Resonances in QCD and their Couplings from Anisotropic Clover Lattices

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hadspec

Spectroscopy in QCD

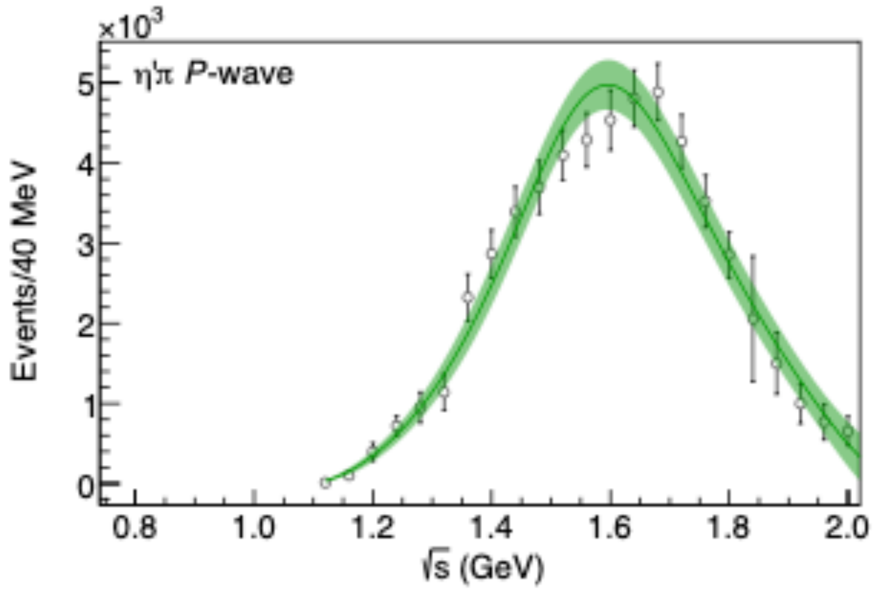
How do quark and gluons combine inside unstable hadrons?

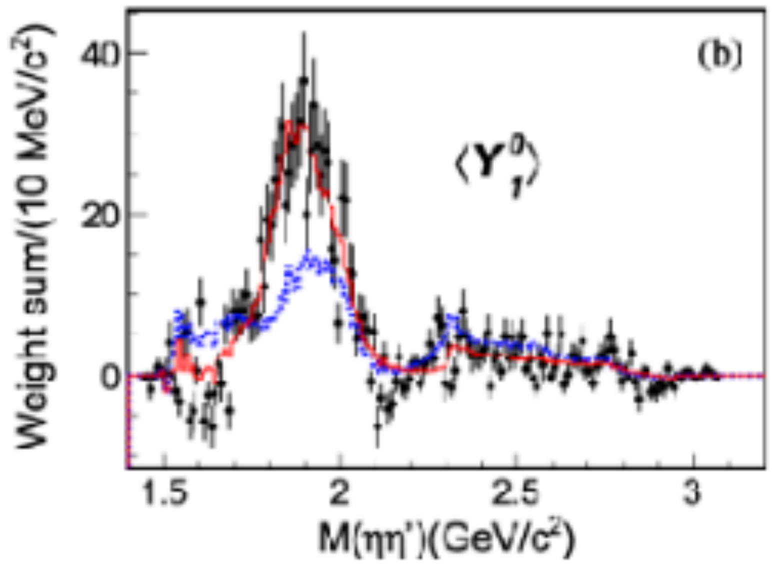
We need a combination of lattice QCD and experiment to answer that question

“hadron spectroscopy explores the possible bound combinations of quarks and gluons allowed by the interactions of QCD”

Guide experimental searches (π_1)

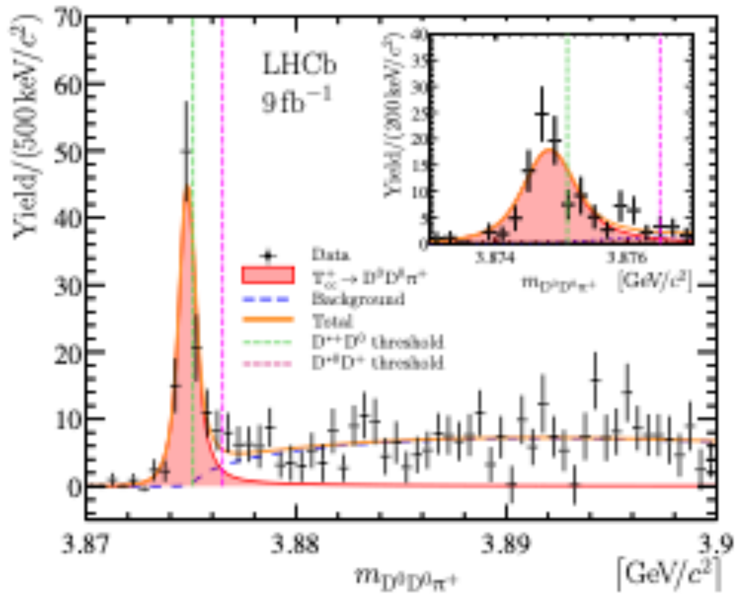
Hybrids

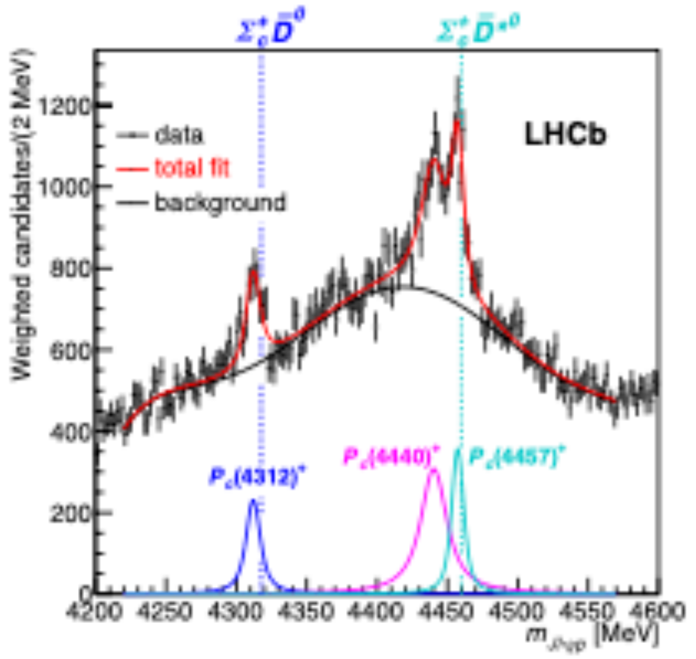




Confirm existence (tetraquarks, pentaquarks, glueballs)

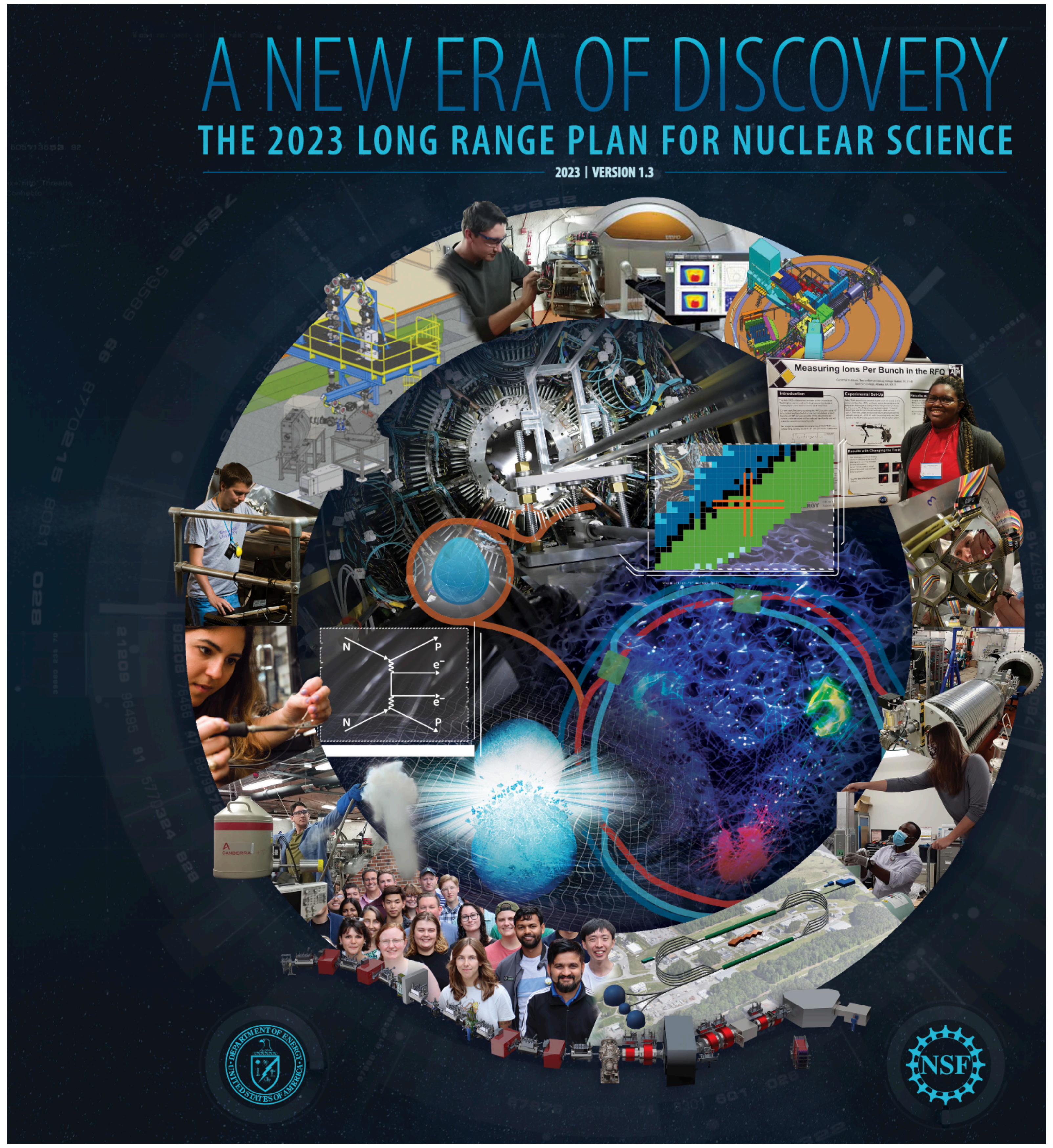
Tetraquarks





Pentaquarks

Understand their nature (*observations are not enough*!)



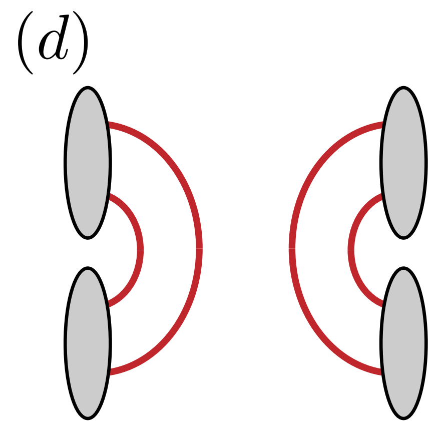
Hadspec: The basics

- Optimal lattice setup for spectroscopy
  - *Improved, stout-smeared lattices*
  - *High anisotropy $\xi \sim 3.5$*

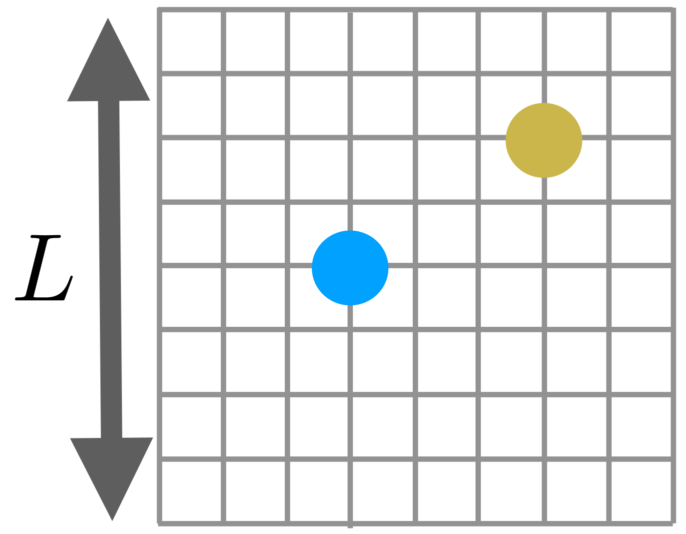
Time evolution

$$\sum_{\mathrm{n}} e^{-E_{\mathrm{n}} t} \langle 0 | O_{\mathrm{f}}(0) | \mathrm{n} \rangle \langle \mathrm{n} | O_{\mathrm{i}}^{\dagger}(0) | 0 \rangle$$

- Efficient energy level extraction
  - *Full distillation (very large N_v available)*
  - *Annihilation lines averaged over many time slices (full time extent)*
  - *Large number of interpolators* $\mathcal{O}_b \sim \bar{q}\,\Gamma_b\, q, \pi\pi, KK, \ldots, 4\pi, \ldots$
  - *Full GEVP solution (many excited states)*



- Finite volume formalism



K-matrix

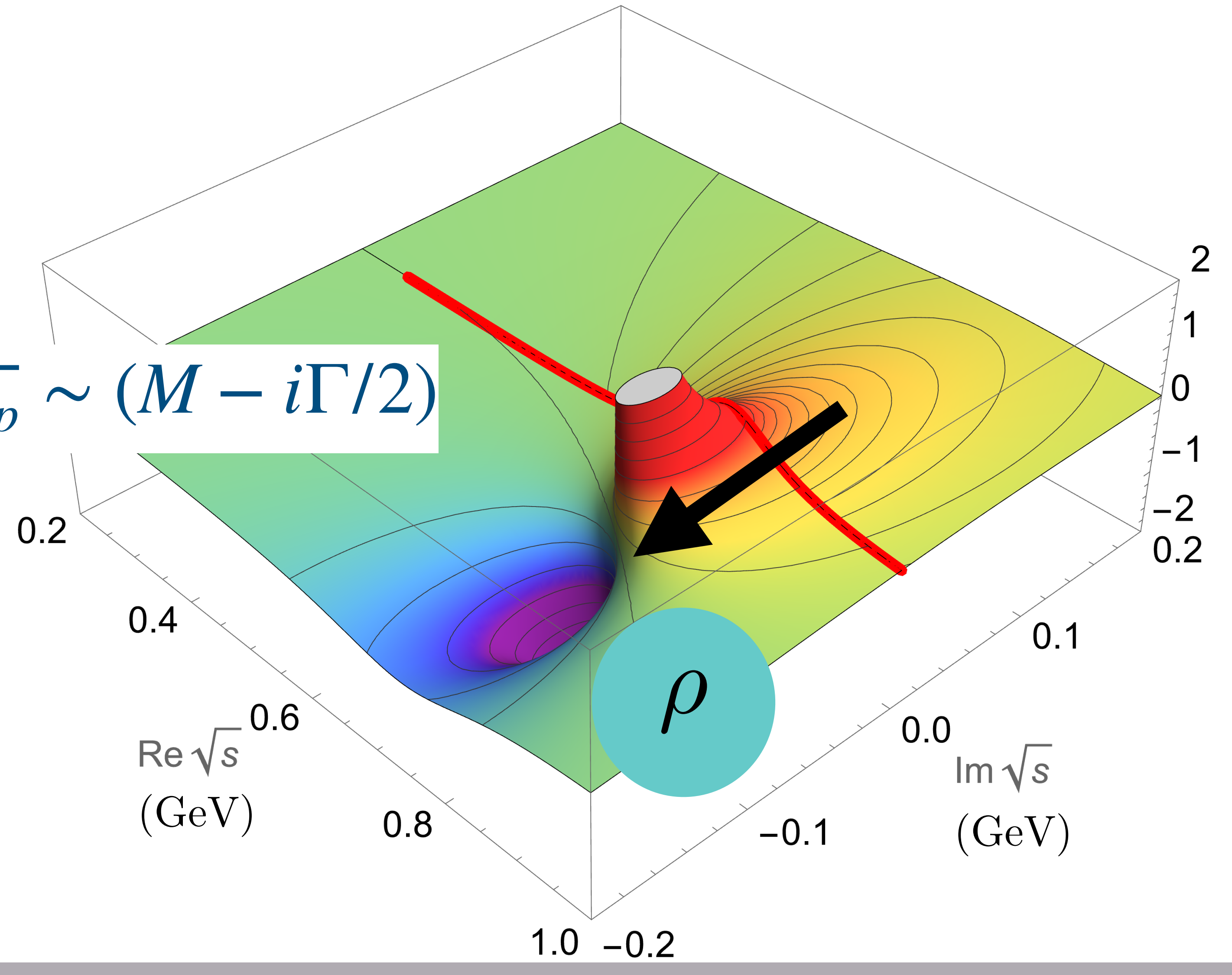
$$\det\left[F^{-1}(P,L) + K\right] = 0$$

Fit-parameters

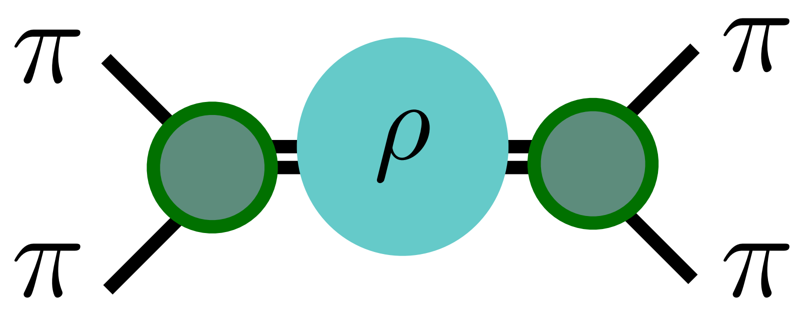
- Infinite volume formalism

$$t(s) = \frac{K}{1 - i\rho(s)K}$$

Pole at $\sqrt{s_p} \sim (M - i\Gamma/2)$



Proposal Goals



1 **Determine the spectrum of ordinary and non-ordinary hadrons**

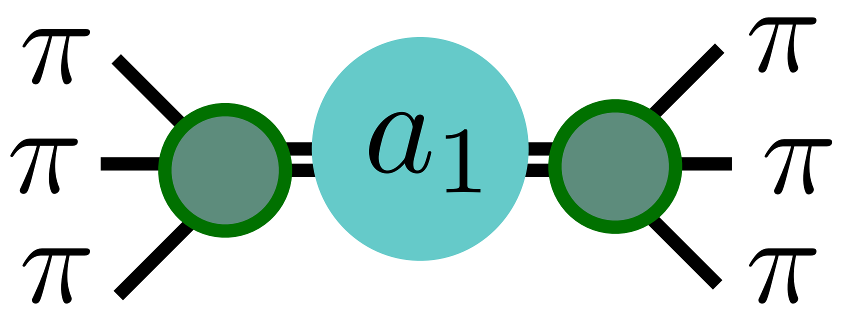
Compute basic parameters of resonances in multiple systems (degenerate, light, charm, different m_π)

