Outline

1. Belle results for $e^+e^- \rightarrow e^+e^- X$
2. Transition form factors
3. Conclusions
Basic Features of Two-Photon Collisions – I

\[ W - \gamma\gamma (X) \text{ c.m. energy, } q_1^2, q_2^2 - 4\text{-momenta squared of virtual photons} \]
\[ \theta^* - X \text{ polar c.m. angle with respect to } e^+e^- \]
Basic Features of Two-Photon Collisions – II

- \( \sigma(e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-f) \propto \alpha^4 \log^2 E/m_e \)
  compared to
- \( \sigma(e^+e^- \rightarrow \gamma^* \rightarrow f) \propto \alpha^2/E^2 \)

- Particles produced in \( \gamma\gamma \) collisions have \( C = +1 \) and \( J^P = 0^\mp, 2^\mp \) while those in single-photon annihilation have \( C = -1 \) and \( J^P = 1^- \)

- Special kinematics:
  - Initial electrons tend to fly in their original directions and lose a small part of their energy
  - The produced system of particles \( f \) has \( E_{\text{tot}} \ll \sqrt{s} = 2E \) and tends to have small transverse momentum
Balance of Transverse Momenta for $\gamma\gamma \rightarrow K^0_S K^0_S$ Events

\[ W = 2.4 - 3.6 \text{ GeV} \]

- Data before background subtraction
- MC $\gamma\gamma \rightarrow K^0_S K^0_S$
- Background
- Data after background subtraction

No. of entries/0.01 GeV/c

\[ \sum p_t^{ee} \text{ (GeV/c)} \]

S.Eidelman, BINP
Classification of $\gamma\gamma$ Experiments

There are three different types of $\gamma\gamma$ experiments depending on whether or not initial electrons are detected:

- Both $e^\pm$ not detected – no tag
  (small $q_{1,2}^2$, quasireal photons)
- One $e^\pm$ is detected – single tag
- Both $e^\pm$ detected – double tag

In some cases experiments have a dedicated tagging system (tagger) to detect outgoing $e^\pm$’s (TPC-2$\gamma$, MD-1 in the past, KEDR in Novosibirsk, KLOE-2 in Frascati - today)

Detectors with a large solid angle (CLEO, BaBar, Belle) can perform single-tag experiments, when one final $e^\pm$ is detected
Studies before Belle

- In the 80-s – SPEAR, PEP at SLAC, PETRA at DESY
- In the 90-s – LEP at CERN, TRISTAN at KEK
- ARGUS at DESY and CLEO: high luminosity for $\gamma\gamma$ (0.5-1 fb$^{-1}$)
- Resonance $\Gamma_{\gamma\gamma}$ ($B_f$) for light mesons and charmonia
- First single-tag and $\sigma(\gamma\gamma \rightarrow \text{hadrons})$ measurements
- Scaling laws for processes with large $Q^2$ using quark counting rules; predictions for $\sigma(\gamma\gamma \rightarrow M\bar{M})$ in pQCD
- For $\pi^+\pi^-$ the prediction is $\frac{d\sigma}{d\cos\theta^*} \sim W^{-6}$, for $p\bar{p} - \sim W^{-10}$
- Predictions of pQCD are asymptotic, but what energy is high enough?
### QCD Studies at Belle

| Final state | $\int Ldt$, fb$^{-1}$ | $W$, GeV | $|\cos \theta^*|$ | Reference |
|-------------|-----------------------|----------|------------------|-----------|
| $\pi^+\pi^-$, $K^+K^-$ | 87.7 | 2.4-4.1 | < 0.6 | H. Nakazawa et al., PLB 615, 39 (2005) |
| $p\bar{p}$ | 89 | 2.025-4 | < 0.6 | C.C.Kuo et al., PLB 621, 41 (2005) |
| $\pi^0\pi^0$ | 223 | 0.6-4.1 | < 0.8 | S.Uehara et al., PRD 79, 052009 (2009) |
| $\eta\pi^0$ | 223 | 0.84-4.0 | < 0.8 | S.Uehara et al., PRD 80, 032001 (2009) |
| $\eta\eta$ | 393 | 1.096-3.8 | < 0.9 | S.Uehara et al., |
| $K^0_S K^0_S$ | 972 | 1.05-4.0 | < 0.8 | S.Uehara et al., PTEP 2013 (2013) 123C01 |
\[ \gamma \gamma \rightarrow \pi^+ \pi^-, \ K^+ K^- \]

\[ \sigma_0 \text{[nb]} \left( |\cos \theta^*| < 0.6 \right) \]

