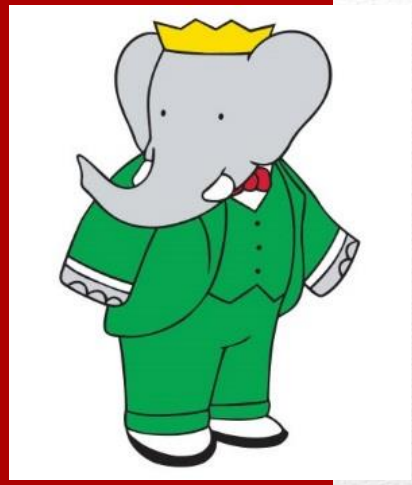
3-body decays of charmonium states at *BaBar*



Alessandro Pilloni

Thomas Jefferson National Accelerator Facility

on behalf of the BaBar Collaboration

Jefferson Lab

Salamanca
September 26th, 2017

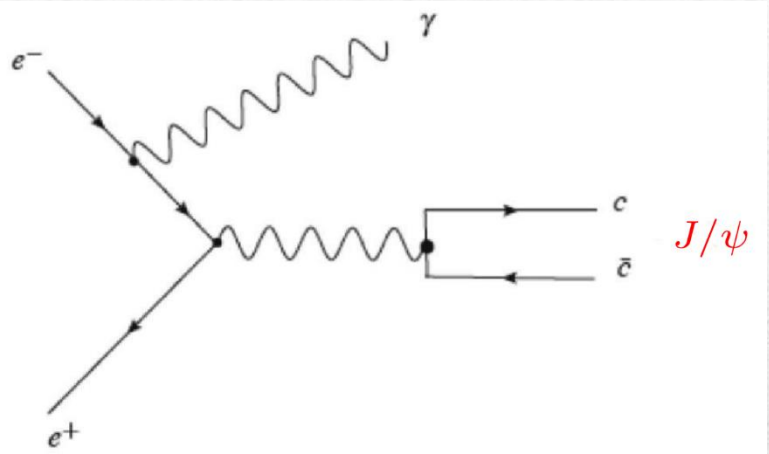
Salamanca HADRON 2017

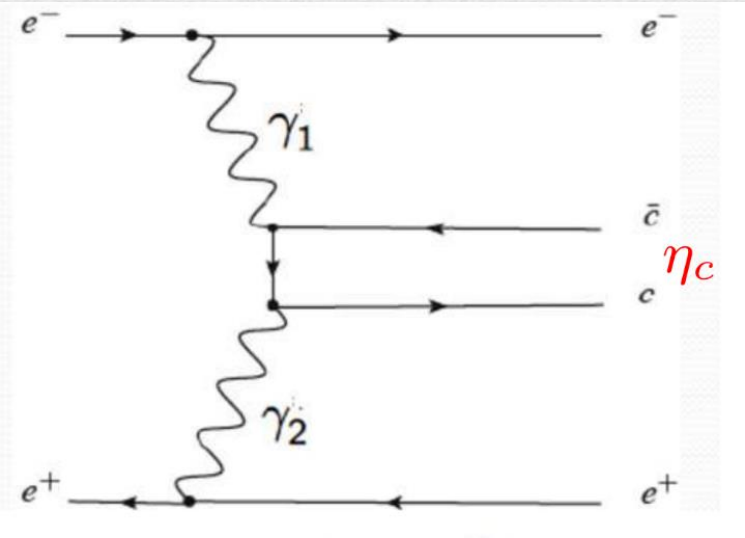
XVII International Conference on Hadron Spectroscopy and Structure

Charmonium decays

Charmonium decays can be used to obtain new information on light meson spectroscopy
At e^+e^- colliders, samples of charmonia can be obtained using different processes

In the Initial State Radiation (ISR) process, we reconstruct events with a (undetected) forward γ_{ISR}
Only $J^{PC} = 1^{--}$ states can be produced.





In two-photon interactions we select events where the e^+ and e^- are scattered at small angles and remain undetected

Only states with $J^{PC} = 0^{\pm+}, 2^{\pm+}, 3^{++}, 4^{\pm+}$ …

Charmonium decays

- 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

  BaBar coll., PRD93, 012005 (2016)
  BaBar coll., PRD89, 112004 (2014)

  - Isobar model
  - Model Independent Partial Wave Analysis (MIPWA)

- Dalitz plot analyses of $J/\psi \to \pi^+\pi^-\pi^0$, $J/\psi \to K^+K^-\pi^0$, and $J/\psi \to K_S^0 K^\pm \pi^\mp$, produced via e^+e^- annihilation with initial-state radiation

  BaBar coll., PRD95, 072007 (2017)

  - Isobar model
  - Veneziano model

Charge conjugated modes are understood

Motivations

- $\eta_c \to K\bar{K}\pi$
  - The existence of a broad κ, or $\mathrm{K}_0^*(800)$, is controversial
  - The major source for the $I = 1/2$ $K\pi$ S-wave is the LASS experiment, $K\ N \to K\pi\ N$. However, the extraction of the partial waves is affected by ambiguities, systematics for the extrapolation to the pion pole, and a contamination from $I = 3/2$ events.
  - The η_c decay is dominated by $\eta_c \to 0^+0^-$, and the $K\pi$ S-wave is purely $I = 1/2$

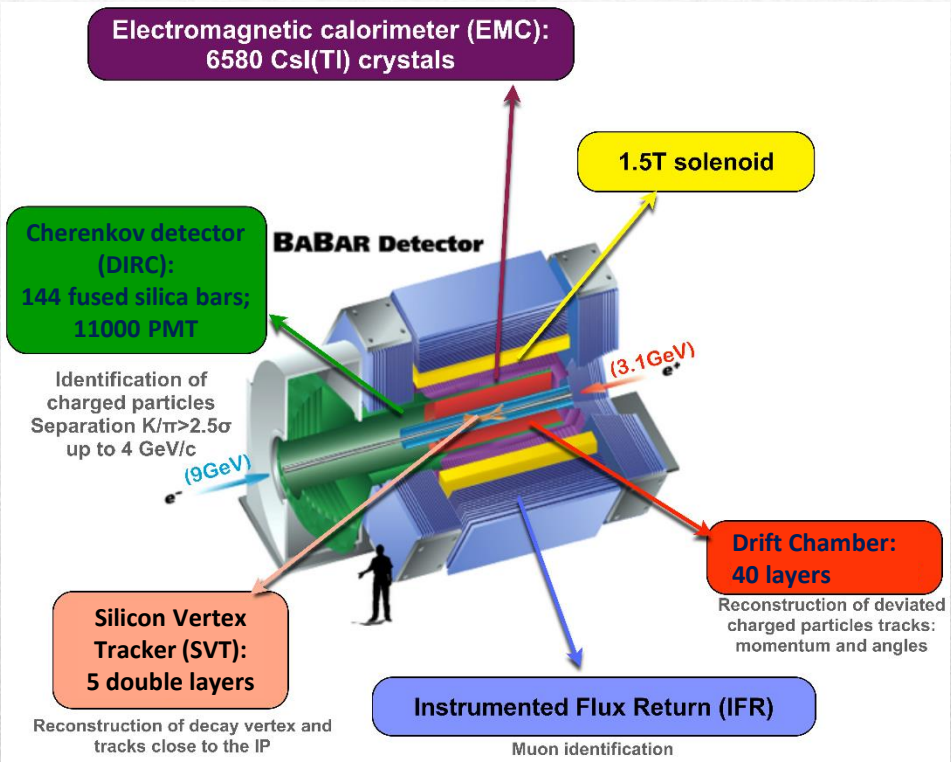
- $J/\psi \to \pi^+\pi^-\pi^0, J/\psi \to K\bar{K}\pi$
  - Source of the $\rho\pi$ puzzle, relevant for phenomenology
  - At high mass the Dalitz shows a broad structure, with a destructive interference of higher resonances
  - This is naturally realized by models implementing Regge asymptotics (Veneziano)

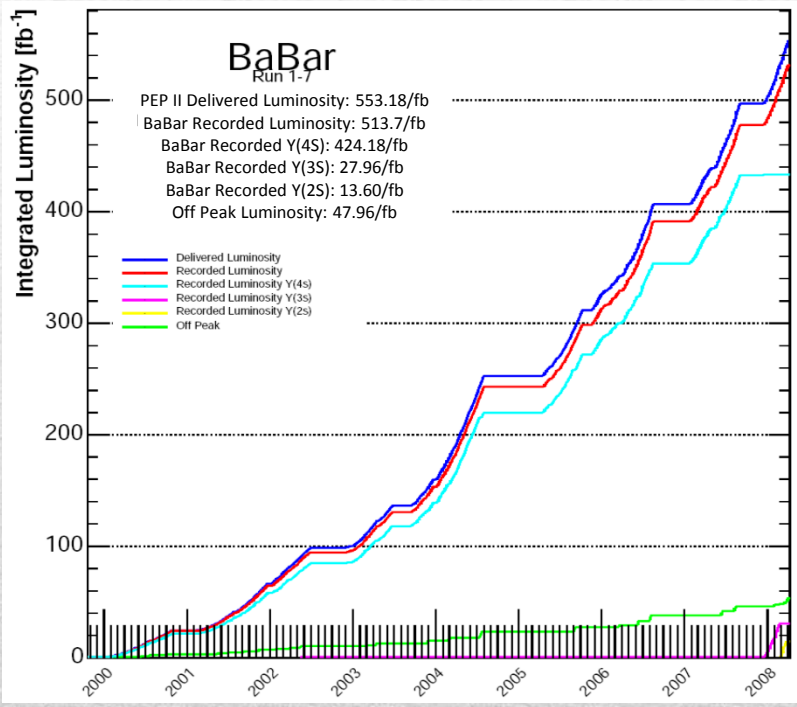
Charge conjugated modes are understood

The *BABAR* experiment

The *BABAR* detector was located at the interaction point of PEP II at SLAC

Asymmetric e^+e^- collider, mostly at $\sqrt{s} \sim 10.58$ GeV





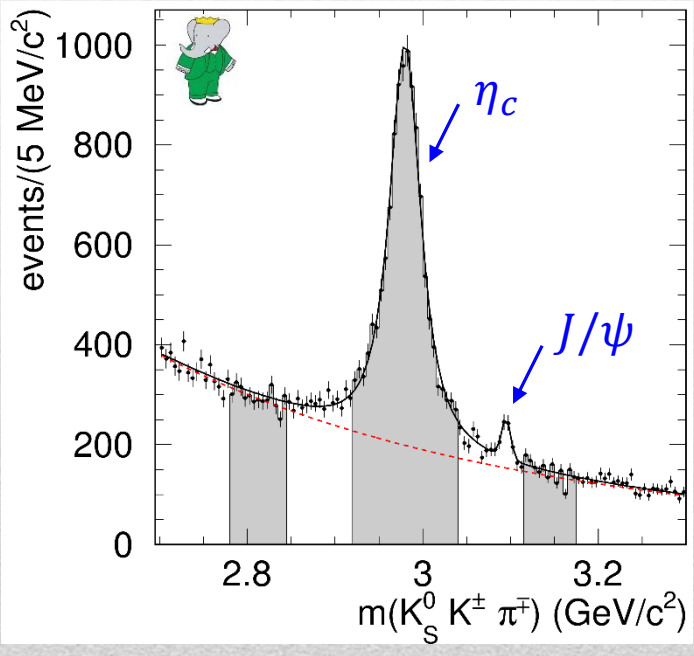
$\int L\,dt \sim 0.5\ \mathrm{ab}^{-1}$ close to the $\Upsilon(4S), \Upsilon(2S), \Upsilon(3S)$ peaks, $670 \times 10^6\ c\bar{c}$ pairs

