Dalitz plot analysis of three-body charmonium decays and study of $\Upsilon(1S)$ radiative decays

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On behalf of the BaBar Collaboration

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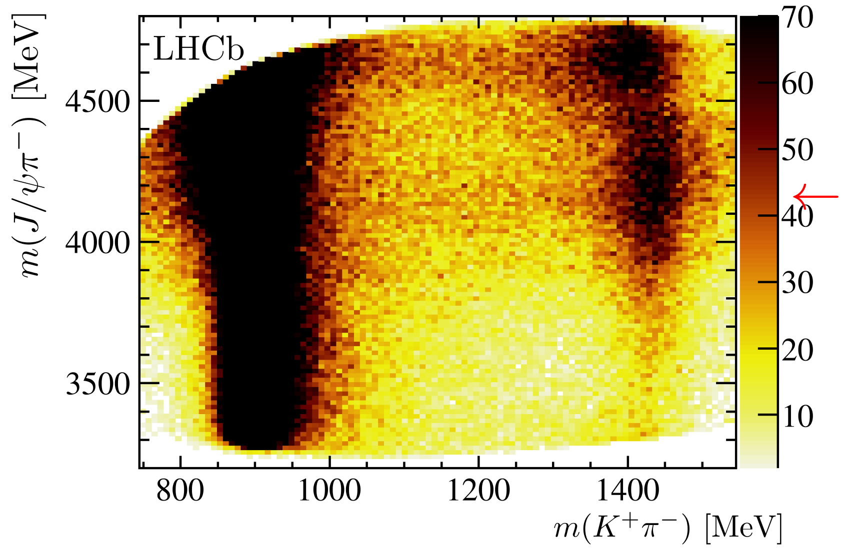
Light meson spectroscopy in heavy flavor decays

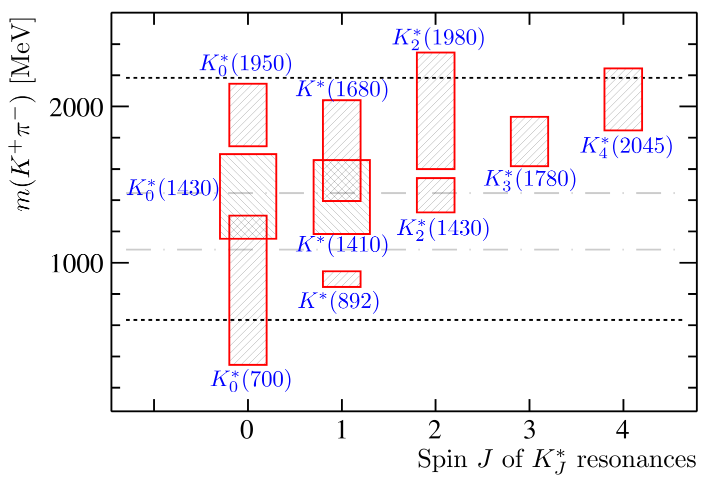
□ An understanding of light meson spectroscopy is of basic importance for many important physics topics.

□ Examples are: Measurement of γ, study and search for CP violations in heavy flavors decays, Dalitz plot analyses of 3-body or 4-body decays, observation of new exotic resonances.

□ The observation of the Z particles in $B \to \psi/\psi' K\pi$ is strongly correlated with an accurate description of the $K\pi$ $\mathcal{S}$-wave. (Phys.Rev.Lett. 122 (2019) 152002),(Phys.Rev.Lett. 112 (2014) 222002)

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



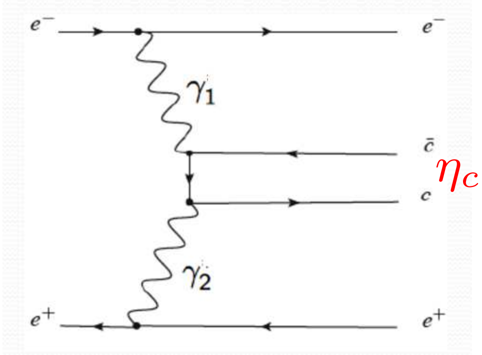


□ Strong resonance production along the $K\pi$ axis.

Dalitz plot analyses of η_c decays.

□ Charmonium decays are used to obtain new information on light meson spectroscopy.

□ In two-photon interactions we select events in which the e^+ and e^- beam particles are scattered at small angles and remain undetected. Require $p_T < 0.08\ GeV/c$.

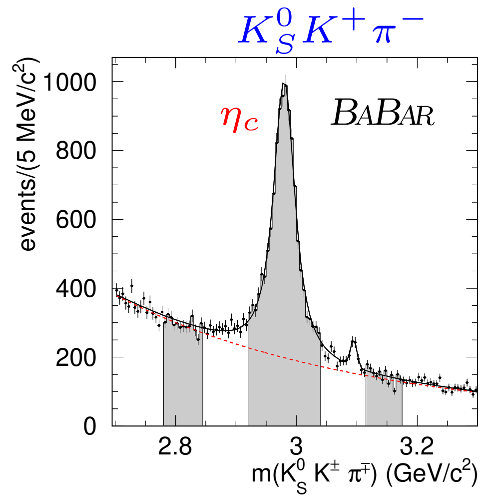


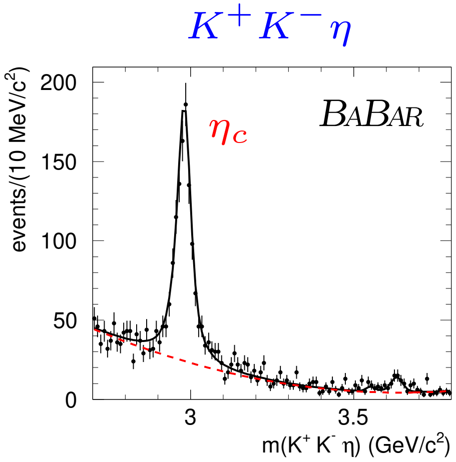
□ We have studied the following final states.

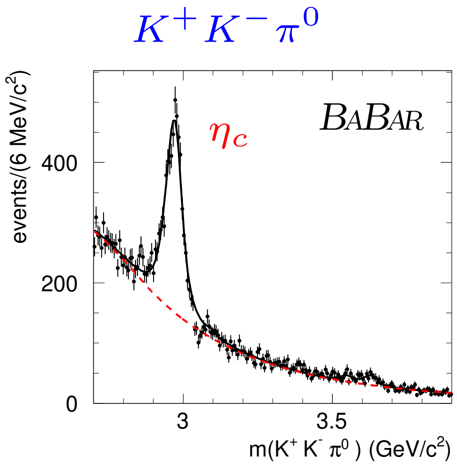
□ $\eta_c \to K^0_S K^+ \pi^-$,12849 evts with $(64.3 \pm 0.4)\%$ purity.

□ $\eta_c \to K^+ K^- \eta$, 1161 evts with $(76.1 \pm 1.3)\%$ purity.

□ $\eta_c \to K^+ K^- \pi^0$, 6494 evts with $(55.2 \pm 0.6)\%$ purity.







