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

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On behalf of the *BABAR* Collaboration

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Physics Motivations: Search for gluonium

☐ The search for gluonium states is still a hot topic for QCD (Y. Chen et al., Phys. Rev. D **73**, 014516 (2006)).

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

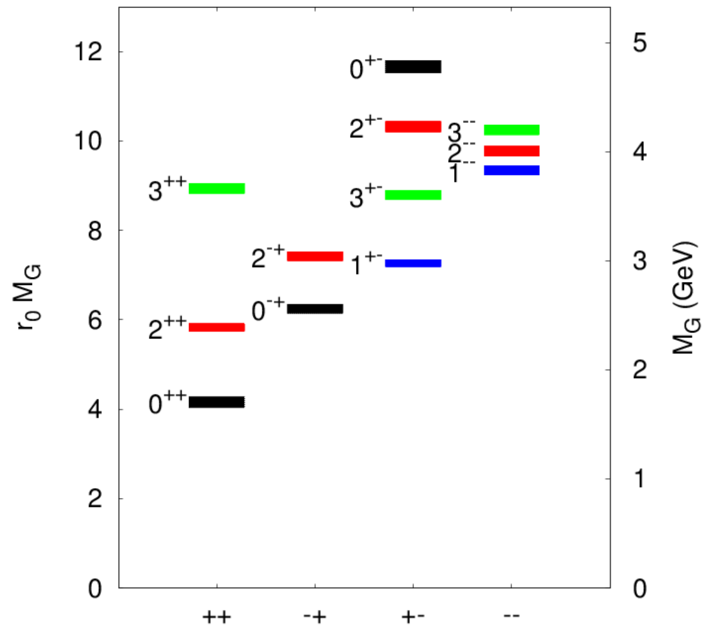
☐ Scalar gluonium candidates are

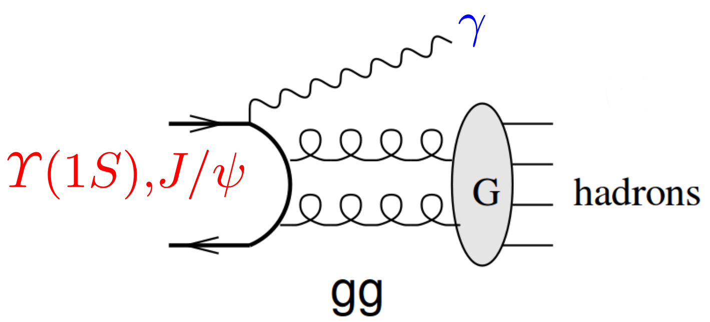
$f_0(500)$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$

☐ 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.

☐ Taking into account the total widths of J/ψ and $\Upsilon(1S)$, and the factor $(\frac{q_b}{q_c})^2(\frac{m_c}{m_b})^2$, radiative $\Upsilon(1S)$ decays are expected to be suppressed by a factor 25.





Analysis Strategy

□ First study of radiative $\Upsilon(1S)$ decays from CLEO (Phys.Rev. D73, (2006) 032001)

□ The data were affected by a large background from $e^+e^- \to \gamma\ Vector$.

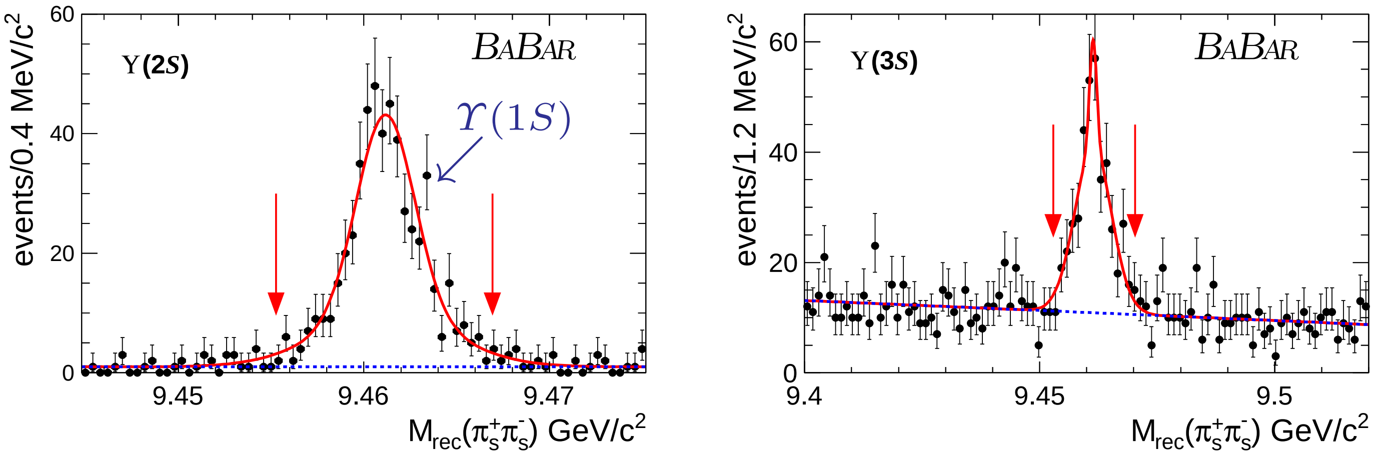
□ In the present analysis (arXiv:1804.04044) we make use of $\Upsilon(2S)$ and $\Upsilon(3S)$ decays with integrated luminosities of 13.6 and 28.0 fb^{-1}.

