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# Light meson scattering: Spectroscopy & exotics Where do we stand?

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JRP. Physics Reports 658-(2016)-1 JRP, A.Rodas, J. Ruiz de Elvira, Eur. Phys. J. Spec. Top. (2021) 230:1539 JRP & A.Rodas, Physics Reports 969-(2022)-1

Quark Confinement and the Hadron Spectrum XV University of Stavanger-Norway. 1-6<sup>th</sup> August 2022





Supported by:

- $\pi$ ,K, $\eta$  are Goldstone Bosons of QCD  $\rightarrow$  Test Chiral Symmetry Breaking
- π,K appear as final products of almost all hadronic processes: B,D, decays, CP violation...
- SPECTROSCOPY: main or relevant source for PDG parameters of many resonances.
  - Relevant for glueball identification
  - CRYPTOEXOTICS: The controversial light scalar resonances appear here: f<sub>0</sub>(500), f<sub>0</sub>(980), a<sub>0</sub>(980) and strange K\*<sub>0</sub>(700).
     Strong indications for predominant non quark-antiquark nature of light scalars

• **EXOTICS**:  $\pi_1(1400)$  and  $\pi_1(1600)$  controversy in  $\pi\eta$  and  $\pi\eta'$  scattering

# Non-ordinary spectroscopic classification

Lightest scalar SU(3) multiplets <2 GeV. Accepted picture at RPP

Light scalar nonet <1 GeV:



Scalar nonet >1 GeV:

One extra state  $f_0(1370)$ ,  $f_0(1500)$ ,  $f_0(1710)$ 



Non-strange heavier!! Hugely Inverted  $q\overline{q}$  hierarchy. Cryptoexotics? (R.Jaffe 1976)

 $f_0(500)$  and  $f_0(980)$  octet/singlet mixtures  $\kappa/K^*_0(700)$  only recently "well established at PDG" Only in 2021 on-line update "Needs Confirmation"

# Why cryptoexotics?

- Inverted hierarchy (tetraquarks, molecules) (Jaffe 76)
- Scalar quark antiquark, expected above 1 GeV in QM but once meson-meson interactions included, and additional companion pole appears at low energies (Van Beveren, Ribeiro, Rupp, Close, Tornqvist, Oller, Oset....)
- Contrary to vectors, do not saturate ChPT parameters, although being lighter (Gasser, Leutwyler, Ecker, De Rafael, Pich, Donoghue....)
- Dynamically generated from LO Unitarized ChPT whereas vectors need NLO (Oller, Oset, Pelaez, Nieves, Arriola...)
- Do not fit in linear Regge trajectories (J,M<sup>2</sup>) (Anisovich, Sarantsev, Anisovich)
- Dispersively calculated Regge trajectories turn non-ordinary (Londergan, Nebreda, Peláez, Szczepaniak, Rodas)
- Non-ordinary 1/Nc leading behavior (Pelaez, Nebreda, Rios, Nieves, Pich, Oller, Ruiz de Elvira

**DISCLAIMER:** time is limited

Relatively old stuff, although now present in PDG review on "Spectroscopy of light mesons"

Here I concentrate on the existence and determination of parameters from meson-meson scattering

Two longstanding sources of trouble In meson-meson scattering

DATA PROBLEM

**MODEL-DEPENDENCE PROBLEM** 

THIS TALK

Overview of effort to discard inconsistent data and eliminate or reduce model dependence: by using DISPERSIVE/ANALYTICITY APPROACHES

# π and K unstable. Beams NOT luminous enough for ππ and πK collisions: Indirect measurements

1) Very few good data from K  $\rightarrow \pi \pi e v$ . But E < M<sub>K</sub>. Geneva-Saclay (77), E865 (01), NA48/2 (2010)

#### 2) ALMOST ALL DATA from Meson-Nucleon scattering (In the 70's and 80's)



CAVEATS: One-Pion-Exchange (OPE) Approximation

In initial state virtual pion not well defined, Chew-Low off-shell extrapolation

More contributions: absorption, A<sub>2</sub> exchange...

