Light-quark mesons in two-photon processes at Belle

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Belle Collaboration

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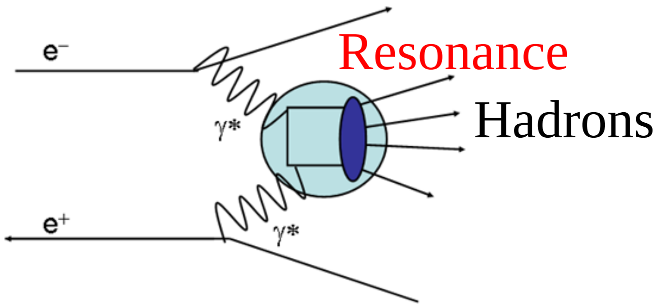
Resonance production and quantum numbers

Resonance formation from two photon collisions



Q = 0 , **C = +,**
for real-photon collisions
J^P= 0^+, 0^-, 2^+, 2^-, 3^+, 4^+, 4^-, 5^+ … **$(even)^{\pm}$, $(odd \neq 1)^+$**

This talk:
Pseudoscalar-meson pair production: J^P=$(even)^+$ only
Vector-meson pair production
$\eta'\pi^+\pi^-$ production

Strict constraints for quantum numbers →**Determination of J^P by PWA**
Quasi-real photon case, "Zero-tag": γ^* can be interpreted as a **real** γ
$\Gamma_{\gamma\gamma}$**:** The cross section is proportional to the two-photon partial decay width of the resonance, useful information to explore **meson's internal structure**

Decay properties of the resonance
Production of **isospin** ***I*=0** (f_J mesons) and ***I*=1** (a_J mesons)
Searches/Discoveries of **new resonances**
Form factors / Test of QCD

KEKB Accelerator and Belle Detector

- Asymmetric $e^- e^+$ collider

  8 GeV e^- (HER) x 3.5 GeV e^+ (LER)

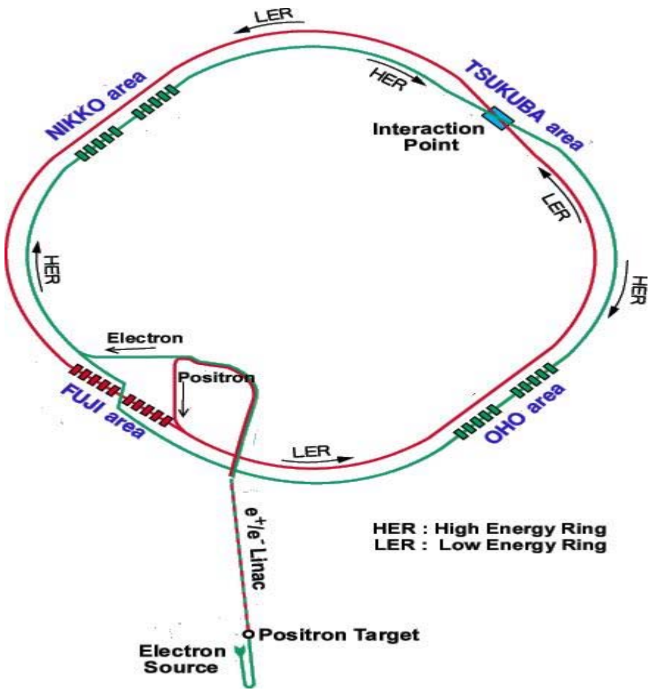
  $\sqrt{s}$= around 10.58 GeV ⇔ ϒ(4S)

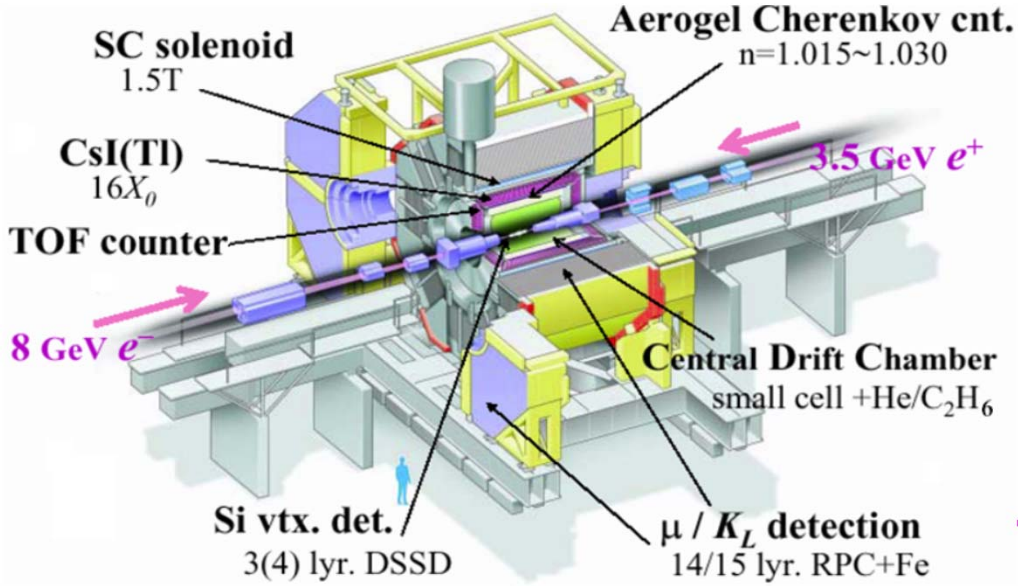
  Beam crossing angle: 22mrad

- World-highest Luminosity

  L_{max}=2.1x10^{34} cm^{-2}s^{-1}

  ∫ Ldt ~ 1040 fb^{-1} (Completed in Jun.2010)





High momentum/energy resolutions

CDC+Solenoid, CsI

Vertex measurement – Si strips

Particle identification

TOF, Aerogel, CDC-dE/dx,

RPC for K_L/muon

"$\gamma\gamma \to$ Pseudoscalar-meson pair" from Belle

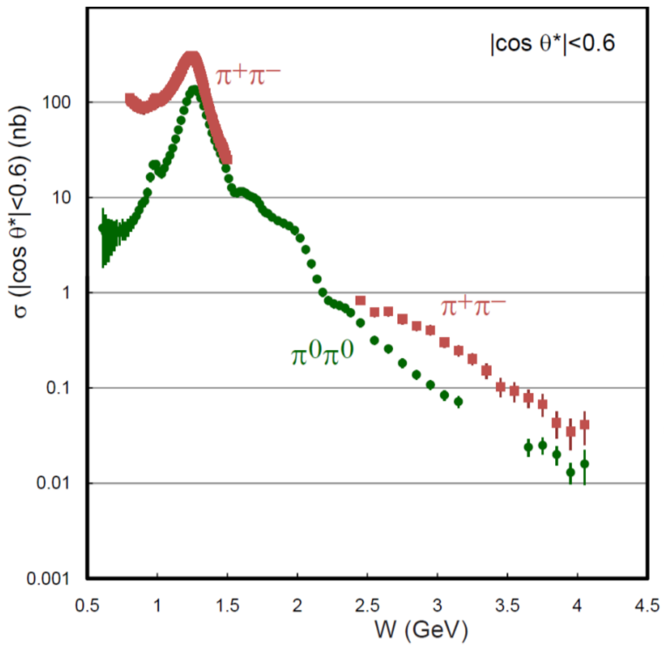
10 papers for 6 processes

Process	Reference	Int.Lum. (fb^{-1})	$\gamma\gamma$ c.m. Energy (GeV)	Light Mesons	QCD	Char-monia
$\pi^+\pi^-$	PLB 615, 39 (2005)	87.7	2.4 - 4.1		√	√
	PRD 75, 051101(R) (2007)	85.9	0.8 - 1.5	√		
	J. Phys. Soc. Jpn. 76, 074102 (2007)	85.9	0.8 – 1.5	√		
K^+K^-	EPJC 32, 323 (2003)	67	1.4 – 2.4	√		
	PLB 615, 39 (2005)	87.7	2.4 – 4.1		√	√
$\pi^0\pi^0$	PRD 78, 052004 (2008)	95	0.6 – 4.0	√		
	PRD 79, 052009 (2009)	223	0.6 – 4.0	√	√	√
$K^0_S K^0_S$	PLB 651, 15 (2007)	397.1	2.4 – 4.0		√	√
	PTEP 2013, 123C01 (2013)	972	1.05 – 4.0	√	√	√
$\eta\pi^0$	PRD 80, 032001 (2009)	223	0.84 – 4.0	√	√	
$\eta\eta$	PRD 82, 114031 (2010)	393	1.1 – 3.8	√	√	√

Differential cross section **$d\sigma/d|\cos\theta^*|$** for these processes are measured.

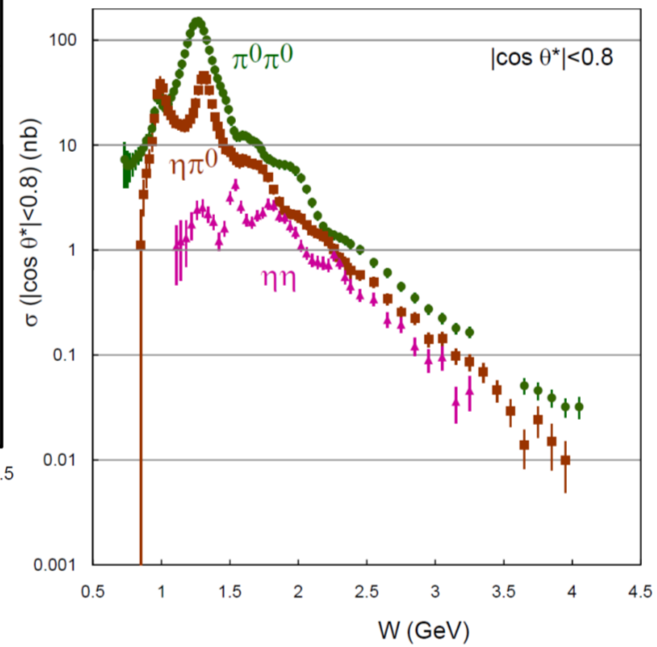
The six processes; in total ~20 peaks

Charged vs Neutral $\pi\pi$

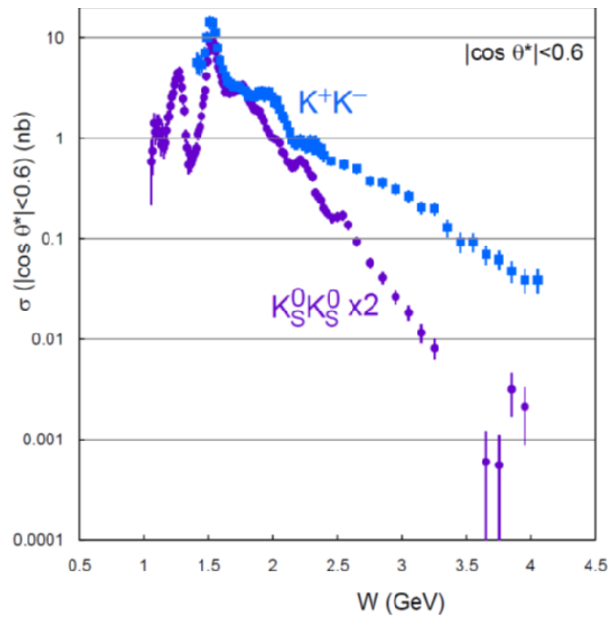


Three neutral-pair processes

$\pi^0\pi^0$, $\eta\pi^0$, $\eta\eta$



Charged vs Neutral $K\bar{K}$



- PWA Formalism
- f_0(980) and a_0(980)
- Tensor mesons f_2(1270), a_2(1320), f_2'(1525)
- Scalars in 1.2 – 1.6 GeV
- 1.6 – 1.8 GeV region
- 1.8 – 2.2 GeV region
- 2.2 – 2.6 GeV region

Horizontal axis:

W -- $\gamma\gamma$ c.m. energy = invariant mass of the two-meson system

Formalism of PWA for P-meson pair final-state processes

- We consider up to J=4 (for W < 3 GeV).

$$\frac{d\sigma}{d\Omega} = \left| S Y_0^{\ 0} + D_0 Y_2^{\ 0} + G_0 Y_4^{\ 0} \right|^2 + \left| D_2 Y_2^{\ 2} + G_2 Y_4^{\ 2} \right|^2$$

- S, D_0, G_0, D_2 , G_2 Partial-wave amplitudes for each wave J_λ

  J = *L* = 0, 2, 4 (even only) with the helicity λ = 0 or 2 (to the $\gamma\gamma$ axis)

