Study of three-body charmonium decays in *BABAR*

Claudia Patrignani
representing the *BABAR* Collaboration

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA
CAMPUS DI RIMINI

Università di Bologna and I.N.F.N.
Claudia.Patrignani@bo.infn.it

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Outline

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

  Phys. Rev. D 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^- annihilations via Initial State Radiation.

  Preliminary

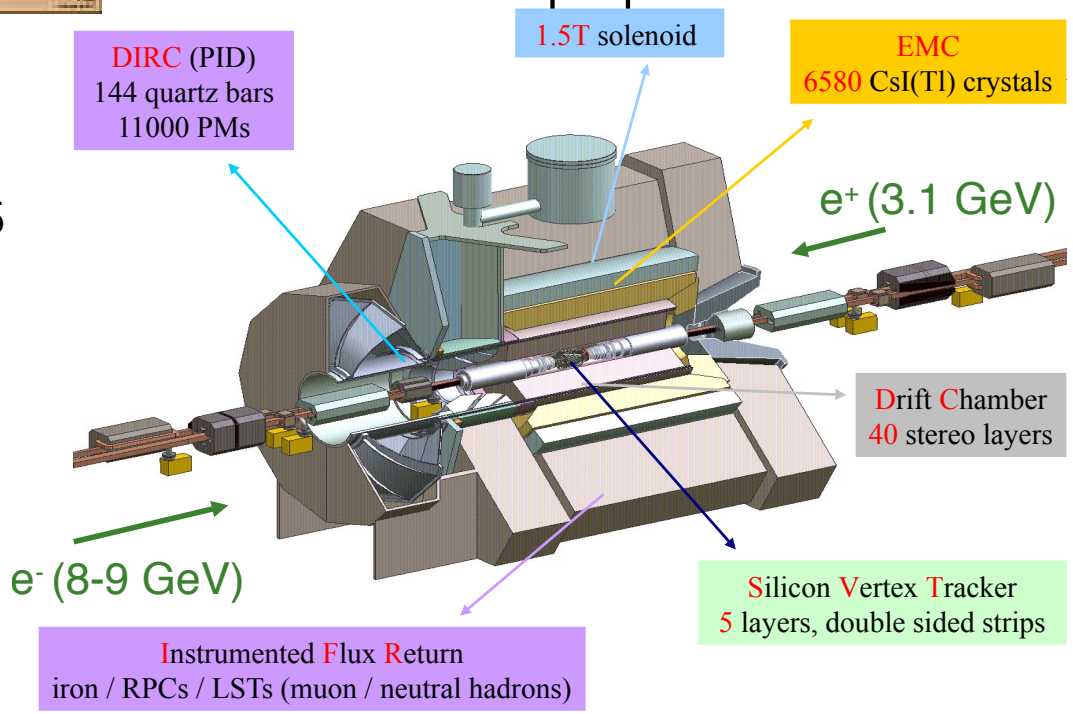
All results are based on a data sample of 519 fb^{-1}

The *BABAR* experiment

PEP-II asymmetric e^+e^- collider operating at center of mass energies near the $\Upsilon(4S)$ (for most of the time)

$$\sqrt{s} = 10.58\,\mathrm{GeV}/c^2$$

General-purpose detector



Asymmetric:

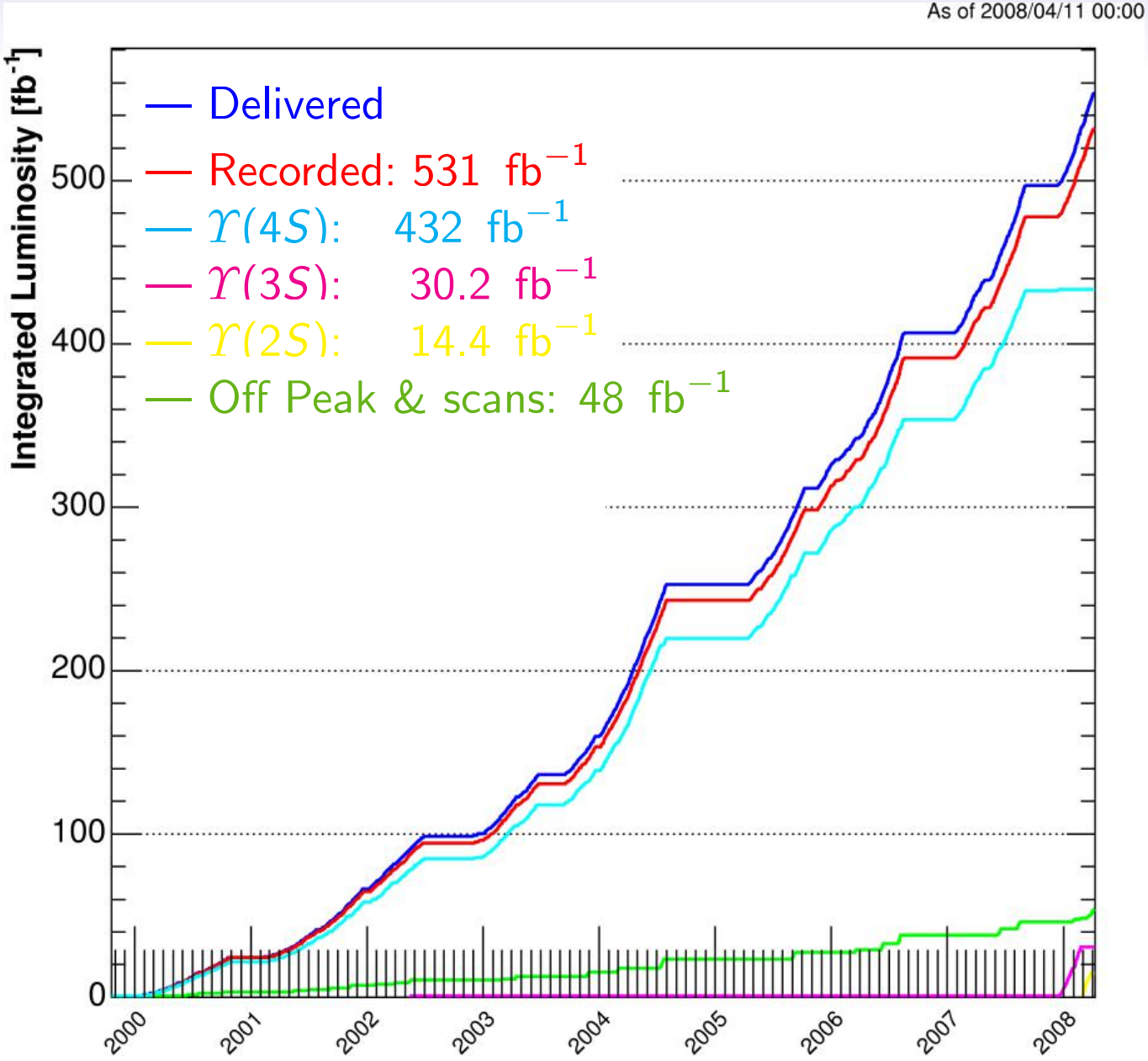
$$-0.9 < \cos\theta^* < 0.85$$

wrt electron beam

excellent performance:

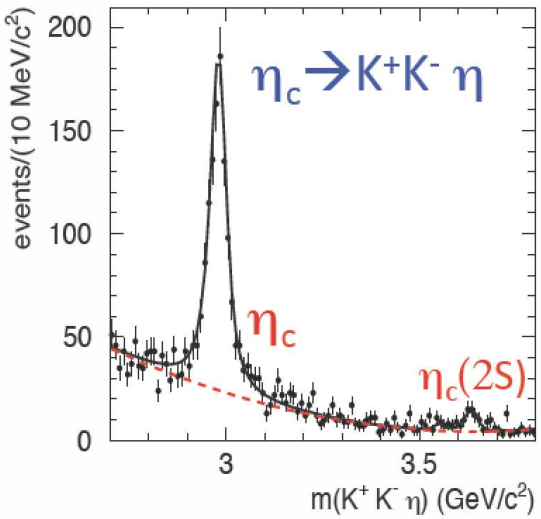
- vertexing
- tracking
- PID
- calorimeter

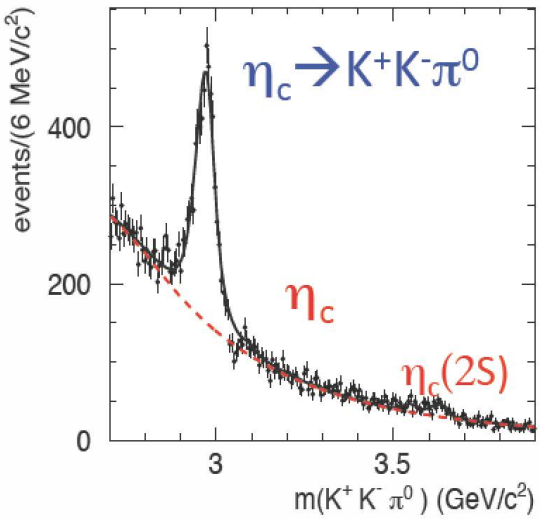
Data samples

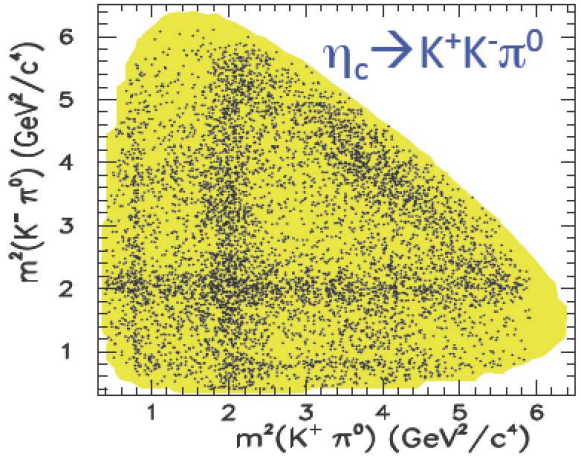


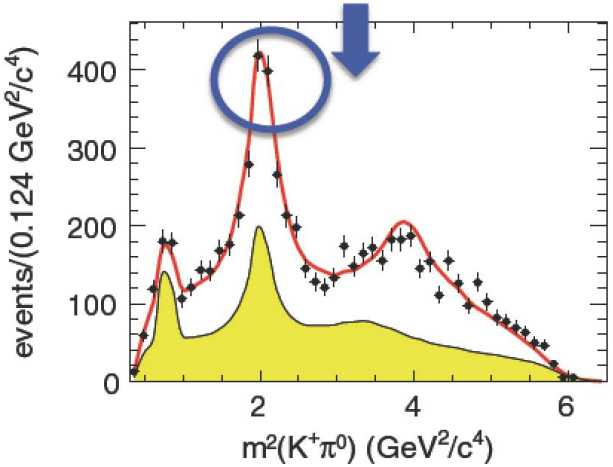
Three body decays of $\eta_c(1S)$

First Dalitz plot analysis of η_c decays to $K^+K^-\pi^0$ and η_c decays to $K^+K^-\eta$ by *BABAR* Phys. Rev. D 89, 112004 (2014)









