Partial Wave Analysis for Electron-Positron and Antiproton-Proton Annihilations

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Outline

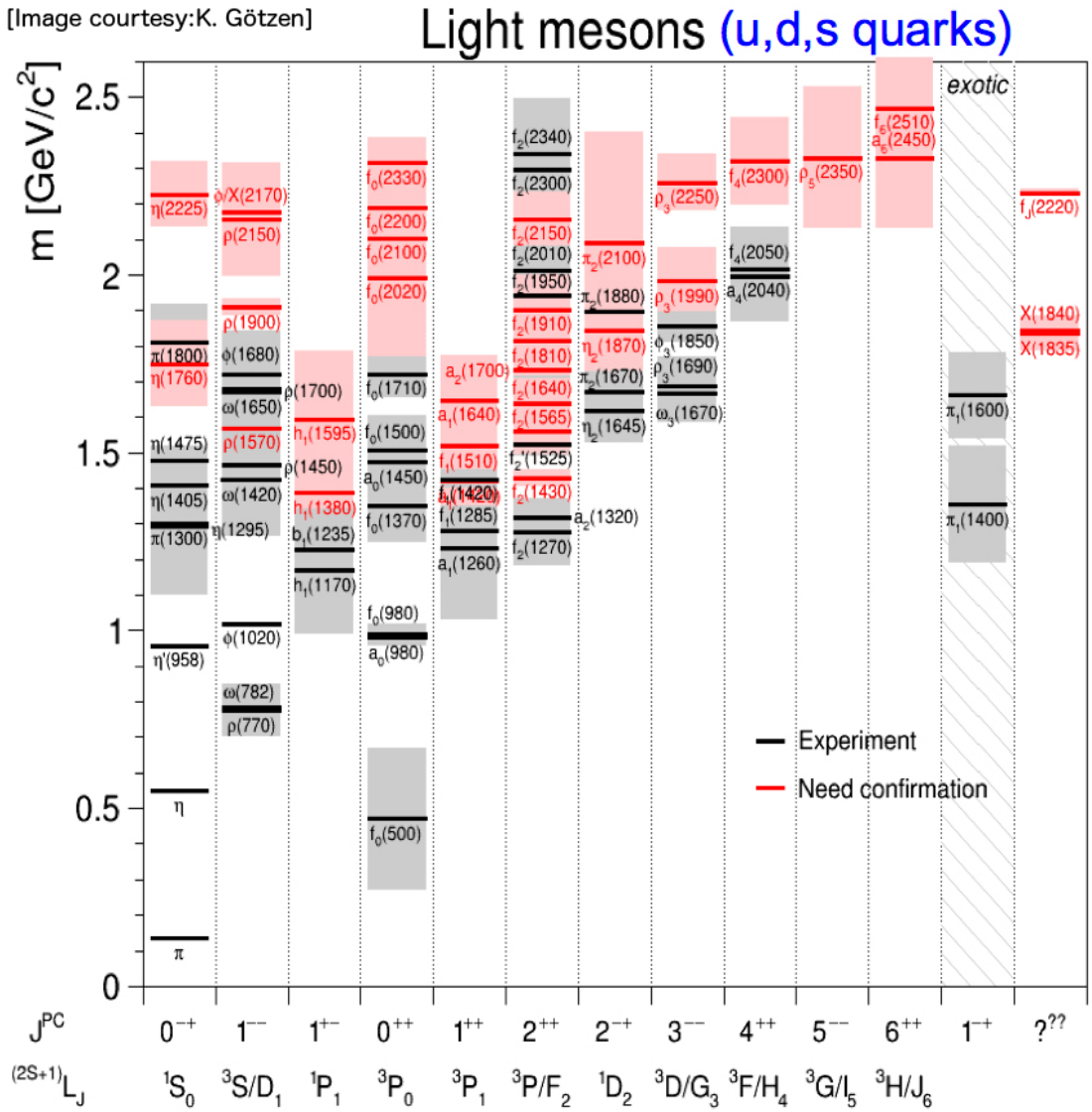
- Challenges in Meson Spectroscopy
- Description of Resonances
- PArtial Wave Interactive ANalysis Software *PAWIAN*
- Isolated Resonances
  - $e^+e^- \to J/\psi \to \gamma\omega\omega$
- Overlapping Resonances in Multiple Channels
  - Coupled Channel Analysis of $\overline{p}p \to (K^+K^-\pi^0)$, $(\pi^0\pi^0\eta)$, $(\pi^0\eta\eta)$
- Summary

Challenges in Meson Spectroscopy

- Many broad and overlapping states discovered
- Theoretical predictions do not match observed states
- Assignment to $q\overline{q}$ multiplets still ambiguous

→ Fundamental to gain deeper understanding of strong interaction

→ Optimally: Combine different **production processes** and **decay modes**!



Description of Resonances

- Breit-Wigner parameterization most commonly used. OK, if resonance is
  - isolated
  - appearing only in one channel
  - far away from thresholds
- *What if these requirements are not fulfilled?*

→ More sophisticated descriptions required

- We use: K-matrix parameterization with consideration of analyticity & unitarity:
  - S-matrix describes two-body scattering process via $S = I + 2i\sqrt{\rho}T\sqrt{\rho}$
  - Where T can be written as $T = (I - iK\rho)^{-1}K$
  - Elements of the K-matrix: $K_{ij} = \sum_\alpha \frac{g_{\alpha i} g_{\alpha j}}{m_\alpha^2 - s} + \sum_k c_{kij} s^k$
  - Extension of formalism to production of resonances using P-vector approach: [I.Aitchison, Nucl.Phys.A 189 (1972) 417]
  - Dynamical function becomes: $F = (I - iK\rho)^{-1}P$ with $P_i = \sum_\alpha \frac{\beta_\alpha g_{\alpha i}}{m_\alpha^2 - s} + \sum_k c_{ki} s^k$
  - Replace standard phase-space factors ρ with function to respect constraints from analyticity (Chew-Mandelstam function [Basdevant, Berger PRD19 (1979) 239])

PArtial Wave Interactive ANalysis Software (PAWIAN)

- PWA software package under development in Bochum to ...

  [B. Kopf et. al., Hyperfine Interact. 229 (2014) no.1-3, 69-74]

  - provide a generic (amplitudes, dynamics, ...) easy-to-use software package (GPLv3)
  - support different production processes ($\overline{p}p$, e^+e^-, $\gamma\gamma$, ...)

$\Rightarrow$ Several analyses have already been performed

$\Rightarrow$ **PAWIAN** features full configuration of hypotheses and other input settings via plain-text configuration files

- Spin-formalism (Canonical, Helicity)
- Decay dynamics (Breit-Wigner, Flatté, K-matrix)

$\Rightarrow$ Event based maximum likelihood fits (Minimizer: MINUIT2, ...)

$\Rightarrow$ Event generator, histogramming, analysis tools, ...

