Dalitz plot analysis of three-body charmonium decays at *BABAR*

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on behalf of *BABAR*

JGU Mainz

11th international workshop on e^+e^- collisions from ϕ to ψ
28th June 2017

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

PRISMA

SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

Outline

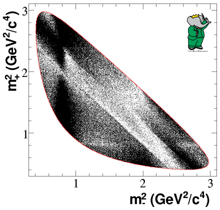
- Introduction: the $K\pi$ $\mathcal{S}$-wave
- BABAR
- Dalitz plot analyses of η_c decays
- Dalitz plot analyses of J/ψ decays
- Summary

The $K\pi$ $\mathcal{S}$-wave

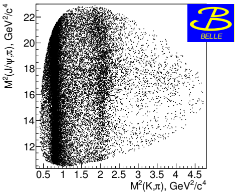
Accurate description of $K\pi$ $\mathcal{S}$-wave fundamental for many important physics topics

Measurement of CKM angle γ in $B \to Dh$ using D three- or four-body decays

Observation of exotic states in heavy flavour decays, *e.g.* $B \to \psi\pi K$, needs accurate description of Dalitz plot, K^* resonances, and $K\pi$ $\mathcal{S}$-wave in particular



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



$\bar{B}^0 \to J/\psi K^- \pi^+$

The $K\pi$ $\mathcal{S}$-wave from LASS

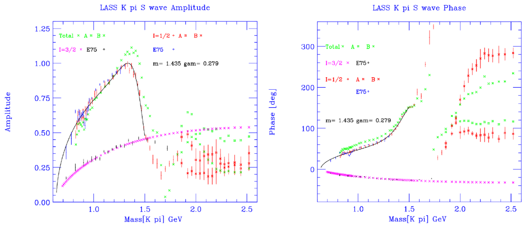
Best measurement from LASS from $K^- p \to K^- \pi^+ n$

Nucl. Phys. B296, 493 (1988)

$K\pi$ $\mathcal{S}$-wave described by coherent sum of effective range and rel. BW for $K_0^*(1430)$

Both $I = 1/2$ and $I = 3/2$ present, need to be separated

PWA result shows two-fold ambiguity for $m(K\pi) > 1.9\,\text{GeV}/c^2$



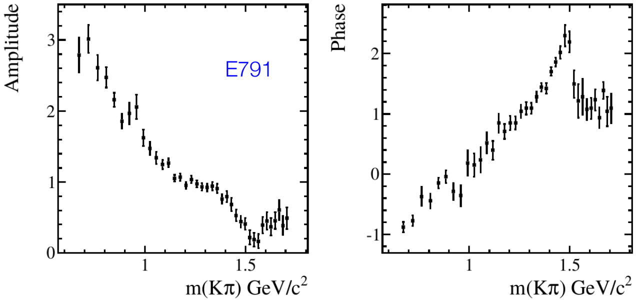
The $K\pi$ S-wave from D^+ decays

Use Dalitz plot analysis of $D^+ \to K^-\pi^+\pi^+$

Model-independent partial wave method E791, Phys. Rev. D 73, 032004

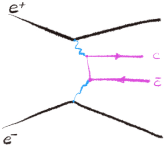
$I = 3/2$ contribution present, not well known

D mass limits range in $m(K\pi)$ to below 1.5 GeV/c^2

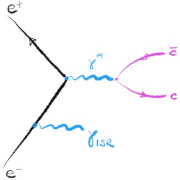


Charmonium as clean source

- Use $\gamma\gamma$ events
  e^+ and e^- escape through beam pipe
  Can produce resonances with
  $$J^{PC} = 0^{\pm+}, 2^{\pm+}, 3^{++}, 4^{\pm+}, \ldots$$
  Here: $\gamma\gamma \to \eta_c$
  $\eta_c \to KK\pi$ expected to be pure $I = 1/2$