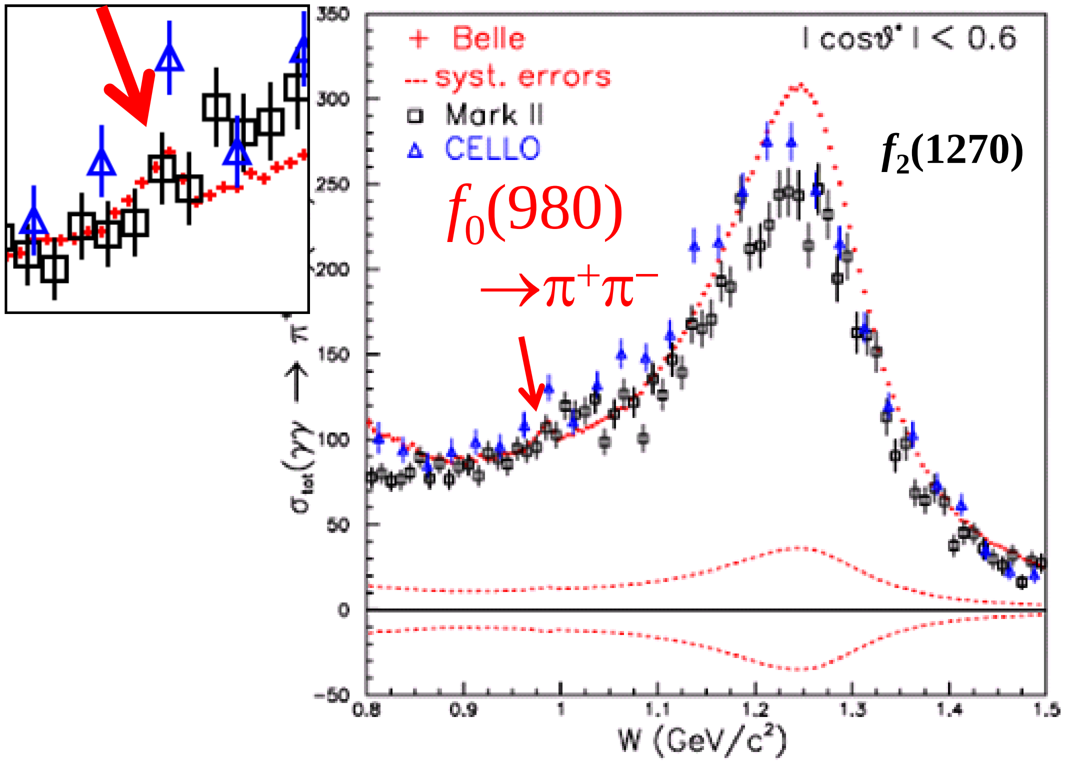
  - Y_J^λ : spherical harmonics
  - $|Y_J^\lambda|$ are NOT mutually independent, as we have no information for the azimuthal-angle direction.

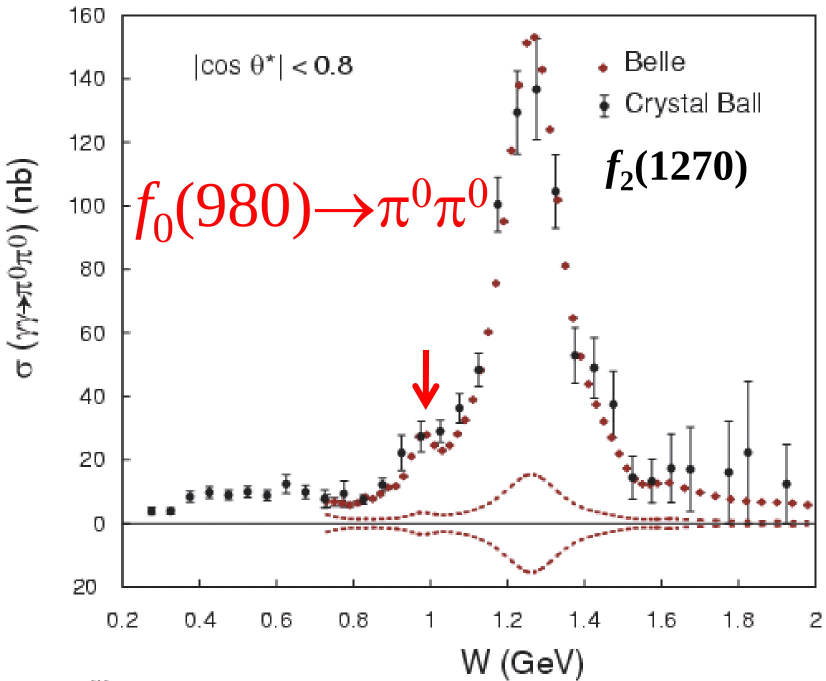
- We cannot determine the partial waves model independently;
  We need **parameterization** based on a model including the W dependence of resonances and continuum components.
- Ancillary model-independent way: **Hat amplitudes;** $\left| Y_J^{\ m} \right|^2$ mutually independent

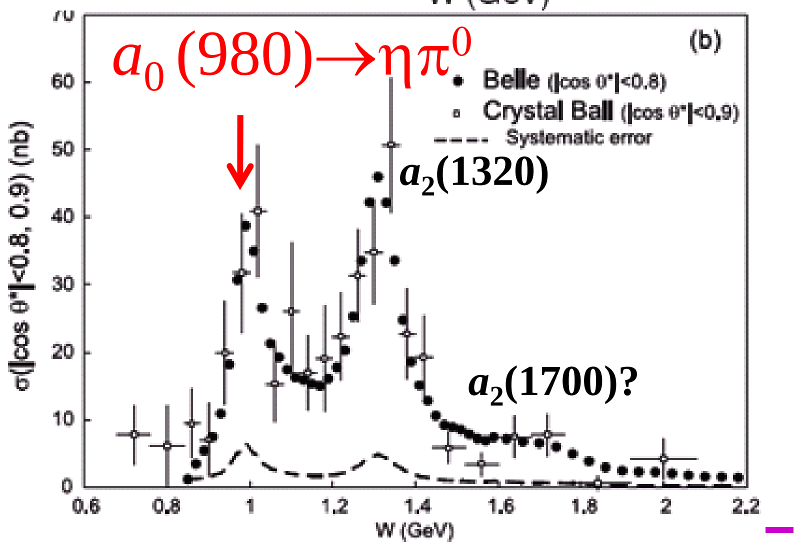
$$\frac{d\sigma}{d\Omega} = \hat{S}^2 \left| Y_0^{\ 0} \right|^2 + \hat{D}_0^{\ 2} \left| Y_2^{\ 0} \right|^2 + \hat{G}_0^{\ 2} \left| Y_4^{\ 0} \right|^2 + \hat{D}_2^{\ 2} \left| Y_2^{\ 2} \right|^2 + \hat{G}_2^{\ 2} \left| Y_4^{\ 2} \right|^2$$

Confirmations of f_0(980) and a_0(980) formations

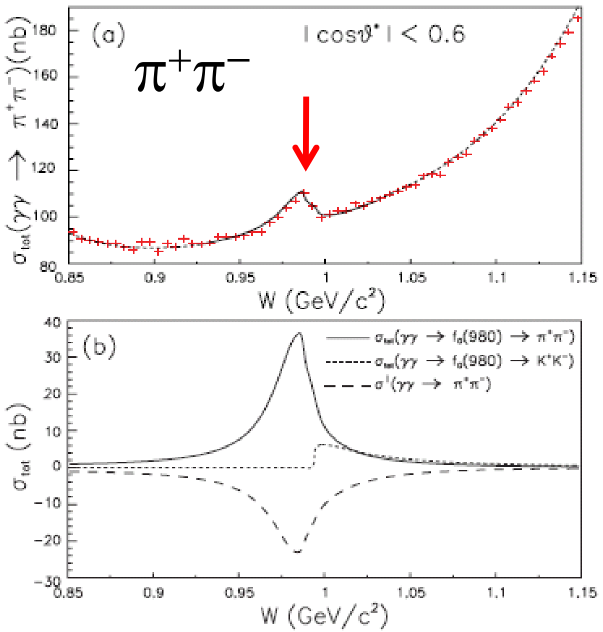
f_0(980) and a_0(980) :
Observed as a peak very clearly in two-photon production, for the first time.

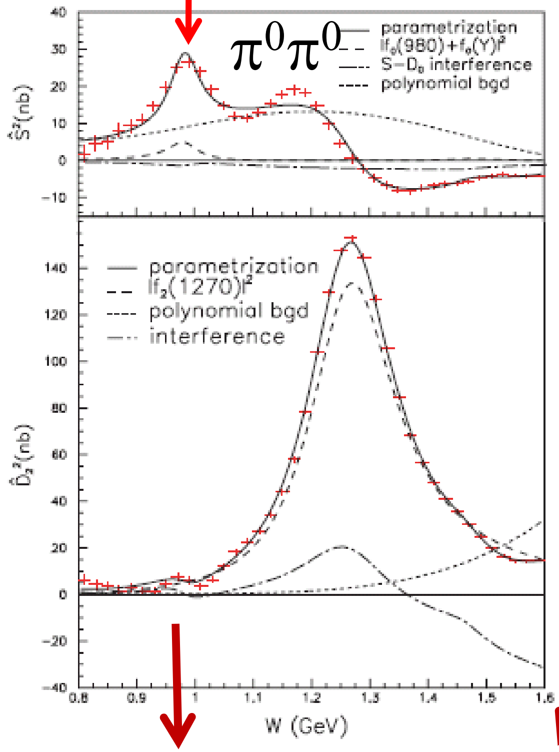


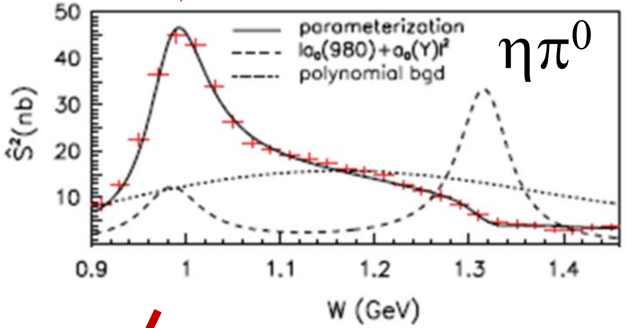




Two-photon decay width of $f_0(980)$ and $a_0(980)$







Meson	$f_0(980)$	$f_0(980)$	$a_0(980)$
M[MeV/c²]	$985.6^{+1.2+1.1}_{-1.5-1.6}$	$982.2\pm1.0^{+8.1}_{-8.0}$	$982.3^{+0.6+3.1}_{-0.7-4.7}$
$\Gamma_{\pi\pi/tot}$[MeV]	$51.3^{+20.9+13.2}_{-17.7-3.8}$	$66.9^{+13.9+8.8}_{-11.8-2.5}$	(Γtot) $75.6\pm1.6^{+17.4}_{-10.0}$
$\Gamma_{\gamma\gamma}$[eV]	$205^{+95+147}_{-83-117}$	$286\pm17^{+211}_{-70}$	$128^{+3+502}_{-2-43}/\mathcal{B}_{\pi^0\eta}$

Predictions for $f_0(980)$

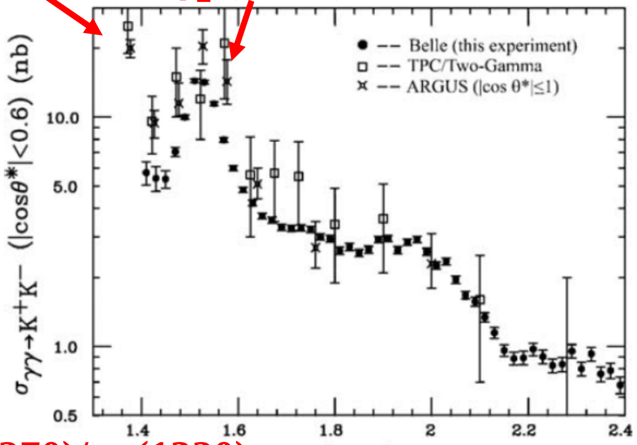
Model	$\Gamma_{\gamma\gamma}$ [eV]
*uu*bar,*dd*bar	1300 – 1800
*ss*bar	300 – 500
*KK*bar molecule	200 – 600
Four-quark	270

$f_2(1270)$-$a_2(1320)$ interference in $K\overline{K}$

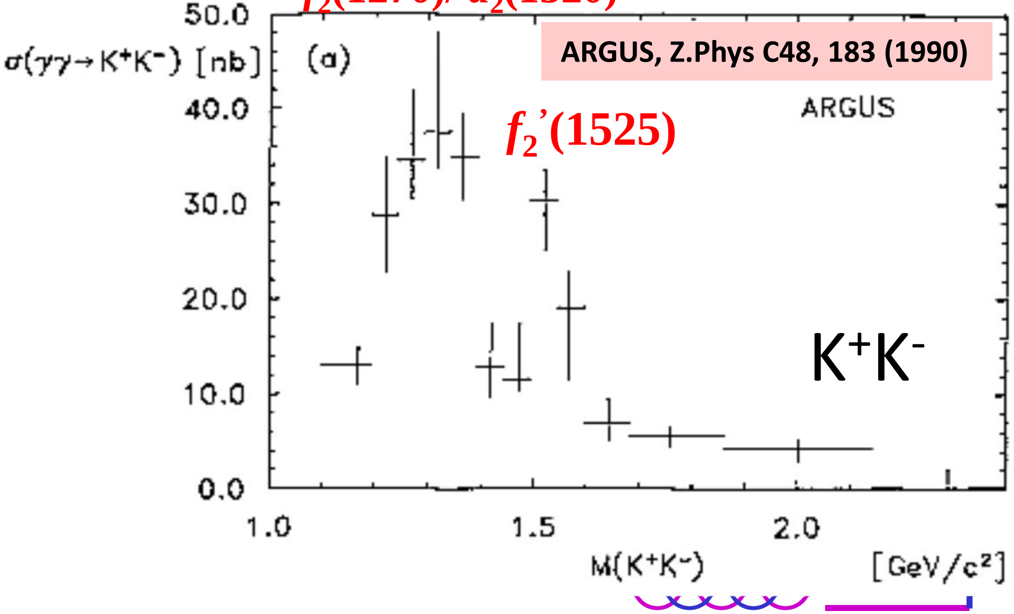
$f_2(1270)$/ $a_2(1320)$ $f_2'(1525)$

K^+K^-

Peak(~1300) >
Peak ($f_2'(1525)$)