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

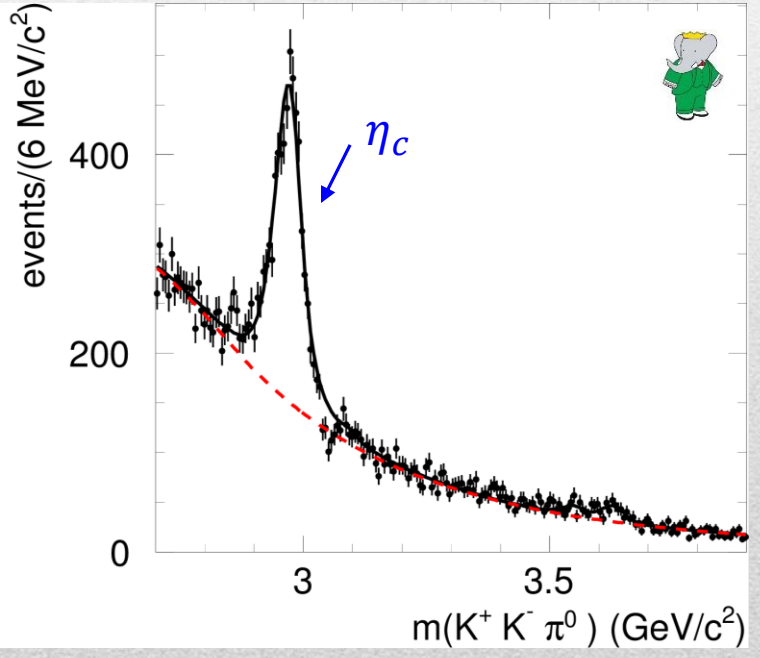
BaBar coll., PRD93, 012005 (2016)
BaBar coll., PRD89, 112004 (2014)

$\gamma\gamma \to \eta_c \to K\bar{K}\pi$: Event selection

- $\gamma\gamma \to \eta_c \to K_S^0(\to \pi^+\pi^-)K^-\pi^+$, 4 tracks, $d(K_S^0) > 0.2$ cm
- $\gamma\gamma \to \eta_c \to K^+K^-\pi^0$ and, 2 tracks, $E_\gamma > 50$ MeV
- PID applied for Kaons and pions
- To select $\gamma\gamma$ events $p_T(\eta_c) < 80$ MeV for $K_S^0K^-\pi^+$ and < 100 MeV for $K^+K^-\pi^0$
- To veto ISR events, $(p_{e^+e^-} - p_{K\bar{K}\pi})^2 > 10\ \mathrm{GeV}^2$



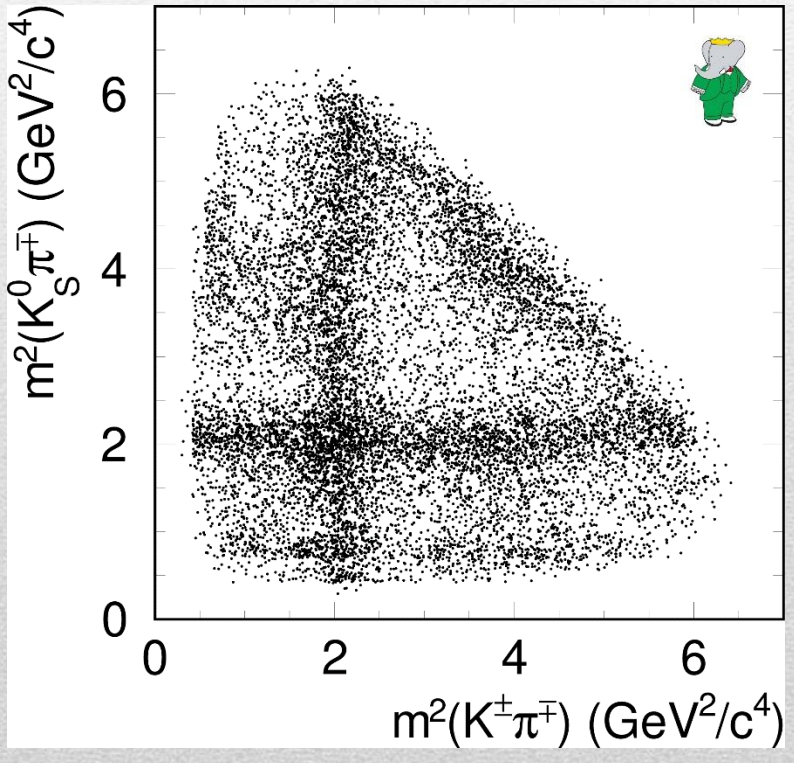
12.8k events, 64% purity

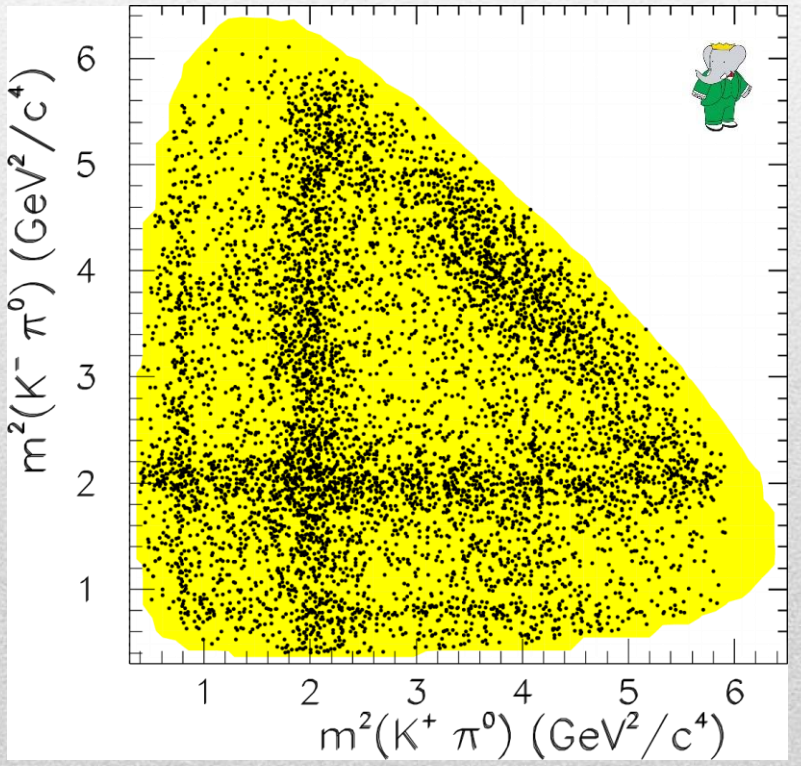


6.5k events, 55% purity

$\gamma\gamma \to \eta_c \to K\bar{K}\pi$: Dalitz plot

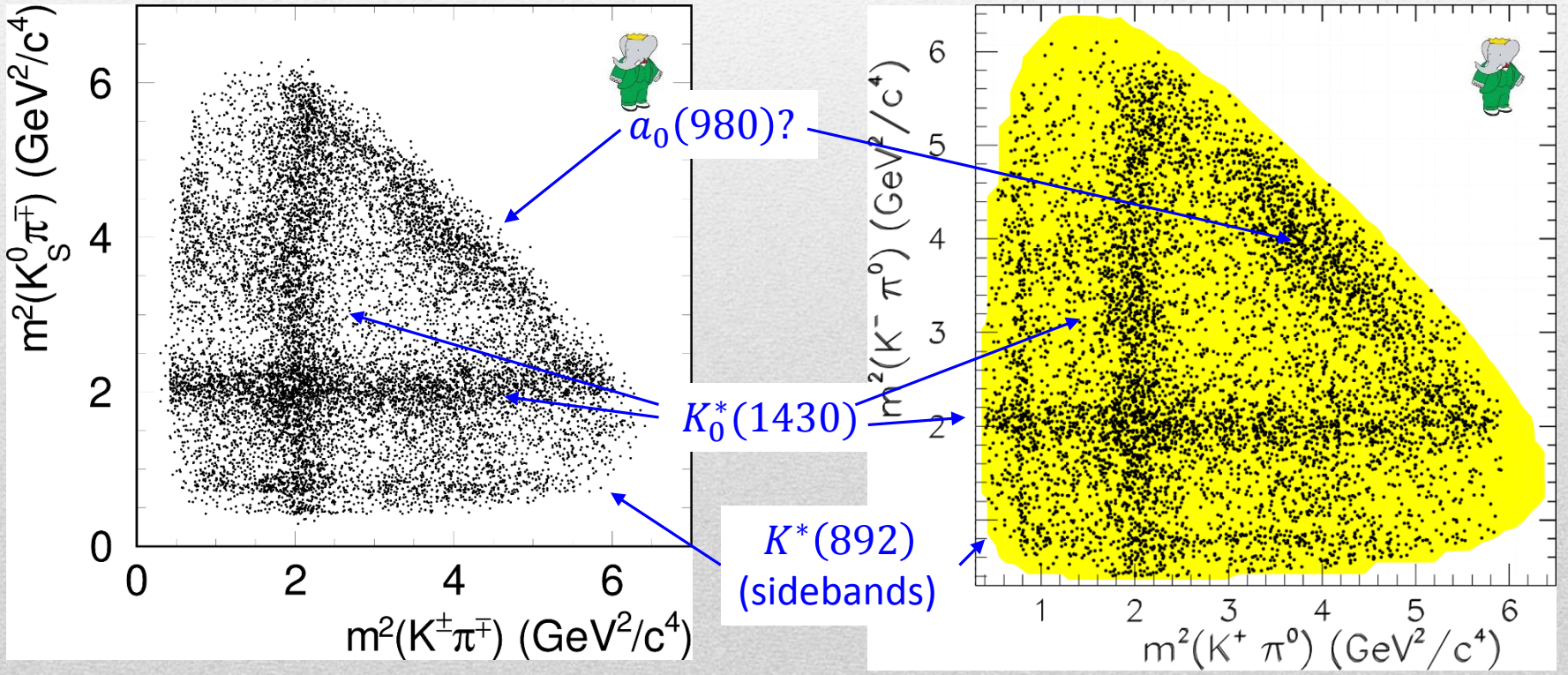
We show the Dalitz plots in the signal region. The two channels look compatible. The sidebands also show resonant content





$\gamma\gamma \to \eta_c \to K\bar{K}\pi$: Dalitz plot

We show the Dalitz plots in the signal region. The two channels look compatible.
The sidebands also show resonant content



