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Related Subjects

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

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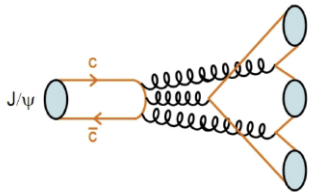
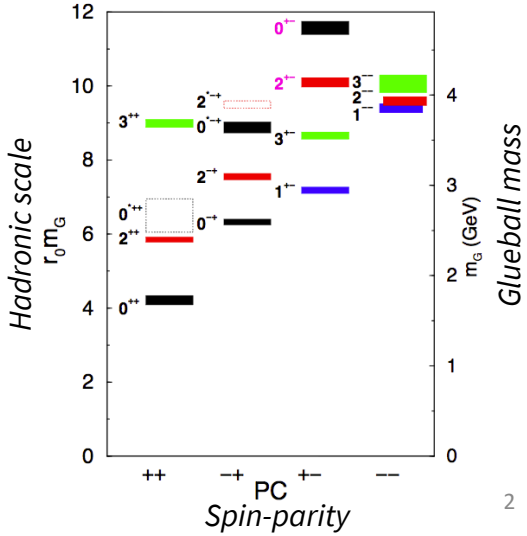
Radiative and hadronic decays of quarkonium

- Radiative or hadronic quarkonium decays can be used to perform spectroscopy of light mesons (f_J, K^*, …).
- They provide also a good laboratory to explore « exotic » QCD states like multiquark states or glueball (bound states of gluons).
- The lowest state $J^{PC}=0^{++}$ is expected to have a mass around 1.5 GeV/c^2, accessible in quarkonium decays.
- One possible candidate for this state could be the $f_0(1710)$ for which more experimental information is important.
- Good understanding of the decay characteristics is crucial: requires very low background which can be achieved for quarkonium produced in e^+e^- collisions.

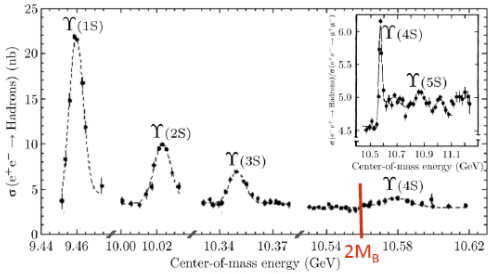


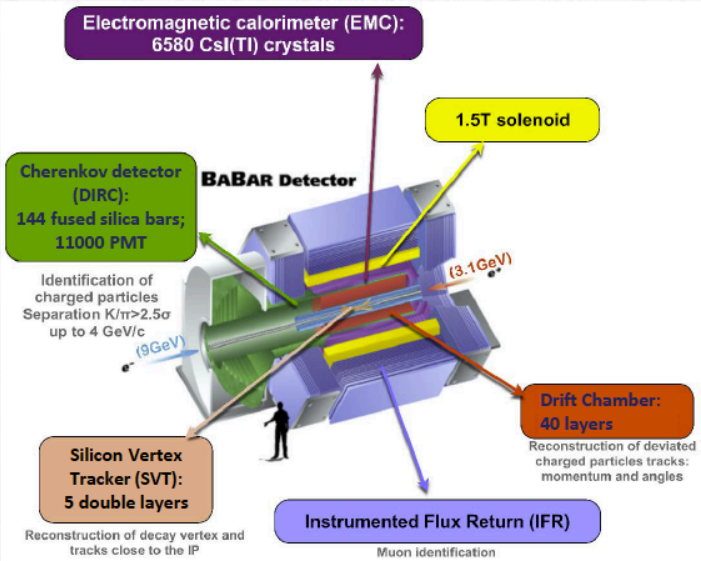
[C. Morningstar, M. Peardon, PRD60 (1999) 034509]

