Two-photon Physics

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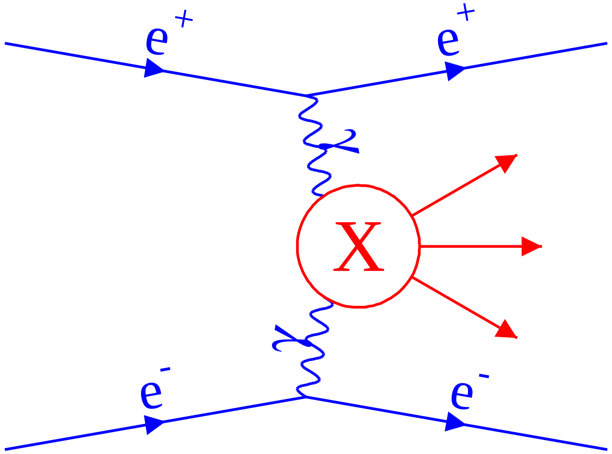
Outline

1. Belle results for $e^+e^- \to e^+e^- X$
2. Transition form factors
3. Conclusions

Basic Features of Two-Photon Collisions – I

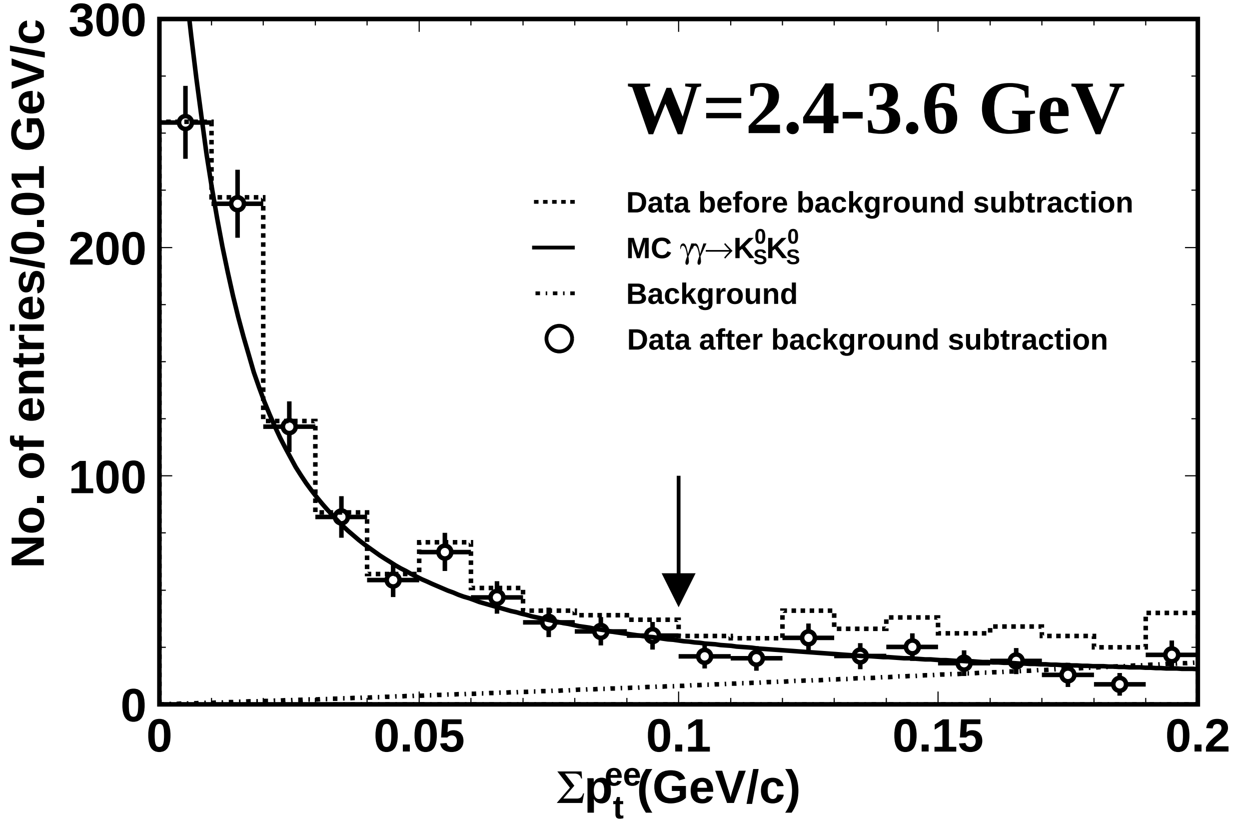


W – $\gamma\gamma$ (X) c.m. energy, q_1^2, q_2^2 – 4-momenta squared of virtual photons
θ^* – X polar c.m. angle with respect to e^+e^-

Basic Features of Two-Photon Collisions – II

- $\sigma(e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^- f) \propto \alpha^4 log^2 E/m_e$
  compared to
  $\sigma(e^+e^- \to \gamma^* \to f) \propto \alpha^2/E^2$
- 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 $E_{\rm tot} \ll \sqrt{s} = 2E$ and tends to have small transverse momentum

Balance of Transverse Momenta for $\gamma\gamma \to K_S^0 K_S^0$ Events



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-2γ, 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

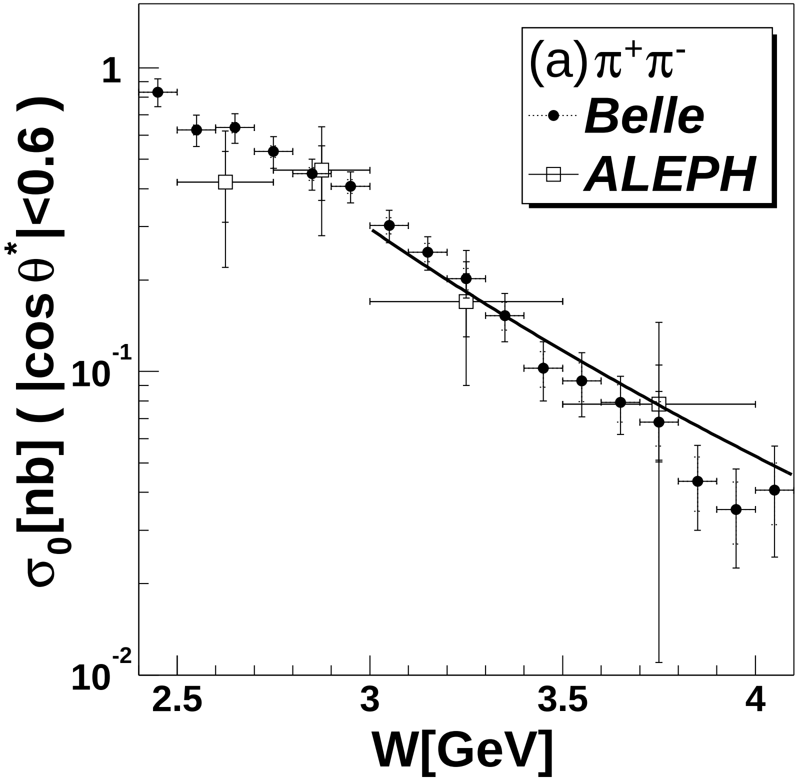
$\gamma\gamma$ Studies before Belle

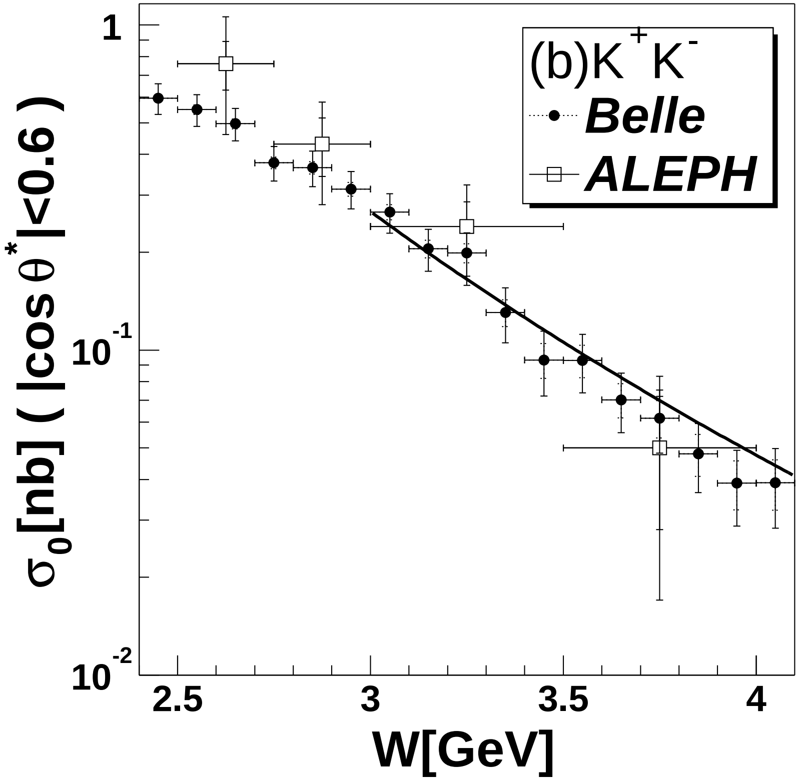
- In the 80-s – SPEAR, PEP at SLAC, PETRA at DESY
- In the 90-s – LEP at CERN, TRISTAN at KEK
- ARGUS at DESY and CLEO: high luminosity for $\gamma\gamma$ (0.5-1 fb^{-1})
- Resonance $\Gamma_{\gamma\gamma}$ ($\mathcal{B}_f$) for light mesons and charmonia
- First single-tag and $\sigma(\gamma\gamma \to$ hadrons) measurements
- Scaling laws for processes with large Q^2 using quark counting rules; predictions for $\sigma(\gamma\gamma \to M\bar{M})$ in pQCD
- For $\pi^+\pi^-$ the prediction is $\frac{d\sigma}{dcos\theta*} \sim W^{-6}$, 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	$\lvert\cos\theta^*\rvert$	Reference
$\pi^+\pi^-$,	87.7	2.4-4.1	< 0.6	H. Nakazawa et al.,
K^+K^-				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.,
			< 1.0	PRD 82, 114031 (2010)
$K^0_S K^0_S$	972	1.05-4.0	< 0.8	S.Uehara et al.,
				PTEP 2013 (2013) 123C01

$\gamma\gamma \to \pi^+\pi^-, \ K^+K^-$





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

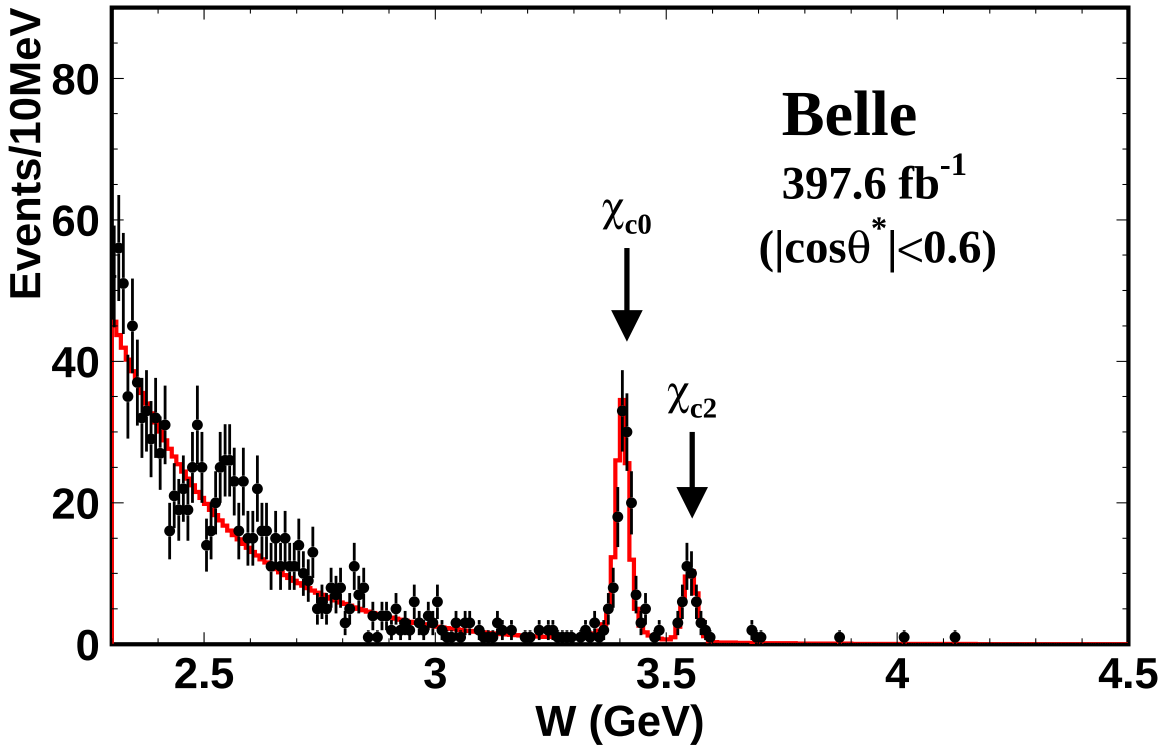
Absolute cross sections not predicted!

