Two-photon processes with hadron-pair production at KEKB/Belle

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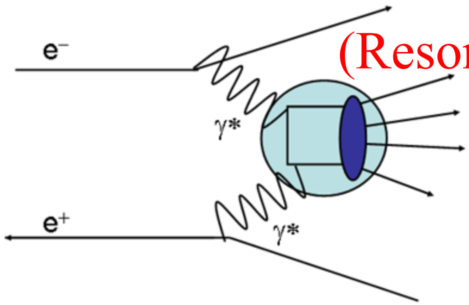
Belle Collaboration

Workshop on Progress on Hadron Structure Functions in 2018
November 18-19, 2018, KEK

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



Q = 0 , **C = +**

$\gamma^{(*)}\gamma^{(*)} \rightarrow$ hadron(s) (Exclusive final state):

Useful to Test of QCD

Measurement of resonance production and its properties

Spectroscopy and new-resonance search

Physics motivations of Single-tag measurements, $\gamma^*\gamma$:

- Q^2 dependence of transition form factor (TFF) of resonances
  $\rightarrow$ Test of QCD in models of meson/exotics, Hadron tomography by GDAs
- Reference of Light-by-Light hadronic contribution for g-2$|_\mu$

No-tag and Single-tag measurements for hadron-pair production

Experimental features

No-tag (No electron observed)

$\gamma\gamma \to hh'$ (quasi-real two-photon collisions)

Relatively large cross section

A p_t-balanced hadron pair observed $\to$ Serious detection difficulty near the hh' mass threshold (every particle has a low-p_t)

C-odd ($\gamma^* \to hh'$) contamination is very small.

Single-tag (only one electron observed)

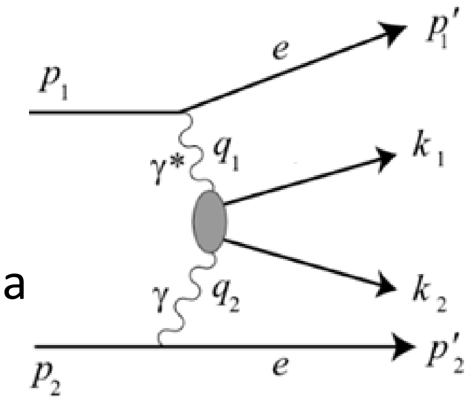
$\gamma^*\gamma \to hh'$ (virtual-photon & quasi-real-photon collisions)

Relatively small cross section

p_t-balance between a tag-electron and the hadron system $\to$ Less difficulty with the hh' mass threshold

C-odd (Bremsstrahlung $\gamma^* \to hh'$) contamination exists for a charged-hadron pair (physically interfering)

No such C-odd backgrounds exist for $\pi^0\pi^0$, $K^0_SK^0_S$ in this talk.



$\gamma^*\gamma$ Cross Section and Form Factor

$\gamma^*\gamma$ cross section: $\sigma(W, Q^2)$

Derived using Equivalent Photon Approximation (luminosity function).

W : $\gamma^*\gamma$ c.m. energy, $Q^2 = -q_1^2$: virtuality of the virtual photon

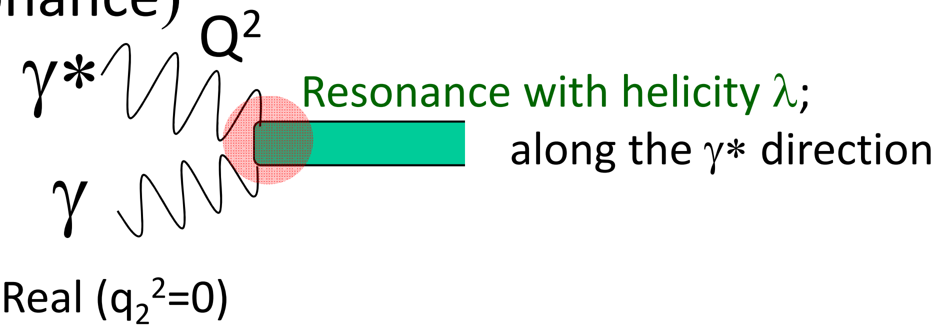
$\sigma(W,Q^2) = \sigma_{TT} + \varepsilon\sigma_{LT}$ (Transverse photon and Longitudinal photon)

This is a similar calculation as that for the no-tag case, where the contribution is integrated in the vicinities of $Q^2 = 0$, and $\sigma(W) = \sigma_{TT}$ only.

Transition form factor (TFF) of a resonance: $F(Q^2)$

Proportional to the helicity amplitude of the resonance production

$$\Sigma_\lambda |F(Q^2)_\lambda|^2 \propto \sigma(\gamma^*\gamma \to \text{Resonance})$$



Belle Results for two-photon reactions

In this talk, we present about the results of :

1. $\gamma\gamma \to$ light-pseudoscaler-meson pair (No-tag)

   General descriptions, High-energy behaviors

2. $\gamma\gamma \to \pi^0\pi^0$, $K^0_S K^0_S$ (No-tag)

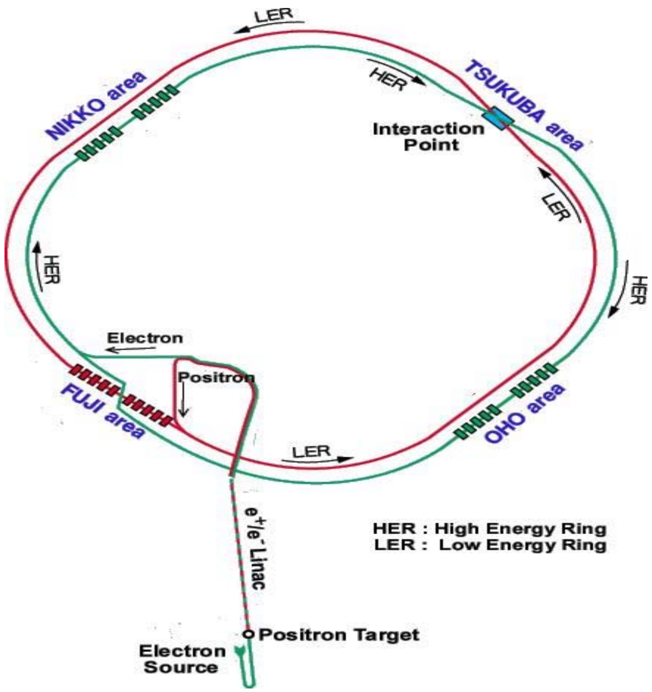
   in Resonance production

3. $\gamma^*\gamma \to \pi^0\pi^0$, $K^0_S K^0_S$ (Single-tag)

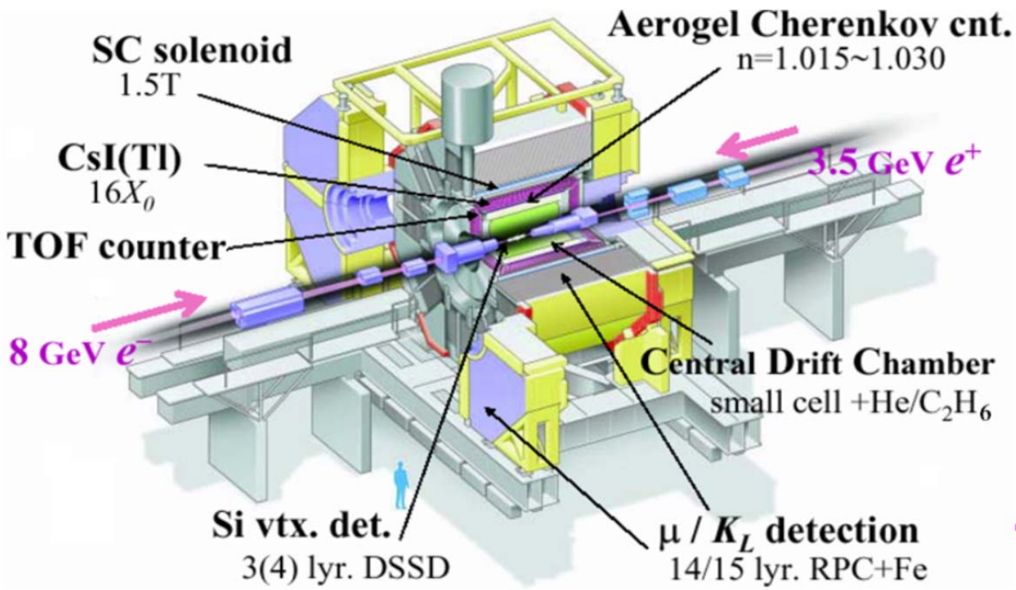
   Cross sections, Resonance TFFs, etc.

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}=2.1×10^{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

No-tag Measurements

1. $\gamma\gamma \rightarrow$ light-pseudoscaler-meson pair (No-tag, General, HE)
2. $\gamma\gamma \rightarrow \pi^0\pi^0$, $K^0_S K^0_S$ (No-tag, Resonance production)

"$\gamma\gamma \to$ light-pseudoscalar-meson pair" from Belle

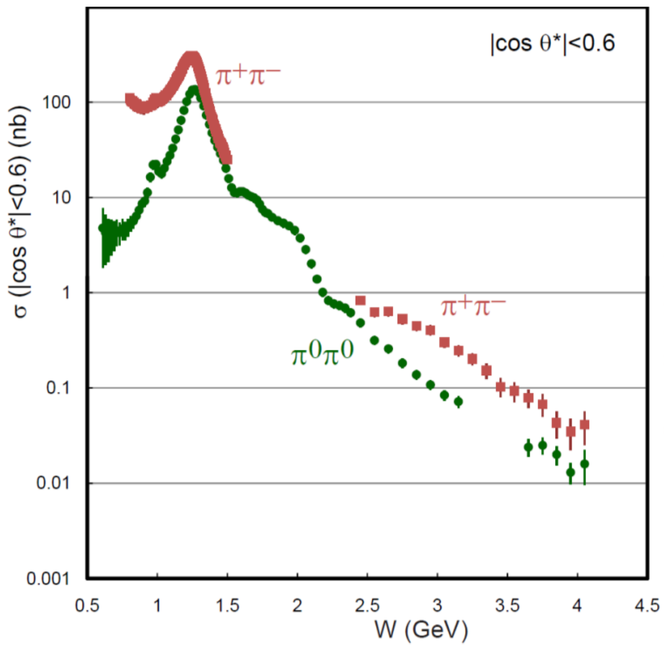
10 papers for 6 processes

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

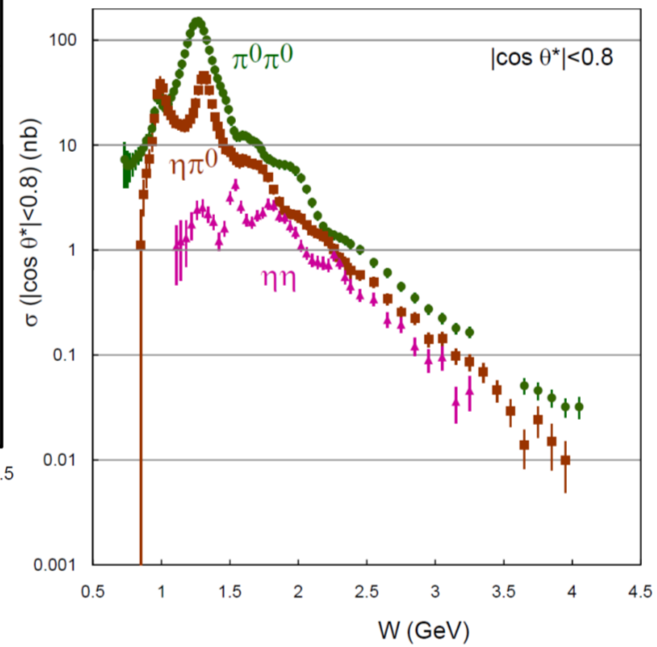
The six processes; in total ~20 peaks

Charged vs Neutral $\pi\pi$

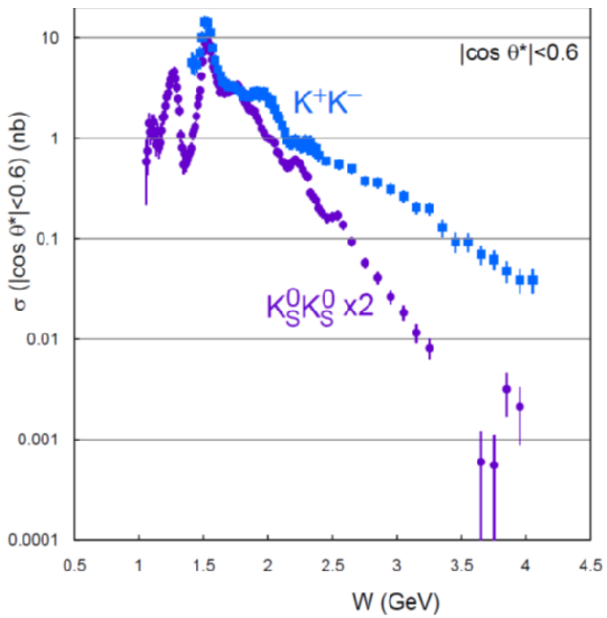


Three neutral-pair processes

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



Charged vs Neutral $K\bar{K}$



Horizontal axis:

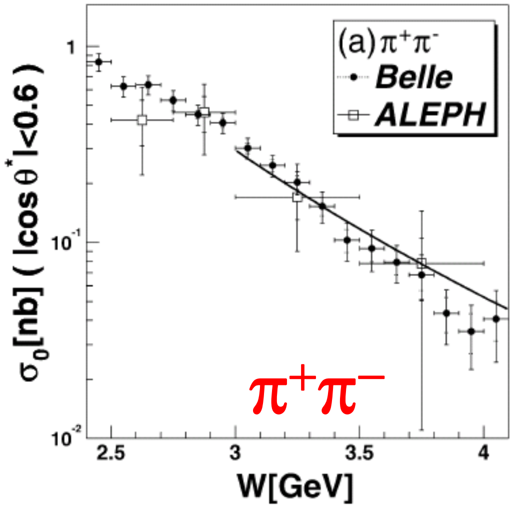
W -- $\gamma\gamma$ c.m. energy = invariant mass of the two-meson system