$f_2(1270)$/ $a_2(1320)$



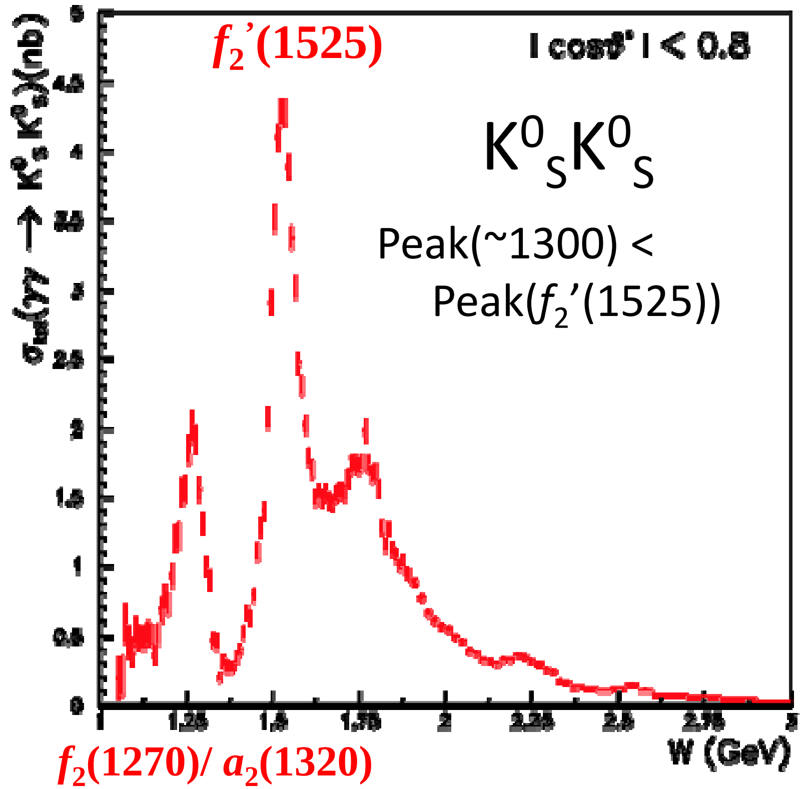
Constructive interference

$f_2(1270)$+$a_2(1320)$ in K^+K^-

Destructive interference

$f_2(1270)$-$a_2(1320)$ in $K^0_SK^0_S$

Explained by a phase relation in isospin composition



Scalars in the 1.2 – 1.6 GeV region

- Hadron experiments report a wide $f_0(1370)$ and a narrow $f_0(1500)$.
- Some of previous two-photon measurements provide a hint of $f_0(1100\text{-}1400) \to \pi\pi$ under the huge peak of $f_2(1270)$
- Belle's $\pi^0\pi^0$ measurement reports $f_0(1470)$.

  May be visible in the line shape.

  $\to$ favorable to the narrow ***f_0(1500)***, but also consistent with $f_0(1370)$.

$f_0(1370)$ [j] $\quad I^G(J^{PC}) = 0^+(0^{++})$

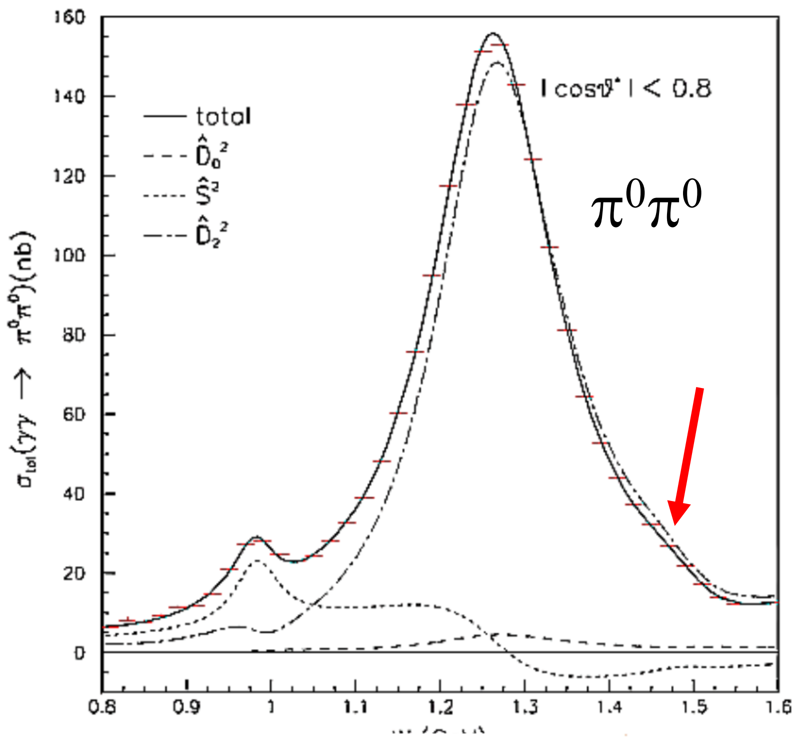
Mass m = 1200 to 1500 MeV
Full width Γ = 200 to 500 MeV

$f_0(1370)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\pi\pi$	seen	672

$f_0(1500)$ [n] $\quad I^G(J^{PC}) = 0^+(0^{++})$

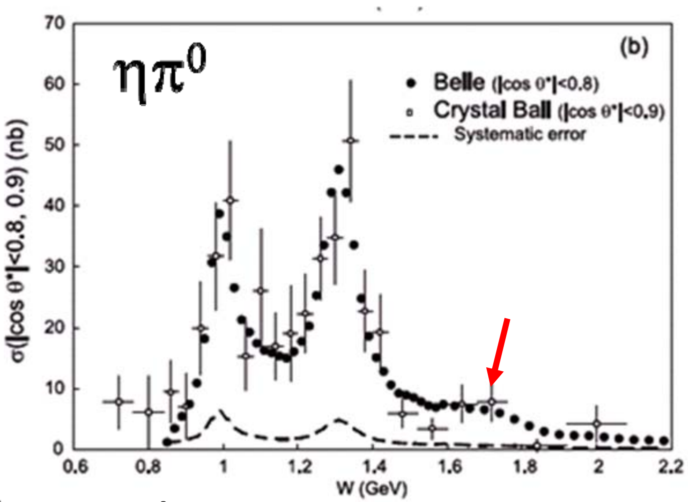
Mass $m = 1505 \pm 6$ MeV (S = 1.3)
Full width $\Gamma = 109 \pm 7$ MeV

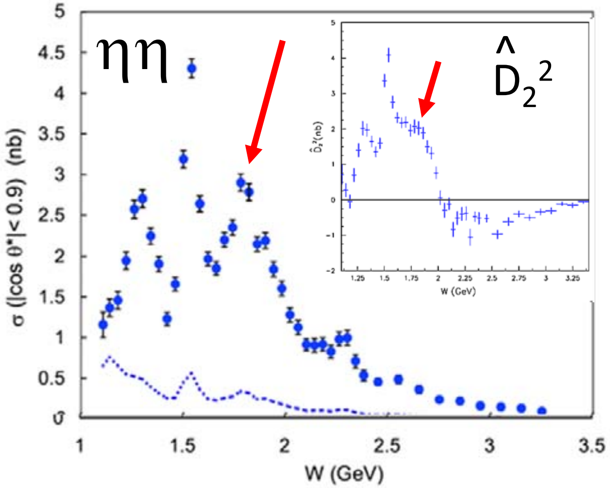
$f_0(1500)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor	p (MeV/c)
$\pi\pi$	(34.9±2.3) %	1.2	741

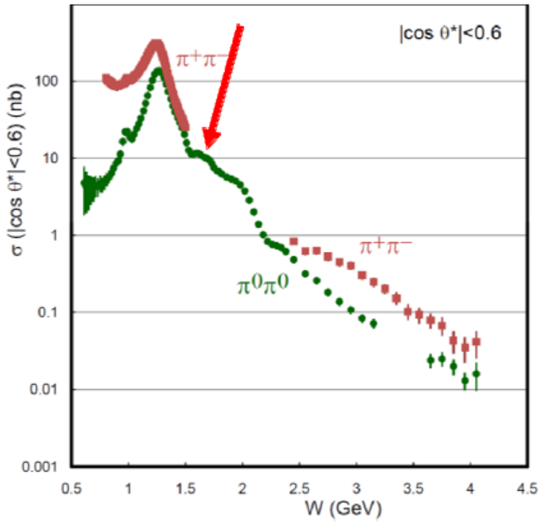


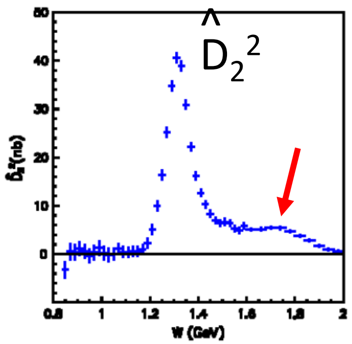
Parameter	Belle ($\pi^0\pi^0$)	Crystal Ball	Unit
Mass	1470^{+6+72}_{-7-255}	1250	MeV/c^2
Γ_{tot}	90^{+2+50}_{-1-22}	268 ± 70	MeV
$\Gamma_{\gamma\gamma}\mathcal{B}(\pi^0\pi^0)$	11^{+4+603}_{-2-7}	430 ± 80	eV

1.6 – 1.8 GeV: Mass region of the greatest difficulty



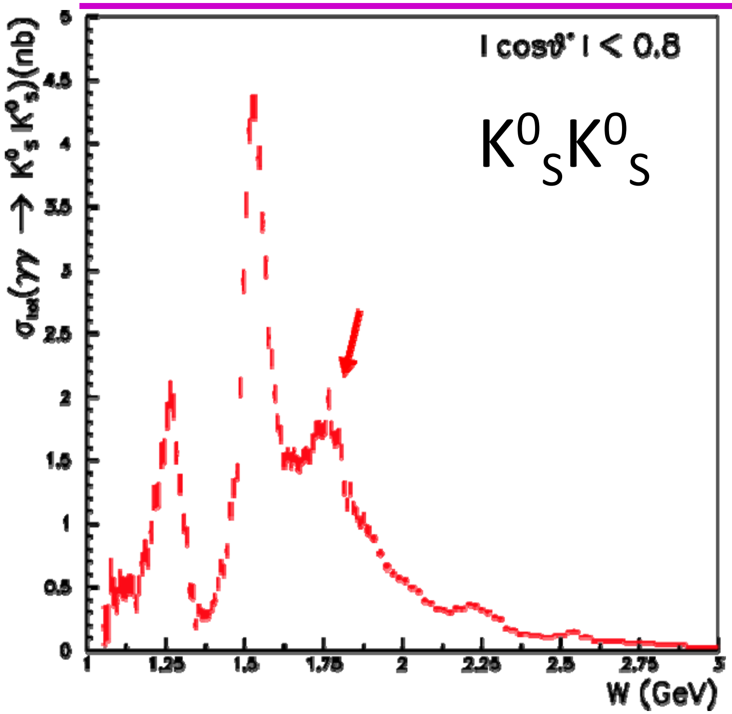


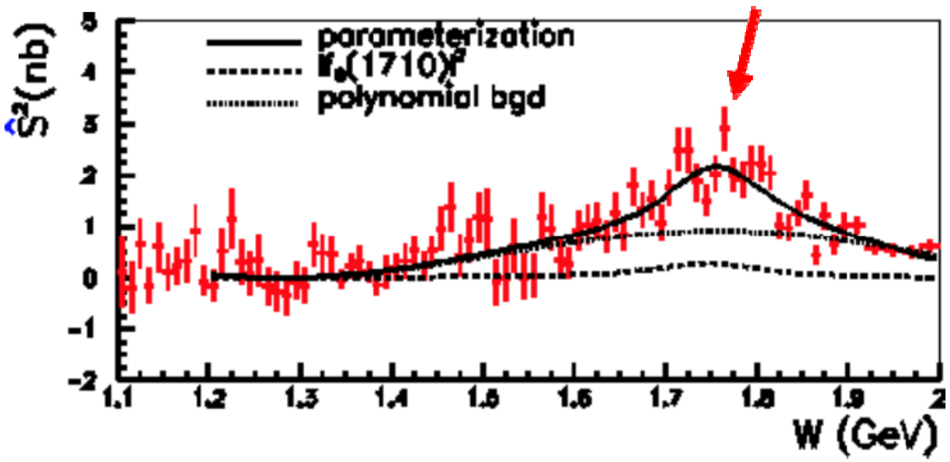




- Extensive studies are performed in the radiative decays of J/ψ ($\to \gamma gg \to \gamma R$).
- $a_2(1700) \to \rho^0\pi^0 \to \pi^+\pi^-\pi^0$ is confirmed by previous two-photon measurements.
- $a_2(1700) \to \eta\pi^0$ seen in our data, but no definite parameters obtained.
- $f_2(1810) \to \eta\eta$ is confirmed in two-photon process.
- An unidentified structure around ~1.6 GeV is seen in $\pi^0\pi^0$. But, its correspondence to a single resonance of the mass is not sure.