Conclusions of QCD Tests

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

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

Charmonia in $\gamma\gamma \to K_S^0 K_S^0$

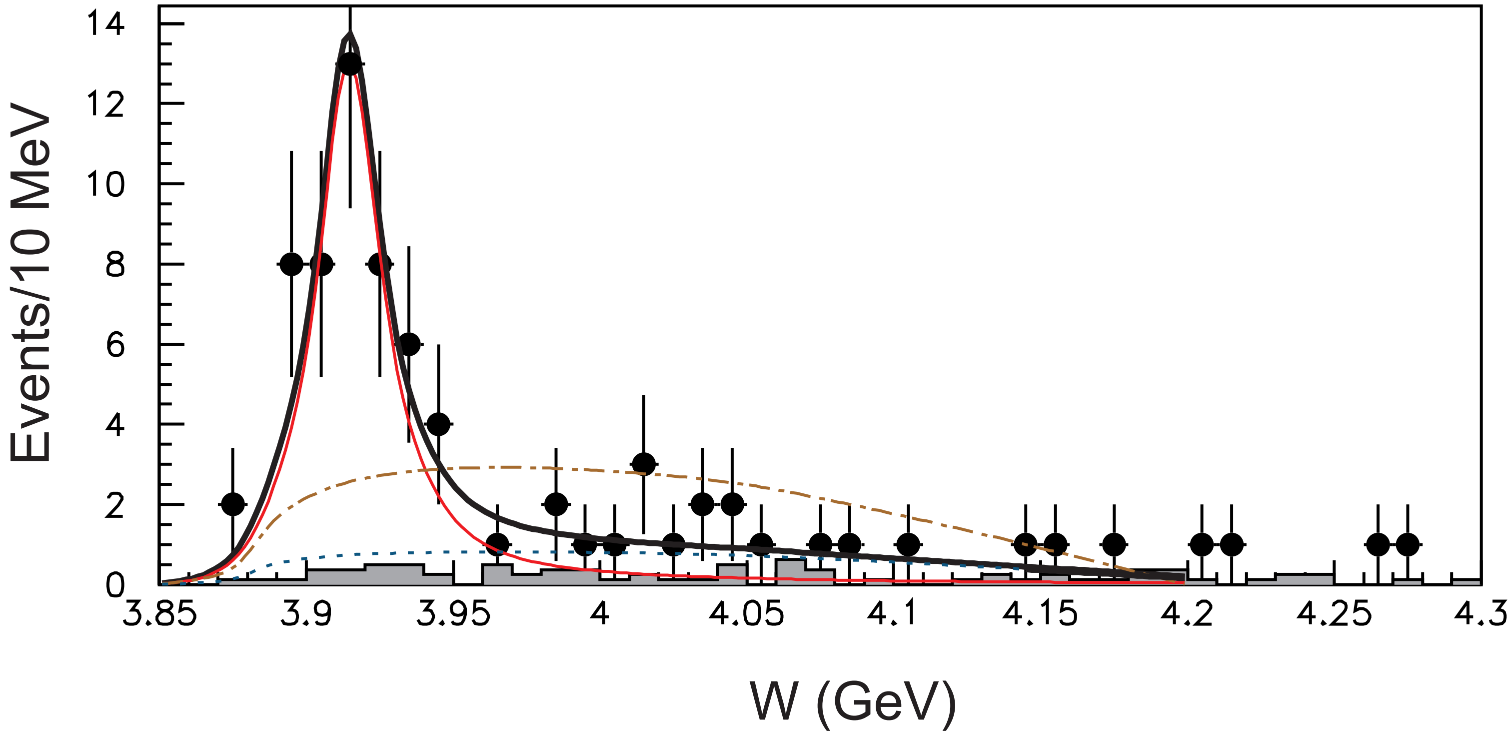


Events of $\gamma\gamma \to$ charmonia are selected without background

Observation of New Charmonium-like States at Belle

Final state	$\int Ldt$, fb^{-1}	W, GeV	Reference
$D^+D^-,\ D^0\bar{D}^0$	395	3.7-4.3	S. Uehara et al., PRL 96, 082003 (2006)
$J/\psi\omega$	694	3.9-4.2	S. Uehara et al., PRL 104, 092001 (2010)
$J/\psi\phi$	825	4.2-5.0	C.P. Shen et al., PRL 104, 112004 (2010)

$\gamma\gamma \to J/\psi\omega$



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

S. Uehara et al. (Belle Collab.), Phys. Rev. Lett. 104, 092001 (2010)

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

Conclusions on Charmonium Studies

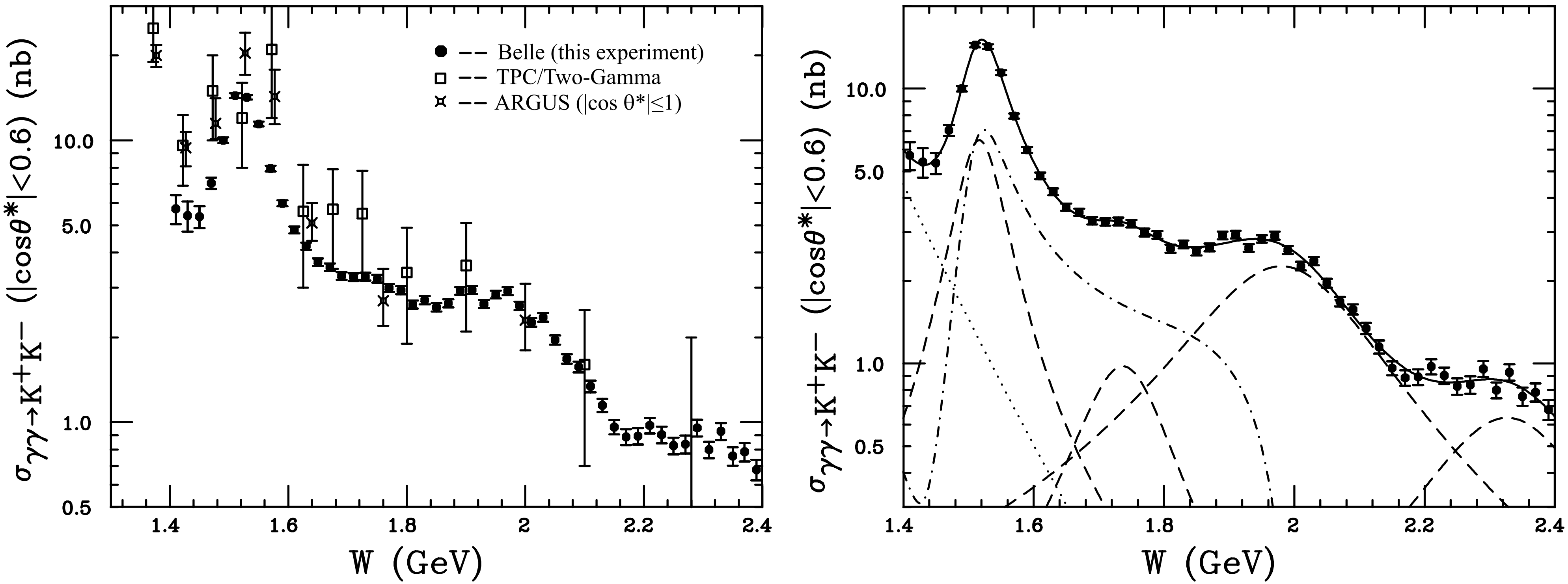
- Various decay modes of $\eta_c(1S)$, $\chi_{c0}(1P)$, $\chi_{c2}(1P)$ into two-, four- and six-body final states studied
- Two-photon width $\Gamma_{2\gamma}\mathcal{B}((c\bar{c}) \to f)$, M, Γ measured, interference effects very important
- More precise branching fractions determined
- For $\eta_c(2S)$ 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

Final state	$\int Ldt$, fb^{-1}	W, GeV	Reference
K^+K^-	67	1.4-2.4	K. Abe et al., EPJC 32, 323 (2003)
$f_0(980) \to \pi^+\pi^-$	87.7	2.4-4.1	T. Mori et al., PRD 75, 051101 (2007)
$\omega\omega,\ \omega\phi,\ \phi\phi$	870	1.6-4.0	Z.-Q. Liu et al., PRL 108, 232001 (2012)
$\eta'\pi^+\pi^-$	673	1.4-3.4	C.C. Zhang et al., PRD 86, 052002 (2012)
$\eta'\pi^+\pi^-$	941	1.0-3.8	Q.N. Xu et al., Preliminary

