Measurements of $\gamma\gamma^* \rightarrow \pi^0$ transition form factor at Belle

S. Uehara (KEK)
Belle

QCD and Fragmentation

RIKEN, Wako, Nov. 9-11, 2012
Two-Photon Collisions and QCD/Hadron Physics

Hadron production from collisions of virtual or quasi-real photons
- Perturbative/Non-perturbative QCD
- Hadron/Photon form factors
- Resonances

Wide energy region and various physics aspects can be studied simultaneously.

Incident photon -- dominated by quasi-real photon
\[ Q^2 \equiv |q^2| \lesssim 0.001 \text{GeV}^2 \]

Zero-tag: Measurement of two real photon collisions

Single-tag: Collisions of a Real and a Virtual photons

"$\gamma\gamma \rightarrow \text{meson pair}$" measurements from Belle

<table>
<thead>
<tr>
<th>Process</th>
<th>Reference</th>
<th>Int.Lum. (fb⁻¹)</th>
<th>$\gamma\gamma$ c.m. Energy (GeV)</th>
<th>Physics covered</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Light Mesons</td>
<td>QCD</td>
</tr>
<tr>
<td>$\pi^+\pi^-$</td>
<td>PLB 615, 39 (2005)</td>
<td>87.7</td>
<td>2.4 – 4.1</td>
<td>$\checkmark$</td>
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<tr>
<td></td>
<td>PRD 75, 051101(R) (2007)</td>
<td>85.9</td>
<td>0.8 – 1.5</td>
<td>$\checkmark$</td>
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<td></td>
<td>J. Phys. Soc. Jpn. 76, 074102 (2007)</td>
<td>85.9</td>
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</tr>
<tr>
<td>$K^+K^-$</td>
<td>EPJC 32, 323 (2003)</td>
<td>67</td>
<td>1.4 – 2.4</td>
<td>$\checkmark$</td>
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</tr>
<tr>
<td>$\pi^0\pi^0$</td>
<td>PRD 78, 052004 (2008)</td>
<td>95</td>
<td>0.6 – 4.0</td>
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<td>PRD 79, 052009 (2009)</td>
<td>223</td>
<td>0.6 – 4.0</td>
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<tr>
<td>$K^0_SK^0_S$</td>
<td>PLB 651, 15 (2007)</td>
<td>397.1</td>
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<tr>
<td>$\eta\pi^0$</td>
<td>PRD 80, 032001 (2009)</td>
<td>223</td>
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<td>$\eta\eta$</td>
<td>PRD 82, 114031 (2010)</td>
<td>393</td>
<td>1.1 – 4.0</td>
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<tr>
<td>$\omega,\omega\phi,\phi\phi$</td>
<td>PRL 108,232001(2012)</td>
<td>870</td>
<td>~2 – 4.0</td>
<td>$\checkmark$</td>
</tr>
</tbody>
</table>
\( \pi^0 \) Transition Form Factor

Coupling of neutral pion with two photons
Good test for QCD at high \( Q^2 \)

Single-tag \( \pi^0 \) production in two-photon process
with a large-\( Q^2 \) and a small-\( Q^2 \) photons

Theoretically calculated from pion distribution amplitude
and decay constant

Measurement:

\[
|F(Q^2)|^2 = |F(Q^2,0)|^2 = \frac{\langle d\sigma/dQ^2 \rangle}{2A(Q^2)}
\]

\[
A(Q^2) = \frac{\sqrt{2} f_{\pi}^2}{3} \int T_H(x, Q^2, \mu) \phi_\pi(x, \mu) dx
\]

Detects e (tag side) and \( \pi^0 \)

\( Q^2 = 2EE'(1 - \cos \theta) \) from energy and polar angle of the tagged electron

\[S.Uehara, Belle, Frag.2012, RIKEN, Nov. 2012\]
BaBar’s Measurement

$\pi^0$ transition form factor (TFF) measured by BaBar is larger than the asymptotic pQCD prediction above $Q^2 > 10\text{GeV}^2$.

Below $Q^2 < 8\text{GeV}^2$, the BaBar result supports the CLEO result.

$\eta$ and $\eta'$ TFFs from BaBar

PRD 84, 052001(2011)

are consistent with QCD predictions.

