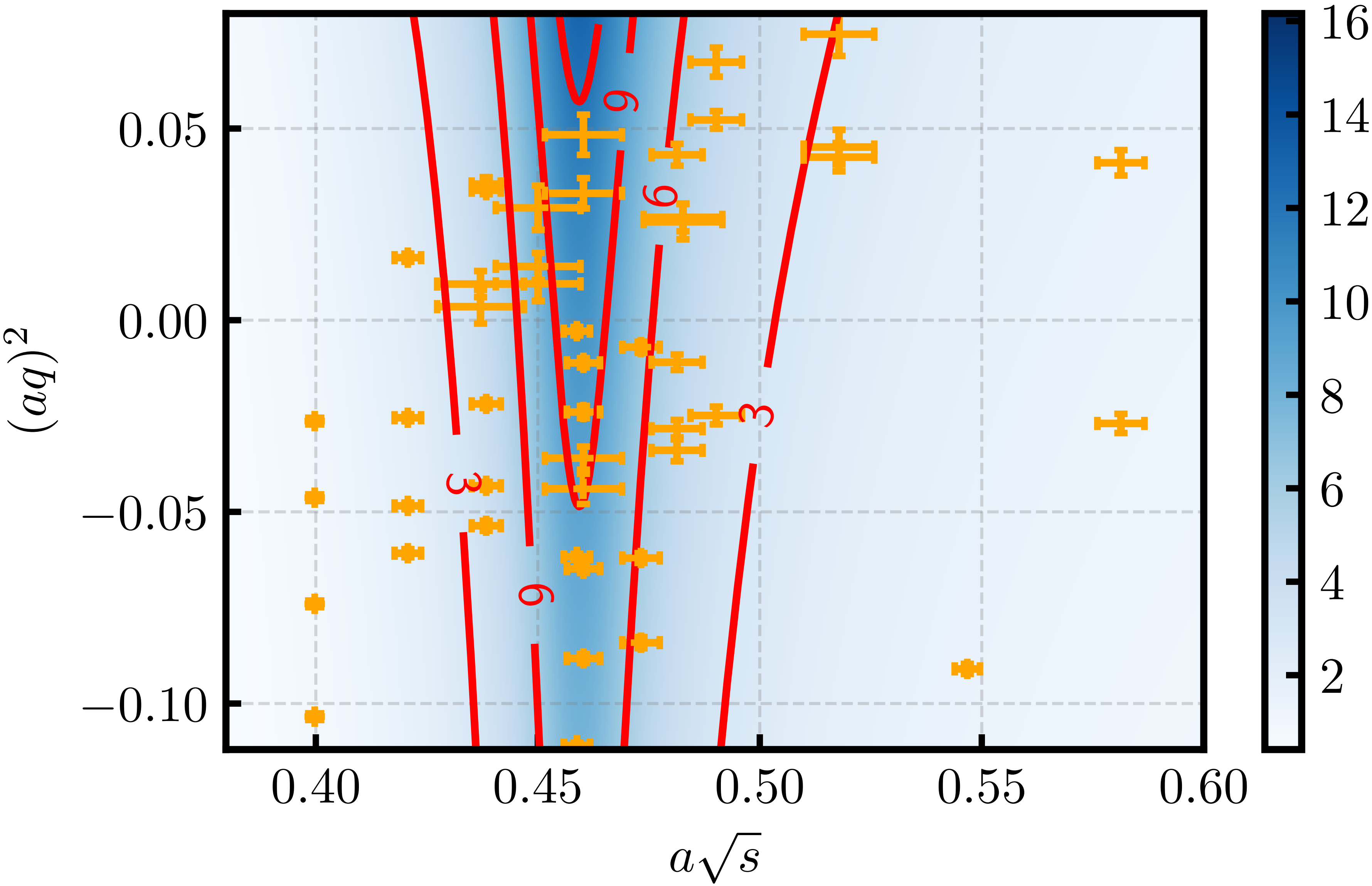
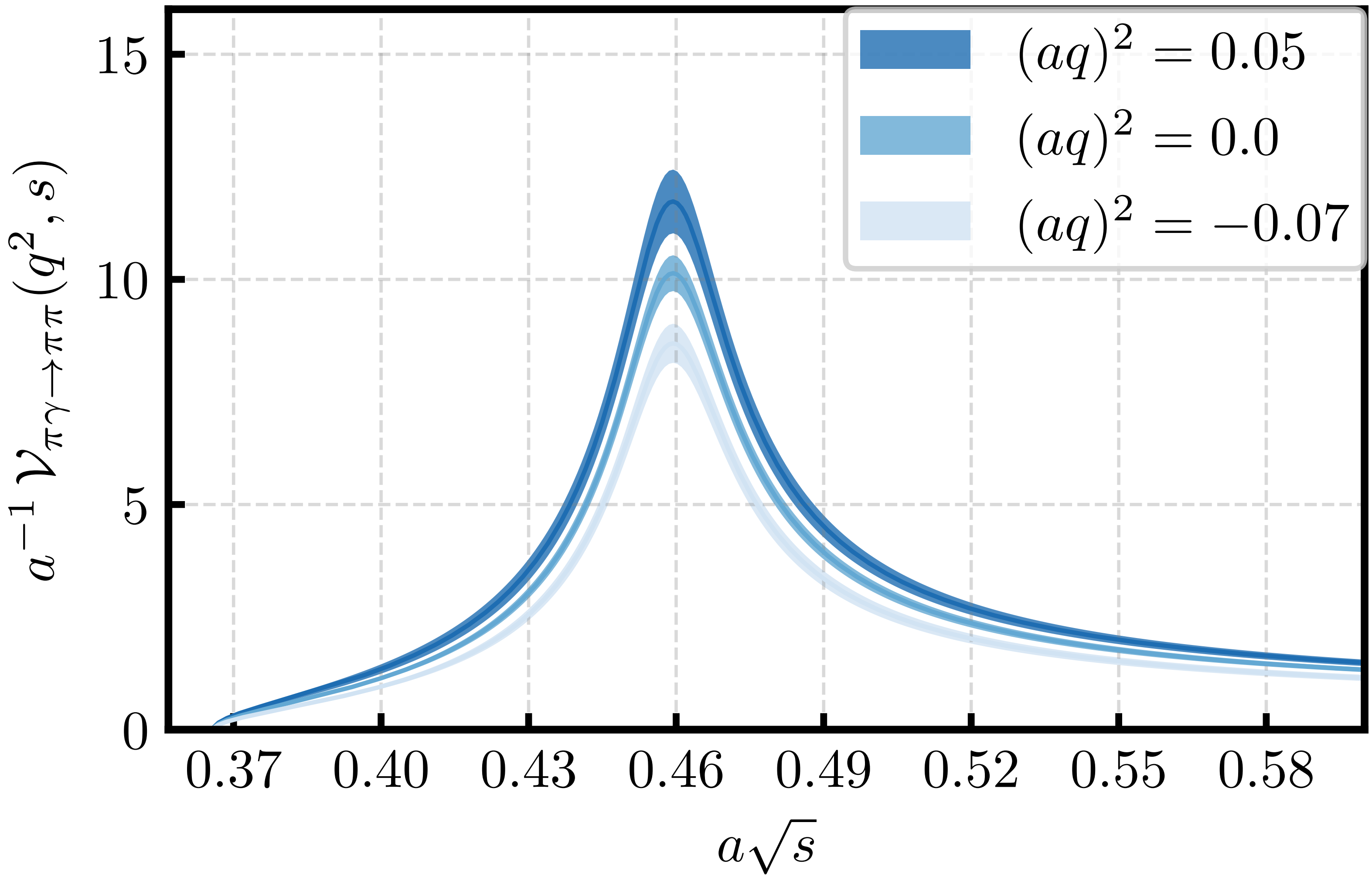
$\mathscr{V}^{IV}_{\pi\gamma\to\pi\pi}(q^2, s)$ top view



