Study of three-body decays of the J/ψ and of radiative decays of the ϒ(1S)

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On behalf of the BABAR Collaboration

Outline

- Radiative and hadronic quarkonium decays
- The BaBar detector & datasets
- Three-body decays of the J/ψ
  - PRD95 (2017) 072007
- Radiative decays of the $\Upsilon(1S)$
  - arXiv:1804.04044, accepted for publication in PRD
- Outlook

Radiative and hadronic quarkonium decays

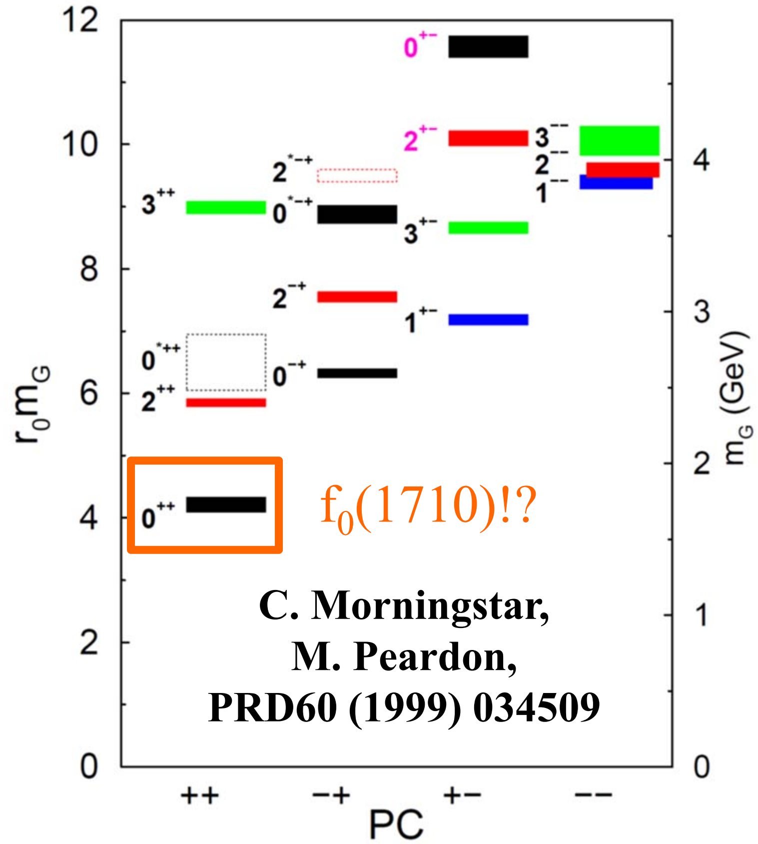
- Useful for light meson spectroscopy
  - f_J states, K*

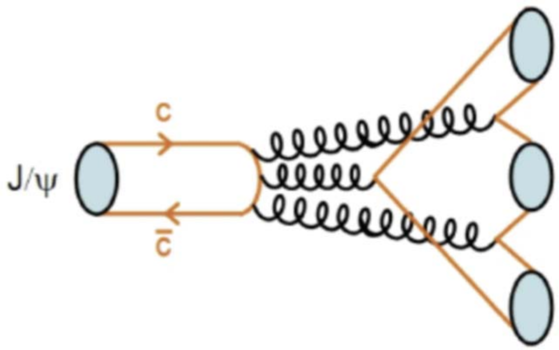
- Good probe to look for exotic QCD states
  - Multiquarks
  - Bound states of gluons ('glueballs')

    → Lowest state ($J^{PC}=0^{++}$) could have a mass around 1.5 GeV/c^2, accessible in quarkonium decays

- More experimental results about $f_0(1710)$ would help

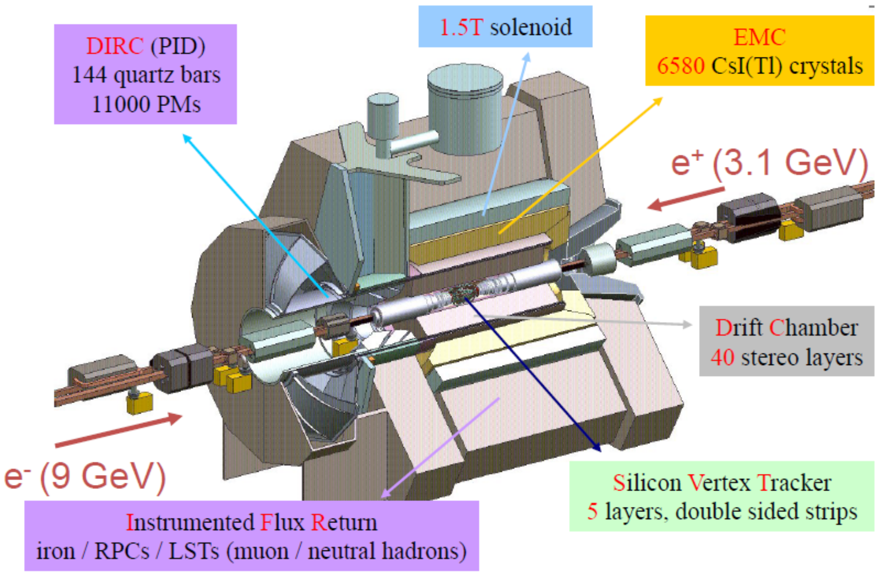
→ Accurate measurements needed
  - Low background: quarkonium decays in B-factories



