Two-photon Physics at Belle, KEKB

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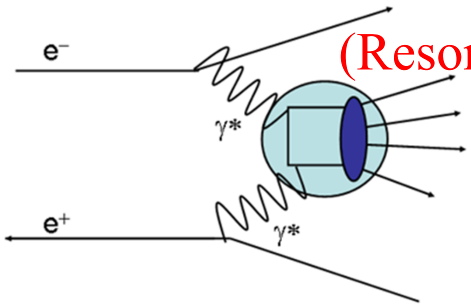
Belle Collaboration

第12回 高エネルギーQCD・核子構造 勉強会
July 7, 2017

Two-photon Physics at e^+e^- collider



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

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**

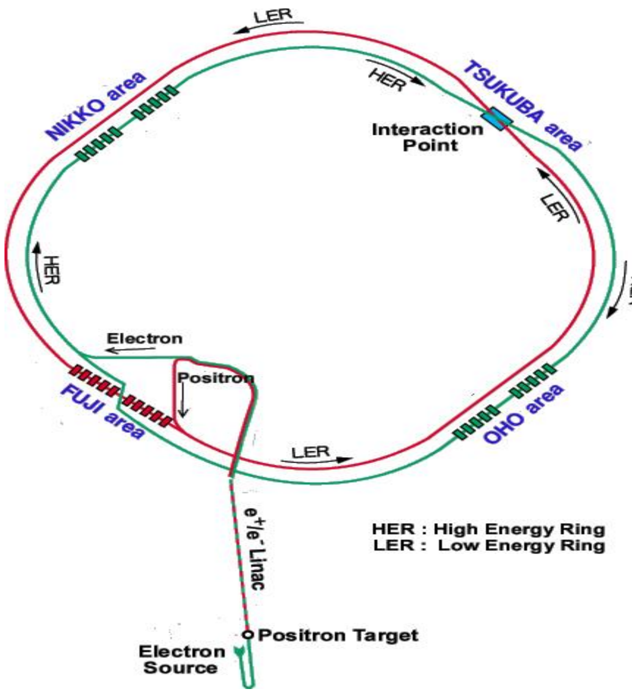
Isospin mixing, interference effects among various processes

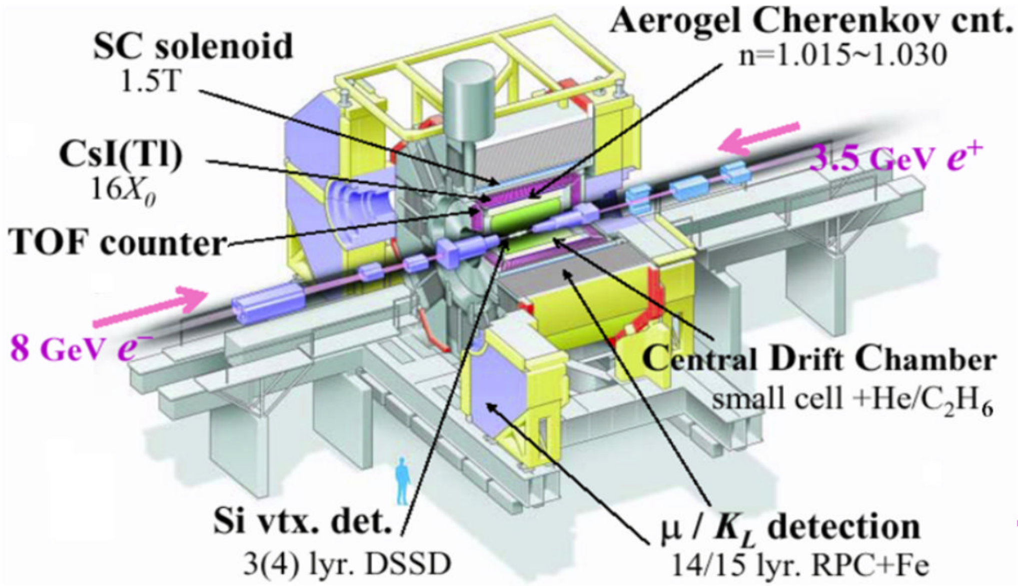
Form factors, Test of QCD (including a use of **highly virtual photons**)

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
  $L_{max}=2.1\times10^{34}\ cm^{-2}s^{-1}$
  ∫ 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

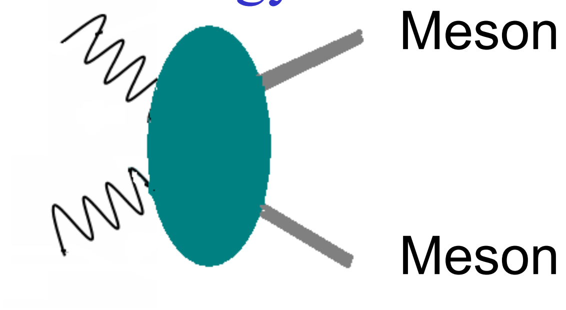
Published Two-photon Results from Belle

Process	Reference	Int. Lum.	$\gamma\gamma$ c.m. energy	Light Mesons	Charm.	**Comments**
$p\bar{p}K^+K^-$	PRD93,112017(2016)	980 fb^{-1}	3.2-5.6 GeV	$\Lambda(1520)$, $\Theta(11540)$	$\chi_{c0,c2}$	Pentaquarks
$\gamma*\gamma\to\pi^0\pi^0$	PRD93, 032003 (2016)	759 fb^{-1}	Q^2<30 GeV^2	f0(980), f2(1270)		Single tag, scalar and tensor meson TFF
$K_S^0K_S^0$	PTEP 2013, 123C01 (2013)	972 fb^{-1}	1.05-4.0 GeV	$f_2(1270)$, $a_2(1320)$, $f_0(2500)$ $f_2'(1525)$, $f_2(2200)$, $f_0(1710)$	$\chi_{c0,c2}$ η_c	Neutral P-meson pair
$\eta'\pi^+\pi^-$	PRD 86, 052002 (2012)	673 fb^{-1}	1.4-3.4 GeV	$\eta(1760)$, X(1835)	η_c	P-, PT- mesons
$\gamma\gamma^*\to\pi^0$	PRD 86, 092007 (2012)	759 fb^{-1}	4 <Q^2< 40 GeV^2			Single tag, pi0 TFF
$\omega\varphi$, $\varphi\varphi$, $\omega\omega$	PRL 108, 232001 (2012)	870 fb^{-1}	< 4.0 GeV		$\chi_{c0,c2}$ η_c	Neutral V-meson pairs
$\eta\eta$	PRD82,114031(2010)	393 fb^{-1}	1.096-3.8 GeV	$f_2(1270)$, $f_2'(1525)$	$\chi_{c0,c2}$	Neutral P-meson pair
$\omega J/\psi$	PRL104, 092001 (2010)	694 fb^{-1}	3.9-4.2 GeV		X(3915)	Exotic charmonium-like
$\phi J/\psi$	PRL 104, 112004 (2010)	825 fb^{-1}	4.2-5.0 GeV		X(4350) 21	Exotic charmonium-like
$\eta\pi^0$	PRD80:032001, 2009	223 fb^{-1}	0.84-4.0 GeV	$a_0(980)$, $a_0(1450)$, $a_2(1320)$		Neutral P-meson pair
$\pi^0\pi^0$	PRD79:052009,2009	223 fb^{-1}	0.6-4.1 GeV	f4(2050), f2(1950)	$\chi_{c0,c2}$	Neutral P-meson pair
$\pi^0\pi^0$	PRD78:052004,2008	972 fb^{-1}	0.6-4.0 GeV	$f_2(1270)$, $f_0(980)$, f2'(1525)	$\chi_{c0,c2}$ η_c	Neutral P-meson pair
four-meson	EPJC53,1(2008)	395 fb^{-1}	1.4-3.4 GeV		$\chi_{c0,c2}$ η_c, $\eta_c(2S)$	Charmonium decays
$K_s^0K_s^0$	PLB 651, 15 (2007)	397.6 fb^{-1}	2.4-4.0 GeV		$\chi_{c0,c2}$	Neutral P-meson pair
$\pi^+\pi^-$	PRD 75, 051101(2007)	85.9 fb^{-1}	0.8-1.5 GeV	$f_0(980)$, $f_2(1270)$, $\eta'(958)$		Charged P-meson pair
$D\bar{D}$	PRL 96, 082003 (2006)	395 fb^{-1}			χ'_{c2}	New charmonium
$p\bar{p}$	PLB 621, 41 (2005)	89 fb^{-1}	2.03-4.0 GeV		η_c	Baryon pair
$\pi^+\pi^-$ /K^+K^-	PLB 615, 39 (2005)	87.7 fb^{-1}	2.4-4.1 GeV		$\chi_{c0,c2}$	Charged P-meson pair
K^+K^-	EPJC32,323(2003)	67 fb^{-1}	1.4-2.4 GeV	f2'(1525)		
$\gamma J/\psi$	PLB 540, 33 (2002)	32.6 fb^{-1}	3.2-3.8 GeV		χ_{c2} 22	Radiative decay of charmonium

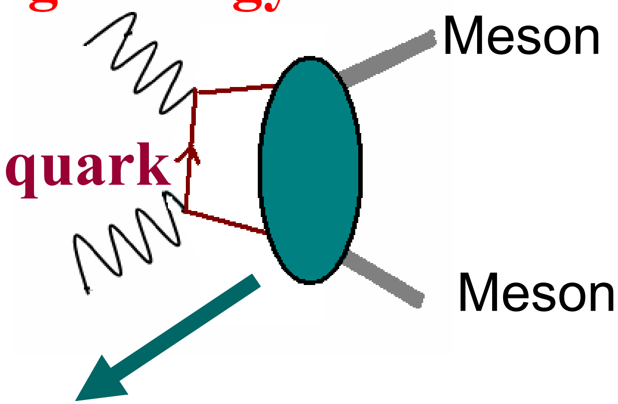
QCD test at high-energy region

Meson-pair production and QCD

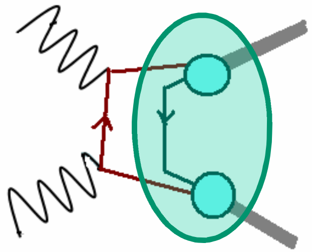
Low energy



High energy



High energy



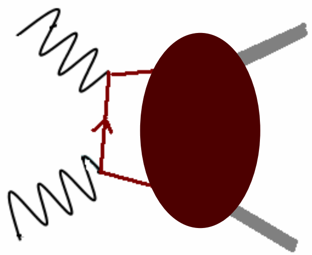
Brodsky and Lepage

Perturbative QCD approach

for exclusive meson production

Works with refined form factors

S.J.Brodsky, G.P.Lepage, PRD 24, 1808 (1981)
M.Benayoun, V.L.Chernyak, NPB329,209(1990)



Kroll, Diehl and Vogt

Handbag model

with soft hadron exchange

M.Diehl, P.Kroll, and C. Vogt, PLB 532, 99 (2002)
M.Diehl, P.Kroll, PLB 683, 165 (2010)

Predicts…

Scattering-angle (of meson) distribution,

Energy -dependence

Cross section ratios under SU(3) sym.

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

10 papers for 6 processes

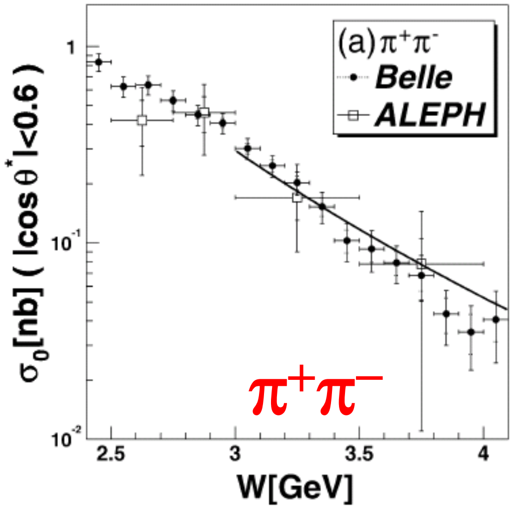
Process	Reference	Int.Lum. (fb^{-1})	$\gamma\gamma$ c.m. Energy (GeV)	Light Mesons	QCD	Char-monia
$\pi^+\pi^-$	PLB 615, 39 (2005)	87.7	2.4 - 4.1		√	√
	PRD 75, 051101(R) (2007)	85.9	0.8 - 1.5	√		
	J. Phys. Soc. Jpn. 76, 074102 (2007)	85.9	0.8 – 1.5	√		
K^+K^-	EPJC 32, 323 (2003)	67	1.4 – 2.4	√		
	PLB 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	√	√	√

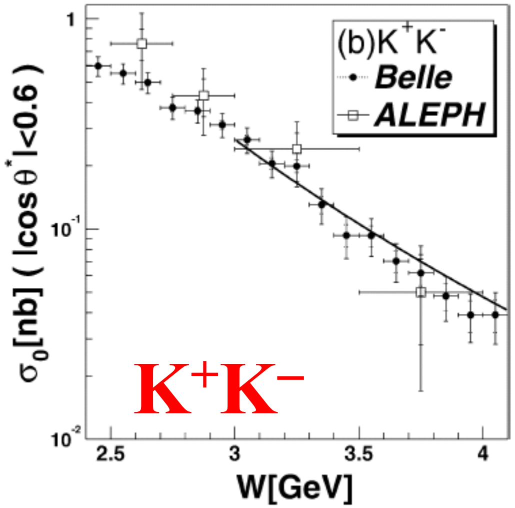
Differential cross section **$d\sigma/d|\cos\theta^*|$** for these processes are measured.

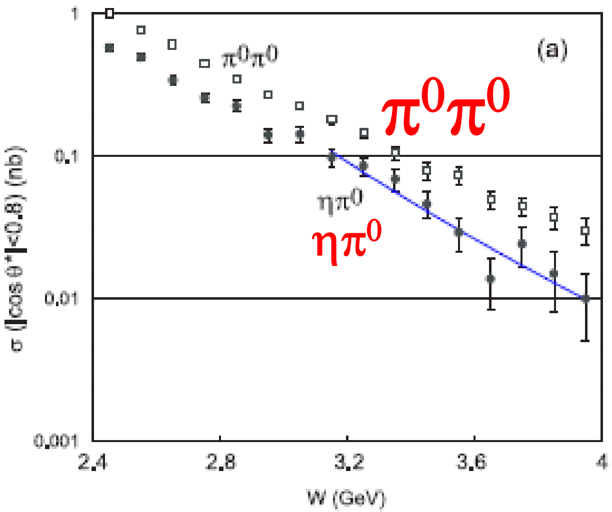
W-dependences at high energies

$W \equiv W_{\gamma\gamma} \equiv \sqrt{s_{\gamma\gamma}}$ Collision's c.m. energy