$f_0(1710)$ formation in $K^0_S K^0_S$





Assuming a single resonance,
J = 0 or 2 ? **J = 0 is much preferred.**

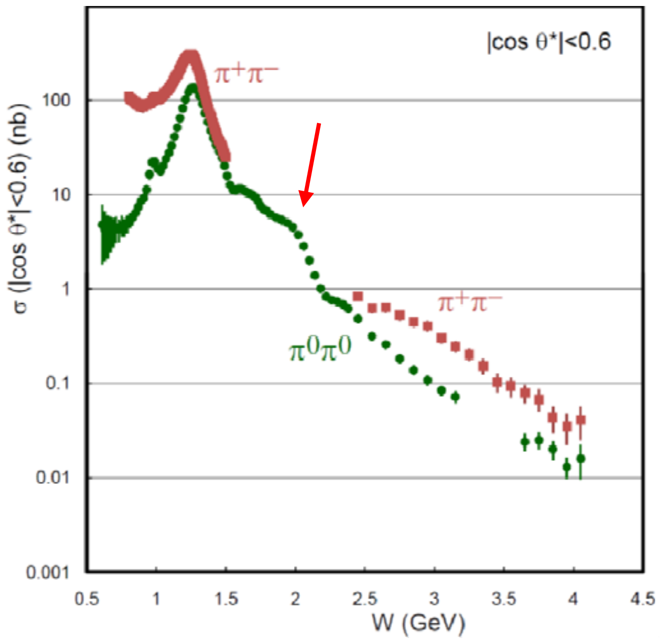
$f_J(1710)$

Parameter	$f_0(1710)$ fit				$f_2(1710)$ fit	
	fit-H	fit-L	H,L combined	PDG	fit-H	fit-L
χ^2/ndf	694.2/585	701.6/585	Two solutions of interference		796.3/585	831.5/585
Mass(f_J) (MeV/c^2)	1750^{+5+29}_{-6-18}	1749^{+5+31}_{-6-42}	1750^{+6+29}_{-7-18}	1720 ± 6	1750^{+6}_{-7}	1729^{+6}_{-7}
$\Gamma_{tot}(f_J)$ (MeV)	138^{+12+96}_{-11-50}	145^{+11+31}_{-10-54}	139^{+11+96}_{-12-50}	135 ± 6	132^{+12}_{-11}	150 ± 10
$\Gamma_{\gamma\gamma}\mathcal{B}(K\bar{K})_{f_J}$ (eV)	12^{+3+227}_{-2-8}	21^{+6+38}_{-4-26}	12^{+3+227}_{-2-8}	unknown	$2.1^{+0.5}_{-0.3}$	1.6 ± 0.2

$f_0(1710) \to K^0_S K^0_S$ is confirmed in two-photon process.

The 1.8 – 2.2 GeV region

- $f_2(1950) \rightarrow \pi^0\pi^0$ shows a broad structure
- Similar structure exists in K^+K^- (but, they can be different states)
- No peak in $\eta\pi^0$, $\eta\eta$ and $K^0_S K^0_S$ in this mass region



Parameter	$f_4(2050)$	"$f_2(1950)$"	Unit
Mass	$1885^{+14}_{-13}{}^{+218}_{-25}$	$2038^{+13}_{-11}{}^{+12}_{-73}$	MeV/c^2
Γ_{tot}	$453 \pm 20^{+31}_{-129}$	$441^{+27}_{-25}{}^{+28}_{-192}$	MeV
$\Gamma_{\gamma\gamma}\mathcal{B}(\pi^0\pi^0)$	$7.7^{+1.2}_{-1.1}{}^{+23.5}_{-5.2}$	$54^{+23}_{-14}{}^{+379}_{-68}$	eV
$\chi^2(ndf)$	323.2 (311)		

I=0 (*f*) and *I*=1 (*a*) interference in $K\bar{K}$

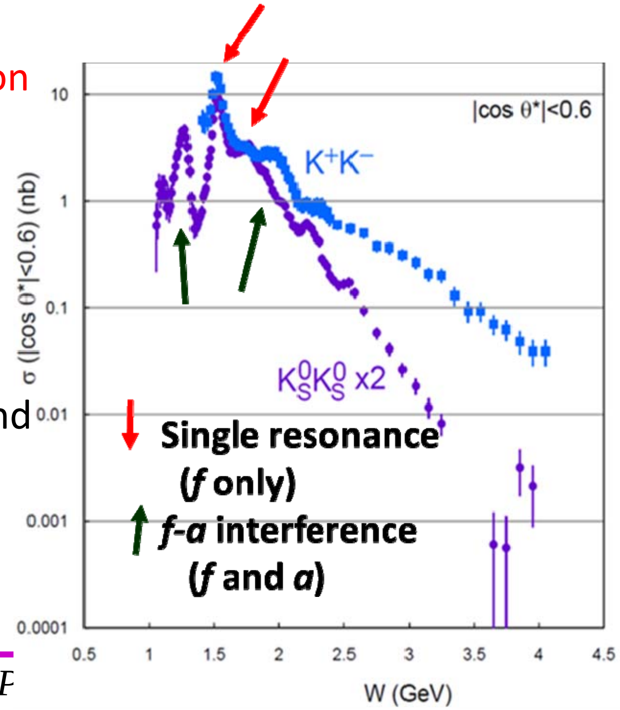
Size of the cross sections for K^+K^- and K^0K^0

A single resonance production of ***f*** **or** ***a*** decaying with the strong interaction

→ The cross sections are **similar size.**

If they are very different

Interference between *I*=0 and *I*=1 resonances



The 2.2 – 2.6 GeV region

- The very narrow $f_J(2220)$ (was $\xi(2220)$) and a wide $f_2(2300)$ are suggested.

  Do the both exist? Really narrow?

- Our $\pi^0\pi^0$ result does not need $f(\sim 2300)$; the high mass $f_2(1950)$ can explain the observed line shape.

- Surely something narrow(?) peaks are found in K^+K^-, $K^0_SK^0_S$ and $\eta\eta$.

  An $s\bar{s}$ state or a glueball flavor insensible?

$f_J(2220)$ $I^G(J^{PC}) = 0^+(2^{++}$ or $4^{++})$

OMITTED FROM SUMMARY TABLE

Needs confirmation. See our mini-review in the 2004 edition of this *Review*, PDG 04.

$f_J(2220)$ MASS

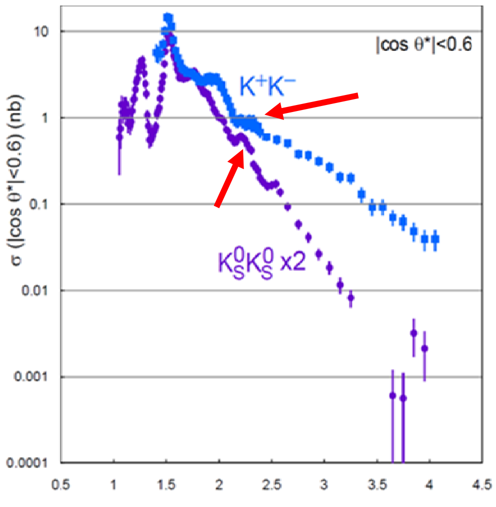
VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
2231.1± 3.5 OUR AVERAGE				

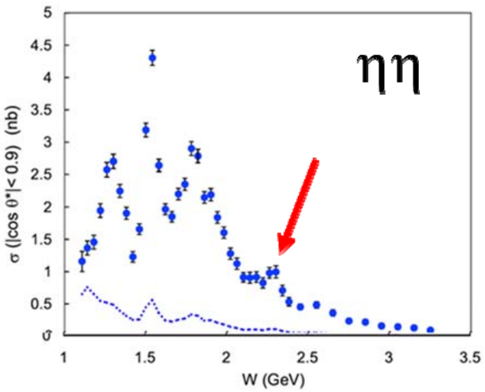
$f_J(2220)$ WIDTH

VALUE (MeV)	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
23^{+8}_{-7} OUR AVERAGE					

$f_J(2220)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi\pi$	seen
Γ_2	$\pi^+\pi^-$	seen
Γ_3	$K\bar{K}$	seen
Γ_4	$p\bar{p}$	
Γ_5	$\gamma\gamma$	not seen
Γ_6	$\eta\eta'(958)$	seen
Γ_7	$\phi\phi$	not seen
Γ_8	$\eta\eta$	not seen





$f_2(2300)$ $I^G(J^{PC}) = 0^+(2^{++})$

Mass $m = 2297 \pm 28$ MeV

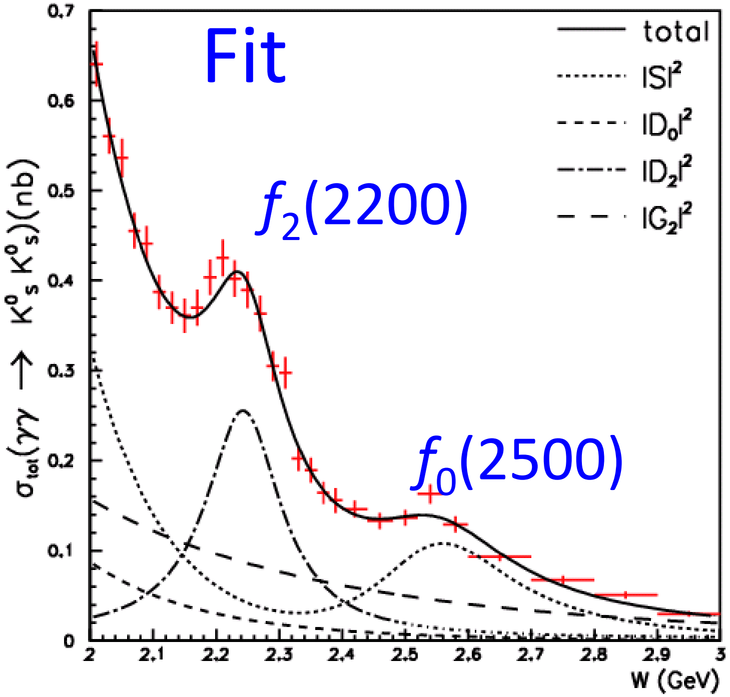
Full width $\Gamma = 149 \pm 40$ MeV

$f_2(2300)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\phi\phi$	seen	529
$K\bar{K}$	seen	1037
$\gamma\gamma$	seen	1149

Fit Results for resonances in $K^0_S K^0_S$

$f_2(2200)$-$f_0(2500)$ is the best solution (in all the J= 0, 2, 4 combinations)

Parameter	$f_2(2200)$	$f_0(2500)$
Mass (MeV/c^2)	2243^{+7+3}_{-6-29}	$2539 \pm 14^{+38}_{-14}$
$\Gamma_{\rm tot}$ (MeV)	$145 \pm 12^{+27}_{-34}$	$274^{+77+126}_{-61-163}$
$\Gamma_{\gamma\gamma}\mathcal{B}(K\bar{K})$ (eV)	$3.2^{+0.5+1.3}_{-0.4-2.2}$	40^{+9+17}_{-7-40}



