Recent developments in the light strange sector

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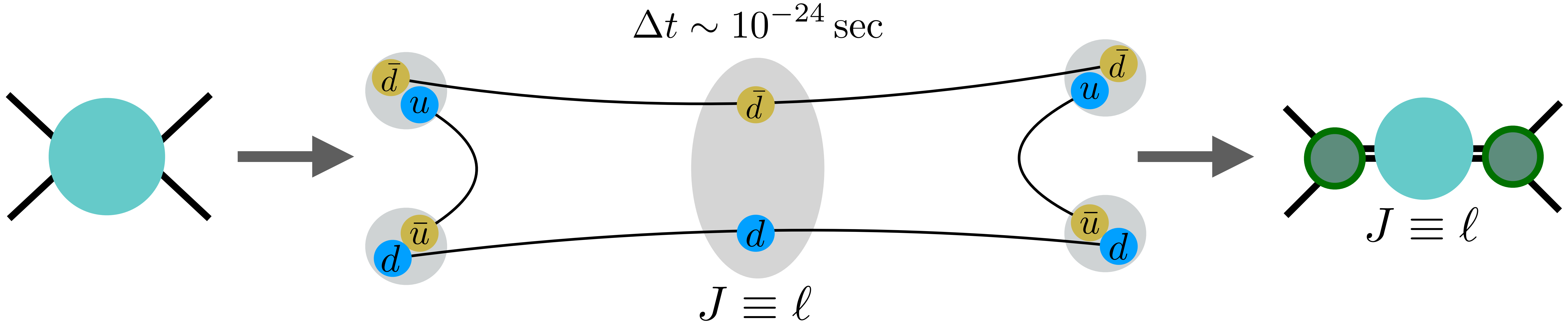
Spectroscopy in QCD

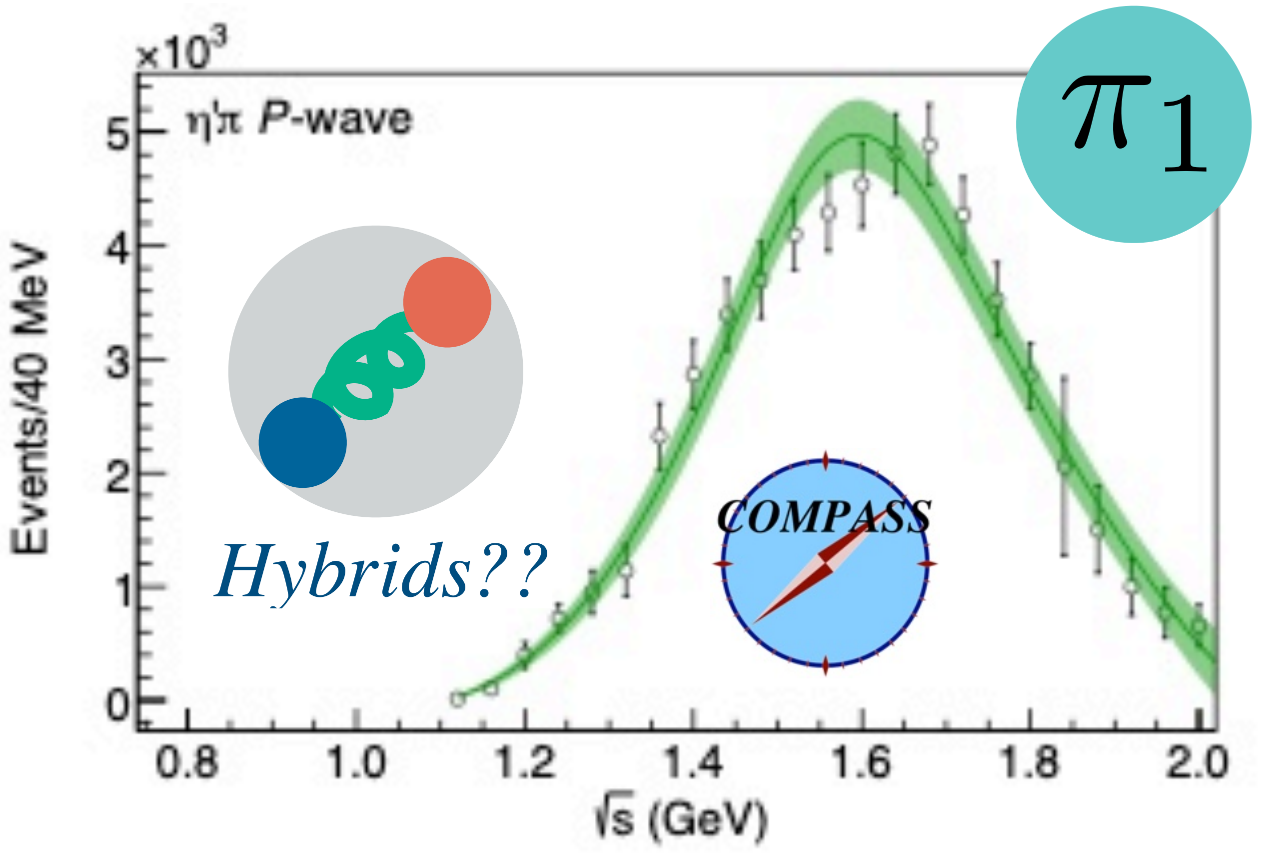
How do quark and gluons combine inside unstable hadrons?

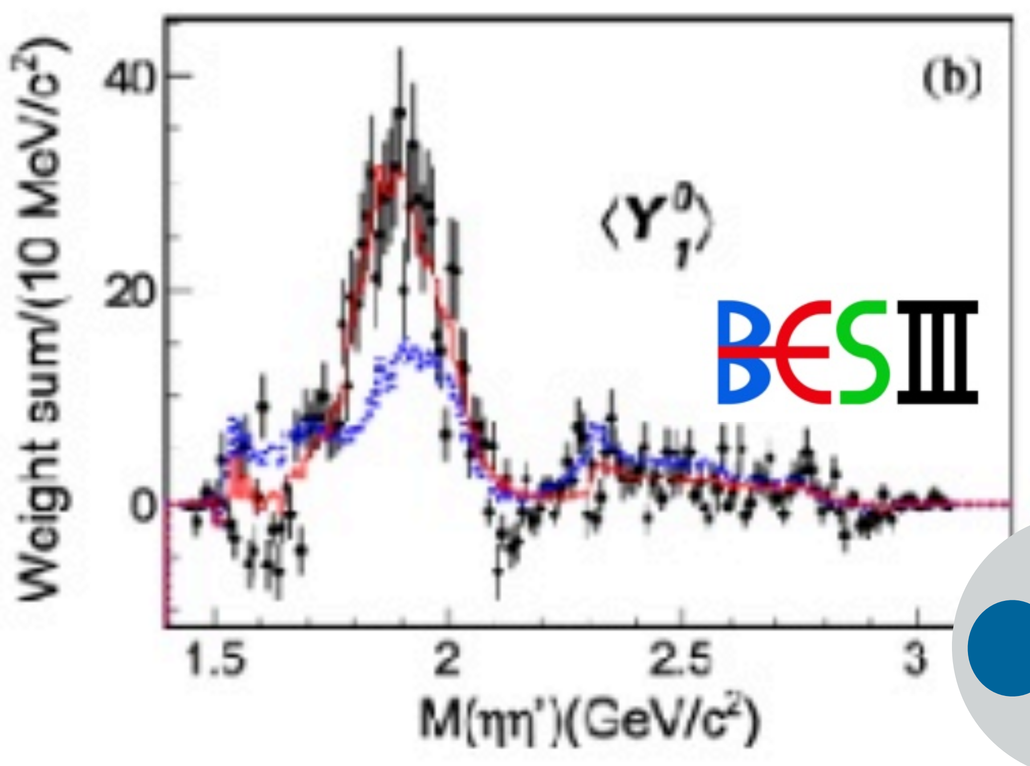
We need a combination of lattice QCD, theory/phenomenology, and experiment to answer this question

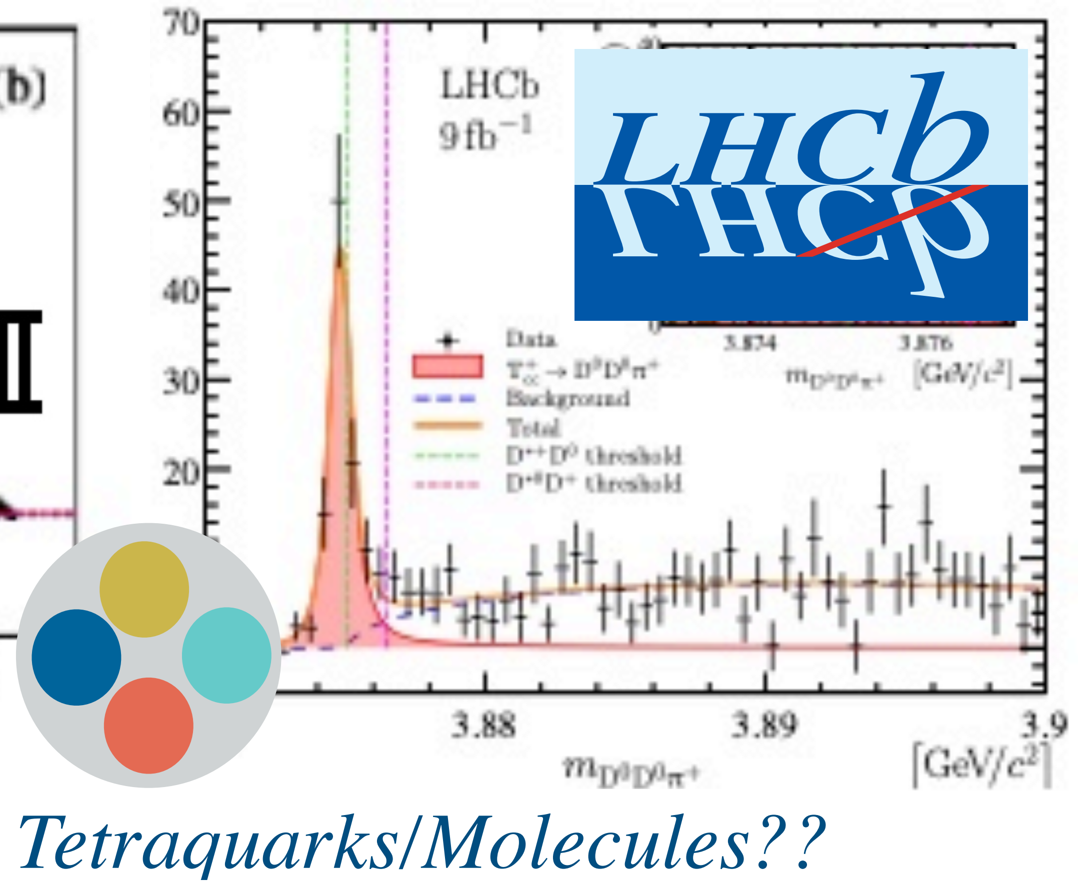
"hadron spectroscopy explores the possible bound combinations of quarks and gluons allowed by the interactions of QCD"

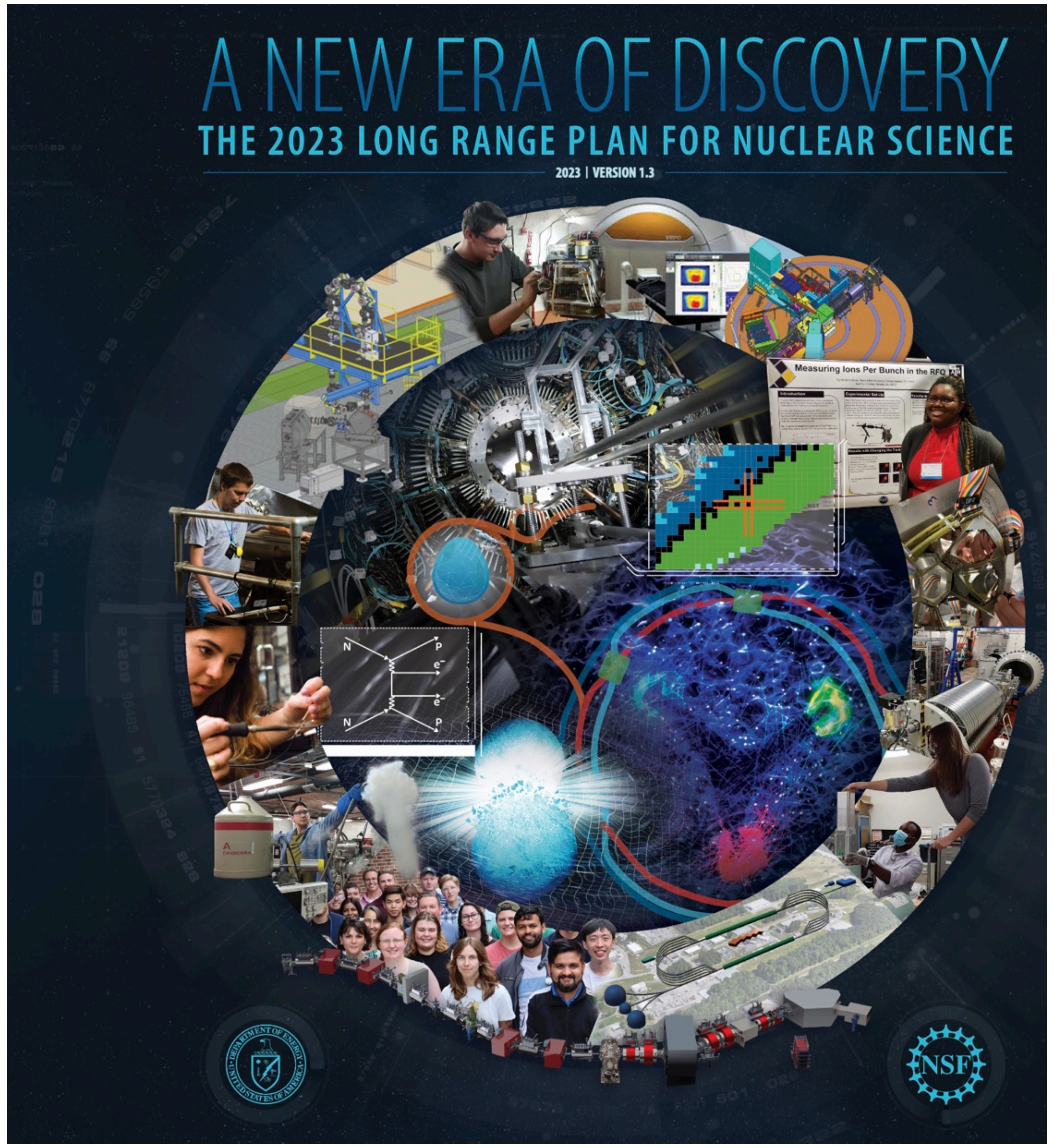


Confirm existence of elusive hadrons







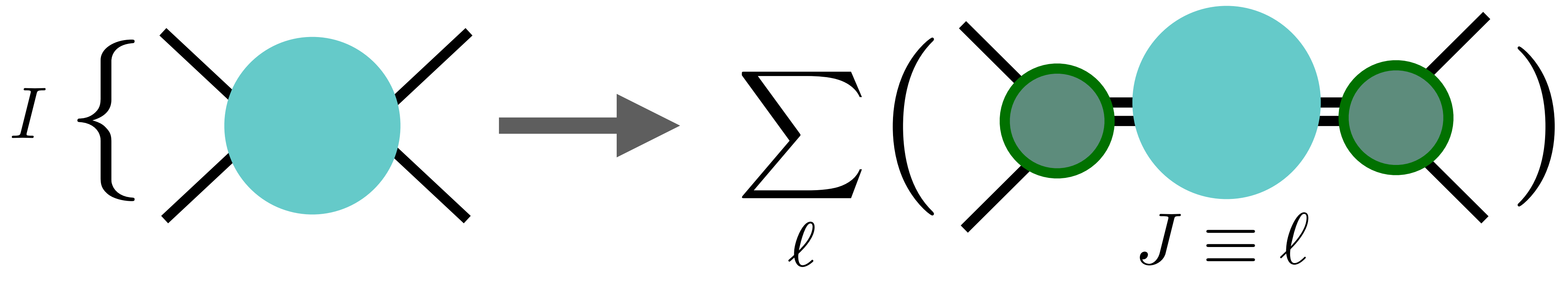


Guide searches

Go beyond standard analyses to understand their nature (Lattice QCD)

Scattering at hadronic energies: Resonances

- **Determine the spectrum**



$$T^I(s,t,u) = 32\pi \sum_\ell (2\ell+1)\, t_\ell^I(s)\, P_\ell(\cos\theta_s)$$

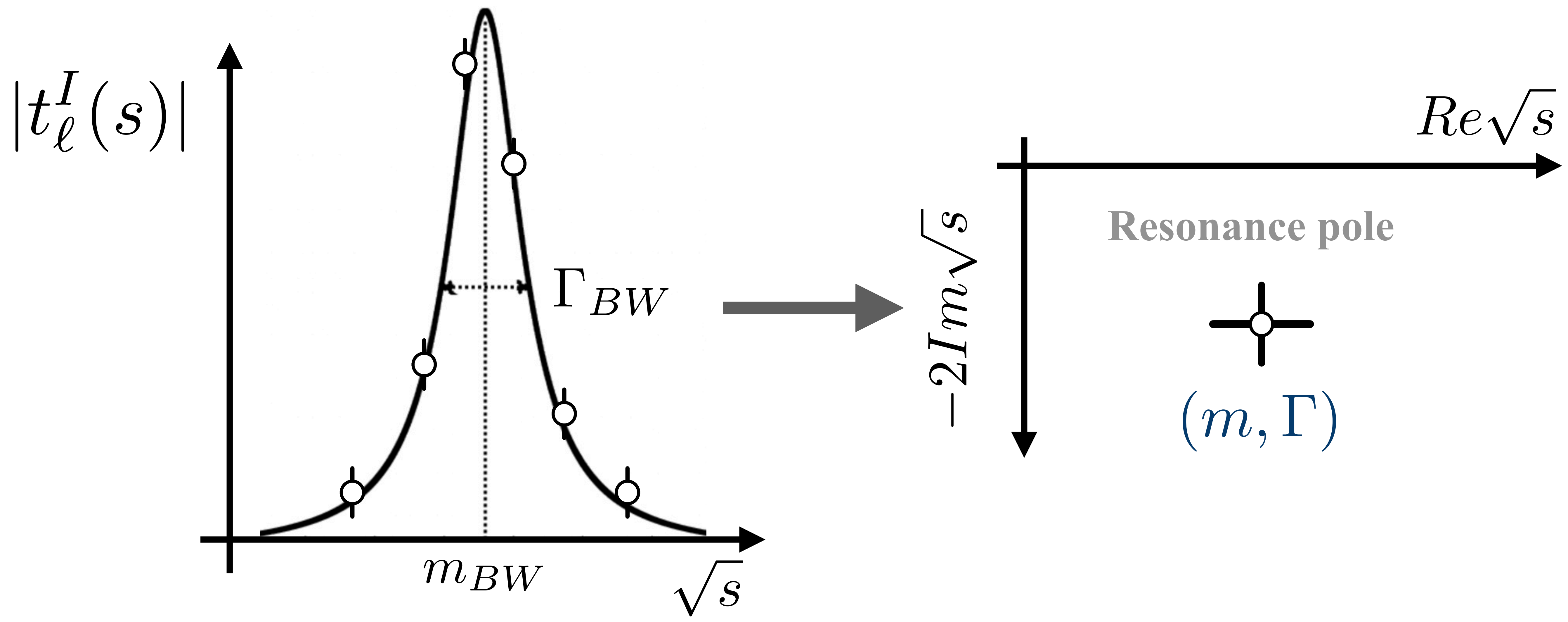
Partial wave, unstable hadrons live here

Assume we have scattering data for well-defined angular momentum

Assume the resonance is narrow and isolated

$$t_\ell^I(s) = \frac{1}{\rho(s)} \frac{\sqrt{s}\,\Gamma_{BW}}{m_{BW}^2 - s - i\sqrt{s}\,\Gamma_{BW}}$$

Pole at $\sqrt{s_p} \sim (m_{BW} - i\Gamma_{BW}/2)$



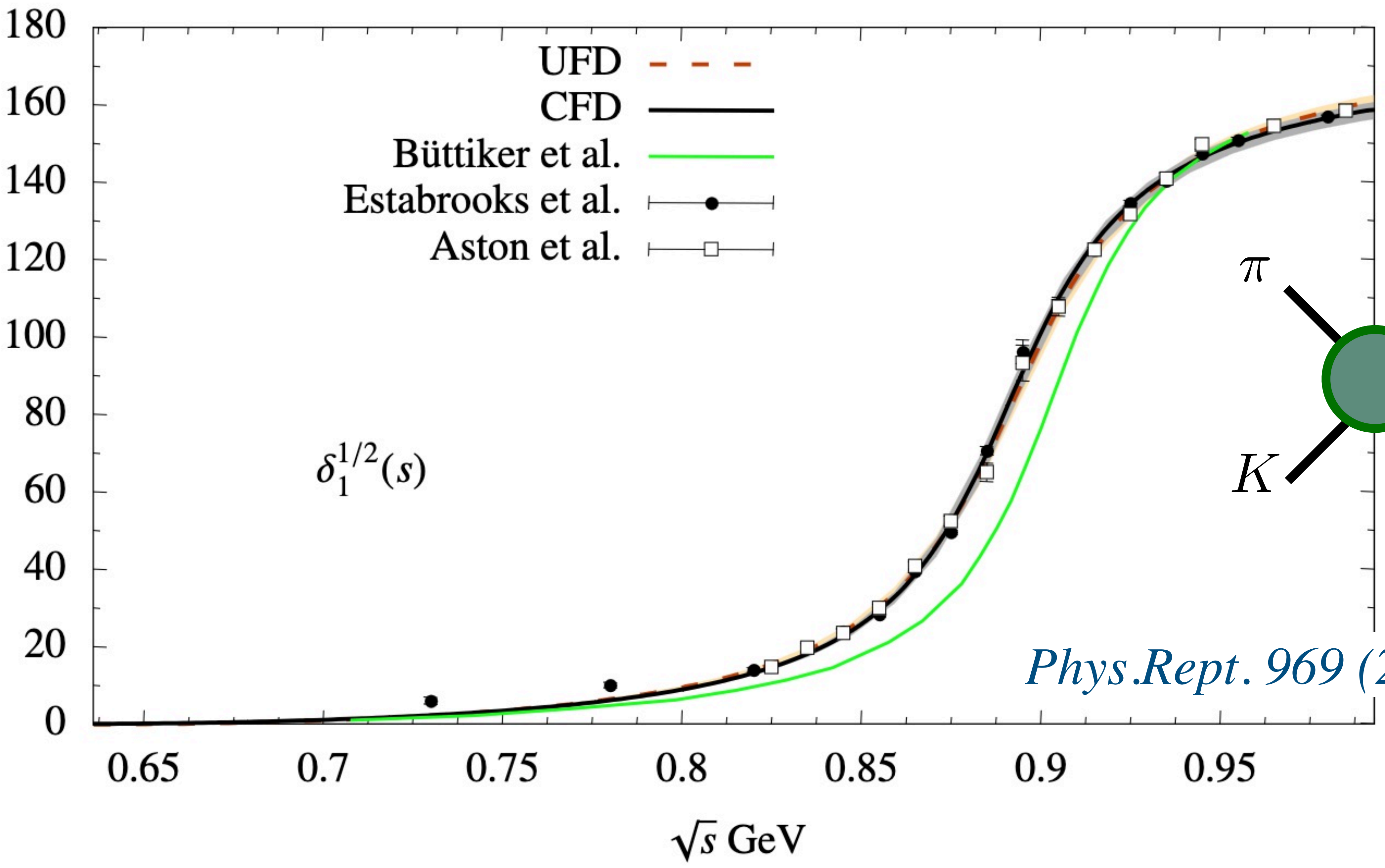
Scattering at hadronic energies: Resonances