$\gamma\gamma \to \eta_c \to K\bar{K}\pi$: DP analysis

Amplitudes

Background (from sidebands)

$$\mathcal{L} = \prod_{n=1}^{N} \left[f_{\rm sig}(m_n)\epsilon(x'_n, y'_n) \frac{\sum_{i,j} c_i c_j^* A_i(x_n, y_n) A_j^*(x_n, y_n)}{\sum_{i,j} c_i c_j^* I_{A_i A_j^*}} + (1 - f_{\rm sig}(m_n)) \frac{\sum_i k_i B_i(x_n, y_n, m_n)}{\sum_i k_i I_{B_i}} \right]$$

Signal fraction

Efficiency

$$A_i(x, y) = \sqrt{2\pi} Y_J^0(\cos\theta) \frac{F_{\eta_c} F}{M_r^2 - M_{AB}^2 - i M_r \Gamma_{\rm tot}(M_{AB})}$$

Resonances are parametrized with relativistic Breit-Wigners

F = Blatt-Weisskopf barrier factor

$\Gamma(m_{K\pi}) \propto p/m_{K\pi} F^2$ for $K_0^*(1430)$,

Γ = constant for the other ones

Alternatively, one can extract the $K\pi$ S-wave without any model assumptions (MIPWA)

E791, PRD73 032004 (2006)

$$A(m_{K\pi}, m_{\bar{K}\pi}) = \frac{1}{\sqrt{2}} \left(a(m_{K\pi}) e^{i\phi_{K\pi}} + a(m_{\bar{K}\pi}) e^{i\phi_{\bar{K}\pi}} \right)$$

- Positive G-parity sets the relative sign of the two terms
- We divide the $K\pi$ mass range in 30 bins, and fit for any bin a complex number
- Still an isobar model, but the lineshape is not predetermined

$\gamma\gamma \to \eta_c \to K\bar{K}\pi$: Results

Isobar

	$\eta_c \to K^0_S K^\pm \pi^\mp$		$\eta_c \to K^+ K^- \pi^0$	
Amplitude	Fraction %	Phase (rad)	Fraction %	Phase (rad)
$K_0^*(1430)\bar{K}$	40.8 ± 2.2	0.	33.8 ± 1.9	0.
$K_0^*(1950)\bar{K}$	14.8 ± 1.7	-1.00 ± 0.07	6.7 ± 1.0	-0.67 ± 0.07
NR	18.0 ± 2.5	1.94 ± 0.09	24.4 ± 2.5	1.49 ± 0.07
$a_0(980)\pi$	10.5 ± 1.2	0.94 ± 0.12	1.9 ± 0.1	0.38 ± 0.24
$a_0(1450)\pi$	1.7 ± 0.5	2.94 ± 0.13	10.0 ± 2.4	-2.4 ± 0.05
$a_0(1950)\pi$	0.7 ± 0.2	-1.76 ± 0.24	—	—
$a_2(1320)\pi$	0.2 ± 0.2	-0.53 ± 0.42	2.1 ± 0.1	0.77 ± 0.20
$K_2^*(1430)\bar{K}$	2.3 ± 0.7	-1.55 ± 0.11	6.8 ± 1.4	-1.67 ± 0.07
Total	88.8 ± 4.3		85.8 ± 3.6	
$\chi^2/N_{\rm cells}$	467/256=1.82		212/130=1.63	

Large nonresonant component

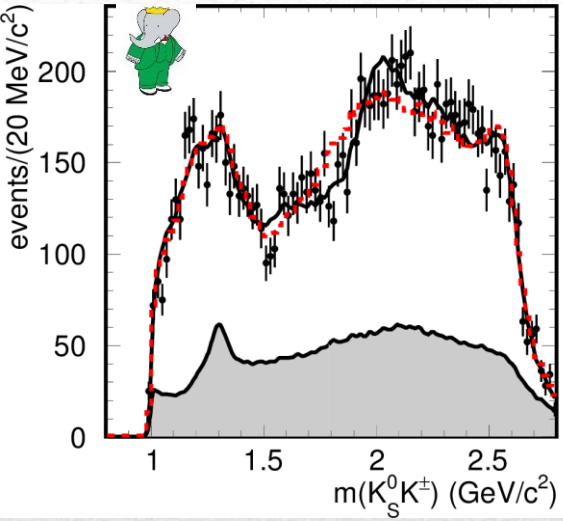
MIPWA

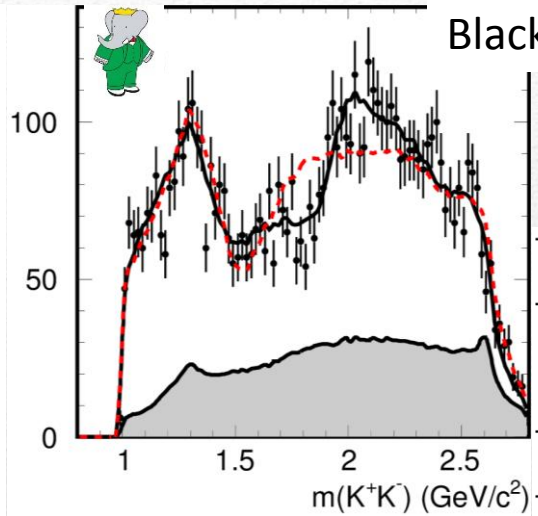
	$\eta_c \to K^0_S K^\pm \pi^\mp$		$\eta_c \to K^+ K^- \pi^0$	
Amplitude	Fraction (%)	Phase (rad)	Fraction (%)	Phase (rad)
($K\pi$ $\mathcal{S}$-wave) $\bar{K}$	$107.3 \pm 2.6 \pm 17.9$	fixed	$125.5 \pm 2.4 \pm 4.2$	fixed
$a_0(980)\pi$	$0.8 \pm 0.5 \pm 0.8$	$1.08 \pm 0.18 \pm 0.18$	$0.0 \pm 0.1 \pm 1.7$	-
$a_0(1450)\pi$	$0.7 \pm 0.2 \pm 1.4$	$2.63 \pm 0.13 \pm 0.17$	$1.2 \pm 0.4 \pm 0.7$	$2.90 \pm 0.12 \pm 0.25$
$a_0(1950)\pi$	$3.1 \pm 0.4 \pm 1.2$	$-1.04 \pm 0.08 \pm 0.77$	$4.4 \pm 0.8 \pm 0.8$	$-1.45 \pm 0.08 \pm 0.27$
$a_2(1320)\pi$	$0.2 \pm 0.1 \pm 0.1$	$1.85 \pm 0.20 \pm 0.20$	$0.6 \pm 0.2 \pm 0.3$	$1.75 \pm 0.23 \pm 0.42$
$K_2^*(1430)\bar{K}$	$4.7 \pm 0.9 \pm 1.4$	$4.92 \pm 0.05 \pm 0.10$	$3.0 \pm 0.8 \pm 4.4$	$5.07 \pm 0.09 \pm 0.30$
Total	$116.8 \pm 2.8 \pm 18.1$		$134.8 \pm 2.7 \pm 6.4$	
$-2\log\mathcal{L}$	-4314.2		-2339	
$\chi^2/N_{\rm cells}$	301/254=1.17		283.2/233=1.22	

χ^2 improved

$\gamma\gamma \to \eta_c \to K\bar{K}\pi$: a new $a_0(1950)$

Red: w/o $a_0(1950)$
Black: w/ $a_0(1950)$





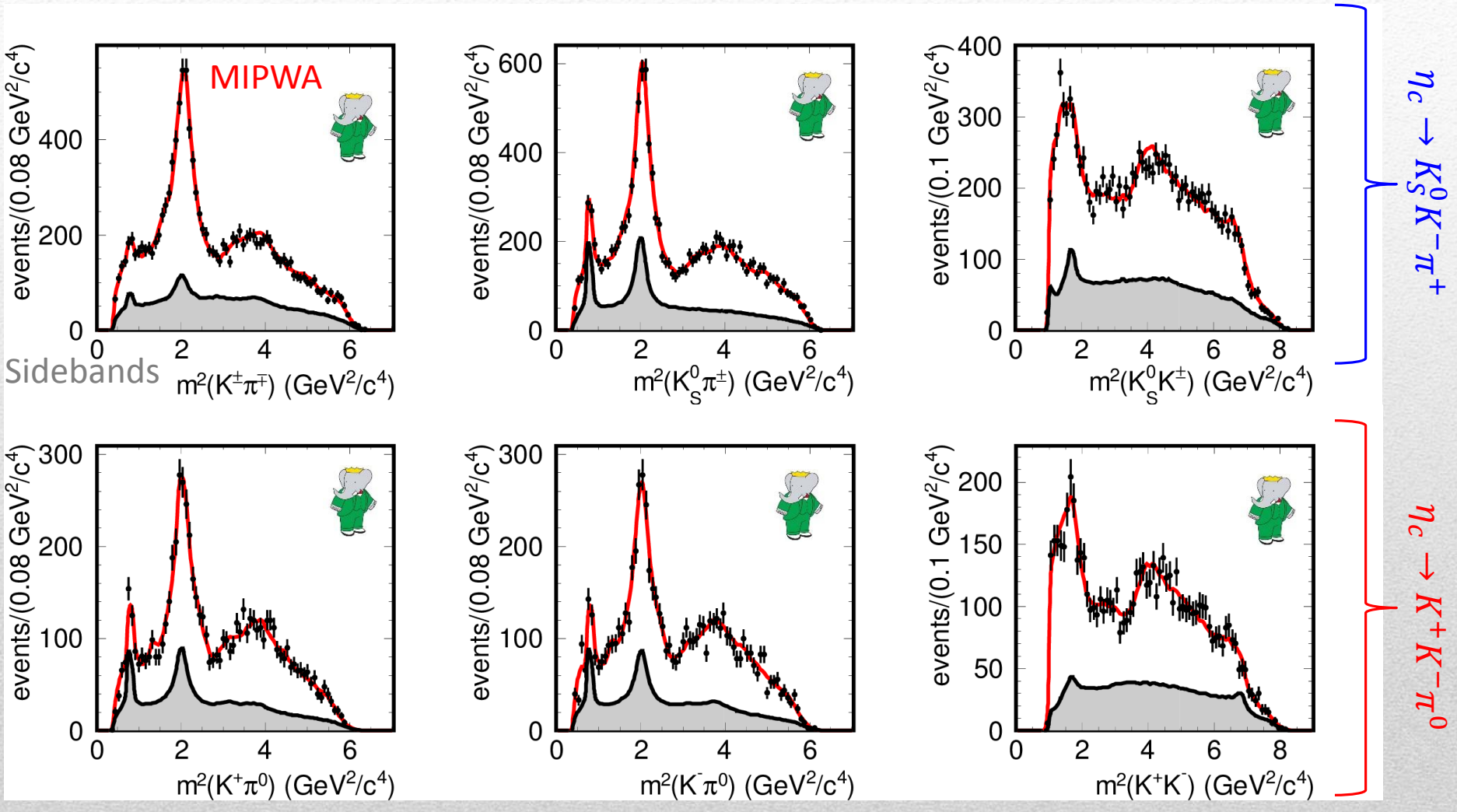
A $a_0(1950)$ improves the description of data