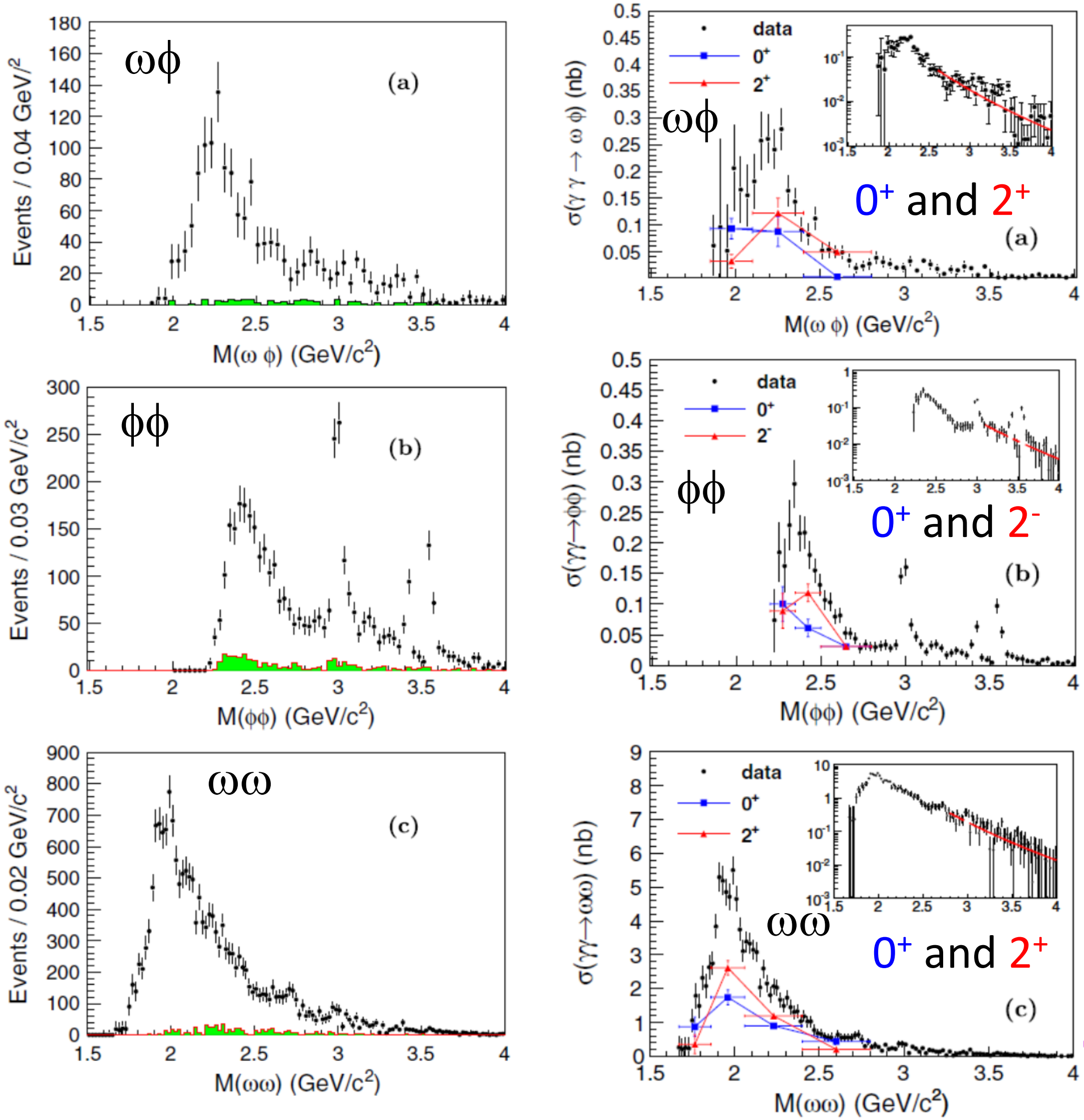
Significances

- 3.4σ for $f_2(2200)$ over $f_0(2200)$
- 4.3σ for $f_0(2500)$ over $f_2(2500)$

- There can be an only wide state around 2240 MeV.
- Narrow appearances in previous measurements may be due to an interference effect and/or statistical fluctuation.
- A high-mass state at 2.5 GeV may be the heaviest light-quark scalar meson so far found.

“γγ → Vector-meson pair” from Belle

Observation of New Resonant Structures in γγ → ωφ, φφ, and ωω



Belle, PRL 108, 232001 (2012)

There is a resonance-like structures at 2.0 – 2.5 GeV in each of the final states.

Preferred J^P combinations are determined by the angular analysis of production and decay of ω and φ.

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

Production of light-quark mesons decaying to the **three pseudoscalar meson final state**. (The η_c production is also presented.)

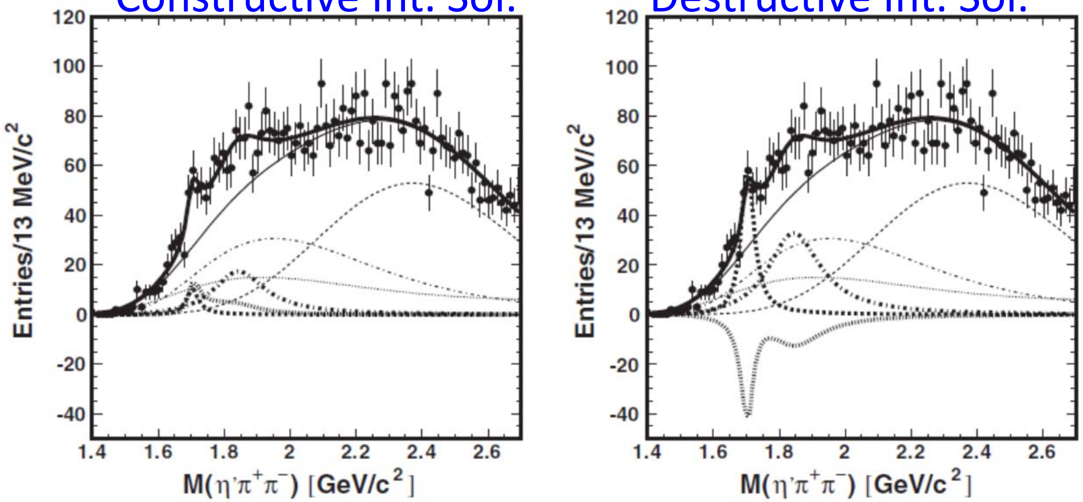
Belle, PRD 86, 052002 (2012)

X(1835) is an exotic resonance candidate found in the radiative decay of J/ψ by BES. Is it gluon-rich, or $q\bar{q}$-rich?

A hint of X(1835) – 2.8σ, but it is not very significant.

η(1760) + X(1835) + Non-Res + Backgrounds

Constructive Int. Sol. Destructive Int. Sol.



Parameter	Two interfering resonances Solution I	Solution II	Reference
	$X(1835)$		
M, MeV/c^2	1836.5 (fixed)		$1836.5 \pm 3.0^{+5.6}_{-2.1}$
Γ, MeV/c^2	190 (fixed)		$190 \pm 9^{+38}_{-36}$
$\Gamma_{\gamma\gamma}\mathcal{B}$, eV/$c^2$	$18.2^{+7.7}_{-6.7} \pm 4.0$	$35^{+12}_{-13} \pm 8$	
$(\Gamma_{\gamma\gamma}\mathcal{B})_{90}$ eV,	<35.6	<83	
S, σ	2.8		
	$\eta(1760)$		
M, MeV/c^2	$1703^{+12}_{-11} \pm 1.8$		1756 ± 9
Γ, MeV/c^2	$42^{+36}_{-22} \pm 15$		96 ± 70
$\Gamma_{\gamma\gamma}\mathcal{B}$, eV/$c^2$	$3.0^{+2.0}_{-1.2} \pm 0.8$	$18^{+13}_{-10} \pm 5$	
S, σ	4.1		
ϕ	$(287^{+42}_{-51})°$	$(139^{+19}_{-9})°$	

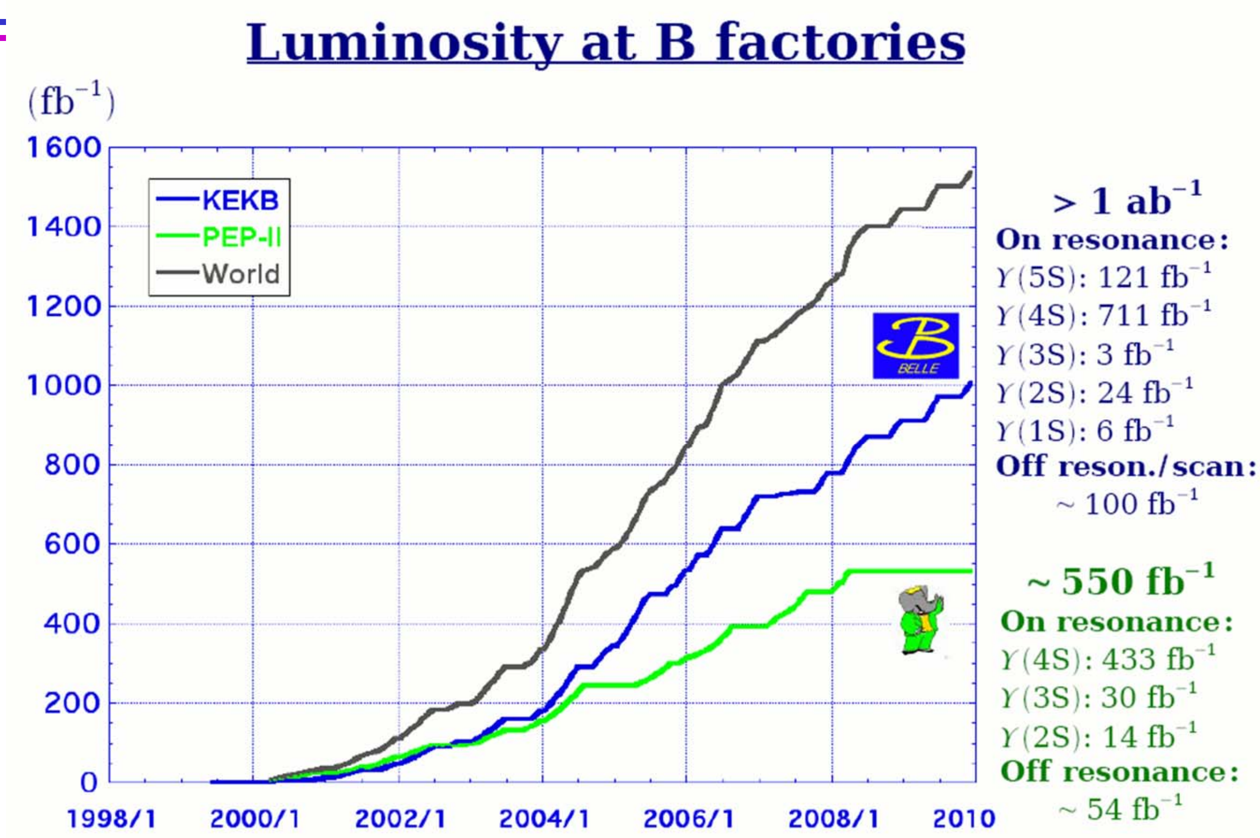
Summary

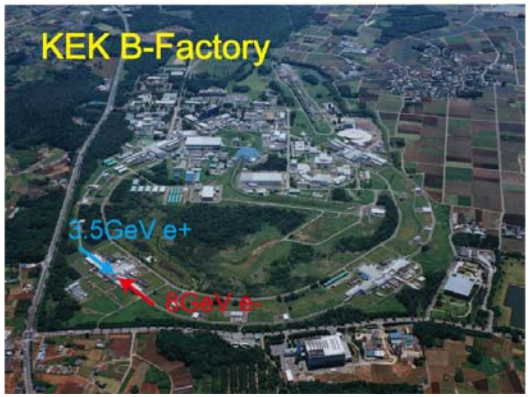
- $\gamma\gamma \rightarrow$ pseudoscalar-meson pair have been measured in six different final states.
- The $\gamma\gamma$-invariant-mass region, 0.6 – 2.6 GeV, is studied for light-meson spectroscopy.
- We measure $\Gamma_{\gamma\gamma}(\times BF)$ for various $J^{PC}=(\text{even})^{++}$ meson states.
- We have confirmed:

  - $\gamma\gamma$ coupling of the scalar mesons $f_0(980)$, $a_0(980)$, $f_0(1710)$
  - $f - a$ interference in the $K\bar{K}$ final states
  - Many clear resonant structures found in 1.6 – 2.6 GeV regions.
- Resonant signals in the 1.6 – 2.6GeV region are also found in the VV and $\eta'\pi\pi$ final states.

Backup

History of integrated luminosity at Belle





1999	The Belle experiment started
2001	CP violation in B mesons was verified and the KEKB accelerator achieved the world's highest luminosity
2002	Anomalous CP violation in b $\rightarrow$ s was measured
2003	The B $\rightarrow$ Kll decay was discovered
2004	The New particle X (3872) was discovered
2005	Direct violation of CP in B $\rightarrow K\pi$ was found. The B $\rightarrow \rho\gamma$ decay was discovered
2006	B $\rightarrow \tau\nu$ was observed
2007	D meson mixing was discovered. A new particle composed of 4 quarks Z (4430) + was discovered
2008	Dr. Makoto Kobayashi and Dr. Toshihide Maskawa were awarded the Nobel Prize in Physics
2010	The Belle experiment was completed

Formalism of PWA for P-meson pair final-state processes

- We consider up to J=4 (for W < 3 GeV).

$$\frac{d\sigma}{d\Omega} = \left|S Y_0^{\ 0} + D_0 Y_2^{\ 0} + G_0 Y_4^{\ 0}\right|^2 + \left|D_2 Y_2^{\ 2} + G_2 Y_4^{\ 2}\right|^2$$

- S, D_0, G_0, D_2 , G_2 Partial-wave amplitudes for each wave J_λ

  $J = L = 0, 2, 4$ (even only) with the helicity $\lambda = 0$ or 2 (to the $\gamma\gamma$ axis)

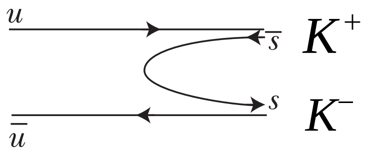
  – Y_J^{λ} : spherical harmonics
  – $|Y_J^{\lambda}|$ are NOT mutually independent, as we have no information for the azimuthal-angle direction.

- We cannot determine the partial waves model independently;
  We need **parameterization** based on a model including the W dependence of resonances and continuum components.