□ *Purity=Signal/(Signal + Background)*

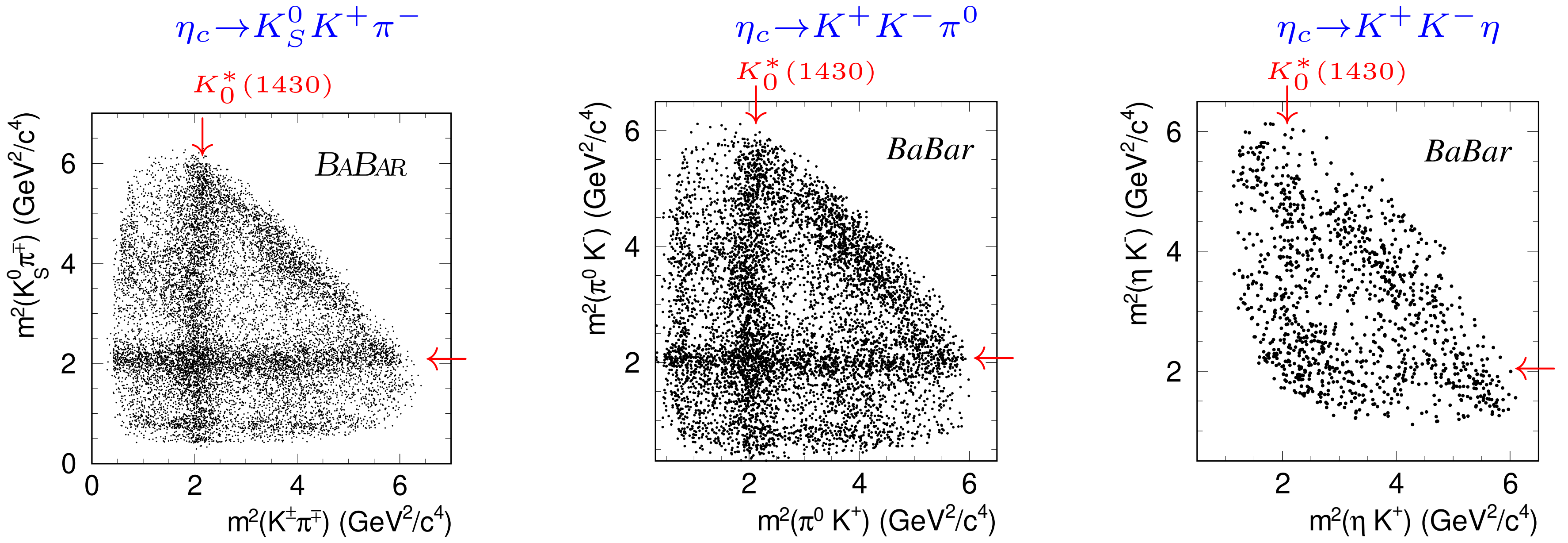
Phys.Rev. D89 (2014) 112004, Phys.Rev. D93 (2016) 012005

Branching fraction and Dalitz plots.

- We measure:

$$\mathcal{R}(\eta_c) = \frac{\mathcal{B}(\eta_c \to K^+ K^- \eta)}{\mathcal{B}(\eta_c \to K^+ K^- \pi^0)} = 0.571 \pm 0.025 \pm 0.051$$

- **Dalitz plots.**



- Dominated by the presence of scalar mesons.
- In particular, strong contribution from $K_0^*(1430)$ in the three Dalitz plots.

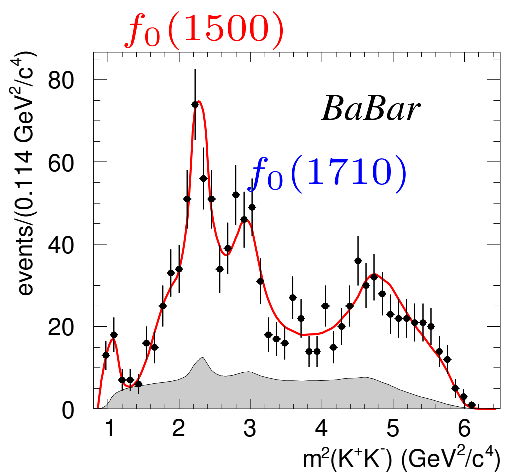
$\eta_c \to \eta K^+ K^-$ Dalitz plot analysis, Isobar model.

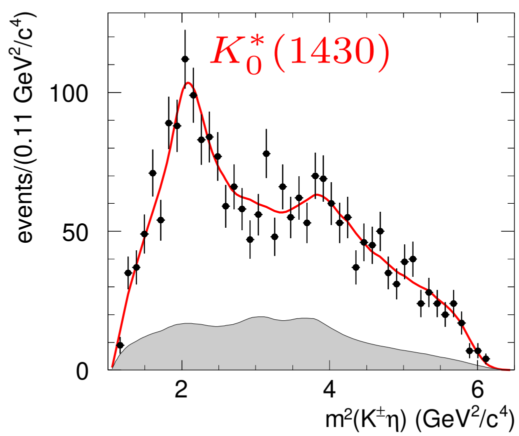
- Unbinned maximum likelihood fits.
- Resonances described by Breit-Wigner functions.

(D. Asner, Review of Particle Physics", Phys. Lett. B 592, 1 (2004)).

- Results from the Dalitz analysis and fit projections.
- Charge conjugated amplitudes symmetrized.

Final state	Fraction %	Phase (radians)
$f_0(1500)\eta$	$23.7 \pm 7.0 \pm 1.8$	0.
$f_0(1710)\eta$	$8.9 \pm 3.2 \pm 0.4$	$2.2 \pm 0.3 \pm 0.1$
$f_0(980)\eta$	$10.4 \pm 3.0 \pm 0.5$	$-0.3 \pm 0.3 \pm 0.1$
$f_2'(1525)\eta$	$7.3 \pm 3.8 \pm 0.4$	$1.0 \pm 0.1 \pm 0.1$
$K_0^*(1430)^+K^-$	$16.4 \pm 4.2 \pm 1.0$	$2.3 \pm 0.2 \pm 0.1$
...		
χ^2/ν	87/65	



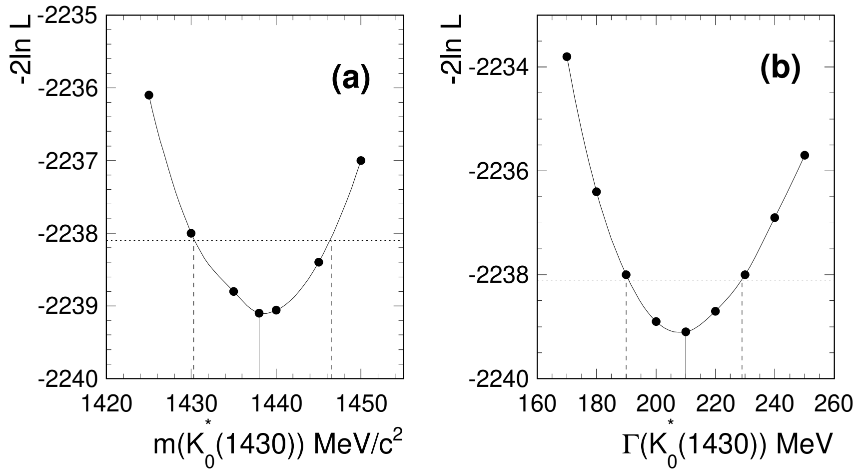


- Largest amplitudes are $f_0(1500)\eta$ and $K_0^*(1430)K$.
- First observation of $K_0^*(1430) \to \eta K$.

