Charmonium rare decay

Junhao Yin
(for the BESIII Collaboration)
Institute of high energy physics, cas
outline

• Why rare decay is interesting

• The rare decay of charmonium on BESIII

• Outlook and summary
Why rare decay is interesting

• The huge $J/\psi$ and $\psi(2S)$ data sample is one possible way for us to approach a precious level where the charmonium rare decay can provide important tests of the SM.
• Rare decays in low energy region may be complementary to high energy colliders.
• A good window for new physics beyond the standard model.
Charmonium rare decays

• Flavor changing weak decays
  • Semileptonic decays of charmonium, $J/\psi \rightarrow D_s^* e\nu$.
  • Non-leptonic two-body weak decays, $J/\psi \rightarrow D^- S^0 / D_0 K^*$

• C/P violation decays
  • $J/\psi \rightarrow \gamma \gamma / \gamma \phi$
  • $\eta_c \rightarrow \pi \pi$

• Lepton flavor violated decays
  • $J/\psi \rightarrow e\mu$

• Invisible decays in charmonium
  • $J/\psi \rightarrow \phi \eta^{(s)}, \eta^{(t)} \rightarrow \text{invisible}$

\[
\begin{align*}
\psi(2S) & \rightarrow \gamma \eta' \\
\psi(2S) & \rightarrow \gamma \eta \\
J/\psi & \rightarrow \gamma \eta_c \\
h_c & \rightarrow \eta' \\
h_c & \rightarrow \gamma \eta
\end{align*}
\]
Semileptonic decays

- $J/\psi$ can decay to charm meson via weak interaction through virtual intermediate bosons in SM framework. In the SM, the inclusive BF of $J/\psi$ decay to single $D$ or $D_s^-$ are predicted to be $10^{-8}$. Using sum rules the BF are predicted to be $\sim10^{-10}$,
- New physics, the BF of $J/\psi \to D(\bar{D})X$ could be enhanced ($10^{-5} \sim 10^{-6}$):
  - Top-color models,
  - Minimal super-symmetric SM with R-parity violation,
  - Two-Higgs-doublet model
- Ratio between $J/\psi \to D_s^* l \nu$ and $D_s l \nu$ is predicted to be $1.5 \sim 3.1$.
- With $2.25 \times 10^8 J/\psi$ events collected at BEPCII, 4 hadronic decay channels is used to reconstruct $D_s : K_S K, KK\pi, KK\pi\pi^0, K_S K\pi\pi$, and $D_s^*$ is reconstructed by $D_s^* \to \gamma D_s$. 
Semileptonic decays

The $D_s$ and lepton are fully constructed and the missing $U$ is used to extract the signal.

$$E_{\text{miss}} = E_{J/\psi} - E_{D_s^*} - E_e \quad \vec{p}_{\text{miss}} = \vec{p}_{J/\psi} - \vec{p}_{D_s^*} - \vec{p}_e \quad U_{\text{miss}} = E_{\text{miss}} - |\vec{p}_{\text{miss}}|$$

A simultaneous unbinned likelihood fit is used determined the signal yields.

$$L_k = \prod_{i=1}^{N_k} \frac{N_{\text{total}} B_k c_{i,k} P_{i,k}^{\text{sig}} + N_k^{bkg} P_{i,k}^{bkg}}{N_{\text{total}} B_k c_{i,k} + N_k^{bkg}}$$

The Bayesian method with a uniform prior is used to estimate the upper limits.

$$\frac{\int_{0}^{N_{\text{up}}} L(N_{\text{total}}) dN_{\text{total}}}{\int_{0}^{\infty} L(N_{\text{total}}) dN_{\text{total}}} = 0.90$$

Phys. Rev. D 90, 112014
Semileptonic decays

$D_s^* \rightarrow \gamma D_s$

The same method as that in $D_S$ to extract the signal and get the upper limits.

Best results ever: $< 3.5 \times 10^{-5}$.  

Phys. Rev. D 90, 112014
Two-body hadronic weak decays

- Use $2.25 \times 10^8 J/\psi$ events collected at BEPCII to search the decay $J/\psi \rightarrow D_s^- \rho^+$ and $D^0 \bar{K}^*0$.
- The $D_s$ and $D^0$ mesons are identified by their semileptonic decays: $D_s \rightarrow \phi e\nu, D^0 \rightarrow K e\nu$.

$$\frac{Br(J/\psi \rightarrow D_s^- \rho^+)}{Br(J/\psi \rightarrow D_s^- \pi^+)} = 4.2$$

Int. J. Mod. Phys. A 14, 937
Two-body hadronic weak decays

- Select candidates of $\rho$ and $K^{*0}$, use the recoiling side of $\rho$ and $K^{*0}$.
- Use the electrons to tag the events and the missing momentum to suppress the backgrounds.