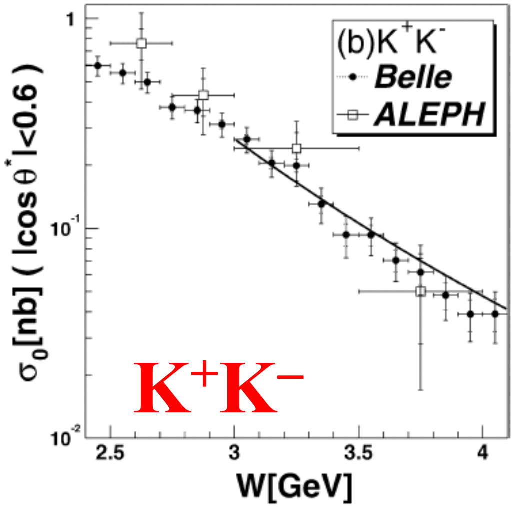
W<~2.5GeV: Dominated by resonances (light meson spectroscopy→ S.Uehara, PWA8/ATHOS3 (2015))

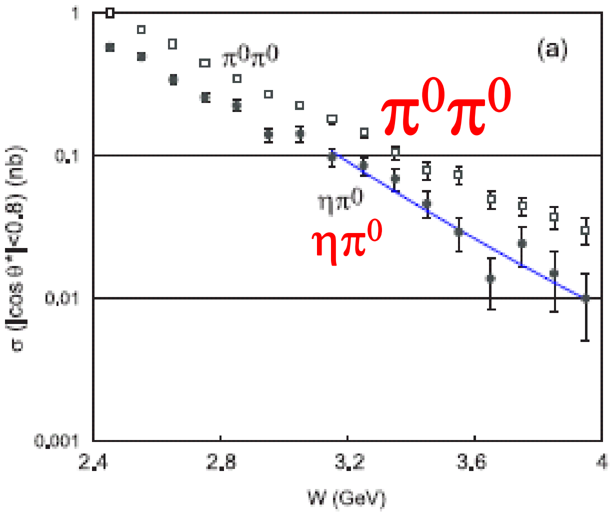
W>~2.5 GeV: Netgative-power law QCD + (χ_c charmonia)

W-dependences at high energies

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

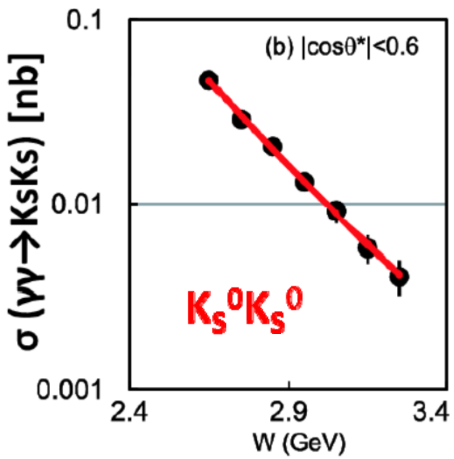


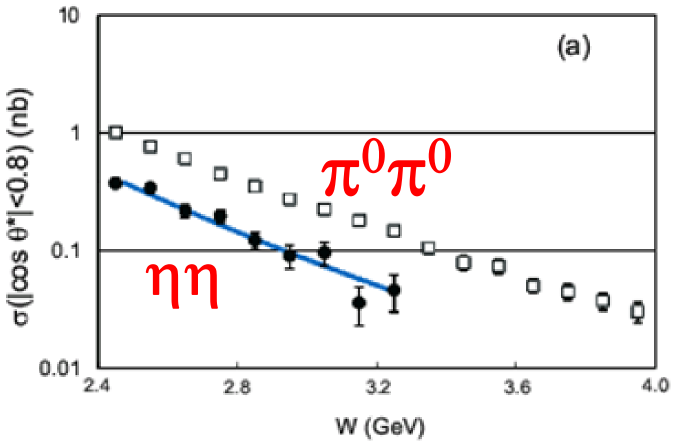




Fitted and reproduced

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
$K_S^0 K_S^0$	$11.0 \pm 0.4 \pm 0.4$	$2.4 - 4.0^\dagger$	< 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	
$\pi^0\pi^0$	$8.0 \pm 0.5 \pm 0.4$	$3.1 - 4.1^\dagger$	< 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	$0.36R_f^2(0.62R_f^2)^\ddagger$		

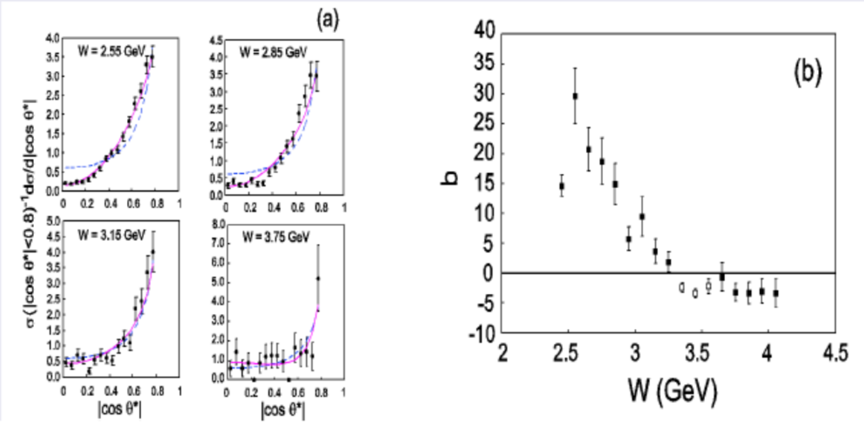
† Exclude χ_{cJ} region, 3.3 - 3.6 GeV.
‡ Assuming η is a member of SU(3) octet (superposition of octet and singlet with mixing angle of $\theta_p = -18°$).
R_f is a ratio of decay constants, $f_\eta^2 / f_{\pi^0}^2$.

- *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

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

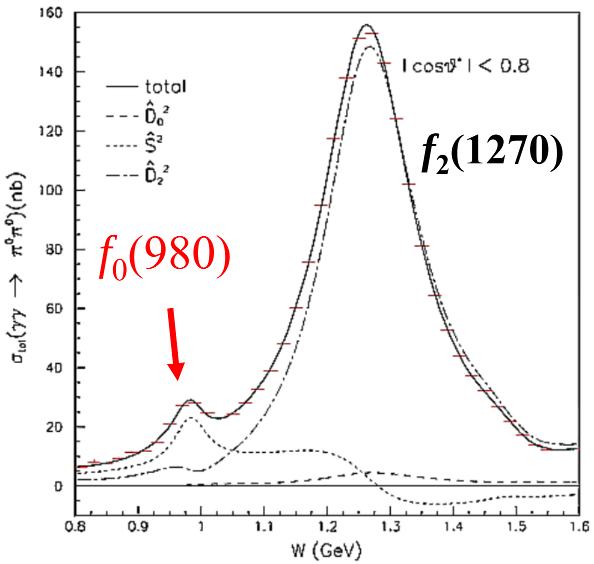
Exclude $\dagger$ χ_{cJ} region, 3.3 - 3.6 GeV

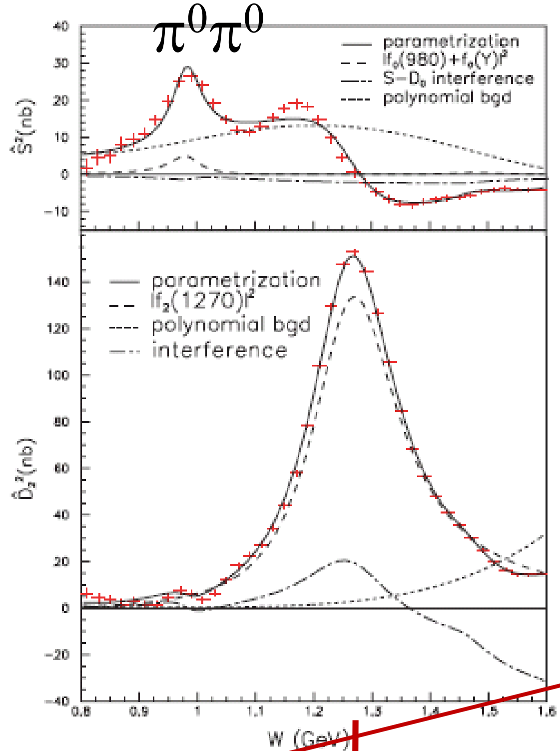
Summarized by H.Nakazawa
Hadron2013

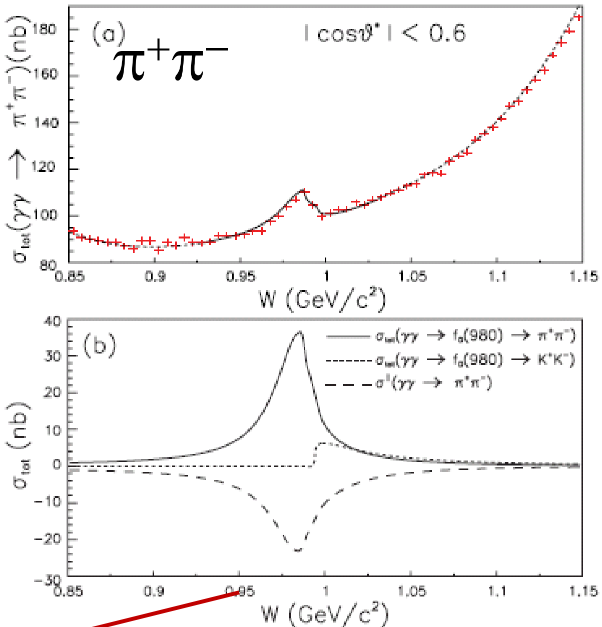
$\gamma\gamma \to \pi^0\pi^0$: f_0 (980) and f_2 (1270)

No-tag
(Q^2=0)

PRD 79, 052009 (2009)







Meson	$f_0(980)$	$f_0(980)$
M[MeV/c²]	$985.6^{+1.2+1.1}_{-1.5-1.6}$	$982.2\pm1.0^{+8.1}_{-8.0}$
$\Gamma_{\pi\pi/tot}$[MeV]	$51.3^{+20.9+13.2}_{-17.7-3.8}$	$66.9^{+13.9+8.8}_{-11.8-2.5}$
$\Gamma_{\gamma\gamma}$[eV]	$205^{+95+147}_{-83-117}$	$286\pm17^{+211}_{-70}$

Predictions for f_0(980)

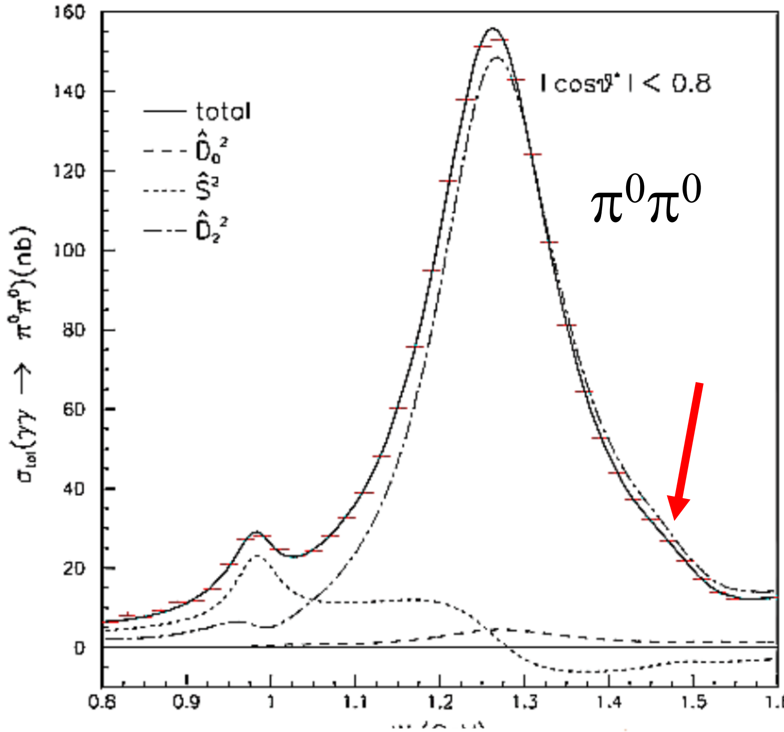
Model	$\Gamma_{\gamma\gamma}$ [eV]
*u*ubar,*d*dbar	1300 – 1800
*s*sbar	300 – 500
*KK*bar molecule	200 – 600
Four-quark	270

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

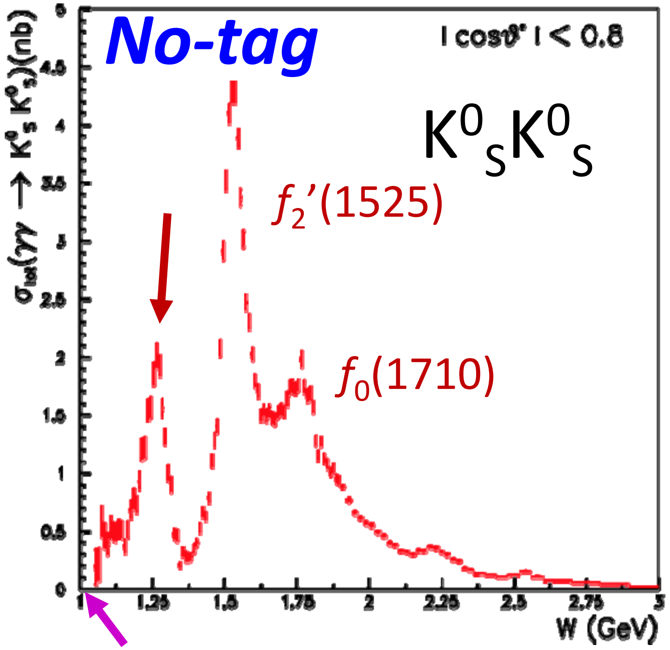
$f_0(1500)$ [n] $\qquad I^G(J^{PC}) = 0^+(0^{++})$