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

\( n = 7.9 \pm 0.4 \pm 1.5 \) for \( \pi^+ \pi^- \) and \( n = 7.3 \pm 0.3 \pm 1.5 \) for \( K^+ K^- \), \( n = 6 \) possible

Absolute cross sections not predicted!
### Conclusions of QCD Tests

<table>
<thead>
<tr>
<th>State</th>
<th>$n$</th>
<th>$W$, GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+\pi^-$</td>
<td>$7.9 \pm 0.4 \pm 1.5$</td>
<td>3.0-4.1</td>
</tr>
<tr>
<td>$K^+K^-$</td>
<td>$7.3 \pm 0.3 \pm 1.5$</td>
<td>3.0-4.1</td>
</tr>
<tr>
<td>$p\bar{p}$</td>
<td>$12.4^{+2.4}_{-2.3}$</td>
<td>2.0-4.0</td>
</tr>
<tr>
<td>$K^0_SK^0_S$</td>
<td>$11.0 \pm 0.4 \pm 0.4$</td>
<td>2.6-4.0</td>
</tr>
<tr>
<td>$\pi^0\pi^0$</td>
<td>$8.0 \pm 0.5 \pm 0.4$</td>
<td>3.1-4.1</td>
</tr>
<tr>
<td>$\eta\pi^0$</td>
<td>$10.5 \pm 1.2 \pm 0.5$</td>
<td>3.1-4.1</td>
</tr>
<tr>
<td>$\eta\eta$</td>
<td>$7.8 \pm 0.6 \pm 0.4$</td>
<td>2.4-3.3</td>
</tr>
</tbody>
</table>

$n = 10$ does not work for $\pi^0\pi^0$, one more puzzle, nor for $\eta\eta$, but here the $W$ range is limited.
Charmonia in $\gamma\gamma \rightarrow K_S^0 K_S^0$

Events of $\gamma\gamma \rightarrow$ charmonia are selected without background
### Observation of New Charmonium-like States 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>$D^+ D^-, D^0 \bar{D}^0$</td>
<td>395</td>
<td>3.7-4.3</td>
<td>S. Uehara et al., PRL 96, 082003 (2006)</td>
</tr>
<tr>
<td>$J/\psi \omega$</td>
<td>694</td>
<td>3.9-4.2</td>
<td>S. Uehara et al., PRL 104, 092001 (2010)</td>
</tr>
<tr>
<td>$J/\psi \phi$</td>
<td>825</td>
<td>4.2-5.0</td>
<td>C.P. Shen et al., PRL 104, 112004 (2010)</td>
</tr>
</tbody>
</table>
Also observed by Belle and BaBar in $B \to J/\psi \omega K$ decays, the same as $\chi_{c2}(2P)$?


J.P. Lees et al. (BaBar Collab.), Phys. Rev. D 86, 072002 (2012)
Conclusions on Charmonium Studies

- Various decay modes of $\eta_c(1S)$, $\chi_c(1P)$, $\chi_{c2}(1P)$ into two-, four- and six-body final states studied.

- Two-photon width $\Gamma_{2\gamma} B((c\bar{c}) \to f)$, $M$, $\Gamma$ measured, interference effects very important.

- More precise branching fractions determined.

- For $\eta_c(2S)$ new decay modes, in addition to $K\bar{K}\pi$, found.