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

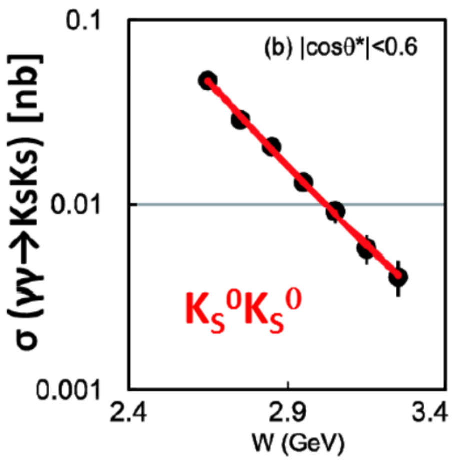


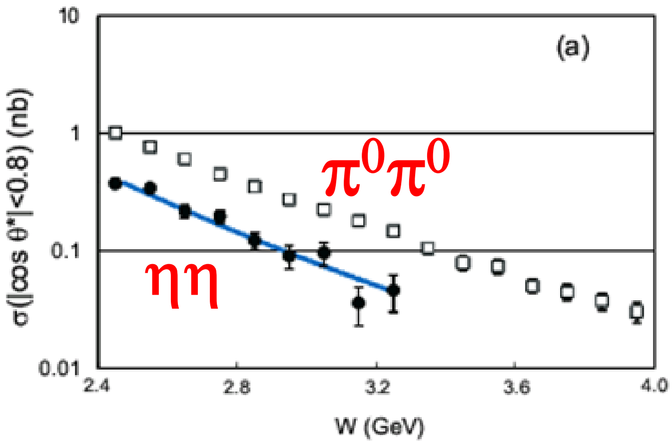




Fitted and reproduced

Slope parameter **n** different among the reactions





Charmonium contributions not included/removed

Cross sections and their ratios

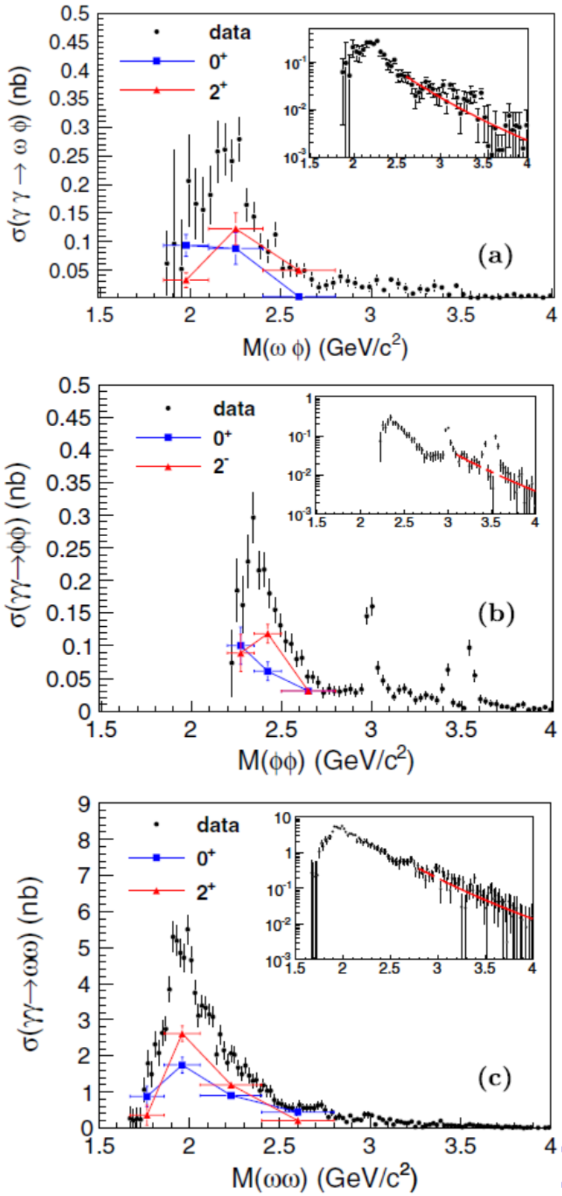
Process	n	W(GeV)	$\lvert\cos\theta^*\rvert$	BL	BC	DKV
$K_S^0 K_S^0$	$11.0 \pm 0.4 \pm 0.4$	2.4 - 4.0†	< 0.8		10	
$\pi^+\pi^-$	$7.9 \pm 0.4 \pm 1.5$	3.0 - 4.1	< 0.6	6	6	
K^+K^-	$7.3 \pm 0.3 \pm 1.5$	3.0 - 4.1	< 0.6	6	6	
$\pi^0\pi^0$	$8.0 \pm 0.5 \pm 0.4$	3.1 - 4.1†	< 0.8		10	
$\eta\pi^0$	$10.5 \pm 1.2 \pm 0.5$	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	$0.24R_f(0.46R_f)^‡$		
$\eta\eta/\pi^0\pi^0$	$0.37 \pm 0.02 \pm 0.03$	2.4 - 3.3	< 0.8	$0.36R_f^2(0.62R_f^2)^‡$		

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

$\gamma\gamma \rightarrow$ Vector-meson pair



ωφ

φφ

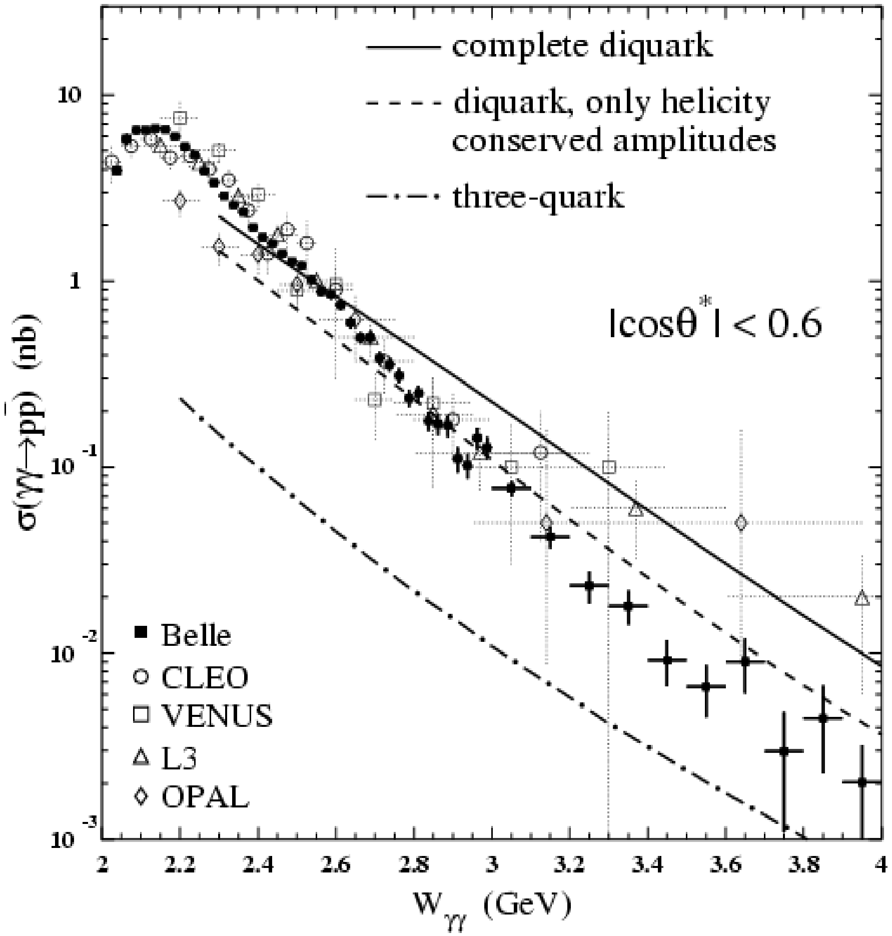
ωω

Belle, PRL 108, 232001 (2012)

Discussion of the Cross-section sizes
by V. Chernyak
(arXiv:1212.1304[hep-ph])

Slope parameters for high W:
n=7.2 $\pm$ 0.6 (ωφ)
8.4 $\pm$ 1.1 (φφ)
9.1 $\pm$ 0.6 (ωω)

p$\bar{p}$ final-state cross sections



PLB 621, 41 (2005)

$W_{\gamma\gamma}^{-n}$ dependence

n=15.1 $\pm^{0.8}_{1.1}$ @ 2.5 – 2.9 GeV

n=12.4 $\pm^{2.4}_{2.3}$ @ 3.2 – 4.0 GeV

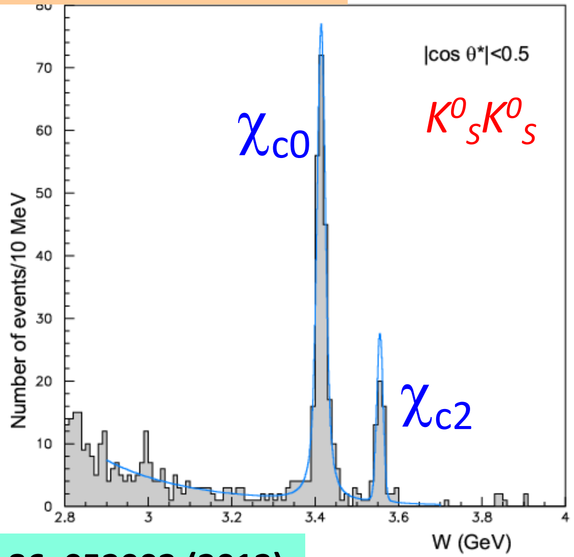
Might agree with a
QCD prediction n= 10
at some energy above 3.1 GeV

Slope – steeper than meson pairs

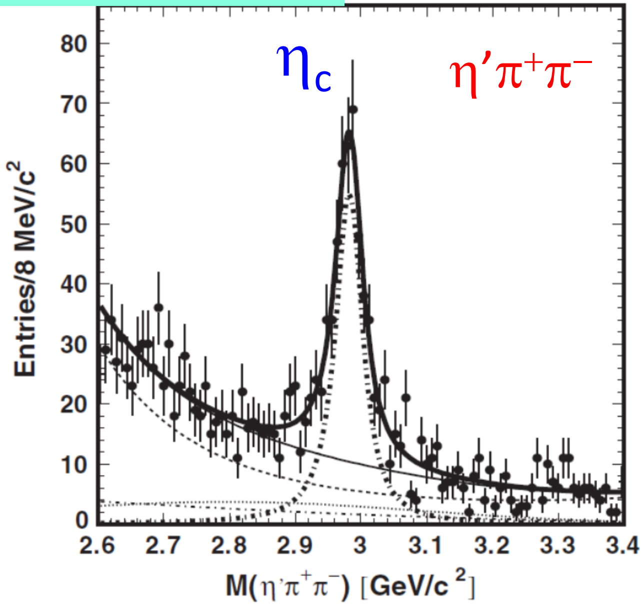
C-even Charmonium(-like) states

Most beautiful signals

PTEP 2013, 123C01 (2013)



PRD 86, 052002 (2012)



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($K^0_S K^0_S$)

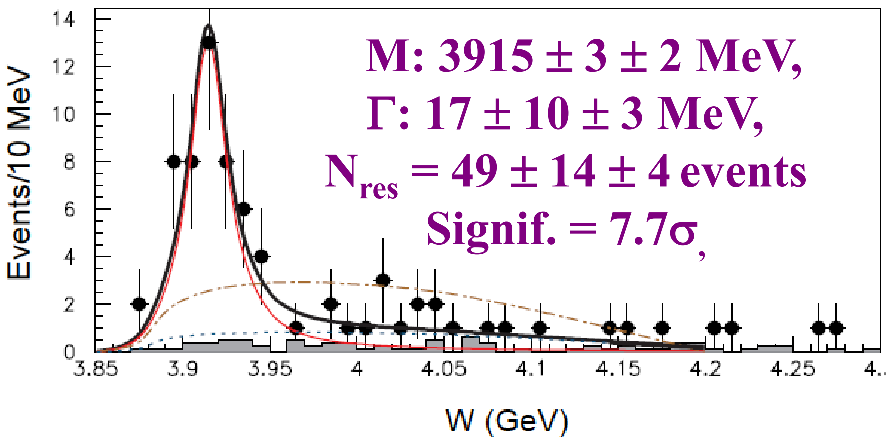
Interference	$\Gamma_{\gamma\gamma}\mathcal{B}(\chi_{c0})$ (eV)	$\Gamma_{\gamma\gamma}\mathcal{B}(\chi_{c2})$ (eV)
not included	$8.09 \pm 0.58 \pm 0.83$	$0.268^{+0.041}_{-0.037} \pm 0.028$
included	$8.7 \pm 1.7 \pm 0.9$	$0.27^{+0.07}_{-0.06} \pm 0.03$
Belle 2007	$7.00 \pm 0.65 \pm 0.71$	$0.31 \pm 0.05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

$\eta_c(1S) \to \eta'\pi^+\pi^-$; $\Gamma_{\gamma\gamma}\mathcal{B}$ is the product of the two-photon decay width and the branching fraction. The world-average values are shown for comparison.

Parameters	This work	PDG
Y	$486^{+40}_{-39} \pm 53$	
M, MeV/c^2	$2982.7 \pm 1.8 \pm 2.2$	2980.3 ± 1.2
Γ, MeV/c^2	$37.8^{+5.8}_{-5.3} \pm 2.8$	26.7 ± 3
$\Gamma_{\gamma\gamma}\mathcal{B}$, eV/$c^2$	$50.5^{+4.2}_{-4.1} \pm 5.6$	194 ± 97
$\mathcal{B}$, %	0.87 ± 0.20	2.7 ± 1.1

Peak of X(3915) in $\gamma\gamma \to \omega J/\psi$ and $\chi_{cJ}(2P)$

694 fb^{-1} **Belle, PRL 104, 092001 (2010)**



The peak is confirmed by BaBar

BaBar, PRD 86, 072002 (2012)

M: 3919.4± 2.2 ± 1.6 MeV,
Γ: 13 ± 6 ± 3 MeV,

Is X(3915) ≡Y(3940) = χ_{c0}(2P) ?

$X(3915)$ was $\chi_{c0}(3915)$ $I^G(J^{PC}) = 0^+(0 \text{ or } 2^{++})$

Mass $m = 3918.4 \pm 1.9$ MeV
Full width $\Gamma = 20 \pm 5$ MeV (S = 1.1)

X(3915) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\omega J/\psi$	seen	222
$\pi^+\pi^-\eta_c(1S)$	not seen	785
$\eta_c\eta$	not seen	665
$\eta_c\pi^0$	not seen	815
$K\overline{K}$	not seen	1896
$\gamma\gamma$	seen	1959

The first 2P charmonium state discovered in two-photon by Belle PRL 96, 082003 (2006)

$\chi_{c2}(2P)$

Mass $m = 3927.2 \pm 2.6$ MeV
Full width $\Gamma = 24 \pm 6$ MeV

The mass is different, a little.

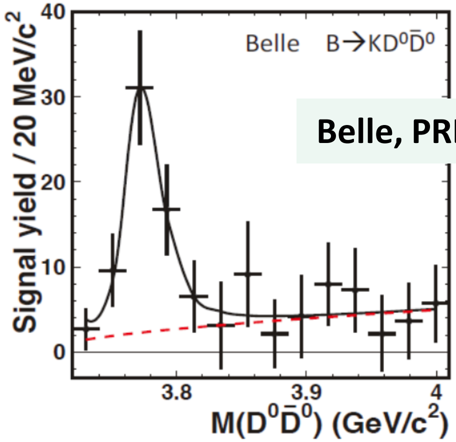
$\chi_{c2}(2P)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\gamma\gamma$	seen	1964
$D\overline{D}$	seen	615
D^+D^-	seen	600
$D^0\overline{D}^0$	seen	615
$\pi^+\pi^-\eta_c(1S)$	not seen	793
$K\overline{K}$	not seen	1901

It is believed as two-photon production of **Y(3940)** discovered in B decays,
but the spin=0 is not finally confirmed, yet.

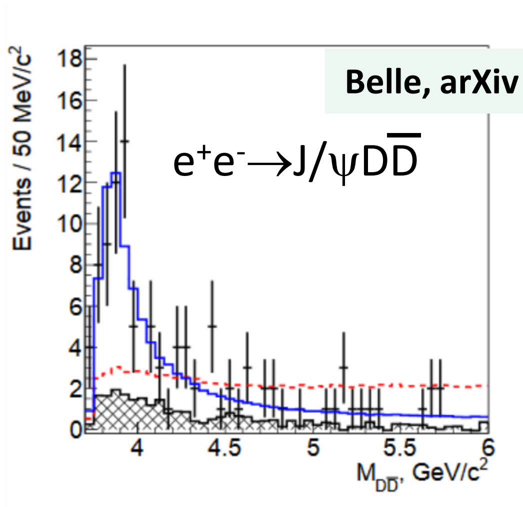
Any $\chi_{c0}(2P) \rightarrow D\bar{D}$ seen?

It is expected that $\chi_{c0}(2P)$ has a large coupling to $D\bar{D}$

No signature of X(3915) in $B \rightarrow D\bar{D}K$



Belle, PRL 100, 092001 (2008)

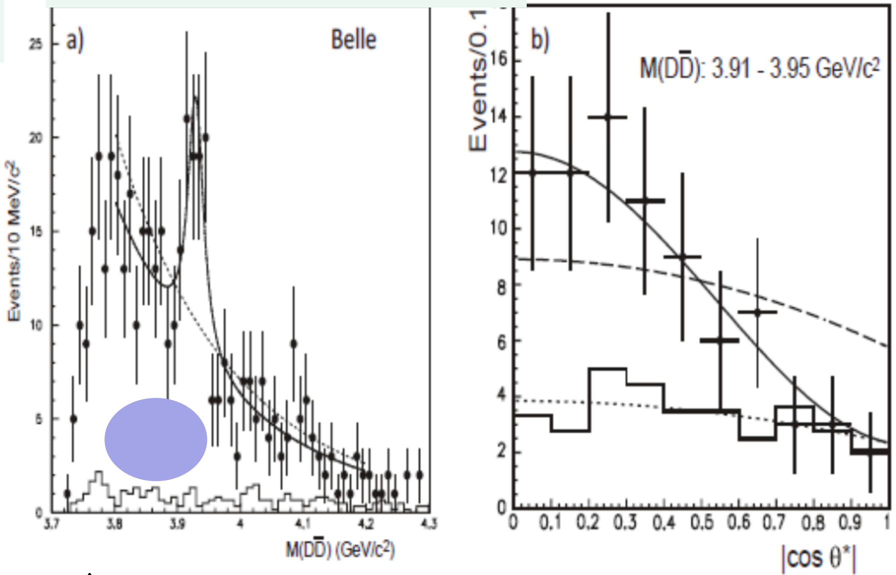


Belle, arXiv 1704.01872(2017)

$\gamma\gamma \rightarrow \chi_{c2}(2P)$ (M=3927MeV) $\rightarrow D\bar{D}$ is discovered

But no Scalar component is found.