Mass m = 1505 ± 6 MeV (S = 1.3)
Full width Γ = 109 ± 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

Resonant structures in $K^0_SK^0_S$



PTEP 2013, 123C01 (2013)

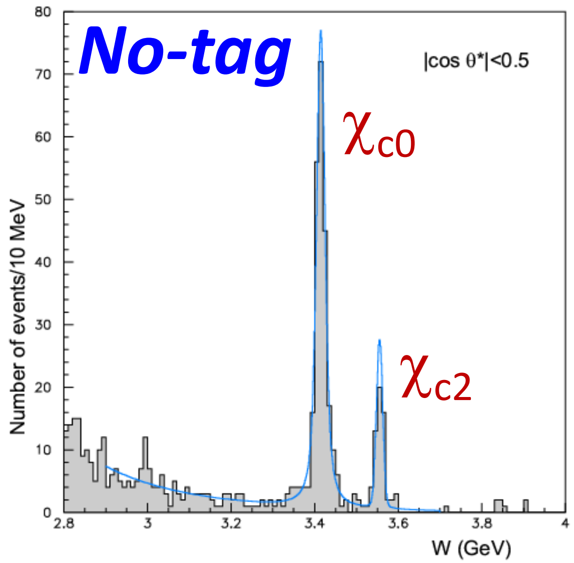
Maximum at the $f_2'(1525)$ peak

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

Two-photon coupling of $f_0(1710)$

No data near the $K^0_SK^0_S$ mass threshold

lack of trigger efficiency for low-p_t tracks



χ_{cJ} 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

Two-photon decay width × $B(K^0_SK^0_S)$

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

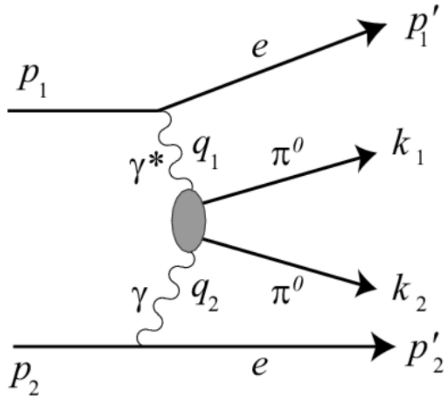
Single-tag Measurements

3. $\gamma^*\gamma \rightarrow \pi^0\pi^0$, $K^0_S K^0_S$ (Single-tag)

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

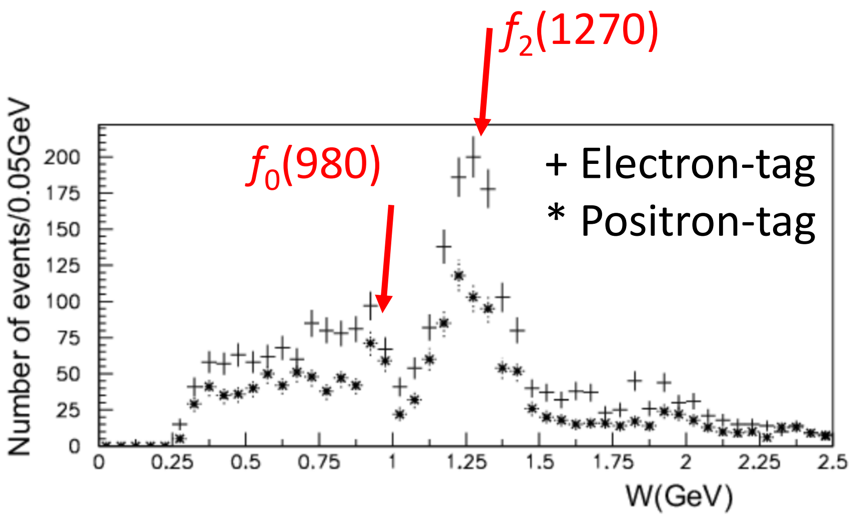
TFF: Transition Form Factor

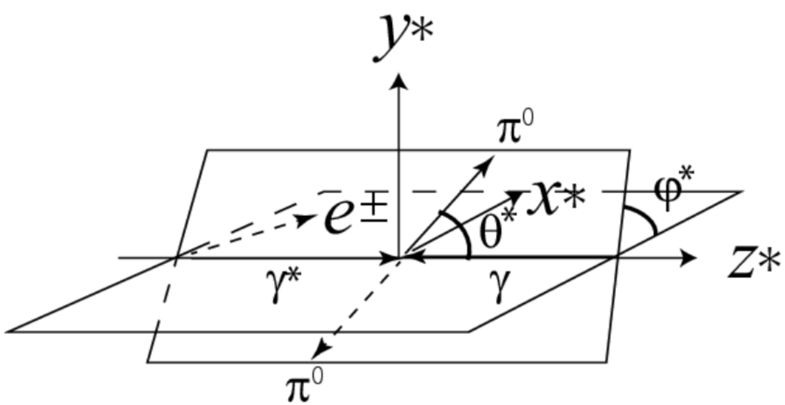
PRD 93, 032003 (2016)



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$|_\mu$

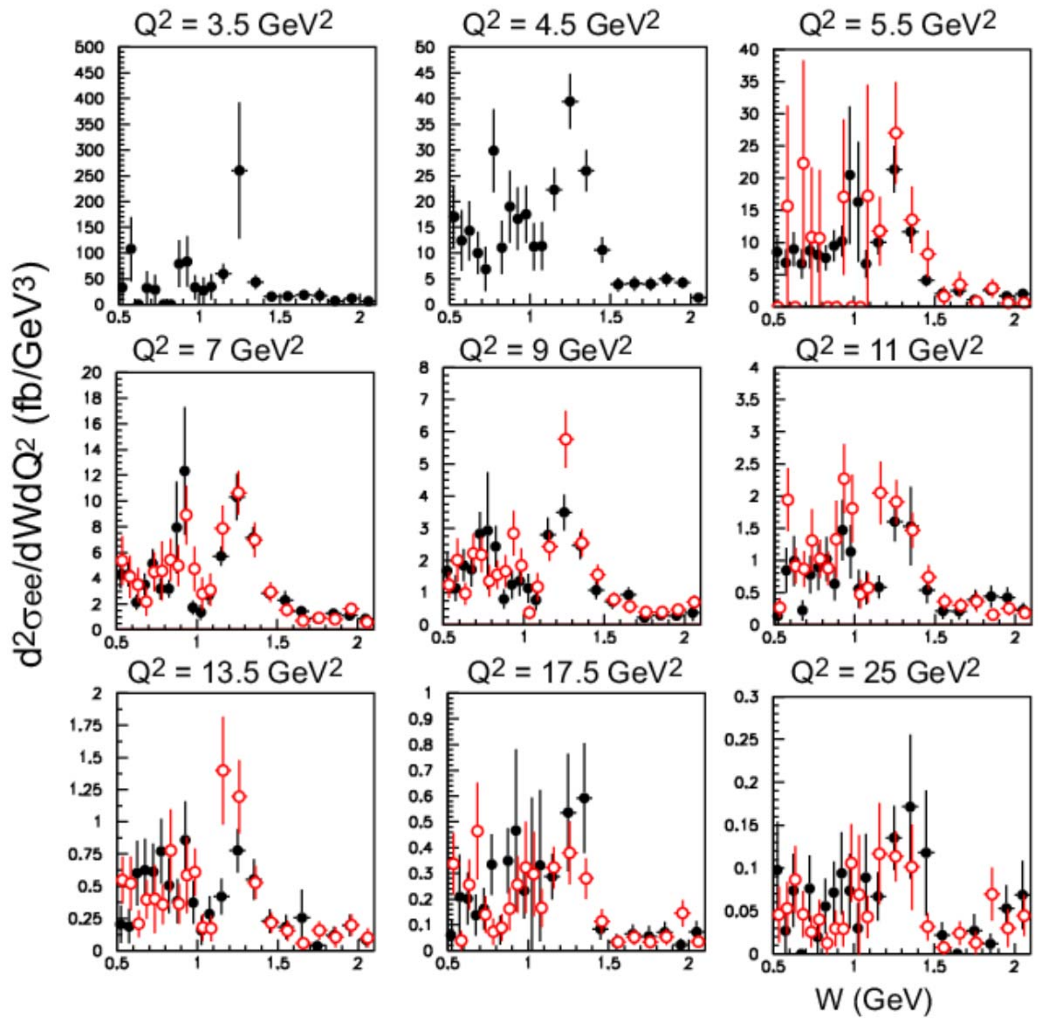




The f_0/f_2 ratio is larger than in the no-tag case.

Cross-section results

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



Formalism of Partial Wave Analysis

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

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

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

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

$$\begin{aligned} t_0 &= |SY_0^0 + D_0Y_2^0|^2 + |D_2Y_2^2|^2 + 2\epsilon_0|D_1Y_2^1|^2, \\ t_1 &= 2\epsilon_1 \Re\left[(D_2^*|Y_2^2| - S^*Y_0^0 - D_0^*Y_2^0)D_1|Y_2^1|\right], \\ t_2 &= -2\epsilon_0 \Re\left[D_2^*|Y_2^2|(SY_0^0 + D_0Y_2^0)\right]. \end{aligned}$$

++ 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

To obtain the resonance amplitudes:

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

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

$D_0 = 4\pi\,[B_{D0}(W) + A_{f2}(W)\sqrt{r_0}]\; Y_2^0$

etc.

We take into account partial waves up to J=2.

J=1 does not couple with a P-meson pair.

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

Partial-Wave (helicity) Contributions to TFF

Resonance amplitude for *f* resonances

$$A_R^J(W) = F_R(Q^2)\sqrt{1+\frac{Q^2}{m_R^2}}\sqrt{\frac{8\pi(2J+1)m_R}{W}} \times \frac{\sqrt{\Gamma_{\rm tot}(W)\Gamma_{\gamma\gamma}(W)\mathcal{B}(K_S^0K_S^0)}}{m_R^2 - W^2 - im_R\Gamma_{\rm tot}(W)}$$

TFF of f_2 (tensor meson) for each helicity, $i = \lambda$

$$\boxed{\sqrt{r_{if}}\, F_{f2}} \quad (i = 0, 1, 2)$$

$$r_{0f} + r_{1f} + r_{2f} = 1$$

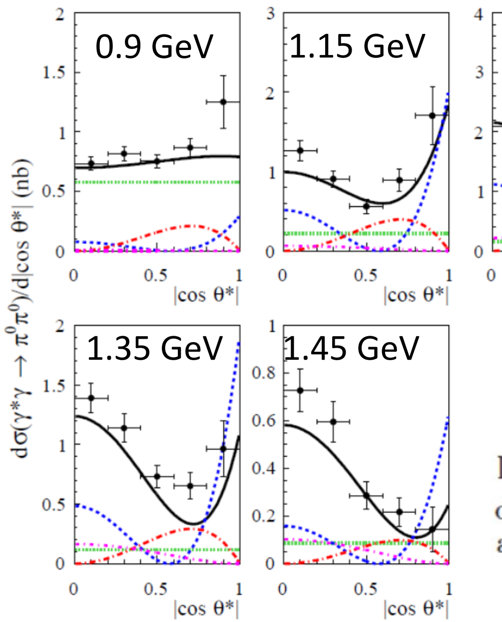
Background amplitudes

$$B_{D0} = \frac{\beta^5 a_{D0}(W_0/W)^{b_{D0}}}{(Q^2/m_0^2+1)^{c_{D0}}},$$ etc. (Nagative-power low for W)

PWA fits

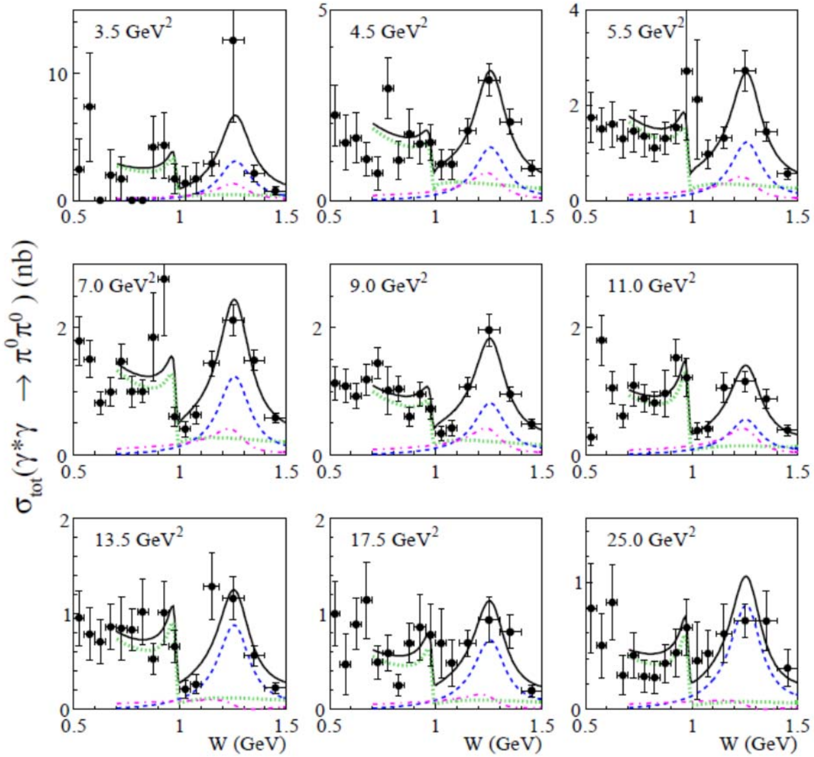
The PWA fit is constructed by parameterized resonant ($f_0(980)$ and $f_2(1270)$) and continuum amplitudes.