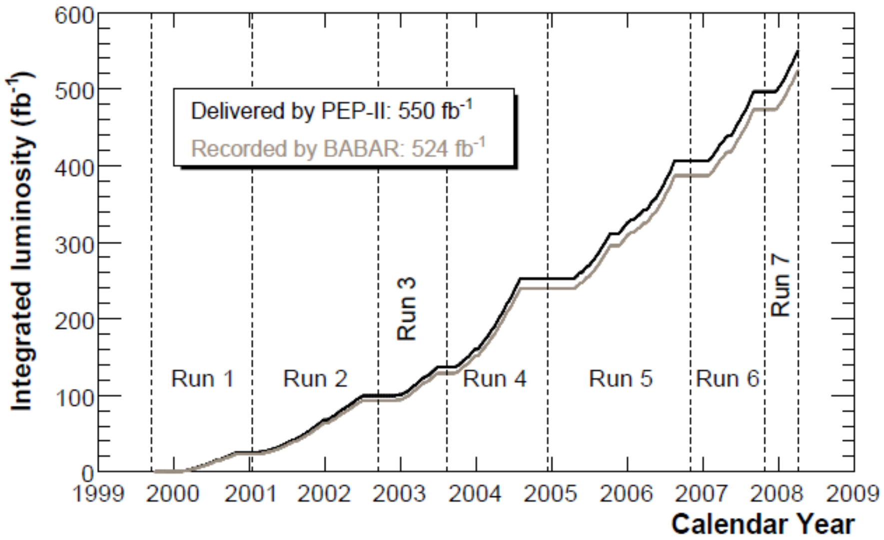


The BaBar experiment at the PEP-II B-Factory

- The BaBar detector



- The BaBar dataset (1999-2008)



- Final detector paper published in 2013
  http://dx.doi.org/10.1016/j.nima.2013.05.107

The *BABAR* Detector: Upgrades, Operation and Performance

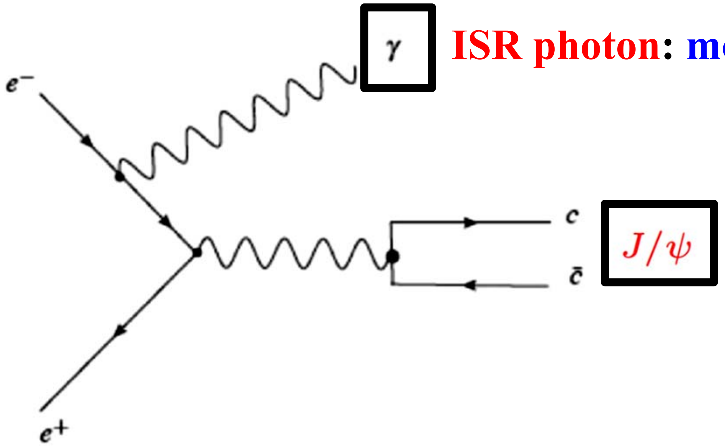
- « The Physics of the B Factories » (BaBar + Belle): http://arxiv.org/abs/1406.6311

- 424 fb^{-1} @ $\Upsilon(4S)$ ⇔ $(471.0 \pm 2.8) \times 10^6$ BB pairs – 'onpeak'
- 44 fb^{-1} recorded 40 MeV below the peak – 'offpeak' – to study background

- 30.6 fb^{-1} @ $\Upsilon(3S)$ and 15.0 fb^{-1} @ $\Upsilon(2S)$ – onpeak + offpeak
- ~3.9 fb^{-1} from the final energy scan up to 11.2 GeV

Three body decays of the J/ψ

- J/ψ produced from electron-positron annihiliation with initial state radiation (ISR)
  - Only $J^{PC}=1^{--}$ states produced



ISR photon: most of the time undetected

Produced alone:
no background from underlying event

- Studied decays
  - $J/\psi \to \pi^+ \pi^- \pi^0$
  - $J/\psi \to K^+ K^- \pi^0$
  - $J/\psi \to K_S^0 K^+ \pi^-$ and charge conjugate (c.c.) final state

- Dalitz plot analysis
  - Resonance contents
  - Branching fractions

Event selection

- Tracking
  - $J/\psi \to K_S^0 (\to \pi^+ \pi^-) K^+ \pi^-$: four charged tracks and K_S flight length > 2 mm
  - $J/\psi \to h^+ h^- \pi^0$; $h = \pi, K$; $\pi^0 \to \gamma\gamma$: two charged tracks and energy(γ) > 100 MeV
- Particle identification for the charged hadrons
- ISR events selection
  - Use the mass recoiling against the 3-hadron system:

$$M^2_{\text{rec}} \equiv (p_{e^-} + p_{e^+} - p_{h_1} - p_{h_2} - p_{h_3})^2 \qquad \textbf{[4-momenta]}$$