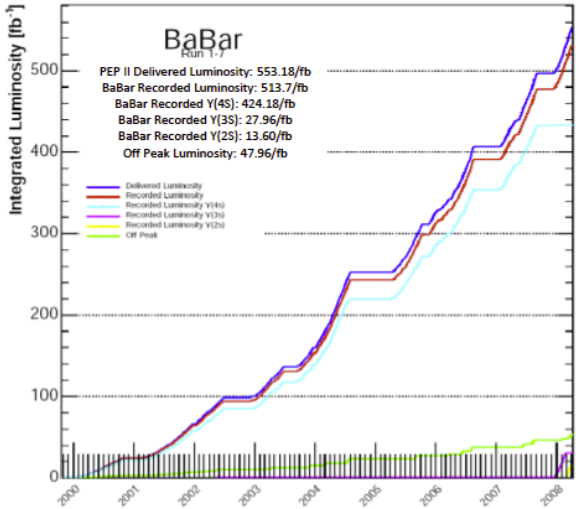


The BaBar experiment

- Asymmetric e^+e^- collisions at 10.58 GeV center of mass energy: 0.5 ab^{-1} *i.e.* 670×10^6 $c\bar{c}$ pairs for J/ψ studies.
- 14 fb^{-1} and 28 fb^{-1} at Y(2S) and Y(3S) peaks.



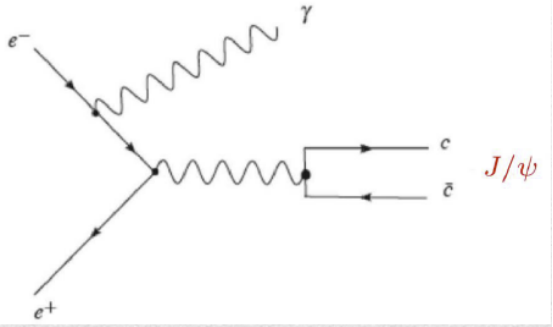




[PRD95 (2017) 072007]

Dalitz plot analysis of J/ψ decays

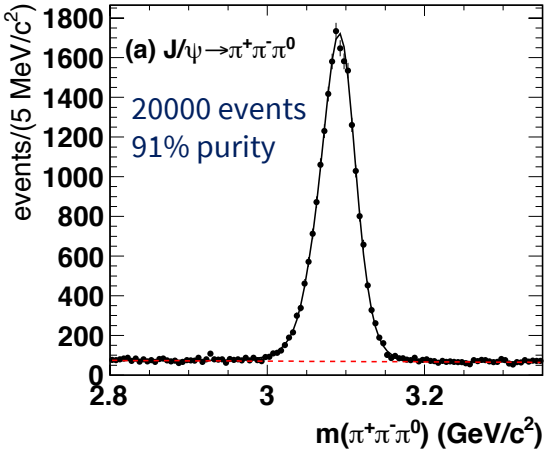
- Results on Dalitz plot analysis of the decays:
  - $J/\psi \rightarrow \pi^+ \pi^- \pi^0$,
  - $J/\psi \rightarrow K^+ K^- \pi^0$,
  - $J/\psi \rightarrow K_s^0 K^+ \pi^-$ + charge conjugate.
- Produced via e^+e^- annihilation with initial-state radiation (ISR):
  - Photon most of the time undetected.
  - Only J/ψ produced: no background from underlying event.
- Investigate these decays with large statistics:
  - $J/\psi \rightarrow \pi^+ \pi^- \pi^0$ shows complex structure with high mass resonances which are investigated with models implementing Regge asymptotics (Veneziano models).
  - $J/\psi \rightarrow K_s^0 K^+ \pi^-$: first Dalitz plot analysis.

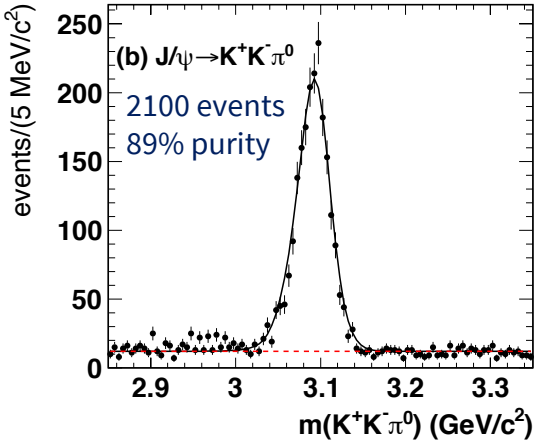


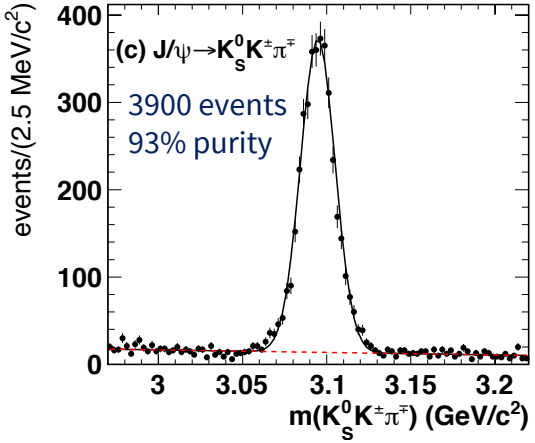
[PRD95 (2017) 072007]