First observation of $K^*(1430)$ as a Breit-Wigner peak

$$\frac{\mathcal{B}(K_0^*(1430)\to\eta K)}{\mathcal{B}(K_0^*(1430)\to\pi K)} = \mathcal{R}(\eta_c)\frac{f_{\eta K}}{f_{\pi K}} = 0.092 \pm 0.025^{+0.010}_{-0.025}$$

Dominance of scalar mesons

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

$\eta_c \to K\bar{K}\pi$ to study $K\pi$ S-wave

Scalar mesons still a puzzle

- too many states: inconsistent with $q\bar{q}$
- large decay widths: overlap between resonances and background

Structure of I=1/2 $K\pi$ S-wave poorly known

- introduces large systematics in 3- or 4-body decays of heavy-flavour mesons

Previous measurements of I=1/2 $K\pi$ S-wave limited to below D^+ mass and have contamination from I=3/2

- LASS Nucl. Phys. B 296,493 (1988)
- E791 Phys. Rev. D 73, 032004 (2006)

Due to I-spin conservation in $\eta_c \to K\bar{K}\pi$ no I=3/2 contribution, and $K\pi$ S-wave can be determined up to $2.5\,\mathrm{GeV}/c^2$

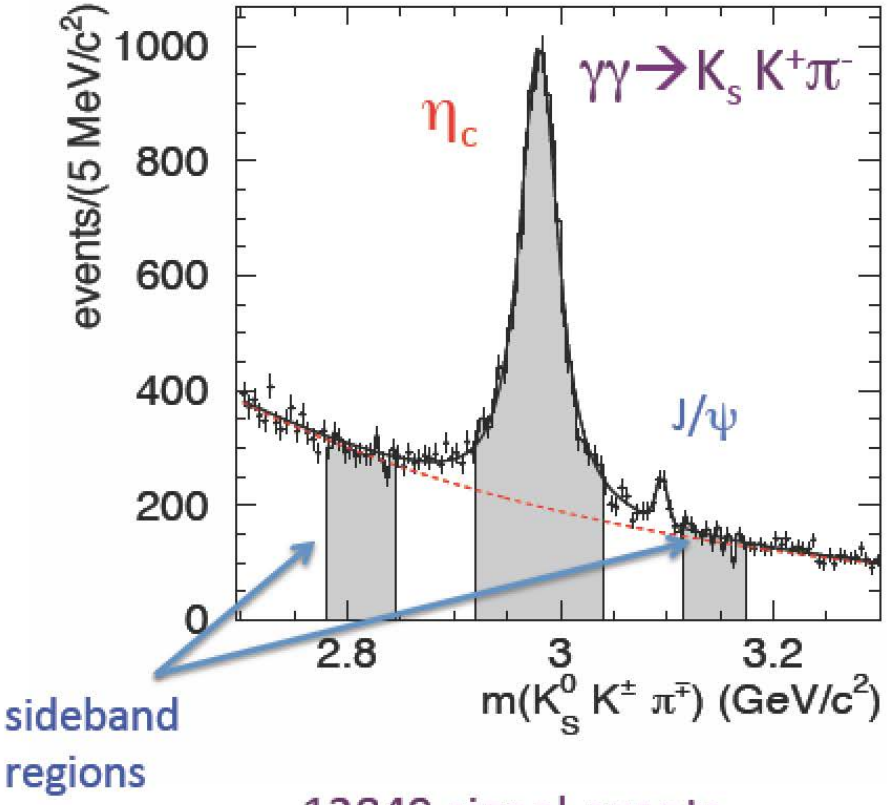
$\gamma\gamma \to \eta_c \to K_s K^+ \pi^-$ or $K^+ K^+ \pi^0$

Phys. Rev. D 93, 012005 (2016)

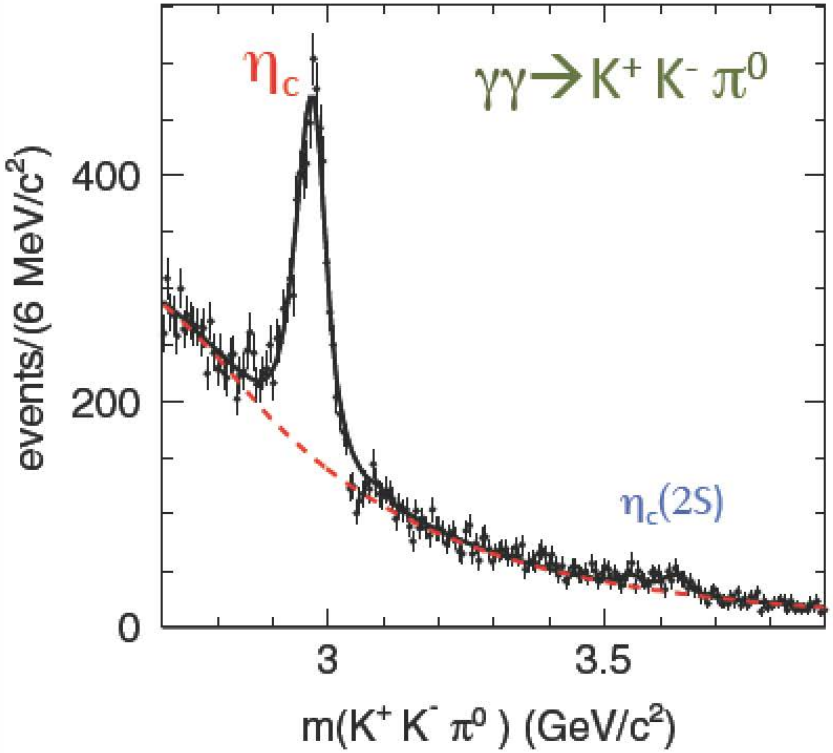
"Standard" selection:

exactly 2 or 4 charged tracks, PID, vertex quality, mass of π^0/ K_s

$\gamma\gamma$ production: η_c has low p_t; suppress ISR requiring large missing mass



12849 signal events with 64.3% purity



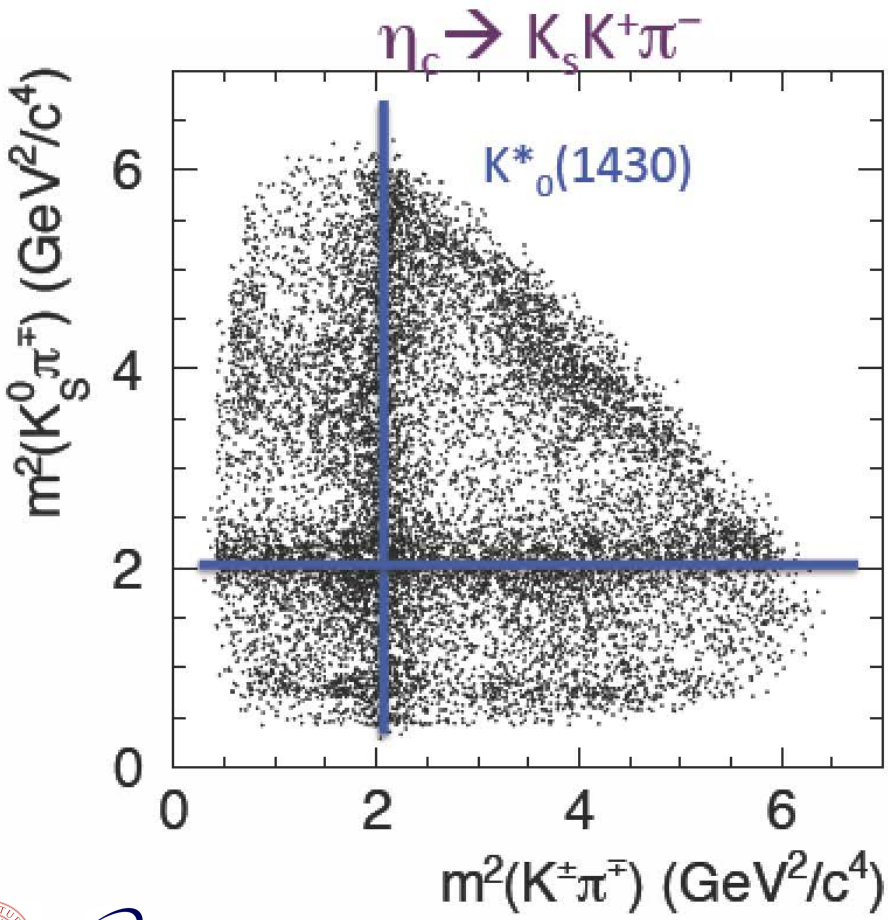
6710 signal events with 55.2% purity

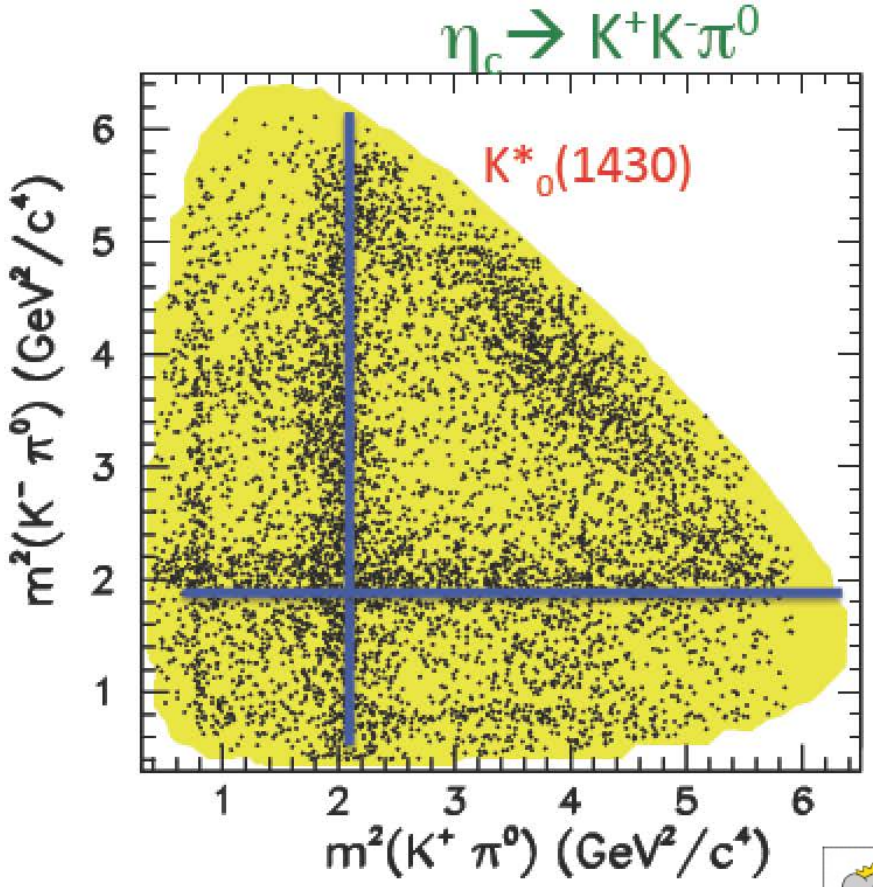
$\eta_c(1S) \to K\bar{K}\pi$ Dalitz plot analysis

