Study of three-body charmonium decays in *BABAR*

Elisa Fioravanti

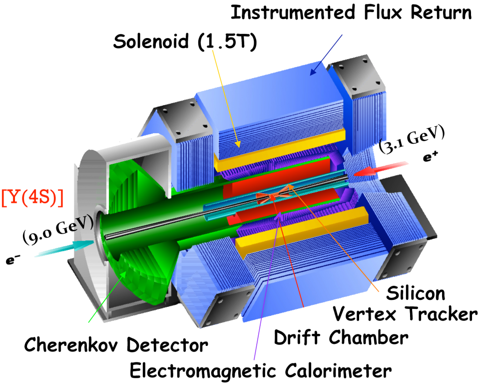
INFN Ferrara
On behalf of the *BABAR* Collaboration

DIS 2016 - Hamburg
11- 15 April 2016

Outline

- The *BABAR* experiment
- Measurement of the $I = 1/2$ $K\pi$ S-wave amplitude from Dalitz plot analyses of $\eta_c \to K\bar{K}\pi$ in two photon interactions.
  PRD 93, 012005 (2016)
- Dalitz plot analysis of $J/\psi \to \pi^+\pi^-\pi^0$ and $J/\psi \to K^+K^-\pi^0$ produced in e^+e^- annihilation via Initial State Radiation.
  Preliminary results
- Summary

The *BABAR* experiment and data sample



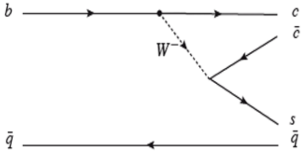
Features

- Data taking: 1999-2008
- Asymmetric beam energies; at the $\Upsilon(4S)$ ($\sqrt{s}$=10.58 GeV): E_{e^-}=9 GeV, E_{e^+}=3.1 GeV; $\mathcal{L}$=431 fb^{-1} + 45 fb^{-1} at 10.54 GeV.
  Primarily for B physics.
- Additional data-taking at the
  - $\Upsilon(3S)$ [30 fb^{-1}]
  - $\Upsilon(2S)$ [14 fb^{-1}]
  $\Rightarrow\sim$ 520 fb^{-1} e.g. for two-photon physics, ISR studies
  - Scan above $\Upsilon(4S)$ [3.9 fb^{-1}]

BABAR is a B factory: 467 million $B\bar{B}$ pairs in the total data sample.
BABAR is also a *c* factory: 1.3 million charm events per fb^{-1} (676 million charm events with 520 fb^{-1}).

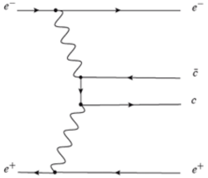
Experimental methods for charmonium production at the B-factories

B meson decays



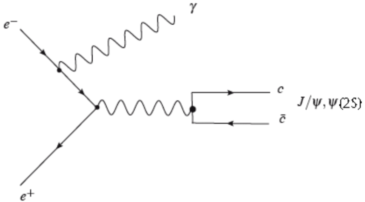
States of any quantum numbers can be produced

Two-photon production



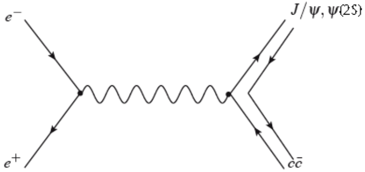
Only states with J^{PC} = $0^{\pm+}$, $2^{\pm+}$, $4^{\pm+}$,......, 3^{++}, 5^{++},....... can be produced

Initial State Radiation (ISR)

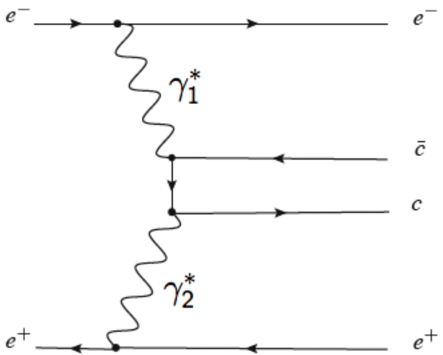


Only states with $J^{PC} = 1^{--}$ can be produced

Double charmonium production



Only charmonium states with C=+1 are allowed to be produced in association with the J/ψ or the ψ(2S)



