Study of three-body decays of the $J/\psi$
and of radiative decays of the $\Upsilon(1S)$

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European Gravitational Observatory – CNRS & INFN Consortium

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 Υ(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**

  - DIRC (PID)
    - 144 quartz bars
    - 11000 PMs
  - 1.5T solenoid
  - EMC
    - 6580 CsI(Tl) crystals
  - Drift Chamber
    - 40 stereo layers
  - Instrumented Flux Return
    - iron / RPCs / LSTs (muon / neutral hadrons)
  - Silicon Vertex Tracker
    - 5 layers, double sided strips

- **The BaBar dataset (1999-2008)**

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


- 424 fb\(^{-1}\) @ \(\Upsilon(4S)\) \(\Leftrightarrow (471.0 \pm 2.8) \times 10^6\) 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 annihilation with initial state radiation (ISR)
  - Only J^{PC}=1^{−} states produced

- Studied decays
  - J/ψ → π^{+} π^{−} π^{0}
  - J/ψ → K^{+} K^{-} π^{0}
  - J/ψ → K_{S}^{0} K^{+} π^{-} and charge conjugate (c.c.) final state

- Dalitz plot analysis
  - Resonance contents
  - Branching fractions
Event selection

• Tracking
  ▪ $J/\psi \rightarrow K_S^0 \rightarrow \pi^+ \pi^-$ $K^+ \pi^-$: four charged tracks and $K_S$ flight length $> 2$ mm
  ▪ $J/\psi \rightarrow h^+ h^- \pi^0$: $h = \pi, K$; $\pi^0 \rightarrow \gamma \gamma$: two charged tracks and energy($\gamma$) $> 100$ MeV

• Particle identification for the charged hadrons

• ISR events selection
  ▪ Use the mass recoiling against the 3-hadron system:
    \[ M_{\text{rec}}^2 \equiv (p_{e^-} + p_{e^+} - p_{h_1} - p_{h_2} - p_{h_3})^2 \]  
    4-momenta
  → Selection cuts: $< 2$ GeV$^2$/c$^4$ for $J/\psi \rightarrow h^+ h^- \pi^0$
  → $< 2.5$ GeV$^2$/c$^4$ for $J/\psi \rightarrow K_S^0 K^+ \pi^-$ and c.c

  ▪ Additional compatibility test if $\gamma_{\text{ISR}}$ detected

• Background source: $e^+ e^- \rightarrow \gamma \pi^+ \pi^-$
  ▪ Rejected using the cut $\cos(\theta_\pi) < 0.95$, $\theta_\pi$: helicity angle 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

- $J/\psi \rightarrow \pi^+ \pi^- \pi^0$
  - Yield: ~20,000
  - Purity: ~91%

- $J/\psi \rightarrow K^+ K^- \pi^0$
  - Yield: ~2,100
  - Purity: ~89%

- $J/\psi \rightarrow K_S^0 K^+ \pi^- + c.c$
  - Yield: ~3,900
  - Purity: ~93%
Branching fraction ratios

• Dominant systematics: efficiencies

• Using $B(J/\psi \rightarrow \pi^+ \pi^- \pi^0) = (2.11 \pm 0.07) \times 10^{-2}$ [PDG] as reference

• $K^+ K^- \pi^0$ final state:

$$R_1 = \frac{B(J/\psi \rightarrow K^+ K^- \pi^0)}{B(J/\psi \rightarrow \pi^+ \pi^- \pi^0)} = 0.120 \pm 0.003 \text{ (stat)} \pm 0.009 \text{ (syst)}$$

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

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

• $K_S^0 K^+ \pi^- + \text{c.c.}$ final state:

$$R_2 = \frac{B(J/\psi \rightarrow K_S^0 K^+ \pi^-)}{B(J/\psi \rightarrow \pi^+ \pi^- \pi^0)} = 0.265 \pm 0.005 \text{ (stat)} \pm 0.021 \text{ (syst)}$$

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

Use an alternative model (‘Veneziano’) for the J/ψ → π⁺ π⁻ π⁰ Dalitz plot
  ▪ Based on Regge trajectories instead of resonances
    → Strong constraint on amplitude analysis
  ▪ Better description of the high-mass region
J/ψ → π⁺ π⁻ π⁰ results