Phys. Rev. D 93, 012005 (2016)

- Unbinned maximum likelihood fits in the η_c mass region
- full interference among amplitudes
  - Isobar model
  - Quasi Model-Independent PWA

E791: Phys. Rev. D 73, 032004 (2006)





Isobar model fit to $\eta_c(1S) \to K\bar{K}\pi$

Phys. Rev. D 93, 012005 (2016)

The $K\pi$ S-wave modeled as interfering non-resonant, $K_0^*(1430)$ and $K_0^*(1950)$

	$\eta_c \to K_S^0 K^\pm \pi^\mp$		$\eta_c \to K^+ K^- \pi^0$		
Amplitude	Fraction (%)	Phase	Fraction (%)	Phase	
$K_0^*(1430)K$	40.8 ± 2.2	0.	28.1 ± 3.3	0.	
$K_0^*(1950)K$	14.8 ± 1.7	-1.00 ± 0.07	6.0 ± 1.2	-0.89 ± 0.09	$K\pi$ $\mathcal{S}$−wave
NR	18.0 ± 2.5	1.94 ± 0.09	29.5 ± 4.4	-4.5 ± 0.08	
$a_0(980)\pi$	10.5 ± 1.2	0.94 ± 0.12	4.8 ± 1.3	0.08 ± 0.23	
$a_0(1450)\pi$	1.7 ± 0.5	2.94 ± 0.13	1.2 ± 0.5	3.05 ± 0.29	
$a_0(1950)\pi$	0.7 ± 0.2	-1.76 ± 0.24	1.0 ± 0.4	-0.54 ± 0.24	
$a_2(1310)\pi$	0.2 ± 0.2	-0.53 ± 0.42	3.7 ± 1.0	-0.45 ± 0.41	
$K_2^*(1430)^0 K$	2.3 ± 0.7	-1.55 ± 0.11	7.4 ± 1.5	-1.71 ± 0.12	
Total	88.8 ± 4.3		81.8 ± 6.1		
$-2\log\mathcal{L}$	-4290.7		-2200.8		
χ^2/N_{cells}	467/256=1.82		383/233=1.63		

Fit fractions and amplitudes do not agree between the two η_c decay modes

The fit has a relatively bad χ^2

Quasi MIPWA of $\eta_c(1S) \to K\bar{K}\pi$

Phys. Rev. D 93, 012005 (2016)

Amplitude is written as a sum of partial waves with A_i and ϕ_i

$$A=|A_1 + c_2A_2e^{\phi 2} + c_3A_3e^{\phi 3}+\ldots|$$

- $\eta_c=0^+ \longrightarrow$ Interference between (Kπ) K systems is constructive.
- Kπ amplitude is symmetrized

$\eta_c=K_sK^+\pi^-$

$$A_{S\text{-wave}} = \frac{1}{\sqrt{2}}\left(a_j^{K^+\pi^-} e^{i\phi_j^{K^+\pi^-}} + a_j^{\bar{K}^0\pi^-} e^{i\phi_j^{\bar{K}^0\pi^-}}\right)$$

where $a^{K^+\pi^-}(m) = a^{K^0_S\pi^-}(m)$ and $\phi^{K^+\pi^-}(m) = \phi^{K^0_S\pi^-}(m)$

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

$$A_{S\text{-wave}} = \frac{1}{\sqrt{2}}\left(a_j^{K^+\pi^0} e^{i\phi_j^{K^+\pi^0}} + a_j^{K^-\pi^0} e^{i\phi_j^{K^-\pi^0}}\right)$$

where $a^{K^+\pi^0}(m) = a^{K^-\pi^0}(m)$ and $\phi^{K^+\pi^0}(m) = \phi^{K^-\pi^0}(m)$

- Mass spectrum is divided into 30 equally spaced mass intervals 60 MeV wide.
- Each interval has 2 new free parameters, A_i and ϕ_i, with a total of 58
- Fix A=1 and $\phi=\pi/2$ in one arbitrary bin (bin 11 with mass=1.45 GeV/c^2)
- Other resonance contributions, A_2, A_3, etc..., are parameterized as Breit-Wigner amplitudes multiplied by their corresponding angular functions.
- Backgrounds are interpolated from sideband regions: K*(892) entirely background.

Quasi MIPWA fit results $\eta_c(1S) \to K K \pi$

Phys. Rev. D 93, 012005 (2016)

Dominance of $K\pi$ S-wave with contributions from $a_0\pi$ and $K^*(1430)K$

$a_0(1950)$: new resonance with 2.5 σ in $K_s^0 K^+\pi^-$ and 4.2 σ in $K^+K^-\pi^0$

	$\eta_c \to K_S^0 K^\pm \pi^\mp$		$\eta_c \to K^+K^-\pi^0$	
Amplitude	Fraction (%)	Phase	Fraction (%)	Phase
($K\pi$ $\mathcal{S}$-wave) $\overline{K}$	$107.3 \pm 2.6 \pm 17.9$	0.	$125.5 \pm 2.4 \pm 4.2$	0.
$a_0(980)\pi$	$0.83 \pm 0.46 \pm 0.80$	$1.08 \pm 0.18 \pm 0.18$	$0.00 \pm 0.03 \pm 1.7$	
$a_0(1450)\pi$	$0.7 \pm 0.2 \pm 1.4$	$2.63 \pm 0.13 \pm 0.17$	$1.2 \pm 0.4 \pm 0.7$	$2.90 \pm 0.12 \pm 0.25$
$a_0(1950)\pi$	$3.1 \pm 0.4 \pm 1.2$	$-1.04 \pm 0.08 \pm 0.77$	$4.4 \pm 0.8 \pm 0.7$	$-1.45 \pm 0.08 \pm 0.27$
$a_2(1320)\pi$	$0.15 \pm 0.06 \pm 0.08$	$1.85 \pm 0.20 \pm 0.23$	$0.61 \pm 0.23 \pm 0.3$	$1.75 \pm 0.23 \pm 0.42$
$K_2^*(1430)^0\overline{K}$	$4.7 \pm 0.9 \pm 1.4$	$4.92 \pm 0.05 \pm 0.1$	$3.0 \pm 0.8 \pm 4.4$	$5.07 \pm 0.09 \pm 0.3$
Total	116.8 ± 2.8		134.8 ± 2.7	
$-2\log\mathcal{L}$	-4314.2		-2339	
χ_2/N_{cells}	301/254=1.17		283.2/233=1.22	

Fit fractions and amplitudes compatible between the two η_c decay modes

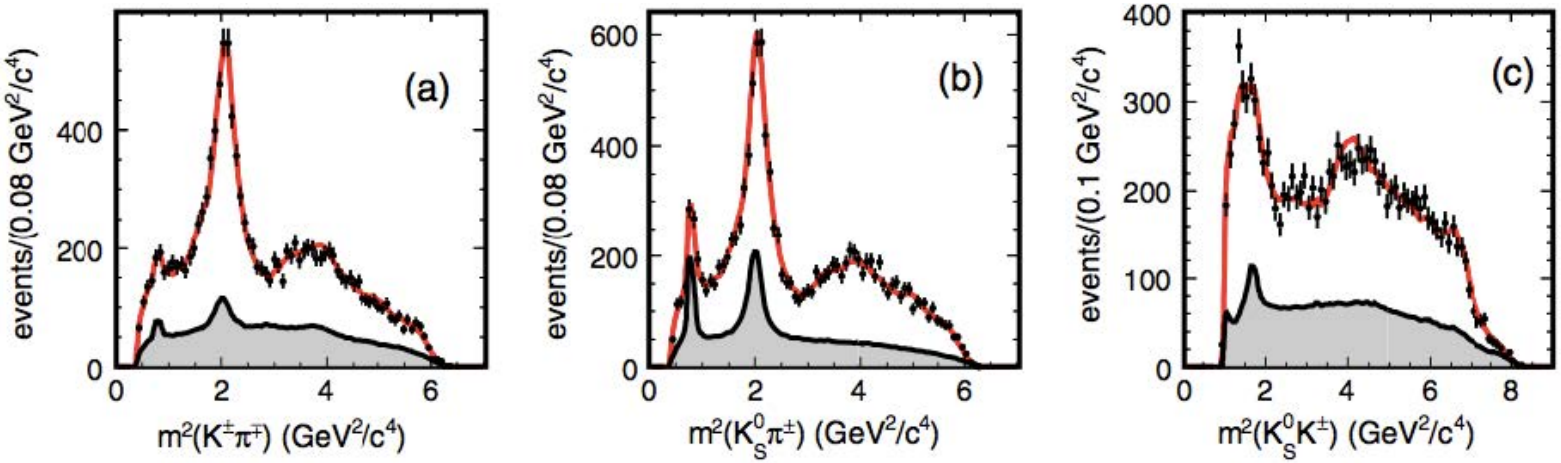
Total fit fraction well above 100% $\Longrightarrow$ significant interference effects