$\eta_c \to \pi^0 K^+ K^-$ Dalitz analysis, Isobar model.

□ The Dalitz analysis of $\eta_c \to \pi^0 K^+ K^-$ allows to obtain the parameters of $K_0^*(1430)$ and its relative branching fraction.

□ We scan the likelihood as a function of the $K_0^*(1430)$ mass and width.



□ And obtain:

$$m(K_0^*(1430)) = 1438 \pm 8 \pm 4 \text{ MeV}/c^2$$

$$\Gamma(K_0^*(1430)) = 210 \pm 20 \pm 12 \; MeV$$

□ We measure:

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

where $f_{\pi K}$ denotes $f_{\pi^0 K}$ fraction after correcting for the $K^0\pi$ decay mode.

Model Independent Partial Wave Analysis

(Phys. Rev. D **73**, 032004 (2006)).

☐ We perform a Model Independent Partial Wave Analysis of the $\eta_c \to K^0_S K^+ \pi^-$ and $\eta_c \to K^+ K^- \pi^0$.

☐ The $K\pi$ $\mathcal{S}$-wave (A_1) is taken as the reference amplitude.

$$A = A_1 + c_2 A_2 e^{i\phi_2} + c_3 A_3 e^{i\phi_3} + ...$$

☐ The $K\pi$ mass spectrum is divided into 30 equally spaced mass intervals 60 MeV wide and for each bin we add to the fit two new free parameters, the amplitude and the phase of the $K\pi$ $\mathcal{S}$-wave (constant inside the bin).

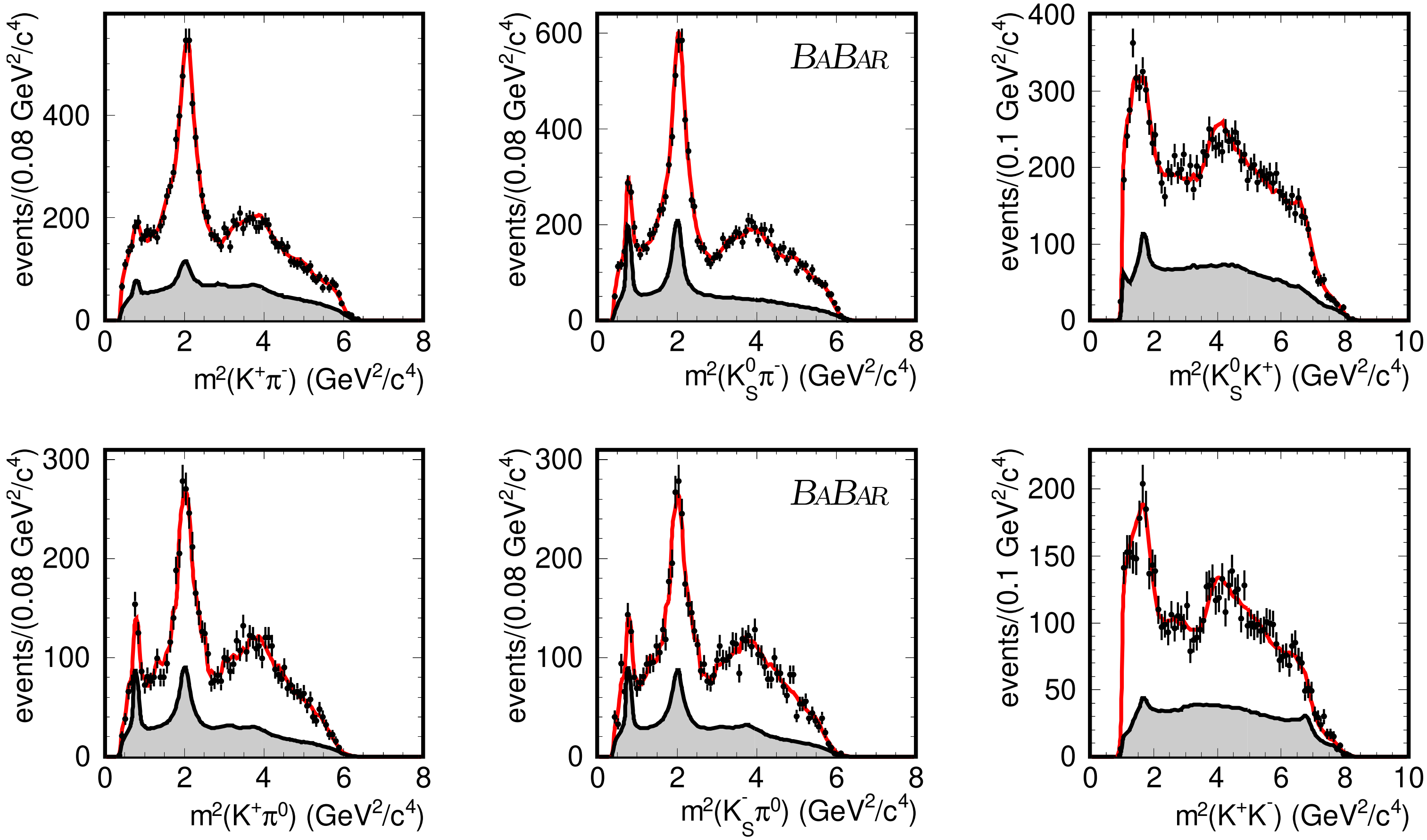
☐ Interference between the two $K\pi$ modes is determined by Isospin conservation.

☐ The $K^*_2(1420)$, $a_0(980)$, $a_0(1400)$, $a_2(1310)$, ... 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 regions.

Dalitz plots mass projections

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



☐ Shaded is contribution from the interpolated background.