Final state	Mass (MeV/c^2)	Width (MeV)
$\eta_c \to K_S^0 K^+ \pi^-$	$1949 \pm 32 \pm 75$	$265 \pm 36 \pm 110$
$\eta_c \to K^+ K^- \pi^0$	$1927 \pm 15 \pm 23$	$274 \pm 28 \pm 30$
Mean	$1931 \pm 14 \pm 22$	$271 \pm 22 \pm 29$

The significance is
2.5σ for $K_S^0 K^- \pi^+$
4.0σ for $K^+ K^- \pi^0$

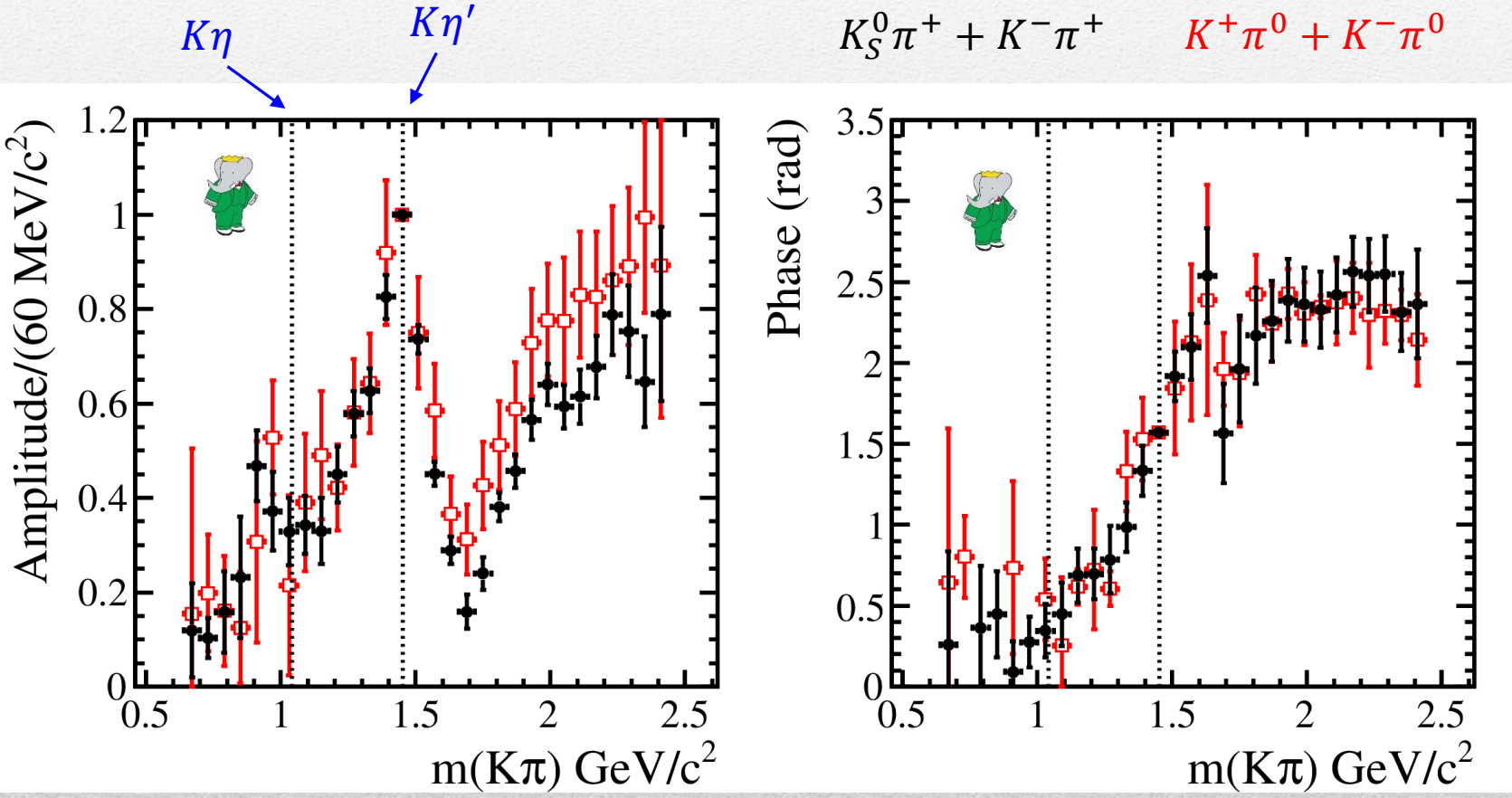
Systematics	$\eta_c \to K_S^0 K^\pm \pi^\mp$			$\eta_c \to K^+ K^- \pi^0$		
	Mass (MeV/c^2)	Width (MeV)	Fraction (%)	Mass (MeV/c^2)	Width (MeV)	Fraction (%)
Fit bias	11	22	0.5	1	10	0.5
Cubic spline	24	79	0.6	14	9	0.2
Marginal components	70	72	0.0	2	8	0.3
η_c purity	3	16	1.0	18	26	0.4
Efficiency	11	8	0.2	1	15	0.2
Total	76	110	1.3	23	30	0.8

$\gamma\gamma \to \eta_c \to K\bar{K}\pi$: results MIPWA



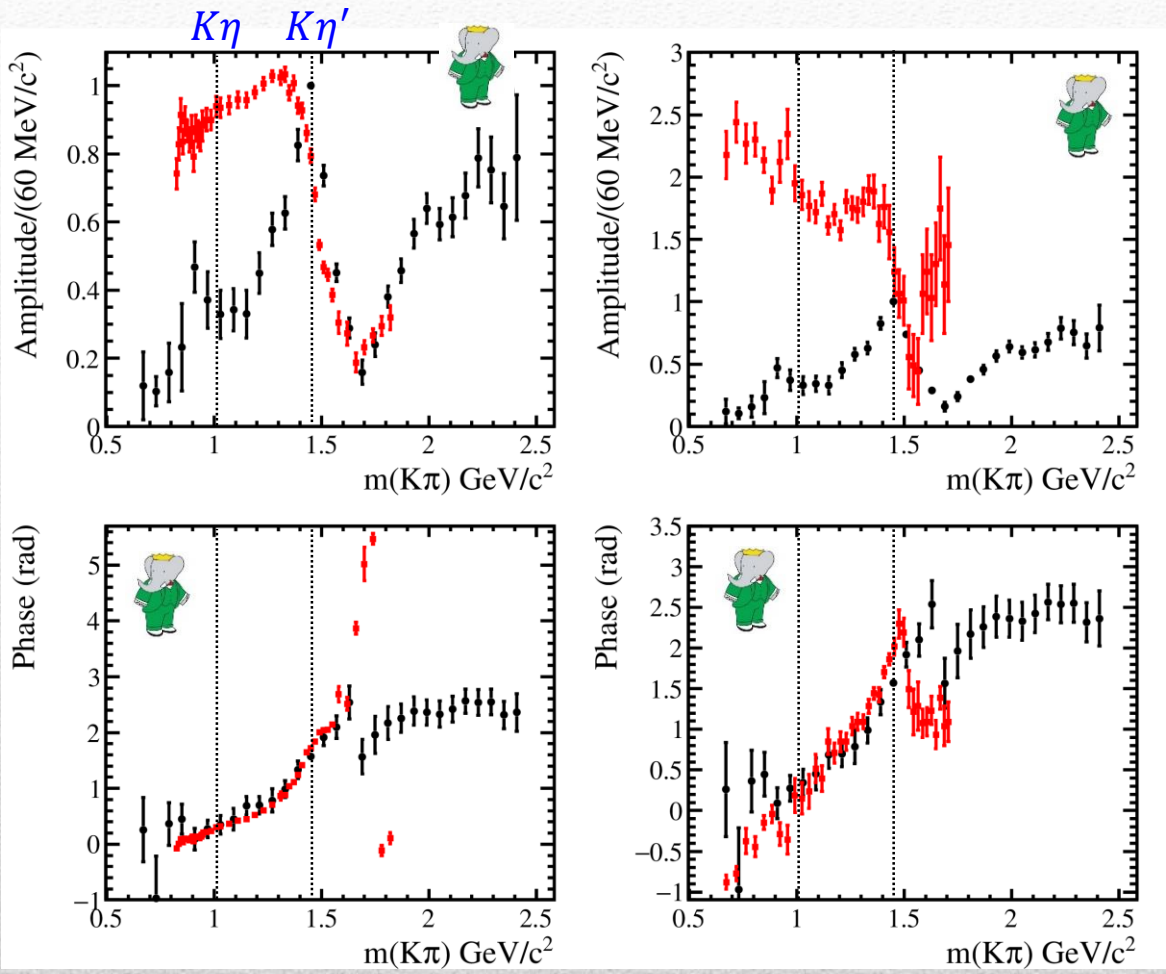
S-wave $K\pi$ from MIPWA

Clear $K_0^*(1430)$ in amplitude and phase, compatible with a Breit-Wigner expectation
Some evidence for a broad $K_0^*(1950)$ contribution



S-wave $K\pi$ from other experiments

LASS $K^-p \to K^-\pi^+p$



E791 $D^+ \to K^-\pi^+\pi^+$

This extraction does not agree with the previous ones,

LASS NPB296, 493 (1988)

E791, PRD73, 032004 (2006)

(arbitrarily rescaled)

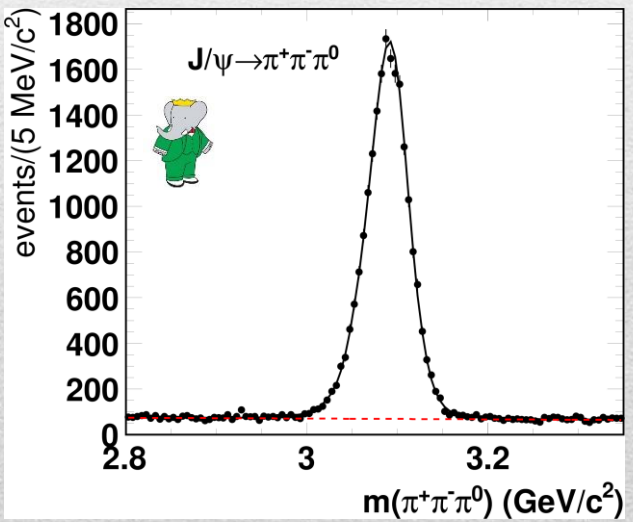
The phase agrees until the $K\eta'$ threshold, as expected by Watson theorem

Dalitz plot analyses of $J/\psi \to \pi^+\pi^-\pi^0$, $J/\psi \to K^+K^-\pi^0$, and $J/\psi \to K_S^0 K^\pm \pi^\mp$, produced via e^+e^- annihilation with initial-state radiation

