Gamma gamma physics at Belle

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On behalf of Belle Collaboration

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\((g-2)_\mu\): Quo vadis, 9th April, Mainz
KEKB and Belle

- Asymmetric $e^+ e^-$ collider
  8 GeV $e^-$ (HER) x 3.5 GeV $e^+$ (LER)
  $\sqrt{s} = 10.58$ GeV $\Leftrightarrow \Upsilon(4S)$
  Beam crossing angle: 22 mrad

- Continuous injection

- Luminosity
  $L_{\text{max}} = 2.1 \times 10^{34}$ cm$^{-2}$s$^{-1}$
  World record!

High momentum/energy resolutions
CDC+Solenoid, CsI
Vertex measurement – Si strips
Particle identification
TOF, Si-aerogel, CDC-dE/dx, 
RPC for $K_L$/muon
Running >10 years
Integrated luminosity of B factories

All can be used for $\gamma\gamma$ study!

- $>1$ ab$^{-1}$
  - On resonance:
    - $\Upsilon(5S)$: 121 fb$^{-1}$
    - $\Upsilon(4S)$: 711 fb$^{-1}$
    - $\Upsilon(3S)$: 3 fb$^{-1}$
    - $\Upsilon(2S)$: 25 fb$^{-1}$
    - $\Upsilon(1S)$: 6 fb$^{-1}$
  - Off resonance/scan:
    - $\sim100$ fb$^{-1}$

- $\sim550$ fb$^{-1}$
  - On resonance:
    - $\Upsilon(4S)$: 433 fb$^{-1}$
    - $\Upsilon(3S)$: 30 fb$^{-1}$
    - $\Upsilon(2S)$: 14 fb$^{-1}$
  - Off resonance:
    - $\sim54$ fb$^{-1}$
Hadron/QCD physics

\(\gamma^*\gamma^*\) interaction in an \(e^+e^-\) Collider

1. Quasi-real photons: both \(\gamma^*\) have small \(Q^2\), \(Q^2<<W_{\gamma\gamma}^2\), \(Q^2<<E_{QCD}^2\), non-tag method, characteristic \(|\Sigma Pt^*|\) distribution.

- Hunt new hadrons, study hadron structure, test pQCD...

\(\Gamma_{\gamma\gamma}^*\text{Br}(\gamma\gamma\rightarrow f)\) or \(\gamma\gamma\rightarrow f\) cross section, \(\gamma\gamma\) coupling constant, provide info. of hadron structure.

**Quantum number constraint:** \(Q=0, C=+, J^P=0^+, 0^-, 2^+, 2^-\) ...

2. High virtuality: large \(Q^2\), double-tag (\(\gamma^*\gamma^*\)) or single-tag method (\(\gamma^*\)).

- Form factor measurement: \(\pi^0\)
- Test pQCD...
Hadron physics with quasi-real photons
Observation of $\chi_{c2}(2P)$

1. Potential model: $M[\chi_{c2}(2P)] \sim 3.9-4.0$ GeV, decay to DD, $J^{PC}=2^{++}$
2. Lum=395 fb$^{-1}$ @ Belle, $\gamma\gamma \rightarrow$ DD process
3. $M(Z(3930)) = 3929 \pm 5 \pm 2$ MeV/$c^2$; $\Gamma(Z(3930)) = 29 \pm 10 \pm 2$ MeV; $\Gamma_{\gamma\gamma} \times Br(Z(3930) \rightarrow DD) = 0.18 \pm 0.05 \pm 0.03$ keV
Observation of $\chi_{c2}(2P)$