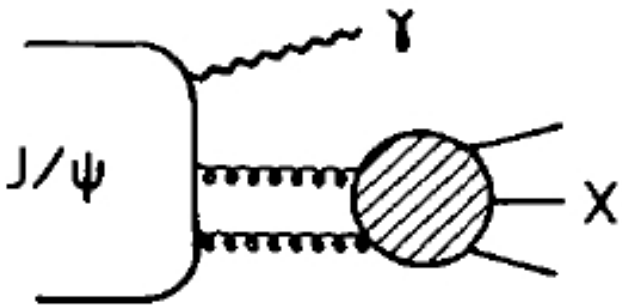
$\Rightarrow$ **Coupled channel analyses** supported

$\Rightarrow$ Parallelization: Multi-threading and server-client (network) modes

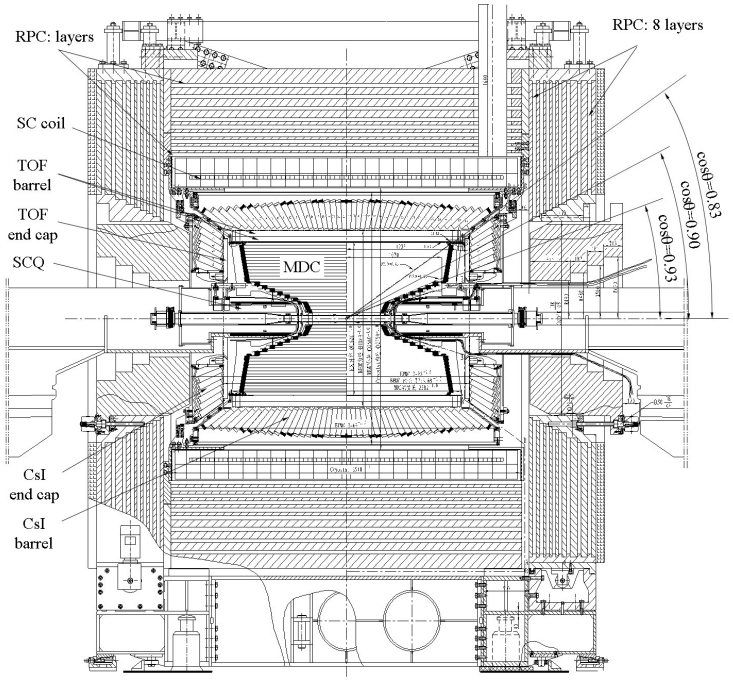
Electron-Positron Annihilation: BESIII@BEPCII

- Experiment at symmetric e^+e^- collider in Beijing
- Energy range: $\sqrt{s} = 2.0 - 4.6\,\text{GeV}$
- BESIII has recorded the worlds largest J/ψ and ψ' data sets:
  - $1.3 \cdot 10^9$ J/ψ events
  - ($10 \cdot 10^9$ J/ψ to come soon!)
  - $0.5 \cdot 10^9$ ψ' events

$\Rightarrow$ Ideally suited to perform hadron spectroscopy with high statistics



- Main Drift Chamber
- Time of Flight System
- Electromagnetic CsI(Tl) Calorimeter
- Superconducting Solenoid (1T)
- RPC muon chambers



Event Selection: $J/\psi \to \gamma\omega\omega$, $\omega \to \pi^+\pi^-\pi^0$, $\pi^0 \to \gamma\gamma$

- Investigation of contributions to the $\omega\omega$ system

→ Highlight today: Observation of $\eta_c \to \omega\omega$

- CLEOc, KEDR: Interference between η_c and non-resonant background in radiative charmonium decays

→ Utilize PWA in η_c mass region to measure $B(\eta_c \to \omega\omega)$

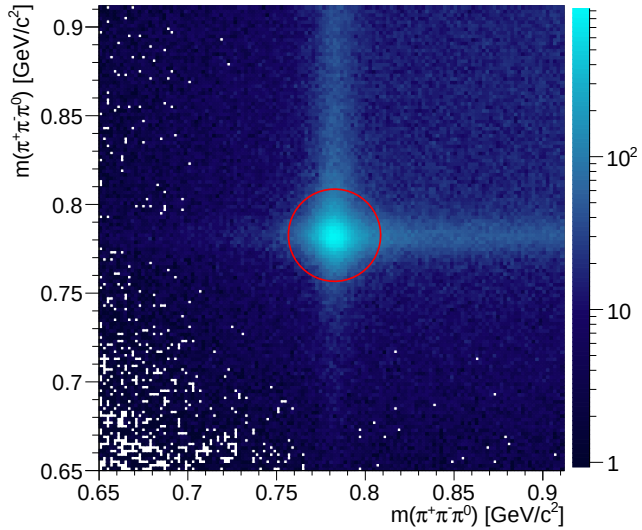
→ Clean event selection is crucial

- Event-based background subtraction using Q-factor method
  [JINST 4, P10003 (2009)]

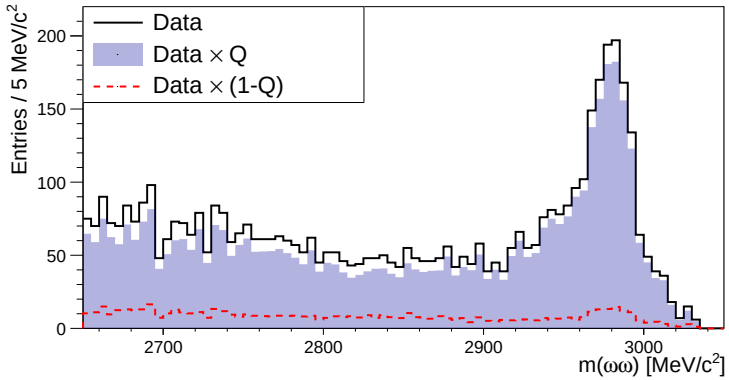
→ Result: 4900 $\omega\omega$ events in η_c region

→ Clear η_c signal

Preselected events (Data)

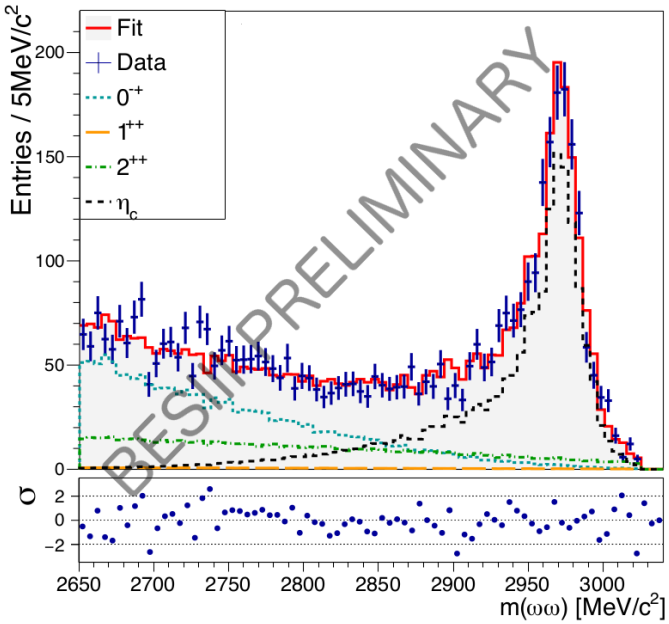


Background subtracted events (Data)