The fit has better χ^2 than the isobar model

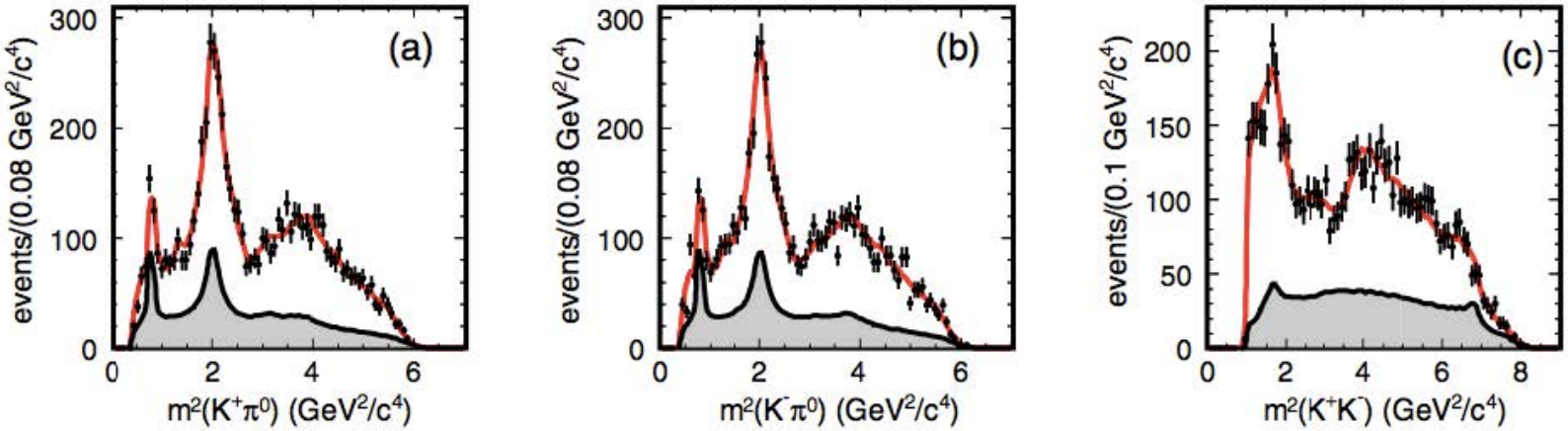
MIPWA fit projections $\eta_c \to K\bar{K}\pi$

Phys. Rev. D 93, 012005 (2016)

- $\eta_c(1S) \to K_s^0 K^+ \pi^-$



- $\eta_c(1S) \to K^- K^+ \pi^0$

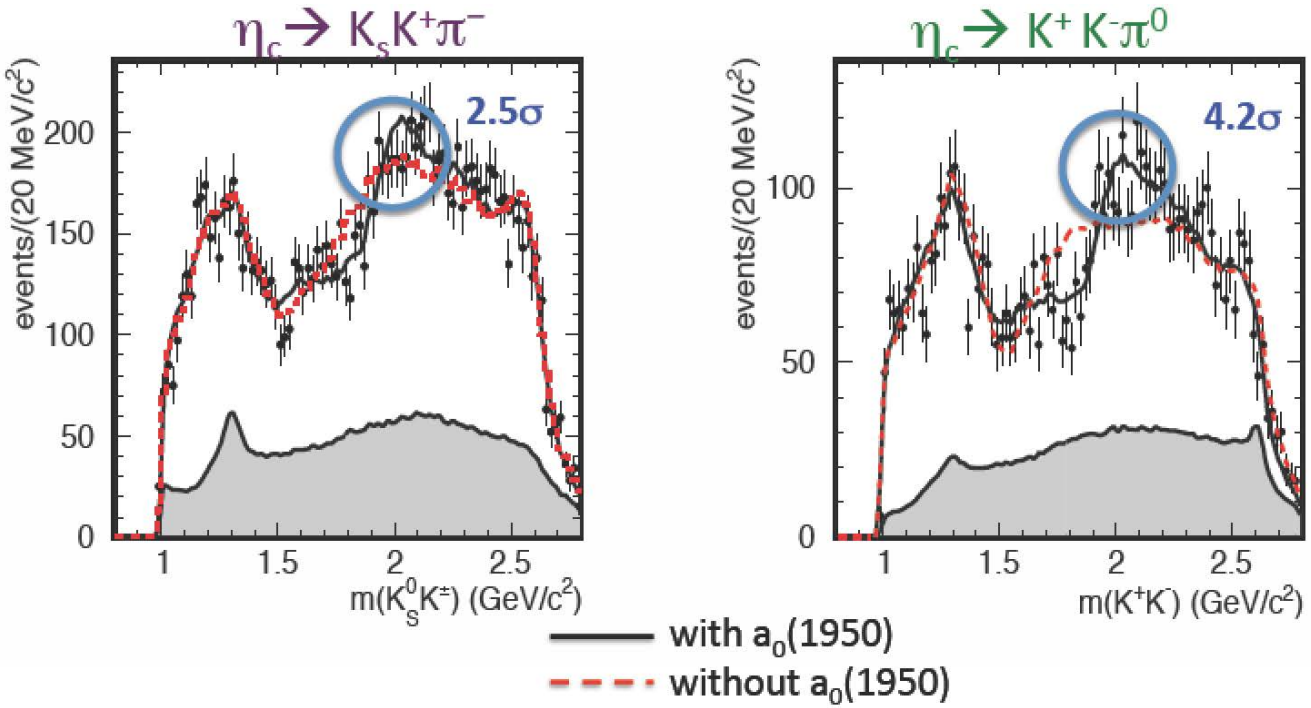


(gray shaded area: background from mass sidebands)

$a_0(1950)$

Phys. Rev. D 93, 012005 (2016)

MIPWA improves adding $a_0(1950)$ for both $K_s K^+\pi^-$ and $K^+K^-\pi^0$



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	$1931 \pm 14 \pm 22$	$271 \pm 22 \pm 29$

large systematics

I=1/2 $K\pi$ S-wave

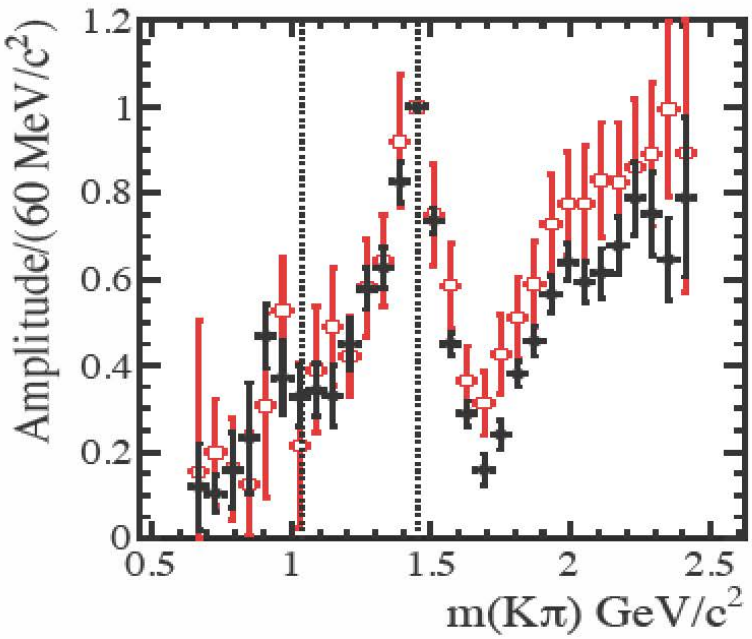
Phys. Rev. D 93, 012005 (2016)

Consistent amplitude and phase from the two modes

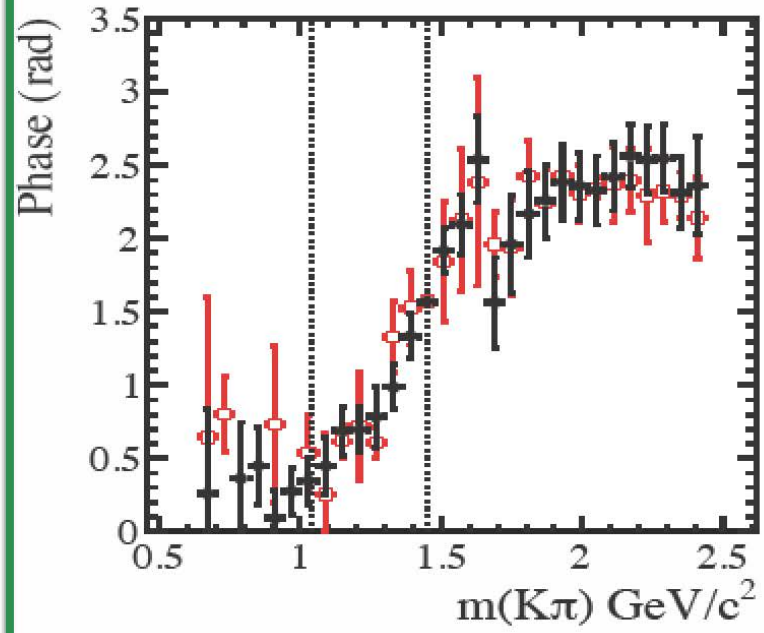
- Amplitude extending up to a mass of 2.5 GeV/c^2.
- Due to isospin conservation, no contribution from I=3/2.