□ We reconstruct the decay chains:

$$\Upsilon(2S)/\Upsilon(3S) \to \pi_s^+\pi_s^-\Upsilon(1S) \to \gamma\pi^+\pi^-$$
$$\to \gamma K^+K^-$$

□ Require momentum balance and compute the recoiling mass

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

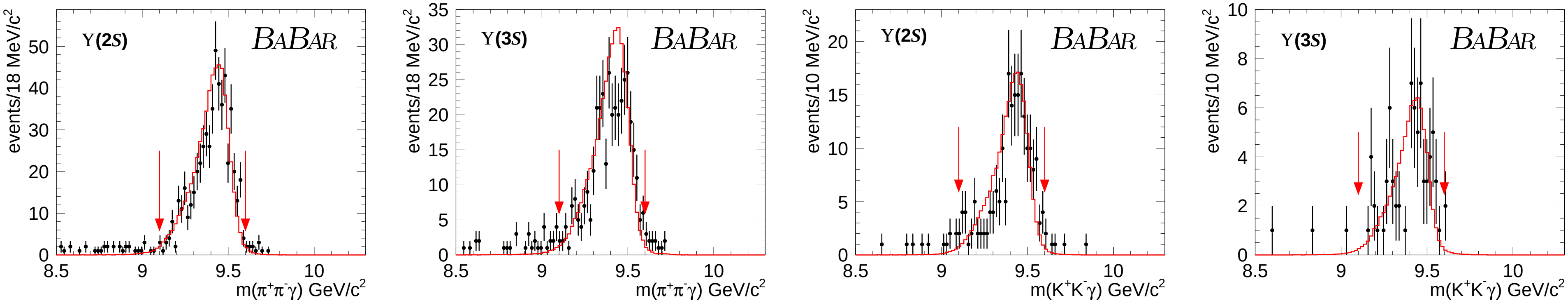


Events reconstruction

□ Select events in the region:

$$|M_{\rm rec}(\pi_s^+\pi_s^-) - m(\Upsilon(1S))_f| < 2.5\sigma,$$

apply “very loose” particle identification and plot the $\pi^+\pi^-\gamma$ and $K^+K^-\gamma$ masses.



□ In red are signal $\Upsilon(1S)$ Monte Carlo simulations.

□ We isolate the decay $\Upsilon(1S)\to\gamma h^+h^-$ requiring

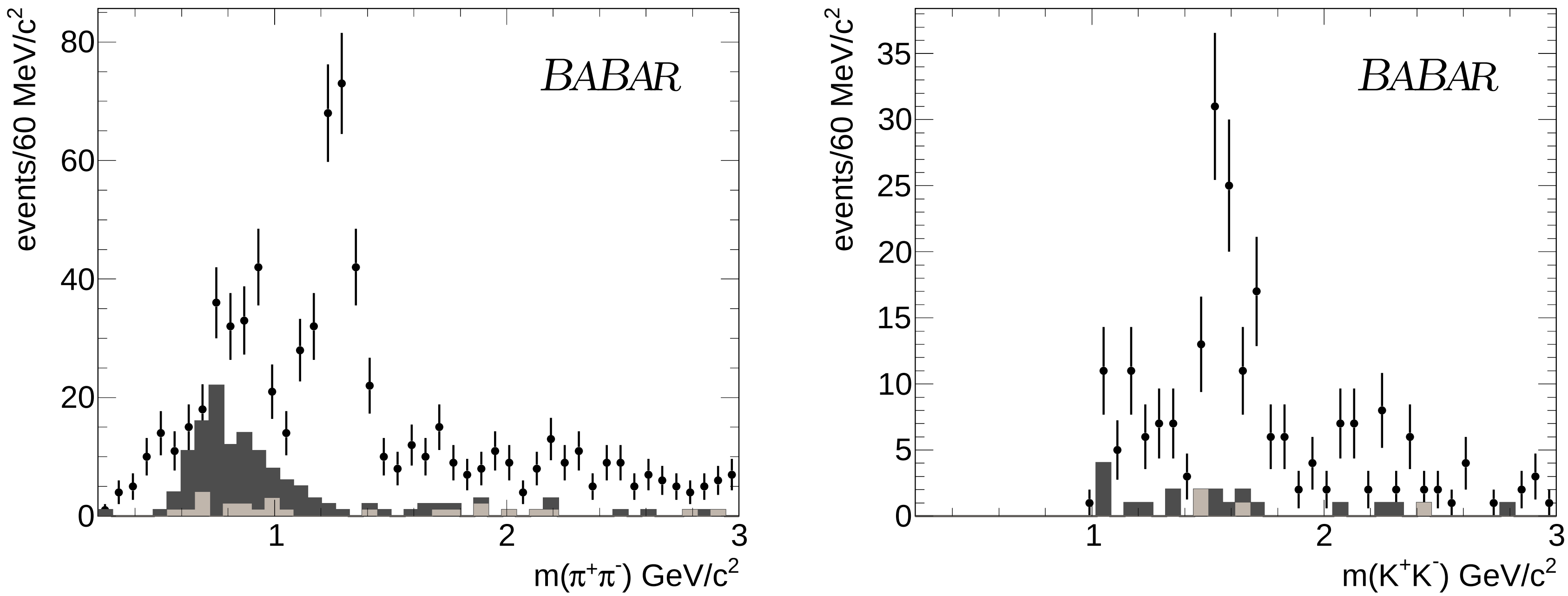
$$\boxed{9.1\ {\rm GeV}/c^2 < m(\gamma h^+h^-) < 9.6\ {\rm GeV}/c^2}$$