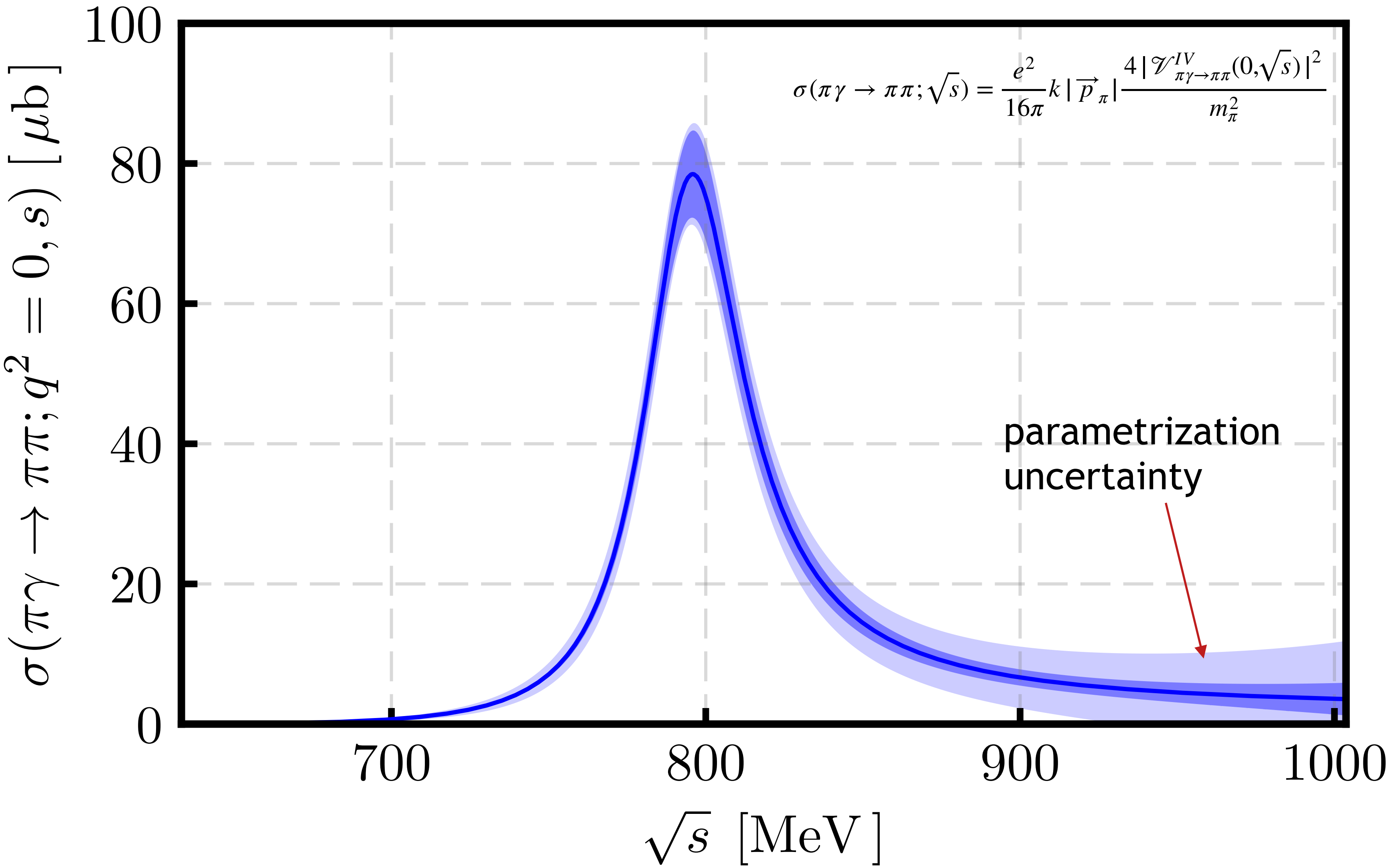
$\mathscr{V}^{IV}_{\pi\gamma\to\pi\pi}(q^2, s)$ cuts in q^2



