# Two-photon Physics

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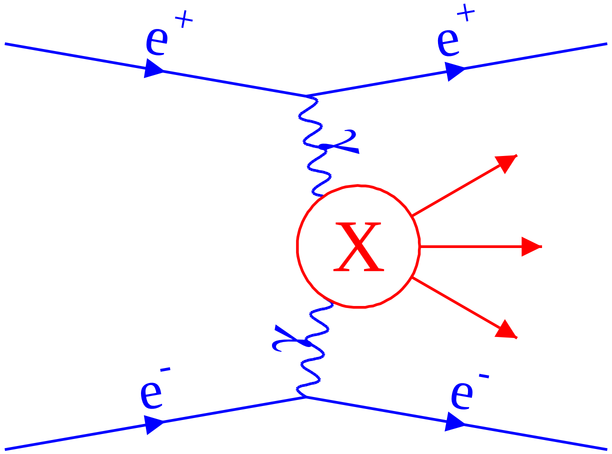
## Outline

1. Basics of $\gamma\gamma$ collisions
2. Belle results (QCD tests, charmonia, light quarks)
3. Transition form factors and $a_\mu^{\mathrm{HLbL}}$
4. Conclusions

## Discovery of Two-Photon Production of an $e^+e^-$ Pair

- The process $e^+e^- \to e^+e^- + e^+e^-$ was observed for the first time at the $\phi$ meson at the VEPP-2 $e^+e^-$ collider in Novosibirsk, V.E. Balakin et al., Phys. Lett. B34, 663 (1971)
- $\sim$ 100 events were observed between $\sqrt{s}$=1016 and 1028 MeV
- The range and multiple scattering of tracks consistent with $e^-/e^+$ nature
- Tracks concentrated in the plane including the beams
- Energy dependence of the cross section was not related to the $\phi$ resonance
- The cross section was consistent with the old calculation in L.D. Landau and E.M. Lifshits, Sov. Phys. 6, 244 (1934)
- First theory in V.M. Budnev, I.F. Ginzburg, G.V. Meledin, V.G. Serbo, Phys.Rept. 15 (1975) 181.
- It was realized that $\gamma\gamma \to$ hadrons is very promising

## Basic Features of Two-Photon Collisions – I

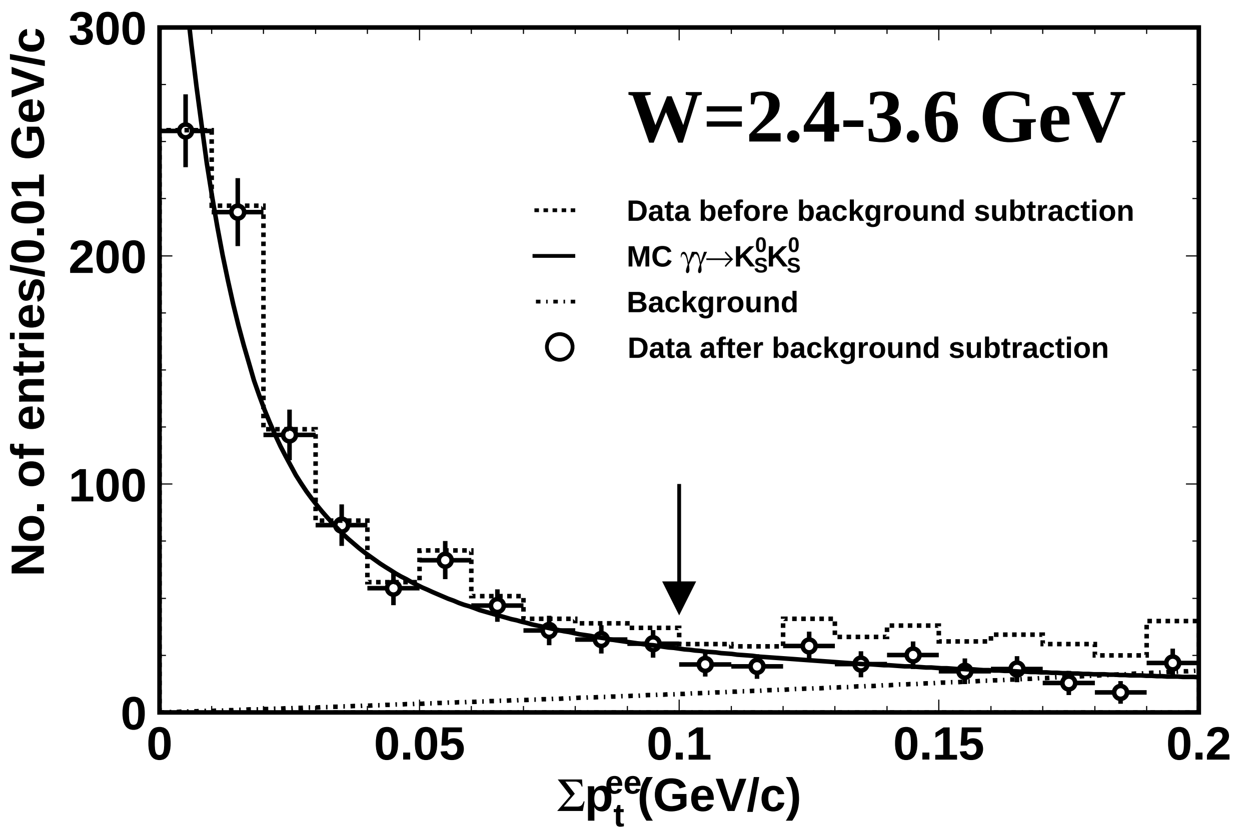



$W$ – $\gamma\gamma$ $(X)$ c.m. energy, $q_1^2$, $q_2^2$ – 4-momenta squared of virtual photons
$\theta^*$ – $X$ polar c.m. angle with respect to $e^+e^-$

## 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 $C = +1$ while those in single-photon annihilation have $C = -1$
- 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 $q^2_{1,2}$, 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

## Brief History of $\gamma\gamma$ Studies before Belle

Fast experimental progress:

- In the 80-s – SPEAR, PEP at SLAC, PETRA at DESY
- In the 90-s – LEP at CERN, TRISTAN at KEK
- A very important role of ARGUS at DESY and CLEO at CESR with high luminosity of $\gamma\gamma$ studies (0.5-1 fb$^{-1}$)
- Mostly resonance studies: measurements of $\Gamma_{\gamma\gamma}$ ($\mathcal{B}_{\gamma\gamma}$) for light mesons ($\pi^0,\ \eta,\ \eta'(958),\ f_0(980),\ a_0(980),\ f_2(1270),\ldots$) and charmonia ($\eta_c,\ \chi_{c0},\ \chi_{c2}$)
- First single-tag and $\sigma(\gamma\gamma \to$ hadrons) measurements
- This stimulated progress of theory

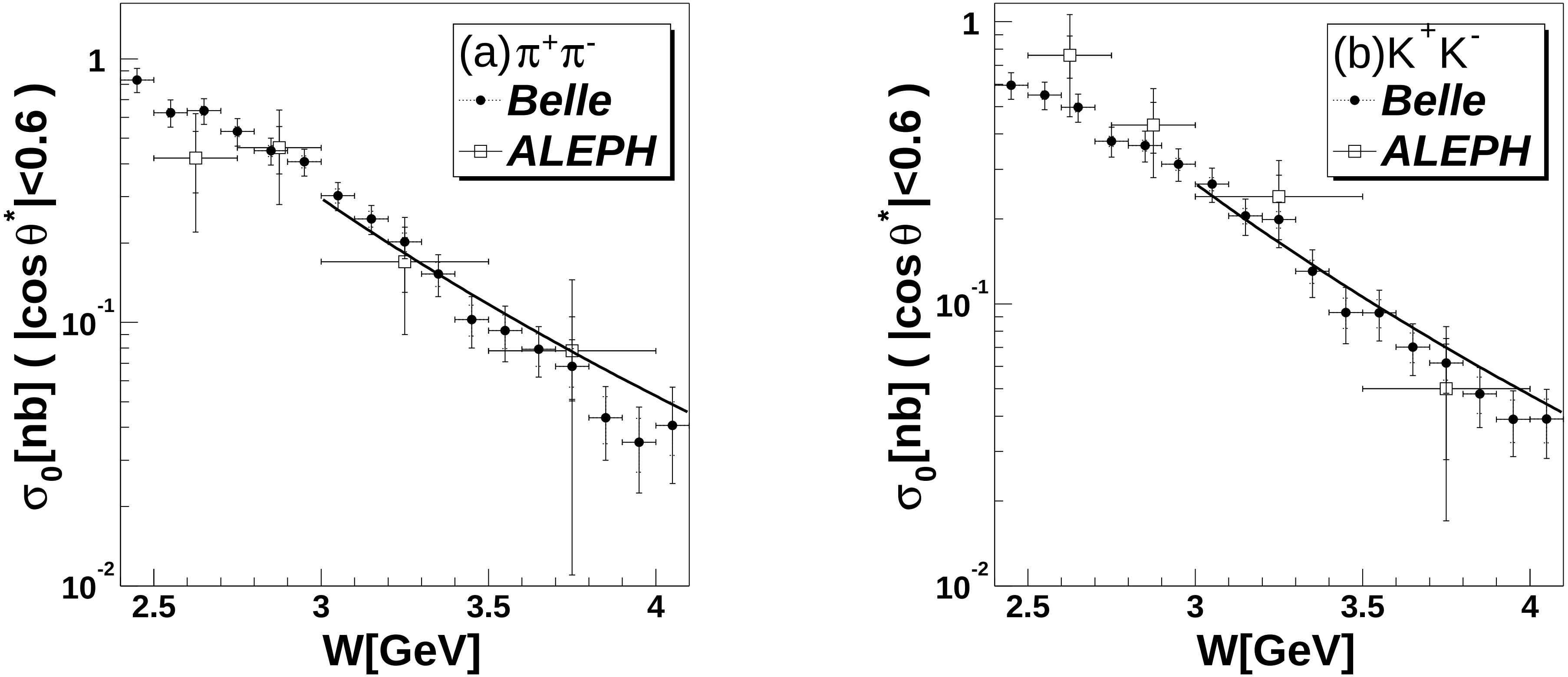
## Some Related Theory

- S.J. Brodsky and G.R. Farrar, Phys. Rev. Lett. 31, 1153 (1973);
  S.J. Brodsky and G.R. Farrar, Phys. Rev. D 11, 1309 (1975);
  S.J. Brodsky and G.P. Lepage, Phys. Rev. D 24, 1808 (1981)
- V.L. Chernyak and A.R. Zhitnisky, Phys. Rept. 112, 173 (1984);
  M. Diehl, P. Kroll, C. Vogt, Phys. Lett. B 532, 99 (2002);
  V.L. Chernyak and SE, Prog. Part. Nucl. Phys. 80,1 (2015)
- Scaling laws for processes with large $Q^2$ using quark counting rules;
  predictions for $\sigma(\gamma\gamma \to M\bar{M})$ in pQCD;
  studies of $\gamma\gamma^* \to P$ at large $Q^2$
- For $\pi^+\pi^-$ the prediction is $\frac{d\sigma}{dcos\theta^*} \sim W^{-6}$, for $p\bar{p}$ – $\sim W^{-10}$
- They relate $\frac{d\sigma}{dt}$ for various processes $\gamma\gamma \to M\bar{M}$,
  where $M$ is a helicity 0 or $\pm1$ meson
- 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 |

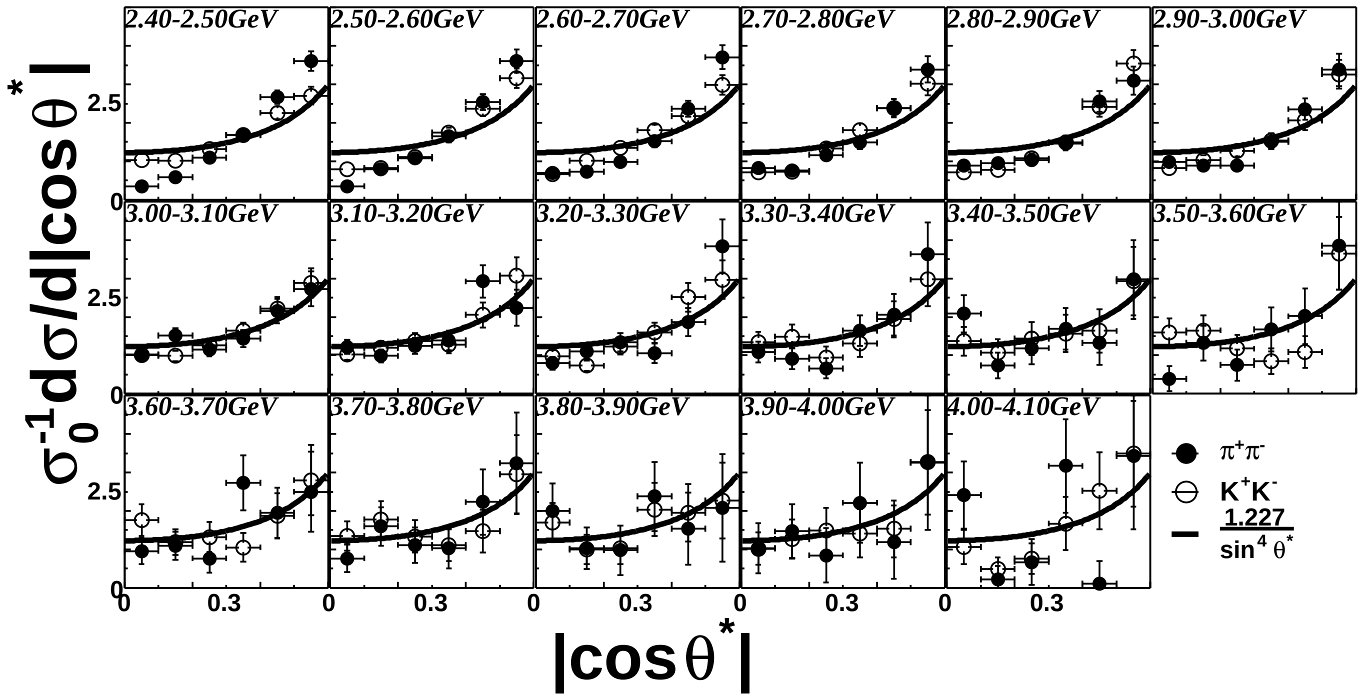
## $\gamma\gamma \to \pi^+\pi^-,\ K^+K^- - \mathrm{I}$




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

Absolute cross sections not predicted!