Explanation within standard QCD calculations is difficult.
Measurement of $\pi^0$ TFF at Belle

**KEKB accelerator and Belle detector**

Asymmetric for beam energy ($e^+: 3.5$ GeV, $e^-: 8$ GeV)

for kinematic coverage of

$e^+$-tag($p$-tag) and $e^-$-tag($e$-tag)

**Available Triggers:**

**HiE **&& **Bhabha(-veto)**

by ECL (electromagnetic calorimeter system)

**HiE** --- $E$(Forward+Barrel) $>$ 1.15 GeV

**Bhabha-veto logic** kills a part of the acceptance

Significant loss of efficiency for some angular patterns

in contrast to BaBar, where a special salvaging logic was prepared.

**Int. Luminosity :**759 fb$^{-1}$ (Larger than BaBar’s)

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Selection Criteria for Signal Events

- Triggered by HiE or CsIBB (≡ Bhabha prescaled by factor 50)
- **1 good track** only, **Electron-ID** \( E/p > 0.8, \ p_e > 1.0 \text{ GeV/c} \) in lab. system
- **2 Photons from \( \pi^0 \)** \( E_{\gamma 1} > 0.2 \text{ GeV}, \ E_{\gamma\gamma} \equiv E_{\gamma 1} + E_{\gamma 2} > 1.0 \text{ GeV} \)
  
  No big energy asymmetry: \( |E_{\gamma 1} - E_{\gamma 2}| / E_{\gamma\gamma} < 0.8 \)
  
  Polar-angle difference: \( \Delta \theta \equiv |\theta_{\gamma 1} - \theta_{\gamma 2}| > \frac{0.18 [\text{rad} \times \text{GeV}]}{E_{\gamma\gamma}} \)

  To reject large background from Radiative Bhabha \((e)e\gamma\) process

- Polar- angle of the electron and the two photons
  \(-0.6235 < \cos \theta < +0.9481 \) and **Bhabha Mask cut**

- e-charge vs. \( p_z \) direction correlation
  \(-Q_{\text{tag}} (p_z^{* e} + p_z^{* \gamma\gamma}) > 0 \) \( (* \ -- \ e^+e^- \text{ c.m.s.}) \)

- **3-body kinematical cut for \( \pi^0 \) energy \( E_{\gamma\gamma}^* \)**
  
  Energy-momentum conservation using direction of \( p_{\gamma\gamma} \), and \( m_{\gamma\gamma} = m_{\pi^0} \)
  
  \[ 0.85 < \left( E_{\text{ratio}} \equiv \frac{E_{\gamma\gamma}^* \text{measured}}{E_{\gamma\gamma}^* \text{expected}} \right) < 1.1 \]

- Bhabha-background rejection, **Acollinearity angle**\((e, \gamma\gamma) < 177^\circ \) in \( e^+e^- \text{ c.m. frame} \)

- Good balances in azimuthal angle and \( p_t \) between e and \( \pi^0 \)

  \[ \text{Acoplanarity angle} \ (e, \gamma\gamma) < 0.1 \text{ rad}, \ |\Sigma p_t| < 0.2 \text{ GeV/c} \]

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\[ S.\text{Uehara, Belle, Frag.2012, RIKEN, Nov. 2012} \]
Background rejection and signal enhancement

$\Delta \theta$ : Polar-angle difference of $\gamma\gamma$
is used to reject 2 clusters from $\gamma \rightarrow ee$

$\pi^0$-mass region only

$E_{ratio} \equiv \frac{E^*_{\gamma\gamma}}{E^*_{\gamma\gamma}}$ measured/expected

- Background from $(e)e\gamma$
- Background from $(e)e\gamma\gamma$
- Backgrounds from the conversion is negligibly small after the cut.

Concentration near $|\Sigma p^*_{t}| = 0$

Bhabha-Mask criteria (Yellow regions for selection)

masks low-efficiency regions due to Bhabha veto in \((\cos \theta_e, \cos \theta_{\gamma\gamma})\)
to reduce uncertainty from trigger inefficiency

Unbiased sample using CsIBB trigger (1/50)

Effects from the Bhabha-veto is compensated in
\[ N_{\text{event(HiE)}} + 50 \times N_{\text{event(CsIBB)}} \]

≡ “Unbiased sample”

Statistically too small for the signal analysis

E-tag \(4 < Q^2 < 6 \text{ GeV}^2\) : HiE+50*CsIBB sample
other regions: HiE sample only

Extensively used for tuning and evaluation of the trigger simulator
Extraction of $\pi^0$ Yield

Fit $M_{\gamma\gamma}$ distribution by
Double Gaussian (for signal) + 2\textsuperscript{nd}-Order Polynomial (for background) in each $Q^2$ bin

