RUB

Search for light Exotics in Coupled Channel PWA with PAWIAN

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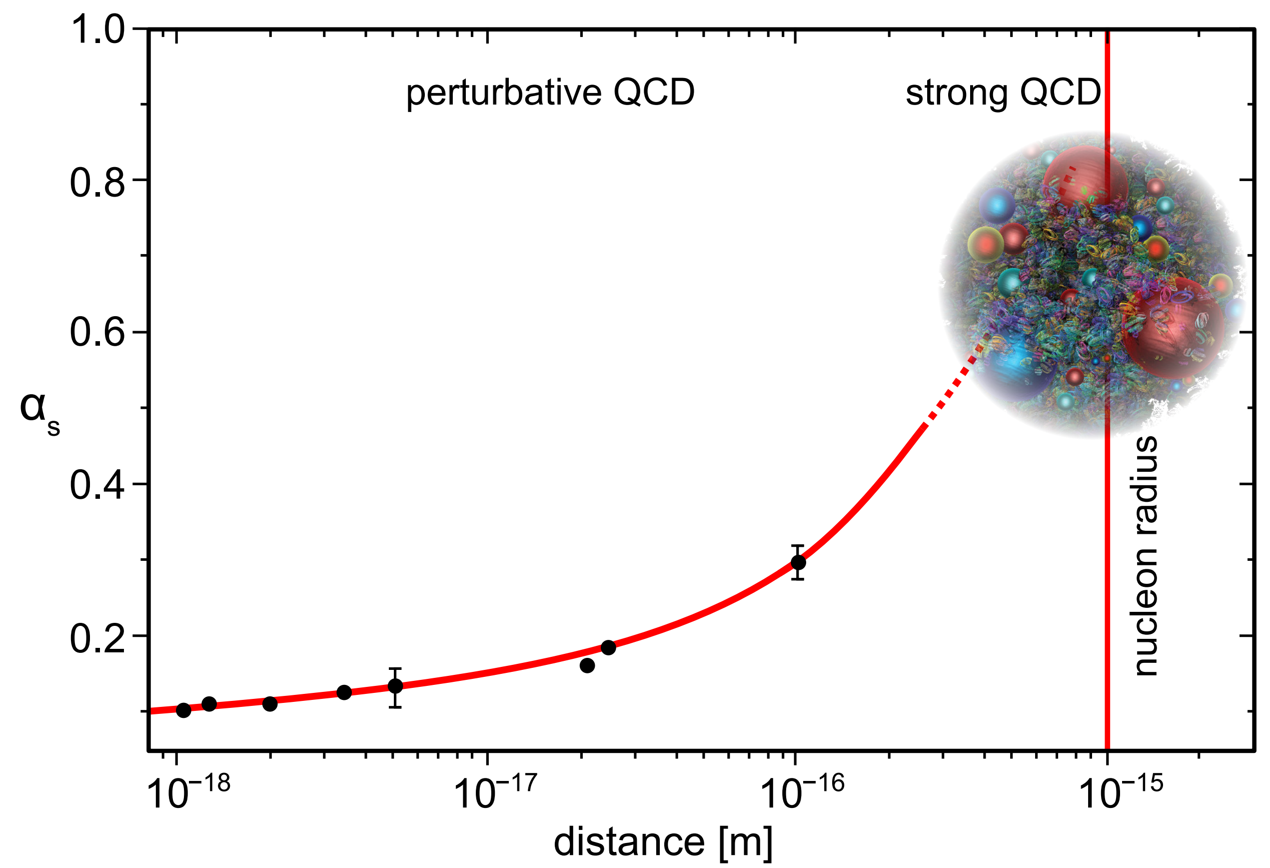
STRONG 2020

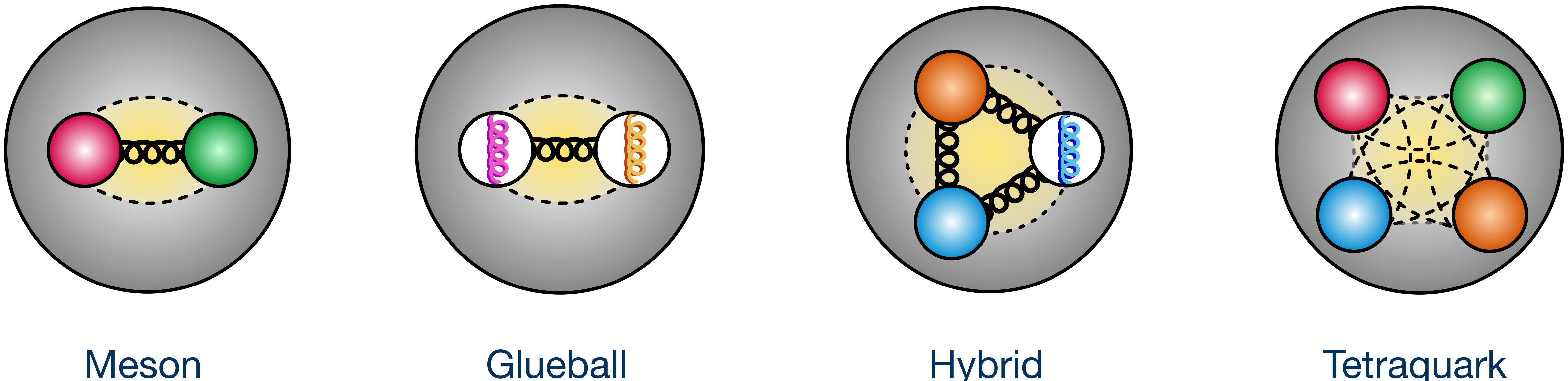
Light Meson Regime

- Light mesons are tricky to tackle for both theory and experiment
- Since $\alpha_s \sim 1$, higher order processes are not suppressed anymore
- Occurring in the non-perturbative regime of QCD ➡ perturbative techniques fail
- Alternative theoretical tools often model dependent or very computational expensive
- Highly populated spectrum: many overlapping, interfering, mixing or distorted states



Production and Decay Information

- Different production mechanism and decay channels must be compared in order to understand a particle's nature and to understand its inner structure



Gluon rich processes

- Charmonium decays
- $\bar{p}p$ annihilation
- pp central production
- …

QED mediated process

- Two-photon production

Motivation

- Determination of pole parameters and coupling strength in different production and decay systems are essential
  - Analyses of only single channels are not sufficient!
  - Coupled channel analyses of data from different production mechanisms and decay systems are needed

- *Advantages compared to single channel fits:*
  - Common and unique description of the dynamics
  - Better description of threshold effects
  - Better fulfilment of the conservation of unitarity
  - More constraints due to common amplitudes

Dynamics

- Breit-Wigner functions are widely used
  - Good approximation for isolated resonances appearing in a single channel
  - But violate the unitarity
  - Extracted resonance parameters are not unique and depend on the production and decay process

➡ More sophisticated descriptions needed for
  - Resonances decaying into multiple channels
  - Several resonances with the same QNs appearing in the same channel
  - ➡ Resonances located at thresholds ➡ distortion of the line shape

➡ Approaches with a proper consideration of unitarity and analyticity need to be used

K-Matrix, N/D-method, Two-Potential, …

K-Matrix Approach

- Scattering theory the S-matrix describes fully two body scattering

$$S = I + 2i\sqrt{\rho}T\sqrt{\rho}$$

- T-matrix can be elegantly expressed by the K-matrix

$$T = (I + iKC)^{-1} K$$

C: generalised phase space factor, e.g. CM-functions
$\rho \to -\operatorname{Im} C$