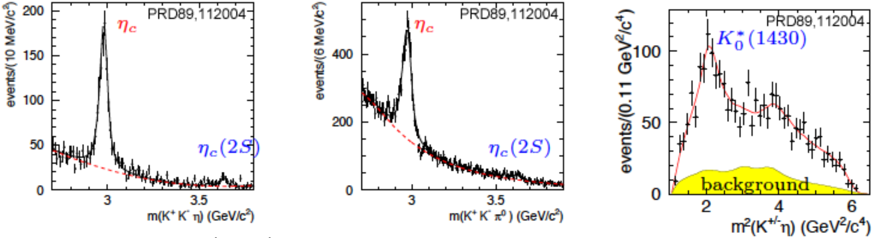
Measurement of the $I = 1/2$ $K\pi$ S-wave amplitude from Dalitz plot analyses of $\eta_c \to K\bar{K}\pi$ in two photon interactions.

PRD 93, 012005 (2016)

The use of charge-conjugate reactions is implied throughout

Introduction

- The *BABAR* Dalitz plot analyses for the decays $\eta_c \to K^+K^-\eta$ and $\eta_c \to K^+K^-\pi^0$ have provided the first clear observations of the $K_0^*(1430)$ as a Breit-Wigner peak; the observation of the decay mode $K_0^*(1430) \to K\eta$ with a BF∼5% was a surprise, but is consistent with measurements of $K\pi$ scattering (Phys. Rev. D 89, 112004 (2014))



- We measured the $K_0^*(1430)$ branching ratio:

$$\frac{\mathcal{B}(K_0^*(1403)\to\eta K)}{\mathcal{B}(K_0^*(1403)\to\pi K)}=0.092\pm0.025^{+0.010}_{-0.025}$$

- We also found that the η_c three-body hadronic decays proceed almost entirely through $\eta_c \to$pseudoscalar+scalar

- Therefore three-body decays of the η_c provide a unique window through which to study the properties of the scalar mesons

Selection of $\gamma\gamma \to K\bar{K}\pi$ - PRD 93, 012005 (2016)

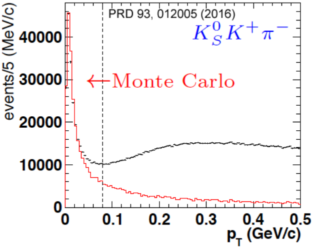
- We study, using 519 fb $^{-1}$, the reactions:

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

Details will be given only for the $K^0_S K^+ \pi^-$ final state

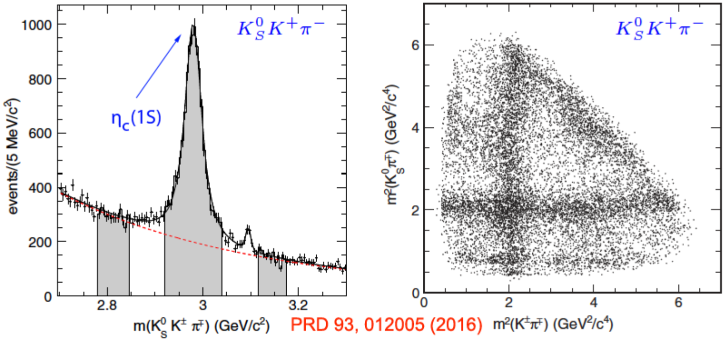
- Select events having only four tracks

- The signal at low p_T indicates the presence of two-photon events. We require $p_T < 0.08$ GeV/c
  p_T: transverse momentum of the $K^0_S K^+ \pi^-$ system with respect to the e^+e^- collision axis.



- We remove ISR events by requiring $M^2_{rec} > 10$ GeV^2/c^4;
  We define $M^2_{rec} = (p_{e^+e^-} - p_{rec})^2$;
  where $p_{e^+e^-}$ is the four-momentum of the initial state and p_{rec} is the four-momentum of the $K^0_S K^+ \pi^-$ system.