$\eta_c \rightarrow K_s K^+ \pi^-$

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



- Clear peak about $K^*_0(1430)$ resonance
- Broad structure likely due to $K^*_0(1950.)$

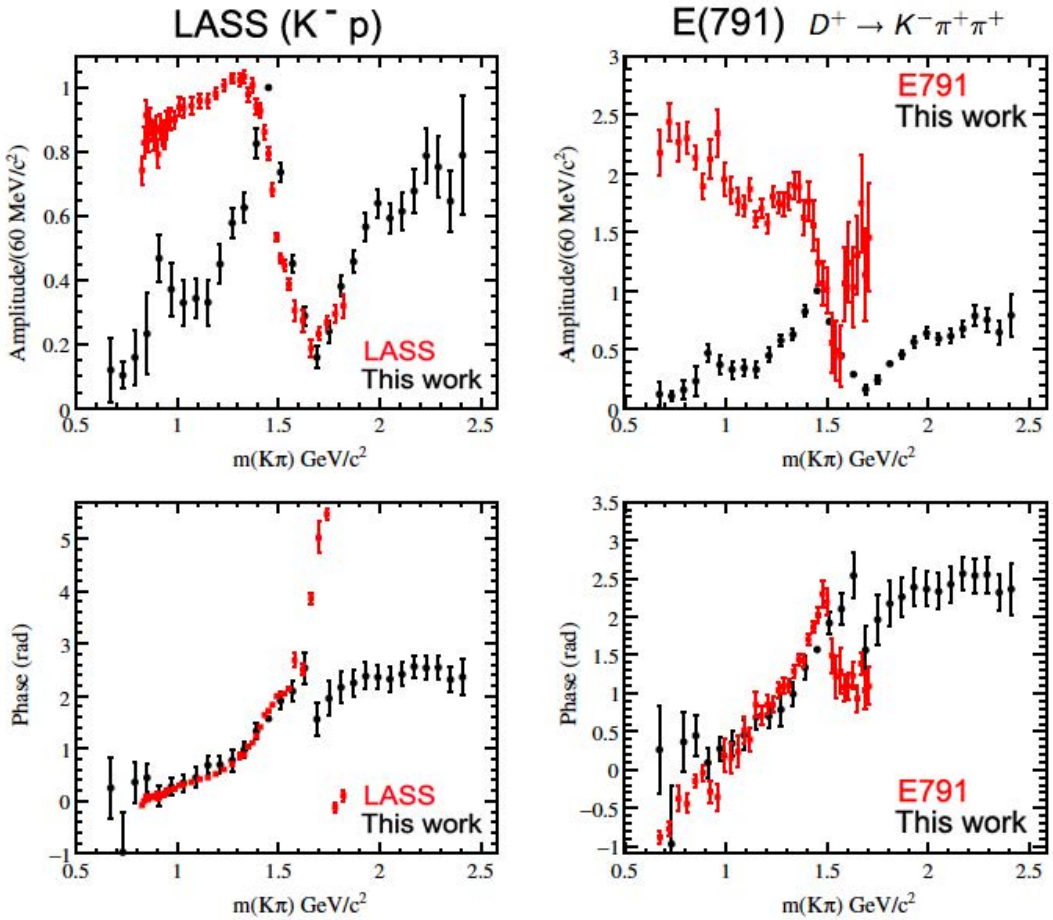


- Phase varies by about π about $K^*_0(1430)$ resonance.
- Drop at 1.7 GeV/c^2 due to interference with $K^*_0(1950)$

I=1/2 $K\pi$ S-wave comparisons

Phys. Rev. D 93, 012005 (2016)

Difficult to disentangle I=1/2 and I=3/2 in LASS and E791



striking difference in mass dependence of amplitudes

N.B. LASS has two-fold ambiguity for mass >1.82 GeV/c^2

$J/\psi \to \pi^+\pi^-\pi^0$ and $J/\psi \to K^+K^-\pi^0$

Preliminary

So far only one unpublished Dalitz-plot analysis of $J/\psi \to \pi^+\pi^-\pi^0$

MARK III; SLAC-PUB-5674, (1991)

Some of the J/ψ branching fractions have only been measured on earlier – much smaller – samples
Branching ratio of $J/\psi \to K^+K^-\pi^0$ based on just 25 events

MARK II; Phys. Rev. Lett. 51, 963 (1983)

The angular analysis of $J/\psi \to K^+K^-\pi^0$ by BES III introduces a broad 1^{--} state in the K^+K^- threshold region possibly interpreted as a tetraquark

BES III; Phys. Rev. Lett. 97, 142002 (2006)

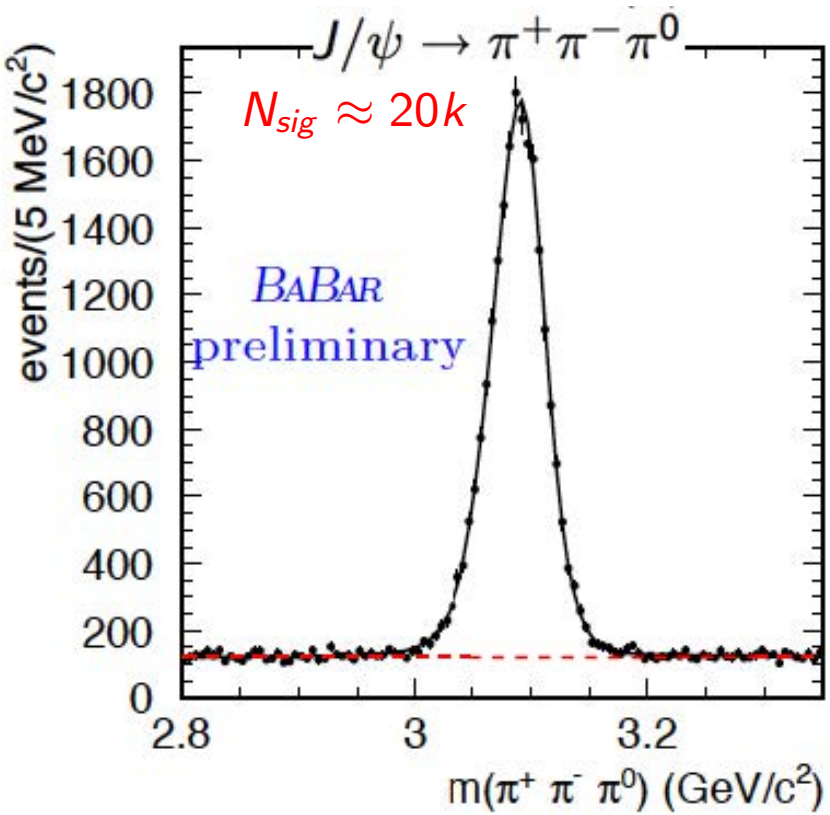
$e^+e^- \to \gamma_{ISR} J/\psi$ with $J/\psi \to \pi^+\pi^-\pi^0$ or $K^+K^-\pi^0$

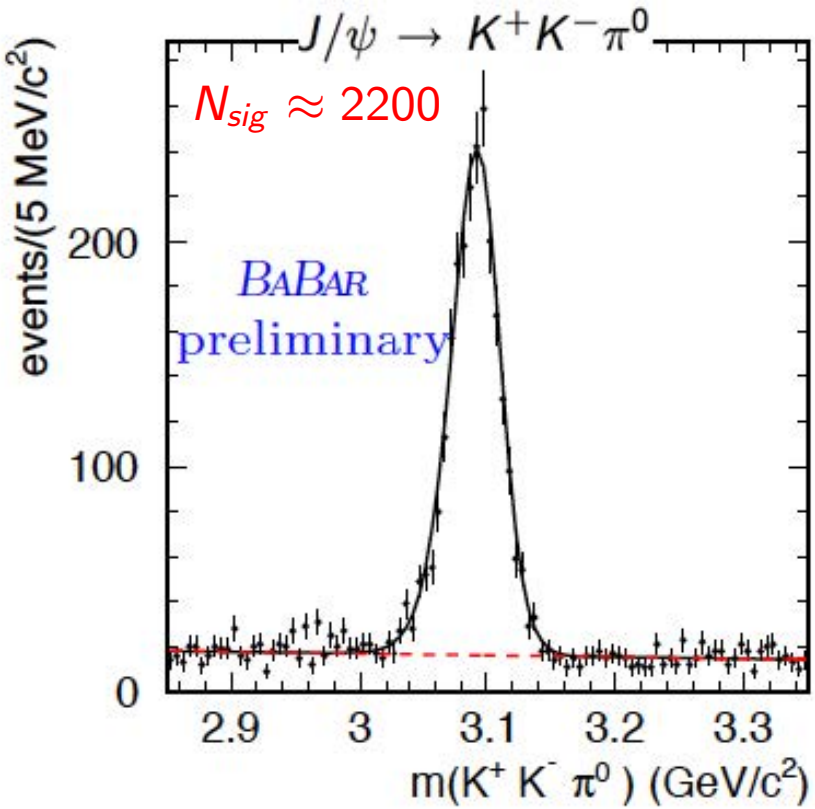
Preliminary

"Standard" selection:

exactly 2 charged tracks, PID, vertex quality, mass of π^0

γ_{ISR} undetected $\Longrightarrow$ missing mass compatible with 0

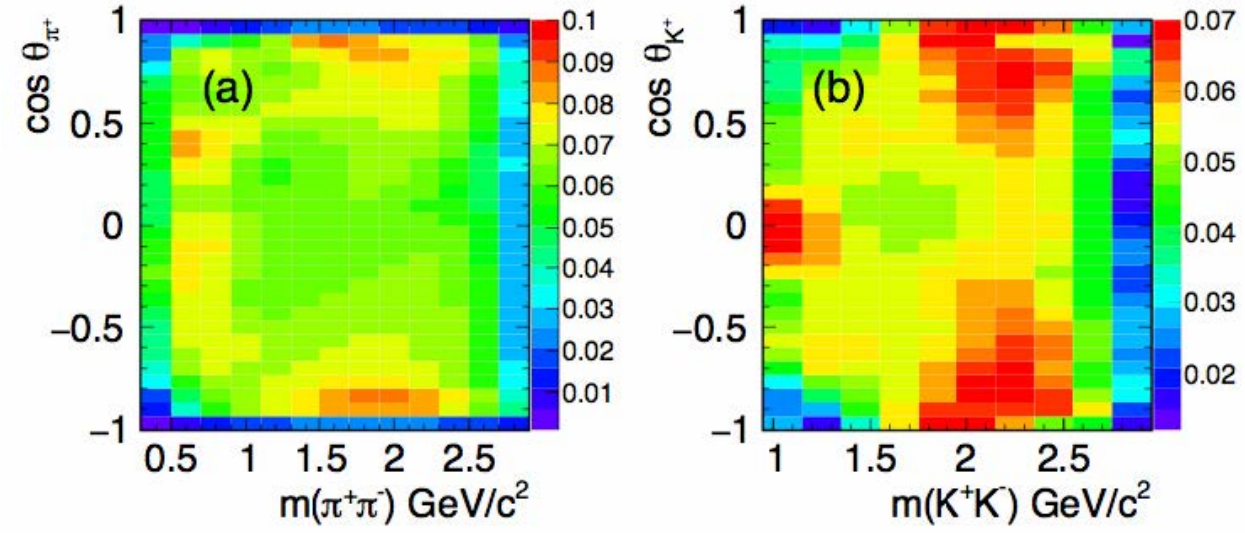




Branching fraction determination

Preliminary

Efficiency determined as a function of the h^+h^- invariant mass and the h^+ angle in the h^+h^- rest frame ("helicity angle")