□ Yields

Final state	Yield $\Upsilon(2S)$	Yield $\Upsilon(3S)$
$\gamma\pi^+\pi^-$	507	277
γK^+K^-	164	63

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

□ Observe rich resonance production.



□ Background is studied using the $M_{\rm rec}(\pi_s^+\pi_s^-)$ sidebands.

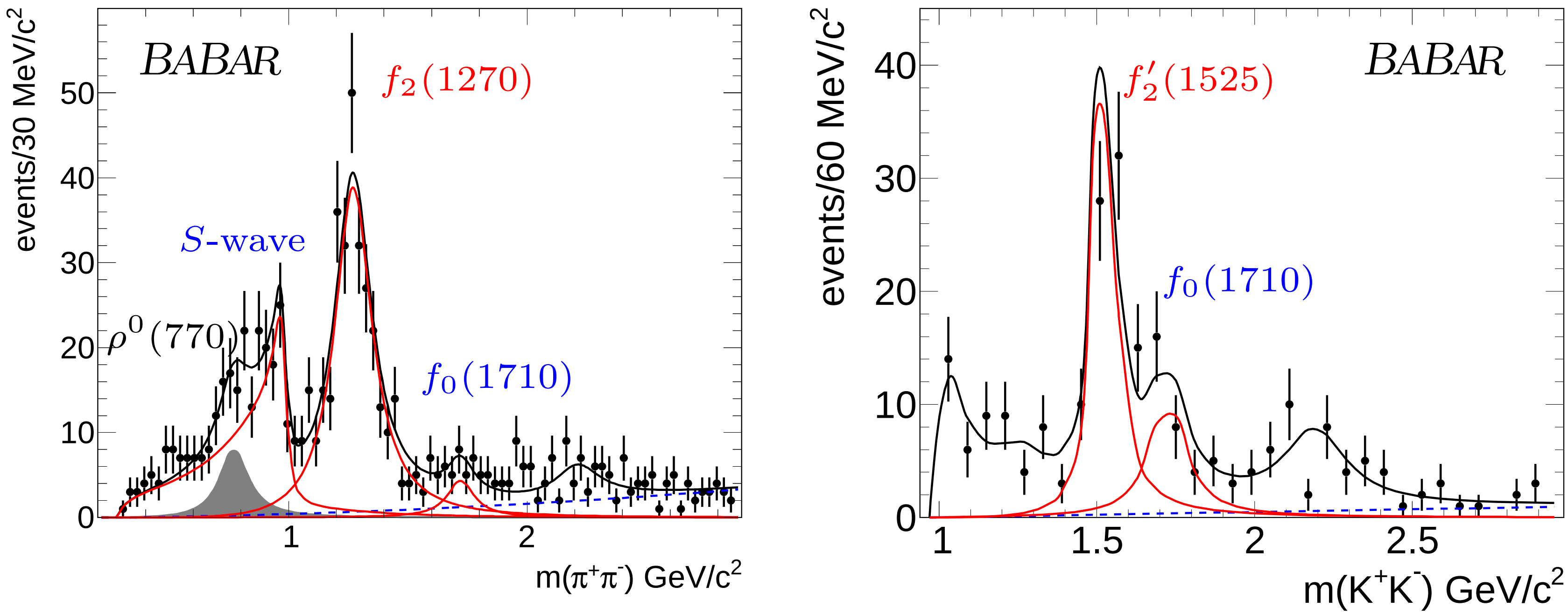
Background contributions. $\Upsilon(3S)$: Dark grey, $\Upsilon(2S)$: Light grey

□ Data from $\Upsilon(2S)$ almost background free.

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

□ Background from $\Upsilon(1S)\to\pi^+\pi^-\pi^0$ with a missing γ consistent with zero.

Fits to the uncorrected $\pi^+\pi^-$ and K^+K^- mass spectra



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

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

- □ The $f_0(980)$ described by a coupled channel Breit-Wigner.
- □ For $f_0(500)$ we obtain:

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

- □ Also included contributions from $f_0(2100) \to \pi^+\pi^-$ and $f_0(2200) \to K^+K^-$.