$K^*(892)$

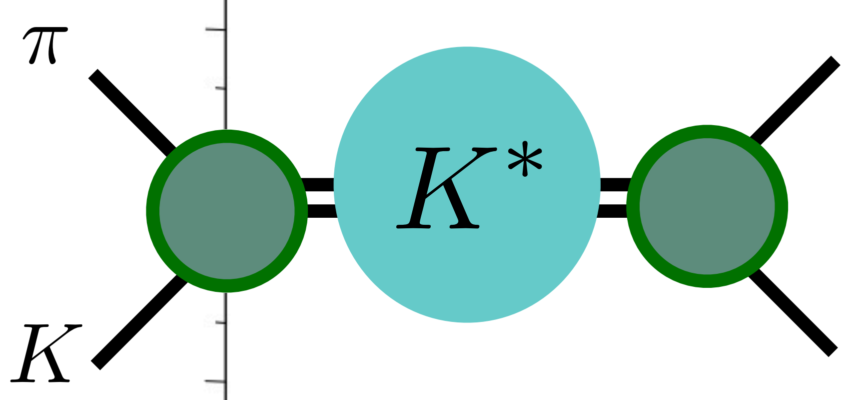
The BW has worked wonders in many cases

$$t_\ell(s) \sim \frac{\sqrt{s}\Gamma(s)}{m^2 - s - i\sqrt{s}\Gamma(s)}$$

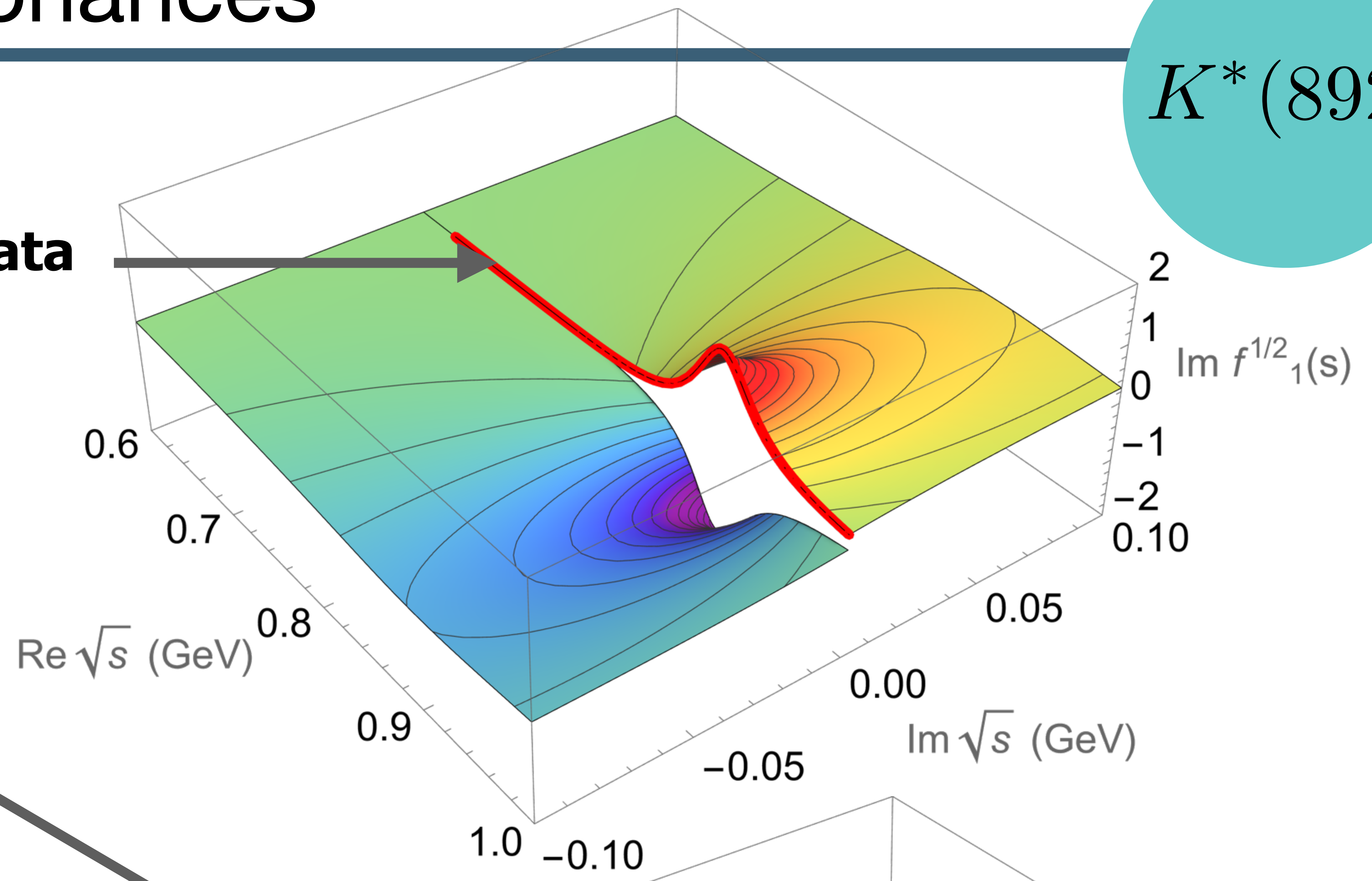
$$\sqrt{s_p} = m + i\Gamma/2$$

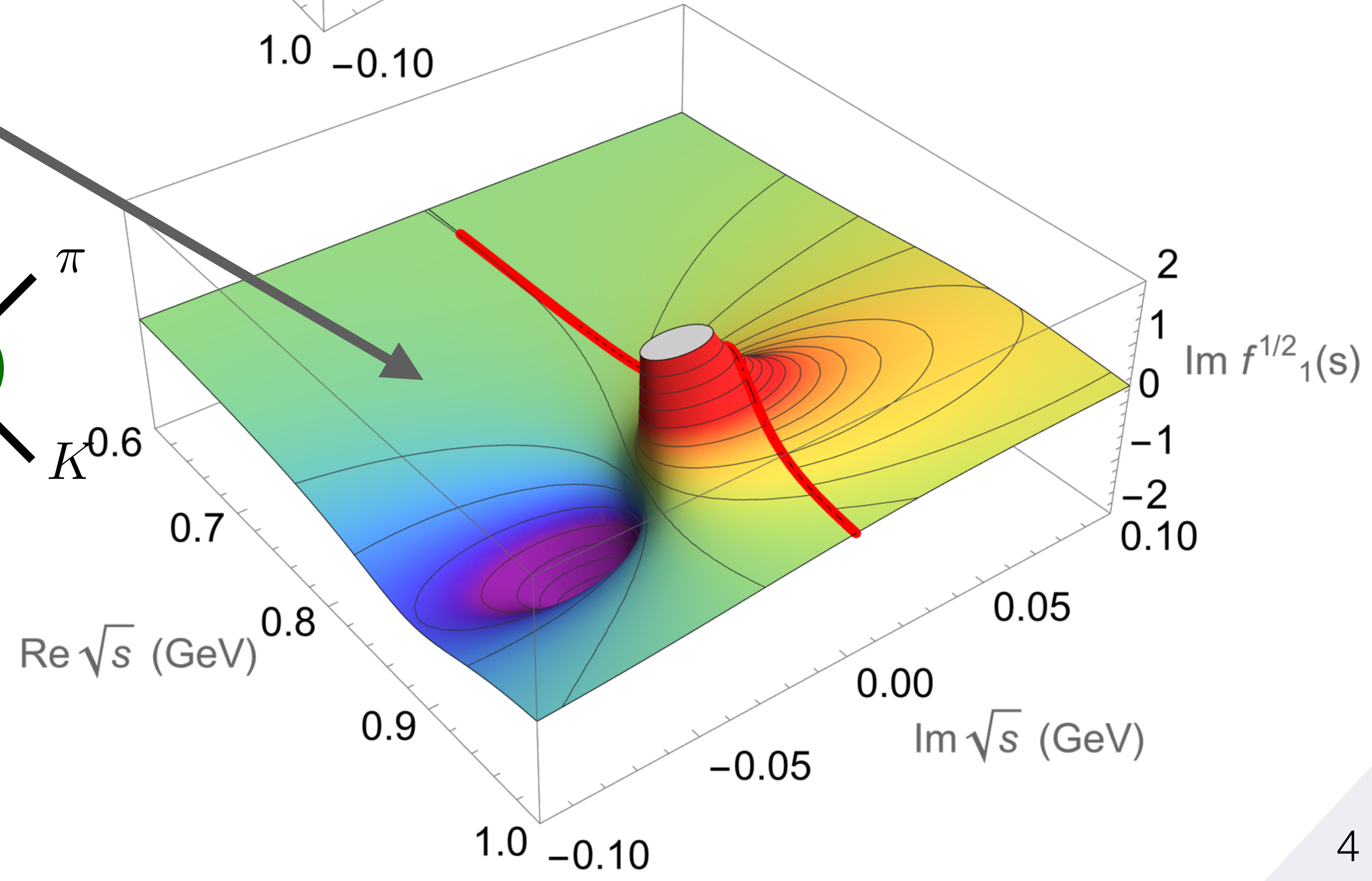


Phys.Rept. 969 (2022) 1-126



Data

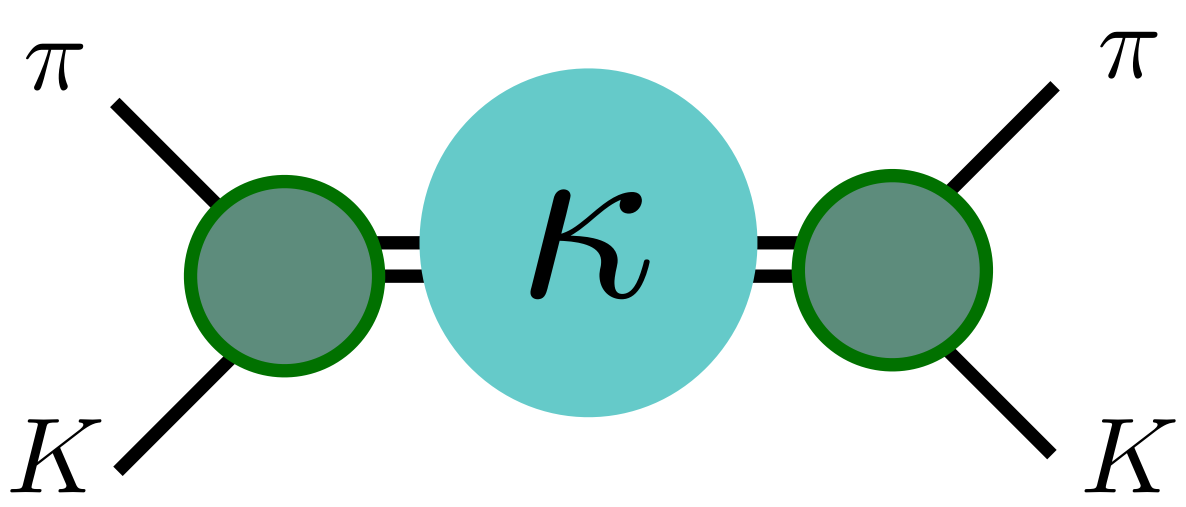




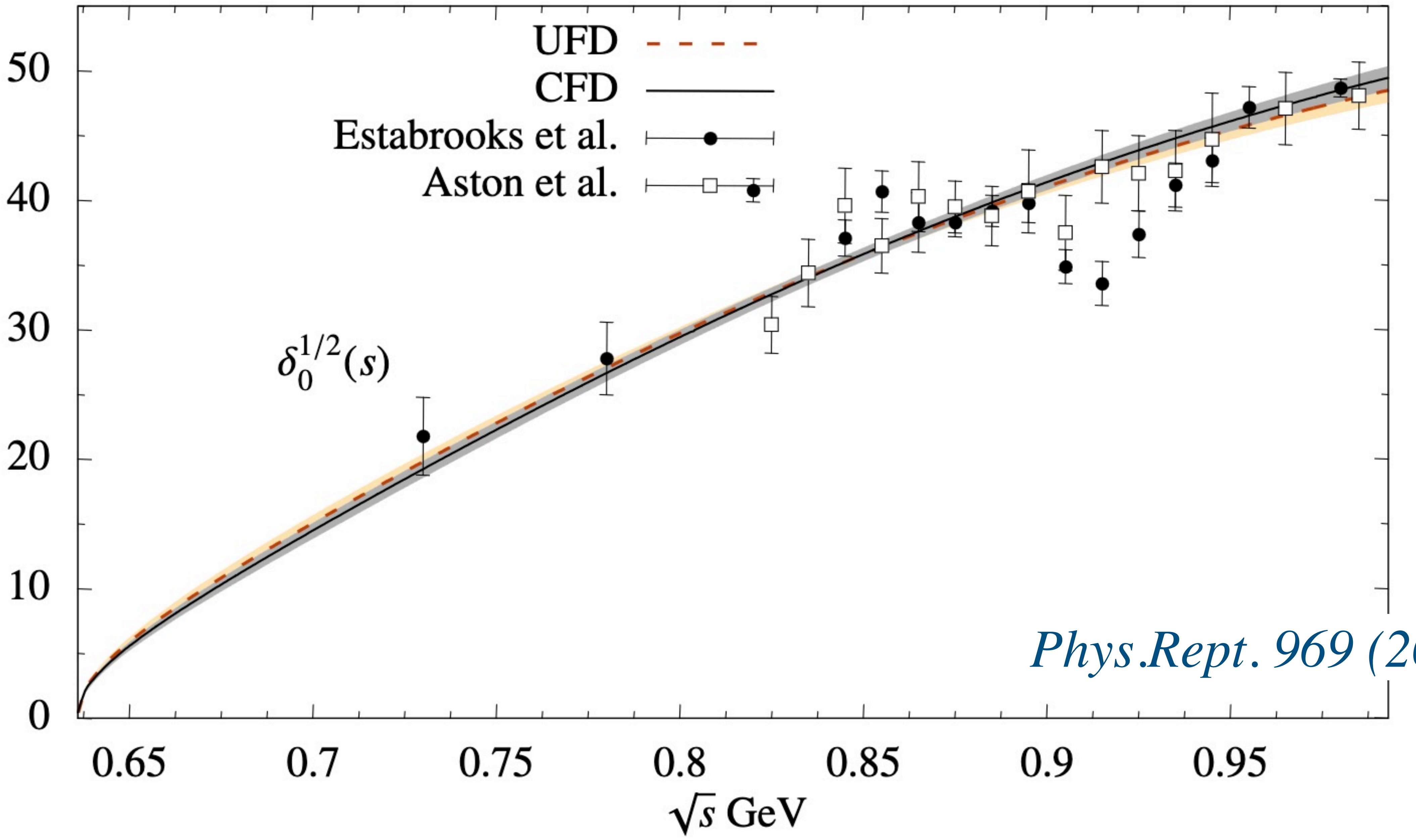
Scattering at hadronic energies: Resonances

Definitely not a BW

$$t_\ell(s) \sim ??$$



What's this??



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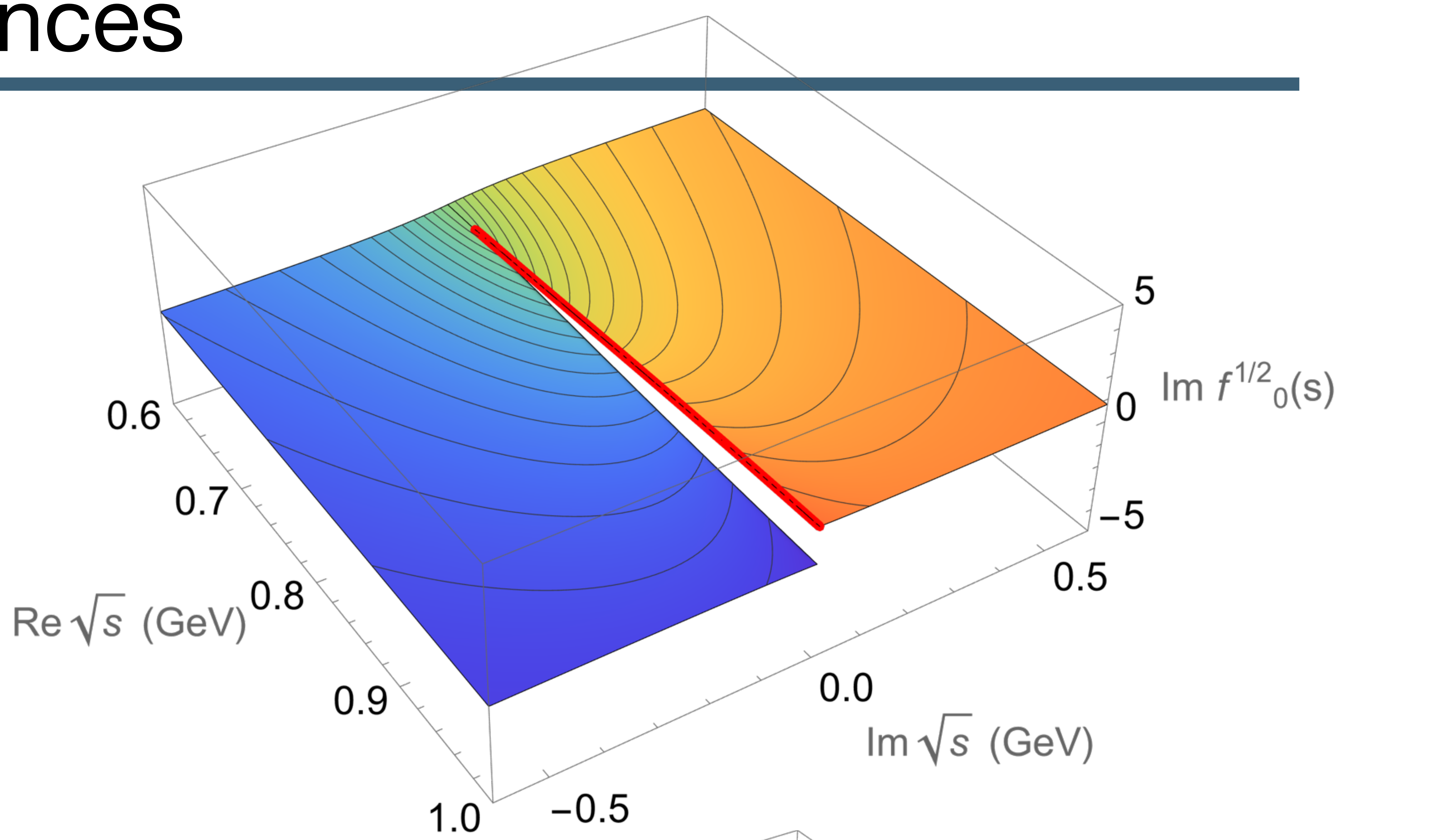
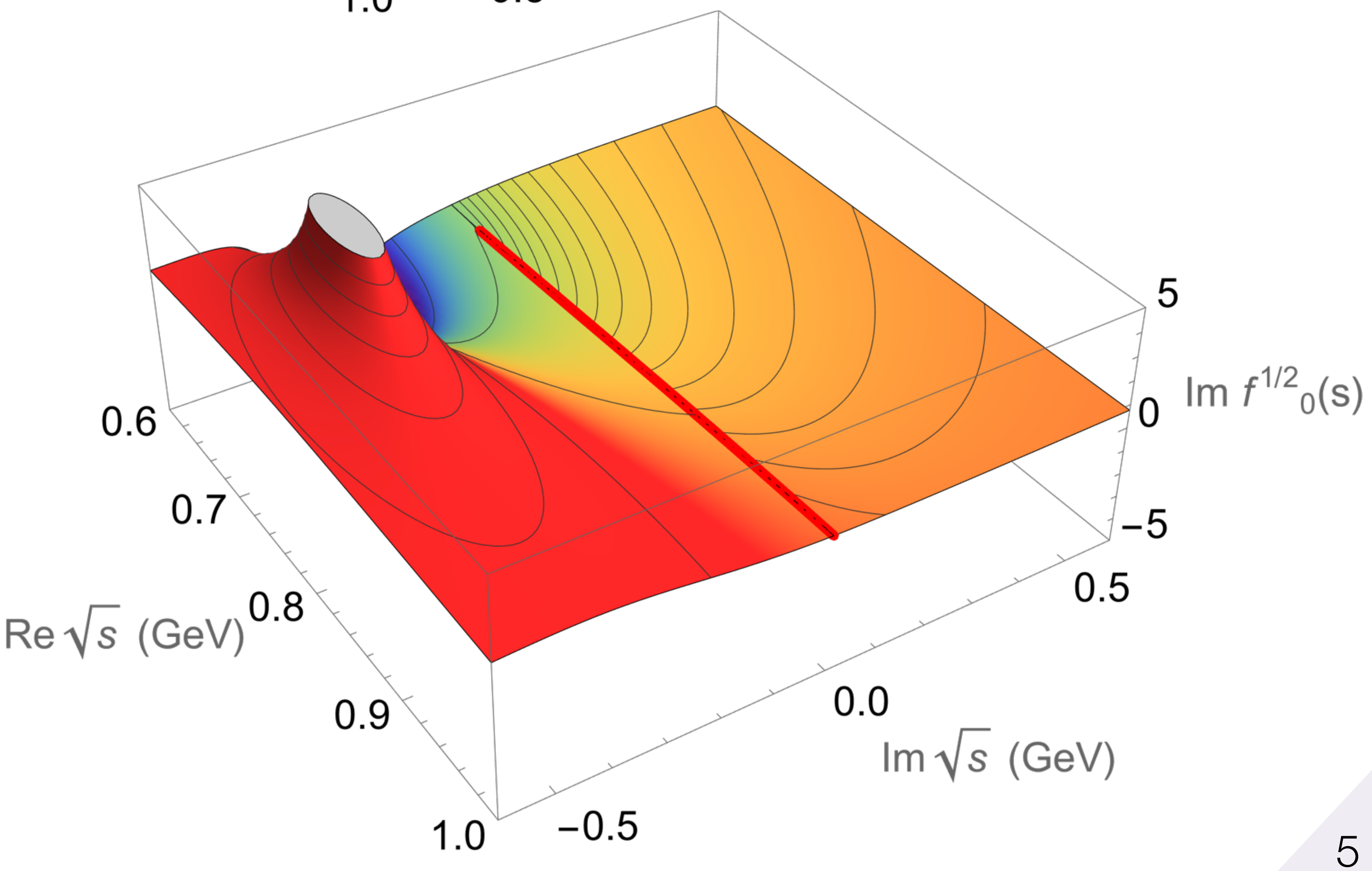




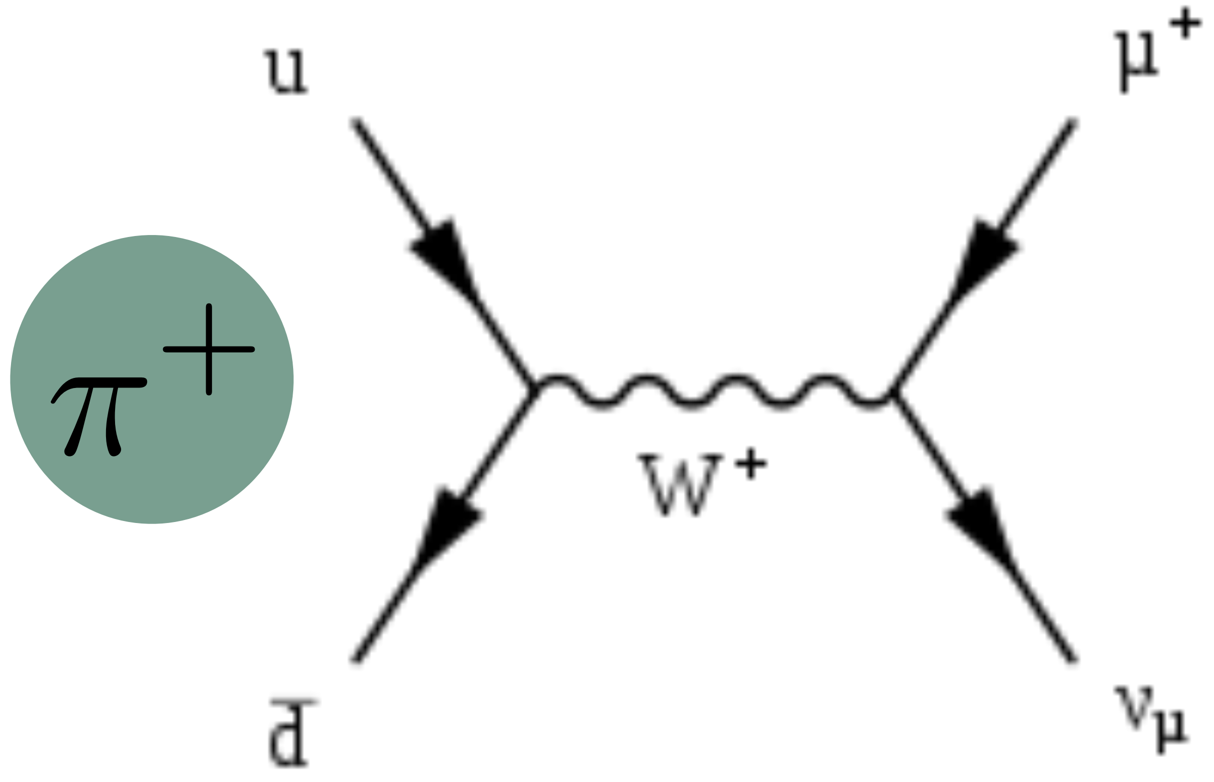
The “data”

Mesons decay

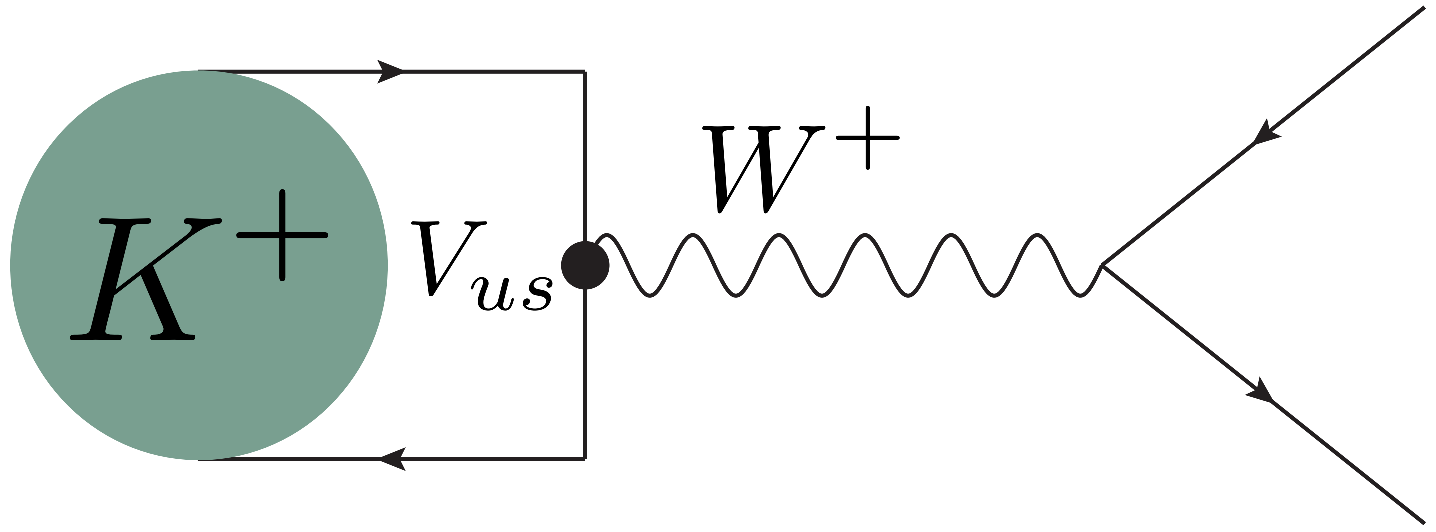
One beam?? (maybe)

Not two beams

$$c\tau_{\pi^+} = 7.8\ \mathrm{m}$$



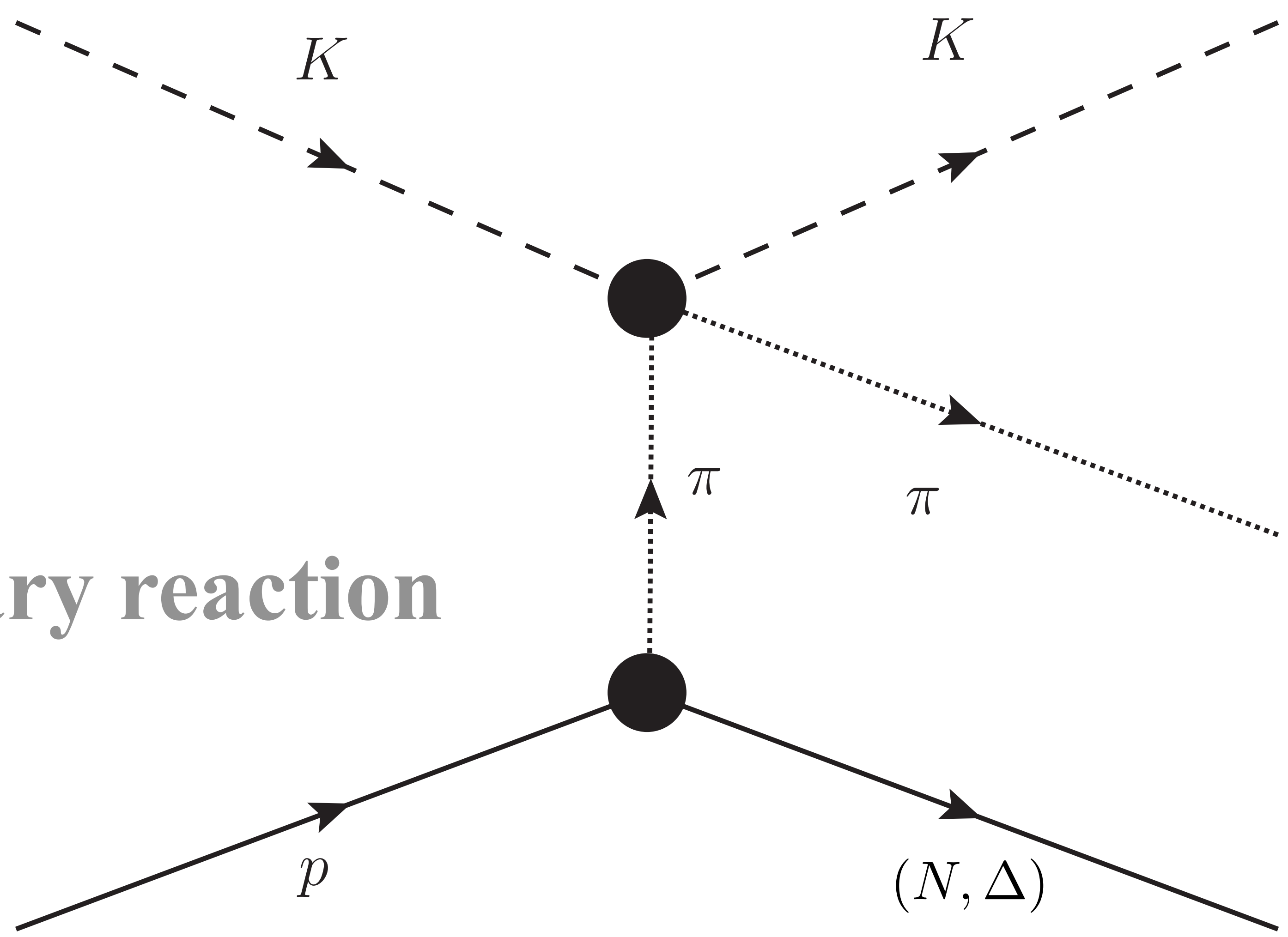
$$c\tau_K = 3.7\ \mathrm{m}$$



“Data” is not data

For meson-meson data must be always modeled

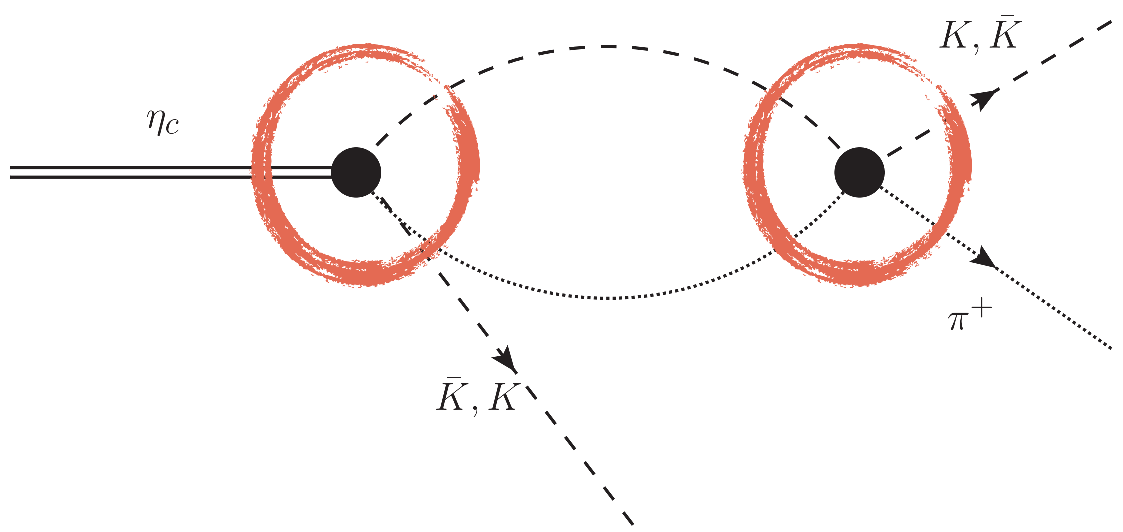
Some systematic uncertainties unknown

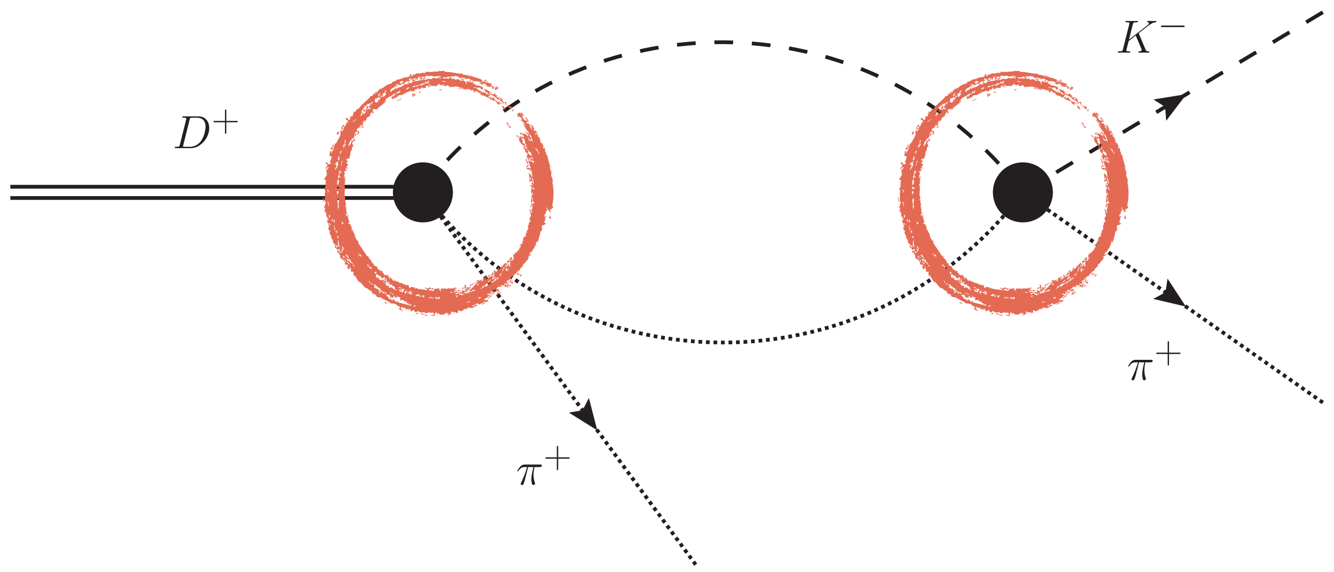


Customary reaction

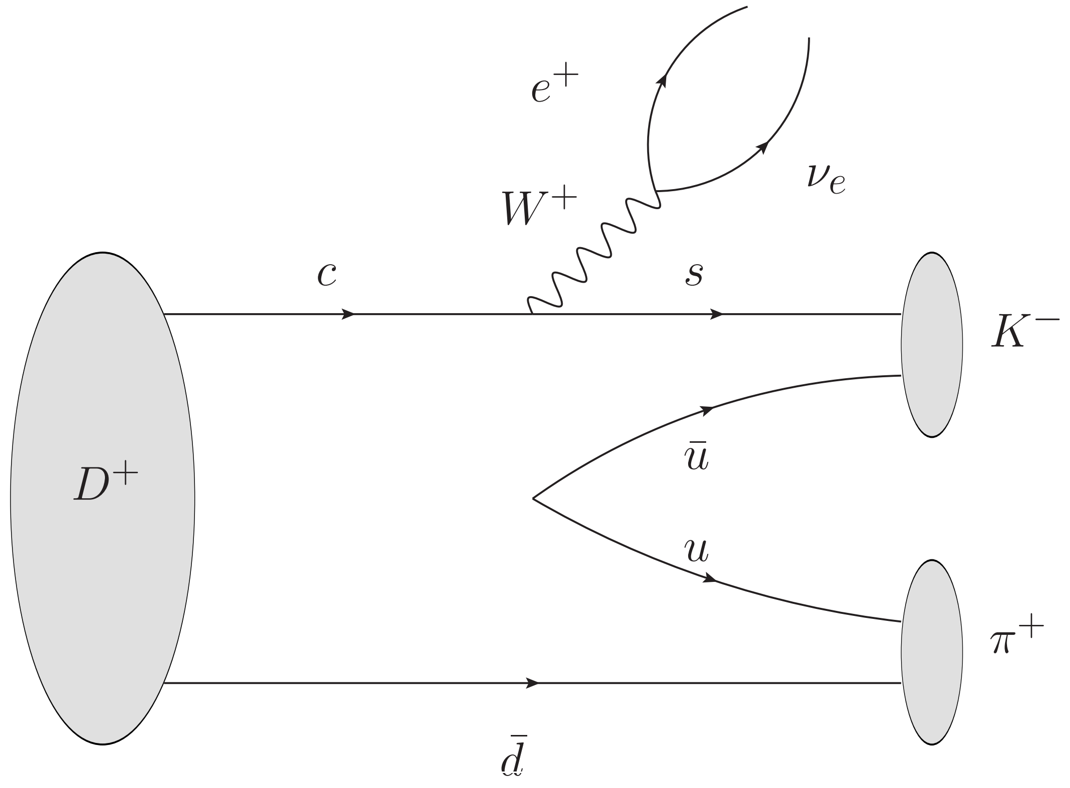
The “data”