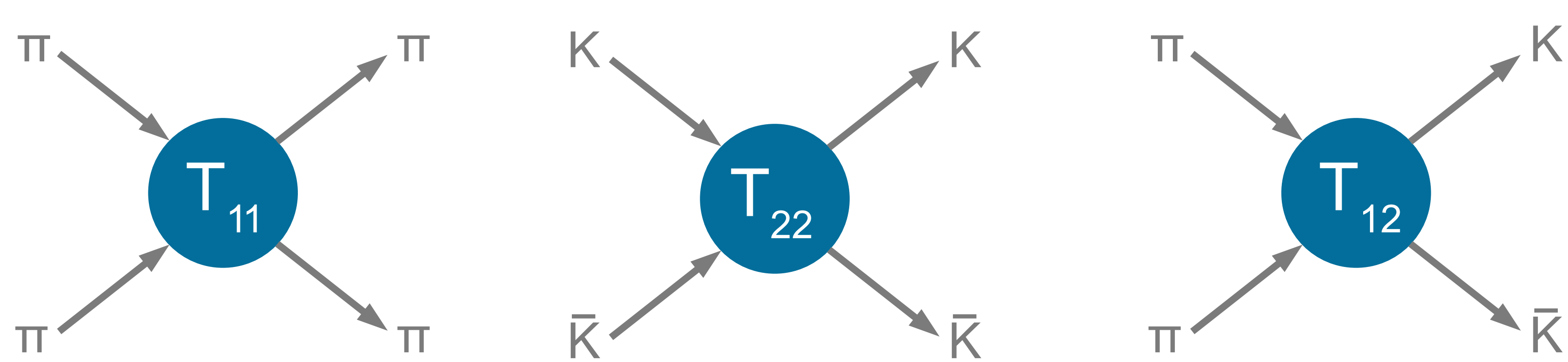
- K-matrix contains singularities ➡ poles and possibly background terms

$$K_{ij} = \sum_{\alpha} \frac{g_{\alpha_i} g_{\alpha_j}}{m_\alpha^2 - s} + \sum_k c_{kij} s^k$$

$g_{\alpha i}$: decay coupling, real
m_α: pole bare mass

- The elements of the matrices express also interactions between different channels
  Example: 1. channel: ππ, 2. channel: $K\bar{K}$

$$T = \begin{pmatrix} T_{11} & T_{12} \\ T_{12} & T_{22} \end{pmatrix}$$



P-Vector Approach

- K-matrix describes only „simple“ scattering processes so far
- Therefore a generalization of the K-matrix formalism to more complex reactions is needed

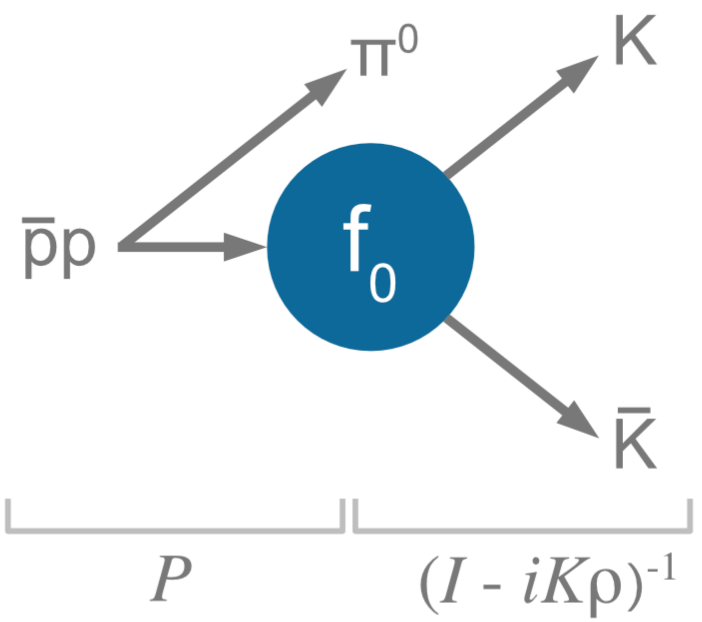
P-vector approach:

$$F = (I + iKC)^{-1} P$$

$$P_i = \sum_{\alpha} \frac{\beta_\alpha g_{\alpha_i}}{m_\alpha^2 - s} + \sum_k c_{ki} s^k$$

$g_{\alpha i}$: decay coupling, real
β_α: production coupling, complex

- By construction P has the same pole structure as K!
- P is allowed to contain background polynomials (effective description of t-channel-like effects)
- Example: $\bar{p}p \to f_0 \pi^0 \to K\bar{K}\pi^0$



The PAWIAN Package

- **PA**rtial **W**ave **I**nteractive **AN**alysis software package developed in Bochum

Production Mechanisms

- Annihilation: $\bar{p}p$, e^+e^-, $\gamma\gamma$-fusion
- Scattering: πp, $\pi\pi$, …

Dynamical Models

- K-matrix
- Two-potential
- Breit-Wigner,…

Spin Formalisms

- helicity
- canonical amplitudes

…

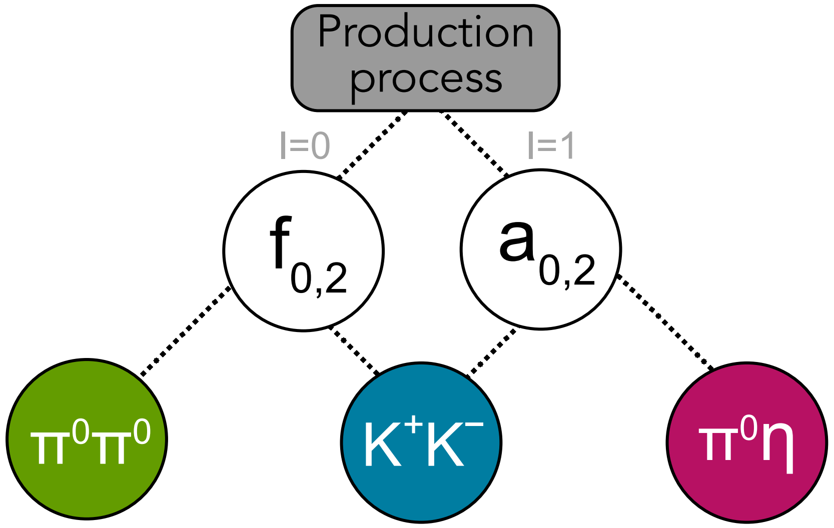
- Hypothesis and other settings defined via configuration files
- Channels with arbitrary number of final state particles
- Event based maximum likelihood fit using e.g. MINUIT2
- Support for server-client mode and cluster submission
- Analysis tools: extraction of pole positions and residues/BF
- Event generation, histogramming, efficiency correction, …

https://gitlab.ep1.rub.de/pwa/Pawian

Coupled Channel Analysis of $\bar{p}p \rightarrow \pi^0\pi^0\eta$, $\pi^0\eta\eta$ and $K^+K^-\pi^0$

- Describing simultaneously
  - Crystal Barrel data sets at 900 MeV/c
  - ππ scattering data for I=0 S- and D-wave and I=1 P-wave

Why these three channels?



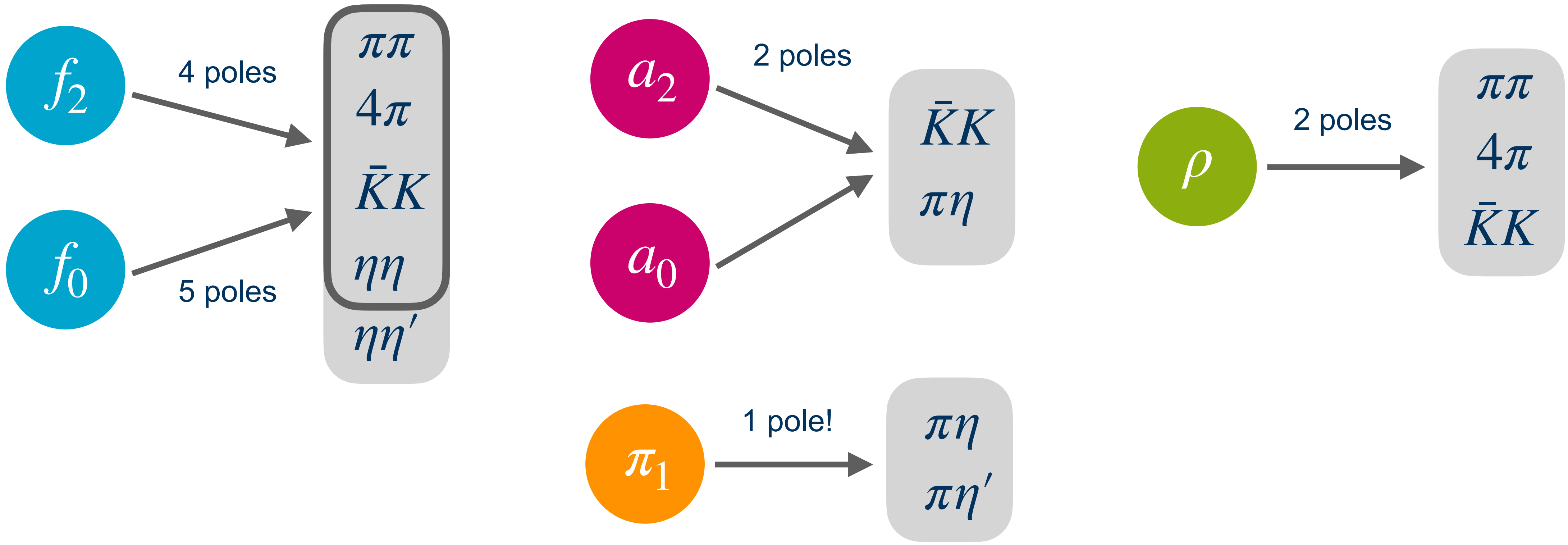
Why scattering data?