Both RTX2080, MI-100 and new "24s" time requested

2 **Develop and implement multi-body decay formalisms to the extraction of resonances**

Capitalizing on recent developments to study 3π systems for I=2 and I=0

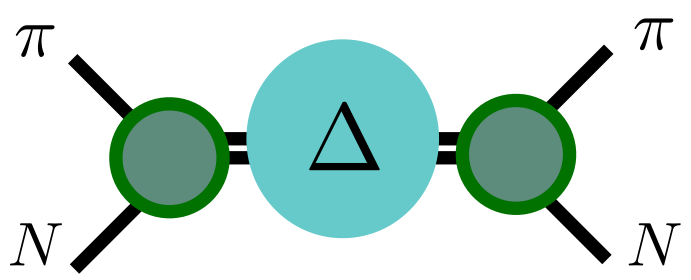
"24s" time requested



3 **Kick start our meson-baryon program**

Long time invested in developing our "machinery" for baryon analyses

We start with realistic projects $N\pi \to \Delta_{1/2^-}$ $N\pi \to \Delta_{3/2^+}$

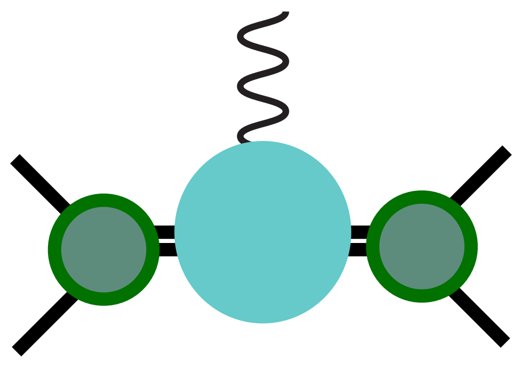


MI-100 time requested

4 **Continue our EM analyses**

More photoproduction analyses in the future

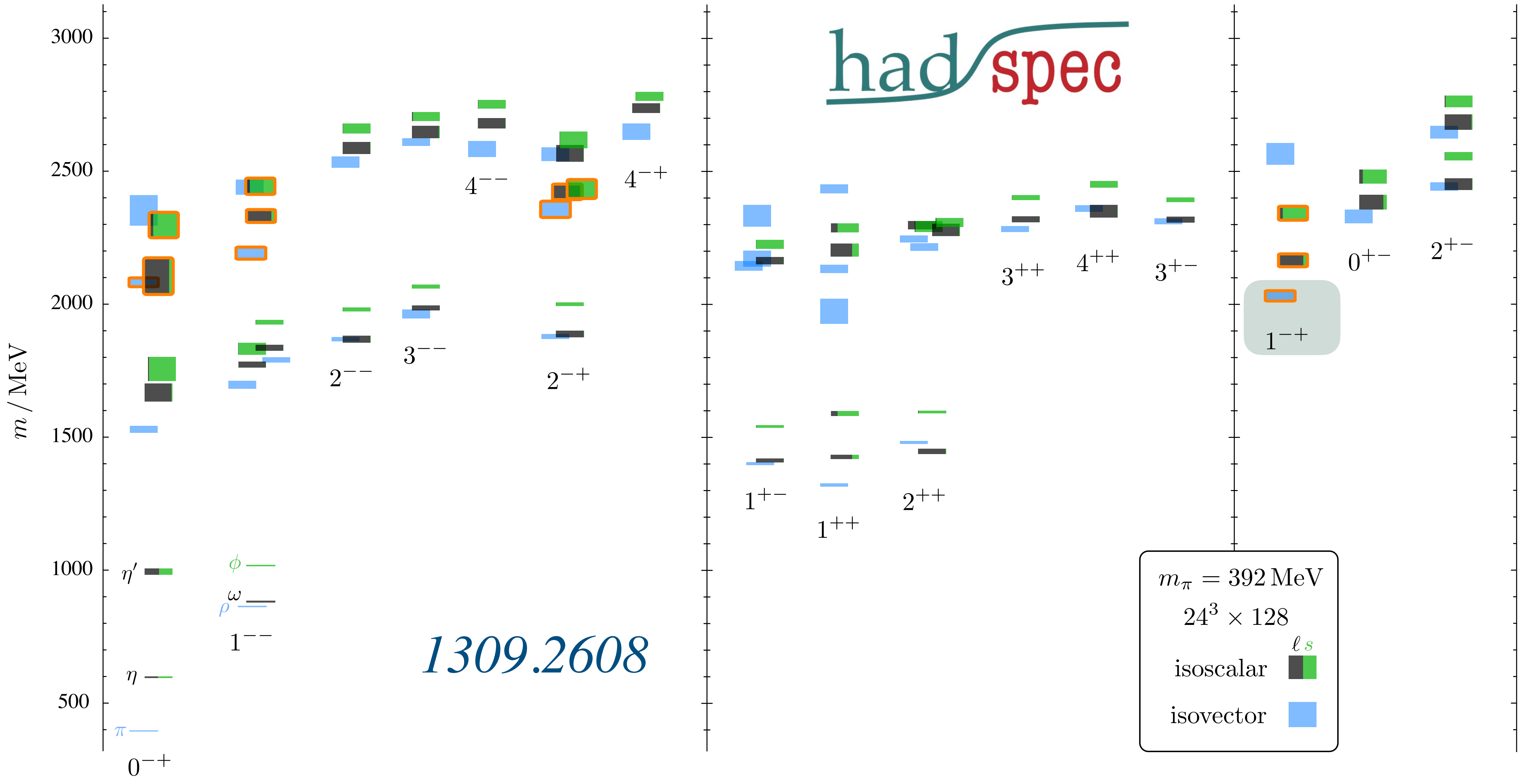
Keep pushing for the first "form factor" numerical evaluations

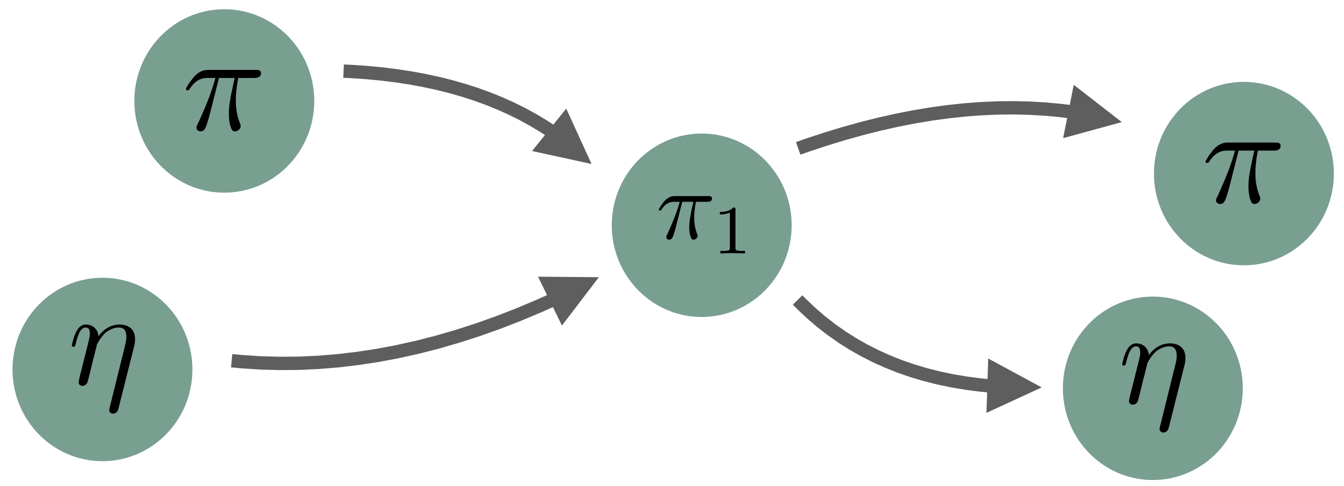


"24s" time requested

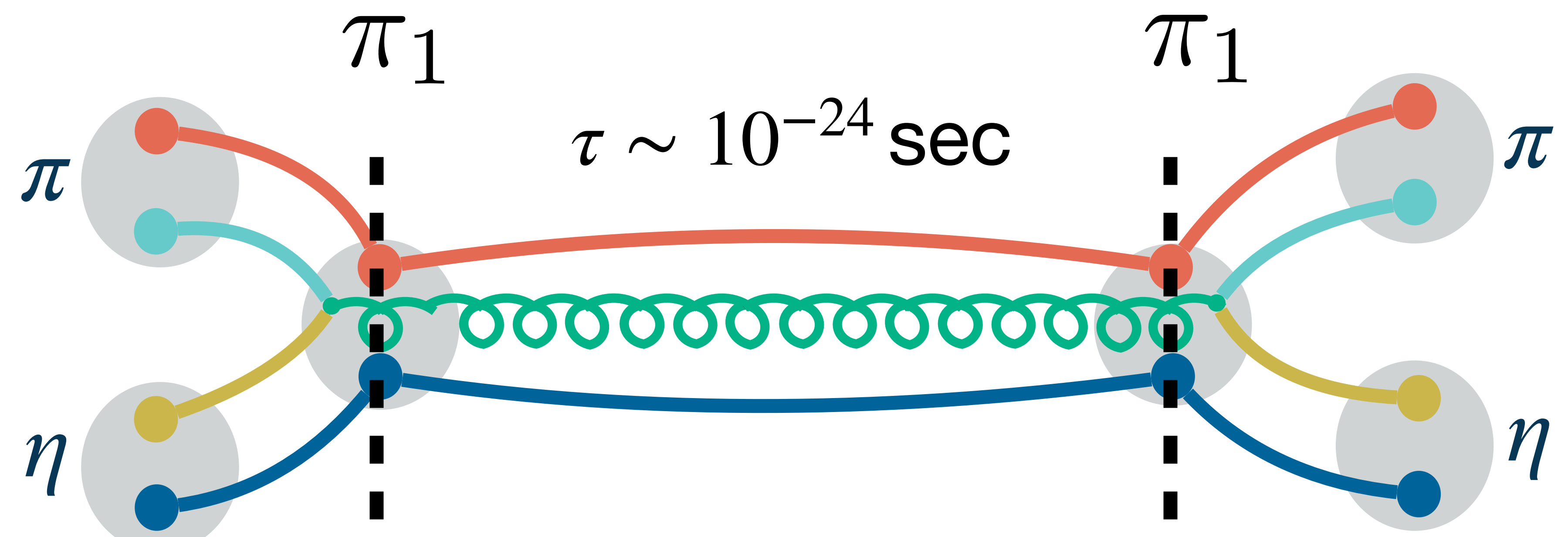
Example: Hybrid exotic candidates

Lattice QCD (and models) predicts a lightest $J^{PC} = 1^{-+}$, isolated hybrid

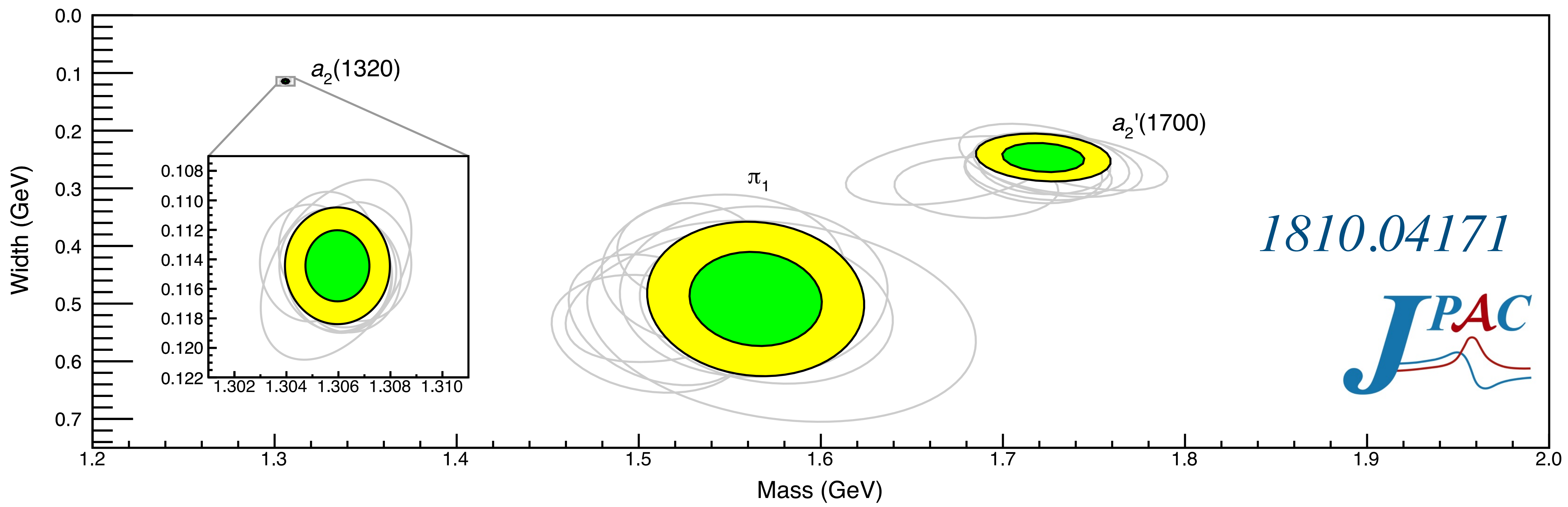


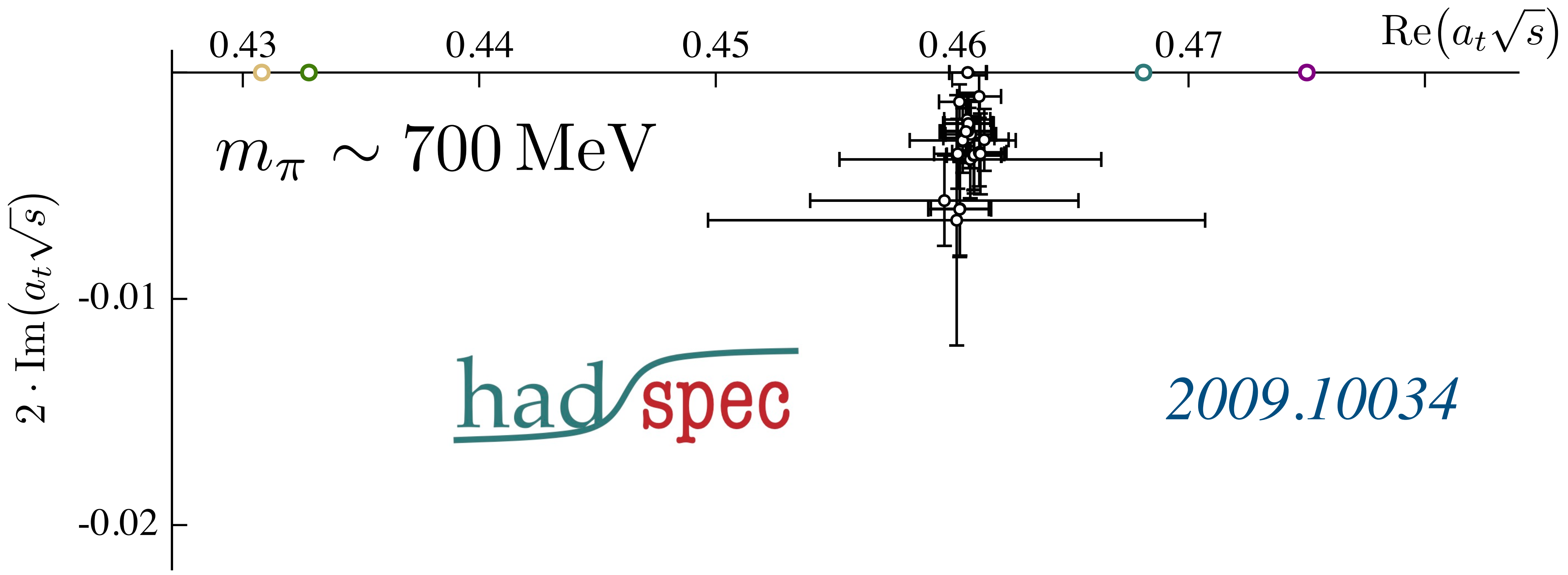


It decays to two pseudo-scalar mesons



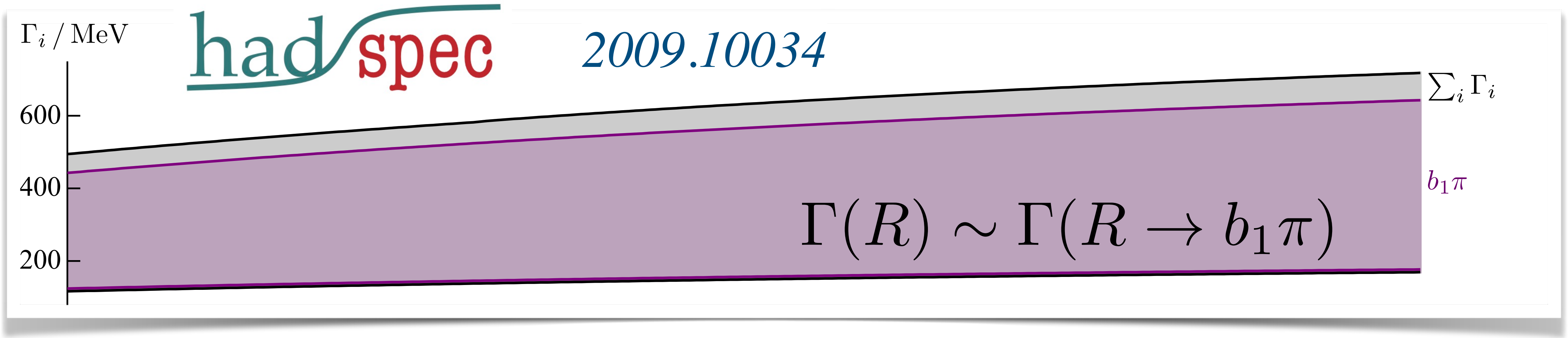
Extracted, recently, both from experiment (JPAC/COMPASS) and Lattice QCD (HadSpec)