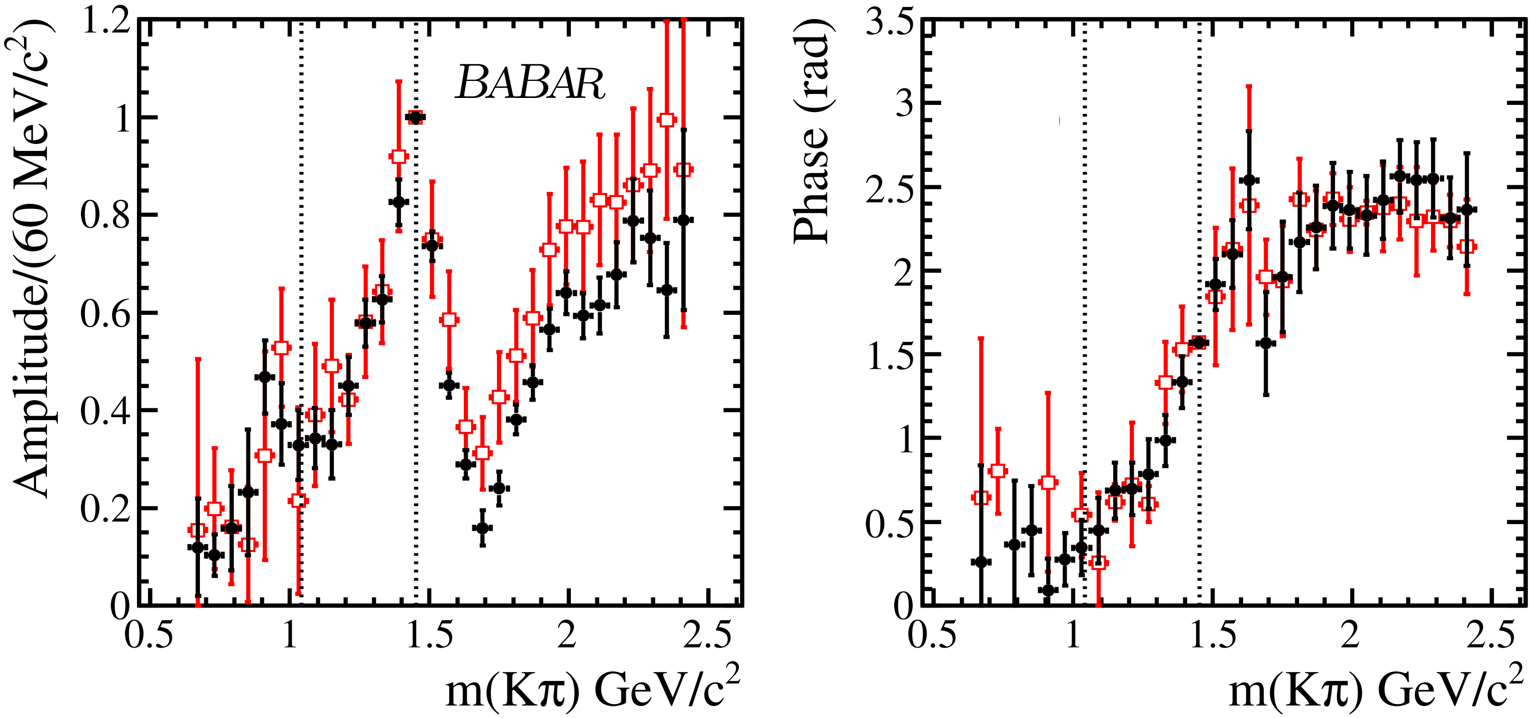
Fit fractions from the MIPWA. Comparison with the Isobar Model

Amplitude	$\eta_c \to K^0_S K^+ \pi^-$ Fraction (%)	$\eta_c \to K^+ K^- \pi^0$ Fraction (%)
$(K\pi\ \mathcal{S}\text{-wave})\ K$	$107.3 \pm 2.6 \pm 17.9$	$125.5 \pm 2.4 \pm 4.2$
$a_0(1950)\pi$	$3.1 \pm 0.4 \pm 1.2$	$4.4 \pm 0.8 \pm 0.7$
$K^*_2(1430)^0 K$	$4.7 \pm 0.9 \pm 1.4$	$3.0 \pm 0.8 \pm 4.4$
$+a_0(980), a_0(1450), a_0(1950)$		
$+a_2(1320), K^*_2(1430)$		
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
$(K^*_0(1950)K)+$		
$Nonresonant$		
$+a_0(980), a_0(1450), a_0(1950)$		
$+a_2(1320), K^*_2(1430)$		
χ_2/N_{cells}	**467/256=1.82**	**383/233=1.63**

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

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

- Fitted amplitude and phase. Average systematic uncertainty is 16%.
- Red: $\eta_c \to K^+K^-\pi^0$. Black: $\eta_c \to K^0_S K^+\pi^-$.
- Clear $K^*_0(1430)$ resonance and corresponding phase motion.
- At high mass broad $K^*_0(1950)$ contribution.

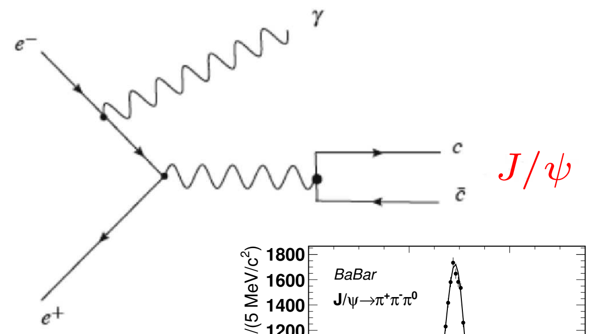


- Dashed lines are $K\eta$ and $K\eta'$ thresholds.
- Good agreement between the two η_c decay modes.

Dalitz plot analysis of $J/\psi \to$ *three body* decays

□ J/ψ samples are obtained from the Initial State Radiation (ISR) process. (Phys.Rev. D95 (2017), 072007)

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



□ We study the following reactions:

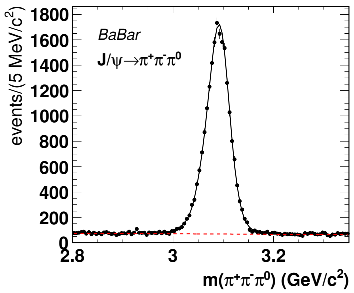
$e^+e^- \to \gamma_{\rm ISR}\ \pi^+\pi^-\pi^0$,

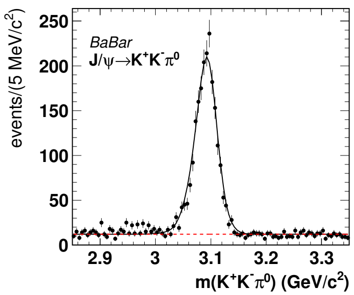
$e^+e^- \to \gamma_{\rm ISR}\ K^+K^-\pi^0$,

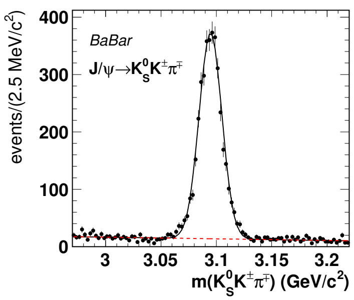
$e^+e^- \to \gamma_{\rm ISR}\ K^0_S K^\pm\pi^\mp$,

where $\gamma_{\rm ISR}$ indicates the (undetected) ISR photon.

□ J/ψ signals.