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

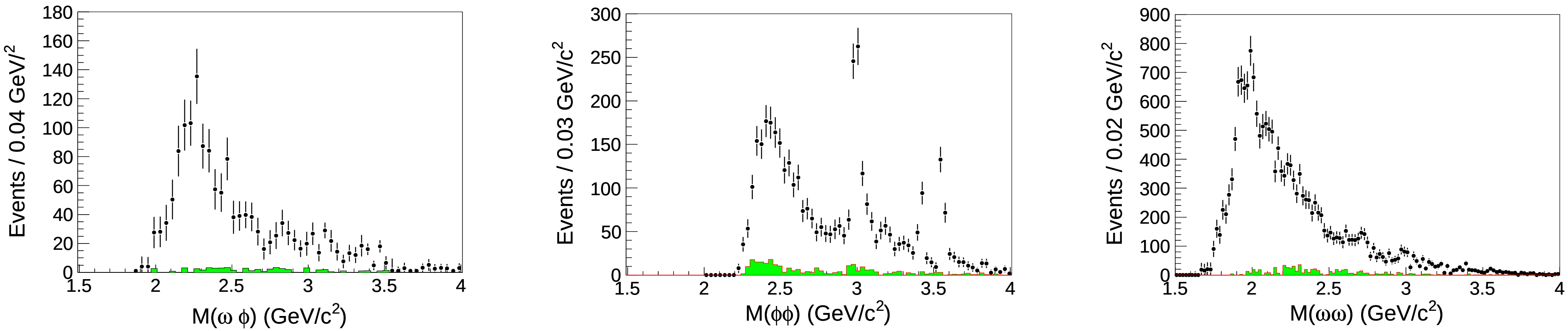
$\gamma\gamma \to K^+K^-$



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

K. Abe et al., Eur. Phys. J. C 32, 323 (2003)

$\gamma\gamma \to \omega\omega,\ \omega\phi,\ \phi\phi$



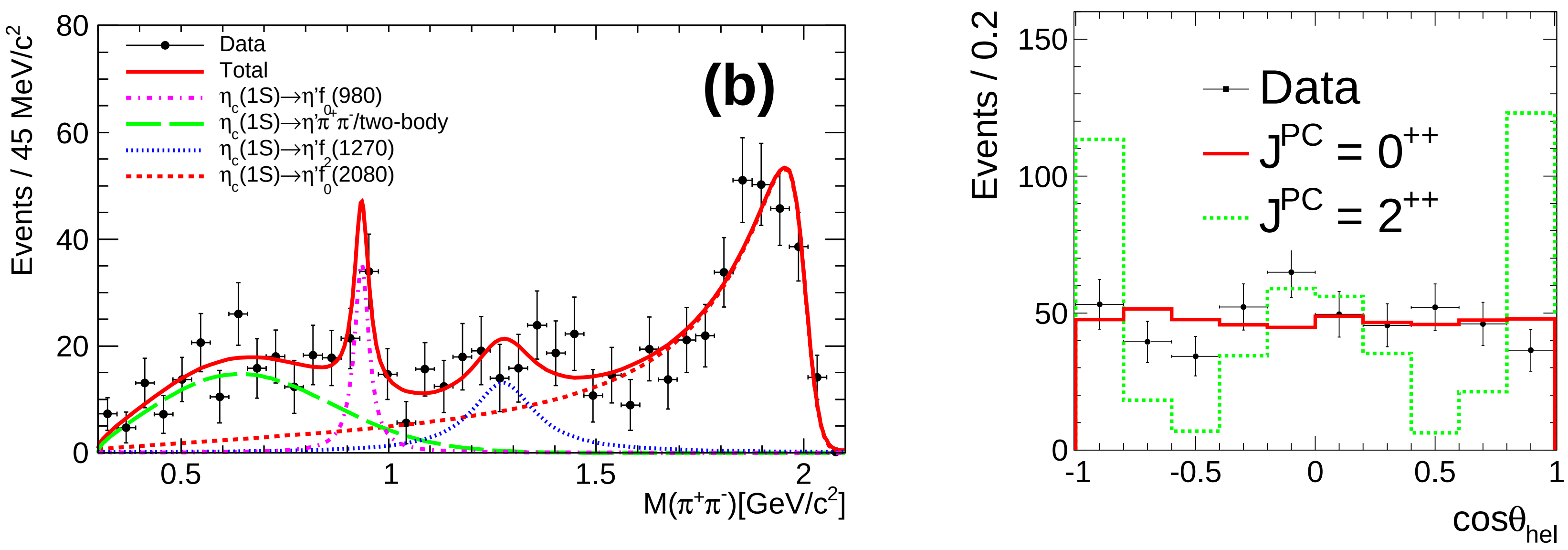
Structures at 1.91 ($\omega\omega$), 2.2 ($\omega\phi$), 2.35 GeV ($\phi\phi$), 0^{++} or 2^{++}

Z.-Q. Liu et al.(Belle Collab.), Phys. Rev. Lett. 108, 232001 (2012)

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

$\gamma\gamma \to \eta'\pi^+\pi^-$ at Belle



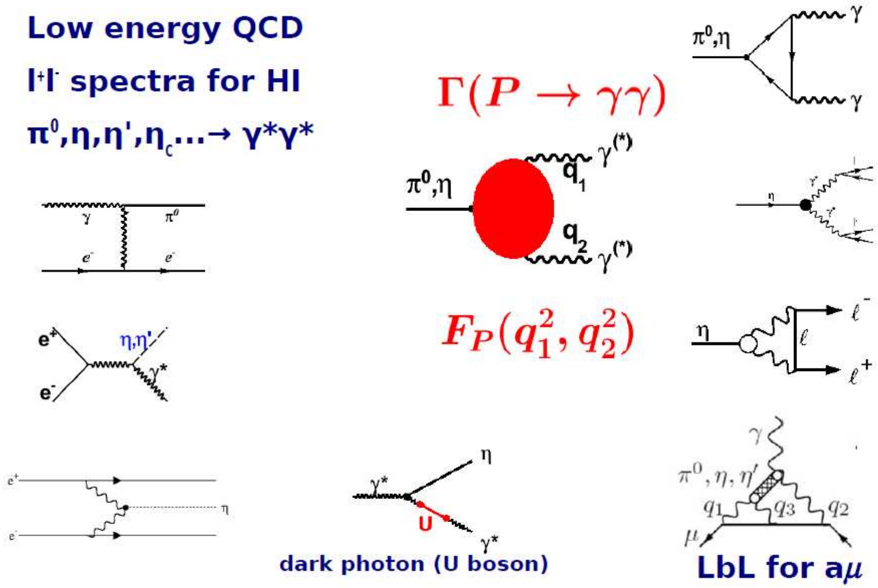
Belle studied $\gamma\gamma \to \eta'\pi^+\pi^-$

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)

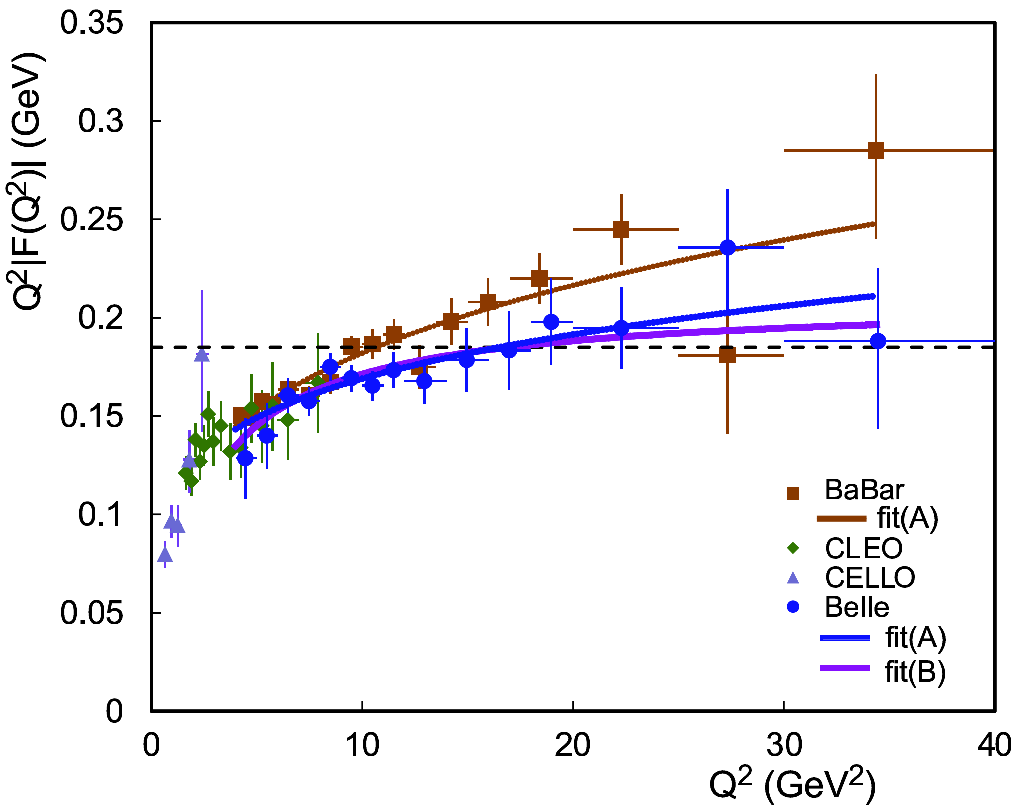


$$P \to \gamma\gamma,\ \gamma e^+e^-,\ e^+e^-e^+e^-,\ e^+e^-,$$

$$e^+e^- \to P\gamma,\ Pe^+e^-, \gamma e^- \to Pe^-, \gamma\gamma^* \to P$$

All of them probe $\mathcal{F}(q_1^2, q_2^2)$ in different q_i^2 regions

Transition Form Factors - II (π^0)

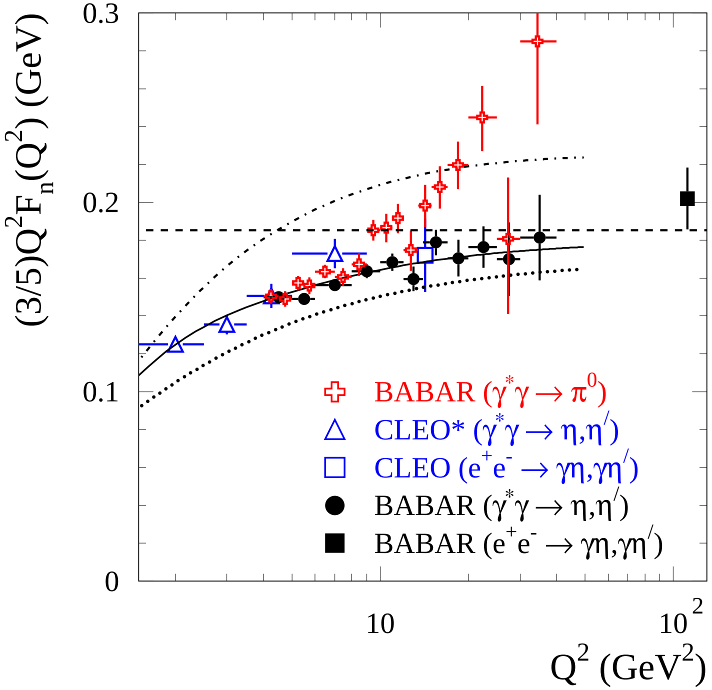


Belle data do not confirm fast rise observed at BaBar

B. Aubert et al. (BaBar Collab.), Phys. Rev. D 80, 052002 (2009),

S. Uehara et al. (Belle Collab.), Phys. Rev. D 86, 092007 (2012)

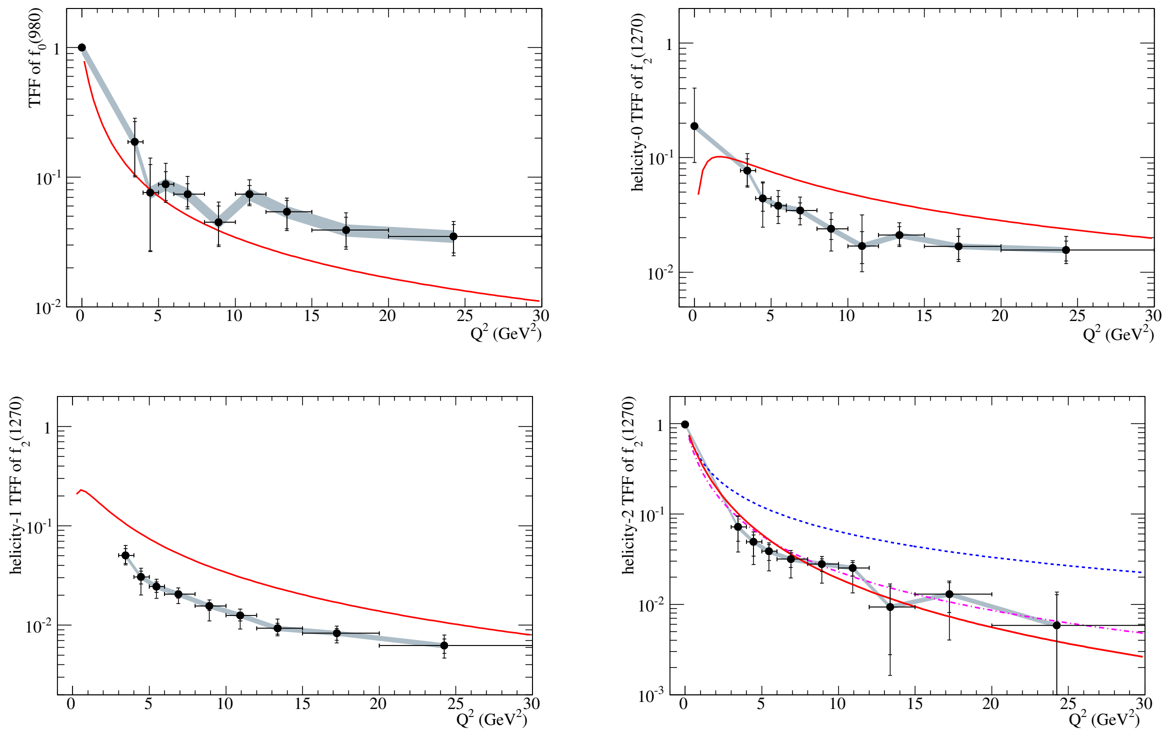
Transition Form Factors - III (η, η' and π^0)