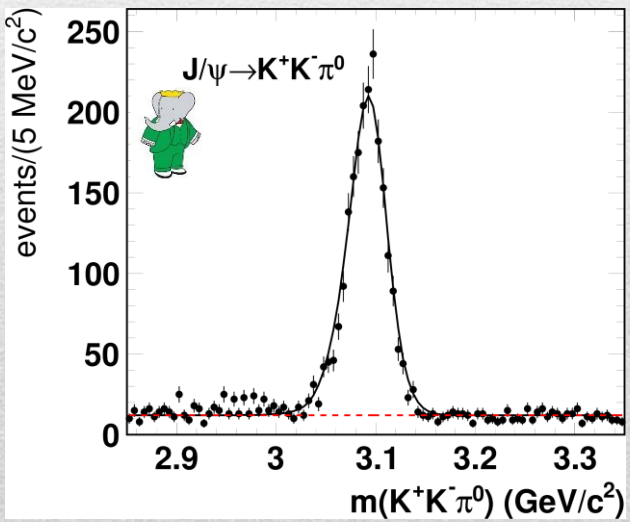
BaBar coll., PRD95, 072007 (2017)

$J/\psi \to 3h$: Event selection

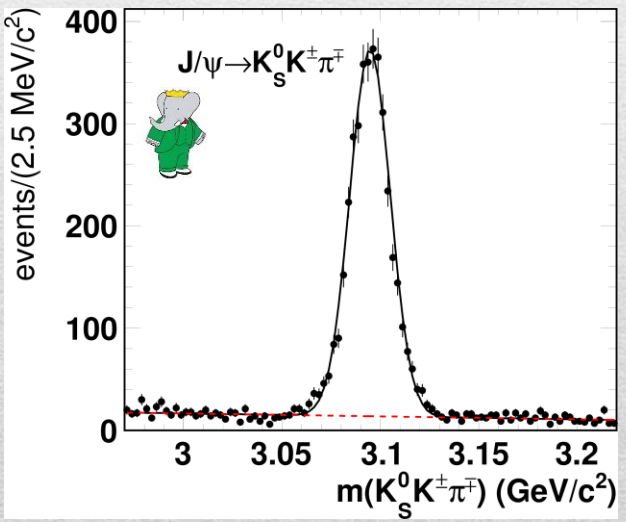
- $J/\psi \to K_S^0(\to \pi^+\pi^-)K^-\pi^+$, 4 tracks, $d(K_S^0) > 0.2$ cm
- $J/\psi \to K^+K^-\pi^0$ and $\to \pi^+\pi^-\pi^0$, 2 tracks, $E_\gamma > 100$ MeV
- PID applied for Kaons and pions
- ISR events, $|(p_{e^+e^-} - p_{h^+h^-\pi^0})^2| < 2\ \mathrm{GeV}^2$, $|\left(p_{e^+e^-} - p_{K_S^0K^-\pi^+}\right)^2| < 1.5\ \mathrm{GeV}^2$
- If γ_{ISR} falls in the acceptance of EMC, the observation of a compatible photon is required
- Small background from $e^+e^- \to \gamma\pi^+\pi^-$, removed with $|\cos\theta_\pi| < 0.95$



20k events, 91.3% purity



2.1k events, 88.8% purity



3.9k events, 93.1% purity

$J/\psi \to 3h$: Branching ratios and Dalitz plots

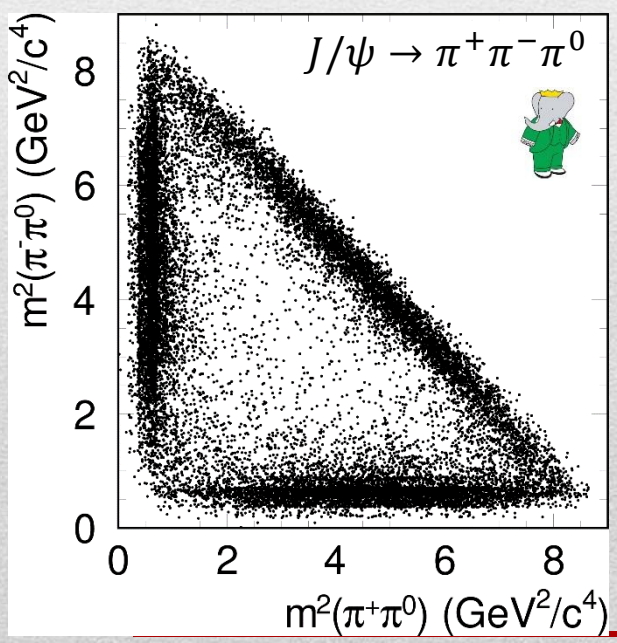
$$R_1 = \frac{BR(J/\psi \to K_S^0 K^- \pi^+)}{BR(J/\psi \to \pi^+\pi^-\pi^0)} = 0.120 \pm 0.003 \pm 0.009$$

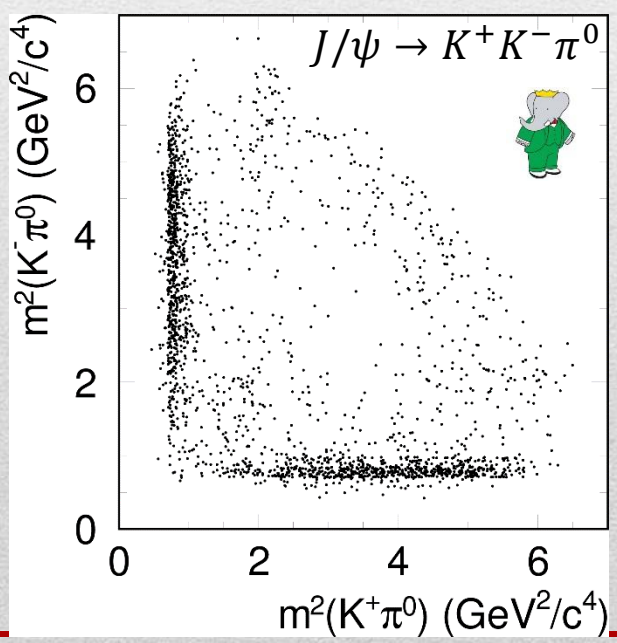
$$R_2 = \frac{BR(J/\psi \to K^+ K^- \pi^0)}{BR(J/\psi \to \pi^+\pi^-\pi^0)} = 0.265 \pm 0.005 \pm 0.021$$

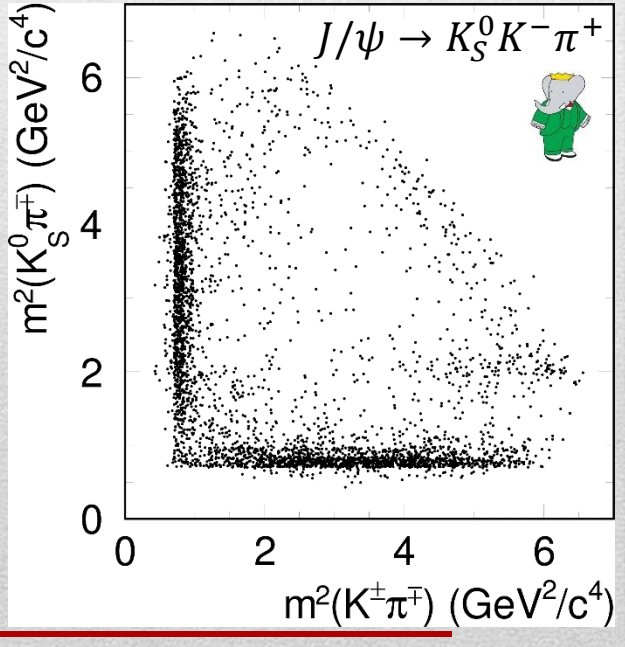
$R_1^{PDG} = 0.133 \pm 0.038$ PDG based on Mark II (25
$R_2^{PDG} = 0.123 \pm 0.033$ events) and Mark I (126 events)

Systematics

Effect	$\mathcal{R}_1$ (%)	$\mathcal{R}_2$ (%)
Efficiency	7.5	7.0
Background subtraction	1.3	1.0
Particle identification	2.0	1.8
K_S^0 reconstruction		1.1
π^0reconstruction		3.0
Mass fits	0.8	0.8
Total	7.9	8.0

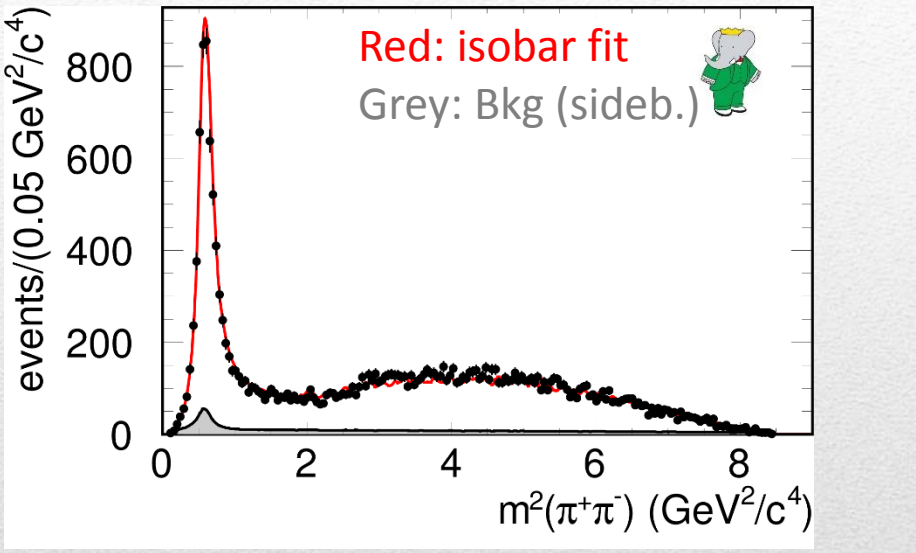


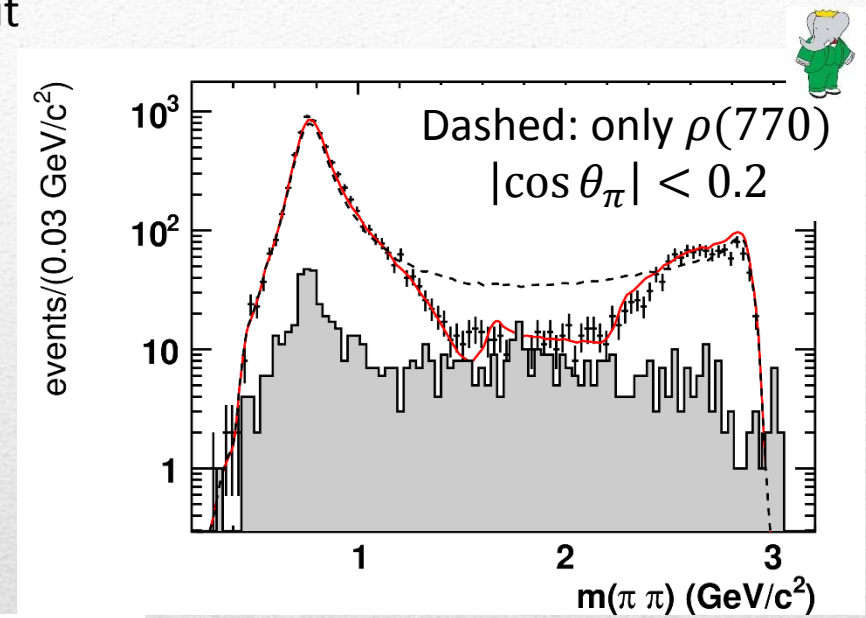




$J/\psi \to \pi^+\pi^-\pi^0$: Isobar model

Relativistic Breit Wigner are used in the fit





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

We free the $\rho(1450)$ and $\rho(1700)$ parameters and get

$$M(\rho(1450)) = 1429 \pm 41 \text{ MeV}$$
$$\Gamma(\rho(1450)) = 576 \pm 29 \text{ MeV}$$
$$M(\rho(1700)) = 1644 \pm 36 \text{ MeV}$$
$$\Gamma(\rho(1700)) = 109 \pm 19 \text{ MeV}$$