0.15 GeV^2

-0.21 GeV^2

$\pi\gamma \to \pi\pi$ cross-section (@ $m_\pi = 320$ MeV)



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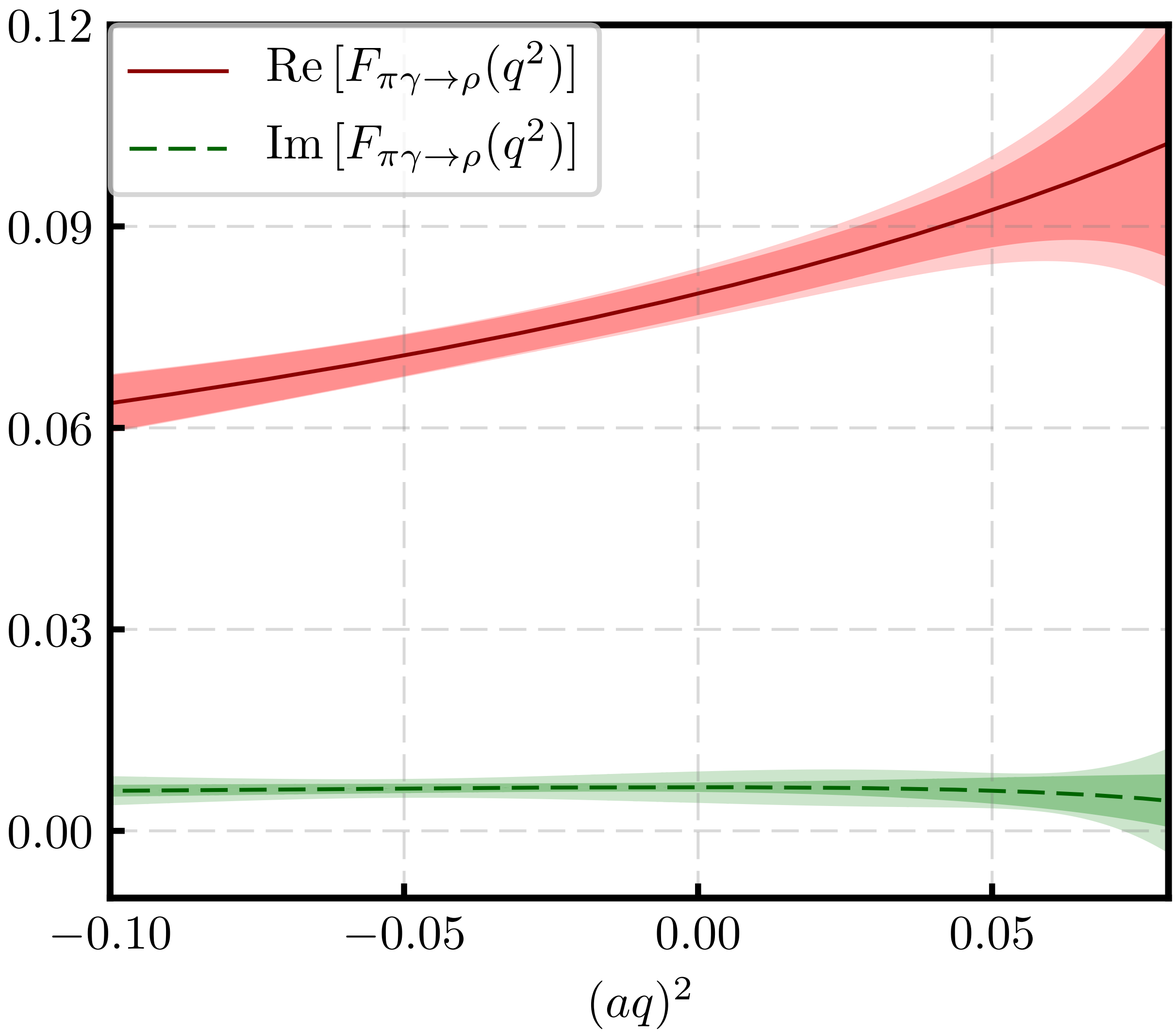
Resonant transition form factor

- analytical continuation to ρ pole $F_{\pi\gamma\to\rho}(q^2) = F(q^2, s = m_R^2 + i m_R \Gamma_R)$