- Processes only characterized by elasticities and phase motions
  ➡ Easy access to resonance parameters
- Quite pure and simple reaction
- Good constraints for f_0, f_2 and ρ resonances

Eur. Phys. J.C 80 (2020) 5, 453

Coupled Channel Analysis of $\bar{p}p \to \pi^0 \pi^0 \eta$, $\pi^0 \eta \eta$ and $K^+ K^- \pi^0$

- Described using the K-Matrix formalism in the P-vector approach
- The whole process from the initial to the final state is described in all phase space dimensions



- **(Kπ) S-wave**: fixed K-Matrix parameterization from FOCUS Phys. Lett. B653 (2007) 1-11

- Breit-Wigner description for the isolated resonances
  - $\phi \to K^+K^-$
  - $K^{*\pm}(892) \to K^\pm\pi^0$

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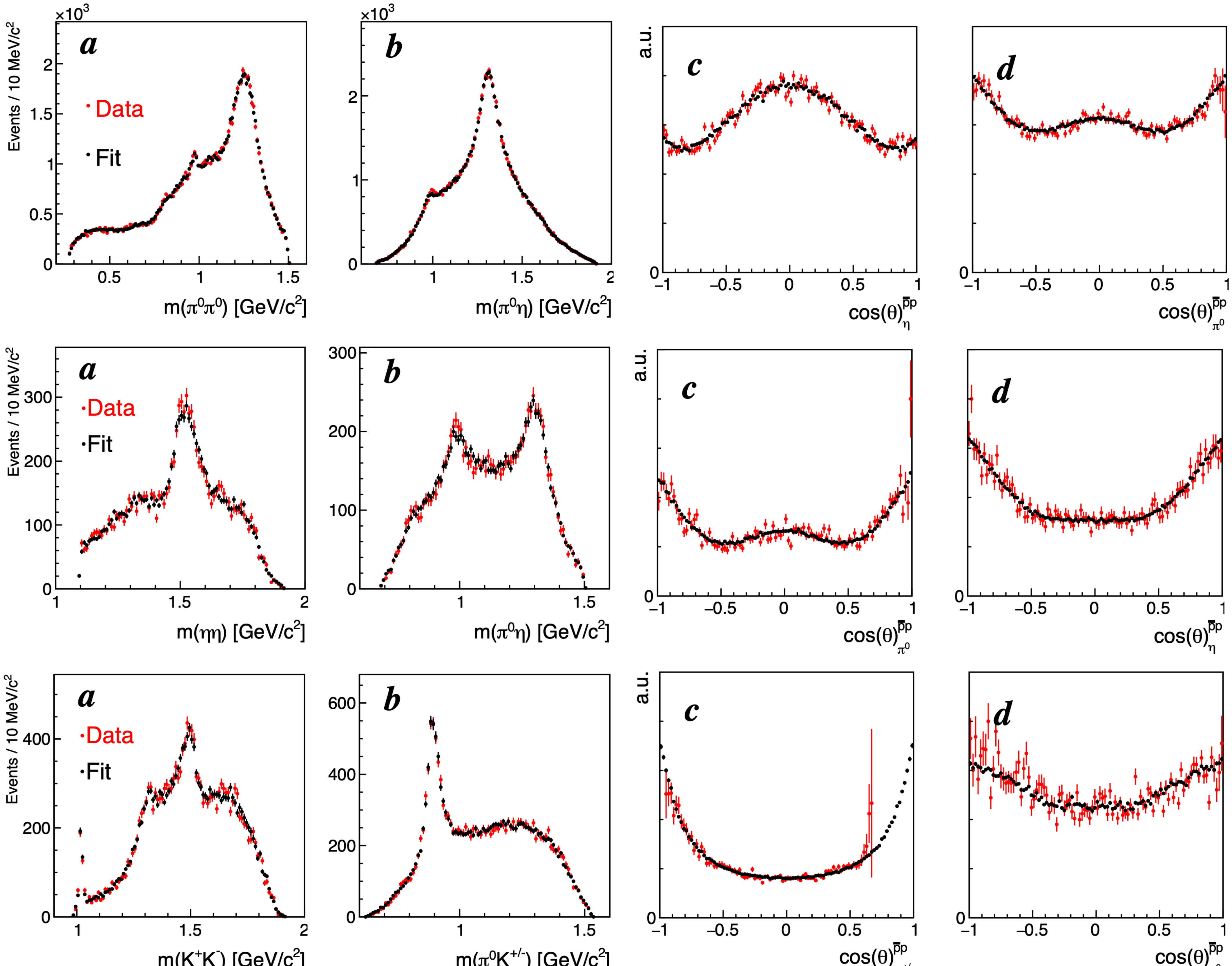
Coupled Channel Analysis of $\bar{p}p \rightarrow \pi^0 \pi^0 \eta$, $\pi^0 \eta \eta$ and $K^+ K^- \pi^0$



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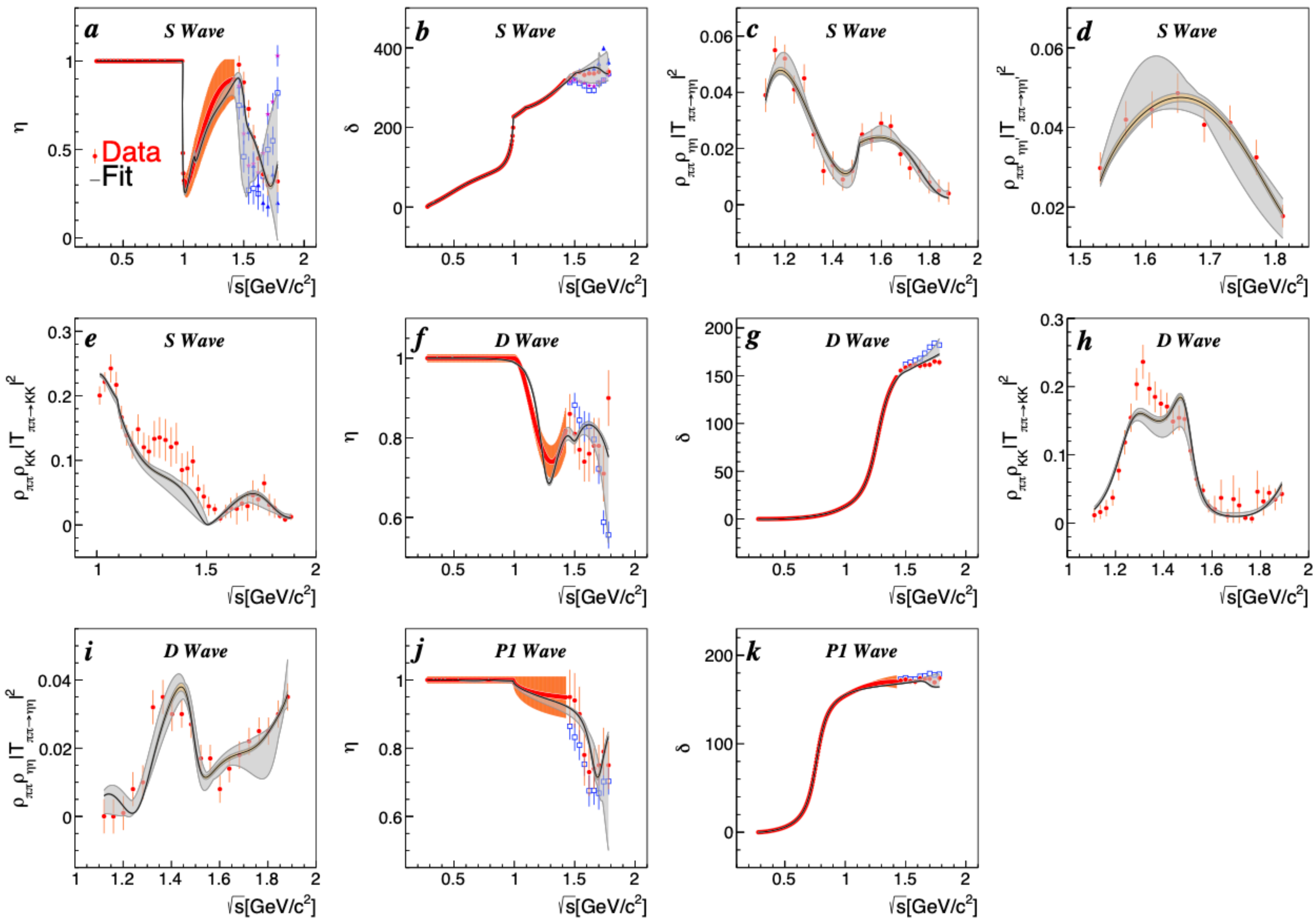
Coupled Channel Analysis of $\bar{p}p \rightarrow \pi^0\,\pi^0\,\eta$, $\pi^0\,\eta\,\eta$ and $K^+\,K^-\,\pi^0$

