Study on the Two-Photon Transition from $\psi(2S)$ to $J/\psi$ at BESIII

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(on behalf of BESIII Collaboration)

List of Contents:

• Introduction
• BEPCII and BESIII Experiment
• Data Analysis
• Systematic Studies on the Enhancement
• Summary
Introduction I

Two-photon transition from \( \psi(2S) \) to \( J/\psi \):

On experimental side:
- delicate measurement
- analogous process to positronium and hydrogen two-photon transition
- CLEO reported \( \Upsilon(3S) \rightarrow \text{rr}\Upsilon(2S) \)
- escaped from experimental measurement

On theoretical side:
- order \( \alpha^2 \) QED transition between two hadrons
- similar process has been studied in heavy-light quark system
- improve understanding of heavy quarkonium characters such as spectrum, decay et al, and the strong interaction
- possibility of testing the hadron-loop effect
Introduction II

naive theoretical pictures:

Potential model:

- **discrete part:**
  double E-1 transition via discrete $\chi_{CJ}$ (nP) (n=1,2) states *(virtual and real parts)*. (including main source of the background) *(well described $\chi_{CJ}$ states)*

- **relativistic correction:**
  relatively higher order $v^2$ operators corrections

Potential model + couple channel:

- besides discrete contribution, the hadron-loop effect also may play a important role.

*Theoretical study is on going. (Z.G. He et al)*
BEPCII and BESIII

BEPCII:
- Beam energy: 1.0 ~ 2.3 GeV
- Luminosity: $1 \times 10^{33}$ cm$^{-2}$s$^{-1}$
- Optimum energy: 1.89 GeV

BESIII Spectrometer:
- MDC: $\sigma(p_T)/p_T = 0.5\% \ @ 1\text{GeV}$
  $dE/dx_{\text{reso}} < 6\%$
- TOF: 80 ps (for bhabha, barrel)
- EMC: $\sigma(E)/E = 2.3\% \times \sqrt{E}$

July 20, 2008: first $e^+e^-$ collision event in BESIII
April 14, 2009: took ~100M $\psi(2S)$ events (~40 days)
May 29, 2009: took ~41 pb$^{-1}$ continuum data @3.65GeV

more in F. A. Harris’s plenary talk
Dataset and Selection Criteria

Dataset:
- ~160pb⁻¹ data taken @3.686GeV in 2009, which was estimated to contain 106 ± 4 million ψ(2S) decays
- 41 pb⁻¹ continuum data @3.65GeV in 2009

Data Selection:
- At most 3 good photon candidates
  - EMC energy threshold: E>0.025GeV(barrel), E>0.050GeV(Endcap)
  - EMC TDC time window (0, 14)
  - energy less than 0.9GeV
  - nearest angle to charged tracks: \( d_{\text{angle}} > 10° \)
- Only one good-lepton-pair candidate
  - closest approach to interaction point:
    - less than 1cm in x-y plane and less than 10cm in z-axis
  - energy deposit in EMC: \( E_{\text{deposit}}/P < 0.6 \) (muon), \( E_{\text{deposit}}/P > 0.7 \) (electron)
  - lepton momentum: 0.8GeV/c < \( P < 2.0 \) GeV/c
- Only the \( \gamma \gamma ll \) combination with least \( \chi^2 \) of 4-momentum-constrain kinematic fit will be kept: \( \chi^2 < 60 \)
Photons

**definition:**
- $\gamma_1$ higher energy photon
- $\gamma_2$ lower energy photon

\[ 0.2 < E_{\gamma_1} < 0.54 \text{ GeV} \]
\[ 0.1 < E_{\gamma_2} < 0.28 \text{ GeV} \]

**PHSP signal:** plotted with the assumption of
\[ Br(\psi(2S) \rightarrow \gamma\gamma J/\psi) = 1 \times 10^{-3} \]

**further photon selections:**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>ee</td>
<td>$0.2 &lt; E_{\gamma_1} &lt; 0.54 \text{ GeV}$</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>$0.1 &lt; E_{\gamma_2} &lt; 0.28 \text{ GeV}$</td>
</tr>
</tbody>
</table>
Scattering Plot: $M_{\gamma\gamma}$ VS $RM_{\gamma_2}$

$RM_{\gamma_2}$: Recoil Mass of lower energy photon $\gamma_2$

box cut: $0.15 < M_{\gamma\gamma} < 0.51$ GeV
$3.43 < RM_{\gamma_2} < 3.49$ GeV

$ee$ channel

$\mu\mu$ channel

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MESON2010, Poland
Projection Plots on $M_{\gamma\gamma}$ and $RM_{\gamma^2}$

- consistent data/MC line-shapes
- good MC description of the tails of $\chi_{CJ}/\pi^{0}/\eta$

BESIII preliminary

black: data
red: MC+cont.+signal
blue: MC+cont.
**J/ψ Momentum inside Box**

clear enhancement from understood bkg.