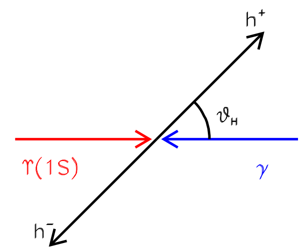
Fitted yields

- □ Simultaneous fit to the $\Upsilon(2S)$ and $\Upsilon(3S)$ data for $\Upsilon(1S)\rightarrow\gamma\pi^+\pi^-$.
- □ $\Upsilon(2S)$ and $\Upsilon(3S)$ data combined for $\Upsilon(1S)\rightarrow\gamma K^+K^-$.

Resonances ($\pi^+\pi^-$)	Yield $\Upsilon(2S)$	Yield $\Upsilon(3S)$	Significance
S-wave	$133 \pm 16 \pm 13$	87 ± 13	12.8σ
$f_2(1270)$	$255 \pm 19 \pm 8$	$77 \pm 7 \pm 4$	15.9σ
$f_0(1710)$	$24 \pm 8 \pm 6$	$6 \pm 8 \pm 3$	2.5σ
Resonances (K^+K^-)	Yield $\Upsilon(2S) + \Upsilon(3S)$		Significance
$f_0(980)$	47 ± 9		5.6σ
$f_J(1500)$	$77 \pm 10 \pm 10$		8.9σ
$f_0(1710)$	$36 \pm 9 \pm 6$		4.7σ

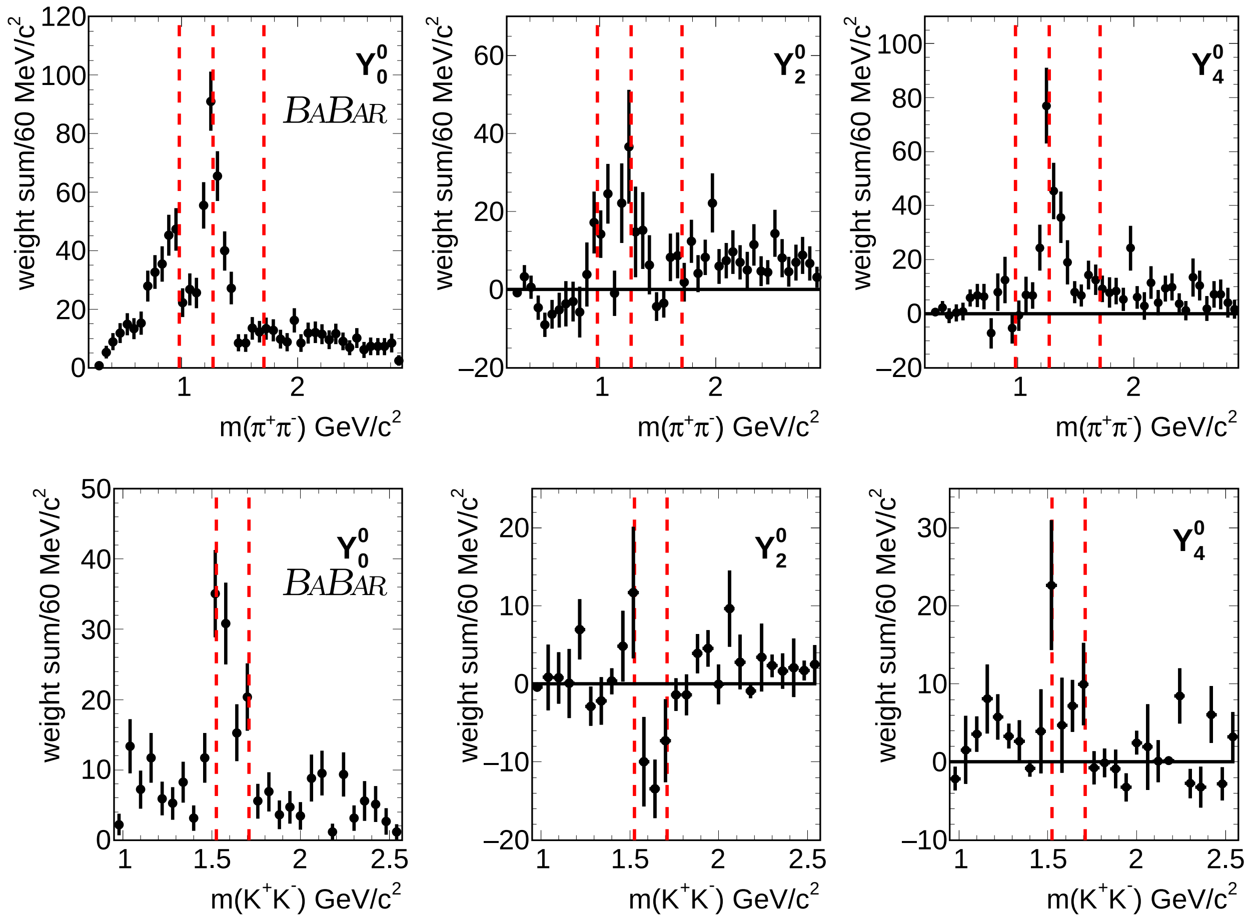
- □ We label with $f_J(1500)$ the total enhancement in the 1500 MeV mass region.
- □ The combined $f_0(1710)$ significance is 5.7σ.
- □ Systematic uncertainties dominated by the uncertainties on PDG resonances parameters.