The $K\bar{K}\pi$ mass spectra in the η_c region - PRD 93, 012005 (2016)



- $\eta_c \to K^0_S K^+ \pi^-$, 12849 events with (64.3$\pm$0.4)% purity
- $\eta_c \to K^+ K^- \pi^0$, 6710 events with (55.2$\pm$0.6)% purity
- Small residual J/ψ signals from ISR
- The Dalitz plots are dominated by the presence of $K_0^*(1430)$
- Purity=$N_{sig}/(N_{sig} + N_{back})$

Dalitz plot analysis of $\eta_c \to K\bar{K}\pi$ - PRD 93, 012005 (2016)

- We perform Dalitz plot analyses of the $K\bar{K}\pi$ systems in the η_c mass region using unbinned maximum likelihood fits.
- Fits performed using:
  - Isobar model: resonances described by Breit-Wigner functions
    D. Asner, Review of Particle Physics; Phys. Lett. B 592, 1 (2004)
  - Model-Independent Partial Wave Analysis (MIPWA)
    Phys. Rev. D 73, 032004 (2006); $D^+ \to K^-\pi^+\pi^+$ (FNAL E791)
    Phys. Rev. D 79, 032003 (2009); $D_s^+ \to \pi^+\pi^-\pi^+$ (*BABAR*)

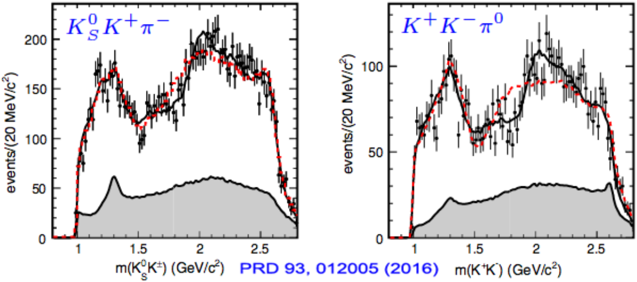
Model-Independent Partial Wave Analysis (MIPWA)

- The $K\pi$ mass spectrum is divided into 30 equally spaced mass intervals 60 MeV wide, and for each interval we add to the fit two new free parameters, the amplitude and the phase of the $K\pi$ S-wave (constant inside the bin)
- The interference between the two $K\pi$ modes is positive for η_c decays (confirmed empirically)
- The $K_2^*(1430)$, $a_0(980)$, $a_0(1450)$, $a_2(1320)$,... contributions are modeled as relativistic Breit-Wigner functions multiplied by the corresponding angular functions.
- Backgrounds are fitted separately and interpolated into the η_c signal region.

- The fits improve when a new high-mass $a_0(1950) \to K\bar{K}$ I=1 resonance is included with free parameters in both η_c decay modes.

Red curve: no $a_0(1950)$

Shaded regions indicate the contributions from the background



Statistical significance for the $a_0(1950)$ effect (including systematics) are:

2.5σ for $\eta_c \to K_S^0 K^+ \pi^-$
4.2σ for $\eta_c \to K^+ K^- \pi^0$

$a_0(1950)$

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

Good agreement between the two η_c decay modes

Fit fractions from the MIPWA. Comparison with the Isobar Model - PRD 93, 012005 (2016)

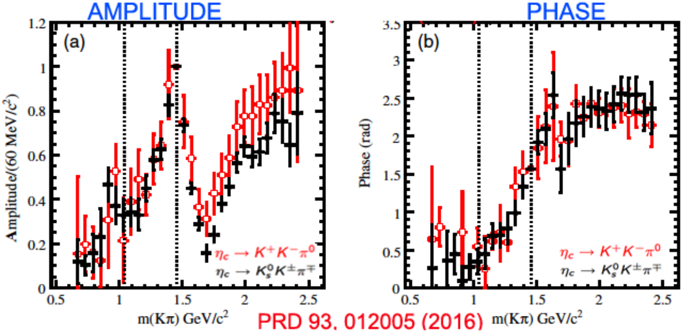
	$\eta_c \to K^0_S K^\pm \pi^\mp$		$\eta_c \to K^+ K^- \pi^0$	
Amplitude	Fraction (%)	Phase (rad)	Fraction (%)	Phase (rad)
$(K\pi S\text{-wave})\ \bar{K}$	$107.3 \pm 2.6 \pm 17.9$	fixed	$125.5 \pm 2.4 \pm 4.2$	fixed
$a_0(980)\pi$	$0.8 \pm 0.5 \pm 0.8$	$1.08 \pm 0.18 \pm 0.18$	$0.0 \pm 0.1 \pm 1.7$	...
$a_0(1450)\pi$	$0.7 \pm 0.2 \pm 1.4$	$2.63 \pm 0.13 \pm 0.17$	$1.2 \pm 0.4 \pm 0.7$	$2.90 \pm 0.12 \pm 0.25$
$a_0(1950)\pi$	$3.1 \pm 0.4 \pm 1.2$	$-1.04 \pm 0.08 \pm 0.77$	$4.4 \pm 0.8 \pm 0.8$	$-1.45 \pm 0.08 \pm 0.27$
$a_2(1320)\pi$	$0.2 \pm 0.1 \pm 0.1$	$1.85 \pm 0.20 \pm 0.20$	$0.6 \pm 0.2 \pm 0.3$	$1.75 \pm 0.23 \pm 0.42$
$K^*_2(1430)\bar{K}$	$4.7 \pm 0.9 \pm 1.4$	$4.92 \pm 0.05 \pm 0.10$	$3.0 \pm 0.8 \pm 4.4$	$5.07 \pm 0.09 \pm 0.30$
Total	$116.8 \pm 2.8 \pm 18.1$		$134.8 \pm 2.7 \pm 6.4$	
$-2 \log \mathcal{L}$	-4314.2		-2339	
χ^2/N_{cells}	$301/254 = 1.17$		$283.2/233 = 1.22$	