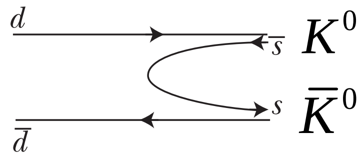
Nature of I=0 and I=1 interference in $K\bar{K}$

- Consider both isospin I=0 and I=1, e.g., f_J and a_J
- Their Constructive and Destructive interference based on OZI (Okubo-Zweig-Iizuka) rule and isospin I_z inversion.

D. Faiman, H.J. Lipkin and H.R. Rubinstein, PL 59B,269 (1975)



$$|u\bar{u}\rangle = \frac{1}{\sqrt{2}}(f_J + a_J)$$



$$|d\bar{d}\rangle = \frac{1}{\sqrt{2}}(f_J - a_J)$$

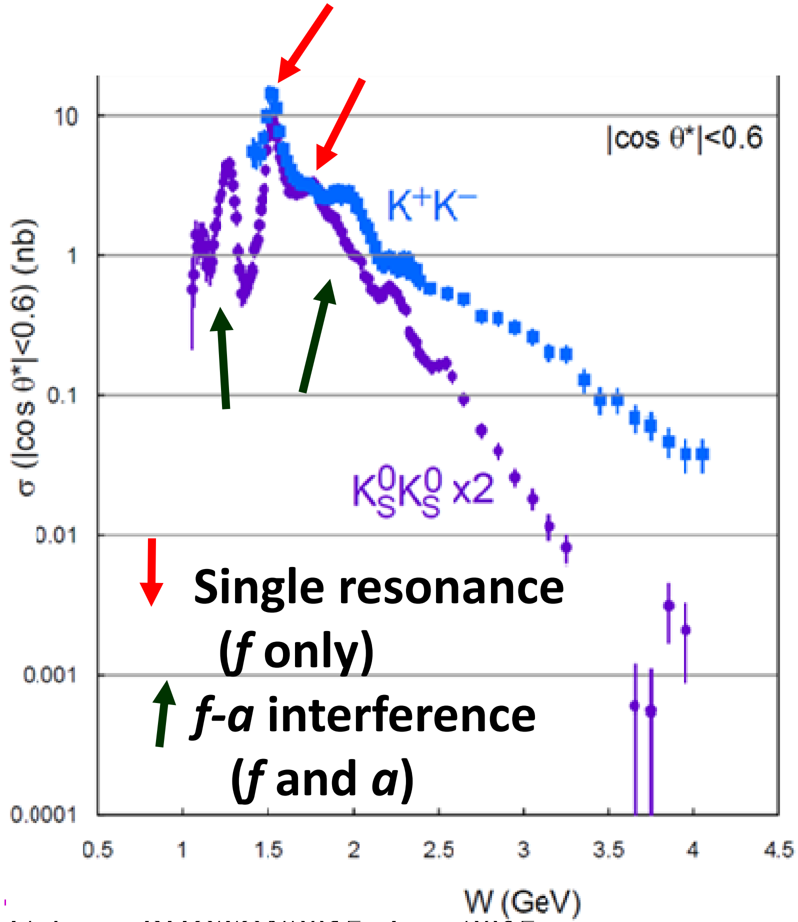
Size of the cross sections for K^+K^- and $K^0\bar{K}^0$

A single resonance production of ***f*** **or** ***a*** decaying with the strong interaction

→ The cross sections are **similar size.**

If they are very different →

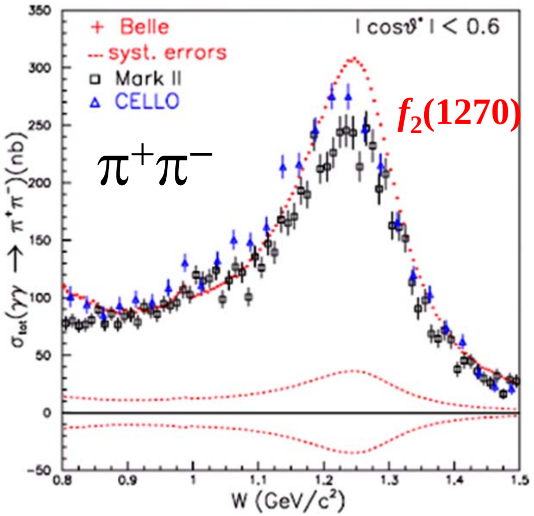
Interference between I=0 and I=1 resonances, or effective (electromagnetic) continuum production

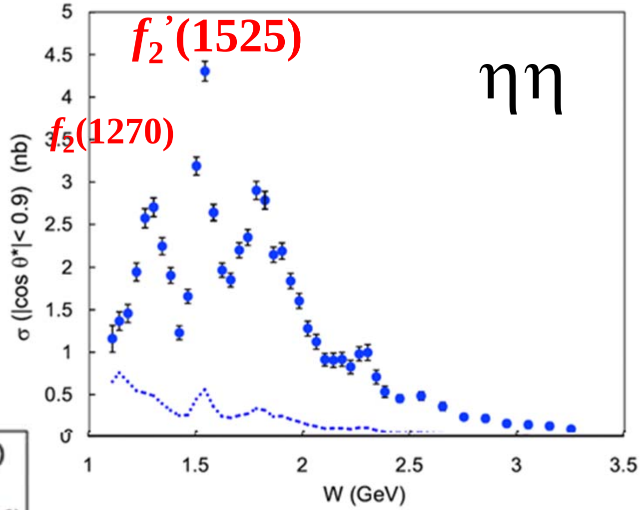


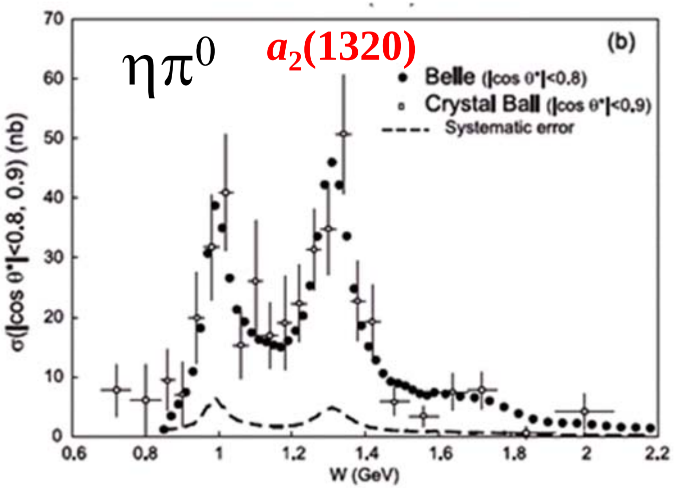
The difference above >~2.4GeV is explained by electric-charge difference of the quarks.

The tensor-meson triplet, $f_2(1270)$, $a_2(1320)$, $f_2'(1525)$

$f_2(1270)$: The largest peak in $\pi^+\pi^-$ and $\pi^0\pi^0$. Also seen in $\eta\eta$
$a_2(1320)$: Large peak in $\eta\pi^0$
$f_2'(1525)$: Large peak in $\eta\eta$, K^+K^-, and $K^0_S K^0_S$

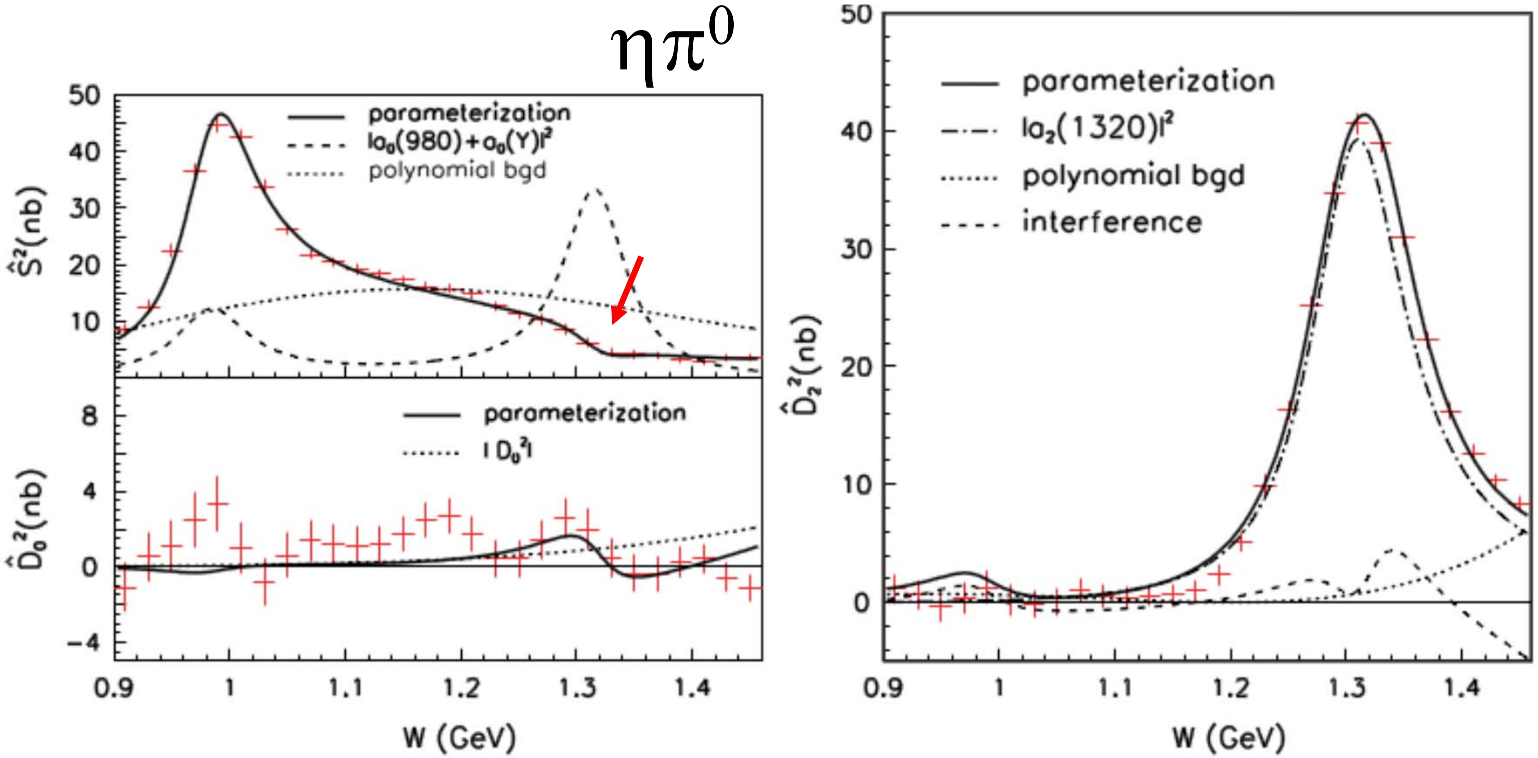






The I=1 sector

- We find a_0(1320)→ $\eta\pi^0$ just under a_2(1320).
- The mass is not compatible with a_0(1450)?

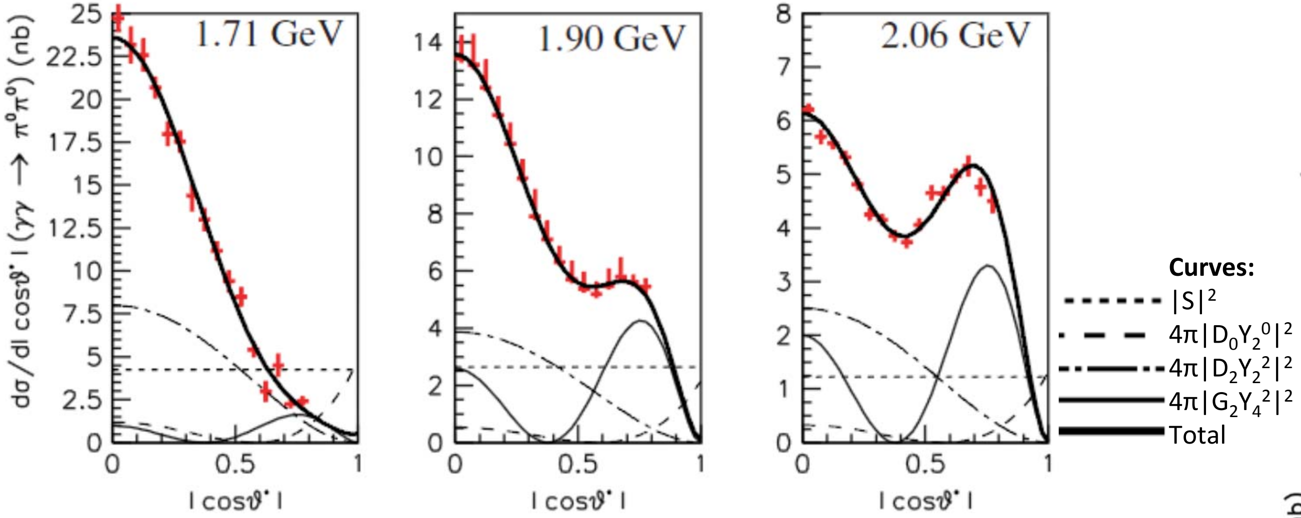


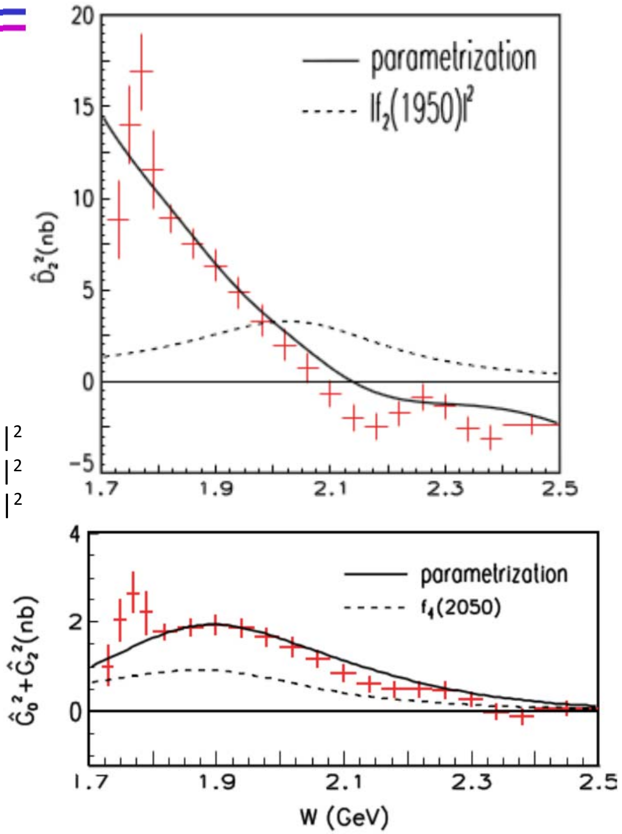
Parameter	This work	a_0(1450) (PDG)	Unit
Mass	$1316.8^{+0.7+24.7}_{-1.0-4.6}$	1474 ± 19	MeV/c^2
Γ_{tot}	$65.0^{+2.1+99.1}_{-5.4-32.6}$	265 ± 13	MeV
$\Gamma_{\gamma\gamma}\mathcal{B}(\eta\pi^0)$	$432 \pm 6^{+1073}_{-256}$	unknown	eV