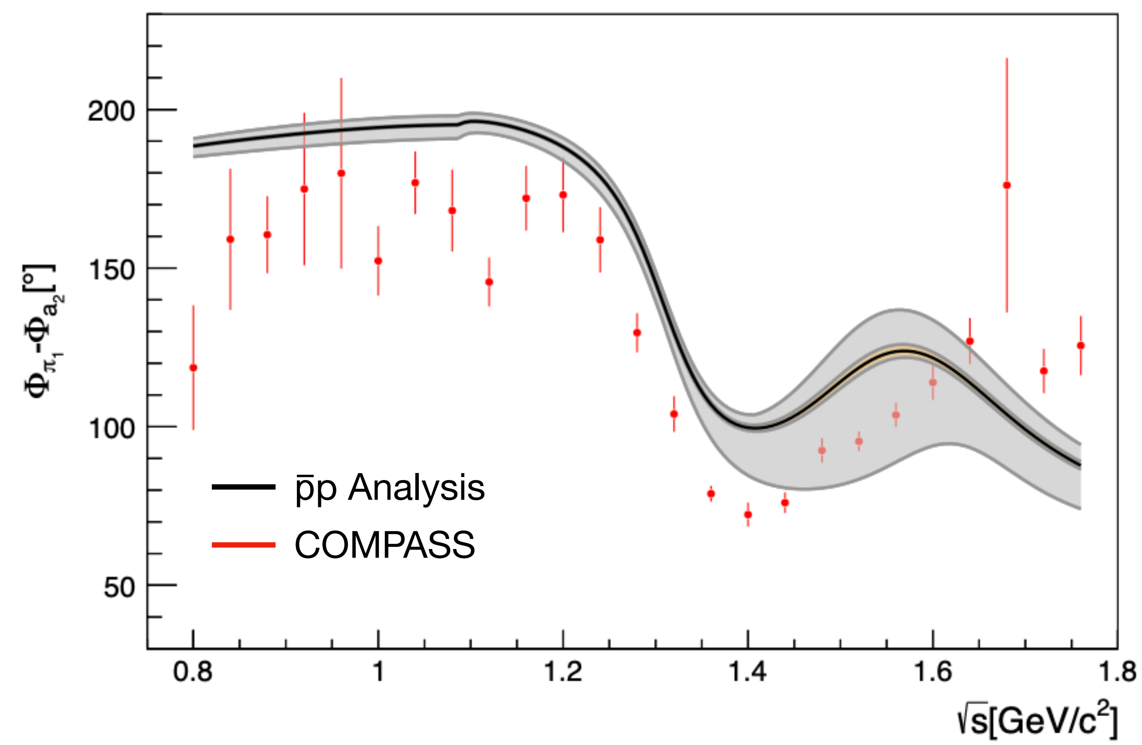


Coupled Channel Analysis of $\bar{p}p \to \pi^0 \pi^0 \eta$, $\pi^0 \eta \eta$ and $K^+ K^- \pi^0$

- Exotic π_1 wave significantly contributing in the $\pi^0\eta$ system!

	contribution (in %) for channel		
	$\pi^0\pi^0\eta$	$\pi^0\eta\eta$	$K^+K^-\pi^0$
$f_0\,\pi^0$		$23.7 \pm 1.2 \pm 2.3$	$7.4 \pm 0.3 \pm 4.1$
$f_0\,\eta$	$10.7 \pm 0.4 \pm 1.8$		
$f_2\,\pi^0$		$30.1 \pm 1.3 \pm 2.7$	$17.1 \pm 0.7 \pm 10.0$
$f_2\,\eta$	$52.3 \pm 0.8 \pm 5.0$		
$\rho\,\pi^0$			$17.2 \pm 1.0 \pm 4.0$
$a_0\,\pi^0$	$22.4 \pm 0.4 \pm 1.0$		$6.1 \pm 0.2 \pm 2.8$
$a_0\,\eta$		$28.6 \pm 1.1 \pm 7.5$	
$a_2\,\pi^0$	$33.0 \pm 0.6 \pm 2.9$		$6.4 \pm 0.2 \pm 2.9$
$a_2\,\eta$		$18.8 \pm 1.1 \pm 5.6$	
$K^*(892)^\pm K^\mp$			$45.0 \pm 1.3 \pm 11.0$
$(K\pi)^\pm_S K^\mp$			$6.1 \pm 0.4 \pm 4.9$
$\phi(1020)\,\pi^0$			$2.5 \pm 0.3 \pm 0.3$
$\pi_1\,\pi^0$	$16.7 \pm 0.5 \pm 3.0$		
Σ	$135.0 \pm 1.2 \pm 8.7$	$101.2 \pm 2.4 \pm 11.7$	$107.8 \pm 1.9 \pm 12.5$

T-Matrix phase difference in agreement!



- K-matrix description with 1 pole and two channels $\pi\eta$ and $\pi\eta'$
- Phase difference between the π_1 and a_2 wave from $T_{\pi\eta\to\pi\eta}$ in good agreement with COMPASS measurement Phys. Lett. B740 (2015) 303-311, Phys. Lett. B811 (2020) 135913 (erratum)
- Obtained pole position of the π_1: M = $(1404.7 \pm 3.5\ (stat.)\ ^{+9.0}_{-17.3}\ (sys.))\ \mathrm{MeV}/c^2$