Hadronic decays require heavier modeling

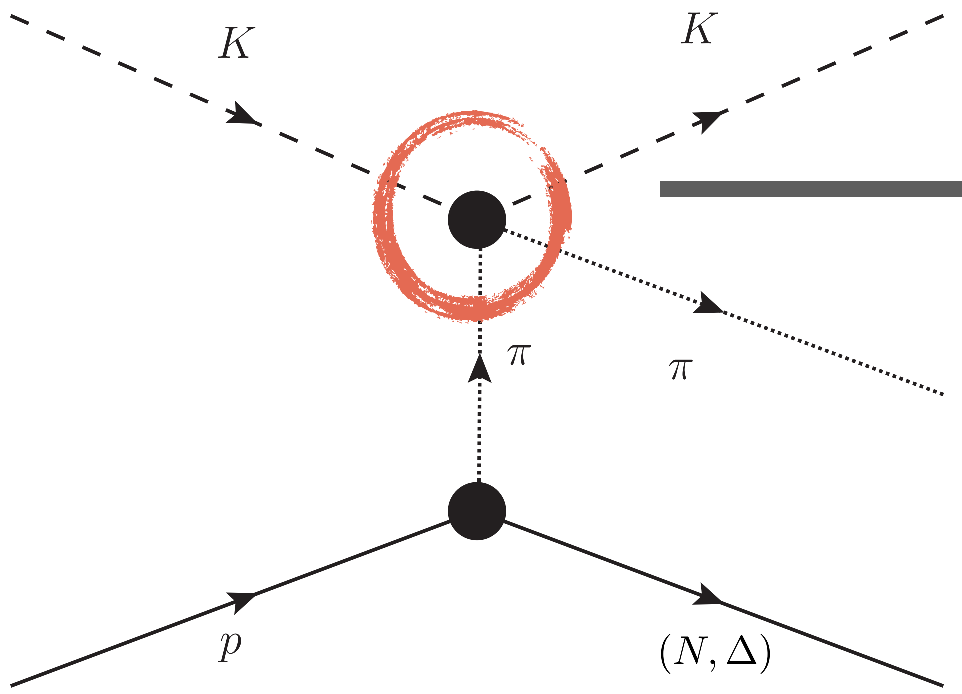


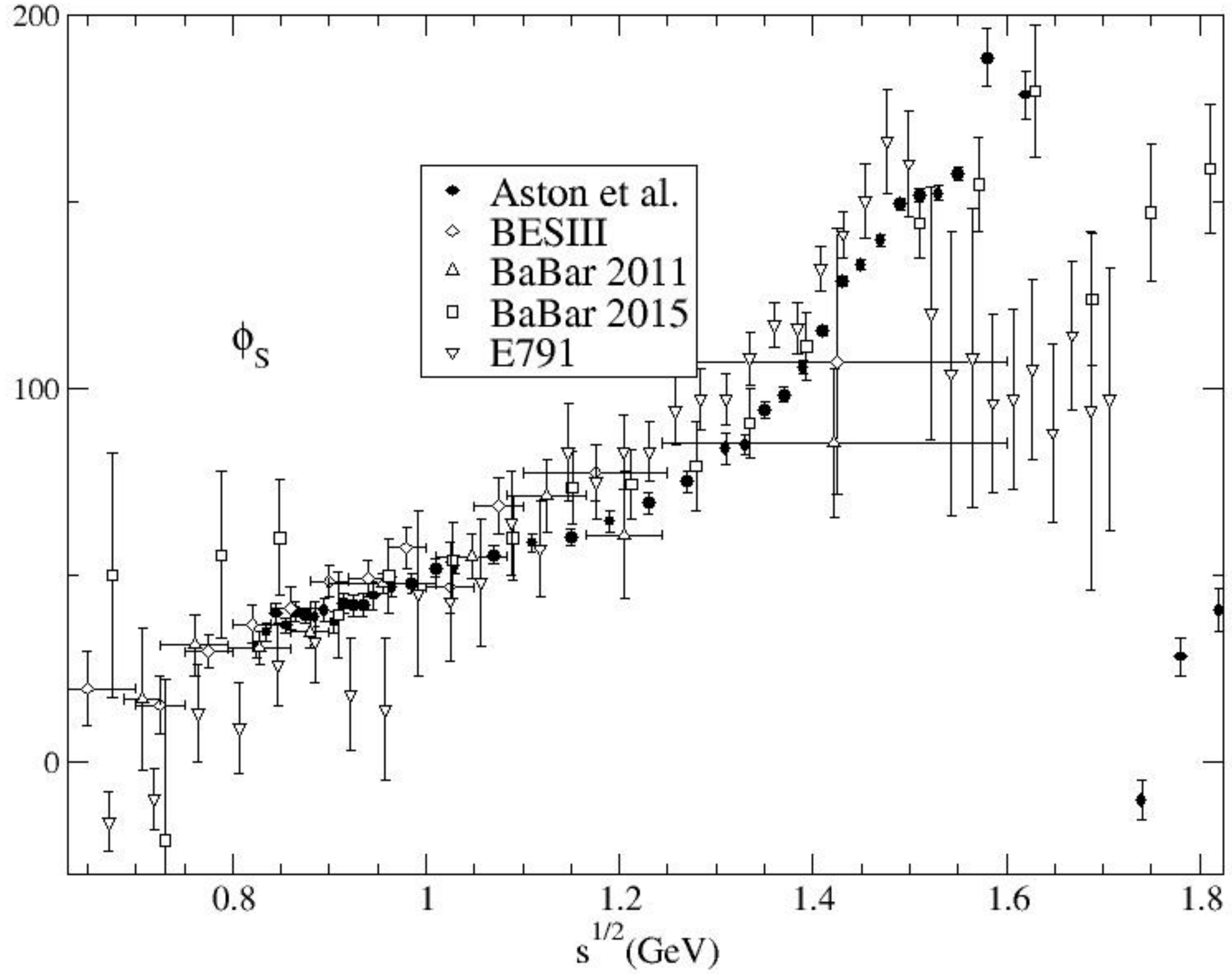


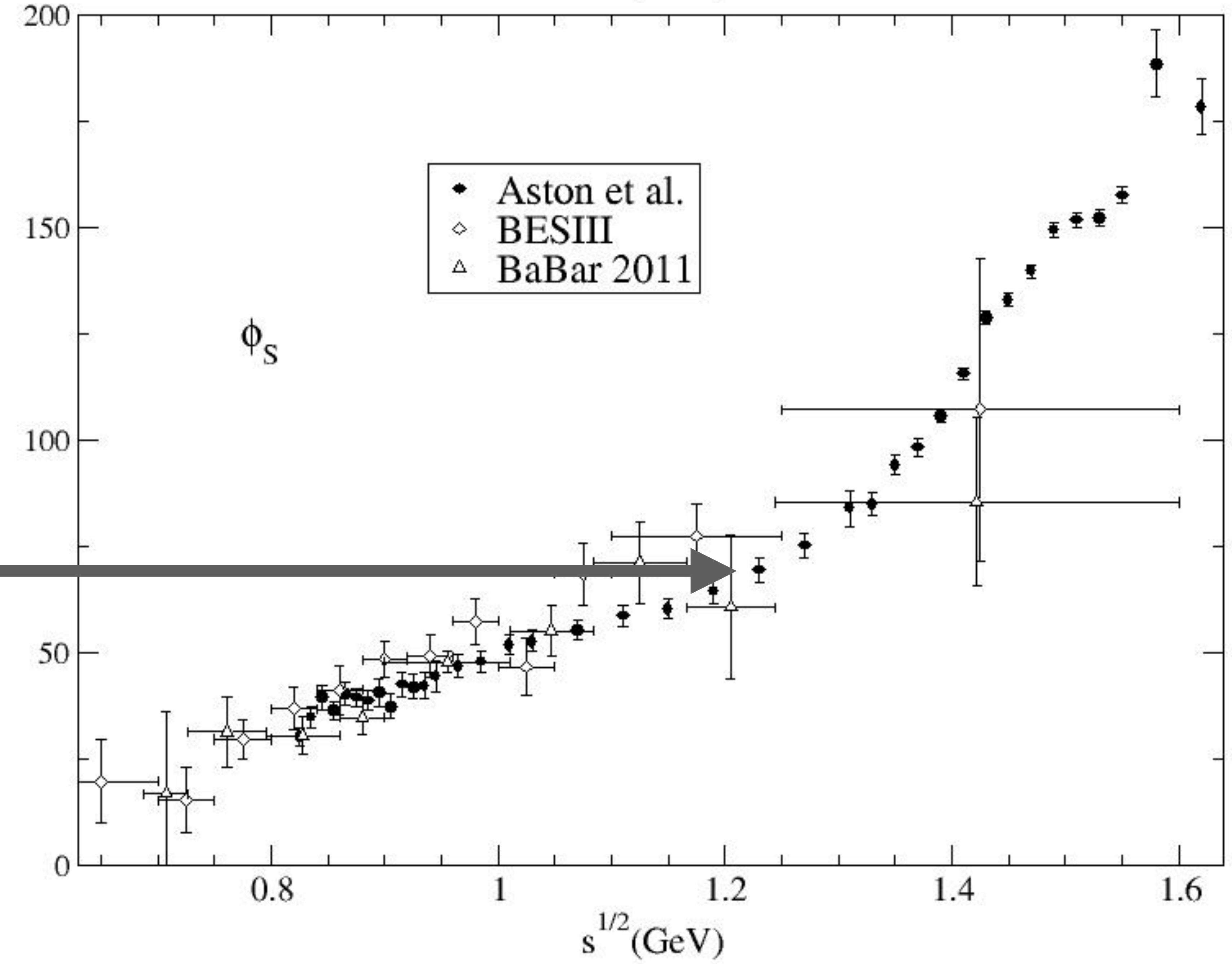
Semileptonic decays do not have great statistics



Production offers most precise results, by far

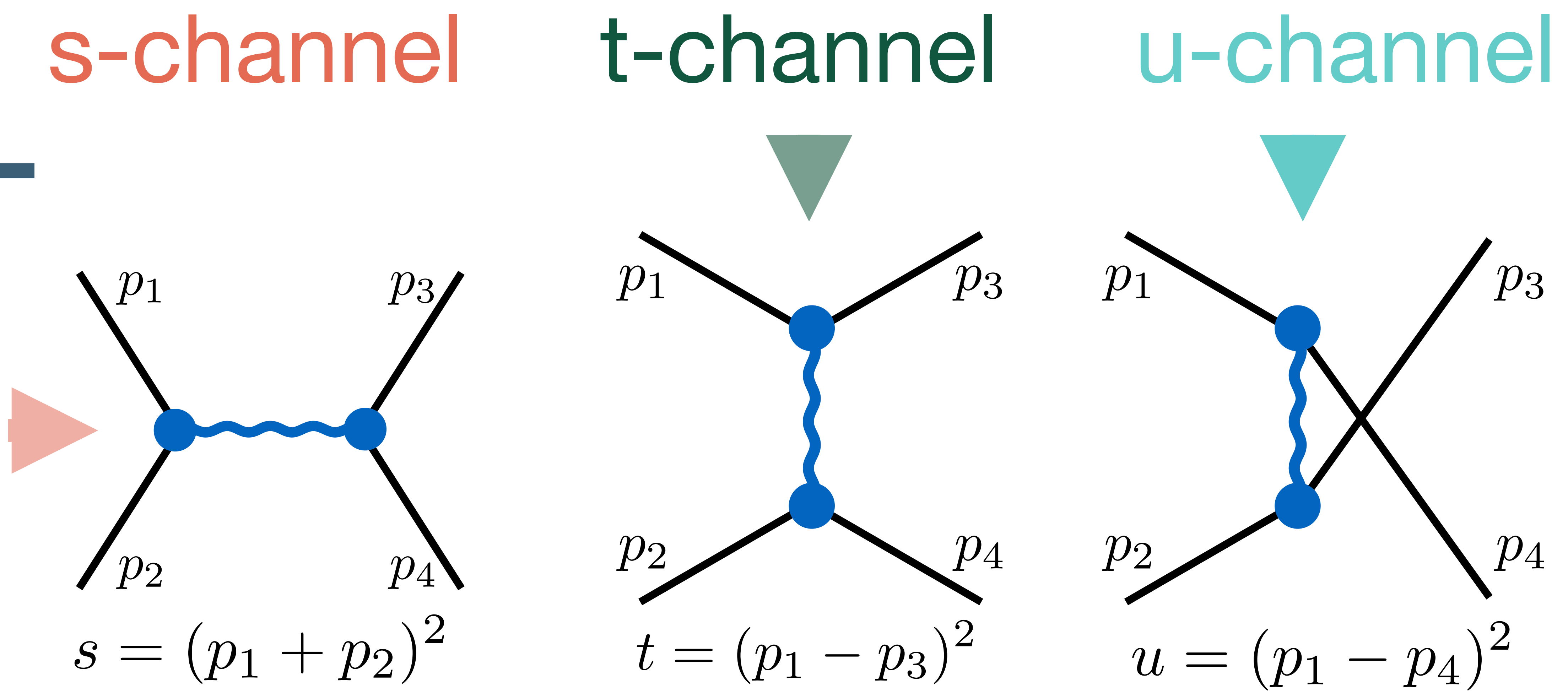






Best theoretical technique: Dispersion relations

Dispersion relations: $\pi\pi$ example



Particles and anti-particles are related

Crossing symmetry relates amplitudes in different channels and isospins

$$F^0(s,t) = \frac{1}{3}F^{(0)}(s,t) + F^{(1)}(s,t) + \frac{5}{3}F^{(2)}(s,t), \quad F^1(s,t) = \frac{1}{3}F^{(0)}(s,t) + \frac{1}{2}F^{(1)}(s,t) - \frac{5}{6}F^{(2)}(s,t), \quad F^2(s,t) = \frac{1}{3}F^{(0)}(s,t) - \frac{1}{2}F^{(1)}(s,t) + \frac{1}{6}F^{(2)}(s,t)$$

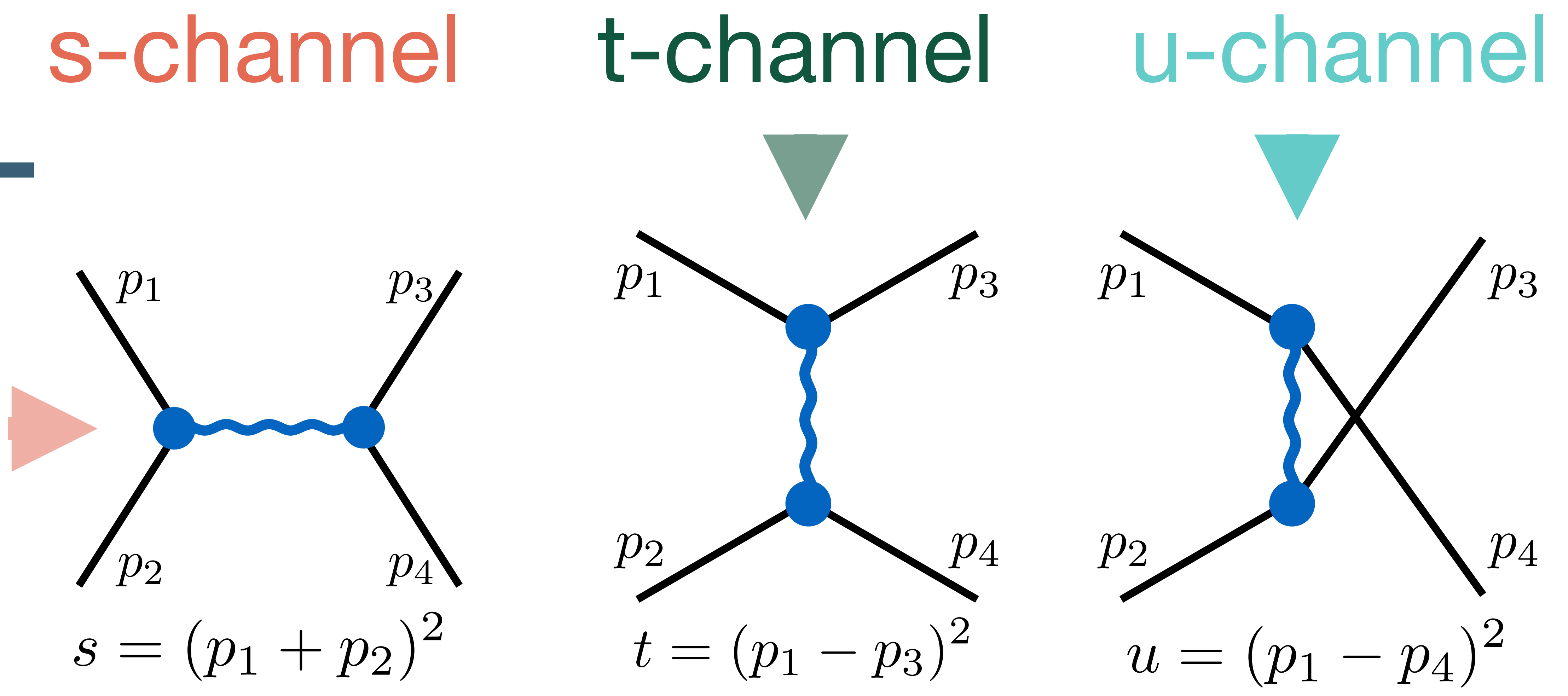
Mandelstam hyphotesis (all related to a singular analytic amplitude)

$$F^{I=0}(s,t,u) = 3\,F(s,t,u) + F(t,s,u) + F(u,t,s), \quad F^{I=1}(s,t,u) = F(t,s,u) - F(u,t,s), \quad F^{I=2}(s,t,u) = F(t,s,u) + F(u,t,s)$$

Dispersion relations offer a framework, by construction, to impose crossing symmetry

$$\mathrm{Re}\,\tilde{f}^I_\ell(s) = \mathrm{ST}^I_\ell(s) + \mathrm{DT}^I_\ell(s) + \sum_{\ell' I'} \mathrm{P.V.}\int_{4m_\pi^2}^{\infty} ds'\; K^{I,I'}_{\ell,\ell'}(s,s')\;\mathrm{Im}\;f^{I'}_{\ell'}(s')$$

Dispersion relations: $\pi\pi$ example



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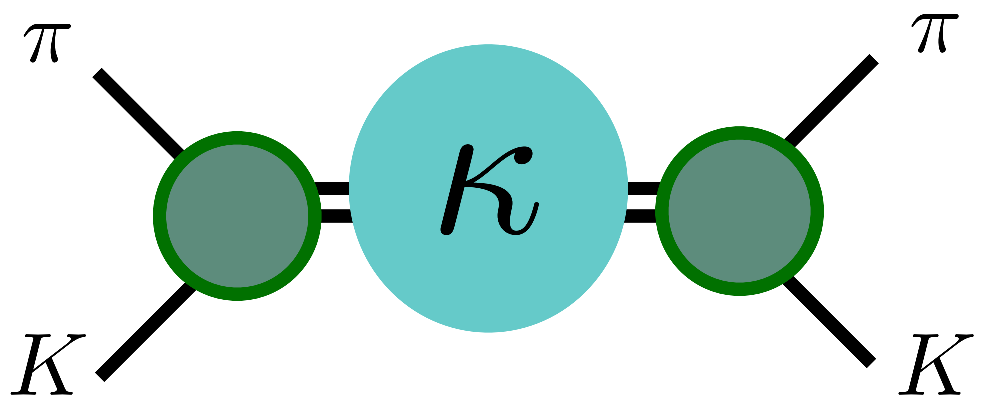
The PW we want   *All the relevant PWs contribute*

Main problem: The κ

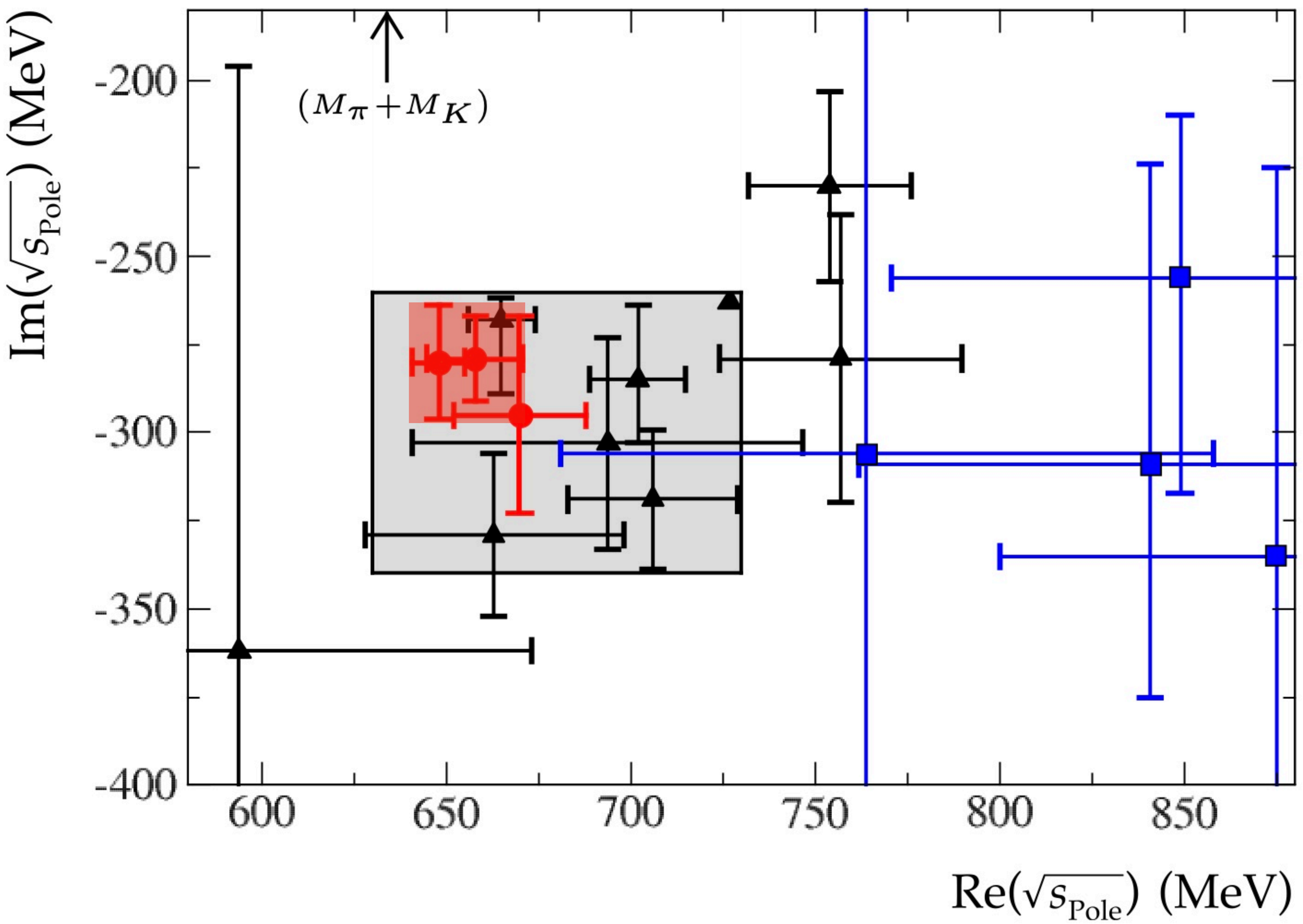
Over 50 years of debate!!



PDG then

"We are beginning to think that κ should be classified along with flying saucers, the Loch Ness Monster, and the Abominable Snowman."

PDG now



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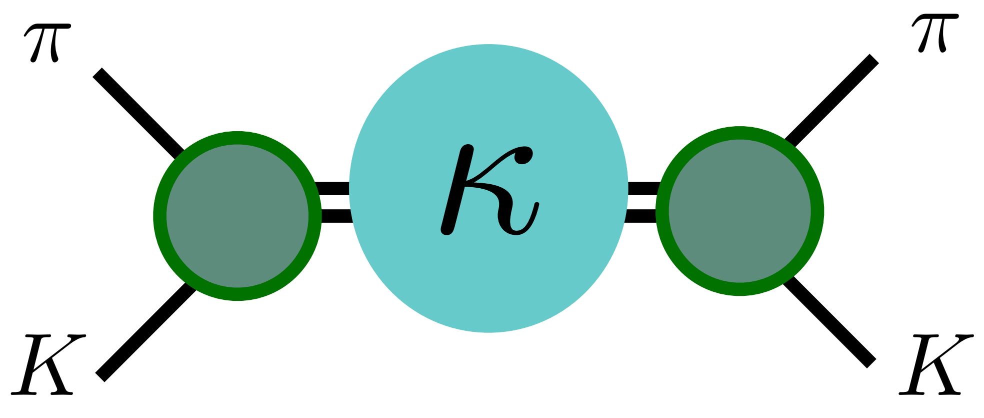

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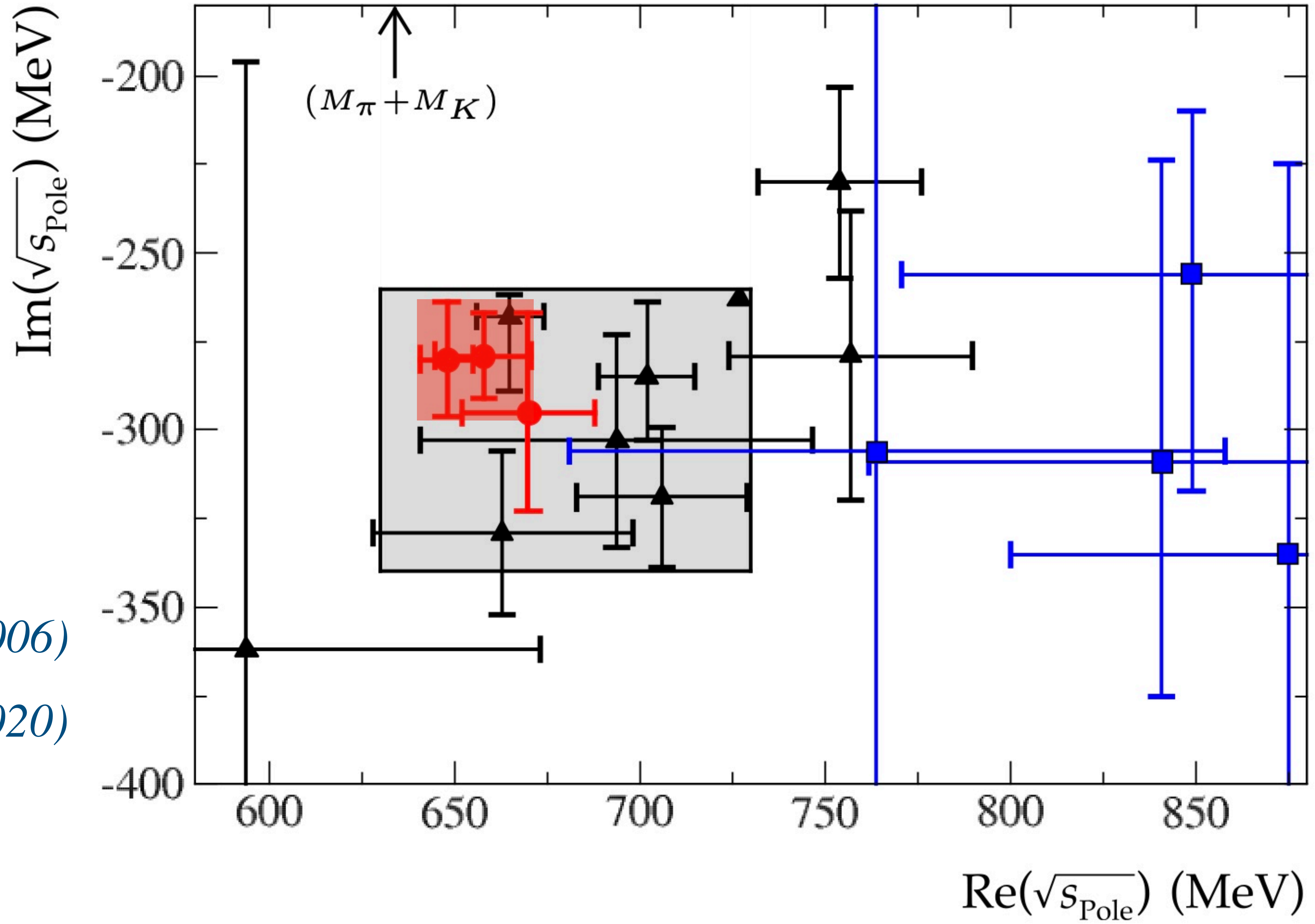
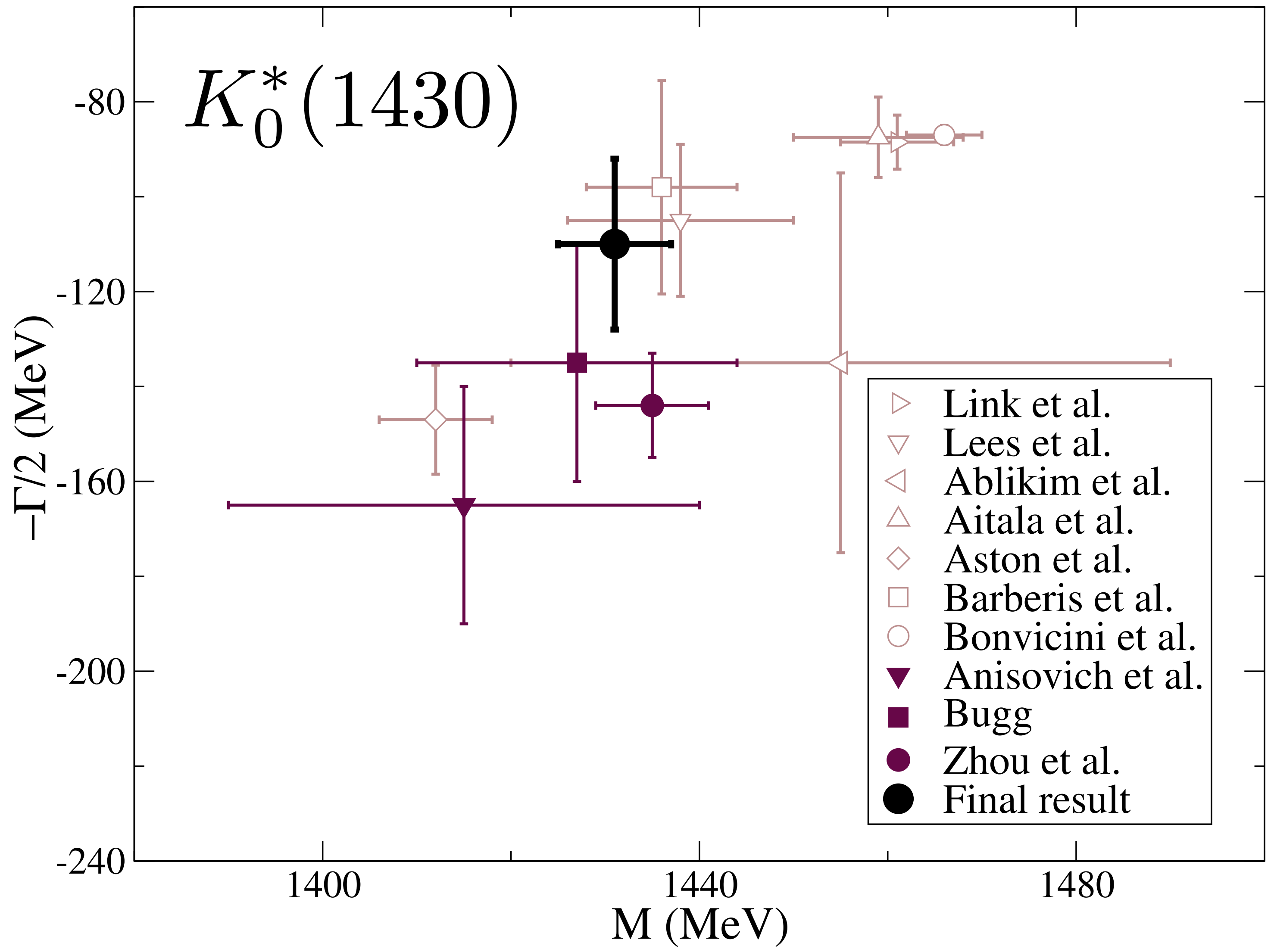
Eur.Phys.J.C 48 (2006)

