Light-hadron spectroscopy with two-photon and other processes at Belle

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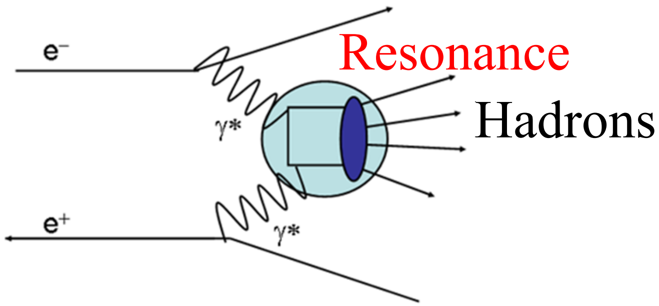
Belle Collaboration

KEK theory center workshop on
Hadron and Nuclear Physics in 2017 (KEK-HN-2017)
Jan. 7 – 10, 2017

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$1)$^+$**

Pseudoscalar-meson pair production: J^P=(even)$^+$ only

Strict constraints for quantum numbers $\rightarrow$**Determination of J^P by PWA**

$\Gamma_{\gamma\gamma}$**:** 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

Searches/Discoveries of **new resonances**

Isospin mixing, **Form factors, Test of QCD**

KEKB Accelerator and Belle Detector

- Asymmetric $e^- e^+$ collider

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

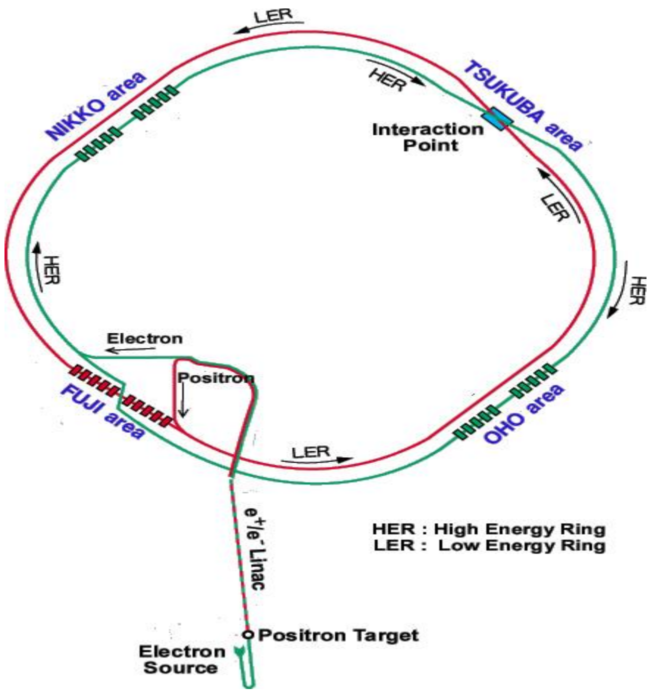
  $\sqrt{s}$= around 10.58 GeV ⇔ $\Upsilon(4S)$

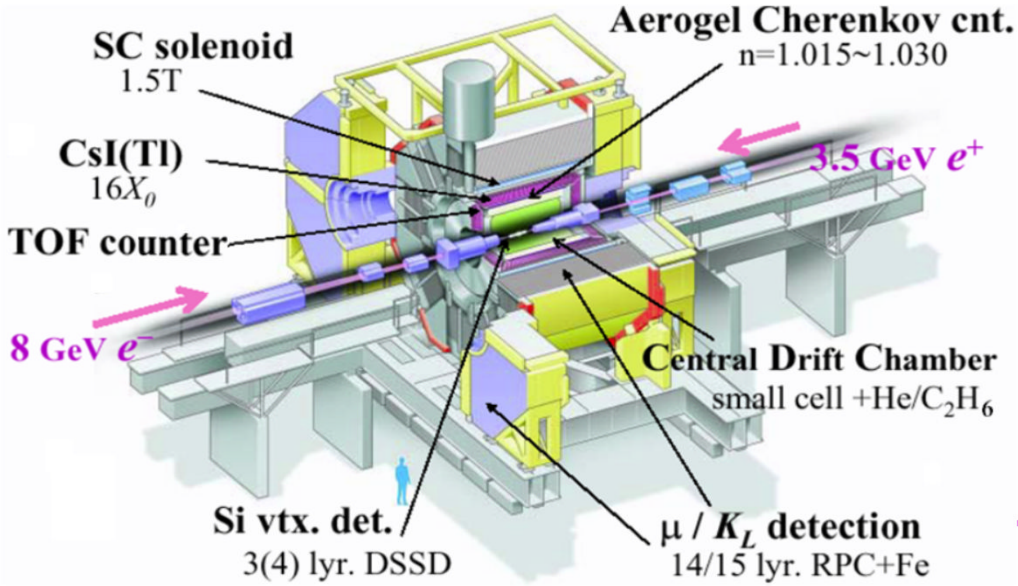
  Beam crossing angle: 22mrad

- World-highest Luminosity

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

  $\int$ 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

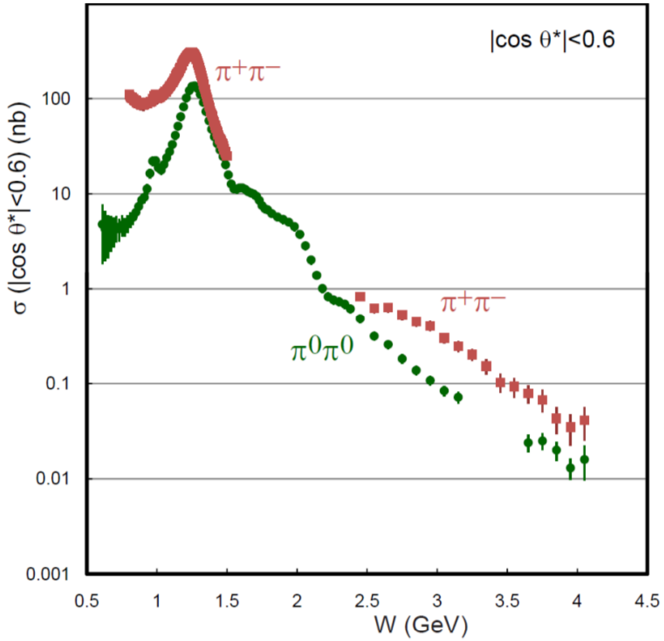
10 papers for 6 processes

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	√	√	√
$K^0_SK^0_S$	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.

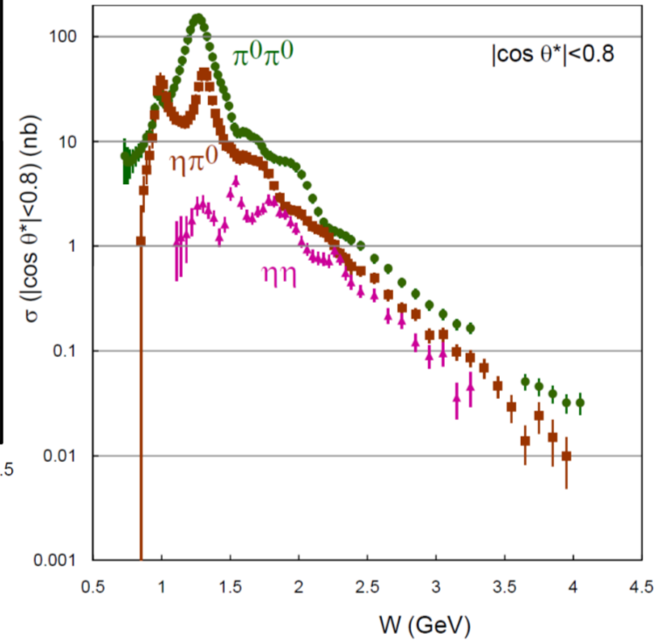
The six processes; in total ~20 peaks

Charged vs Neutral $\pi\pi$

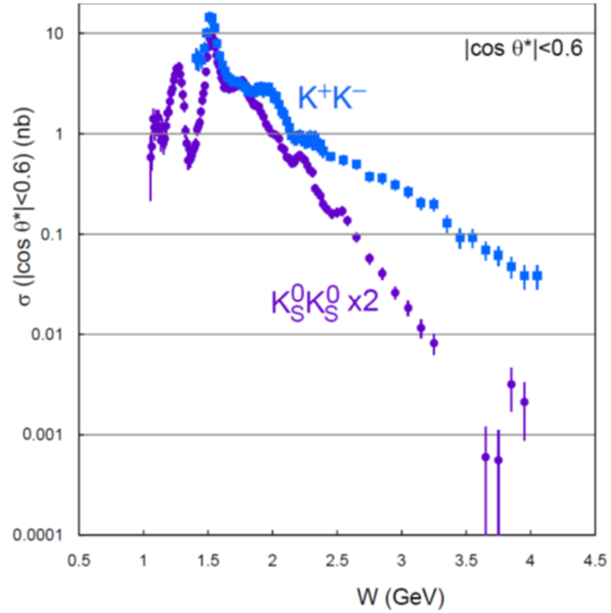


Three neutral-pair processes

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



Charged vs Neutral $K\bar{K}$



Horizontal axis:

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

W<~2.5GeV: Dominated by resonances

W>~2.5 GeV: (Netgative) Power law works + (χ_c charmonia)

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)

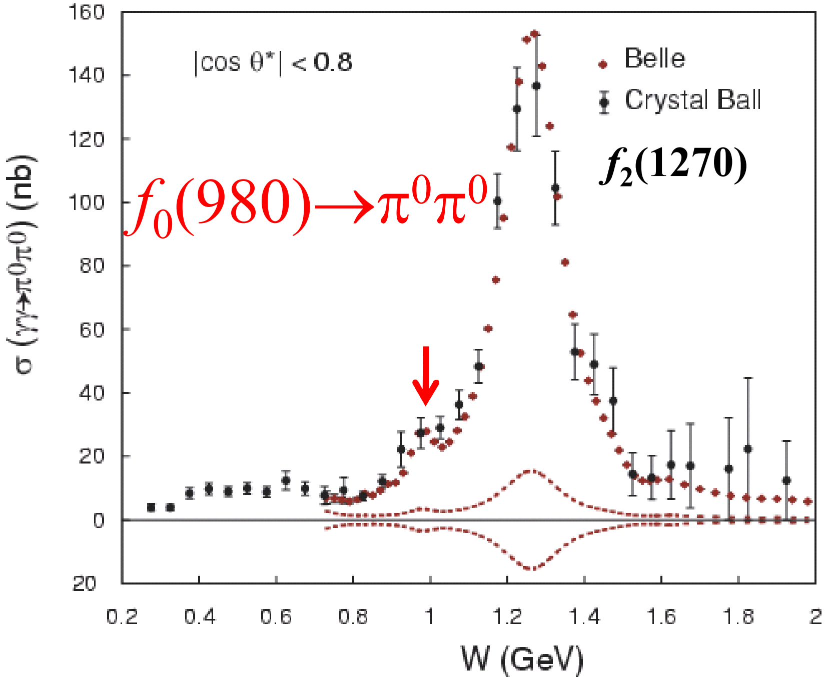
  – Y_J^λ : spherical harmonics
  – $|Y_J^\lambda|$ are NOT mutually independent, as we have no information for the azimuthal-angle direction.

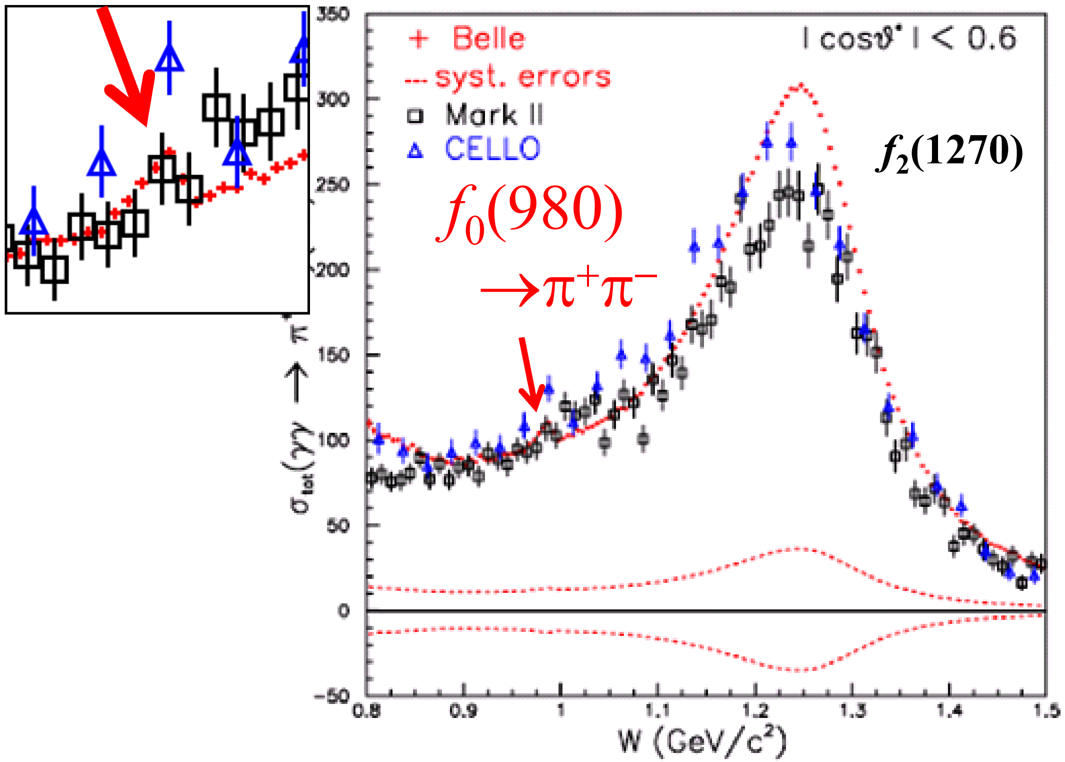
- We cannot determine the partial waves model independently;
  We need **parameterization** based on a model including the W dependence of resonances and continuum components.
- Ancillary model-independent way: **Hat amplitudes;** $\left| Y_J^{\ m} \right|^2$ mutually independent