$\pi^0$-mass resolution
the narrower Gaussian component $6 – 9$ MeV (dependent on $Q^2 = 4 – 40$ GeV$^2$) consistent between the exp. and MC
the wider $\sim 2.4$ times larger than the narrower

<table>
<thead>
<tr>
<th>Positron-tag</th>
<th>Electron-tag</th>
</tr>
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<tbody>
<tr>
<td>p-tag, HIE, Mask noFix, 9-10 GeV$^2$</td>
<td>e-tag, HIE, Mask noFix, 9-10 GeV$^2$</td>
</tr>
<tr>
<td>p-tag, HIE, Mask noFix, 16-18 GeV$^2$</td>
<td>e-tag, HIE, Mask Fix, 16-18 GeV$^2$</td>
</tr>
<tr>
<td>p-tag, HIE, Mask Fix, 30-40 GeV$^2$</td>
<td>e-tag, HIE, Mask Fix, 30-40 GeV$^2$</td>
</tr>
<tr>
<td>e-tag, HIE, noMask noFix, 4-5 GeV$^2$</td>
<td>e-tag, CsiBB, noMask Fix, 4-5 GeV$^2$</td>
</tr>
</tbody>
</table>

Signal Yields; $Q^2$ Unfolding

$Q^2$ – unfolding is applied using inverted migration matrix that takes into account the effects from:
- Detector resolution
- ISR at the tagged electron

Signal yields

- Before the unfolding
- After the unfolding
Calibration of Bhabha-veto Thresholds using Radiative-Bhabha (VC) Events

Bhabha-veto threshold is measured in real data of Virtual-Compton process of \((e)e\gamma\) and is tuned in Trigger Simulator.

MC generator **Rabhat** treats \(t\)-channel mass singularity

\[ \text{VC process has a similar topology to the signal process} \]

- Require a single \(\gamma\) instead of \(\pi^0\)
- Big cross section (~ \(\text{O}(1\text{nb})\))
- In unbiased sample, enough statistics available

\[
Y_{\text{ratio}} = \frac{50 \times N(\text{CsBB})}{N(\text{HiE}) + 50 \times N(\text{CsBB})}
\]

**Trigger Efficiency for Bhabha (-veto) as a function of energy deposit**

\(\rightarrow\) tune MC (trigger simulator)

\[ S.\text{Uehara, Belle, Frag.2012, RIKEN, Nov. 2012} \]
Comparisons in Radiative Bhabha (VC) samples

MC (Rabhat) is normalized by int. luminosity

Lowest order-only -- $\delta$(rad.corr.)~ -6% ($\pm$4%) applied

For HiE (Bhabha-Masked) sample

$Q^2$ dependences

Lab. angle distributions

$d$ (rad.corr.)~ $\gamma$

For yields

$Q^2$ (GeV$^2$)

Horizontal line (1): Expectation

5-10% disagreement is explained by uncertainties in radiative correction and systematic uncertainty in the measurement

dots: Exp. histograms: MC

$\cos \theta$

$\epsilon_{DR}$: Exp./MC Ratio for Efficiency for “Bhabha-Mask” × “Bhabha-veto” shows a better agreement between Exp. and MC

Efficiency for the Signal Process

The trigger efficiency is defined for the acceptance after the selection.

Up-down structures are reflection of Bhabha-mask and –veto correlated to $Q^2$ in $(\cos\theta_e, \cos\theta_{\gamma\gamma})$ plane.
Checks of Signal Details with MC

\( \pi^0 \)-polar-angle distribution

- **Q^2 = 6 - 8 GeV^2**
- **Q^2 = 10 - 12 GeV^2**
- **Q^2 = 16 - 18 GeV^2**

**Radiative tails**

- Radiative energy fraction
- Acoplanarity angle for e\( \pi^0 \)
- p_t-balance for e\( \pi^0 \)

Peaking ($\pi^0$) Backgrounds

(e)$\pi^0X$ --- Backgrounds peaking at the pion mass, which leak near to ($E_{ratio}=1$, $|\Sigma p_t|=0$)

(1) **Study of wrong-sign events** (defined by the charge vs. $z$-direction correlation)

No $\pi^0$ is there (1.2 ± 0.9 events)

Backgrounds from $e^+e^-$ annihilation and particle misidentification (of muon or hadron) are negligibly small.