Belle, PRL 96, 082003 (2006)



↑ The 3.8 GeV region is contaminated by $D\bar{D}^*$ production, according to the p_t distribution

←From double-charmonium production study

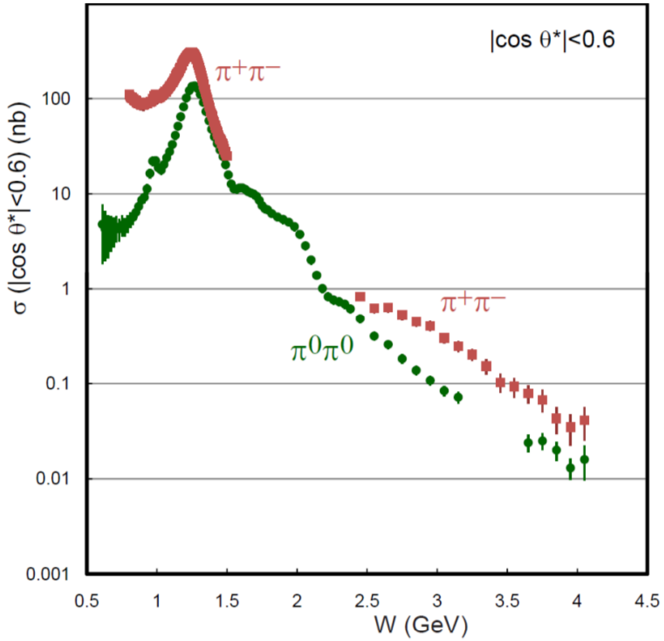
$\chi_{c0}(2P)$ is lighter (3800-3900MeV) and much broader?

See S.L. Olsen, PRD 91, 057501 (2015)

Light-meson spectroscopy

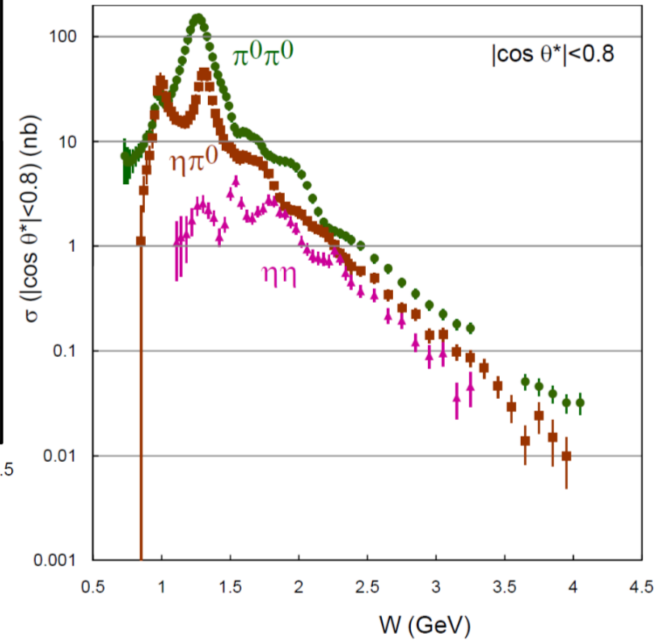
The six processes; in total ~20 peaks

Charged vs Neutral $\pi\pi$

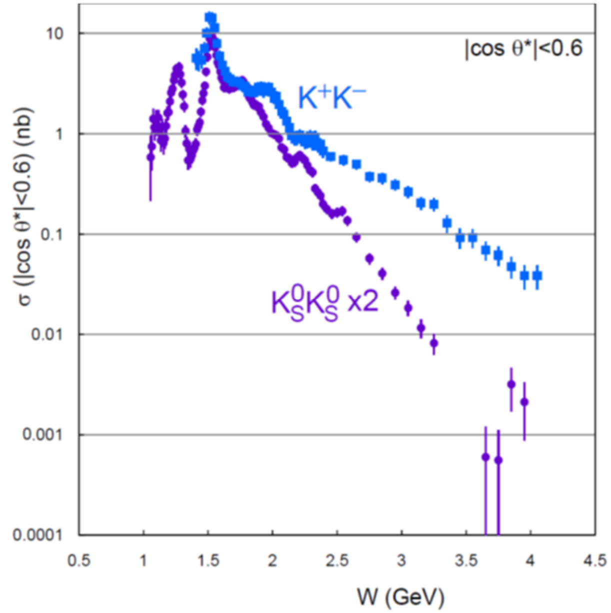


Three neutral-pair processes

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



Charged vs Neutral $K\bar{K}$



Horizontal axis:

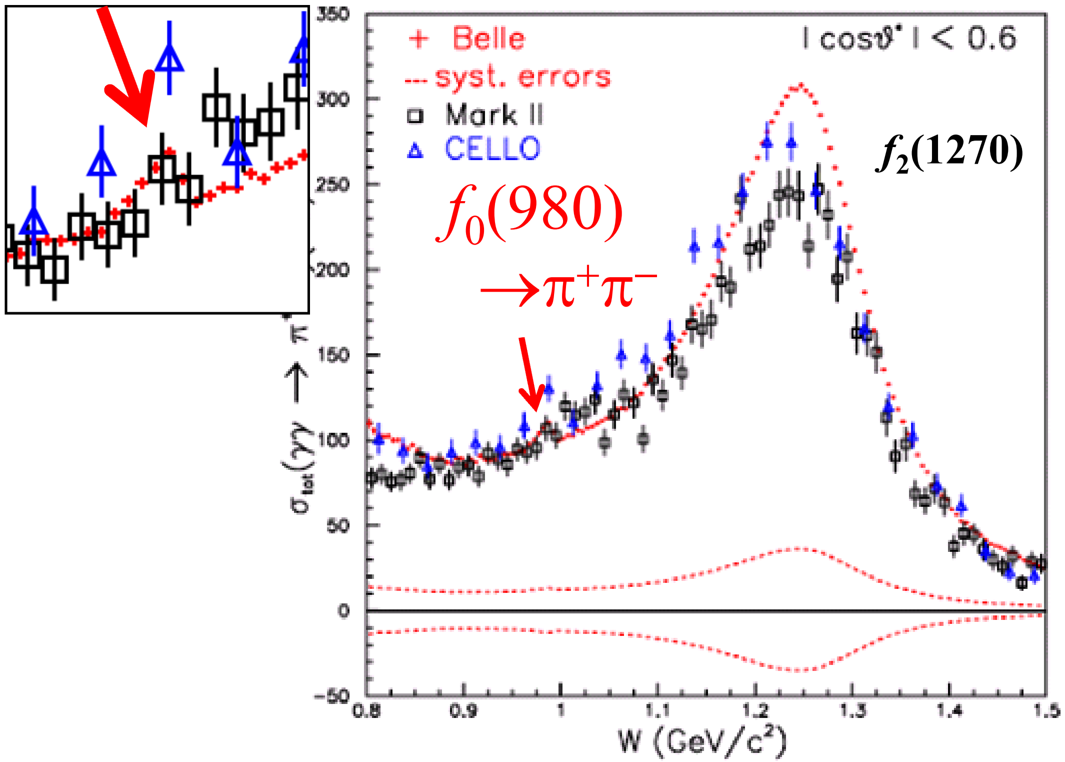
W -- $\gamma\gamma$ c.m. energy = invariant mass of the two-meson system

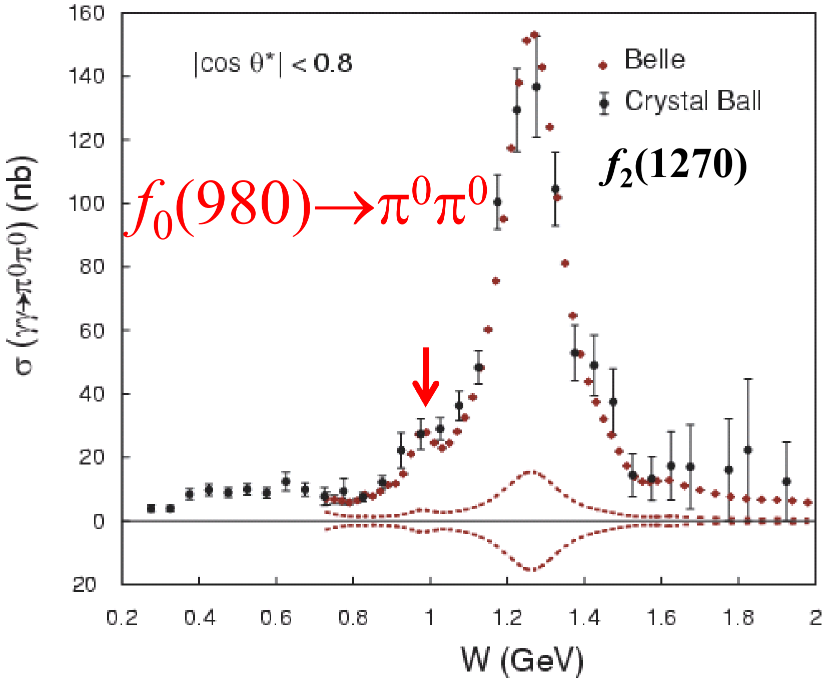
W<~2.5GeV: Dominated by resonances

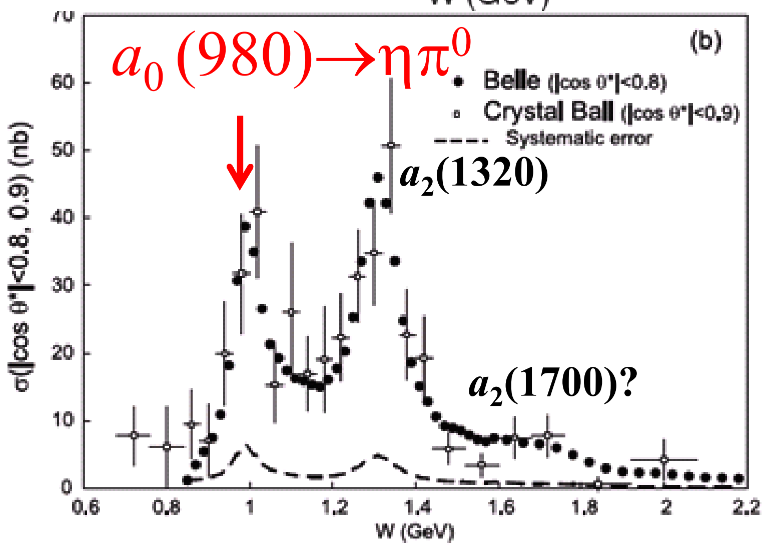
W>~2.5 GeV: (Netgative) Power law works + (χ_c charmonia)

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

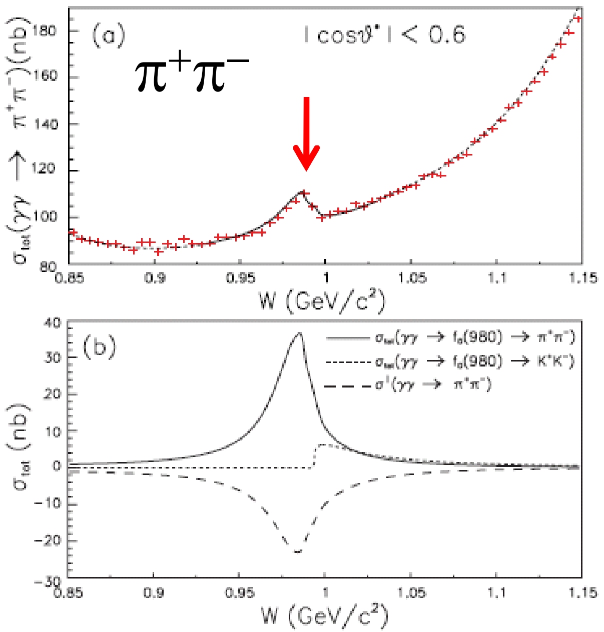
$f_0(980)$ and $a_0(980)$:
Observed as a peak very clearly in two-photon production, for the first time.

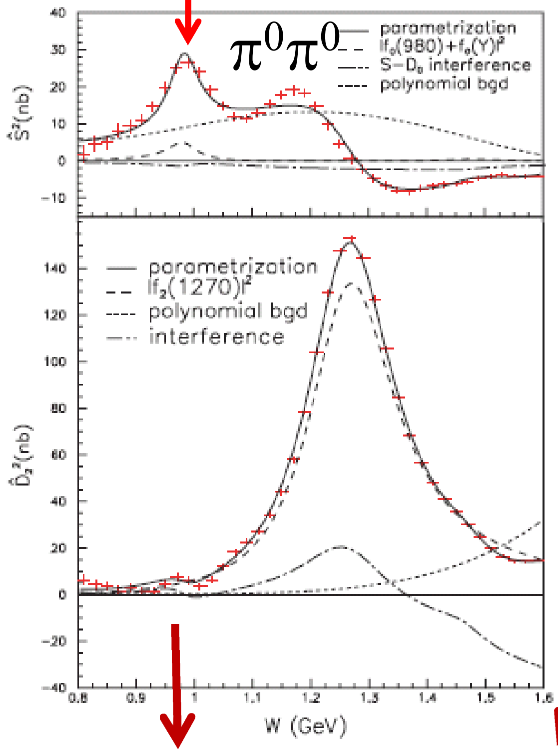


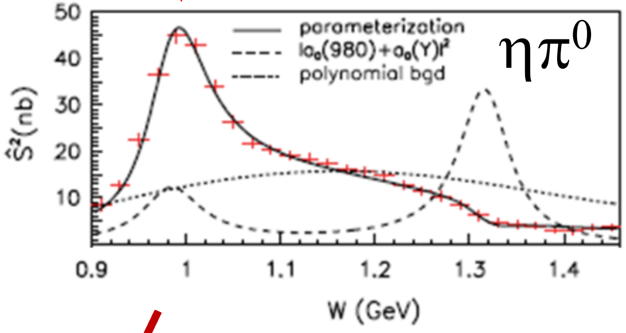




Two-photon decay width of $f_0(980)$ and $a_0(980)$







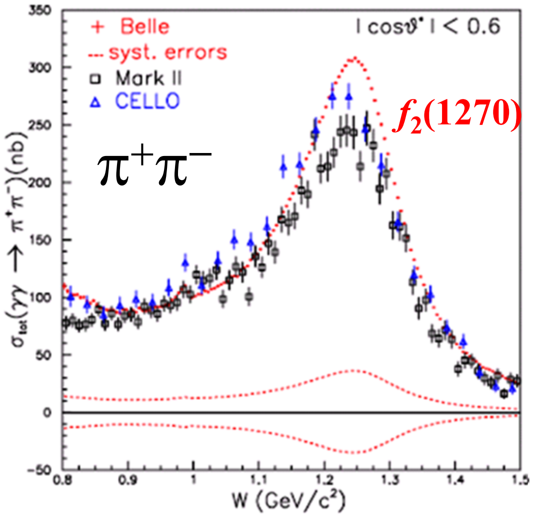
Meson	$f_0(980)$	$f_0(980)$	$a_0(980)$
M[MeV/c^2]	$985.6^{+1.2+1.1}_{-1.5-1.6}$	$982.2 \pm 1.0^{+8.1}_{-8.0}$	$982.3^{+0.6+3.1}_{-0.7-4.7}$
$\Gamma_{\pi\pi/tot}$[MeV]	$51.3^{+20.9+13.2}_{-17.7-3.8}$	$66.9^{+13.9+8.8}_{-11.8-2.5}$	(Γtot) $75.6 \pm 1.6^{+17.4}_{-10.0}$
$\Gamma_{\gamma\gamma}$[eV]	$205^{+95+147}_{-83-117}$	$286 \pm 17^{+211}_{-70}$	$128^{+3+502}_{-2-43} / \mathcal{B}_{\pi^0\eta}$

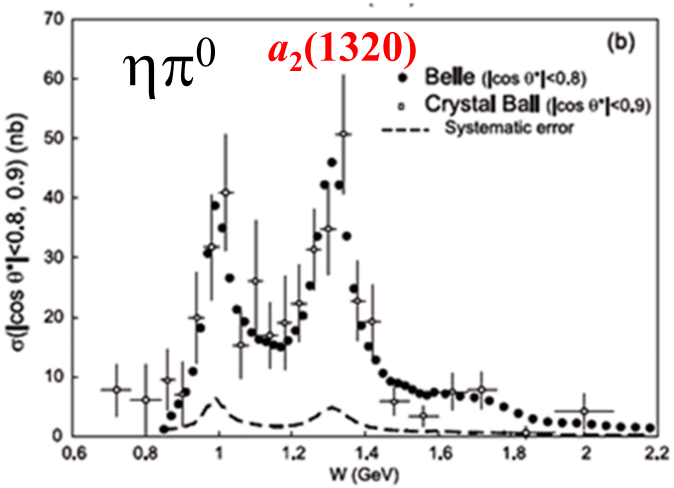
Predictions for $f_0(980)$

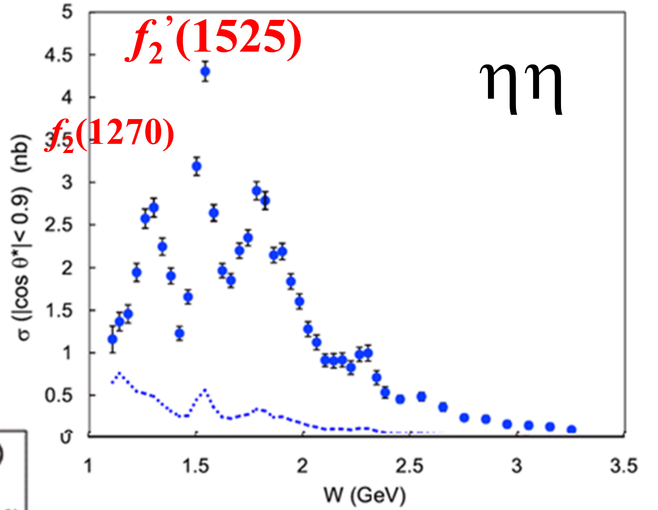
Model	$\Gamma_{\gamma\gamma}$ [eV]
*uu*bar,*dd*bar	1300 – 1800
*ss*bar	300 – 500
*KK*bar molecule	200 – 600
Four-quark	270