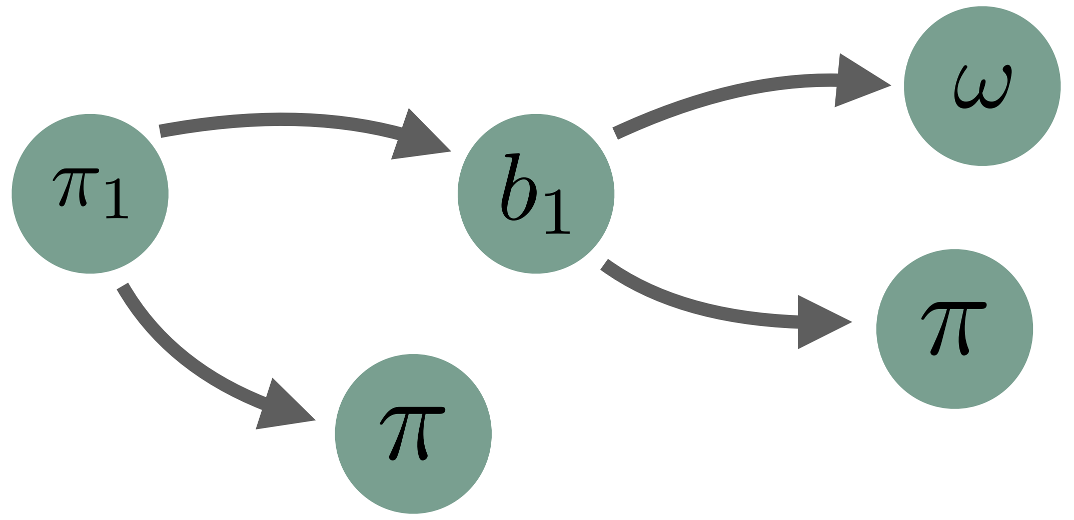
Example: Hybrid exotic candidates

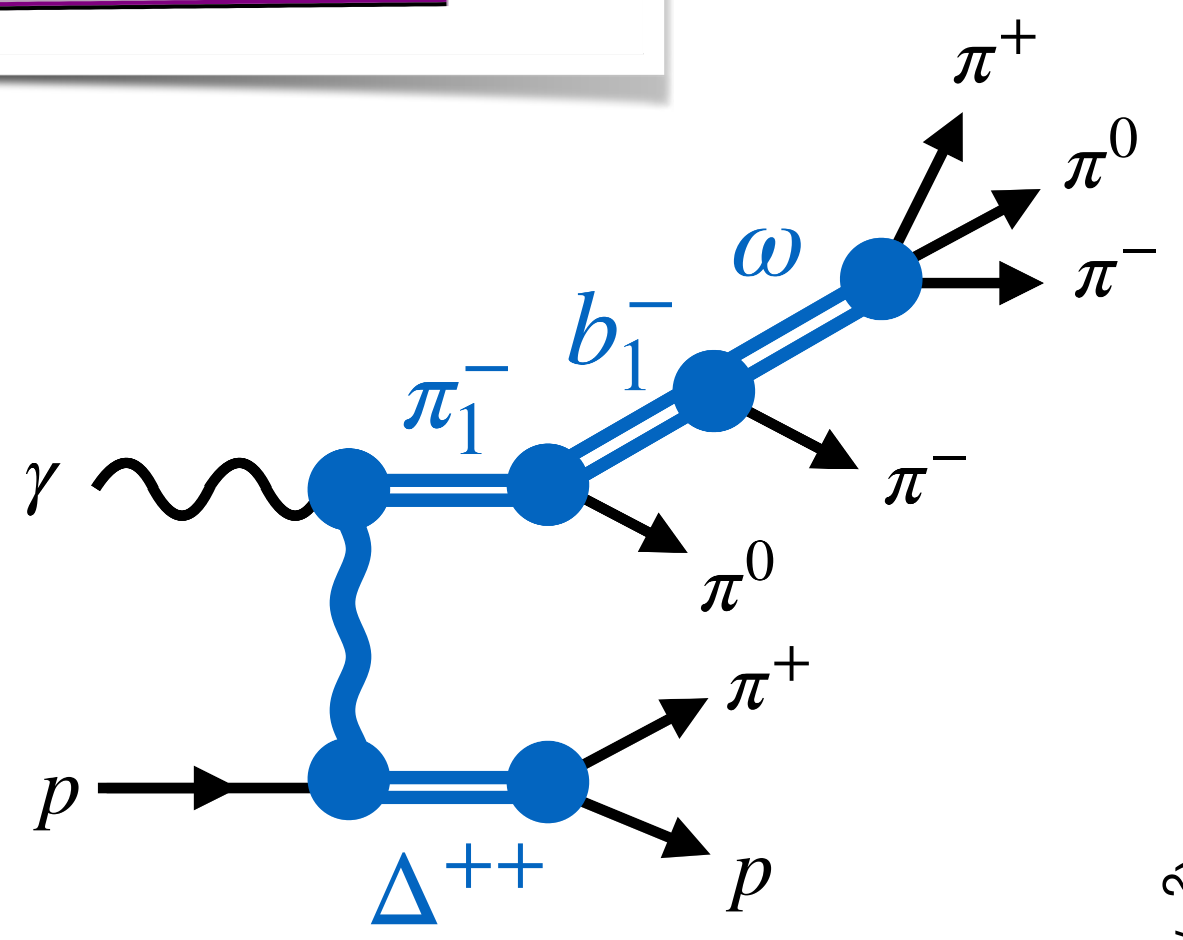
Out of 8 possible decay modes, Lattice QCD predicts a dominant one



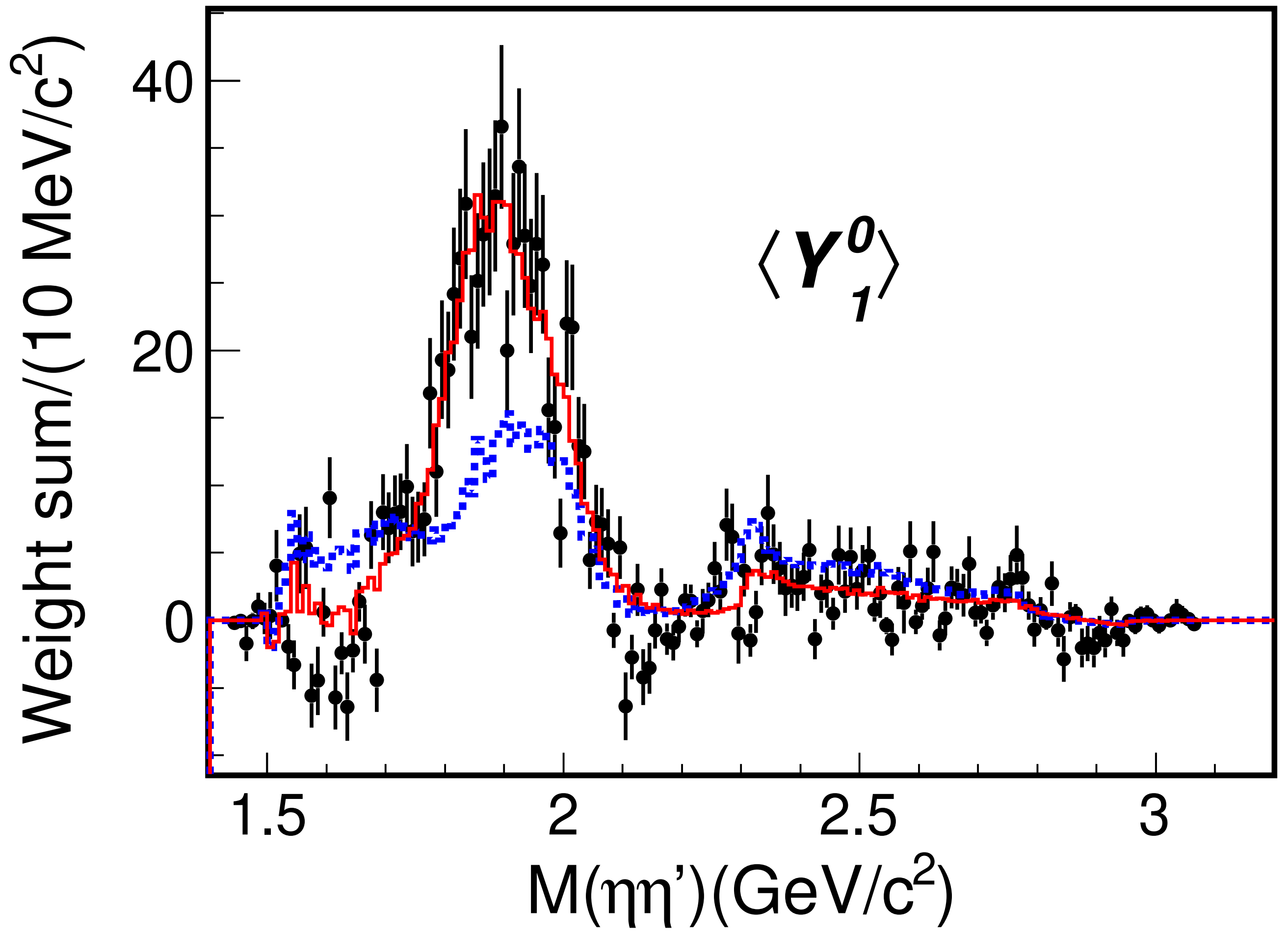
	thr./MeV	$\lvert c_i^{\rm phys}\rvert$/MeV	Γ_i/MeV
$\eta\pi$	688	$0 \to 43$	$0 \to 1$
$\rho\pi$	910	$0 \to 203$	$0 \to 20$
$\eta'\pi$	1098	$0 \to 173$	$0 \to 12$
$b_1\pi$	1375	$799 \to 1559$	$139 \to 529$
K^*K	1386	$0 \to 87$	$0 \to 2$
$f_1(1285)\pi$	1425	$0 \to 363$	$0 \to 24$
$\rho\omega\{^1P_1\}$	1552	$\lesssim 19$	$\lesssim 0.03$
$\rho\omega\{^3P_1\}$	1552	$\lesssim 32$	$\lesssim 0.09$
$\rho\omega\{^5P_1\}$	1552	$\lesssim 19$	$\lesssim 0.03$
$f_1(1420)\pi$	1560	$0 \to 245$	$0 \to 2$
			$\Gamma = \sum_i \Gamma_i = 139 \to 590$

We "know" final decay (final states)





Octet partner found by BESIII (there should be two!!!)



Not-so-expected discovery

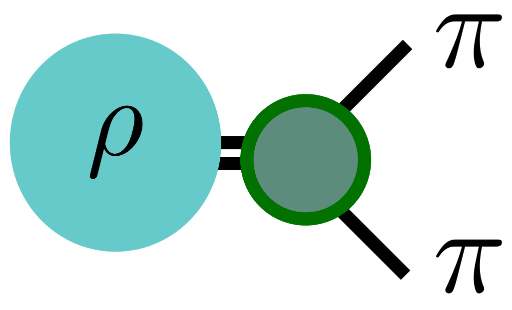
1 *Opportunity to capitalize on previously used lattices for extraction!*

$m_\pi \sim 700\,\mathrm{MeV}$

Three body decays

Stable for $m_\pi \sim 700$ MeV

Decays for $m_\pi \lesssim 500$ MeV



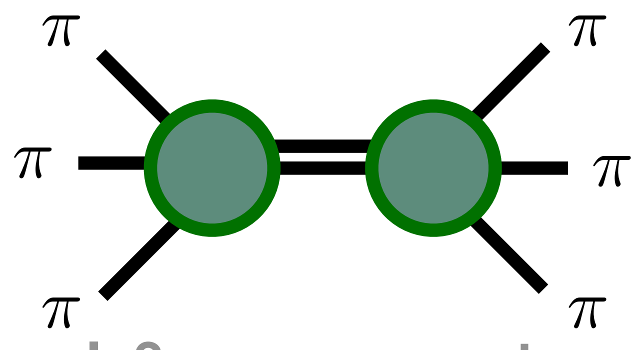
When decreasing $m_\pi \rightarrow$ multi-body thresholds open

Plethora of formalism works on how to extract 3b amplitudes from the spectrum (not discussed here)

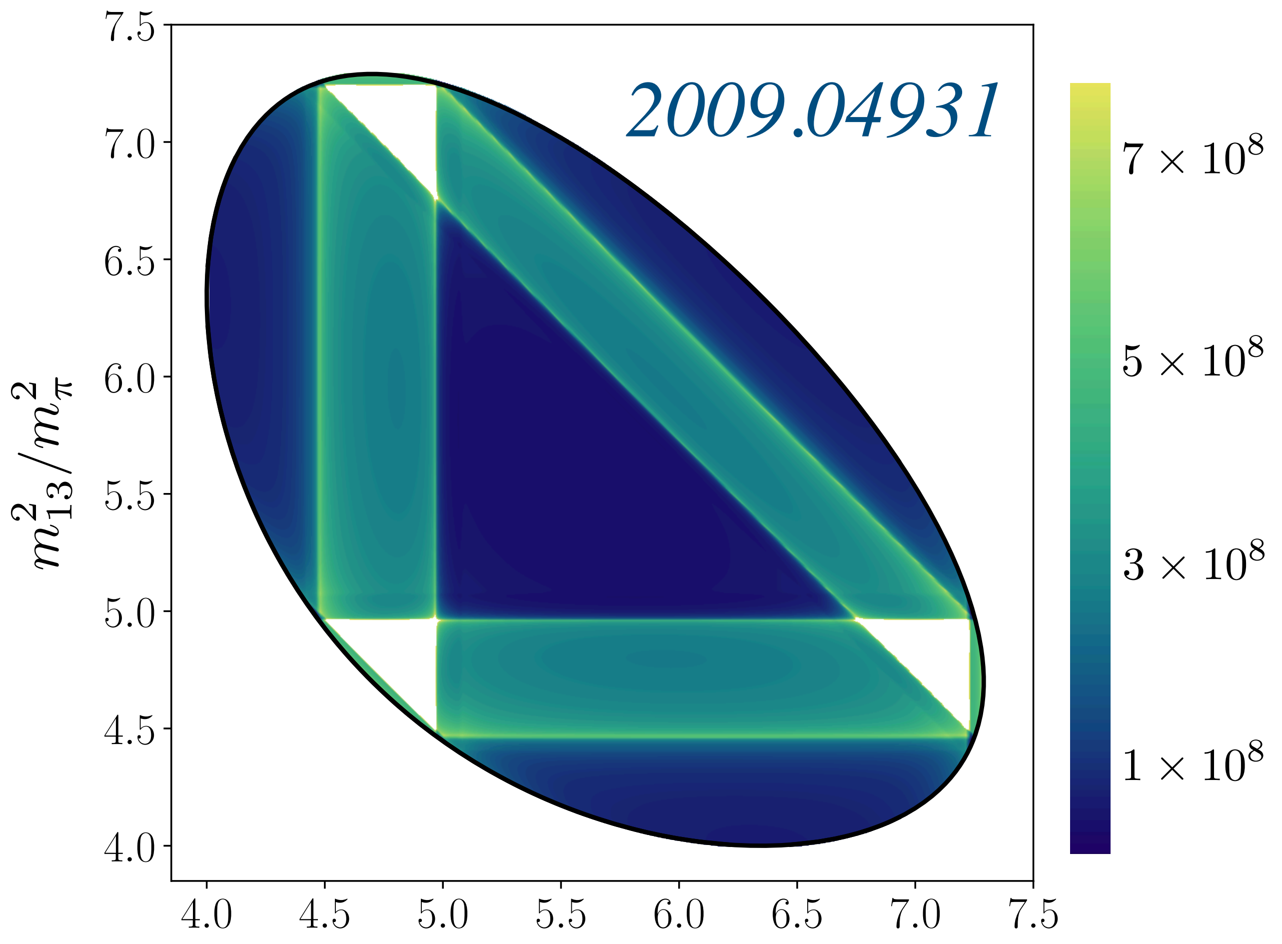
$$\rho(s) \rightarrow \int d\sigma_1 \int d\sigma_3\, F(s, \sigma_1, \sigma_3)$$

$2 \rightarrow 2$ amplitudes inside

Much more cumbersome



I=3, non-resonant



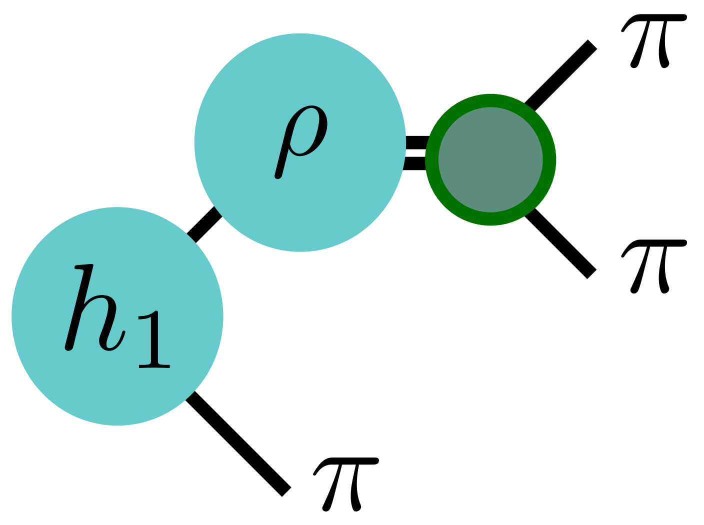
HadSpec has also been leading numerical calculations