- New charmonium and charmonium-like states seen.
## 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>K. Abe et al., EPJC 32, 323 (2003)</td>
</tr>
<tr>
<td>$f_0(980) \rightarrow \pi^+ \pi^-$</td>
<td>87.7</td>
<td>2.4-4.1</td>
<td>T. Mori et al., PRD 75, 051101 (2007)</td>
</tr>
<tr>
<td>$\omega \omega$, $\omega \phi$, $\phi \phi$</td>
<td>870</td>
<td>1.6-4.0</td>
<td>Z.-Q. Liu et al., PRL 108, 232001 (2012)</td>
</tr>
<tr>
<td>$\eta' \pi^+ \pi^-$</td>
<td>673</td>
<td>1.4-3.4</td>
<td>C.C. Zhang et al., PRD 86, 052002 (2012)</td>
</tr>
<tr>
<td>$\eta' \pi^+ \pi^-$</td>
<td>941</td>
<td>1.0-3.8</td>
<td>Q.N. Xu et al., Preliminary</td>
</tr>
</tbody>
</table>

In addition, systematic partial wave analysis was performed for the $\pi^+ \pi^-$, $\pi^0 \pi^0$, $\eta \pi^0$, $\eta \eta$ final states.
$\gamma\gamma \rightarrow K^+K^-$

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

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
Theory: $\sigma(\omega\omega) \ll \sigma(\phi\phi) \ll \sigma(\omega\phi)$, 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
Belle studied $\gamma\gamma \rightarrow \eta' \pi^+ \pi^-$ and observed $\eta_c(1S)$, $\eta_c(2S) + f_0(980)$, $f_2(1270)$, $f_0(2080)$

$M = 2083^{+63}_{-66} \pm 32$ MeV, $\Gamma = 178^{+60}_{-178} \pm 55$ MeV

Preliminary, to be submitted to Phys. Rev. D
Transition Form Factors - I (General)

Low energy QCD

$\pi^0, \eta, \eta', \eta'' \ldots \rightarrow \gamma^* \gamma^*$

$\Gamma(P \rightarrow \gamma \gamma)$

$F_P(q_1^2, q_2^2)$

$P \rightarrow \gamma \gamma, \gamma e^+ e^-, e^+ e^- e^+ e^-, e^+ e^-,$

$e^+ e^- \rightarrow P \gamma, P e^+ e^-, \gamma e^- \rightarrow P e^-, \gamma \gamma^* \rightarrow P$

All of them probe $\mathcal{F}(q_1^2, q_2^2)$ in different $q_i^2$ regions
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 $u$, $d$ part of the meson distribution amplitude,

$\eta$ and $\eta'$ transition $f/f$ follow QCD

Belle is completing analysis of $\gamma\gamma^* \to \pi^0\pi^0$,

$Q^2 < 30$ GeV$^2$, $f_0(980)$ and $f_2(1270)$ clearly seen
Belle studied $\gamma\gamma^* \rightarrow \pi^0\pi^0$ at $Q^2 < 30$ GeV$^2$ and $0.5$ GeV $< W < 2.1$ GeV in M. Masuda et al., Phys. Rev. D93 (2016)032003

Transition Form Factors - $V(\gamma\gamma^* \rightarrow K_S^0 K_S^0$ at Belle)

Belle studied $\gamma\gamma^* \rightarrow K_S^0 K_S^0$ at $Q^2 < 30$ GeV$^2$ and $1.0 < W < 2.6$ GeV in M. Masuda et al., Phys. Rev. D97 (2018) 052003