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

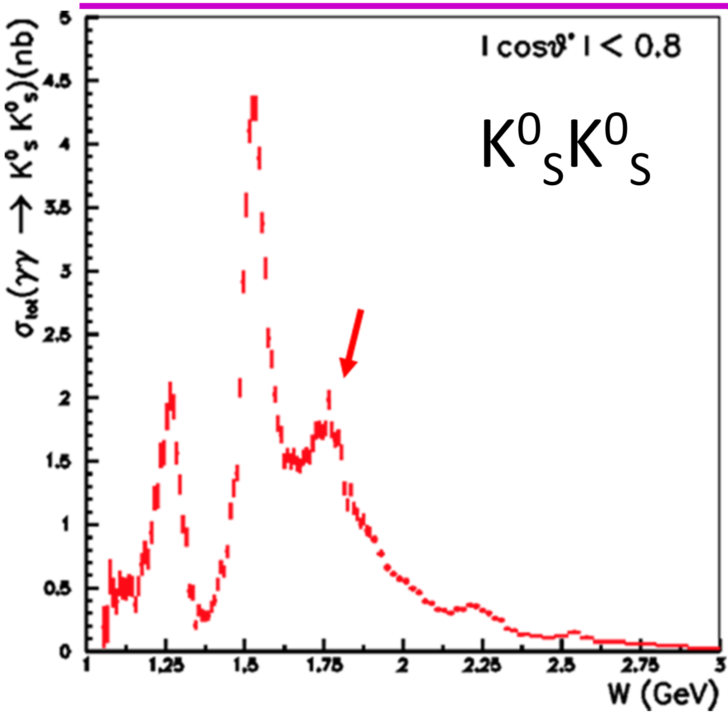
$f_2(1270)$: The largest peak in $\pi^+\pi^-$ and $\pi^0\pi^0$. Also seen in $\eta\eta$
$a_2(1320)$: Large peak in $\eta\pi^0$
$f_2'(1525)$: Large peak in $\eta\eta$, K^+K^-, and $K^0_SK^0_S$

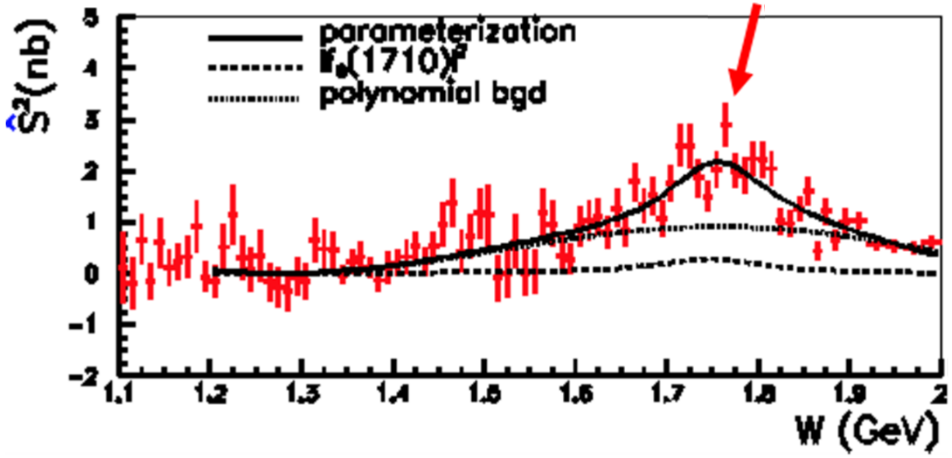






$f_0(1710)$ formation in $K^0_S K^0_S$





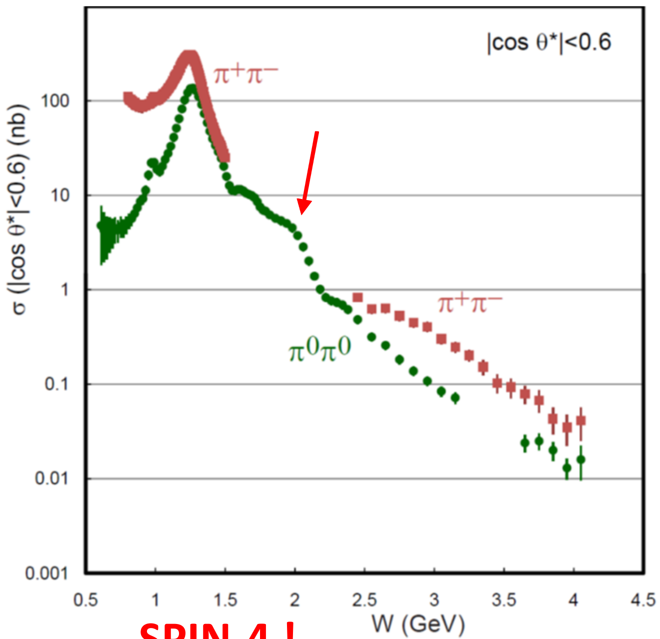
Assuming a single resonance,
J = 0 or 2 ? **J = 0 is much preferred.**

Parameter $f_J(1710)$	$f_0(1710)$ fit				$f_2(1710)$ 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

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

The 1.8 – 2.2 GeV region

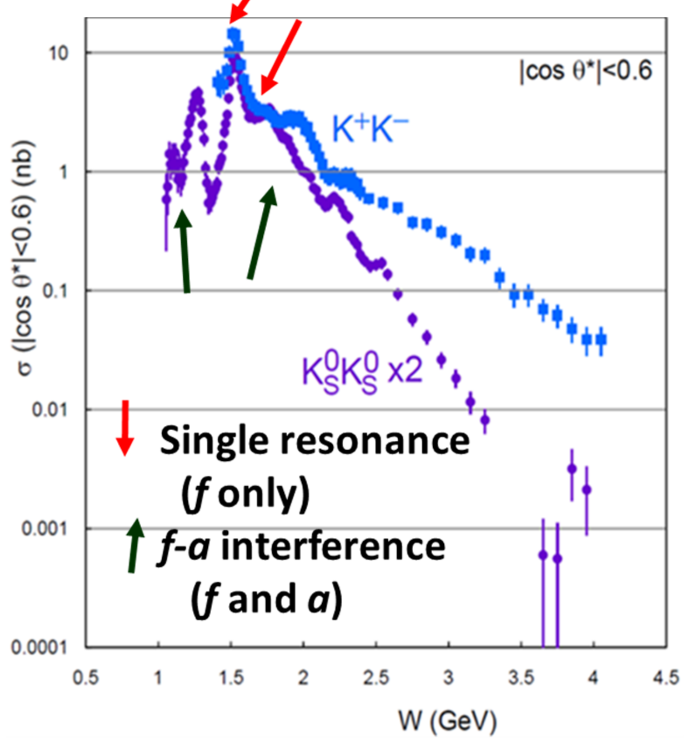
- $f_2(1950) \rightarrow \pi^0\pi^0$ shows a broad structure
- Similar structure exists in K^+K^- (but, they can be different states)
- No peak in $\eta\pi^0$, $\eta\eta$ and $K^0_S K^0_S$ in this mass region



SPIN-4 !

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)		

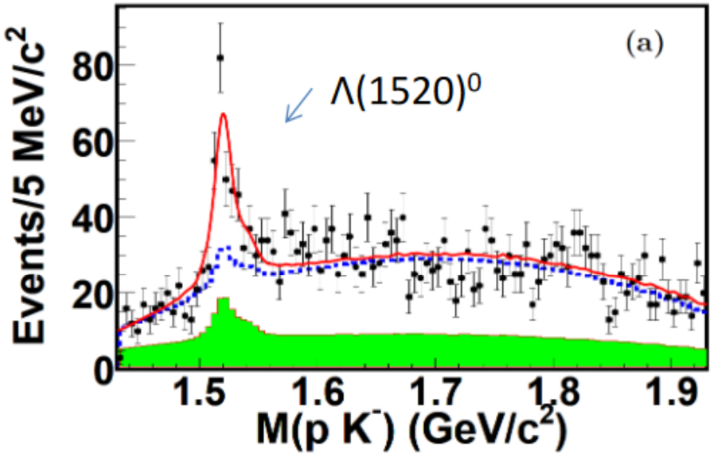
I=0 (*f*) and *I*=1 (*a*) interference in $K\bar{K}$



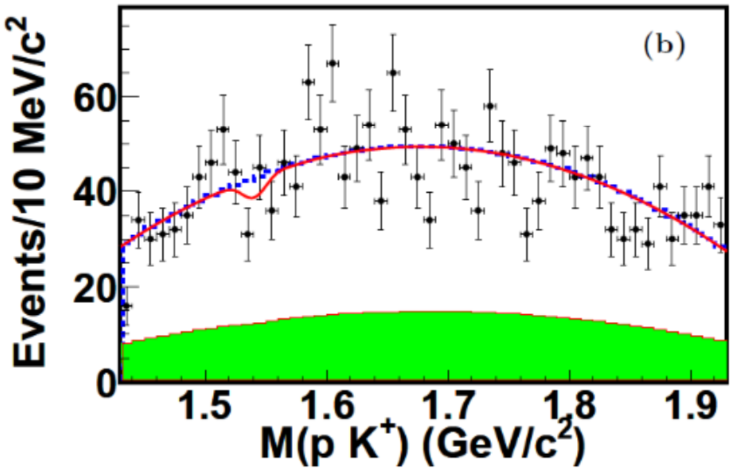
Search for exotic baryons (Pentaquarks)

$\gamma\gamma \to p\bar{p}K^+K^-$

PRD 93, 1120137(2016)



Simultaneous fit: $\Lambda(1520)^0$ and $\Theta(1540)^0$ signal are included.
The shaded histogram: $\sum Pt^*$ sideband
288 ± 48 $\Lambda(1520)^0$events, 8.6σ
22 ± 34 $\Theta(1540)^0$ events, 1.4σ



Similar simultaneous fit: $\Theta(1540)^{++}$ signal
Solid line: the simultaneous fit
The dotted curve: background estimate
The shaded histogram: $\sum Pt^*$ sideband
-16 ± 34 $\Theta(1540)^{++}$ events

Single-tag measurement and meson TFFs

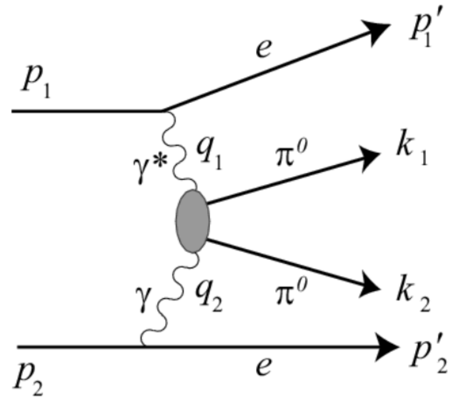
TFF: transition form factor

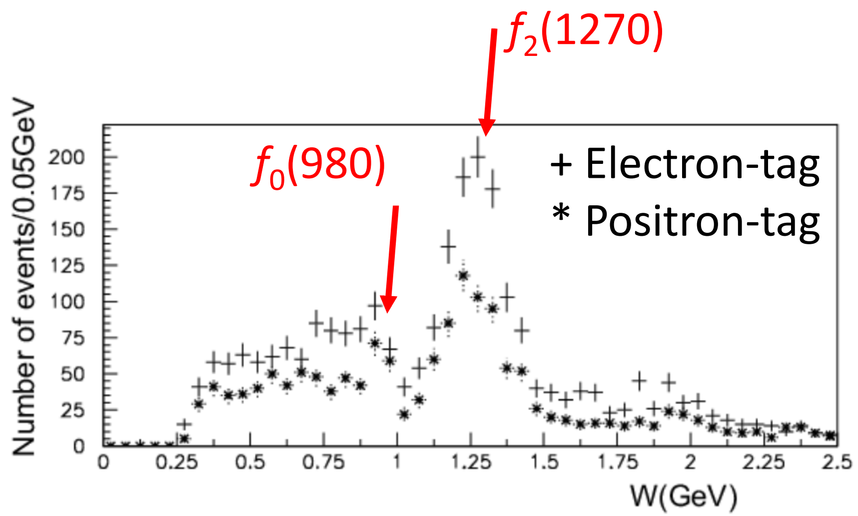
$\gamma^*\gamma \rightarrow \pi^0\pi^0$: f_0 (980) and f_2 (1270) TFF's

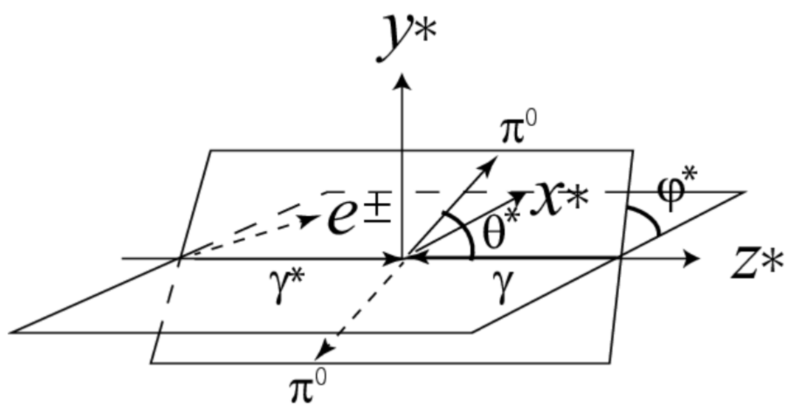
Physics motivations:

- 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$|_\mu$

PRD 93, 032003 (2016)







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

Formalism of PWA

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

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

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

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

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

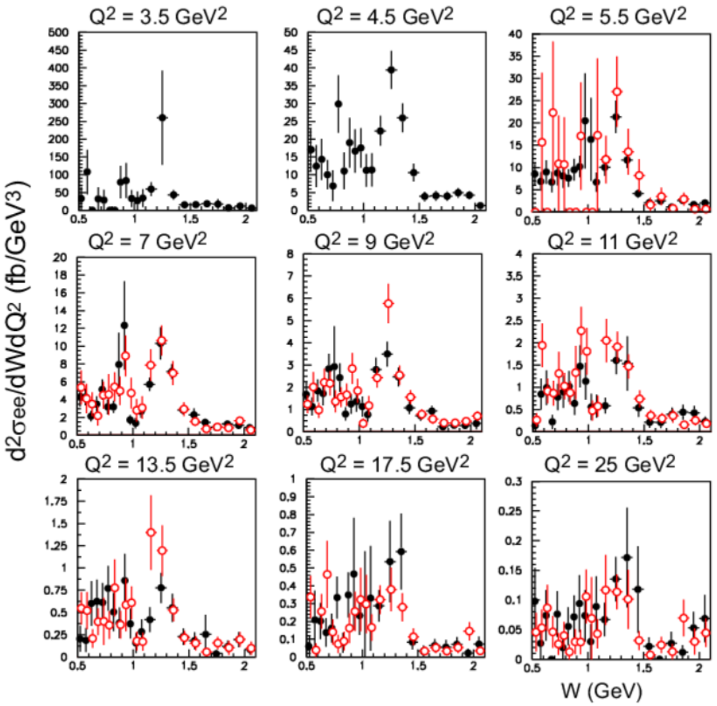
$M_{++} = S + D_0$,
$S = B_S(W) + A_{f0}(W)$
$D_0 = 4\pi\, [B_{D0}(W) + A_{f2}(W)\sqrt{r_{20}}]\; Y_2^0$
etc.