J/ψ event selection

- $J/\psi \to K_s^0 K^+ \pi^-$, $K_s^0 \to \pi^+ \pi^-$: 4 tracks and K_s^0 distance to interaction point > 2 mm.
- $J/\psi \to \pi^+ \pi^- \pi^0$ and $J/\psi \to K^+ K^- \pi^0$: 2 tracks and E(γ)>100 MeV.
- Particle identification for charged K and π.
- To select J/ψ coming from ISR events:
  - $\left|(p_{e^+} + p_{e^-}) - (p_{h^+} + p_{h^-} + p_{\pi^0})\right|^2 < 2\ \mathrm{GeV}^2$ or $\left|(p_{e^+} + p_{e^-}) - (p_{K_S^0} + p_{K^-} + p_{\pi^+})\right|^2 < 1.5\ \mathrm{GeV}^2$.
  - If ISR photon is in calorimeter acceptance, require measurement compatible with its properties.
- Background from $e^+e^- \to \gamma\, \pi^+ \pi^-$ rejected with $|\cos\theta_\pi| < 0.95$ where θ_π is helicity angle of pion for the ππ system.



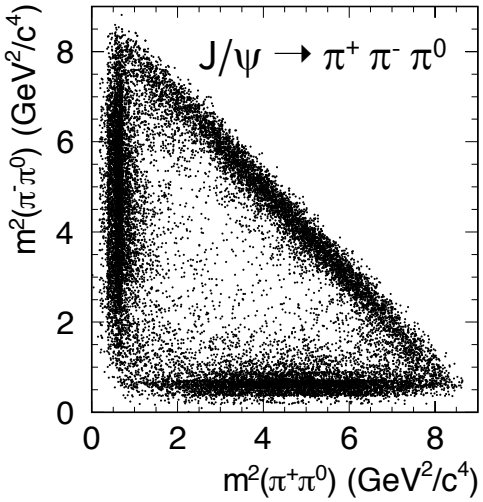


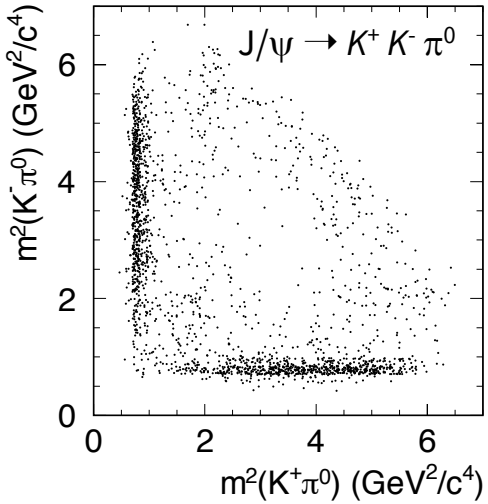


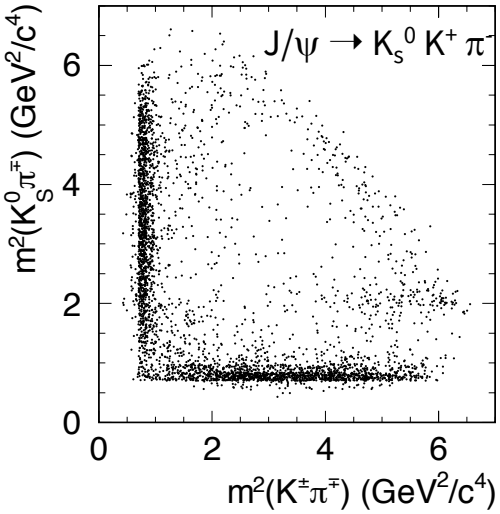
[PRD95 (2017) 072007]

J/ψ branching fractions and Dalitz plots

- $\mathcal{R}_1 = \frac{\mathcal{B}(J/\psi \to K^+K^-\pi^0)}{\mathcal{B}(J/\psi \to \pi^+\pi^-\pi^0)}$ = 0.120 ± 0.003 (stat) ± 0.009 (syst) [PDG: 0.133 ± 0.038 [MARK II, PRL51 (1983) 963]]
- $\mathcal{R}_2 = \frac{\mathcal{B}(J/\psi \to K^0_S K^\pm \pi^\mp)}{\mathcal{B}(J/\psi \to \pi^+\pi^-\pi^0)}$ = 0.265 ± 0.005 (stat) ± 0.021 (syst) [PDG: 0.123 ± 0.033 [MARK I, PRD15 (1977) 1814]]
- With main systematic uncertainties from knowledge of efficiencies.