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

- Veneziano model
  - 7 Regge trajectories
  → 19 free parameters

<table>
<thead>
<tr>
<th>Final state</th>
<th>Amplitude</th>
<th>Isobar fraction (%)</th>
<th>Phase (radians)</th>
<th>Veneziano fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ρ(770)π</td>
<td>1</td>
<td>114.2 ± 1.1 ± 2.6</td>
<td>0.</td>
<td>133.1 ± 3.3</td>
</tr>
<tr>
<td>ρ(1450)π</td>
<td>0.513 ± 0.039</td>
<td>10.9 ± 1.7 ± 2.7</td>
<td>−2.63 ± 0.04 ± 0.06</td>
<td>0.80 ± 0.27</td>
</tr>
<tr>
<td>ρ(1700)π</td>
<td>0.067 ± 0.007</td>
<td>0.8 ± 0.2 ± 0.5</td>
<td>−0.46 ± 0.17 ± 0.21</td>
<td>2.20 ± 0.60</td>
</tr>
<tr>
<td>ρ(2150)π</td>
<td>0.042 ± 0.008</td>
<td>0.04 ± 0.01 ± 0.20</td>
<td>1.70 ± 0.21 ± 0.12</td>
<td>6.00 ± 2.50</td>
</tr>
<tr>
<td>ω(783)π⁰</td>
<td>0.013 ± 0.002</td>
<td>0.08 ± 0.03 ± 0.02</td>
<td>2.78 ± 0.20 ± 0.31</td>
<td>0.40 ± 0.08</td>
</tr>
<tr>
<td>ρ3(1690)π</td>
<td></td>
<td>127.8 ± 2.0 ± 4.3</td>
<td>142.5 ± 2.8</td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td>687/519 = 1.32</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

→ Fit results, background from sidebands; dashed line: fit without ρ(1450)
$J/\psi \rightarrow K^+ K^- \pi^0$ and $J/\psi \rightarrow K_S^0 K^+ \pi^-$ results

• Isobar model only

• $J/\psi \rightarrow K^+ K^- \pi^0$

$\chi^2 / \nu \quad 132/137 = 0.96$

<table>
<thead>
<tr>
<th>Final state</th>
<th>fraction (%)</th>
<th>phase (radians)</th>
</tr>
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<tbody>
<tr>
<td>$K^*(892)^\pm K^\mp$</td>
<td>92.4 ± 1.5 ± 3.4</td>
<td>0.</td>
</tr>
<tr>
<td>$\rho(1450)^\pi^0$</td>
<td>9.3 ± 2.0 ± 0.6</td>
<td>3.78 ± 0.28 ± 0.08</td>
</tr>
<tr>
<td>$K^*(1410)^\pm K^\mp$</td>
<td>2.3 ± 1.1 ± 0.7</td>
<td>3.29 ± 0.26 ± 0.39</td>
</tr>
<tr>
<td>$K_2^*(1430)^\pm K^\mp$</td>
<td>3.5 ± 1.3 ± 0.9</td>
<td>-2.32 ± 0.22 ± 0.05</td>
</tr>
<tr>
<td>Total</td>
<td>107.4 ± 2.8</td>
<td></td>
</tr>
</tbody>
</table>

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

$\chi^2 / \nu \quad 274/217 = 1.26$

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<tr>
<th>Final state</th>
<th>fraction (%)</th>
<th>phase (radians)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^*(892)\bar{K}$</td>
<td>90.5 ± 0.9 ± 3.8</td>
<td>0.</td>
</tr>
<tr>
<td>$\rho(1450)^\pi^\mp$</td>
<td>6.3 ± 0.8 ± 0.6</td>
<td>-3.25 ± 0.13 ± 0.21</td>
</tr>
<tr>
<td>$K_1^*(1410)\bar{K}$</td>
<td>1.5 ± 0.5 ± 0.9</td>
<td>1.42 ± 0.31 ± 0.35</td>
</tr>
<tr>
<td>$K_2^*(1430)\bar{K}$</td>
<td>7.1 ± 1.3 ± 1.2</td>
<td>-2.54 ± 0.12 ± 0.12</td>
</tr>
<tr>
<td>Total</td>
<td>105.3 ± 3.1</td>
<td></td>
</tr>
</tbody>
</table>
**ρ(1450) branching fraction**