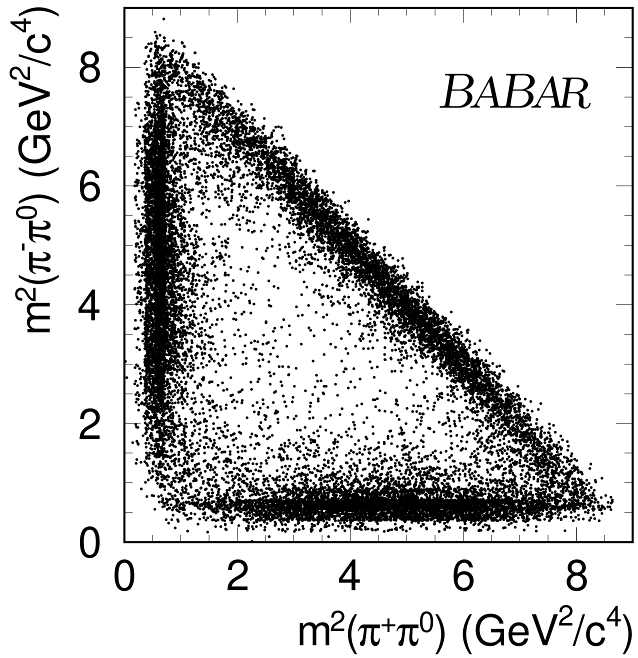
J/ψ decay mode	Signal region (GeV/c^2)	Event yields	Purity %
$\pi^+\pi^-\pi^0$	3.028-3.149	20417	91.3 ± 0.2
$K^+K^-\pi^0$	3.043-3.138	2102	88.8 ± 0.7
$K^0_S K^\pm\pi^\mp$	3.069-3.121	3907	93.1 ± 0.4

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

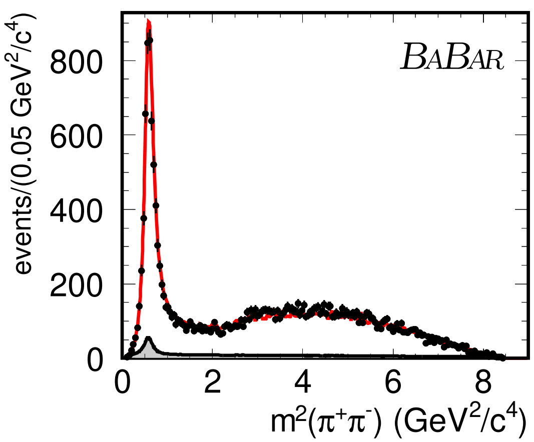
- □ Dominated by three $\rho(770)\pi$ contributions.
- □ Dalitz plot analysis performed using:

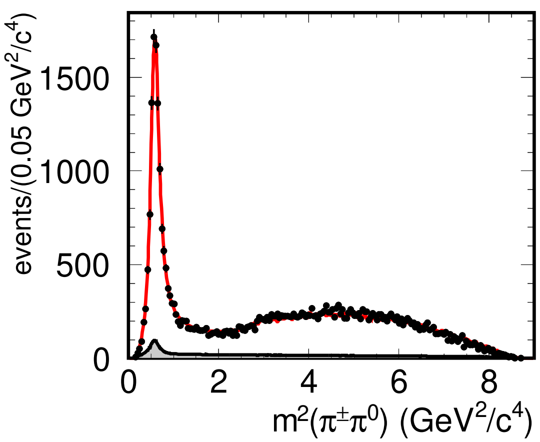
  - Isobar model using Zemach tensors;
    C. Zemach, Phys Rev. **133**, B1201 (1964),
    C. Dionisi et. al., Nucl. Phys. **B169**, 1 (1980).
  - Veneziano model.

(A. P. Szczepaniak, M.R. Pennington, Phys. Lett. **B737**, 283 (2014)).



- □ Dalitz plot projections.





- □ Shaded is the background interpolated by sidebands.

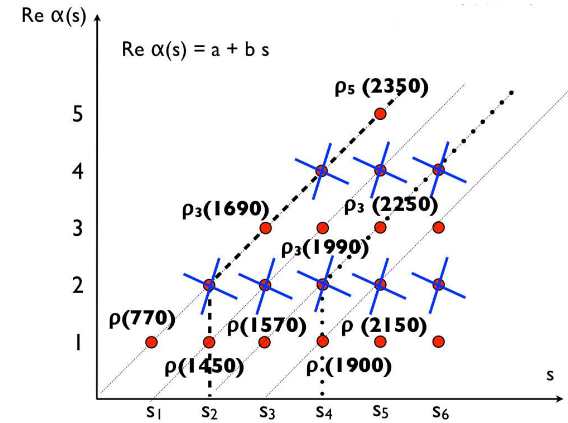
$J/\psi \to \pi^+\pi^-\pi^0$ Dalitz plot analysis with Veneziano model

- The Veneziano model deals with trajectories (Phys.Lett. N737, 283 (2014)).
- The amplitudes are written as:

$$A_{X\to abc} = \sum_{n,m} c_{X\to abc}(n,m) A_{n,m}$$

with $1 \le m \le n$.

- The complexity of the model is related to n, the number of Regge trajectories included in the fit.
- The fit requires n=7, with 19 free parameters.

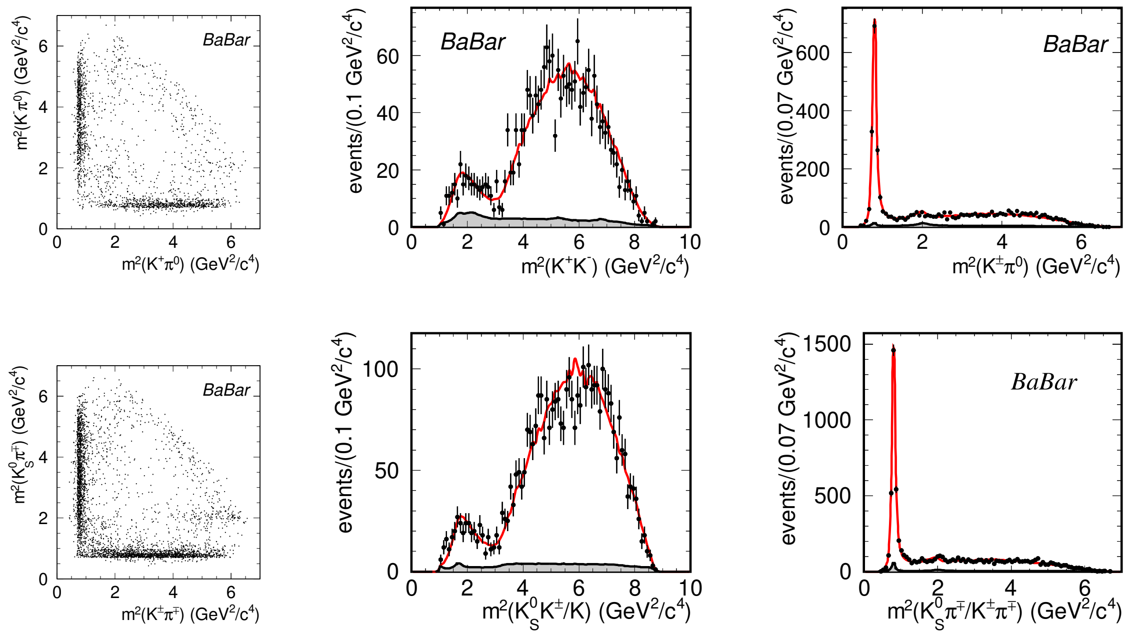


Final state	Amplitude	Isobar fraction (%)	Phase (radians)	Veneziano fraction (%)
$\rho(770)\pi$	1.	$114.2 \pm 1.1 \pm 2.6$	0.	133.1 ± 3.3
$\rho(1450)\pi$	0.513 ± 0.039	$10.9 \pm 1.7 \pm 2.7$	$-2.63 \pm 0.04 \pm 0.06$	0.80 ± 0.27
$\rho(1700)\pi$	0.067 ± 0.007	$0.8 \pm 0.2 \pm 0.5$	$-0.46 \pm 0.17 \pm 0.21$	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		$687/519 = 1.32$		$596/508 = 1.17$

- The two models have similar quality, but different fractions. The Veneziano model fits better the data.