[PRD95 (2017) 072007]

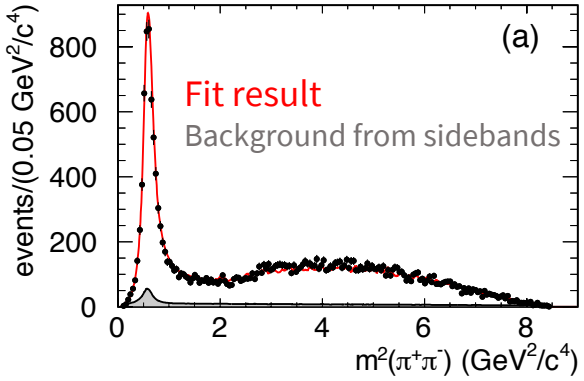
$J/\psi \to \pi^+ \pi^- \pi^0$ isobar model

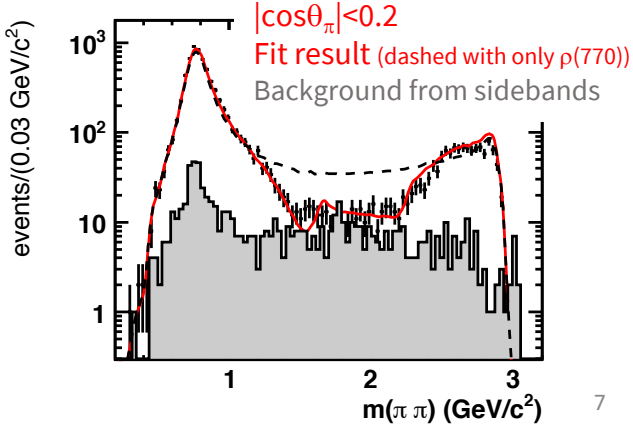
- Dalitz plot analysis in the J/ψ signal region, describing resonances by relativistic Breit Wigner shapes. Total of 8 free parameters.

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		$687/519 = 1.32$	

- When leaving free the $\rho(1450)$ and $\rho(1700)$, the best fit is obtained for:

$$
\begin{aligned}
m(\rho(1450)) &= 1429 \pm 41 \text{ MeV}/c^2, \\
\Gamma(\rho(1450)) &= 576 \pm 29 \text{ MeV}, \\
m(\rho(1700)) &= 1644 \pm 36 \text{ MeV}/c^2, \\
\Gamma(\rho(1700)) &= 109 \pm 19 \text{ MeV}.
\end{aligned}
$$





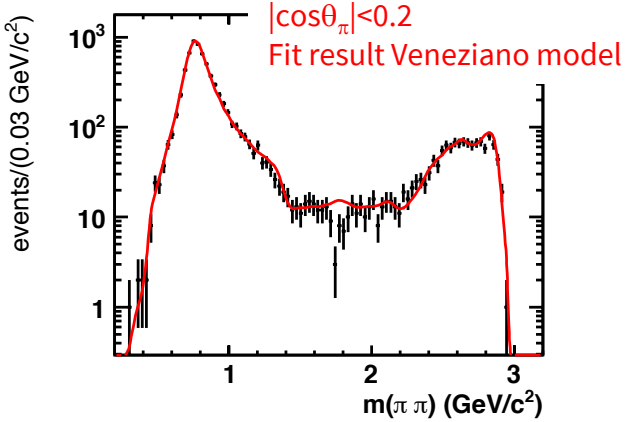
[PRD95 (2017) 072007]

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

- Veneziano model = alternative model to describe better the high mass region [Szczepaniak, Pennington, PLB737 (2014) 283].

$$A(s,t,\lambda) = \epsilon_{\mu\nu\rho\sigma} p^+_\mu p^-_\nu p^0_\sigma \epsilon(p^\psi,\lambda) \sum_{1\le m\le n} \frac{\Gamma(n-\alpha(s))\,\Gamma(n-\alpha(t))}{\Gamma(n+m-\alpha(s)-\alpha(t))} \qquad \alpha(s) = \alpha_0 + \alpha' s + i\gamma\sqrt{s-s_0}$$