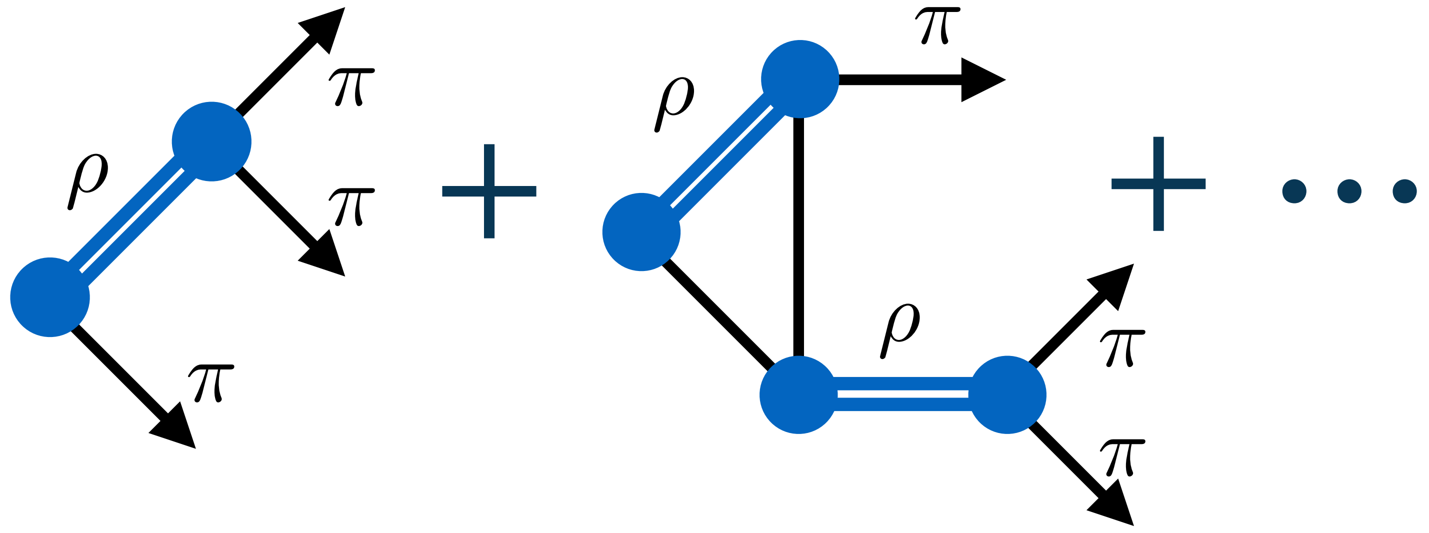
Full 3b amplitude

Published on PRL (editor's choice)

2 Proposal capitalizes on these achievements

Expensive, looking at I=2 final states

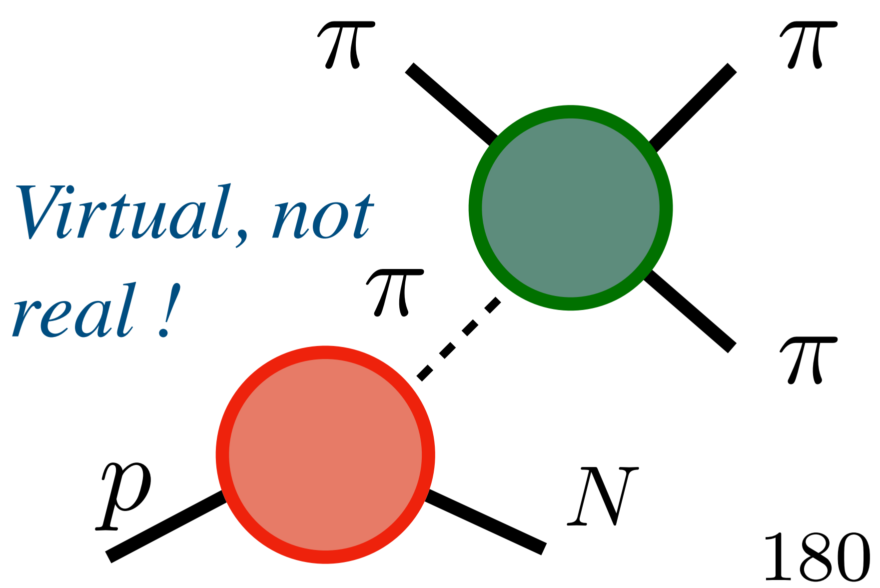




Cheaper, looking at I=0 final states (same $\rho\pi$ intermediate state, but less contractions graphs)

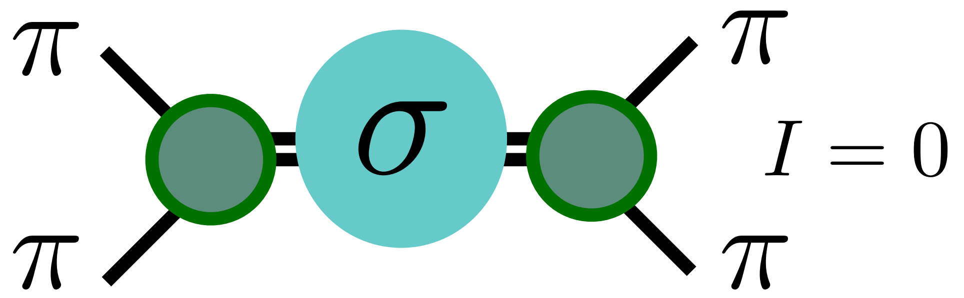
Lowering m_π

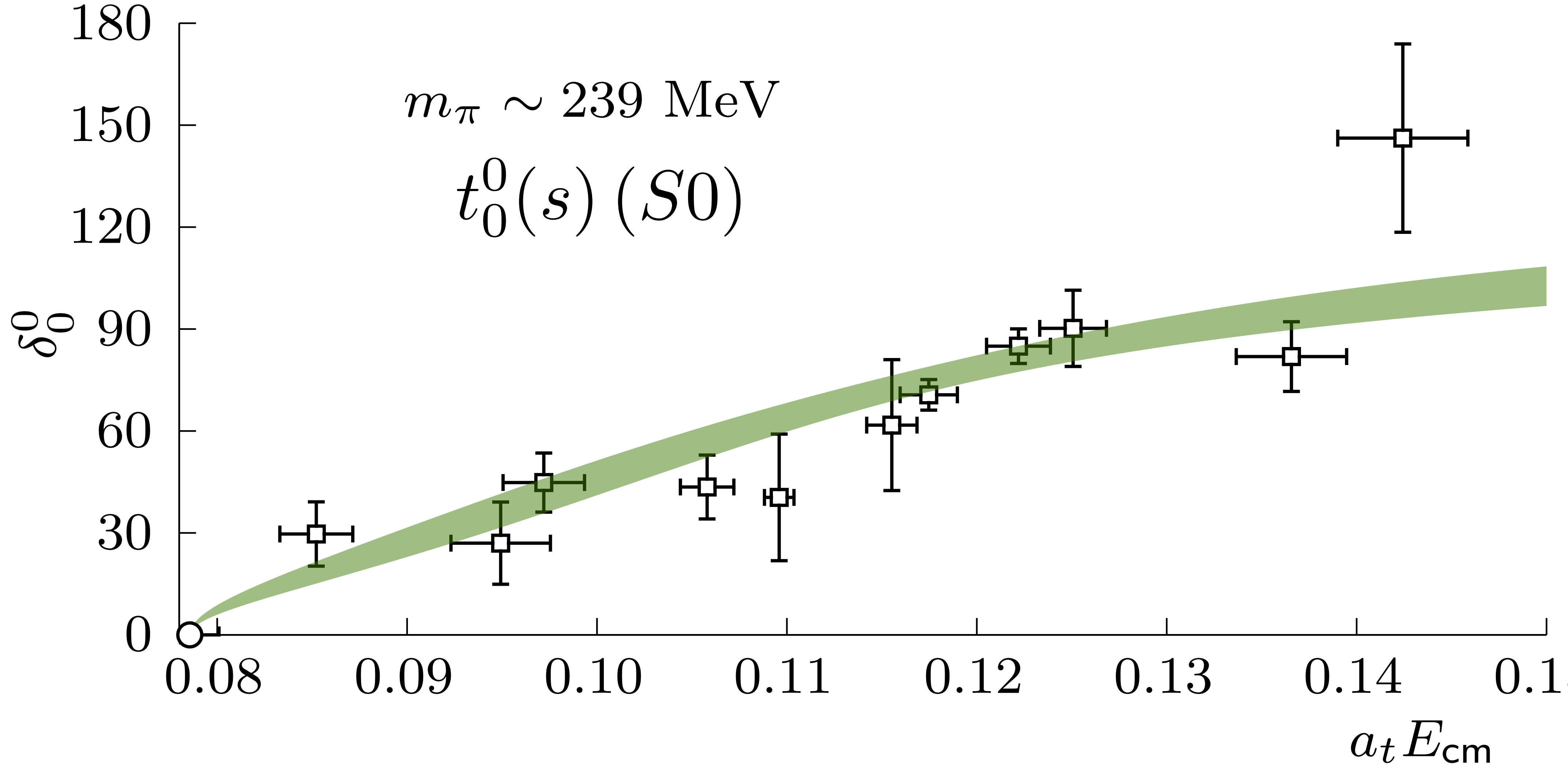
Light meson-scattering experiments are "modeled"



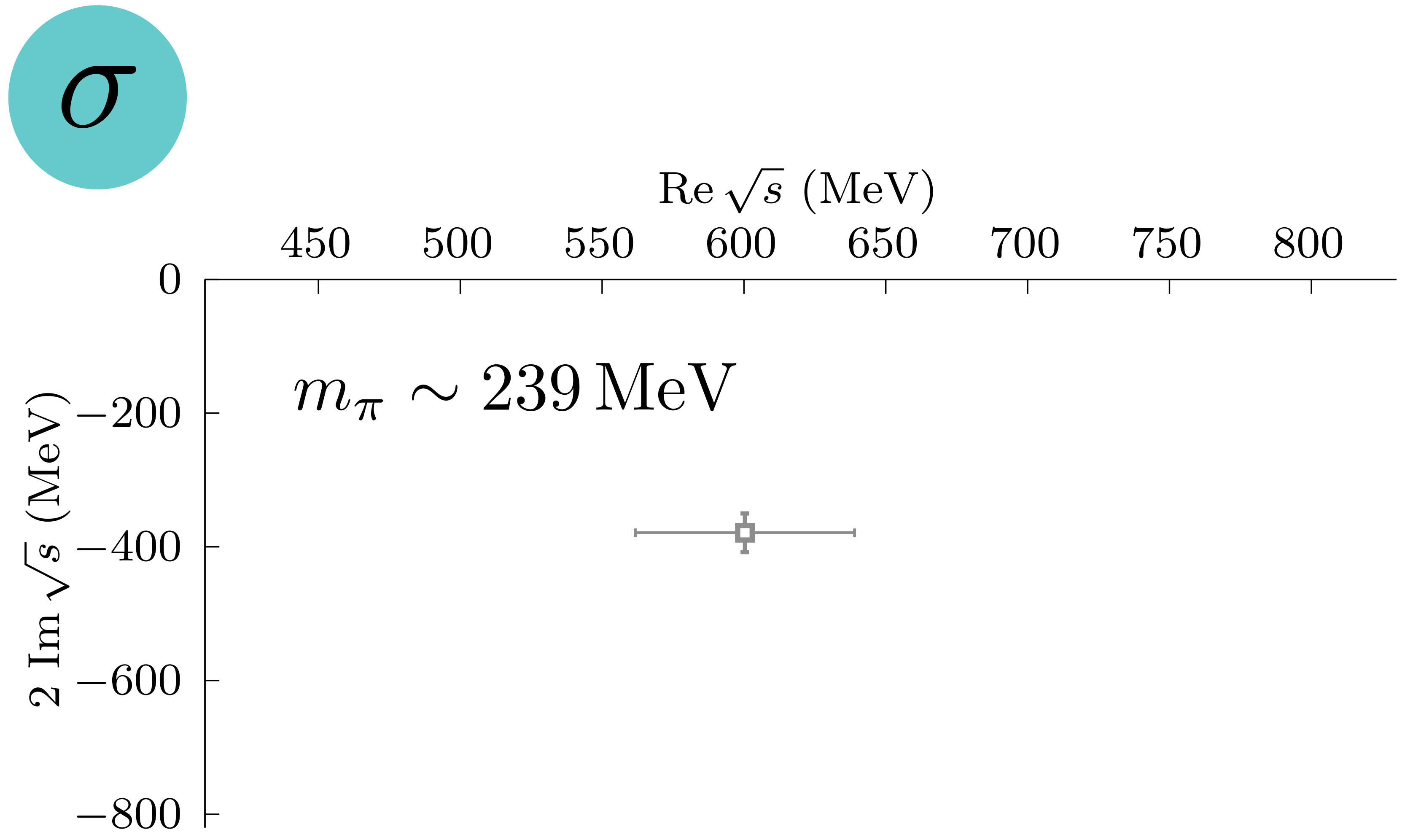
Example, LASS (SLAC) experiments in the 70s and 80s

If we reduce m_π even further, for some cases, infinite volume formalism takes over systematic uncertainties





First, one has to perform "many" fits to data to see the amplitude spread



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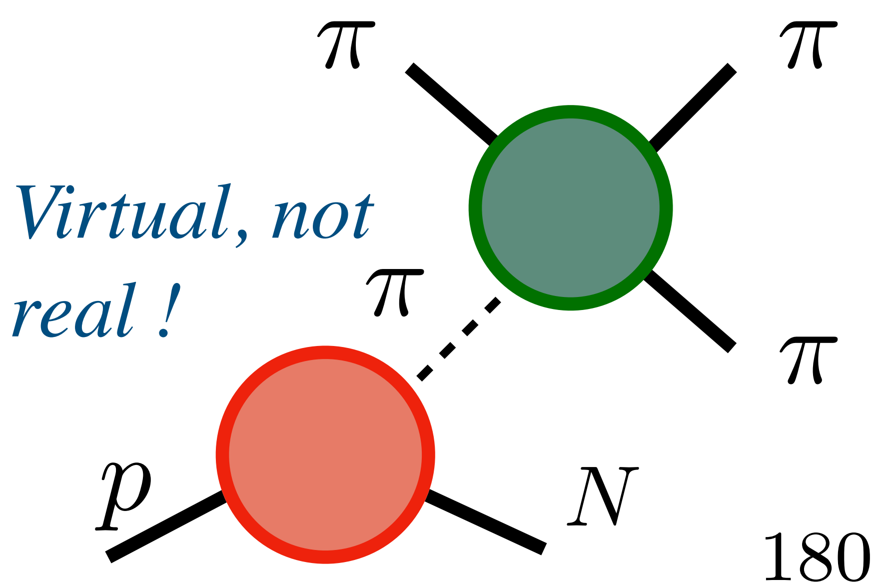

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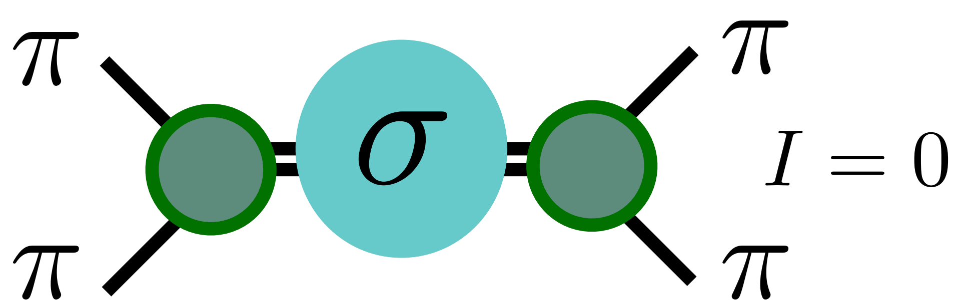