$J/\psi \to K^+K^-\pi^0$ and $J/\psi \to K^0_S K^\pm \pi^\mp$ Dalitz plot analyses

- Clear K^{*+} and K^{*-} bands. Broad structure in the low K^+K^- mass region.
- $J/\psi \to K^+K^-\pi^0$
- $J/\psi \to K^0_S K^\pm \pi^\mp$



- Similar resonances contributions:

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

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	$132/137 = 0.96$	

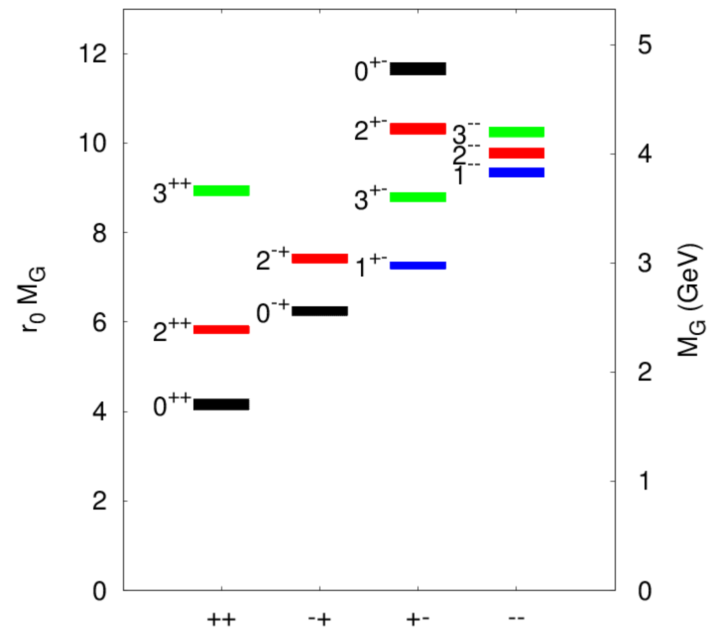
Study of $\Upsilon(1S)$ radiative decays to $\gamma\pi^+\pi^-$ and γK^+K^-

☐ Physics Motivations: Search for gluonium.

☐ The search for gluonium states is still a hot topic for QCD.

☐ Glueball spectrum from Lattice QCD.

☐ The $J^{PC} = 0^{++}$ glueball is expected in the mass region between 1.5 and 2.0 GeV.



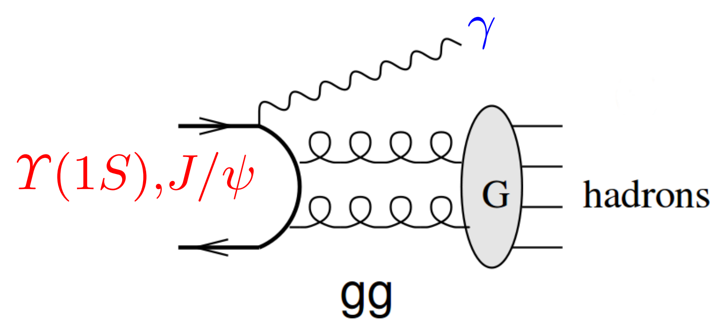
☐ Scalar gluonium candidates are:

$f_0(500)$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$

☐ J/ψ radiative decays have been extensively studied in a search for gluonium states.

☐ A similar work could be done in $\Upsilon(1S)$ radiative decays.

☐ Challenging: radiative $\Upsilon(1S)$ decays branching fractions expected to be suppressed by a factor 25 with respect to the corresponding J/ψ branching fractions.



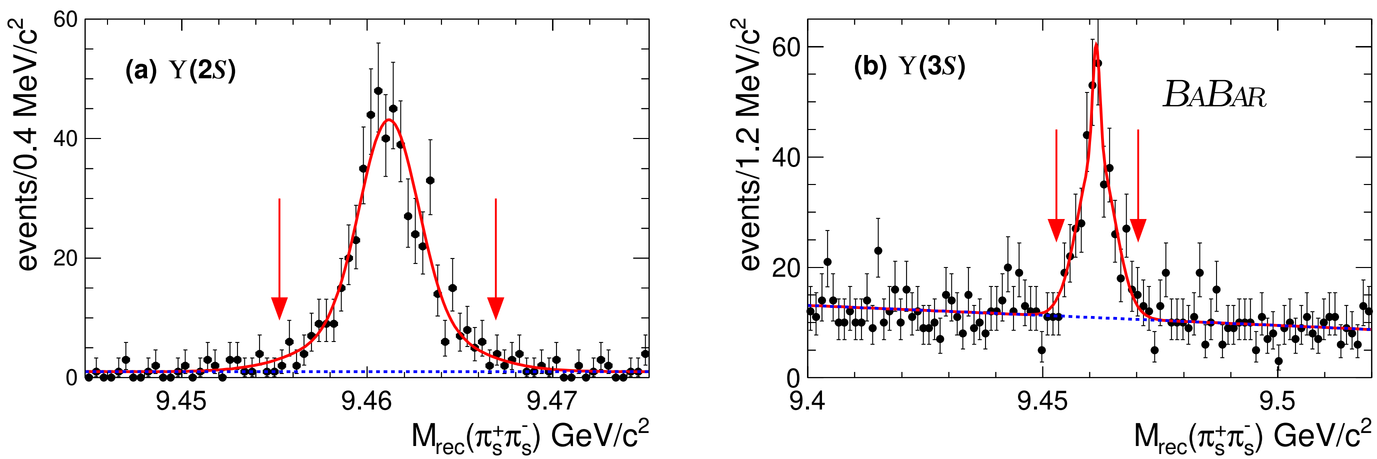
Analysis Strategy

- In the present analysis we make use of $\Upsilon(2S)$ and $\Upsilon(3S)$ decays with integrated luminosities of 13.6 and 28.0 fb^{-1} Phys.Rev. D97 (2018) no.11, 112006.
- We reconstruct the decay chains:

$$\Upsilon(2S)/\Upsilon(3S) \to \pi_s^+ \pi_s^- \Upsilon(1S) \begin{array}{l} \to \gamma \pi^+ \pi^- \\ \to \gamma K^+ K^- \end{array}$$

- Require momentum balance and compute the recoiling mass.