ISOBAR MODEL

Amplitude	Fraction %	Phase (rad)
$K^*_0(1430)\bar{K}$	40.8 ± 2.2	0.
$K^*_0(1950)\bar{K}$	14.8 ± 1.7	-1.00 ± 0.07
NR	18.0 ± 2.5	1.94 ± 0.09
χ^2/N_{cells}	$467/256 = 1.82$	

- For the MIPWA, good agreement between the two η_c decay modes
- $(K\pi$ S-wave) $\bar{K}$ amplitude is dominant with small contributions from $K^*_2(1430)^0\bar{K}$ and $a_0(1950)\pi$ amplitudes.
- Good description of the data with the MIPWA
- Poorer description of the data with the Isobar Model

$K\pi$ S-wave amplitude (a) and phase (b) from $\eta_c \to K^0_s K^\pm \pi^\mp$ (black points) and $\eta_c \to K^+K^-\pi^0$ (red points). Dashed lines are $K\eta$ and $K\eta'$ thresholds.

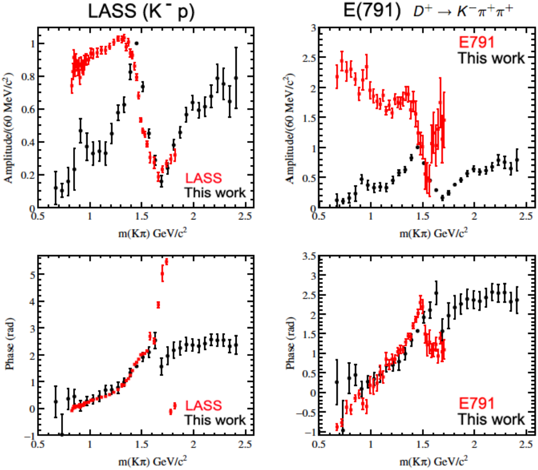


- Amplitude: clear peak related to the $K_0^*(1430)$ resonance which shows a rapid drop around 1.7 GeV/c^2 where a broad structure is present which can be related to the $K_0^*(1950)$ resonance
- Phase: We see the expected behavior for the resonance phase which varies by about π in the $K_0^*(1430)$ resonance region. The phase shows a drop around 1.7 GeV/c^2 related to interference with the $K_0^*(1950)$ resonance

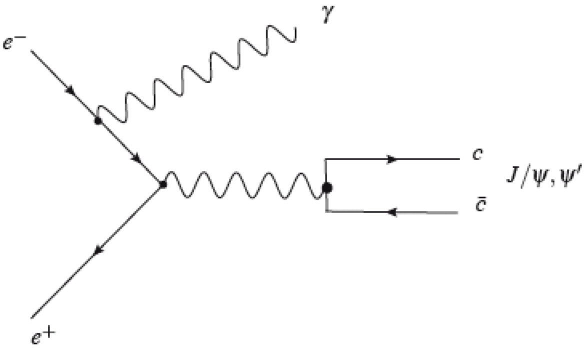
Good agreement between the two η_c decay modes

Comparison with the LASS and E791 experiments - PRD 93, 012005 (2016)

- Black is $\eta_c \to K^0_S K^+ \pi^-$ from the present analysis
- Phase before the $K\eta'$ threshold are similar, as expected from Watson theorem (PR88,1163(1952))
- Amplitudes are very different



- LASS: Nucl. Phys. B 296, 493 (1988); E791: PRD 73, 032004 (2006)



Dalitz plot analyses of $J/\psi \to \pi^+\pi^-\pi^0$ and $J/\psi \to K^+K^-\pi^0$ produced via e^+e^- annihilation with Initial State Radiation.