### Status of $P \rightarrow l^+l^-$ Decay Searches

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$\mathcal{B}_{\text{exp}}$</th>
<th>Events</th>
<th>Group</th>
<th>$\mathcal{B}_{\text{unit.bound}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0 \rightarrow e^+e^-$</td>
<td>$(6.46 \pm 0.33) \cdot 10^{-8}$</td>
<td>794</td>
<td>KTEV, 2008</td>
<td>$4.8 \cdot 10^{-8}$</td>
</tr>
<tr>
<td>$\eta \rightarrow e^+e^-$</td>
<td>$&lt; 2.3 \cdot 10^{-6}$</td>
<td>–</td>
<td>HADES, 2014</td>
<td>$1.8 \cdot 10^{-9}$</td>
</tr>
<tr>
<td>$\eta \rightarrow \mu^+\mu^-$</td>
<td>$(5.7 \pm 0.9) \cdot 10^{-6}$</td>
<td>114</td>
<td>SATURNEII, 1994</td>
<td>$4.3 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$\eta' \rightarrow e^+e^-$</td>
<td>$&lt; 1.2 \cdot 10^{-8}$</td>
<td>–</td>
<td>CMD-3, 2014</td>
<td>$3.75 \cdot 10^{-11}$</td>
</tr>
<tr>
<td>$K^0_L \rightarrow e^+e^-$</td>
<td>$(9^{+6}_{-4}) \cdot 10^{-12}$</td>
<td>4</td>
<td>B871, 1998</td>
<td>$3.0 \cdot 10^{-12}$</td>
</tr>
<tr>
<td>$K^0_L \rightarrow \mu^+\mu^-$</td>
<td>$(6.84 \pm 0.11) \cdot 10^{-9}$</td>
<td>6210</td>
<td>B871, 2000</td>
<td>$6.8 \cdot 10^{-9}$</td>
</tr>
</tbody>
</table>

$\mathcal{B}$'s can be enhanced by photon virtuality and transition f/f

All results but CMD-3 were obtained using hadron beams

CMD-3 searched for the inverse reaction $e^+e^- \rightarrow \eta' \rightarrow \eta\pi^+\pi^-$
Search for C-even resonances in $e^+e^-$

Direct production of C-even states in $e^+e^-$ is possible via a $\gamma\gamma$:

The unitarity bound (UB) assuming 2 real photons is

$$B_{P \rightarrow l^+l^-} = B_{P \rightarrow \gamma\gamma} \frac{\alpha^2}{2\beta} \left( \frac{m_e}{m_P} \right)^2 \left[ \ln \left( \frac{1+\beta}{1-\beta} \right) \right]^2, \beta = \sqrt{1 - 4 \left( \frac{m_e}{m_P} \right)^2}.$$  

“Standard” mechanism via $e^+e^- \rightarrow e^+e^- P$ involves two almost real photons and provides $\Gamma(P \rightarrow \gamma\gamma)$ only
Search for $e^+e^- \rightarrow \eta'$ with CMD-3 – I

CMD-3 repeated a search for the process $e^+e^- \rightarrow \eta'(958) \rightarrow \eta\pi^+\pi^-$, $\eta \rightarrow 2\gamma$ using $\int Ldt = 2.69$ pb$^{-1}$ collected with the CMD-3 detector at the VEPP-2000 c.m. energy $E_{c.m.} \approx m_{\eta'} = 957.78 \pm 0.06$ MeV/$c^2$.

The total width of the $\eta'$ is rather small, $(198 \pm 9)$ keV, it is very important to have c.m. energy close to this value. The collider beam energy was continuously monitored during the whole period of data taking (12 days) using the Back-Scattering-Laser-Light system providing the accuracy of $6 \cdot 10^{-5}$.

Search for $e^+e^- \rightarrow \eta'$ with CMD-3 – II

From the absence of the signal

$$\Gamma_{\eta' \rightarrow e^+e^-} \mathcal{B}_{\eta' \rightarrow \pi\pi\eta} \mathcal{B}_{\eta \rightarrow \gamma\gamma} < 0.00041 \text{ eV at } 90\% \text{ C.L.}.$$  

and with $\mathcal{B}_{\eta' \rightarrow \pi\pi\eta}$ and $\mathcal{B}_{\eta \rightarrow \gamma\gamma}$ from PDG:

$$\Gamma_{\eta' \rightarrow e^+e^-} < 0.0024 \text{ eV}$$

<table>
<thead>
<tr>
<th>Group</th>
<th>ND, 1988</th>
<th>CMD-3, 2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_{\eta' \rightarrow e^+e^-}, \text{ eV}$</td>
<td>$&lt; 0.06$</td>
<td>$&lt; 0.0024$</td>
</tr>
<tr>
<td>$\Gamma_{\eta'}, \text{ keV}$</td>
<td>$\sim 300$</td>
<td>$198 \pm 9$</td>
</tr>
<tr>
<td>$\mathcal{B}_{\eta' \rightarrow e^+e^-}, 10^{-8}$</td>
<td>$&lt; 21$</td>
<td>$&lt; 1.2$</td>
</tr>
</tbody>
</table>

