Studies of Light Quark Mesons in $\gamma\gamma$ Processes at Belle

Simon Eidelman

Budker Institute of Nuclear Physics SB RAS
and Novosibirsk State University,
Novosibirsk, Russia

Outline

1. Meson Spectroscopy
2. Transition form factors
3. Conclusions
• Two-photon collisions provide a complementary way of studying mesons (decays of heavier $D$, $B$, $\tau$, initial state radiation, continuum, ...)

• $e^+e^-$ are an ideal “clean” place for $\gamma\gamma$, but even LHC starts contributing (recent work by ATLAS)

• Spectroscopy for different quantum numbers ($M$, $\Gamma$, $\Gamma_{\gamma\gamma}$) (no-tag, both $e^\pm$ not detected, small $q_{1,2}^2$, quasireal photons)

• Two-photon width reflects the internal structure and origin

• QCD tests, transition form factors (single-and double-tag)

## Predictions for the two-photon width of the $f_0(980)$

<table>
<thead>
<tr>
<th>Origin</th>
<th>$u\bar{u}, d\bar{d}$</th>
<th>$s\bar{s}$</th>
<th>$K\bar{K}$</th>
<th>Tetraquark</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_{\gamma\gamma}$, eV</td>
<td>1300-1800</td>
<td>300-500</td>
<td>200-600</td>
<td>270</td>
</tr>
</tbody>
</table>
Basic Features of Two-Photon Collisions

\[ W - \gamma\gamma (X) \] c.m. energy, \( q_1^2, q_2^2 \) - 4-momenta squared of virtual photons,
\[ \theta^* - X \] polar c.m. angle with respect to \( e^+e^- \),
Particles produced in \( \gamma\gamma \) collisions have \( C = +1 \),
The produced system has \( E_{\text{tot}} \ll \sqrt{s} = 2E \) and low \( p_t \)
World highest luminosity of $2.11 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, $\int Ldt \sim 1 \text{ ab}^{-1}$
### Studies of Light-Quark Mesons at Belle

<table>
<thead>
<tr>
<th>Final state</th>
<th>$\int L dt$, fb$^{-1}$</th>
<th>$W$, GeV</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ K^-$</td>
<td>67</td>
<td>1.4-2.4</td>
<td>EPJC 32, 323 (2003)</td>
</tr>
<tr>
<td>$\pi^+ \pi^-$</td>
<td>87.7</td>
<td>2.4-4.1</td>
<td>PRD 75, 051101 (2007)</td>
</tr>
<tr>
<td>$\pi^0 \pi^0$</td>
<td>95</td>
<td>0.6-4.0</td>
<td>PRD 78, 052004 (2008)</td>
</tr>
<tr>
<td></td>
<td>223</td>
<td>0.6-4.1</td>
<td>PRD 79, 052009 (2009)</td>
</tr>
<tr>
<td>$\eta \pi^0$</td>
<td>223</td>
<td>0.84-4.0</td>
<td>PRD 80, 032001 (2009)</td>
</tr>
<tr>
<td>$\eta \eta$</td>
<td>393</td>
<td>1.1-3.8</td>
<td>PRD 82, 114031 (2010)</td>
</tr>
<tr>
<td>$\omega \omega$, $\omega \phi$, $\phi \phi$</td>
<td>870</td>
<td>1.6-4.0</td>
<td>PRL 108, 232001 (2012)</td>
</tr>
<tr>
<td>$\eta' \pi^+ \pi^-$</td>
<td>673</td>
<td>1.4-3.4</td>
<td>PRD 86, 052002 (2012)</td>
</tr>
<tr>
<td>$K^0_S K^0_S$</td>
<td>972</td>
<td>1.0 - 4.0</td>
<td>PTEP 2013, 123C01 (2013)</td>
</tr>
</tbody>
</table>
$\gamma\gamma \rightarrow K^+K^-$

$f_2'(1525)$ and 3 more states at 1.7, 2.0 and 2.3 GeV (tensors?)

The data confirm the “peak” solution of
T. Mori et al. (Belle Collab.), Phys. Rev. D 75, 051101 (2007)
$\gamma\gamma \rightarrow \eta\pi^0$

$a_0(980), a_2(1320)$ seen, a hint of $a_2(1700)$

Instead of $a_0(1450)$ a state at 1317 MeV, $a_0(Y)$, seen

S. Uehara et al. (Belle Collab.), Phys. Rev. D 80, 032001 (2009)
## Two-photon Widths of the $f_0(980)$ and $a_0(980)$

<table>
<thead>
<tr>
<th>State</th>
<th>$f_0(980)$, $\pi^+\pi^-$</th>
<th>$f_0(980)$, $\pi^0\pi^0$</th>
<th>$a_0(980)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass, MeV</td>
<td>$985.6^{+1.2}<em>{-1.5}^{+1.1}</em>{-1.6}$</td>
<td>$982.2 \pm 1.0^{+8.1}_{8.0}$</td>
<td>$982.3^{+0.6}<em>{-0.7}^{+3.1}</em>{-4.7}$</td>
</tr>
<tr>
<td>$\Gamma(\pi\pi)$, MeV</td>
<td>$51.3^{+20.9}<em>{-17.7}^{+13.2}</em>{-3.8}$</td>
<td>$66.9 \pm 2.2^{+17.6}_{12.5}$</td>
<td>$75.6 \pm 1.6^{+17.4}_{10.0}$</td>
</tr>
<tr>
<td>$\Gamma(\gamma\gamma)$, eV</td>
<td>$205^{+95}<em>{-83}^{+147}</em>{-117}$</td>
<td>$286 \pm 17^{+211}_{70}$</td>
<td>$128^{+3}<em>{-2}^{+502}</em>{-43}$</td>
</tr>
</tbody>
</table>