Legendre polynomial moments



- We define the helicity angle θ_H as the angle formed by the h^+ (where $h = \pi, K$), in the h^+h^- rest frame, and the γ in the $h^+h^-\gamma$ rest frame.

- Efficiency corrected $\pi^+\pi^-$ and K^+K^- mass spectra weighted by Legendre polynomial moments $Y_L^0(cos\theta_H)$.



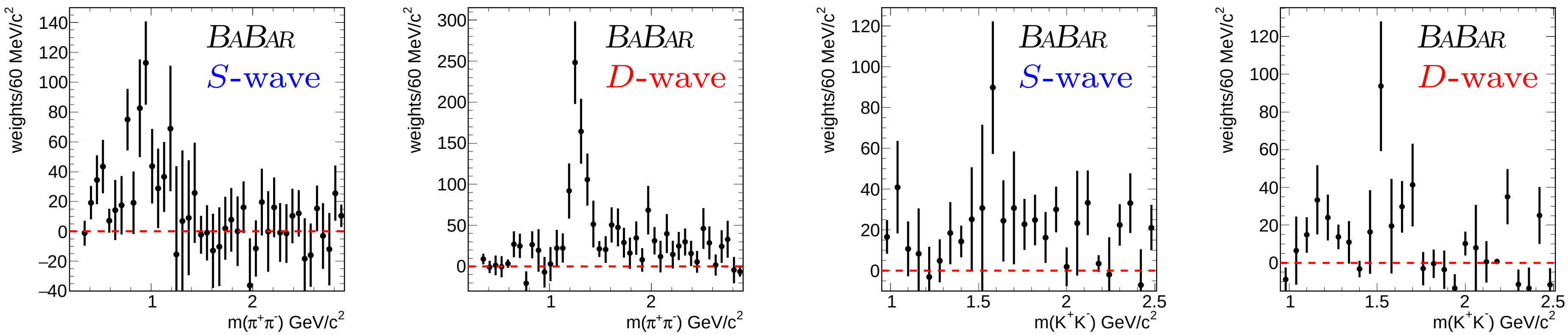
- Y_2^0 is related to the S-D interference, visible at the $f_2(1270)$ and $f_2'(1525)$ masses.
- Y_4^0 is related to D-wave, visible at the $f_2(1270)$ and $f_2'(1525)$ masses.

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 efficiency corrected S-wave$\to\pi^+\pi^-$ yield

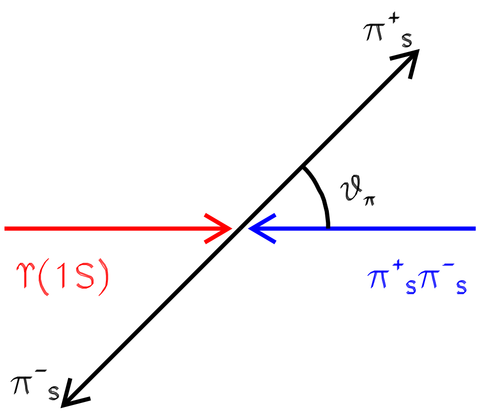
$$N(S\!-\!\text{wave}) = 629 \pm 128,$$

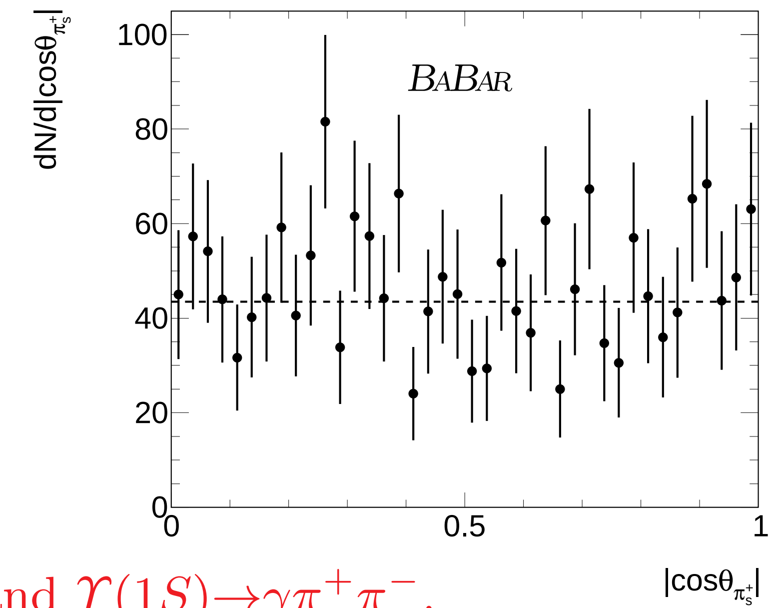
in agreement with the results from the fit to the $\pi^+\pi^-$ mass spectrum.