The weighted efficiency is

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

$f_i = +1$ in signal window

$f_i = -1$ in mass sidebands

Based on the observed signal yields we determine

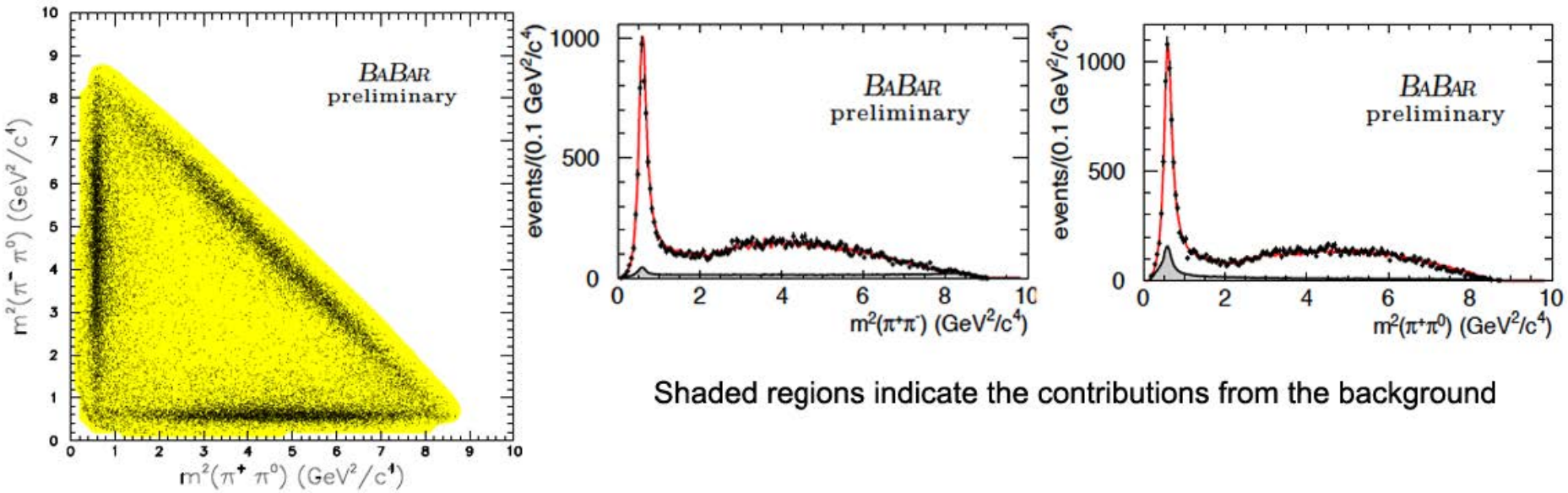
$$\mathcal{R} = \frac{\mathcal{B}(J/\psi \to K^+K^-\pi^0)}{\mathcal{B}(J/\psi \to \pi^+\pi^-\pi^0)} = 0.0929 \pm 0.002 \pm 0.002$$

somewhat different, but not incompatible, with the ratio in PDG (where the $K^+K^-\pi^0$ is based on just 25 events)

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

Preliminary

Decay dominated by $\rho\pi$



Shaded regions indicate the contributions from the background

The Dalitz plot is analysed using

- Isobar model using Zemach tensors

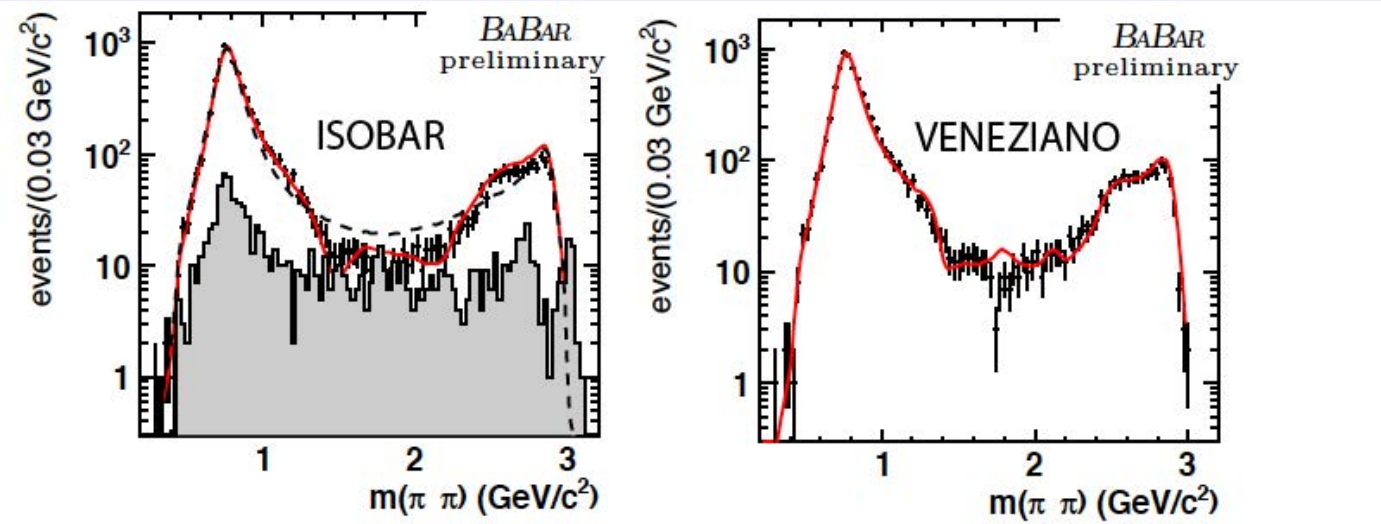
  C.Zemach, Phys. Rev. 133, B1201 (1964)

- Veneziano model (Regge trajectories rather than resonances) with 5 trajectories

  Szczepaniak, Pennington, Phys. Lett. B737, 283 (2014)

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

Preliminary

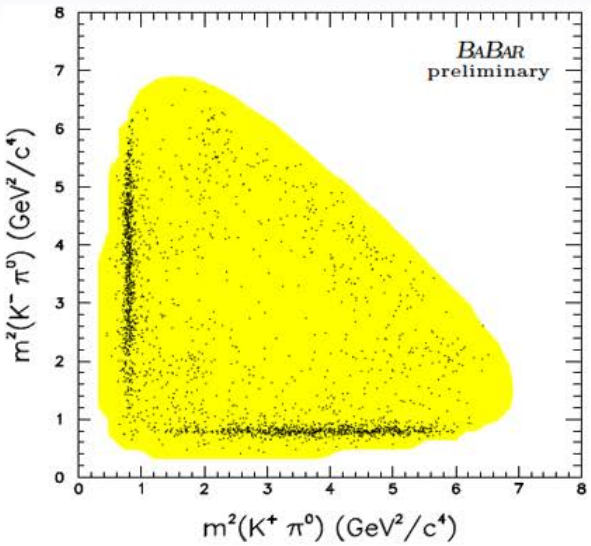


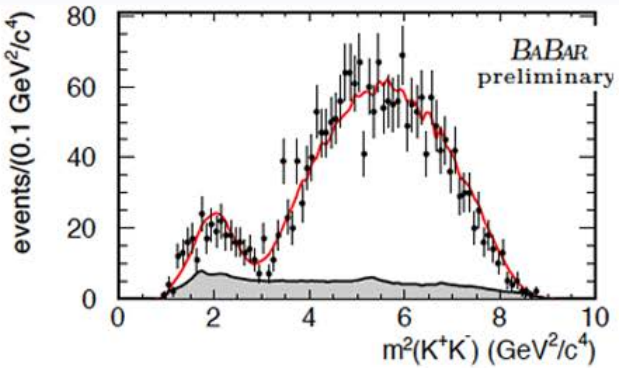
The two methods give similarly good description of data but different fit fractions

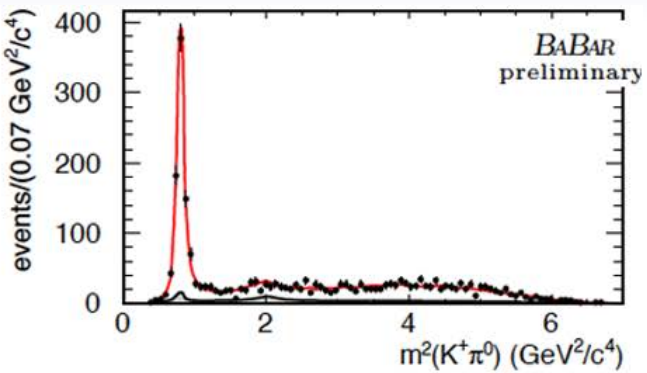
Final state	Isobar fraction %	Phase (radians)	Veneziano fraction %
$\rho(770)\pi$	$119.0 \pm 1.1 \pm 3.3$	0.	120.0 ± 1.9
$\rho(1450)\pi$	$16.9 \pm 2.0 \pm 3.1$	$3.92 \pm 0.05 \pm 0.11$	1.53 ± 0.13
$\rho(1700)\pi$	$0.1 \pm 0.1 \pm 0.2$	$1.01 \pm 0.35 \pm 0.79$	0.84 ± 0.08
$\rho(2150)\pi$	$0.04 \pm 0.05 \pm 0.02$	$1.89 \pm 0.30 \pm 0.48$	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

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

Preliminary







Shaded regions indicate the contribution from the background

Isobar model fit

- Decay dominated by K^*K
- The broad K^+K^- structure attributed to $\rho(1450)$

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	$105.6 \pm 3.4 \pm 3.0$	
$\chi^2/\nu = 94/92$		

$\rho(1450$

Preliminary

Resonance parameters from the isobar-model fit to $J/\psi \to K^+K^-\pi^0$:

$M(\rho(1450)) = 1361 \pm 43\,\mathrm{MeV}/c^2$ $\Gamma(\rho(1450)) = 479 \pm 63\,\mathrm{MeV}$

In $J/\psi \to \pi^+\pi^-\pi^0$ the fit fraction for $\rho(1450)^0\pi^0$ is

$$ff_{\pi^+\pi^-\pi^0}(J/\psi \to \rho(1450)^0\pi^0) = ([(16.9 \pm 2.0 \pm 3.1]/3)\%$$