$u\bar{u}, d\bar{d}$ structure of the $f_0(980)$ excluded
$f_2(1270)$, $f_2'(1525)$ observed, evidence for $f_2$ at 1737 MeV
A broad ($\sim 480$ MeV) scalar structure at 1262 MeV, $f(1370)$ or $f_0(1500)$ or mixture?
\( \gamma\gamma \to \omega\omega, \omega\phi, \phi\phi \)

**Structures at 1.91 (\( \omega\omega \)), 2.2 (\( \omega\phi \)), 2.35 GeV (\( \phi\phi \)), 0^{++} \) or 2^{++}

Theory: \( \sim 1/W^6 \), experiment – steeper, 
\( \sigma(\omega\omega) \ll \sigma(\phi\phi) \ll \sigma(\omega\phi) \), correctly predicts \( \sigma(\phi\phi), \sigma(\omega\phi) \) at 4 GeV, 
but in experiment \( \sigma(\omega\omega) \) is too high, V. Chernyak, arXiv:1212.1304 
$\gamma\gamma \rightarrow \eta'\pi^+\pi^-$

$\eta(1760) \rightarrow \eta'\pi^+\pi^-$ observed for the first time

No evidence found for $X(1835)$ observed by BES near $p\bar{p}$ threshold

C.C. Zhang et al. (Belle Collab.), Phys. Rev. D 86, 052002 (2012)
Destructive interference between $f_2(1270)$ and $a_2(1320)$ observed.

Parameters of $f_2'(1525)$ determined, presence of $f_0(1710)$ favored.

S. Uehara et al., PTEP 2013, 123C01 (2013)
Evidence for $f_2(2200)$ and first evidence for $f_0(2500)$

S. Uehara et al., PTEP 2013, 123C01 (2013)
Summary of Spectroscopy Studies

\[ \sigma (|\cos \theta| < 0.6) \text{ (nb)} \] 

\[ |\cos \theta| < 0.6 \]

\[ |\cos \theta| < 0.8 \]

\[ |\cos \theta| < 0.6 \]

\[ \sim 20 \text{ structures observed in 8 final states!} \]
The Pion Distribution Amplitude – I
At sufficiently high $Q^2$ the TFF $F(Q^2)$

$$F(Q^2) = \frac{\sqrt{2}f_\pi}{3} \int_0^1 dx \frac{\phi_\pi(x)}{xQ^2} + O(1/Q^4), \quad (1)$$

where $f_\pi \simeq 0.131$ GeV is the pion decay constant, $x$ is the fraction of momentum carried by a quark ($q$) or antiquark ($\bar{q}$) in the parent pion, $\phi_\pi(x, Q^2)$ is the leading-twist pion distribution amplitude (DA) at $x$ and $Q^2$ in all hard exclusive processes with a pion.

The asymptotic pion DA is $\phi_\pi^{\text{asy}} = 6x(1-x)$, so that $Q^2F(Q^2)$ at $Q^2 \to \infty$ is

$$Q^2F(Q^2) = \sqrt{2}f_\pi \simeq 0.185 \text{ GeV.} \quad (2)$$

Early measurements from CELLO and CLEO support this:
the asymptotic value is approached from below.
Belle data do not confirm fast rise observed at BaBar

B. Aubert et al. (BaBar Collab.), Phys. Rev. D 80, 052002 (2009),
S. Uehara et al. (Belle Collab.), Phys. Rev. D 86, 092007 (2012)
The $f_0(980)$ TFF agrees with the prediction up to 10 GeV$^2$, but does not confirm steep fall at higher $Q^2$.


M. Masuda et al. (Belle Collab.), 1508.06757, Phys. Rev. D
The helicity-0 and -1 TFF of the $f_2(1270)$ are 1.5-2 times smaller than the prediction of [1], the helicity-2 is well described in [1] and [2]


M. Masuda et al. (Belle Collab.), 1508.06757, Phys. Rev. D
Conclusions

- $e^+e^- \rightarrow e^+e^- +$ hadrons is easily studied at $e^+e^-$ colliders

- $\gamma\gamma$ physics is quite rich: two-photon widths, spectroscopy of light-quark mesons, QCD tests, transition $f/f$ in $\gamma\gamma^* \rightarrow R$, $J^{PC}(R) = 0^-, 0^+, 1^-, 2^+$

- Resonance studies are very sensitive to interference with non-resonant continuum

- Various QCD tests for $\gamma\gamma \rightarrow \pi^+\pi^-, \pi^0\pi^0, \eta\pi^0, \eta\eta, K^+K^-, K^0_SK^0_S, pp$

- Many results for various charmonia (discovery of $\chi_{c2}(2P)$)

- $\gamma\gamma$ physics is very promising for various QCD studies: resonance studies test various models (potential, tetraquark, molecule), energy and angular dependence of cross sections – pQCD

- Belle published $20 \gamma\gamma$ papers with 1060 citations

- Further theoretical and experimental efforts needed
Backup slides
### Parameters of $a_0(Y)$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$a_0(Y)$</th>
<th>$a_0(1450)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass, MeV</td>
<td>$1316.8^{+0.7+24.7}_{-1.0-4.6}$</td>
<td>$1474 \pm 19$</td>
</tr>
<tr>
<td>Width, MeV</td>
<td>$65.0^{+2.1+99.1}_{-5.4-32.0}$</td>
<td>$265 \pm 13$</td>
</tr>
<tr>
<td>$\Gamma_{\gamma\gamma} \mathcal{B}(\eta\pi^0)$, eV</td>
<td>$432 \pm 6^{+1073}_{-256}$</td>
<td>–</td>
</tr>
</tbody>
</table>