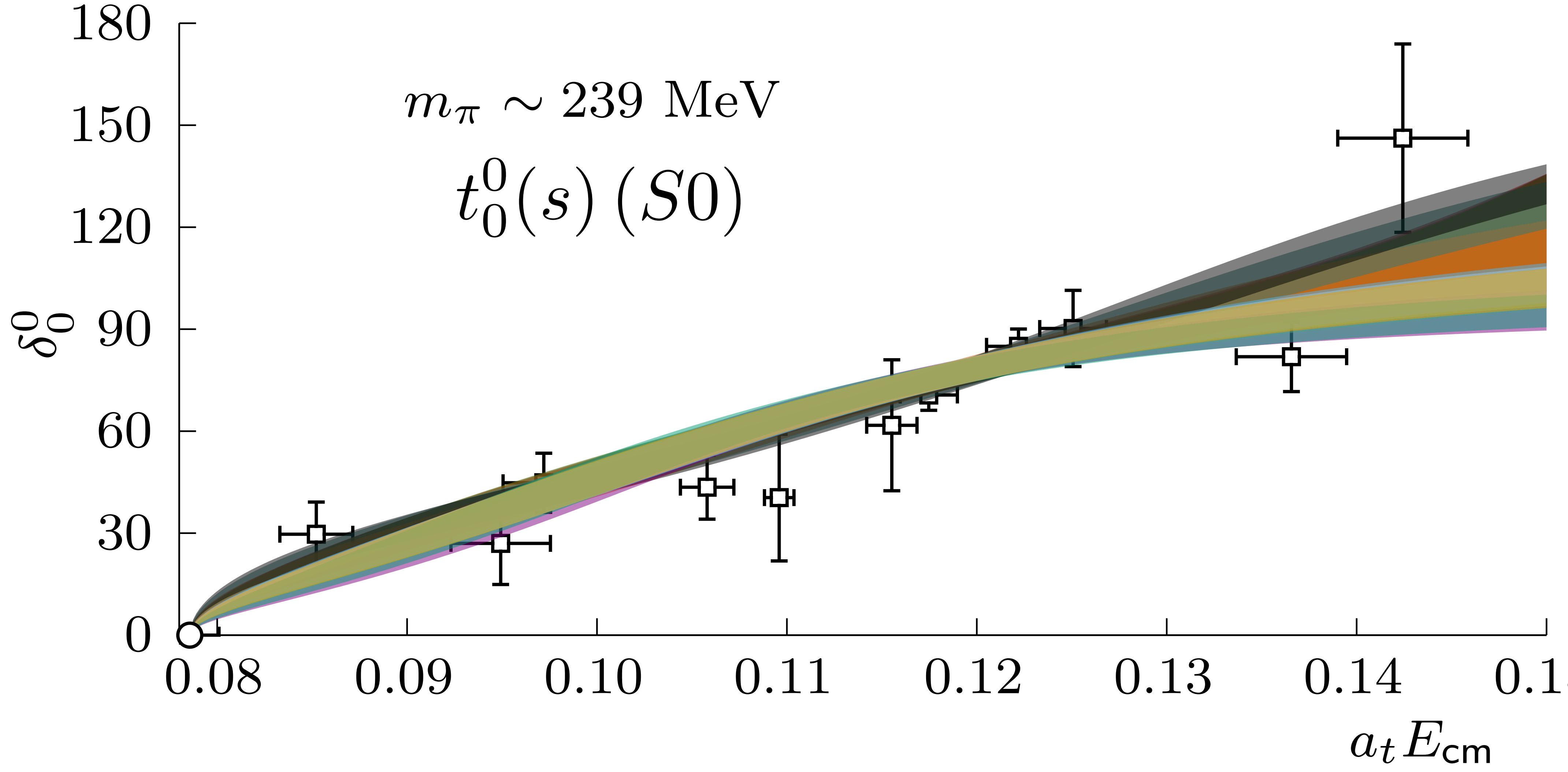

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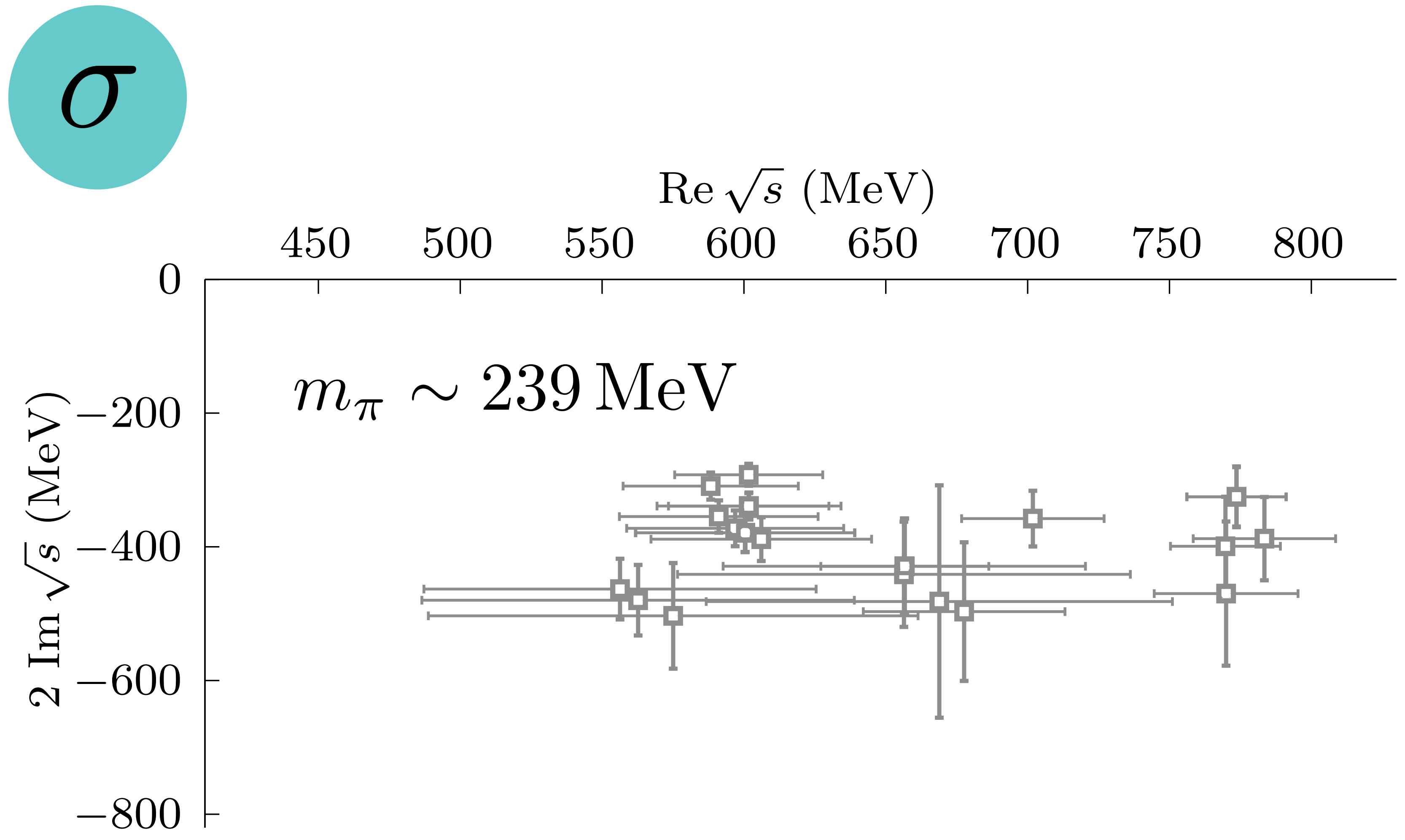
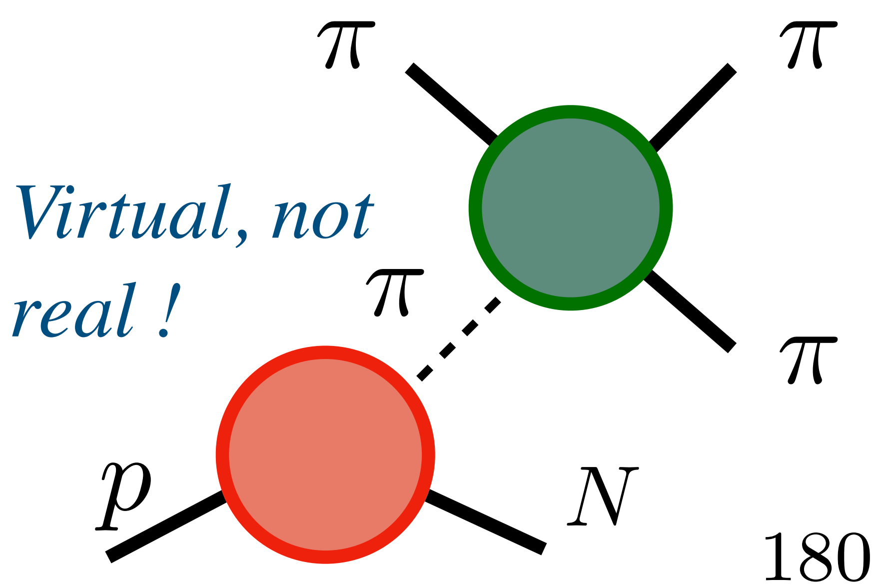
At this point, amplitude systematic spreads can be as large as over $10\times$ the statistical uncertainties



Lowering m_π



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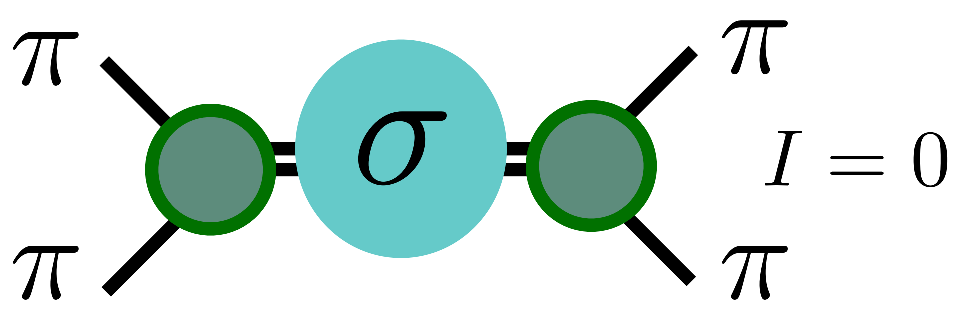

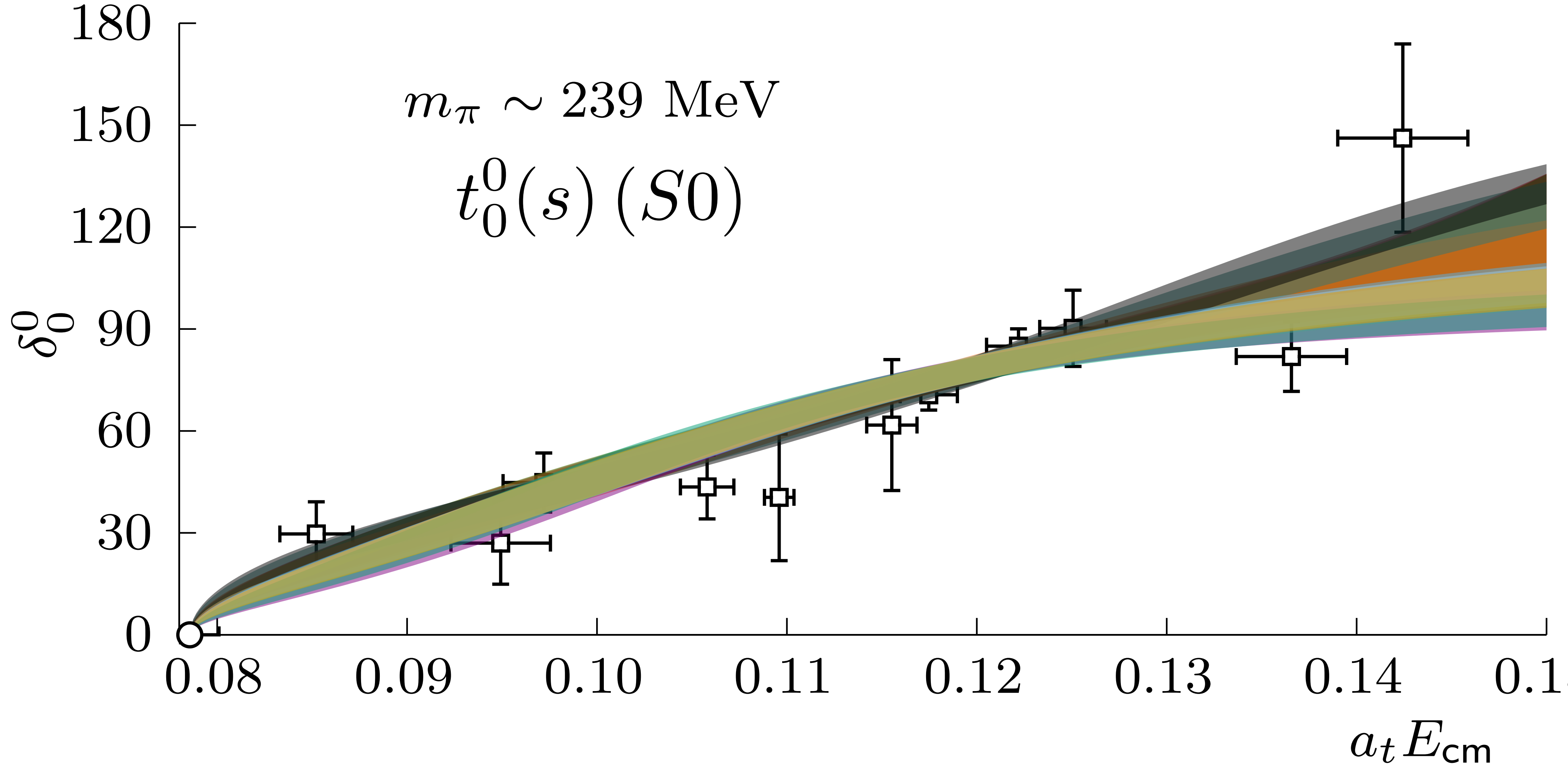

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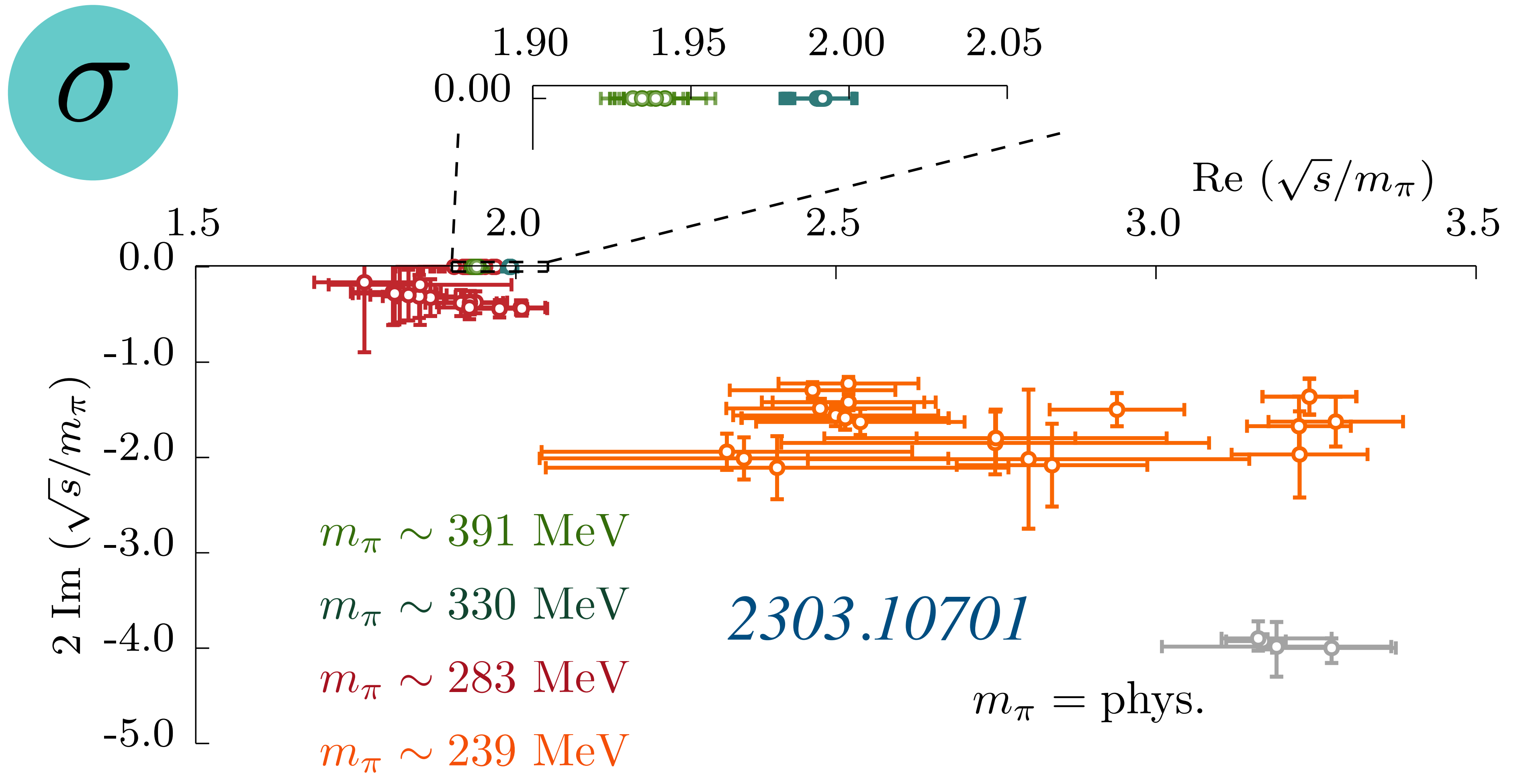
We need a better infinite volume formalism than “naive” amplitude fitting



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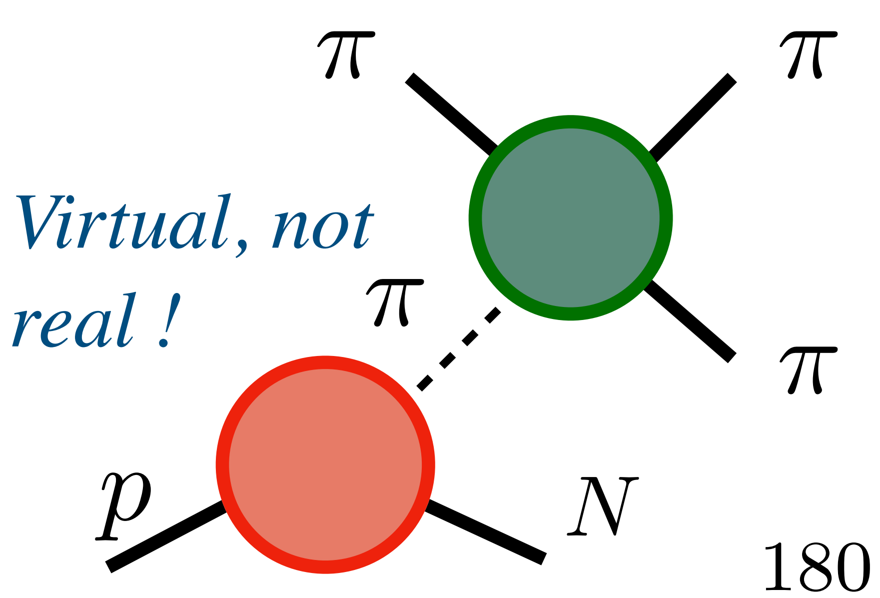

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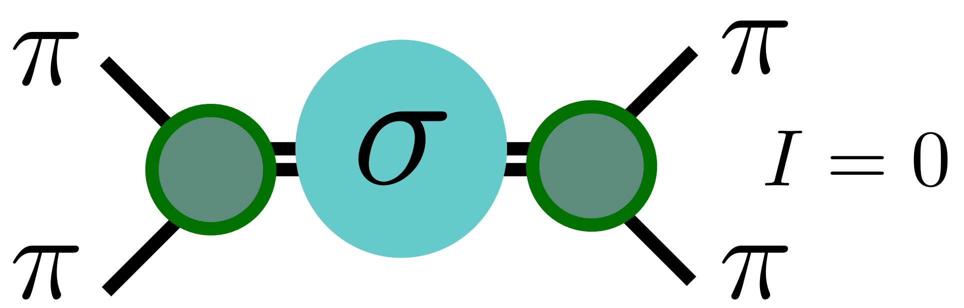