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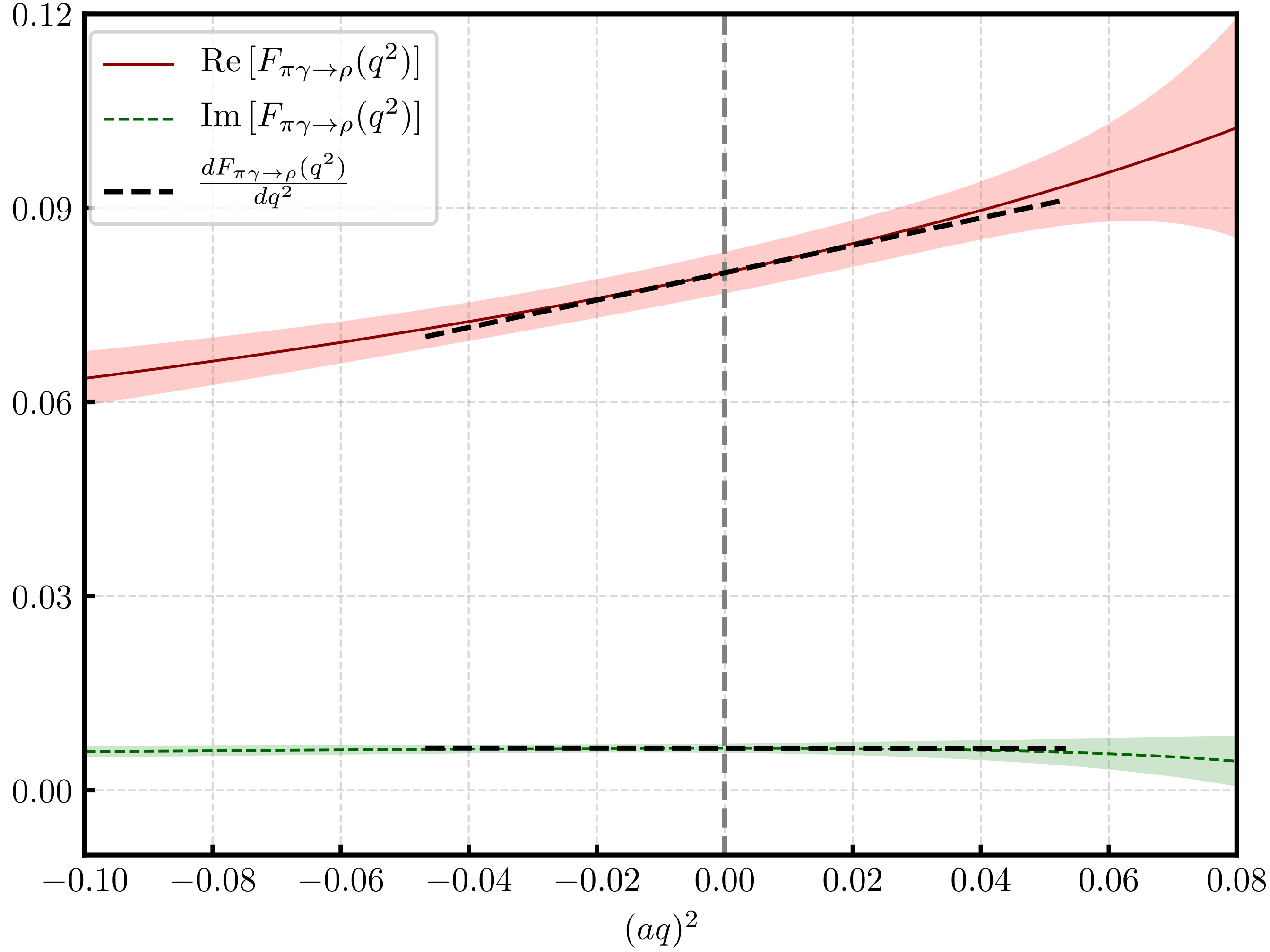
slope of $F_{\pi\gamma\to\rho}(q^2)$