  → Selection cuts: < 2 GeV^2/c^4 for $J/\psi \to h^+ h^- \pi^0$
  < 2.5 GeV^2/c^4 for $J/\psi \to K_S^0 K^+ \pi^-$ and c.c

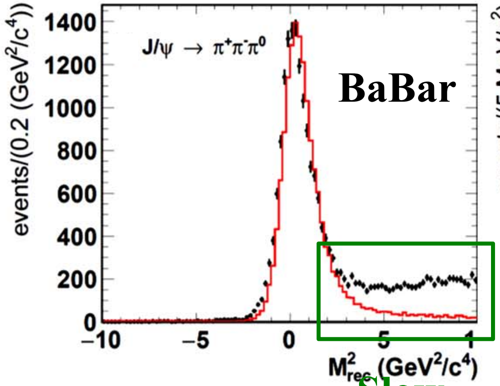
  - Additional compatibility test if γ_{ISR} detected
- Background source: $e^+ e^- \to \gamma \pi^+ \pi^-$
  - Rejected using the cut $\cos(\theta_\pi) < 0.95$, θ_π: helicity ange in the $\pi\pi$ system
- Mass spectrum fit
  - Resolutions from Monte-Carlo
  - Model: Crystal-Ball + Gaussian functions
  - First-order polynomials to describe background

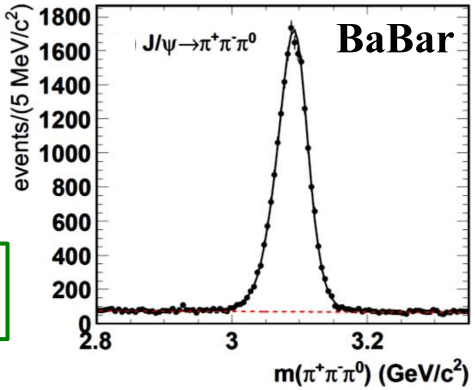
Event selection

Data vs. Monte-Carlo

Fits

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

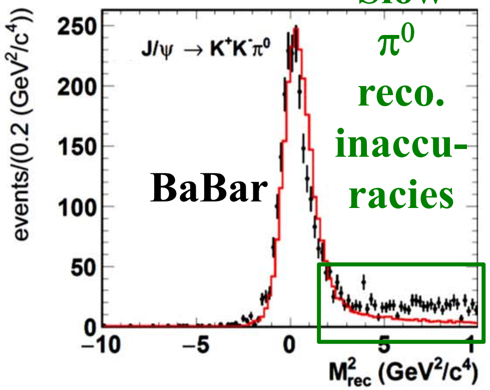


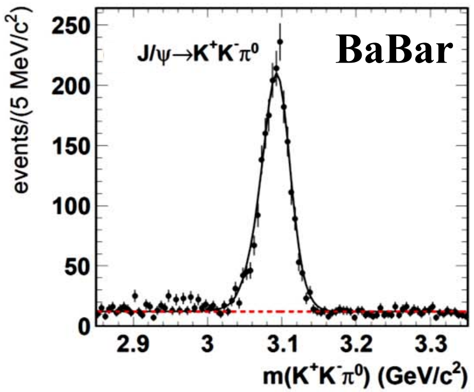


- Yield: ~20,000
- Purity: ~91%

Slow π^0 reco. inaccuracies

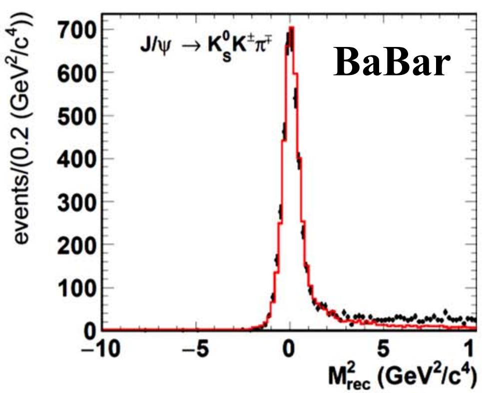
- $J/\psi \to K^+ K^- \pi^0$

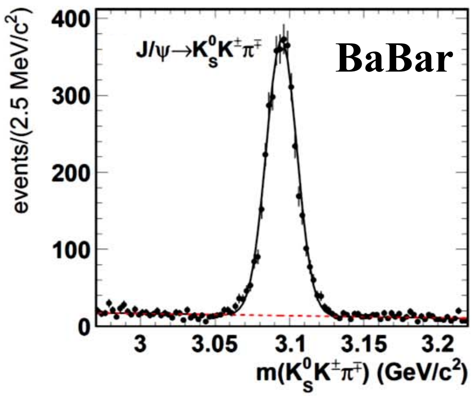




- Yield: ~2,100
- Purity: ~89%

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





- Yield: ~3,900
- Purity: ~93%

Branching fraction ratios

- Dominant systematics: efficiencies
- Using $B(J/\psi \to \pi^+ \pi^- \pi^0) = (2.11 \pm 0.07) \times 10^{-2}$ [PDG] as reference
- $K^+ K^- \pi^0$ final state:

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

  - In agreement with an old measurement from Mark-II with 25 signal events:

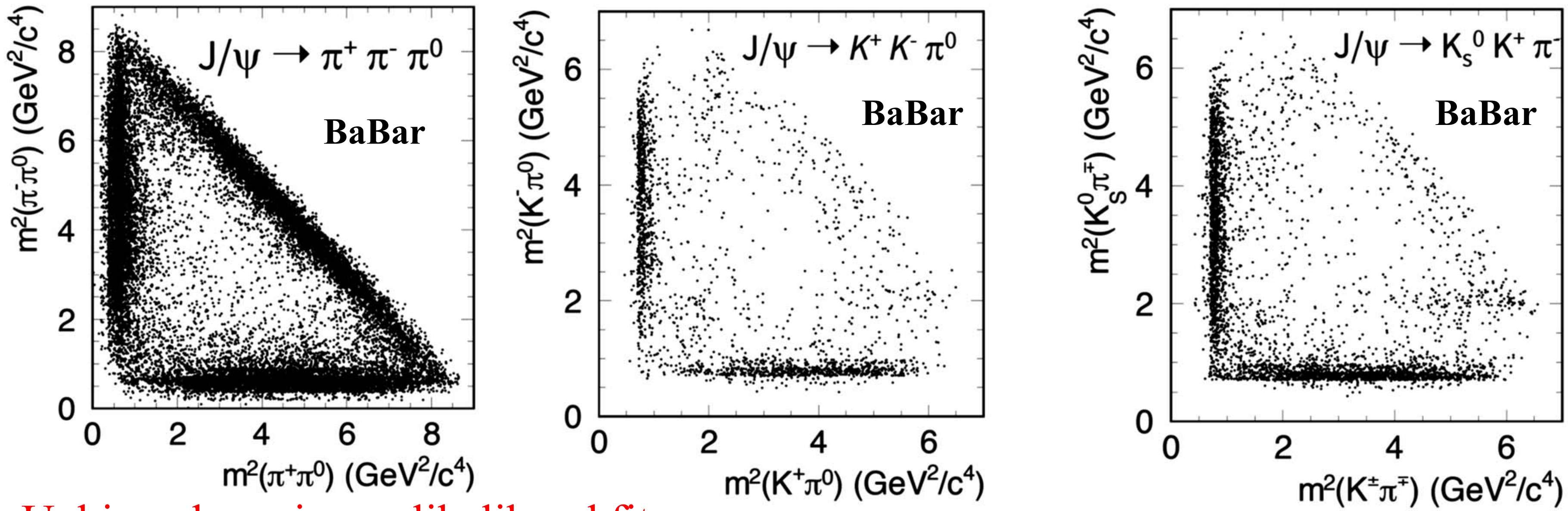
$$\mathcal{B}(J/\psi \to K^+K^-\pi^0) = (2.8 \pm 0.8) \times 10^{-3}$$

- $K_S^0 K^+ \pi^-$ + c.c. final state:

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

  - Result from Mark-I (126 signal events): $\mathcal{B}(J/\psi \to K_S^0 K^\pm \pi^\mp) = (26 \pm 7) \times 10^{-4}$
    $\to$ 3.6 sigmas discrepancy

Dalitz plots



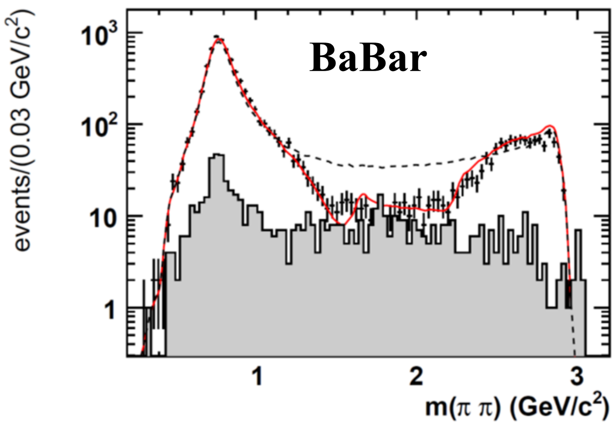
- Unbinned maximum likelihood fits
- J/ψ mass sideband regions used for background estimation
- Isobar model used to describe all three Dalitz plots
  - Sum of interfering resonances: too many partial waves $\Rightarrow$ unconstrained analysis
- Use an alternative model ('Veneziano') for the $J/\psi \to \pi^+ \pi^- \pi^0$ Dalitz plot
  - Based on Regge trajectories instead of resonances
    $\rightarrow$ Strong constraint on amplitude analysis
  - Better description of the high-mass region
  - Szczepaniak, Pennington, PLB737 (2014) 283 / **G. Veneziano, Nuovo Cim. 57, 190 (1968).**

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

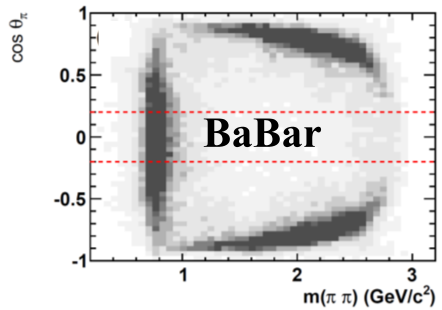
- Isobar model
  - Resonances described by relativistic Breit-Wigner shapes
  - Nominal fit: 8 free parameters