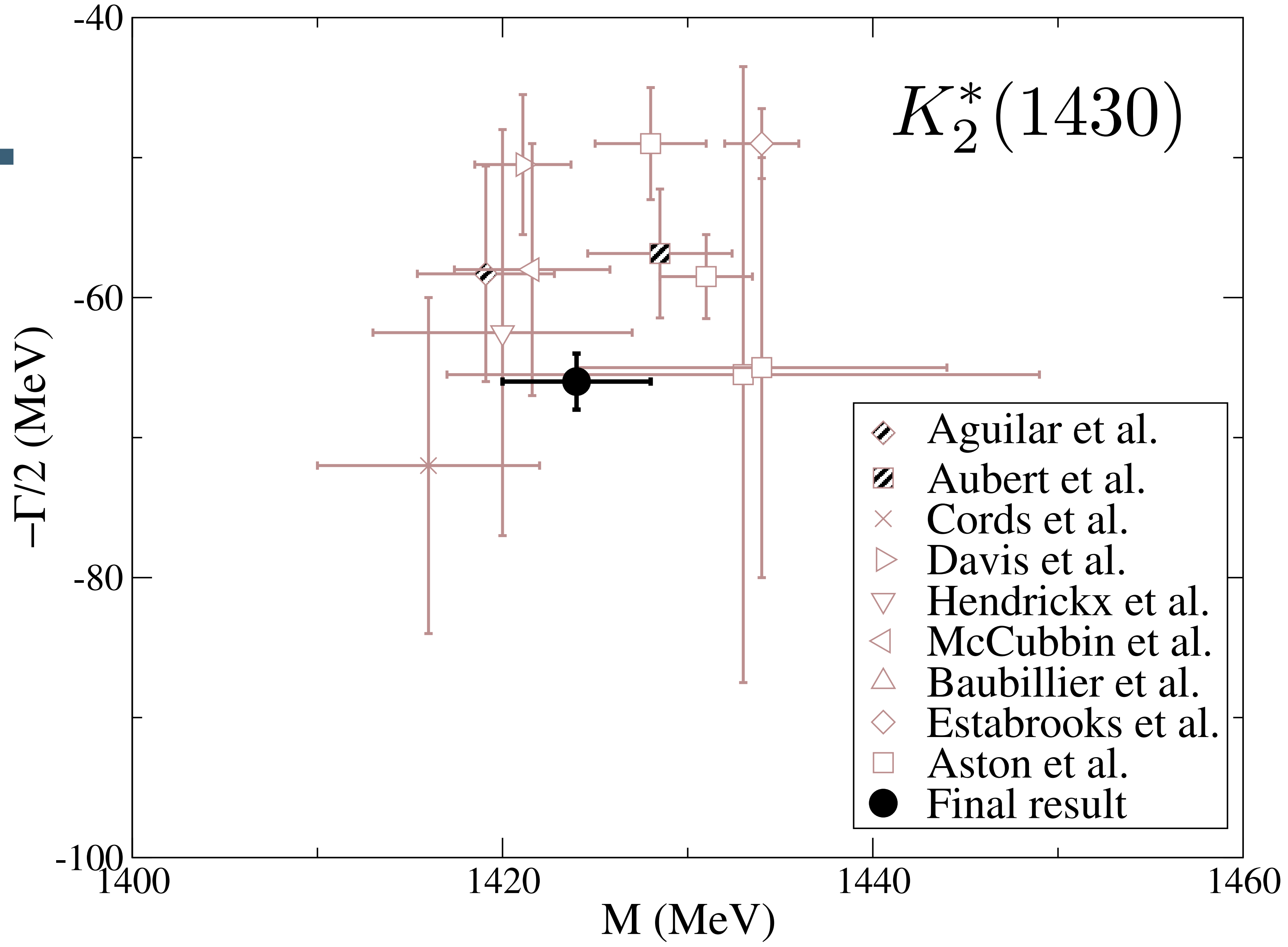
Phys.Rev.Lett. 124 (2020)



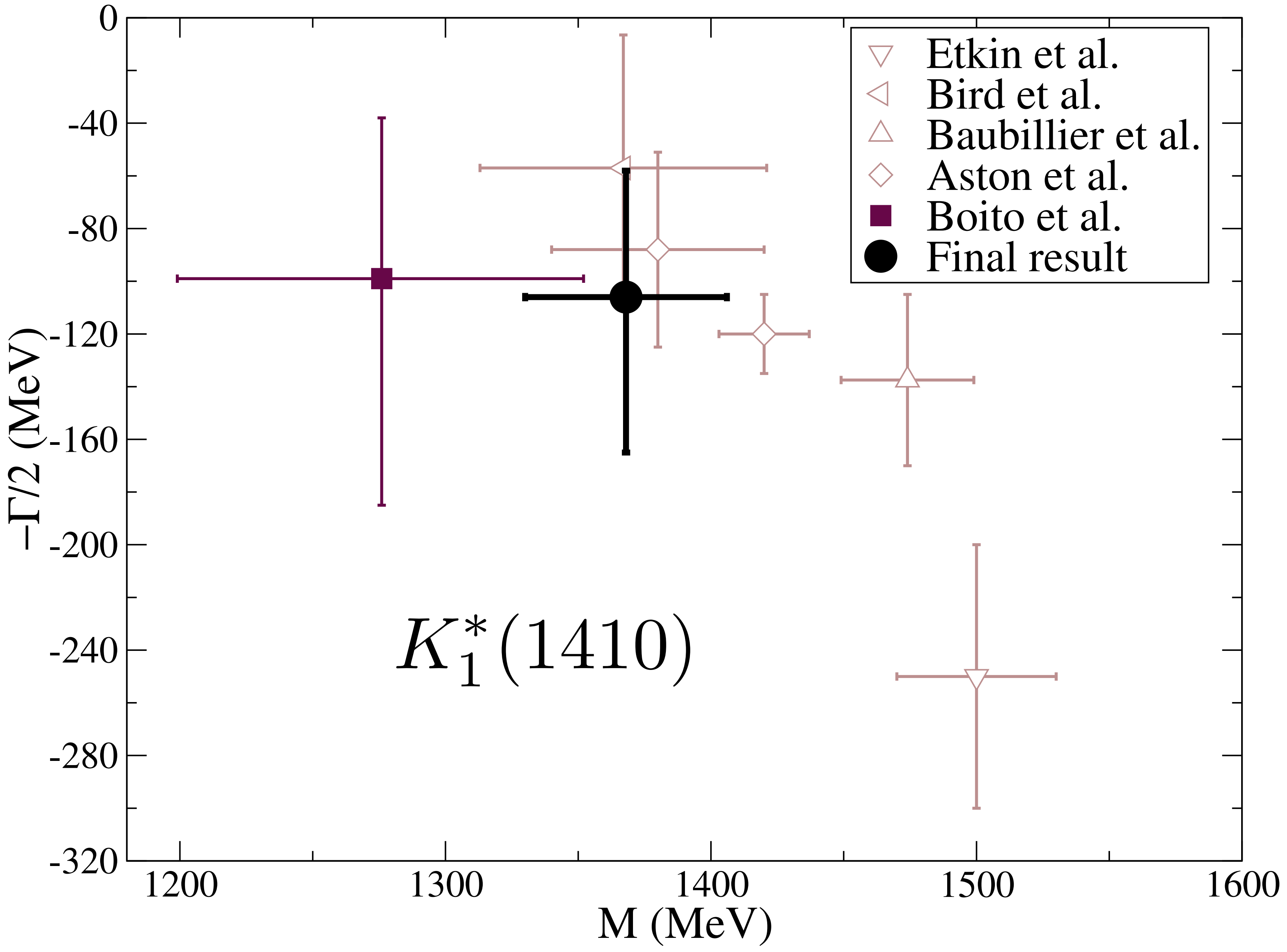
Main problem: Other resonances

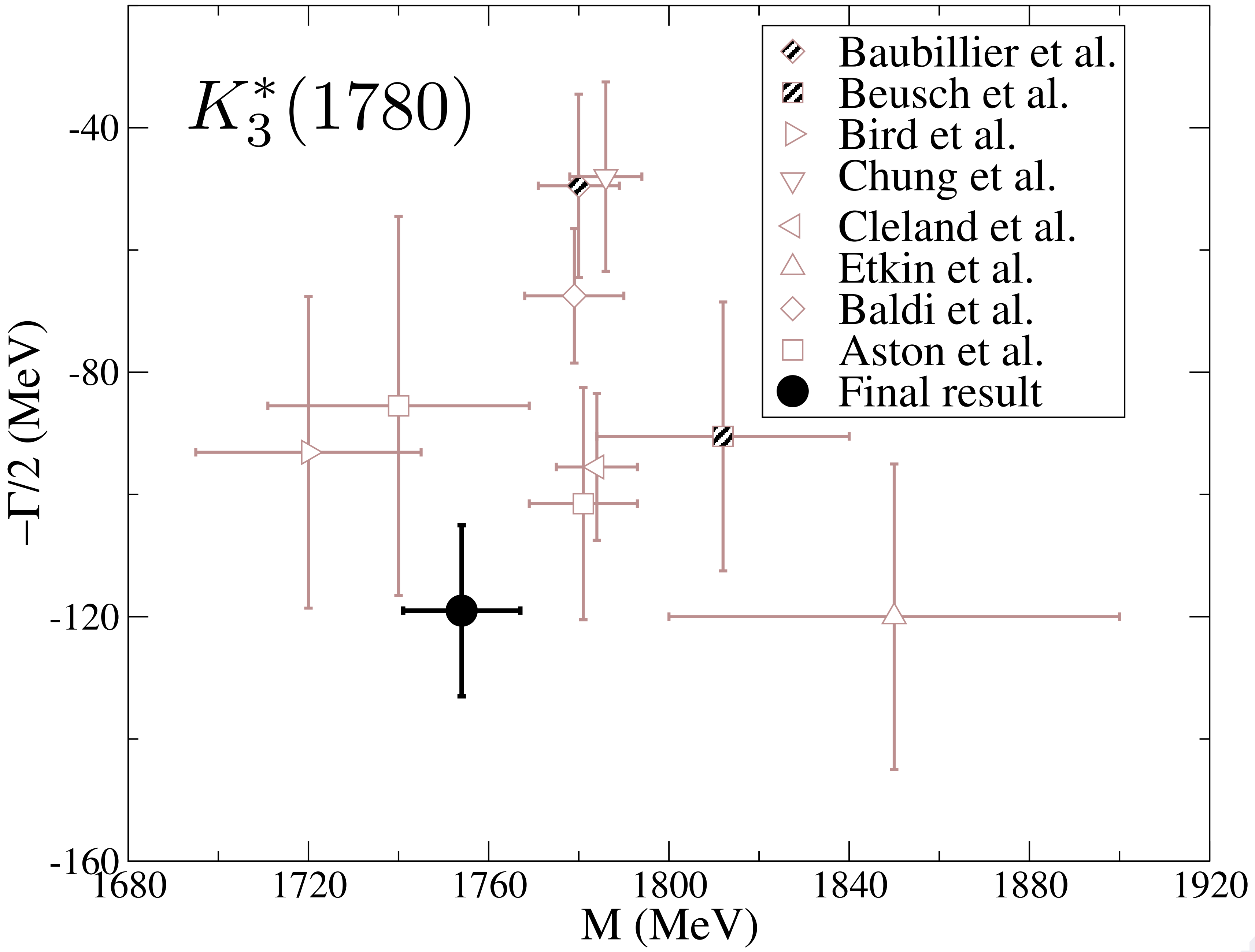
Heavier K^* are poorly known





Different production mechanisms lead to not very consistent results





Scattering should provide a clean extraction of these states

Recent applications: Heavier particles

K_0^*

Second lightest resonance

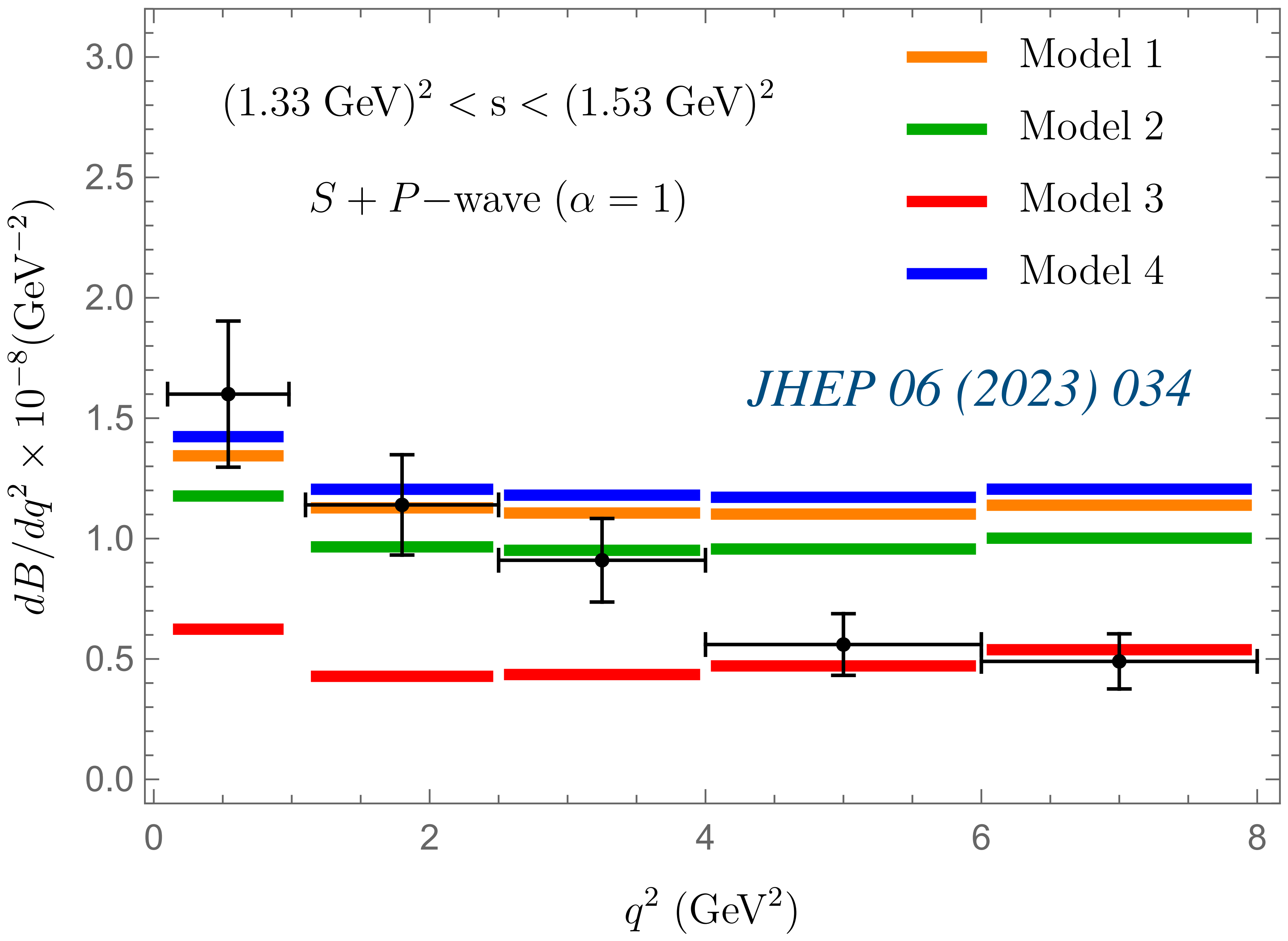
Extremely broad → extremely short-lived

Correlated with chiral symmetry-breaking phenomena

Not well-understood → new observables ??

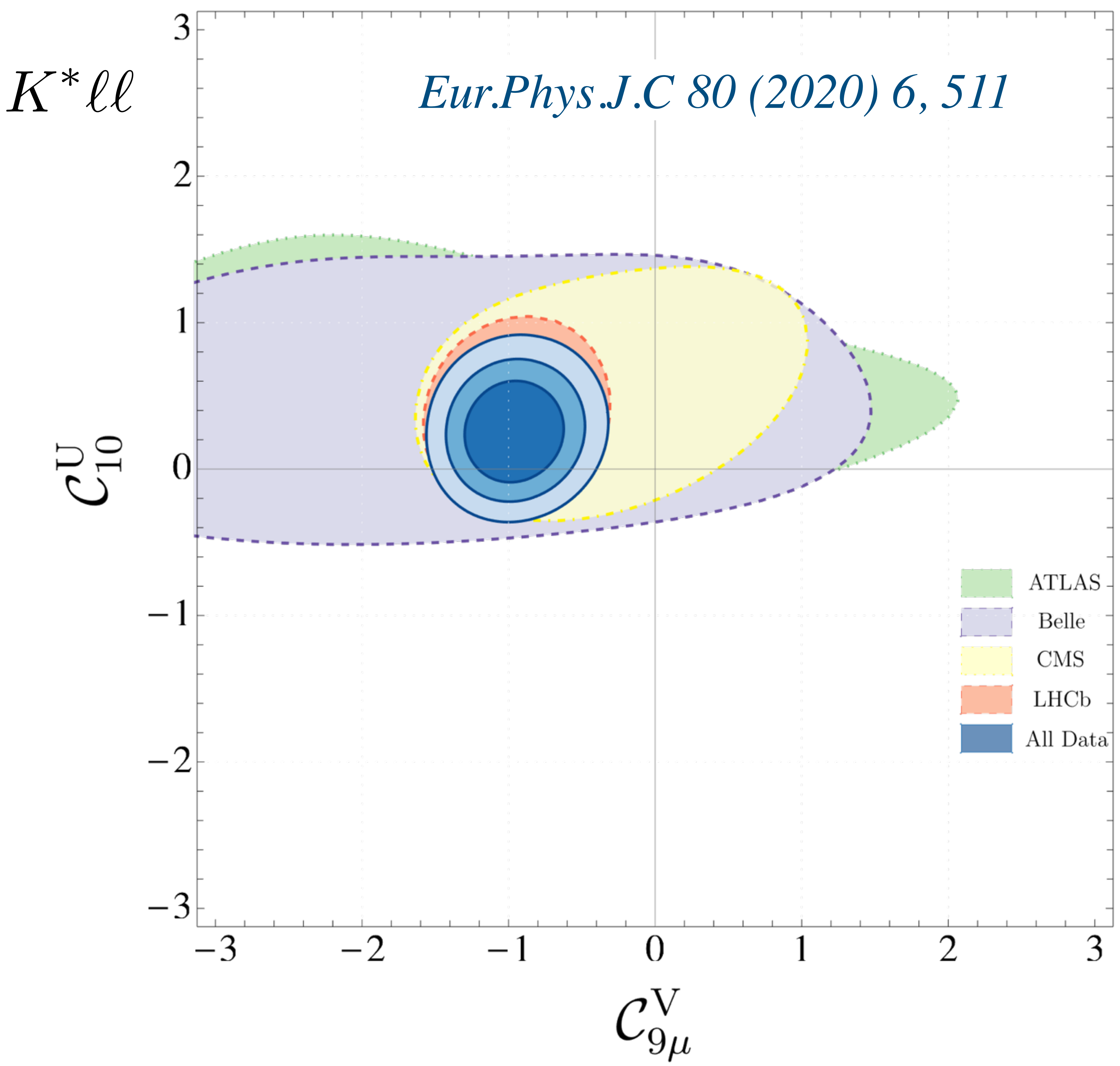
Input to hadron physics observables

$B \to K\pi$



$B \to K^* \ell\ell$

K_0^* K^*



Recent applications: Heavier particles

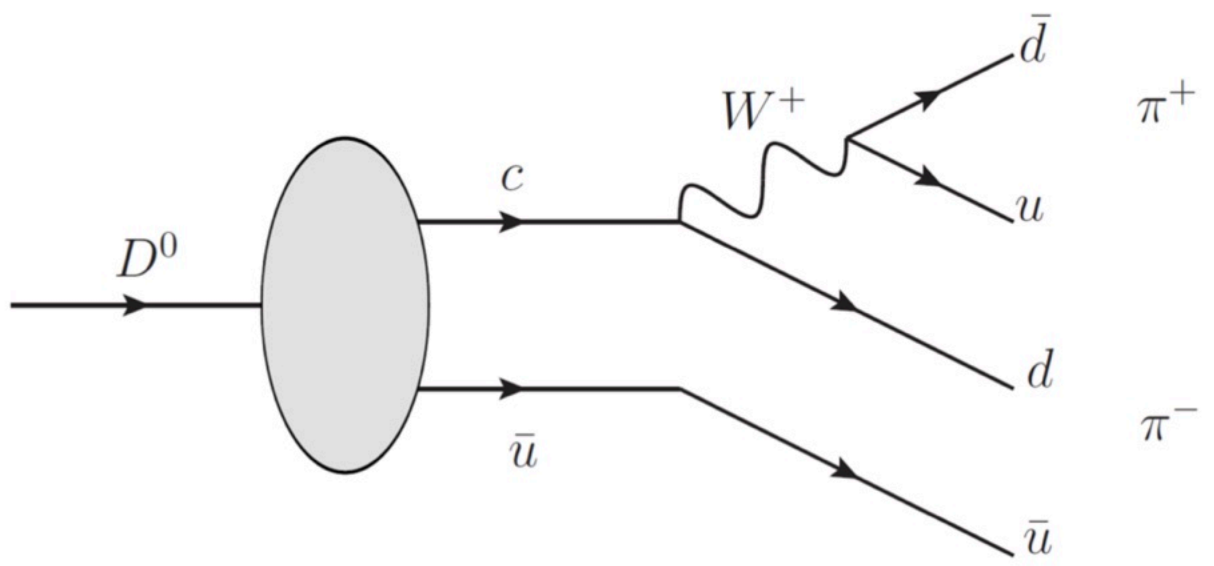
Understanding decays of charmonia and bottomonia

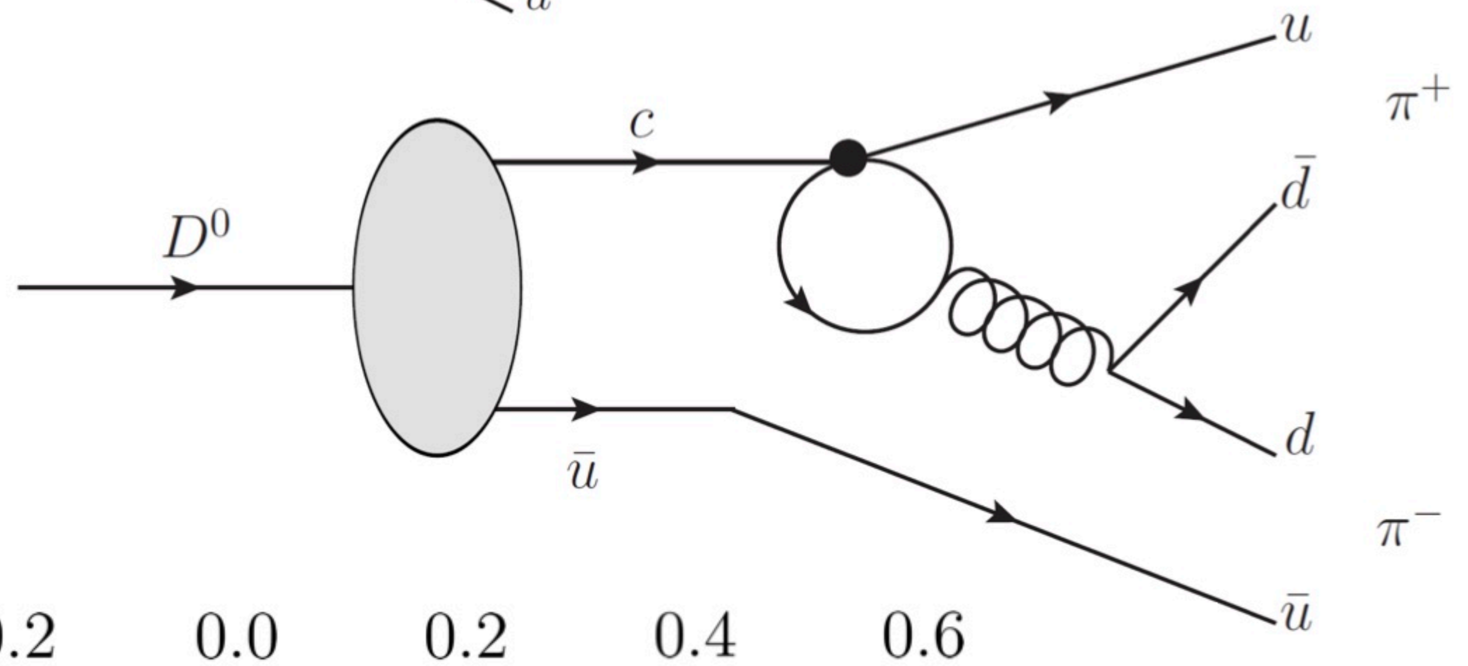
Lineshapes dominated by final state interactions (FSI)