Much more stringent than that of ND, but still 300 times higher than the unitarity bound.
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 and charmonia, 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

- Studies of TFF are in progress at MAMI, JLAB, VEPP-2000, BEPC-II, Julich, . . ., can be also studied via $R \rightarrow e^+e^-$, e.g. in $e^+e^- \rightarrow c\bar{c} \rightarrow f$

- Taggers provide much broader possibilities for $\gamma\gamma^*$ and $\gamma^*\gamma^*$

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

- Further theoretical and experimental efforts needed
Backup slides
$\gamma \gamma^* \rightarrow \pi^0 \pi^0$ at Belle
Muon $\frac{(g-2)}{2}$ – I (Comparison to Experiment)

<table>
<thead>
<tr>
<th>Contribution</th>
<th>$a_\mu, 10^{-10}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td>11659208.9 ± 5.4 ± 3.3(6.3)$_{\text{tot}}$</td>
</tr>
<tr>
<td>QED</td>
<td>11658471.9 ± 0.008</td>
</tr>
<tr>
<td>Electroweak</td>
<td>15.4 ± 0.1 ± 0.2</td>
</tr>
<tr>
<td>Hadronic</td>
<td>692.3 ± 4.2 ± 2.6 ± 0.2(4.9)$_{\text{tot}}$</td>
</tr>
<tr>
<td>Theory</td>
<td>11659180.2 ± 4.9</td>
</tr>
<tr>
<td>Exp.–Theory</td>
<td>28.7 ± 8.0 (3.6\sigma)</td>
</tr>
</tbody>
</table>

The difference between experiment and theory is (3.2-3.6)\sigma!
Measurements of the beam energy show good stability of the collider energy. The average value of the c.m. energy is $E_{c.m.}^{av.} = 957.678 \pm 0.014$ MeV with a few deviations of up to 0.2 MeV, corresponding to less than 5% of the integrated luminosity, which are still within an energy spread of the collider.

The collider beams have an energy spread mainly due to the quantum effects. For VEPP-2000 the c.m. energy spread $\sigma_{E_{c.m.}} = (0.246 \pm 0.030)$ MeV.
Search for $e^+e^- \rightarrow \eta'$ with CMD-3 – III
Production from B-decay  
(broad $D^{**}$, $D_{sJ}$, $X(3872)$, $Y(3940)$)

Production from continuum  
($D_{sJ}$, $\eta_c(2S)$, $X(3940)$, $\Sigma(2800)$)

Two-photon production  
($\eta_c(2S)$, $\chi_{c2}(2P)$)

Initial state radiation  
($Y(4260)$, $Y(4360)$, $Y(4660)$)
$\gamma^* \rightarrow VP - I$

\begin{itemize}
  \item (a) $\phi\eta$
  \item (b) $\phi\eta'$
  \item (c) $\rho\eta$
  \item (d) $\rho\eta'$
\end{itemize}

Solid – $1/s^4$, dashed – $1/s^3$
\[ \gamma^* \rightarrow VP - II \]

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi \eta )</td>
<td>(1.4 \pm 0.4 \pm 0.1)</td>
<td>3.3-4.3</td>
<td>2.4-3.4</td>
<td>(2.9 \pm 0.5 \pm 0.1)</td>
</tr>
<tr>
<td>( \phi \eta' )</td>
<td>(5.3 \pm 1.1 \pm 0.4)</td>
<td>4.4-5.8</td>
<td>3.5-5.0</td>
<td>–</td>
</tr>
<tr>
<td>( \phi \eta'' )</td>
<td>(3.1 \pm 0.5 \pm 0.1)</td>
<td>2.4-3.1</td>
<td>2.4-3.5</td>
<td>–</td>
</tr>
<tr>
<td>( \phi \eta''' )</td>
<td>(3.3 \pm 0.6 \pm 0.2)</td>
<td>1.5-2.1</td>
<td>1.6-2.3</td>
<td>–</td>
</tr>
</tbody>
</table>

G.S. Adams et al. (CLEO)  
B. Aubert et al. (BaBar)  
K. Belous et al. (Belle)  
C.D.Lu et al. (Light cone)  
V.V. Braguta et al. (Light cone)

For all final states Belle surpassed the previous measurements both in statistics and the quality of detection.