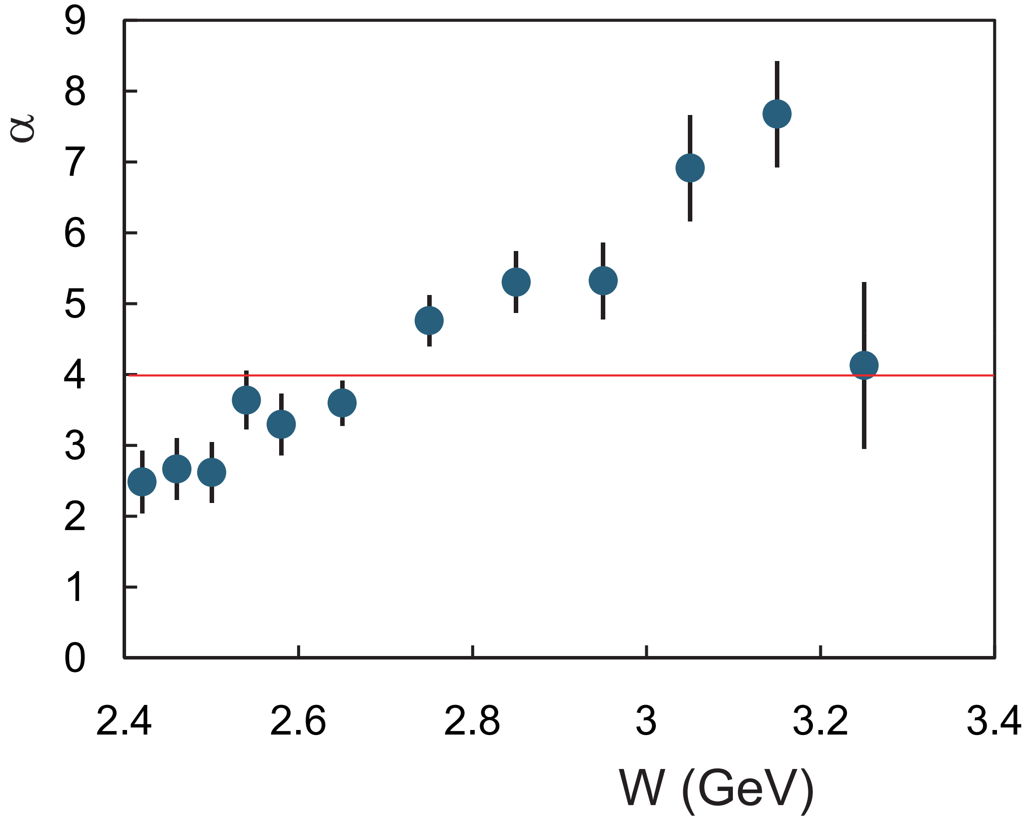
# $\gamma\gamma \to \pi^+\pi^-,\ K^+K^-$ – II




$$\frac{d\sigma}{d|cos\theta^*|} \sim \frac{1}{sin^4\theta^*}$$

Agreement at > 3.0 GeV, effects of resonances below?

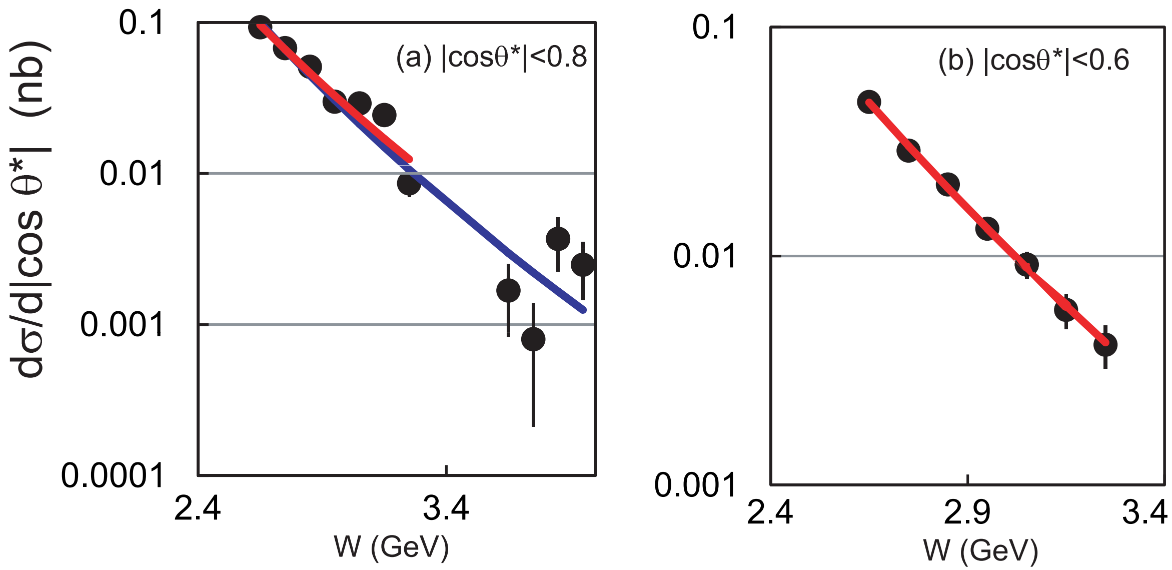
# $\gamma\gamma \to K_S^0 K_S^0$ – I




For neutrals the leading term is numerically small, $\rho(\theta^*) \sim 1/sin^\alpha\theta^*$

$d\sigma/d|cos\theta^*| \sim |\rho(\theta^*)|^2/W^{10}$, but $\rho(\theta^*)$ and normalization unknown

## $\gamma\gamma \to K_S^0 K_S^0$ – II



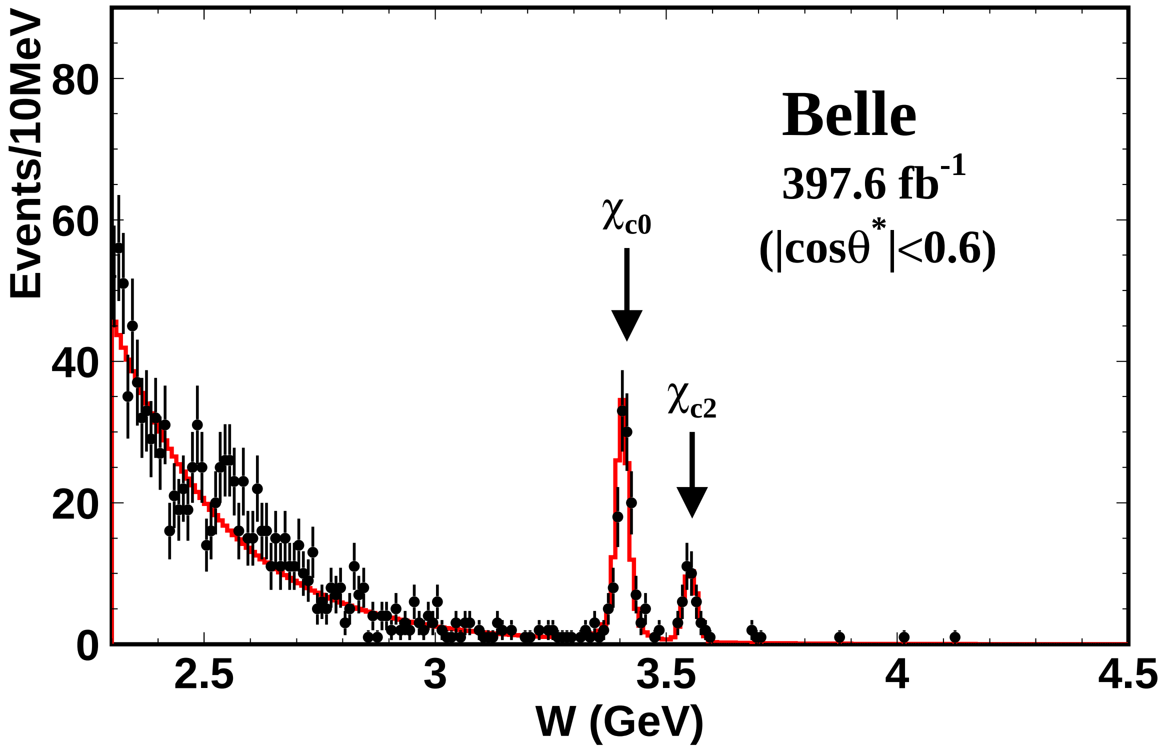

$n = 11.0 \pm 0.4 \pm 0.4$ is consistent with $n = 10$

## 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 |

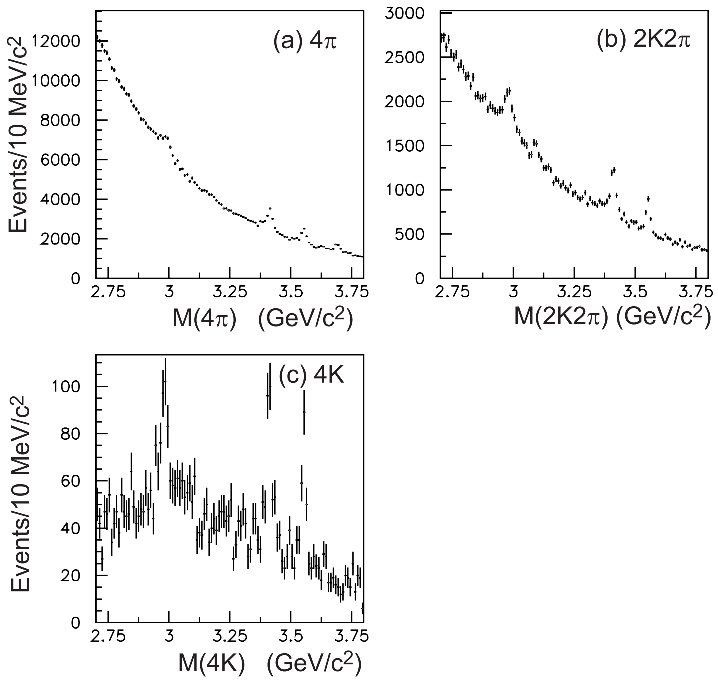
$n = 10$ does not work for $\pi^0\pi^0$, one more puzzle,
nor for $\eta\eta$, but here the $W$ range is limited

## Charmonia in $\gamma\gamma \to K^0_S K^0_S$




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

# Four- and Six-prong Final States




In three final states with four prongs – $2(\pi^+\pi^-)$, $\pi^+\pi^-K^+K^-$, $2(K^+K^-)$

Belle clearly sees $\eta_c$, $\chi_{c0}$ and $\chi_{c2}$, but not $\eta_c(2S)$

In three final states with six prongs – $3(\pi^+\pi^-)$, $K^+K^-2(\pi^+\pi^-)$ and $K^0_SK^\pm\pi^\mp\pi^+\pi^-$