The u, d part of the meson distribution amplitude, η and η' 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

Transition Form Factors - IV ($\gamma\gamma^* \to \pi^0\pi^0$ at Belle)

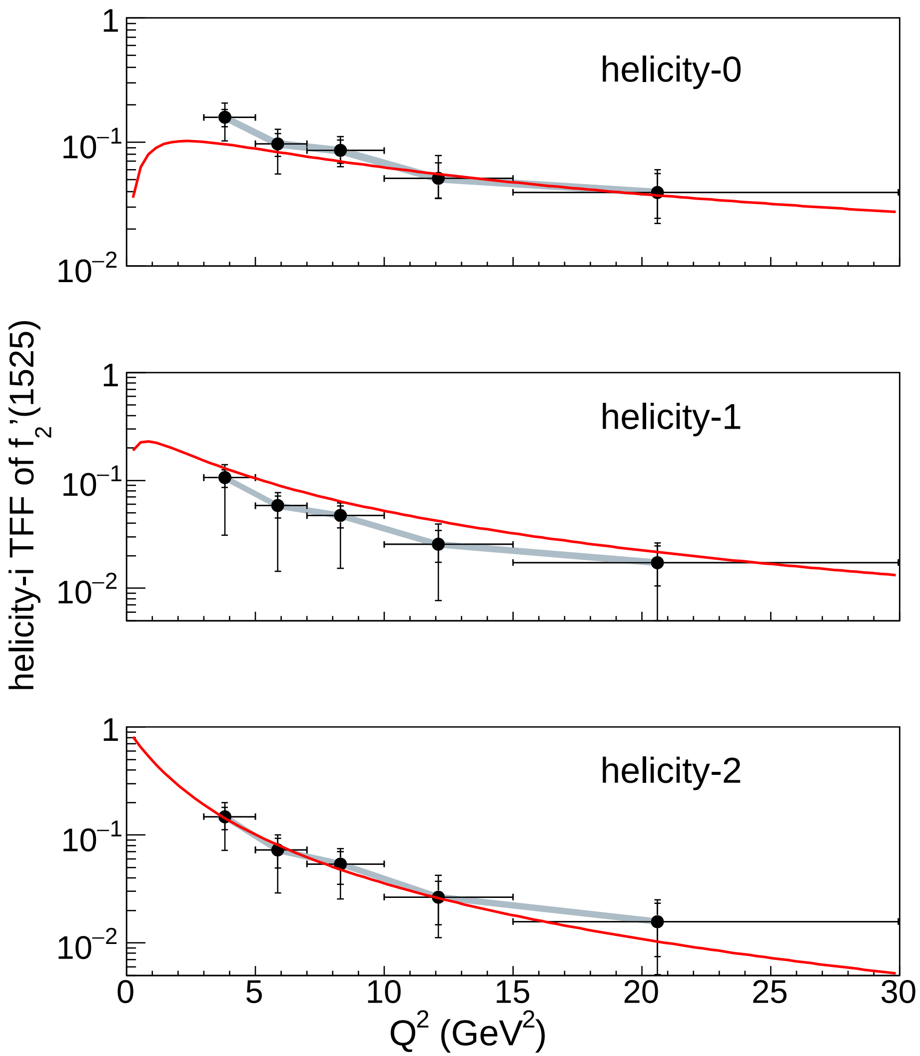


Belle studied $\gamma\gamma^* \to \pi^0\pi^0$ at $Q^2 < 30$ GeV^2 and 0.5GeV $< W <$ 2.1GeV in M. Masuda et al., Phys. Rev. D93 (2016)032003

Theory I — G.A.Schuler et al., Nucl. Phys. B523 (1998) 423

Theory II — V. Pascalutsa et al., Phys. Rev. D85 (2012) 116001

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



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

Theory — G.A.Schuler et al., Nucl. Phys. B523 (1998) 423

Status of $P \to l^+l^-$ Decay Searches

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

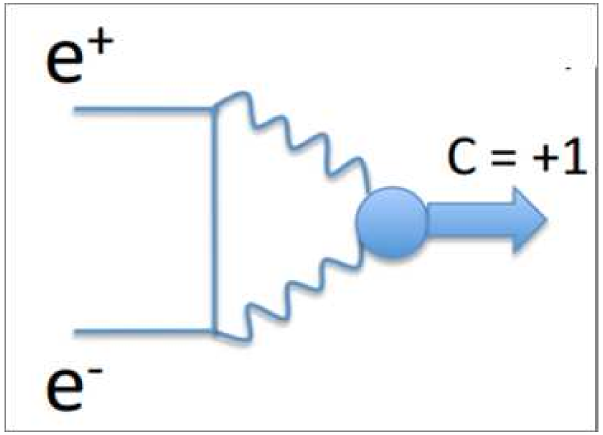
$\mathcal{B}$'s can be enhanced by photon virtuality and transition f/f

All results but CMD-3 were obtained using hadron beams

CMD-3 searched for the inverse reaction $e^+e^- \to \eta' \to \eta\pi^+\pi^-$

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

$$\mathcal{B}_{P\to l^+l^-} = \mathcal{B}_{P\to\gamma\gamma}\frac{\alpha^2}{2\beta}(\frac{m_e}{m_P})^2[\ln(\frac{1+\beta}{1-\beta})]^2, \beta = \sqrt{1-4(\frac{m_e}{m_P})^2}.$$

"Standard" mechanism via $e^+e^- \to e^+e^-P$ involves two almost real photons and provides $\Gamma(P\to\gamma\gamma)$ only

Search for $e^+e^- \to \eta'$ with CMD-3 – I

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

The total width of the η' is rather small, (198 ± 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 $6 \cdot 10^{-5}$

R.R. Akhmetshin et al., Phys. Lett. B 740, 273 (2015)

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

From the absence of the signal

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

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

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

Group	ND, 1988	CMD-3, 2014
$\Gamma_{\eta' \to e^+e^-}$, eV	< 0.06	< 0.0024
$\Gamma_{\eta'}$, keV	~ 300	198 ± 9
$\mathcal{B}_{\eta' \to e^+e^-}, 10^{-8}$	< 21	< 1.2

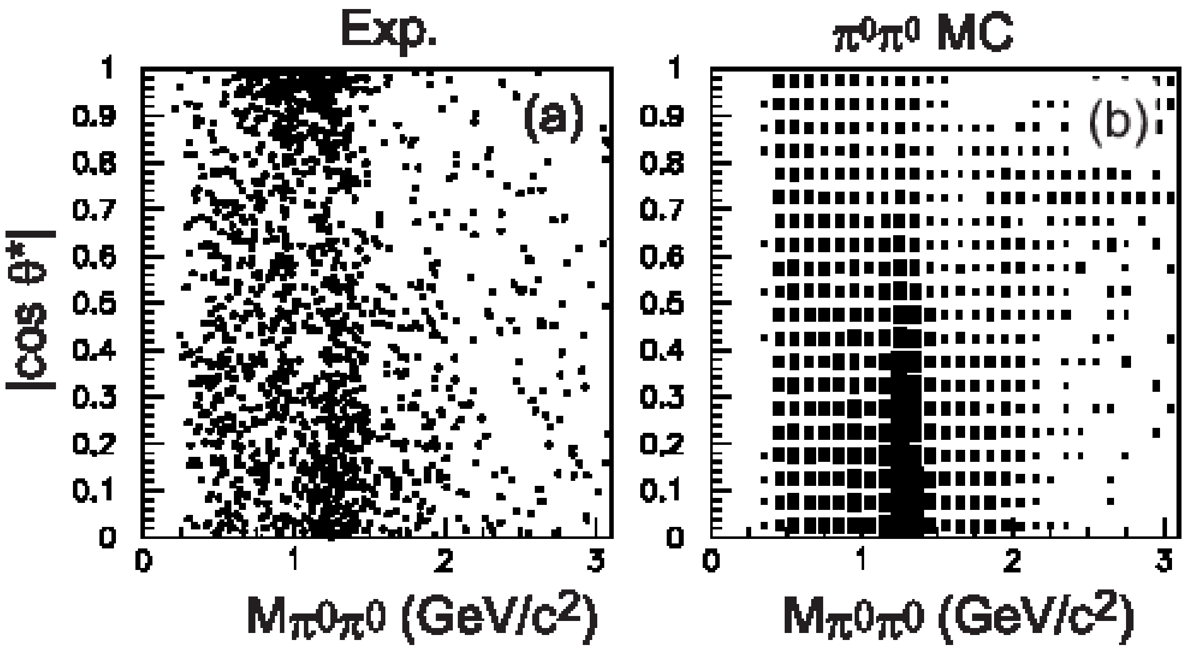
Much more stringent than that of ND, but
still 300 times higher than the unitarity bound

Conclusions

- $e^+e^- \to e^+e^- +$ 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 $\gamma\gamma^* \to R$, $J^{PC}(R) = 0^{-+},\ 0^{++},\ 1^{-+},\ 2^{++}$
- 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 $R \to e^+e^-$, e.g. in $e^+e^- \to c\bar{c} \to f$
- 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

$\gamma\gamma^* \to \pi^0\pi^0$ at Belle



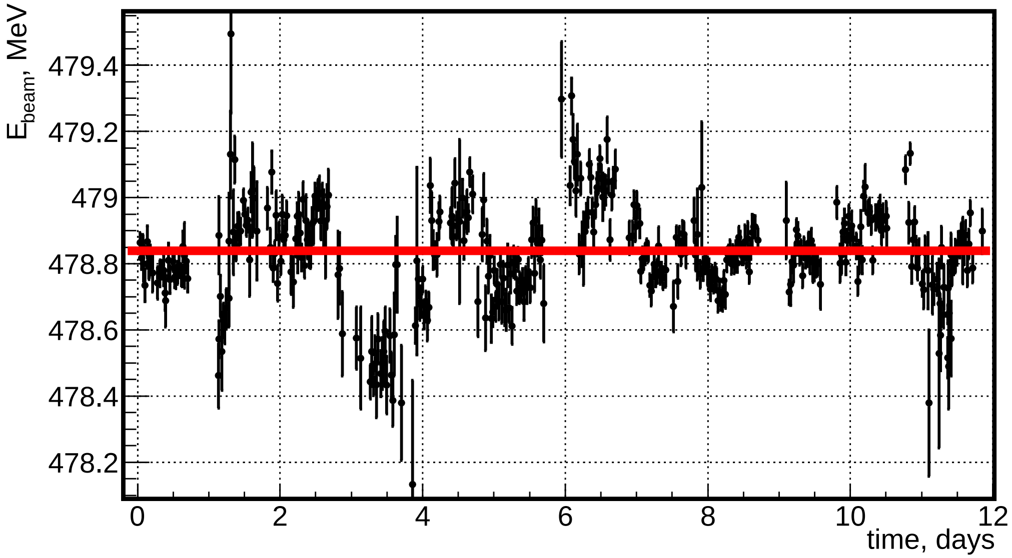
Muon $\frac{(g-2)}{2}$ – I (Comparison to Experiment)

Contribution	$a_\mu, 10^{-10}$
Experiment	$11659208.9 \pm 5.4 \pm 3.3(6.3)_{\mathrm{tot}}$
QED	11658471.9 ± 0.008
Electroweak	$15.4 \pm 0.1 \pm 0.2$
Hadronic	$692.3 \pm 4.2 \pm 2.6 \pm 0.2(4.9)_{\mathrm{tot}}$
Theory	11659180.2 ± 4.9
Exp.–Theory	$28.7 \pm 8.0\ (3.6\sigma)$

The difference between experiment and theory is (3.2-3.6)σ!