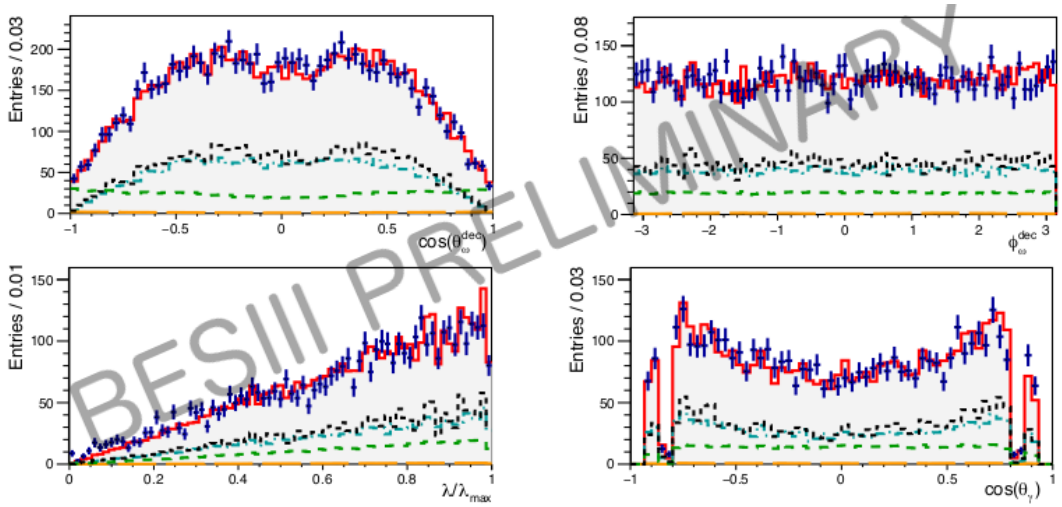


$\eta_c \to \omega\omega$ Branching Fraction

Preliminary



Component	Fit Fraction [%]
0^-	32.6 ± 2.2
1^+	0.8 ± 0.4
2^{++}	16.2 ± 2.0
η_c	38.0 ± 2.1
Sum	$\mathbf{87.6 \pm 2}$



- η_c line shape is distorted in radiative decays

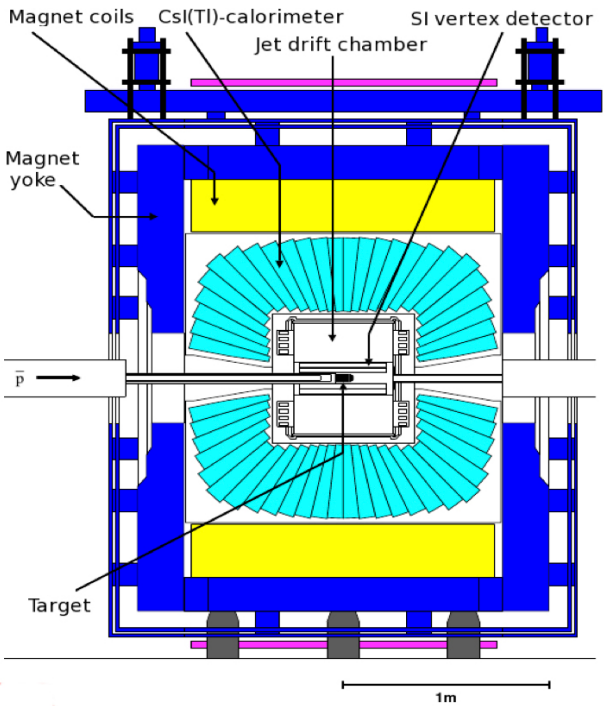
$\Rightarrow$ Sophisticated parameterization incl. energy dependence of the $M1$ transition matrix element
[Phys. Rev. Lett. 102 011801 (2009)]
[Phys. Rev. D73 054005 (2006)]

- PWA to account for interference
- First measurement of this branching fraction

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

- Fixed target experiment at LEAR (CERN)
- Data taking: 1989-1996
- $\bar{p}p$ annihilation in flight and at rest
- $p_{\bar{p}} = (0.105...2.0)\,\mathrm{GeV}/c$

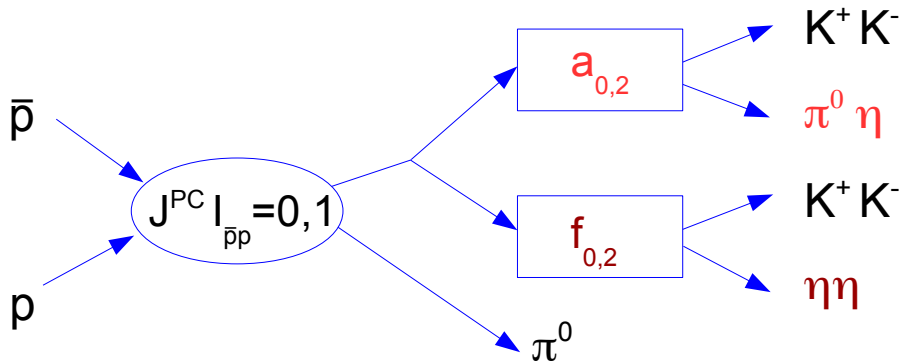
  $\Rightarrow$ Momentum overlap with $\overline{\mathrm{P}}$ANDA !



- Many $f_{0,2}$ and $a_{0,2}$ appear in two or all three channels
- Exotic candidate $\pi_1(1400)$ only seen in $\bar{p}p$ data at rest

$\to$ Also visible in flight?

- Coupled analysis enables to distiguish a and f resonances:

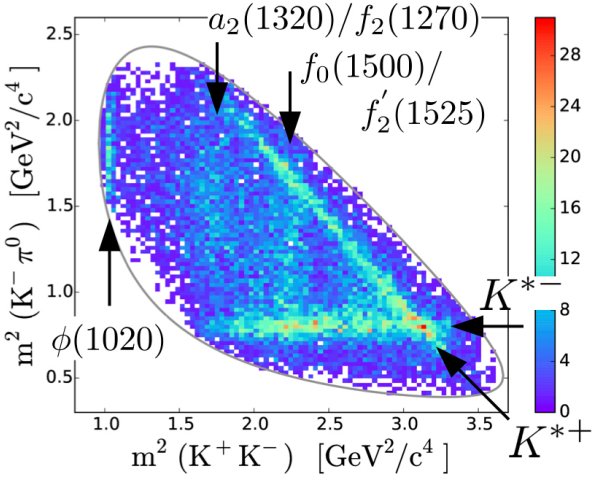


- Simultaneous fit of $\overline{p}p \to K^+K^-\pi^0$, $\pi^0\pi^0\eta$, $\pi^0\eta\eta$ channels