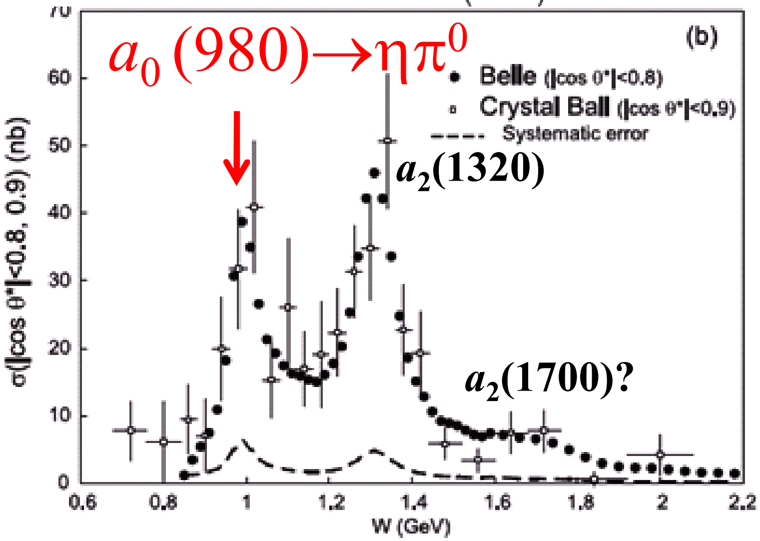
$$\frac{d\sigma}{d\Omega} = \hat{S}^2 \left| Y_0^{\ 0} \right|^2 + \hat{D}_0^{\ 2} \left| Y_2^{\ 0} \right|^2 + \hat{G}_0^{\ 2} \left| Y_4^{\ 0} \right|^2 + \hat{D}_2^{\ 2} \left| Y_2^{\ 2} \right|^2 + \hat{G}_2^{\ 2} \left| Y_4^{\ 2} \right|^2$$

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

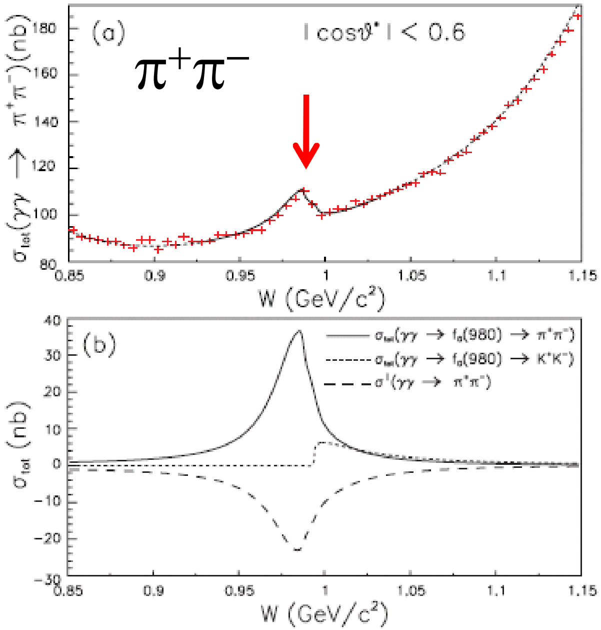
$f_0(980)$ and $a_0(980)$:
Observed as a peak very clearly in two-photon production, for the first time.

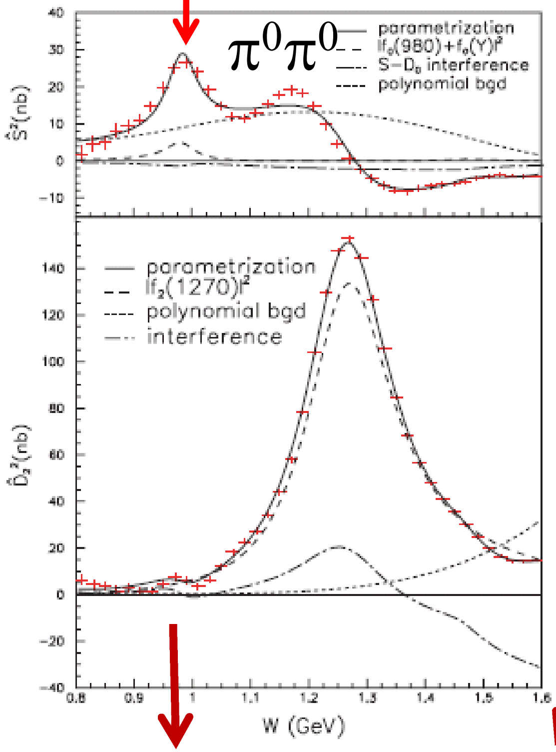


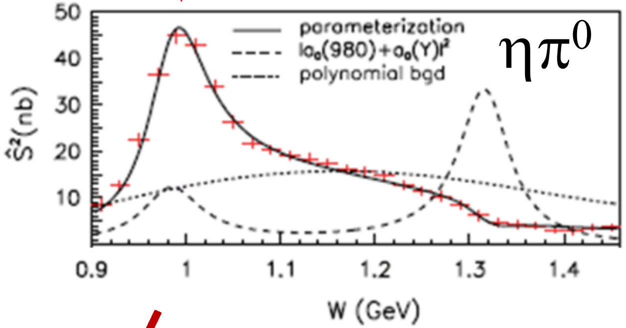




Two-photon decay width of $f_0(980)$ and $a_0(980)$







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

Predictions for $f_0(980)$

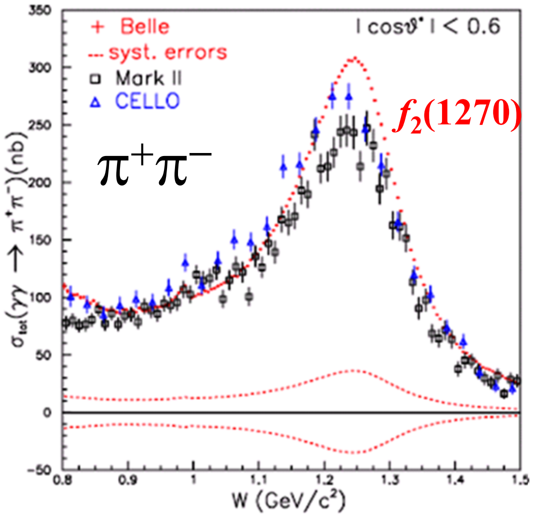
Model	$\Gamma_{\gamma\gamma}$ [eV]
*uu*bar,*dd*bar	1300 – 1800
*ss*bar	300 – 500
*KK*bar molecule	200 – 600
Four-quark	270

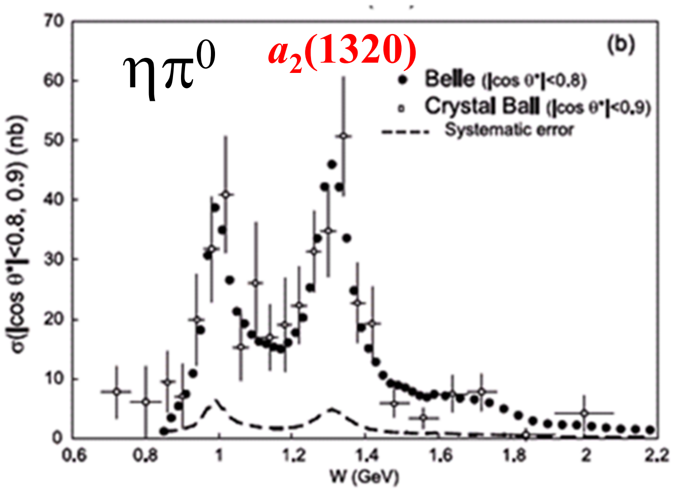
The tensor-meson triplet, $f_2(1270)$, $a_2(1320)$, $f_2'(1525)$

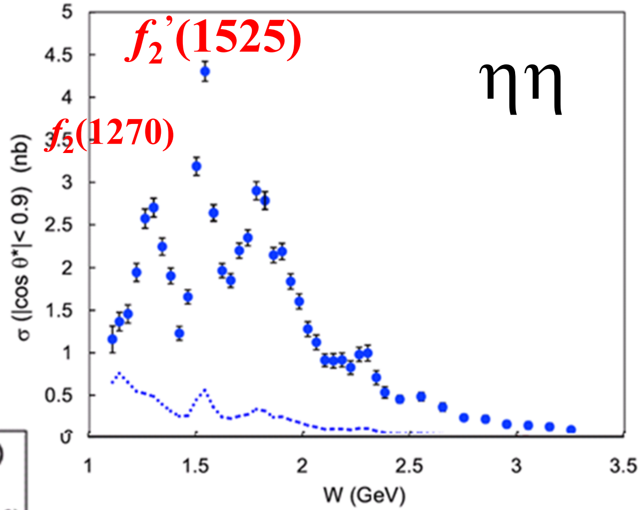
$f_2(1270)$: The largest peak in $\pi^+\pi^-$ and $\pi^0\pi^0$. Also seen in $\eta\eta$

$a_2(1320)$: Large peak in $\eta\pi^0$

$f_2'(1525)$: Large peak in $\eta\eta$, K^+K^-, and $K^0_SK^0_S$







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

Constructive interference

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

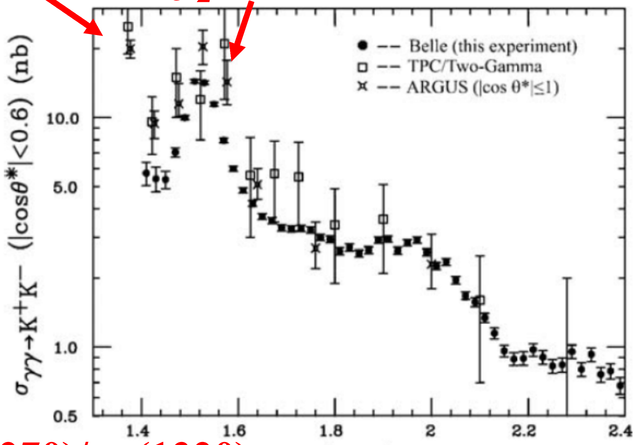
Destructive interference

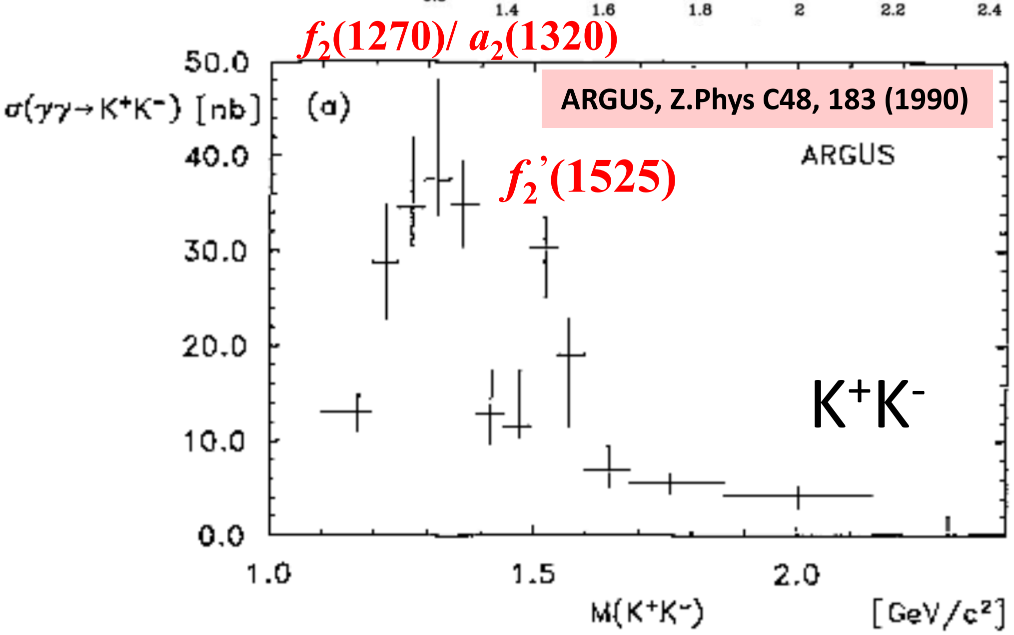
$f_2(1270)-a_2(1320)$ in $K^0{}_S K^0{}_S$

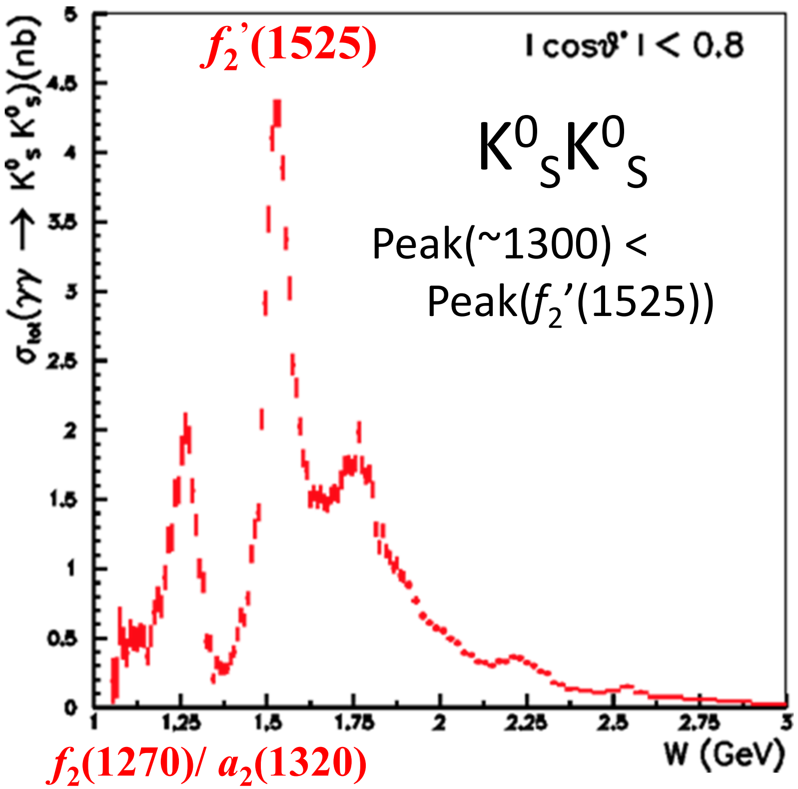
Explained by a phase relation in isospin composition

K^+K^-

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







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

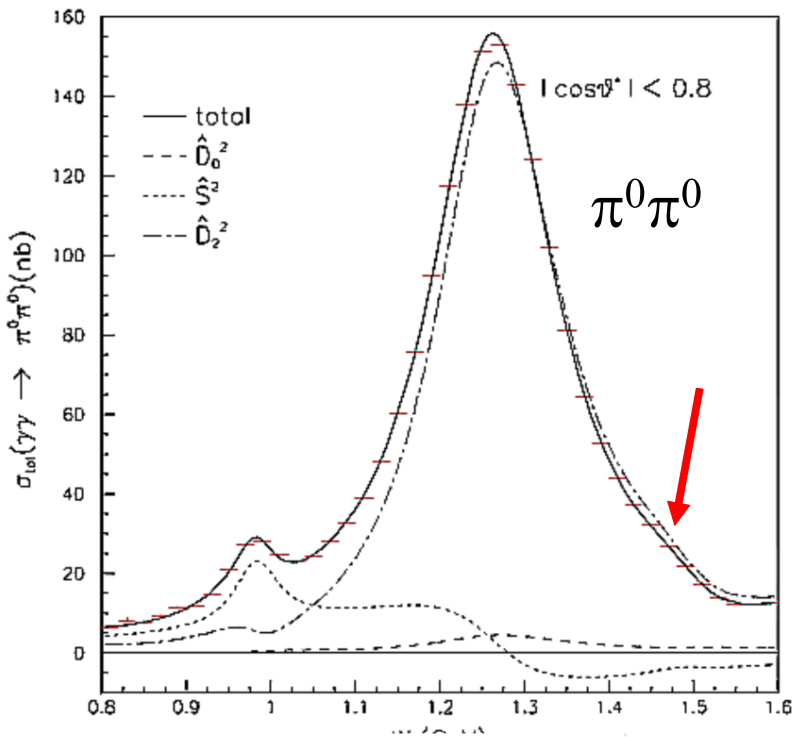
Mass m = 1200 to 1500 MeV
Full width Γ = 200 to 500 MeV