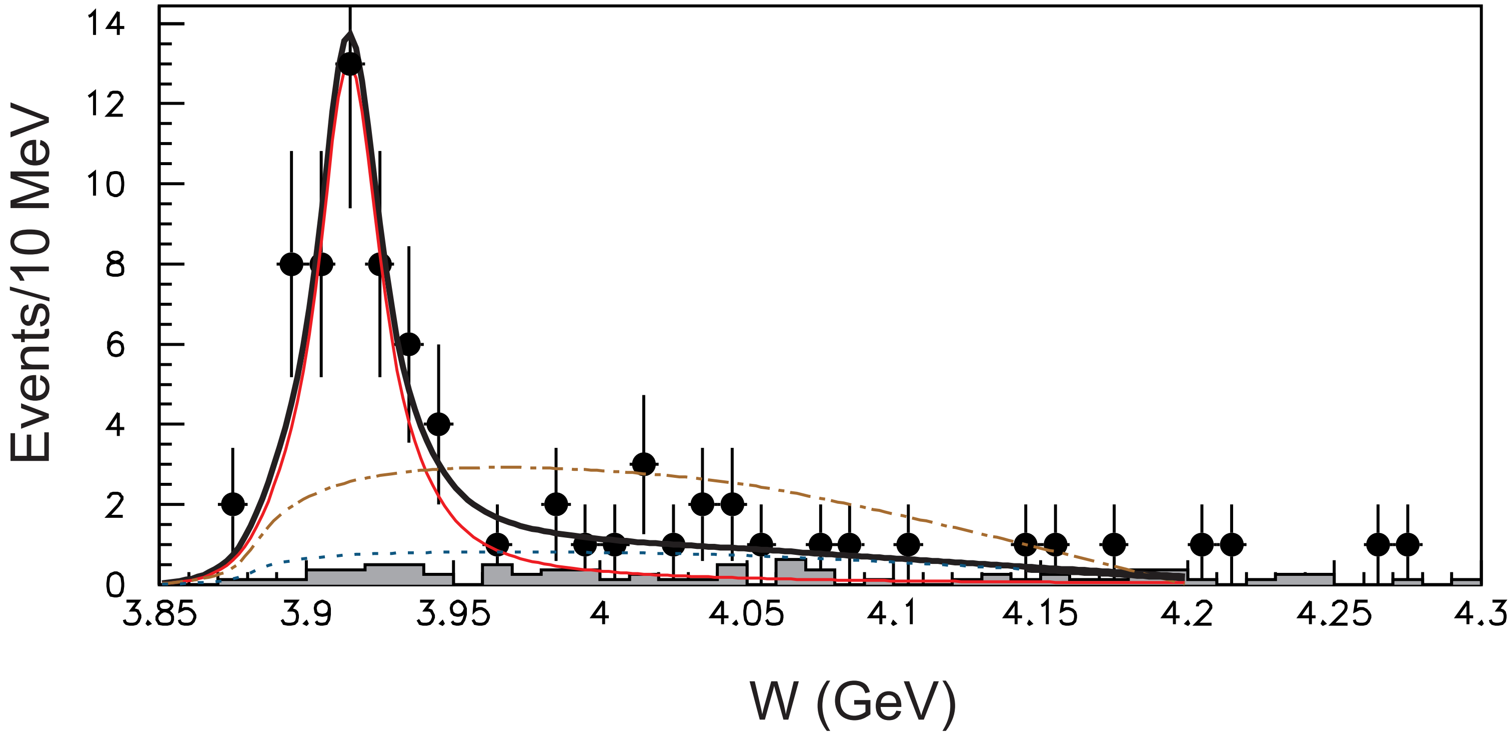
Belle sees $\eta_c(1S)$, $\chi_{c0}$, $\chi_{c2}$ and $\eta_c(2S)$

$\eta_c(2S)$ also seen by BaBar in $K^+K^-3\pi$, Phys. Rev. D84, 012004 (2011)

## 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

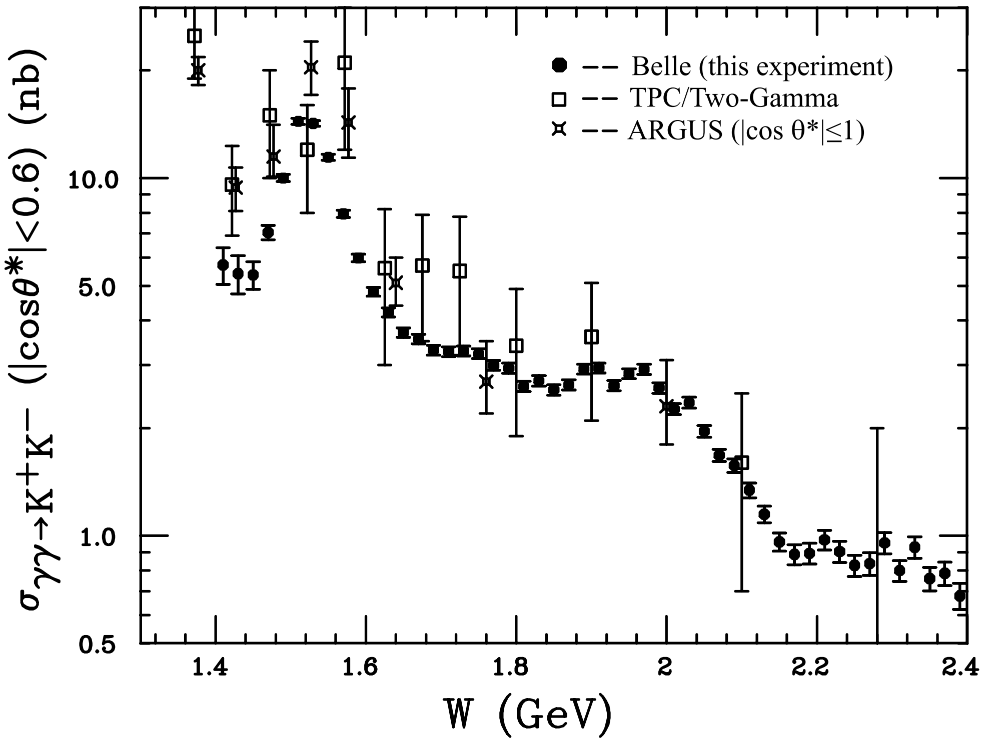
- Various decay modes of $\eta_c(1S)$, $\chi_{c0}(1P)$, $\chi_{c2}(1P)$ into two-, four- and six-body final states studied
- Two-photon width $\Gamma_{2\gamma}\mathcal{B}((c\bar{c}) \to f)$, $M$, $\Gamma$ measured, interference effects very important
- More precise branching fractions determined
- For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

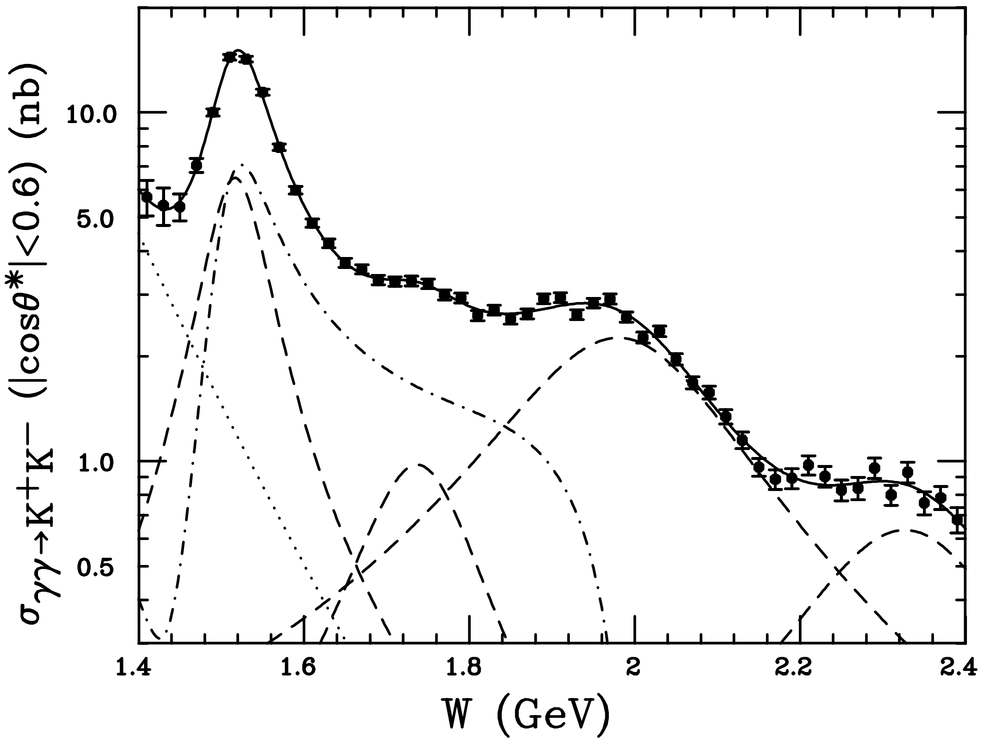
## Studies of Light-Quark Mesons at Belle

| 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) |

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

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

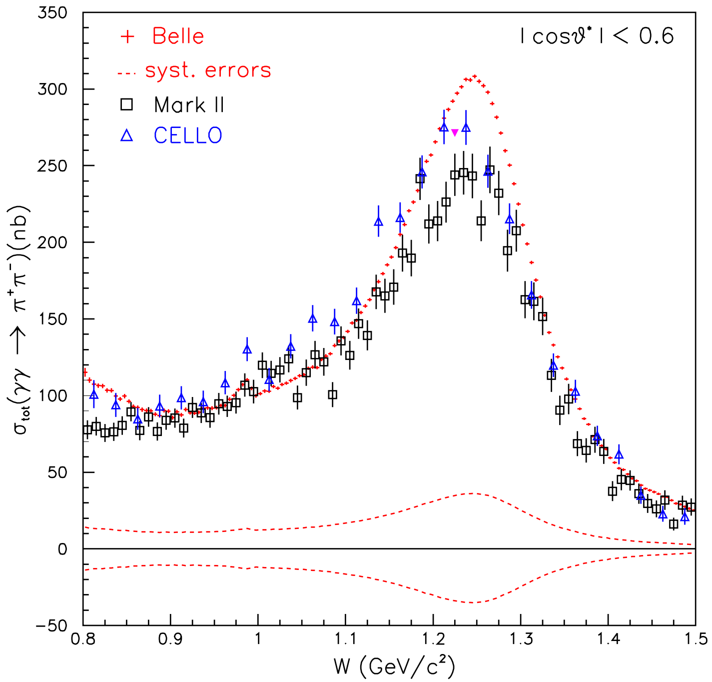



$f_2'(1525)$ and 3 more states at 1.7, 2.0 and 2.3 GeV (tensors?)

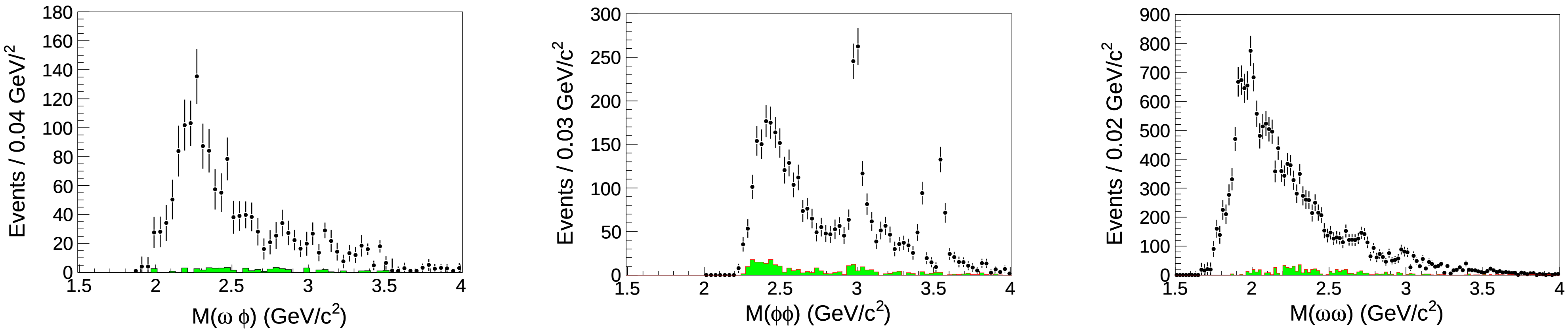
K. Abe et al., Eur. Phys. J. C 32, 323 (2003)

## $\gamma\gamma \to \pi^+\pi^-$ and $f_0(980)$




T. Mori et al. (Belle Collab.), Phys. Rev. D 75, 051101 (2007)

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



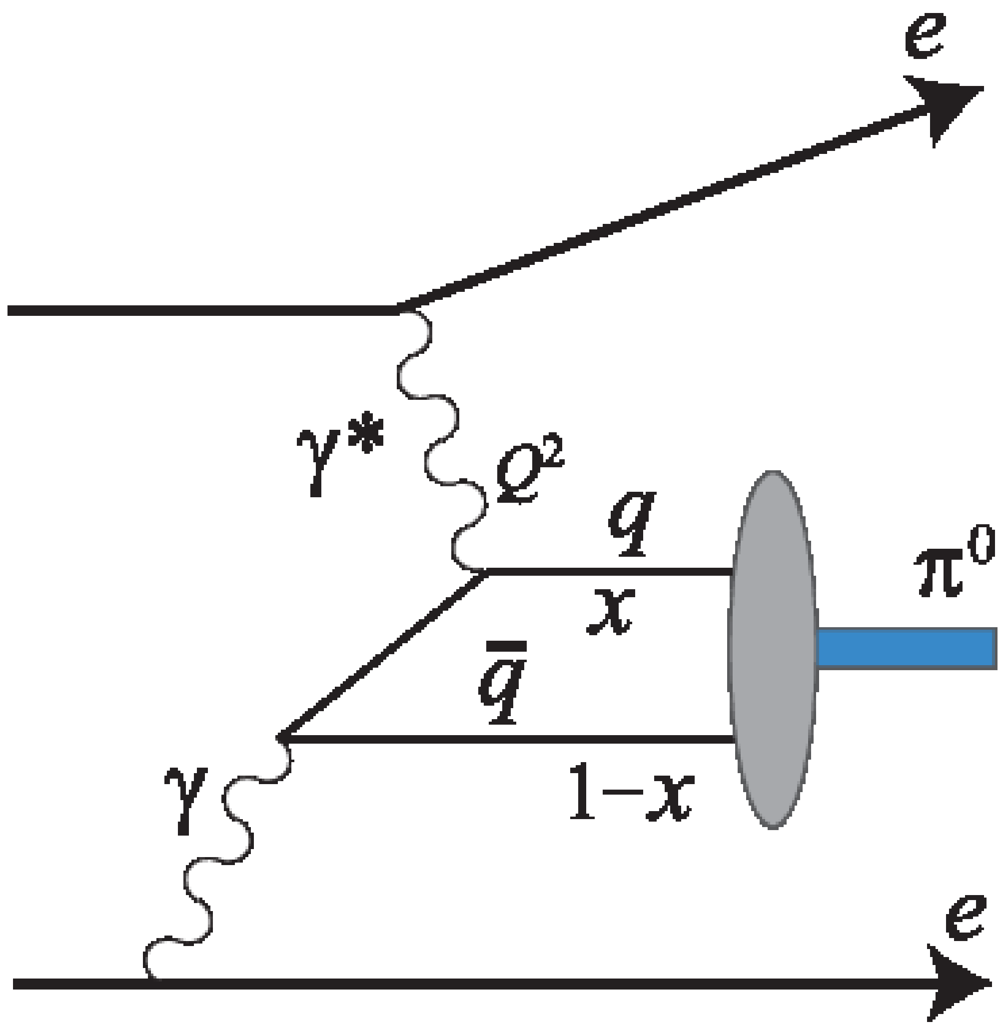

Structures at 1.91 ($\omega\omega$), 2.2 ($\omega\phi$), 2.35 GeV ($\phi\phi$), $0^{++}$ or $2^{++}$

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

# The Pion Distribution Amplitude – I



## The Pion Distribution Amplitude – II

At sufficiently high $Q^2$ the TFF $F(Q^2)$

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

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.