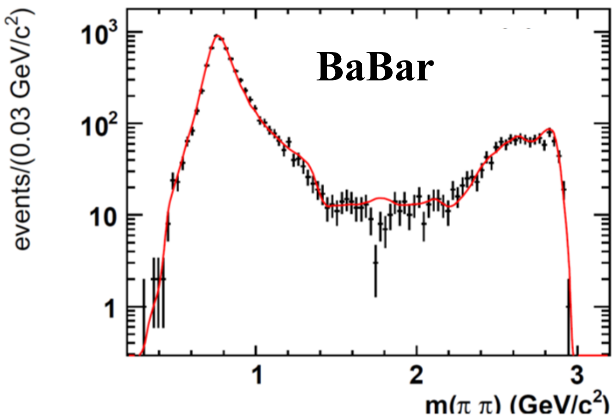
- Veneziano model
  - 7 Regge trajectories
    → 19 free parameters

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		$687/519 = 1.32$		$596/508 = 1.17$



Cut on π^+ helicity angle



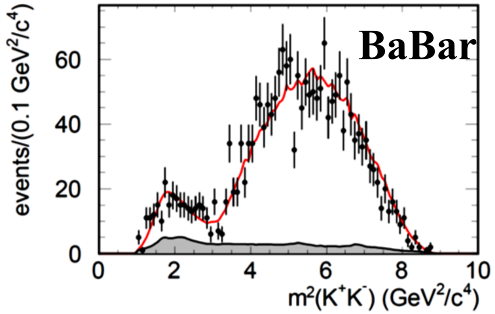


→ Fit results, background from sidebands; dashed line: fit without $\rho(1450)$

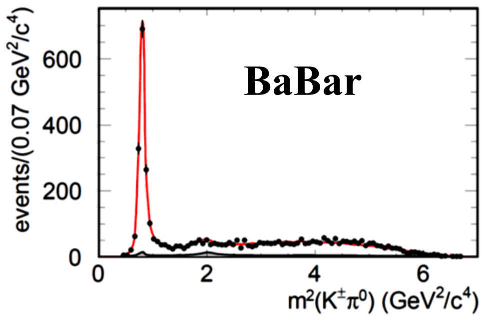
$J/\psi \to K^+ K^- \pi^0$ and $J/\psi \to K_S^0 K^+ \pi^-$ results

- Isobar model only

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



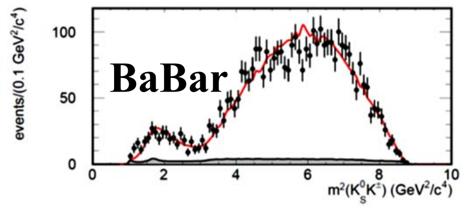
$m^2(K^+K^-)$



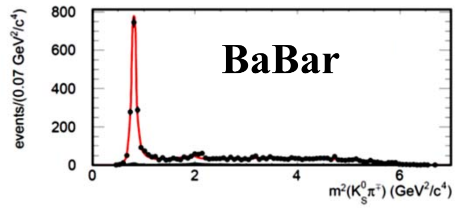
$m^2(K^+\pi^0)$

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	$132/137 = 0.96$	

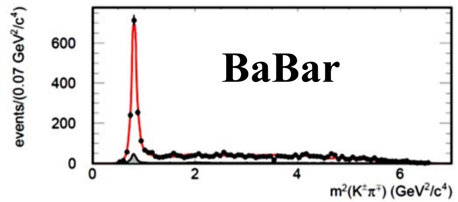
- $J/\psi \to K_S^0 K^+ \pi^-$ and charge conjugate



$m^2(K_S^0K^+)$



$m^2(K_S^0\pi^-)$



$m^2(K^+\pi^-)$

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	$274/217 = 1.26$	

ρ(1450) branching fraction

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

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

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

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

→ Ratio of branching fractions

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

Radiative decays of the $\Upsilon(1S)$

- $\Upsilon(1S)$ radiative decays suppressed by a factor ~25 with respect to J/ψ
  $\rightarrow$ Challenging analysis

- Decays
  - $\Upsilon(1S) \rightarrow \pi^+ \pi^- \gamma$
  - $\Upsilon(1S) \rightarrow K^+ K^- \gamma$

- $\Upsilon(1S)$ production modes
  - $\Upsilon(3S) \rightarrow \pi_s^+ \pi_s^- \Upsilon(1S)$
  - $\Upsilon(2S) \rightarrow \pi_s^+ \pi_s^- \Upsilon(1S)$

  Using $\Upsilon(3S)$ and $\Upsilon(2S)$ on-resonance datasets

  Soft pions

- Branching fractions normalized to the dominant $\Upsilon(1S) \rightarrow \mu^+ \mu^-$ decay
  - ~435,000 events in the $\Upsilon(2S)$ dataset
  - ~132,000 events in the $\Upsilon(3S)$ dataset