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

\[ B_1 = \frac{\mathcal{B}(J/\psi \rightarrow \rho(1450)^0 \pi^0) \mathcal{B}(\rho(1450)^0 \rightarrow \pi^+ \pi^-)}{\mathcal{B}(J/\psi \rightarrow \pi^+ \pi^- \pi^0)} \]

\[ = (3.6 \pm 0.6\text{(stat)} \pm 0.9\text{(sys)})\%. \]

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

\[ B_2 = \frac{\mathcal{B}(J/\psi \rightarrow \rho(1450)^0 \pi^0) \mathcal{B}(\rho(1450)^0 \rightarrow K^+ K^-)}{\mathcal{B}(J/\psi \rightarrow K^+ K^- \pi^0)} \]

\[ = (9.3 \pm 2.0\text{(stat)} \pm 0.6\text{(sys)})\%. \]

→ Ratio of branching fractions

\[ \frac{\mathcal{B}(\rho(1450)^0 \rightarrow K^+ K^-)}{\mathcal{B}(\rho(1450)^0 \rightarrow \pi^+ \pi^-)} = 0.307 \pm 0.084\text{(stat)} \pm 0.082\text{(sys)} \]
Radiative decays of the $\Upsilon(1S)$

- $\Upsilon(1S)$ radiative decays suppressed by a factor $\sim 25$ with respect to $J/\psi$ → Challenging analysis

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

- $\Upsilon(1S)$ production modes
  - $\Upsilon(3S) \rightarrow \begin{bmatrix} \pi_s^+ \pi_s^- \end{bmatrix} \Upsilon(1S)$
  - $\Upsilon(2S) \rightarrow \begin{bmatrix} \pi_s^+ \pi_s^- \end{bmatrix} \Upsilon(1S)$ → Using $\Upsilon(3S)$ and $\Upsilon(2S)$ on-resonance datasets

- Soft pions

- Branching fractions normalized to the dominant $\Upsilon(1S) \rightarrow \mu^+ \mu^-$ decay
  - $\sim 435,000$ events in the $\Upsilon(2S)$ dataset
  - $\sim 132,000$ events in the $\Upsilon(3S)$ dataset
  → For a resonance $R$:

$$B(R) = \frac{N_R(\Upsilon(nS) \rightarrow \pi_s^+ \pi_s^- \Upsilon(1S) \rightarrow R \gamma)}{N(\Upsilon(nS) \rightarrow \pi_s^+ \pi_s^- \Upsilon(1S) \rightarrow \mu^+ \mu^-)} \times B(\Upsilon(1S) \rightarrow \mu^+ \mu^-) \quad (2.48 \pm 0.05\% \text{ [PDG]})$$

Same number of charged tracks
\textbf{\(\Upsilon(1S)\) 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
- Momentum balance: 
  \[ \chi^2 = \sum_{i=1}^{3} \frac{(\Delta p_i - (\Delta p_i))^2}{\sigma_i^2} \]
  with \( \Delta p_i = p_i^{e^+} + p_i^{e^-} - (p_i^\gamma + p_i^{\pi^+} + p_i^{\pi^-} + p_i^{h^+} + p_i^{h^-}) \)
  - Means and with computed from Monte-Carlo (MC) simulations
- Mass recoiling to the two soft pions close to the \(\Upsilon(1S)\) mass
  - \( \pm 2.5 \sigma \)
  \[ M_{\text{rec}}^2(\pi^+_s \pi^-_s) = |p_{e^+} + p_{e^-} - p_{\pi^+_s} - p_{\pi^-_s}|^2 \]

\[ \text{BaBar} \]

\[ \Upsilon(1S) \rightarrow \pi^+\pi^-\gamma \]

\[ \Upsilon(1S) \rightarrow K^+K^-\gamma \]

14 events
\[ \pi^+\pi^- \text{ mass spectrum} \]