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

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

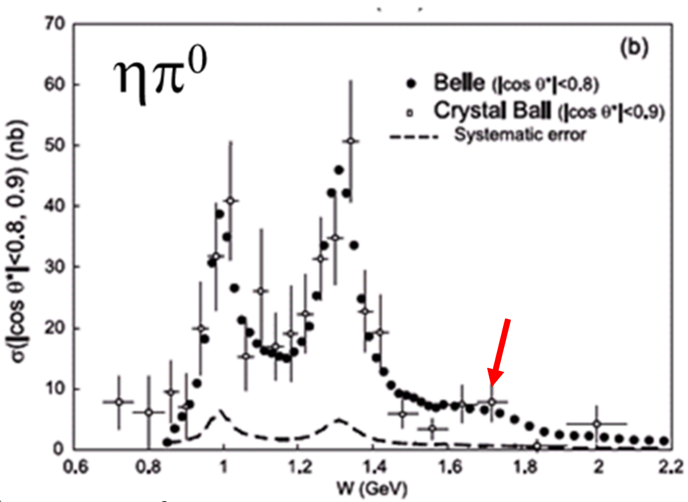
Mass $m = 1505 \pm 6$ MeV (S = 1.3)
Full width $\Gamma = 109 \pm 7$ MeV

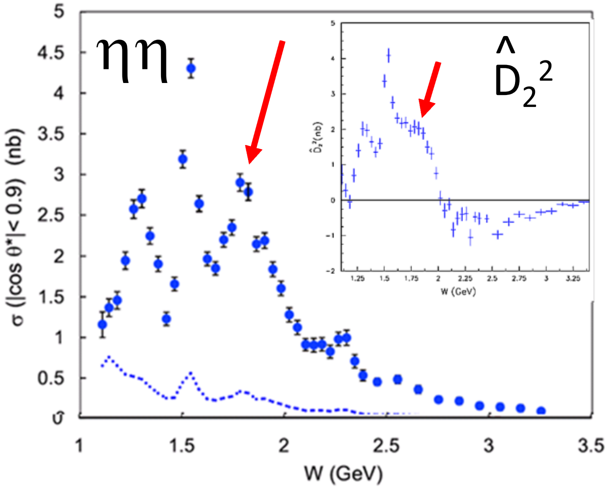
$f_0(1500)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor	p (MeV/c)
$\pi\pi$	(34.9±2.3) %	1.2	741

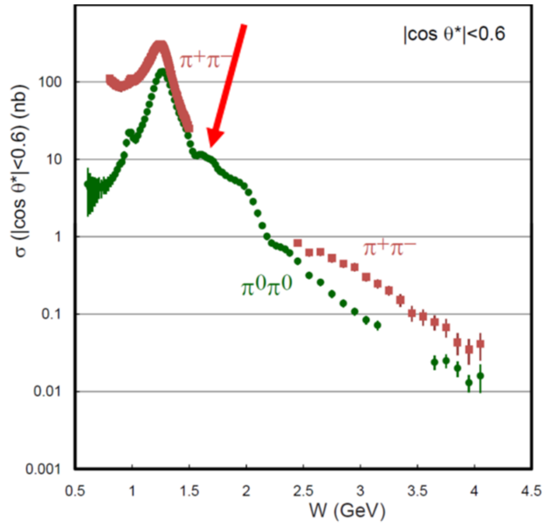


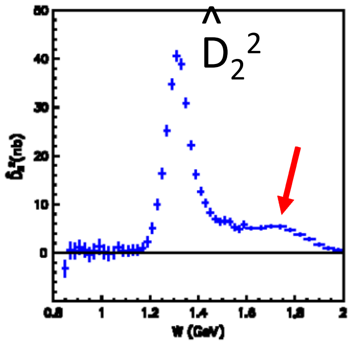
Parameter	Belle ($\pi^0\pi^0$)	Crystal Ball	Unit
Mass	1470^{+6+72}_{-7-255}	1250	MeV/c^2
Γ_{tot}	90^{+2+50}_{-1-22}	268 ± 70	MeV
$\Gamma_{\gamma\gamma}\mathcal{B}(\pi^0\pi^0)$	11^{+4+603}_{-2-7}	430 ± 80	eV

1.6 – 1.8 GeV: Mass region of the greatest difficulty



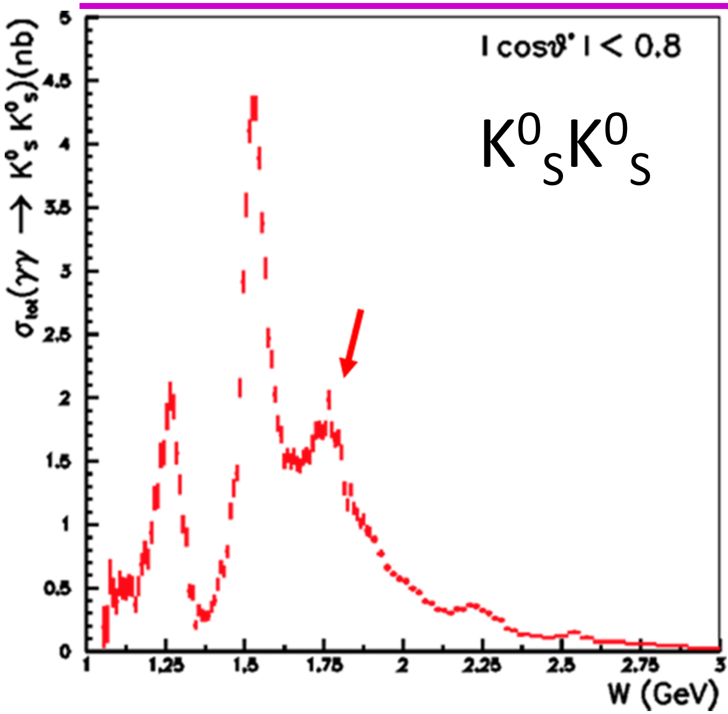


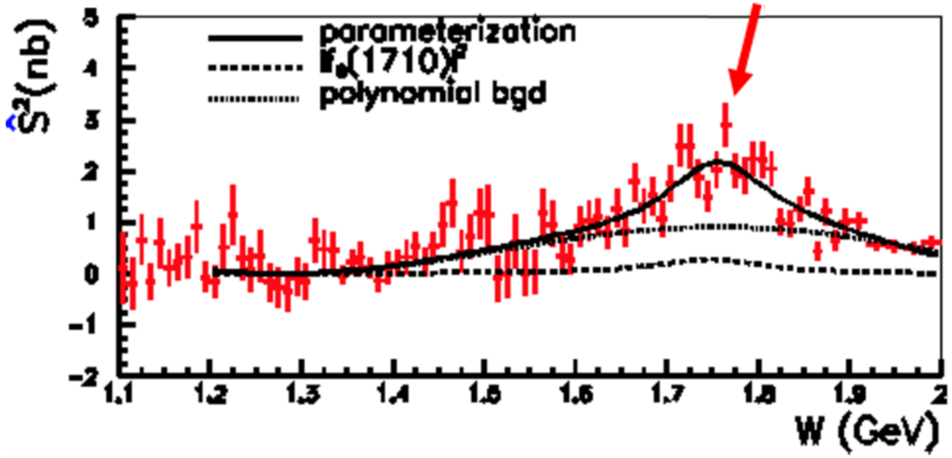




- Extensive studies are performed in the radiative decays of J/ψ ($\rightarrow \gamma gg \rightarrow \gamma$R).
- $a_2(1700) \rightarrow \rho^0\pi^0 \rightarrow \pi^+\pi^-\pi^0$ is confirmed by previous two-photon measurements.
- $a_2(1700) \rightarrow \eta\pi^0$ seen in our data, but no definite parameters obtained.
- $f_2(1810) \rightarrow \eta\eta$ 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 $K^0_S K^0_S$





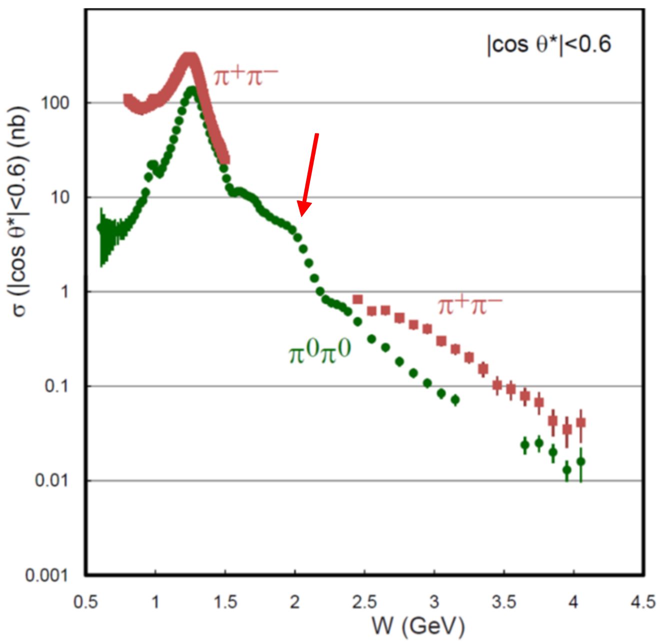
Assuming a single resonance,
J = 0 or 2 ? **J = 0 is much preferred.**

Parameter $f_J(1710)$	$f_0(1710)$ fit fit-H	fit-L	H,L combined	PDG	$f_2(1710)$ fit 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

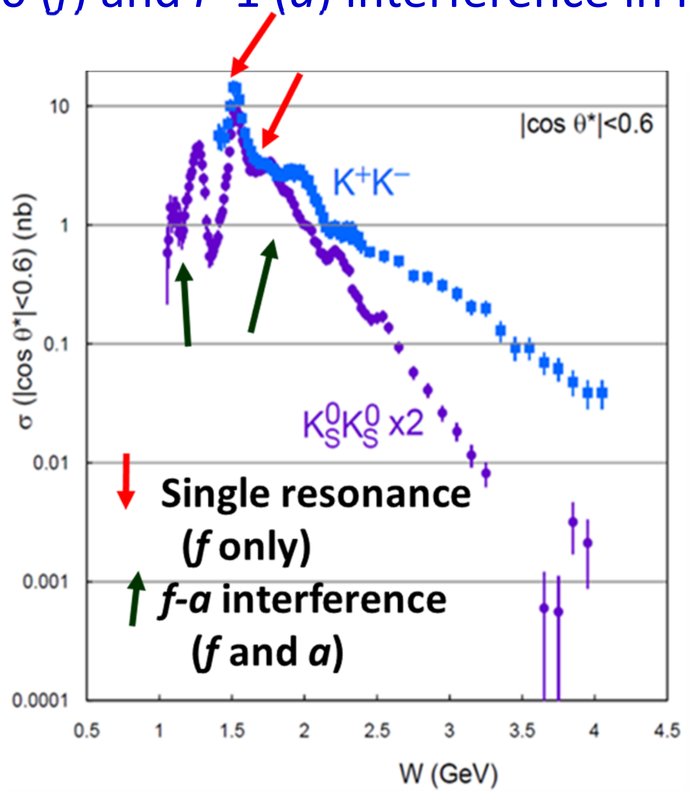
$f_0(1710) \to K^0_S K^0_S$ is confirmed in two-photon process.

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



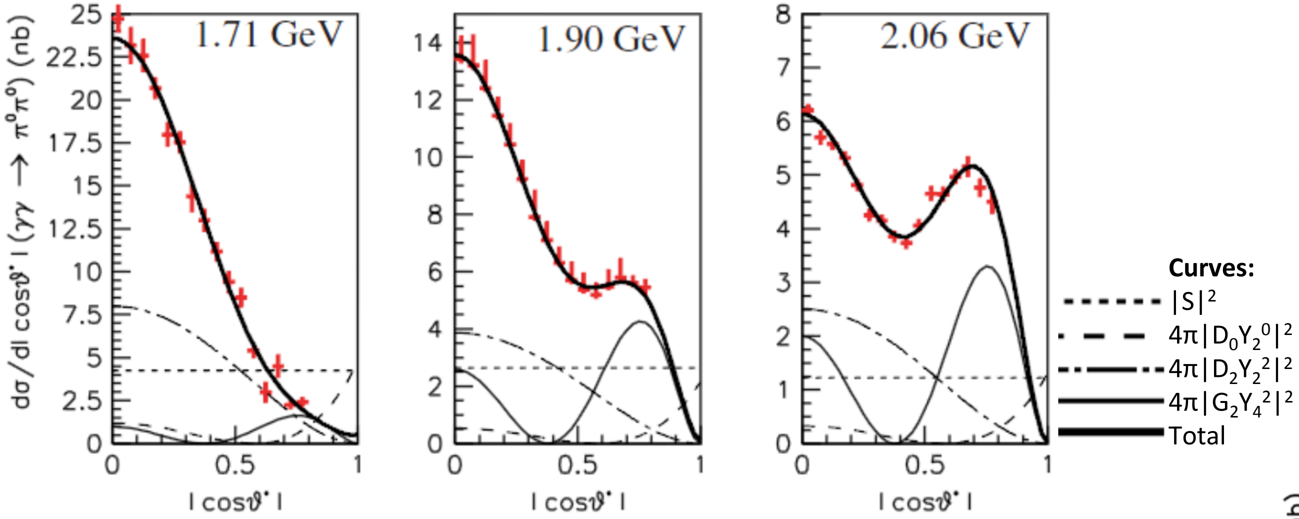
I=0 (f) and I=1 (a) interference in $K\bar{K}$

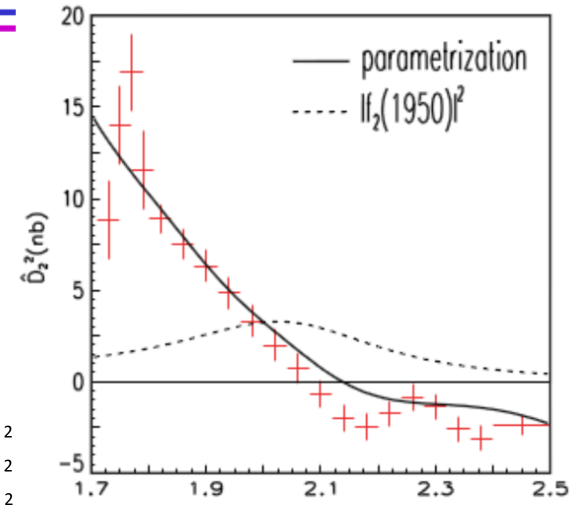


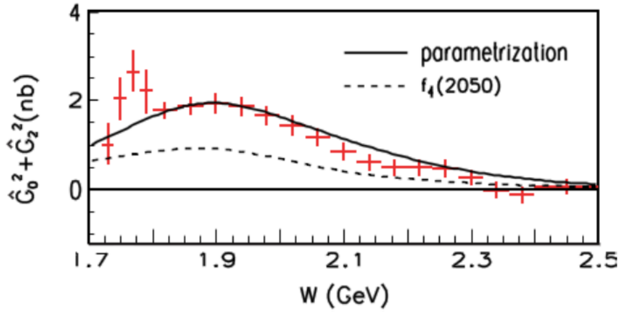
Parameter	$f_4(2050)$	"$f_2(1950)$"	Unit
Mass	$1885^{+14}_{-13}{}^{+218}_{-25}$	$2038^{+13}_{-11}{}^{+12}_{-73}$	MeV/c^2
$\Gamma_{\rm tot}$	$453 \pm 20\,^{+31}_{-129}$	$441^{+27}_{-25}{}^{+28}_{-192}$	MeV
$\Gamma_{\gamma\gamma}\mathcal{B}(\pi^0\pi^0)$	$7.7^{+1.2}_{-1.1}{}^{+23.5}_{-5.2}$	$54^{+23}_{-14}{}^{+379}_{-68}$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

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

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







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$\chi^2(ndf)$	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.)