In $J/\psi \to K^+K^-\pi^0$ the fit fraction for $\rho(1450)^0\pi^0$ is

$$ff_{K^+K^-\pi^0}(J/\psi \to \rho(1450)^0\pi^0) = ((11.5 \pm 2.1 \pm 2.1)\%$$

Taking into account the value of

$$\mathcal{R} = \frac{\mathcal{B}(J/\psi \to K^+K^-\pi^0)}{\mathcal{B}(J/\psi \to \pi^+\pi^-\pi^0)} = (9.29 \pm 0.02 \pm 0.02)\%$$

$$\frac{\mathcal{B}(\rho(1450)^0 \to K^+K^-)}{\mathcal{B}(\rho(1450) \to \pi^+\pi^-)} = \frac{ff_{K^+K^-\pi^0}(J/\psi \to \rho(1450)^0\pi^0)}{ff_{\pi^+\pi^-\pi^0}(J/\psi \to \rho(1450)^0\pi^0)}\mathcal{R} = (19.0 \pm 4.2 \pm 4.9)\%$$

Conclusions

- The Dalitz plot of $\eta_c \to K\bar{K}\pi$ produced in two photon interactions has been fitted both with an isobar model and a MIPWA
  - We have obtained a new determination of the I=1/2 Kπ S-wave amplitude which extends up to invariant masses of 2.5 GeV/c^2

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- A preliminary analisis of the Dalitz plot of $J/\psi \to \pi^+\pi^-\pi^0$ and $J/\psi \to K^+K^-\pi^0$ produced in e^+e^- has been presented.
  - We have obtained a new determination of the branching fractions nearly an order of magnitude more precise than previous measurements
  - We also have presented a new determination of the $\rho(1450)$ resonance parameters and its branching fractions

Preliminary

Backup slides

$\eta_c(1S) \to K\bar{K}\pi$ efficiency

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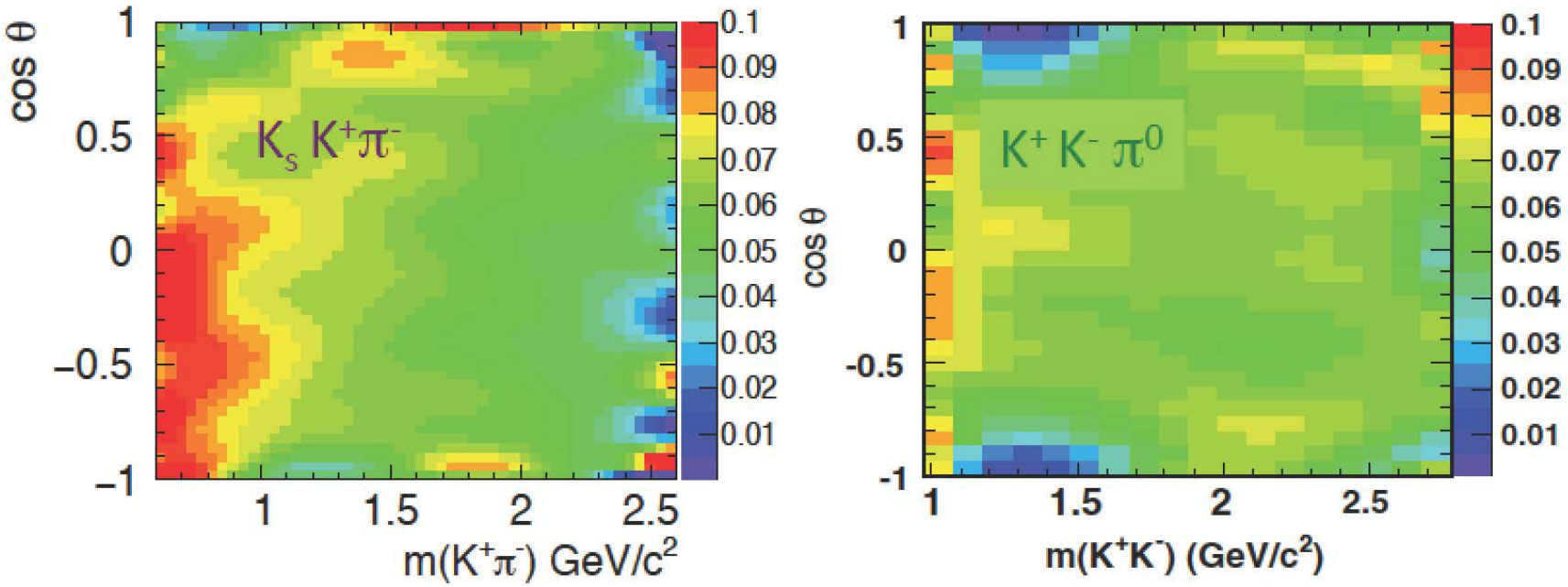
- MC signal events in which the η_c decays uniformly in phase space.
- Restrict mass regions to η_c signal region.
- Efficiency: $N_{reconstructed}/N_{generated}$
- Express as a function of $m(K^+K^-)$ and $\cos\theta_{K^+}$
- $\cos\theta_{K^+}$: angle, in K^+K^- rest frame, between the direction of the K^+ and the boost from $K_sK^-\eta$ or $K^+K^-\pi^0$ rest frame.

$$\epsilon(\cos\theta) = \sum_{L=0}^{12} a_L(m) Y_L^0(\cos\theta)$$



Efficiency loss due to low momentum kaons (<200 MeV/c)

K_s and $\pi^\pm$ (<100 MeV/c)

$K^{\pm}\pi^{\mp}$ Legendre moments

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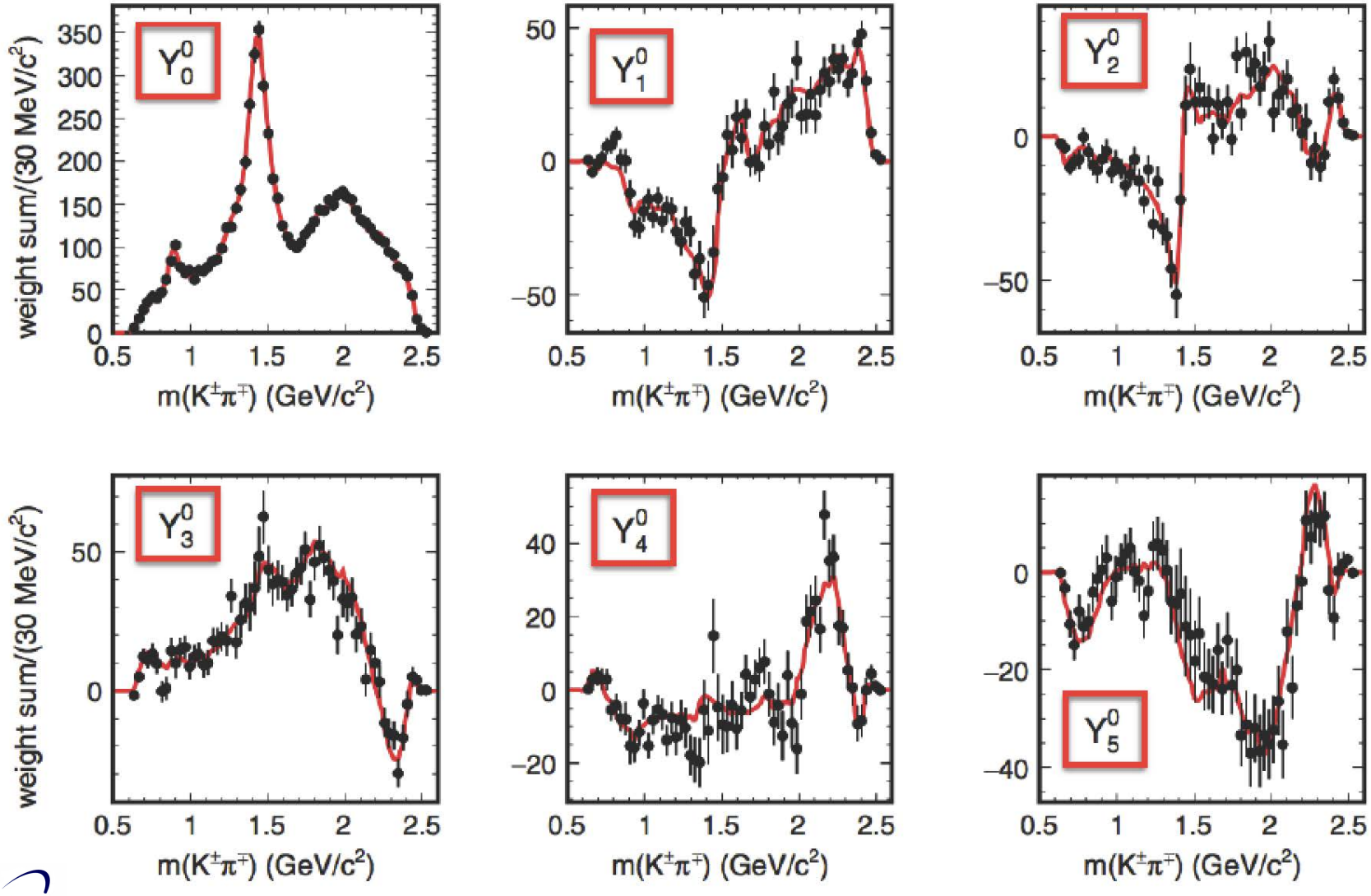
$\eta_c(1S) \to K_s^0 K^+ \pi^-$

data (dots) vs MIPWA fit (red line)



$K\pi$ Legendre moments

$\eta_c(1S) \to K^+K^-\pi^0$

data (dots) vs MIPWA fit (red line)