(2) **Background processes**

No $\pi^0$ is there (1.2 ± 0.9 events)

$\gamma\gamma^* \rightarrow \pi^0\pi^0$
$ee \rightarrow (e)e\rho^0/\omega$, $\rho^0/\omega \rightarrow \pi^0\gamma$

are experimentally observed

We build background MC’s normalized to these observations

**Background contamination** estimated

$\pi^0\pi^0$: 2% uniformly for $Q^2$

$\pi^0\gamma$: 0.8% @ $Q^2 < 12$ GeV$^2$

1 – 3% @ 12 – 40 GeV$^2$
The cross sections from p-tag and e-tag are evaluated, separately, and then combined.
Transition Form Factor

\[ Q^2 |F(Q^2)| = Q^2 \sqrt{\frac{d\sigma/dQ^2}{2A(Q^2)}} \]

Representative value \( Q^2 \) is used for

Q\(^2\) point that gives the cross section with the same size as the mean over the bin calculated using an approximated dependence, \( d\sigma/dQ^2 \sim Q^{-7} \)
Systematic Uncertainties

For Cross Section:

Q$^2$ independent:  
- Tracking                                1%
- e-ID                                     1%
- $\gamma\gamma$ reconstruction              3%
- kinematical selection        2%
- geometrical selection       2%
- beam background             2%
- integrated luminosity    1.4%
- radiative correction         3%
- form-factor effect           1.0%

( subtotal      6%)

Q$^2$ dependent:  
- Extraction of $\pi^0$-yield  5–10%   estimated variation of fit (single Gauss + linear fit)
- Trigger efficiency             2–12%

estimated by studies of trigger threshold & Rad.Bhabha events

- Peaking-background       1 – 4%   8 – 14% in total

For Transition Form Factor:

Half of the above values, as $|F|\sim \sqrt{d\sigma/dQ^2}$

with added by an uncertainty of  2A(Q$^2$) -- 2% (form-factor effect for the low-Q$^2$ photon)
Comparisons with Previous Measurements and Fits

**Fit A (suggested by BaBar)**

\[ Q^2 |F(Q^2)| = A \left( \frac{Q^2}{10 \text{GeV}^2} \right)^\beta \]

- **BaBar:**
  - \( A = 0.182 \pm 0.002 \) (± 0.004) GeV
  - \( \beta = 0.25 \pm 0.02 \)

- **Belle:**
  - \( A = 0.169 \pm 0.006 \) GeV
  - \( \beta = 0.18 \pm 0.05 \)

\( \chi^2/\text{ndf} = 6.90/13 \) ~1.5σ difference from BaBar

**Fit B (with an asymptotic parameter)**

\[ Q^2 |F(Q^2)| = BQ^2/(Q^2+C) \]

- **Belle:**
  - \( B = 0.209 \pm 0.016 \) GeV
  - \( C = 2.2 \pm 0.8 \) GeV²

\( \chi^2/\text{ndf} = 7.07/13 \)

B is consistent with the QCD value (0.185GeV)

No rapid growth above \( Q^2 > 9 \text{GeV}^2 \) is seen in Belle result.

~ 2.3σ difference between Belle and BaBar in 9 – 20 GeV²

Summary

• The $\pi^0$ transition form factor is measured at Belle in the range, $4 \text{ GeV}^2 \lesssim Q^2 \lesssim 40 \text{ GeV}^2$.

There was a significant effect from Bhabha-veto, but the trigger simulator to estimate the signal efficiency is tuned, reliably, calibrating it using radiative Bhabha events.

• No rapid growth of $\pi^0$ TFF is observed for the region $Q^2 > 9 \text{GeV}^2$.

• Phenomenological fits are applied for $Q^2$ dependence of $\pi^0$ TFF.

Belle
To appear in Phys. Rev. D
For future (SuperKEKB & Belle II)

Luminosity

“x40” \(\rightarrow 8 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}\)

Target of

the integrated luminosity \(50 \text{ ab}^{-1}\)
When 50ab$^{-1}$ data at Belle II analyzed, ...

Assumptions:
- Integrated luminosity 50 ab$^{-1}$ (x 66)
- No large Bhabha-Veto inefficiency (x 2.5 @ high $Q^2$)
- Systematic errors from $\pi^0$-fit and trigger can be reduced
- Other systematics stay the same

$Q^2 > 60$ GeV$^2$
Close to back-to-back topology of $e\pi^0$ in $e^+e^-$ c.m. frame

Huge background from Bhabha
Backup
Resonance production
Resonance production and quantum numbers

Resonance formation or partial-waves

\[
\begin{align*}
\text{Resonance} & \quad \begin{array}{c}
Q = 0 , \quad C = + , \\
J^P = 0^+ , 0^- , 2^+ , 2^- , 3^+ , 4^+ , 4^- , 5^+ , \ldots \\
\text{(even) }^\pm , \text{ (odd } \neq 1)^+ 
\end{array}
\end{align*}
\]