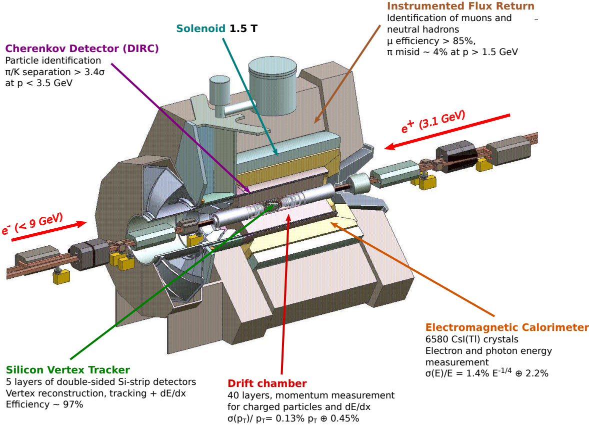
- ISR production of J/ψ:
  $e^+e^- \to \gamma_{ISR}c\bar{c}$: only $J^P = 1^-$ states produced
  ISR photon (mostly) undetected in this analysis
  $e^+e^- \to \gamma_{ISR}J/\psi$



- Both processes require large luminosity to yield sufficient statistics
  ➡ *B* factory!

The BABAR experiment

- PEP-II: e^+e^- collider, $3.1 \times 9\,\text{GeV}^2$ $\sqrt{s} = 10.58\,\text{GeV}\ [\Upsilon(4S)]$
- Asymmetric beam energies c.m. lab boost $\beta\gamma = 0.56$
- Asymmetric detector
  - acceptance in c.m. $-0.9 \lesssim \cos\theta^* \lesssim 0.85$
  - detects $\approx 15\%$ of ISR γ
  - contains $\approx 50\%$ of events with fwd/bwd γ_{ISR}
- excellent performance
  - Good tracking, mass resolution
  - Good γ, π^0 reco.
  - Full PID for e, μ, π, K, p



- High luminosity
  - $\mathcal{L}_{\text{peak}} = 12.069 \times 10^{33}\,\text{cm}^{-2}\,\text{s}^{-1}$
  - $513.7(18)\,\text{fb}^{-1}$ accumulated (1.7 billion $e^+e^- \to q\bar{q}$ events)

η_c from two-photon interactions

Make use of three final states with 3 pseudoscalars:

$$\gamma\gamma \to K_S^0 K^+ \pi^- + c.c.$$
$$\gamma\gamma \to K^+ K^- \pi^0$$
$$\gamma\gamma \to K^+ K^- \eta \quad \text{with } \eta \to \gamma\gamma, \pi^+\pi^-\pi^0$$

We find η_c three-body decay almost entirely saturated by

$$\eta_c \to \text{pseudoscalar} + \text{scalar}$$

Three-body η_c decays are unique window into properties of scalar mesons

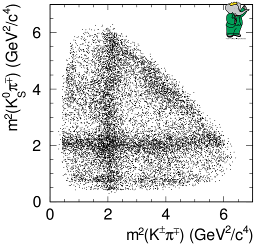
BABAR, Phys. Rev. D **89**, 112004 (2014); Phys. Rev. D **93**, 012005 (2016).

Dalitz plots

BaBar, Phys. Rev. D **89**, 112004 (2014)

Phys. Rev. D **93**, 012005 (2016)