For $\gamma\gamma \rightarrow \pi^+\pi^-$, $K^+K^-$ Belle used a data sample of $87.7 \text{ fb}^{-1}$ to study angular dependence, energy behavior and the ratio $\frac{\sigma(\pi^+\pi^-)}{\sigma(K^+K^-)}$.


The best previous experiment (ALEPH) had a data sample of $837.5 \text{ pb}^{-1}$.

$\gamma\gamma \rightarrow \pi^+\pi^-, K^+K^-$ II

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure}
\caption{Graph showing the cross-section $\sigma_0^{-1} d\sigma/d|\cos\theta|$ vs $|\cos\theta|$ for different energy ranges.}
\end{figure}

S. Eidelman, BINP
\( \gamma \gamma \rightarrow \pi^+ \pi^-, K^+ K^- \ - \text{III} \)
2.5 < W_{\gamma\gamma} < 3.0 \text{ GeV}

- Belle
- OPAL (2.55–2.95 GeV)
- CLEO △ L3

\[ \frac{[d\sigma/d\cos\theta^*]|_{\cos\theta^* < 0.3}}{[d\sigma/d\cos\theta^*]|_{\cos\theta^* < 0.3}} \]

\[ |\cos\theta^*| \]

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

- Belle △ L3 (3.0–4.5 GeV)

\[ \frac{[d\sigma/d\cos\theta^*]|_{\cos\theta^* < 0.3}}{[d\sigma/d\cos\theta^*]|_{\cos\theta^* < 0.3}} \]

\[ |\cos\theta^*| \]

**Power corrections are still significant**

**Diquark and handbag models need improvement**
\( \gamma\gamma \rightarrow 4 \text{ Charged Tracks} \) – I

$\gamma\gamma \rightarrow 4$ Charged Tracks – II

(a) $\chi_c \rightarrow 4\pi$

(b) $\chi_{c0} \rightarrow 4\pi$

(c) $\chi_{c2} \rightarrow 4\pi$

(d) $\pi^+ \rightarrow 2K2\pi$

(e) $\chi_{c0} \rightarrow 2K2\pi$

(f) $\chi_{c2} \rightarrow 2K2\pi$

(g) $\eta_c \rightarrow 4K$

(h) $\chi_{c0} \rightarrow 4K$

(i) $\chi_{c2} \rightarrow 4K$

$M(2K2\pi) (\text{GeV}/c^2)$

$M(4\pi) (\text{GeV}/c^2)$

$M(4K) (\text{GeV}/c^2)$

Events/10 MeV/c^2
Four-prong Final States

In each of the three final states – $2(\pi^+\pi^-)$, $\pi^+\pi^-K^+K^-$, $2(K^+K^-)$ – three charmonia – $\eta_c$, $\chi_{c0}$ and $\chi_{c2}$ are clearly seen.

They also study dynamics and see: $\eta_c \rightarrow K^{*0}\bar{K}^{*0}$, $f_2f'_2$, $\phi\phi$, $f_2f_2$

But $\eta_c(2S)$ not seen, the only mode observed is $K\bar{K}\pi$
Six-prong Final States and $\eta_c(2S)$ – I

Preliminary Belle results with 923 fb$^{-1}$:

$3(\pi^+\pi^-) - 6\pi, K^+K^-2(\pi^+\pi^-) - 2K4\pi,$

$2(K^+K^-)\pi^+\pi^- - 4K2\pi, K_S^0K^\pm\pi^+\pi^- - K_S^0K3\pi$

$\eta_c(1S), \chi_{c0}$ and $\chi_{c2}$ are also clearly seen
### Six-prong Final States and $\eta_c(2S)$ - II