  Γ = $(628.3 \pm 27.1\ (stat.)\ ^{+35.8}_{-138.2}\ (sys.))\ \ \mathrm{MeV}$

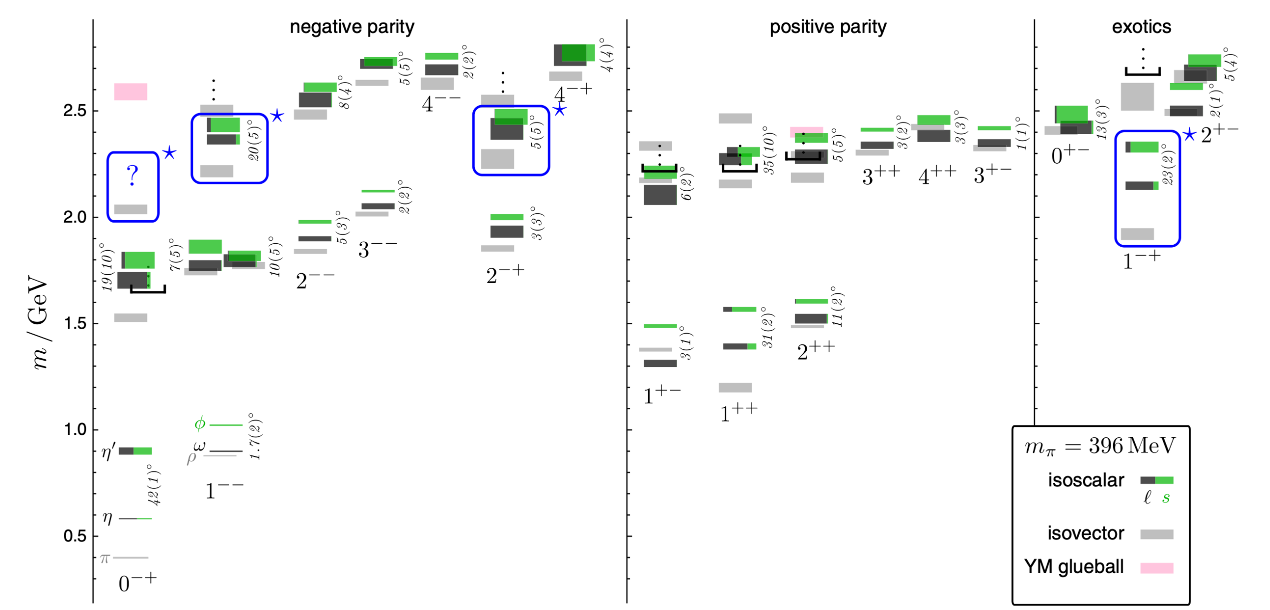
Status of the Lightest Hybrid Candidate

- Two π_1 hybrid candidates below 2 GeV are listed in PDG
  - one at around 1.4 GeV only seen in $\pi\eta$
  - the other at around 1.6 GeV seen in $\pi\eta'$ but not in $\pi\eta$

➡ Parameters obtained by Breit-Wigner fits!

Decay	$\pi_1(1400)$	$\pi_1(1600)$
$\pi\eta$	seen	not seen
$\pi\eta'$	not seen	seen
$\rho\pi$	not seen	seen
$b_1(1235)\pi$	not seen	seen
$f_1(1285)\pi$	not seen	seen

based on PDG

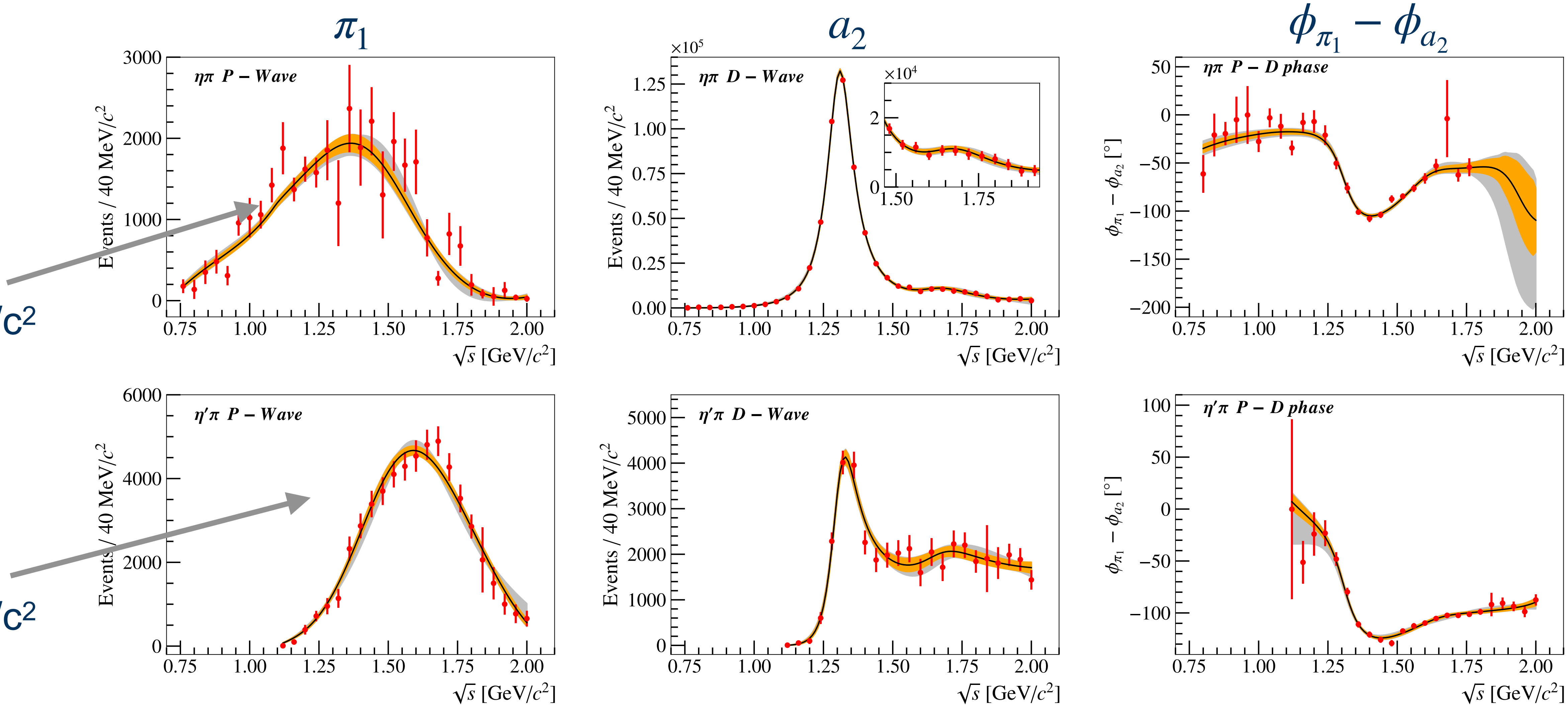


Phys.Rev. D84 (2011) 074023

➡ But: Only one π_1 state predicted slightly below 2 GeV

Coupled Channel Analysis of p̄p and COMPASS Data

- Extension: simultaneous fit of ππ-scattering data, p̄p ➞ $\pi^0 \pi^0 \eta$, $\pi^0 \eta \eta$ and $K^+ K^- \pi^0$ and $\pi^- p \rightarrow \pi^- \eta(')\pi$
- Good description with one pole scenario for the 1^{-+} wave using K-matrix
- ➡ Confirmation of the JPAC analysis



1.4 GeV/c²

1.6 GeV/c²

Obtained pole position:

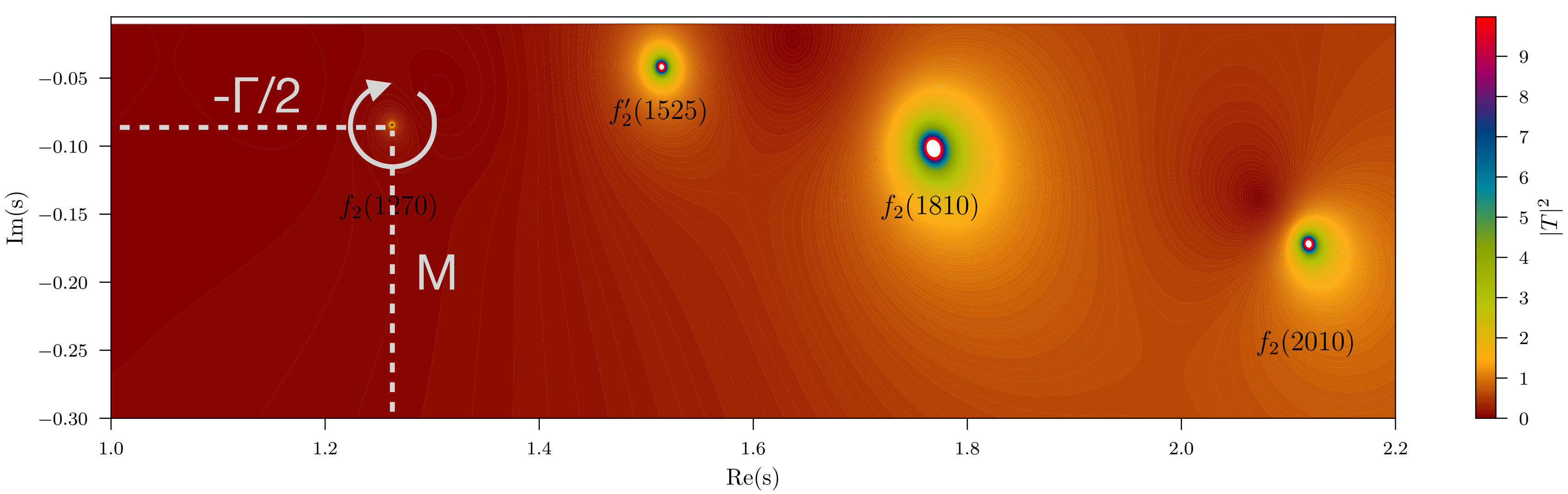
$$M = 1623 \pm 47^{+24}_{-75}\ \mathrm{MeV}/c^2$$
$$\Gamma = 455 \pm 88^{+144}_{-175}\ \mathrm{MeV}$$