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



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

Final result of the PWA fits to the
γ*γ cross sections

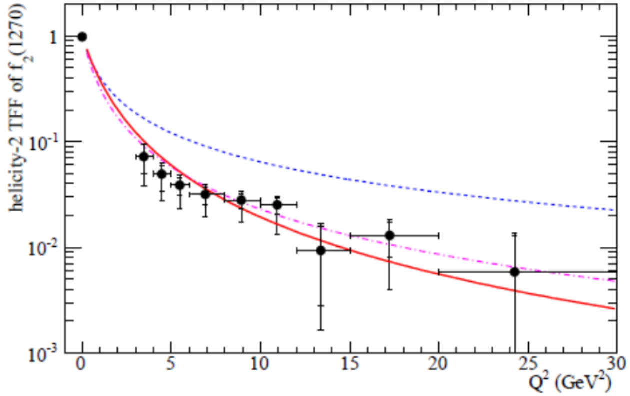


Significant contributions from
hel.=0 and 1 in contrast
to the no-tag (Q^2=0) case

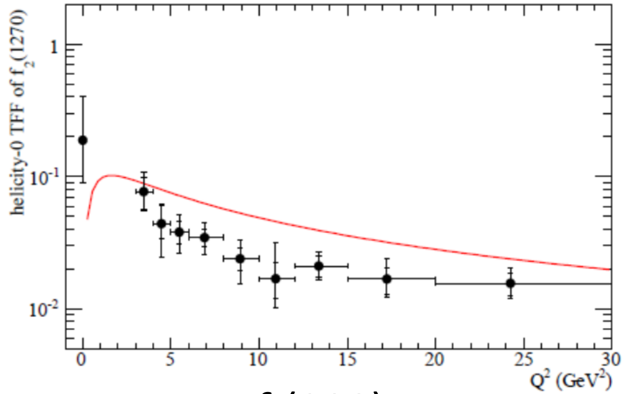
Q^2 dependence of resonant amplitudes

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

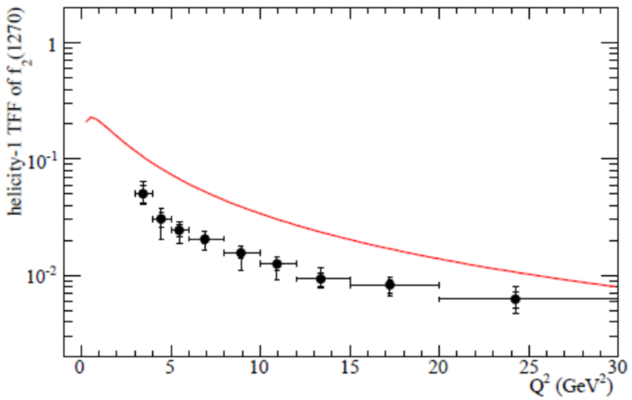
$f_2(1270)$, helicity = 2



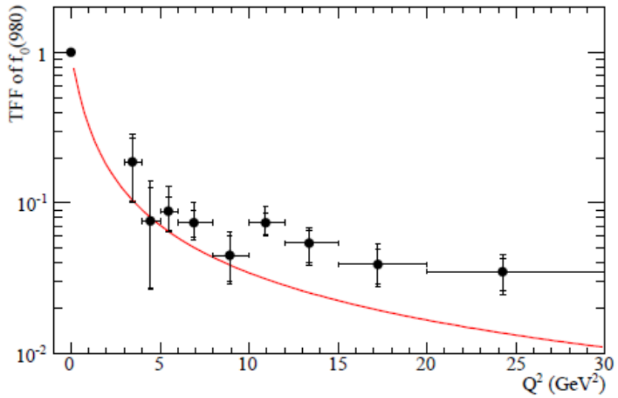
$f_2(1270)$, helicity = 0



$f_2(1270)$, 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

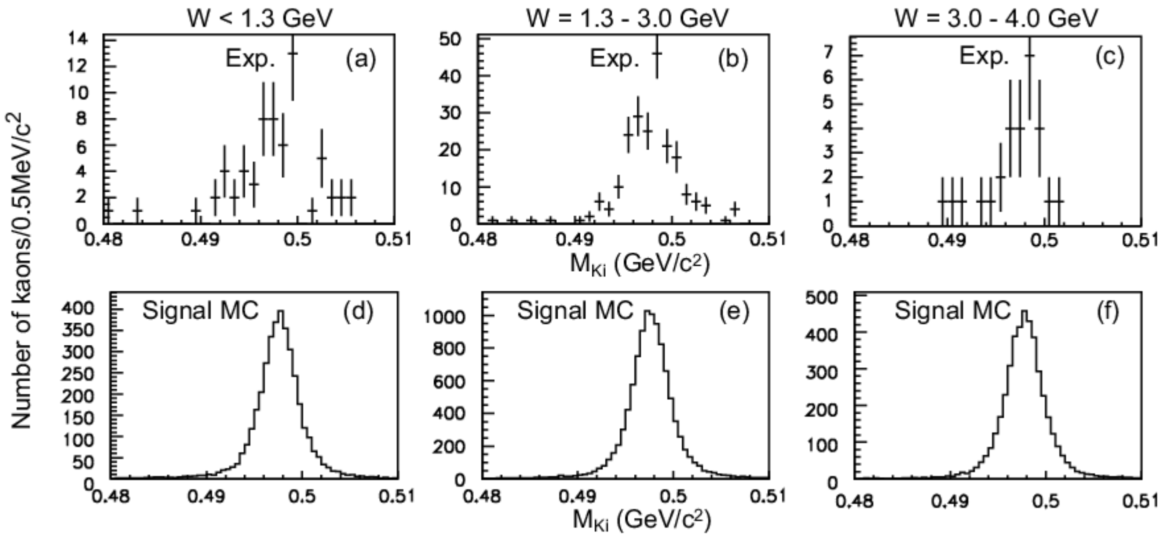
Single-tag $K^0_S K^0_S$ production

PRD 97, 052003 (2018)

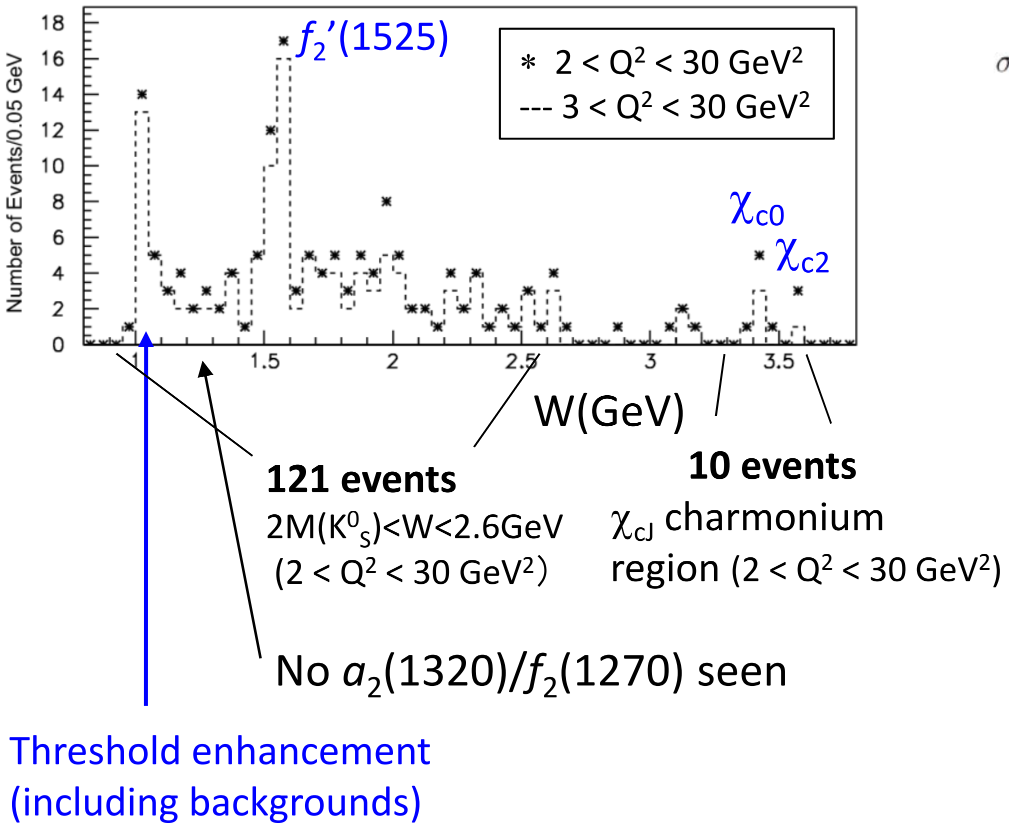
$e^+e^- \to e\ (e)\ K^0_S\ K^0_S,\ \ K^0_S \to \pi^+ \pi^-$ 759 fb^{-1}

Topology: 1 electron(or positron) and 4 charged pions

Reconstructed K^0_S mass
(with a looser cut)

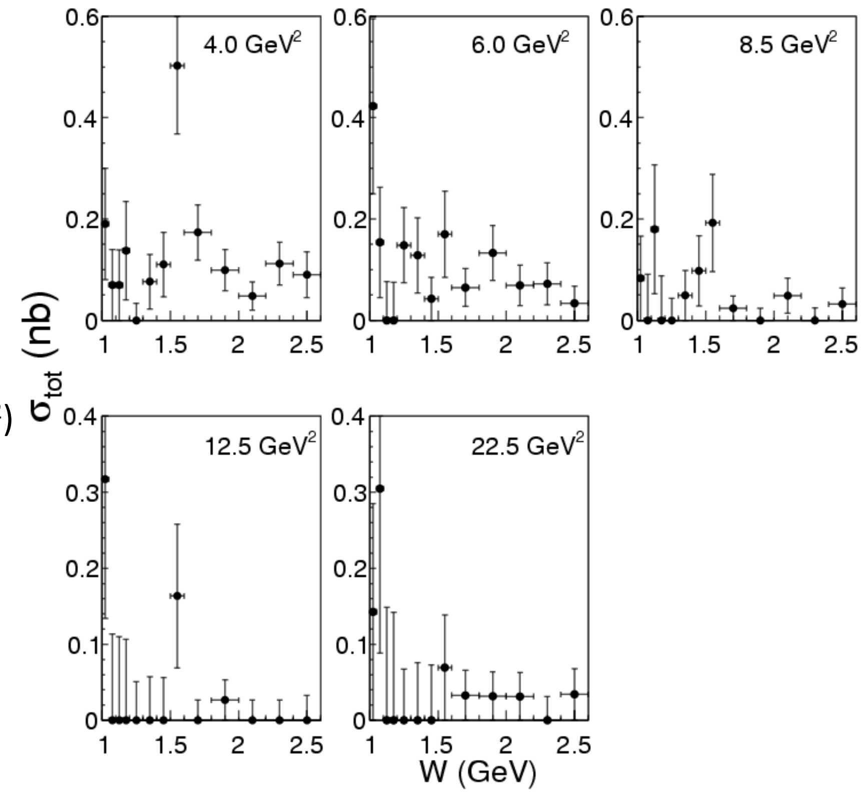


W dependence and $\gamma*\gamma$ cross section at Q^2 bins



Cross section in the resonant-mass region

$$\sigma_{\rm tot}(\gamma^*\gamma \to K_S^0 K_S^0) = \frac{1}{2\frac{d^2L_{\gamma^*\gamma}}{dW\,dQ^2}} \frac{Y(W,Q^2)}{(1+\delta)\varepsilon(W,Q^2)\Delta W \Delta Q^2 \int \mathcal{L}dt\mathcal{B}^2}$$

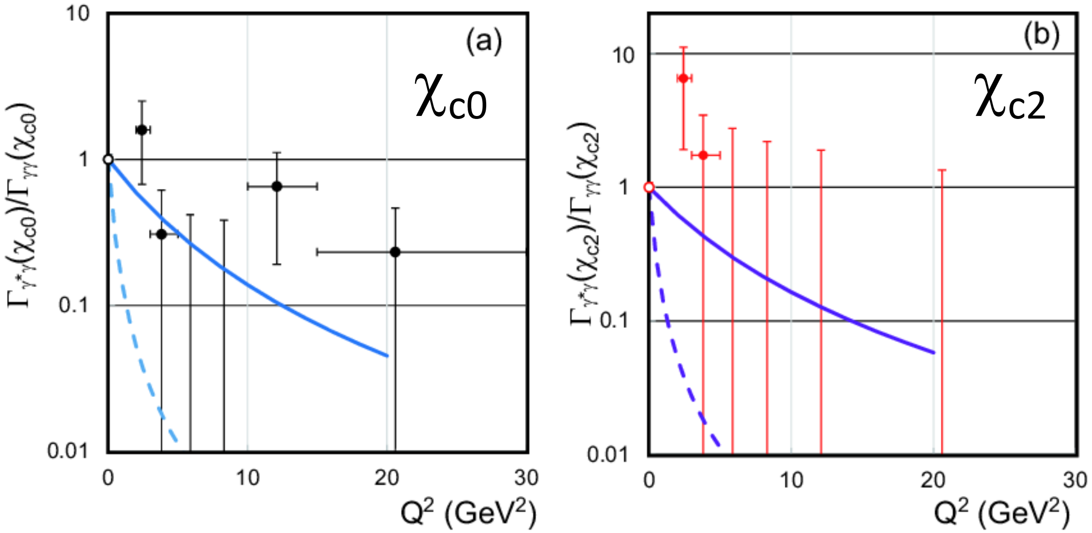


χ_{cJ} charmonia

Assume that in total 7 events (3 events) peaking near the χ_{c0} (χ_{c2}) mass are purely from the charmonium (backgrounds are estimated <1 event in total)

$$\frac{d\sigma_{ee}}{dQ^2} = 4\pi^2 \left(1 + \frac{Q^2}{M_R^2}\right) \frac{(2J+1)}{M_R^2} \frac{2d^2 L_{\gamma^*\gamma}}{dW\,dQ^2} \Gamma_{\gamma^*\gamma}(Q^2)\mathcal{B}(K_S^0 K_S^0)$$