See Discussion in PDG-RPP2014, NOTE ON SCALAR MESONS BELOW 2GeV (pp 784 – 791)

J=2 and J=4 components in $\pi^0\pi^0$

Angular (|cos θ*|) dependence of the differential cross section



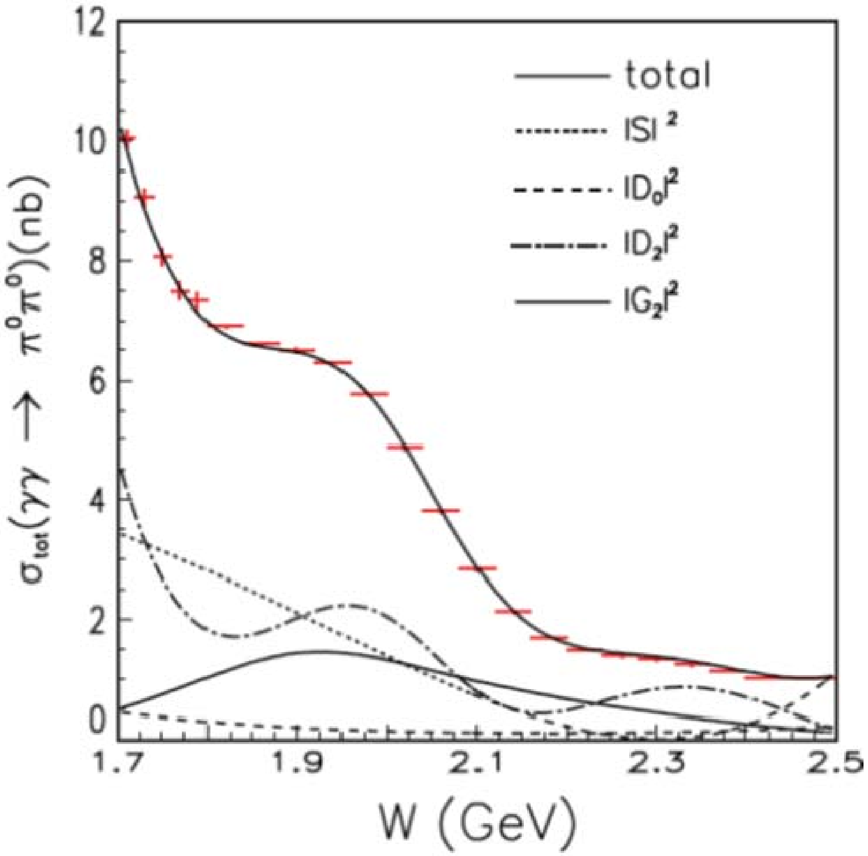


Parameter	$f_4(2050)$	"$f_2(1950)$"	Unit
Mass	$1885^{+14}_{-13}{}^{+218}_{-25}$	$2038^{+13}_{-11}{}^{+12}_{-73}$	MeV/c^2
Γ_{tot}	$453 \pm 20^{+31}_{-129}$	$441^{+27}_{-25}{}^{+28}_{-192}$	MeV
$\Gamma_{\gamma\gamma}\mathcal{B}(\pi^0\pi^0)$	$7.7^{+1.2}_{-1.1}{}^{+23.5}_{-5.2}$	$54^{+23}_{-14}{}^{+379}_{-68}$	eV
$\chi^2(ndf)$	323.2 (311)		

The mass-magnitude relation to the spin between f_2 and f_4 is opposite between our measurement and PDG.

(That is possible between the J=2(2P) and J=4(1F) states.)

Fit to $\pi^0\pi^0$ (W = 1.7 – 2.5 GeV)



Parameter	$f_4(2050)$	"$f_2(1950)$"	Unit
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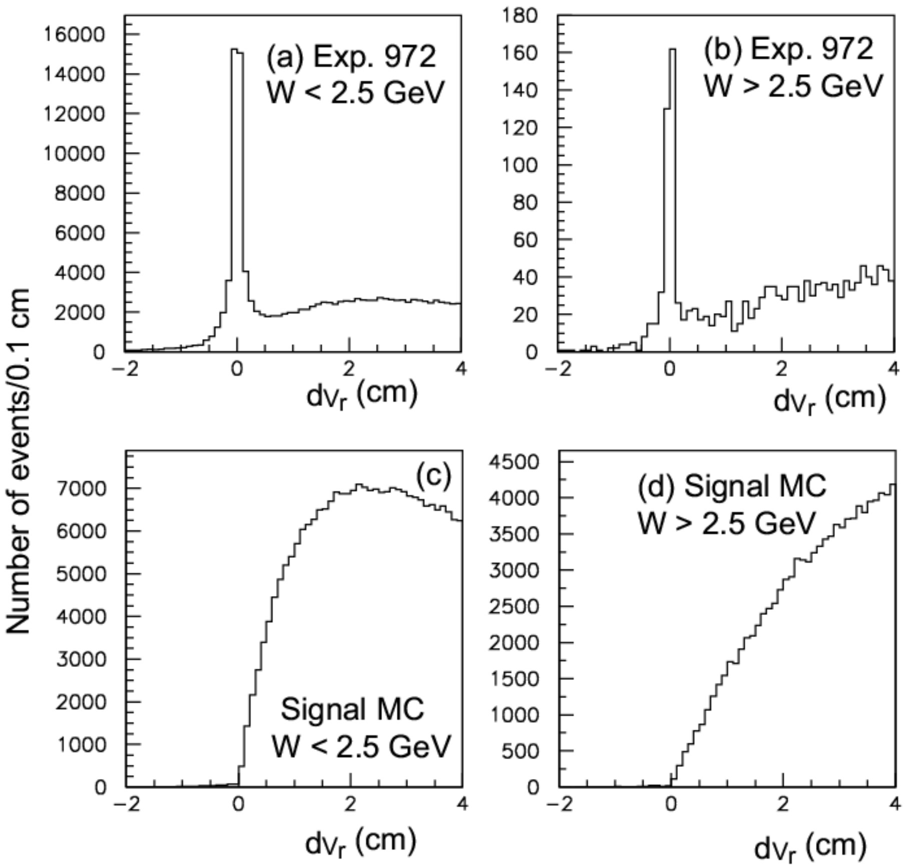
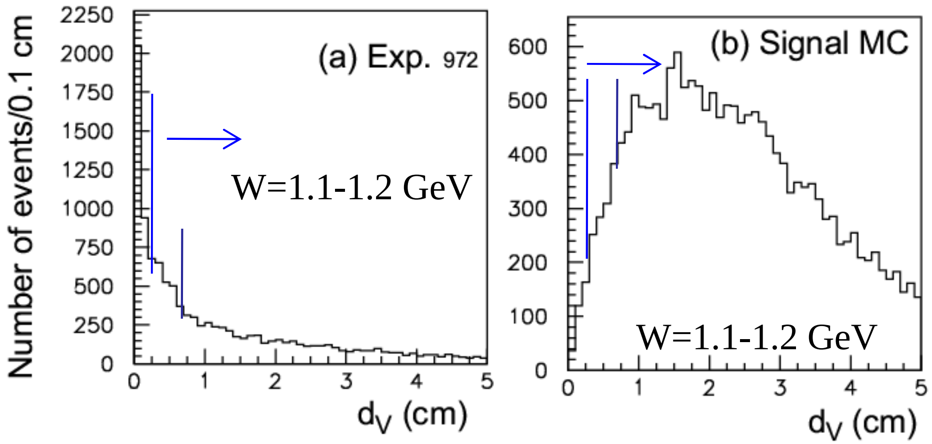
$\chi^2(ndf)$	323.2 (311)		

Ks Ks vertex distances

2D vertex distance

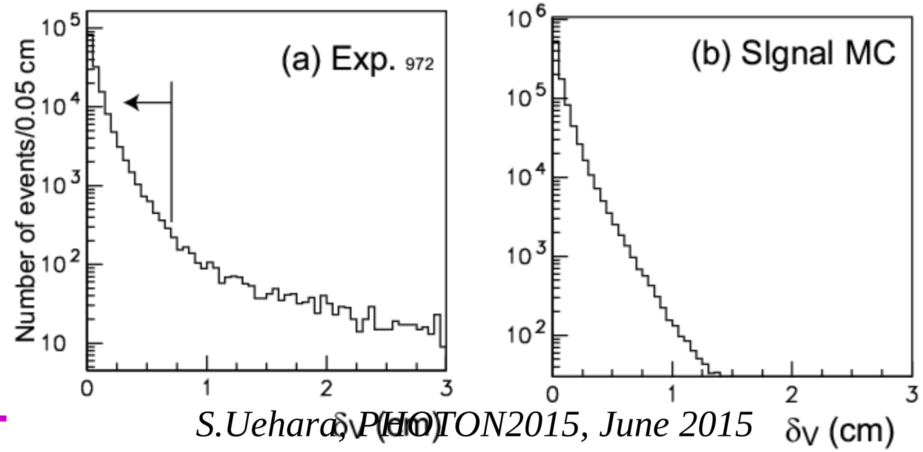


3D vertex distance



Sharp peaks near 0cm seen only in Exp.are from Direct 4π ($\pi^+\pi^-\pi^+\pi^-$) production backgrounds.

Tr. mometum diff. and vertex position diff. must be in parallel



Systematic errors

Source	Uncertainty(%)
Tracking efficiency (for 4 tracks)	2
Beam background effect	1
Pion identification (for 4 tracks)	2
Non-exclusive and four-pion backgrounds	2 – 19
Geometrical coverage and fit uncertainty	4
$K_S^0 K\pi$ background subtraction	1 – 2
K_S^0-pair reconstruction	5 – 3
Trigger efficiency	5 – 7
$E_{\rm ECL}$ cut	1
Integrated luminosity and luminosity function	5 – 4
L4 efficiency	1 – 10
Total	9 – 25, typically 10

From correlation study of different Exp# settings in data and signal MC (Beam background effect)

A Half of the subtraction + 2% from pt-fit (quad.sum) (Non-exclusive and four-pion backgrounds)

Loose-cut sample (K_S^0-pair reconstruction)

Correlation of the two triggers (Trigger efficiency)

About 10% of the inefficiency (L4 efficiency)

Fitting the region W > 2 GeV

- Parameterization

$$i - wave = B.W.e^{i\phi_i} + B_i$$

$$B_i = b_i \left(\frac{W}{W0} \right)^{-c_i} e^{i\phi_i}$$

(assume power behavior

for non-resonant background:

i = S, D_0, D_2 and G_2; (we assume G_0=0))

