Recent Two-photon results at Belle

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Two-photon processes at Belle

- **No-tag method**
  - Apply tight transverse momentum cut to select exclusive two-photon events
  - Small virtuality, almost real photons → Measurement of $\Gamma_{\gamma\gamma}$
  - Beam particles escape to beam pipes with small scattering angle
  - $\gamma\gamma$ axis $\approx$ $e^+e^-$ axis
Two-photon Process

- Process with almost real photons
- (Differential) Cross section at $W \geq 2.4$ GeV
  - pQCD leading-order calculation for hadron pair production
    - $\sigma (\gamma \gamma \rightarrow h h') \sim W^n (W \rightarrow \infty)$
      - $n = 6$ for charged meson pair
      - $n = 10$ for baryon pair
    - $\frac{d\sigma}{d|\cos \theta^*|} \sim \sin^{-4} \theta^*$ for charged meson pair
      - Consistent with $\gamma \gamma \rightarrow \pi^+ \pi^-, K^+K^-$ for $W > 3.1$ GeV
      - Handbag model (non pQCD) $\sim \sin^{-4} \theta^*$ also for neutral pair

- Resonance study
  - $C = \text{even} (\leftrightarrow C = \text{odd} \text{ for } X \text{ in } e^+e^- \rightarrow X), \ J \neq 1$
  - Comparison with calculations for $\Gamma_{\gamma \gamma}$
  - $W \leq 3.0\text{GeV}$
    - Light meson study by Partial Wave Analysis
      - Provides information to solve light scalar meson puzzle
  - $W \geq 3.0\text{GeV}$
    - Charmonium study, XYZ search
How to derive

**Differential cross section and invariant mass spectrum for** \( \gamma \gamma \rightarrow h h' \)

\[
\frac{d\sigma}{d |\cos \theta^*|} = \frac{\Delta Y - \Delta B}{\Delta W \Delta |\cos \theta^*|} \epsilon \frac{dL_{\gamma\gamma}}{dW} \int Ldt
\]

\[
\sigma(W) = \sum \frac{d\sigma}{d |\cos \theta^*|} \Delta |\cos \theta^*| 
\]

**Two-photon decay width** \( \Gamma_{\gamma \gamma} \)

- For a narrow resonance

\[
\Gamma_{\gamma \gamma}(R) Br(R \rightarrow X) = \frac{N_R m_R^2}{4(2J + 1)\pi^2 \epsilon \frac{dL_{\gamma\gamma}}{dW}(m_R)} \int Ldt
\]

**Luminosity function**

\[
\sigma(e^+ e^- \rightarrow e^+ e^- X) = \int \frac{dL_{\gamma\gamma}}{dW} dW
\]
Contents

- $\gamma \gamma \rightarrow \pi^0 \pi^0$
- $\gamma \gamma \rightarrow \eta \pi^0$
- $\gamma \gamma \rightarrow \Phi \ J/\psi$
- $\gamma \gamma \rightarrow \omega \ J/\psi$
\[ \gamma \gamma \rightarrow \pi^0 \pi^0 \]

- PRD78, 052004 (95/fb)  W<1.6GeV
- PRD79, 052009 (223/fb)  W>1.7GeV
- \(|\cos \theta^*| < 0.8\)

Number of events

\[ W(\text{GeV}) \]

Number of events/20 MeV

bkg

W<1.6GeV
W>1.7GeV

Feb 17, 2010

Recent Two-Photon results at Belle (NCU)
**$\gamma \gamma \rightarrow \pi^0 \pi^0$**: Partial Wave Analysis for $f_0(980)$ region

\[
\frac{d\sigma}{4\pi d|\cos \theta^*|} = |SY_0^0 + D_0 Y_2^0|^2 + |D_2 Y_2^2|^2 = \hat{S}^2 |Y_0^0|^2 + \hat{D}_0^2 |Y_2^0|^2 + \hat{D}_2^2 |Y_2^2|^2
\]

<table>
<thead>
<tr>
<th>Model</th>
<th>$\Gamma_{\gamma \gamma}$ [keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$uubar, ddbar$</td>
<td>1.3-1.8</td>
</tr>
<tr>
<td>$ssbar$</td>
<td>0.3-0.5</td>
</tr>
<tr>
<td>$KKbar$ molecule</td>
<td>0.2-0.6</td>
</tr>
<tr>
<td>Four-quark</td>
<td>0.27</td>
</tr>
</tbody>
</table>