$$D^0 \to \pi^+\pi^- \qquad D^0 \to K^+K^-$$

$$B^\pm \to K^\pm\pi^+\pi^- \qquad B^\pm \to \pi^\pm K^+K^-$$

$$B^+ \to \pi^+\pi^+\pi^-$$



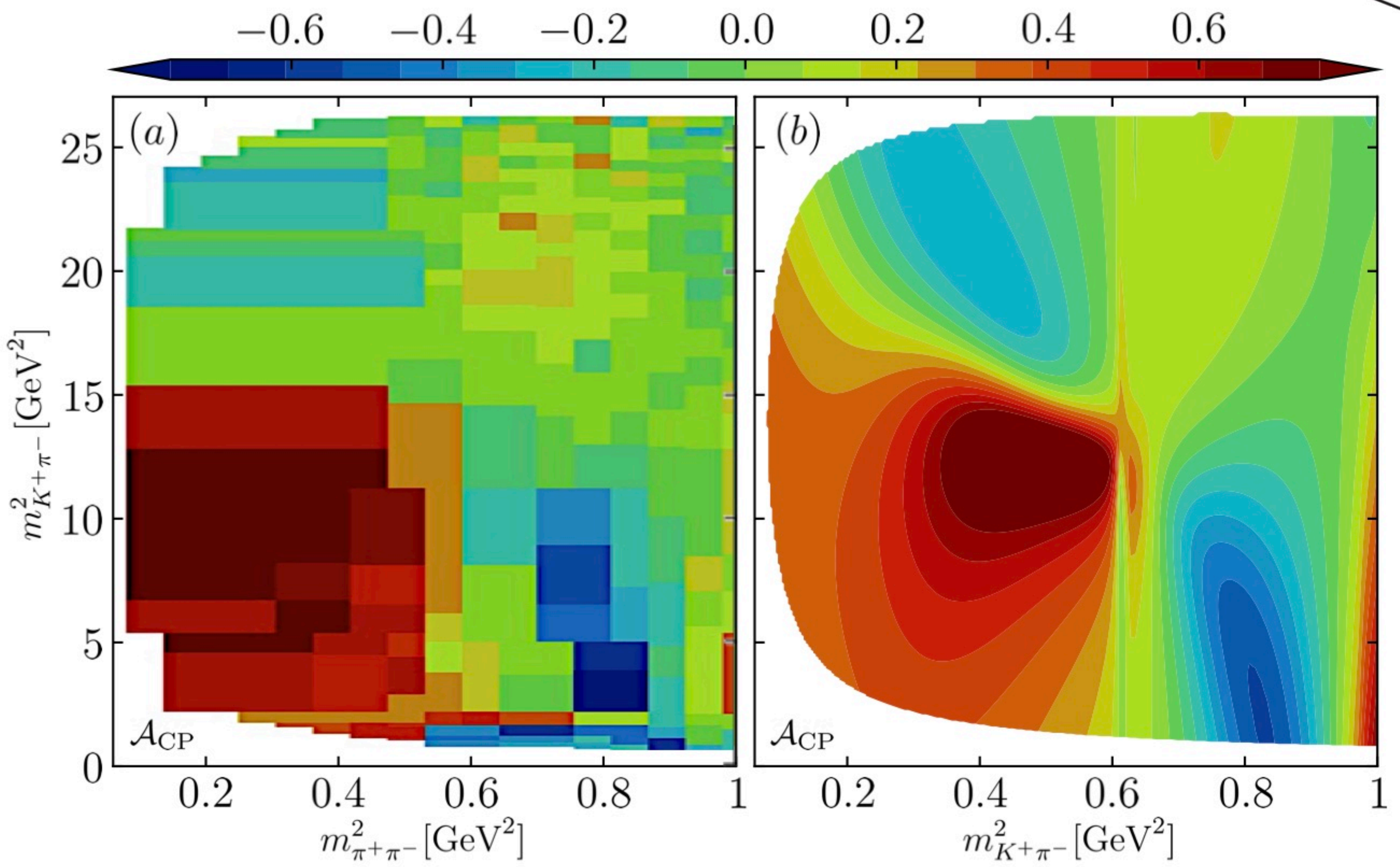


Understanding CP violation in this sector

Largest violating signal in these decays

Phys.Rev.Lett. 130 (2023) 20, 201901

Phys.Rev.Lett. 136 (2026) 11, 111901

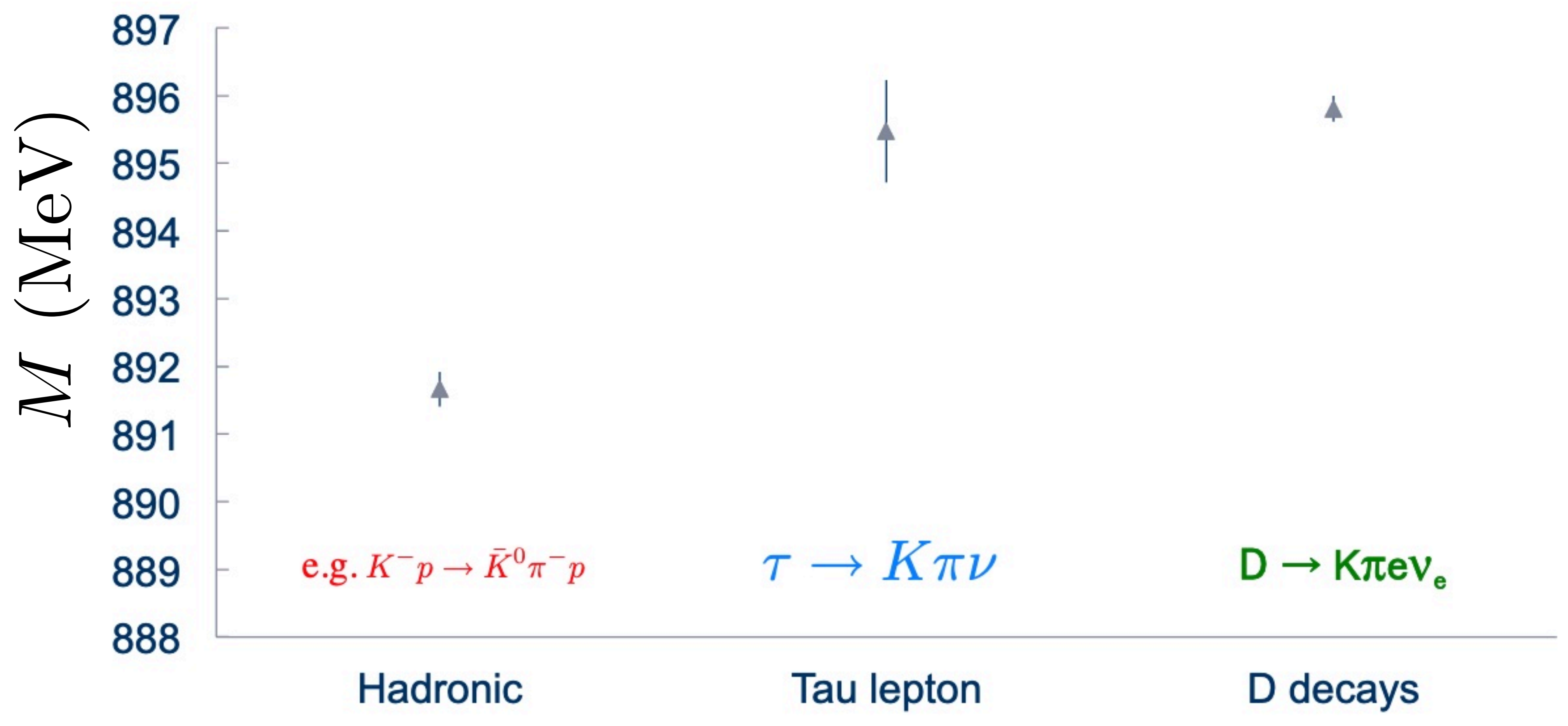


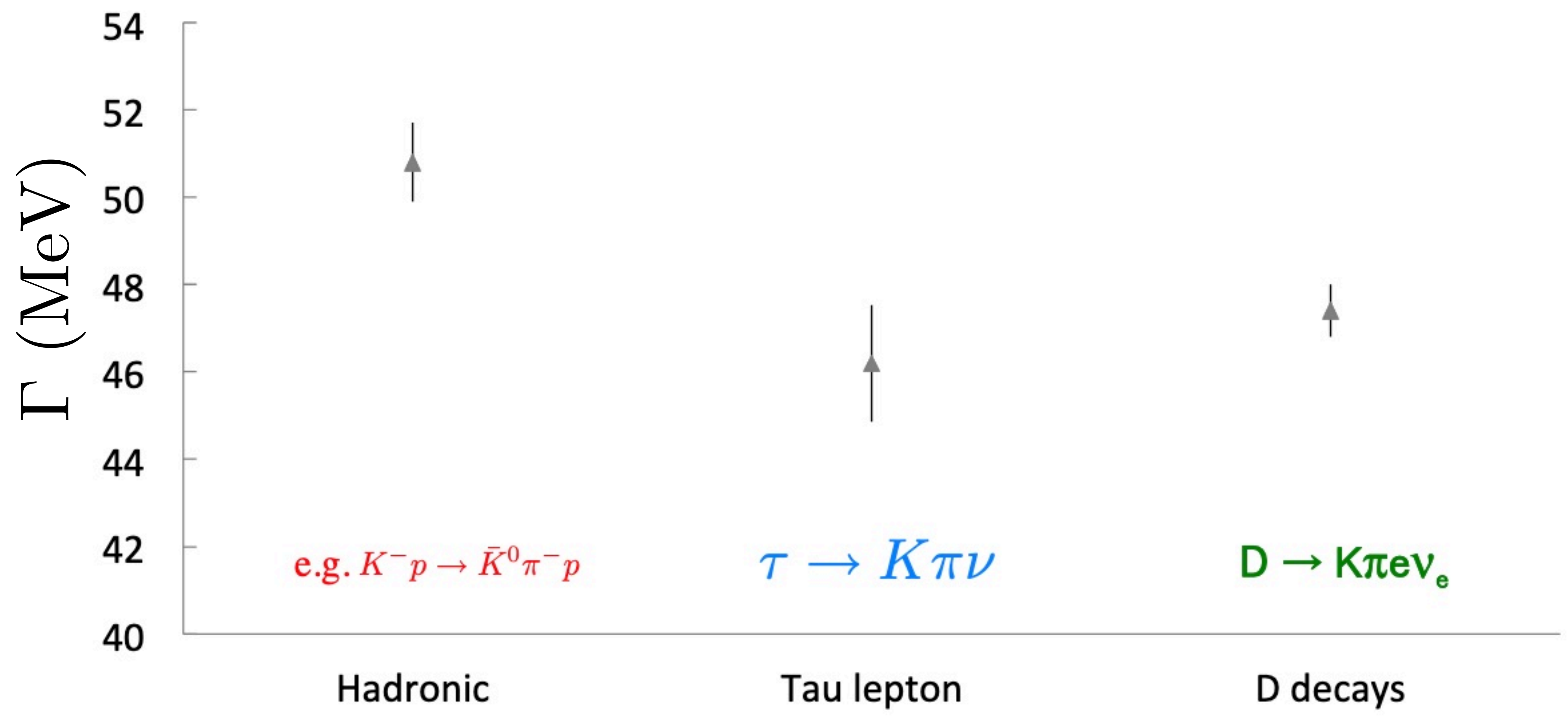
$$B^\pm \to K^\pm\pi^+\pi^-$$

Other decays related to precision physics

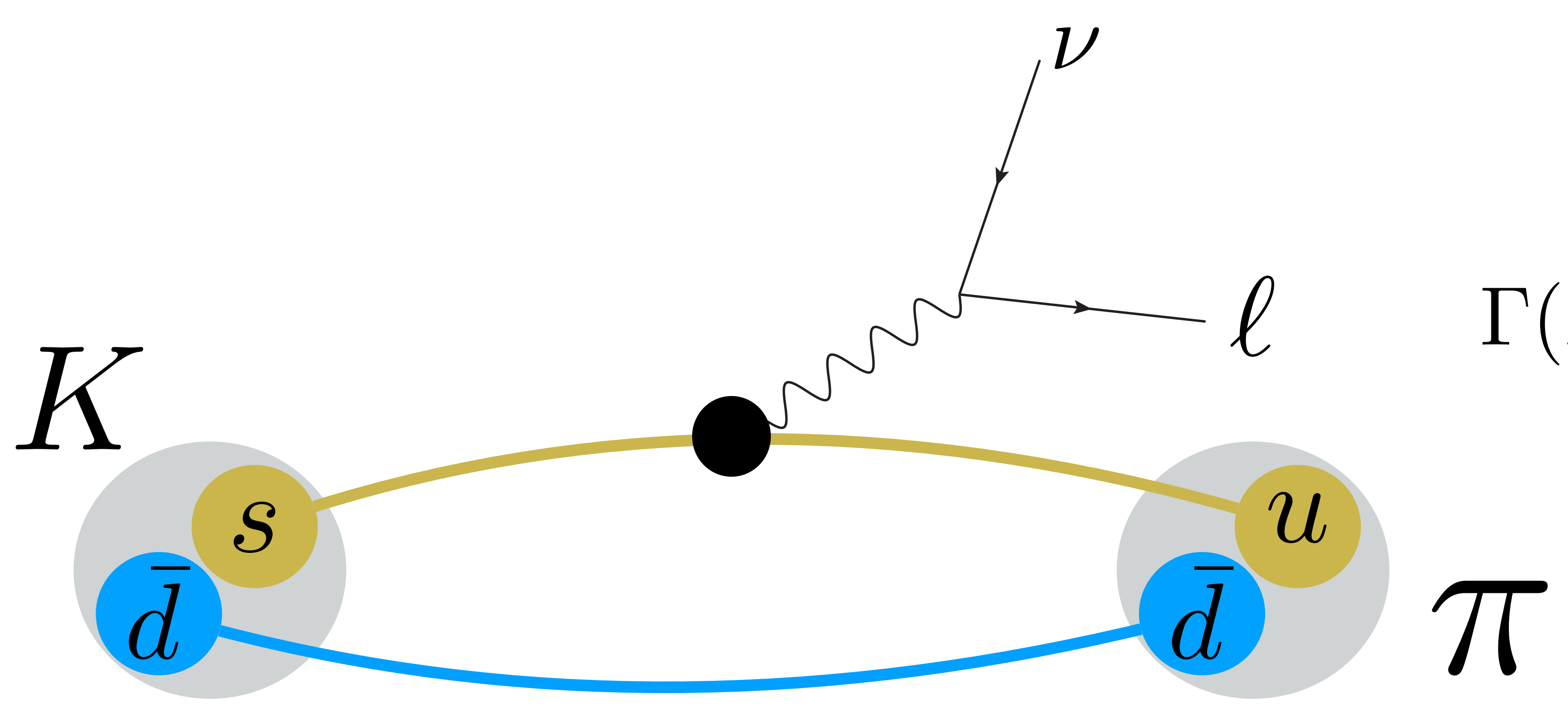
Other applications: EW physics

Not even the narrow $K^*(892)$ is so well known





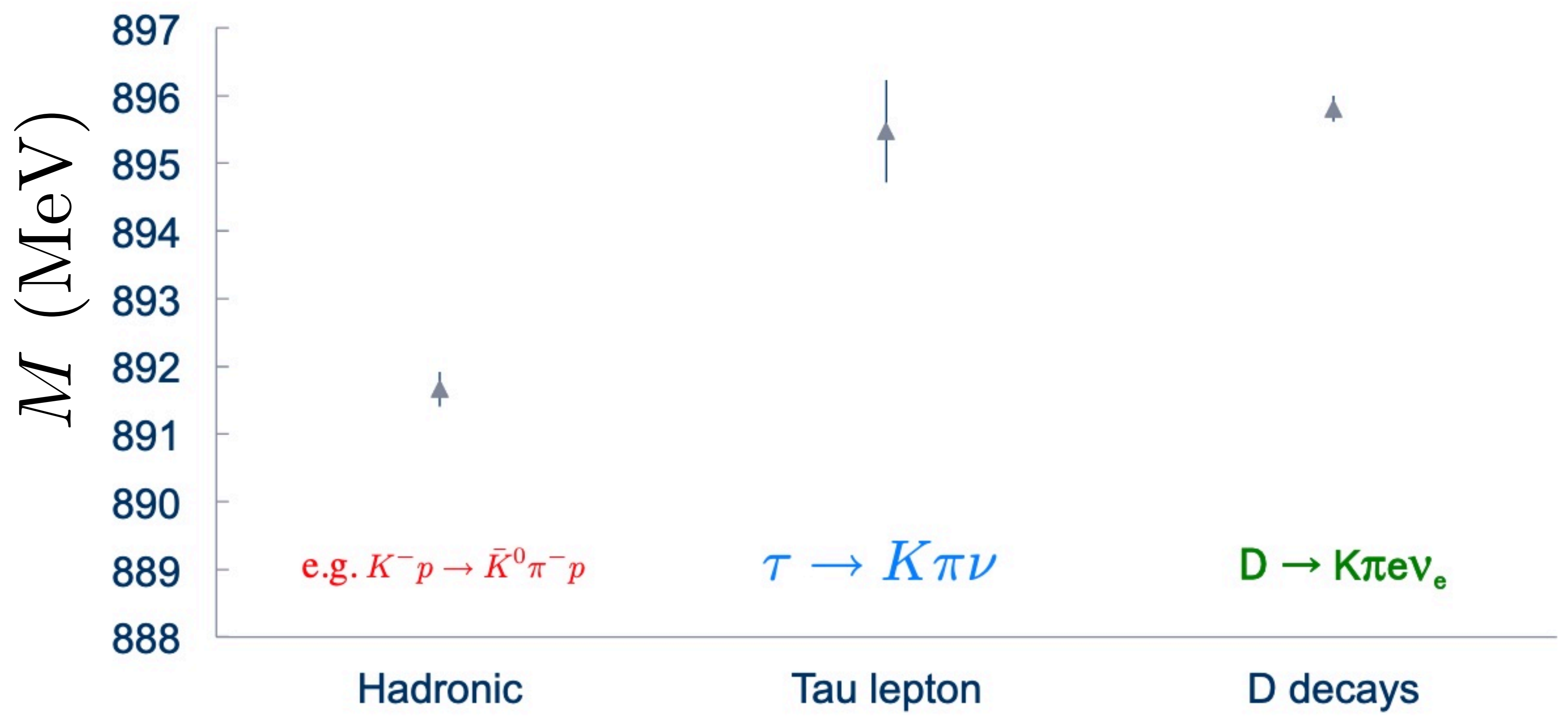
Flavor determinations and BSM searches often rely on hadronic determinations as input

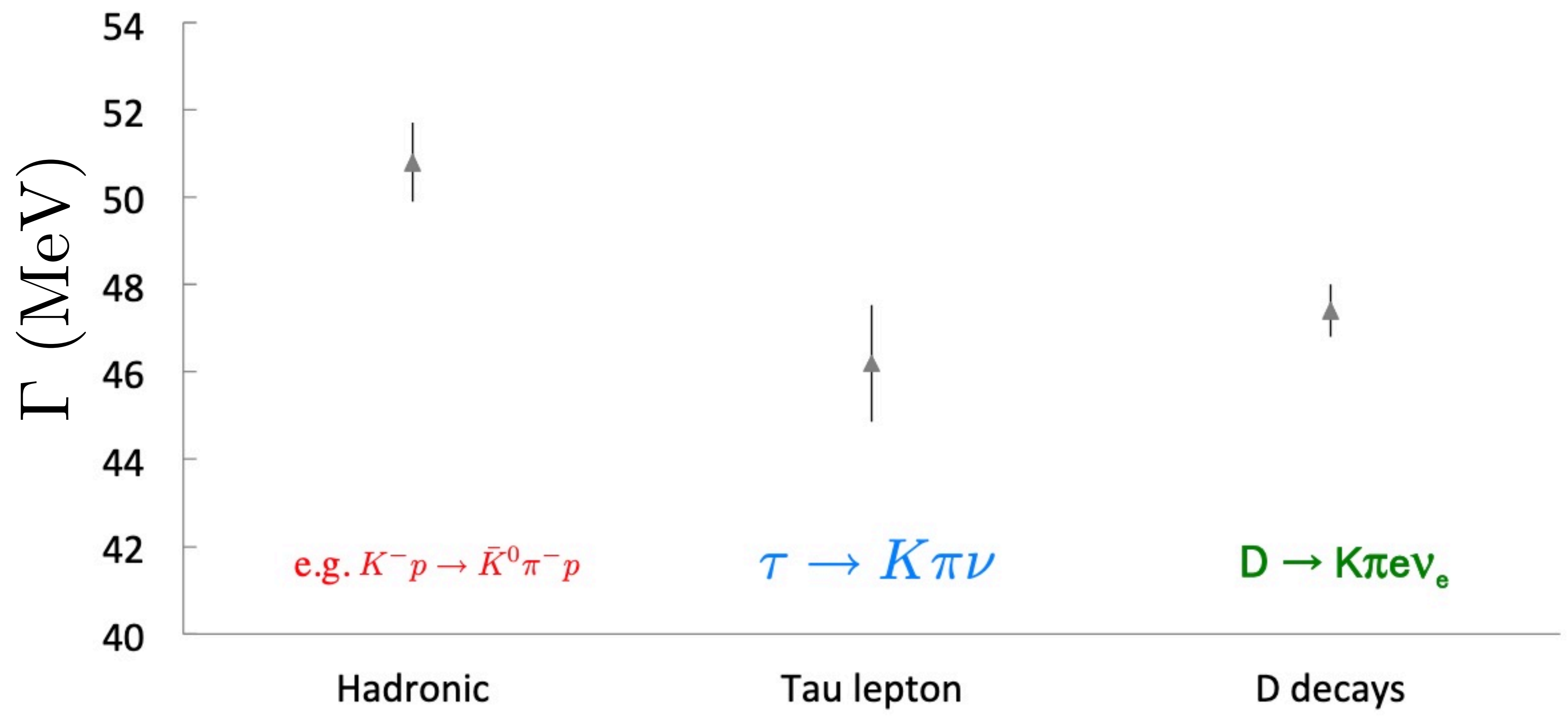


$$\Gamma(K \to \pi l v[\gamma]) = \frac{G_F^2 m_K^5}{192\pi^3} C_K^2 S_E^K \, |V_{us}|^2 \left| f_+^{K^0\pi^-}(0) \right|^2 I_K^l \left(1 + \delta_{\rm EM}^{Kl} + \delta_{\rm SU(2)}^{K\pi}\right)^2$$

Other applications: EW physics

Not even the narrow $K^*(892)$ is so well known





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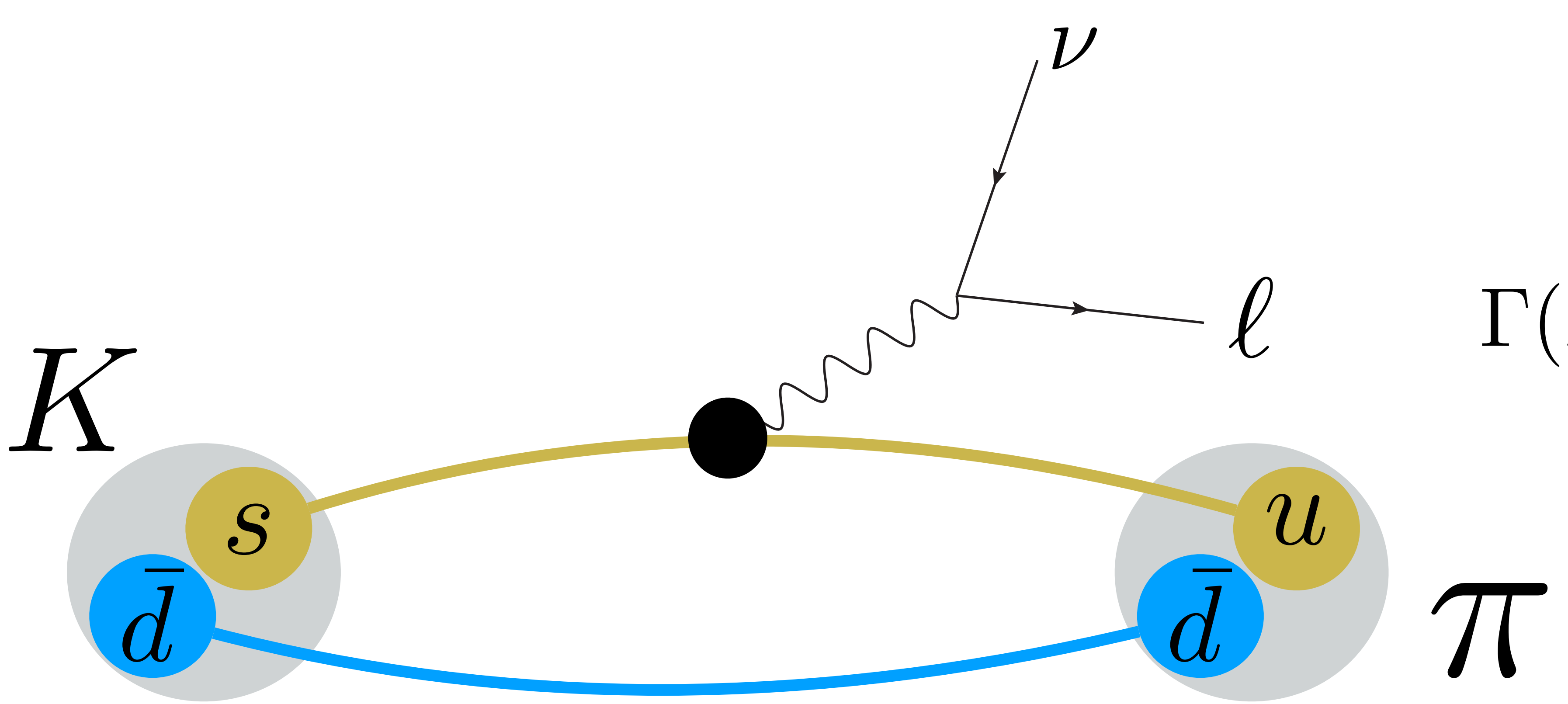

CKM

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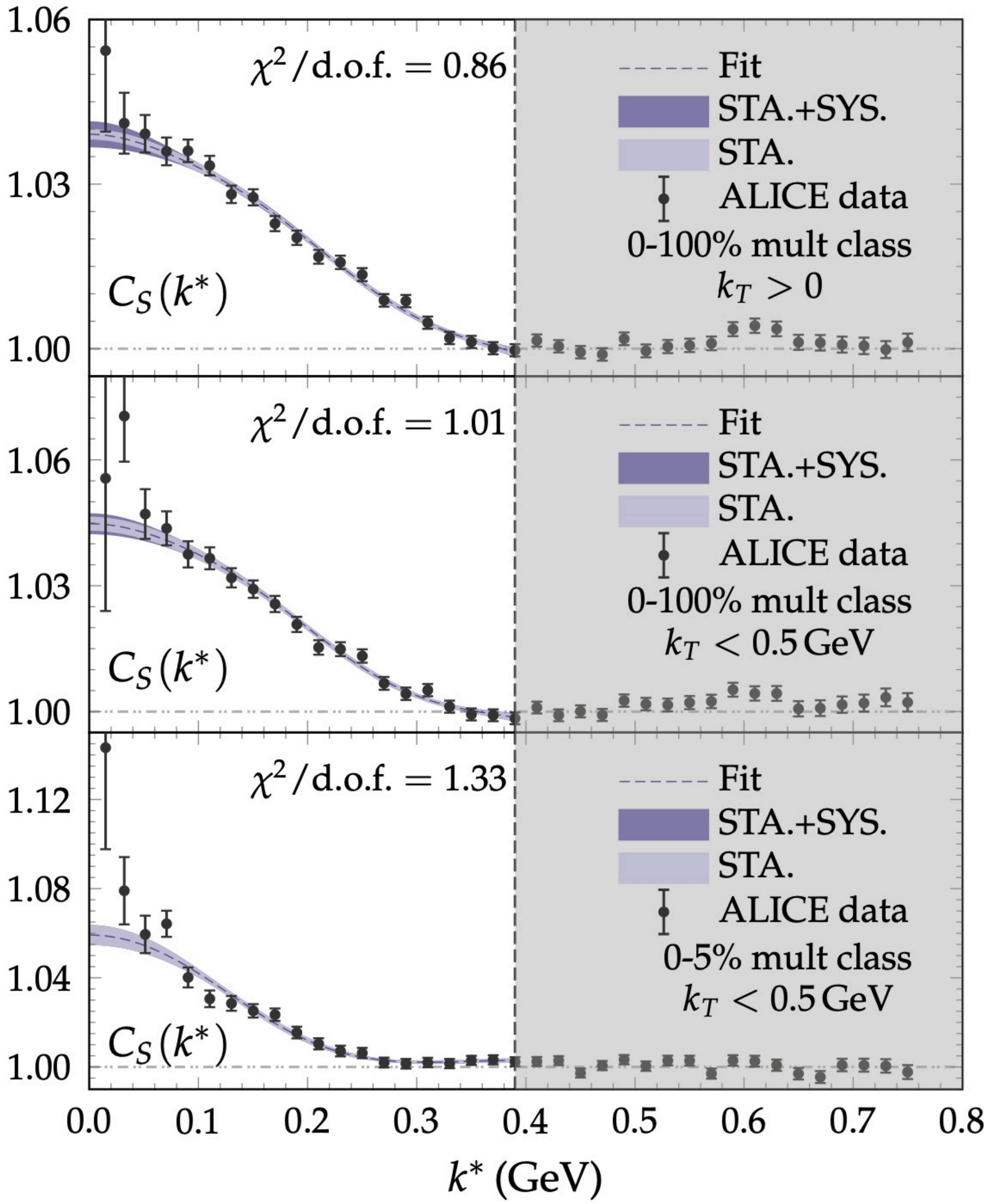
Vector+Scalar πK form factors

Recent applications: Femtoscopy

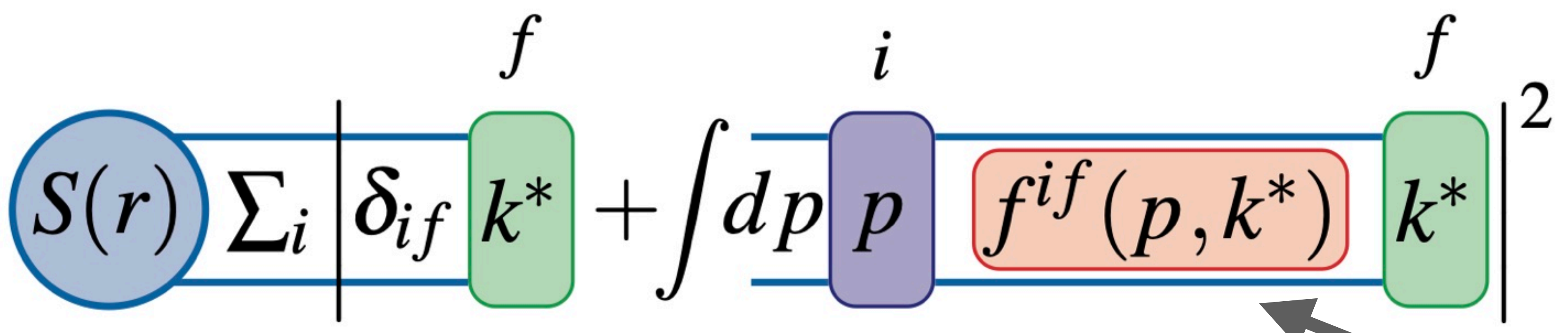
ALICE femtoscopy program is devoted to resonance structure studies

Phys.Lett.B 856 (2024) 138915



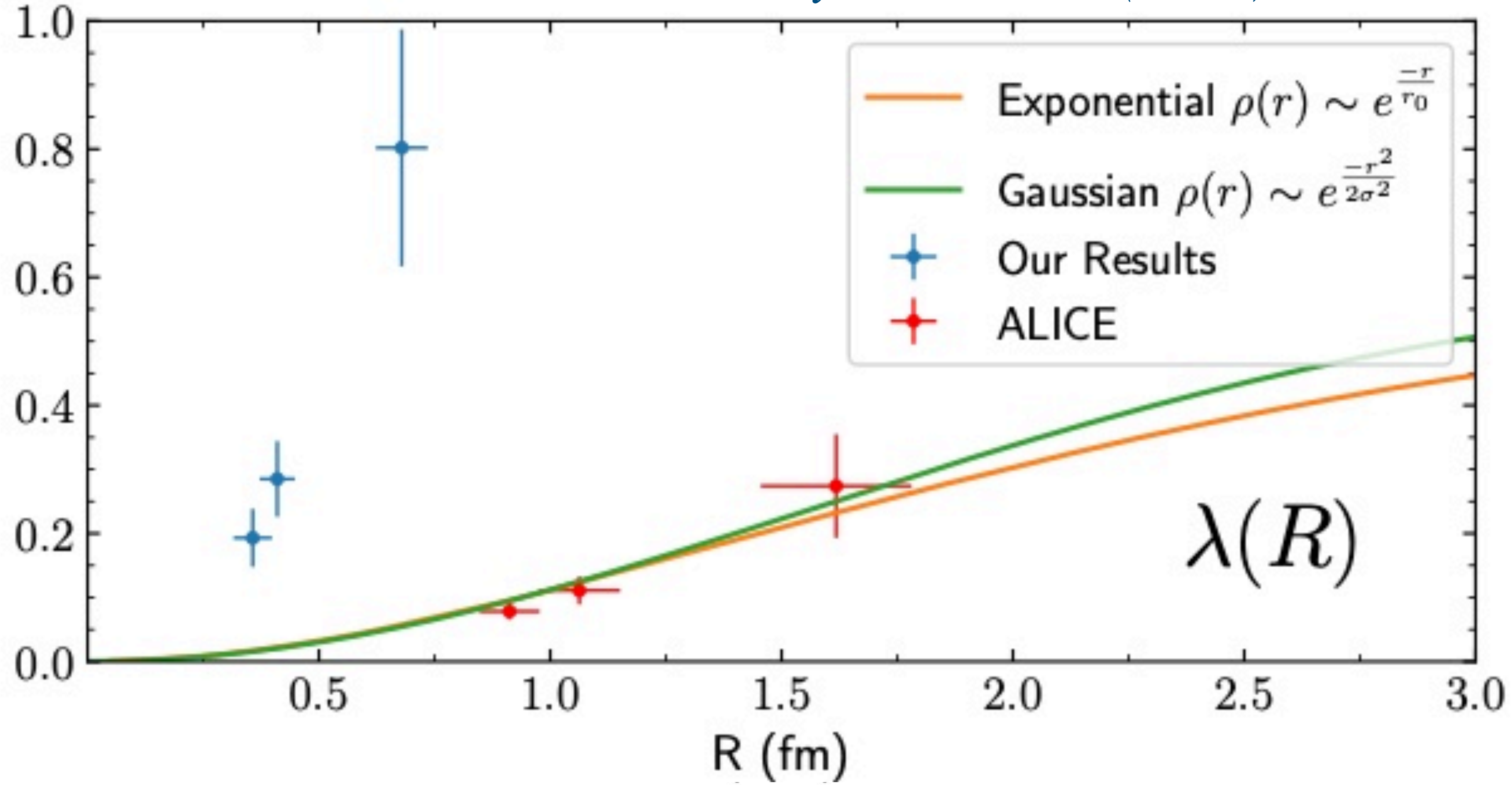
Understanding these correlations "gives*" an idea of the size of the source producing them

$$C\left(k^*\right) = \int d^3 r S(r) \left|\psi^*\left(k^*, r\right)\right|^2$$



πK scattering amplitude

Phys.Lett.B 866 (2025) 139552



ALICE claimed evidence for a κ tetraquark, using naive amplitude analysis

The correct theory shows no ordinary $q\bar{q}$ or tetraquark

Summary

Light meson spectroscopy is crucial to hadron physics

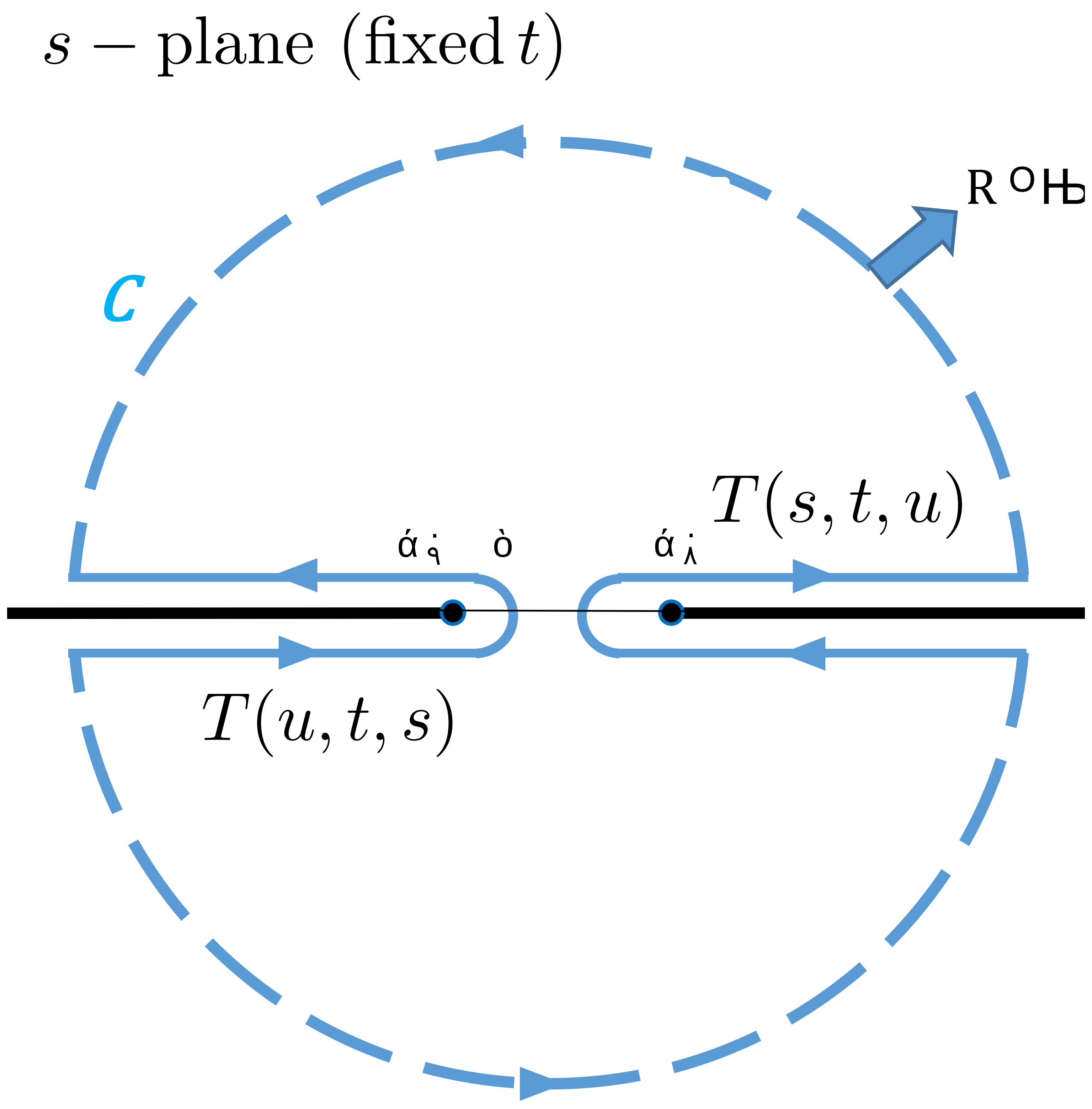
- "Exotic" matter identification and understanding
- Heavier hadron decays at higher energy colliders
- CP-violating processes, diffraction, Primakoff, etc.
- Precision and BSM physics studies