**Further cut:** $0.30\text{ GeV/c} < P_{ll} < 0.55\text{ GeV/c}$
Dilepton Invariant Mass

understood backgrounds:
- QCD background from psi(2S) decay
- QED background from continuum data

significant enhancement around J/ψ peak
Background Components

estimated with MC Simulation and continuum data

- relative branching fractions based on PDG
- take $\psi(2S)$ decay bkg. shape and magnitude as the main background description

<table>
<thead>
<tr>
<th>bkg. channels</th>
<th>ee chnl (ex.)</th>
<th>$\mu\mu$ chnl (ex.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma(\gamma J/\psi)<em>{\chi</em>{c0}}$</td>
<td>263.1 ± 3.2</td>
<td>367.2 ± 3.7</td>
</tr>
<tr>
<td>$\gamma(\gamma J/\psi)<em>{\chi</em>{c1}}$</td>
<td>517.6 ± 5.1</td>
<td>659.1 ± 5.7</td>
</tr>
<tr>
<td>$\gamma(\gamma J/\psi)<em>{\chi</em>{c2}}$</td>
<td>86.9 ± 2.1</td>
<td>116.1 ± 2.5</td>
</tr>
<tr>
<td>$(\gamma\gamma)_{\pi^0} J/\psi$</td>
<td>0.5 ± 0.2</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>$(\gamma\gamma)_{\eta} J/\psi$</td>
<td>0.6 ± 0.2</td>
<td>1.3 ± 0.3</td>
</tr>
<tr>
<td>$(\gamma\gamma)<em>{\pi^0}(\gamma\gamma)</em>{\pi^0} J/\psi$</td>
<td>755.2 ± 6.3</td>
<td>1179.8 ± 7.8</td>
</tr>
<tr>
<td>$(\gamma\gamma)<em>{\pi^0}(ee\gamma)</em>{\pi^0} J/\psi$</td>
<td>8.9 ± 0.7</td>
<td>12.9 ± 0.8</td>
</tr>
<tr>
<td>continuum@3.65 GeV</td>
<td>375.4</td>
<td>36.8</td>
</tr>
</tbody>
</table>

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**Signal Estimation**

**unbinned maximum likelihood fit with composition of three PDFs:**

- **signal (red):** shape from phase-space-like MC simulation
- **ψ(2S) bkg. (blue):** shape and magnitude from exclusive MC simulation
- **other bkg. (green):** 1\textsuperscript{st}-order polynomial

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**ee channel**

\[ M_{ll} [\text{GeV}/c^2] \]

**µµ channel**

\[ M_{ll} [\text{GeV}/c^2] \]

**BESIII preliminary**

- nbg = 226.5 ± 30.3
- nsg = 495.8 ± 37.9

**BESIII preliminary**

- nbg = 112.8 ± 23.6
- nsg = 615.9 ± 40.9

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2010-6-10
MESON2010, Poland
Significance Estimation

floating all fitting components

**ee channel**

- w/ signal: $-\ln L = -20977.9$
- w/o signal: $-\ln L = -20899.3$

Significance: $12.5\sigma$

**μμ channel**

- w/ signal: $-\ln L = -28838.7$
- w/o signal: $-\ln L = -28738.1$

Significance: $14.3\sigma$
### Preliminary Numerical Results and Systematic Uncertainties

<table>
<thead>
<tr>
<th></th>
<th>ee channel</th>
<th>uu channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>signals</td>
<td>495.8 ± 37.9</td>
<td>615.9 ± 40.9</td>
</tr>
<tr>
<td>efficiency</td>
<td>(7.44 ± 0.02)%</td>
<td>(9.92 ± 0.02)%</td>
</tr>
<tr>
<td>significance</td>
<td>12.5σ</td>
<td>14.3σ</td>
</tr>
<tr>
<td>BR(ψ(2S) → γγJ/ψ)</td>
<td>(1.06 ± 0.08) × 10⁻³</td>
<td>(0.99 ± 0.07) × 10⁻³</td>
</tr>
</tbody>
</table>

### sources of systematic uncertainties

- lepton tracking
- photon detection
- photon number cut
- kinematic fit
- BRs of ψ(2S) decay bkg.
- χ_CJ decay width uncertainties
- bkg. shape
- fitting range
- extrapolation from box region to full phase space
- signal MC simulation
- ψ(2S) total number
- J/ψ decay BR
- interferences

statistically consistent
\( \pi^0 \pi^0 J/\psi \) Background Validation

simple fit: two Gaussian plus 1\textsuperscript{st}-order polynominal
assuming right bump comes from \( \pi^0 \pi^0 J/\psi \) process

\[ \epsilon_{ee}^{\pi^0 \pi^0 J/\psi} = 0.073 \times (1 \pm 0.0083)\% \]