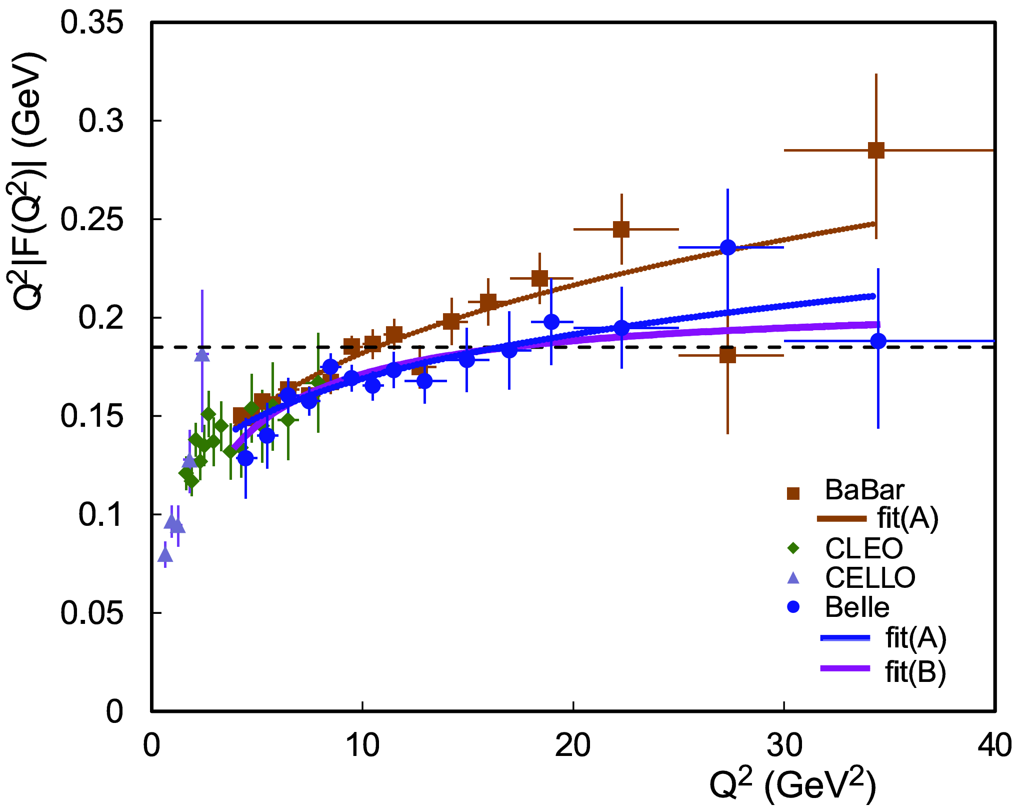
The asymptotic pion DA is $\phi_\pi^{\mathrm{asy}} = 6x(1-x)$, so that $Q^2 F(Q^2)$ at $Q^2 \to \infty$ is

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

Early measurements from CELLO and CLEO support this:

the asymptotic value is approached from below.

# Transition Form Factors - I ($\pi^0$)

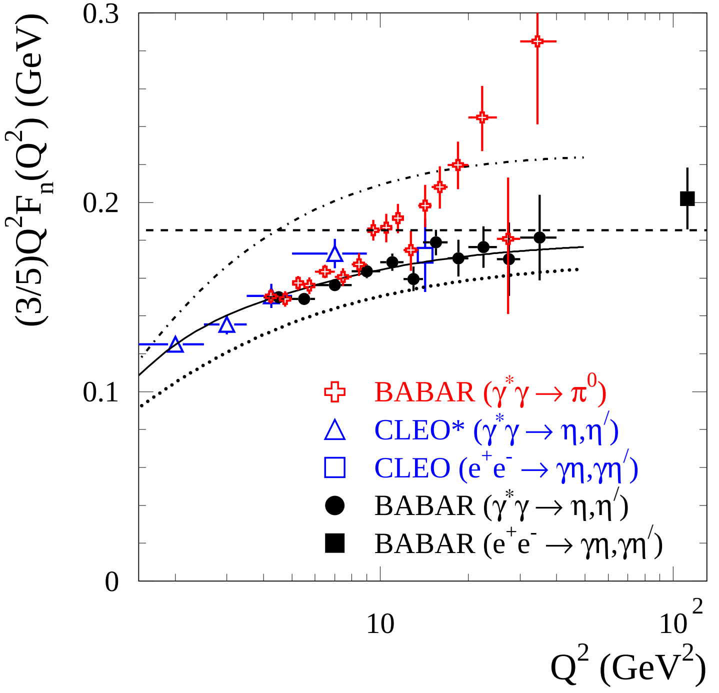



Belle data do not confirm fast rise observed at BaBar

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 - II ($\eta$, $\eta'$ and $\pi^0$)



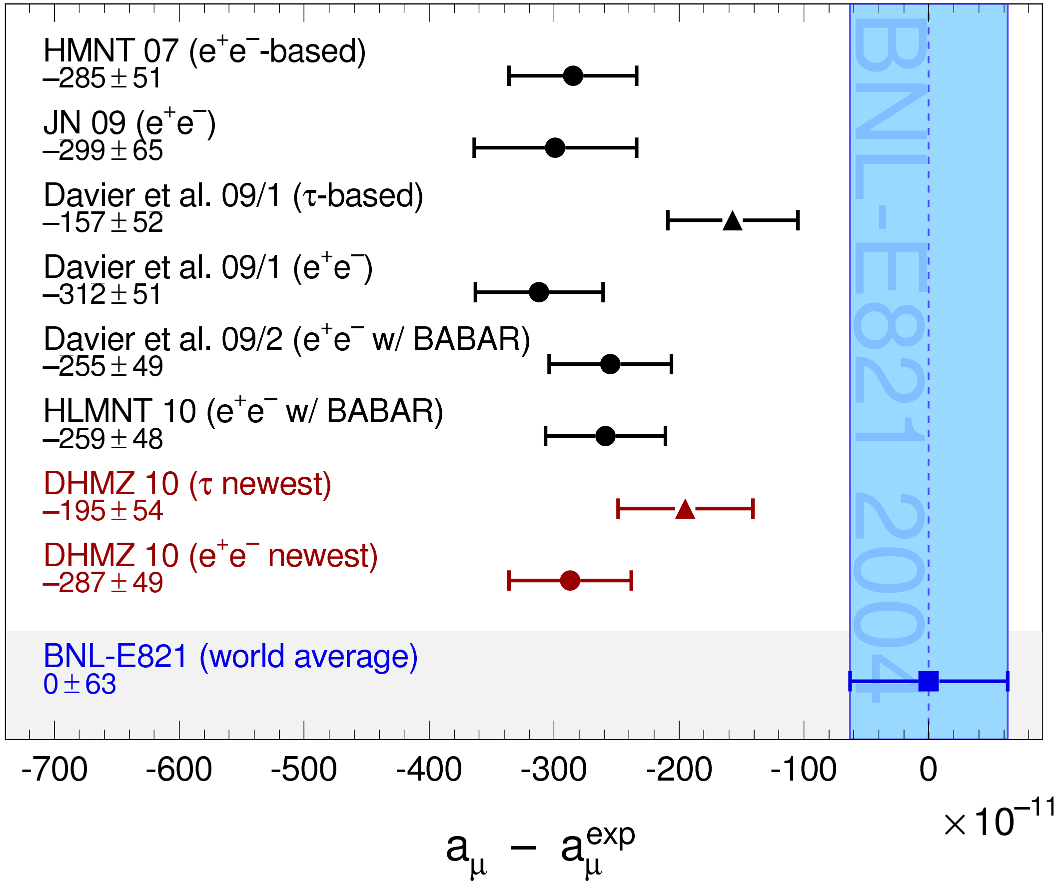

The $u$, $d$ part of the meson distribution amplitude,

$\eta$ 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

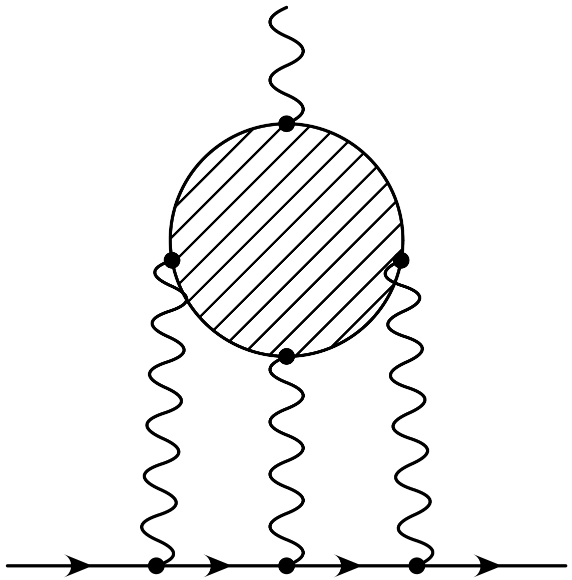
# Muon $\frac{(g-2)}{2}$ (Comparison to Experiment)




The difference between experiment and theory is (3.2-3.6)$\sigma$!

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

# Muon $\frac{(g-2)}{2}$ (Hadronic Light-by-Light – I)



Various approaches used:

- Vector Dominance and Chiral models
- Data on $\gamma\gamma^* \to \pi^0, \eta, \eta'$ (single-tag)
- QCD small-distance constraints
- Effective field theory
- Lattice

The "accepted" value is $(10.5 \pm 2.6) \cdot 10^{-10}$,

J. Prades, E. de Rafael and A. Vainshtein, arXiv:0901.0306

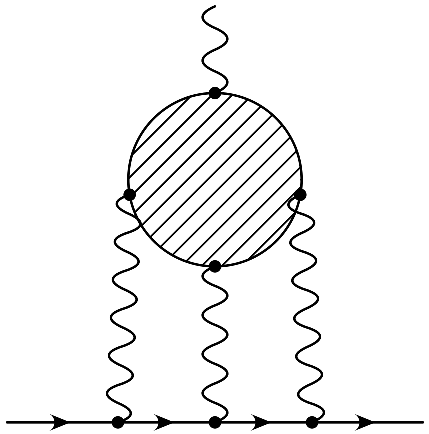
The uncertainty is already comparable to 4.2 of the leading-order term,

with the progress of $R$ measurements (VEPP-2000, BEPC-II, ISR) limitations arise

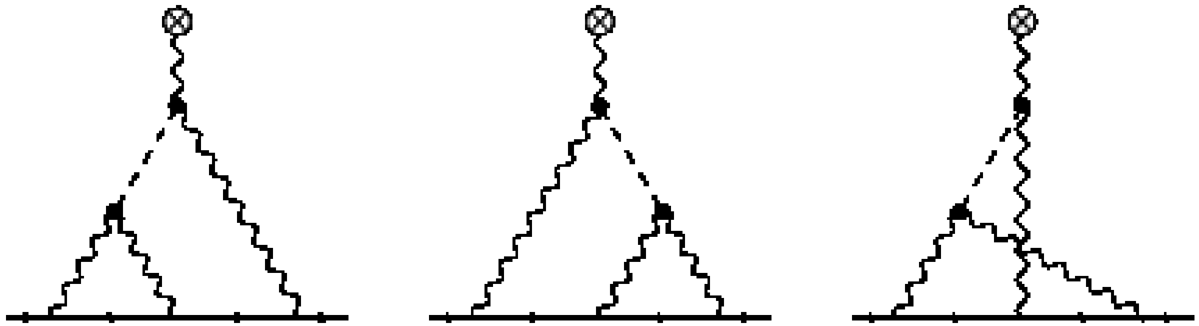
Experimental data on $\gamma\gamma \to$ hadrons and on transition form factors

studied in other processes are needed to model $\mathcal{F}(q_1^2, q_2^2)$

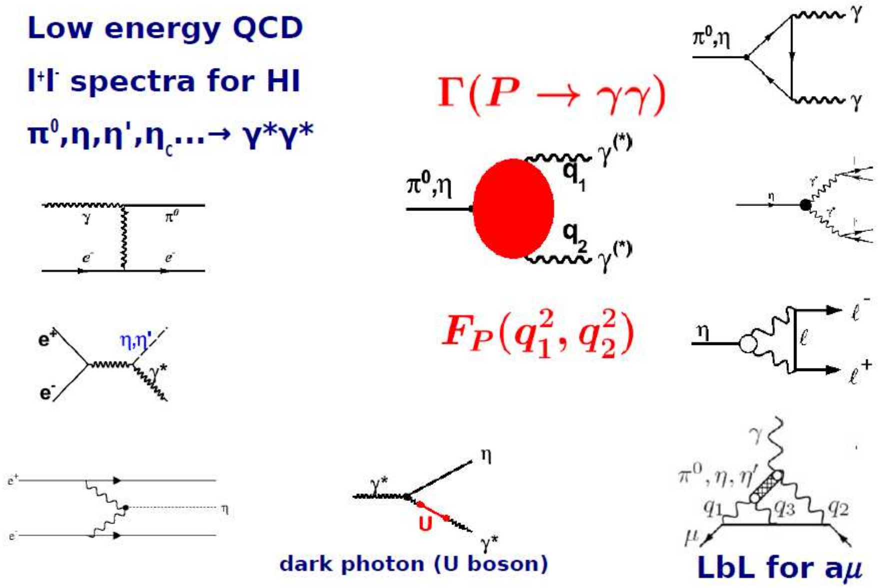
## Muon $\frac{(g-2)}{2}$ – IV (Hadronic Light-by-Light – II)