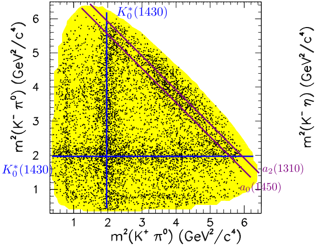
$\eta_c \to K^0_S K^\pm \pi^\mp$



12849 events

purity $(64.3 \pm 0.4)\%$

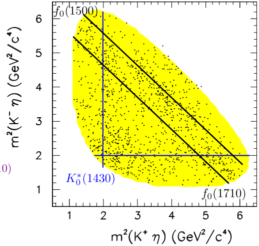
$\eta_c \to K^+ K^- \pi^0$



6494 events

purity $(55.2 \pm 0.6)\%$

$\eta_c \to K^+ K^- \eta$



1161 events

purity $(76.1 \pm 1.3)\%$

Dominated by presence of scalar mesons

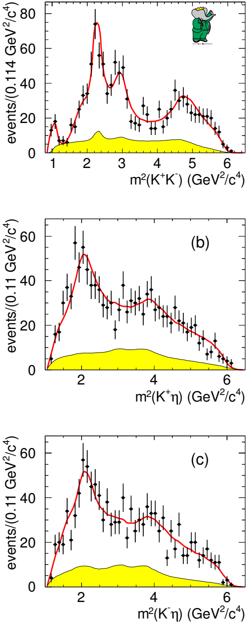
in particular, strong contributions from $K_0^*(1430)$ in all three Dalitz plots

$\mathcal{DP}$ analysis with isobar model: $\eta_c \to K^+K^-\eta$

Resonances described by rel. BW

Symmetrise charge conjugated amplitudes

Final state	Fraction %	Phase (radians)
$f_0(1500)\eta$	$23.7 \pm 7.0 \pm 1.8$	0.
$f_0(1710)\eta$	$8.9 \pm 3.2 \pm 0.4$	$2.2 \pm 0.3 \pm 0.1$
$K_0^*(1430)^+K^-$	$16.4 \pm 4.2 \pm 1.0$	$2.3 \pm 0.2 \pm 0.1$
$f_0(2200)\eta$	$11.2 \pm 2.8 \pm 0.5$	$2.1 \pm 0.3 \pm 0.1$
$K_0^*(1950)^+K^-$	$2.1 \pm 1.3 \pm 0.2$	$-0.2 \pm 0.4 \pm 0.1$
$f_2'(1525)\eta$	$7.3 \pm 3.8 \pm 0.4$	$1.0 \pm 0.1 \pm 0.1$
$f_0(1350)\eta$	$5.0 \pm 3.7 \pm 0.5$	$0.9 \pm 0.2 \pm 0.1$
$f_0(980)\eta$	$10.4 \pm 3.0 \pm 0.5$	$-0.3 \pm 0.3 \pm 0.1$
NR	$15.5 \pm 6.9 \pm 1.0$	$-1.2 \pm 0.4 \pm 0.1$
Sum	$100.0 \pm 11.2 \pm 2.5$	
χ^2/ν	87/65	



Largest amplitudes: $f_0(1500)\eta$ and $K_0^*(1430)K$

First observation of $K_0^*(1430) \to K\eta$

MIPWA result

Model-independent PWA to measure S-wave

Divide $K\pi$ mass spectrum in 30 intervals (60 MeV wide); in each bin, amplitude and phase of S-wave are assumed to be constant.

Use this as reference, fix amplitude to 1 and phase to $\pi/2$ at 1.45 GeV

Isospin conservation to relate the two $K\pi$ modes in each DP

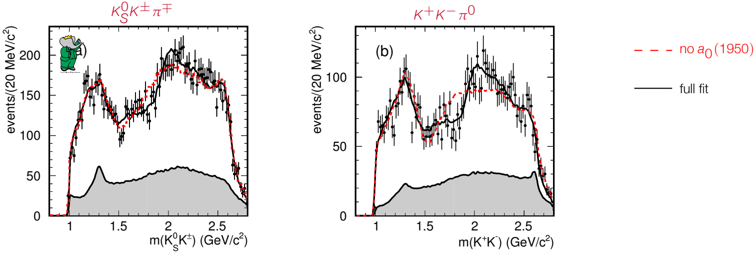
Model other resonant contributions as rel. BW

$a_0(1950)$

BABAR, Phys. Rev. D **93**, 012005 (2016)

Fit improved if additional $I = 1$ resonance in $K\bar{K}$ is added.