Preliminary results

Introduction

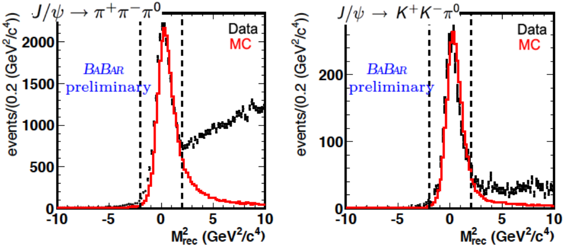
- Only an unpublished Mark III Dalitz plot analysis exists for the decay $J/\psi \to \pi^+\pi^-\pi^0$ (SLAC-PUB-5674, (1991))
- Although large samples of J/ψ decays exist, some branching fractions remain poorly measured. In particular the $J/\psi \to K^+K^-\pi^0$ branching fraction has been measured by Mark II using only 25 events (Phys. Rev. Lett. 51, 963 (1983)).
- The BESIII experiment has performed an angular analysis of $J/\psi \to K^+K^-\pi^0$. The analysis requires the presence of a broad $J^{PC} = 1^{--}$ state in the K^+K^- threshold region, which is interpreted as a multi-quark state (Phys. Rev. Lett. 97, 142002 (2006))

- We study, using 519 fb^{-1}, the reactions:

$$e^+e^- \rightarrow \gamma_{ISR}\ \pi^+\pi^-\pi^0$$
$$e^+e^- \rightarrow \gamma_{ISR}\ K^+K^-\pi^0$$

where γ_{ISR} is the undetected ISR photon

- We select events having only two tracks and one mass-constrained π^0
- We compute $M^2_{rec} = (p_{e^-} + p_{e^+} - p_{h^+} - p_{h^-} - p_{\pi^0})^2$ where $h = \pi/K$
- This quantity should peak near zero for ISR events



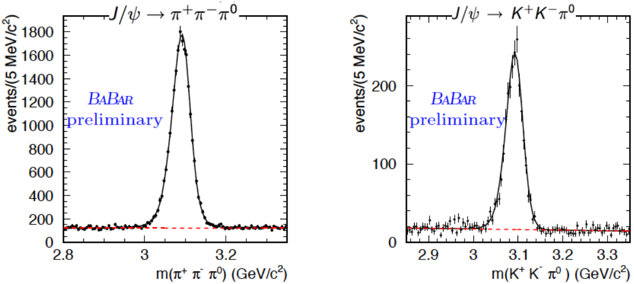
Plot of M^2_{rec} in the J/ψ signal region. In red are Monte Carlo simulations.

- We select events in the ISR region by requiring $|M^2_{rec}| < 2$ GeV^2/c^4

J/ψ signals and yields

We fit the J/ψ invariant mass distribution using the Monte Carlo resolution functions described by Crystal Ball* + Gaussian functions

J/ψ decay mode	χ^2/NDF	J/ψ mass (MeV)	Fitted events	weight
$J/\psi \to \pi^+\pi^-\pi^0$	84/115	3099.8 ± 0.2	19916 ± 141	15.223 ± 0.079
$J/\psi \to K^+K^-\pi^0$	111/95	3101.0 ± 0.2	2201 ± 47	18.110 ± 0.184

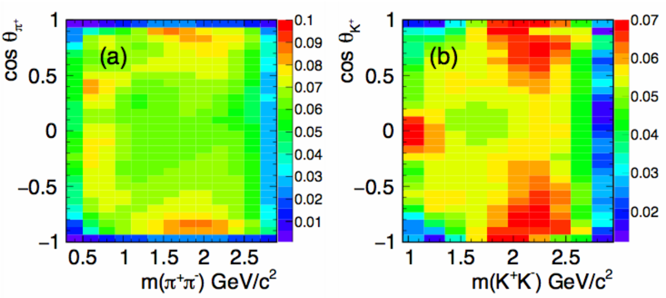


* M.J.Oreglia, Ph.D Thesis, SLAC-236(1980), Appendix D

J. E. Gaiser, Ph.D Thesis, SLAC-255 (1982), Appendix E

Efficiency and Branching fractions

The efficiency is mapped and fitted on the $(m(h^+h^-), cos\theta_h)$ plane, where the helicity angle θ_h is the angle in the h^+h^- rest frame between the directions of the h^+ and the boost from the J/ψ rest frame (h=π/K)



We obtain the weighted efficiencies:

$$\epsilon_{h^+h^-\pi^0} = \frac{\sum_{i=1}^{N} f_i}{\sum_{i=01}^{N} f_i/\epsilon(m_i, cos\theta_i)}$$

where $f = 1$ for events in the signal region and $f = -1$ for events in the sideband regions.