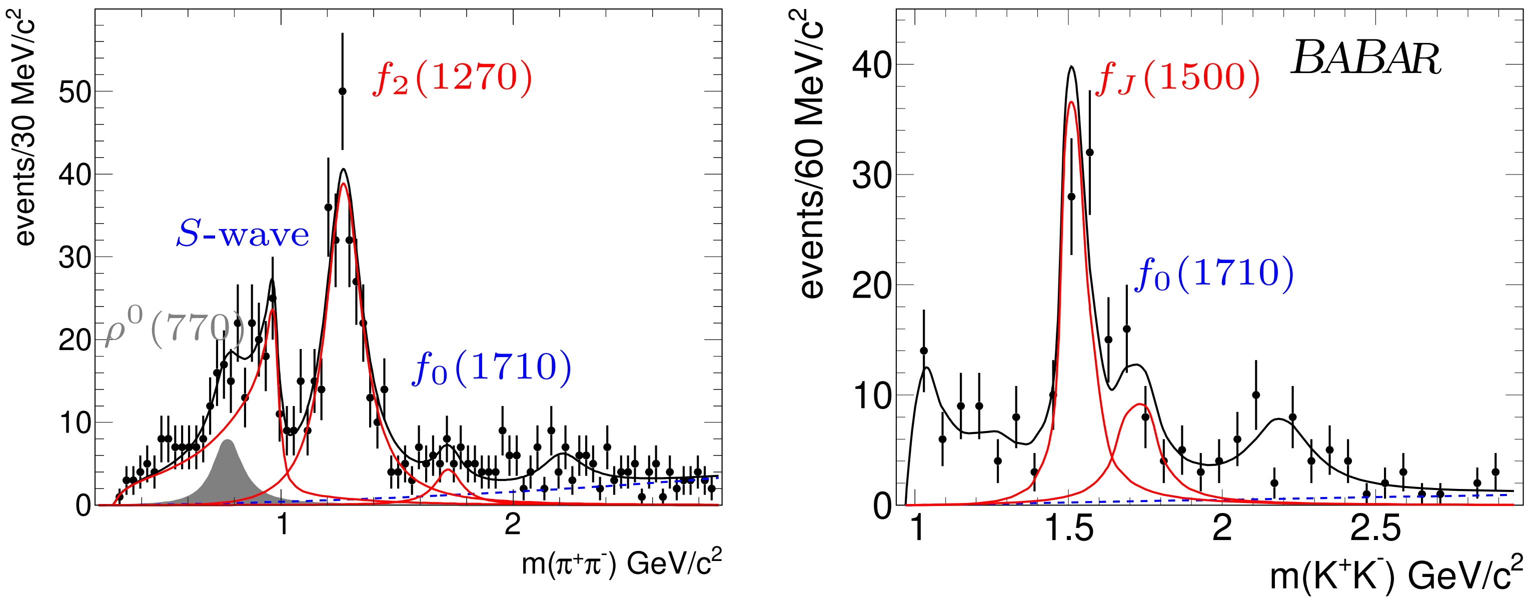
$$M^2_{\rm rec}(\pi_s^+ \pi_s^-) = |p_{e^+} + p_{e^-} - p_{\pi_s^+} - p_{\pi_s^-}|^2,$$



- Require: $|M^2_{\rm rec}(\pi_s^+ \pi_s^-) - m(\Upsilon(1S))_f| < 2.5\sigma$
- Select the $\Upsilon(1S)$: $9.1\ {\rm GeV}/c^2 < m(\gamma h^+ h^-) < 9.6\ {\rm GeV}/c^2$

Combined $\pi^+\pi^-$ and K^+K^- mass spectra

□ Observe rich resonance production.



□ The total S-wave is described by a coherent sum of $f_0(500)$ and $f_0(980)$ as:

$$S\text{-wave} = \left| BW_{f_0(500)}(m) + cBW_{f_0(980)}(m)e^{i\phi} \right|^2 .$$

□ The $f_0(980)$ described by a coupled channel Breit-Wigner.

□ For $f_0(500)$ we obtain:

$$m(f_0(500)) = 0.856 \pm 0.086\ \mathrm{GeV}/c^2, \Gamma(f_0(500)) = 1.279 \pm 0.324\ \mathrm{GeV},\ \phi = 2.41 \pm 0.43\ rad$$

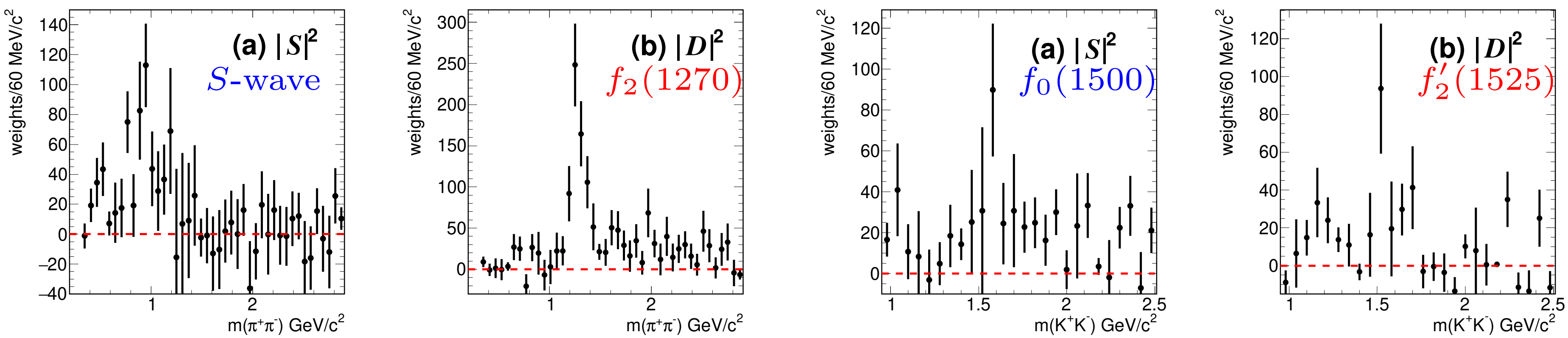
□ Contaminations from a $\rho^0(770) \to \pi^+\pi^-$ in the $\Upsilon(3S)$ data to $\gamma\pi^+\pi^-$.

Simple Partial Wave Analysis.

□ In a simplified procedure, the Y_L^0 moments are related to the S and D waves by the system of equations:

$$\sqrt{4\pi}\langle Y_0^0\rangle = S^2 + D^2,$$
$$\sqrt{4\pi}\langle Y_2^0\rangle = 2SD\cos\phi_{SD} + 0.639D^2,$$
$$\sqrt{4\pi}\langle Y_4^0\rangle = 0.857D^2,$$

□ The system can be solved directly for S and D waves:



□ We obtain an estimate of the S-wave$\to\pi^+\pi^-$ yield

$$N(S\text{–wave}) = 629 \pm 128,$$

□ The K^+K^- mass spectrum shows evidence for both $f_0(1500)$ and $f_2'(1525)$.

Measured $\Upsilon(1S) \to \gamma R$ branching fractions

☐ We label with $f_J(1500)$ the total enhancement in the 1500 MeV mass region.