We do what we can, but data is not great

- Unresolved tensions
- Unkown systematics
- Uncovered energy regions

Analyticity: Dispersion relations

Our amplitude has two branch-cuts



Use Cauchy's theorem over contour C, assume that circular parts go to zero

$$T(s,t,u) = \frac{1}{2\pi i}\int_C \frac{T(s',t,u'(s',t))}{s'-s}ds' \quad \text{+ maybe subtractions}$$

How is this useful?? → "hooks" are given by (Schwarz reflection principle)

$$T(s+i\epsilon,t,u-i\epsilon) - T(s-i\epsilon,t,u+i\epsilon) = 2i\,\mathrm{Im}\,T(s,t,u) \longrightarrow \textbf{data}$$

Project the integral into partial waves to get your dispersion relations (ex. Roy eqs.):

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

Initial fit to data

Final dispersive output

Roy vs Steiner equations

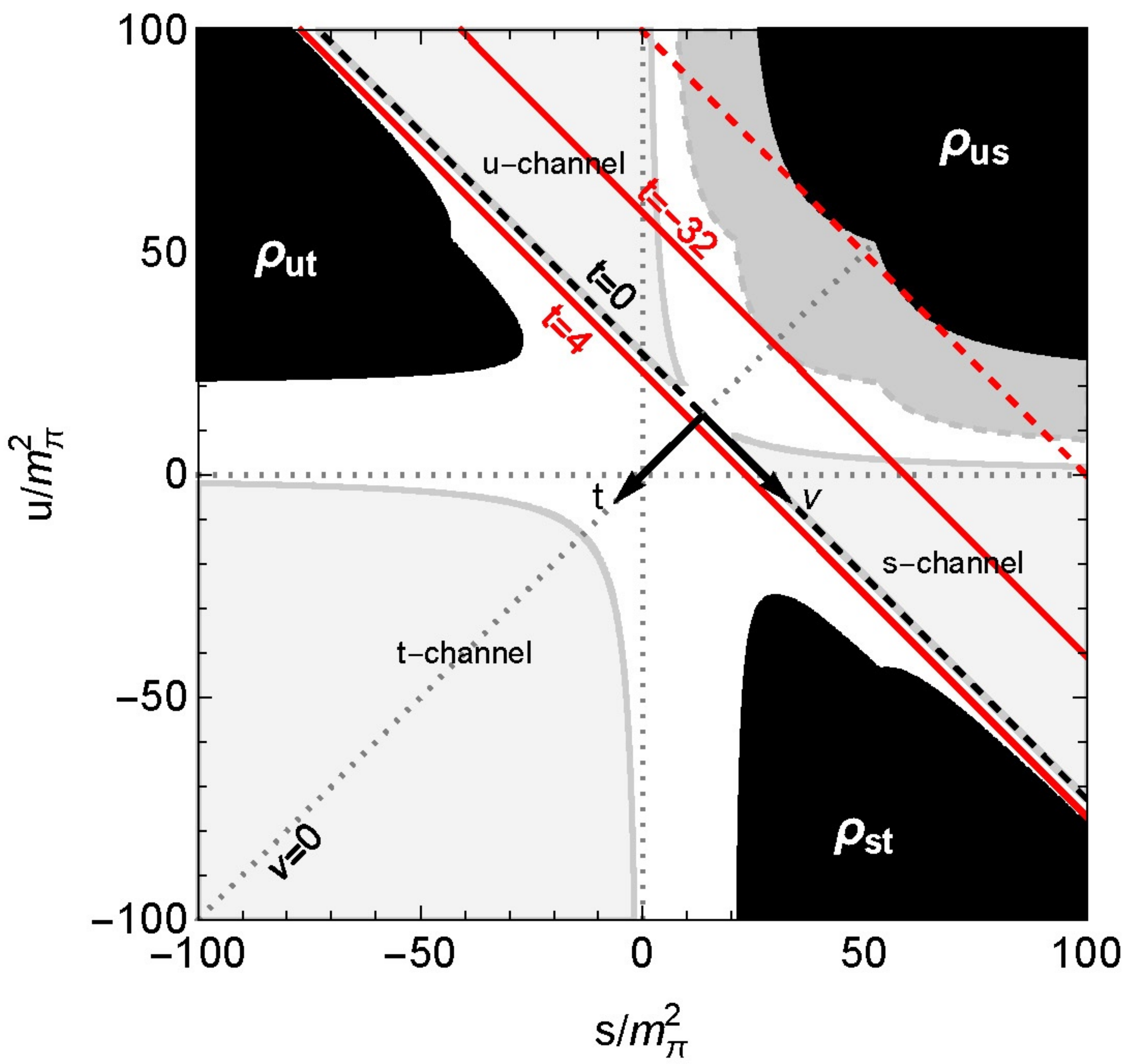
Both impose exact crossing in s-u, not everywhere

Roy eqs: *Roy Phys.Lett. B 36 (1971)*

Fixed t

Limited validity region when masses are unequal

Used for $\pi\pi$



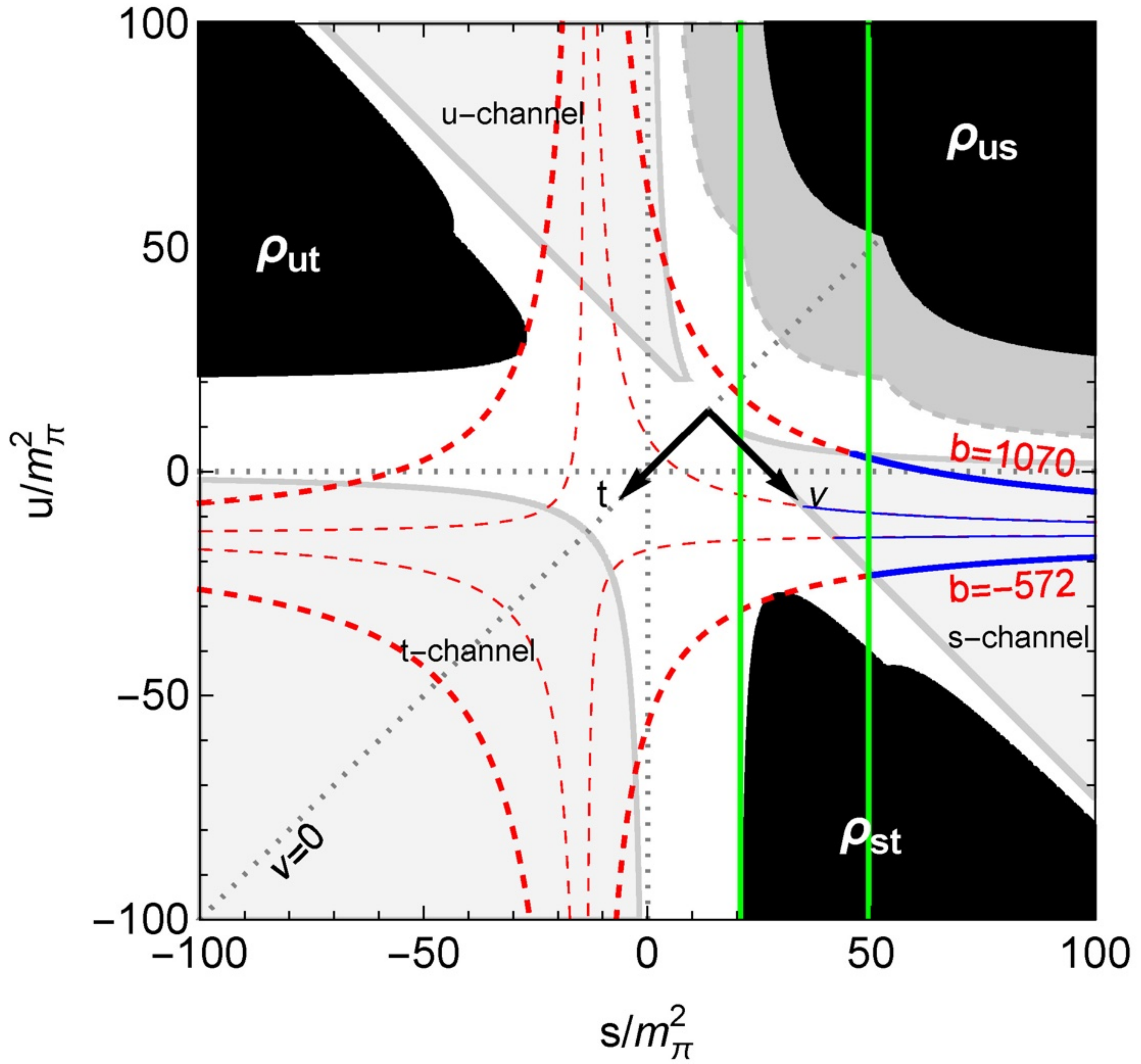
Hite/Steiner eqs: *Nuovo Cim.A 18 (1973)*

$(s-a)(u-a)=b$

More cumbersome than fixed-t

Regge contributions tend to be more suppressed

Used for πK and πN



DRs: How to ?

1- Select a relevant basis of partial waves (at relatively low energy)

$$T^I(s,t,u) = 32\pi \sum_\ell (2\ell+1) t_\ell^I(s) P_\ell(\cos\theta_s) \qquad t_\ell^I(s) \sim q^\ell(s)$$

2- Fit them

3- Select/build a Regge description of high-energy region

$$\int_{4m_\pi^2}^{\infty} ds' K_{\ell\ell'}^{II'}(s',s)\, \mathrm{Im}\, t_{\ell'}^{I'}(s') = \int_{4m_\pi^2}^{\Lambda} ds' \cdots + \underbrace{\int_{\Lambda}^{\infty} ds' \cdots}_{\text{Regge}}$$

4- Define a sensible approach to solve/constrain these DRs

Should we solve them?

Should we use them as constrain?

Should we use them to select?

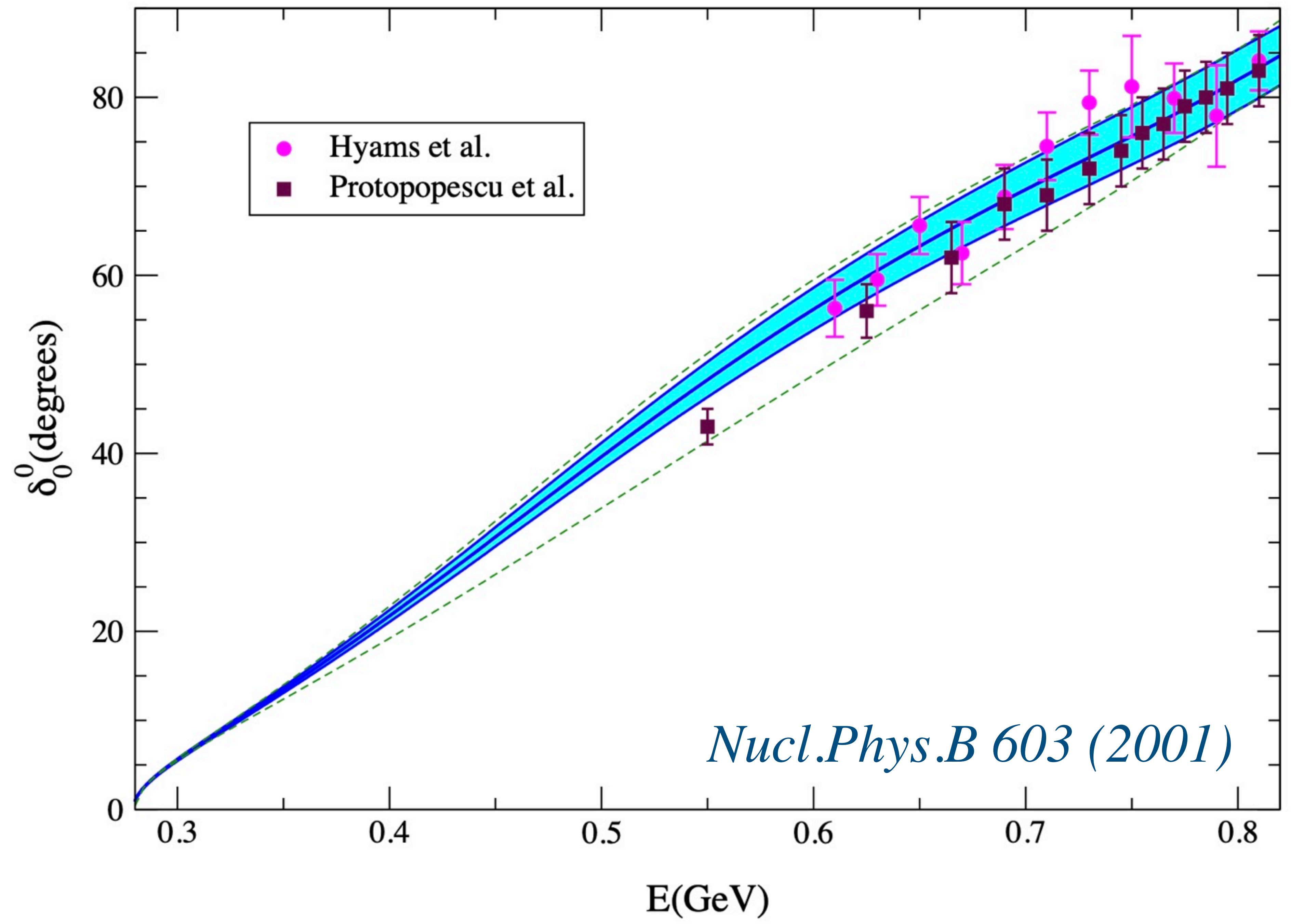
5- Use your DR to obtain observables !!

$$t_\ell^I(s) \rightarrow \tilde{t}_\ell^I(s)$$

DRs: Solving vs constraining

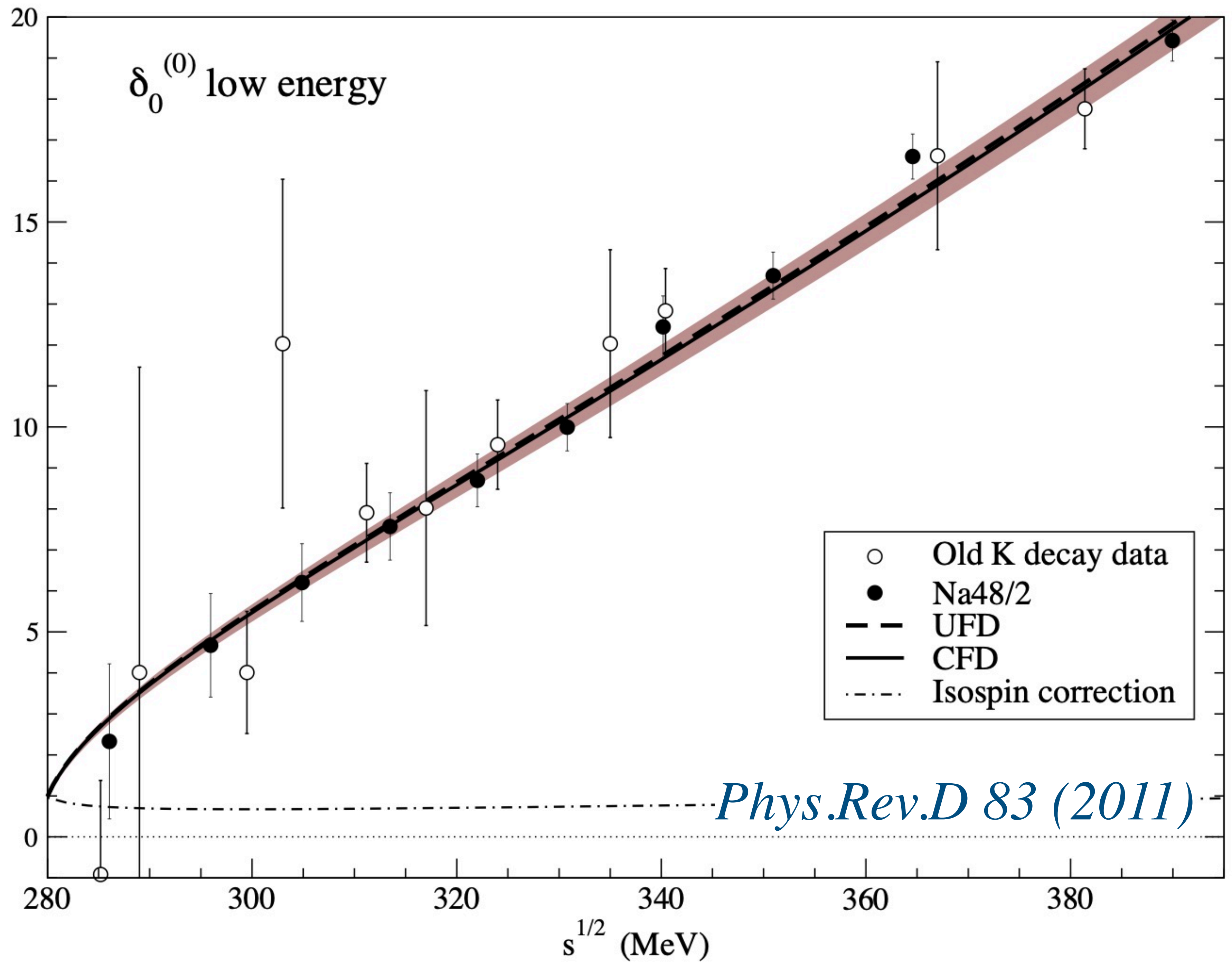
Solving:

- ✓ **Unique solution**
- ✓ **Very accurate unitary fulfilment**
- ✓ **Phase shifts are a "prediction"**
- ✗ **Boundary conditions have to be set**



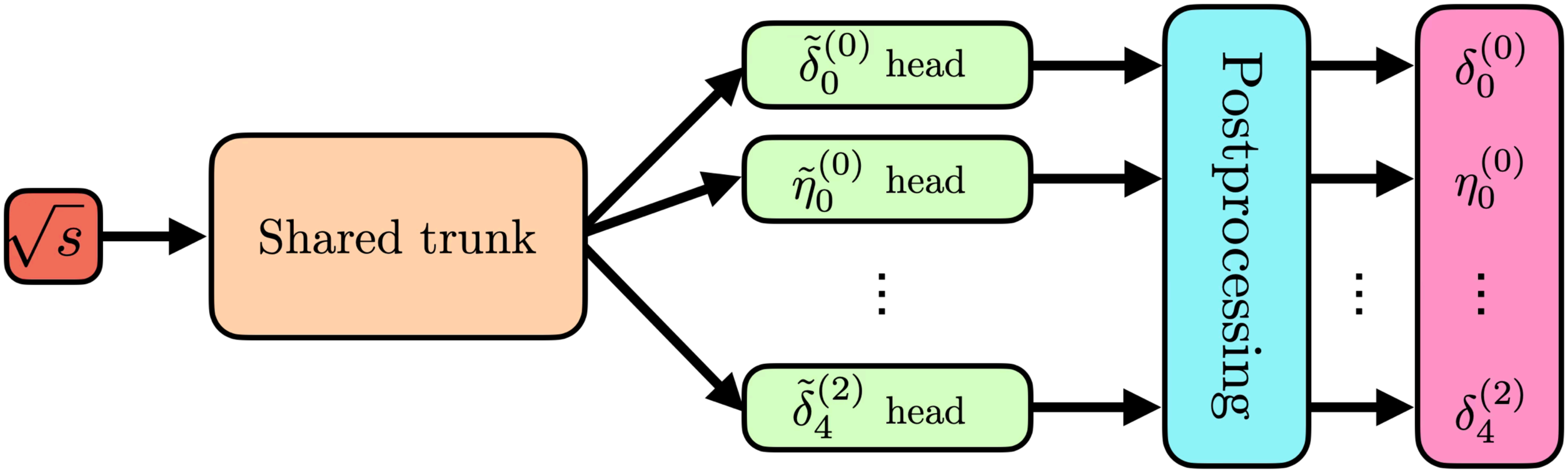
Constraining:

- ✓ **Data plays a central role**
- ✓ **Can select between incompatible experimental results**
- ✗ **Unitarity is slightly violated**



$\pi\pi$ scattering: NN

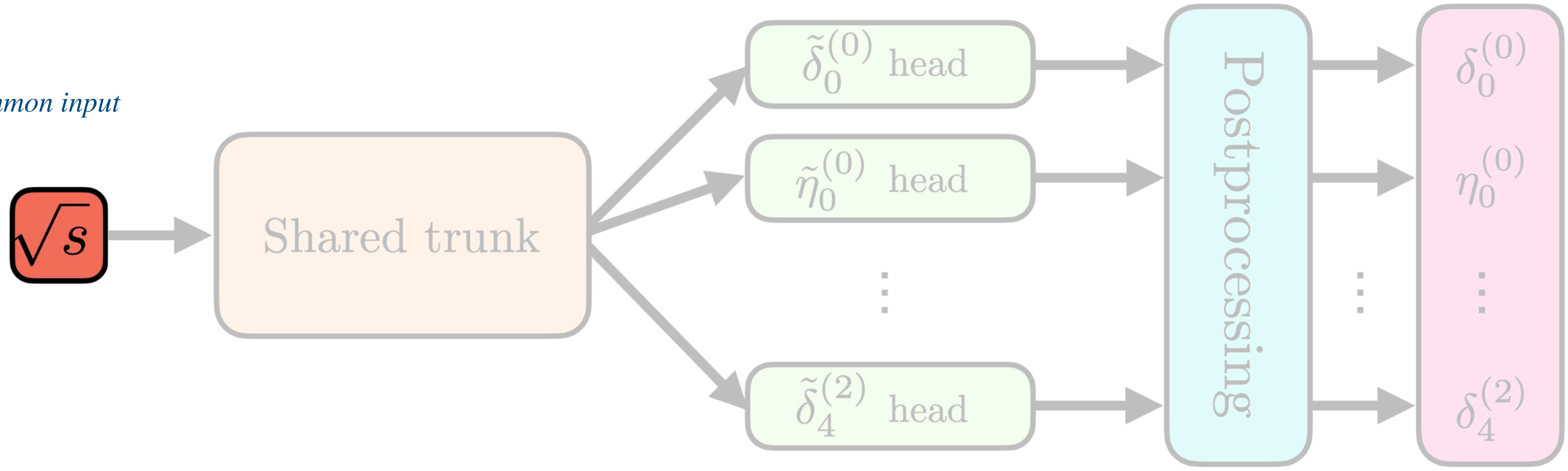
Hybrid multi-tasking architecture



$\pi\pi$ scattering: NN

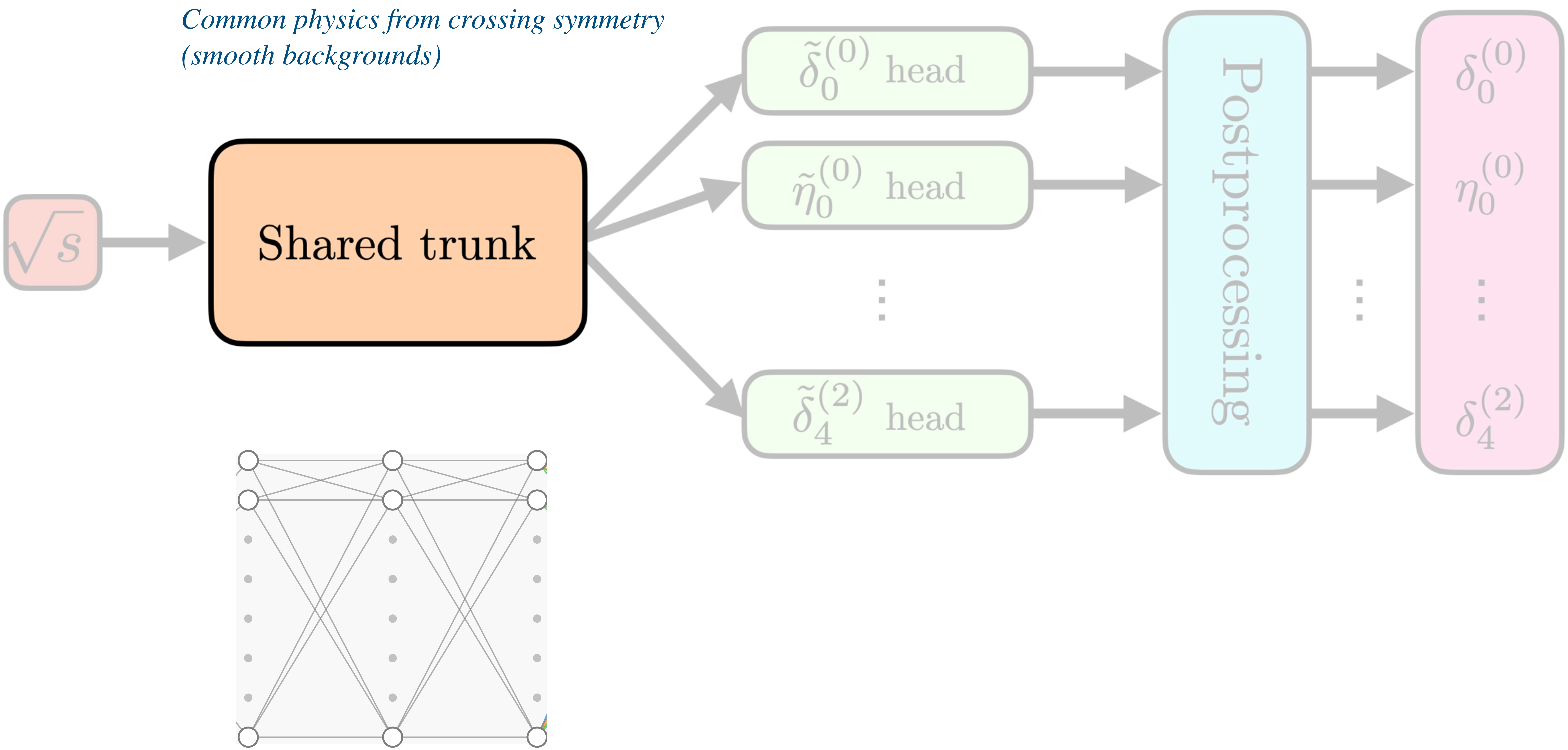
Hybrid multi-tasking architecture

Common input



$\pi\pi$ scattering: NN

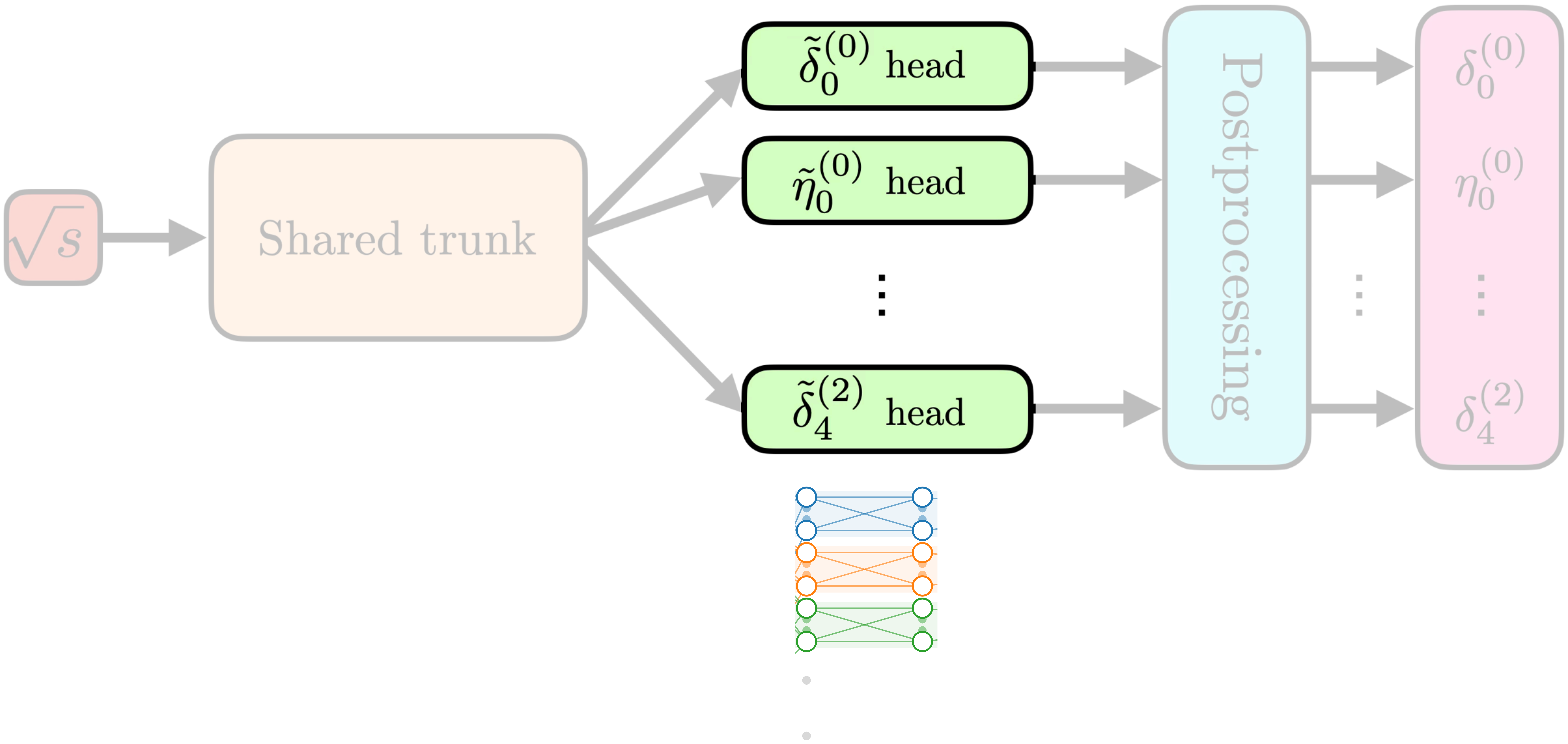
Hybrid multi-tasking architecture



$\pi\pi$ scattering: NN

Hybrid multi-tasking architecture

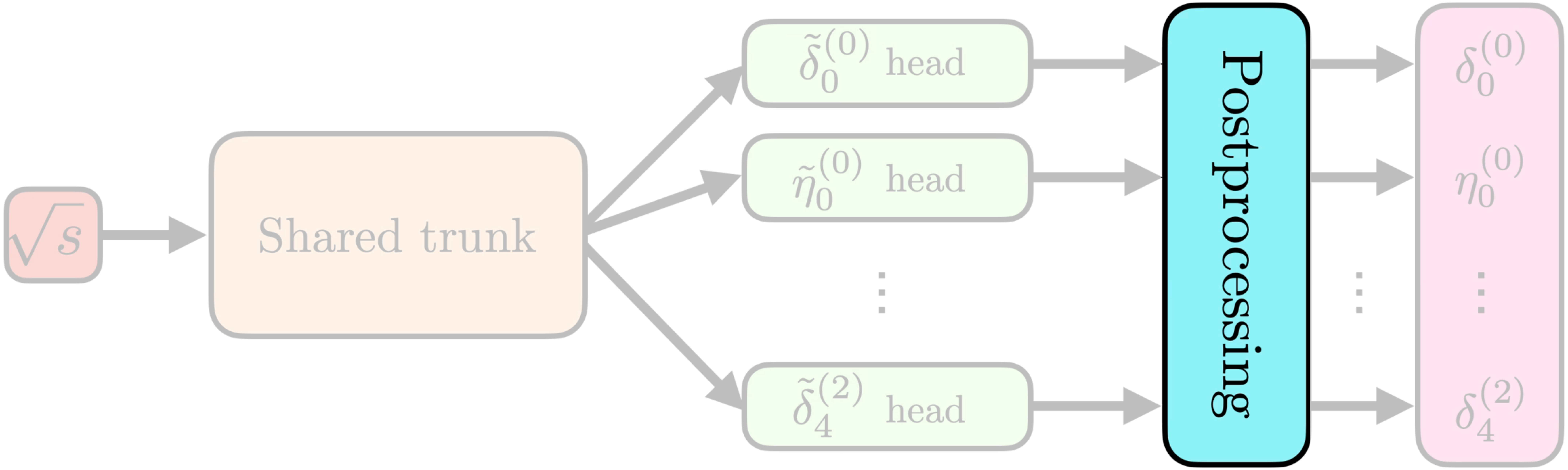
Local dynamic effects (low correlation)