B.W.= $f_J(2200)$ and/or $f_J(2500)$ with J=0, 2 and 4

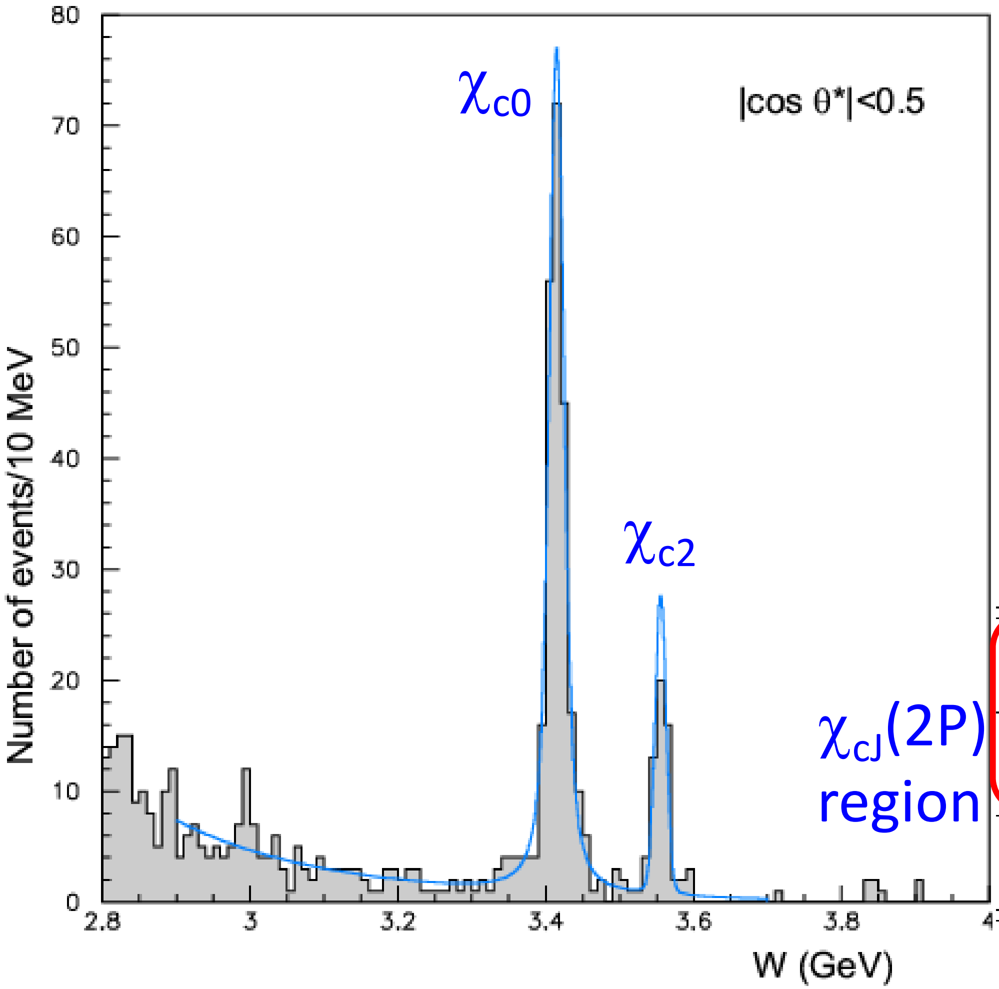
- Then fit *dσ/dΩ* (typically 16 free parameters)

Fit results for 13 assumptions

Assumption	No. of sol.	χ^2	ndf
f_0-f_0	2	293.3, 293.9	214
f_0-f_2	4	320.9, 321.9, 324.5, 327.6	214
f_0-f_4	1	291.4	214
f_2-f_0	1	228.3	214
f_2-f_2	1	260.4	214
f_2-f_4	1	323.6, 306.7	214
f_4-f_0	1	411.6	214
f_4-f_2	2	468.6, 472.1	214
f_4-f_4	4	459.6, 464.1, 466.4, 467.5	214
Only-f_0	1	390.0	218
Only-f_2	1	323.6	218
Only-f_4	1	518.7	218
No resonances	1	659.32	222

S.Uehara, PHOTON2015, June 2015

Charmonia χ_{c0} and χ_{c2}



Yield

Interference	$N_{\chi_{c0}}$	$N_{\chi_{c2}}$	$-2\ln\mathcal{L}/ndf$
not included	$248.3^{+17.9}_{-17.2}$	$53.0^{+8.1}_{-7.4}$	57.34/73
included	266 ± 53	53^{+14}_{-12}	57.22/71

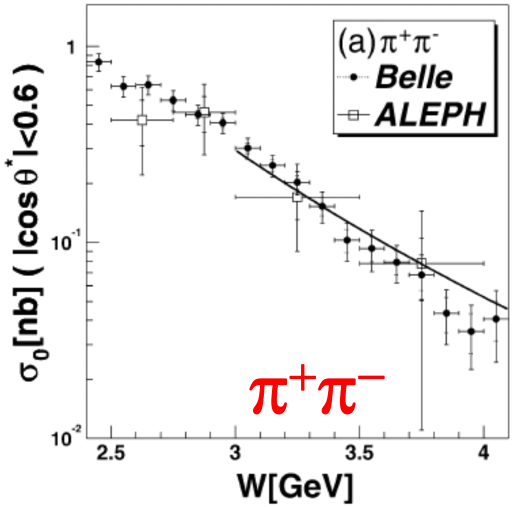
Interference between χ_{c0} and continuum

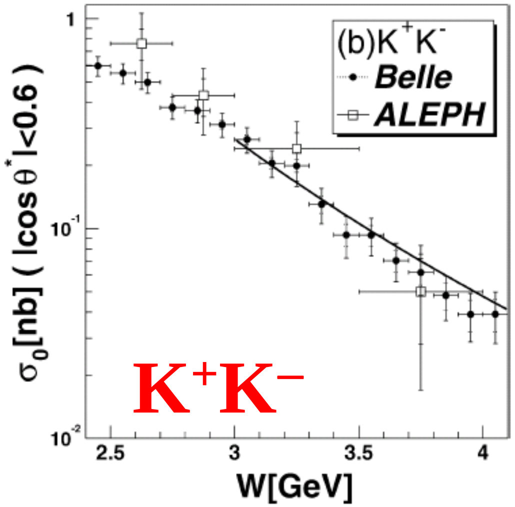
Product of two-photon decay width and B($K^0_S K^0_S$)

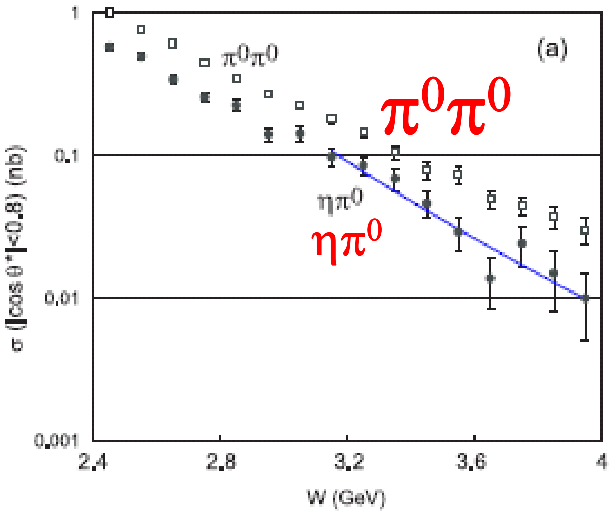
Interference	$\Gamma_{\gamma\gamma}\mathcal{B}(\chi_{c0})$ (eV)	$\Gamma_{\gamma\gamma}\mathcal{B}(\chi_{c2})$ (eV)
not included	$8.09 \pm 0.58 \pm 0.83$	$0.268^{+0.041}_{-0.037} \pm 0.028$
included	$8.7 \pm 1.7 \pm 0.9$	$0.27^{+0.07}_{-0.06} \pm 0.03$
Belle 2007	$7.00 \pm 0.65 \pm 0.71$	$0.31 \pm 0.05 \pm 0.03$
PDG 2012	7.3 ± 0.5	0.297 ± 0.026

W-dependences at high energies

Assume or expect $\sigma(W) \sim W^{-n}$

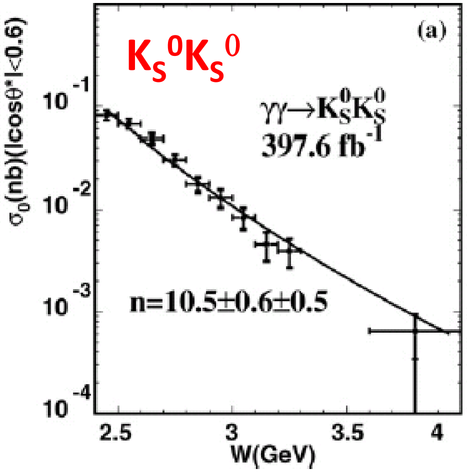


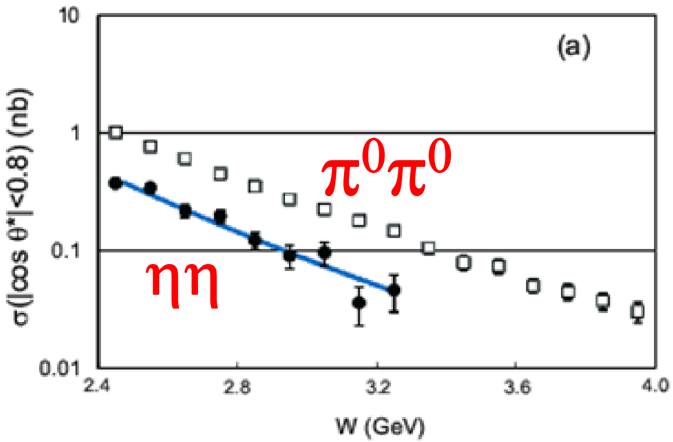




Fitted and reproduced

Slope parameter **n** different among the reactions



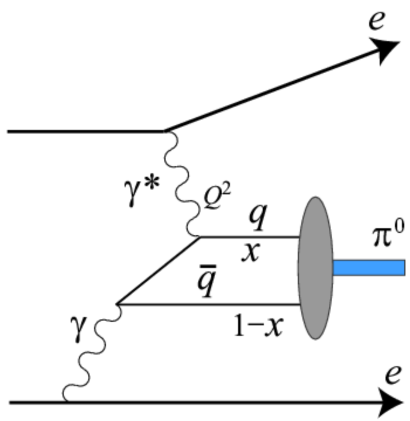


Charmonium contributions
not included/removed

π^0 Transition Form Factor

$\gamma\gamma^* \rightarrow \pi^0$

Coupling of neutral pion with two photons
Good test for QCD at high Q^2



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

Theoretically calculated from pion distribution amplitude and decay constant

$$F(Q^2) = \frac{\sqrt{2} f_\pi}{3} \int T_H(x, Q^2, \mu) \phi_\pi(x, \mu) dx$$

Measurement:

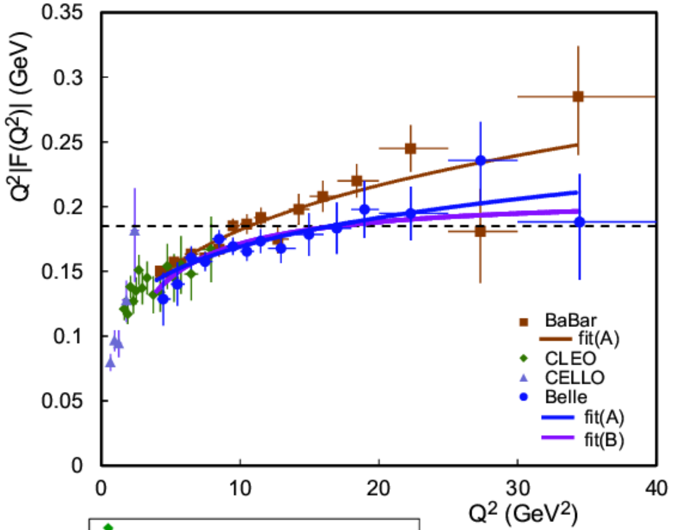
$|F(Q^2)|^2 = |F(Q^2,0)|^2 = (\mathbf{d\sigma/dQ^2})/(2A(Q^2))$ A(Q^2) is calculated by QED

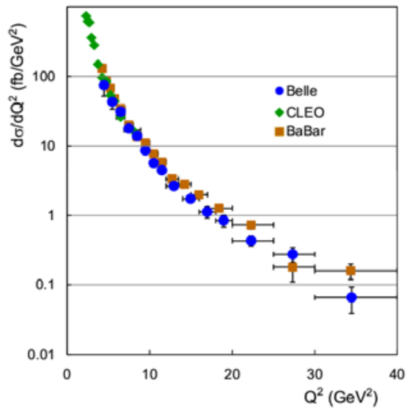
$|F(0,0)|^2 = 64\pi\Gamma_{\gamma\gamma}/\{(4\pi\alpha)^2 m_R^3\}$

Detects e (tag side) and π^0

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

Comparisons with Previous Measurements and Fits





No rapid growth above $Q^2 > 9 GeV^2$ is seen in Belle result.

~ 2.3σ difference between Belle and BaBar in 9 – 20 GeV^2

Fit A (suggested by BaBar)

$Q^2|F(Q^2)| = A\,(Q^2/10GeV^2)^{\beta}$

BaBar:

$A = 0.182 \pm 0.002\ (\pm 0.004)$ GeV

$\beta = 0.25 \pm 0.02$

Belle:

$A = 0.169 \pm 0.006$ GeV

$\beta = 0.18 \pm 0.05$

$\chi^2/ndf = 6.90/13$ ~1.5σ difference from BaBar

Fit B (with an asymptotic parameter)

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

Belle:

$B = 0.209 \pm 0.016$ GeV

$C = 2.2 \pm 0.8\ GeV^2$

$\chi^2/ndf = 7.07/13$

B is consistent with the QCD value (0.185GeV)