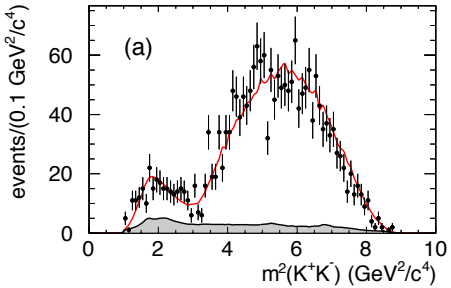
- The model deals with Regge trajectories instead of single resonances. The complexity of the model is related to the number of trajectories, *n*, to include in the fit. Here: *n*=7 i.e. 19 free parameters.

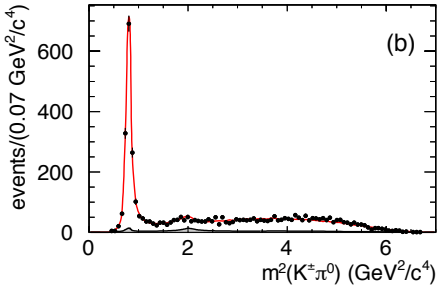


Final state	Isobar fraction (%)	Veneziano fraction (%)
$\rho(770)\pi$	$114.2 \pm 1.1 \pm 2.6$	133.1 ± 3.3
$\rho(1450)\pi$	$10.9 \pm 1.7 \pm 2.7$	0.80 ± 0.27
$\rho(1700)\pi$	$0.8 \pm 0.2 \pm 0.5$	2.20 ± 0.60
$\rho(2150)\pi$	$0.04 \pm 0.01 \pm 0.20$	6.00 ± 2.50
$\omega(783)\pi^0$	$0.08 \pm 0.03 \pm 0.02$	
$\rho_3(1690)\pi$		0.40 ± 0.08
Sum	$127.8 \pm 2.0 \pm 4.3$	142.5 ± 2.8
χ^2/ν	$687/519 = 1.32$	$596/508 = 1.17$

[PRD95 (2017) 072007]

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

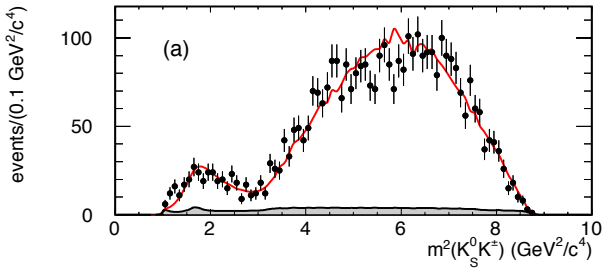


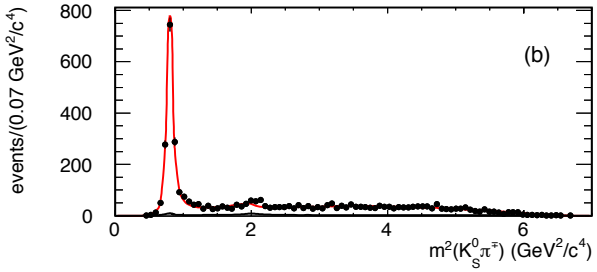


- $J/\psi \to K^+ K^- \pi^0$ can be used to extract

$$\frac{B(\rho(1450)^0 \to K^+K^-)}{B(\rho(1450)^0 \to \pi^+\pi^-)}$$

$= 0.307 \pm 0.084$ (stat) ± 0.092 (syst).





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	$274/217 = 1.26$	

[arXiv:1804.04044]