$\pi\pi$ scattering: NN

Hybrid multi-tasking architecture

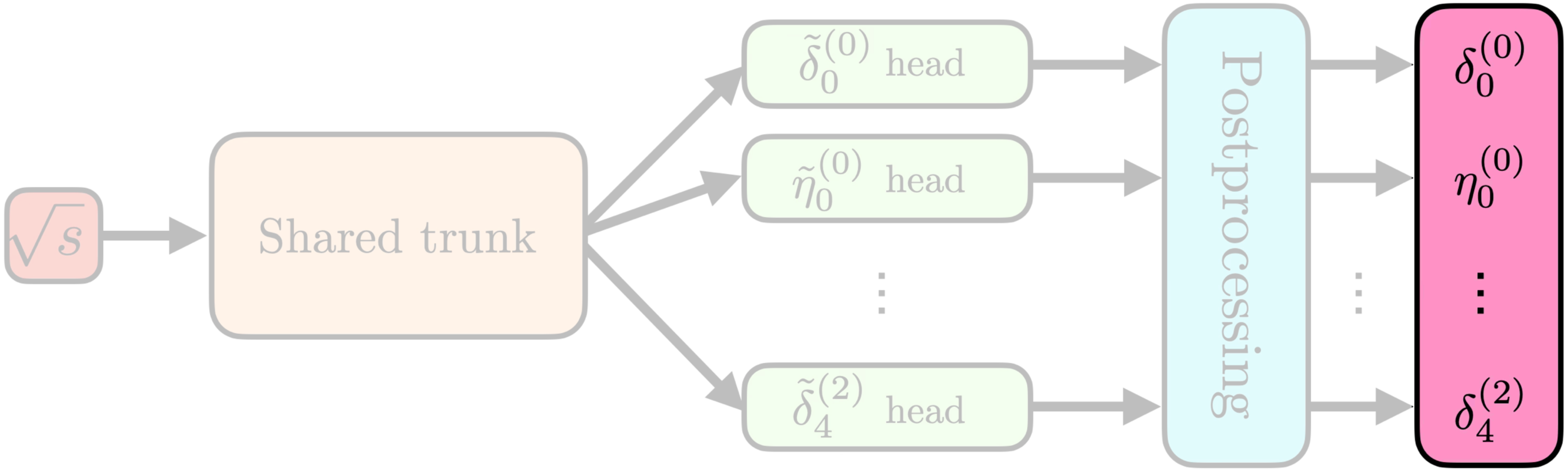
Enforcing kinematic behaviors and unitarity



$\pi\pi$ scattering: NN

Hybrid multi-tasking architecture

NN lineshapes



$\pi\pi$ scattering: data grouping

We have: flexible NN that fits data, while respecting S-matrix principles, for "all" waves, at once

Perfect "model" to asses if data is compatible or incompatible

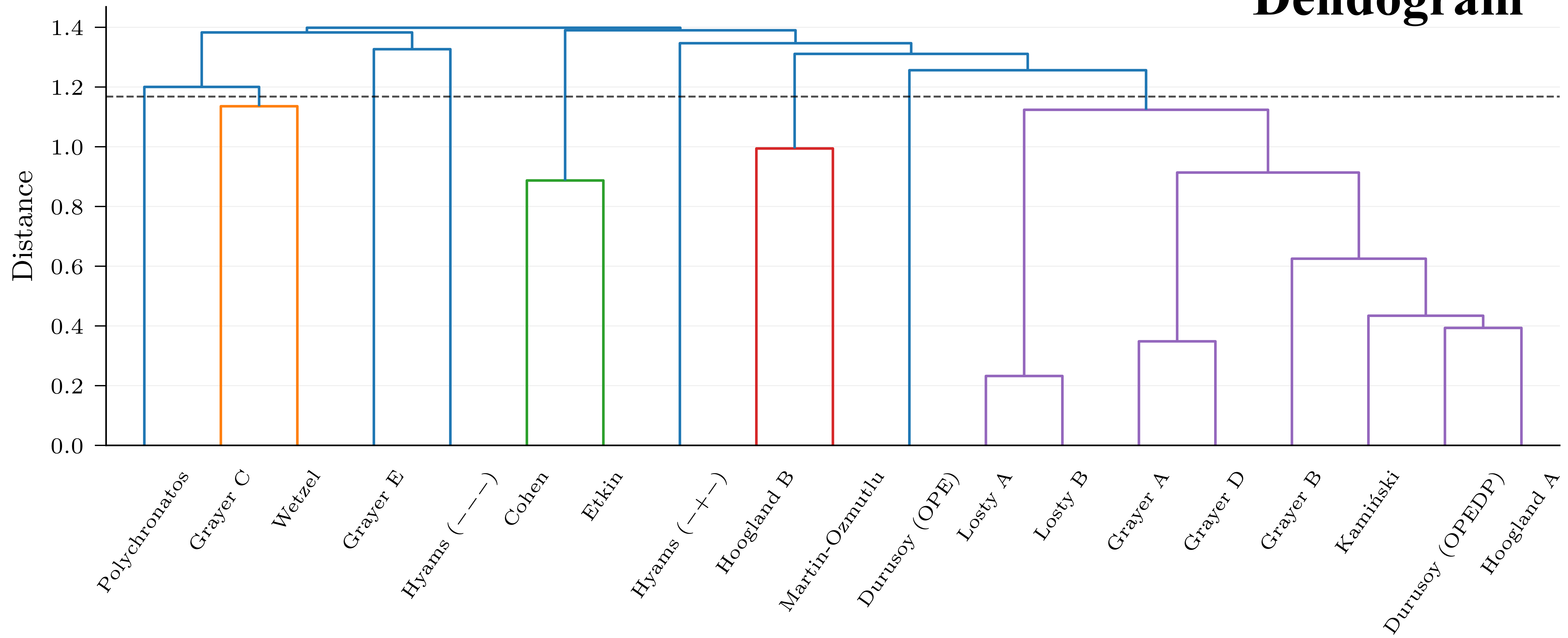
Not possible with customary PWA models:

- *PWs are disconnected, but data lives in all at once*
- *Not flexible enough, could be data problems, could be model problems*
- *Model testing does not satisfy S-matrix for each test*

1- Data reweighting and resampling

We now use this framework to group data by "overall distance"

Dendogram



Start by reweighting experiments and refitting

Determine how experiment I affects experiment j

$$z_{ij} = \frac{\langle \chi^2_{\text{disc},i} \rangle_j - \langle \chi^2_{\text{base}} \rangle_j}{\sqrt{s^2_{\text{base},j}/n_{\text{base}} + s^2_{\text{disc},j}/n_{\text{disc}}}}$$

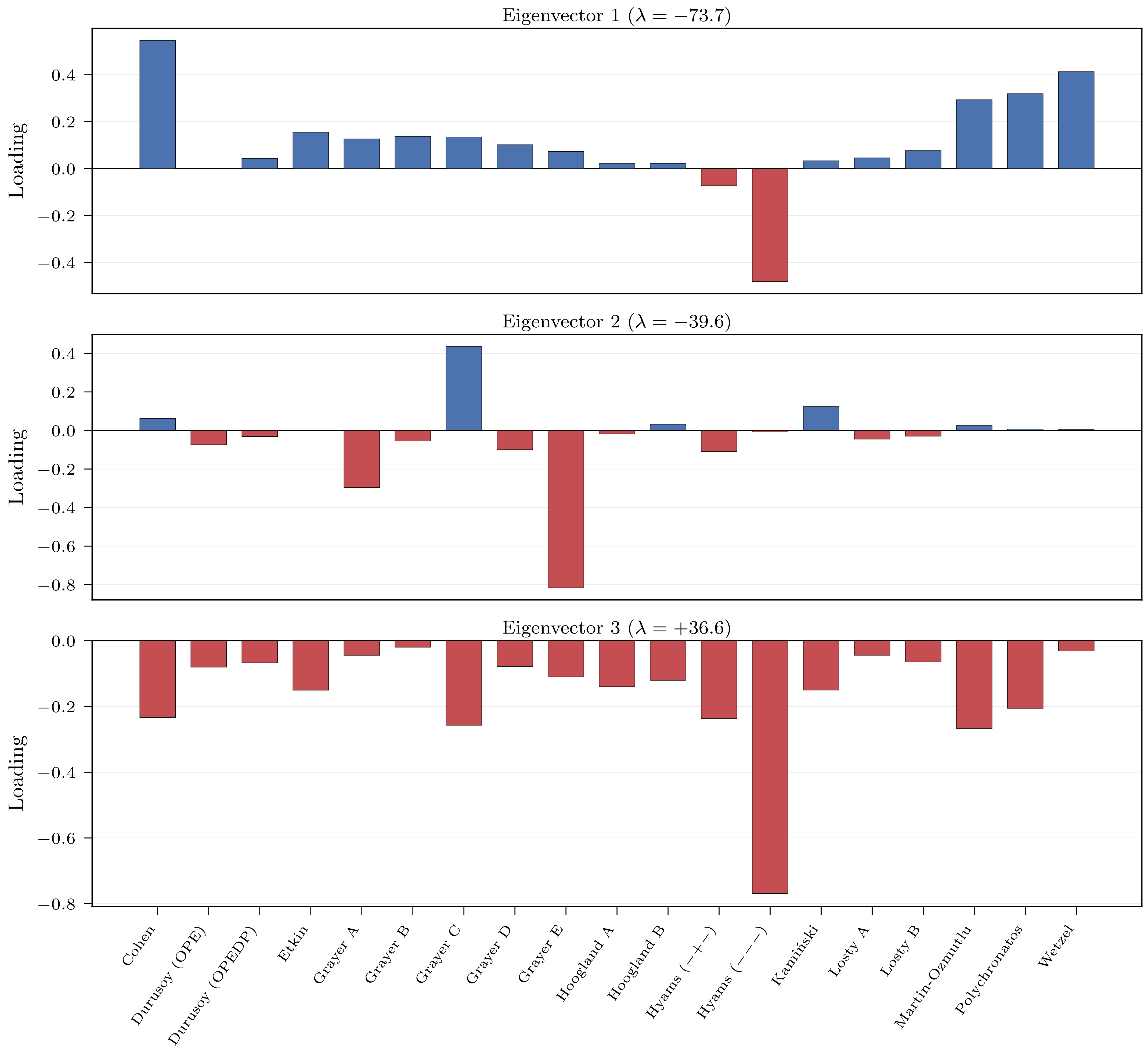
Symmetrize (made up) to create response matrix

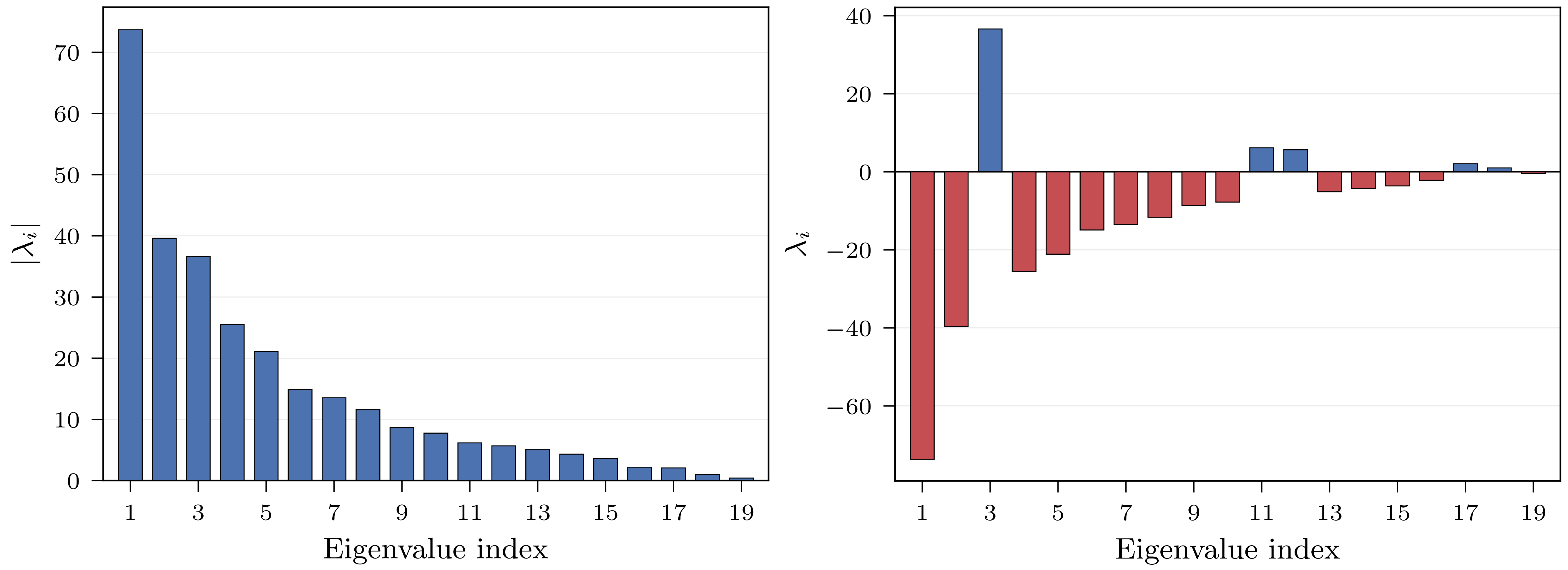
$$C_{ij} = \frac{z_{ij} + z_{ji}}{2}$$

$\pi\pi$ scattering: data prunning

2- Principal component analysis (distillation)

Reduce C_{ij} dimensions by picking most relevant eigenvectors





Exp. contribution to main eigenvectors

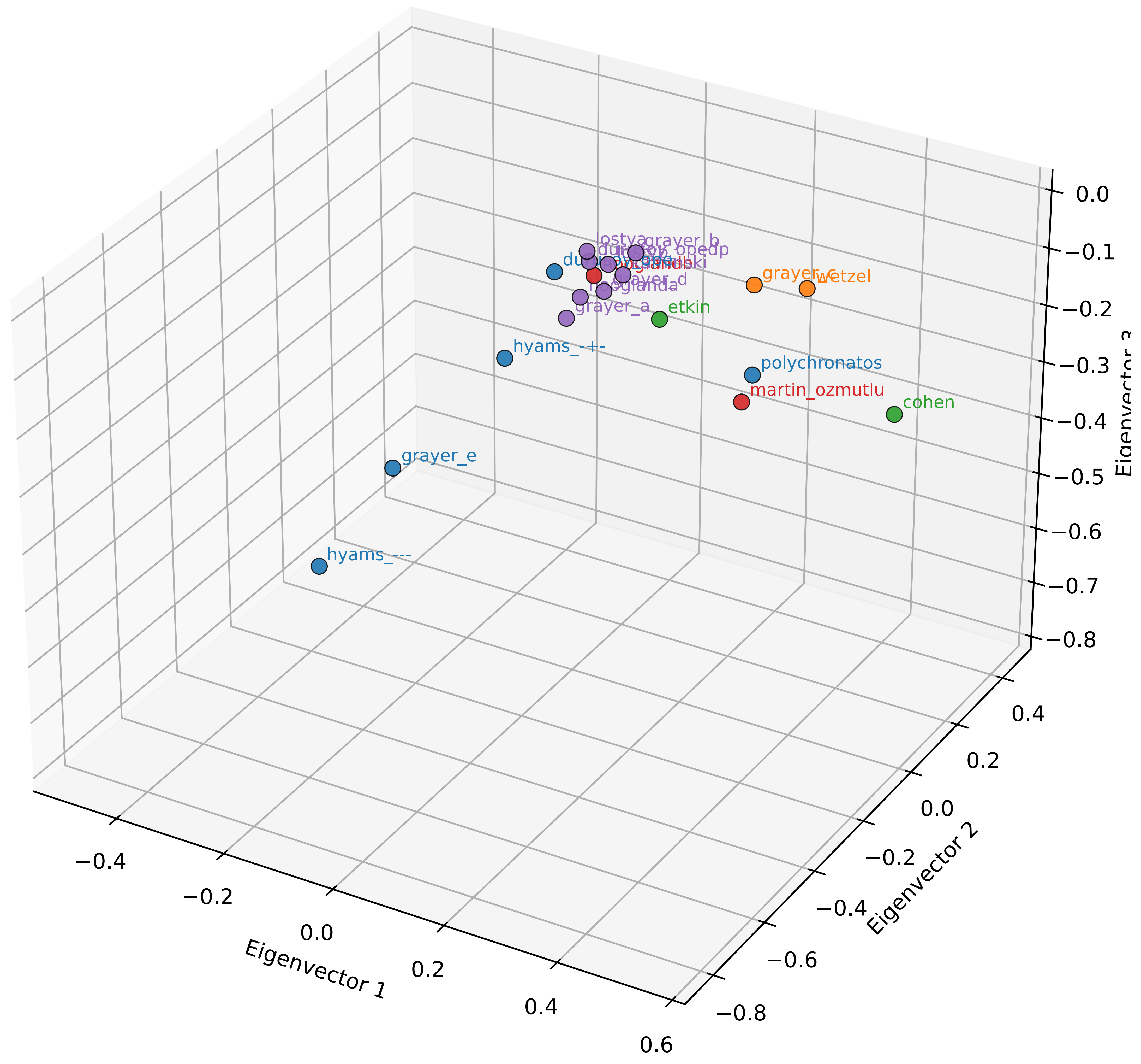
We create a smaller dimensional space in which we place the experiments given by these coefficients, and measure their euclidean distances

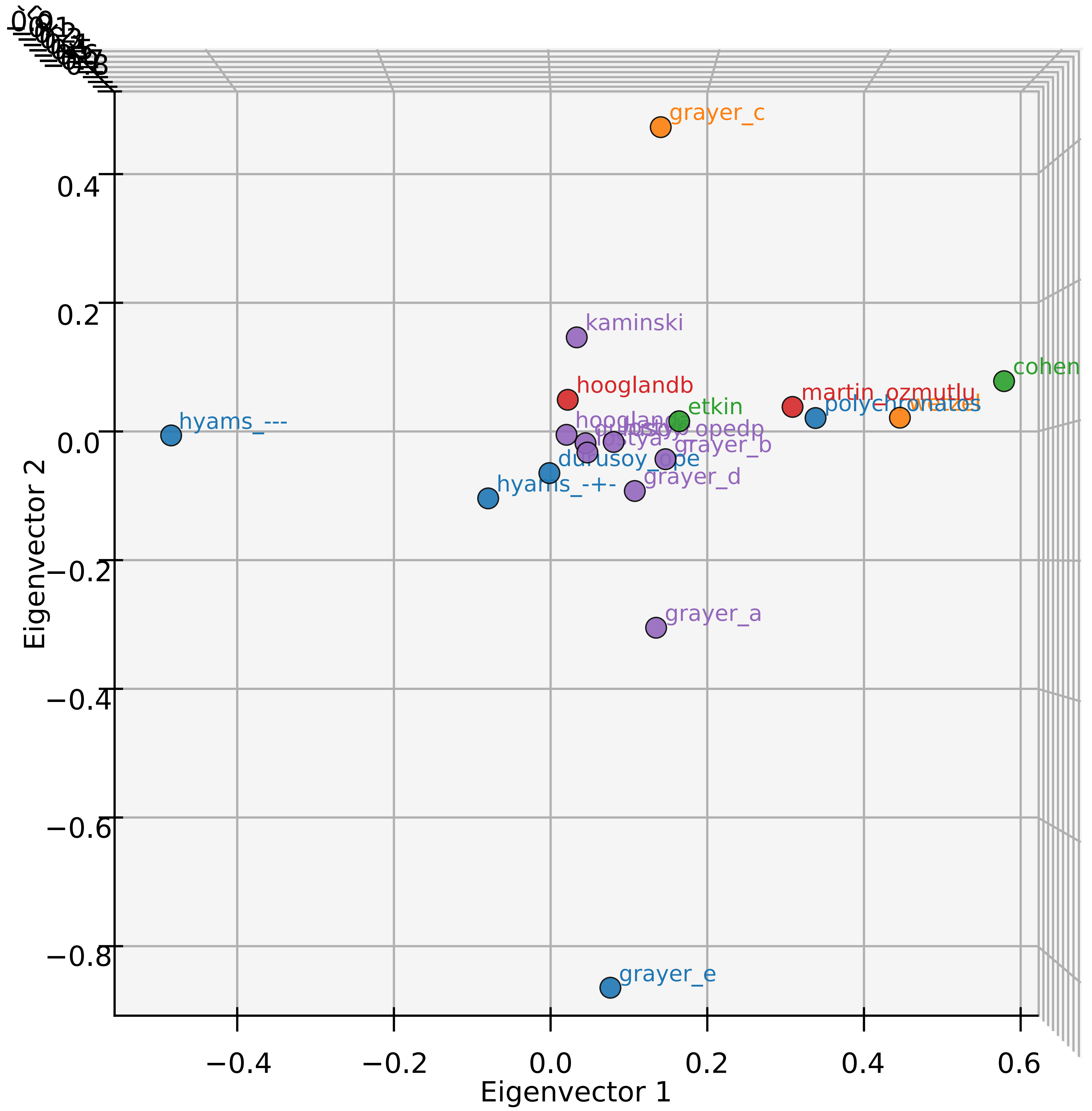
We grouped them in the dendogram by distance

$\pi\pi$ scattering: data prunning

2- Principal component analysis (distillation)

In 3D, we can view the grouping process





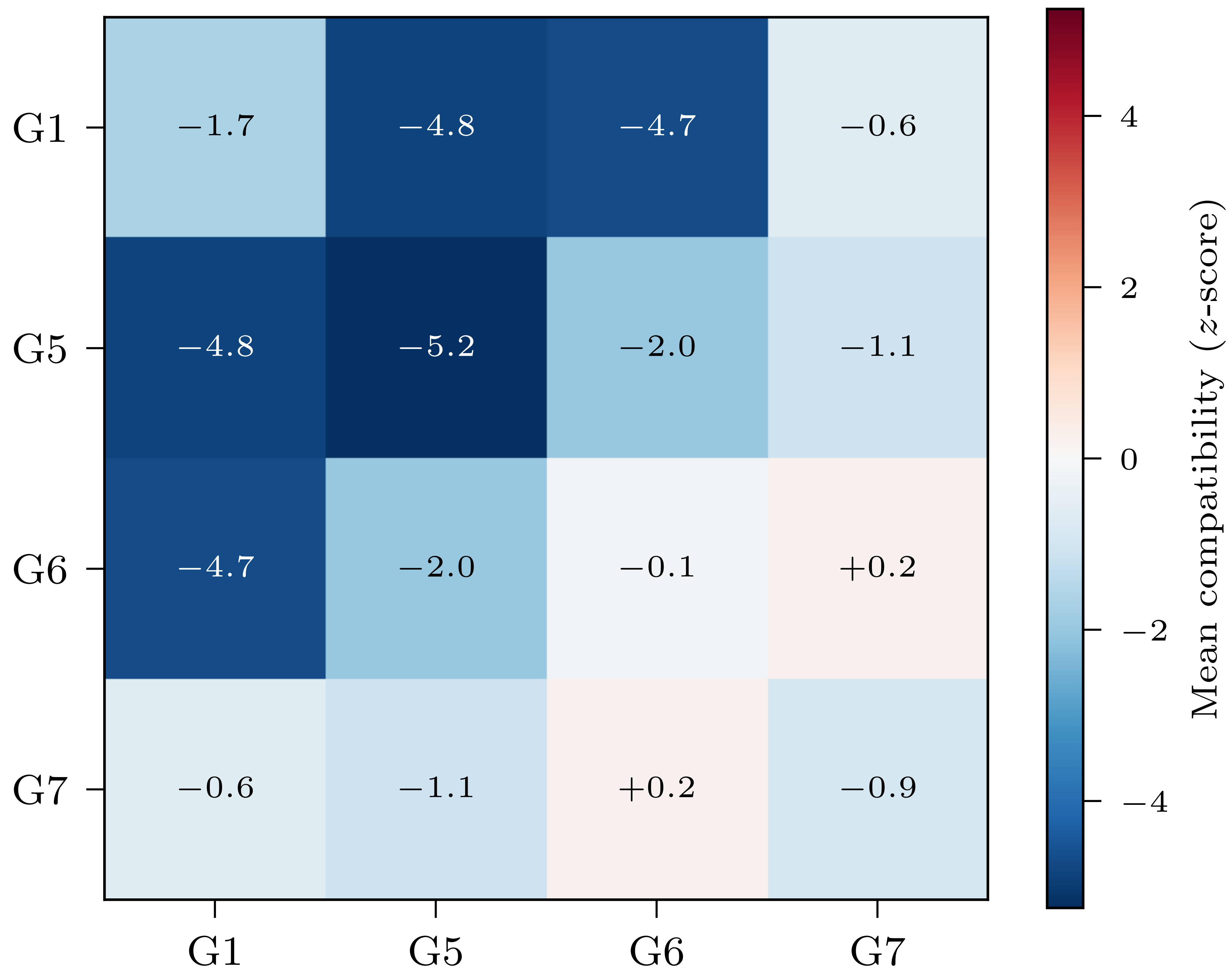
$\pi\pi$ scattering: data prunning

3- Now, we study the compatibility between groups

Define new response in reduced dimensionality

$$\bar{C}_{\ell,\ell} = \frac{2}{|G_\ell|(|G_\ell|-1)} \sum_{\substack{i,j\in G_\ell \\ i<j}} C_{ij}$$

$$\bar{C}_{\ell,m} = \frac{1}{|G_\ell|\,|G_m|} \sum_{i\in G_\ell} \sum_{j\in G_m} C_{ij}$$



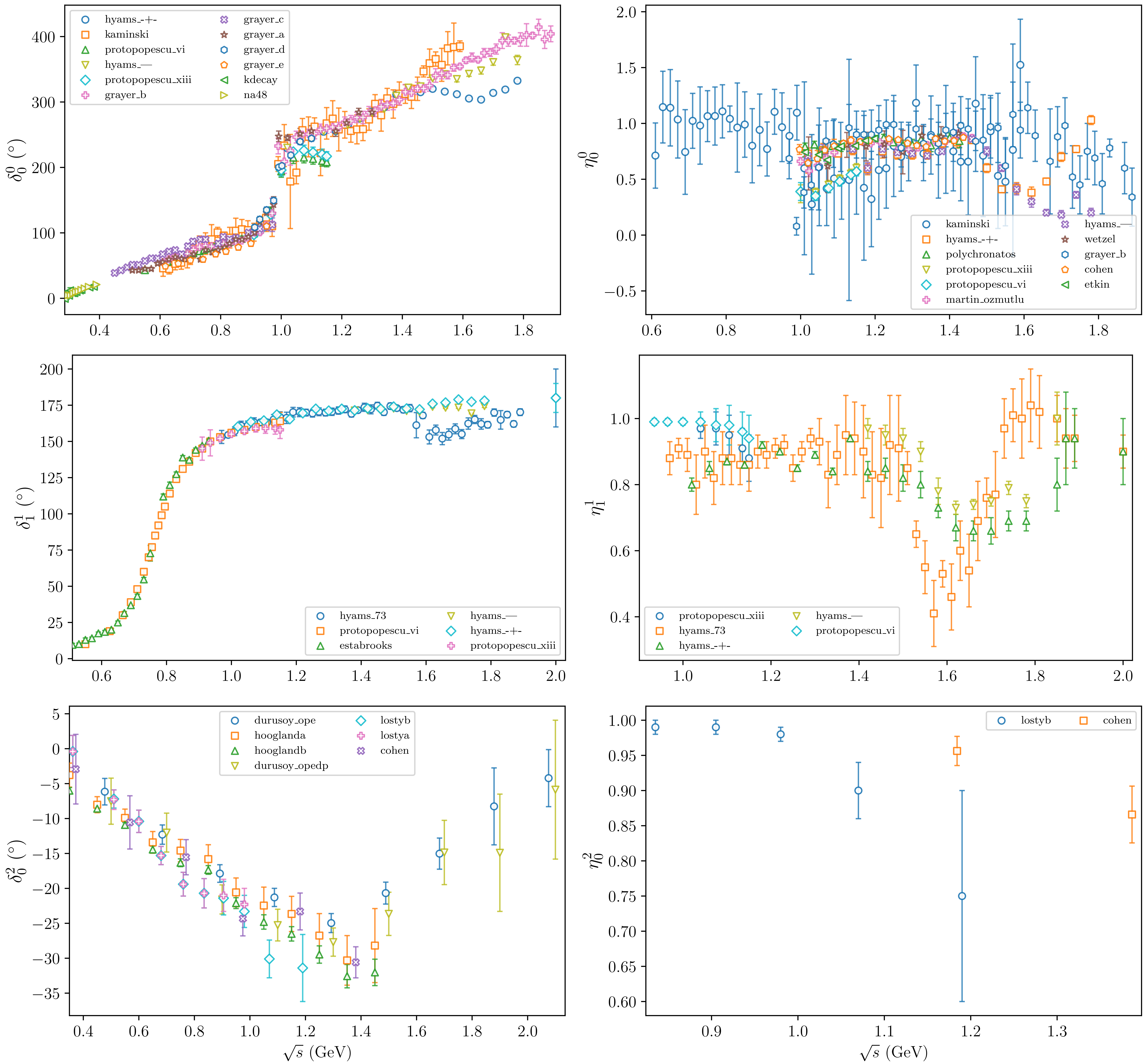
4- Prunning/selection

Remove groups iteratively until responses are "within one sigma"