  Same number of charged tracks

  $\rightarrow$ For a resonance R:

$$\mathcal{B}(R) = \frac{N_R(\Upsilon(nS)\rightarrow\pi_s^+\pi_s^-\Upsilon(1S)(\rightarrow R\gamma))}{N(\Upsilon(nS)\rightarrow\pi_s^+\pi_s^-\Upsilon(1S)(\rightarrow\mu^+\mu^-))} \times \mathcal{B}(\Upsilon(1S)\rightarrow\mu^+\mu^-)$$

(2.48 ± 0.05)% [PDG]

Υ(1S) event selection

- Exactly four charged tracks with transverse momentum greater than 100 MeV/c
- Exactly one photon with energy greater than 2.5 GeV
- Charged particle identification
  - Very loose: high efficiency, low purity

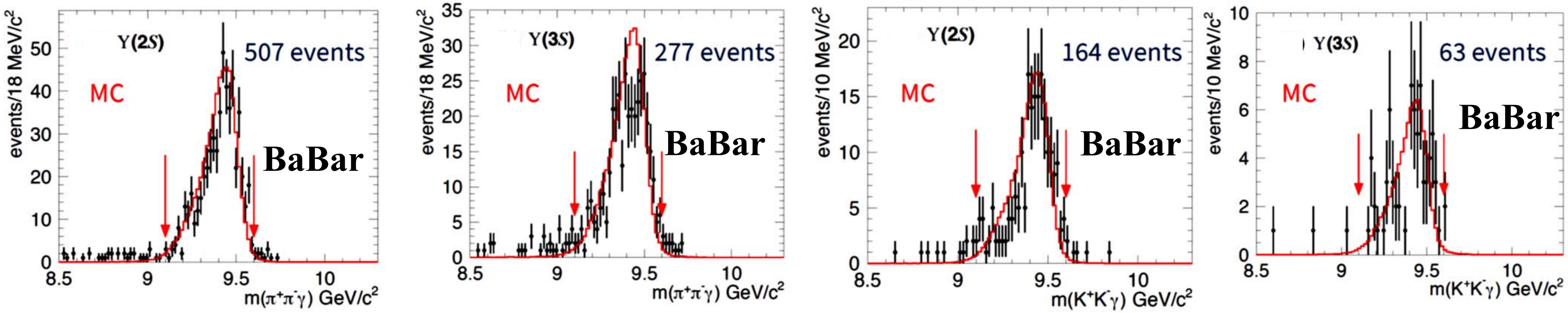
[3-momenta]

- Momentum balance: $\chi^2 = \sum_{i=1}^{3} \frac{(\Delta \mathbf{p}_i - \langle \Delta \mathbf{p}_i \rangle)^2}{\sigma_i^2}$ with $\Delta p_i = p_i^{e^-} + p_i^{e^+} - \left(p_i^{\gamma} + p_i^{\pi_s^+} + p_i^{\pi_s^-} + p_i^{h^+} + p_i^{h^-}\right)$
  - Means and with computed from Monte-Carlo (MC) simulations
- Mass recoiling to the two soft pions close to the Υ(1S) mass

[4-momenta]

  - ± 2.5 σ

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



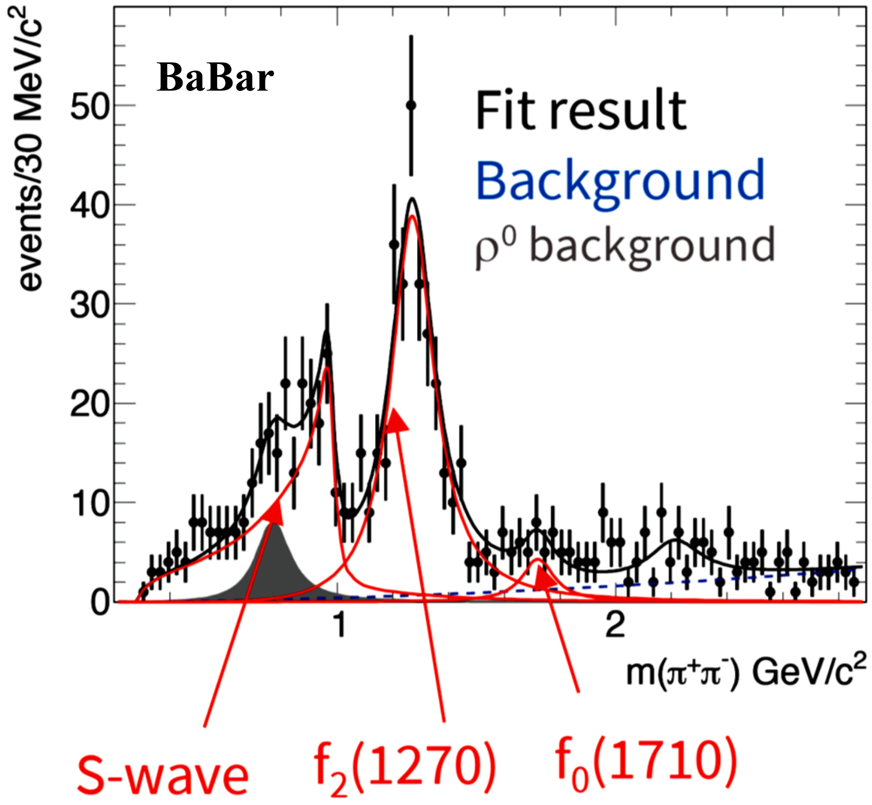
Υ(1S) → $\pi^+\pi^-\gamma$ Υ(1S) → $K^+K^-\gamma$