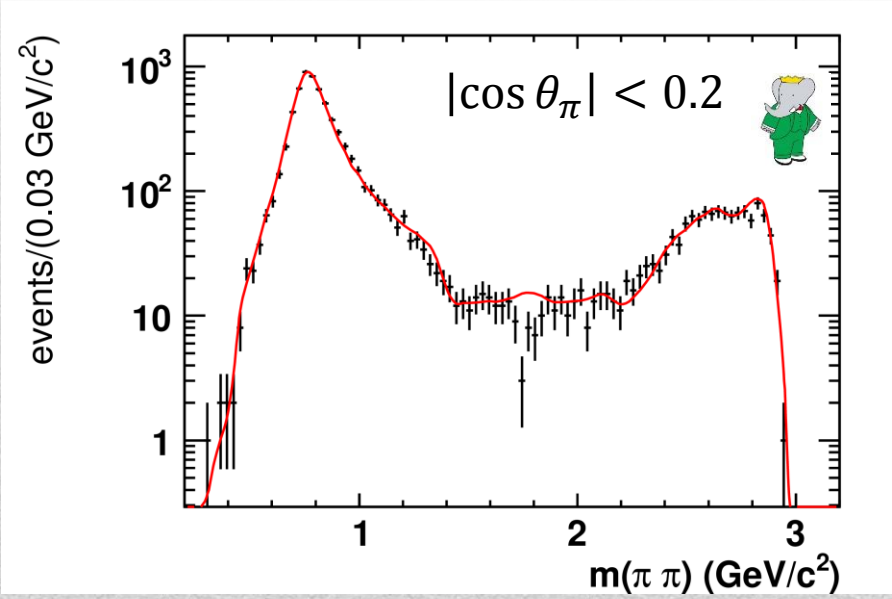
$J/\psi \to \pi^+\pi^-\pi^0$: Veneziano model

$$A(s,t,\lambda) = \epsilon_{\mu\nu\rho\sigma} p^+_\mu p^-_\nu p^0_\sigma \epsilon(p^\psi,\lambda) \sum_{1\le m\le n} \frac{\Gamma(n-\alpha(s))\,\Gamma(n-\alpha(t))}{\Gamma(n+m-\alpha(s)-\alpha(t))}$$

$$\alpha(s) = \alpha_0 + \alpha' s + i\gamma\sqrt{s-s_0}$$

Final state	Veneziano fraction (%)
$\rho(770)\pi$	133.1 ± 3.3
$\rho(1450)\pi$	0.80 ± 0.27
$\rho(1700)\pi$	2.20 ± 0.60
$\rho(2150)\pi$	6.00 ± 2.50
$\omega(783)\pi^0$	
$\rho_3(1690)\pi$	0.40 ± 0.08
Sum	142.5 ± 2.8
χ^2/ν	$596/508 = 1.17$

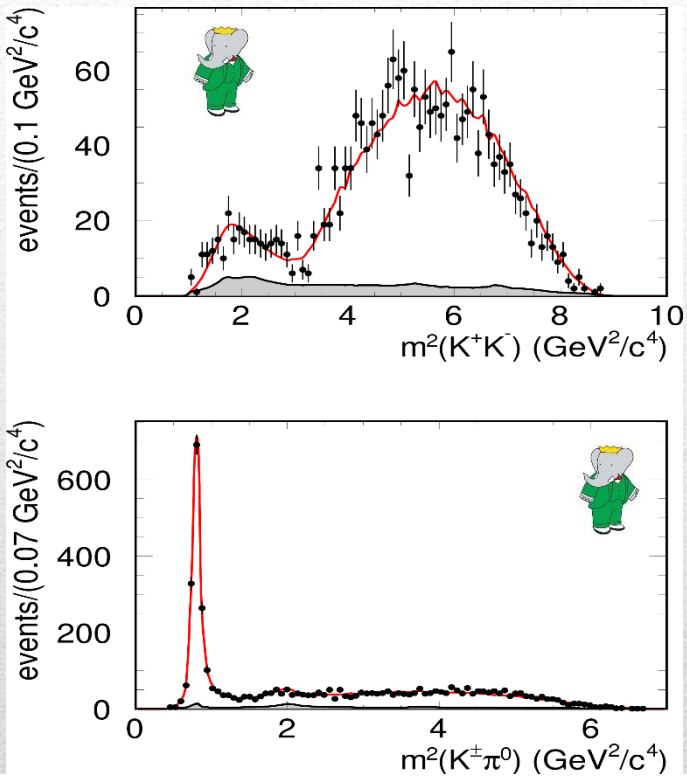
The Veneziano amplitude has a natural smooth behavior at higher energies

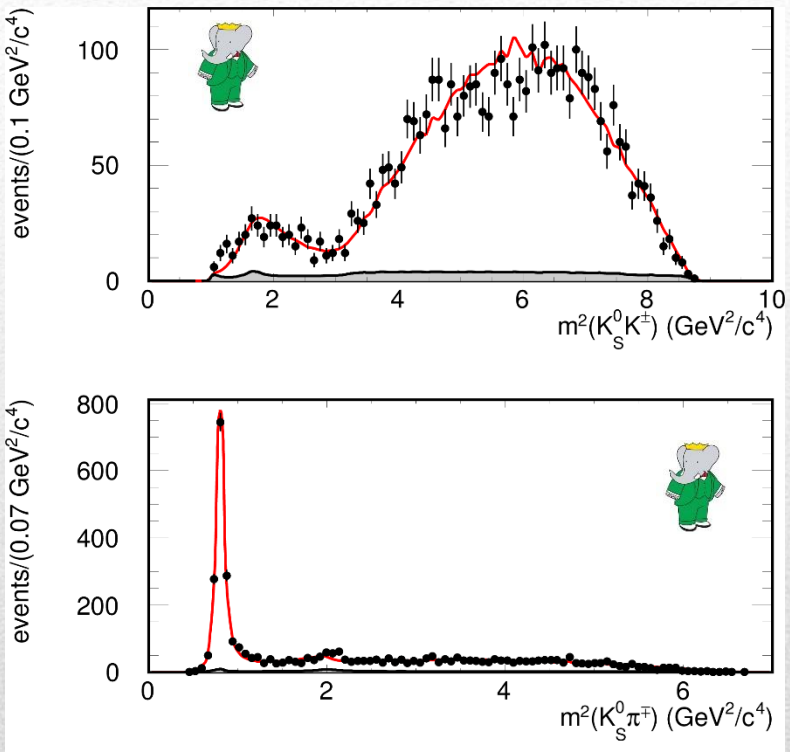


Data description equivalent to the isobar model

Pennington, Szczepaniak, PLB737, 283 (2014)

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

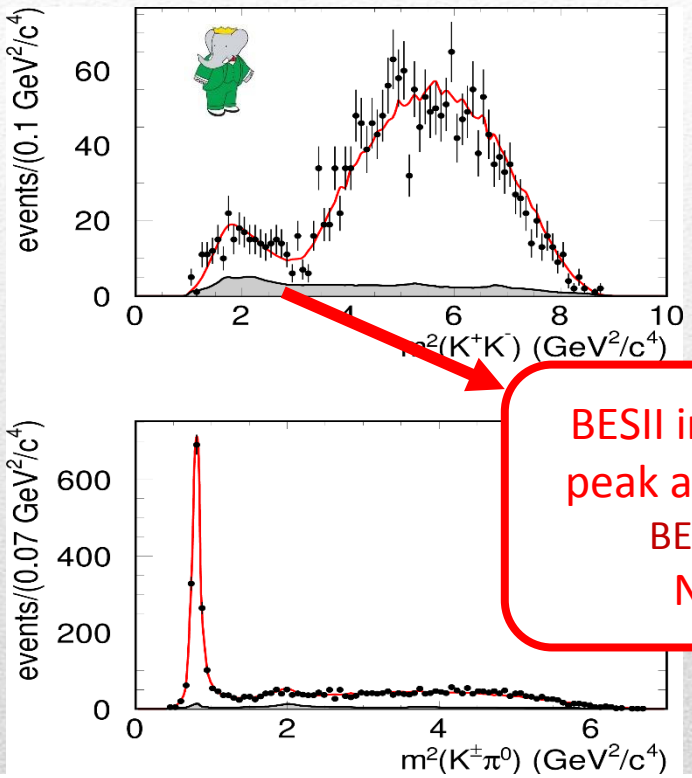


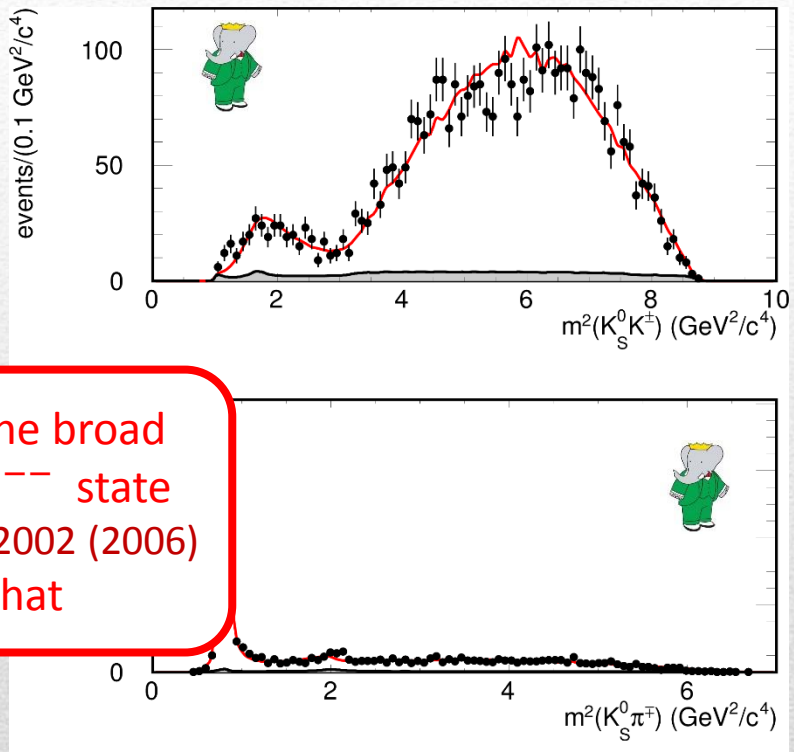


Final state	fraction (%)	phase (radians)
$K^*(892)^\pm K^\mp$	$92.4 \pm 1.5 \pm 3.4$	0.
$\rho(1450)^0\pi^0$	$9.3 \pm 2.0 \pm 0.6$	$3.78 \pm 0.28 \pm 0.08$
$K^*(1410)^\pm K^\mp$	$2.3 \pm 1.1 \pm 0.7$	$3.29 \pm 0.26 \pm 0.39$
$K_2^*(1430)^\pm K^\mp$	$3.5 \pm 1.3 \pm 0.9$	$-2.32 \pm 0.22 \pm 0.05$
Total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