Experiment: G.W. Bennett et al., Phys. Rev. D 73, 072003 (2006)

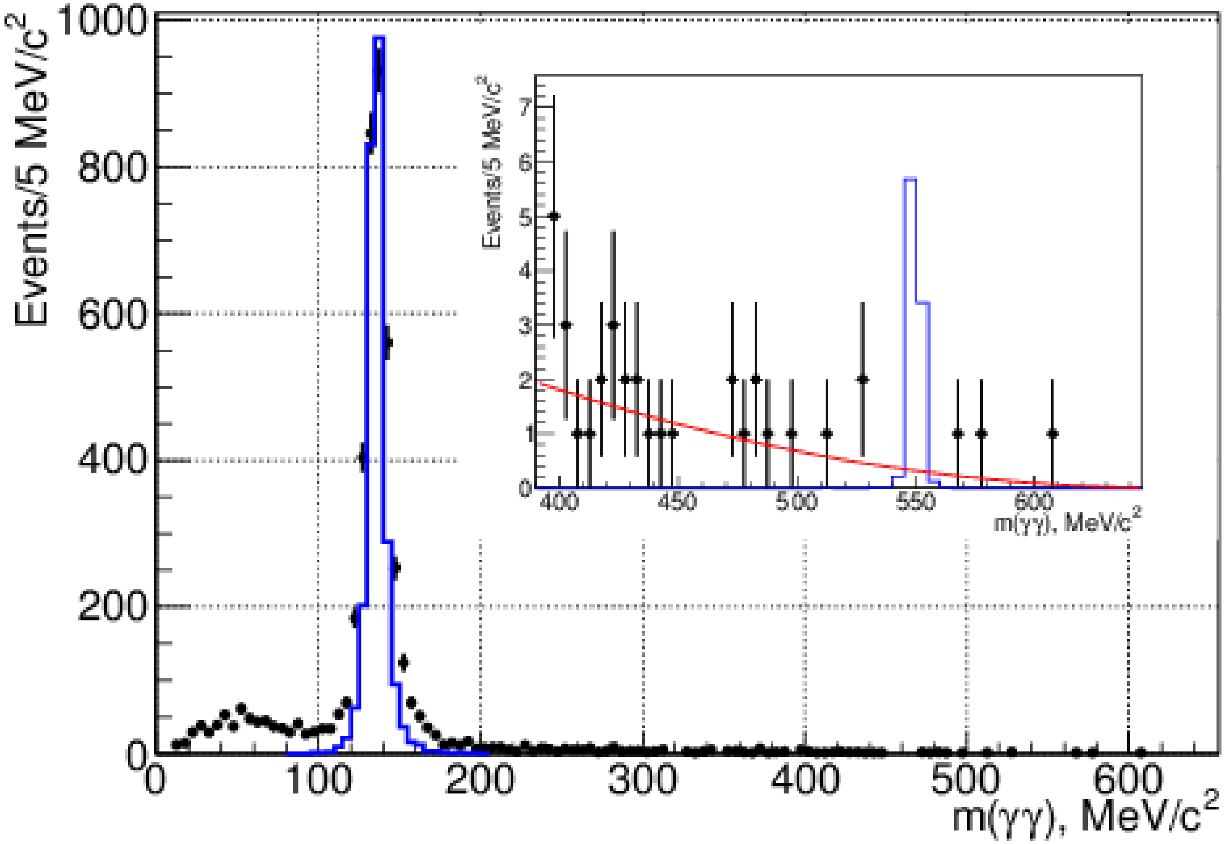
$e^+e^- \to \eta' \to \eta\pi^+\pi^-$



Measurements of the beam energy show good stability of the collider energy. The average value of the c.m. energy is $E^{av.}_{c.m.} = 957.678 \pm 0.014$ 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

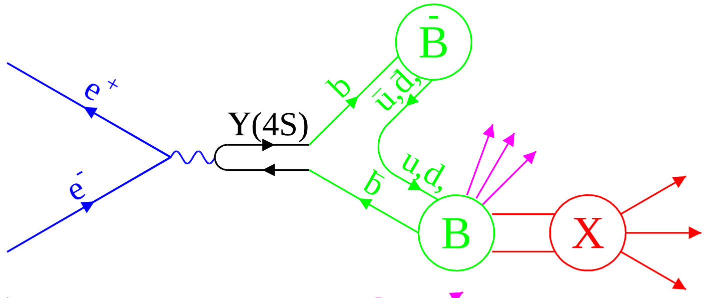
The collider beams have an energy spread mainly due to the quantum effects. For VEPP-2000 the c.m. energy spread $\sigma_{E_{c.m.}} = (0.246 \pm 0.030)$ MeV

Search for $e^+e^- \to \eta'$ with CMD-3 – III

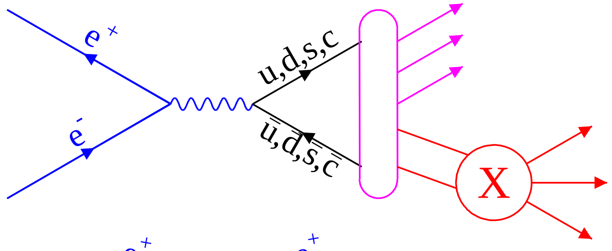


Particle Production at B Factories

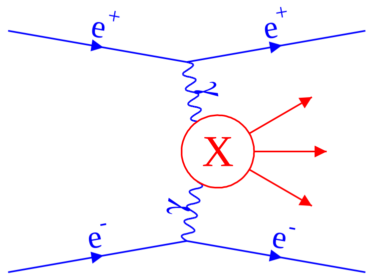
Production from B-decay
(broad D^{**}, D_{sJ}, $X(3872)$, $Y(3940)$)



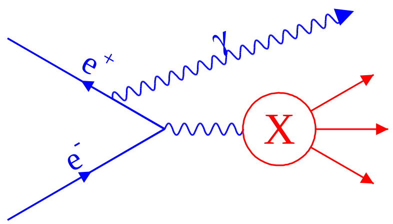
Production from continuum
(D_{sJ}, $\eta_c(2S)$, $X(3940)$, $\Sigma(2800)$)



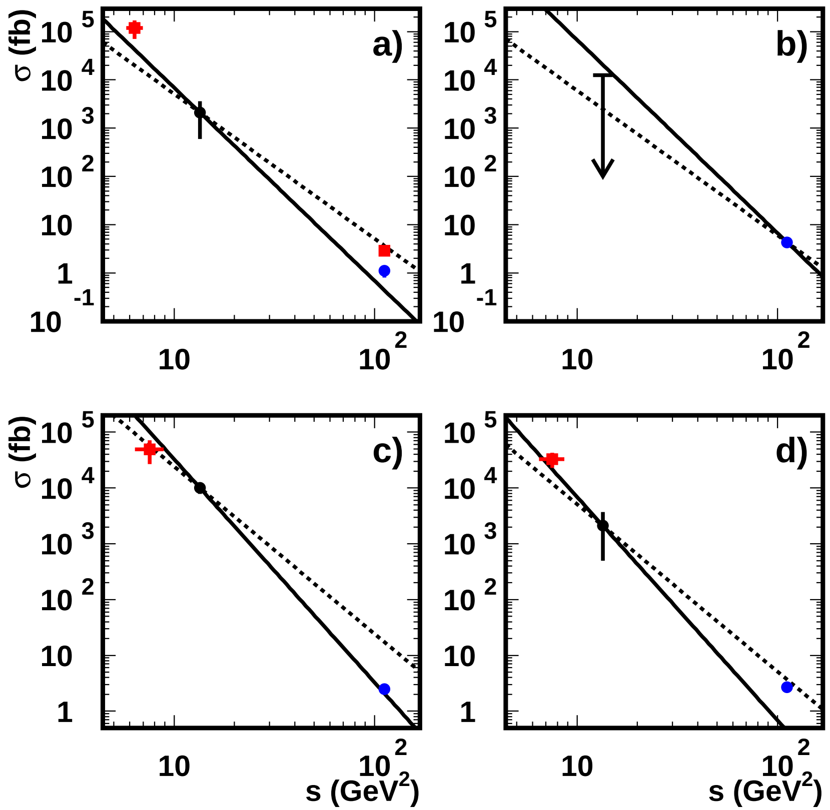
Two-photon production
($\eta_c(2S)$, $\chi_{c2}(2P)$)



Initial state radiation
($Y(4260)$, $Y(4360)$, $Y(4660)$)



$\gamma^* \to VP$ – I



(a) $\phi\eta$, (b) $\phi\eta'$, (c) $\rho\eta$, (d) $\rho\eta'$

Solid – $1/s^4$, dashed – $1/s^3$

$\gamma^* \to VP$ – II

Mode	Belle [3]	[4]	[5]	BaBar [2]
$\phi\eta$	$1.4 \pm 0.4 \pm 0.1$	3.3-4.3	2.4-3.4	$2.9 \pm 0.5 \pm 0.1$
$\phi\eta'$	$5.3 \pm 1.1 \pm 0.4$	4.4-5.8	3.5-5.0	–
$\phi\eta$	$3.1 \pm 0.5 \pm 0.1$	2.4-3.1	2.4-3.5	–
$\phi\eta'$	$3.3 \pm 0.6 \pm 0.2$	1.5-2.1	1.6-2.3	–