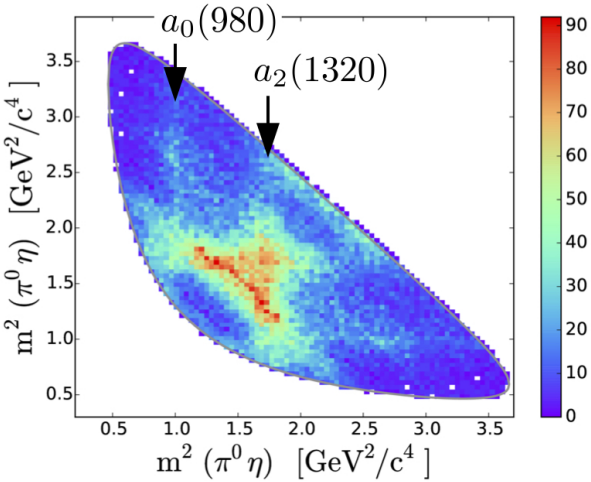
$\to$ Advantages: Common amplitudes, common description of the dynamics (K-matrix), less fit parameters

- Clean data samples were prepared at $p_{\overline{p}} = 0.9\,\mathrm{GeV}/c$
- Kinematic fits, event-based background subtraction

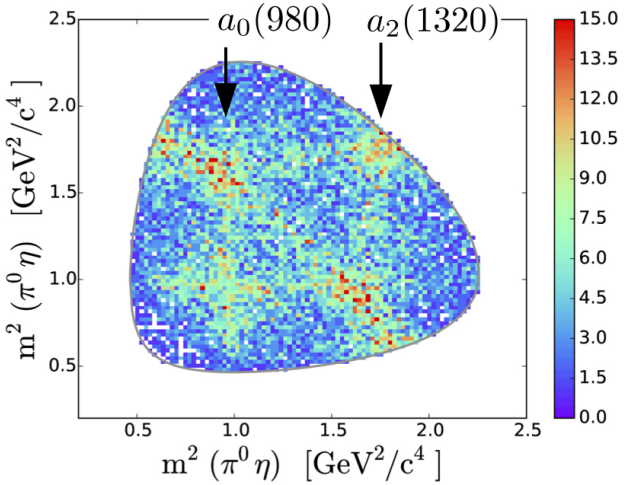
$K^+K^-\pi^0$ ($\sim$ 17.5k events)



$\pi^0\pi^0\eta$ ($\sim$ 90.4k events)



$\pi^0\eta\eta$ ($\sim$ 10.5k events)



- Additional constraints by coupling to **scattering data** (phase & elasticity):
  - $I = 0$ $S-$ and $D-$wave $\pi\pi \to \pi\pi$, $K\overline{K}$, $\eta\eta$ ($\eta\eta'$),
    $I = 1$ P-wave $\pi\pi \to \pi\pi$

PRD 83 (2011) 074004, Nucl.Phys.B 64 (1973) 134-162,
Nucl.Phys.B 269 (1986) 485, Nuov.Cim.A 80 (1984) 363

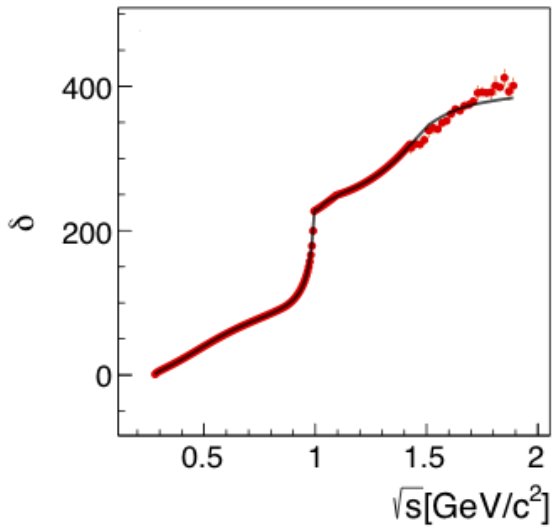
- f_0 K-Matrix: 5-poles, 5-channels
- f_2 K-Matrix: 4-poles, 4-channels
- ρ K-Matrix: 3-poles, 3-channels
- a_0 and a_2 K-Matrix: 2 poles, 2 channels (each)

→ **All pole positions and coupling strengths are free parameters!**

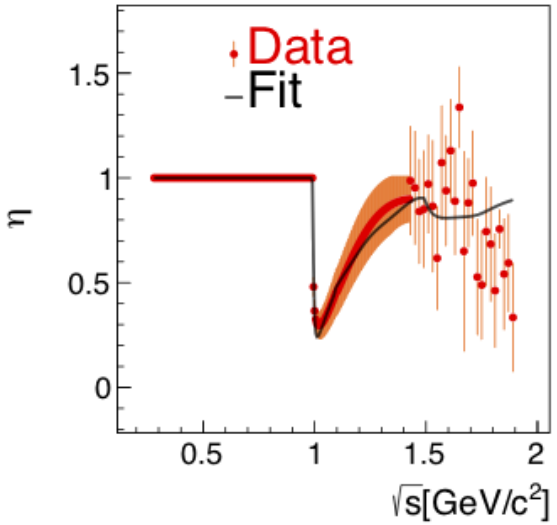
- $(K\pi)_S$-wave K-Matrix: 1-pole, 2-channel [Phys.Lett.B653 (2007) 1-11]
- Breit-Wigner description for isolated resonances ($\phi(1020)$, $K^{*\pm}(892)$, $\pi_1(1400)$)
- Overall: Good description of data for $\overline{p}p$ channels and also for scattering data:

$\pi\pi \to \pi\pi$, $I = 0$ S-wave:

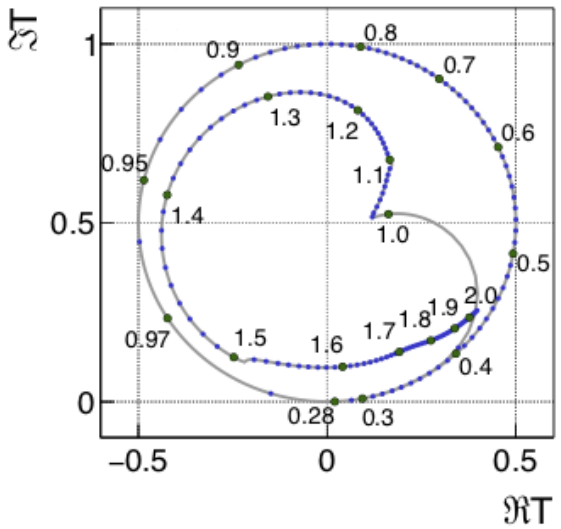
Phase



Elasticity

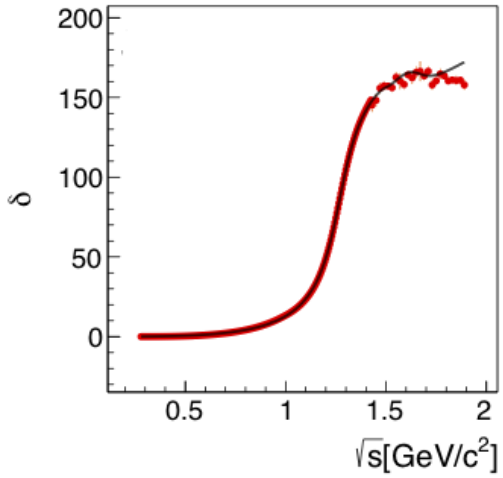


Argand diagram

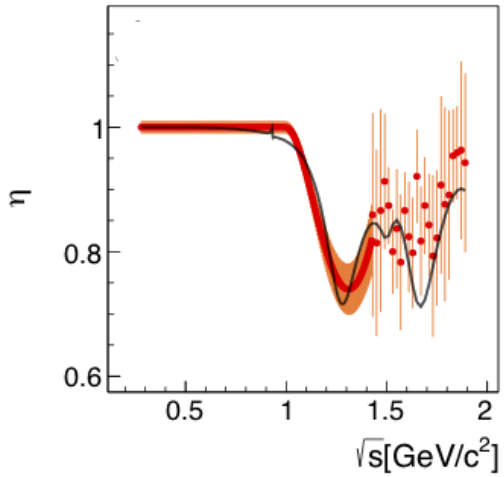


$\pi\pi \to \pi\pi$, $I = 0$ D-wave:

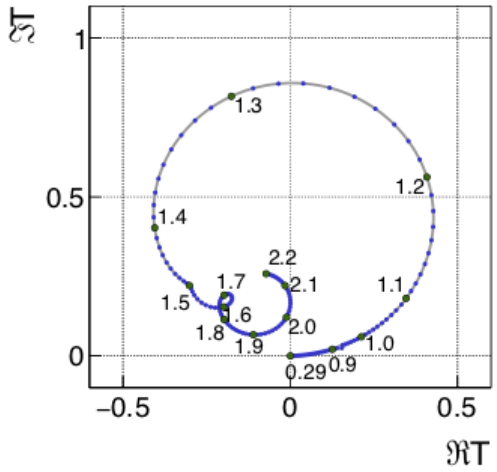
Phase



Elasticity

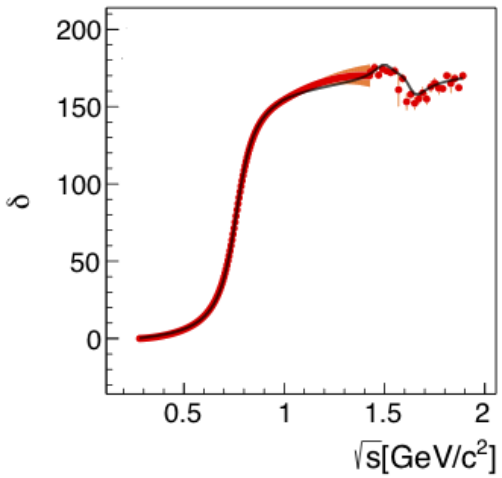


Argand diagram

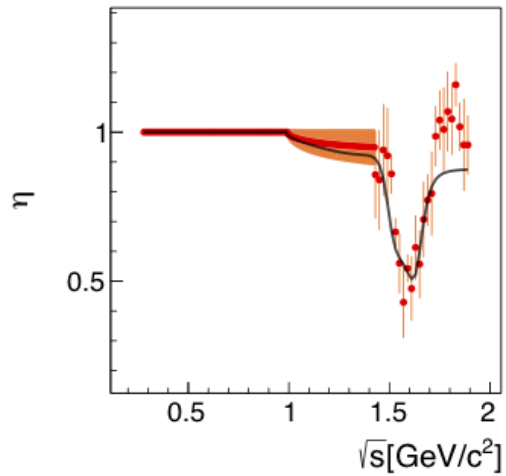


$\pi\pi \to \pi\pi$, $I = 1$ P-wave:

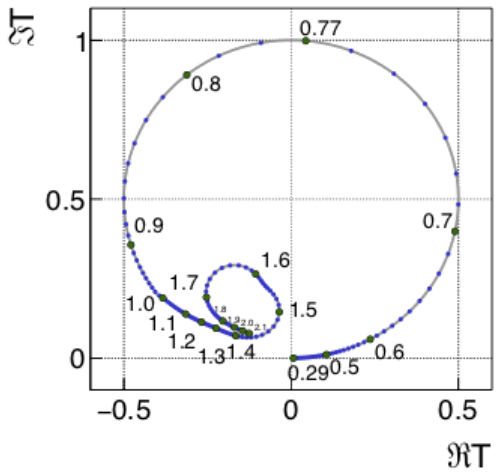
Phase

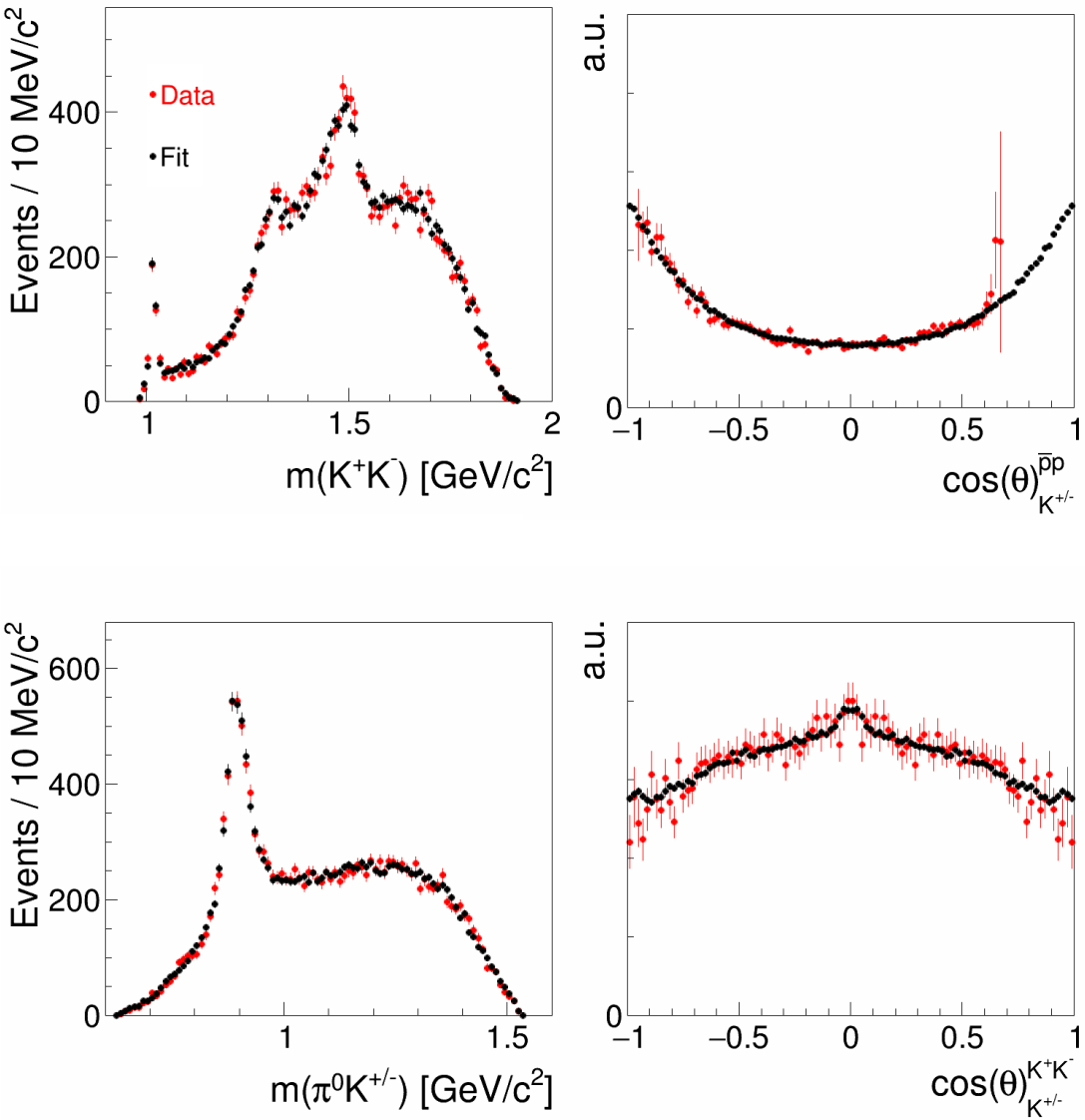


Elasticity



Argand diagram

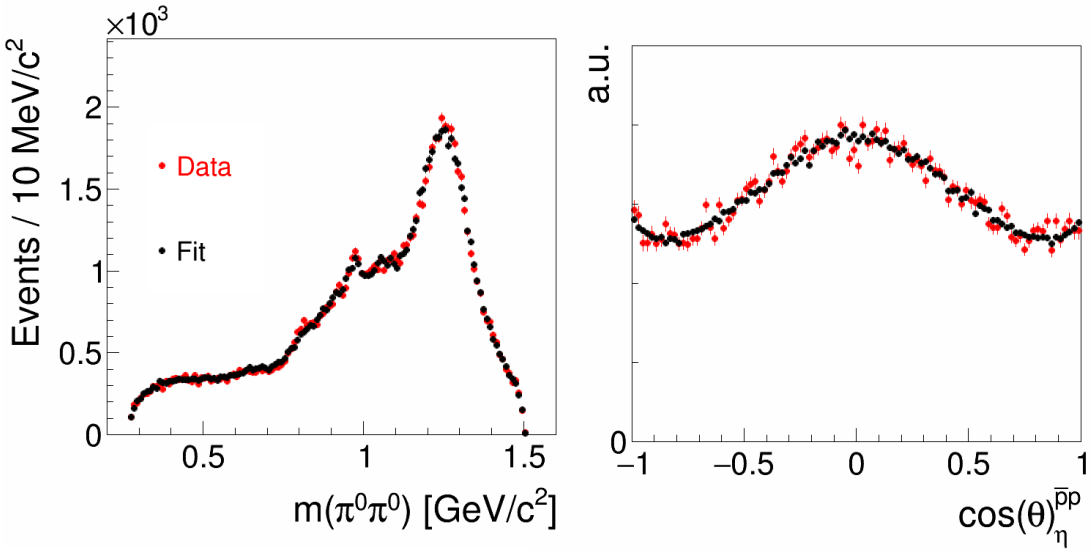


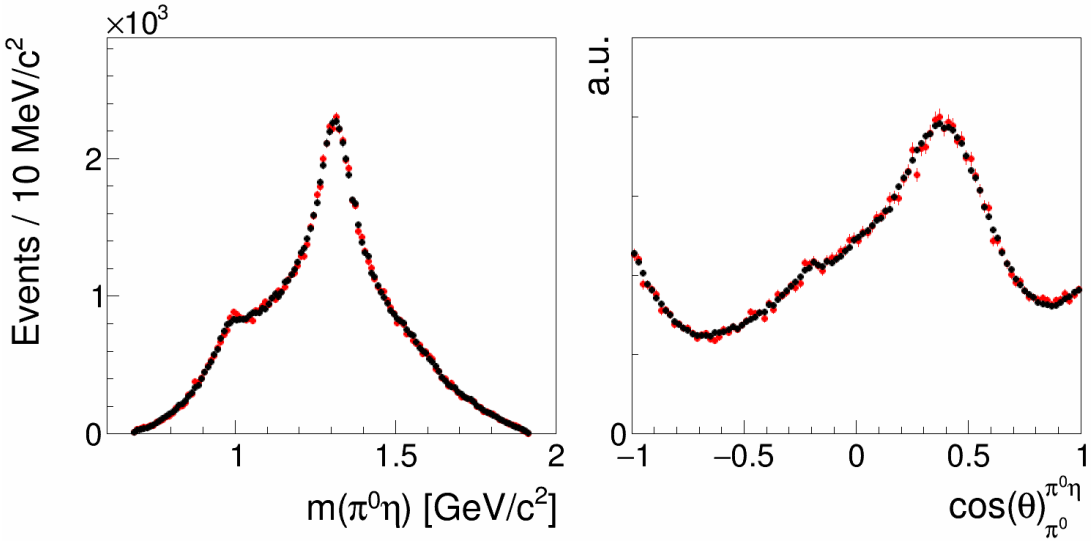


Fit quality: $p = 0.848$

[Aslan,Zech
NIM A 537 (2005) 626-636]