$\pi^+\pi^-$ mass spectrum

- Simultaneous fit to the $\Upsilon(3S)$ and $\Upsilon(2S)$ datasets – 16 free parameters
  - S-wave: coherent sum of $f_0(500)$ and $f_0(980)$

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

  - $f_2(1270)$ and $f_0(1710)$
  - Combinatorial background
  - ρ_0 background for $\Upsilon(3S)$ dataset



→ Significant S-wave contribution
  - $f_0(500)$ fitted parameters
    $m = 0.856 \pm 0.086$ GeV/c^2
    $\Gamma = 1.279 \pm 0.324$ GeV
  - $\phi = 2.41 \pm 0.43$ rad

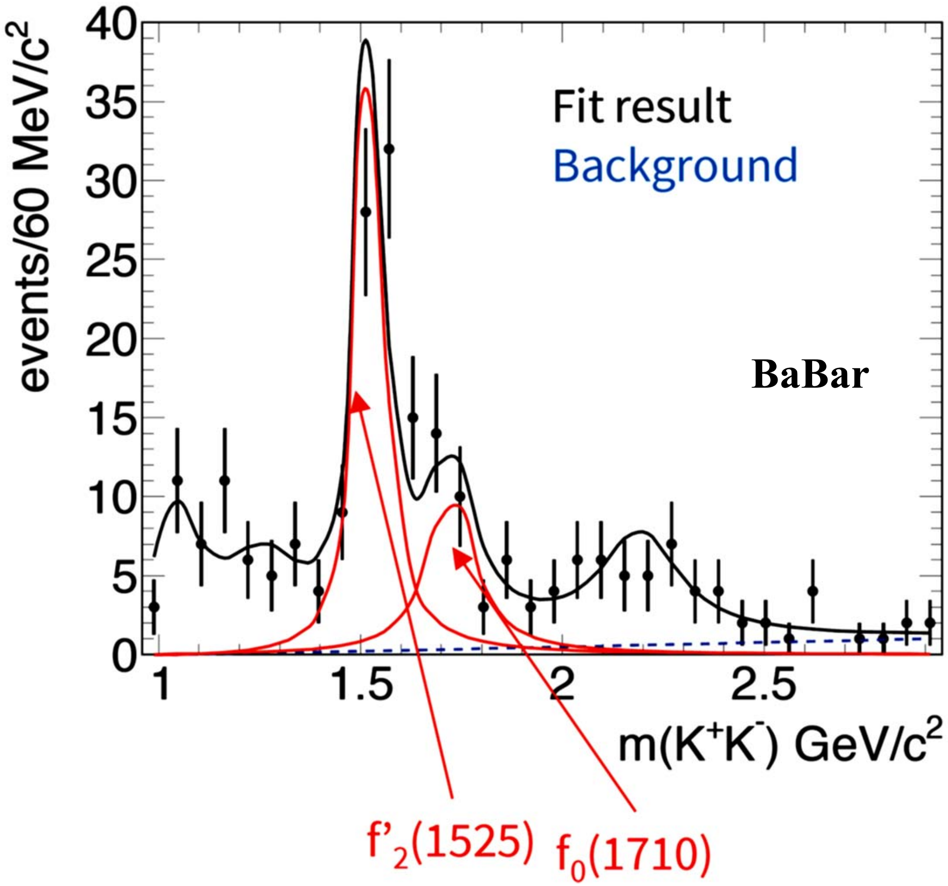
→ Hint for $f_0(1710)$

→ No $f_J(1500)$ visible
  - Contrary to K^+K^- mass spectrum
    → See next slide

Resonances ($\pi^+\pi^-$)	Yield $\Upsilon(2S)$	Yield $\Upsilon(3S)$	Significance (σ)
S-wave	$133 \pm 16 \pm 13$	87 ± 13 (stat only)	12.8
$f_2(1270)$	$255 \pm 19 \pm 8$	$77 \pm 7 \pm 4$	15.9
$f_0(1710)$	$24 \pm 8 \pm 6$	$6 \pm 8 \pm 3$	2.5
$f_0(2100)$	33 ± 9 (stat only)	8 ± 15 (stat only)	
$\rho(770)^0$		54 ± 23 (stat only)	

K^+K^- mass spectrum

- Combination of the 2 K^+K^- spectra
  - 6 free parameters / fit
  - $f_0(980)$
  - $f_2(1270)$
  - $f'_2(1525)$ and $f_0(1500)$
    - Unable to separate contributions
      - → Labelled $f_J(1500)$
      - → Angular analysis needed
  - $f_0(1710)$
  - $f_0(2200)$
  - Combinatorial background