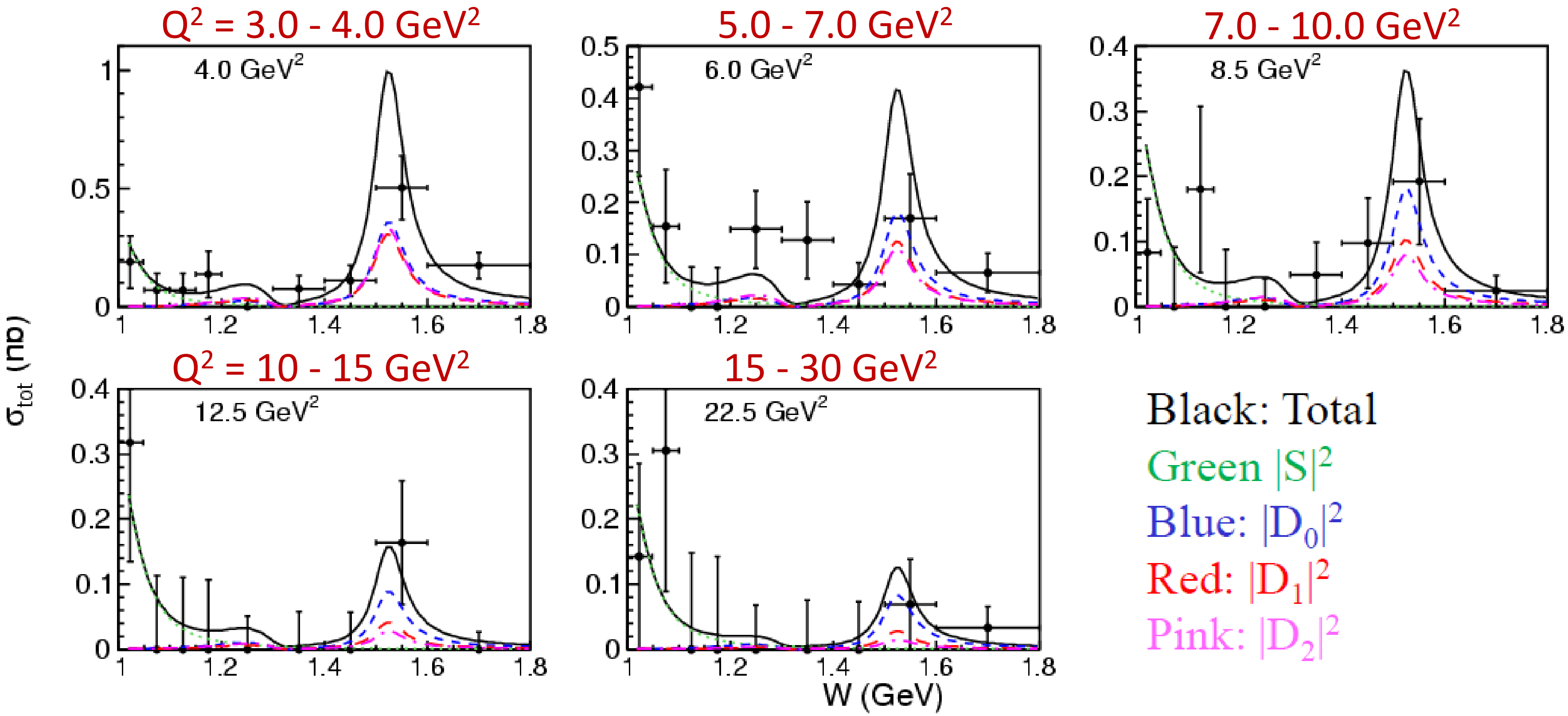
: Definition of $\Gamma_{\gamma^*\gamma}$



The first measurement of χ_{cJ} in the single-tag two-photon production

Solid curve: SBG with the charmonium-mass scale ← much favored
Dashed curve: With the ρ-mass scale (VDM like)

PWA for $f_2'(1525)$: fit results in W dependence at Q^2 bins



Show indications of:

- Non-zero D_0 and D_1 components in the f_2' (1525).
- $f_2(1270)/a_2(1320)$ not visible
- An enhancement near the threshold (0.995 GeV).

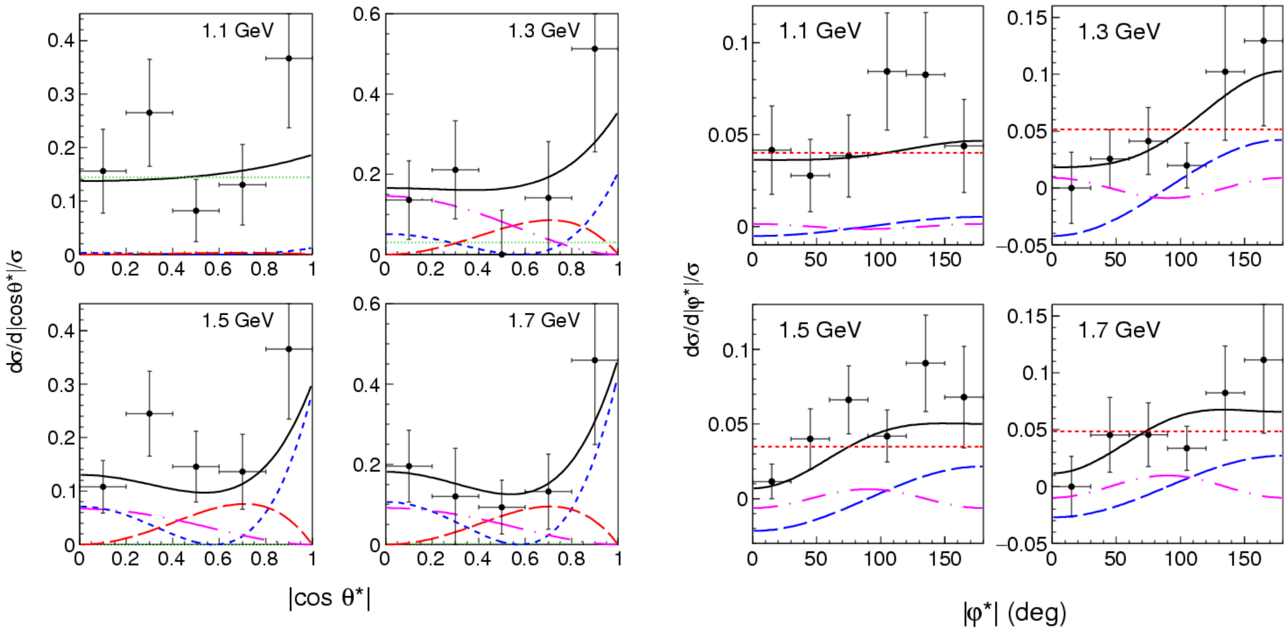
Angular dependence and the PWA fits

Due to a lack of statistics, we use Q^2-integrated angular differential cross section derived with the following convention (MC generated isotropically)

$$d^2\sigma/d|\cos\theta^*|d|\varphi^*| \propto N_{\rm EXP}(|\cos\theta^*|, |\varphi^*|)/N_{\rm MC}(|\cos\theta^*|, |\varphi^*|)$$

Q^2: integrated over the full range between 3 and 30 GeV^2
W: 4 bins

|cos θ*| dependence (|φ*| integrated) |φ*| dependence (|cos θ*| integrated)

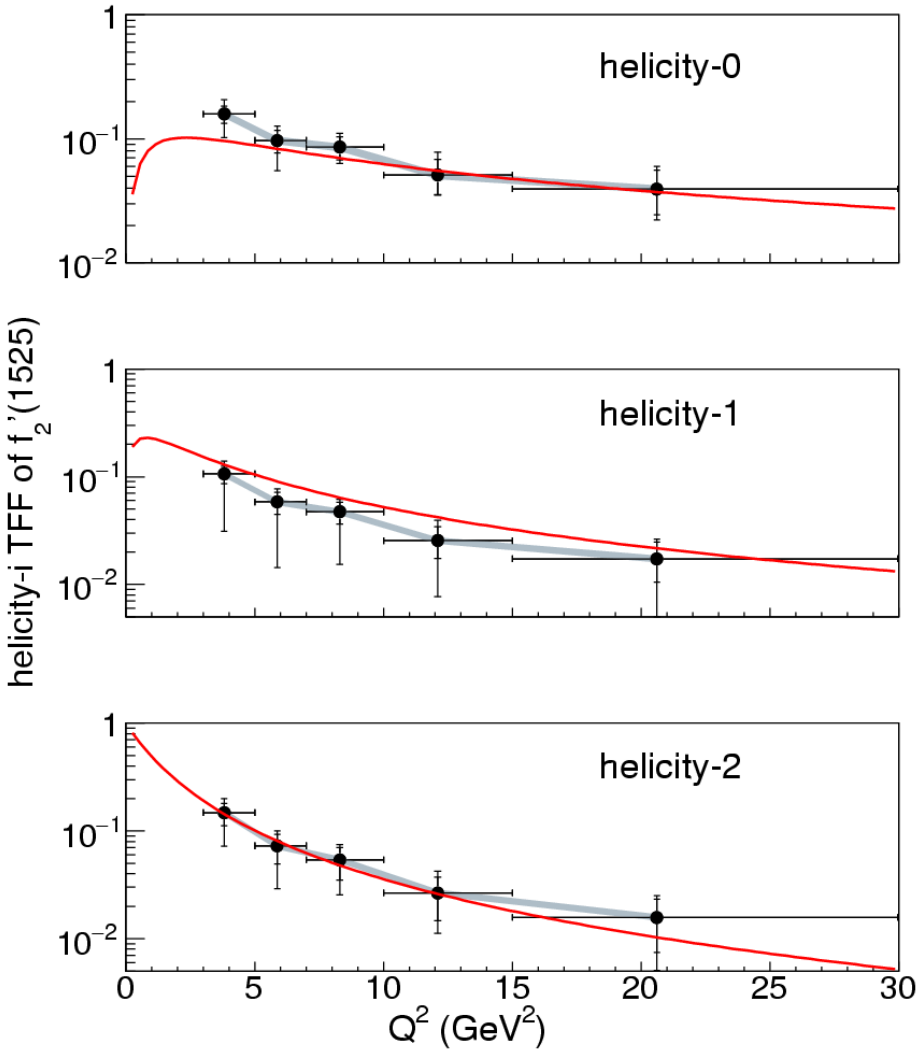


We regard this as the angular dependence at $<Q^2> = 6.5$ GeV^2

Fit:
Black: total
Red: t_0
Blue: $t_1 \cos\varphi^*$
Magenta: $t_2 \cos 2\varphi^*$

The fit is applied to the two-dimensional angular-dependence data.
Forward enhancement is from the helicity-0 component.

$f'_2(1525)$ TFF Result



Shorter error bars ; statistical
Longer error bars ; statistical and systematic
Shaded areas; overall systematic

— Schuler, Berends, van Glick (SBG)
Nucl. Phys. B 523, 423, (1998).

helicity-0 and -2 -- agree well with SBG.
helicity-1 -- slightly smaller, but not inconsistent.

Note: the Q^2 dependence of each helicity fraction is assumed as follows

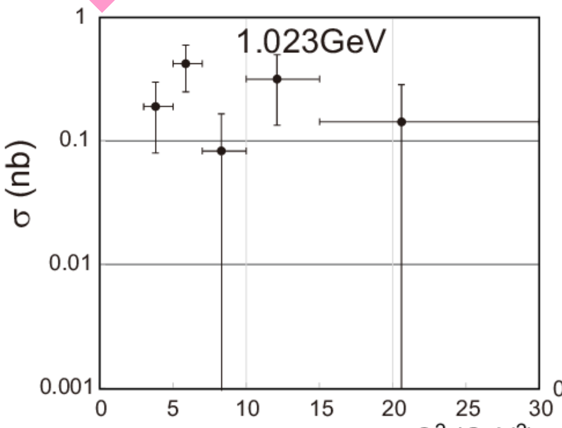
$$r_{0fp} : r_{1fp} : r_{2fp} = k_0 Q^2 : k_1 \sqrt{Q^2} : 1$$

Fractions k_0 and k_1 are floated.

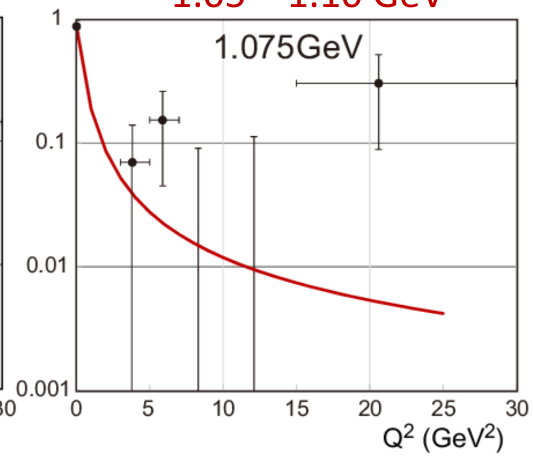
The Threshold Enhancement

No $Q^2=0$ measurement

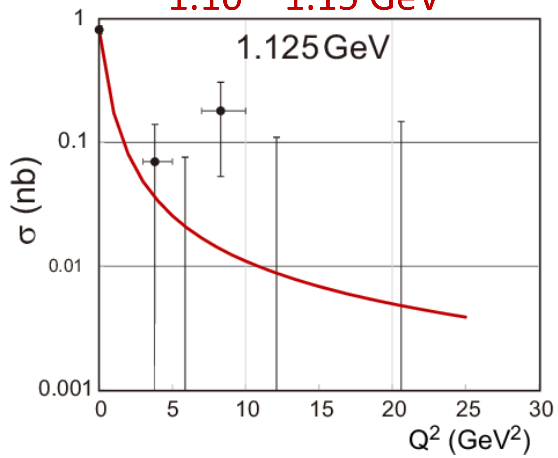
Mass threshold – 1.05 GeV



1.05 – 1.10 GeV



1.10 – 1.15 GeV



SBG:

$J^P=0^+$ state with $M=0.98 GeV/c^2$

The threshold enhancement exists.