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

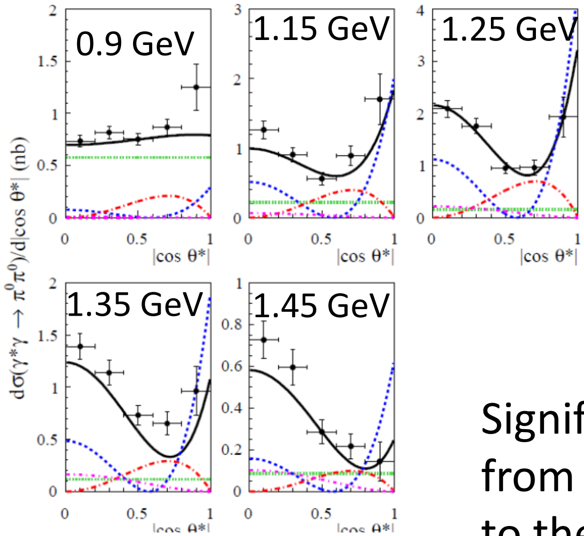
++ etc. --- Helicity state of the incident photons
S, D_0 etc. -- Partial-wave amplitude in $\pi^0\pi^0$ scattering
B, A_f -- Background and *f*-resonance components.
ε_0, ε_1 --- A spin-dependent flux factor ratio for the virtual-photons

Cross-section results and fit

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



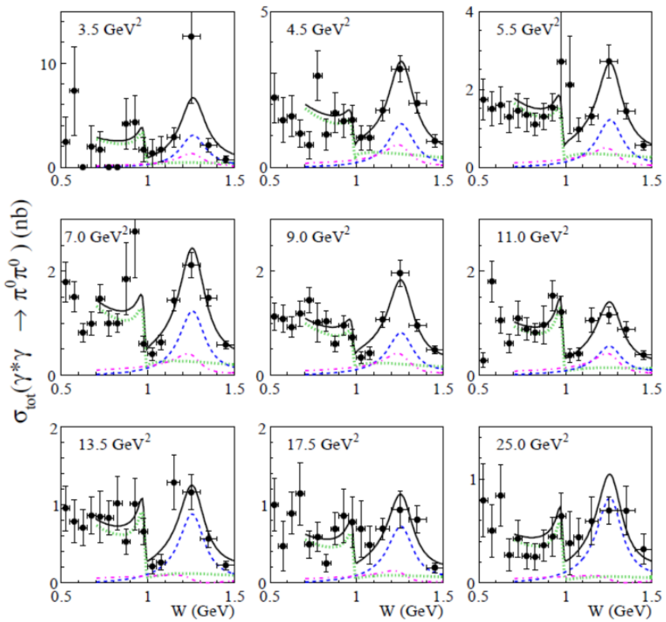
The curves are PWA fit constructed by parameterized resonant (f_0(980) and f_2(1270)) and continuum amplitudes.



|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

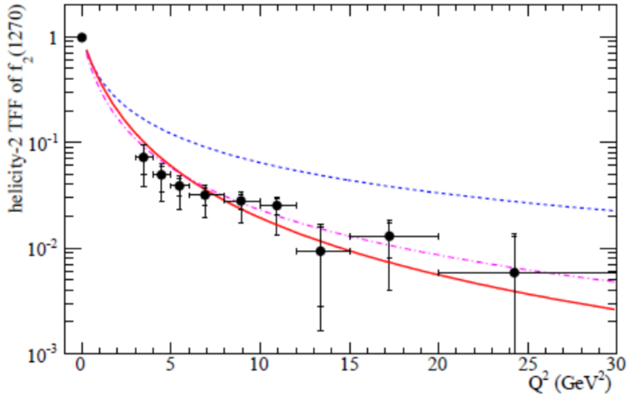


Final result of γ*γ cross sections and PWA fits

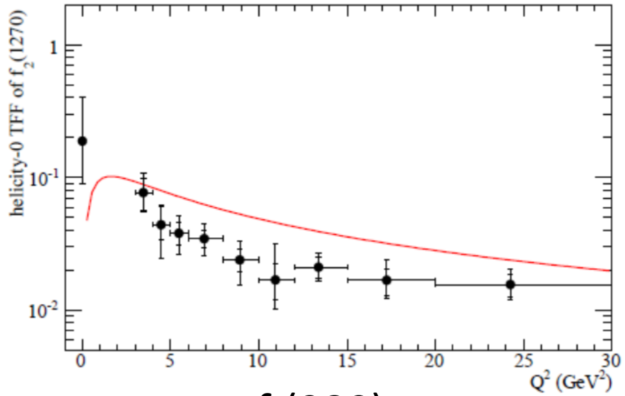
Q^2 dependence of resonant amplitudes

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

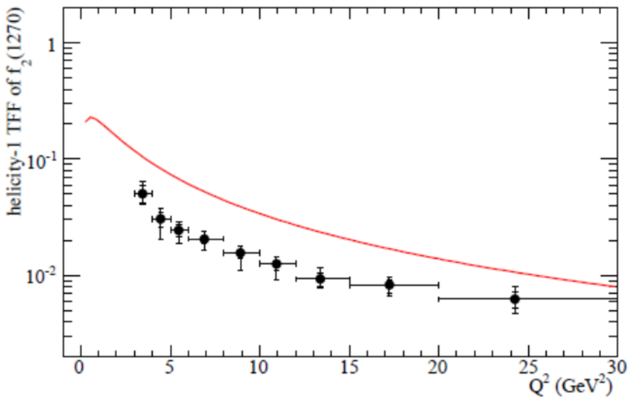
$f_2(1270)$, helicity = 2



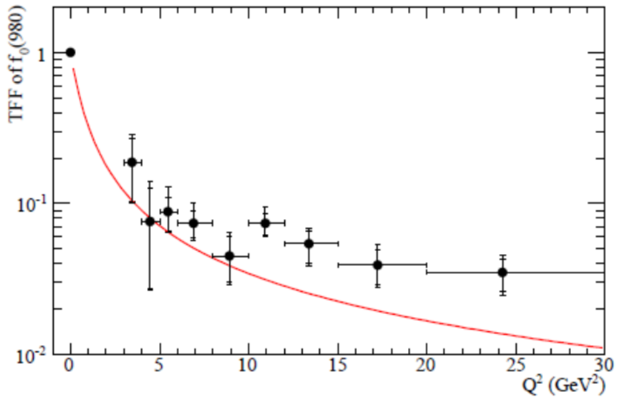
$f_2(1270)$, helicity = 0



$f_2(1270)$, 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

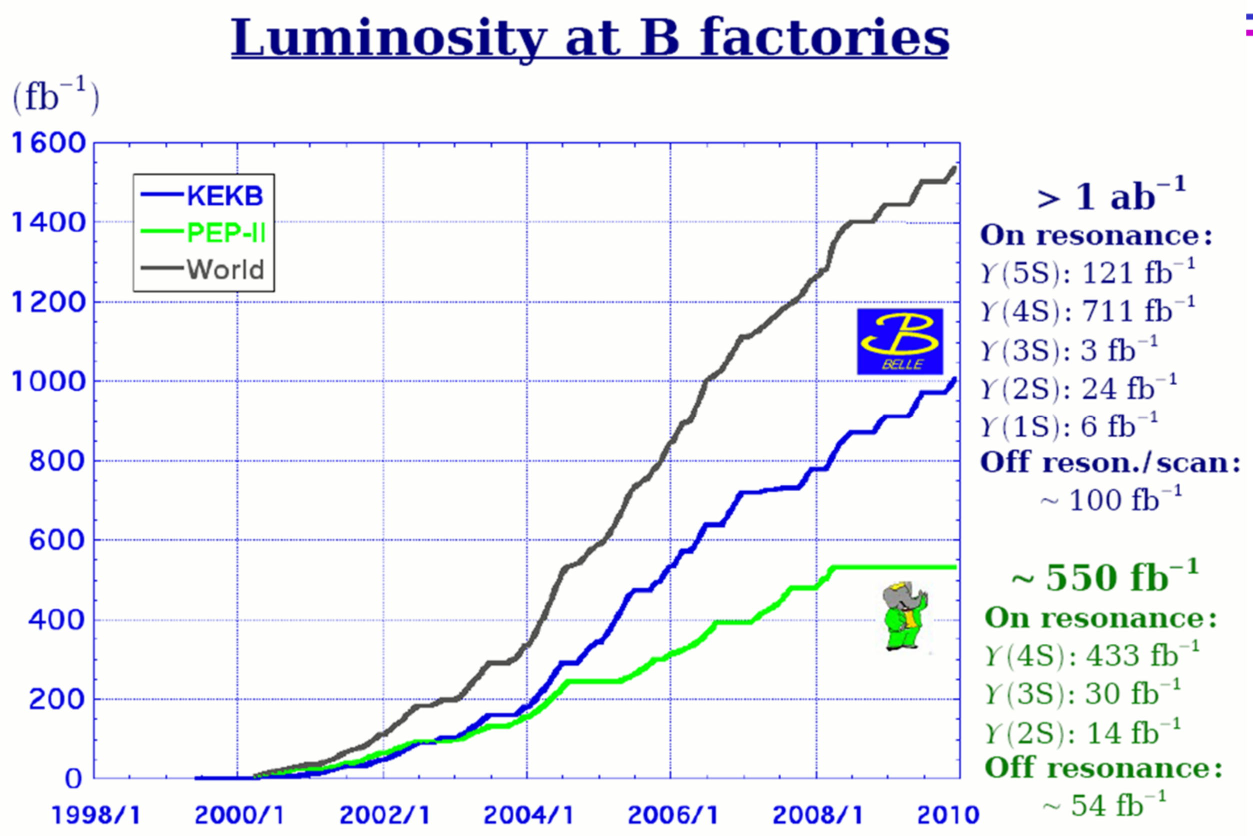
Summary

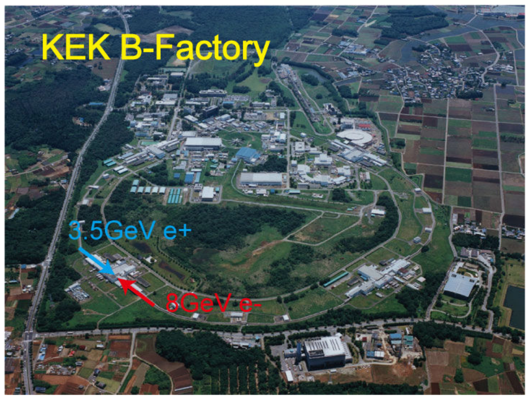
Highlights of Two-photon physics results from Belle

- Systematic QCD test with many kinds of meson pair channels @ 3 – 4 GeV
- Discovery/observations of new charmonium(like) states χ_{c2}(2P), X(3915) etc.
- Precise determination of $\Gamma\gamma\gamma$ and BF for the charmonium ground states
- Comprehensive light-meson spectroscopy
  - Observation of scalar states
  - Discrimination of tensor mesons in the couplings to two photons
  - Confirmation of isospin (0 and 1)mixing
- Studies related to glueball, tetraquark, and pentaquark exotic systems
- First measurement of scalar and tensor-meson TFFs

Backup

History of integrated luminosity at Belle

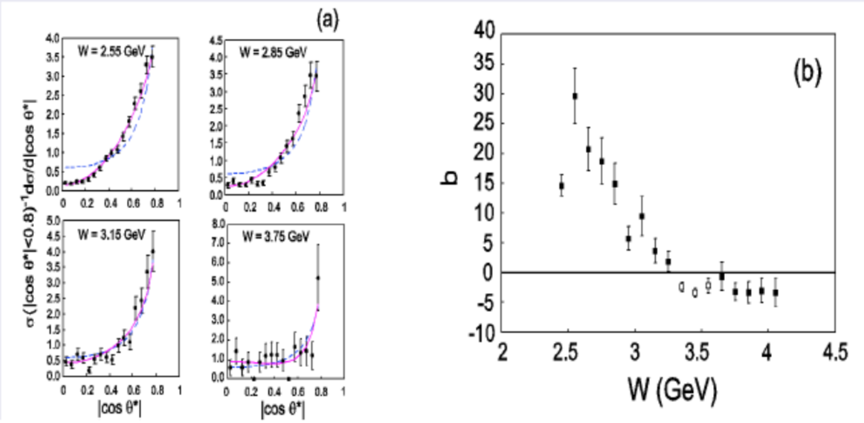




1999	The Belle experiment started
2001	CP violation in B mesons was verified and the KEKB accelerator achieved the world's highest luminosity
2002	Anomalous CP violation in b → s was measured
2003	The B → Kll decay was discovered
2004	The New particle X (3872) was discovered
2005	Direct violation of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

Angular dependence

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



$d\sigma/d|\cos\theta^*| \propto \sin^{-4}\theta^*$ 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	$\vert\cos\theta^*\vert$
$K_S K_S$	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

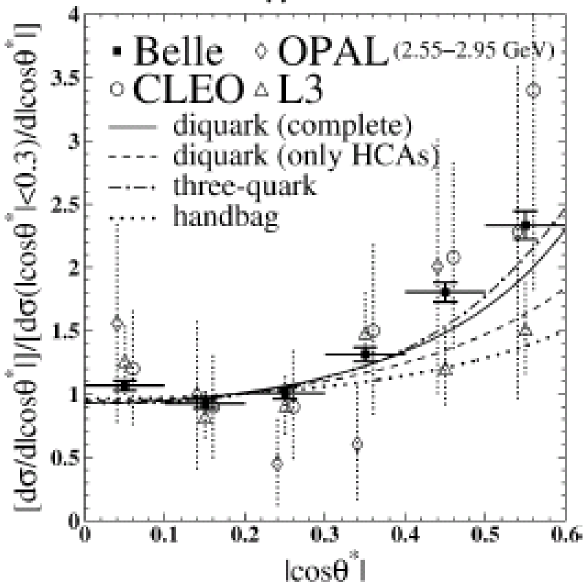
Angular dependence: $\gamma\gamma \to p\bar{p}$

Baryon production mechanism

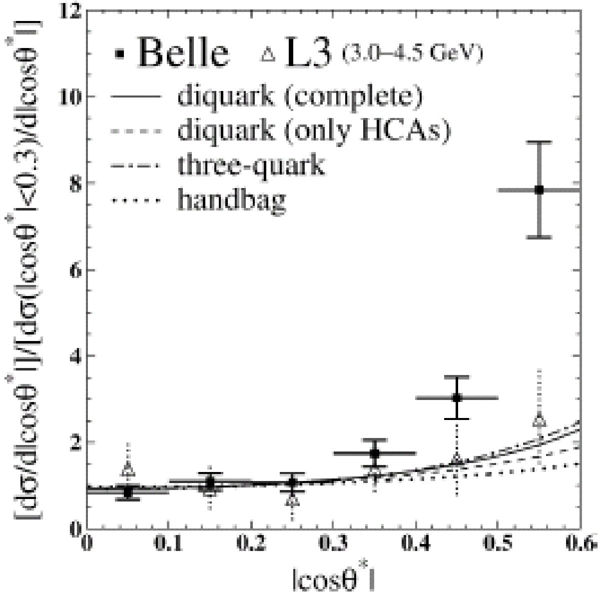
Couple with a single quark?.. or a diquark?

Angular and W dependences, Cross-section size

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



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

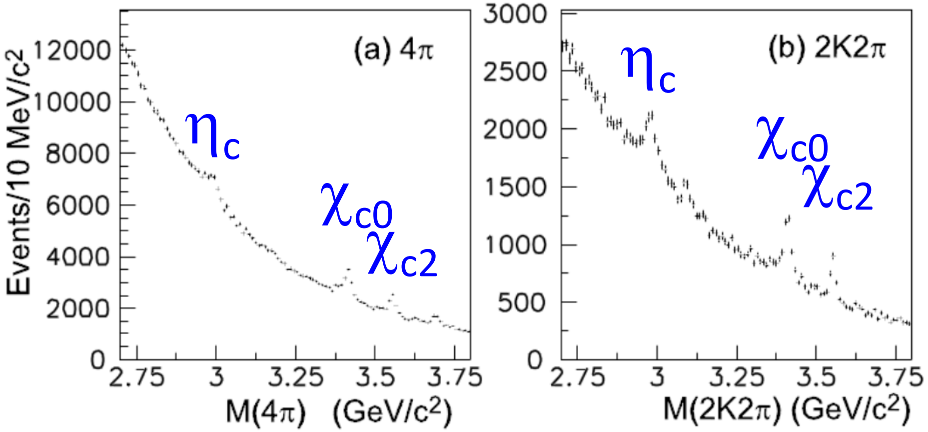


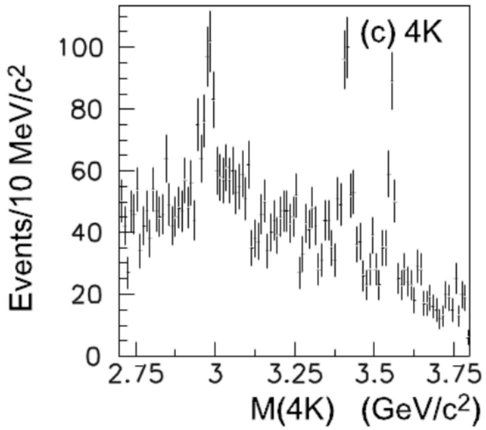
Model predictions are normalized for $|\cos\theta^*|<0.3$.