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^-, $K^0_S K^0_S$ and $\eta\eta$.

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

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

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

$f_J(2220)$ MASS

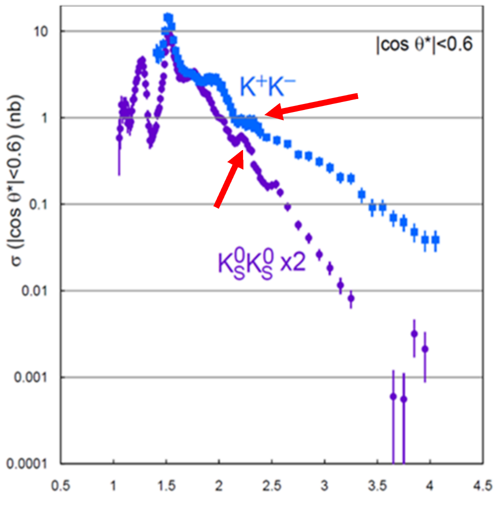
VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
2231.1 ± 3.5 OUR AVERAGE				

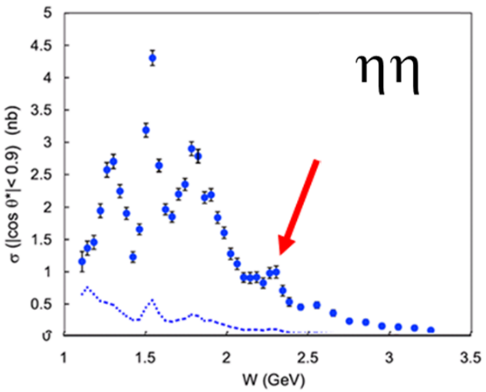
$f_J(2220)$ WIDTH

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	$K\overline{K}$	seen
Γ_4	$p\overline{p}$	
Γ_5	$\gamma\gamma$	not seen
Γ_6	$\eta\eta'(958)$	seen
Γ_7	$\phi\phi$	not seen
Γ_8	$\eta\eta$	not seen





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

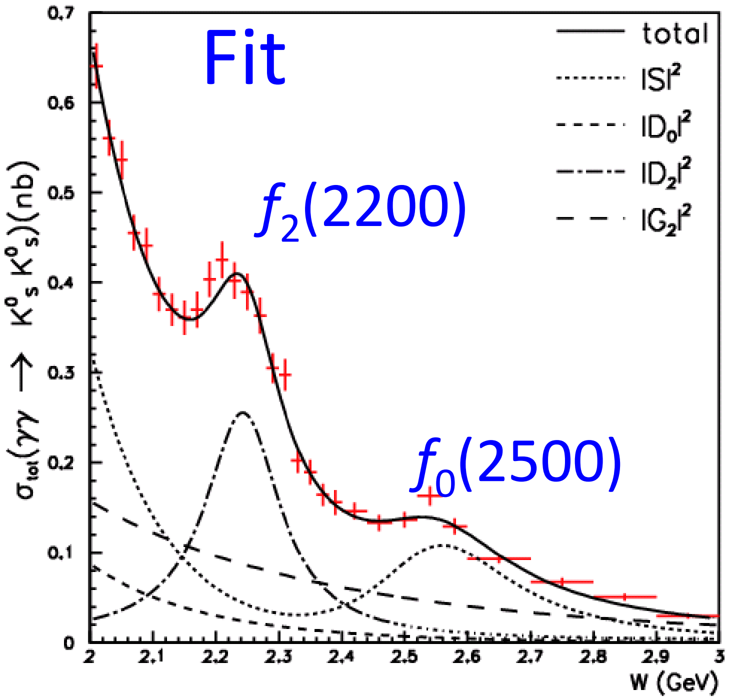
Mass $m = 2297 \pm 28$ MeV
Full width $\Gamma = 149 \pm 40$ MeV

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



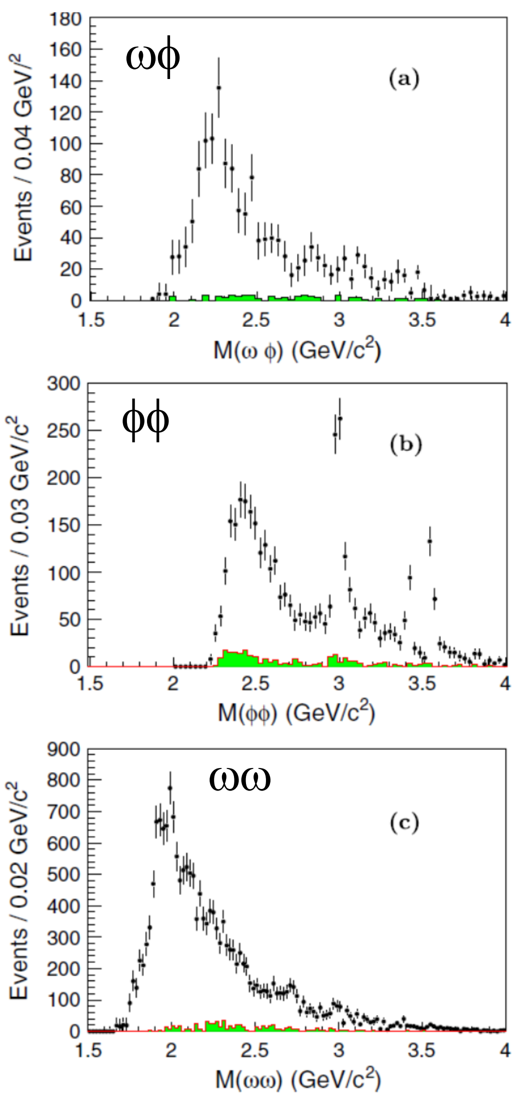
Significances

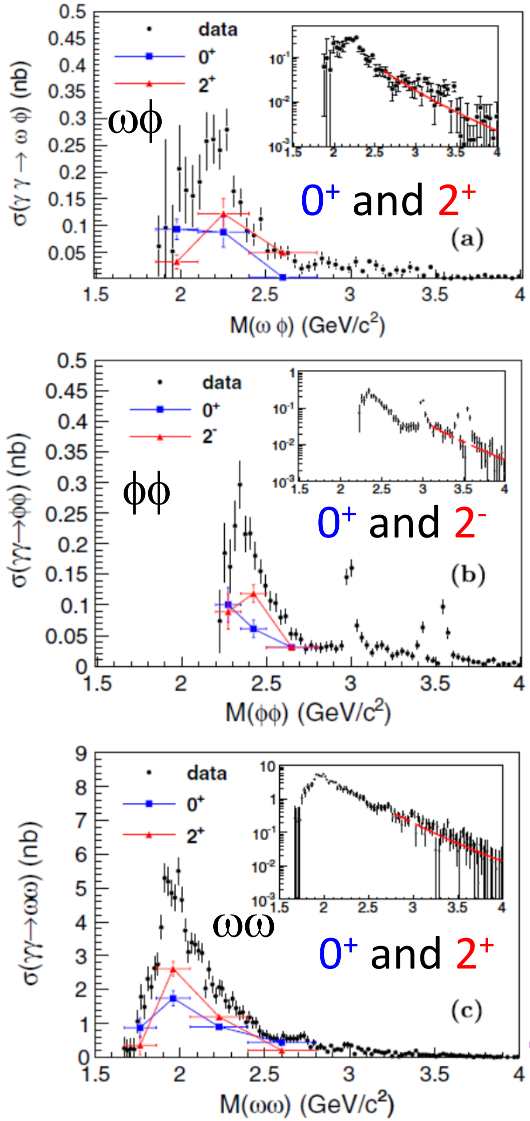
- 3.4σ for $f_2(2200)$ over $f_0(2200)$
- 4.3σ for $f_0(2500)$ over $f_2(2500)$

- 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.

“$\gamma\gamma \rightarrow$ Vector-meson pair” from Belle

Observation of New Resonant Structures in $\gamma\gamma \rightarrow \omega\phi$, $\phi\phi$, and $\omega\omega$





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.

Cross-section size for $\omega\phi$ cannot be well explained.

Slope parameters for high W:
n=7.2 ± 0.6 ($\omega\phi$)
8.4 ± 1.1 ($\phi\phi$)
9.1 ± 0.6 ($\omega\omega$)

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

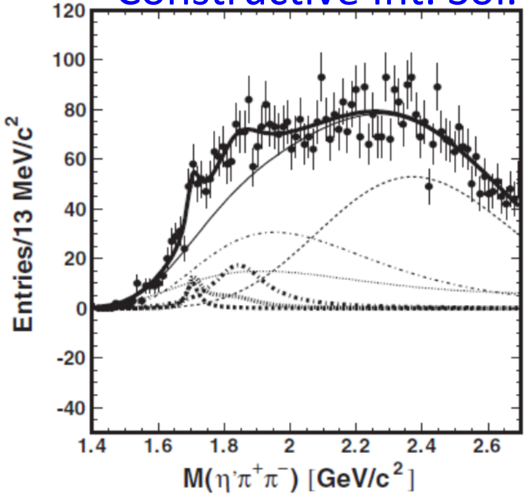
Production of light-quark mesons decaying to the **three pseudoscalar meson final state**. (The η_c production is also presented.)

Belle, PRD 86, 052002 (2012)

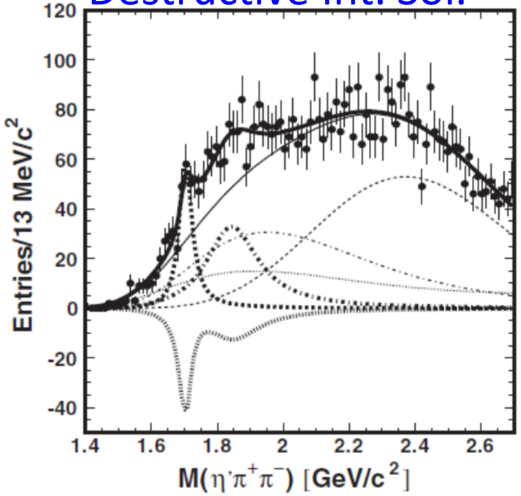
X(1835) is an exotic resonance candidate found in the radiative decay of J/ψ by BES. Is it gluon-rich, or $q\bar{q}$-rich?

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

Constructive Int. Sol.



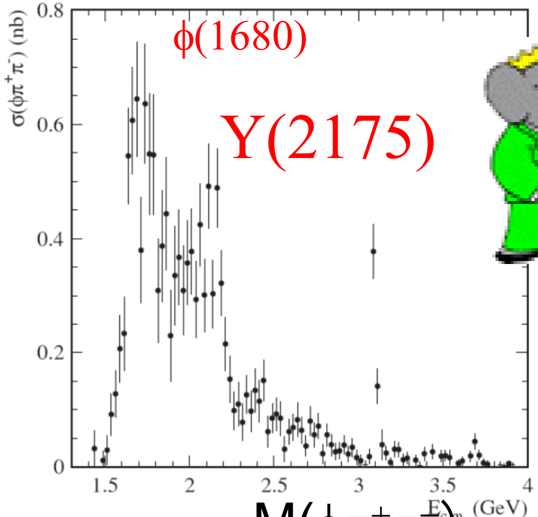
Destructive Int. Sol.