Consistent with $\pi^+ \pi^- \cdot$ mode (PRD75,051101)
$uubar$, $ddbar$ disfavored compared to other models
\[ \gamma \gamma \rightarrow \pi^0 \pi^0 : f_2(1950), f_4(2050) \]

\[
\frac{d\sigma}{4\pi d|\cos \theta^*|} = |SY_0^0 + D_2^0 Y_2^0 + G_4^0 Y_4^0|^2 + |D_2^0 Y_2^0 + G_4^0 Y_4^0|^2
\]

\[
= \hat{S}^2 |Y_0^0|^2 + \hat{D}_0^2 |Y_2^0|^2 + \hat{D}_2^2 |Y_2^0|^2 + \hat{G}_0^2 |Y_4^0|^2 + \hat{G}_2^2 |Y_4^0|^2
\]

| \begin{tabular}{l|c} 
M(f_4(2050)) & 1885^{+14}_{-13} \text{ MeV/c}^2 \\
\Gamma(f_4(2050)) & 453 \pm 20 \text{ MeV} \\
\Gamma_{\gamma \gamma B(\pi^0 \pi^0)} & 7.7^{+1.2}_{-1.1} \text{ eV} \\
M(f_2(1950)) & 2038^{+13}_{-11} \text{ MeV/c}^2 \\
\Gamma(f_2(1950)) & 441^{+27}_{-25} \text{ MeV} \\
\Gamma_{\gamma \gamma B(\pi^0 \pi^0)} & 54^{+23}_{-14} \text{ eV} 
\end{tabular} |

| \begin{tabular}{l|c|c|c} 
\chi^2 (ndf) & Nominal & Fixed f_4(2050) & No f_4(2050) & No f_2(1950) \\
\hline
\chi^2 (ndf) & 323.2(311) & 594.4(313) & 1397.8(315) & 2306.8(315) 
\end{tabular} |

Inclusion of both \( f_2(1950) \) and \( f_4(2050) \) gives much better \( \chi^2 \)
$\gamma \gamma \rightarrow \pi^0 \pi^0$: Higher region

$|\cos \theta^*|$: $a(\sin^4 \theta^* + b \cos^2 \theta^*)$

$\sigma \sim W^n$: $n = 6.9 \pm 0.6 \pm 0.7$

$\sigma(\pi^0 \pi^0)/\sigma(\pi^+ \pi^-) = 0.32 \pm 0.03 \pm 0.05$

- Significant $b$ term contribution
- Cross section ratio slightly smaller than Isospin symmetry, 0.5
- $\chi_{c0}$ observed with 7 $\sigma$
\[ \gamma \gamma \rightarrow \eta \pi^0 \]

\[ \sigma(|\cos \theta^*|<0.8) \text{ nb} \]

- PRD80, 032001 (2009). 223/fb
- \( a_J \) resonances (Isospin=1)
- \(|\cos \theta^*| < 0.8\)

- \( a_0(980), a_2(1320), a_2(1700) \) seen
- Consistent with Crystal Ball measurement (PRD33, 1847 (1986))
\[ \gamma \gamma \rightarrow \eta \pi^0 : \]

Partial Wave Analysis in 0.9 < W < 1.5 GeV

\[
\frac{d\sigma}{4\pi d|\cos \theta^*|} = |S Y_0^0 + D_0 Y_2^0|^2 + |D_2 Y_2^2|^2 = \hat{S}^2 |Y_0^0|^2 + \hat{D}_0^2 |Y_2^2|^2 + \hat{D}_2^2 |Y_2^2|^2
\]

- Fit with \(a_0(980), a_2(1320)\) and \(a_0(Y)\)

<table>
<thead>
<tr>
<th>(a_0(980))</th>
<th>(a_0(Y))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(M [\text{MeV/c}^2])</td>
<td>(982.3^{+0.6}<em>{-0.7}^{+3.1}</em>{-4.7})</td>
</tr>
<tr>
<td>(\Gamma [\text{MeV}])</td>
<td>(75.6^{+1.6}<em>{-1.0}^{+17.4}</em>{-10.0})</td>
</tr>
<tr>
<td>(\Gamma_{\gamma \gamma}[\text{eV}])</td>
<td>(128^{+3.2}<em>{-2.0}^{+502}</em>{-43.0})</td>
</tr>
<tr>
<td>(M [\text{MeV/c}^2])</td>
<td>(1316.8^{+0.7}<em>{-1.0}^{+24.7}</em>{-4.6})</td>
</tr>
<tr>
<td>(\Gamma [\text{MeV}])</td>
<td>(65.0^{+2.1}<em>{-5.4}^{+99.1}</em>{-32.6})</td>
</tr>
<tr>
<td>(\Gamma_{\gamma \gamma}[\text{eV}])</td>
<td>(432^{+6.0}<em>{-2.0}^{+1073}</em>{-256})</td>
</tr>
</tbody>
</table>