Strict constraints for quantum numbers
Pseudoscalar-pair production: \( J^P = \text{(even)}^+ \) only
\( \Gamma_{\gamma\gamma} \), two-photon partial decay width of the resonance, from the cross-section measurement, important information for the meson’s internal structure

Decay properties
Searches/Discoveries of new resonances, including “XYZ”

Confirmations of $f_0(980)$ and $a_0(980)$

True nature of $f_0(980)$ and $a_0(980)$ is not clarified, well. We observe them as a peak very clearly in two-photon production for the first time.

- Measurements of $\Gamma_{\gamma\gamma}$
Two-photon decay width of $f_0(980)$ and $a_0(980)$

<table>
<thead>
<tr>
<th>Meson</th>
<th>$f_0(980)$</th>
<th>$f_0(980)$</th>
<th>$a_0(980)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M[\text{MeV}/c^2]$</td>
<td>$985.6^{+1.2+1.1}_{-1.5-1.6}$</td>
<td>$982.2\pm1.0^{+8.1}_{-8.0}$</td>
<td>$982.3^{+0.6+3.1}_{-0.7-4.7}$</td>
</tr>
<tr>
<td>$\Gamma_{\pi\pi/\text{tot}}[\text{MeV}]$</td>
<td>$51.3^{+20.9+13.2}_{-17.7-3.8}$</td>
<td>$66.9^{+13.9+8.8}_{-11.8-2.5}$</td>
<td>$75.6\pm1.6^{+17.4}_{-10.0}$</td>
</tr>
<tr>
<td>$\Gamma_{\gamma\gamma}[\text{eV}]$</td>
<td>$205^{+95+147}_{-83-117}$</td>
<td>$286\pm17^{+211}_{-70}$</td>
<td>$128^{+3+502}<em>{-243}/B</em>{\pi^0\eta}$</td>
</tr>
<tr>
<td>Channel</td>
<td>$\gamma\gamma \rightarrow \pi^+\pi$</td>
<td>$\gamma\gamma \rightarrow \pi^0\pi^0$</td>
<td>$\gamma\gamma \rightarrow \pi^0\eta$</td>
</tr>
</tbody>
</table>

Predictions

<table>
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<tr>
<th>Model</th>
<th>$\Gamma_{\gamma\gamma}$ [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$uubar, d\bar{d}bar$</td>
<td>$1300 - 1800$</td>
</tr>
<tr>
<td>$s\bar{s}bar$</td>
<td>$300 - 500$</td>
</tr>
<tr>
<td>$KK$ bar molecule</td>
<td>$200 - 600$</td>
</tr>
<tr>
<td>Four-quark</td>
<td>$270$</td>
</tr>
</tbody>
</table>
Summary of resonances seen in $\gamma\gamma \rightarrow MM'$

$f_0(980) \rightarrow \pi^+\pi^-, \pi^0\pi^0 \quad a_0(980) \rightarrow \eta\pi^0$

The $1^3P_2$ tensor-meson triplet $f_2(1270), f'_2(1525), a_2(1320)$

$f_0(Y) \rightarrow \pi^+\pi^-, \pi^0\pi^0, \eta\eta$ unidentified in $1.2 - 1.5$ GeV

$a_0(Y) \rightarrow \eta\pi^0$ unidentified in $1.2 - 1.5$ GeV

$f_2(X) \rightarrow \pi^0\pi^0, \eta\eta$ unidentified in $1.7 - 2.0$ GeV

Signatures of $a_2(1700)?, f_4, a_4$, and/or others? seen in $1.7 - 2.3$ GeV in $\pi^0\pi^0, \eta\pi^0, \eta\eta$ and $K^+K^-$

$\chi_{c0}, \chi_{c2} \rightarrow \pi^+\pi^-, K^+K^-, \pi^0\pi^0, K^0_S K^0_S, \eta\eta$
\( \gamma \gamma \rightarrow Z(3930) \rightarrow DD \) discovered /confirmed

PRL 96, 082003 (2006)

Belle, PRL 96, 082003 (2006)

\[ m(3930) = 3929 \pm 5 \pm 2 \text{ MeV/c}^2 \]
\[ \Gamma(3930) = 29 \pm 10 \pm 2 \text{ MeV} \]
\[ \Gamma_{\gamma\gamma} \cdot BF(Z(3930 \rightarrow DD)) = 0.18 \pm 0.05 \pm 0.03 \text{ keV} \]