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

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	$(287^{+42}_{-51})°$	$(139^{+19}_{-9})°$	

Exotic in $s\bar{s}$ sector ? ; (ISR) $e^+e^- \to Y(2175) \to \phi\pi^+\pi^-$



M(φπ⁺π⁻)

PRD76,012008(2007)

BaBar: A clear structure above φ(1680),
Identified as Y(2175) (**φ(2170)** on PDG).

$$m_x = 2.175 \pm 0.010 \pm 0.015\ \mathrm{GeV}/c^2$$

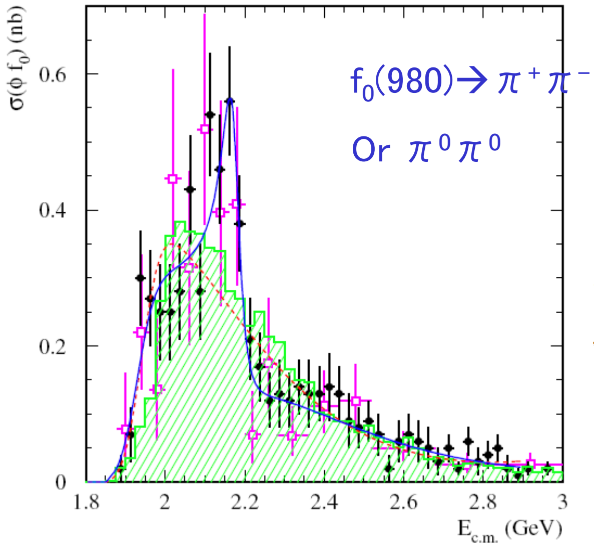
$$\Gamma_x = 0.058 \pm 0.016 \pm 0.020\ \mathrm{GeV}/c^2$$

BESII confirms

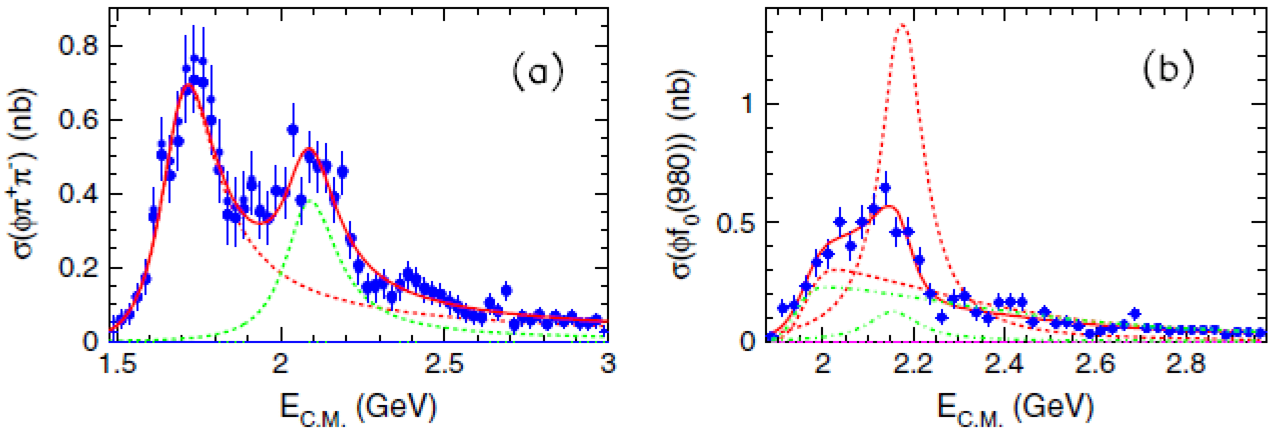
Mass = $2.186 \pm 0.010 \pm 0.006$ GeV/c²
Width = $0.065 \pm 0.023 \pm 0.017$ GeV/c²

M(Y(2175)) = $2079 \pm 13\ ^{+79}_{-28}$ MeV/c²
Γ (Y(2175))= $192 \pm 23\ ^{+25}_{-61}$ MeV/c²

PRD 80, 031101(R) (2009)



M(φf₀(980))

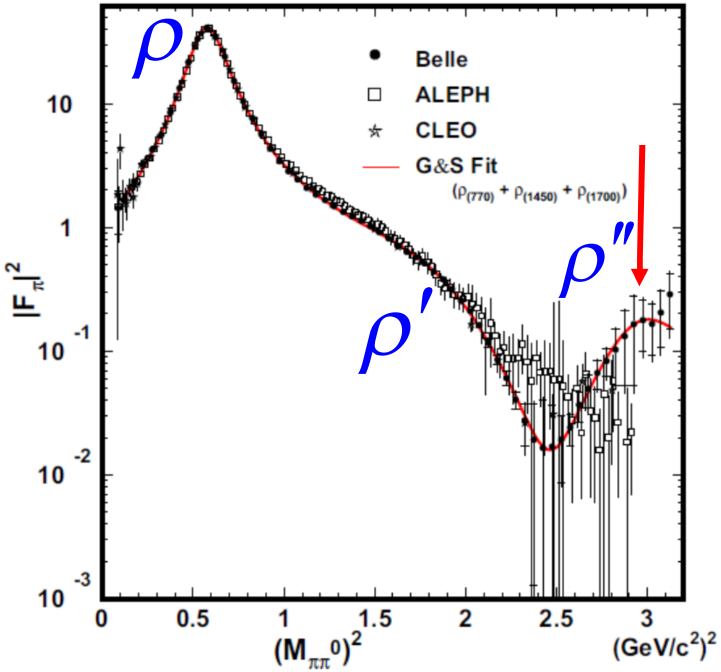


$\rho(1700)$ in $\tau^- \to \pi^- \pi^0 \nu$ Decay

PRD 78, 072006 (2008)

From 64M $\tau^+\tau^-$ pairs, Belle

selects 5.5M $\tau^- \to \pi^- \pi^0 \nu_\tau$ events!



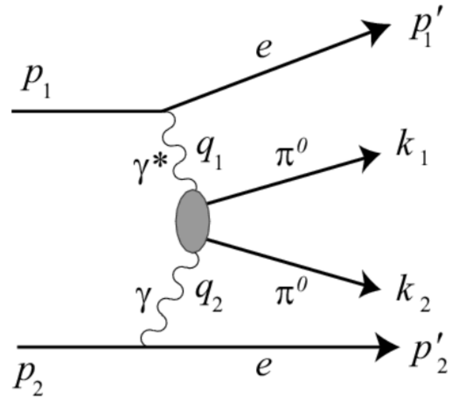
- Error bars include both statistical and systematic
- Interference between ρ' and ρ"
- ——— Fit with BW

Fit parameter	Norm fixed
Norm $\lvert F_\pi(0)\rvert^2$	[1.0]
M_ρ (MeV)	774.6±0.2±0.5
Γ_ρ (MeV)	148.1±0.4±1.7
$M_{\rho'}$ (MeV)	1446±7±28
$\Gamma_{\rho'}$ (MeV)	434±16±60
$\lvert\beta\rvert$	$0.15 \pm 0.05 \pm^{0.15}_{0.04}$
ϕ_β (degree)	$202 \pm 4 \pm^{41}_{8}$
$M_{\rho''}$ (MeV)	1728±17±89
$\Gamma_{\rho''}$ (MeV)	$164 \pm 21 \pm^{89}_{26}$
$\lvert\gamma\rvert$	$0.028 \pm 0.020 \pm^{0.059}_{0.009}$
ϕ_γ (degree)	$24 \pm 9 \pm^{118}_{28}$
χ^2/d.o.f	80/52

$\gamma^*\gamma \to \pi^0\pi^0$: f_0 (980) and f_2 (1270) TFF's

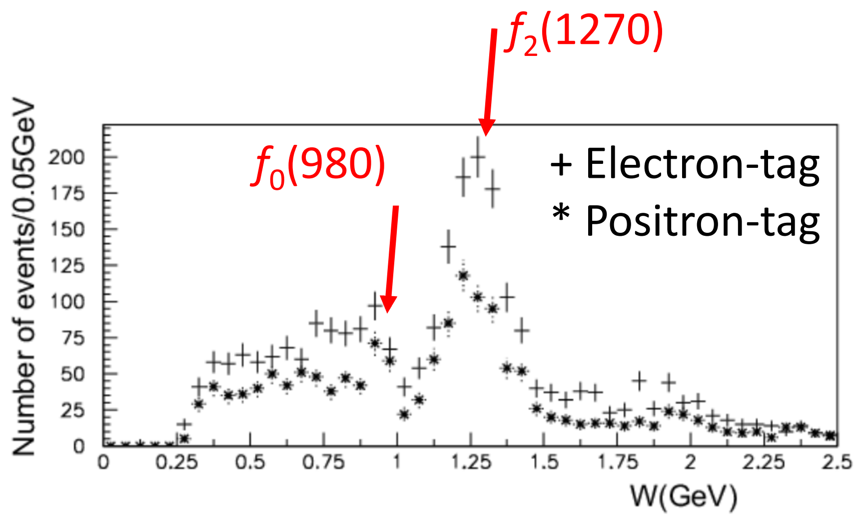
TFF: Transition Form Factor

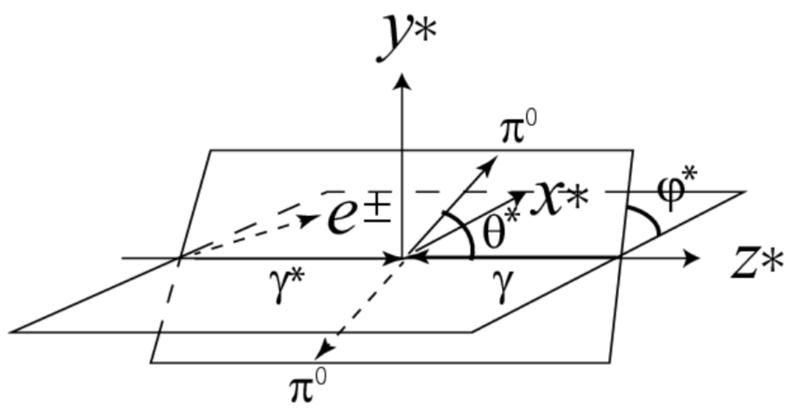
PRD 93, 032003 (2016)



Physics motivations:

- Q^2 dependence of TFF for scalar and tensor mesons
  (This is the first measurement)
- Test of QCD of $q\bar{q}$ meson model
- Light-by-Light – hadronic contribution for g-2$|_\mu$





The f_0/f_2 ratio is larger than in the no-tag case.

Formalism of PWA

$$|F(Q^2)| = \sqrt{\frac{\sigma_R^\lambda(Q^2)}{\sigma_R(0)(1+\frac{Q^2}{M^2})}}$$

TFF is defined for each resonance R produced with each helicity λ

$$\frac{d\sigma(\gamma^*\gamma \to \pi^0\pi^0)}{d\Omega} = \sum_{n=0}^{2} t_n \cos(n\varphi^*),$$

$$\begin{aligned} t_0 &= |M_{++}|^2 + |M_{+-}|^2 + 2\epsilon_0|M_{0+}|^2, \\ t_1 &= 2\epsilon_1 \Re\left((M_{+-}^* - M_{++}^*)M_{0+}\right), \\ t_2 &= -2\epsilon_0\Re(M_{+-}^* M_{++}), \end{aligned}$$

To obtain the resonance amplitudes:

Perform PWA, parameterizing W dependence of the resonance and continuum components of each helicity amplitude, e.g.,

$M_{++} = S + D_0$,

$S = B_S(W) + A_{f0}(W)$

$D_0 = 4\pi\, [B_{D0}(W) + A_{f2}(W)\sqrt{r_{20}}]\, Y_2^0$

etc.

Determine each component as well as the relative phase by a fit

++ etc. --- Helicity state of the incident photons

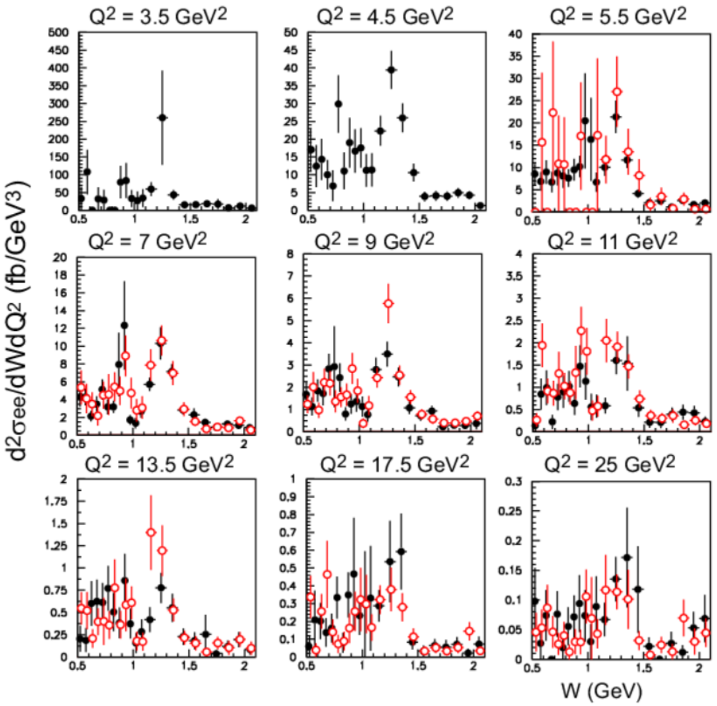
S, D_0 etc. -- Partial-wave amplitude in $\pi^0\pi^0$ scattering

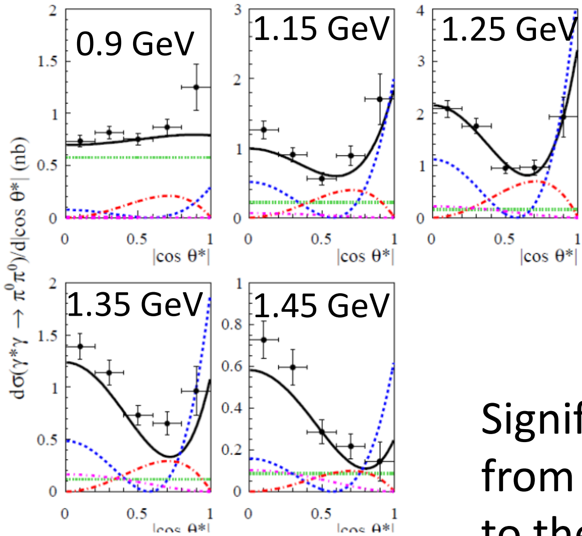
B, A_f -- Background and f-resonance components.

ε_0, ε_1 --- A spin-dependent flux factor ratio for the virtual-photons

Cross-section results and fit

Consistency check between electron-tag(•) and positron-tag(o)

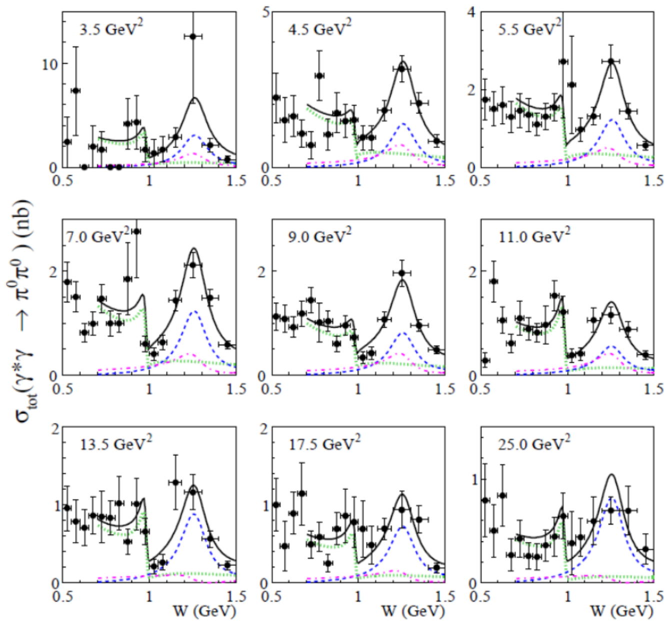




|cos θ*| dependence for Q^2 = 9 GeV^2 and different W bins

lines: solid= total, dotted= $|S|^2$, dashed= $|D_0|^2$, and dash-dotted= $|D_2|^2$

Significant contributions from hel.=0 and 1 in contrast to the no-tag (Q^2=0) case



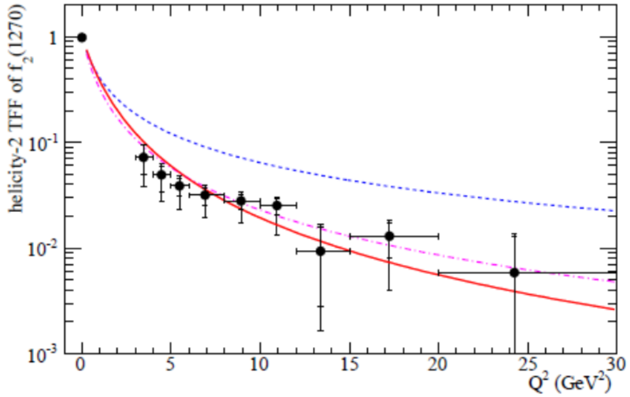
Final result of γ*γ cross sections and PWA fits

The curves are PWA fit constructed by parameterized resonant (f_0(980) and f_2(1270)) and continuum amplitudes.