- Simultaneous fit to the \( \Upsilon(3S) \) and \( \Upsilon(2S) \) datasets – 16 free parameters
  - S-wave: coherent sum of \( f_0(500) \) and \( f_0(980) \)
  - \( S\)-wave: coherent sum
    - \( f_2(1270) \) and \( f_0(1710) \)
    - Combinatorial background
    - \( \rho^0 \) 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
**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 \(f_3(1500)\)
      - Angular analysis needed
  - \(f_0(1710)\)
  - \(f_0(2200)\)
  - Combinatorial background

<table>
<thead>
<tr>
<th>Resonances (K^+K^-)</th>
<th>Yield</th>
<th>(\Upsilon(2S) + \Upsilon(3S))</th>
<th>Significance ((\sigma))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(f_0(980))</td>
<td></td>
<td>47 ± 9</td>
<td>5.6</td>
</tr>
<tr>
<td>(f_3(1500))</td>
<td></td>
<td>77 ± 10 ± 10</td>
<td>8.9</td>
</tr>
<tr>
<td>(f_0(1710))</td>
<td></td>
<td>36 ± 9 ± 6</td>
<td>4.7</td>
</tr>
<tr>
<td>(f_2(1270))</td>
<td></td>
<td>15 ± 8</td>
<td></td>
</tr>
<tr>
<td>(f_0(2200))</td>
<td></td>
<td>38 ± 8</td>
<td></td>
</tr>
</tbody>
</table>
# Branching fractions

<table>
<thead>
<tr>
<th>Resonance</th>
<th>(B(10^{-5})) (BABAR)</th>
<th>CLEO</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\pi\pi) S-wave</td>
<td>4.63 ± 0.56 ± 0.48</td>
<td>((f_0(980)) 1.8^{+0.8}_{-0.7} ± 0.1)</td>
</tr>
<tr>
<td>(f_2(1270))</td>
<td>10.15 ± 0.59 ([+0.54]_{-0.43})</td>
<td>10.2 ± 0.8 ± 0.7</td>
</tr>
<tr>
<td>(f_0(1710) \rightarrow \pi\pi)</td>
<td>0.79 ± 0.26 ± 0.17</td>
<td></td>
</tr>
<tr>
<td>(f_J(1500) \rightarrow K\bar{K})</td>
<td>3.97 ± 0.52 ± 0.55</td>
<td>3.7([+0.9]_{-0.7}) ± 0.8</td>
</tr>
<tr>
<td>(f_2'(1525))</td>
<td>2.13 ± 0.28 ± 0.72</td>
<td></td>
</tr>
<tr>
<td>(f_0(1500) \rightarrow K\bar{K})</td>
<td>2.08 ± 0.27 ± 0.65</td>
<td></td>
</tr>
<tr>
<td>(f_0(1710) \rightarrow K\bar{K})</td>
<td>2.02 ± 0.51 ± 0.35</td>
<td>0.76 ± 0.32 ± 0.08</td>
</tr>
</tbody>
</table>

- \(f_0(1710)\) combined significance: 5.7 \(\sigma\)
- First observation in \(\Upsilon(1S)\) radiative decays

- Measurement \[
\frac{B(f_0(1710) \rightarrow \pi\pi)}{B(f_0(1710) \rightarrow K\bar{K})} = 0.64 \pm 0.27_{\text{stat}} \pm 0.18_{\text{sys}}
\]

in agreement with the world average value of \(0.41^{+0.11}_{-0.17}\)
Angular analysis

• Partial wave analysis (PWA)
  - Efficiency-corrected mass spectra weighted by Legendre polynomial moments($\theta_H$)
    → S- and D-wave contributions for both final states
  
  Consistent with mass spectrum fit

• 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/ψ → π⁺ π⁻ π⁰
    → Complementary description of resonance structure
  ▪ First measurement of J/ψ → K_s⁰ K⁺ π⁻ and charge conjugate

→ PRD95 (2017) 072007

• Studies of radiative γ(1S) → π⁺ π⁻ γ and γ(1S) → K⁺ K⁻ γ decays
  ▪ Observation of various resonances:
    broad S-wave, f₀(980), f₂(1270), f₀(1710), f’₂(1525) and f₀(1500)
    → Observation of the f₀(1710) state in these decays
  ▪ Spin-parity and branching fraction measurements

→ arXiv:1804.04044, accepted for publication in PRD