BaBar, PRD 81, 092003 (2010)

\[ m(3930) = 3926.7 \pm 2.7 \pm 1.1 \text{ MeV/c}^2 \]
\[ \Gamma(3930) = 21.3 \pm 6.8 \pm 3.6 \text{ MeV} \]

384 fb\(^{-1}\)

Belle and Babar results are consistent

Confirms that \( Z(3930) = \chi_{c2}(2P) \)

Peak in $\gamma \gamma \rightarrow \omega J/\psi$

Two-photon production of $Y(3940)$?
reported in $B$ decay

or

New decay mode of $Z(3930)/\chi_{c2}(2P)$?
$\gamma \gamma \rightarrow \phi J/\psi$

$Y(4140)$, reported by CDF in B-meson decays, is NOT seen in two-photon process by Belle.

Instead, a **new peak** is seen at around 4.35 GeV in the same process

$M=4350.6^{+4.6}_{-5.1} \pm 0.7$ MeV/c$^2$

$\Gamma=13^{+18}_{-9} \pm 4$ MeV
Many meson-pair production processes from two-photon collisions are studied at Belle.

- Cross sections in the 2 – 4 GeV region are compared with predictions based on QCD, systematically.
- Any comprehensive reproducibility by theoretical models is not obtained, yet.
  Further comparison with theories is now possible.
- Belle discovers/confirms several interesting meson states produced in two-photon fusion:
  \[ \Gamma_{\gamma\gamma} \text{ for } f_0(980) \text{ and } a_0(980) \text{ are measured} \]
  \[ \text{New charmonium-like states are found} \]
  \[ Z(3930) = \chi_{c2}(2P), X(3915) = Y(3940) ?, \ X(4350) \]
BaBar at PEP-II

e^+e^-\rightarrow Y(4S) and nearby continuum:
E_{\text{cms}} \sim 10.6 \text{ GeV}

530 \text{ fb}^{-1} \text{ in total}
Experimental Analysis; $\gamma\gamma \rightarrow \eta\eta$

$\eta(548\text{MeV}) \rightarrow \gamma\gamma$ (Only 4 photons are visible in this process)

Triggered by ECL triggers ($\Sigma E > 1.1\text{GeV}$ or $\geq 4$ clusters)

$\sqrt{s} = 9.4 - 11.0\ \text{GeV}$ \hspace{1cm} $\int L dt = 393\ \text{fb}^{-1}$

Selection of $\eta\eta$ signal events
- Just 4 $\gamma$’s with $E_\gamma > 100$ MeV, No $\pi^0$ candidate

$\eta$ reconstruction
- Two $2\gamma$ sets each satisfying $0.52 < M_{\gamma\gamma} < 0.57\text{GeV}$
- Apply energy correction for each $\eta$, scaling to the nominal mass
- $p_t$-balance $< 50$ MeV/c

$W$: $\gamma\gamma$ energy in its c.m.s.
$\theta^*$: scattering angle of the meson in the $\gamma\gamma$ c.m.s.

$1.096\text{GeV}$ (mass threshold) $< W < 3.8\ \text{GeV}$

$|\cos \theta^*| < 0.9$ or $< 1.0$

Baryon pair: $\gamma \gamma \rightarrow p\bar{p}$

Baryon production mechanism
Couple with a single quark?.. or a diquark?
Angular and W dependences, Cross-section size

$2.5 < W_{\gamma\gamma} < 3.0 \text{ GeV}$

$3 < W_{\gamma\gamma} < 4 \text{ GeV}$

Model predictions are normalized for $|\cos\theta^*|<0.3$.
Agreement is not very good in $W>3 \text{ GeV}$

Subtract charmonium contributions

$\eta_c$ : observation in this process

Cross sections; $W$ dependence

$W_{\gamma\gamma}^{-n}$ dependence
$n = 15.1 \pm 0.8 \quad @ \quad 2.5 - 2.9 \text{ GeV}$
$n = 12.4 \pm 2.4 \quad @ \quad 3.2 - 4.0 \text{ GeV}$

Might agree with a QCD prediction $n = 10$
at some energy above 3.1 GeV

Slope – steeper than meson pairs
Energy-correlations in the skim file, $\Sigma E_\gamma > 1.0$ GeV

Similar distribution to Signal-MC.
But, the exp. events are dominated by backgrounds (Radiative Bhabha)
Effect of Bhabha-veto in angle correlation