The main contribution is due to a single-meson exchange ($\pi^0$, $\eta$, $\eta'$)



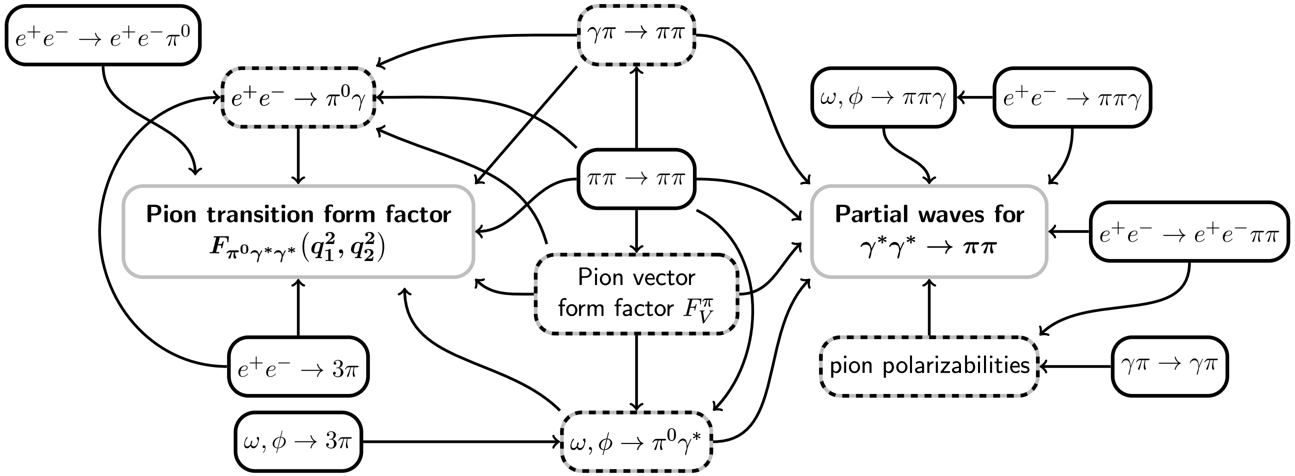
# Transition Form Factors - I (General)




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

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

# Transition Form Factors and Hadronic LbL




The new dispersive approach relates $a_\mu^{\mathrm{had,LbL}}$ to data:

G. Colangelo et al., JHEP 1409, 91 (2014), Phys. Lett. B 738, 6 (2014)

Also sum rules for TFF: V. Pascalutsa et al., Phys. Rev. D 85, 111601 (2012)

Measurements of various processes are in order

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

| Decay mode | $\mathcal{B}_{\text{exp}}$ | Events | Group | $\mathcal{B}_{\text{unit.bound}}$ |
|---|---|---|---|---|
| $\pi^0 \to e^+e^-$ | $(6.46 \pm 0.33) \cdot 10^{-8}$ | 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 | $3.75 \cdot 10^{-11}$ |
| $K_L^0 \to e^+e^-$ | $(9^{+6}_{-4}) \cdot 10^{-12}$ | 4 | B871, 1998 | $3.0 \cdot 10^{-12}$ |
| $K_L^0 \to \mu^+\mu^-$ | $(6.84 \pm 0.11) \cdot 10^{-9}$ | 6210 | B871, 2000 | $6.8 \cdot 10^{-9}$ |

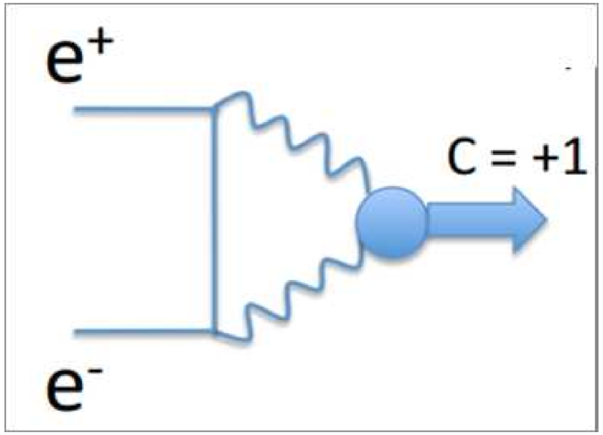
$\mathcal{B}$'s can be enhanced by photon virtuality and transition f/f

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

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

"Standard" mechanism via $e^+e^- \to e^+e^-P$ 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 $E_{\mathrm{c.m.}} \approx m_{\eta'} = 957.78 \pm 0.06$ 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 $6 \cdot 10^{-5}$

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 | $\sim 300$ | $198 \pm 9$ |
| $\mathcal{B}_{\eta' \to e^+e^-}, 10^{-8}$ | $< 21$ | $< 1.2$ |

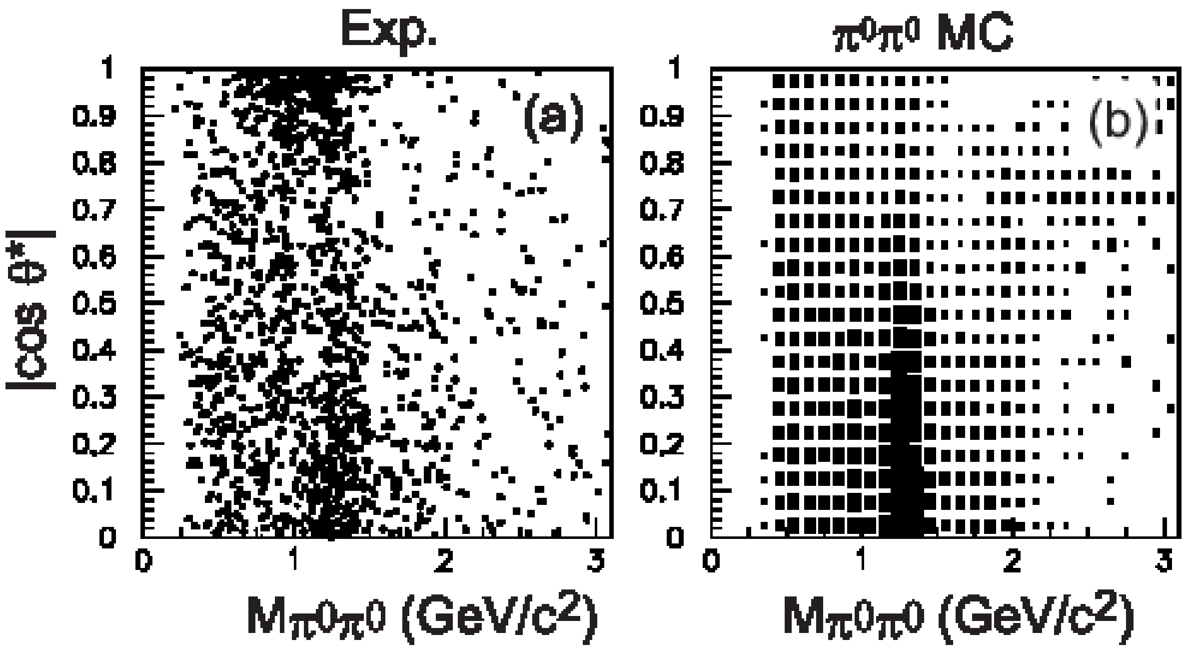
Much more stringent than that of ND, but
still 300 times higher than the unitarity bound

## 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



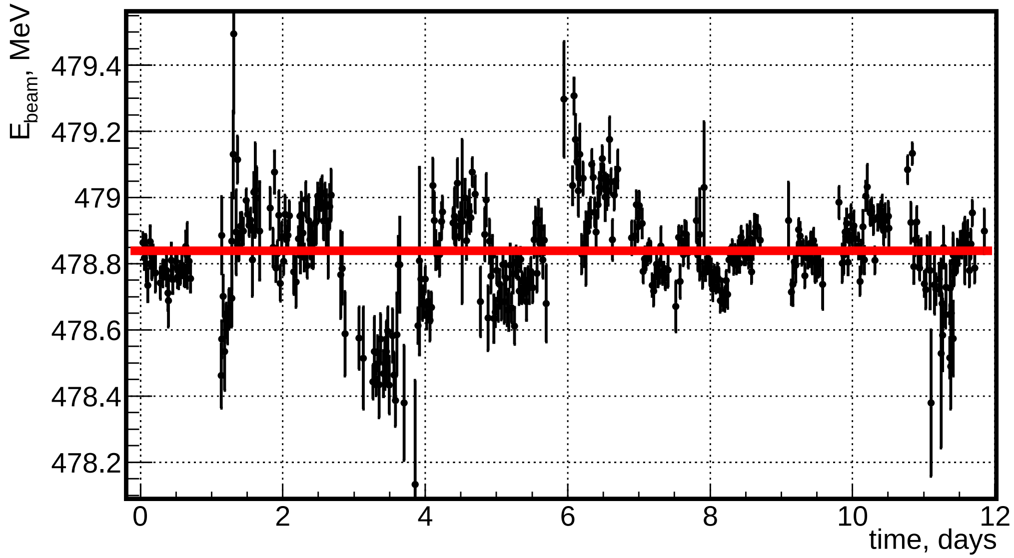
# Muon $\frac{(g-2)}{2}$ – I (Comparison to Experiment)

| Contribution | $a_\mu, 10^{-10}$ |
|---|---|
| Experiment | $11659208.9 \pm 5.4 \pm 3.3(6.3)_{\mathrm{tot}}$ |
| QED | $11658471.9 \pm 0.008$ |
| 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 | $11659180.2 \pm 4.9$ |
| Exp.–Theory | $28.7 \pm 8.0\ (3.6\sigma)$ |

The difference between experiment and theory is (3.2-3.6)$\sigma$!

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

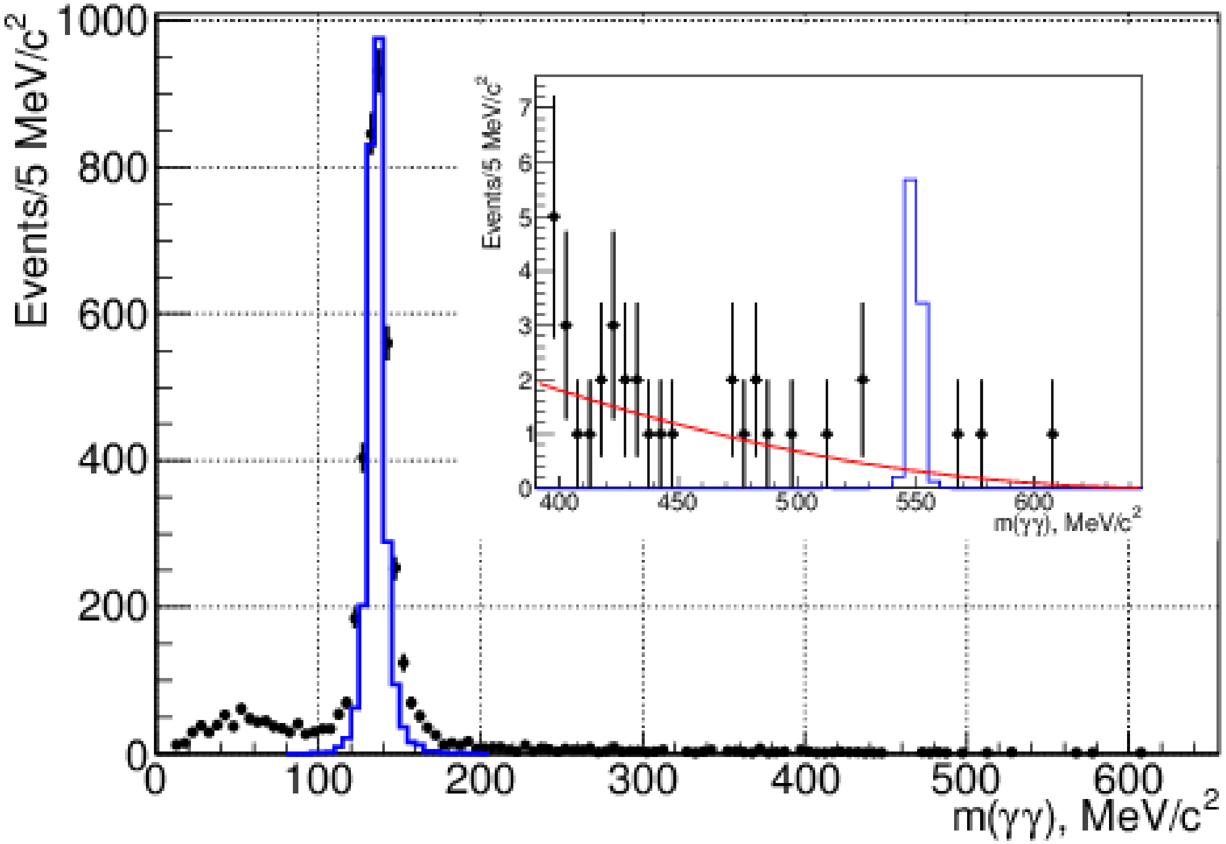
## $e^+e^- \to \eta' \to \eta\pi^+\pi^-$