□ The K^+K^- mass spectrum shows evidence for both $f_0(1510)$ and $f_2'(1525)$.

$\pi_s^+\pi_s^-$ system angular analysis.

□ We compute the helicity angle θ_π defined as the angle formed by the π_s^+, in the $\pi_s^+\pi_s^-$ rest frame, with respect to the direction of the $\pi_s^+\pi_s^-$ system in the $\Upsilon(1S)\pi_s^+\pi_s^-$ rest frame.



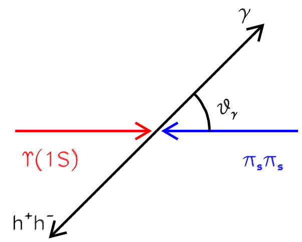


□ $|cos\theta_\pi|$ distribution for the $\Upsilon(2S)$ data and $\Upsilon(1S)\rightarrow\gamma\pi^+\pi^-$.

□ This distribution is expected to be uniform if $(\pi_s^+\pi_s^-)$ is an S-wave system.

□ The distribution is consistent with this hypothesis with a p-value of 65%.

Full angular analysis.



□ We define θ_γ as the angle formed by the radiative photon in the $h^+h^-\gamma$ rest frame with respect to the $\Upsilon(1S)$ direction in the $\Upsilon(2S)/\Upsilon(3S)$ rest frame.

□ For $\Upsilon(nS)\to\pi_s^+\pi_s^-\Upsilon(1S)(\to\gamma R)$, the expected angular distribution for a spin 2 resonance R is given by (arXiv:1804.04044)

$$\begin{aligned} W_2(\theta_\gamma,\theta_H) = \frac{dU(\theta_\gamma,\theta_H)}{d\cos\theta_\gamma\, d\cos\theta_H} \quad = \quad & \frac{15}{1024}|E_{00}|^2 \Big[6|A_{01}|^2 \left(22|C_{10}|^2 + 8|C_{11}|^2 + 9|C_{12}|^2\right) + \\ & 2|A_{00}|^2 \left(22|C_{10}|^2 + 24|C_{11}|^2 + 9|C_{12}|^2\right) + \\ & 24\left(|A_{00}|^2 + 3|A_{01}|^2\right)\left(2|C_{10}|^2 - |C_{12}|^2\right)\cos 2\theta_H + \\ & 6\left(|A_{00}|^2 \left(6|C_{10}|^2 - 8|C_{11}|^2 + |C_{12}|^2\right) + \right. \\ & \left. |A_{01}|^2 \left(18|C_{10}|^2 - 8|C_{11}|^2 + 3|C_{12}|^2\right)\right)\cos 4\theta_H - \\ & 2\left(|A_{00}|^2 - |A_{01}|^2\right)\cos 2\theta_\gamma \left(22|C_{10}|^2 - 24|C_{11}|^2 + 9|C_{12}|^2 + \right. \\ & 12\left(2|C_{10}|^2 - |C_{12}|^2\right)\cos 2\theta_H + \\ & \left. 3\left(6|C_{10}|^2 + 8|C_{11}|^2 + |C_{12}|^2\right)\cos 4\theta_H\right)\Big]. \end{aligned} \tag{1}$$

□ The expected angular distribution for a spin 0 resonance is given by

$$W_0(\theta_\gamma) = \frac{dU(\theta_\gamma)}{d\cos\theta_\gamma} = \frac{3}{8}|C_{10}|^2|E_{00}|^2 \left(|A_{00}|^2 + 3|A_{01}|^2 - (|A_{00}|^2 - |A_{01}|^2)\cos 2\theta_\gamma\right).$$

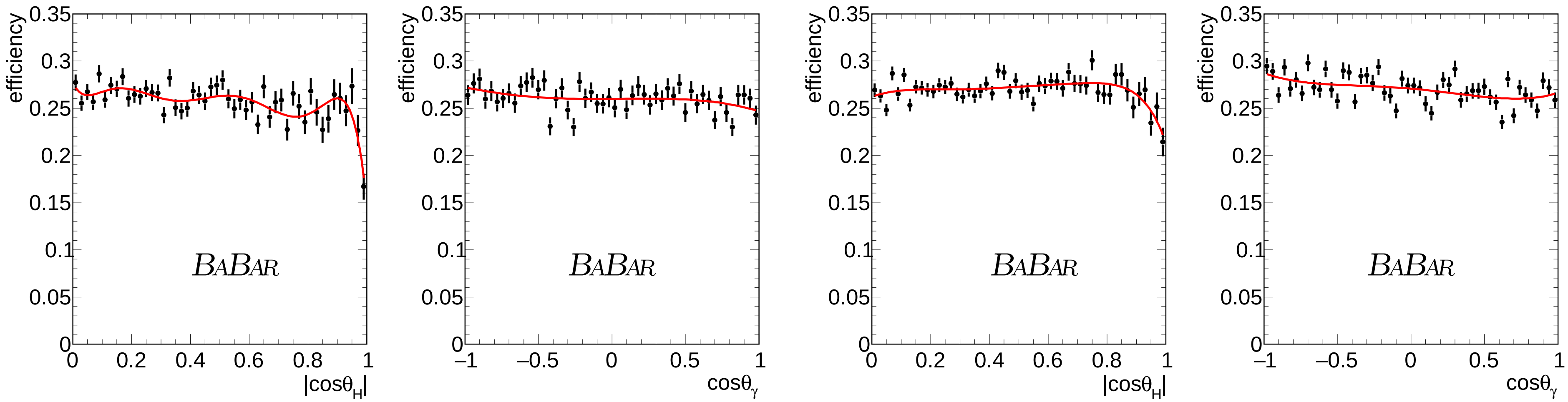
□ The A_{ij} and C_{kl} represent the helicity contributions.