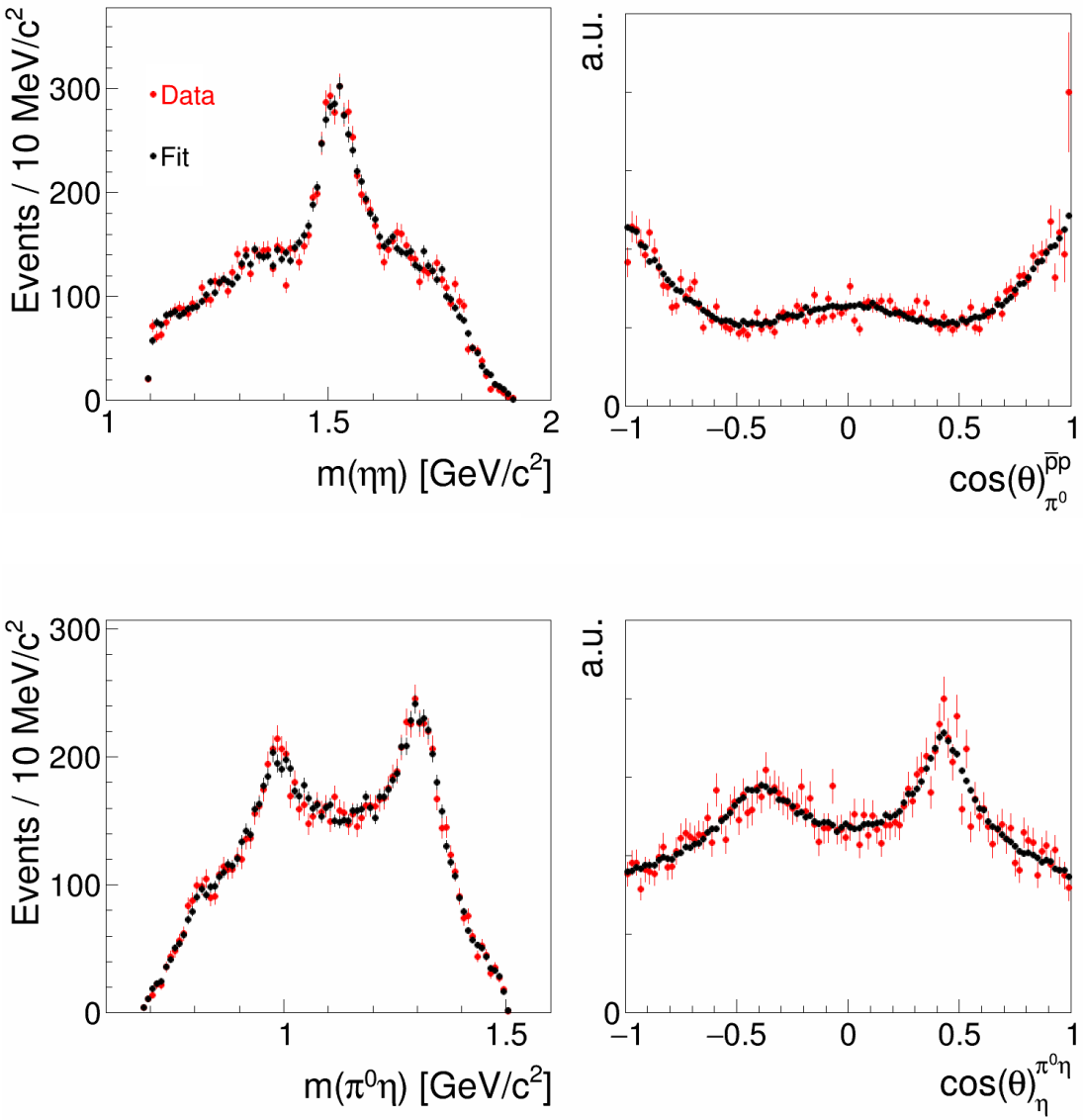
	contribution (in %)
$f_0\,\pi^0$	$15.0 \pm 0.4 \pm 3.0$
$f_2\,\pi^0$	$16.1 \pm 0.7 \pm 3.5$
$\rho\,\pi^0$	$16.1 \pm 1.2 \pm 5.0$
$a_0\,\pi^0$	$0.3 \pm 0.0 \pm 1.0$
$a_2\,\pi^0$	$7.1 \pm 0.2 \pm 3.0$
$K^*(892)^\pm K^\mp$	$38.5 \pm 1.3 \pm 2.8$
$(K\pi)^\pm_S K^\mp$	$15.6 \pm 0.8 \pm 4.2$
$\phi(1020)\,\pi^0$	$2.4 \pm 0.3 \pm 0.7$
Σ	$111.0 \pm 2.1 \pm 6.0$





Fit quality: $p = 0.356$

	contribution (in %)
$f_0\,\eta$	23.6 ± 0.5± 11.0
$f_2\,\eta$	35.8 ± 0.6± 5.9
$a_0\,\pi^0$	22.9 ± 0.4± 15.0
$a_2\,\pi^0$	35.4 ± 0.6± 5.9
$\pi_1(1400)\,\pi^0$	13.2 ± 0.4± 6.0
Σ	130.7 ± 1.1 ± 22.7

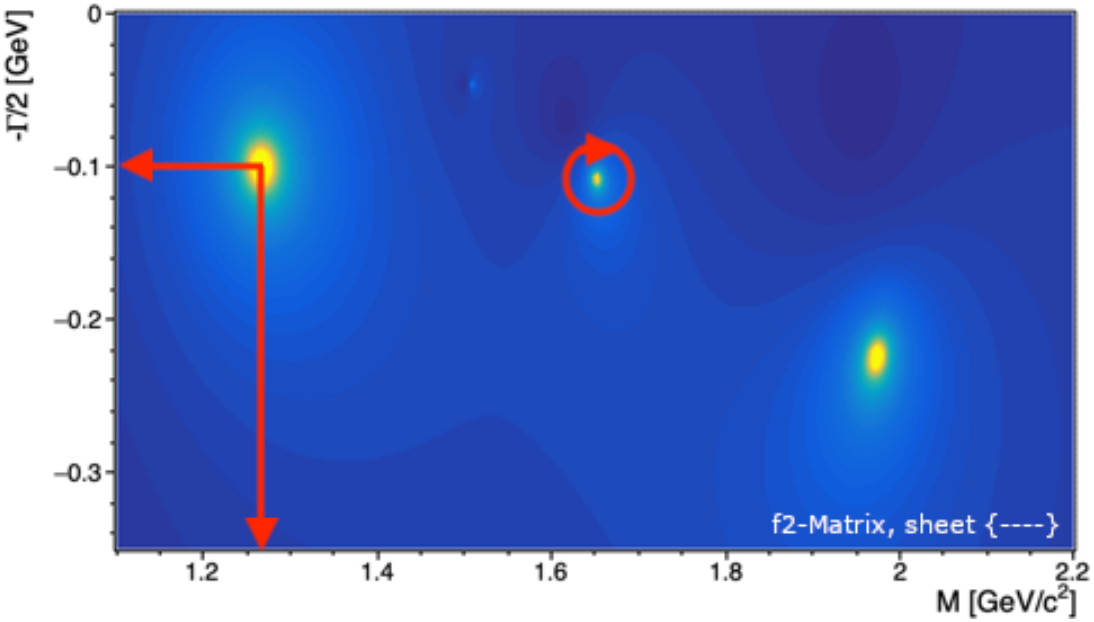


Fit quality: $p = 0.478$

	contribution (in %)
$f_0\,\pi^0$	$49.6 \pm 1.9 \pm 15.4$
$f_2\,\pi^0$	$19.2 \pm 1.2 \pm 6.9$
$a_0\,\eta$	$12.8 \pm 0.7 \pm 4.9$
$a_2\,\eta$	$28.6 \pm 1.5 \pm 5.8$
Σ	$110.2 \pm 2.8 \pm 14.7$

- No significant contribution of $\pi_1(1400) \to \pi^0\eta$

Extracted Resonance Parameters (Example) Preliminary



- All resonance parameters are encoded in the K-matrix

→ Masses and width from position of poles in complex plane of the T-matrix (Riemann sheet closest to the physical sheet)