For \(a_0(Y)\), nominal \(a_0(1450)\) and background from \(a_2(1320)\) disfavored
$\gamma \gamma \rightarrow \eta \pi^0$: Higher region

- Consistent with $\sin^4 \theta^*$ for $W > 2.7$ GeV
- $W^{-n}$ dependence of $\sigma$
  $n = 10.5 \pm 1.2 \pm 0.5$
  consistent with $K_sK_s$ ($10.5 \pm 0.6 \pm 0.5$)
- $\sigma(\eta\pi^0) / \sigma(\pi^0\pi^0) = 0.48 \pm 0.05 \pm 0.04$
  - Not conclusive whether constant or not
\[ \gamma \gamma \rightarrow \phi J/\psi \]

- 825/fb
- No signal of Y(4140)
  - \( D_s^{**}D_s^{*-} \) molecule disfavored
- Evidence for a new structure X(4350)
  - Tetraquark?, \( D_s^{**}D_{s0}^{*-} \) molecular?, \( \chi_{c2}' \)?

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CDF (PRL102, 242002)

- Y(4140)
- X(4350)

- \( \# \text{event} = 8.8^{+4.2}_{-3.2} \)
- Significance = 3.2\( \sigma \) (including systematic error)
- \( M = 4350.6^{+4.6}_{-5.1} \pm 0.7 \) MeV/c\(^2\)
- \( \Gamma = 13.3^{+17.9}_{-9.1} \pm 4.1 \) MeV
- \( \Gamma_{\gamma\gamma B} = 6.7^{+3.2}_{-2.4} \pm 1.1 \) eV for 0\(^+\)
  - 1.5\(^+0.7\)\(_{-0.6}\) eV for 2\(^+\)
\[ \gamma \gamma \rightarrow \omega \ J/\psi \]

**X(3915)**

- Comparable with Y(3940) and Z(3930)
- Measured \( \Gamma_{\gamma \gamma} (X) \) \( \Gamma_{\omega \ J/\psi} (X) \) compatible with D*\D* state

### XYZ near X(3915)

<table>
<thead>
<tr>
<th>( X(3940) )</th>
<th>0?+</th>
<th>( e^+e^- \rightarrow J/\psi X )</th>
<th>3943( \pm 6 ) MeV/c(^2)</th>
<th>&lt;52 MeV</th>
<th><strong>Belle</strong>(PRL98, 081001 (2007))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Y(3940) )</td>
<td>??+</td>
<td>( B^- \rightarrow K^- Y, \ Y \rightarrow \omega J/\psi )</td>
<td>3943( \pm 11 \pm 13 ) MeV/c(^2)</td>
<td>87( \pm 22 \pm 26 ) MeV</td>
<td><strong>Belle</strong>(PRL94, 181002 (2005))</td>
</tr>
<tr>
<td>( Z(3930) )</td>
<td>2++</td>
<td>( \gamma \gamma \rightarrow Z, \ Z \rightarrow D\bar{D} )</td>
<td>3929( \pm 5 \pm 2 ) MeV/c(^2)</td>
<td>29( \pm 10 ) MeV</td>
<td><strong>Belle</strong>(PRL96, 081003 (2006))</td>
</tr>
</tbody>
</table>
Summary

- Pure neutral final states $\pi^0\pi^0$ and $\eta\pi^0$ have been studied in two-photon process
  - Light quark resonances are studied by Partial Wave Analysis
  - $\chi_{cJ}$ mesons are observed in $\pi^0\pi^0$ final states
  - Differential cross section and cross section are compared with QCD predictions
- $X(3915)$ has been observed in $\gamma\gamma \rightarrow \omega J/\psi$
  - Comparable parameters with $Y(3940)$ and $Z(3930)$
- Evidence of $X(4350)$ was found in $\gamma\gamma \rightarrow \Phi J/\psi$
  - A new structure (?)
  - No signal of CDF $Y(4140)$
Pt-balance

(a) $\Sigma p_t^\gamma$ (GeV/c) vs. $W$ (GeV)

(b) $W < 3.95$ GeV

Events/10 MeV/c

Entries/20 MeV/c

$\Sigma p_t^\gamma$ (GeV/c)