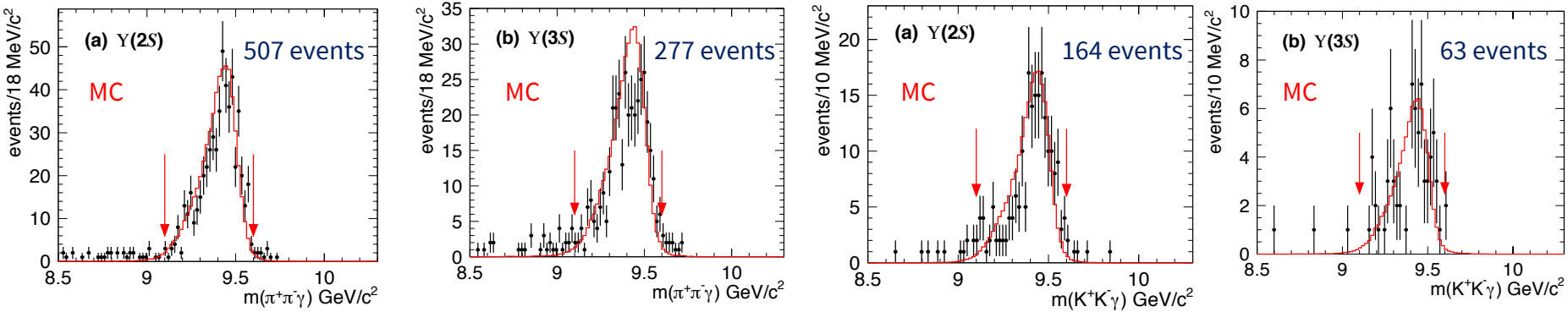
Study of Υ(1S) radiative decays

- Radiative decays suppressed in Υ system compared to charmonium system: challenging analysis.
- Measurement of branching fractions and resonance structure of:
  - $\Upsilon(1S) \rightarrow \pi^+\pi^-\gamma$,
  - $\Upsilon(1S) \rightarrow K^+K^-\gamma$.
- Υ(1S) are produced from Υ(2S) and Υ(3S) decays in the modes $\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$ and $\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$ where the two pions are soft: this allows to obtain clean signal using the 13.6 fb^{-1} and 28 fb^{-1} of Υ(2S) and Υ(3S) on-resonance data.
- Branching fractions are normalized to the $\Upsilon(1S) \rightarrow \mu^+\mu^-$ decay for which are reconstructed:
  - 435000 $\Upsilon(2S) \rightarrow \pi^+\pi^-[\Upsilon(1S) \rightarrow \mu^+\mu^-]$,
  - 132000 $\Upsilon(3S) \rightarrow \pi^+\pi^-[\Upsilon(1S) \rightarrow \mu^+\mu^-]$.

[arXiv:1804.04044]

Υ(1S) event selection

- Exactly 4 charged tracks with p_T>100 MeV/c.
- Exactly 1 photon with E>2.5 GeV.
- Particle identification for charged K and π.
- Momentum balance in the event, $\Delta p_i = p_i^{e^-} + p_i^{e^+} - \left(p_i^{\gamma} + p_i^{\pi_s^+} + p_i^{\pi_s^-} + p_i^{h^+} + p_i^{h^-}\right)$, should be close to 0.
- The recoiling mass to the two soft pions in Υ(2S)→ $\pi^+\pi^-$Υ(1S) and Υ(3S)→ $\pi^+\pi^-$Υ(1S), $M_{rec}^2 = \left|p_{e^-} + p_{e^+} - p_{\pi^+} - p_{\pi^-}\right|^2$, should be close to the Υ(1S) mass.



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

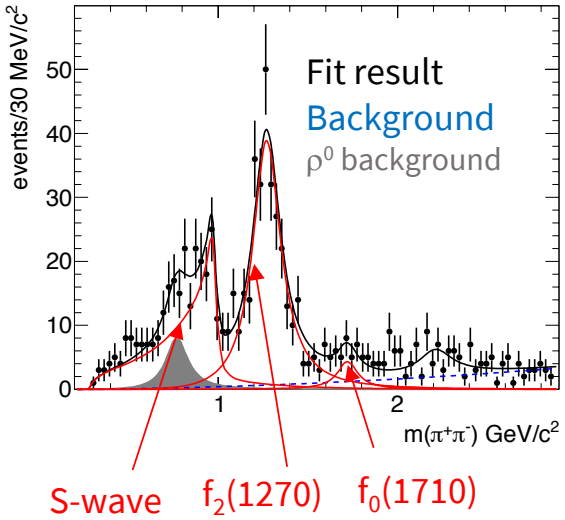
[arXiv:1804.04044]

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

- Summed over the Y(2S) and Y(3S) samples.
- Fit with mass function sum of (16 free parameters):
  - *s*-wave term: sum of $f_0(500)$ described by relativistic Breit Wigner and $f_0(980)$ described by Flatté formalism.
  - $f_2(1270)$ and $f_0(1710)$ as relativistic Breit Wigner.
  - Combinatorial background.
  - ρ^0 background for Y(3S) data, as indicated from mass sidebands.