1. Scatter angle distribution of final D meson; favor Spin-2 option
2. It should be the $\chi_{c2}(2P)$

$\chi_{c2}(2P)$

$J^G(J^{PC}) = 0^+(2^{++})$

Mass $m = 3927.2 \pm 2.6$ MeV
Full width $\Gamma = 24 \pm 6$ MeV

Confirmed by BaBar, mass & width agree with Belle

BaBar, $L = 384$ fb$^{-1}$
PRD81,092003(2010)
**χ_{c0}(2P) candidate**

1. Belle $\gamma\gamma \rightarrow \omega J/\psi$ process using “zero-tag” events.

2. Observe a structure near 3.9 GeV, $X(3915)$ significance 7.7σ

3. Mass=$(3915\pm3\pm2)$ MeV, width=$(17\pm10\pm3)$ MeV

4. Candidate for $\chi_{c0}(2P)$
1. Confirmed by BaBar: $M=3919.4 \pm 2.2 \pm 1.6$ MeV; Width=$(13 \pm 6 \pm 3)$ MeV
2. Further angular analysis supports $J^{PC}=0^{++}$
3. Belle: $\Gamma_{\gamma\gamma} \cdot Br(X(3915) \rightarrow \omega J/\psi)=(61 \pm 17 \pm 8)$ eV; BaBar=$(52 \pm 10 \pm 3)$ eV
4. If one assume $\Gamma_{\gamma\gamma} <\text{keV}$, $Br[X(3915) \rightarrow \omega J/\psi]$~(1-6)%
\[ \gamma \gamma \rightarrow \omega \phi, \phi \phi, \omega \omega \]

- \( \gamma \gamma \rightarrow VV \): “golden” channel \( \rightarrow \) 4-quark hadron
- VV pair well “glued” to \( \gamma \gamma \) system,
- Models: MIT bag... (Sov. Phys. Usp. 34,1991)
- Example: \( \gamma \gamma \rightarrow \rho^+\rho^-, \rho^0\rho^0, K^+K^- ... \) (L3 & ARGUS)
- Enhancements near \( \rho^0\rho^0 \) threshold, but not \( \rho^+\rho^- \)?

1. Un-tag method
2. Signal events: \(|\Sigma P_t^*|\)
   (vector sum) \( \sim 0 \)
3. Fit \(|\Sigma P_t^*|\) distribution \( \rightarrow \)
   signal events yield
4. Background estimated through \( \omega/\phi \) sideband

![Graph showing data, good fit, and background fit with 870 fb⁻¹ data points]
1. (a) $\omega\phi$ (b) $\phi\phi$ (c) $\omega\omega$ mass spectrum in two-photon process.

2. Background is estimated from sideband, i.e. 4K, $6\pi$…

3. Obvious enhancement below $2.8\text{GeV}/c^2$

4. Charmonia is observed significantly in $\phi\phi$ mode.
Spin-Parity results for $M(VV)<2.8\text{GeV}/c^2$

Angle definition:

1. Five kinematically independent angles: $\cos\theta$, $\cos\theta^*$, $\cos\theta^{**}$, $\phi^*$, $\phi^{**}$

2. Transversity angle: $\phi_T = |\phi^* + \phi^{**}|$; Polar-angle product: $\Pi_\theta = (\sin\theta^*)^2 \times (\sin\theta^{**})^2$

3. (a)4x4 (b)5x5 (c)10x10 bins. Fig (a) shows $\Pi_\theta$ distribution in each $\phi_T$ bin, i.e. $\Pi_\theta$ distribution while $\phi_T \in [0.0.25)$ for first 4 bins and similarity for others.

4. Fit 2-D angle distribution $f(\phi_T, \Pi_\theta)$ to extract different $J^P$ components.

(a). $0^+$ S-Wave or $2^+$ S-Wave

(b). $0^+$ S-Wave and $2^-$ P-Wave

(c). $0^+$ S-Wave and $2^+ S$-Wave
Cross section measurement

1. (a) $\omega\phi$ (b) $\phi\phi$ (c) $\omega\omega$ cross section together with different $J^P$ component contribution.

2. Efficiency is got through MC simulation and re-weighed according to mass dependent spin-parity analysis result.

3. Sys. error would be (a)15% (b)11% (c)13%

4. Power law ($W^{-n}$) fit for high energy region:
   
   $n=7.2\pm 0.6(a), 8.4\pm1.1(b), 9.1\pm0.6(c)$. 