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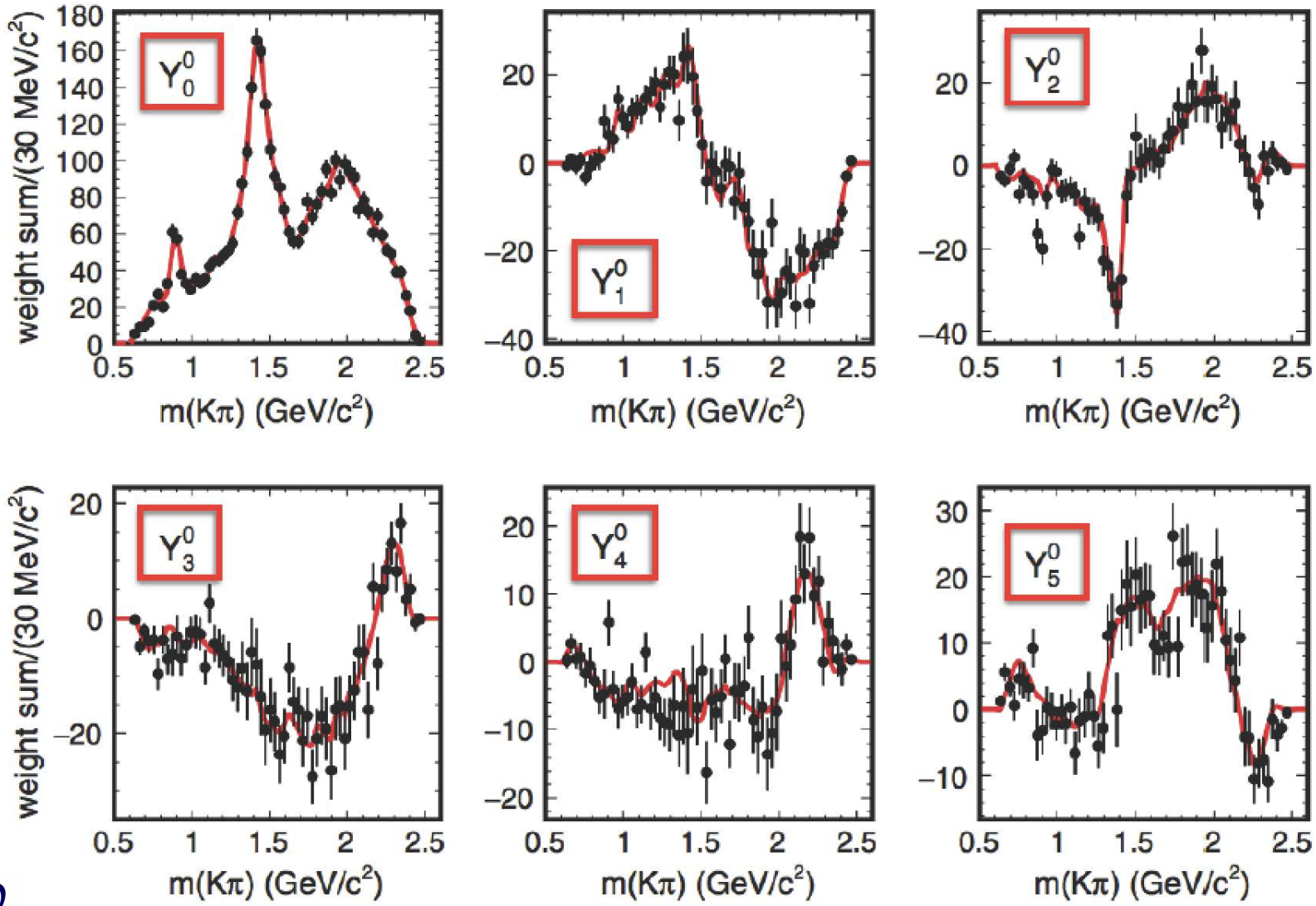

K_sK Legendre moments

$\eta_c(1S) \to K_s^0 K^+ \pi^-$

data (dots) vs MIPWA fit (red line)

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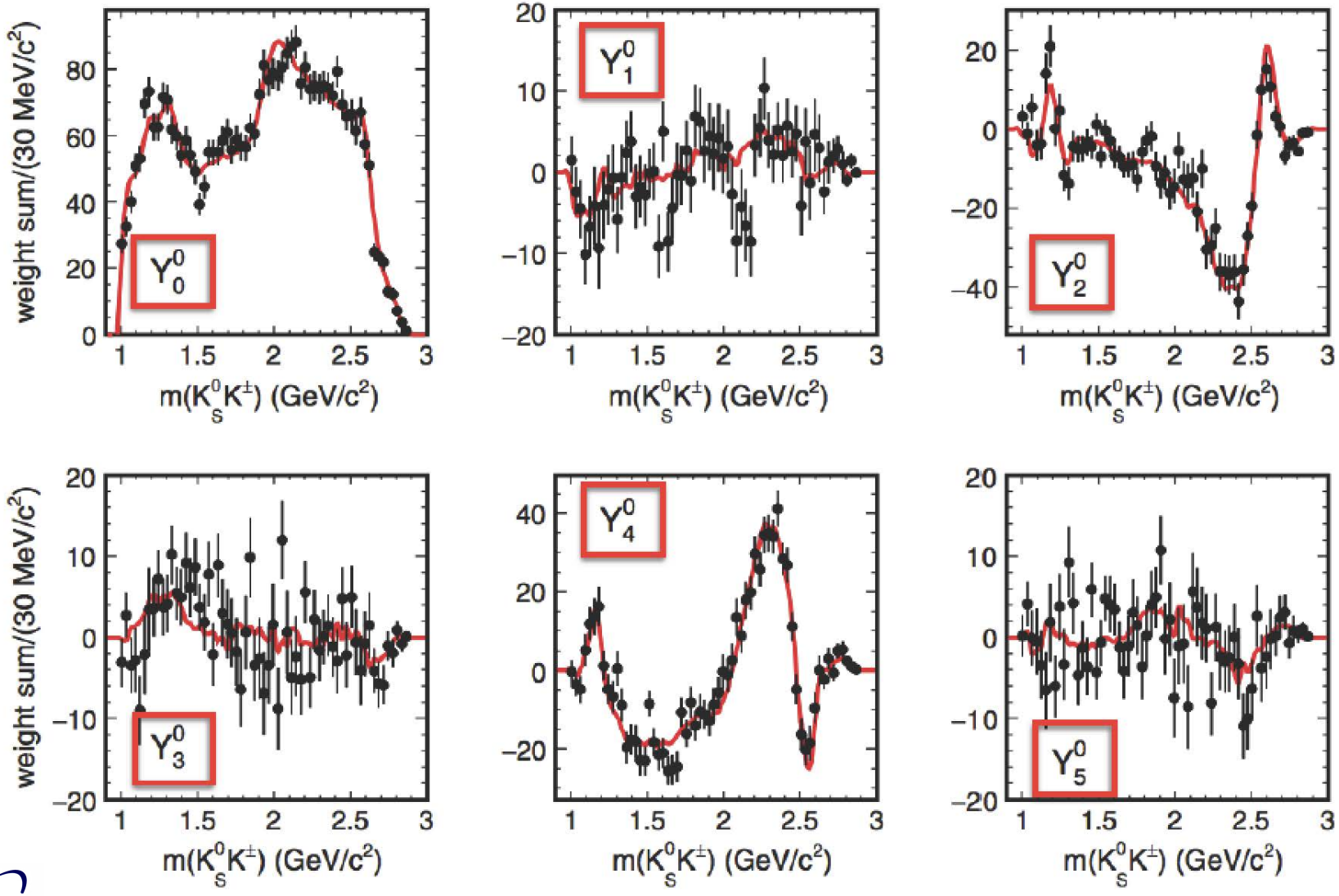

K^+K^- Legendre moments

$\eta_c(1S) \to K^+K^-\pi^0$

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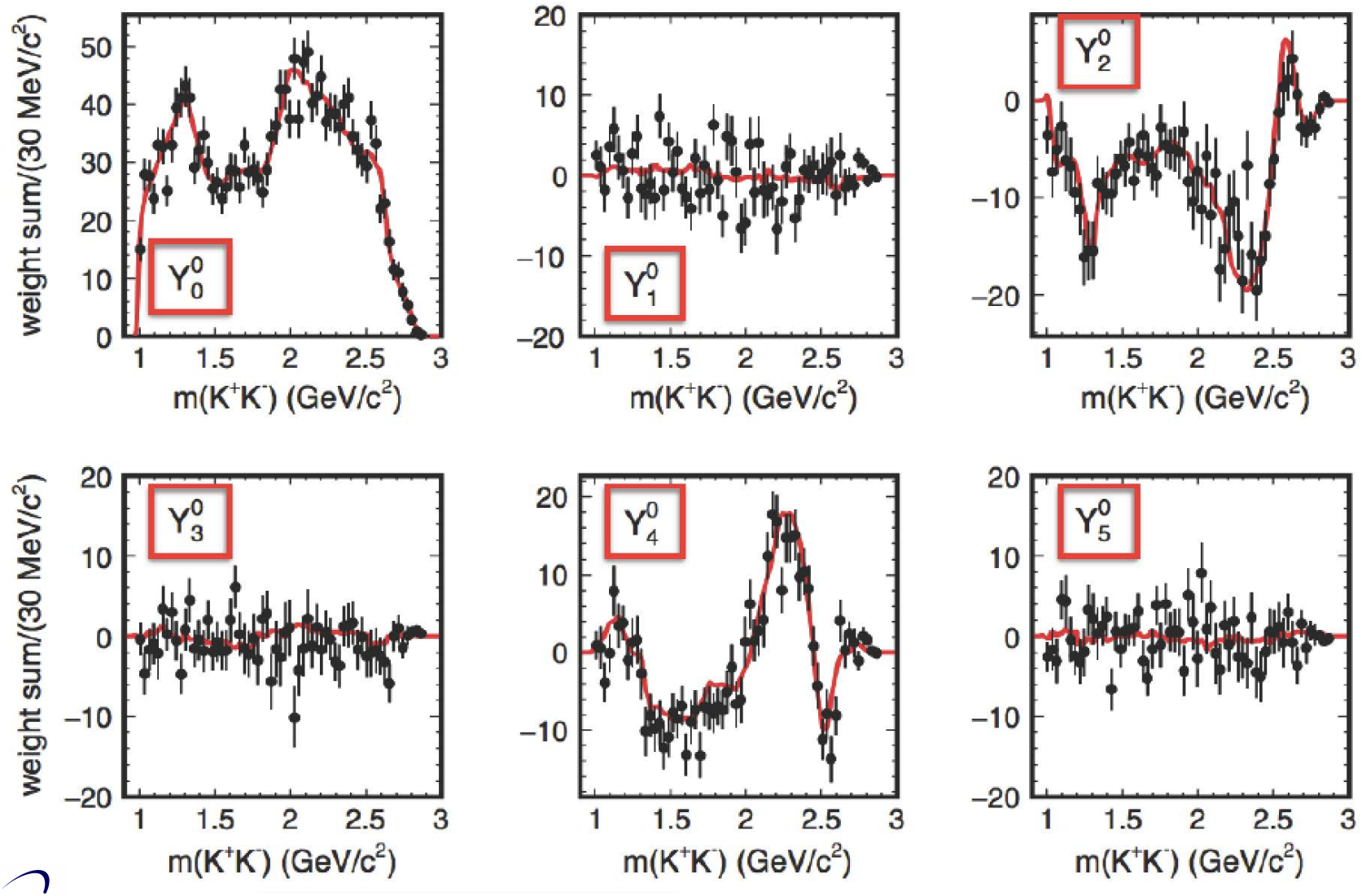
data (dots) vs MIPWA fit (red line)