Final state	fraction (%)	phase (radians)
$K^*(892)\bar{K}$	$90.5 \pm 0.9 \pm 3.8$	0.
$\rho(1450)^\pm\pi^\mp$	$6.3 \pm 0.8 \pm 0.6$	$-3.25 \pm 0.13 \pm 0.21$
$K_1^*(1410)\bar{K}$	$1.5 \pm 0.5 \pm 0.9$	$1.42 \pm 0.31 \pm 0.35$
$K_2^*(1430)\bar{K}$	$7.1 \pm 1.3 \pm 1.2$	$-2.54 \pm 0.12 \pm 0.12$
Total	105.3 ± 3.1	
χ^2/ν	$274/217 = 1.26$	

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





BESII interpreted the broad peak as an exotic 1^{--} state

BESII, PRL97, 142002 (2006)

No need for that

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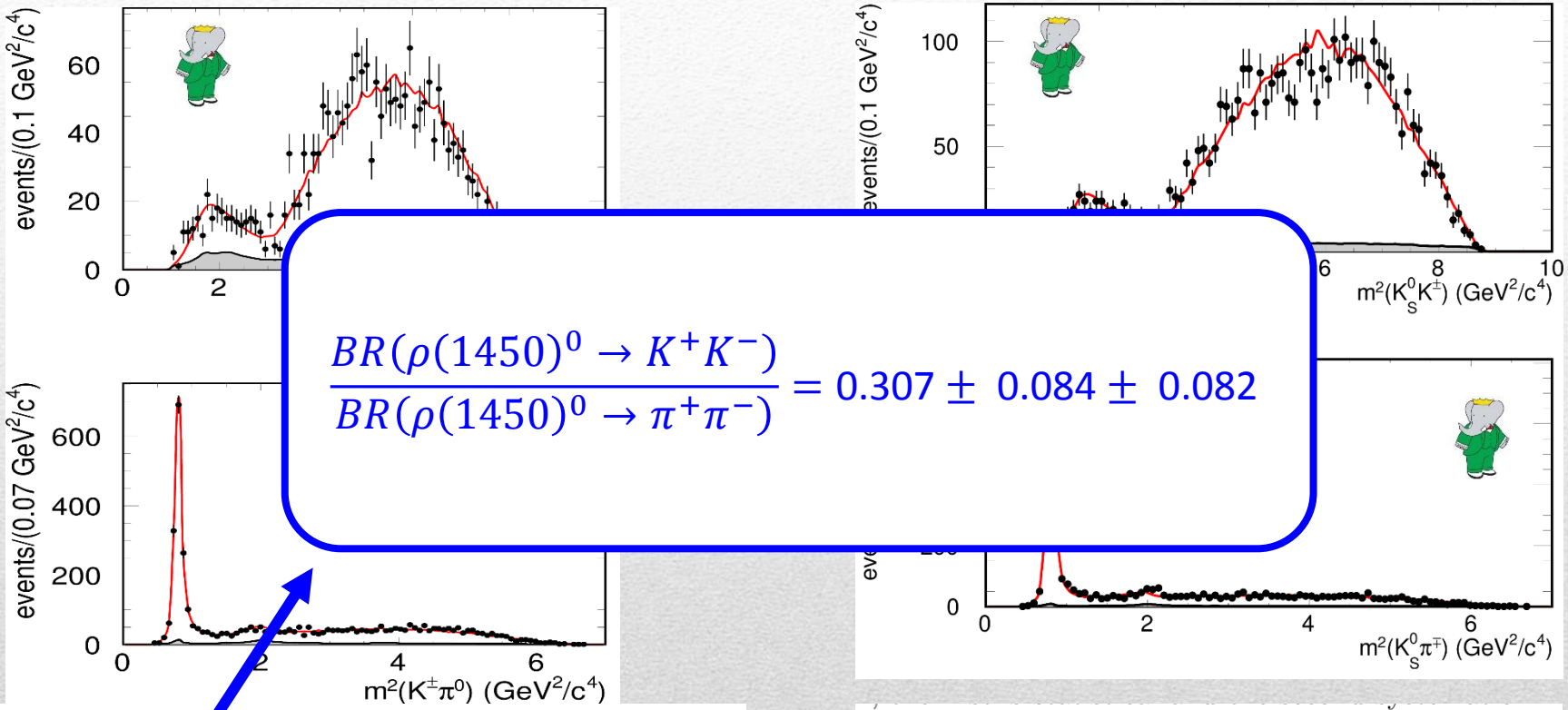
$J/\psi \to K^+K^-\pi^0$ and $\to K_S^0 K^-\pi^+$



$$\frac{BR(\rho(1450)^0 \to K^+K^-)}{BR(\rho(1450)^0 \to \pi^+\pi^-)} = 0.307 \pm 0.084 \pm 0.082$$

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Summary

- 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

  BaBar coll., PRD93, 012005 (2016)

  - MIPWA allows to extract a reliable $K\pi$ S-wave, which does not look to agree with other experiments

- Dalitz plot analyses of $J/\psi \to \pi^+\pi^-\pi^0$, $J/\psi \to K^+K^-\pi^0$, and $J/\psi \to K_S^0 K^\pm \pi^\mp$, produced via e^+e^- annihilation with initial-state radiation

  BaBar coll., PRD95, 072007 (2017)

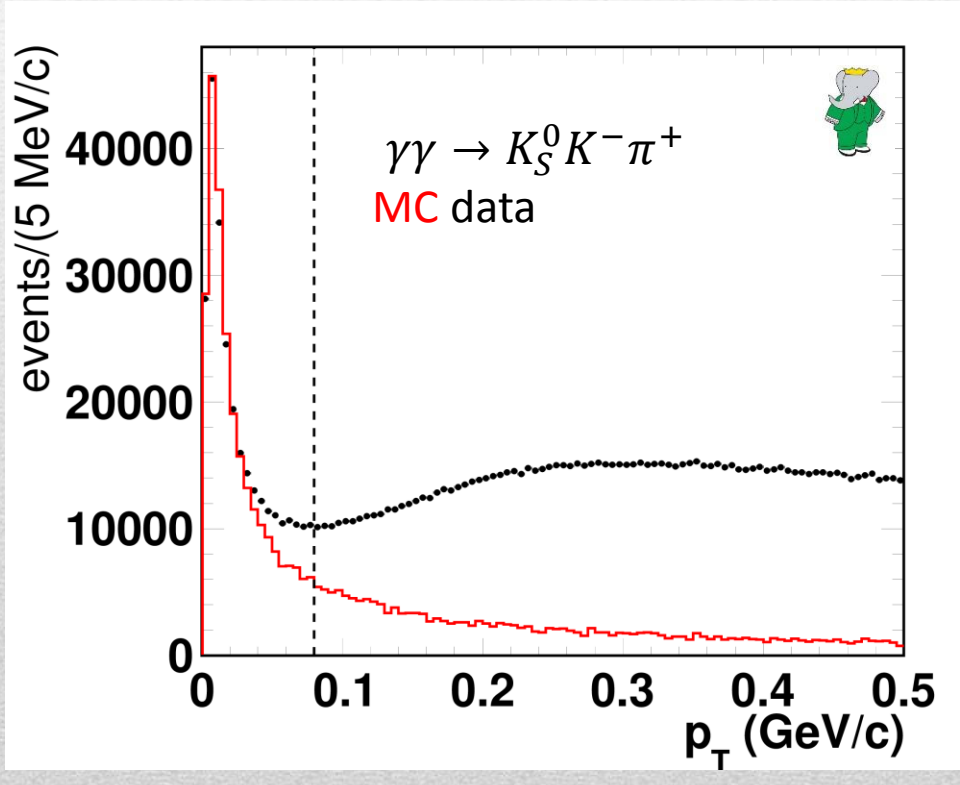
  - The Isobar and Veneziano model offer a complementary description of the Dalitz plot for the $\pi^+\pi^-\pi^0$

Thank you!