Resonances (K^+K^-)	Yield $\Upsilon(2S) + \Upsilon(3S)$	Significance (σ)
$f_0(980)$	47 ± 9	5.6
$f_J(1500)$	$77 \pm 10 \pm 10$	8.9
$f_0(1710)$	$36 \pm 9 \pm 6$	4.7
$f_2(1270)$	15 ± 8	
$f_0(2200)$	38 ± 8	

Branching fractions

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

Good agreement with CLEO

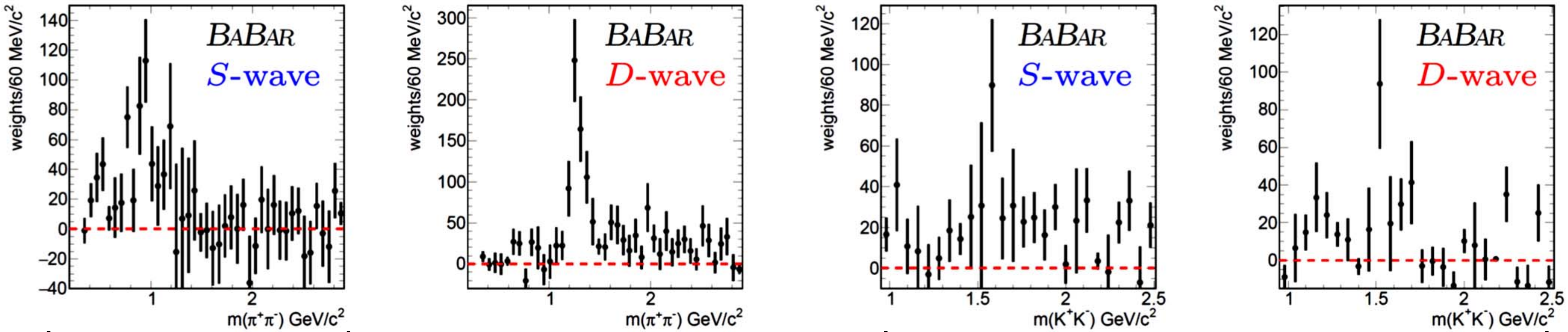
- $f_0(1710)$ combined significance: 5.7 σ
  → First observation in $\Upsilon(1S)$ radiative decays
- Measurement $\dfrac{\mathcal{B}(f_0(1710)\to\pi\pi)}{\mathcal{B}(f_0(1710)\to K\bar{K})} = \boxed{0.64 \pm 0.27_{\rm stat} \pm 0.18_{\rm sys}}$

in agreement with the world average value of $0.41^{+0.11}_{-0.17}$

Angular analysis

- Partial wave analysis (PWA)
  - Efficiency-corrected mass spectra weighted by Legendre polynomial moments(θ_H)

  → S- and D-wave contributions for both final states

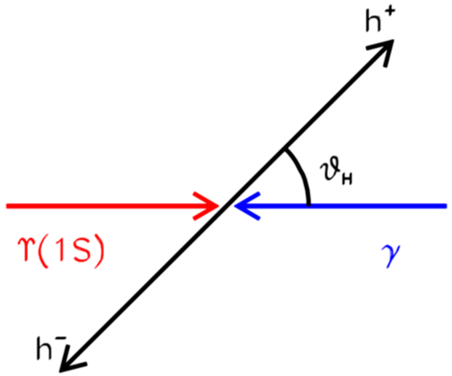


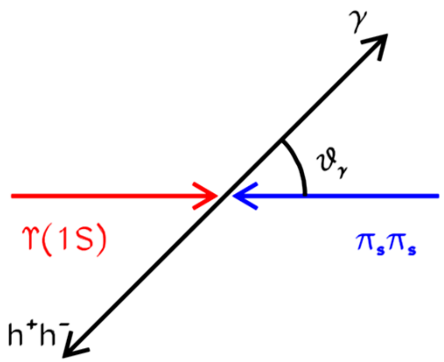
Consistent with mass spectrum fit

Evidence for both $f_0(1500)$ and $f'_2(1525)$

- Full angular analysis in resonance mass windows
  - $f_2(1270) \rightarrow \pi^+ \pi^-$
  - S-wave $\rightarrow \pi^+ \pi^-$
  - $f'_2(1525) \rightarrow K^+K^-$

  → In agreement with PWA





Outlook

- High-statistics Dalitz plot analysis of J/ψ decays
  - Comparison of Isobar and Veneziano models for $J/\psi \to \pi^+ \pi^- \pi^0$
    $\to$ Complementary description of resonance structure
  - First measurement of $J/\psi \to K_S^0 K^+ \pi^-$ and charge conjugate

$\to$ PRD95 (2017) 072007

- Studies of radiative $\Upsilon(1S) \to \pi^+ \pi^- \gamma$ and $\Upsilon(1S) \to K^+ K^- \gamma$ decays
  - Observation of various resonances:
    broad S-wave, $f_0(980)$, $f_2(1270)$, $f_0(1710)$, $f'_2(1525)$ and $f_0(1500)$
    $\to$ Observation of the $f_0(1710)$ state in these decays
  - Spin-parity and branching fraction measurements

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