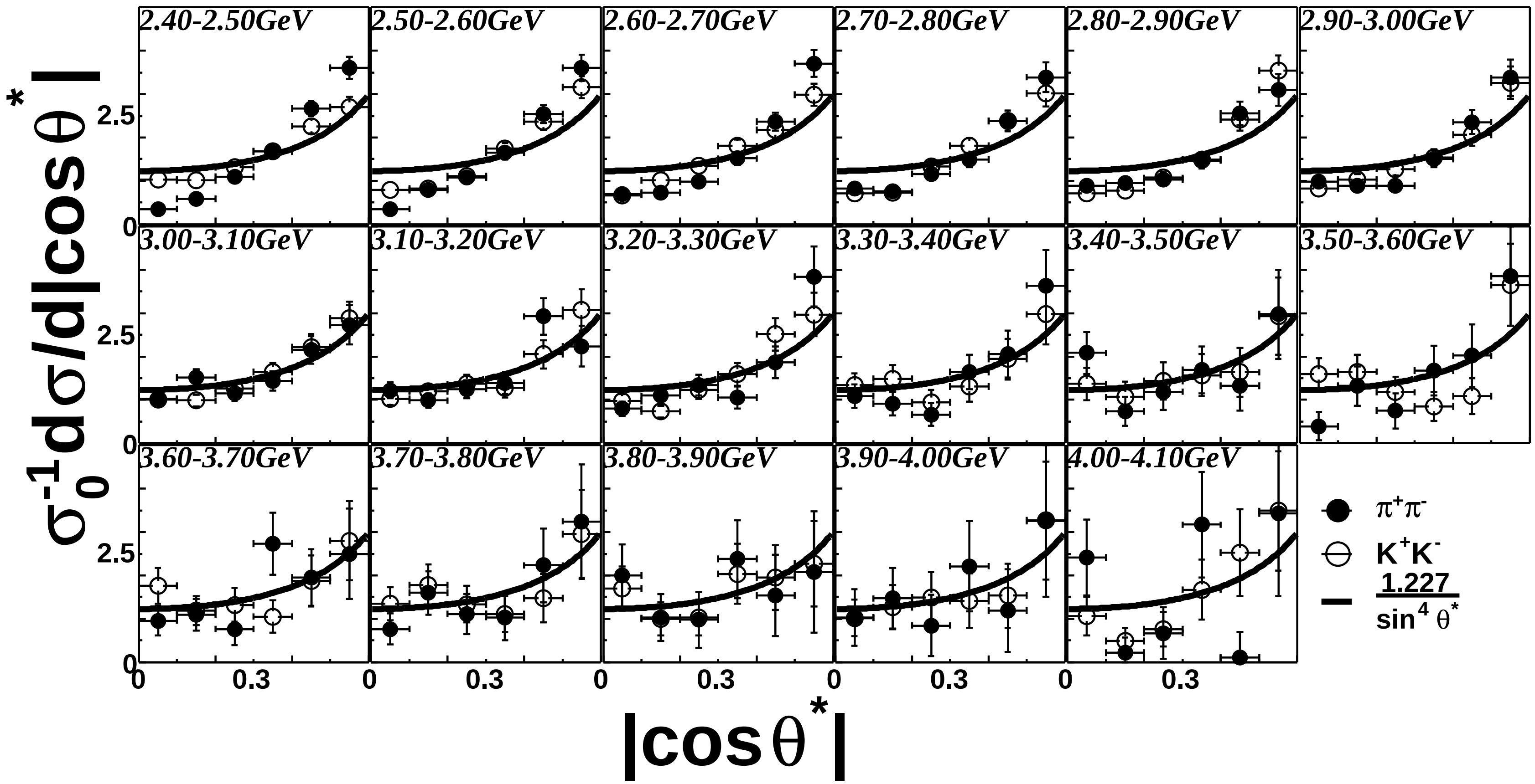
G.S. Adams et al. (CLEO) Phys. Rev. D 73, 012002 (2006) [1]
B. Aubert et al. (BaBar) Phys. Rev. D 74, 111103 (2006) [2]
K. Belous et al. (Belle) Phys. Lett. B 681, 400 (2009) [3]

C.D.Lu et al. (Light cone) Phys. Rev. D 75, 094020 (2007) [4]
V.V. Braguta et al. (Light cone) Phys. Rev. D 78, 074032 (2008) [5]

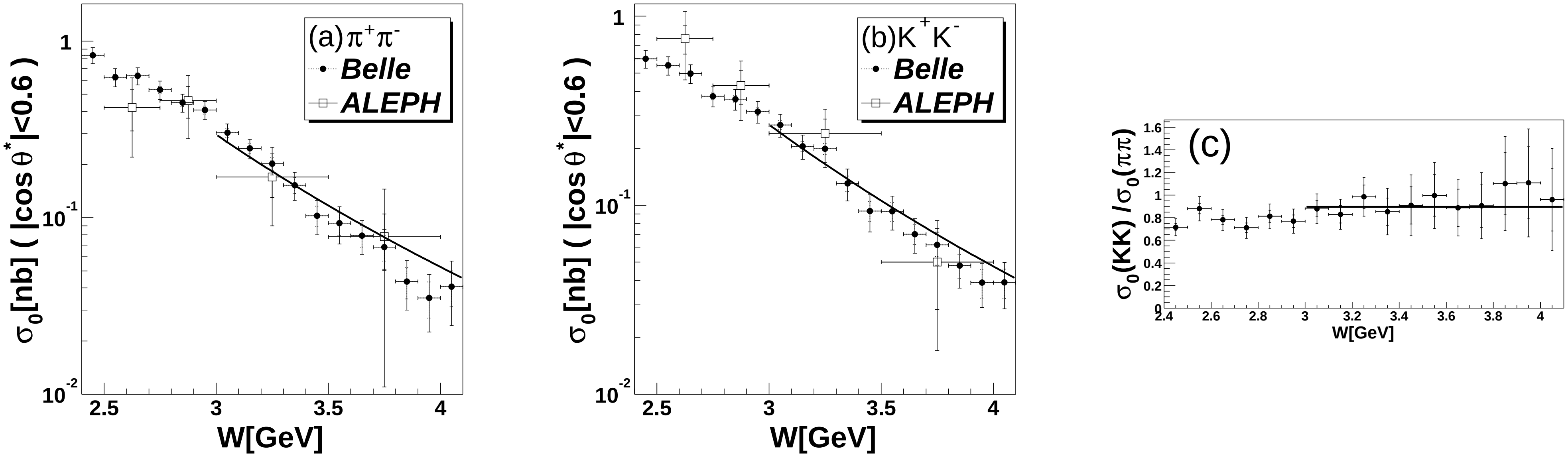
$\gamma\gamma \to \pi^+\pi^-,\ K^+K^-$ – I

- For all final states Belle surpassed the previous measurements both in statistics and the quality of detection
- For $\gamma\gamma \to \pi^+\pi^-,\ K^+K^-$ Belle used a data sample of 87.7 fb^{-1} to study angular dependence, energy behavior and the ratio $\frac{\sigma(\pi^+\pi^-)}{\sigma(K^+K^-)}$
  H. Nakazawa et al., Phys. Lett. B 615, 39 (2005)
- The best previous experiment (ALEPH) had a data sample of 837.5 pb^{-1}
  A. Heister et al., Phys. Lett. B 569, 140 (2003)