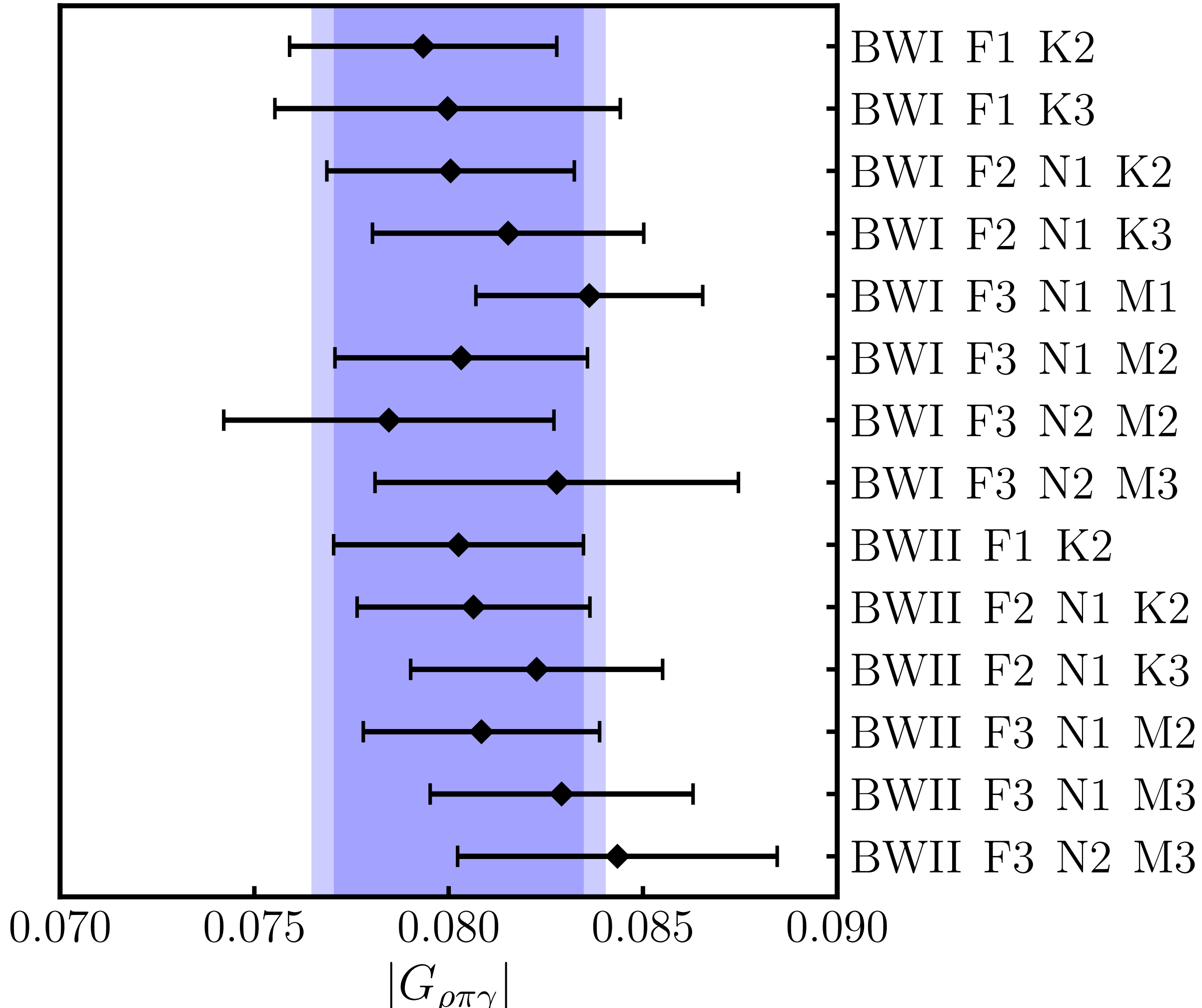
$$\left.\frac{dF_{\pi\gamma\to\rho}(q^2)}{dq^2}\right|_{q^2=0} = 0.63(22)\ \text{GeV}^{-2}$$

Photocoupling

$$G_{\rho\pi\gamma} = F_{\pi\gamma\to\rho}(0)$$

uncertainties:

- path integral ✓
- spectrum ✓
- R-mapping ✓
- spacing ⊗
- m_π ⊗
- higher L ⊗



$$|G_{\rho\pi\gamma}| = 0.0802(32)(20)$$

some properties of the ρ @ ($m_\pi = 320$ MeV)

	$g_{\rho\pi\pi}$	$G_{\rho\pi\gamma}$	m_ρ
this study	5.69(20)	0.0802(38)	797(7)
PDG	5.98	0.0736(73)	775.26

- photoproduction: these and HadSpec results only [HadSpec 2015, 2016]
- comparison: apples to oranges
- lattice results still need extrapolation $m_\pi \to m_\pi^{phys}$
- missing: continuum limit
- qualitatively good

Future outlook

- coupled channel resonances? (technical challenge)

$$|\langle 1|J|2\rangle|^2 = \left[V_{\pi\gamma\to\pi\pi}, V_{\pi\gamma\to K\bar{K}}\right] \begin{bmatrix} R_{\pi\pi,\pi\pi} & R_{\pi\pi,K\bar{K}} \\ R_{K\bar{K},\pi\pi} & R_{K\bar{K},K\bar{K}} \end{bmatrix} \begin{bmatrix} V_{\pi\gamma\to\pi\pi} \\ V_{\pi\gamma\to K\bar{K}} \end{bmatrix}$$

- probe contents of resonances?

- other channels and resonances

Summary

- strong $\pi\pi$ scattering
- ρ photoproduction on π
- interesting future ahead