Needs Meson-N partial-wave extraction. Problems with phase shift ambiguities, etc...

As a consequence... VERY LARGE SYSTEMATIC UNCERTAINTIES

# CONFLICTING DATA SETS & SYSTEMATIC uncertainties larger than STATISTICAL



## MODEL PROBLEM: many models used to fit data and extract resonances...

Narrow resonances when far from other resonances or singularities (thresholds, cuts, etc...) produce typical peaks and rapid 180° phase motions



These were the "easy ones" and models are usually fine. For instance, they may be reasonably well approximated by Breit-Wigner shapes  $M \Gamma(s)$ 

$$\sim \frac{1}{M^2 - s - iM \Gamma(s)}$$



## MODEL PROBLEM: Resonances in meson-meson scattering

#### "Breit-Wigner" shapes are easily recognizable... but life is not that easy



Nevertheless there are resonances (poles) in these regions: the  $\sigma/f_0(500)$ ,  $f_0(1370)$  and  $\kappa/K_0^*(700)$  light scalars

The not so easy ones...

- Light scalars are wide, or even extremely wide and frequently overlap with one another or with thresholds like KK.
- Very often they do not produce clear peaks, nor rapid phase motions, and "peak searching" not valid anymore
- Moreover since they are not clear-cut peaks, their shape, apparent position, width...
   can be different depending on the process where they are observed.

- Model fits to different process or partial data can yield different resonances
- Meson-meson scattering has the strongest theory constraints and is the most reliable theoretically to go to the complex plane. (non-linear unitarity condition)

The universal features of resonances are their pole positions and residues \*  $\sqrt{s_{pole}} \approx M-i \Gamma/2$ 

\*in the Riemann sheet obtained from an analytic continuation through the physical cut



The Review of Particle Physics has been adding pole determinations for more and more resonances unfortunately keeping also Breit-Wigner parameters even when not applicable

However, analytic continuations are a delicate mathematical problem and a good control of the analytic structure is needed. Many models fail at this.





- Threshold behavior Chiral symmetry

- Subthreshold behavior - Other cuts Left & circular Chiral symmetry→Adler zeros

What is a dispersion relation.? Very Briefly and for  $\pi \pi$ 

 CAUSALITY ⇒ Amplitudes t(s) are ANALYTIC in complex s plane with cuts due to thresholds (also in crossed channels)

- Cauchy Theorem:

If  $t(s) \rightarrow 0$  fast enough at high s, curved part vanishes

$$t(s) = \frac{1}{\pi} \int_{th}^{\infty} \frac{Im t(s')}{s - s'} ds' + LC$$

Otherwise, determined up to polynomial (subtractions)



1) Calculating t(s) as an integral where there is not data

Good for: 2) Constraining data analysis: Input =output
3) ONLY MODEL INDEPENDENT extrapolation to complex s-plane

Last decades

Effort to eliminate or reduce model dependence by using dispersive approaches often combined with Chiral Perturbation Theory (ChPT).

## We need to get rid of one variable to write CAUCHY THEOREM for the other

1) Fix one variable in terms of the other (fixed-t, hyperbolic relations...)

Most popular: t<sub>0</sub>=0, Forward Dispersion Relations (FDRs). (Kaminski, Pelaez , Yndurain, Garcia Martin, Ruiz de Elvira, Rodas )

PROS: One eq. per amplitude. Simple. High energy reliable. Applicable to all energies Precision

CONS: No direct access to poles... until recently (see below)

## 2) Integrate one variable: Partial wave dispersion relations

 "Roy-like" equations. GKPY eqs, Roy Steiner Equation-Crossing to rewrite Left/circular cuts with. crossing in terms of physical region.
 CONS: Different partial waves or channels coupled. In practice, limited to a finite energy PROS: Directly partial waves. Better to look for poles. Precision

- Unitarized Amplitudes (IAM, N/D, Chew-Mandelstam...)