$\gamma\gamma \to \pi^+\pi^-,\ K^+K^- - \text{II}$

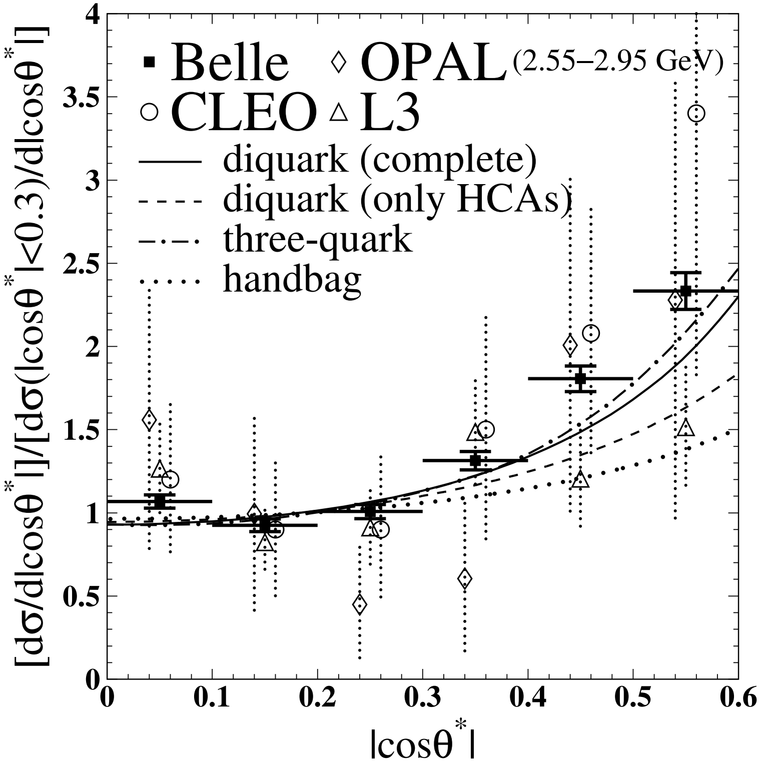


$\gamma\gamma \to \pi^+\pi^-,\ K^+K^-$ – III

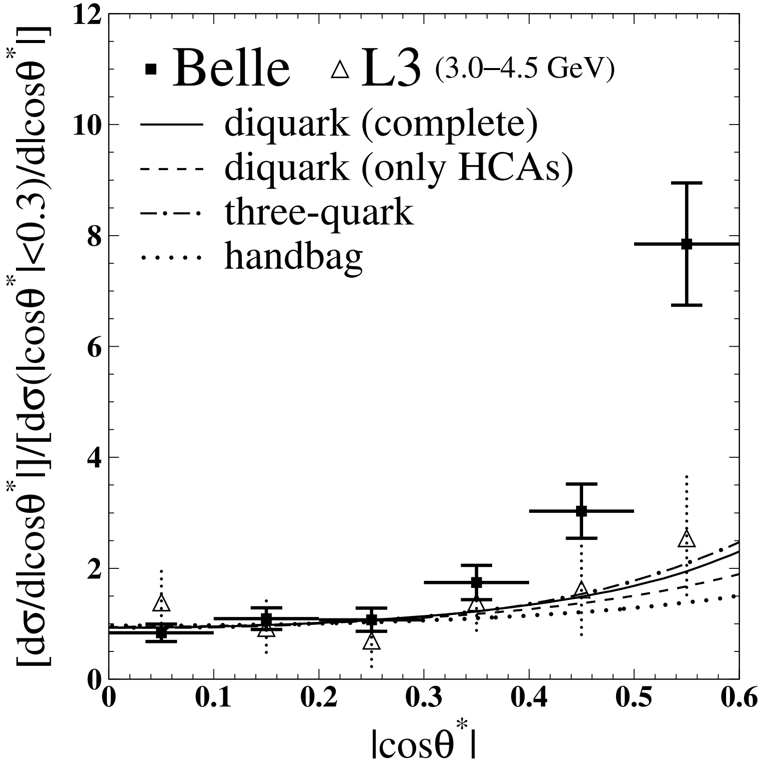


$\gamma\gamma \to p\bar{p}$ – II

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



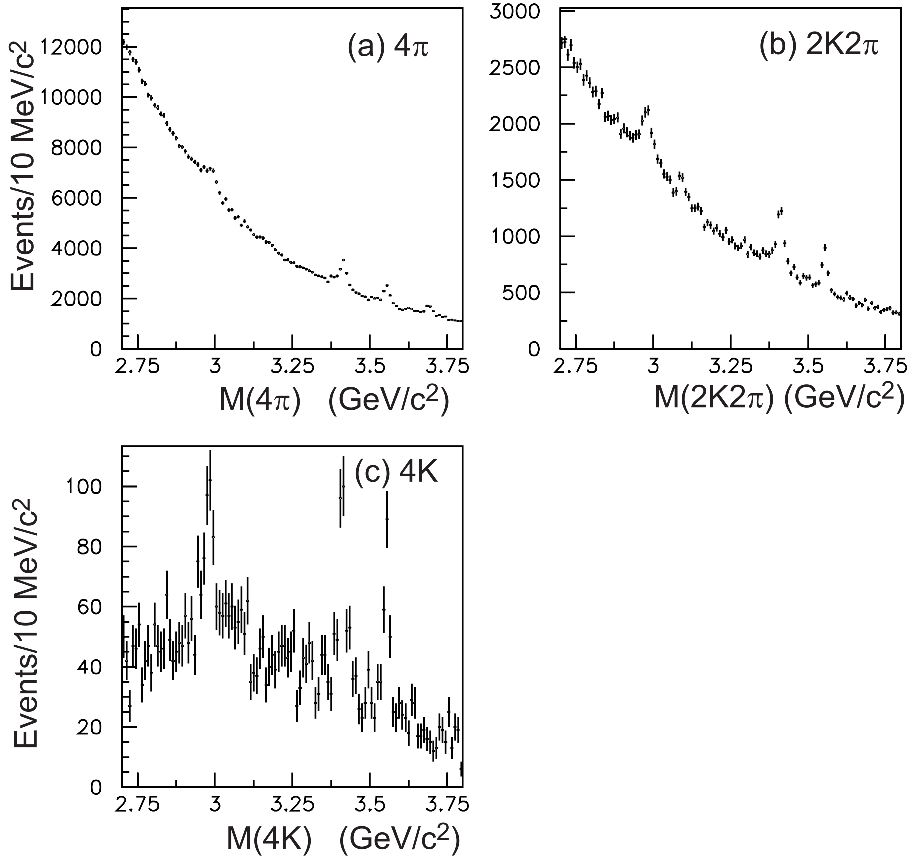
$3 < W_{\gamma\gamma} < 4$ GeV



Power corrections are still significant

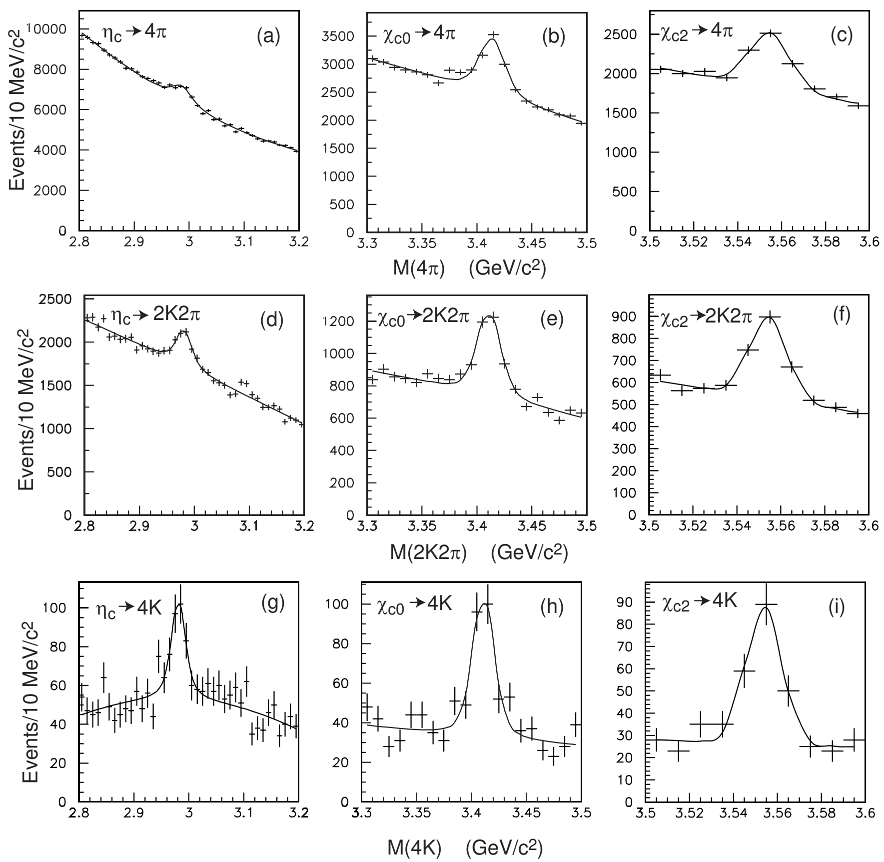
Diquark and handbag models need improvement

$\gamma\gamma \to$ 4 Charged Tracks – I

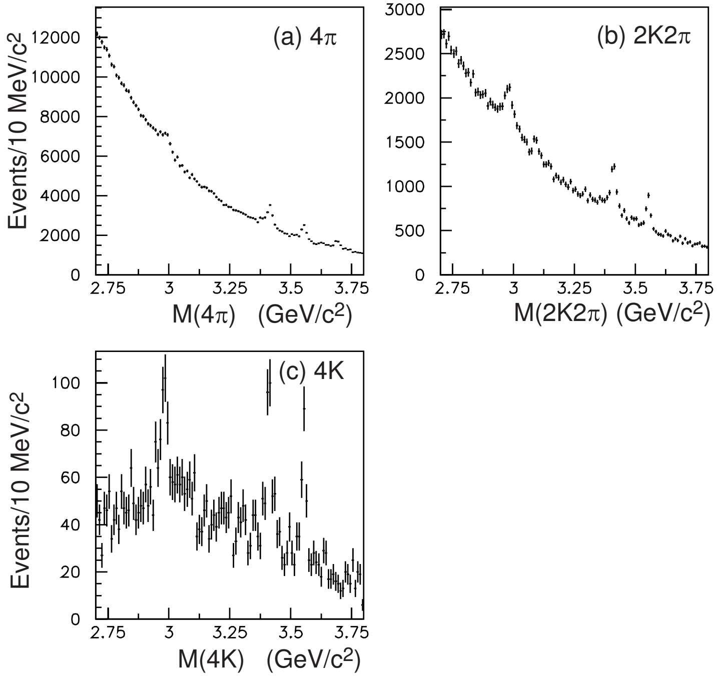


S. Uehara et al. (Belle Collab.), Eur. Phys. J. 53, 1 (2007)

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



Four-prong Final States

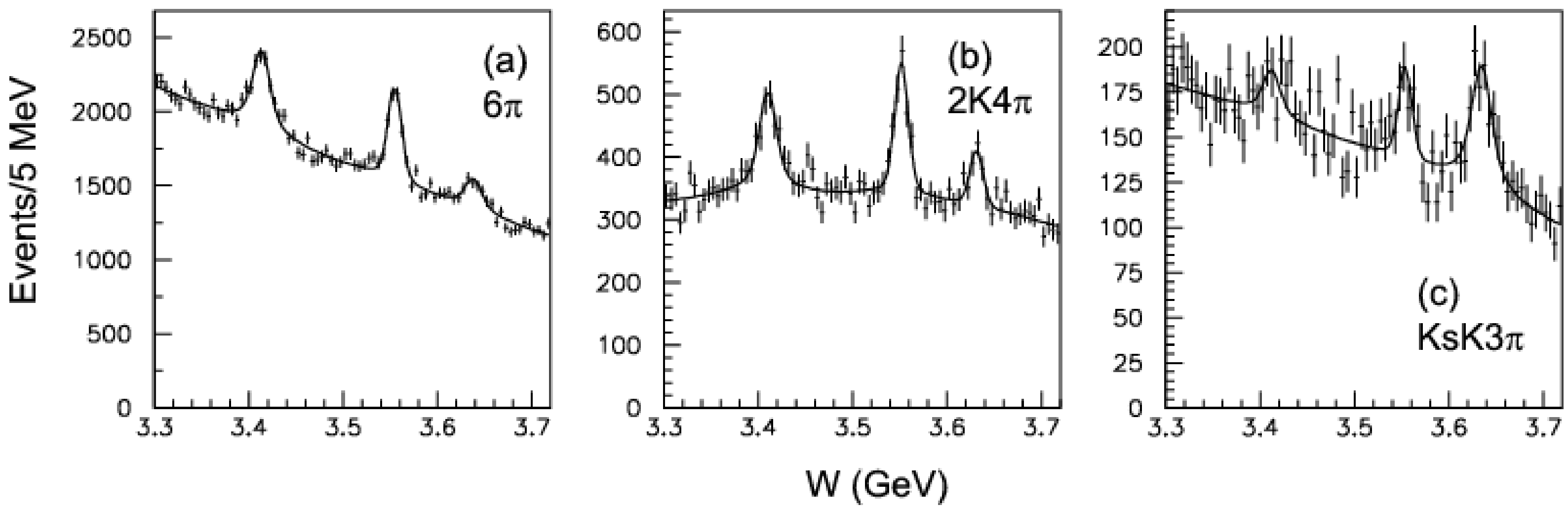


In each of the three final states – $2(\pi^+\pi^-)$, $\pi^+\pi^-K^+K^-$, $2(K^+K^-)$ – three charmonia – η_c, χ_{c0} and χ_{c2} are clearly seen

They also study dynamics and see: $\eta_c \to K^{*0}\bar{K}^{*0}$, $f_2 f_2'$, $\phi\phi$, $f_2 f_2$

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}:

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

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

$\eta_c(1S)$, χ_{c0} and χ_{c2} are also clearly seen

Six-prong Final States and $\eta_c(2S)$ - II

Mode	M, MeV/c^2	Γ, MeV	N_{ev}	S, σ	$\Gamma_{\gamma\gamma}\mathcal{B}$, eV
6π	$3638.9 \pm 1.6 \pm 2.3$	10.7 ± 4.9	1485 ± 274	8.5	$20.1 \pm 3.7 \pm 3.2$
$2K4\pi$	$3634.7 \pm 1.6 \pm 2.8$	$1.4^{+6.3}_{-1.4} (< 13)$	407 ± 91	6.2	$10.2 \pm 2.3 \pm 3.4$
$K_S K 3\pi$	$3636.5 \pm 1.8 \pm 2.4$	15.9 ± 5.7	563 ± 71	8.7	$30.7 \pm 3.9 \pm 3.7$
$K^+K^-3\pi$	$3640.5 \pm 3.2 \pm 2.5$	13.4 (fixed)	1201 ± 228	5.3	$30.0 \pm 6.0 \pm 5.0$

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

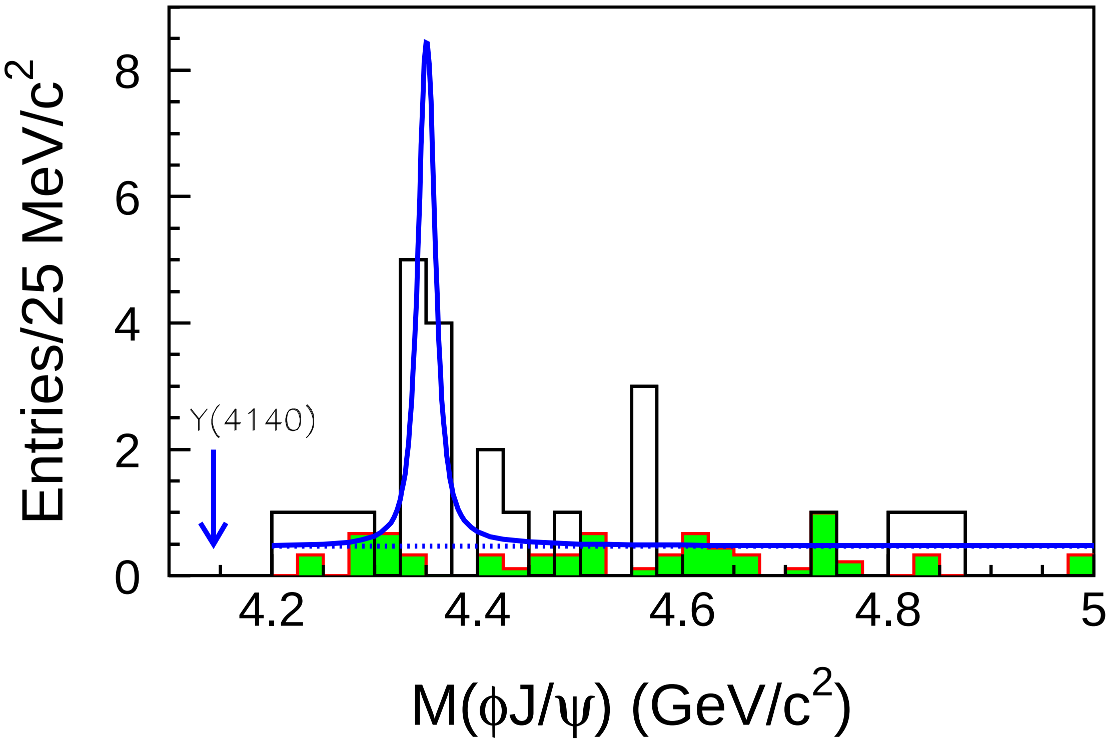
consistent with Belle results on $B^\pm \to K^\pm (K_S K \pi)^0$:

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)