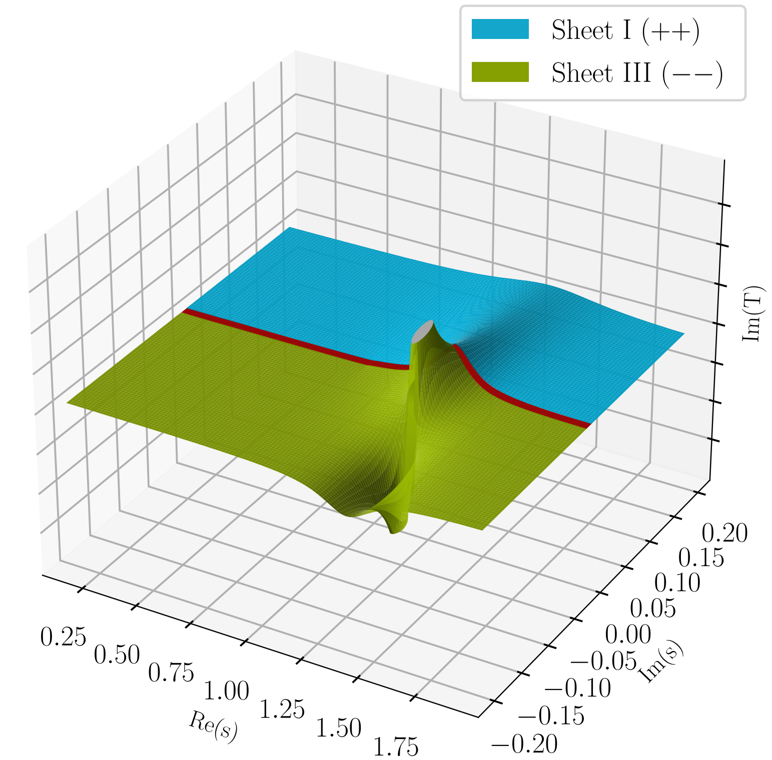
Eur. Phys. J. C (2021) 81, 1056

Extraction of Resonance Properties

- K-matrix and thus the pole itself contains all resonance properties
- Masses and widths defined by the pole position in the complex energy plane of the T-matrix sheet closest to the physical sheet

Example: f_2-wave





example for 2 channel case

- Partial decay widths can be extracted via the residues:

$$Res^{\alpha}_{k\to k} = \frac{1}{2\pi i} \oint_{C_{z_\alpha}} \sqrt{\rho_k} \cdot T_{k\to k}(z) \cdot \sqrt{\rho_k}\ \mathrm{d}z$$

➡ More than 50 different resonance properties extracted on the relevant Riemann-sheets for a_0, a_2, f_0 and f_2 and ρ resonances!

Coupled Channel Analysis of p̄p and COMPASS Data

name	relevant data	Breit-Wigner mass [MeV/c^2]	Breit-Wigner width Γ [MeV]
$K^*(892)^\pm$	$\bar{p}p$	$893.8 \pm 1.0 \pm 0.8$	$56.3 \pm 2.0 \pm 1.0$
$\phi(1020)$	$\bar{p}p$	$1018.4 \pm 0.5 \pm 0.2$	4.2 (fixed)

name	relevant data	pole mass [MeV/c^2]	pole width Γ [MeV]
$f_0(980)^{---++}$	scat	$977.8 \pm 0.6 \pm 1.4$	$98.8 \pm 6.6 \pm 11.2$
$f_0(980)^{--+++}$	scat	$992.6 \pm 0.3 \pm 0.5$	$61.2 \pm 1.2 \pm 1.7$
$f_0(1370)$	scat	$1281 \pm 11 \pm 26$	$410 \pm 12 \pm 50$
$f_0(1500)$	$\bar{p}p$ + scat	$1511.0 \pm 8.5\,^{+3.5}_{-14.0}$	$81.1 \pm 4.5\,^{+26.9}_{-0.5}$
$f_0(1710)$	$\bar{p}p$ + scat	$1794.3 \pm 6.1\,^{+47.0}_{-61.2}$	$281 \pm 32\,^{+12}_{-80}$
$f_2(1810)$	scat	$1769 \pm 26\,^{+3}_{-26}$	$201 \pm 57\,^{+13}_{-87}$
$f_2(X)$	scat	$2119.9 \pm 6.4\,^{+25.7}_{-1.1}$	$343 \pm 11\,^{+32}_{-11}$

name	relevant data	pole mass [MeV/c^2]	pole width Γ [MeV]	$\Gamma_{\pi\eta'}/\Gamma_{\pi\eta}$ [%]
π_1	$\bar{p}p + \pi p$	$1623 \pm 47\,^{+24}_{-75}$	$455 \pm 88\,^{+144}_{-175}$	$554 \pm 110\,^{+180}_{-27}$

name	relevant data	pole mass [MeV/c^2]	pole width Γ [MeV]	$\Gamma_{KK}/\Gamma_{\pi\eta}$ [%]
$a_0(980)^{--}$	$\bar{p}p$	$1002.7 \pm 8.8 \pm 4.2$	$132 \pm 11 \pm 8$	$14.8 \pm 7.1 \pm 3.6$
$a_0(980)^{-+}$	$\bar{p}p$	$1003.3 \pm 8.0 \pm 3.7$	$101.1 \pm 7.2 \pm 3.0$	$13.5 \pm 6.2 \pm 3.1$
$a_0(1450)$	$\bar{p}p$	$1303.0 \pm 3.8 \pm 1.9$	$109.0 \pm 5.0 \pm 2.9$	$396 \pm 72 \pm 72$

name	relevant data	pole mass [MeV/c^2]	pole width Γ [MeV]	$\Gamma_{KK}/\Gamma_{\pi\eta}$ [%]	$\Gamma_{\pi\eta'}/\Gamma_{\pi\eta}$ [%]
$a_2(1320)$	$\bar{p}p + \pi p$	$1318.7 \pm 1.9\,^{+1.3}_{-1.3}$	$107.5 \pm 4.6\,^{+3.3}_{-1.8}$	$31 \pm 22\,^{+9}_{-11}$	$4.6 \pm 1.5\,^{+7.0}_{-0.6}$
$a_2(1700)$	$\bar{p}p + \pi p$	$1686 \pm 22\,^{+19}_{-7}$	$412 \pm 75\,^{+64}_{-57}$	$2.9 \pm 4.0\,^{+1.1}_{-1.2}$	$3.5 \pm 4.4\,^{+6.9}_{-1.2}$

name	relevant data	pole mass [MeV/c^2]	pole width Γ [MeV]	$\Gamma_{\pi\pi}/\Gamma$ [%]	Γ_{KK}/Γ [%]	$\Gamma_{\eta\eta}/\Gamma$ [%]
$f_2(1270)$	$\bar{p}p$ + scat	$1262.4 \pm 0.2\,^{+0.2}_{-0.3}$	$168.0 \pm 0.7\,^{+1.7}_{-0.1}$	$87.7 \pm 0.3\,^{+4.8}_{-4.4}$	$2.6 \pm 0.1\,^{+0.1}_{-0.2}$	$0.3 \pm 0.1\,^{+0.0}_{-0.1}$
$f_2'(1525)$	$\bar{p}p$ + scat	$1514.7 \pm 5.2\,^{+0.3}_{-7.4}$	$82.3 \pm 5.2\,^{+11.6}_{-4.5}$	$2.1 \pm 0.3\,^{+0.8}_{-0.0}$	$67.2 \pm 4.2\,^{+5.0}_{-3.8}$	$9.8 \pm 3.8\,^{+1.7}_{-3.3}$
$\rho(1700)$	$\bar{p}p$ + scat	$1700 \pm 27\,^{+13}_{-16}$	$181 \pm 25\,^{+0.0}_{-16}$	$13.6 \pm 1.2\,^{+0.9}_{-0.5}$	$0.8 \pm 0.1\,^{+0.0}_{-0.0}$	-