2-body unitarity exact on dispersion relation for inverse amplitude (single or coupled channels) Ideally combined with ChPT for these approximations, but additional bare/preexisting resonances could be added, simple models for real part, use of Lagrangians, effective theories etc... CONS: Unphysical cuts, higher energies, multibody, approximated PROS: Directly partial waves. Better to look for poles. Connection with QCD through ChPT in UChPT

Precision Dispersive studies

- SOLVE equations: (Ananthanarayan, Colangelo, Gasser, Leutwyler, Caprini, Moussallam, Stern...)
   S and P wave solution for Roy or GKPY equations unique at low energy Needs input on other waves and high energy.
   NO scattering DATA used at low energies (√s ≤ 0.8 ~1 *GeV*)
   Good if interested in low energy scattering and do not trust data.
   Uses ChPT input for threshold parameters
- Impose Dispersion Relations on fits to data. (García-Martín, Kaminski, JRP, Ruiz de Elvira, Ynduráin)
  Also known as "DATA driven dispersive analyses"
  Also needs input on other waves and high energy.

# FIRST STEP: Simple Unconstrained Fits (UFD) to data

# Estimation of statistical and SYSTEMATIC errors $\pi\pi \rightarrow \pi\pi$ partial-wave data



## FIRST STEP: Simple Unconstrained Fits (UFD) to data

Estimation of statistical and SYSTEMATIC errors  $\pi K$  and  $\pi \pi \rightarrow K K$  partial-wave Data



#### SECOND STEP: Check dispersion relations: $\pi\pi \rightarrow \pi\pi$

In general, data does not satisfy well DR. Sometimes very badly indeed



# THIRD STEP: Use dispersion relations as constraints for the fits: $\pi\pi \rightarrow \pi\pi$

Very good fulfillment: Constrained Fits to Data



## S0 wave: from UFD to CFD

The changes from Unconstrained to Constrained fits are not too large, but relevant in some regions



# From Unconstrained (UFD) to Constrained Fits to data (CFD)

JRP, A.Rodas-PhysRevLett.124.172001-2020

# S-waves. The most interesting for the $K_0^*$ resonances and the $K_0^*(700)$ in particular



## Unconstrained fits (UFD): LARGE inconsistencies with 3 Roy-Steiner Eqs.

One or no subtraction for F- lie on opposite sides of input

#### The most relevant wave for the kappa resonance.



#### **Constrained fits (UFD): Consistent within uncertainties**







Dispersion relations provide model-independent analytic continuation to <u>first</u> Riemann sheet, but the most relevant resonance poles live in the CONTIGUOUS sheet

• For elastic resonances, only second sheet, S<sup>II</sup>=1/S<sup>I</sup>

 $\sigma/f_0(500)$ , κ/K<sub>0</sub>\*(700). Purely Dispersive Determination WHERE DO WE STAND? Light Scalars at RPP 2021 (on-line update). "Note on Light Scalar Mesons below 1 GeV"

"Roy-like" and "Breit-Wigner" poles identified separately from the rest Not all from meson-meson scattering



# κ/K<sub>0</sub>\*(700) estimate 2021 No longer "Needs Confirmation"





JRP, A.Rodas-PhysRevLett.124.172001-2020

😕 But still Breit-Wigners!!

WHERE DO WE STAND? Light Scalars at RPP 2021 (on-line update). "Note on Light Scalar Mesons below 1 GeV"

 $f_0(980)$  and  $a_0(980)$  poles also provided. Less controversial, smaller uncertainties Not all from meson-meson scattering



From scattering "Roy-like"

Dispersion relations provide model-independent analytic continuation to <u>first</u> Riemann sheet, but the most relevant resonance poles live in the CONTIGUOUS sheet

• For elastic resonances (only second sheet), S<sup>II</sup>=1/S<sup>I</sup>

σ/f<sub>0</sub>(500), κ/K<sub>0</sub>\*(700), f<sub>0</sub>(980), Purely Dispersive Determination from meson-meson scattering

• To reach the contiguous sheet in the inelastic case, we need an analytic continuation to the second sheet by means of general analytic functions reproducing the Dispersion Relation in the real axis or the upper-half complex plane.