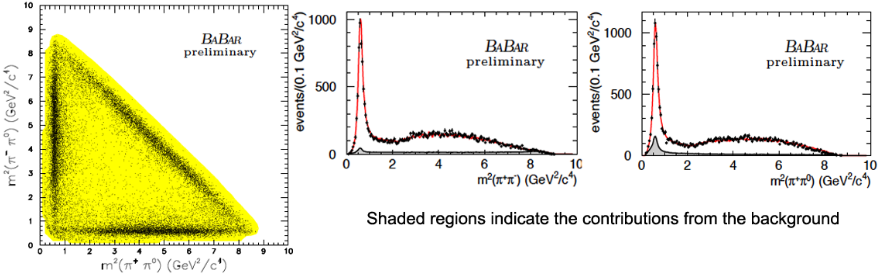
Efficiency and Branching fractions

- We obtain:

$$\mathcal{R} = \frac{\mathcal{B}(J/\psi \to K^+K^-\pi^0)}{\mathcal{B}(J/\psi \to \pi^+\pi^-\pi^0)} = 0.0929 \pm 0.002 \pm 0.002$$

- In PRL 51, 963 (1983), the value $\mathcal{B}(J/\psi \to K^+K^-\pi^0) = (2.8 \pm 0.8) \times 10^{-3}$ is reported on the basis of 25 events.
  In addition, the value $\mathcal{B}(J/\psi \to \pi^+\pi^-\pi^0) = (2.11 \pm 0.07) \times 10^{-2}$ is reported in PDG 2014.
  These values then yield $\mathcal{R} = 0.133 \pm 0.038$, which differs by only $\sim 1\sigma$ from our result.
- We note also that in PRD 15, 1814 (1977) the value $\mathcal{B}(J/\psi \to K\bar{K}\pi) = (7.8 \pm 2.1) \times 10^{-3}$ is reported on the basis of a sample of events for the final states $K_S K^\pm \pi^\mp$. From isospin invariance, this would yield the value $\mathcal{B}(J/\psi \to K^+K^-\pi^0) = (1.30 \pm 0.35) \times 10^{-3}$ and the corresponding ratio-value $\mathcal{R} = 0.062 \pm 0.017$.
- The weighted average of these two measurements is $\mathcal{R} = 0.074 \pm 0.016$, which again differs only by $\sim 1\sigma$ from our measurement.
- Our value is more precise than this average by a factor of ~ 7.

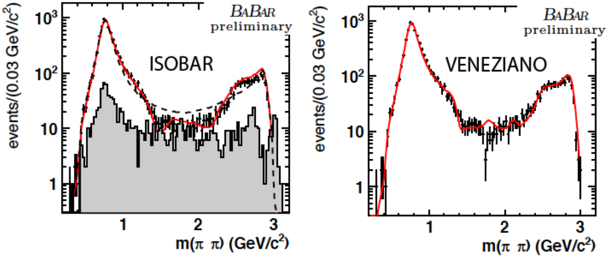
$J/\psi \to \pi^+\pi^-\pi^0$: Dalitz plot and projections



Shaded regions indicate the contributions from the background

- Dominated by $\rho(770)\pi$ contributions
- Dalitz plot analyses performed using:
  - Isobar model using Zemach tensors [C.Zemach, Phys. Rev. 133, B1201 (1964)]
  - Veneziano model [A.P.Szczepaniak, M.R. Pennington, Phys. Lett. B 737, 283 (2014)]: the dynamical assumptions behind this model are the resonance dominance of the low-energy spectrum and resonance-Regge duality. The complexity of the model is related to *n*, the number of Regge trajectories included in the fit (the fit requires n=5).