$\pi\pi$ scattering: data

Data collected for 7 partial waves

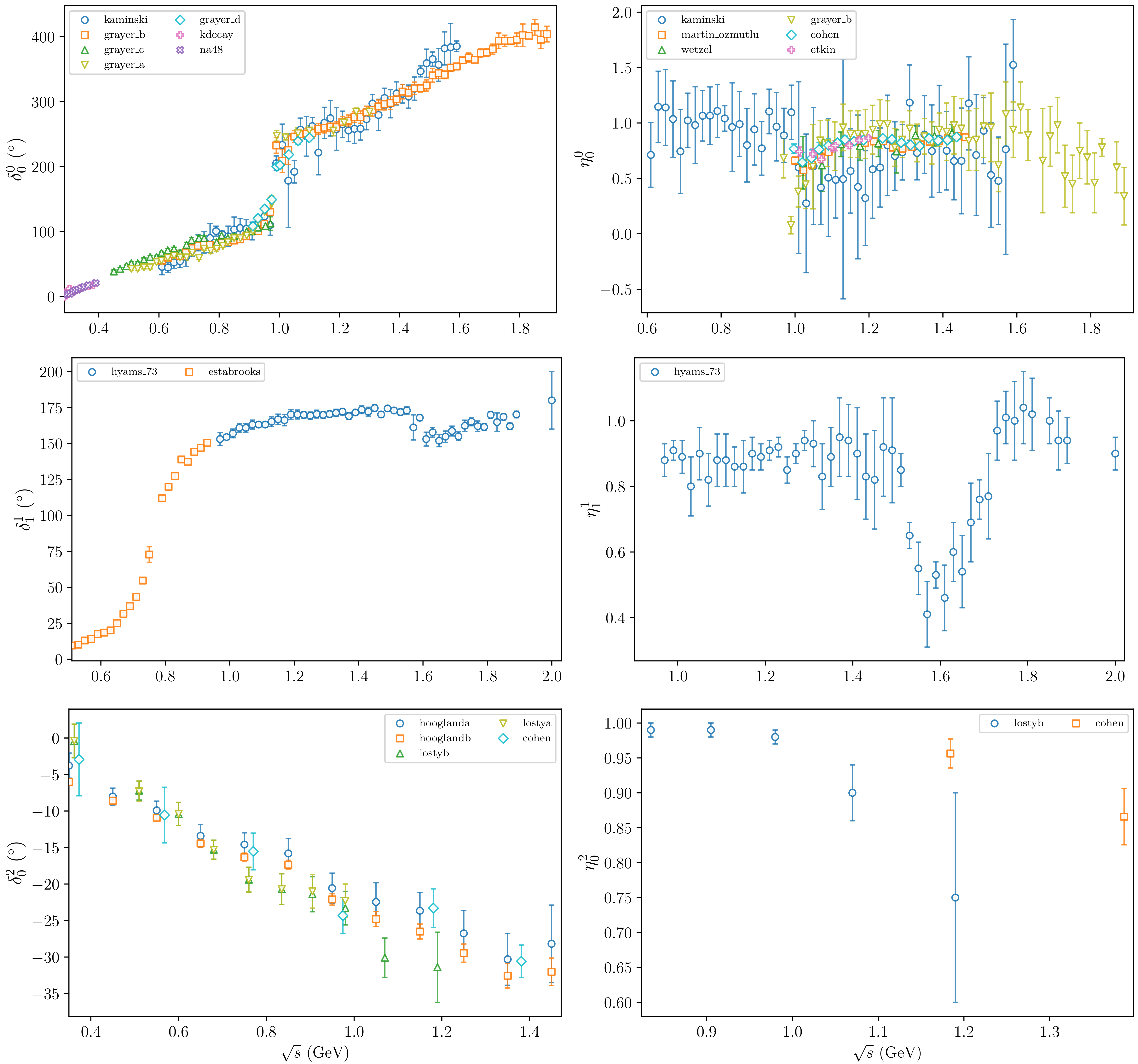
Over 1000 initial data points



$\pi\pi$ scattering: data

Data collected for 7 partial waves

Over 600 final data points in the fitting region



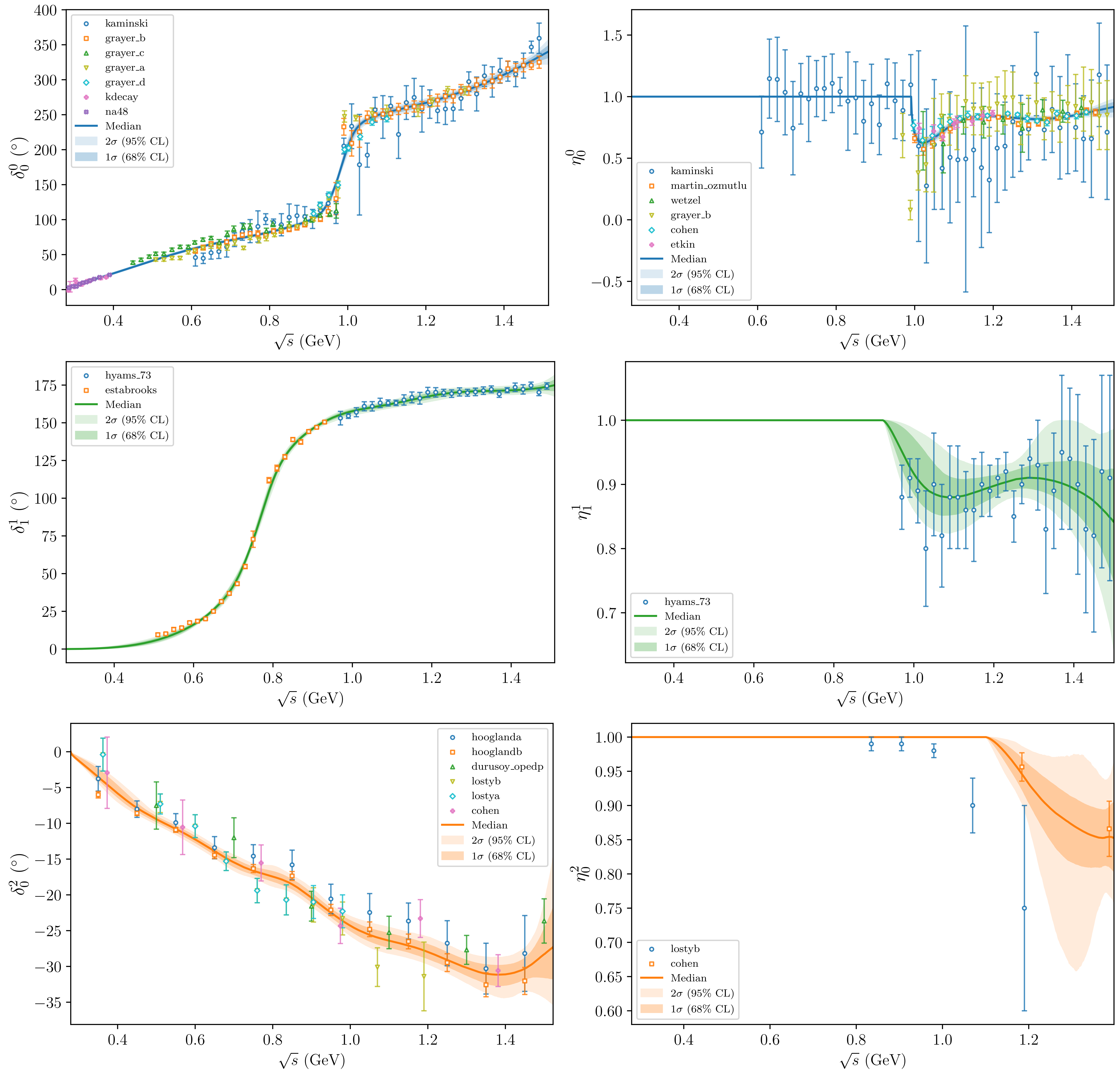
$\pi\pi$ scattering: results

Data collected for 7 partial waves

- Over 600 final data points in the fitting region

Very good data description

- Fits produce $\chi^2/\text{ndof} \sim 3$
- 2σ band calculated from 5k resamples



$\pi\pi$ scattering: results

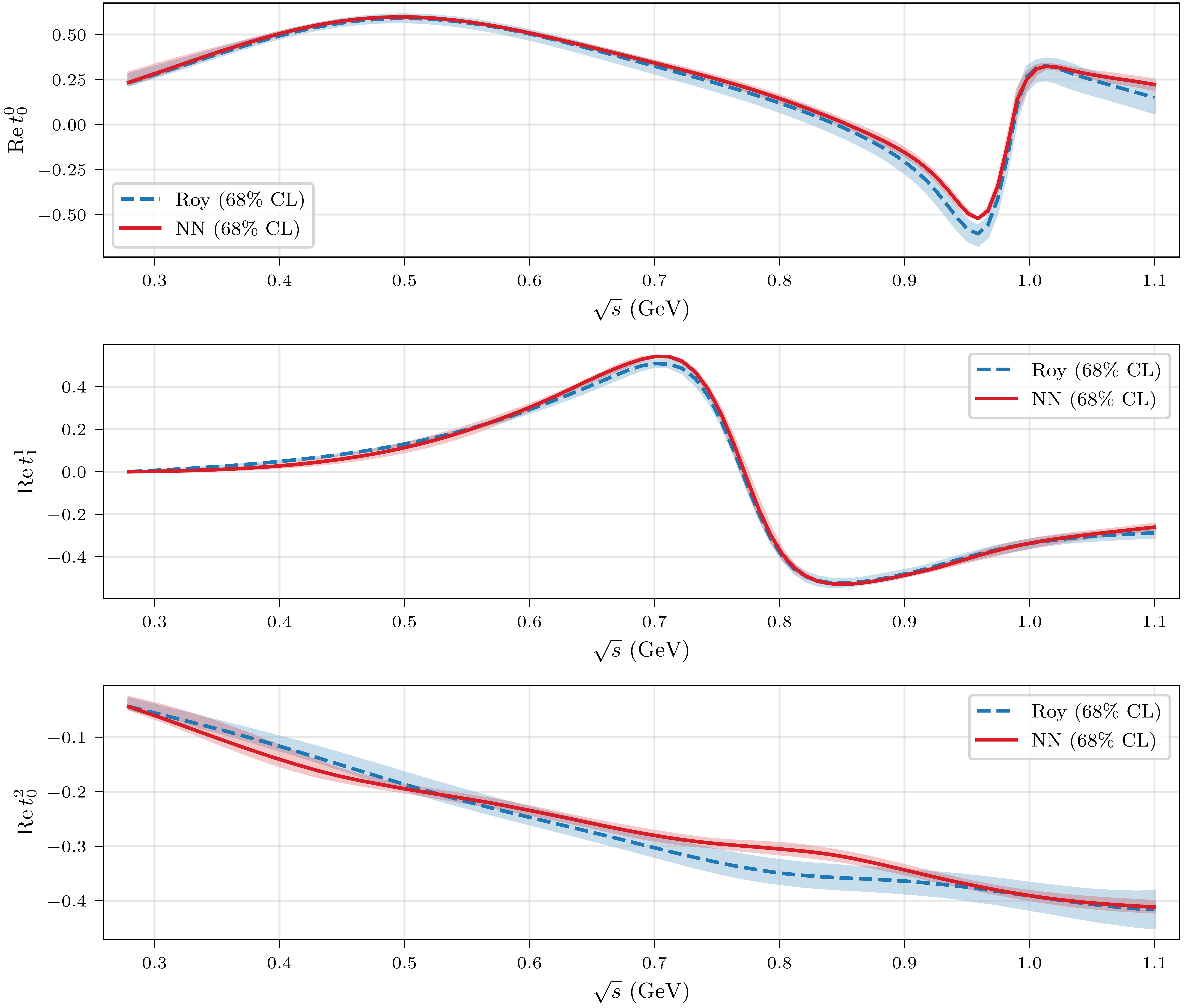
Data collected for 7 partial waves

- **Over 600 final data points in the fitting region**

Very good data description

- **Fits produce χ^2/ndof ~ 3**
- **2σ band calculated from 5k resamples**

Dispersion relations are satisfied numerically



$\pi\pi$ scattering: results

Data collected for 7 partial waves

- Over 600 final data points in the fitting region

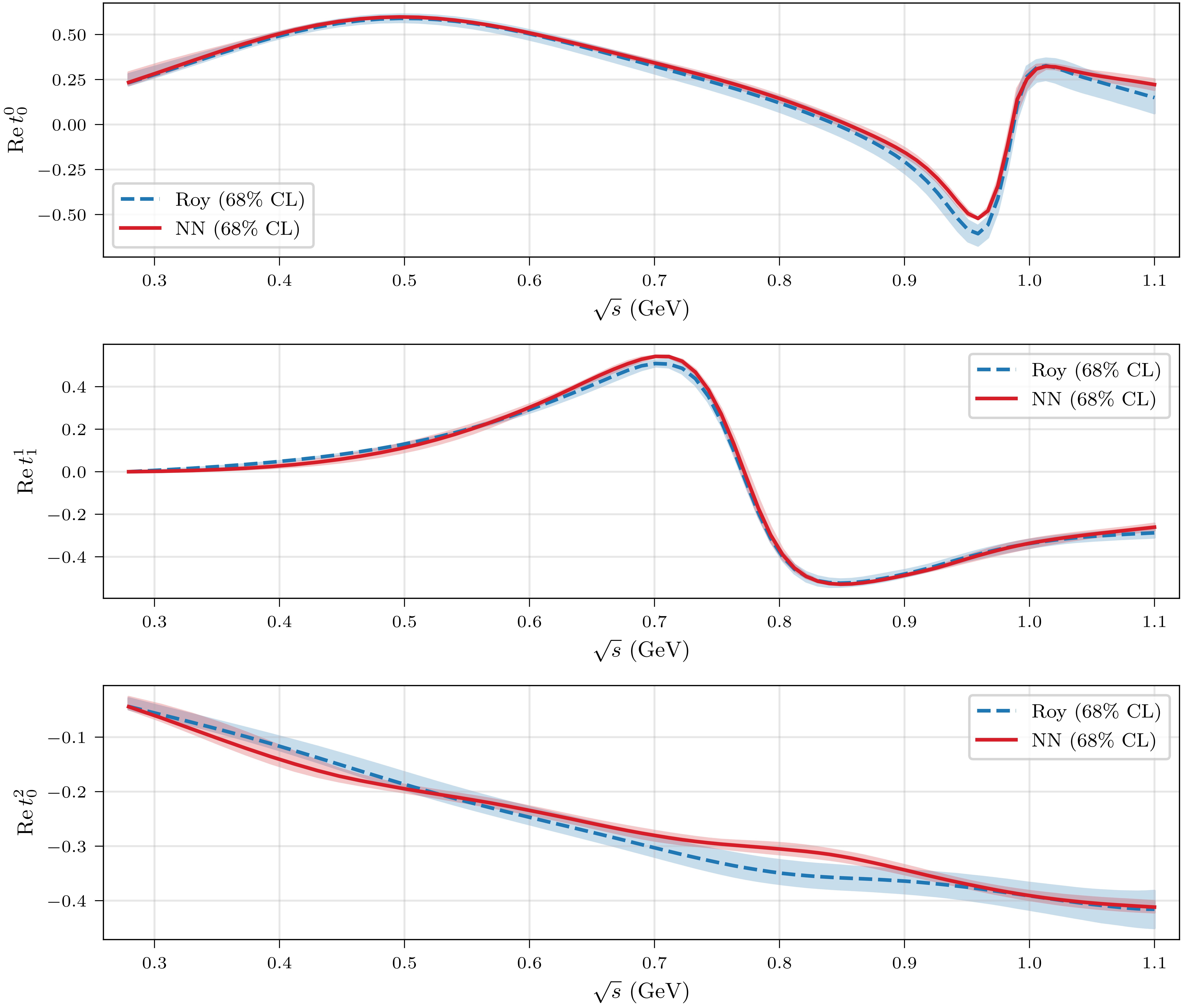
Very good data description

- Fits produce χ^2/ndof ~ 3
- 2σ band calculated from 5k resamples

Dispersion relations are satisfied numerically

Stable under architecture perturbations

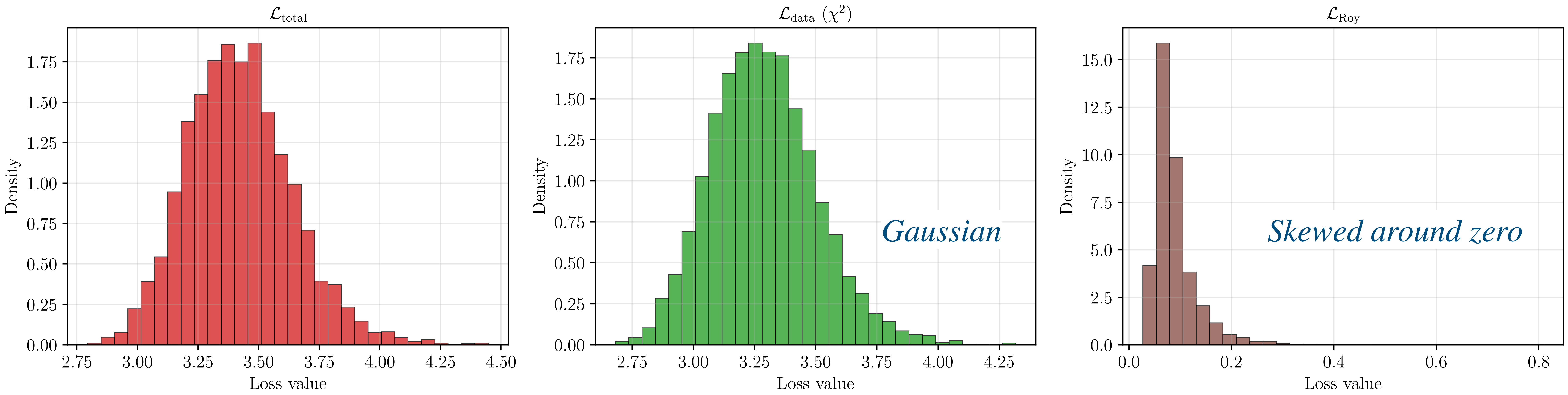
Rank	Source	Trunk	N_{par}	$\mathcal{L}_{\text{total}}$
1	Sweep	$[8, 12]$, GELU	2332	2.29
2	Sweep	$[16, 8]$, SiLU	2142	2.32
3	Sweep	$[12]$, GELU	1742	2.33
4	Sweep	$[16]$, SiLU	980	2.36
5	Sweep	$[16, 16]$, SELU	2714	2.39
6	Sweep	$[12, 8, 4]$, SELU	1376	2.40
7	Sweep	$[8, 12]$, GELU	1658	2.46
8	Prod.	$[8, 12]$, tanh/SiLU	1156	2.46
9	Sweep	$[12, 12]$, GELU	1204	2.47
10	Sweep	$[16, 8]$, GELU	1162	2.49



$\pi\pi$ scattering: results

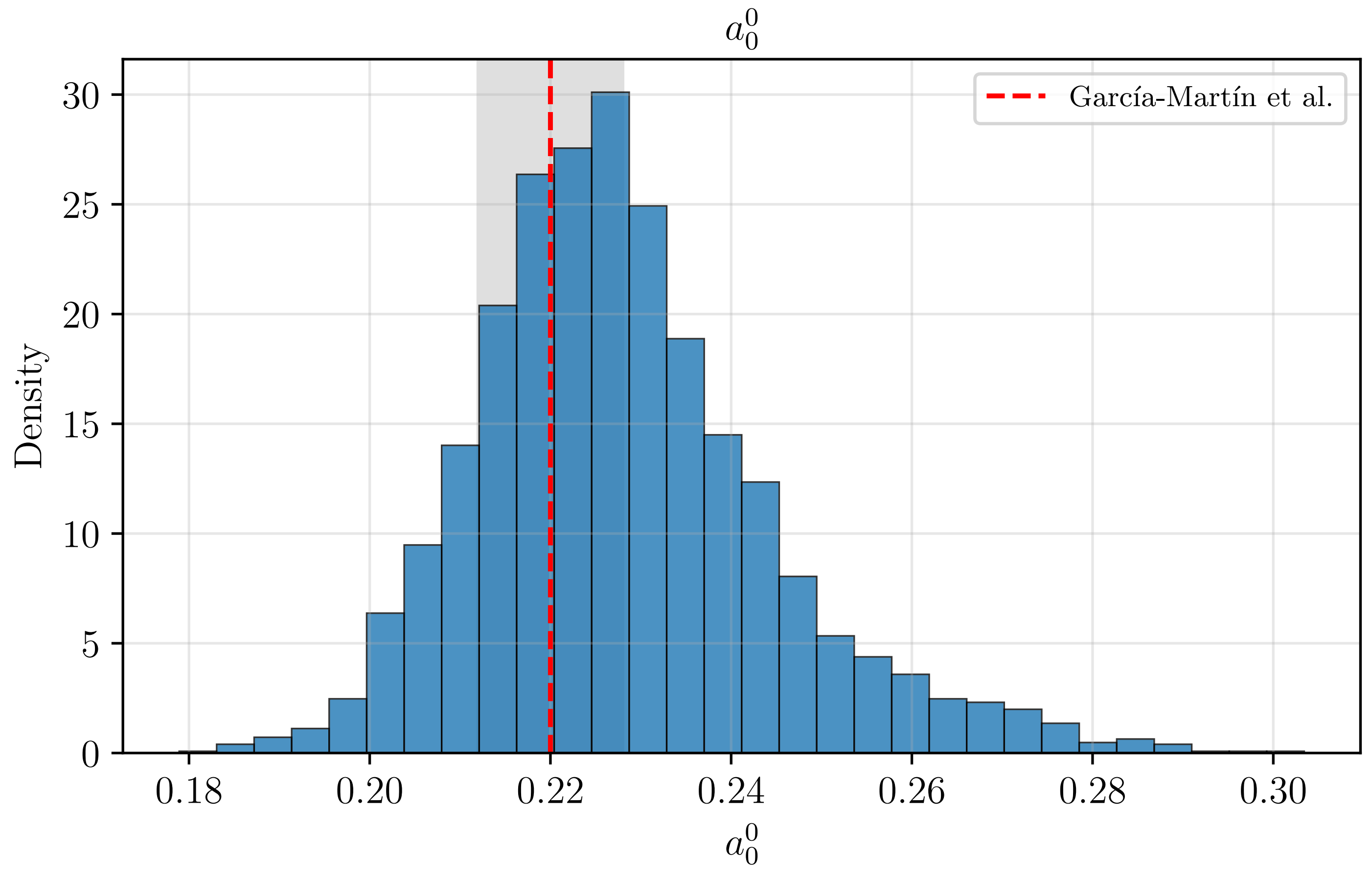
Final residues are reasonable statistically

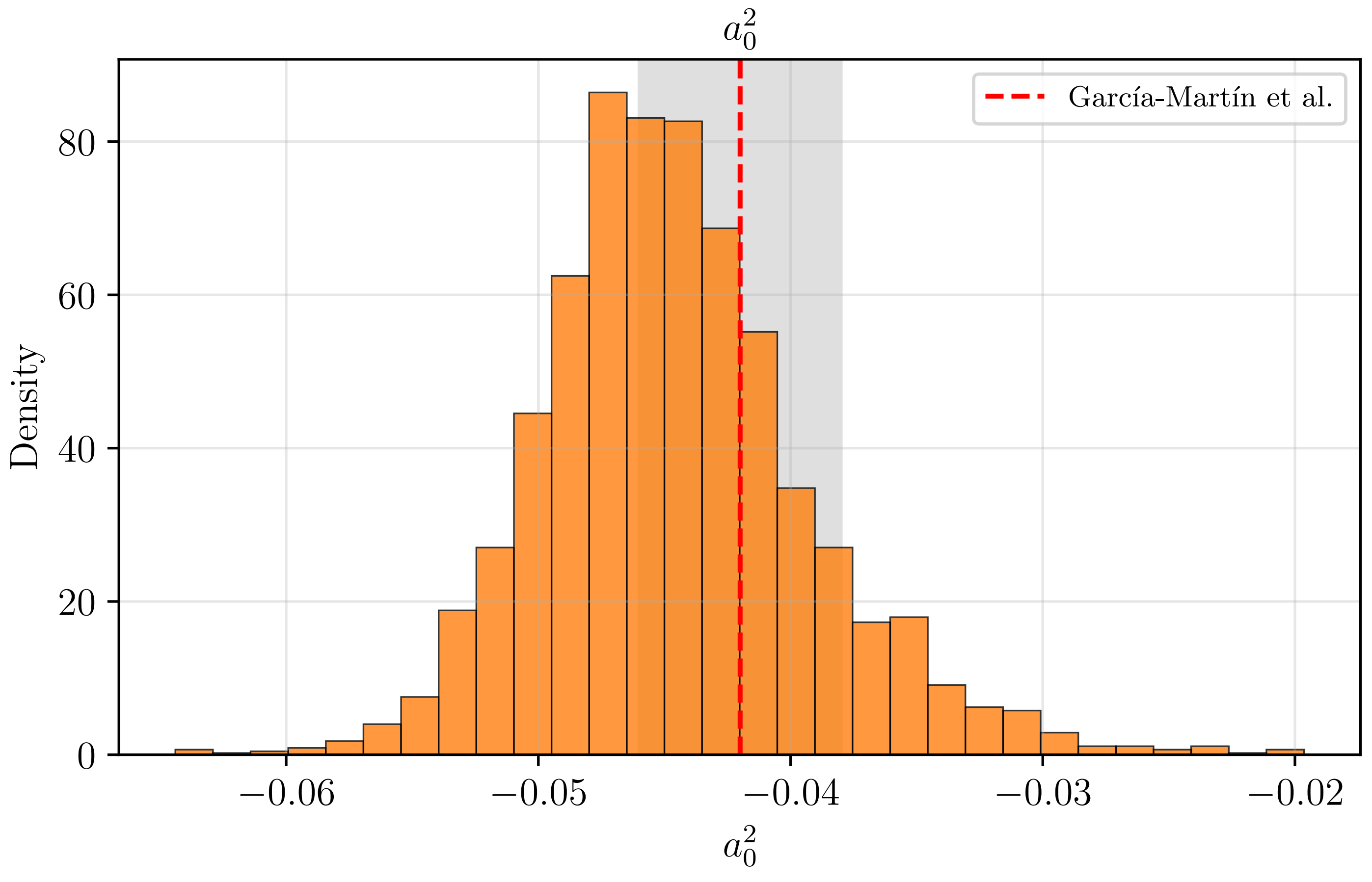
Loss dominated by experimental data

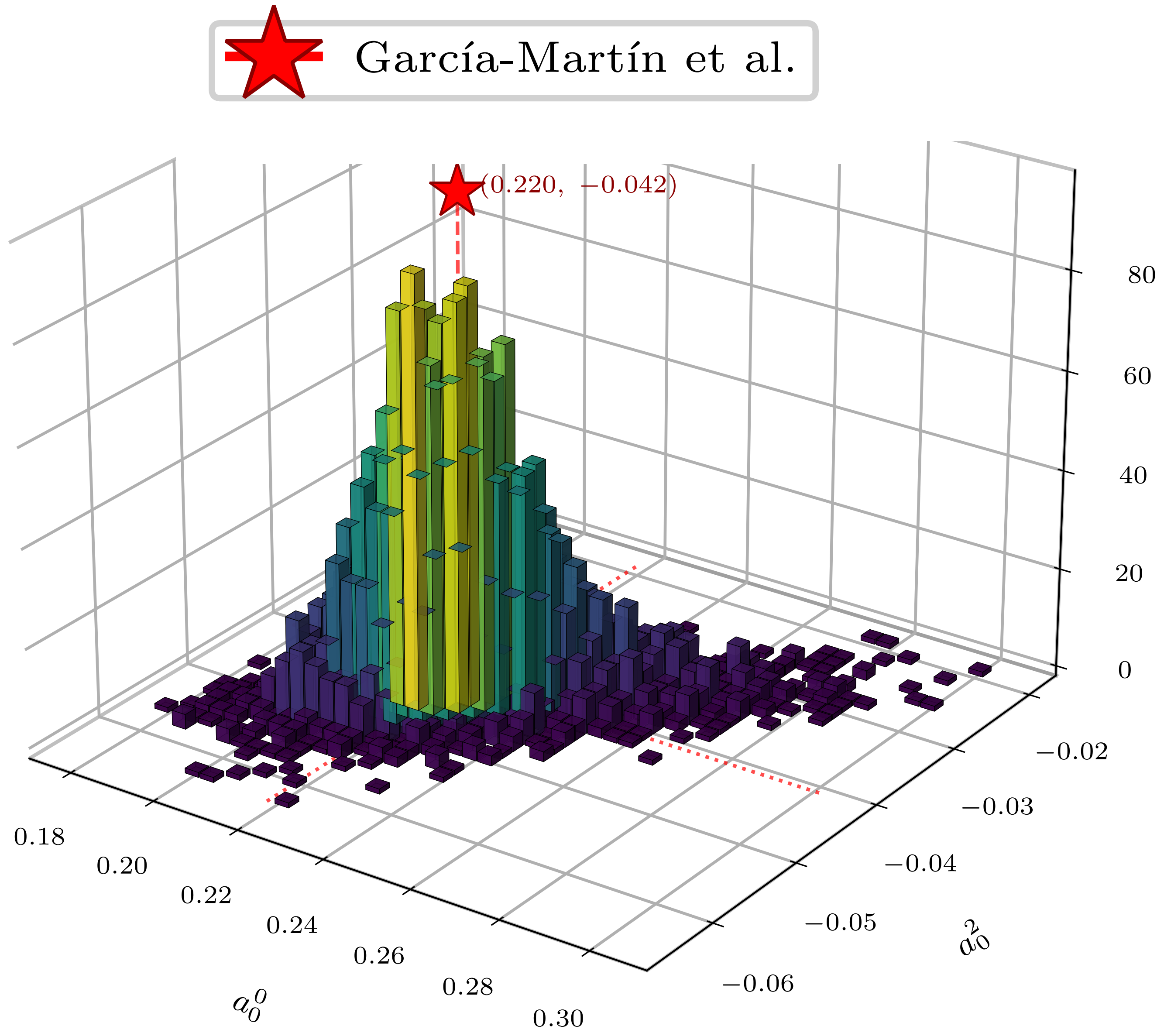


Scattering lengths compatible with most competitive results

Our errors are substantially larger



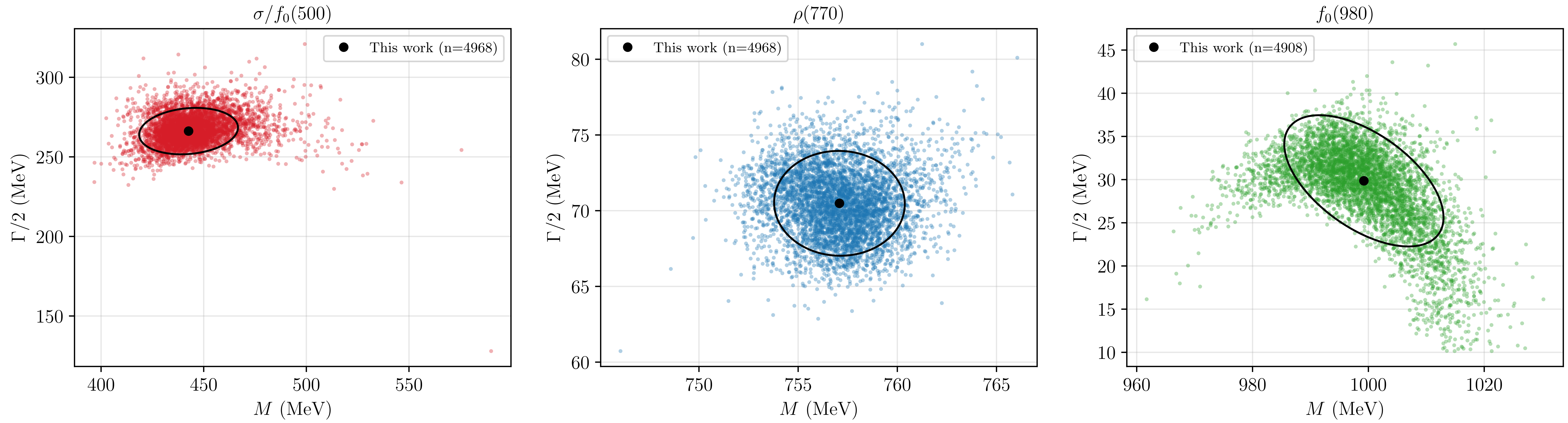




$\pi\pi$ scattering: results

Pole positions are stable

Accurate and competitive with most well-known dispersive analyses



We also extracted couplings