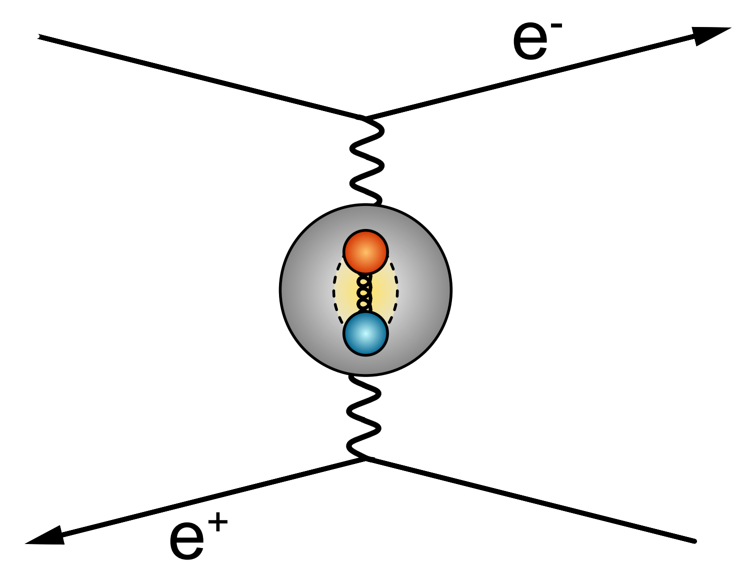
Several resonance properties measured simultaneously within one fit!

Two-Photon Reactions

- Two photon widths ➡ information about inner structure of resonances!
- Complementary information on glueball candidates!

Untagged reactions:

- Scattering angles of electron and positron are small and are not detectable
- Quasi real photons carrying small virtuality ➡ spin 1 strongly suppressed
- All resonances with quantum numbers $0^{\pm+}, 2^{\pm+}, \ldots$ can be directly produced

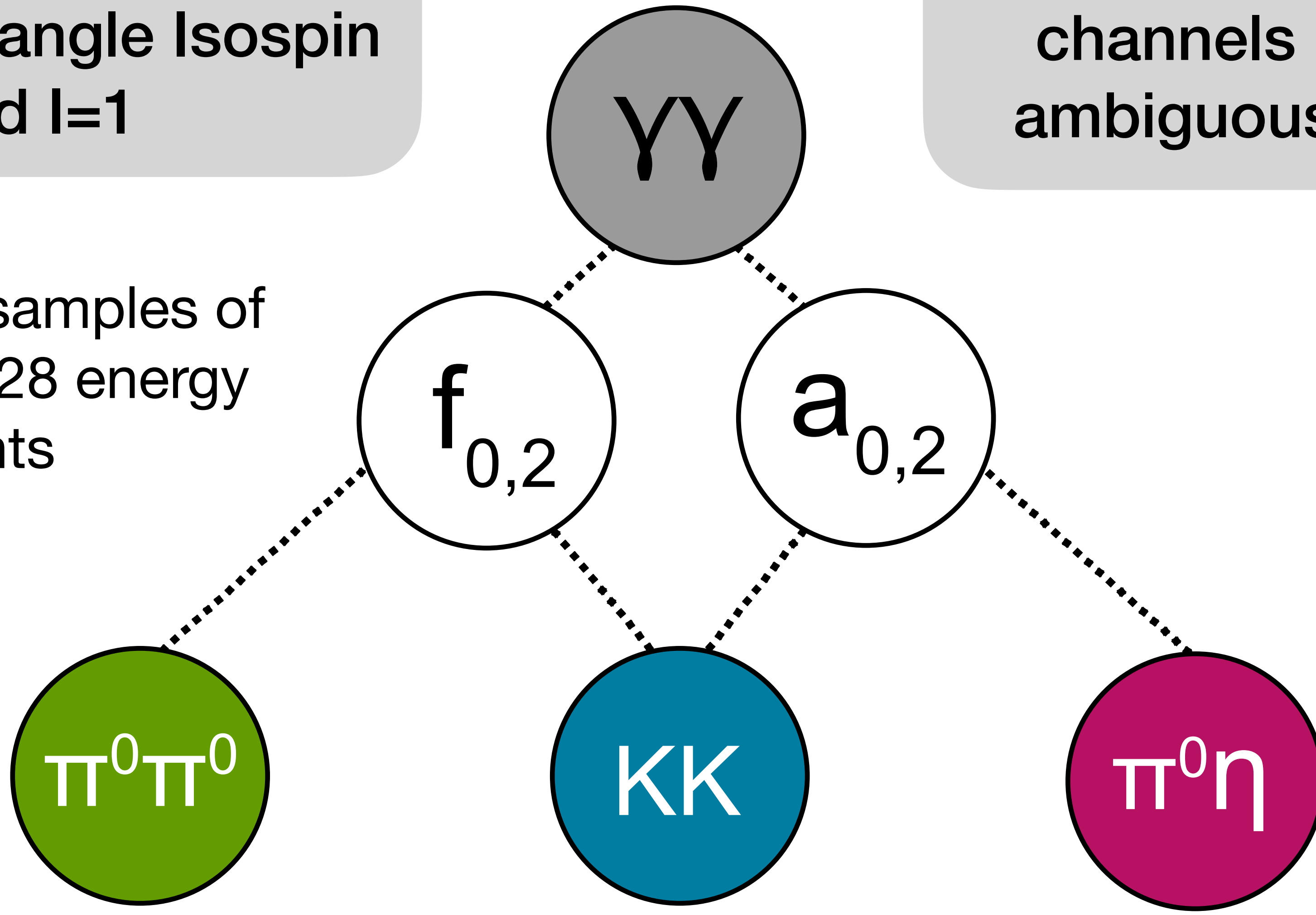


Coupled Channel Analysis of Two-Photon Data

By combining these channels,
one can disentangle Isospin I=0 and I=1

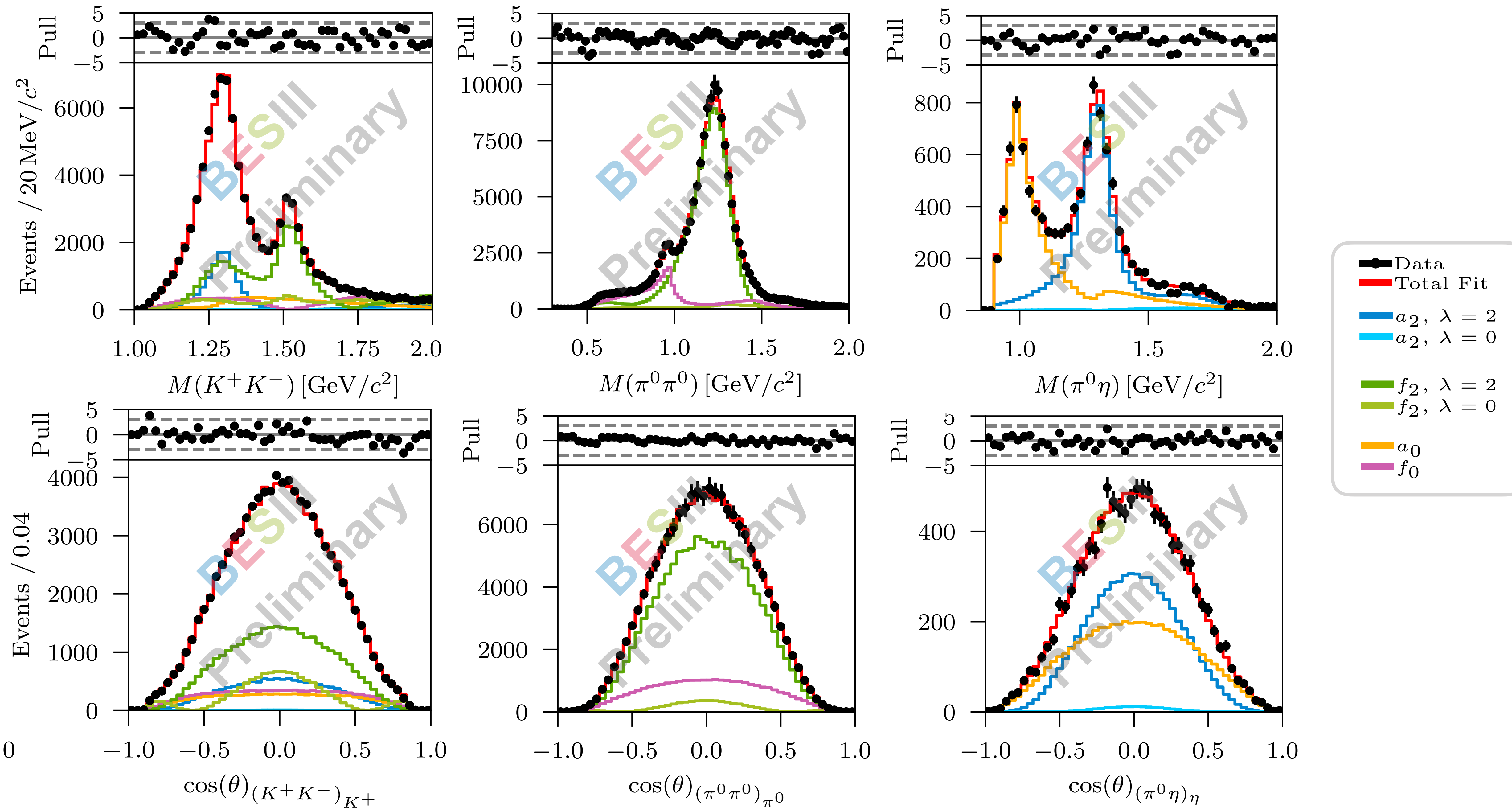
Additional constraints by shared parameters between channels help to avoid ambiguous descriptions