Fits to the angular distributions

- □ We perform a 2D unbinned maximum likelihod fits in the resonances mass windows.

$$\mathcal{L} = \prod_{n=1}^{N} \Big[f_{\rm sig} \frac{\epsilon(\cos\theta_H, \cos\theta_\gamma) W_s(\theta_H, \theta_\gamma)}{\int W_s(\theta_H, \theta_\gamma)\epsilon(\cos\theta_H, \cos\theta_\gamma) d\cos\theta_H d\cos\theta_\gamma} +$$
$$(1 - f_{\rm sig}) \frac{\epsilon(\cos\theta_H, \cos\theta_\gamma) W_b(\theta_H, \theta_\gamma)}{\int W_b(\theta_H, \theta_\gamma)\epsilon(\cos\theta_H, \cos\theta_\gamma) d\cos\theta_H d\cos\theta_\gamma} \Big]$$

- □ f_{sig} is the signal fraction and $\epsilon(\cos\theta_H, \cos\theta_\gamma)$ is the fitted efficiency.
- □ W_s and W_b are the functions describing signal and background (due to the the tails of nearby adjacent resonances) contributions.
- □ Efficiency distributions in the $f_2(1270)$ and $f_2'(1525)$ mass regions.



Resonances full angular analysis

□ Unbinned maximum likelihod fits in the resonances mass windows.

$f_2(1270)\to\pi^+\pi^-$

In grey background from S-wave

S-wave$\to\pi^+\pi^-$

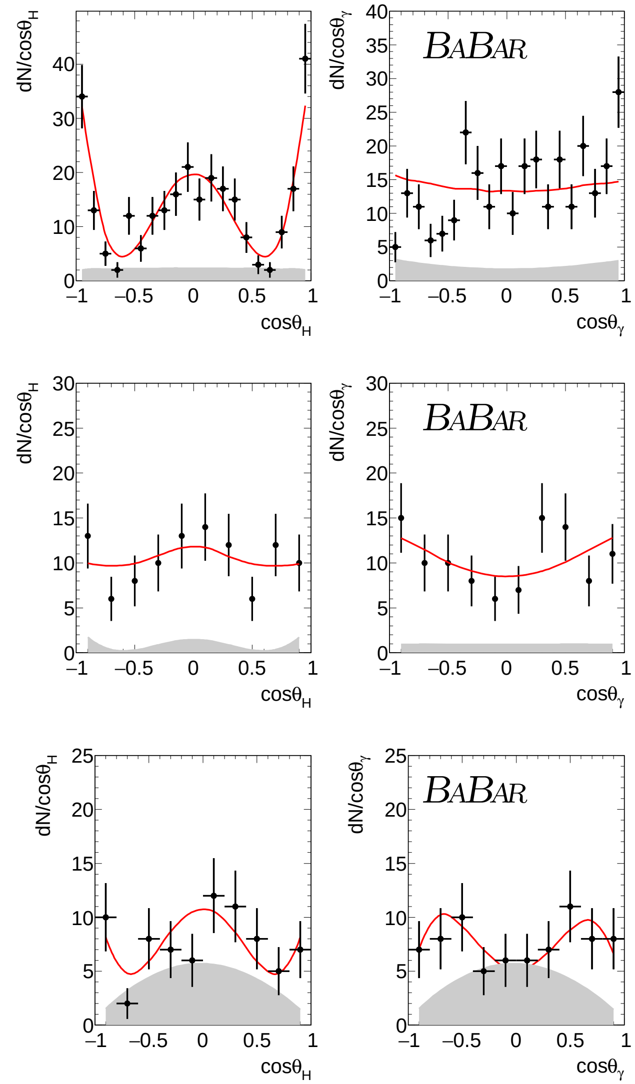
$\Upsilon(2S)$ data only

In grey background from $f_2(1270)$

$f_2'(1525)\to K^+K^-$

In grey contribution from $f_0(1500)$

□ We obtain a $f_0(1500)$ contribution of $(52 \pm 14)\%$, in agreement with the results from the simple PWA.