\[ J/\psi \rightarrow D_s^- \rho^+ \]

\[ D_s^- \rightarrow \phi e^- \bar{\nu}_e, \phi \rightarrow K^+ K^- \]
Two-body hadronic weak decays

Phys. Rev. D 89, 071101

<table>
<thead>
<tr>
<th>Sources</th>
<th>$J/\psi \rightarrow D_s^- \rho^+$</th>
<th>$J/\psi \rightarrow D^0 K^{*0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDC tracking</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Photon detection</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Particle ID</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>$x^0$ kinematic fit</td>
<td>0.2</td>
<td>1.0</td>
</tr>
<tr>
<td>$\phi$ mass window</td>
<td>1.0</td>
<td>–</td>
</tr>
<tr>
<td>$\rho^+$ mass window</td>
<td>1.0</td>
<td>–</td>
</tr>
<tr>
<td>$K^-$ mass window</td>
<td>–</td>
<td>0.5</td>
</tr>
<tr>
<td>$U_{\text{miss}}$ window</td>
<td>1.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Intermediate decays</td>
<td>5.7</td>
<td>1.1</td>
</tr>
<tr>
<td>MC statistics</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Number of $J/\psi$ events</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Total</td>
<td>8.6</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Given for the first time.

\[
J/\psi \rightarrow D_s^- K^{*0}
\]

\[
\bar{D}^0 \rightarrow K^+ e^- \bar{\nu}_e
\]

\[
\bar{K}^{*0} \rightarrow K^- \pi^+
\]
C/P-parity violation decays

- \( J/\psi \rightarrow \gamma \gamma / \gamma \phi \)

- In SM, C invariance is held in strong and EM interactions.
- Evidence for C violation in the EM sector would immediately indicate physics beyond the SM.
- Use \( 1.06 \times 10^8 \, \psi(2S) \) data and via \( \psi(2S) \rightarrow \pi^+\pi^- \, J/\psi \) to study the decay \( J/\psi \rightarrow \gamma \gamma / \gamma \phi \).
- Require \( |\cos \pi^+\pi^-| < 0.95 \) exactly two photons for \( \gamma \gamma \) channel. \( \cos \pi^+\pi^- < 0.95 \) and \( E_\gamma > 1.0 \) GeV for \( \gamma \phi \) channel.
C/P-parity violation decays

- $J/\psi \rightarrow \gamma\gamma/\gamma\phi$

- The peak in $J/\psi \rightarrow \gamma\gamma$ is dominated by background with similar final states.
- MC study for $J/\psi \rightarrow \gamma\phi$ shows that there are no peaking background.

<table>
<thead>
<tr>
<th>Background channel</th>
<th>Expected counts ($N^{\text{bkg}}$)</th>
<th>$\gamma\gamma$</th>
<th>$\gamma\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi \rightarrow \gamma\pi^0, \pi^0 \rightarrow 2\gamma$</td>
<td>18.5 ± 1.9</td>
<td>29.2 ± 7.1</td>
<td>0.0 ± 4.6</td>
</tr>
<tr>
<td>$J/\psi \rightarrow \gamma\eta, \eta \rightarrow 2\gamma$</td>
<td>24.6 ± 1.6</td>
<td>46.5 ± 2.5</td>
<td>negligible</td>
</tr>
<tr>
<td>$J/\psi \rightarrow \gamma\eta_c, \eta_c \rightarrow 2\gamma$</td>
<td>1.3 ± 0.3</td>
<td>2.8 ± 2.5</td>
<td>6.9</td>
</tr>
<tr>
<td>$J/\psi \rightarrow 3\gamma$</td>
<td>0.9 ± 0.3</td>
<td>30.7 ± 0.07</td>
<td>30.89 ± 0.07</td>
</tr>
<tr>
<td>Total</td>
<td>45.3 ± 2.5</td>
<td>0.9 ± 0.3</td>
<td>10.6 ± 0.1</td>
</tr>
</tbody>
</table>

- The upper limits of $J/\psi \rightarrow \gamma\gamma$ is one order of the magnitude more stringent than the previous one.
C/P-parity violation decays

• \( \eta_c \rightarrow \pi\pi \)

- The decay \( \eta_c \rightarrow \pi^+\pi^-/\pi^0\pi^0 \) violate both P and CP invariance and provide an excellent laboratory for testing the validity of symmetries. BF\(\sim\)10\(^{-27}\).
- Higher branching fractions are possible by introducing a CP violating term in the QCD lagrangian (BF\(\sim\)10\(^{-17}\)) or allowing CP violation in the extended Higgs sector (BF\(\sim\)10\(^{-15}\)).