Resonance	$\mathcal{B}(10^{-5})$ (BaBar)	CLEO (Phys.Rev. D73 (2006) 032001)
$\pi\pi$ S-wave	$4.63 \pm 0.56 \pm 0.48$	$(f_0(980))$ $1.8^{+0.8}_{-0.7} \pm 0.1$
$f_2(1270)$	10.15 ± 0.59 $^{+0.54}_{-0.43}$	$10.2 \pm 0.8 \pm 0.7$
$f_0(1710) \to \pi\pi$	$0.79 \pm 0.26 \pm 0.17$	
$f_J(1500) \to K\bar{K}$	$3.97 \pm 0.52 \pm 0.55$	$3.7^{+0.9}_{-0.7} \pm 0.8$
$f_2'(1525)$	$2.13 \pm 0.28 \pm 0.72$	
$f_0(1500) \to K\bar{K}$	$2.08 \pm 0.27 \pm 0.65$	
$f_0(1710) \to K\bar{K}$	$2.02 \pm 0.51 \pm 0.35$	$0.76 \pm 0.32 \pm 0.08$

☐ For $f_0(1710)$, reference (R. Zhu, JHEP **1509**, 166 (2015)), in the gluonium hypothesis, computes a branching fraction of $\mathcal{B}(\Upsilon(1S) \to \gamma f_0(1710)) = 0.96^{+0.55}_{-0.23} \times 10^{-4}$.

☐ For $f_0(1500) \to K\bar{K}$, ref. (X. G. He et al., Phys. Rev. D **66**, 074015 (2002)) expects $\mathcal{B}(\Upsilon(1S) \to \gamma f_0(1500))$ in the range $2 \sim 4 \times 10^{-5}$, consistent with our measurement.

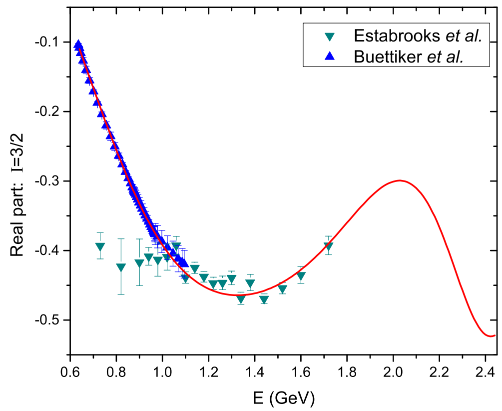
☐ Ref. (R. Zhu, JHEP **1509**, 166 (2015)) estimates for $f_0(1370)$ a branching fraction of $\mathcal{B}(\Upsilon(1S) \to \gamma f_0(1370)) = 3.2^{+1.8}_{-0.8} \times 10^{-5}$, in the range of our measurement of the branching fraction of $\mathcal{B}(\Upsilon(1S) \to \gamma(\pi\pi S\text{-wave}))$.

Backup Slides.

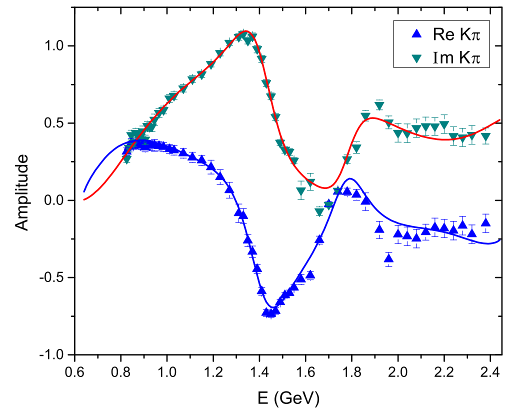
Overall fit of LASS and η_c data.

- K-matrix fit (**preliminary**). (A. Palano, M. Pennington, arXiv:1701.04881)

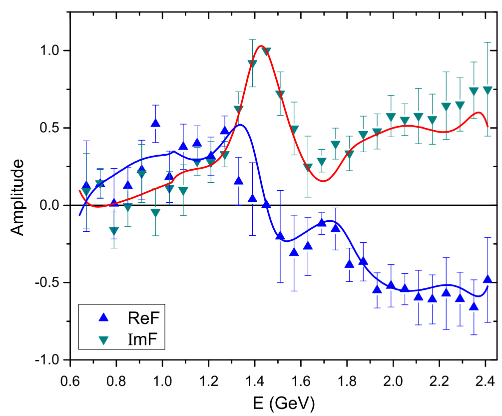
Elastic $K^-\pi^- \to K^-\pi^-$



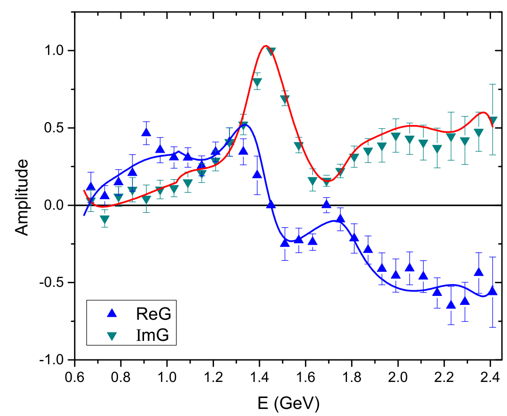
$LASS : K^-\pi^+ \to K^-\pi^+$



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



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

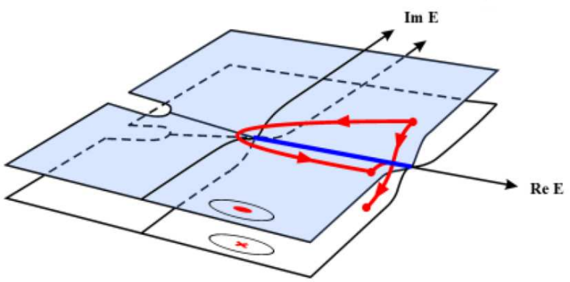


- Data fitted in terms of Real and Imaginary parts of the complex amplitudes.
- Solution A for the LASS data.
- Curves are fit results. Red: Imaginary, Blue: Real.

Overall K-matrix fit of LASS and η_c data.

□ Measured pole positions.

Pole 1	$E_{P1} = 659 - i302\,\text{MeV}$	on Sheet II
Pole 2	$E_{P2} = 1409 - i128\,\text{MeV}$	on Sheet III
Pole 3	$E_{P3} = 1768 - i107\,\text{MeV}$	on Sheet III



□ Pole 1 is identified with the κ, the pole position of which was found to be at $[(658 \pm 7) - i\ (278 \pm 13)]$ MeV, in the dispersive analysis of (arXiv:0310283, Eur.Phys.J. C33, 409 (2004)).

□ Pole 2 is identified with $K_0^*(1430)$, to be compared with $[(1438 \pm 8 \pm 4) - i\ (105 \pm 20 \pm 12)]$ MeV using the Breit-Wigner form.

□ Pole 3 may be identified with the $K_0^*(1950)$ with a pole mass closer to that of the reanalysis of the LASS by Anisovich (Phys. Lett.B413, 137 (1997)) with a pole at $E = (1820 \pm 20) - i(125 \pm 50)$ MeV.