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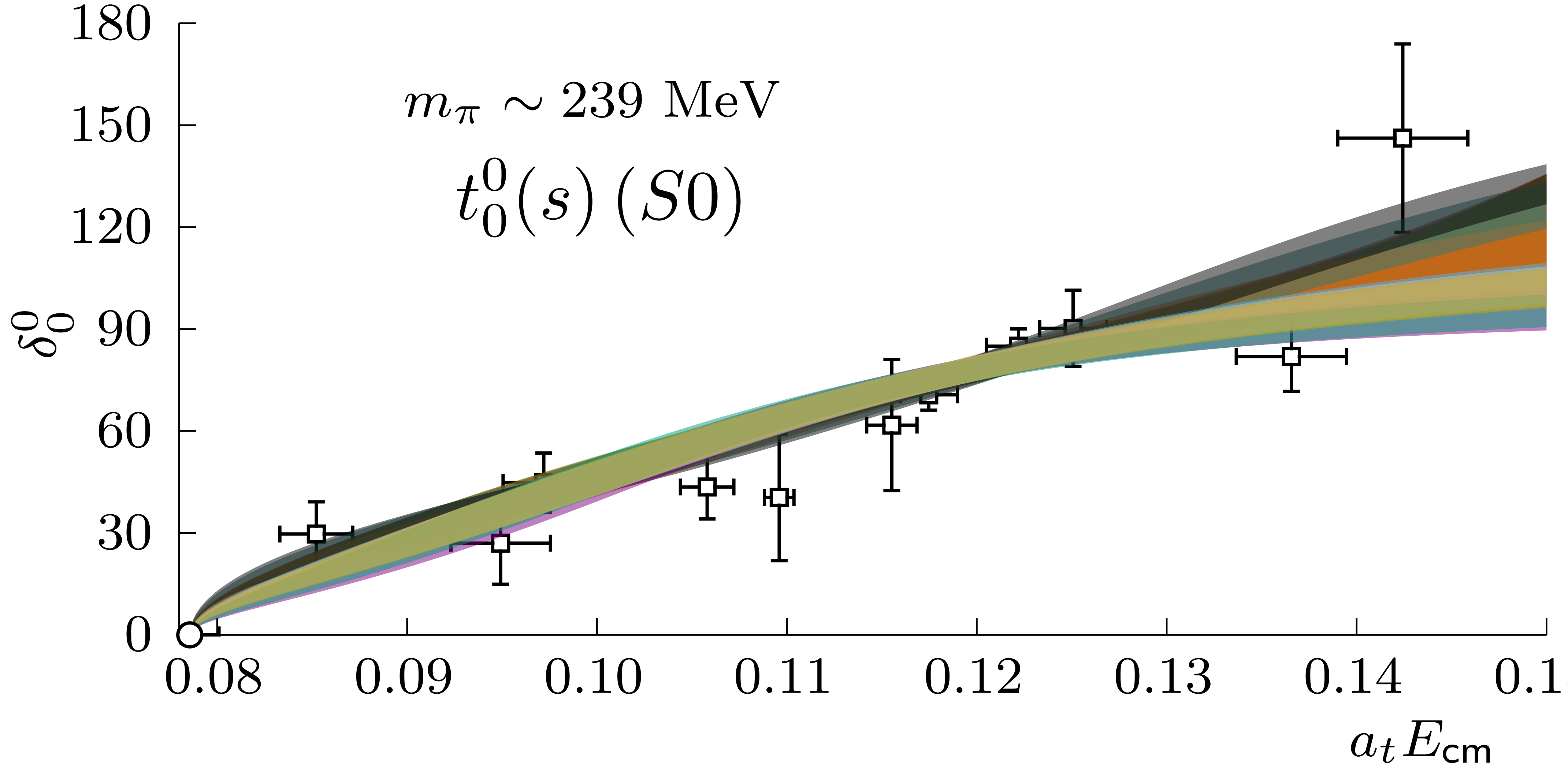
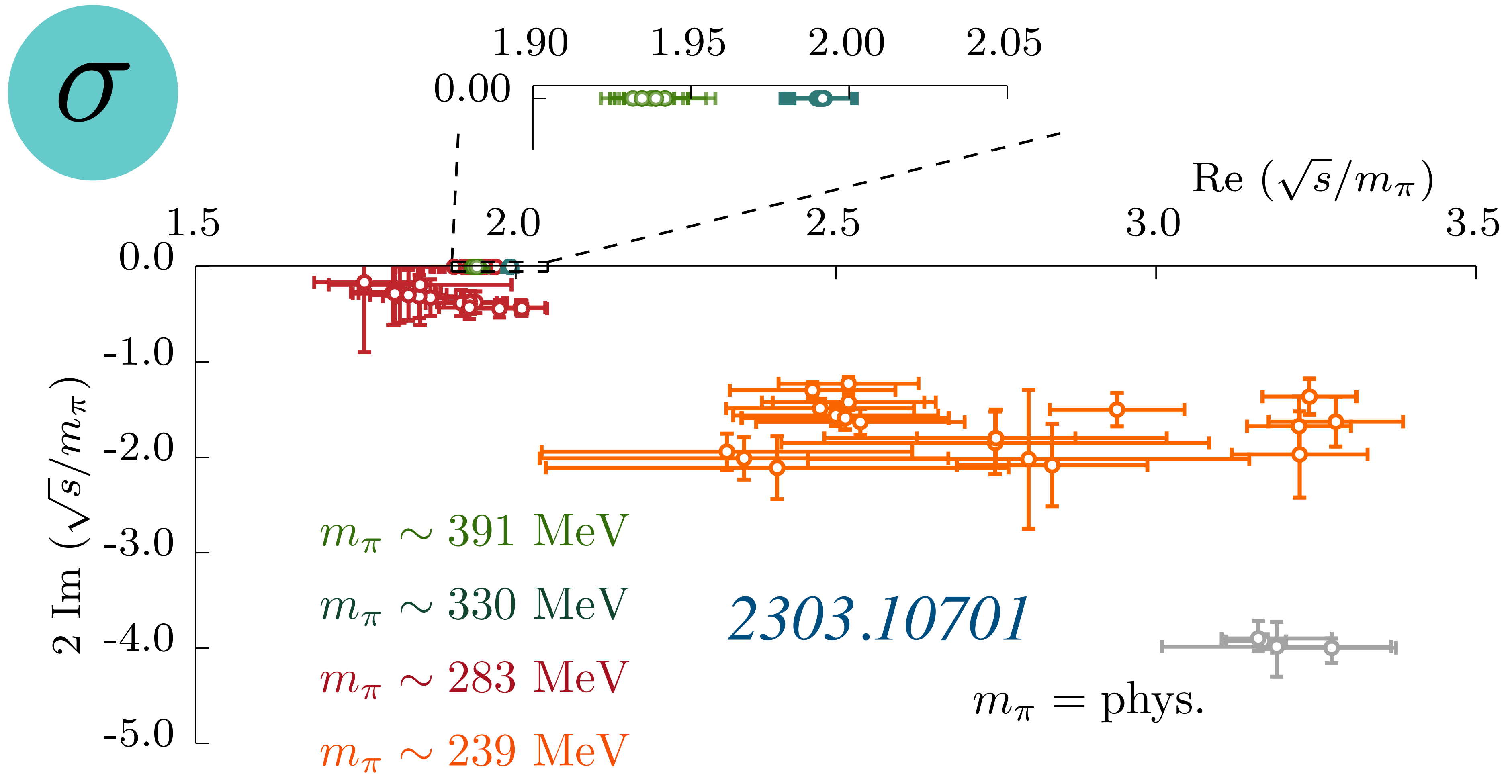
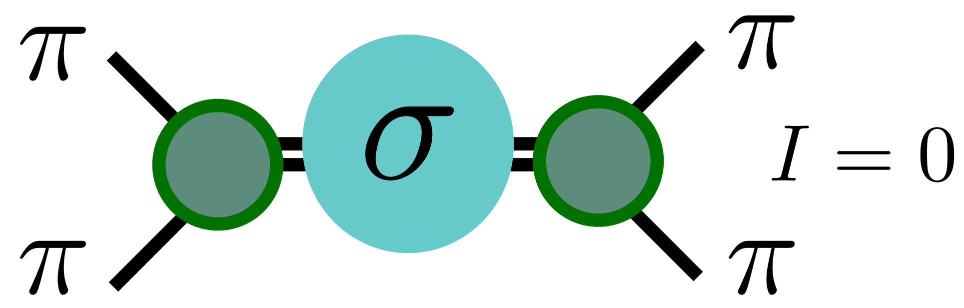
Implement a full dispersive approach

$$t_\ell^I(s) \to \tilde{t}_\ell^I(s) = \tau_\ell^I(s) + \sum_{I',\ell'} \int_{4m_\pi^2}^{\infty} ds' K_{\ell\ell'}^{II'}(s',s)\,\mathrm{Im}\,t_{\ell'}^{I'}(s')$$





Dispersion relations for $\pi\pi$

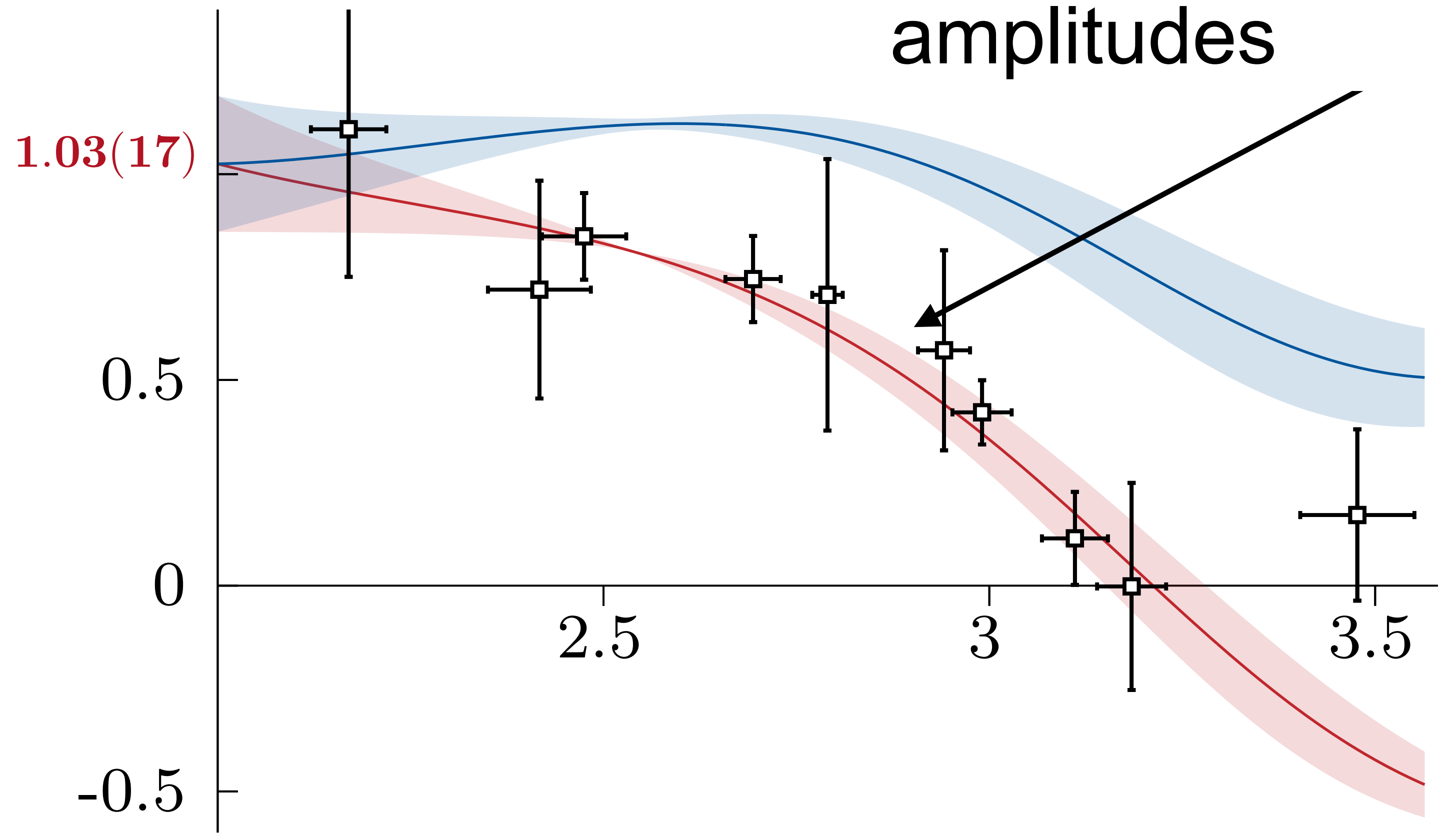


To succeed, input and out must be similar in value

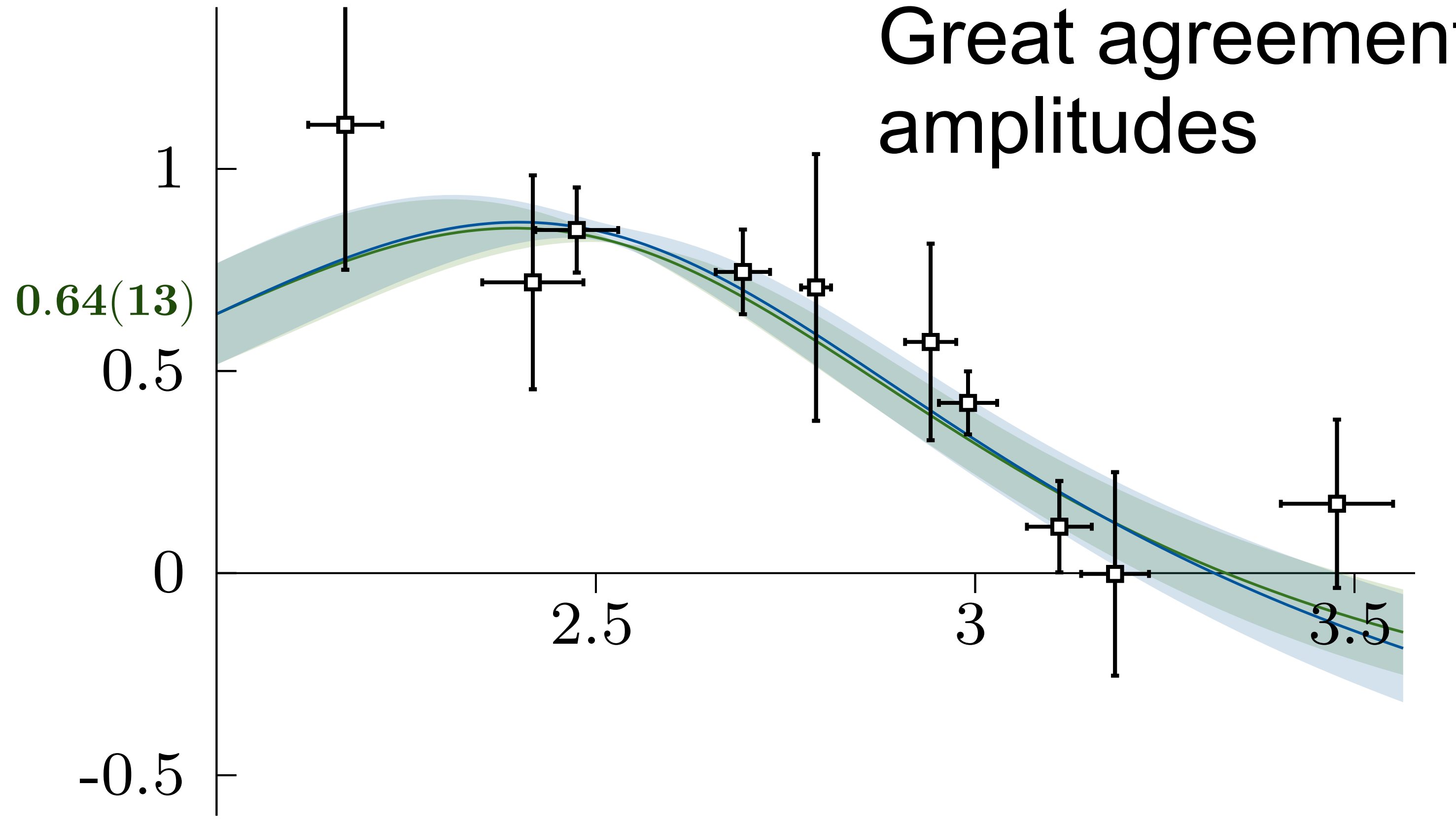
$$t^I_\ell(s) \to \tilde{t}^I_\ell(s) = \tau^I_\ell(s) + \sum_{I',\ell'} \int_{4m_\pi^2}^{\infty} ds' K^{II'}_{\ell\ell'}(s',s)\, \mathrm{Im}\, t^{I'}_{\ell'}(s')$$

Output *Input*

Bad agreement, we discard these amplitudes



Great agreement, we select these amplitudes



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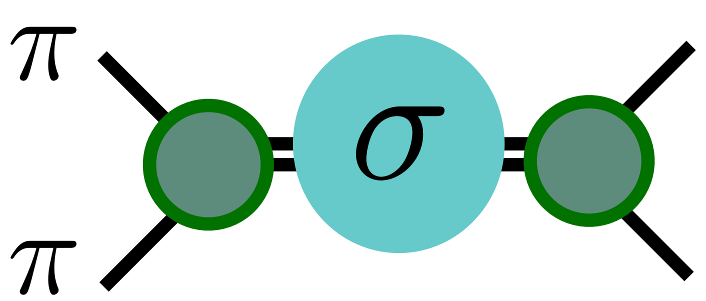