Bhabha-mask is not applied

Bhabha-veto patterns in trigger

Brown: No HiE
Red: strongly vetoed
Other: weakly vetoed

\( \gamma \gamma \) from \( \pi^0 \) and from backgrounds

Energy asymmetry to reject low-energy photon background

\[ \Delta \theta \] – Polar-angle difference of \( \gamma \gamma \)

Used to reject 2 clusters from \( \gamma \rightarrow ee \)
**Kenematical Criteria**

\[
\frac{E_{\text{ratio}}}{E_{\gamma\gamma}^*} = \frac{E_{\text{measured}}^*}{E_{\gamma\gamma}^*_{\text{expected}}}
\]

- **Signal**
  - \(\pi^0X\) (non-exclusive) background

- **Concentration** near \(\Sigma p_t = 0\)

\(\pi^0\)-mass region only

Study of **wrong-sign events** defined by the charge vs direction relation.

The tail around $E_{\text{ratio}} \sim 0.75$ is consistent with the expected radiative tail of the signal process.
Double Gaussian (for signal) + 2\textsuperscript{nd}-\textit{order} Polynomial (background)

\[ f(x) \sim a + bx + cx^2 + \frac{A}{\sqrt{2\pi}\sigma} \left\{ r e^{-\frac{(x-m)^2}{2\sigma^2}} + \frac{1-r}{k} e^{-\frac{(x-(m+\Delta m))^2}{2(k\sigma)^2}} \right\} \]
Conversion factor for $|F(Q^2)| : 2A(Q^2)$

Use the cross section formula by

“Brodsky-Kinoshita-Terazawa”  (PRD 4, 1532(1971))

Not using EPA --- not trivial

CLEO, PRD57, 33(1998)

EPA – Equivalent Photon Approximation

Assume being factorized as

$$\sigma_{ee} \sim \int \sigma_{\gamma\gamma}(Q_1^2, Q_2^2) N_\gamma(Q_1^2) N_\gamma(Q_2^2)$$

(we do not assume this)

We assume only the form factors is factorized

$$\sigma_{ee} \sim \int a(Q_1^2, Q_2^2) |F(Q_1^2, Q_2^2)|^2, \quad \text{and}$$

$$F(Q_1^2, Q_2^2) = F(0, 0) f(Q_1^2) f(Q_2^2), \quad f(0) = 1$$

Furthermore,

we assume $f(Q^2) = 1/(1+Q^2/m_\rho^2)$ when $Q^2 < m_\rho^2$

But, $f(Q^2)$ is unknown for $Q^2 > m_\rho^2$ (what we measure)

Define as $F(Q^2) \equiv F(Q^2, 0) = F(0, Q^2) = F(0, 0) f(Q^2)$

Conversion factor for $|F(Q^2)|$ (cont.)

\[ c = F(0, 0) \rightarrow F(Q_1^2, Q_2^2) = c f(Q_1^2) f(Q_2^2) = c f(Q_1^2)/(1+Q_2^2/m_r^2) \]

-- factorization assumption

Assume some values for $c$ and $f(Q_1^2)$

\[ \rightarrow \frac{d\sigma}{dQ_1^2} = A(Q_1^2) c^2 |f(Q_1^2)|^2 \quad \text{(by BKT formula)} \]

conversion factor $A(Q_1^2)$ is determined by the calculation

- Single-tag measurement $d\sigma/dQ^2$

Factor 2: Ele-tag + Pos-tag

\[
\frac{(d\sigma/dQ^2)}{2A(Q^2)} = c^2 |f(Q^2)|^2 = c^2 |f(Q^2)|^2 |f(0)|^2
\]

\[ = |F(Q^2, 0)|^2 = |F(Q^2)|^2 \]

with the same scheme for the efficiency determination and event generation $\rightarrow$ Signal MC

Calculation of $A(Q^2)$ coincides BaBar’s calculation with the same BKT and the same $f(Q_2^2)$ within 0.1%.

ISR and Radiative Correction

\( r_k \) --- Energy fraction of the ISR photon wrt. the beam energy

The \( r_k \) range for the signals is constrained by \( E_{\text{ratio cut}} \)
which roughly corresponds to \(-0.03 < r_k < 0.10\)

MC event generation includes the ISR effect by exponentiation technique for \( r_k < 0.25 \)

\( r_k \) distribution is consistent between the data and the signal MC,
The selected events are contained in \( r_k < 0.10 \)

Radiative correction for cross section

\[ 1 + \delta = 1.02 \] (definition: \( \sigma_{\text{LO+NLO}} = \sigma_{\text{LO}}(1+\delta) \),
including +0.03 hadron-loop in vacuum polarization.
with small \( Q^2 \) dependence (~1% effect).