Several methods in the literature

- Sequences of Padés
- Continued Fractions
- Laurent-Pietarinen functions
- Conformal expansions...

**These methods** <u>avoid specific parameterizations</u>, reducing drastically the model-dependence Tested then with the  $\sigma/f_0(500)$  and  $\kappa/K_0^*(700)$ . Compatible results.

# The method can be used for inelastic resonances too. Provides resonance parameters WITHOUT ASSUMING SPECIFIC FUNCTIONAL FORM



Using Padé Sequences, the kappa: (670±18)-i(295±28) MeV Consistent with dispersive value JRP, A.Rodas & J. Ruiz de Elvira. Eur. Phys. J. C (2017) 77:91

 $f_0(1370)$  and  $f_0(1500)$  poles from dispersive meson-meson + analytic continuation

Roy  $\pi\pi \rightarrow \pi\pi$  equations strict applicability only up to 1.1 GeV.

However, Forward Dispersion Relations applicability up to 1.42 GeV in our fits.

Continued fractions provide stable pole description absent in original experimental  $\pi\pi \rightarrow \pi\pi$  data analyses.

Also in <u>extrapolation</u> of Roy-like equations

Roy-Steiner eqs. for  $\pi\pi \rightarrow KK$  are applicable there. Analytically continued **also find f<sub>0</sub>(1370)** Larger uncertainty But ~2 $\sigma$  tension on mass due to DATA

JRP, A.Rodas & J. Ruiz de Elvira. e-Print: 2206.14822 [hep-ph]





#### WHERE DO WE STAND? Recent developments on Exotics from meson-meson scattering

Candidates:  $\pi_1(1400)$  and  $\pi_1(1600)$  with J=1<sup>-+</sup> @Crystal Barrel, Brookhaven and COMPASS Exotic P-wave in  $\pi\eta \rightarrow \pi\eta$  and  $\pi\eta' \rightarrow \pi\eta'$  scattering coupled to other channels as well. But not real data on scattering of  $\pi\eta$  and  $\pi\eta'$ . Just  $\pi p \rightarrow \eta \pi p$ ,  $\pi p \rightarrow \eta' \pi p$ Various analyses used BW.

# Recent "Analytic" methods:

Rodas et al. (JPAC Collab) PRL122.042002 (2019) N/D method for final state. Sampling of large # of models Input: COMPASS data



Kopf et al. Eur. Phys. J. C (2021) 81:1056 K-matrix/Chew-Mandelstam analytic parameterization Input:Crystal Ball+COMPASS Consistent with JPAC but slightly narrower

Lattice: HadSpec Collab.PRD103, 054502 (2021) Actual scattering (caveats: in a box, dicretization, large pion mass, extrapolation)



#### SUMMARY

- Over the last years, and as late as 2021, the use of techniques based on analyticity and dispersion relations applied to meson-meson scattering has finally settled the longstanding controversy about the existence of two light scalar nonets below 2 GeV

- It is of the uttermost importance to characterize resonances by their poles. Some simple parameterizations may be useful to describe data, but using them to characterize resonant states only creates confusion.

- Models should be consistent with the dispersive data analyses and with the poles found there.

- The present picture is that of a light scalar nonet below 1 GeV of a non-ordinary quarkantiquark nature (Criptoexotic). All its members are now identified

- Another nonet exists around 1.5 GeV, with one  $f_0$  state too many. The f0(1370) is found in meson-meson scattering from dispersively constrained meson-meson scattering

- Methods based on analyticity show that it is possible to describe the two exotic  $\pi_1$  with just asingle pole/resonance