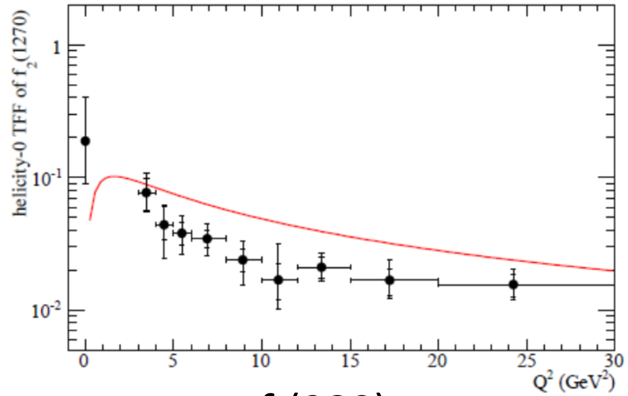
Q^2 dependence of resonant amplitudes

$$|F(Q^2)| = \sqrt{\frac{\sigma_R^{\lambda}(Q^2)}{\sigma_R(0)\left(1+\frac{Q^2}{M^2}\right)}}$$

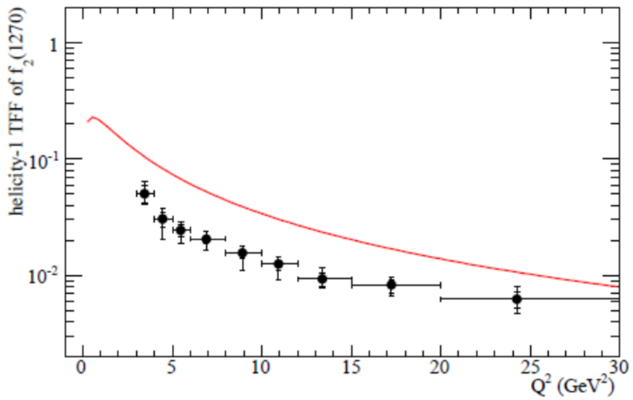
$f_2(1270)$, helicity = 2



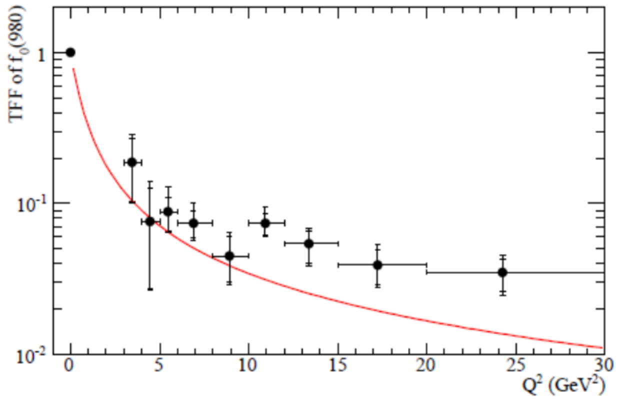
$f_2(1270)$, helicity = 0



$f_2(1270)$, helicity = 1



$f_0(980)$



Theoretical predictions:

Schuler, Berends, van Gulik, a heavy quark approx. NPB 523, 423 (1998)

Pascalutes, Pauk, Vanderhaeghen, saturated sum rule, PRD 85, 116001 (2012), η's

ibid., axial-vector mesons

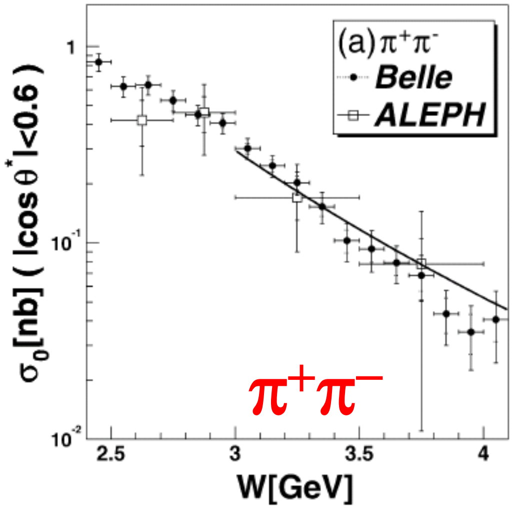
Summary

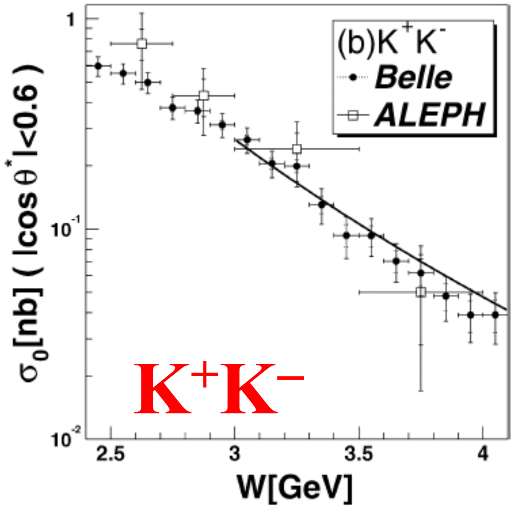
- $\gamma\gamma \to$ pseudoscalar-meson pair have been measured in six different final states. Measure $\Gamma\gamma\gamma(\times BF)$ for various $J^{PC}=(even)^{++}$ mesons
- The $\gamma\gamma$-invariant-mass region, 0.6 – 2.6 GeV, is studied for light-meson spectroscopy.
- We have confirmed:
  - $\gamma\gamma$ 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.
- Other topics: Y(2175), $\rho(1700)$, TFFs for $f_0(980)$ and $f_2(1270)$.

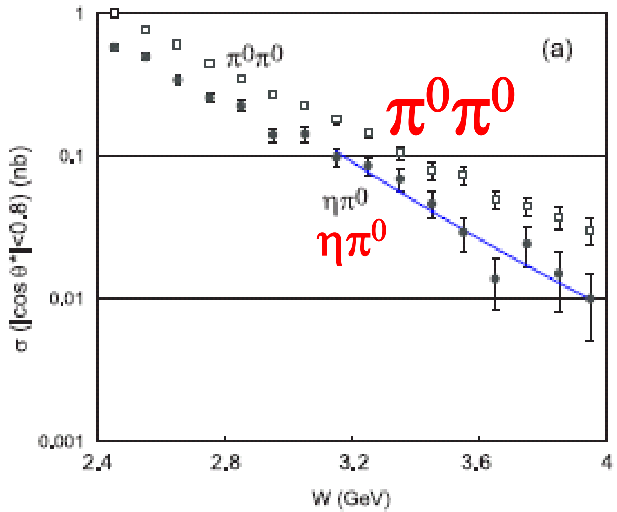
Backup

W-dependences at high energies

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



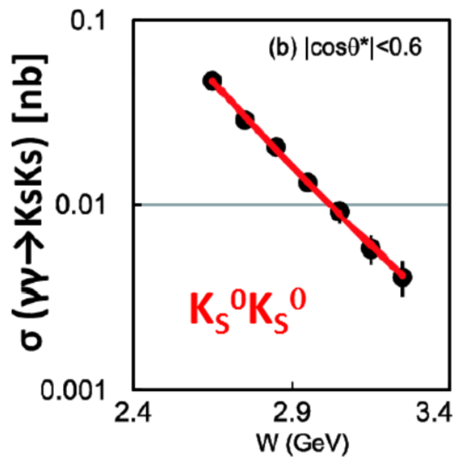


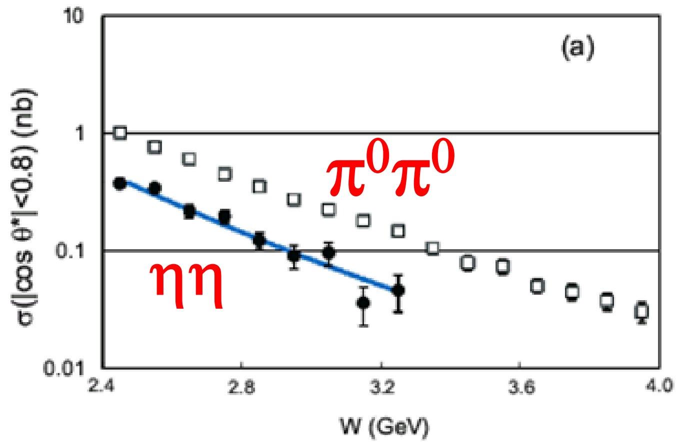


Fitted and reproduced

Slope parameter **n** different among the reactions

Charmonium contributions not included/removed





Cross sections and their ratios

Process	n	W(GeV)	$\lvert\cos\theta^*\rvert$	BL	BC	DKV
$K_S^0 K_S^0$	$11.0 \pm 0.4 \pm 0.4$	2.4 - 4.0†	< 0.8		10	
$\pi^+\pi^-$	$7.9 \pm 0.4 \pm 1.5$	3.0 - 4.1	< 0.6	6	6	
K^+K^-	$7.3 \pm 0.3 \pm 1.5$	3.0 - 4.1	< 0.6	6	6	
$\pi^0\pi^0$	$8.0 \pm 0.5 \pm 0.4$	3.1 - 4.1†	< 0.8		10	
$\eta\pi^0$	$10.5 \pm 1.2 \pm 0.5$	3.1 - 4.1	< 0.8		10	
$\eta\eta$	$7.8 \pm 0.6 \pm 0.4$	2.4 – 3.3	< 0.8		10	
Process	σ_0 ratio	W(GeV)	$\lvert\cos\theta^*\rvert$	BL	BC	DKV
$K^+K^-/\pi^+\pi^-$	$0.89 \pm 0.04 \pm 0.15$	3.0 - 4.1	< 0.6	2.3	1.06	
$K_S K_S/K^+K^-$	~ 0.10 to ~ 0.03	2.4 - 4.0	< 0.6		0.005	2/25
$\pi^0\pi^0/\pi^+\pi^-$	$0.32 \pm 0.03 \pm 0.06$	3.1 - 4.1	< 0.6		0.04-0.07	0.5
$\eta\pi^0/\pi^0\pi^0$	$0.48 \pm 0.05 \pm 0.04$	3.1 - 4.0	< 0.8	$0.24R_f(0.46R_f)^\ddagger$		
$\eta\eta/\pi^0\pi^0$	$0.37 \pm 0.02 \pm 0.03$	2.4 - 3.3	< 0.8	$0.36R_f^2(0.62R_f^2)^\ddagger$		

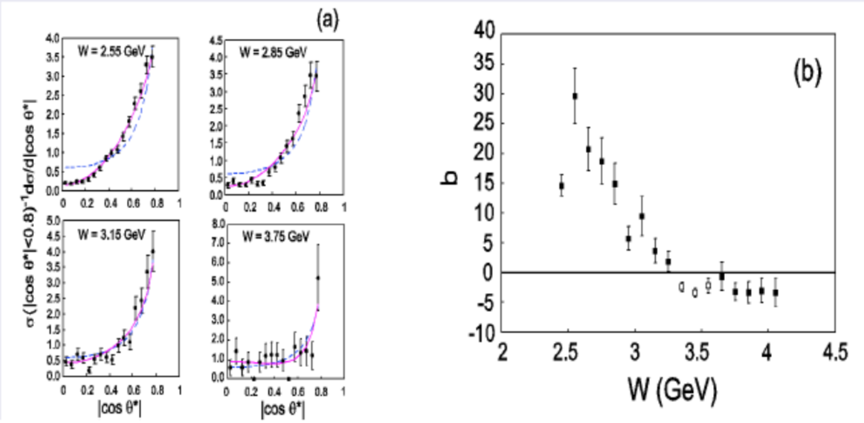
$\dagger$ Exclude χ_{cJ} region, 3.3 - 3.6 GeV.
$\ddagger$ Assuming η is a member of SU(3) octet (superposition of octet and singlet with mixing angle of $\theta_p = -18°$).
R_f is a ratio of decay constants, $f_\eta^2/f_{\pi^0}^2$.

- n ranges 7 to 11. Close or not far from QCD prediction of 6 and 10.
- Cross section ratios tend to be constant above 3 GeV.