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



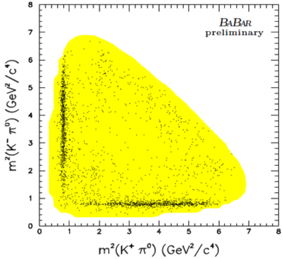
Shaded region indicates the contribution from the background

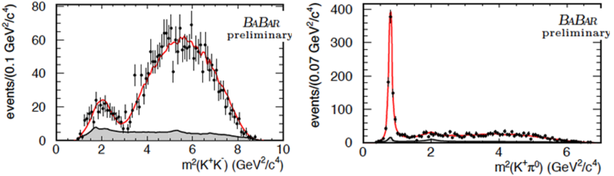
Isobar model: the dashed curve is the result of the fit with only the $\rho(770)$ resonance.

Final state	Isobar fraction %	Phase (radians)	Veneziano fraction %
$\rho(770)\pi$	$119.0 \pm 1.1 \pm 3.3$	$0.$	120.0 ± 1.9
$\rho(1450)\pi$	$16.9 \pm 2.0 \pm 3.1$	$3.92 \pm 0.05 \pm 0.11$	1.53 ± 0.13
$\rho(1700)\pi$	$0.1 \pm 0.1 \pm 0.2$	$1.01 \pm 0.35 \pm 0.79$	0.84 ± 0.08
$\rho(2150)\pi$	$0.04 \pm 0.05 \pm 0.02$	$1.89 \pm 0.30 \pm 0.48$	2.03 ± 0.17
$\rho_3(1690)\pi$			0.09 ± 0.02
Sum	$136.0 \pm 2.3 \pm 4.3$		124.5 ± 2.3
χ^2/ν	$764/552$		$780/554$

The two models give similar data representation, but different fractions.

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





Shaded regions indicate the contribution from the background

- The decay is dominated by K*(892)$\bar{K}$ amplitudes
- We make use of the Isobar model only
- Broad enhancement in the K^+K^- mass spectrum attributed to the presence of the $\rho(1450)$ resonance:
  m(ρ(1450))=1361±43 MeV/c^2
  Γ(ρ(1450))=479±63 MeV

Final state	fraction %	phase
$K^*(892)K$	$87.8 \pm 2.0 \pm 1.7$	0.
$\rho(1450)^0\pi^0$	$11.5 \pm 2.1 \pm 2.1$	$-2.81 \pm 0.25 \pm 0.36$
$K^*(1410)K$	$1.7 \pm 0.7 \pm 1.1$	$2.89 \pm 0.35 \pm 0.08$
$K_2^*(1430)K$	$3.8 \pm 1.4 \pm 0.5$	$-2.42 \pm 0.22 \pm 0.07$
$\rho(1700)^0\pi^0$	$0.9 \pm 1.0 \pm 0.6$	$1.06 \pm 0.20 \pm 0.7$
Total	$105.6 \pm 3.4 \pm 3.0$	
$\chi^2/\nu = 94/92$		

$\rho(1450)$ branching fraction

- We perform a measurement of the $\rho(1450)$ relative branching fraction using the isobar model only
- We have measured the ratio:
  $\mathcal{R} = \mathcal{B}(J/\psi \to K^+K^-\pi^0)/\mathcal{B}(J/\psi \to \pi^+\pi^-\pi^0) = 0.0929 \pm 0.002 \pm 0.002$
- From the Dalitz plot analysis of $J/\psi \to \pi^+\pi^-\pi^0$ we obtain:
  $\mathcal{B}_1 = \mathcal{B}(J/\psi \to \rho(1450)^0\pi^0)$=[(16.9$\pm$2.0$\pm$3.1)/3]%=(5.63$\pm$0.67$\pm$1.03)%
- From the Dalitz plot analysis of $J/\psi \to K^+K^-\pi^0$ we obtain:
  $\mathcal{B}_2 = \mathcal{B}(J/\psi \to \rho(1450)^0\pi^0) = (11.5 \pm 2.1 \pm 2.1)\%$
- We therefore obtain: $\frac{\mathcal{B}(\rho(1450)^0 \to K^+K^-)}{\mathcal{B}(\rho(1450)^0 \to \pi^+\pi^-)} = \frac{\mathcal{B}_2}{\mathcal{B}_1} \cdot \mathcal{R} = 0.190 \pm 0.042 \pm 0.049$