- Not inconsistent with SBG.
- The limited statistics currently preclude a conclusive interpretation.

Summary

• Belle Experiment at KEKB has measured $\gamma\gamma$ (no-tag) and $\gamma^*\gamma$ (single-tag) hadron pair production for different final-state particles.
In this talk, light-pseudoscalar-meson pair production processes are reported.

• We measure the cross sections, resonance properties for light mesons and charmonia, etc., in relation to QCD tests and exploration of hadron structures.

• We have measured the scalar- and tensor-meson TFFs from the $\gamma^*\gamma$ cross sections in the high Q^2 region, 3 $GeV^2 < Q^2 <$ 30 GeV^2.

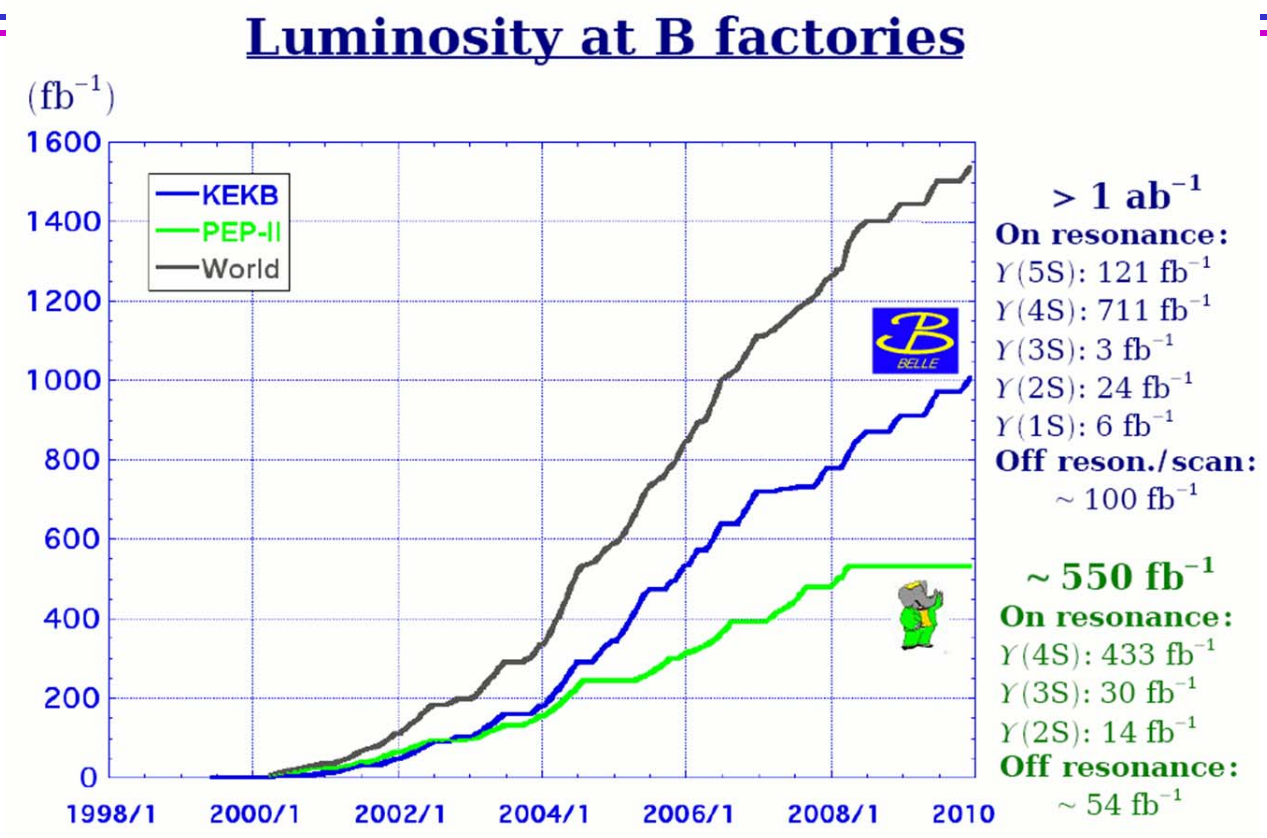
• In the most recent publication (**PRD 97, 052003 (2018)**), we report :

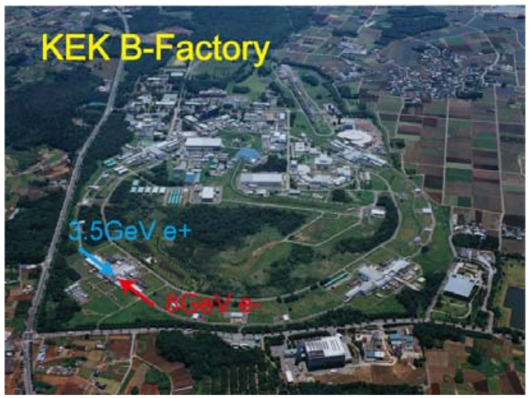
Cross section for $\gamma^*\gamma \to K^0_S K^0_S$ for $2M(K^0_S) < W <$ 2.6 GeV, 3 $GeV^2 < Q^2 <$ 30 GeV^2
Q^2 dependence of $\Gamma_{\gamma^*\gamma}$ of χ_{c0} and χ_{c2}. Preferable to the charmonium mass scale.
Q^2 dependence of the $f_2'(1525)$ TFF.
Signature of an enhancement near the $K^0_S K^0_S$ mass threshold is observed.

The measured Q^2 dependences are not inconsistent to theoretical predictions.

Backup

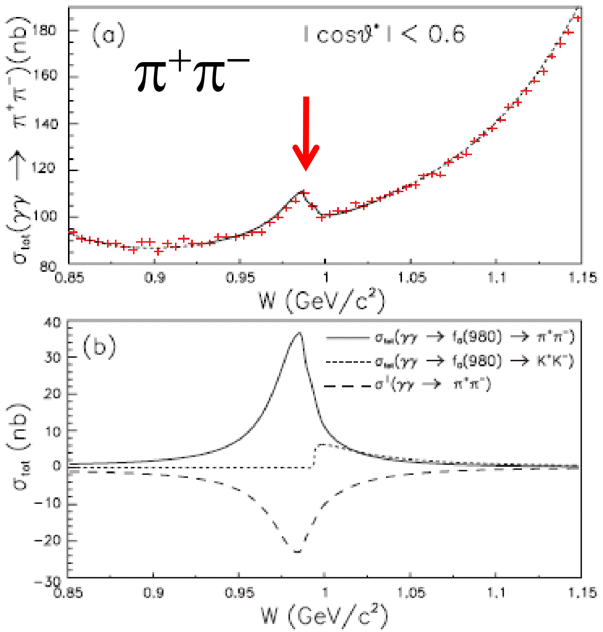
History of integrated luminosity at Belle

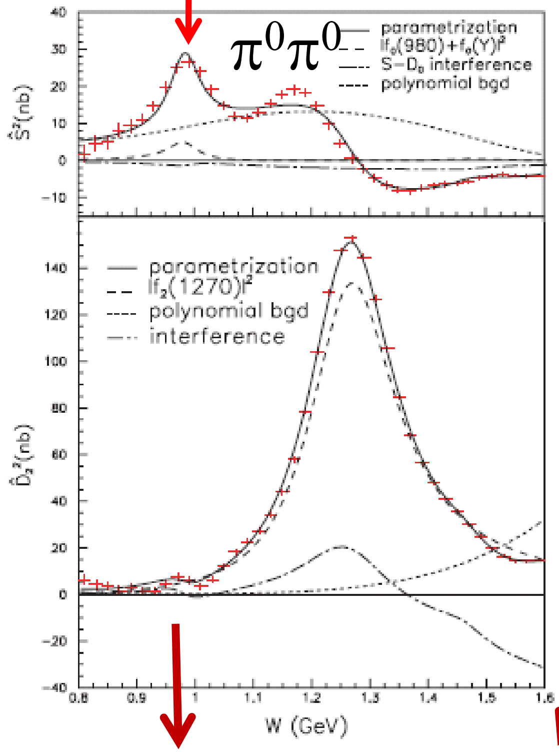


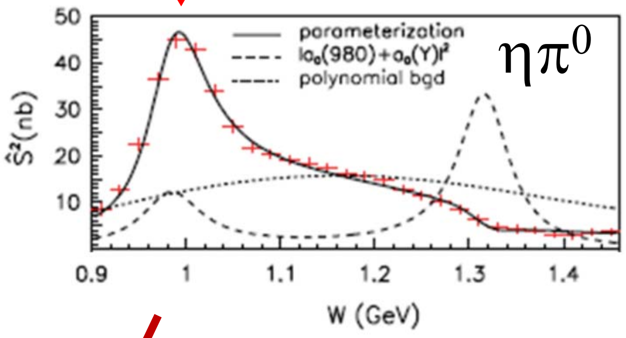


1999	The Belle experiment started
2001	CP violation in B mesons was verified and the KEKB accelerator achieved the world's highest luminosity
2002	Anomalous CP violation in $b \to s$ was measured
2003	The $B \to Kll$ decay was discovered
2004	The New particle X (3872) was discovered
2005	Direct violation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

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





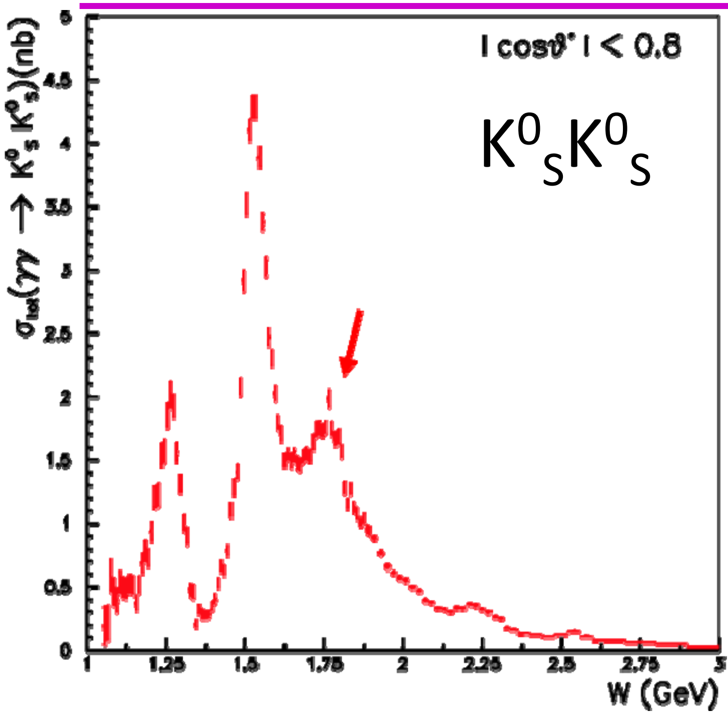


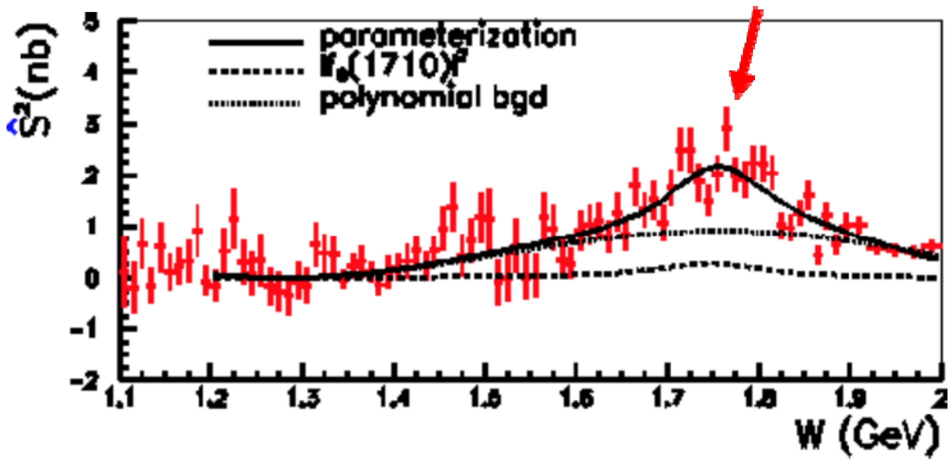
Meson	$f_0(980)$	$f_0(980)$	$a_0(980)$
M[MeV/c²]	$985.6^{+1.2+1.1}_{-1.5-1.6}$	$982.2\pm1.0^{+8.1}_{-8.0}$	$982.3^{+0.6+3.1}_{-0.7-4.7}$
$\Gamma_{\pi\pi/tot}$[MeV]	$51.3^{+20.9+13.2}_{-17.7-3.8}$	$66.9^{+13.9+8.8}_{-11.8-2.5}$	(Γtot) $75.6\pm1.6^{+17.4}_{-10.0}$
$\Gamma_{\gamma\gamma}$[eV]	$205^{+95+147}_{-83-117}$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