Summarized by H.Nakazawa Hadron2013

Angular dependence

$\gamma\gamma \to \pi^0\pi^0$



dσ/d|cosθ*|∝sin^{-4}θ* is predicted by $q\bar{q}$-meson model and perturbative QCD

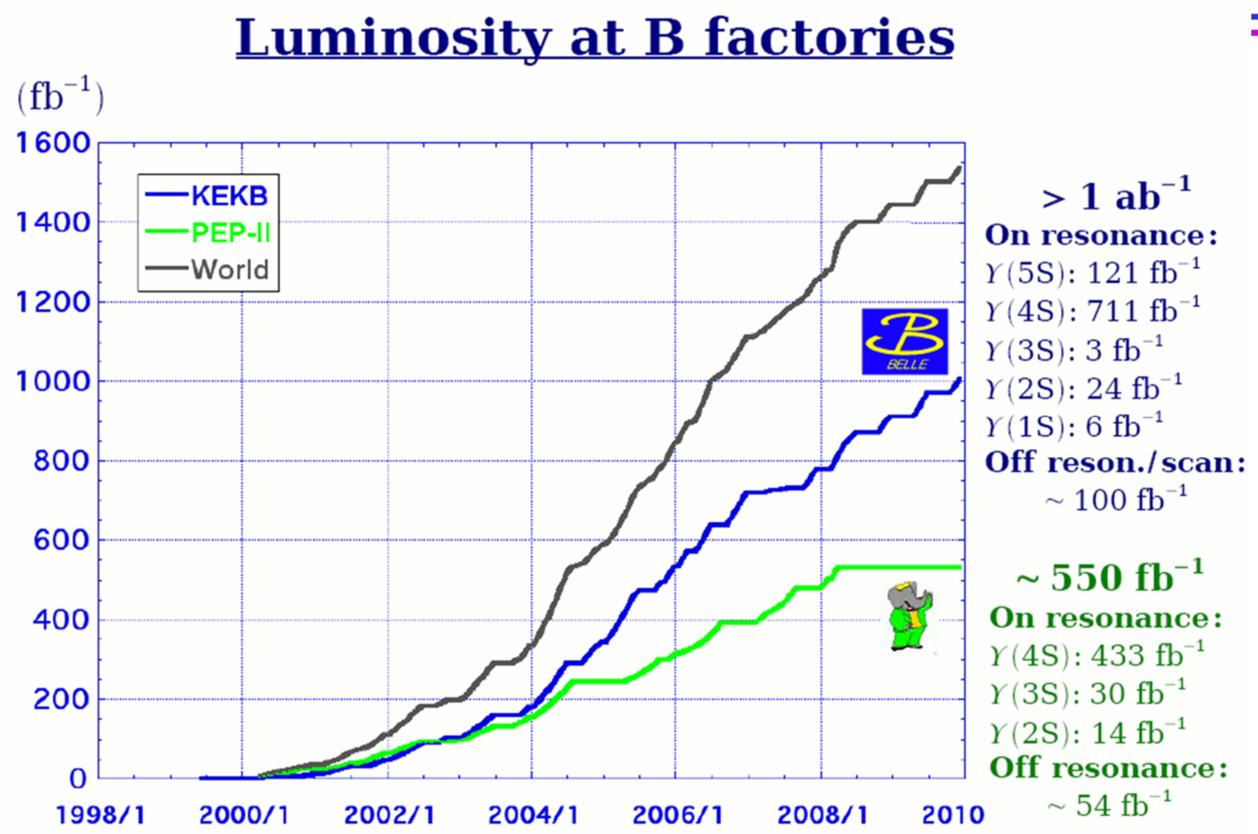
- Fit to $\sin^{-4}\theta^* + b\cos\theta^*$
- b becomes constant above 3.2 GeV.

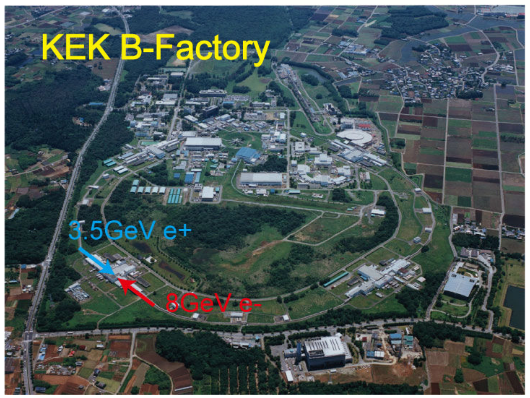
mode	α in $\sin^{-\alpha}\theta^*$	GeV	$\lvert\cos\theta^*\rvert$
$K_S K_S$	3 – 8	2.6 - 3.3	< 0.8
$\pi^+\pi^-$	Good agreement with 4	3.0 - 4.1	< 0.6
K^+K^-	Good agreement with 4	3.0 - 4.1	< 0.6
$\pi^0\pi^0$	Better agreement with $\sin^{-4}\theta^* + b\cos\theta^*$ Approaches $\sin^{-4}\theta^*$ above 3.1 GeV	2.4 - 4.1†	< 0.8
$\eta\pi^0$	Good agreement with 4 above 2.7 GeV	3.1 - 4.1	< 0.8
$\eta\eta$	Poor agreement with 4 Close to 6 above 3 GeV	2.4 - 3.3	< 0.9

Exclude † χ_{cJ} region, 3.3 - 3.6 GeV

Summarized by H.Nakazawa
Hadron2013

History of integrated luminosity at Belle

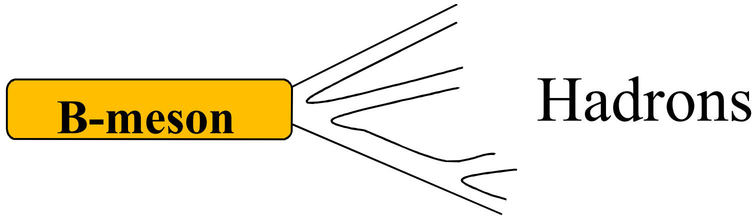




1999	The Belle experiment started
2001	CP violation in B mesons was verified and the KEKB accelerator achieved the world's highest luminosity
2002	Anomalous CP violation in b → s was measured
2003	The B → Kll decay was discovered
2004	The New particle X (3872) was discovered
2005	Direct violation of CP in B → Kπ was found. The B → $\rho\gamma$ decay was discovered
2006	B → $\tau\nu$ 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

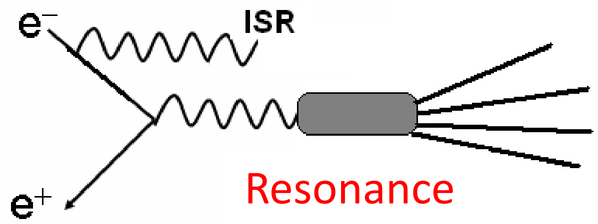
Introduction : Hadron production processes at B-factory Experiments

Hadronic decays of B meson

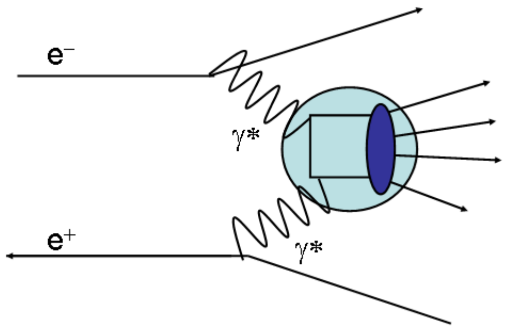


e^+e^- annihilation processes

ISR processes →



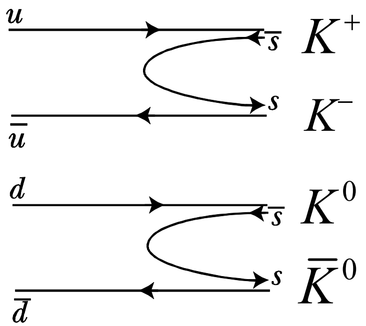
two-photon collisions



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)



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

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

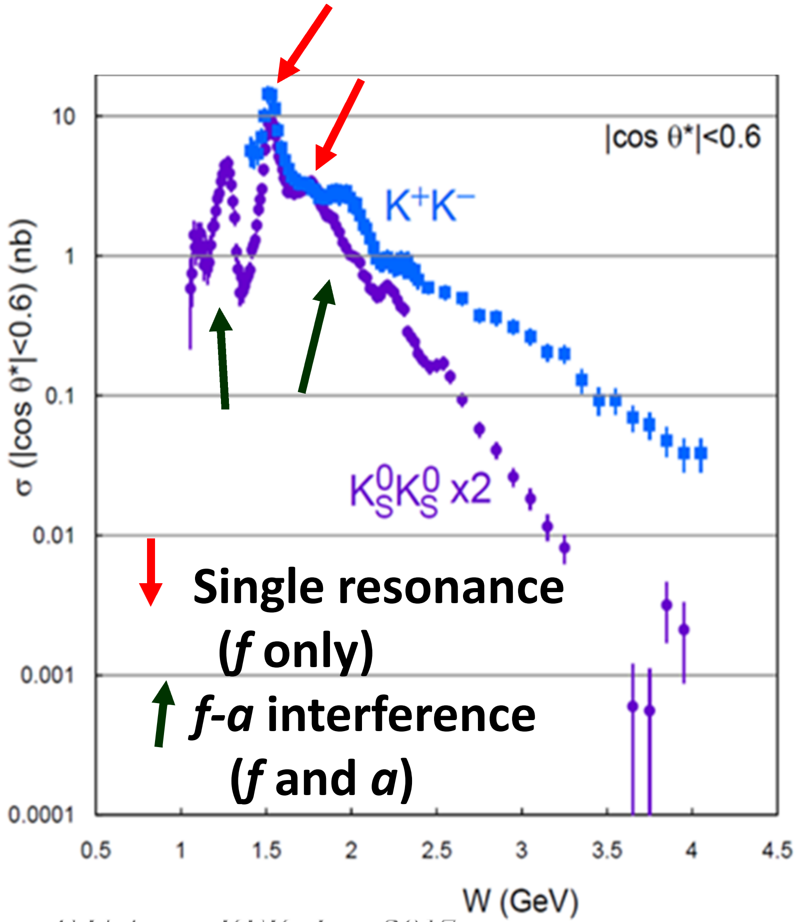
Size of the cross sections for K^+K^- and $K^0\bar{K}^0$

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

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

If they are very different →

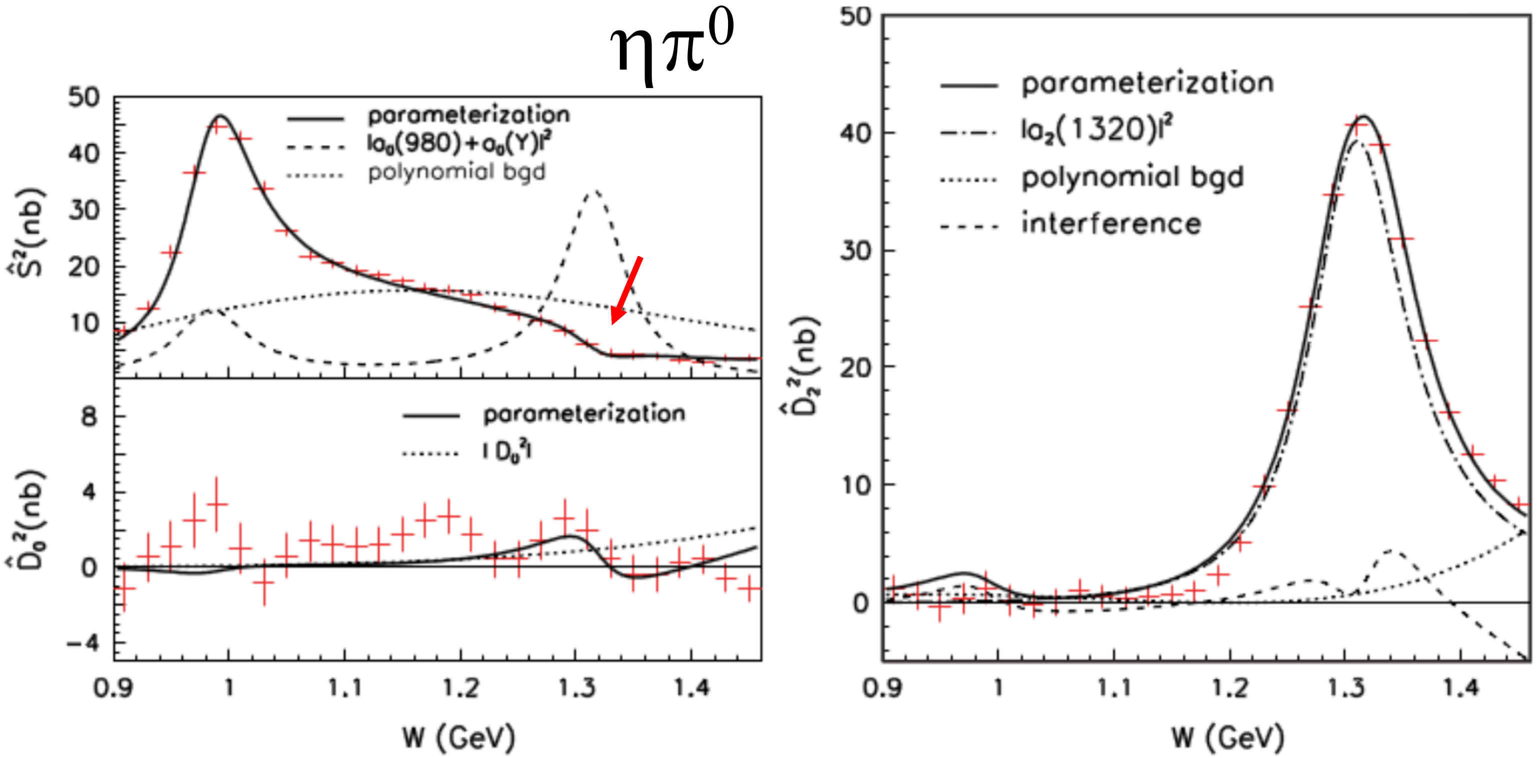
Interference between I=0 and I=1 resonances, or effective (electromagnetic) continuum production



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

The I=1 sector

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

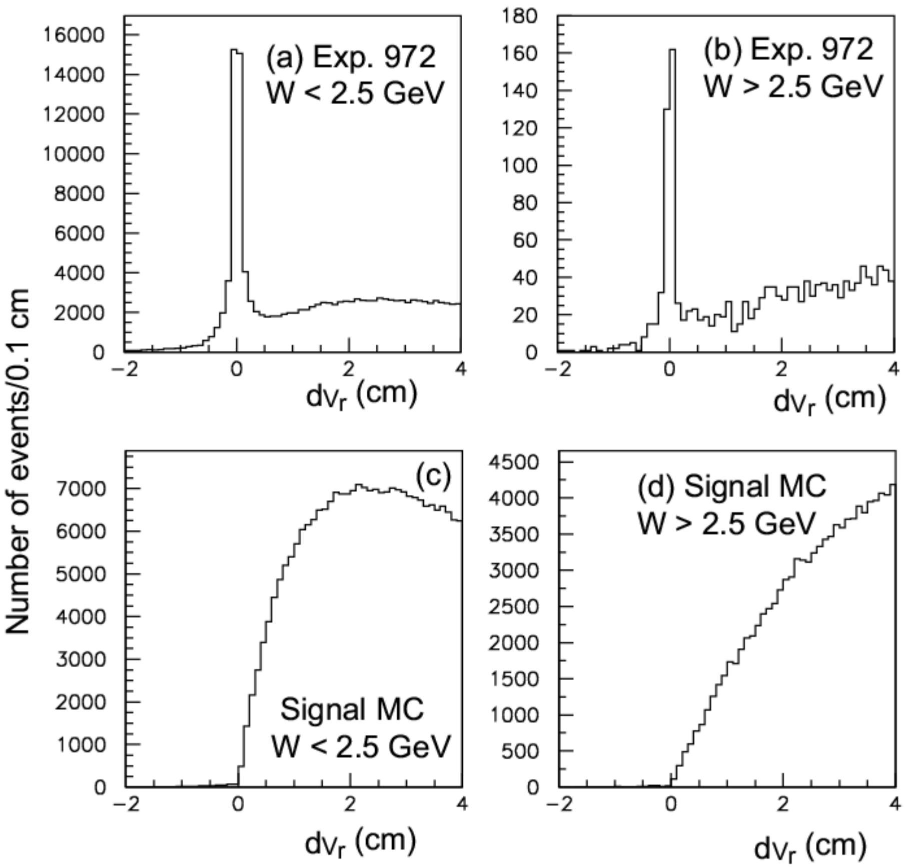


Parameter	This work	$a_0(1450)$ (PDG)	Unit
Mass	$1316.8^{+0.7+24.7}_{-1.0-4.6}$	1474 ± 19	MeV/c^2
Γ_{tot}	$65.0^{+2.1+99.1}_{-5.4-32.6}$	265 ± 13	MeV
$\Gamma_{\gamma\gamma}\mathcal{B}(\eta\pi^0)$	$432 \pm 6^{+1073}_{-256}$	unknown	eV