All final selected poles are compatible with one another, spread is reduced

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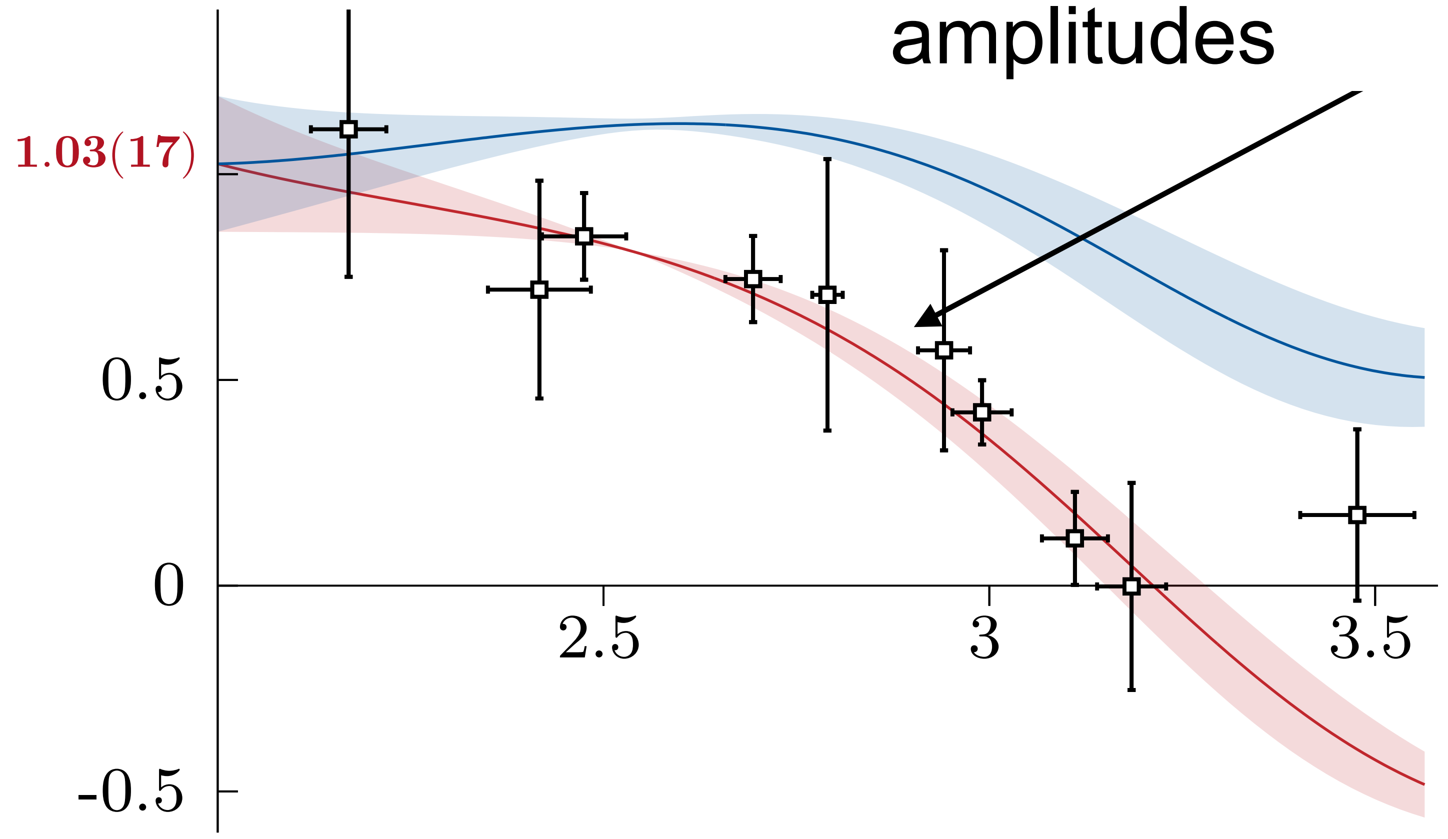

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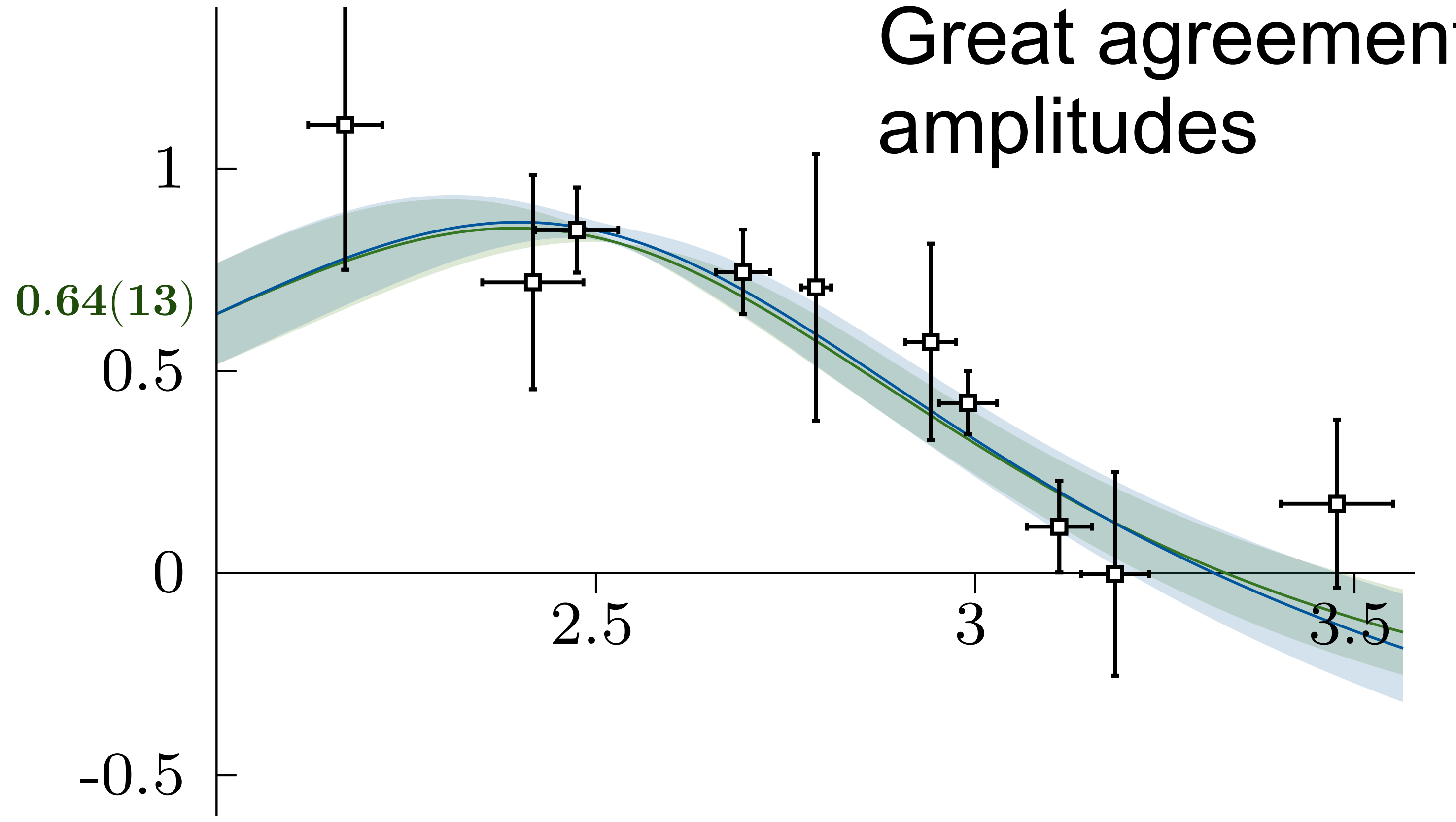
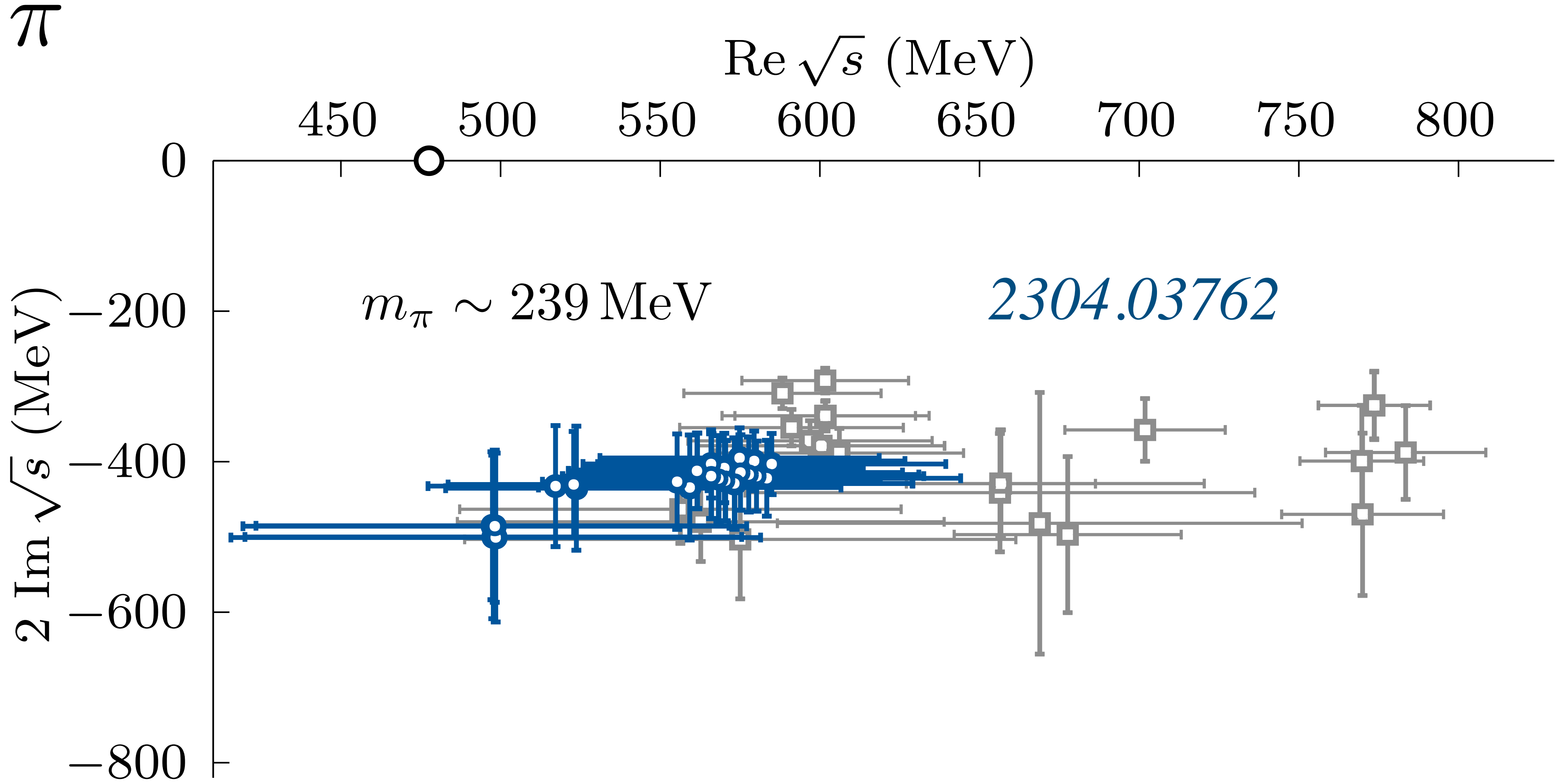
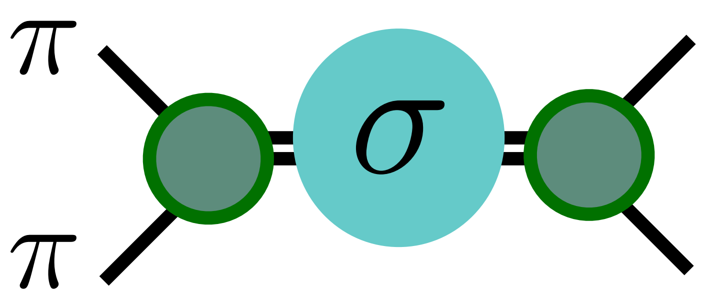




1 We are requesting computing time (most of it) to go to lower m_π

The lower m_π, the more relevant this approach becomes

Dispersion relations for $\pi\pi$



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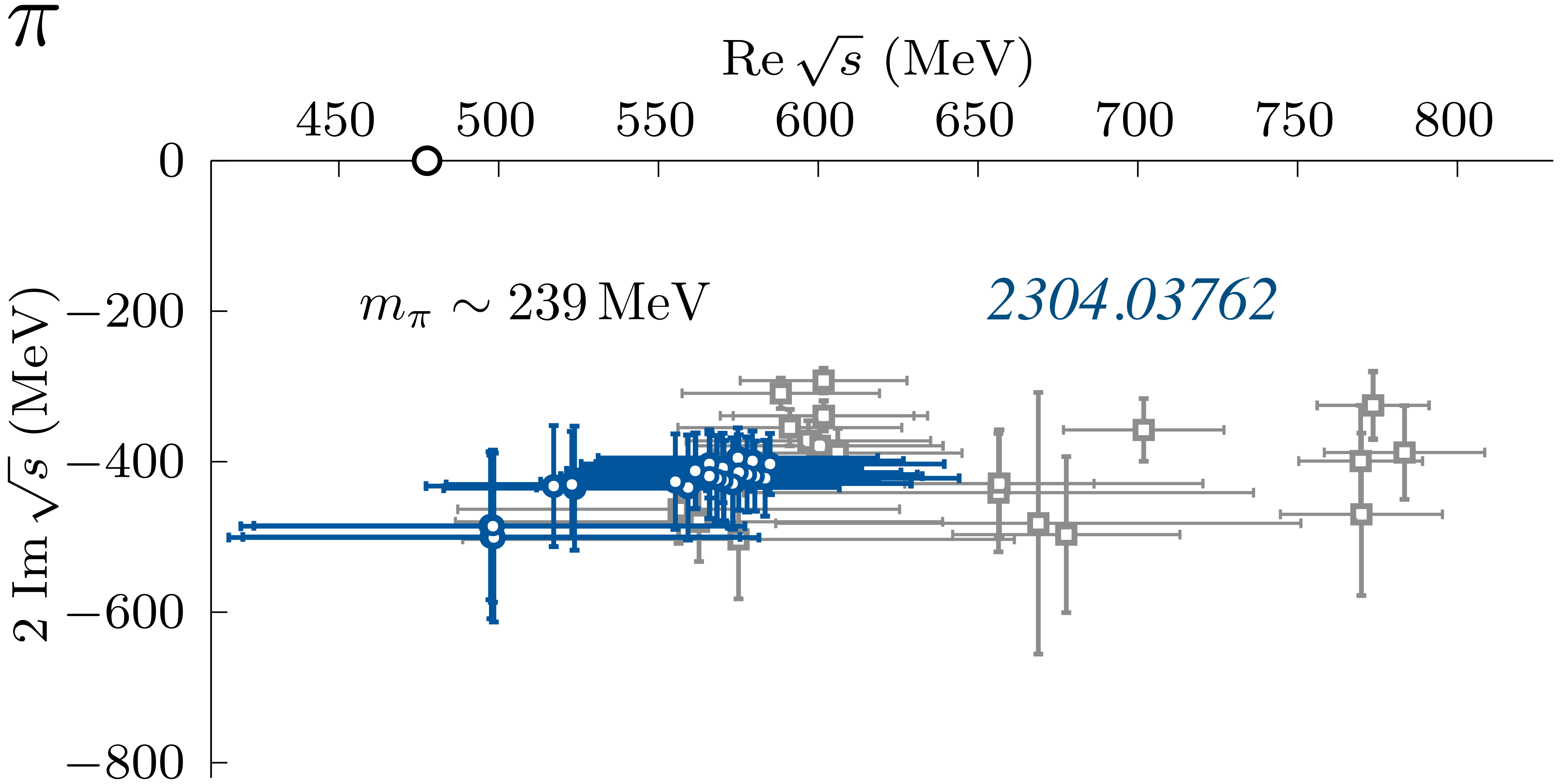

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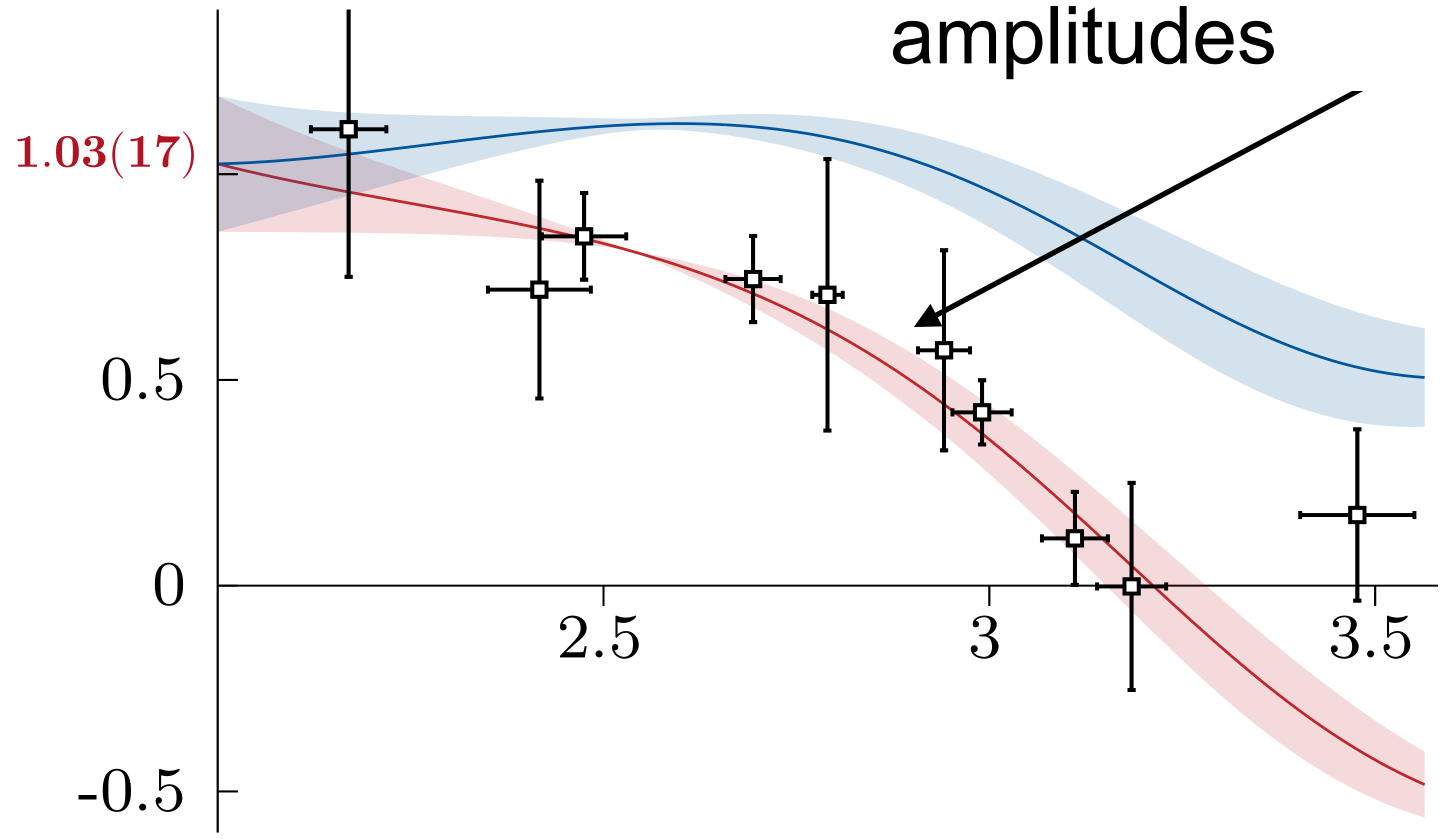