Agreement is not very good in W>3 GeV

Three C-even ground charmonium states

Four-charged-meson final states

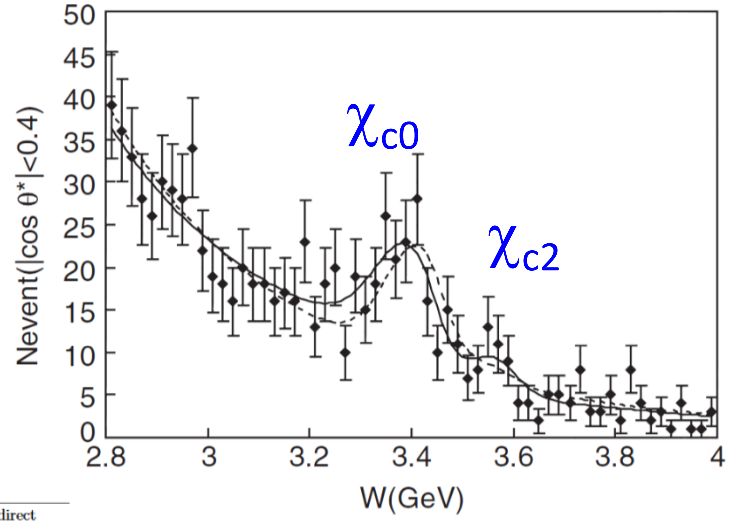




EPJ C 53, 1 (2008)

Process	Isospin ·BF factor	This paper $\mathcal{G}$ (eV)	Direct $\mathcal{G}$ (eV)	Indirect $\mathcal{G}$ (eV)
$\eta_c \to \pi^+\pi^-\pi^+\pi^-$	1.0	$40.7 \pm 3.7 \pm 5.3$	$180 \pm 70 \pm 20$	83 ± 24
$\eta_c \to K^+K^-\pi^+\pi^-$	1.0	$25.7 \pm 3.2 \pm 4.9$	210 ± 70	102 ± 30
$\eta_c \to K^+K^-K^+K^-$	1.0	$5.6 \pm 1.1 \pm 1.6$	280 ± 70	11 ± 5
$\eta_c \to \rho\rho$	0.333	< 39	–	130 ± 43
$\eta_c \to f_2 f_2$	0.320	$69 \pm 17 \pm 12$	–	74 ± 36
$\eta_c \to K^*\bar{K}^*$	0.333	$32.4 \pm 4.2 \pm 5.8$	–	66 ± 22
$\eta_c \to f_2 f_2'$	0.251	$49 \pm 9 \pm 13$	–	–
$\eta_c \to \phi\phi$	0.243	$6.8 \pm 1.2 \pm 1.3$	–	19 ± 5
$\chi_{c0} \to \pi^+\pi^-\pi^+\pi^-$	1.0	$44.7 \pm 3.6 \pm 4.9$	$75 \pm 13 \pm 8$	69 ± 13
$\chi_{c0} \to K^+K^-\pi^+\pi^-$	1.0	$38.8 \pm 3.7 \pm 4.7$	–	53 ± 12
$\chi_{c0} \to K^+K^-K^+K^-$	1.0	$7.9 \pm 1.3 \pm 1.1$	–	7.8 ± 1.6
$\chi_{c0} \to K^{*0}K^-\pi^+$ or c.c.	0.667	$16.7 \pm 6.1 \pm 3.0$	–	34 ± 13
$\chi_{c0} \to \rho\rho$	0.333	< 12	–	–
$\chi_{c0} \to K^*\bar{K}^*$	0.333	< 18	–	5.1 ± 1.9
$\chi_{c0} \to \phi\phi$	0.243	$2.3 \pm 0.9 \pm 0.4$	–	2.7 ± 0.8
$\chi_{c2} \to \pi^+\pi^-\pi^+\pi^-$	1.0	$5.01 \pm 0.44 \pm 0.55$	$6.4 \pm 1.8 \pm 0.8$	7.2 ± 1.2
$\chi_{c2} \to K^+K^-\pi^+\pi^-$	1.0	$4.42 \pm 0.42 \pm 0.53$	–	5.8 ± 2.1
$\chi_{c2} \to K^+K^-K^+K^-$	1.0	$1.10 \pm 0.21 \pm 0.15$	–	1.03 ± 0.18
$\chi_{c2} \to \rho^0\pi^+\pi^-$	1.0	$3.2 \pm 1.9 \pm 0.5$	–	3.9 ± 2.3
$\chi_{c2} \to \rho\rho$	0.333	< 7.8	–	–
$\chi_{c2} \to K^*\bar{K}^*$	0.333	$2.4 \pm 0.5 \pm 0.8$	–	2.2 ± 0.5
$\chi_{c2} \to \phi\phi$	0.243	$0.58 \pm 0.18 \pm 0.16$	–	1.0 ± 0.3
$\eta_c(2S) \to \pi^+\pi^-\pi^+\pi^-$	1.0	< 6.5	–	–
$\eta_c(2S) \to K^+K^-\pi^+\pi^-$	1.0	< 5.0	–	–
$\eta_c(2S) \to K^+K^-K^+K^-$	1.0	< 2.9	–	–

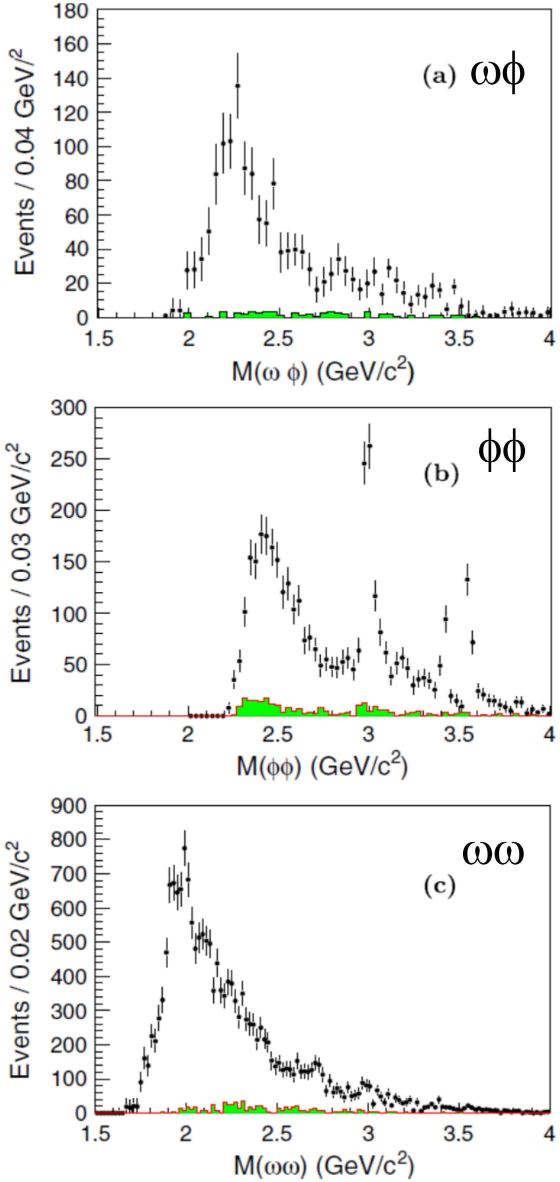
$\pi^0\pi^0$ final state



Interference	$N_{\chi_{c0}}$	k	ϕ	$N_{\chi c2}$
Without	100 ± 16	···	···	13^{+11}_{-10}
With	103^{+60}_{-42}	$0.82^{+0.18}_{-0.48}$	$(1.1 \pm 0.3)\pi$	34 ± 13

Interference	$\Gamma_{\gamma\gamma}\mathcal{B}(\chi_{c0})$ (eV)	$\Gamma_{\gamma\gamma}\mathcal{B}(\chi_{c2})$ (eV)
Without	$9.7 \pm 1.5 \pm 1.2$	$0.18^{+0.15}_{-0.14} \pm 0.08$
With	$9.9^{+5.8}_{-4.0} \pm 1.6$	$0.48 \pm 0.18 \pm 0.07 \pm 0.14$

Decays to Vector-meson pair



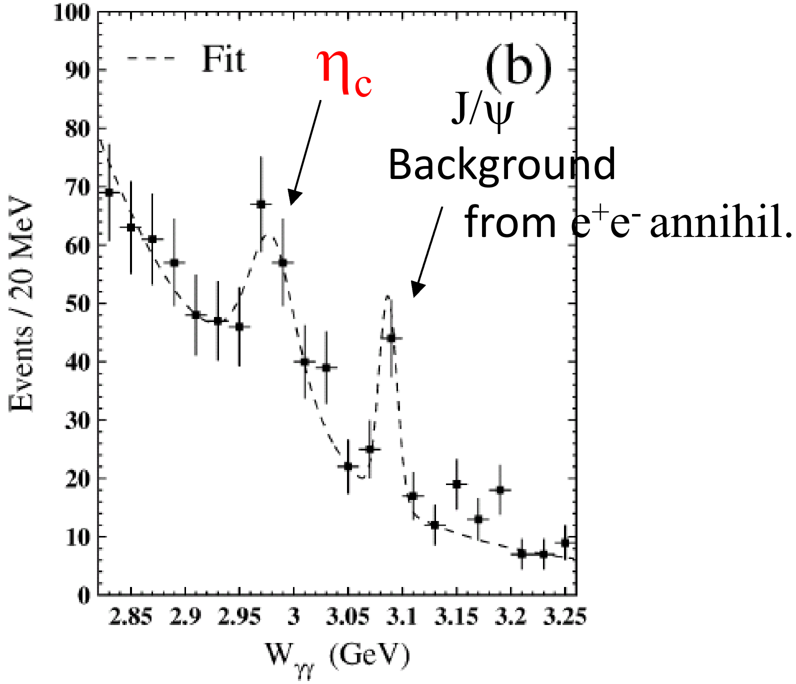
PRL 108, 232001 (2012)

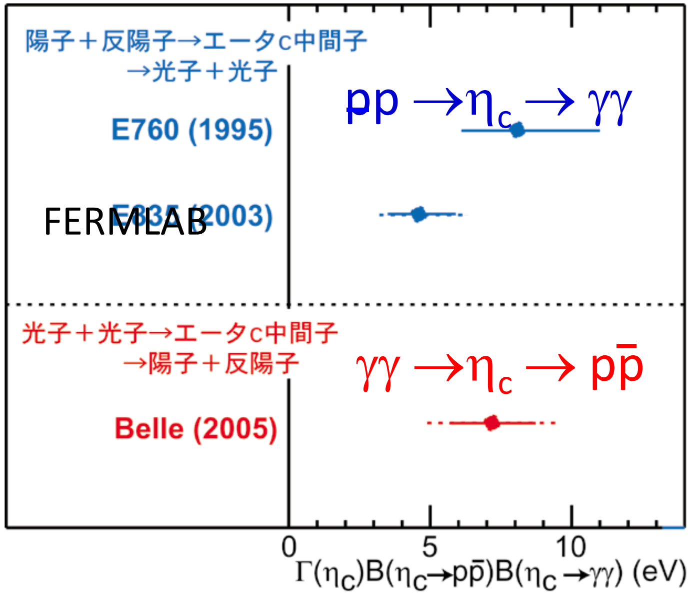
$\Gamma_{\gamma\gamma}\mathcal{B}(X \to VV)$ (eV) and the numbers of events (in brackets) for η_c, χ_{c0} and χ_{c2}

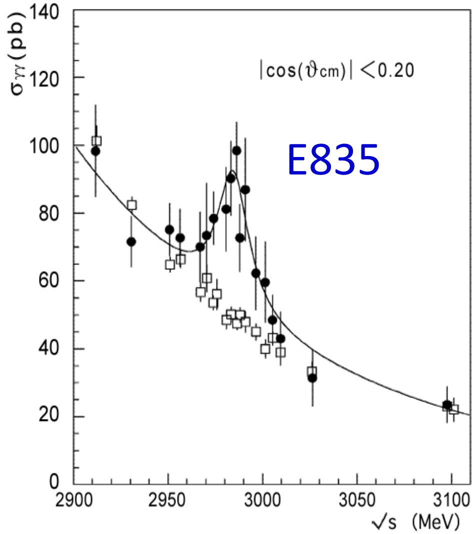
Mode	$\omega\phi$	$\phi\phi$	$\omega\omega$
η_c	<0.49 [<7.9]	$7.75 \pm 0.66 \pm 0.62$ [386 ± 31]	$8.67 \pm 2.86 \pm 0.96$ [85 ± 29]
χ_{c0}	<0.34 [<4.3]	$1.72 \pm 0.33 \pm 0.14$ [56 ± 11]	<3.9 [<35]
χ_{c2}	<0.04 [<2.4]	$0.62 \pm 0.07 \pm 0.05$ [89 ± 11]	<0.64 [<28]

Baryon pair: $\gamma\gamma \to p\bar{p}$

PLB 621, 41 (2005)



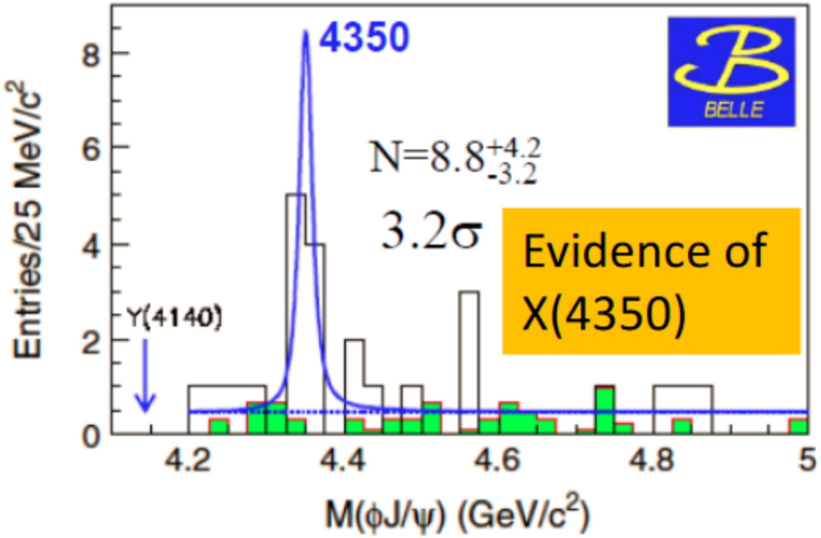




Evidence of X(4350) in ϕ J/ψ

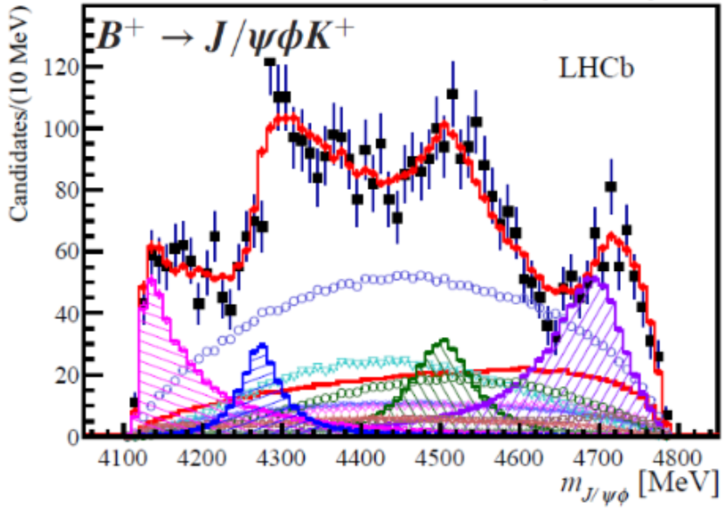
Two-photon

PRL 104,112004 (2010)



B decays

PRL118 (2017) 022003



X(4140) , X(4274) , X(4500) , and X(4700)

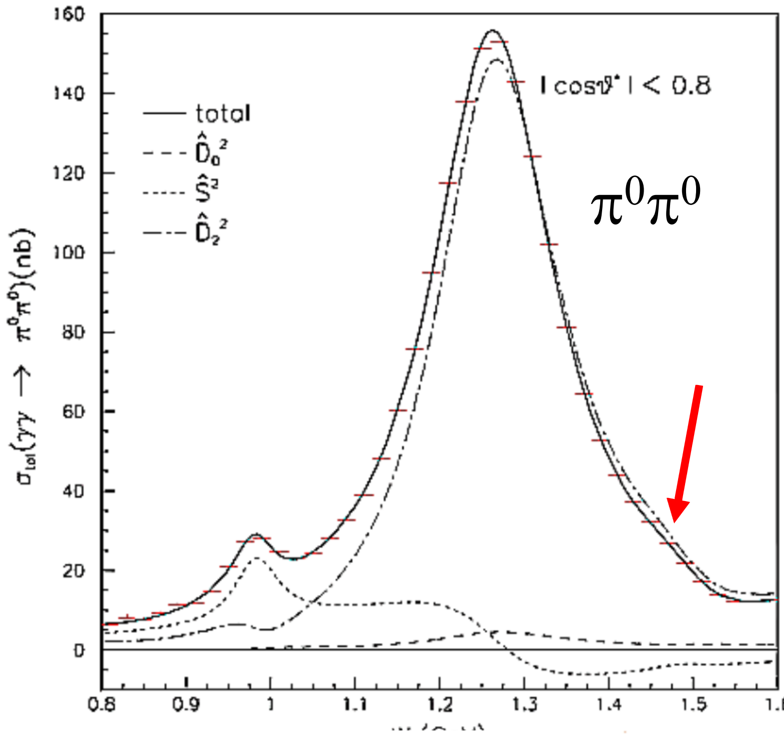
Scalars in the 1.2 – 1.6 GeV region

- 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.