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

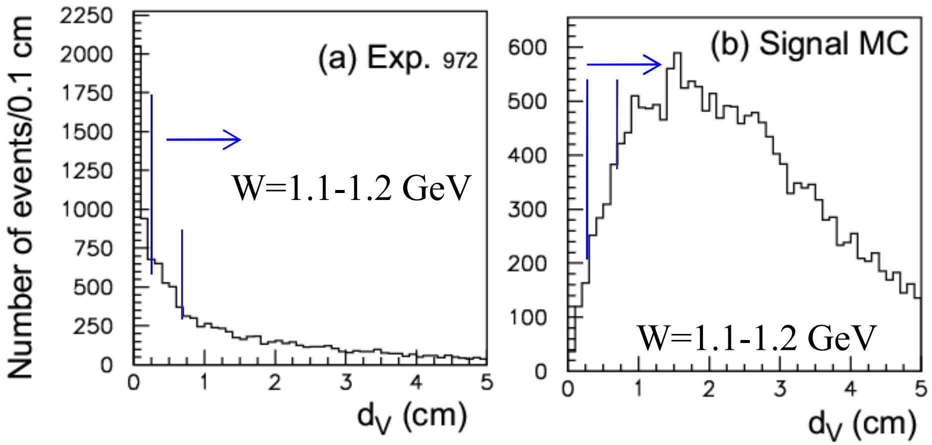
Ks Ks vertex distances

2D vertex distance

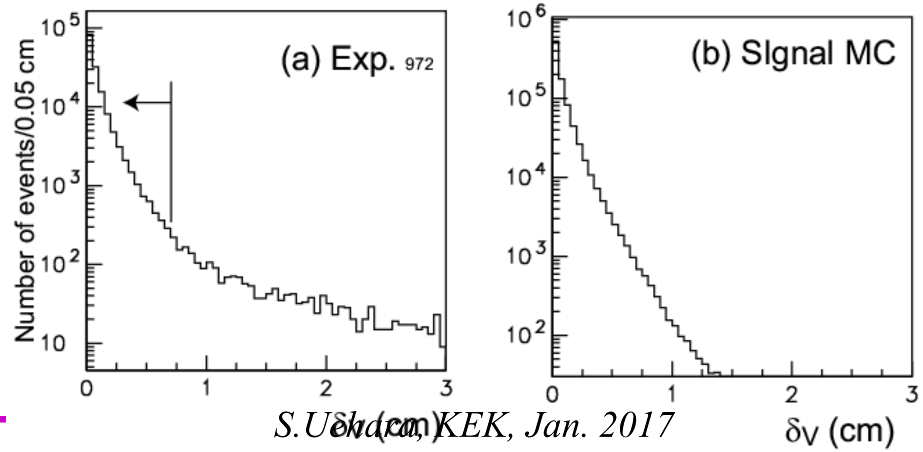


Sharp peaks near 0cm seen only in Exp.are from Direct 4π ($\pi^+\pi^-\pi^+\pi^-$) production backgrounds.

3D vertex distance



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_{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

A Half of the subtraction + 2% from pt-fit (quad.sum)

Loose-cut sample

Correlation of the two triggers

About 10% of the inefficiency

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))

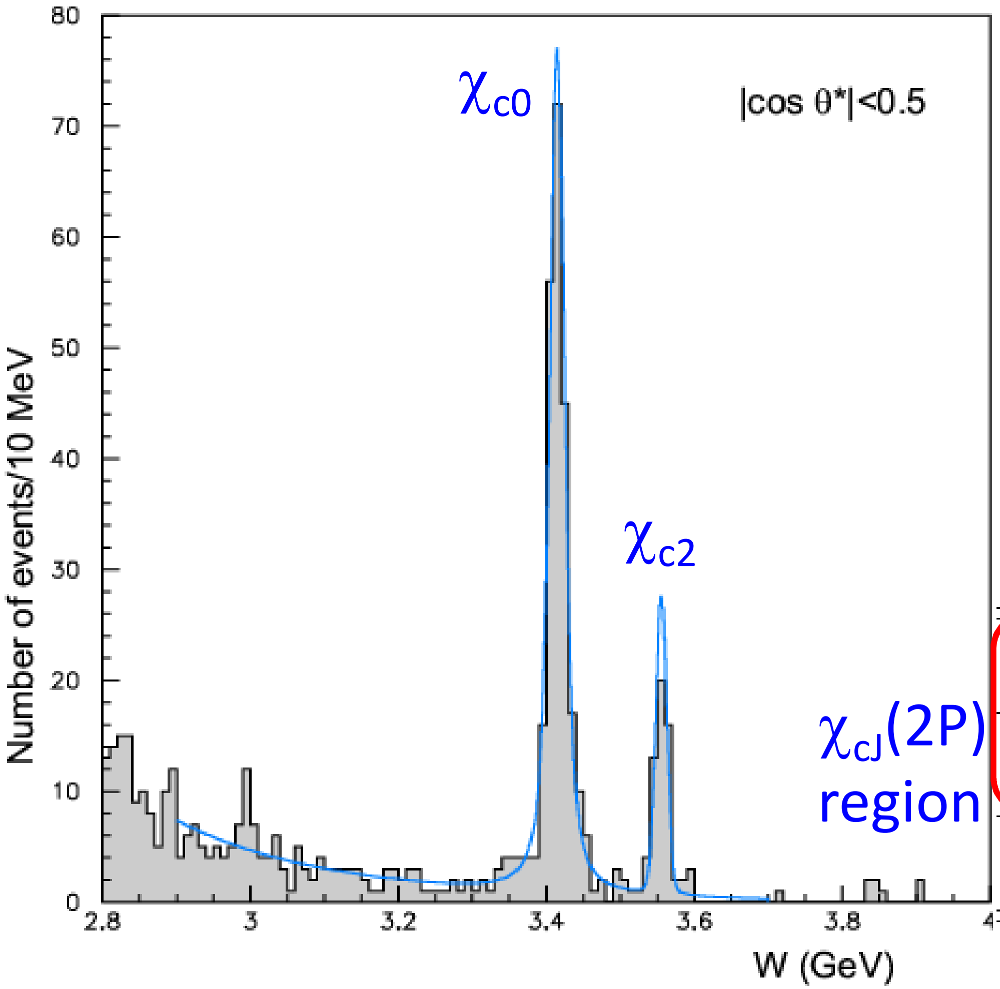
B.W.= f_J(2200) and/or f_J(2500) with J=0, 2 and 4

- 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

Charmonia χ_{c0} and χ_{c2}



Yield

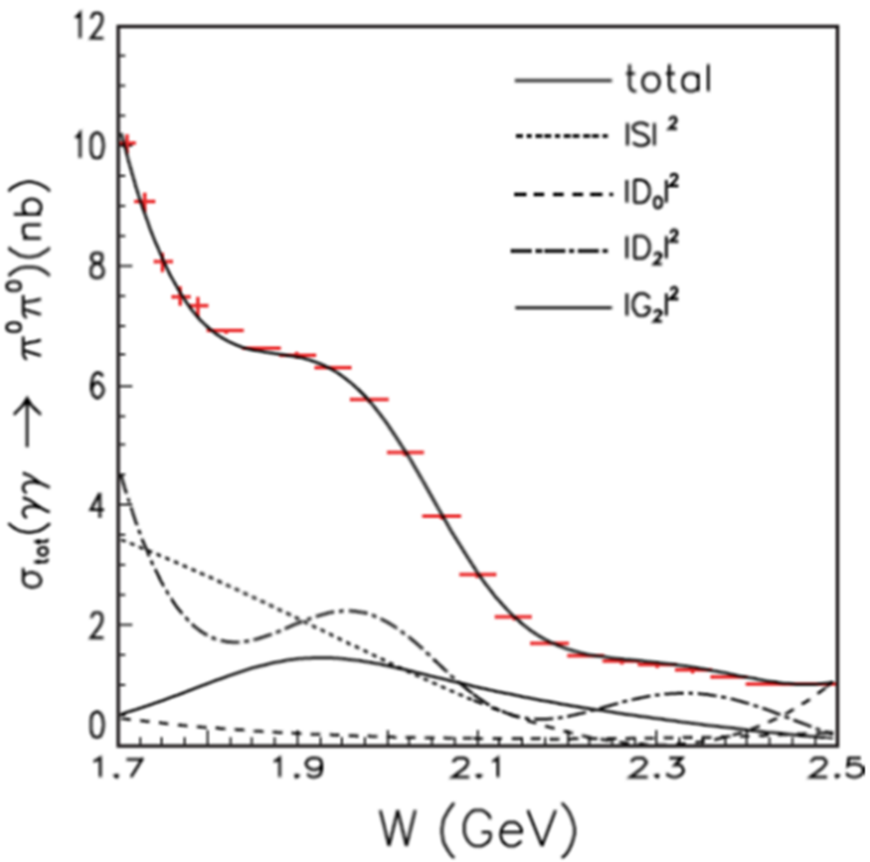
Interference	$N_{\chi c0}$	$N_{\chi c2}$	$-2\ln\mathcal{L}/ndf$
not included	$248.3^{+17.9}_{-17.2}$	$53.0^{+8.1}_{-7.4}$	$57.34/73$
included	266 ± 53	53^{+14}_{-12}	$57.22/71$

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

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



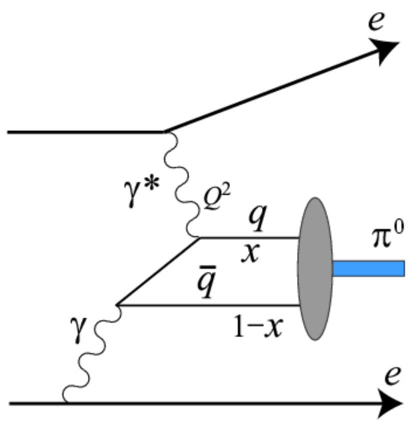
Parameter	$f_4(2050)$	"$f_2(1950)$"	Unit
Mass	$1885^{+14}_{-13}{}^{+218}_{-25}$	$2038^{+13}_{-11}{}^{+12}_{-73}$	MeV/c^2
Γ_{tot}	$453 \pm 20^{+31}_{-129}$	$441^{+27}_{-25}{}^{+28}_{-192}$	MeV
$\Gamma_{\gamma\gamma}\mathcal{B}(\pi^0\pi^0)$	$7.7^{+1.2}_{-1.1}{}^{+23.5}_{-5.2}$	$54^{+23}_{-14}{}^{+379}_{-68}$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

π^0 Transition Form Factor

PRD 86, 092007 (2012)

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

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:

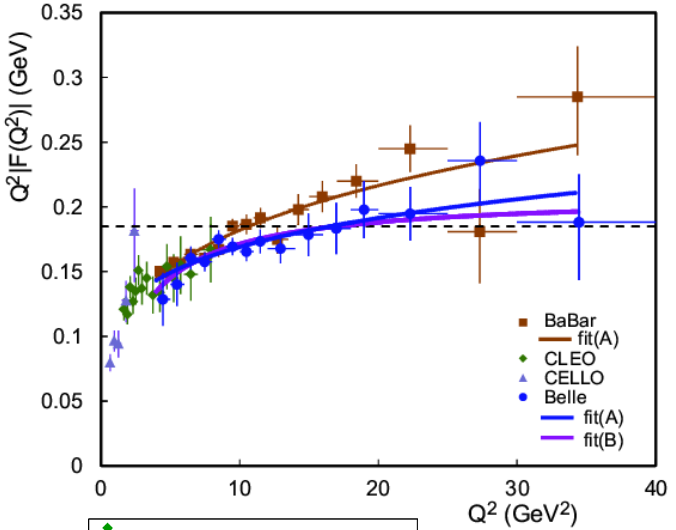
$|F(Q^2)|^2 = |F(Q^2,0)|^2 = (d\sigma/dQ^2)/(2A(Q^2))$ A(Q^2) is calculated by QED

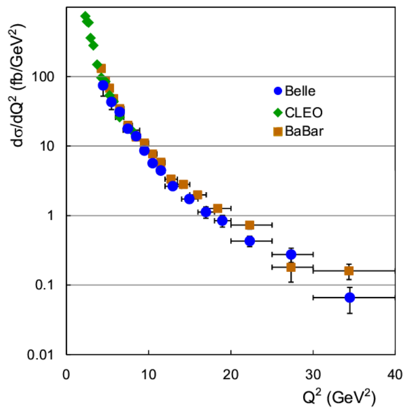
$|F(0,0)|^2 = 64\pi\Gamma_{\gamma\gamma}/\{(4\pi\alpha)^2 m_R^3\}$

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

$\beta = 0.25 \pm 0.02$

BaBar, PRD 80, 052002 (2009)

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)

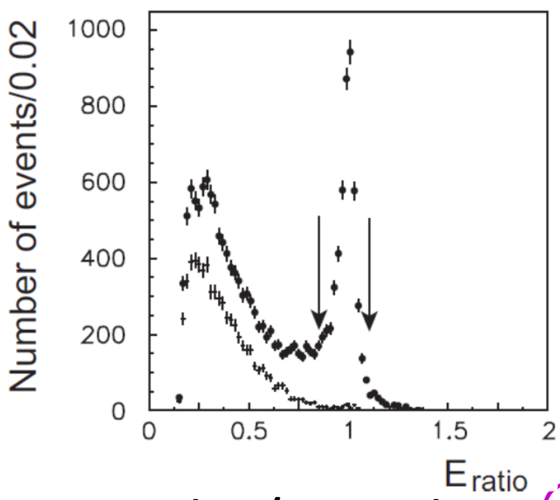
Selection of the $\pi^0\pi^0$ signals

Important selection criteria:

One electron and two π^0's

Three-body kinematics for tagged-*e*, untagged-*e* and the $\pi^0\pi^0$ system

Small acoplanarity angle and pt-balance for tagged-*e* and the $\pi^0\pi^0$



Measured $E_{\pi\pi}$/Expected $E_{\pi\pi}$