$\gamma\gamma \to J/\psi\phi$



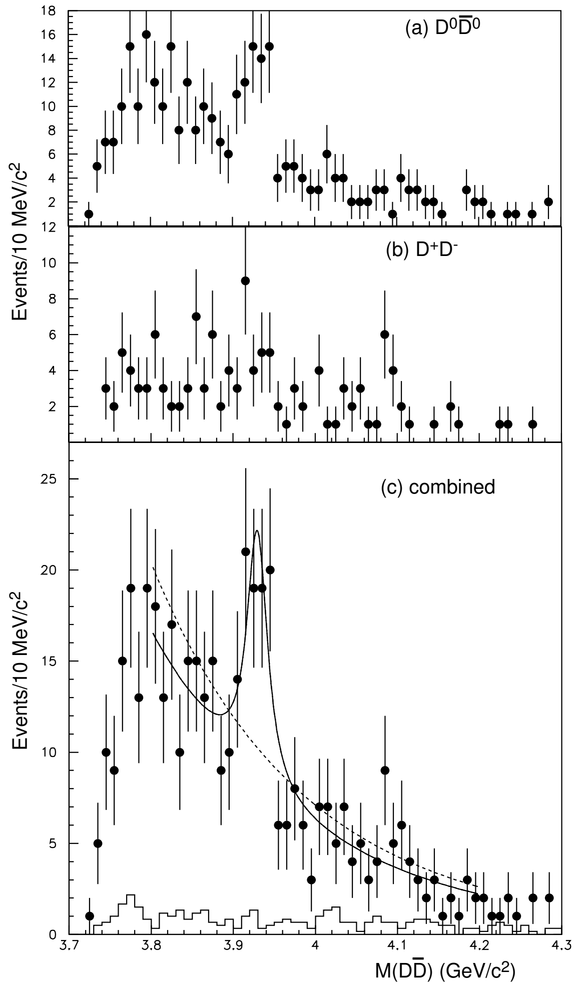
The $Y(4140)$ and $Y(4274)$ states of CDF not seen (also disproved by LHCb)

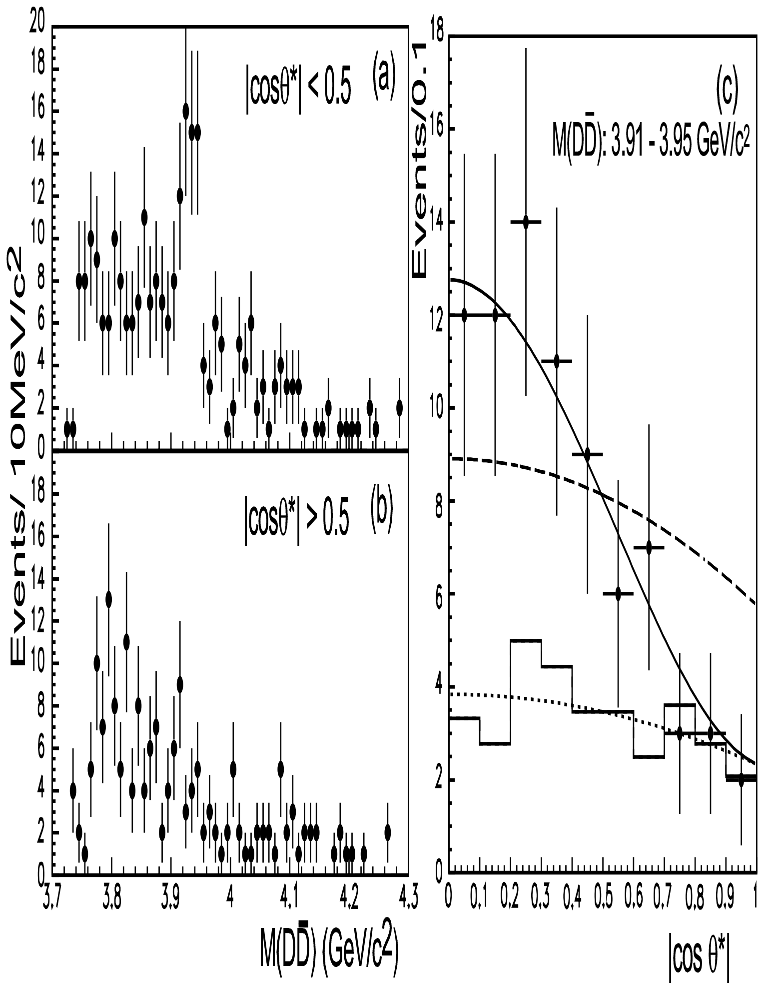
C.P. Shen et al., Phys. Rev. Lett..104, 112004 (2010)

Observation of New Charmonium-like States at Belle

Final state	$\int Ldt$, fb^{-1}	W, GeV	Reference
D^+D^-, $D^0\bar{D}^0$	395	3.7-4.3	S. Uehara et al., PRL 96, 082003 (2006)
$J/\psi\omega$	694	3.9-4.2	S. Uehara et al., PRL 104, 092001 (2010)
$J/\psi\phi$	825	4.2-5.0	C.P. Shen et al., PRL 104, 112004 (2010)

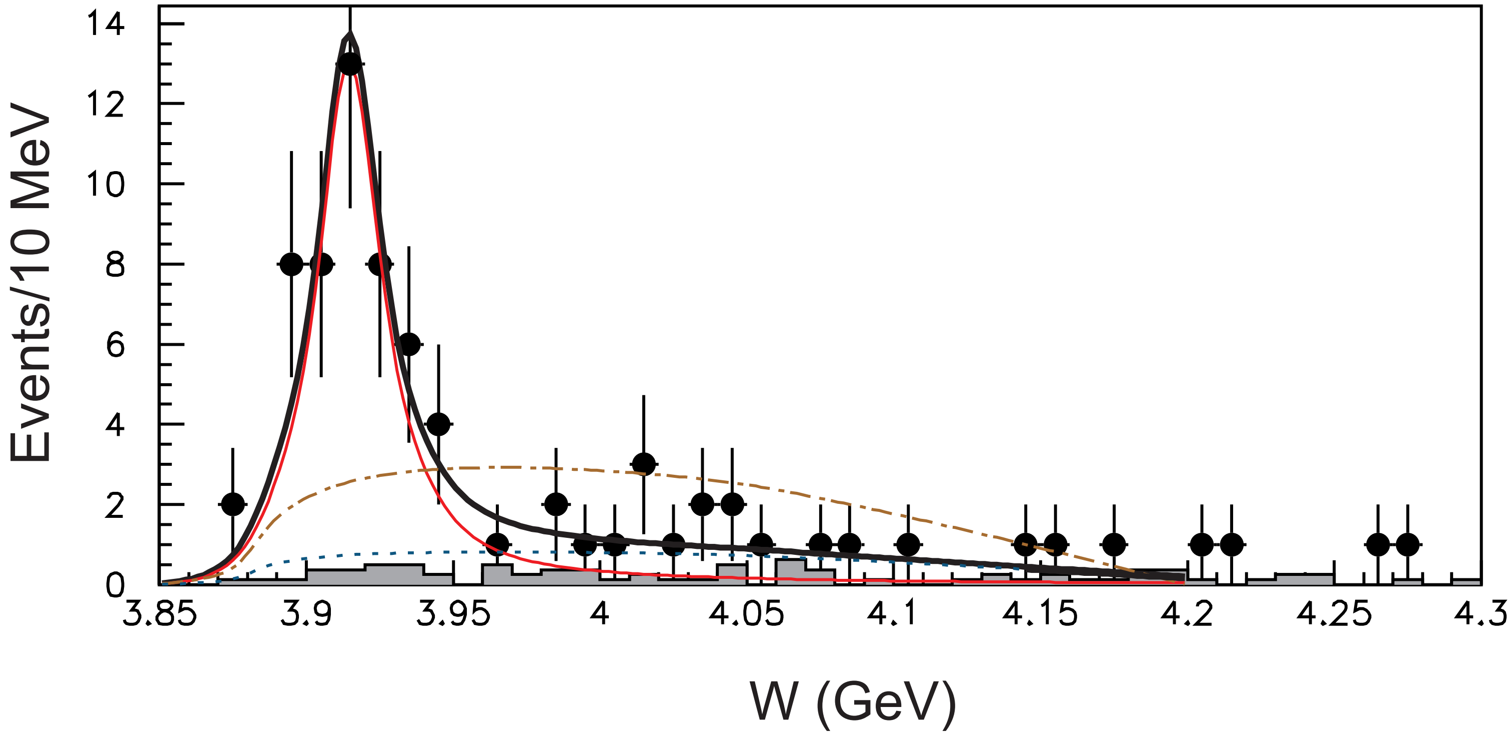
$\gamma\gamma \to D^+D^-,\ D^0\bar{D}^0$ and $\chi_{c2}(2P)$





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

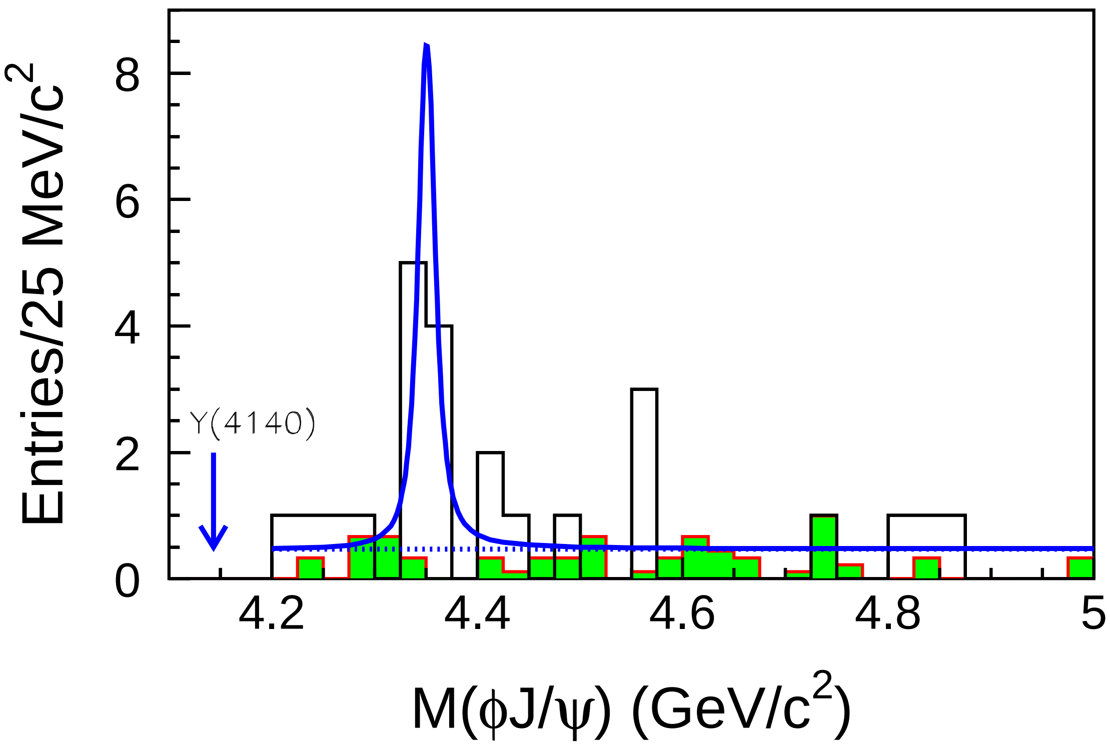
$\gamma\gamma \to J/\psi\omega$



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

S. Uehara et al. (Belle Collab.), Phys. Rev. Lett..104, 092001 (2010)

$\gamma\gamma \to J/\psi\phi$



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

C.P. Shen et al., Phys. Rev. Lett..104, 112004 (2010)

$\gamma\gamma \to \omega\omega,\ \omega\phi,\ \phi\phi$ – II