  $\rightarrow$ favorable to the narrow ***f_0(1500)***,

  but also consistent with $f_0(1370)$.



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

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

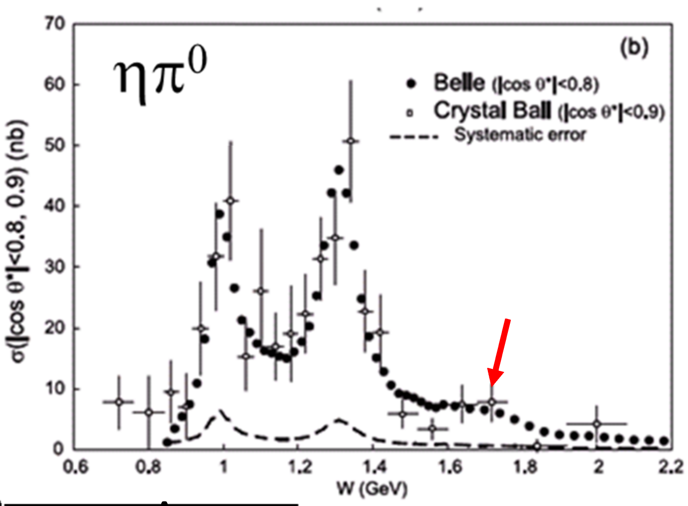
$f_0(1500)$ [n] $\qquad I^G(J^{PC}) = 0^+(0^{++})$

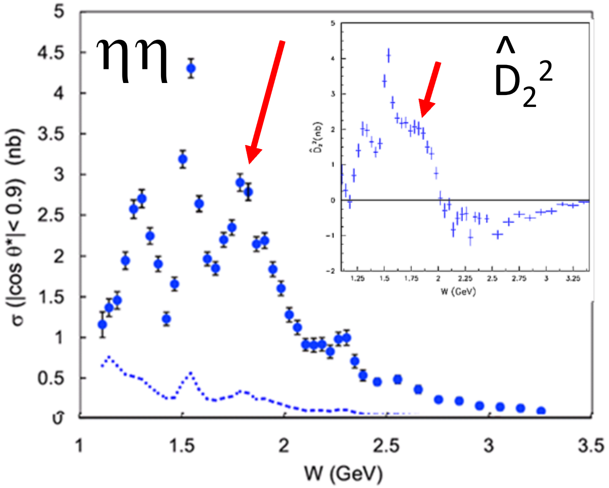
Mass $m = 1505 \pm 6$ MeV (S = 1.3)
Full width $\Gamma = 109 \pm 7$ MeV

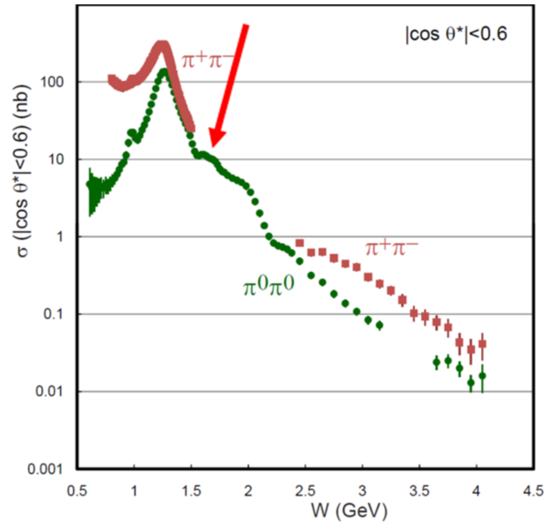
$f_0(1500)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor	p (MeV/c)
$\pi\pi$	(34.9±2.3) %	1.2	741

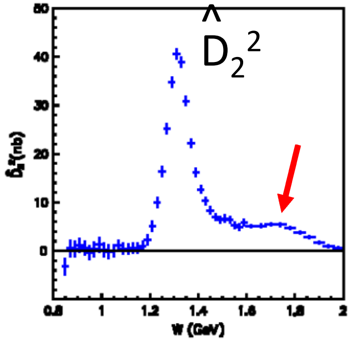
Parameter	Belle ($\pi^0\pi^0$)	Crystal Ball	Unit
Mass	1470^{+6+72}_{-7-255}	1250	MeV/c^2
Γ_{tot}	90^{+2+50}_{-1-22}	268 ± 70	MeV
$\Gamma_{\gamma\gamma}\mathcal{B}(\pi^0\pi^0)$	11^{+4+603}_{-2-7}	430 ± 80	eV

1.6 – 1.8 GeV: Mass region of the greatest difficulty



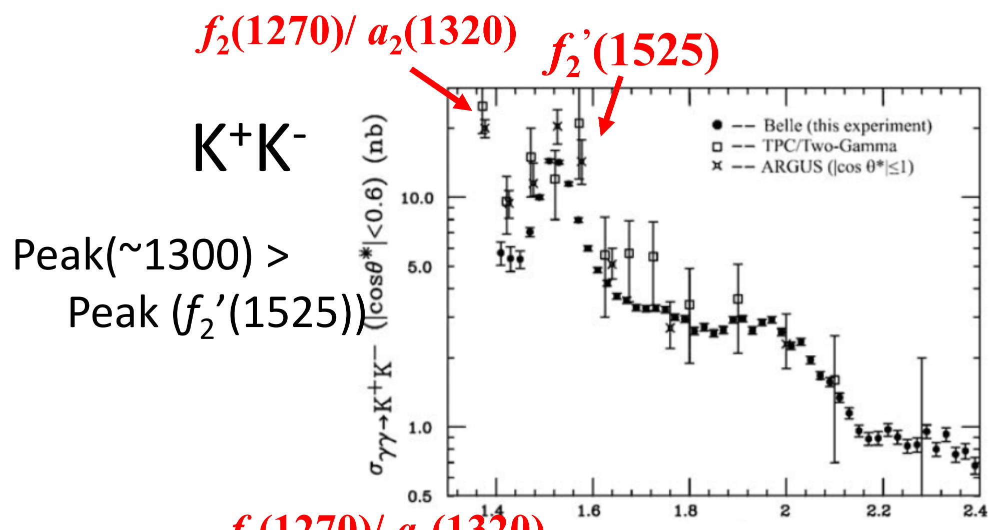


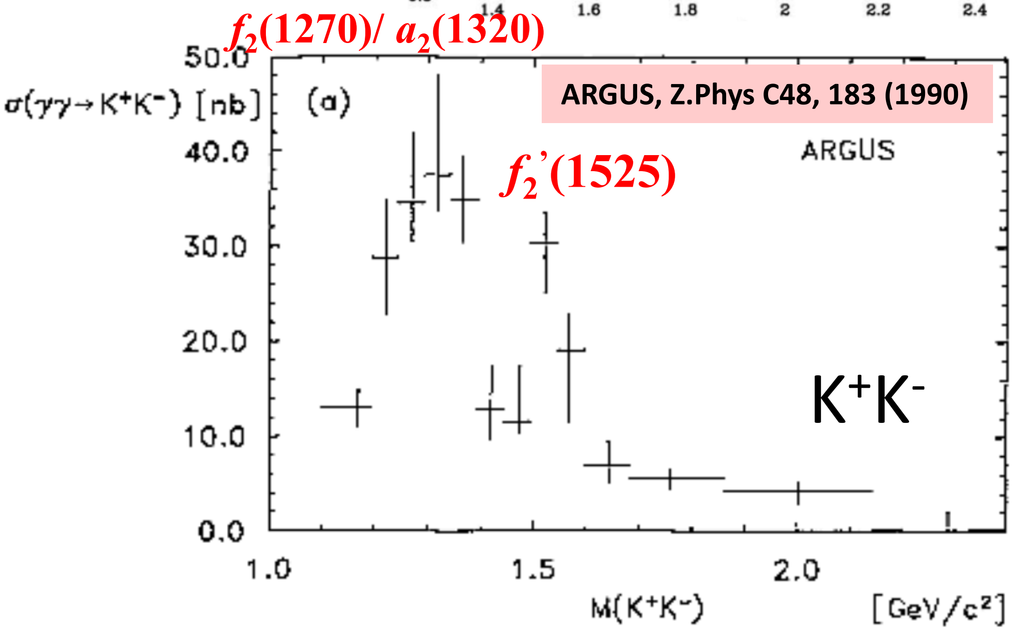




- Extensive studies are performed in the radiative decays of J/ψ ($\rightarrow \gamma gg \rightarrow \gamma R$).
- $a_2(1700) \rightarrow \rho^0\pi^0 \rightarrow \pi^+\pi^-\pi^0$ is confirmed by previous two-photon measurements.
- $a_2(1700) \rightarrow \eta\pi^0$ seen in our data, but no definite parameters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

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





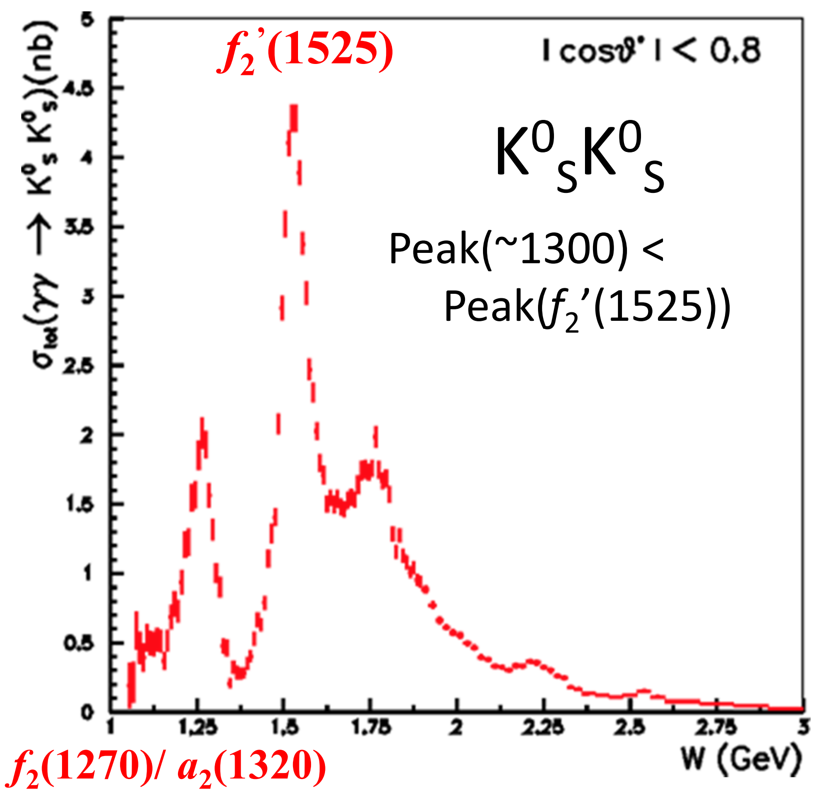
Constructive interference

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

Destructive interference

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

Explained by a phase relation in isospin composition



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 $f(\sim2300)$; 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

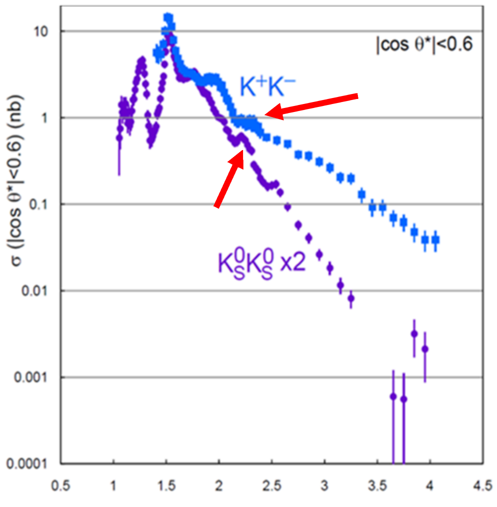
VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
2231.1± 3.5 OUR AVERAGE				

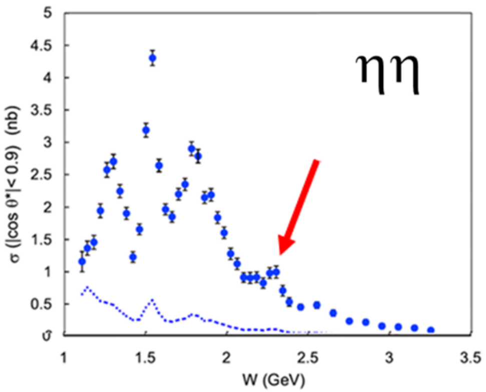
$f_J(2220)$ WIDTH

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	$K\overline{K}$	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





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

Mass $m = 2297 \pm 28$ MeV

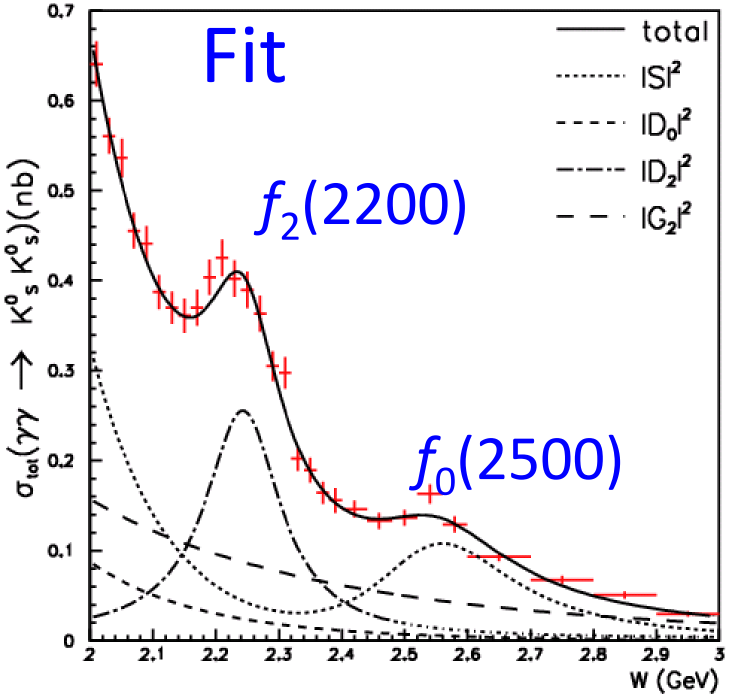
Full width $\Gamma = 149 \pm 40$ MeV

$f_2(2300)$ 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}	$2539 \pm 14^{+38}_{-14}$
Γ_{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.

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

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

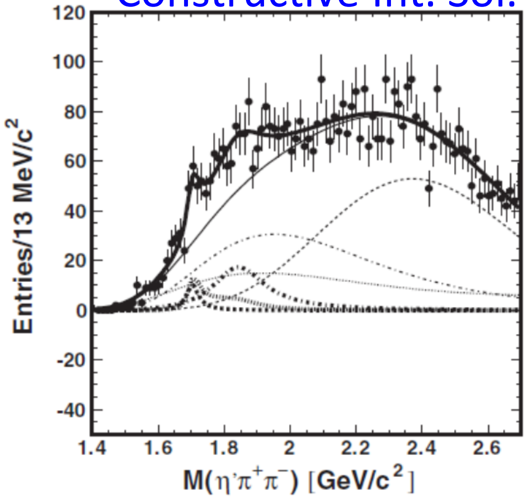
Belle, PRD 86, 052002 (2012)

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?

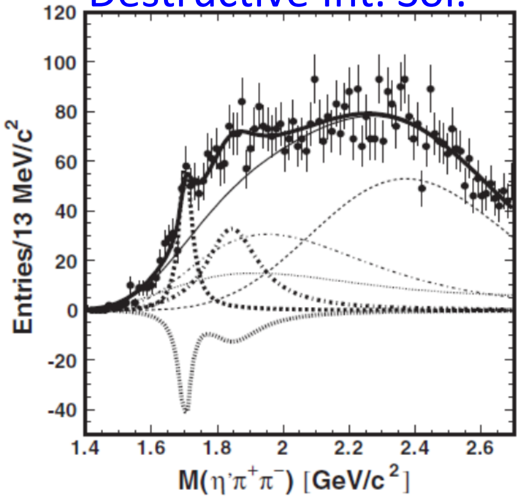
A hint of X(1835) – 2.8σ, but it is not very significant.

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

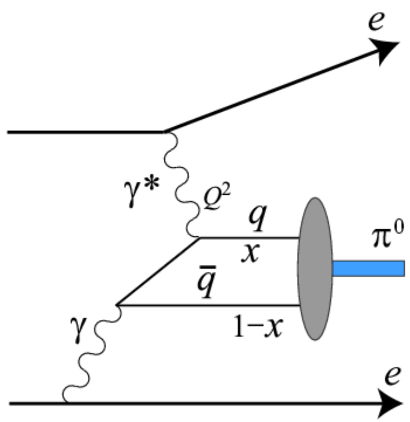
π^0 Transition Form Factor (TFF)

PRD 86, 092007 (2012)

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

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

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

BaBar has reported a significant deviation from the expectation.