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

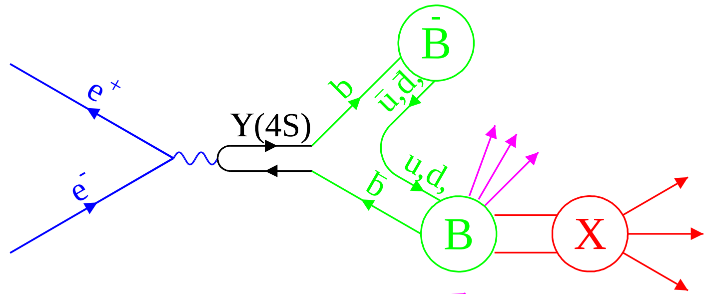
# Search for $e^+e^- \to \eta'$ with CMD-3 – III



# Particle Production at B Factories

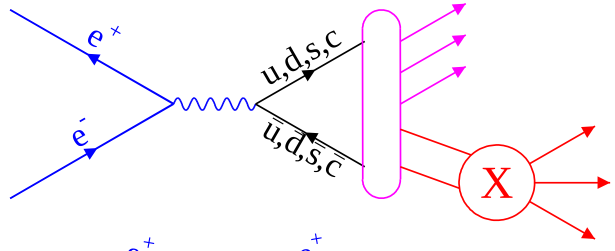
Production from B-decay

(broad $D^{**}$, $D_{sJ}$, $X(3872)$, $Y(3940)$)



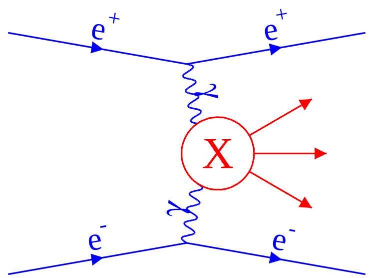

Production from continuum

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



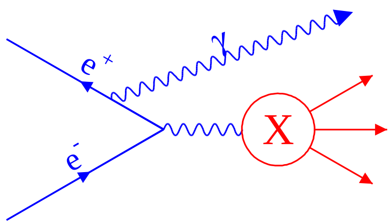

Two-photon production

($\eta_c(2S)$, $\chi_{c2}(2P)$)

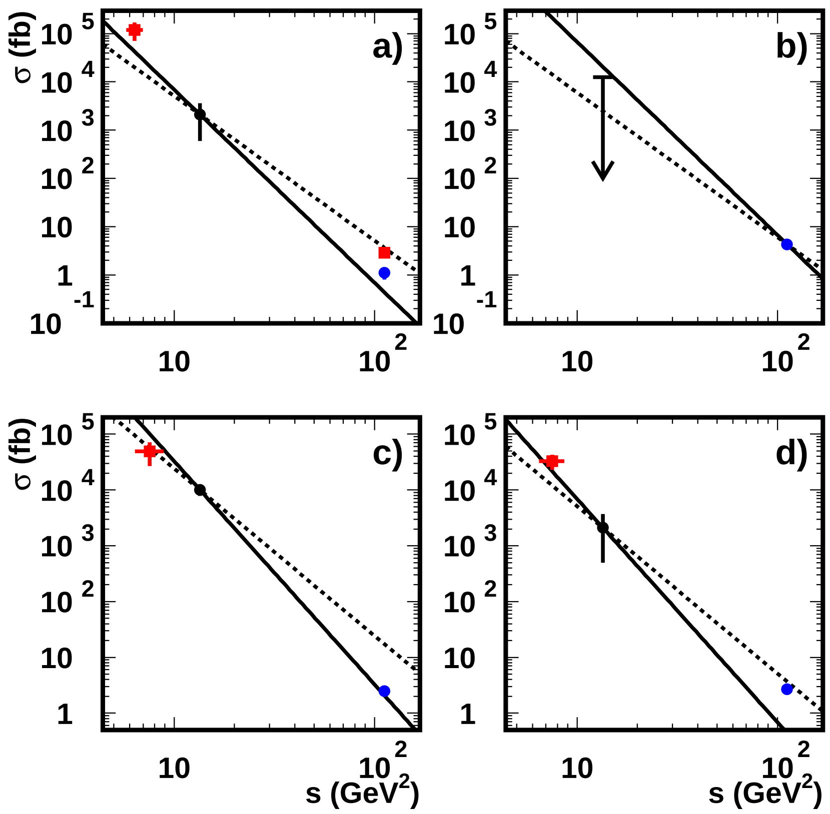



Initial state radiation

($Y(4260)$, $Y(4360)$, $Y(4660)$)



# $\gamma^* \to VP$ – 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

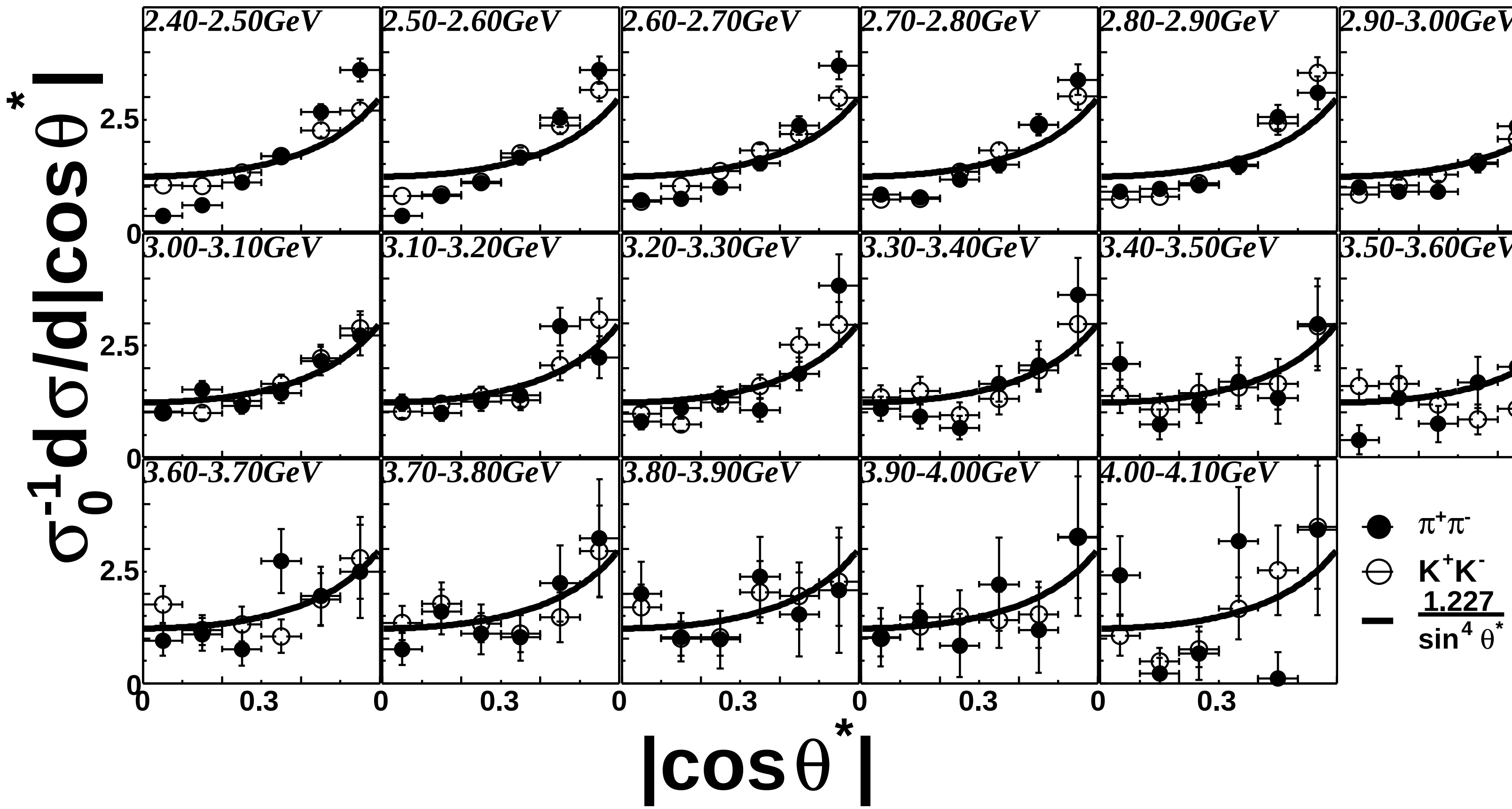
| Mode | Belle [3] | [4] | [5] | BaBar [2] |
|---|---|---|---|---|
| $\phi\eta$ | $1.4 \pm 0.4 \pm 0.1$ | 3.3-4.3 | 2.4-3.4 | $2.9 \pm 0.5 \pm 0.1$ |
| $\phi\eta'$ | $5.3 \pm 1.1 \pm 0.4$ | 4.4-5.8 | 3.5-5.0 | – |
| $\phi\eta$ | $3.1 \pm 0.5 \pm 0.1$ | 2.4-3.1 | 2.4-3.5 | – |
| $\phi\eta'$ | $3.3 \pm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

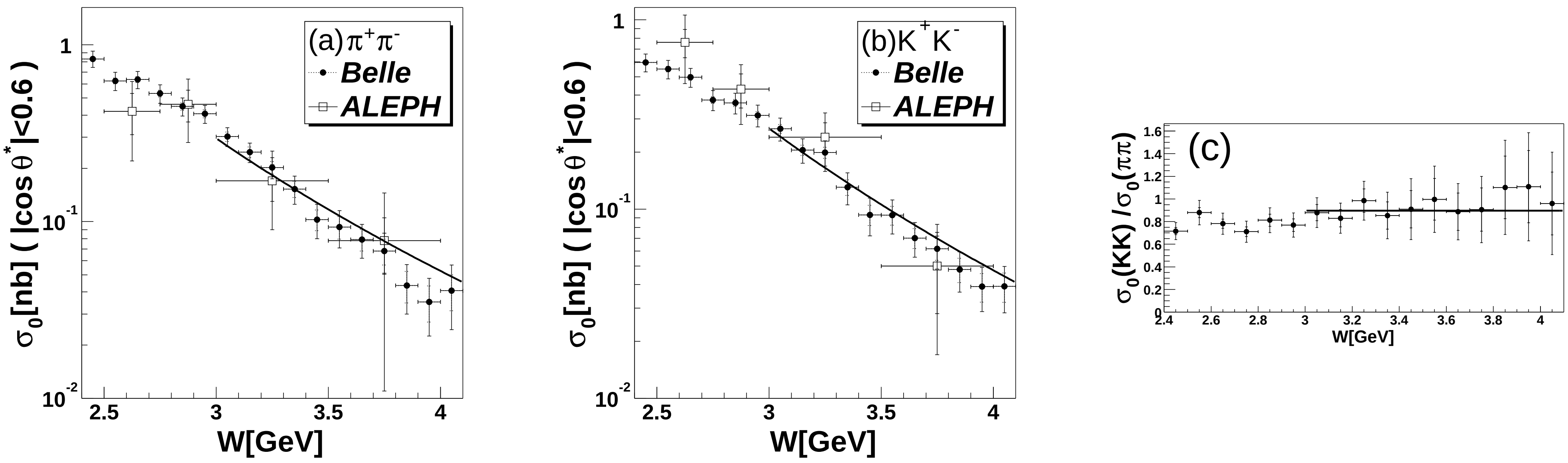
## $\gamma\gamma \to \pi^+\pi^-,\ K^+K^-$ – I

- 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)

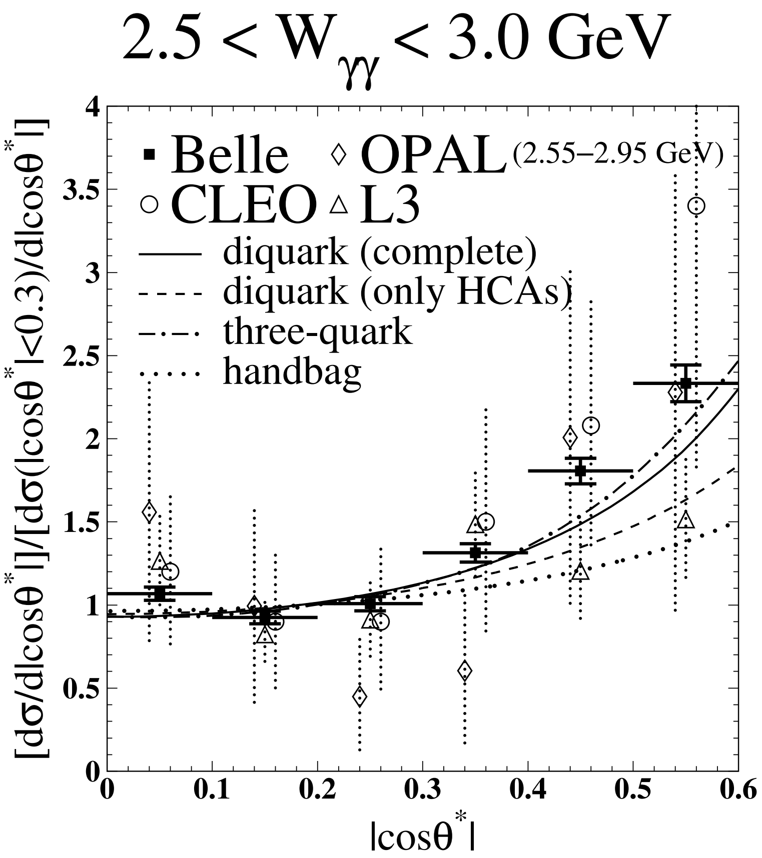
## $\gamma\gamma \to \pi^+\pi^-,\ K^+K^-$ – II