Summary

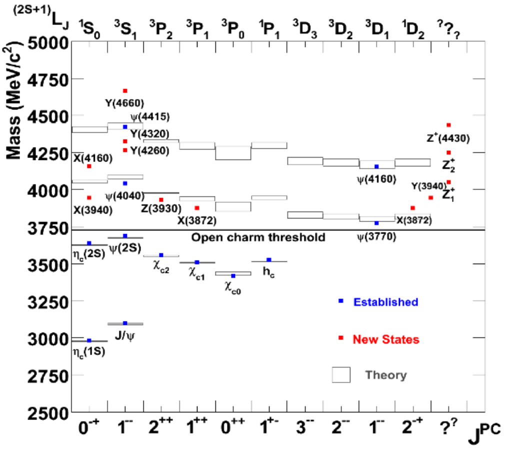
- We show the results on the Dalitz plot analyses of $\eta_c \to K_s^0 K^+ \pi^-$ and $\eta_c \to K^+ K^- \pi^0$ produced in two-photon interactions (PRD 93, 012005 (2016))
  - We extract for the first time the $K\pi$ S-wave amplitude and phase using a MIPWA.

- We show preliminary results on Dalitz plot analyses of Initial State Radiation data on the decays $J/\psi \to \pi^+\pi^-\pi^0$ and $J/\psi \to K^+K^-\pi^0$; the analyses make use of Isobar and Veneziano models.
  - $\mathcal{R} = \frac{\mathcal{B}(J/\psi \to K^+K^-\pi^0)}{\mathcal{B}(J/\psi \to \pi^+\pi^-\pi^0)} = 0.0929 \pm 0.002 \pm 0.002$
    This value represents an improvement in precision by a factor of $\sim$7 over the previous measurements.

THANKS FOR YOUR ATTENTION!

BACKUP SLIDES

Charmonium spectrum

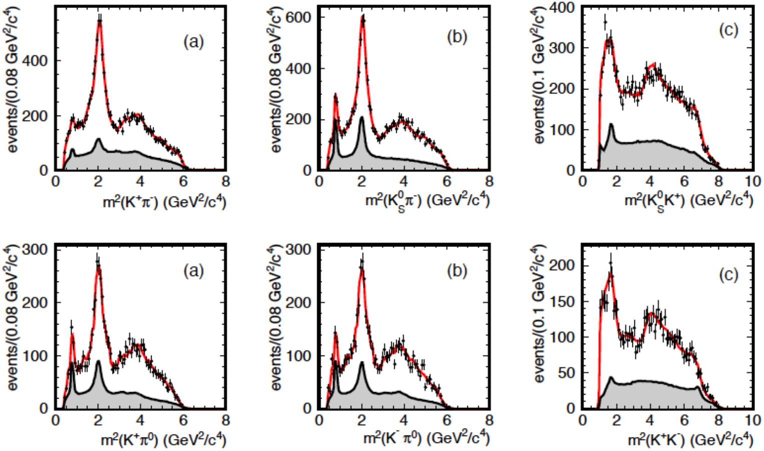


- Below the $D\bar{D}$ threshold, all expected states have been observed, with properties in good agreement with theory; there are no additional states.
- Many unexpected states have been reported above the $D\bar{D}$ threshold, seemingly too many with $J^{PC} = 1^{--}$. Several exotic hypotheses as to their nature: tetraquarks, hadronic molecules, hybrids, glueballs, hadro-quarkonia.
- These result mainly from Belle and *BABAR*, with significant contributions also from CDF, D0, CLEO, LHCb and BES.

Eur. Phys. J.C71, 1534 (2011)

Dalitz plot mass projections

Dalitz plot projections with fit results for $\eta_c \rightarrow K^0_S K^+ \pi^-$ (top) and $\eta_c \rightarrow K^+ K^- \pi^0$ (bottom)

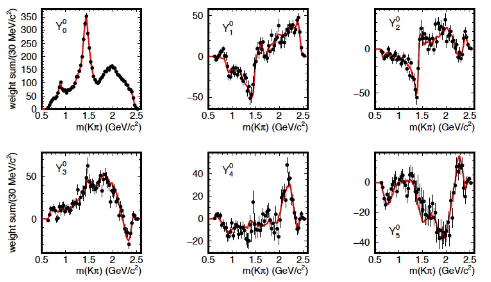


Shaded is contribution from the interpolated background

$K^*(890)$ contributions entirely from background

Legendre polynomial moments: $\eta_c \to K^0_S K^+ \pi^-$

Mass projections weighted by Y^0_L moments and compared with fit results.
$m(K^+\pi^-) + m(K^0_S\pi^-)$ projections



$m(K^0_S K^+)$ projections
Good agreement in all the projections
Similarly for $\eta_c \to K^+K^-\pi^0$