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)	

- Significant *s*-wave contribution with:
  - $M(f_0(500)) = 0.856 \pm 0.086$ GeV/c2, $\Gamma(f_0(500)) = 1.279 \pm 0.324$ GeV,
  - fraction of $f_0(500)$ component of (27.7±3.1)%.



- After efficiency correction:

Resonance	$\Upsilon(2S)$ corrected yield	$\Upsilon(3S)$ corrected yield
S-wave	$541 \pm 65 \pm 53$	
$f_2(1270)$	$1043 \pm 78 \pm 36$	$285 \pm 26 \pm 15$
$f_0(1710)$	$95 \pm 32 \pm 24$	$22 \pm 29 \pm 11$

[arXiv:1804.04044]

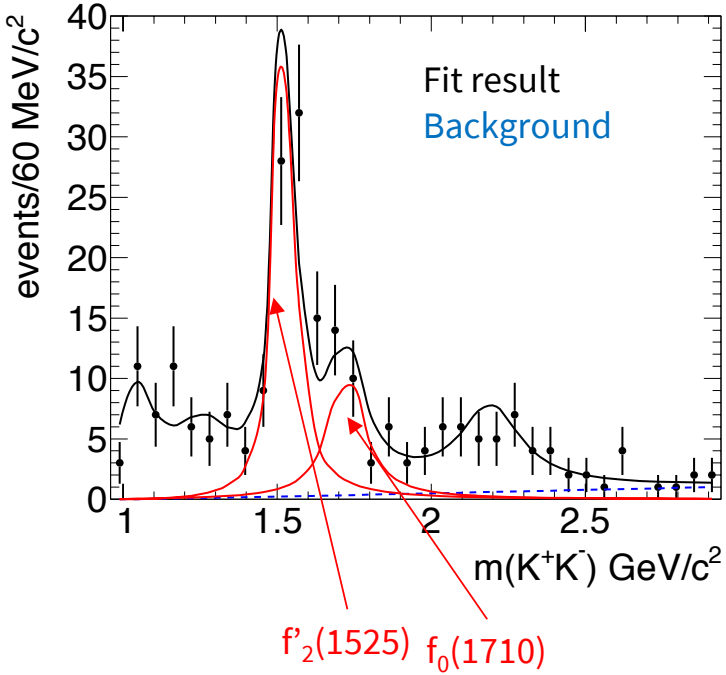
K^+K^- mass spectrum

- Summed over the Y(2S) and Y(3S) samples.
- Fit with mass function sum of (6 free parameters):
  - $f_0(980)$ described by Flatté formalism.
  - $f_2(1270)$, $f'_2(1525)$, $f_0(1500)$ (sum of both noted as $f_J(1500)$) and $f_0(1710)$ as relativistic Breit Wigner.
  - 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	

- After efficiency correction:

Resonance	$\Upsilon(2S)/\Upsilon(3S)$ corrected yield
$f_J(1500)$	$281 \pm 37 \pm 38$
$f_0(1710)$	$143 \pm 36 \pm 24$

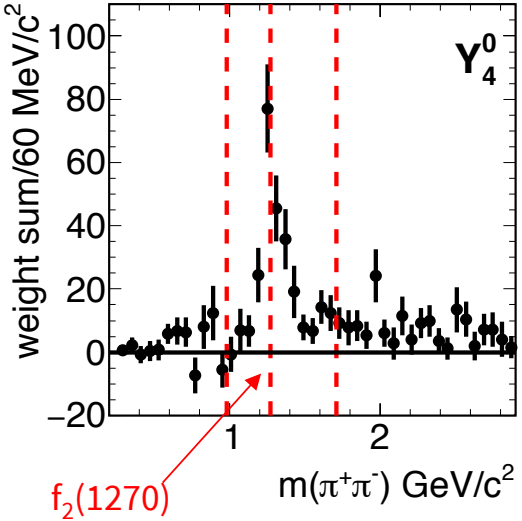


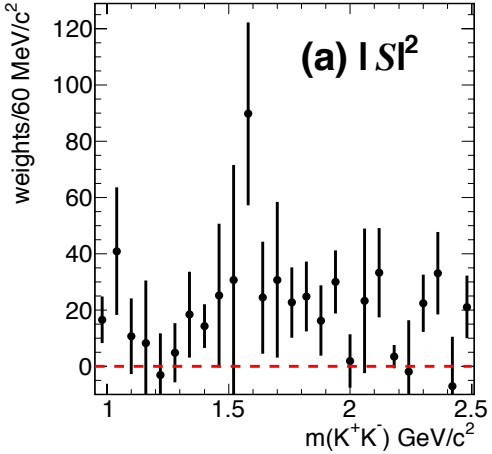
[arXiv:1804.04044]