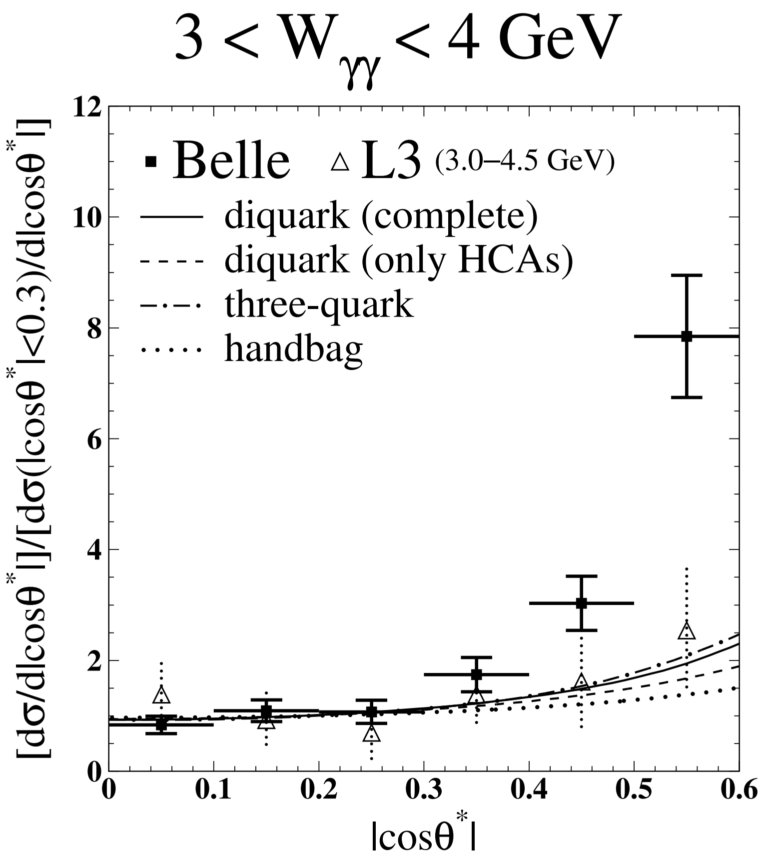


# $\gamma\gamma \to \pi^+\pi^-,\ K^+K^-$ – III



# $\gamma\gamma \to p\bar{p}$ – II

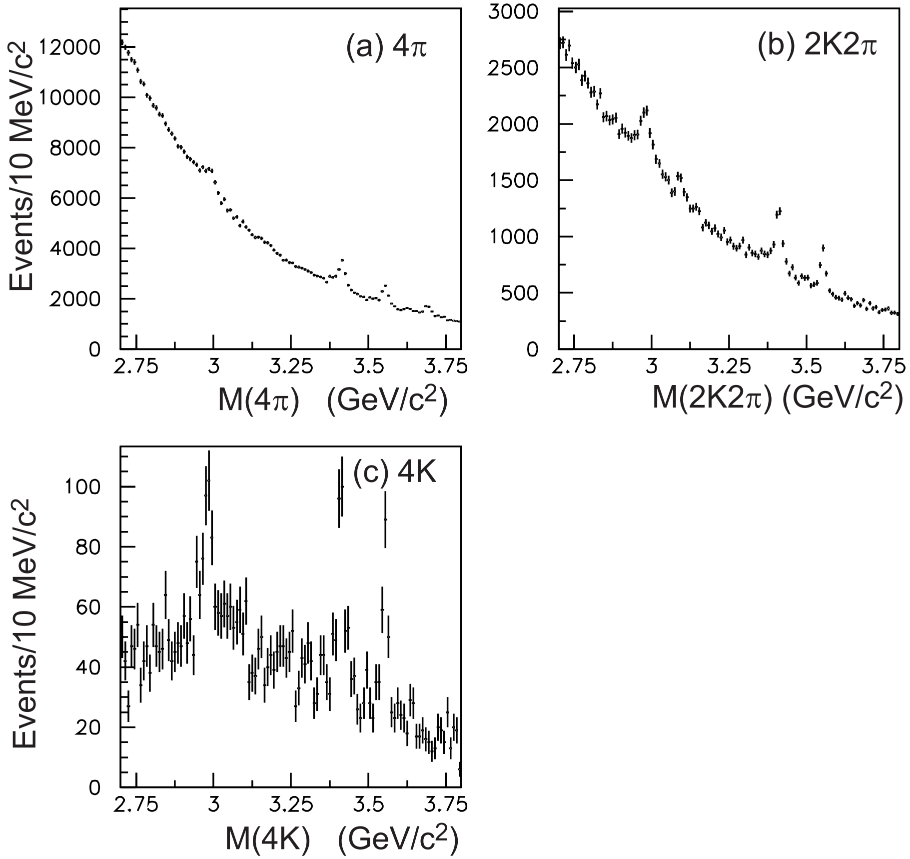



Power corrections are still significant

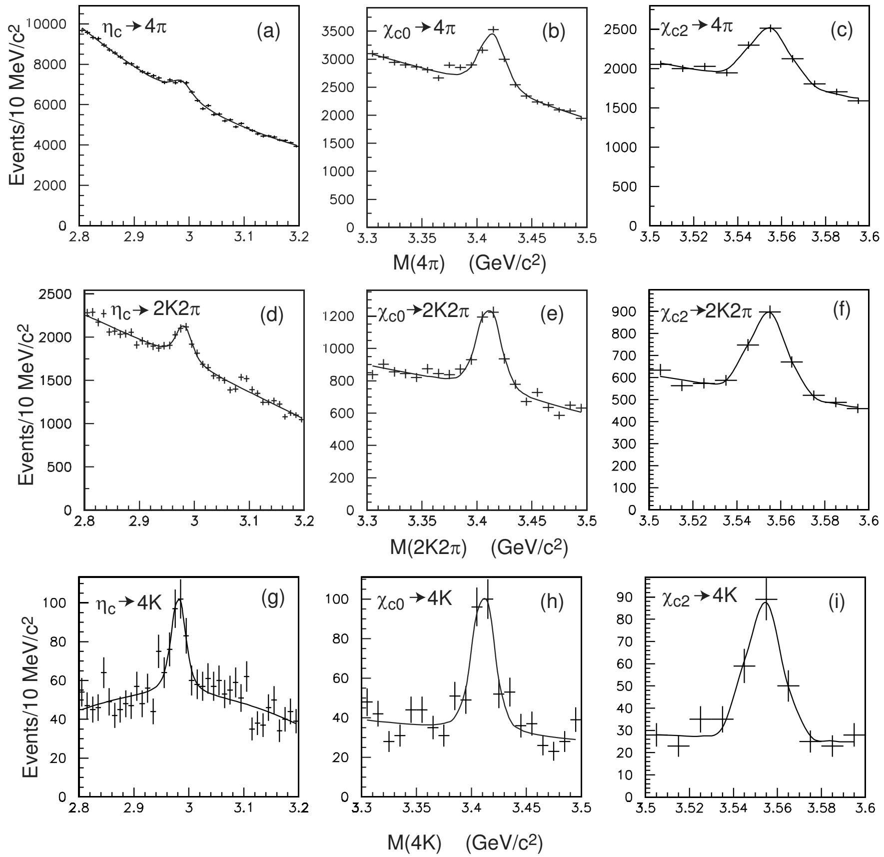
Diquark and handbag models need improvement

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

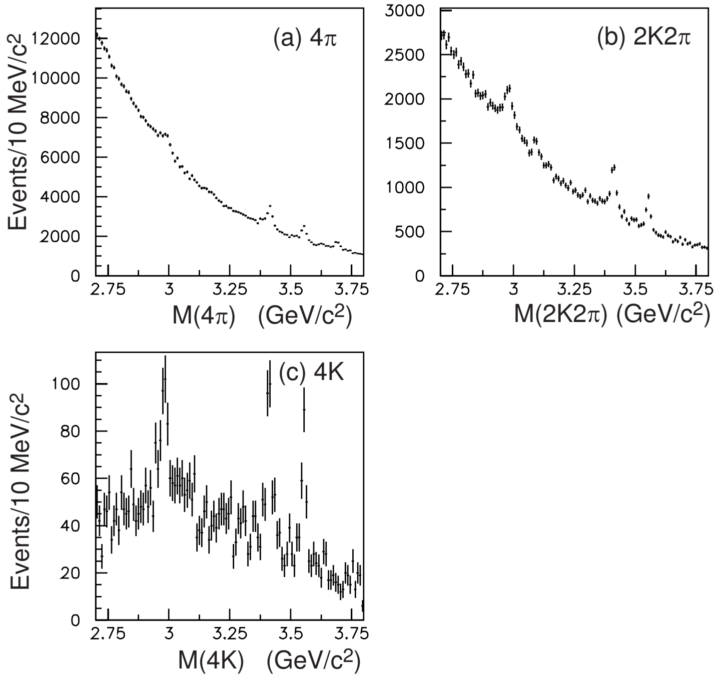



S. Uehara et al. (Belle Collab.), Eur. Phys. J. 53, 1 (2007)

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



# Four-prong Final States

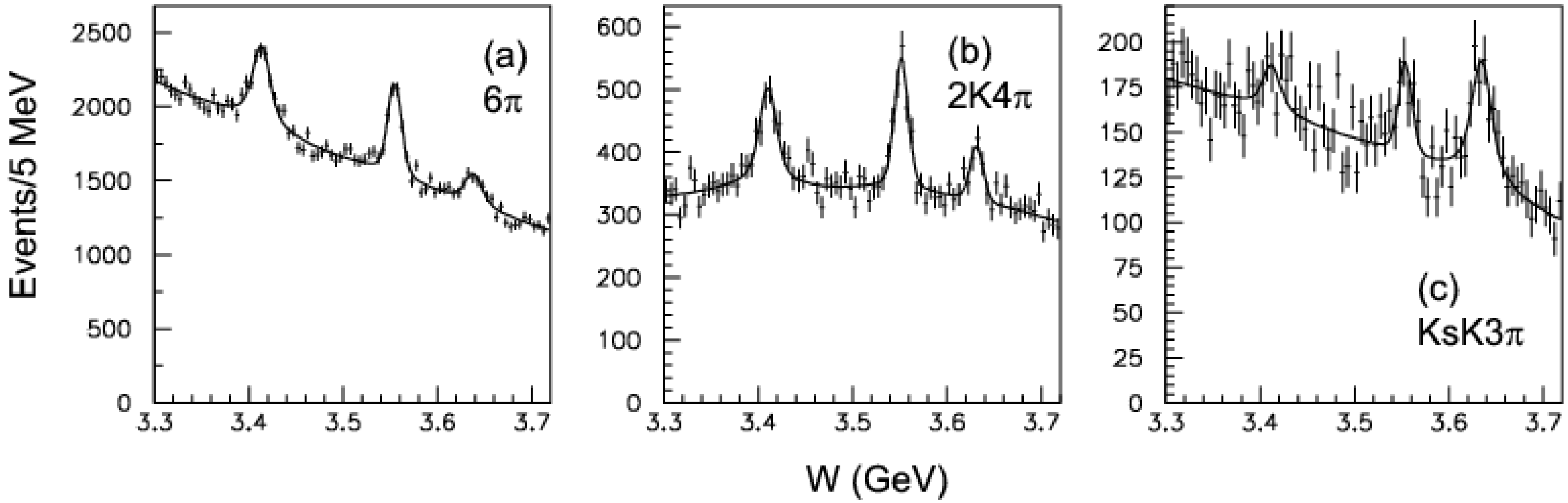



In each of the three final states – $2(\pi^+\pi^-)$, $\pi^+\pi^-K^+K^-$, $2(K^+K^-)$ – three charmonia – $\eta_c$, $\chi_{c0}$ and $\chi_{c2}$ are clearly seen

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$^{-1}$:

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

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

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

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

| Mode | $M$, MeV/$c^2$ | $\Gamma$, MeV | $N_{\rm ev}$ | S, $\sigma$ | $\Gamma_{\gamma\gamma}\mathcal{B}$, eV |
|---|---|---|---|---|---|
| $6\pi$ | $3638.9 \pm 1.6 \pm 2.3$ | $10.7 \pm 4.9$ | $1485 \pm 274$ | 8.5 | $20.1 \pm 3.7 \pm 3.2$ |
| $2K4\pi$ | $3634.7 \pm 1.6 \pm 2.8$ | $1.4^{+6.3}_{-1.4} (< 13)$ | $407 \pm 91$ | 6.2 | $10.2 \pm 2.3 \pm 3.4$ |
| $K_S K 3\pi$ | $3636.5 \pm 1.8 \pm 2.4$ | $15.9 \pm 5.7$ | $563 \pm 71$ | 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) | $1201 \pm 228$ | 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