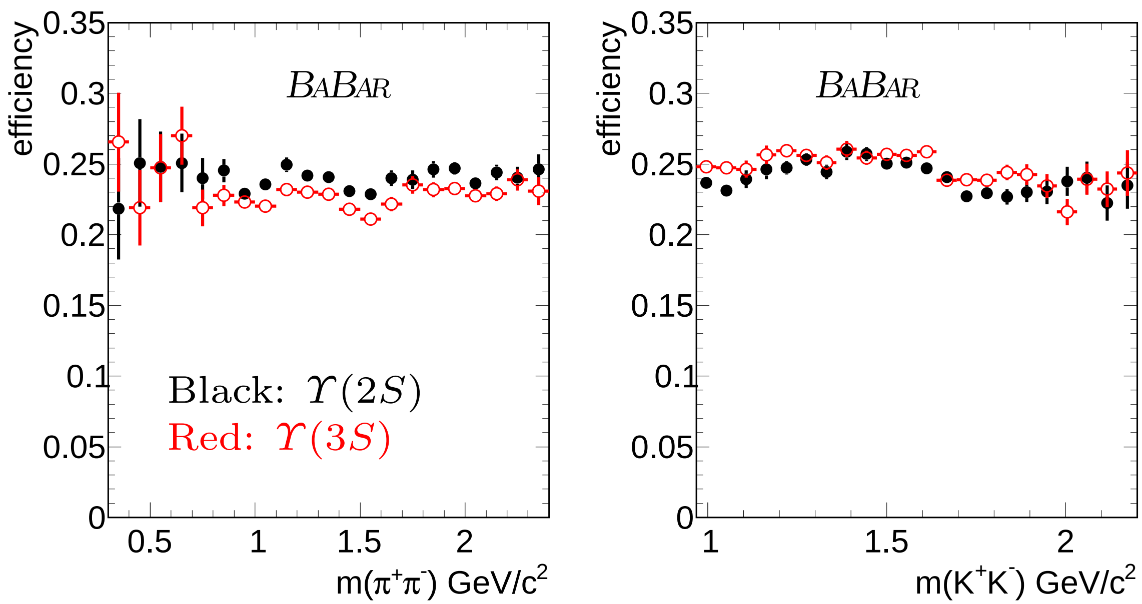
Efficiency corrections

□ To obtain the efficiency correction weight w_R for the resonance R we divide each event by the efficiency $\epsilon(\cos\theta_H, \cos\theta_\gamma)$

$$w_R = \frac{\sum_{i=1}^{N_R} 1/\epsilon_i(\cos\theta_H, \cos\theta_\gamma)}{N_R},$$

where N_R is the number of events in the resonance mass range.

□ Efficiency consistent with being uniform as a function of mass.



Evaluation of the Branching fractions

□ We determine the branching fraction $\mathcal{B}(R)$ for the decay of $\Upsilon(1S)$ to photon and resonance R using the expression

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

where N_R indicates the efficiency-corrected yield for the given resonance.

□ We make use of the reference channel $\Upsilon(1S)\to\mu^+\mu^-$ which has the same number of charged tracks.

□ $\mathcal{B}(\Upsilon(1S)\to\mu^+\mu^-) = 2.48 \pm 0.05\%$ (from PDG).

□ The reference channel yields are

$$N(\Upsilon(2S)\to\pi_s^+\pi_s^-\Upsilon(1S)(\to\mu^+\mu^-)) = (4.35 \pm 0.12_{\rm sys}) \times 10^5$$

and

$$N(\Upsilon(3S)\to\pi_s^+\pi_s^-\Upsilon(1S)(\to\mu^+\mu^-)) = (1.32 \pm 0.04_{\rm sys}) \times 10^5$$

Measured $\Upsilon(1S)\to\gamma R$ 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 between BaBar and CLEO for $f_2(1270)$ and $f_J(1500)$.

□ We report the first observation of $f_0(1710)$ in $\Upsilon(1S)$ radiative decay with a significance of 5.7σ and measure

$$\frac{\mathcal{B}(f_0(1710)\to\pi\pi)}{\mathcal{B}(f_0(1710)\to K\bar{K})} = 0.64 \pm 0.27_{\text{stat}} \pm 0.18_{\text{sys}},$$

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

Summary and conclusions

□ We have studied the $\Upsilon(1S)$ radiative decays to $\gamma\pi^+\pi^-$ and γK^+K^- using *BABAR* data recorded at center-of-mass energies at the $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances.

□ We report the observation of broad S-wave, $f_0(980)$, $f_2(1270)$, $f_0(1710)$, $f_2'(1525)$ and $f_0(1500)$ resonances.

□ For $f_0(1710)$, Ref.(R. Zhu, JHEP **1509**, 166 (2015)), in the gluonium hypothesis, predicts $\mathcal{B}(\Upsilon(1S)\to\gamma f_0(1710) = 0.96^{+0.55}_{-0.23} \times 10^{-4}$. Due to the presence of additional decay modes our result is consistent as well as for the dominance of an $s\bar{s}$ decay mode.

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

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

□ These results may contribute to the long-standing issue of the identification of a scalar glueball.