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

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

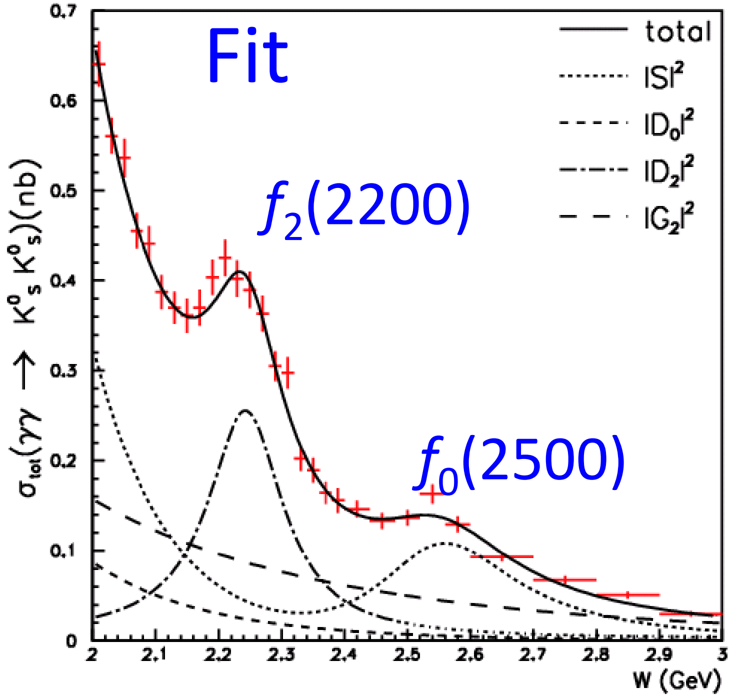
Fit Results for resonances in $K^0_S K^0_S$

$f_2(2200)$-$f_0(2500)$ 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

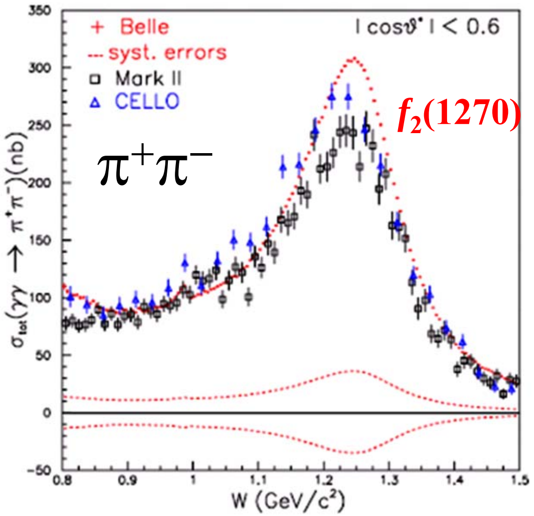
- 3.4σ for $f_2(2200)$ over $f_0(2200)$
- 4.3σ for $f_0(2500)$ over $f_2(2500)$

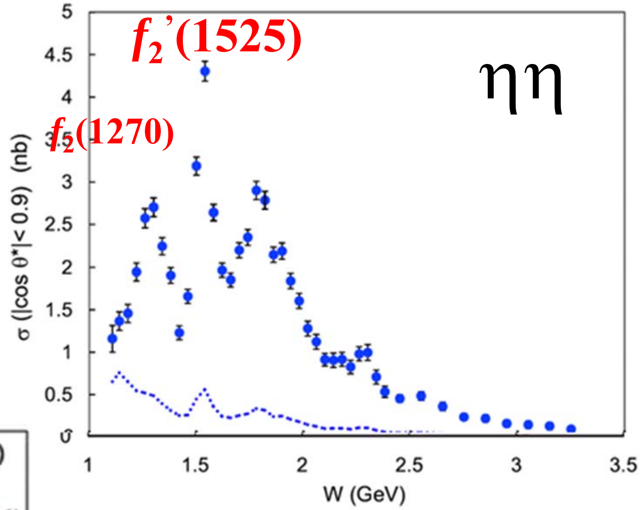


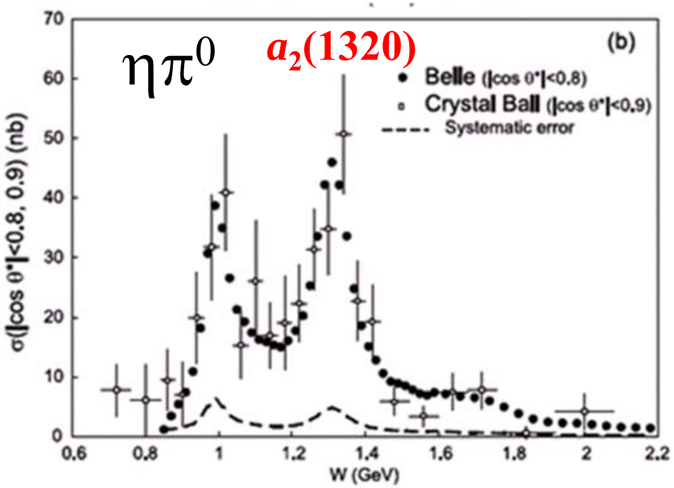
- There can be an only wide state around 2240 MeV.
- Narrow appearances in previous measurements may be due to an interference effect and/or statistical fluctuation.
- A high-mass state at 2.5 GeV may be the heaviest light-quark scalar meson so far found.

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 $K^0_S K^0_S$





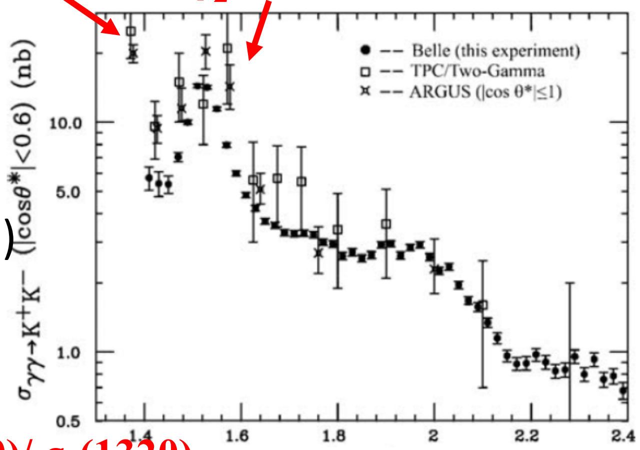


$f_2(1270)$-$a_2(1320)$ interference in $K\bar{K}$

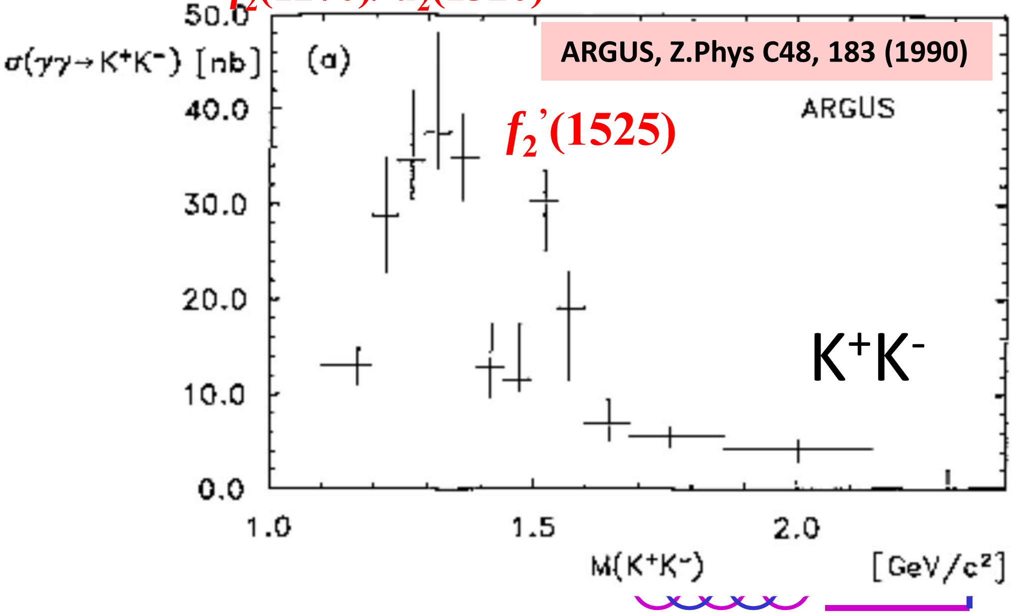
$f_2(1270)$/ $a_2(1320)$ $f_2'(1525)$

K^+K^-

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



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



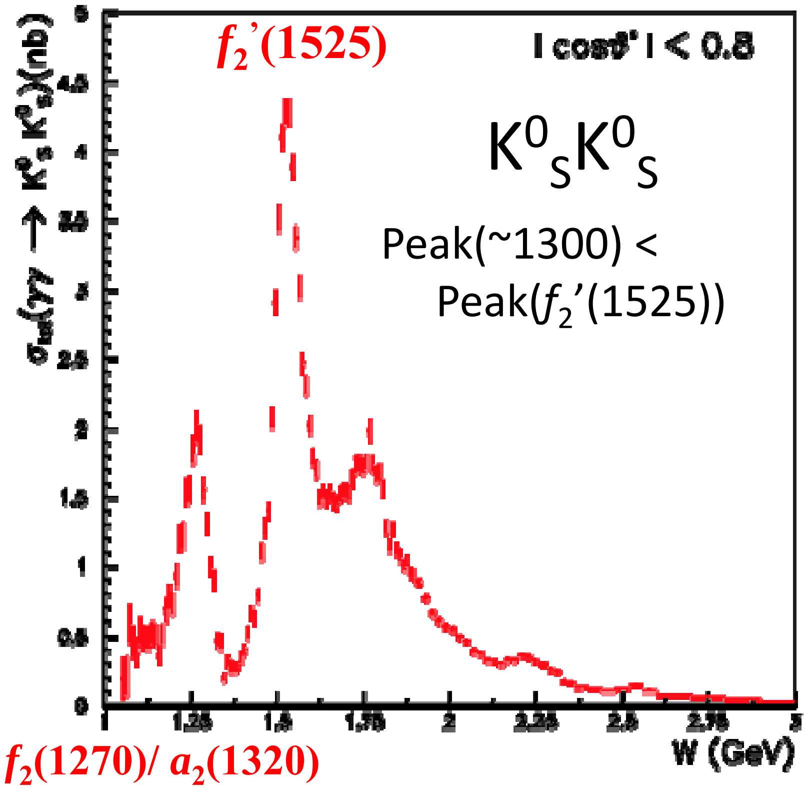
Constructive interference

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

Destructive interference

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

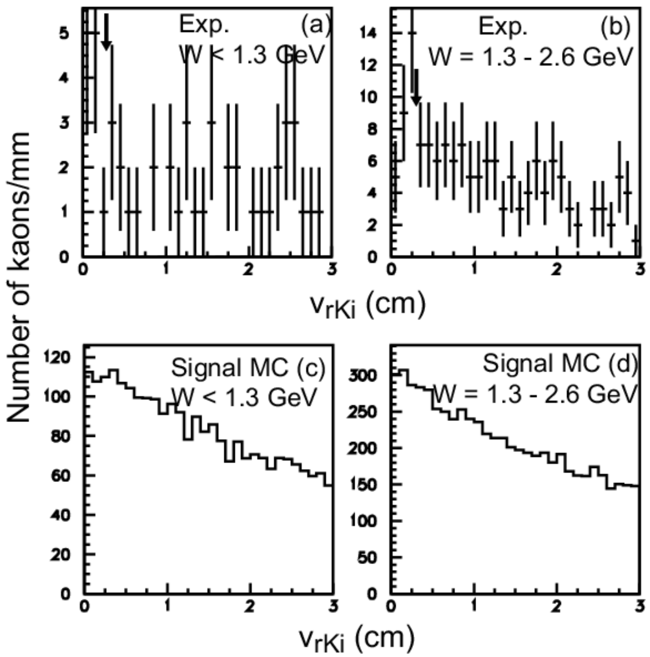
Explained by a phase relation in isospin composition



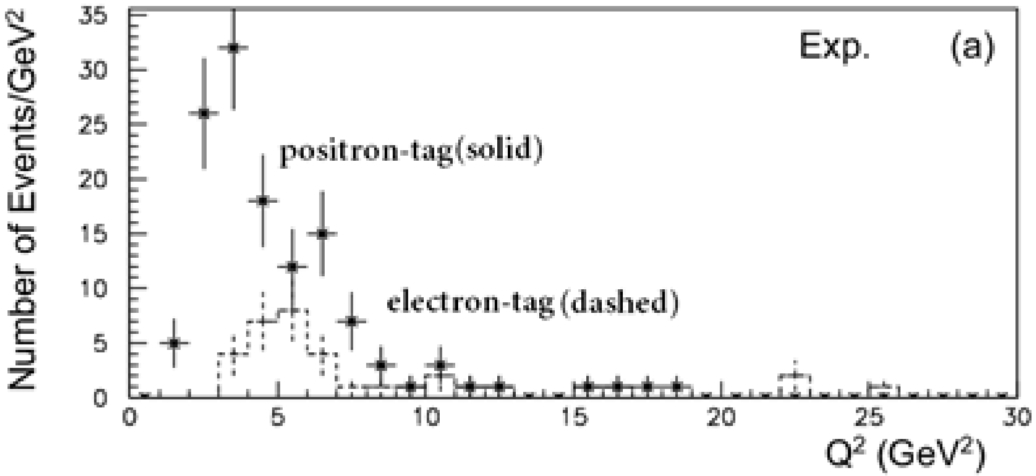
$f_2(1270)$/ $a_2(1320)$

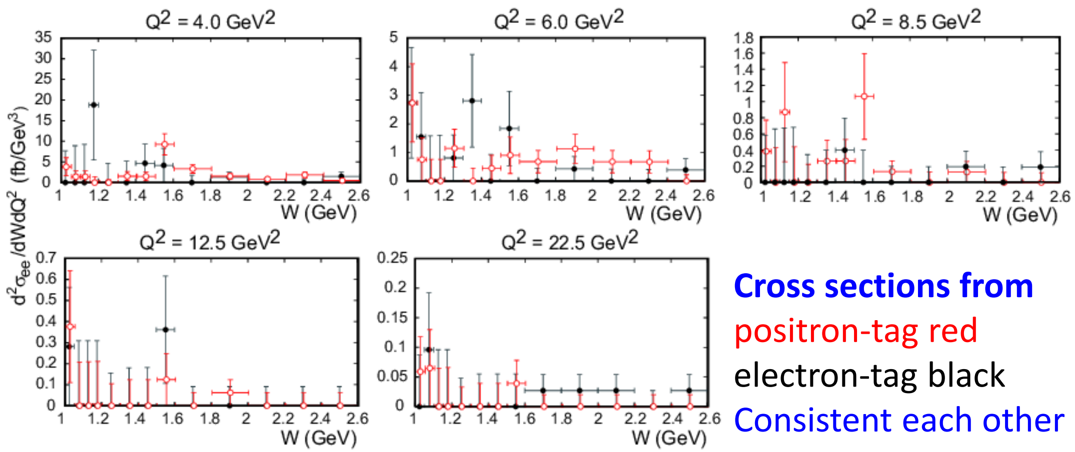
$K^0_S K^0_S$ Experimental data

Searching for non-$K^0_S K^0_S$ background,
looking for an enhancement near v_r=0
in a loosely selected sample