Final state	Mass (MeV/c^2)	Width (MeV)
$\eta_c \to K^0_S K^\pm \pi^\mp$	$1949 \pm 32 \pm 76$	$265 \pm 36 \pm 110$
$\eta_c \to K^+ K^- \pi^0$	$1927 \pm 15 \pm 23$	$274 \pm 28 \pm 30$
Weighted mean	$1931 \pm 14 \pm 22$	$271 \pm 22 \pm 29$



Statistical significance for $a_0(1950)$:

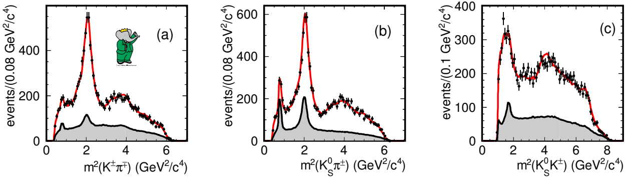
2.5σ in $\eta_c \to K^0_S K^\pm \pi^\mp$

4.2σ in $\eta_c \to K^+ K^- \pi^0$

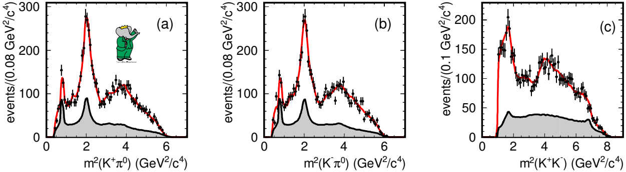
Dalitz plot mass projections

BABAR, Phys. Rev. D **93**, 012005 (2016)

$K_S^0 K^{\pm} \pi^{\mp}$



$K^+ K^- \pi^0$



Shaded histogram: interpolated background contribution

1^- contributions ($K^*(892)$, ...) entirely from background

MIPWA and isobar model

Amplitude	$\eta_c \to K^0_S K^+ \pi^-$ Fraction (%)	$\eta_c \to K^+ K^- \pi^0$ Fraction (%)
$(K\pi\ \mathcal{S}\text{-wave})\ K$	$107.3 \pm 2.6 \pm 17.9$	$125.5 \pm 2.4 \pm 4.2$
$a_0(1950)\pi$	$3.1 \pm 0.4 \pm 1.2$	$4.4 \pm 0.8 \pm 0.7$
$K_2^*(1430)^0 K$	$4.7 \pm 0.9 \pm 1.4$	$3.0 \pm 0.8 \pm 4.4$
χ_2/N_{cells}	**301/254=1.17**	**283.2/233=1.22**
	Isobar Model	
$(K_0^*(1430)K)+$	73.6 ± 3.7	63.6 ± 5.6
$(K_0^*(1950)K)+$		
$Nonresonant$		
χ_2/N_{cells}	**457/254=1.82**	**383/233=1.63**

Good agreement between two η_c decay modes for MIPWA

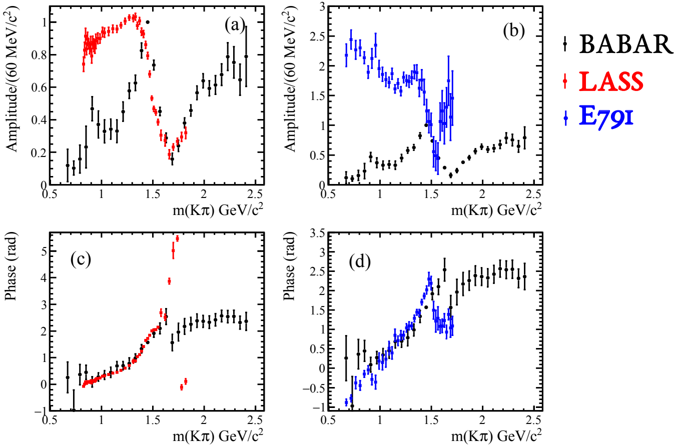
$(K\pi\ \mathcal{S}\text{-wave})K$ amplitude dominant, small contributions from $K_2^*(1430)K$ and $a_0(1950)\pi$

Spin-1 resonances entirely from background

Description of data better with MIPWA than with Isobar Model

$K\pi$ S-wave, compared to LASS and E791

PRD **93**, 012005 (2016)