Using data samples of 21.7 fb^{-1} at 28 energy points



Coupled Channel Analysis of Two-Photon Data

- Using obtained parameterization and fix all pole and decay parameters
- All structures can be well described
- Dominant contribution of $(J, \lambda) = (2{,}2), (0{,}0)$
- Best fit result using all 14 resonances and P-vector background terms: 1. order for f_2, a_2, a_0 -waves

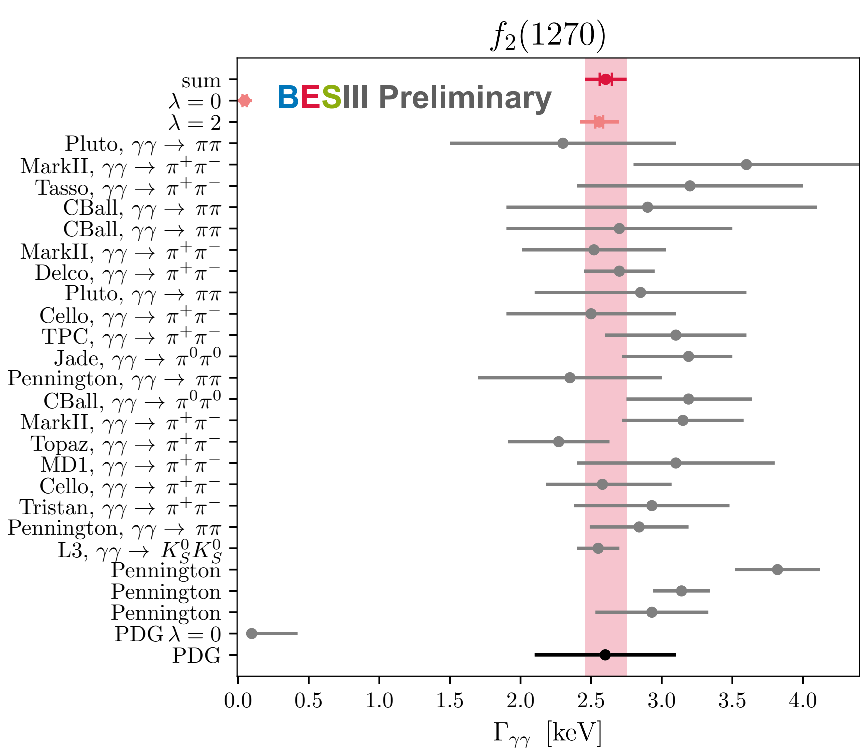


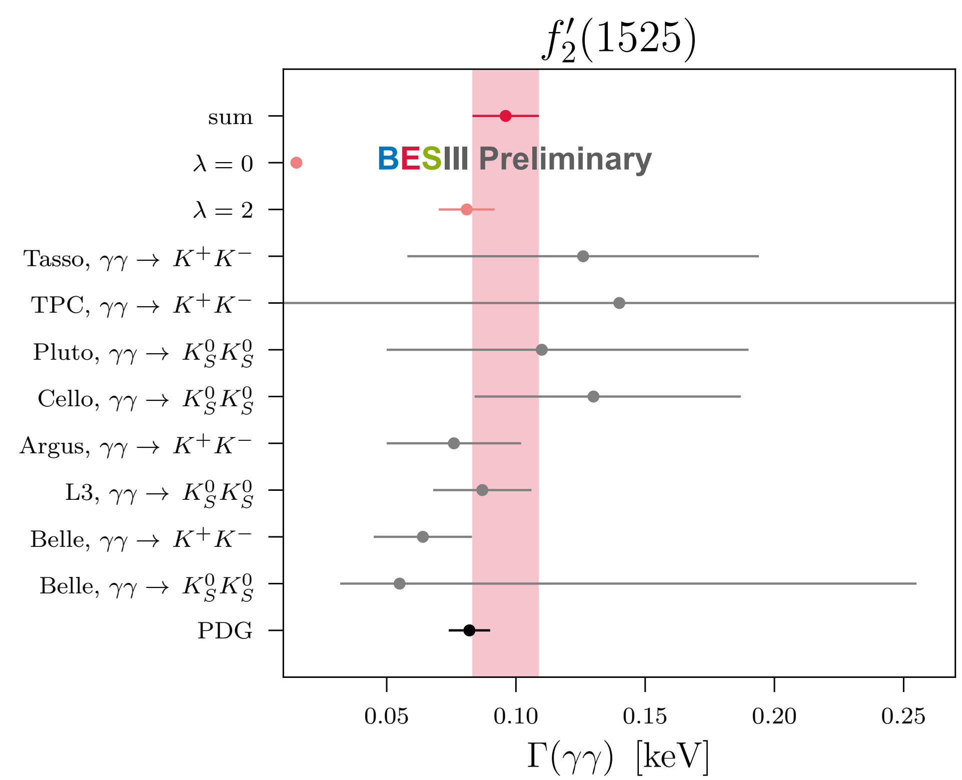
Determination of the Coupling Strength

- Determination of the two-photon width using the F-vector pole residue itself
- More accurate method than based on Breit-Wigner peak intensities
  - Also heavily interfering resonances can be separated…
  - Helicity contributions can be determined

$$\Gamma(X \to \gamma\gamma) = \frac{\alpha^2}{4\,(2J+1)\,M_R} \cdot \frac{Res_X(\gamma\gamma \to FS)}{\Gamma_{dec}}$$

Phys. Rev. D **90**, 036004





- First determination of the helicity contributions for the $f_2'(1525)$
- Most accurate measurement for $f_2(1270)$ and $a_2(1320)$
- Scalar mesons $f_0(1370)$, $f_0(1500)$ und $f_0(1710)$ measured for the first time

Summary

- Determination of the resonance parameters and coupling strengths to different production and decay processes important for classifying states
- PAWIAN proofs to be a powerful tool to perform coupled channel analysis of various mechanisms and channels using K-matrix
- Sophisticated descriptions of the dynamics needed by taking into account analyticity and unitarity

- Analyses of $\bar{p}p$-, $\gamma\gamma$-, $p\pi$- and $\pi\pi$-data
  - Peaks at 1.4 GeV in $\pi\eta$ and at 1.6 GeV in $\pi\eta'$ of the spin exotic 1^{-+} wave can be described by just one pole
- Two-photon data can be well described using the obtained parameterization
- Many coupling strength could be determined for the first time
- Stay tuned for further coupled channel analyses!


Thank You!