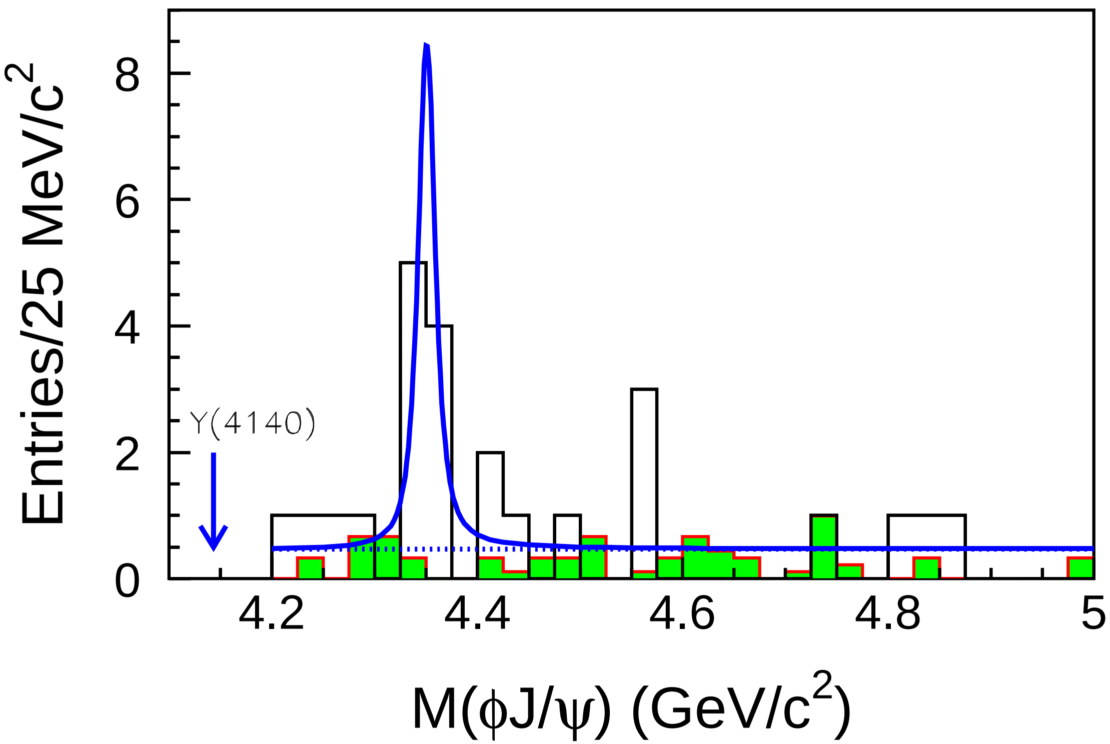
consistent with Belle results on $B^\pm \to K^\pm (K_S K\pi)^0$:

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

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

BaBar: P. del Amo Sanchez et al., Phys. Rev. D84, 012004 (2011)

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



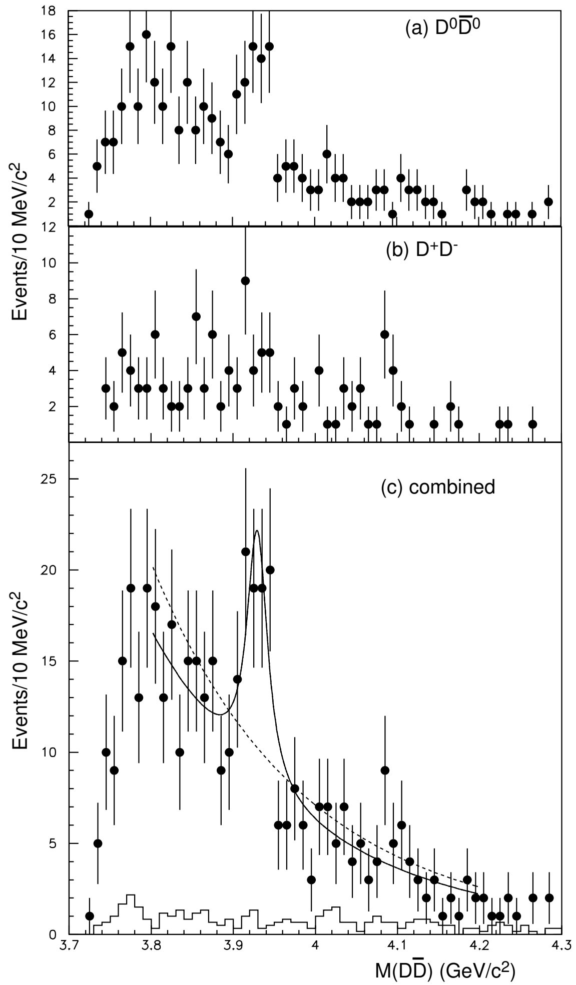

The $Y(4140)$ and $Y(4274)$ states of CDF not seen (also disproved by LHCb)

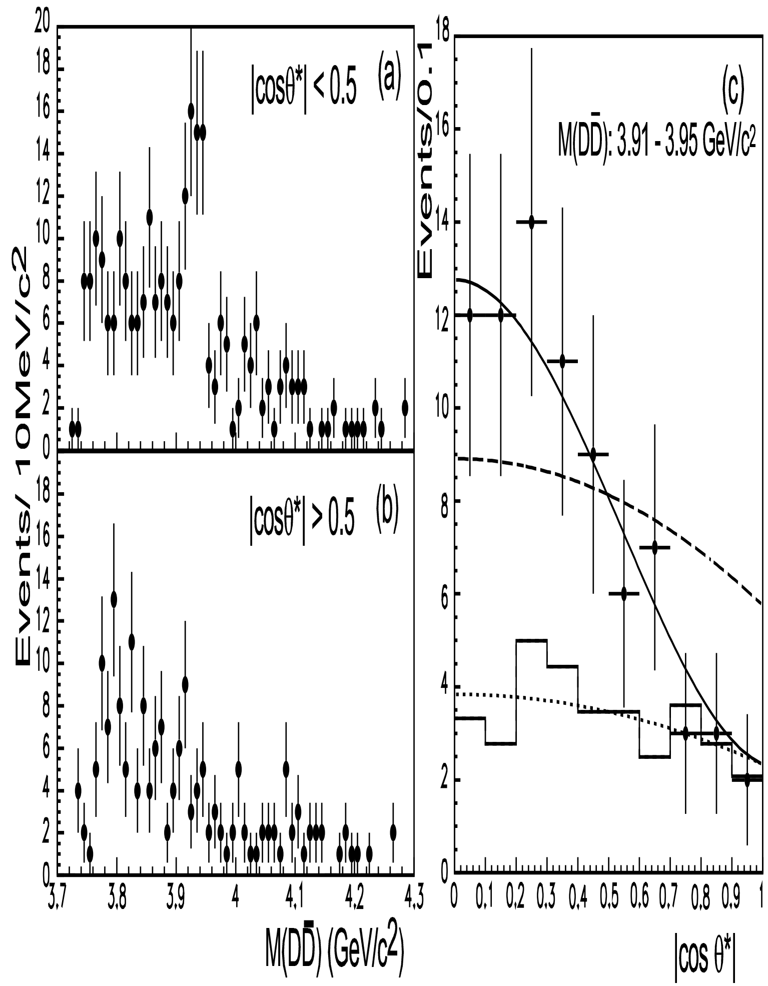
C.P. Shen et al., Phys. Rev. Lett..104, 112004 (2010)

## Observation of New Charmonium-like States at Belle

| Final state | $\int L dt$, 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) |

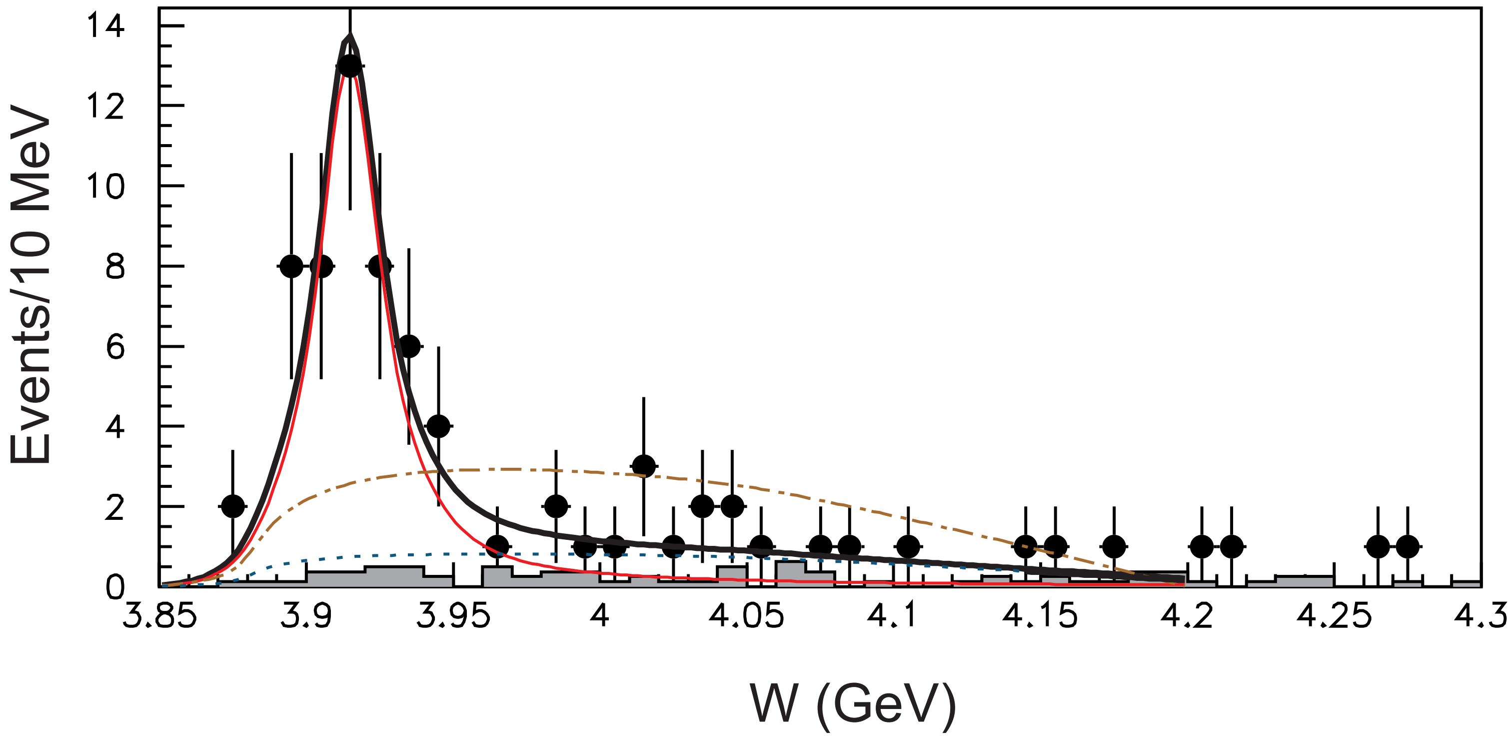
# $\gamma\gamma \to D^+D^-,\ D^0\bar{D}^0$ and $\chi_{c2}(2P)$




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

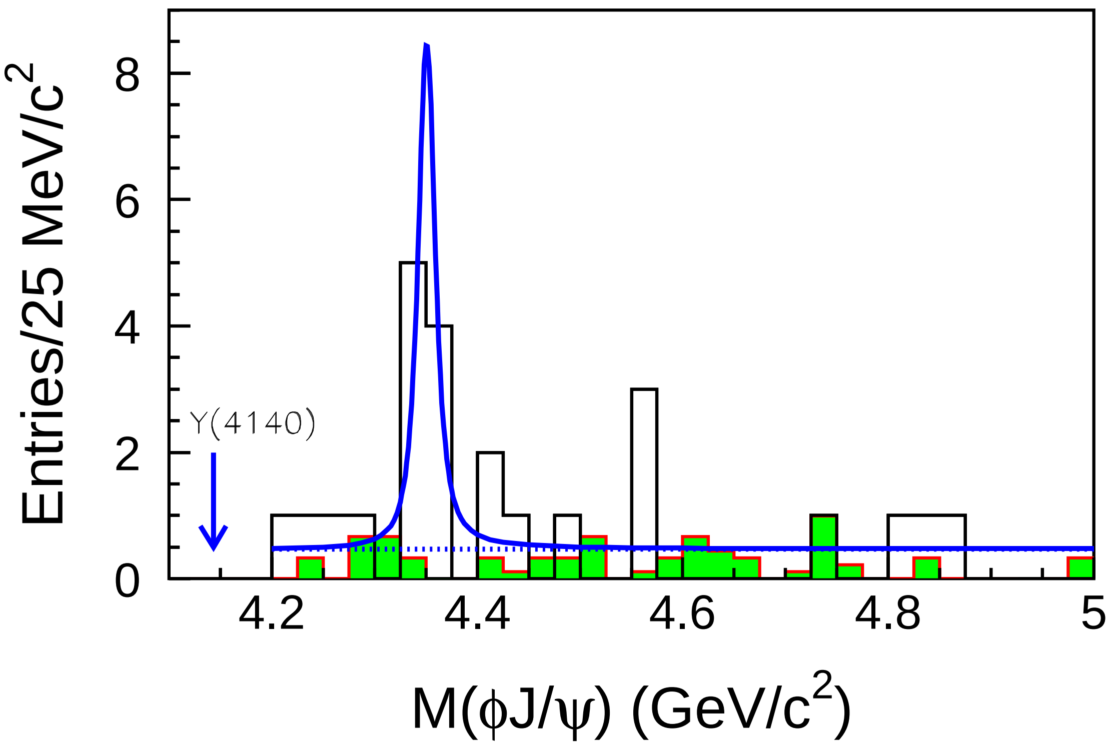
## $\gamma\gamma \to J/\psi\omega$




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