<table>
<thead>
<tr>
<th>Mode</th>
<th>$M$, MeV/$c^2$</th>
<th>$\Gamma$, MeV</th>
<th>$N_{ev}$</th>
<th>$S, \sigma$</th>
<th>$\Gamma_{\gamma\gamma}B$, eV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$6\pi$</td>
<td>$3638.9 \pm 1.6 \pm 2.3$</td>
<td>$10.7 \pm 4.9$</td>
<td>$1485 \pm 274$</td>
<td>$8.5$</td>
<td>$20.1 \pm 3.7 \pm 3.2$</td>
</tr>
<tr>
<td>$2K4\pi$</td>
<td>$3634.7 \pm 1.6 \pm 2.8$</td>
<td>$1.4^{+6.3}_{-1.4}(&lt; 13)$</td>
<td>$407 \pm 91$</td>
<td>$6.2$</td>
<td>$10.2 \pm 2.3 \pm 3.4$</td>
</tr>
<tr>
<td>$K_SK3\pi$</td>
<td>$3636.5 \pm 1.8 \pm 2.4$</td>
<td>$15.9 \pm 5.7$</td>
<td>$563 \pm 71$</td>
<td>$8.7$</td>
<td>$30.7 \pm 3.9 \pm 3.7$</td>
</tr>
<tr>
<td>$K^+K^-3\pi$</td>
<td>$3640.5 \pm 3.2 \pm 2.5$</td>
<td>$13.4$ (fixed)</td>
<td>$1201 \pm 228$</td>
<td>$5.3$</td>
<td>$30.0 \pm 6.0 \pm 5.0$</td>
</tr>
</tbody>
</table>

Averaging Belle results over 3 modes of $\eta_c(2S)$:

- Mass = $3636.9 \pm 1.1 \pm 2.5 \pm 5.0$ MeV, Width = $9.9 \pm 3.2 \pm 2.6 \pm 2.0$ MeV

  consistent with Belle results on $B^\pm \rightarrow K^\pm(K_SK\pi)^0$:

- Mass = $3636.1^{+3.0+0.5}_{-3.4-2.0}$ MeV, Width = $6.6^{+4.9+3.0}_{-3.4-0.9}$ MeV

  and with BaBar results on $K^+K^-3\pi$

**BaBar**: P. del Amo Sanchez et al., Phys. Rev. D84, 012004 (2011)
The $Y(4140)$ and $Y(4274)$ states of CDF not seen (also disproved by LHCb)

Observation of New Charmonium-like States at Belle

<table>
<thead>
<tr>
<th>Final state</th>
<th>$\int Ldt$, fb$^{-1}$</th>
<th>$W$, GeV</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^+ D^-, D^0 \bar{D}^0$</td>
<td>395</td>
<td>3.7-4.3</td>
<td>S. Uehara et al., PRL 96, 082003 (2006)</td>
</tr>
<tr>
<td>$J/\psi \omega$</td>
<td>694</td>
<td>3.9-4.2</td>
<td>S. Uehara et al., PRL 104, 092001 (2010)</td>
</tr>
<tr>
<td>$J/\psi \phi$</td>
<td>825</td>
<td>4.2-5.0</td>
<td>C.P. Shen et al., PRL 104, 112004 (2010)</td>
</tr>
</tbody>
</table>
\[ \gamma\gamma \rightarrow D^+ D^- , \ D^0 \bar{D}^0 \text{ and } \chi_{c2}(2P) \]

Compatible with \( \chi_{c2}(2P) \), confirmed by BaBar

S. Eidelman, BINP
Also observed by Belle and BaBar in $B \to J/\psi\omega K$ decays, the same as $\chi_{c2}(2P)$?

The $Y(4140)$ and $Y(4274)$ states of CDF not seen (also disproved by LHCb)

\( \gamma \gamma \rightarrow \omega \omega, \omega \phi, \phi \phi - \text{II} \)