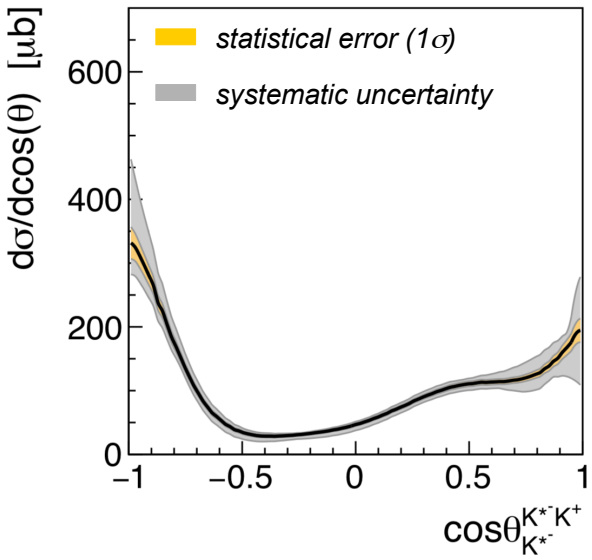
→ $\approx$ 50 resonance properties extracted from this coupled channel fit

- Partial widths / branching fractions extracted using the residues of the poles:

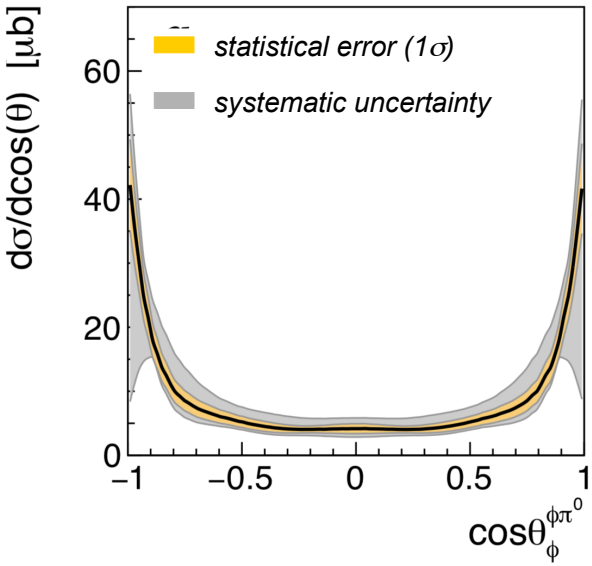
$$Res^{\alpha}_{k\to k} = \frac{1}{2\pi i} \oint_{C_{z_\alpha}} \sqrt{\rho_k} \cdot T_{k\to k}(z) \cdot \sqrt{\rho_k}\, dz$$

name	pole mass [MeV/c^2]	pole width Γ [MeV]	$\Gamma_{\pi\pi}/\Gamma$ [%]	Γ_{KK}/Γ [%]	$\Gamma_{\eta\eta}/\Gamma$ [%]
$f_2(1270)$	$1266.5 \pm 0.3 \pm 0.7$	$199.6 \pm 0.5 \pm 11.0$	$88.1 \pm 0.1 \pm 4.5$	$6.6 \pm 0.5 \pm 4.3$	$0.0 \pm 0.4 \pm 0.1$
$f_2'(1525)$	$1507.4 \pm 0.5 \pm 2.8$	$92.5 \pm 1.0 \pm 15.1$	$4.6 \pm 0.8 \pm 2.1$	$48.9 \pm 1.5 \pm 10.0$	$4.5 \pm 1.9 \pm 0.5$
$f_2(1640)$	$1651.8 \pm 1.1 \pm 16.9$	$215.3 \pm 3.0 \pm 20.8$	$18.6 \pm 1.0 \pm 3.7$	$19.8 \pm 3.6 \pm 5.0$	$0.1 \pm 2.3 \pm 0.1$
$f_2(1950)$	$1973.5 \pm 5.2 \pm 31.1$	$448.5 \pm 8.9 \pm 61.9$	$25.5 \pm 1.2 \pm 7.7$	$88.9 \pm 3.0 \pm 11.1$	$0.1 \pm 4.6 \pm 0.1$

$\bar{p}p \to K^*(892)^- K^+$

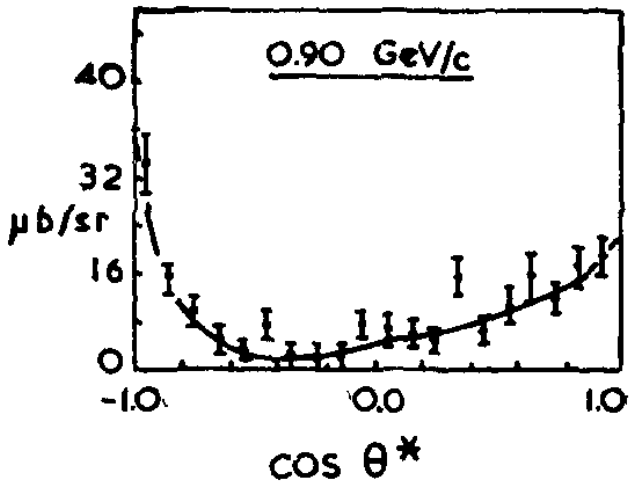


$\bar{p}p \to \phi\pi^0$

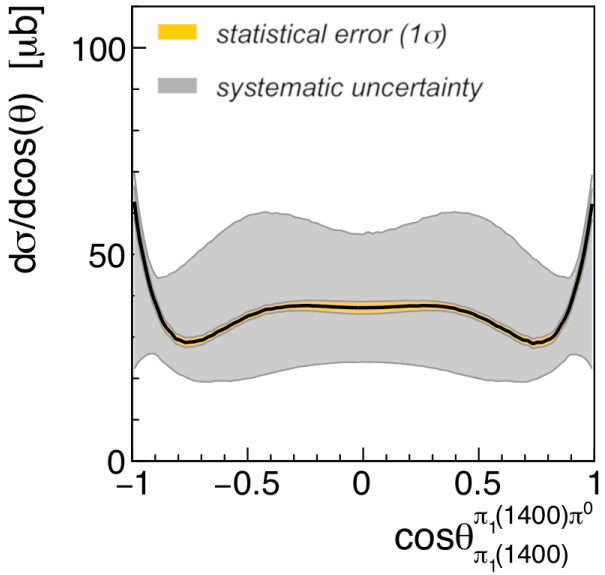


Similar shape compared to K^+K^-?

$\bar{p}p \to K^- K^+$ [PLB47 (1973) 531]



$\bar{p}p \to \pi_1(1400)\pi^0$



Summary

- PAWIAN software package is in a good shape

- e^+e^- annihilations at BESIII:
  - Large J/ψ and ψ' data sets well suited for light hadron spectroscopy

  $\Rightarrow$ Example: First measurement of $\eta_c \to \omega\omega$ branching fraction

- $\overline{p}p$ annihilations at Crystal Barrel / LEAR:
  - Analysis of in-flight $\overline{p}p$ data with relevance for $\overline{\text{P}}$ANDA

  $\Rightarrow$ Coupled channel analysis of $\overline{p}p \to K^+K^-\pi^0$, $\pi^0\pi^0\eta$, $\pi^0\eta\eta$
    - Significant contribution of the spin-exotic $\pi_1(1400)$ in $\pi^0\pi^0\eta$?
    - Not shown today: Spin density matrix elements for K^*, ϕ and π_1

$\Rightarrow$ Future: Coupling of e^+e^- and $\overline{p}p$ data $\Rightarrow$ Stay tuned for more results!

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