Phase almost equal up to η' threshold (Watson theorem)
Amplitudes very different

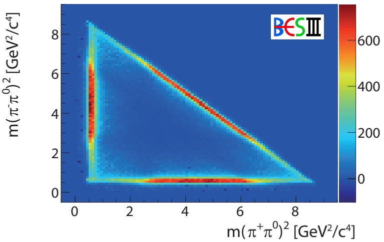
$J/\psi \to 3\pi, KK\pi$

Previous analyses: old preliminary DP of $J/\psi \to 3\pi$

BESIII shows DP of $J/\psi \to 3\pi$ from 225×10^6 J/ψ , but does not (yet) perform PWA BESIII, Phys. Lett. B 710, 594 (2012)

MarkII: $\mathcal{B}(J/\psi \to K^+K^-\pi^-)$ with 25 events

BESII: $J/\psi \to K^+K^-\pi^-$ angular analysis, requires broad $J^{PC} = 1^{--}$ state in K^+K^- threshold region BESII, Phys. Rev. Lett. **97**, 142002 (2006)



Branching ratios

BABAR, Phys. Rev. D **95**, 072007 (2017)

Measure following branching ratios:

$$\mathcal{R}_1 \equiv \frac{\mathcal{B}(J/\psi \to K^+K^-\pi^0)}{\mathcal{B}(J/\psi \to \pi^+\pi^-\pi^0)} = 0.120 \pm 0.003(\text{stat}) \pm 0.009(\text{syst})$$

Agrees with $\mathcal{R}_1^{\text{PDG}} = 0.133 \pm 0.038$ obtained from PDG values for $\mathcal{B}(J/\psi \to K^+K^-\pi^0)$ (Mark II, 25 events) and $\mathcal{B}(J/\psi \to \pi^+\pi^-\pi^0)$

$$\mathcal{R}_2 \equiv \frac{\mathcal{B}(J/\psi \to K^0_S K^\pm\pi^\mp)}{\mathcal{B}(J/\psi \to \pi^+\pi^-\pi^0)} = 0.265 \pm 0.005(\text{stat}) \pm 0.021(\text{syst})$$

Using $\mathcal{B}(J/\psi \to K^0_S K^\pm\pi^\mp) = (26 \pm 7) \times 10^{-4}$ from Mark I (126 events): $\mathcal{R}_2^{\text{PDG}} = 0.123 \pm 0.033$, 3.6$\sigma$ deviation from our measurement

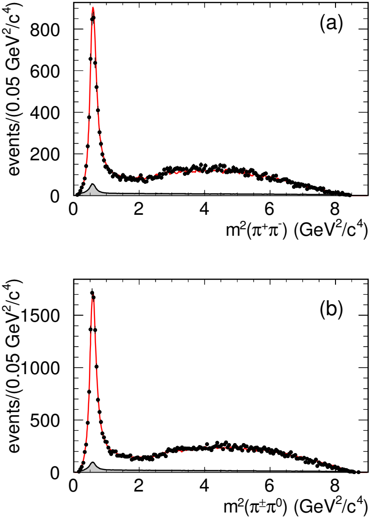
$J/\psi \to \pi^+\pi^-\pi^0$ Dalitz plot

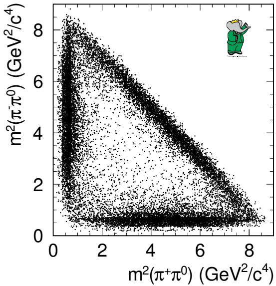
BABAR, Phys. Rev. D **95**, 072007 (2017)

Dominated by the three $\rho(770)\pi$ contribut

DP analysis:

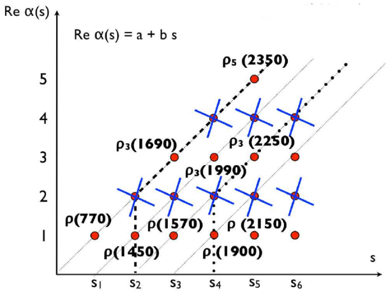
- Isobar model, using Zemach tensors
- Veneziano model
  (Szczepaniak & Pennington, PLB 737, 283 (2014))