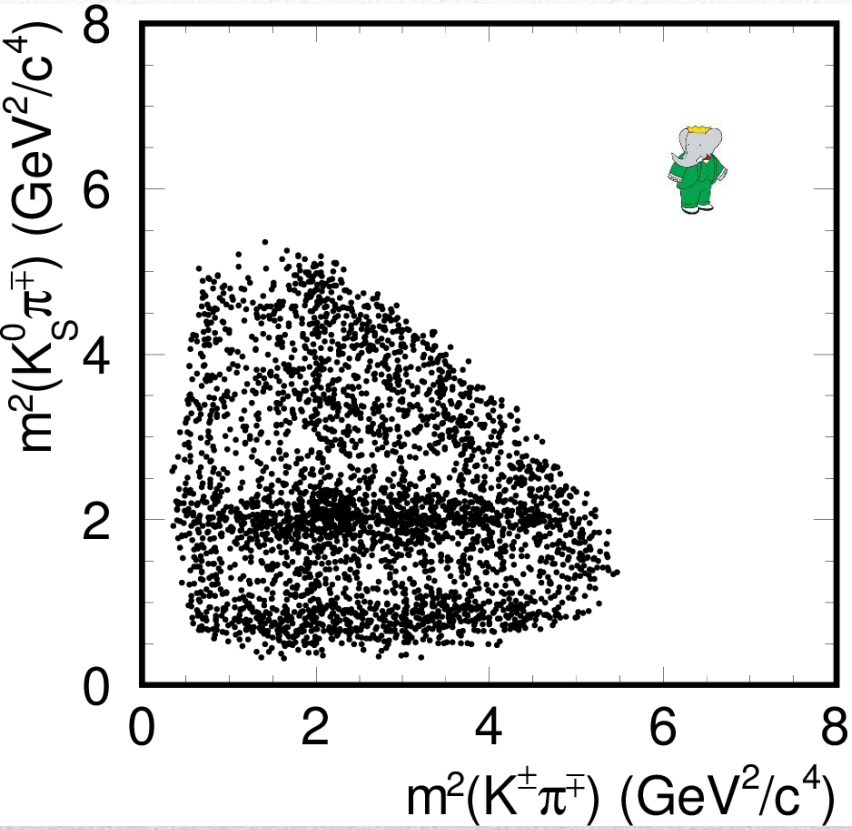
BACKUP

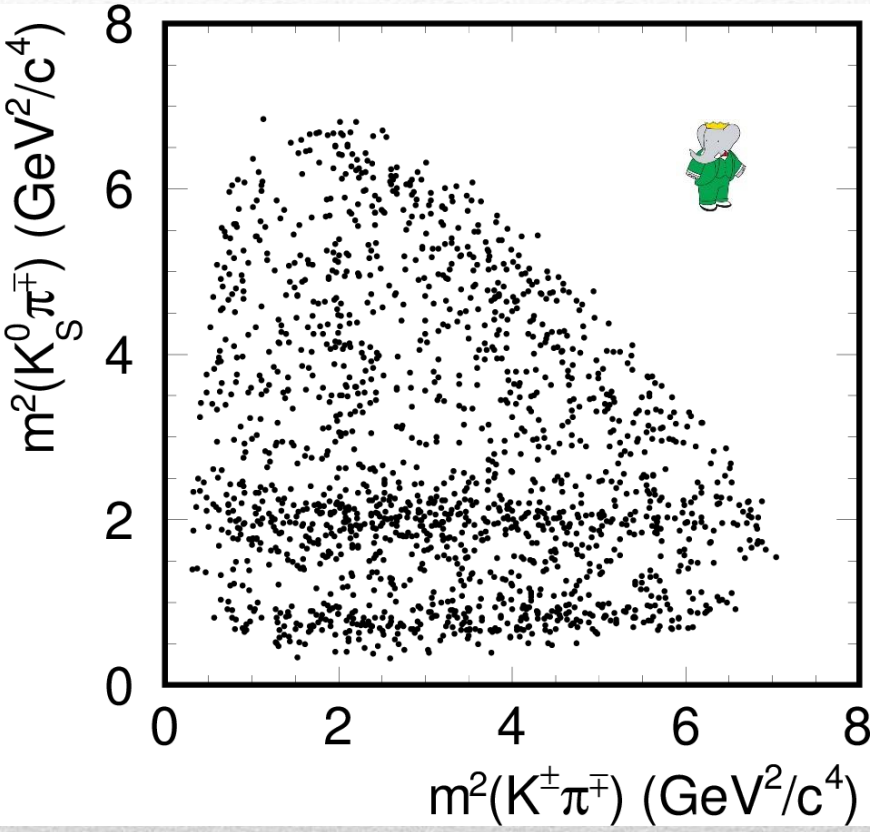
$\gamma\gamma \to \eta_c \to K\bar{K}\pi$: Event selection

- $\gamma\gamma \to \eta_c \to K_S^0(\to \pi^+\pi^-)K^-\pi^+$, 4 tracks, $d(K_S^0) > 0.2$ cm, $m(K_S^0)$ consistent with PDG
- $\gamma\gamma \to \eta_c \to K^+K^-\pi^0$ and, 2 tracks, $E_\gamma > 50$ MeV
- PID applied for Kaons and pions
- To select $\gamma\gamma$ events $p_T(\eta_c) < 80$ MeV, to veto ISR events, $(p_{e^+e^-} - p_{K\bar{K}\pi})^2 > 10$ GeV^2



$\eta_c \to K\bar{K}\pi$: Sidebands



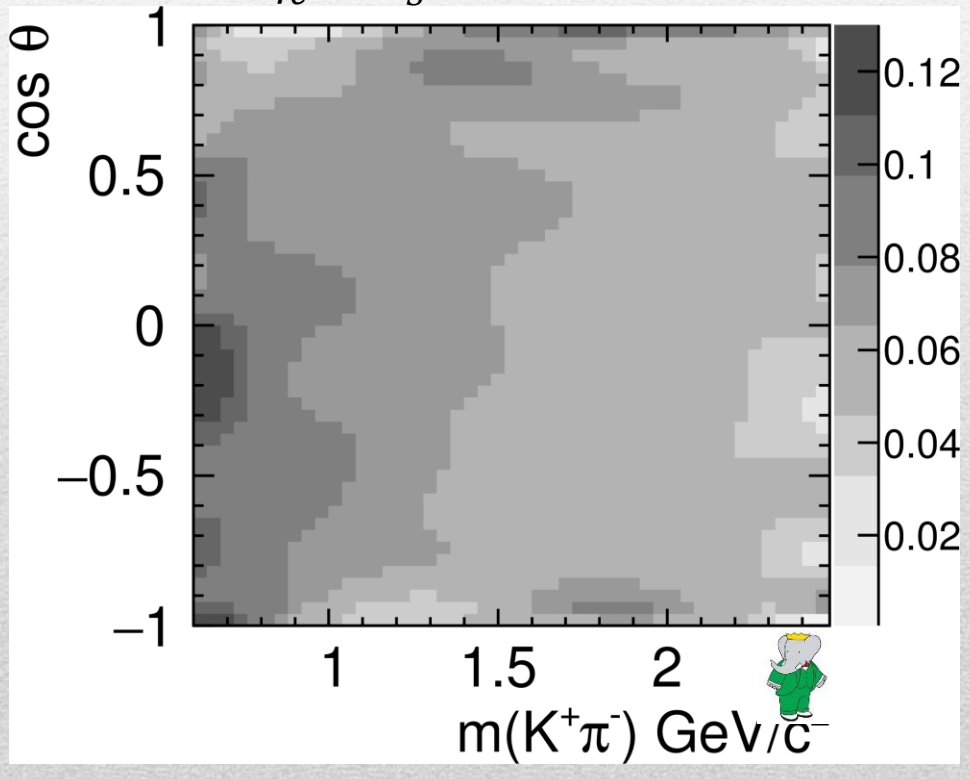


$\gamma\gamma \to \eta_c \to K\bar{K}\pi$: Efficiency

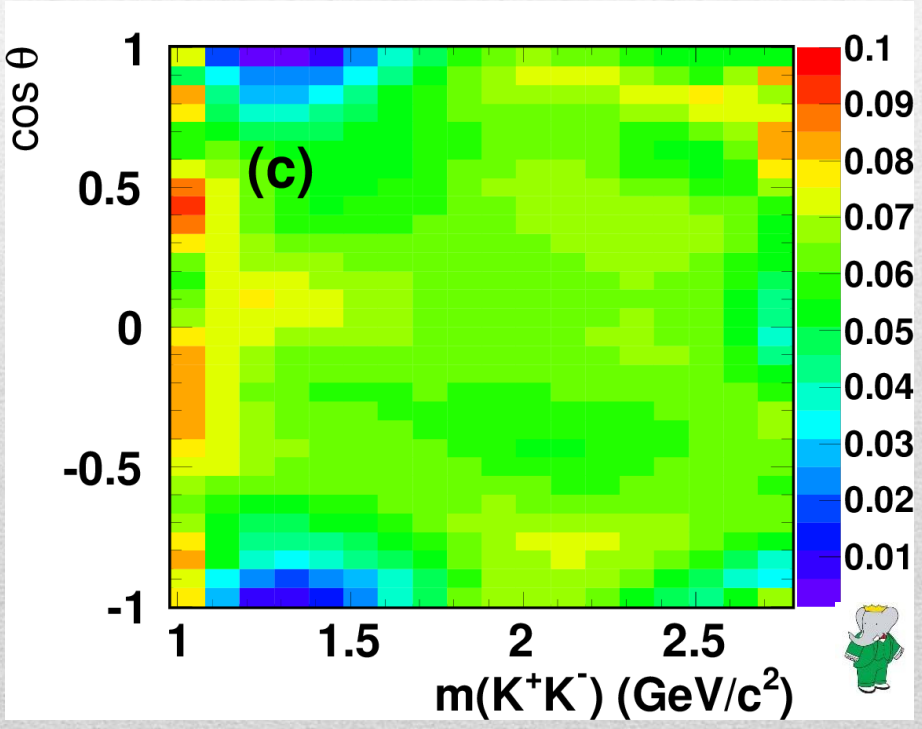
$$\sum_{L=1}^{12} a_L(m)\, Y_L(\cos\,\theta)$$

$a_L(m)$: 7th order polynomial

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

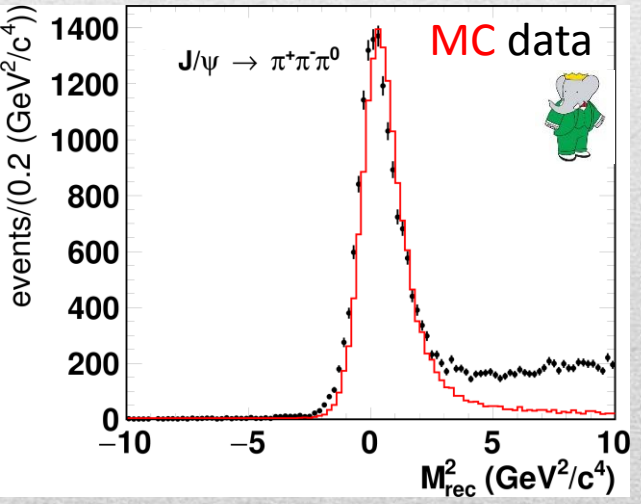


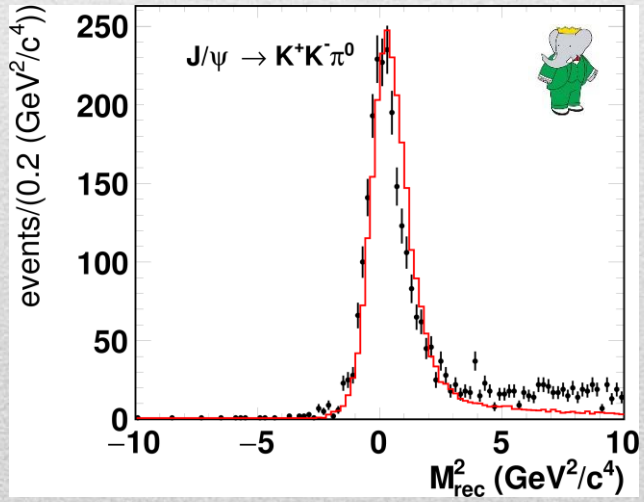
$\eta_c \to K^+ K^- \pi^0$

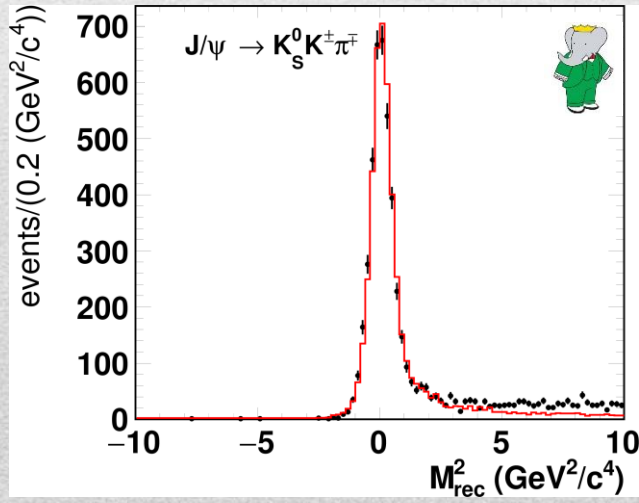


$J/\psi \to 3h$: Event selection

M^2_{miss} cuts







$J/\psi \to 3h$: Efficiency

$$\sum_{L=1}^{12} a_L(m)\, Y_L(\cos\,\theta)$$

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