Measurement:

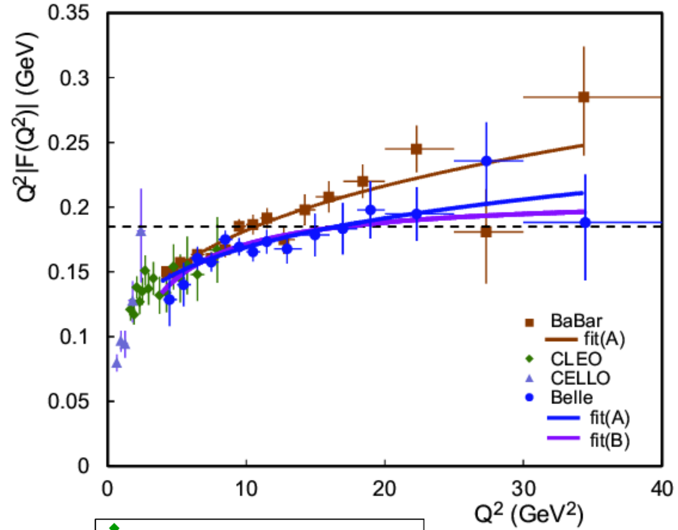
$|F(Q^2)|^2 = |F(Q^2,0)|^2 = (\mathbf{d\sigma/dQ^2})/(2A(Q^2))$ A(Q^2) is calculated by QED

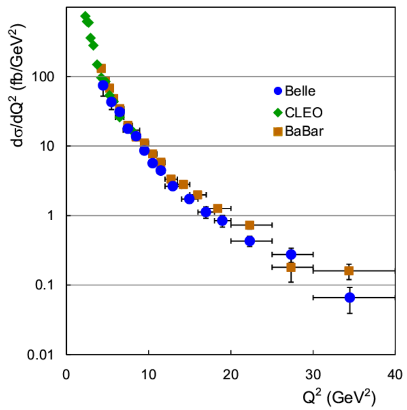
$|F(0,0)|^2 = 64\pi\Gamma_{\gamma\gamma}/\{(4\pi\alpha)^2 m_R^3\}$

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>9GeV^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)

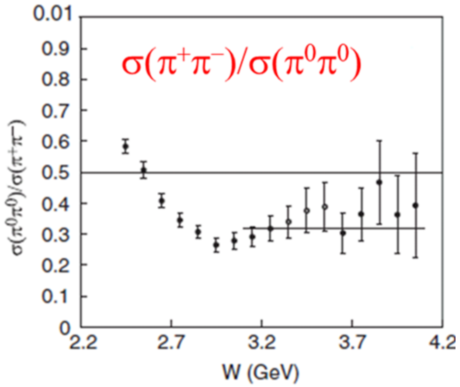
Physics at Belle II, SuperKEKB

Physics of High W

- W-dependence of hadron-pair production $\sigma \propto W^{-n}$

Predictions: n = 6 (charged mesons), n=10 (neutral mesons) n=10 (proton)

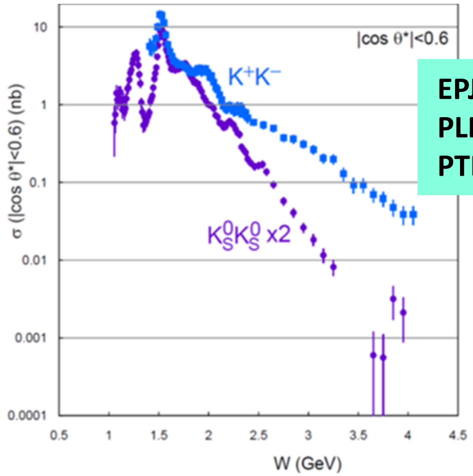
at W High Enough. (We don't know where is "high enough".)



W is still not high enough?

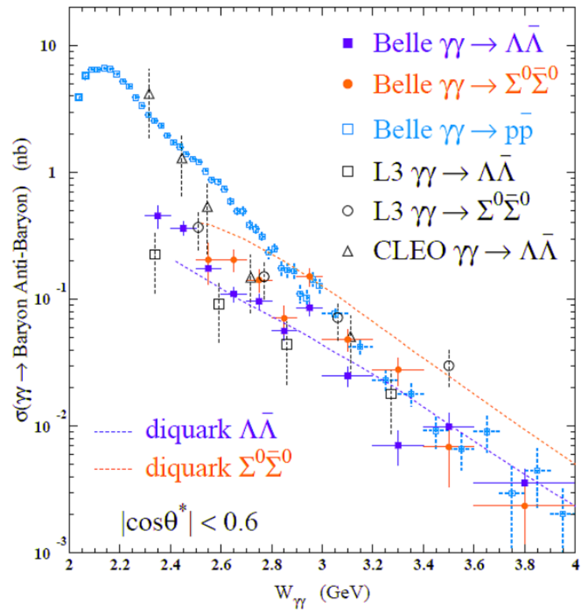
Final-state interaction important

for $\pi\pi$ even in high W?



EPJC 32, 323 (2003)
PLB 615, 39 (2005)
PTEP 2013, 123C01 (2013)

$K\bar{K}$ is different and agrees with prediction



Baryon-pair production processes are statistically limited (because of large n)

Proton pair, Hyperon (Λ, Σ) pair, Δ pair

$\sigma(\Lambda\bar{\Lambda})/\sigma(p\bar{p})$ ~ 1 at high W?

PLB 621, 41 (2005)
hep-ex/0609048 (Unpublished)

Analysis of $D\bar{D}$ at around 3.80 GeV

Search for $\chi_{c0}(2P) \to D^0\bar{D}^0$ / D^+D^-

The target is enhancements around 3.80 – 3.85 GeV?

Possible backgrounds:

A difference between charged pair and neutral pair seems to indicate the contribution of $D^*\bar{D}$ which has a charge (isospin) asymmetry in D* decay

$\chi_{c2}(2P) \to D^*\bar{D}$, then $M(D\bar{D}) \sim 3.80$ GeV

Backgrounds systematically to be solved

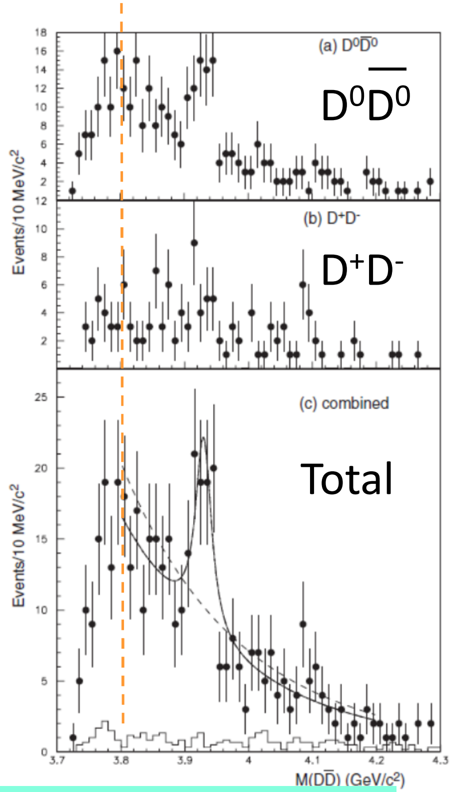
$\chi_{c2}(2P) \to D^{*0}\bar{D}^0 \to D^0\bar{D}^0(\pi^0/\gamma)$

$\chi_{c2}(2P) \to D^{*+}D^- \to D^+D^-(\pi^0)$

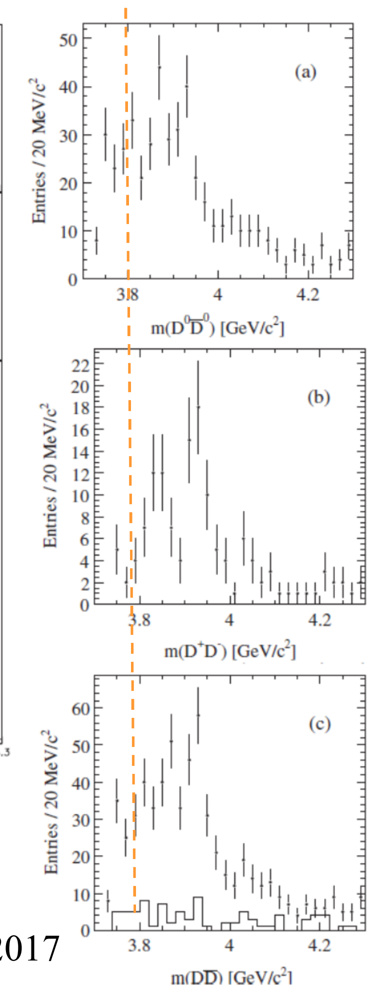
$\chi_{c2}(2P) \to D^{*+}D^- \to D^0D^-(\pi^+)$

A small P_t-unbalance for $D\bar{D}$ is also important information as a sign of the extra π/γ.

Belle



BaBar



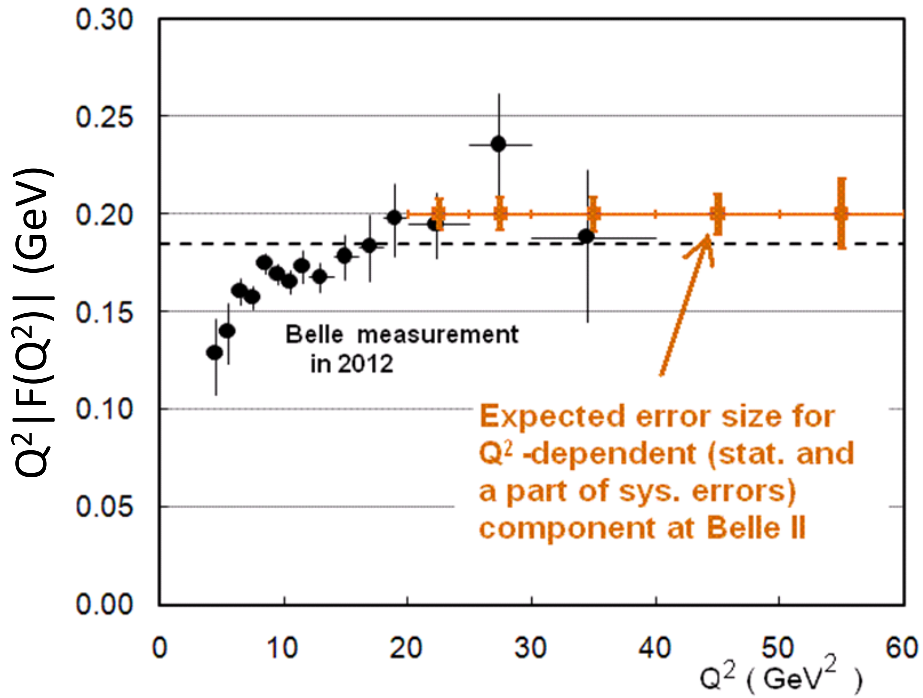
PRL 96, 082003 (2006)
PRD 81, 092003 (2010)

Single-tag TFF's for π^0, $K^0_S K^0_S$, etc.

Stat. error estimation for π^0-TFF measurement in the high Q^2 region

Assumptions:

- Integrated luminosity 50 ab^{-1} (x 66)
- No large Bhabha-Veto inefficiency (x 2.5 @ high Q^2)
- Systematic errors from π^0-fit and trigger can be reduced
- Other systematics stay the same



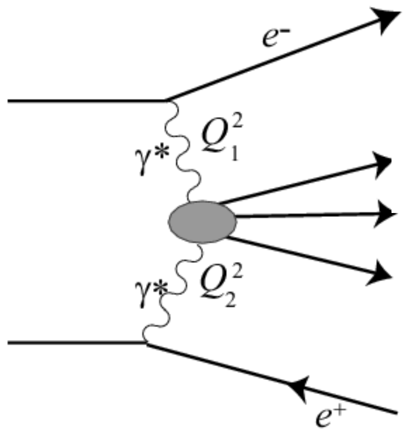
Q^2 > 60 GeV^2

Close to back-to-back topology of $e\pi^0$ in e^+e^- c.m. frame

Huge background from Bhabha

$K^0_S K^0_S$ about 200 events to be observed for Belle.
More than 10,000 events expected for Belle II.

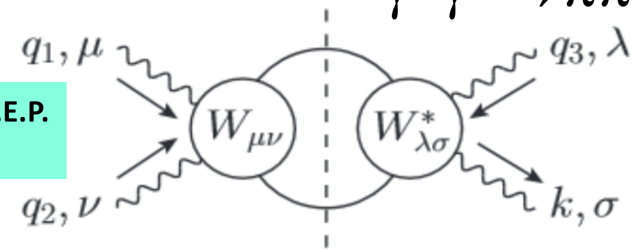
Double-tag processes



Hadronic Light-by-Light (hLbL) contribution is important for muon g-2 theoretical cal.

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

G.Colangelo et al., J.H.E.P. 1409, 091 (2014)



At the present, the error from the hLBL contribution is the same order of that of the experiment of muon g-2. In near future, an improvement is needed.

Test of QCD

M.Diehl et al., EPJ C22, 439 (2001)

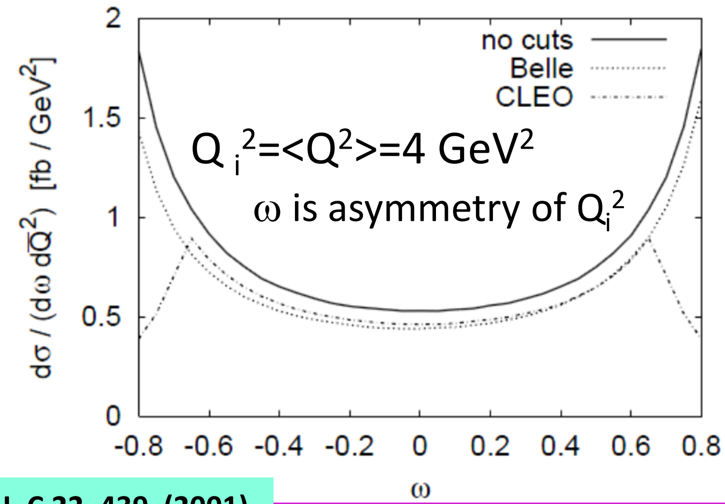
$\gamma^*\gamma^* \to \pi^0$

$Q_1^2 \sim Q_2^2$

Dependence on Distribution Amplitude is small

The ee-based cross section ~ O(0.1fb)

Feasible at Belle II

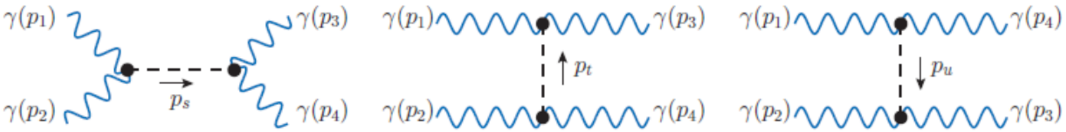


M. Diehl, et al., Eur. Phys. J. C 22, 439 (2001)

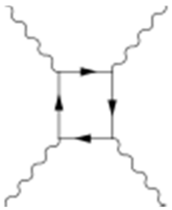
The elastic scattering

- $\gamma\gamma \rightarrow \gamma\gamma$ So far, it is observed only at the peaks of π^0, η and η'.
- Interference with lepton's and quark's box diagrams may be seen near η_c peak. BF($\eta_c \rightarrow \gamma\gamma$) = 1.5 x 10^{-4} is known.
- At an e^+e^- collider, the Double-Radiation Bhabha process is also unseparated and interfering background.

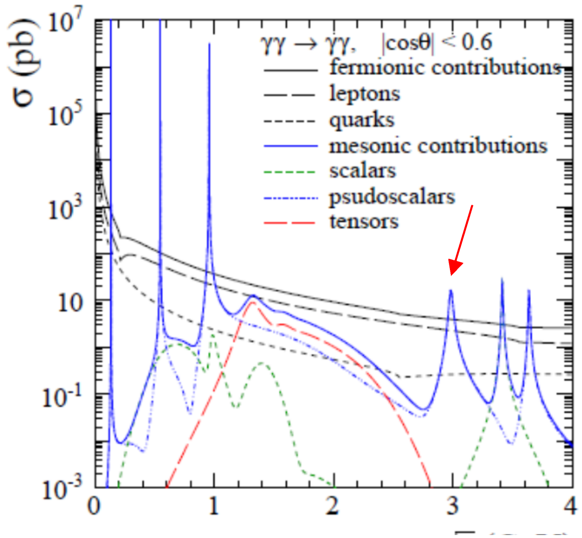
Resonant (s,t,u):



Non-resonant:



Double radiation:



We will need O(10 ab^{-1}) to overcome background fluctuation in the continuum component.

P.Lebiedowicz and A. Szczurek
arXiv 1705.06535[hep-ph]