- Based on \(2.25 \times 10^8\) \(J/\psi\) events, via \(J/\psi \rightarrow \gamma\eta_c\). For \(\eta_c \rightarrow \pi^+\pi^-\):
  - Paring the photons in an event and reject the background of \(J/\psi \rightarrow \pi^+\pi^-\pi^0\).
  - 0.4 GeV < \(E_{\pi}^{EMC}\) < 1.2 GeV to suppress the \(J/\psi \rightarrow e^+e^-/\mu^+\mu^-\) background.

- For \(\eta_c \rightarrow \pi^0\pi^0\):
  - The photon pairs with minimized \(\chi = \sqrt{(M(\gamma\gamma)_{1} - M_{\pi^0})^2 + (M(\gamma\gamma)_{2} - M_{\pi^0})^2}\) is chosen.
  - Events satisfied \(0.72 < M(\gamma\pi^0) < 0.82\) GeV/c\(^2\) is rejected to reduce the \(J/\psi \rightarrow \omega\pi^0\) background.
C/P-parity violation decays

- $\eta_c \rightarrow \pi \pi$

<table>
<thead>
<tr>
<th>Process</th>
<th>$N_{\text{sig}}^{UP}$</th>
<th>$\varepsilon$ (%)</th>
<th>$\sigma_{\text{sys}}$ (%)</th>
<th>$S$</th>
<th>$B^{UP}$</th>
<th>$B_{PDG}^{UP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_c \rightarrow \pi^+ \pi^-$</td>
<td>92</td>
<td>25.27</td>
<td>27</td>
<td>1.5$\sigma$</td>
<td>$1.3 \times 10^{-4}$</td>
<td>$6 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\eta_c \rightarrow \pi^0 \pi^0$</td>
<td>40</td>
<td>35.70</td>
<td>28</td>
<td>0.1$\sigma$</td>
<td>$4.2 \times 10^{-5}$</td>
<td>$4 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

- The systematic error mainly come from the BF of $J/\psi \rightarrow \gamma \eta_c$.
- Our results is smaller compared to the upper limits provided in PDG.
- Provide experimental limits for theoretical models predicting how much CP and P violation there may be in $\eta_c$ meson decays.
Lepton flavor violated decays

- $J/\psi \rightarrow e\mu$
  - With finite neutrino masses included, the SM allows for LFV, yet which is beyond current experimental sensitivity.
  - Theoretical models enhance LFV: SUSY, include SUSY-based grand unified theories, SUSY with a right-handed neutrino, gauge-mediated SUSY breaking, SUSY with vector-like leptons, SUSY with R-parity violation, models with a Z’ and models violating Lorentz invariance.
  - We present our results here with $2.25 \times 10^8 J/\psi$ events for $J/\psi \rightarrow e\mu$. 
Lepton flavor violated decays

- The reconstructed total momentum and energy is used to extract the signal.
- The selection criteria is optimized using a blind fashion with a sensitive FOM:

\[
FOM = \frac{\epsilon}{\sum_{N_{obs}=0}^{\infty} P(N_{obs}|N_{exp}) \cdot UL(N_{obs}|N_{exp})}
\]

- The background is studied using an inclusive MC with four times the size of data.

\[Br(J/\psi \rightarrow e\mu) < 1.5 \times 10^{-7}\]
Most stringent limit obtained.

\[<1.1 \times 10^{-6}\]
(best results before)

Phys. Rev. D 87, 112007
Invisible decays in charmonium

• $J/\psi \to \eta \phi$, $\eta \to$ invisible

- The invisible decays of $J/\psi$ and other mesons provide a good filed to search for new physics beyond the SM.
- Could be light dark matter constituents according to $q \bar{q} \to (\gamma) \chi \chi$.
- Based on $2.25 \times 10^8$ $J/\psi$ events. No good charged tracks allowed besides the $K^+K^-$ and no good photons inside a cone of 1.0 rad around the recoil direction against the $\phi$ candidate and $|\cos \theta_{\text{recoil}}| < 0.7$.
- The $N_{\eta}^{up} = 3.34$ and $N_{\eta'}^{up} = 10.1$. And give the upper limits of the ratio to the $Br(\eta(\eta') \to \gamma\gamma)$ to cancel the common systematic error.

\[
\frac{Br(\eta(\eta') \to \text{invisible})}{Br(\eta(\eta') \to \gamma\gamma)} < 2.6(2.4) \times 10^{-4(2)}
\]

Phys. Rev. D 87, 012009
Summary and outlook

• BESIII collaboration has performed dedicated studies on charmonium rare decays and the best upper limits branching fractions of the world obtained with 225 M $J/\psi$ and 106 M $\psi(2S)$. By now the results are still consistent with the SM.

• 1.3 B $J/\psi$ and 0.45 B $\psi(2S)$ events has been collected and more searches of charmonium rare decays with better precision can be obtained.

• The invisible decays of $J/\psi$ or other particles can be searched with the largest $J/\psi$ and $\psi(2S)$ samples in the world.

Thanks!