Our cross section and TFF are converted to those for the LO.

Study of Radiative Bhabha samples

Experimental $\text{(e)\text{e}\gamma}$ sample with the similar topology to $\text{(e)\text{e}\pi^0}$

10,000 times larger statistics (but physics is different…)

Angle-angle ($\cos \theta_\gamma$ vs. $\cos \theta_e$) Bhabha-Veto pattern in Exp.data

Exp. Data

HiE

CsiBB

Unbiased: HiE + 50*CsiBB

Veto-structure is compensated!

← MC(Rabhat)

Tuning of Bhabha-veto thresholds

Looking at $\frac{N(\text{HiE})}{N(\text{Unbiased})}$ as a function of E-deposit in each ECL-Bhabha trigger segment

Experimental Rad. Bhabha sample

Tuned MC

Comparisons of Radiative Bhabha (VC) samples

Angular $\cos \theta \in (-1,+1)$ distributions for $\gamma$ and $e$

Unbiased

Dots: Exp.
Histograms: MC

HiE (Bhabha-Masked)

Comparison of Bhabha Mask*Veto efficiency for Radiative Bhabha events

Bhabha mask*veto efficiency from MC is confident
Within 5 – 12% error depending on $Q^2$

\( \pi^0\pi^0 \) background MC

Experimentally identified \( \gamma\gamma^* \rightarrow \pi^0\pi^0 \)

Background contamination in signal is estimated by the \( \pi^0\pi^0 \) background MC which is normalized to the observation, as 2%
Representative value $\bar{Q}^2$ is used for each $Q^2$ bin

$Q^2$ point that gives the cross section with the same size as the mean over the bin calculated using an approximated dependence, $d\sigma/dQ^2 \sim Q^{-7}$

BaBar’s Efficiency and Cross section

FIG. 4 (color online). The detection efficiency as a function of the momentum transfer squared for events with a tagged electron (squares), a tagged positron (triangles), and their sum (circles).

FIG. 21 (color online). The $e^+e^- \rightarrow e^+e^- \pi^0$ differential cross section obtained in this experiment compared to that from the CLEO experiment [12].

Integrated luminosities and beam energies

**Luminosity at B factories**

- **KEKB**
- **PEP-II**
- **World**

> 1 ab$^{-1}$

**On resonance:**
- $\Upsilon(5S)$: 121 fb$^{-1}$
- $\Upsilon(4S)$: 711 fb$^{-1}$
- $\Upsilon(3S)$: 3 fb$^{-1}$
- $\Upsilon(2S)$: 24 fb$^{-1}$
- $\Upsilon(1S)$: 6 fb$^{-1}$

**Off resonance/scan:**
- $\sim 100$ fb$^{-1}$

$\sim 550$ fb$^{-1}$

**On resonance:**
- $\Upsilon(4S)$: 433 fb$^{-1}$
- $\Upsilon(3S)$: 30 fb$^{-1}$
- $\Upsilon(2S)$: 14 fb$^{-1}$

**Off resonance:**
- $\sim 54$ fb$^{-1}$

Cross sections integrated over angle

\[ \sigma(|\cos \theta^*|<0.6) \]

\[ p + p - p + p - p_0 \]
\[ K + K^- \]
\[ \eta \pi^0 \] and \[ \eta \eta \] are shown in other slides
Zero-tag measurement

- $e^+ e^-$ escape down beam pipe at small recoil angles.
- Reactions involve small virtuality photons with $\left| \sum_i p_t^i (M_i) \right| \sim 0$.

$$\frac{d\sigma}{d|\cos\theta^*|} = \frac{\Delta N}{\Delta W \Delta|\cos\theta^*|} \frac{dL_{\gamma\gamma}}{dW} \text{eff} \int \mathcal{L} dt,$$

\( \frac{dL_{\gamma\gamma}}{dW} : \text{Luminosity Function} \)

- For a resonance $R$, two-photon decay width $\Gamma_{\gamma\gamma}$ is measured from

$$\sigma(W) = 8\pi(2J+1) \frac{\Gamma_{\gamma\gamma}(R) \Gamma_R B(R \rightarrow \text{final states})}{(W^2-M_R^2)^2+M_R^2 \Gamma_R^2}$$

\[ W = M(\gamma\gamma) = M(\text{Mesons}) \]

S. Uehara, Belle, Frag. 2012, RIKEN, Nov. 2015