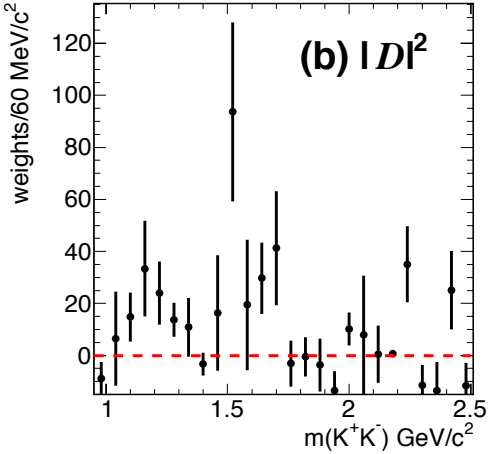
Legendre polynomial moments

- Information about the spin structure, and proportions of *S* and *D* wave amplitudes can be obtained from distributions of Legendre polynomial Y_n^0.
- In the case of the K+K- spectrum, this partial wave analysis shows that the $f_J(1500)$ component is composed of both spin 0 and 2 resonances.

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







[arXiv:1804.04044]

Helicity amplitude fits

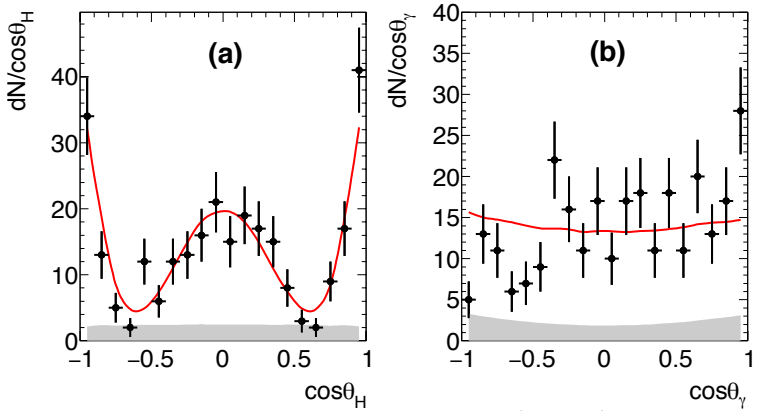
- Complete spin-parity analysis is performed fitting the angular distributions expected for the various spin hypotheses, as a function of the decay angles in the Υ(2/3S) decay chain, with unbinned likelihood fit in each resonance region.
  - θ_H: helicity angle of π or K,
  - θ_γ: photon angle.
- Branching fractions extracted using fractions from these fits and the previous ones.

Spin 2:

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

Spin 0:

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



Fit for spin 2 hypothesis, in $f_2(1270)$ region

Resonance	$\mathcal{B}(10^{-5})$
$\pi\pi$ S-wave	$4.63 \pm 0.56 \pm 0.48$
$f_2(1270)$	$10.15 \pm 0.59 \,^{+0.54}_{-0.43}$
$f_0(1710)\to\pi\pi$	$0.79 \pm 0.26 \pm 0.17$
$f_J(1500)\to KK$	$3.97 \pm 0.52 \pm 0.55$
$f_2'(1525)$	$2.13 \pm 0.28 \pm 0.72$
$f_0(1500)\to K\bar{K}$	$2.08 \pm 0.27 \pm 0.65$
$f_0(1710)\to KK$	$2.02 \pm 0.51 \pm 0.35$

Conclusions

- Dalitz plot analysis of J/ψ decays with high statistics:
  - Provide complementary description of the resonance structures in the $J/\psi \to \pi^+ \pi^- \pi^0$ with Veneziano model.
  - First measurement of the $J/\psi \to K_S^0 K^+ \pi^-$.
- Studies of radiative Υ(1S) decays in $\Upsilon(1S) \to \pi^+\pi^-\gamma$ and $\Upsilon(1S) \to K^+K^-\gamma$.
  - Spin-parity and branching fraction measurents.
  - Observation of the $f_0(1710)$ state in these decays, which can be used to gain information on glueball.