No enhancement.
<1 event background
in the final candidates

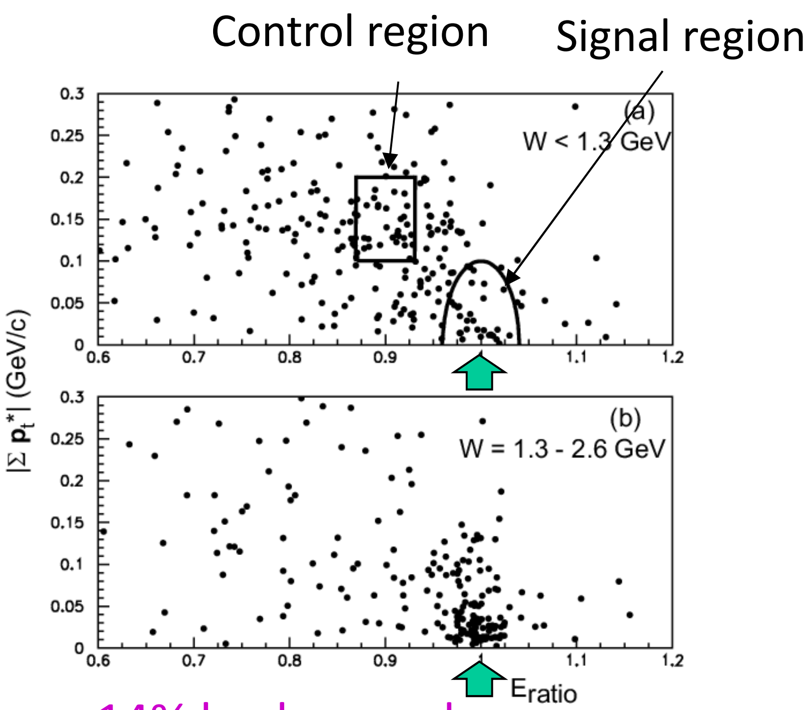




Cross sections from
positron-tag red
electron-tag black
Consistent each other

Background processes

Rejection of non-exclusive background,
$K^0_S K^0_S X$ using $|\Sigma p_t^*|$ vs. E_{ratio}



14% background
only for W<1.3 GeV

Systematic uncertainty

TABLE V: Sources of systematic uncertainties. The values are indicated for specific W ranges. DCS stands for the differential cross section.

Source	Uncertainty (%)
Tracking	2
Electron-ID	1
Pion-ID (for four pions)	2
K^0_S reconstruction (for two K^0_S's)	3
Kinematic selection	4
Geometrical acceptance	1
Trigger efficiency	1 – 3
Background effect for the efficiency	2
Angular dependence of DCS	6 – 22
Background subtraction	3 – 7
No unfolding applied	1
Radiative correction	3
Luminosity function	4
Integrated luminosity	1.4
Total	13 – 24

Total: 13% - 24%

Formalism of PWA and parametrizations

Problems: Low statistics

Only 3 out of *S*, D_0, D_1 and D_2 are independent

Non-unique solution (multiple solutions for resonances)

→ Parametrization of the amplitudes with modelled W and Q^2 dependences

$$S = A_{BW} e^{i\phi_{BW}} + B_S e^{i\phi_{BS}},$$
$$D_i = \sqrt{r_{ifa}(Q^2)}(A_{f_2(1270)} - A_{a_2(1320)})e^{i\phi_{faDi}} + \sqrt{r_{ifp}(Q^2)} A_{f_2'(1525)} e^{i\phi_{fpDi}} + B_{Di} e^{i\phi_{BDi}},$$

$$B_S = \frac{\beta a_S (W_0/W)^{b_S}}{(Q^2/m_0^2+1)^{c_S}},$$
$$B_{D0} = \frac{\beta^5 a_{D0} (W_0/W)^{b_{D0}}}{(Q^2/m_0^2+1)^{c_{D0}}},$$
$$B_{D1} = \frac{\beta^5 Q^2 a_{D1} (W_0/W)^{b_{D1}}}{(Q^2/m_0^2+1)^{c_{D1}}},$$
$$B_{D2} = \frac{\beta^5 a_{D2} (W_0/W)^{b_{D2}}}{(Q^2/m_0^2+1)^{c_{D2}}},$$

$\beta = \sqrt{1 - 4m_{K_S^0}^2/W^2}$ is the K_S^0 velocity

$$A_{BW}(W) = \sqrt{\frac{8\pi m_S}{W}} \frac{f_S}{m_S^2 - W^2 - i m_S g_S} \times \frac{1}{(Q^2/m_0^2+1)^{p_S}},$$

Nominal fit

Bs = 0

$$r_{0fp} : r_{1fp} : r_{2fp} = k_0 Q^2 : k_1 \sqrt{Q^2} : 1$$

-Destructive interference between $f_2(1270)$ and $a_2(1320)$

-$r_i(Q^2)$ and TFF for $f_2(1270)$ and $a_2(1320)$ are the same; use the values obtained in single-tag $\pi^0\pi^0$

Determine each component and the relative phase by a fit

Fit results

TABLE VI: Fitted parameters of cross sections and the number of solutions obtained under the conditions noted below. In each category, only solutions assuming $k_0 \neq 0 \bigcap k_1 \neq 0$ are shown. Only the single solution that gives the minimum χ^2 in category 3 is shown, while two viable solutions in categories 1 and 2 are shown.

Parameter	Category 1		Category 2		Category 3
Conditions	$A_{BW} \neq 0 \bigcap B_S = 0$		$A_{BW} = 0 \bigcap B_S \neq 0$		$A_{BW} = B_S = 0$
Number of solutions	2		2		3
	Solution 1a	Solution 1b	Solution 2a	Solution 2b	
χ^2_P/ndf	152.4/150	159.8/150	154.9/151	156.1/151	293.9/155
k_0 (GeV^{-2})	$0.30^{+0.31}_{-0.14}$	$0.31^{+0.34}_{-0.15}$	$0.31^{+0.34}_{-0.15}$	$0.29^{+0.31}_{-0.14}$	$0.33^{+0.31}_{-0.14}$
k_1 (GeV^{-1})	$0.27^{+0.30}_{-0.14}$	$0.27^{+0.44}_{-0.15}$	$0.29^{+0.33}_{-0.15}$	$0.24^{+0.29}_{-0.13}$	$0.23^{+0.25}_{-0.12}$
$F_{f2p}(0.0); (\times 10^{-2})$	100 ± 7				
$F_{f2p}(4.0); (\times 10^{-2})$	$24.1^{+2.6}_{-2.5}$	$24.4^{+2.7}_{-2.6}$	$24.3^{+2.6}_{-2.5}$	$24.4^{+2.6}_{-2.5}$	$27.1^{+2.7}_{-2.6}$
$F_{f2p}(6.0); (\times 10^{-2})$	$13.4^{+2.6}_{-2.5}$	$13.9^{+2.5}_{-2.4}$	$14.3^{+2.5}_{-2.3}$	$14.4^{+2.5}_{-2.3}$	$15.5^{+2.5}_{-2.4}$
$F_{f2p}(8.5); (\times 10^{-2})$	$11.2^{+2.3}_{-2.2}$	$11.3^{+2.3}_{-2.2}$	$11.5^{+2.3}_{-2.2}$	$11.6^{+2.3}_{-2.1}$	$12.4^{+2.3}_{-2.2}$
$F_{f2p}(12.5); (\times 10^{-2})$	$6.3^{+2.1}_{-1.9}$	$6.3^{+2.1}_{-1.9}$	$6.3^{+2.1}_{-1.9}$	$6.3^{+2.1}_{-1.9}$	$7.0^{+2.1}_{-1.9}$
$F_{f2p}(22.5); (\times 10^{-2})$	$4.6^{+1.9}_{-1.7}$	$4.6^{+1.9}_{-1.7}$	$4.6^{+1.9}_{-1.7}$	$4.7^{+1.9}_{-1.7}$	$5.1^{+2.0}_{-1.8}$
ϕ_{fpD1} (°);	33^{+28}_{-81}	177^{+27}_{-27}	112^{+23}_{-35}	108^{+24}_{-37}	47^{+24}_{-33}
ϕ_{fpD2} (°);	199^{+34}_{-75}	218^{+27}_{-29}	209^{+30}_{-35}	213^{+28}_{-33}	218^{+23}_{-27}
ϕ_{faD1} (°);	137^{+27}_{-34}	328^{+34}_{-39}	18^{+28}_{-30}	340^{+33}_{-33}	234^{+22}_{-24}
ϕ_{faD2} (°);	166^{+30}_{-32}	180^{+29}_{-29}	162^{+29}_{-32}	182^{+27}_{-28}	0 (fixed)
f_S ($\sqrt{\mathrm{nb}}\ \mathrm{GeV}^2$);($\times 10^{-2}$)	$1.3^{+1.1}_{-0.6}$	$0.9^{+0.8}_{-0.4}$	0 (fixed)		0 (fixed)
g_S (GeV)	$0.10^{+0.05}_{-0.04}$	$0.06^{+0.05}_{-0.05}$	0 (fixed)		0 (fixed)
p_S	$0.06^{+0.25}_{-0.24}$	$0.01^{+0.26}_{-0.25}$	0 (fixed)		0 (fixed)
ϕ_{BW} (°);	297^{+21}_{-21}	150^{+35}_{-24}	0 (fixed)		0 (fixed)
a_S ($\sqrt{\mathrm{nb}}$); ($\times 10^{-3}$)	0 (fixed)		$4.3^{+12.5}_{-5.9}$	$2.2^{+5.7}_{-3.0}$	0 (fixed)
b_S	0 (fixed)		$19.6^{+4.6}_{-4.1}$	$21.9^{+6.0}_{-4.0}$	0 (fixed)
c_S	0 (fixed)		$0.00^{+0.23}_{-0.06}$	$0.00^{+0.21}_{-0.05}$	0 (fixed)
ϕ_{BS} (°);	0 (fixed)		99^{+19}_{-21}	311^{+20}_{-18}	0 (fixed)

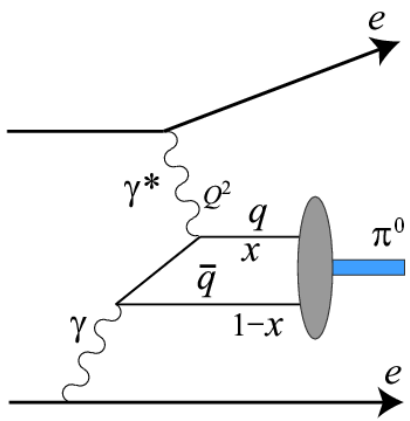
π^0 Transition Form Factor (TFF)

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:

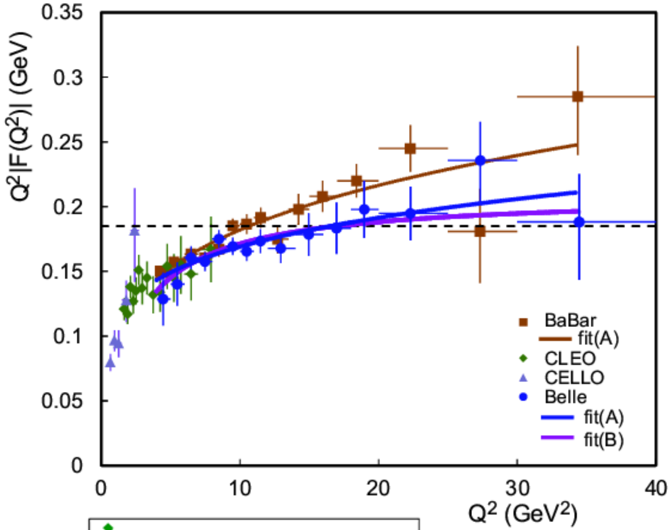
$|F(Q^2)|^2 = |F(Q^2,0)|^2 = (\mathbf{d\sigma/dQ^2})/(2A(Q^2))$ $A(Q^2)$ is calculated by QED

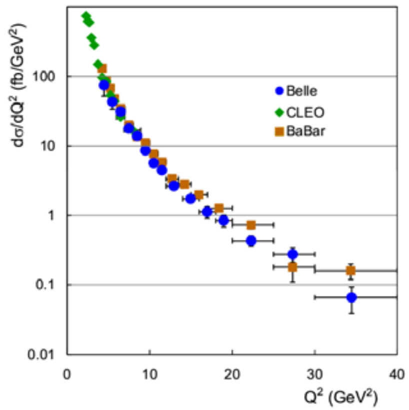
$|F(0,0)|^2 = 64\pi\Gamma_{\gamma\gamma}/\{(4\pi\alpha)^2 m_R^3\}$

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 $Q^2>9\text{GeV}^2$ is seen in Belle result.

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

Fit A (suggested by BaBar)

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

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

$\beta = 0.18 \pm 0.05$

$\chi^2/\text{ndf} = 6.90/13$ ~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

$C = 2.2 \pm 0.8\ \text{GeV}^2$

$\chi^2/\text{ndf} = 7.07/13$

B is consistent with the QCD value (0.185GeV)