BR: \((16.16 \pm 1.03)\%\)

\[ \epsilon_{\mu\mu}^{\pi^0 \pi^0 J/\psi} = 0.114 \times (1 \pm 0.0066)\% \]

BR: \((16.73 \pm 0.76)\%\)

agree well with PDG value: 16.84%
Test Enhancement in Different Box Region

- existence of the enhancement is robust
- variation of the measurements in different regions:
  - statistical fluctuation
  - physics mechanism of signal process
  - to be included in the systematic uncertainties

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>(RM_{\gamma_2} (\text{GeV}/c^2))</td>
<td>(M_{\gamma}(\text{GeV}/c^2))</td>
<td>(Br_{ee} \times 10^{-3})</td>
<td>(Br_{\mu\mu} \times 10^{-3})</td>
</tr>
<tr>
<td>(3.43, 3.49)</td>
<td>(0.15, 0.33)</td>
<td>1.17 ± 0.13</td>
<td>1.25 ± 0.11</td>
</tr>
<tr>
<td>(3.43, 3.49)</td>
<td>(0.33, 0.51)</td>
<td>0.97 ± 0.10</td>
<td>0.79 ± 0.08</td>
</tr>
<tr>
<td>(3.43, 3.46)</td>
<td>(0.15, 0.51)</td>
<td>0.97 ± 0.11</td>
<td>1.04 ± 0.08</td>
</tr>
<tr>
<td>(3.46, 3.49)</td>
<td>(0.15, 0.51)</td>
<td>1.16 ± 0.12</td>
<td>0.98 ± 0.10</td>
</tr>
</tbody>
</table>
## Compilation of Preliminary Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$J/\psi \rightarrow ee$</th>
<th>$J/\psi \rightarrow \mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>lepton tracking</td>
<td>$-0.7$</td>
<td>$+1.0$</td>
</tr>
<tr>
<td>photon detection</td>
<td>$\pm1.0$</td>
<td>$\pm1.0$</td>
</tr>
<tr>
<td>photon number cut</td>
<td>$+3.8$</td>
<td>$\pm1.0$</td>
</tr>
<tr>
<td>4C KF</td>
<td>$+1.1$</td>
<td>$+1.1$</td>
</tr>
<tr>
<td>relative branching fraction</td>
<td>$+11.3$, $-11.6$</td>
<td>$+12.5$, $-12.8$</td>
</tr>
<tr>
<td>$\chi_{CJ}$ decay width</td>
<td>$+7.4$, $-5.2$</td>
<td>$+10.5$, $-4.2$</td>
</tr>
<tr>
<td>$\chi_{CJ}$ inter-interferences</td>
<td>$-4.7$</td>
<td>$-6.1$</td>
</tr>
<tr>
<td>background shape</td>
<td>$\pm0.1$</td>
<td>$\pm0.1$</td>
</tr>
<tr>
<td>fitting range</td>
<td>$+0.9$, $-2.8$</td>
<td>$-5.1$</td>
</tr>
<tr>
<td>$\psi(2S)$ Total Number</td>
<td>$+7.9$, $-7.5$</td>
<td>$+8.7$, $-8.4$</td>
</tr>
<tr>
<td>$Br(J/\psi \rightarrow ll)$</td>
<td>$\pm1.0$</td>
<td>$\pm1.0$</td>
</tr>
<tr>
<td>total</td>
<td>$+15.4$</td>
<td>$+18.6$</td>
</tr>
<tr>
<td></td>
<td>$-16.7$</td>
<td>$-17.8$</td>
</tr>
</tbody>
</table>

- **big sources**
- **another important source, physics mechanism MC simulation of the signal process, not included yet**
- **possible signal-$\chi_{CJ}$-decay interference not included**
Thanks to the high-luminosity of BEPCII and high-quality BESIII data, a significant enhancement of two-photon transition of $\psi(2S)$ to $J/\psi$ was observed for the first time in the world: significance $>10\sigma$

The branching ratio was measured at BESIII with combination of two independent channels.

Preliminary result shows:

$$Br(\psi(2S) \rightarrow \gamma\gamma J/\psi) = (1.02 \pm 0.05\text{ (stat.)}^{+0.19}_{-0.20}\text{ (syst.)}) \times 10^{-3}.$$
Thank You!
Dziękuję!
谢谢！
Backup Slides