Charmonium results

1. Clear $\eta_c$, $\chi_{c0}$ and $\chi_{c2}$ signal in (b)$\phi\phi$ mode and first evidence for (c)$\eta_c \rightarrow \omega\omega$.

2. Measurement of $\Gamma_{\gamma\gamma} * Br(VV)$

**TABLE II: Results of $\Gamma_{\gamma\gamma} B(X \rightarrow VV)$ (eV) for $\eta_c$, $\chi_{c0}$ and $\chi_{c2}$.**

<table>
<thead>
<tr>
<th>mode</th>
<th>$\omega\phi$</th>
<th>$\phi\phi$</th>
<th>$\omega\omega$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_c$</td>
<td>$&lt; 0.49$</td>
<td>$7.75 \pm 0.66 \pm 0.62$</td>
<td>$8.67 \pm 2.86 \pm 0.96$</td>
</tr>
<tr>
<td>$\chi_{c0}$</td>
<td>$&lt; 0.34$</td>
<td>$1.72 \pm 0.33 \pm 0.14$</td>
<td>$&lt; 3.9$</td>
</tr>
<tr>
<td>$\chi_{c2}$</td>
<td>$&lt; 0.04$</td>
<td>$0.62 \pm 0.07 \pm 0.05$</td>
<td>$&lt; 0.64$</td>
</tr>
</tbody>
</table>

Belle, PRL108, 232001(2012)
\[ \gamma \gamma \rightarrow PP' \]

Angular dependence

\[ \sigma(\pi^0 \pi^0)/\sigma(\pi^+ \pi^-) \]

Energy dependence

\[ \sigma(\eta \pi^0)/\sigma(\pi^0 \pi^0) \]

Cross-section ratio

\[ d\sigma/d|\cos \theta^*| = a(\sin^{-4} \theta^* + b \cos^2 \theta^*). \]

Difference of the slopes

\[ \sigma \sim W^{-n} \]
Form factor measurement with single-tag events
$\pi^0$ Transition Form Factor (TFF) by BaBar

- Coupling of neutral pion with two photons
- Good test for QCD at high $Q^2$ ($\to \infty$):
  \[ Q^2 F(Q^2) = \sqrt{2} f_\pi \approx 0.185 \, \text{GeV} \]
- $\pi^0$ transition form factor (TFF) measured by BaBar
- 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 pQCD predictions.
- Understand this situation for the $\pi^0$ TFF’s within standard QCD calculations is difficult
- Suggest New Physics beyond standard QCD!
$\pi^0$ Transition Form Factor (TFF)

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

\[
|F(Q^2)|^2 = \lim_{Q_2^2 \to 0} |F(Q^2, Q_2^2)|^2
\]

- Detect $e^+/e^-$ (tag side) and $\pi^0$

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

Event Generator:

2. EPA (equivalent photon approximation) $\rightarrow$ TFF measurement
Extraction of $\pi^0$ Yield

- Int. Luminosity: 759 fb$^{-1}$
- Fit $M(\gamma\gamma)$ distribution in each $Q^2$ bin
- Double Gaussian (for signal)
  + 2$^{nd}$-order Polynomial (for background)

Belle
PRD 86, 092007 (2012)
Background contamination in signal is estimated by the $\pi^0\pi^0$ background MC which is normalized to the observation, as 2%
1. Cross sections from p-tag and e-tag are combined

2. No rapid growth above $Q^2 > 9\text{GeV}^2$ ($\sim 2.3\sigma$ difference between Belle and BaBar in $9 - 20 \text{GeV}^2$)

3. Fit with an asymptotic parameter

$$Q^2 |F(Q^2)| = BQ^2/(Q^2+C)$$

$$B = 0.209 \pm 0.016 \text{ GeV}$$

Consistent with QCD prediction (0.185 GeV).
Summary

• Using non-tag two photon events, Belle study hadron spectrum, including charmonium, light hadrons.
• Using single-tag two photon events, Belle has measured the $\pi^0$ transition form factor.

Thank you (谢谢)!
Efficiency for the Signal Process at Belle

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

Up-down structures in the efficiencies are due to complicated Bhabha-veto trigger condition.