$J/\psi \to \pi^+\pi^-\pi^0$ *Dalitz plot analysis with Veneziano model*

Veneziano model deals with trajectories rather than with single amplitudes Phys Lett B737, 283 (2014)



Amplitude written as

$$\mathcal{A}_{X\to abc} = \sum_{m,n} c_{X\to abc} A_{n,m}$$

to cancel unphysical poles (here: no resonances with even spin $J = 2n$ in this decay)

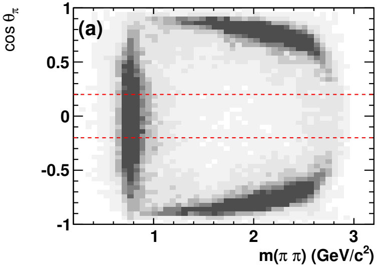
Complexity of model related to n, number of Regge trajectories included in the fit

Fit to our data requires $n = 7$, with 19 free parameters

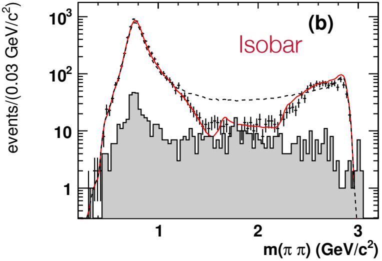
$J/\psi \to \pi^+\pi^-\pi^0$ *Dalitz plot analysis*

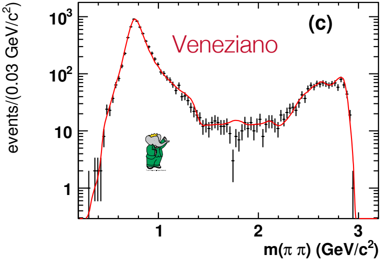
*B*A*B*AR, Phys. Rev. D **95**, 072007 (2017)

Plot all combinations of π helicity angle vs $m(\pi\pi)$
Consider $m(\pi\pi)$ mass projections for $|\cos\theta_\pi| < 0.2$ to remove reflections from other combinations



Dashed line: fit without ρ'





$J/\psi \to \pi^+\pi^-\pi^0$ Dalitz plot analysis

BaBar, Phys. Rev. D **95**, 072007 (2017)

Final state	Amplitude	Isobar fraction (%)	Phase (radians)	Veneziano fraction (%)
$\rho(770)\pi$	1.	$114.2 \pm 1.1 \pm 2.6$	0.	133.1 ± 3.3
$\rho(1450)\pi$	0.513 ± 0.039	$10.9 \pm 1.7 \pm 2.7$	$-2.63 \pm 0.04 \pm 0.06$	0.80 ± 0.27
$\rho(1700)\pi$	0.067 ± 0.007	$0.8 \pm 0.2 \pm 0.5$	$-0.46 \pm 0.17 \pm 0.21$	2.20 ± 0.60
$\rho(2150)\pi$	0.042 ± 0.008	$0.04 \pm 0.01 \pm 0.20$	$1.70 \pm 0.21 \pm 0.12$	6.00 ± 2.50
$\omega(783)\pi^0$	0.013 ± 0.002	$0.08 \pm 0.03 \pm 0.02$	$2.78 \pm 0.20 \pm 0.31$	
$\rho_3(1690)\pi$				0.40 ± 0.08
Sum		$127.8 \pm 2.0 \pm 4.3$		142.5 ± 2.8
χ^2/ν		$687/519 = 1.32$		$596/508 = 1.17$

Similar description of data, but different fit fractions.
Veneziano model fits better to data.

Other resonances contributing?