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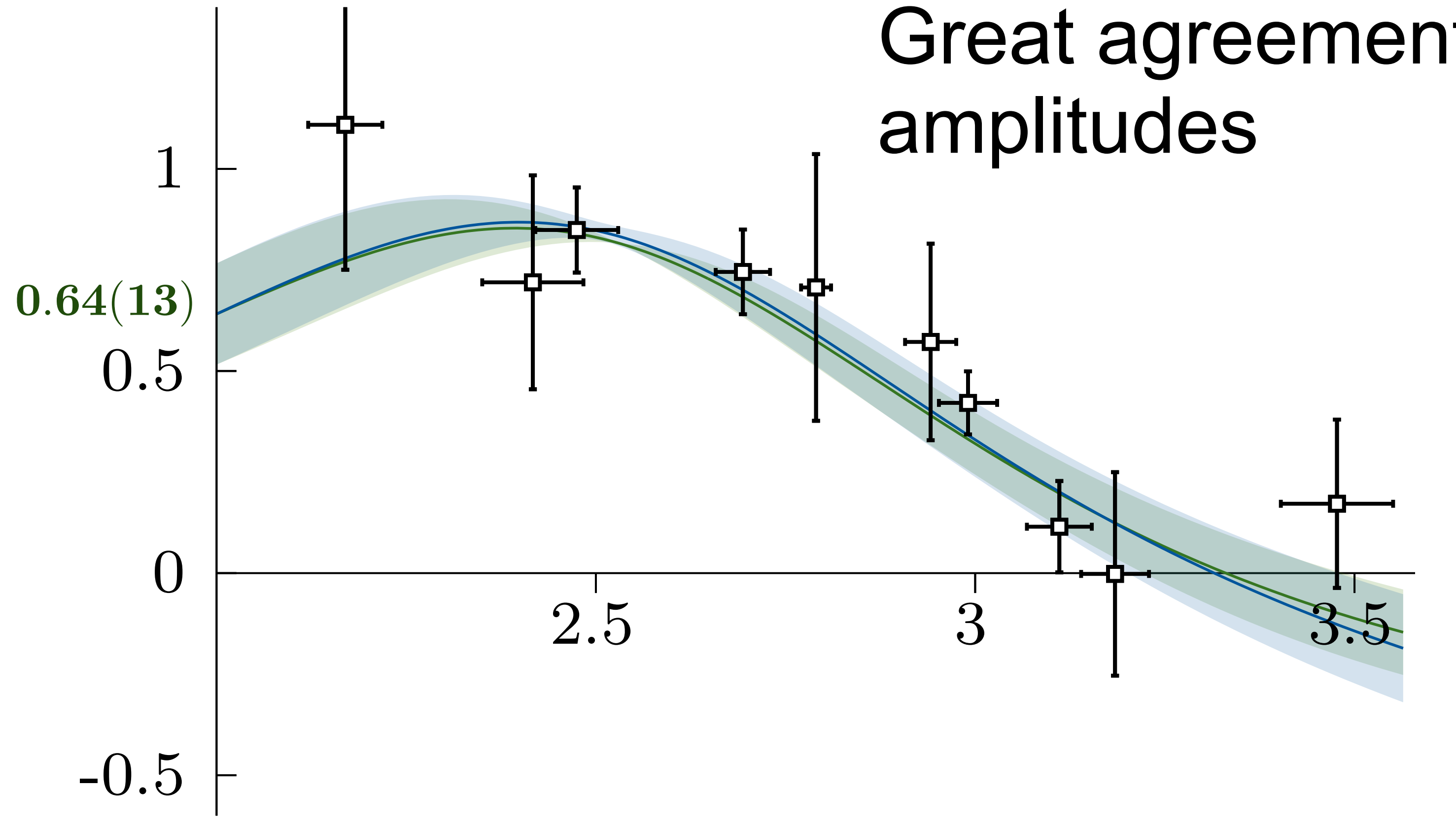

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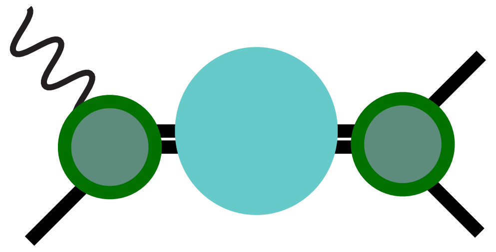
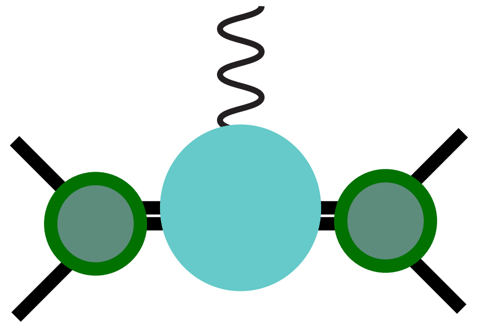
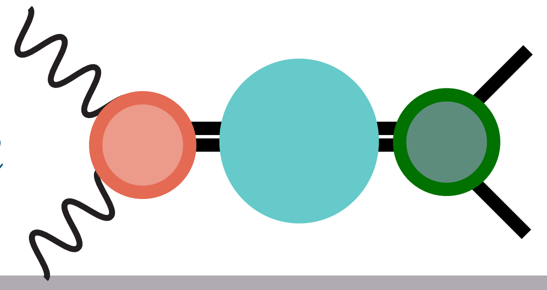
The lower m_π, the more relevant this approach becomes

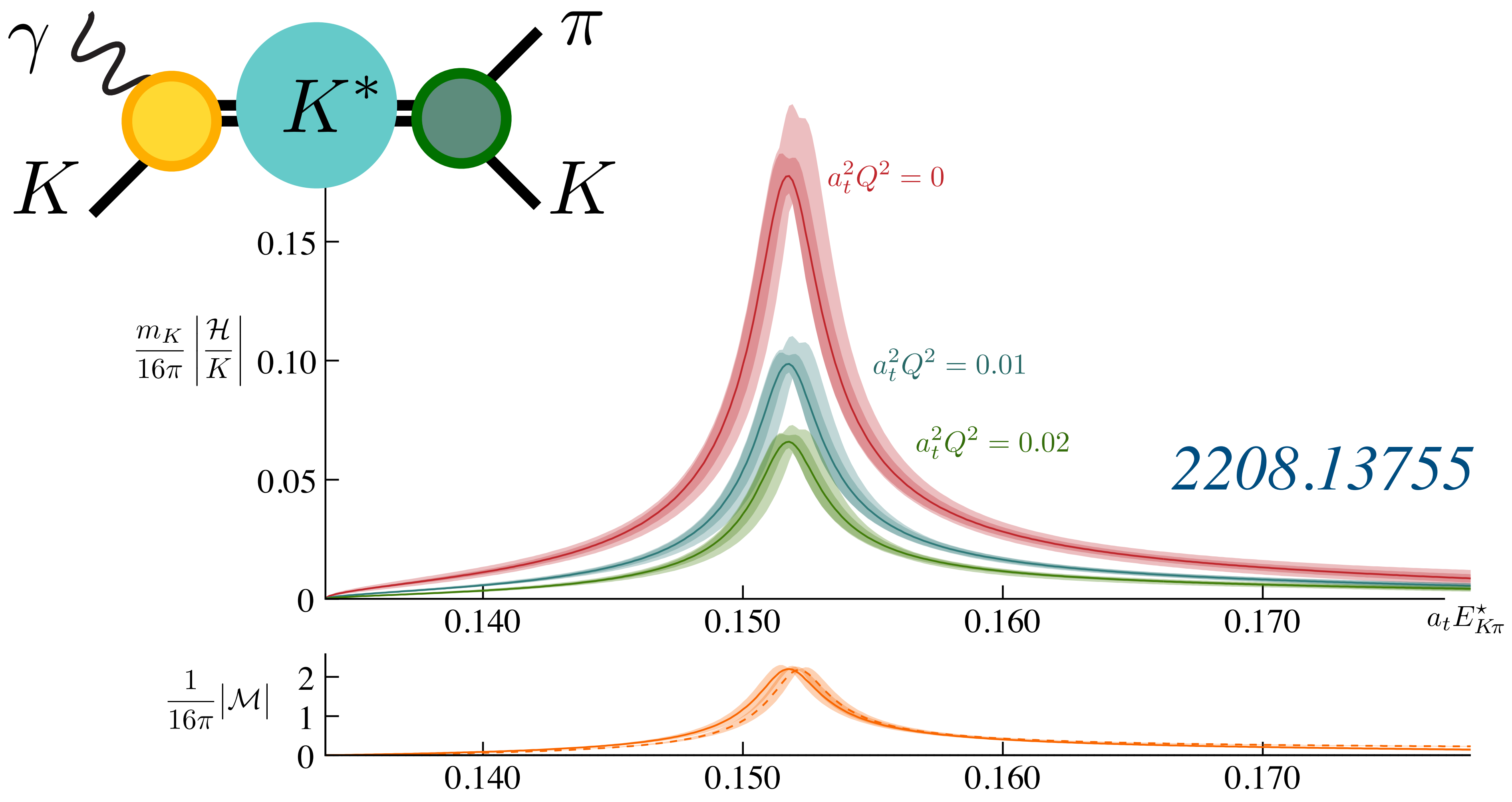
4 Also requesting time for EM current analyses

"Photoproduction"  *1502.04314*

Resonance "form factors"  *1509.08507*

"Photon" fusion  *2210.08051*

Other projects

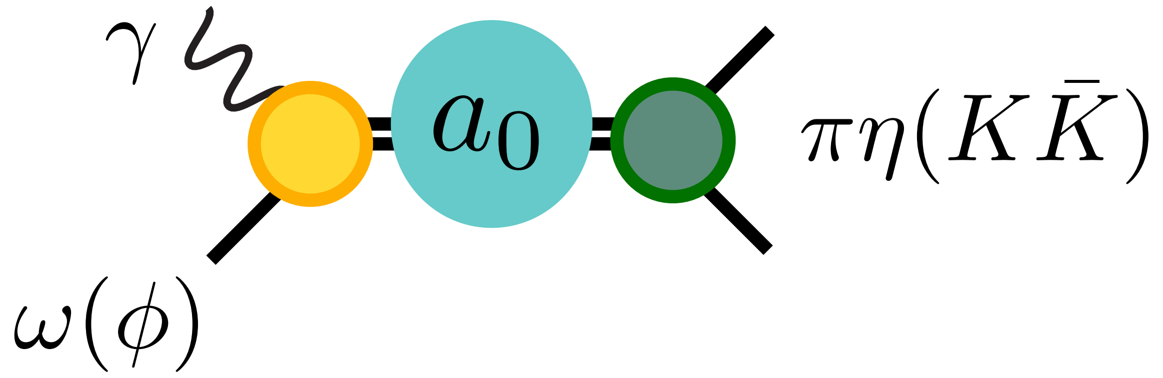


2208.13755

4 EM properties of hadrons

Present: The K radiative transition*

Future: The $a_0(980)$, a coupled-channel analysis on photo production



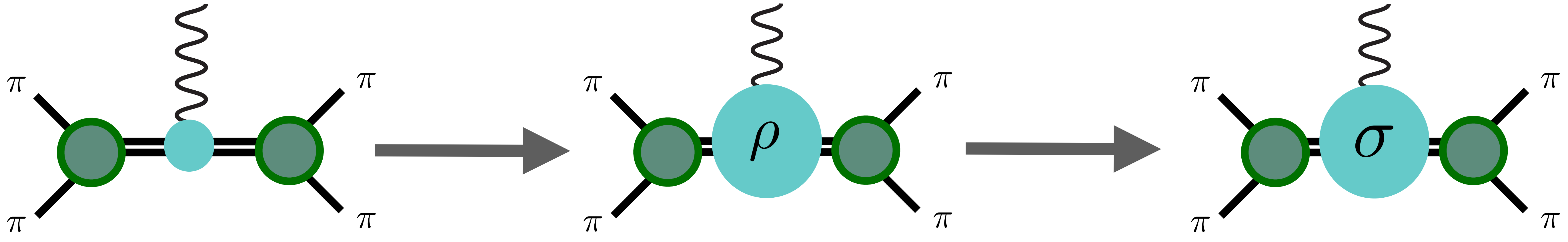
Learning about it's flavor composition

Learning about it's size

4 Form factors of hadrons

After first explorations on non-resonant systems

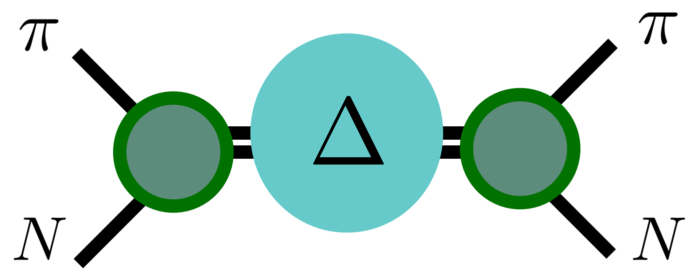
Probing unstable (and stable) hadrons



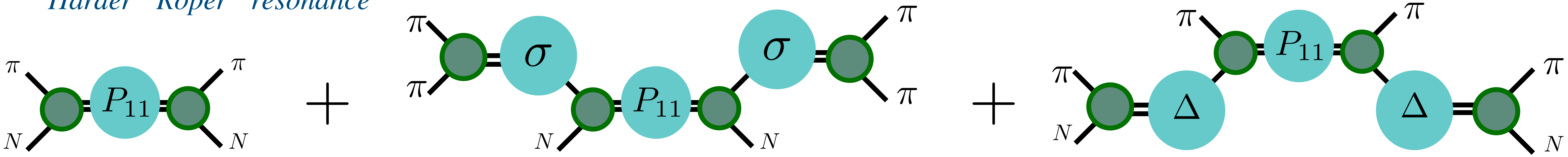
3 Meson-baryon projects are ongoing

Several challenges: operator construction, very expensive wick contractions, multi-body thresholds

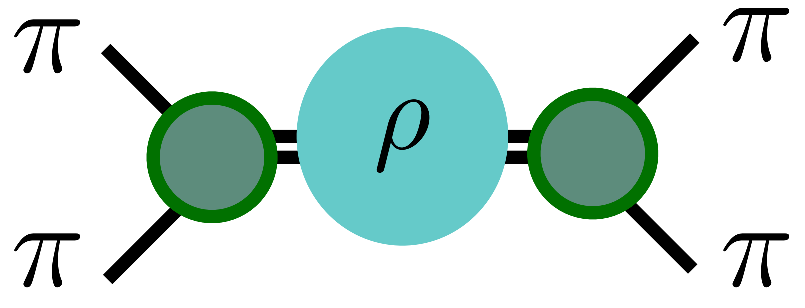
Simpler, two-body analyses



Harder "Roper" resonance



Proposal summary

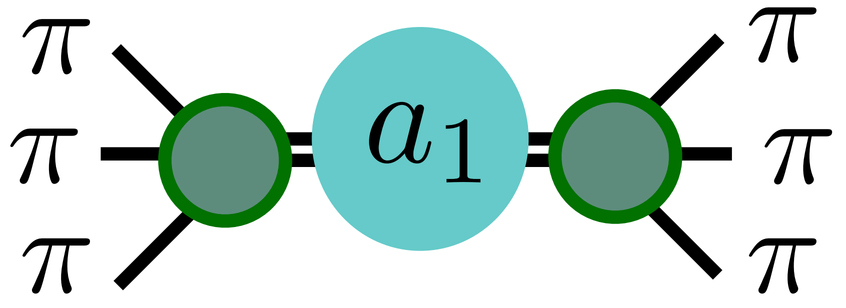


1 **Determine the spectrum of ordinary and non-ordinary hadrons**

Ready to compute exotic reactions at higher m_π
Pushing lower m_π calculations for meson-meson scattering processes

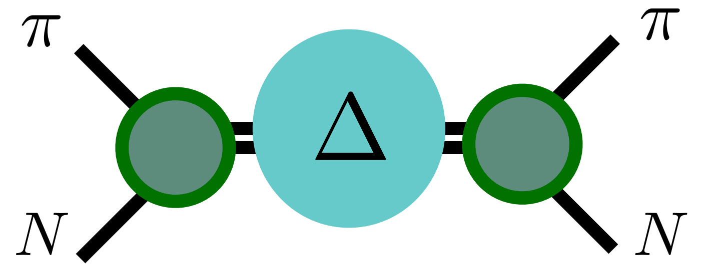
2 **Develop and implement multi-body decay formalisms to the extraction of resonances**

Technology ready for 3π systems with intermediate resonances
Getting closer to 3b baryonic systems!



3 **Kick start our meson-baryon program**

First explorations for Δ resonances are underway
The Roper resonance will also be extracted, in the longer future



4 **Continue our EM analyses**

Working on photo production processes for coupled-channels
Working on elastic form factors of scattering processes