Small, but significant (4.9σ) contribution from isospin-violating decay $J/\psi \to \omega\pi^0$

Parameters of $\rho(1450)$ determined in the fit:

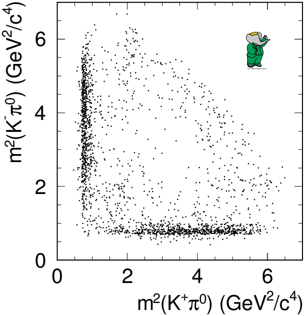
$$m(\rho(1450)) = 1429 \pm 41 \text{ MeV}/c^2,$$
$$\Gamma(\rho(1450)) = 576 \pm 29 \text{ MeV}$$

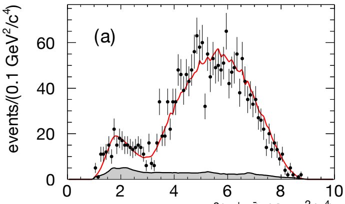
$J/\psi \to K^+K^-\pi^0$ *Dalitz plot analysis*

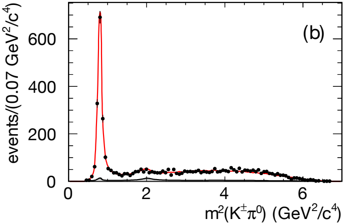
BABAR, Phys. Rev. D **95**, 072007 (2017)

- Clear bands from K^{*+} and K^{*-}
- Broad structure in the low $K^+ K^-$ mass region
- Only use isobar model to fit DP

Final state	fraction (%)	phase (rad)
$K^*(892)^{\pm}K^{\mp}$	$92.4 \pm 1.5 \pm 3.4$	0.
$\rho(1450)^0\pi^0$	$9.3 \pm 2.0 \pm 0.6$	$3.78 \pm 0.28 \pm 0.08$
$K^*(1410)^{\pm}K^{\mp}$	$2.3 \pm 1.1 \pm 0.7$	$3.29 \pm 0.26 \pm 0.39$
$K_2^*(1430)^{\pm}K^{\mp}$	$3.5 \pm 1.3 \pm 0.9$	$-2.32 \pm 0.22 \pm 0.05$
Total	107.4 ± 2.8	
χ^2/ν	$132/137 = 0.96$	







$\rho^0(1450)$ *branching ratio*

BaBar, Phys. Rev. D **95**, 072007 (2017)

Parameters of low-mass $K\bar{K}$ structure consistent with $\rho(1450)$

We obtain ratios

$$\mathcal{B}_1 = \frac{\mathcal{B}(J/\psi \to \rho(1450)^0\pi^0)\mathcal{B}(\rho(1450)^0 \to \pi^+\pi^-)}{\mathcal{B}(J/\psi \to \pi^+\pi^-\pi^0)} = (3.6 \pm 0.6(\text{stat}) \pm 0.9(\text{syst}))\%$$

$$\mathcal{B}_2 = \frac{\mathcal{B}(J/\psi \to \rho(1450)^0\pi^0)\mathcal{B}(\rho(1450)^0 \to K^+K^-)}{\mathcal{B}(J/\psi \to K^+K^-\pi^0)} = (9.3 \pm 2.0(\text{stat}) \pm 0.6(\text{syst}))\%$$

Branching ratio of $\rho^0(1450)$:

$$\frac{\mathcal{B}(\rho(1450)^0 \to K^+K^-)}{\mathcal{B}(\rho(1450)^0 \to \pi^+\pi^-)} = 0.307 \pm 0.084(\text{stat}) \pm 0.082(\text{syst})$$

Summary

Use charmonium decays to $KK\pi$ and 3π to obtain information on $K\pi$ $\mathcal{S}$-wave and $K\bar{K}$, $\pi\pi$ dynamics

Decays of η_C:
Dominated by two-body *SP* final states
Determination of $I = 1/2$ $K\pi$ *S*-wave amplitude and phase in a MIPWA up to $K\pi$ mass of $2.5\,\mathrm{GeV}/c^2$. Find very different amplitude compared to previous experiments in different processes

Dalitz plot analyses of $J/\psi \to 3\pi, KK\pi$:
isobar and Veneziano models for 3π decay,
1^- structure in K^+K^- mass attributed to $\rho(1450) \to K\bar{K}$