Meson-pair production in two-photon processes at KEKB

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Belle collaboration

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Outline

Introduction
 -Two-photon collisions by KEKB

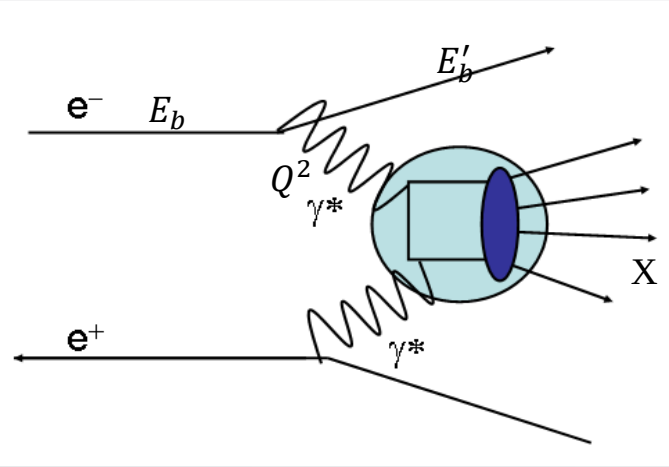
Main topic
 - Meson pair production in no-tag processes
  High W region; test QCD
  Low W region; spectroscopy in ωφ, φφ, ωω, ππ, KK, ηπ …
 - $\pi^0\pi^0$ in single-tag processes

Prospects
 -no-tag, single-tag, double-tag, elastic scattering

Two-photon collisions in e^+e^- experiment

$$e^+e^- \to e^+e^-h:$$

$$\sigma(e^+e^- \to e^+e^-h) = \int \sigma(\gamma\gamma \to h)\frac{dL_{\gamma\gamma}}{dW}dW$$



Photon virtuality :

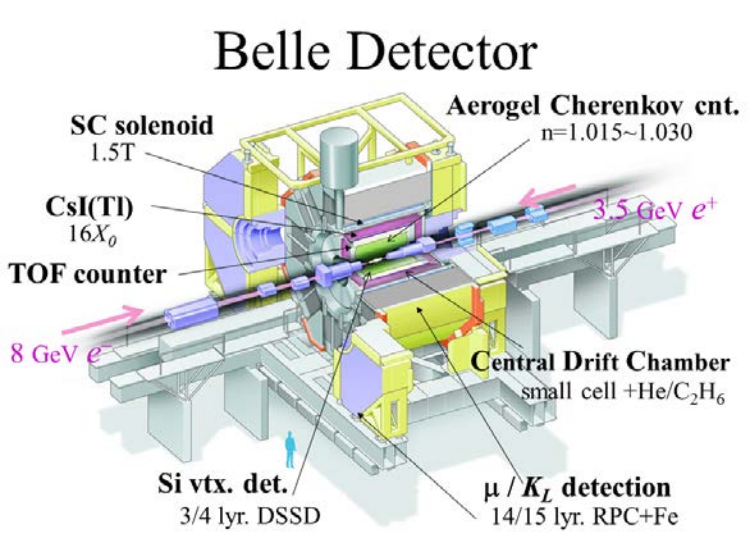
$Q^2 \cong 4E_bE_b'\sin^2(\theta/2)$ $(Q^2 \gg {m_e}^2)$

- No-tag $\gamma\gamma \to h$
  - study light mesons ($W \lesssim 3$ GeV)
    $J^{PC}=0^{++},0^{-+}, 2^{++},2^{-+}, 3^{++}$, … (even)$^{\pm+}$, (odd $\neq 1)^{++}$
  - test pQCD ($W \gtrsim 3$ GeV)
  - charmonium(-like) state ($W \gtrsim 3$ GeV)

- Single-tag $\gamma^*\gamma \to h$
  - transition form factor (TFF) for h
  - for $\gamma^*\gamma \to h\bar{h}$
    generalized distribution amplitude (GDA)
    ⇔ Generalized parton distribution (GPD)
    Kawamura and Kumano PRD 89 054007 (2014)

-Double-tag $\gamma^*\gamma^* \to h$
  - ππ; provide information for theoretical calculation of muon g − 2.

Measurement of two-photon collisions with KEKB accelerator and Belle detector



-**Beam energies** e^+(3.5 GeV) and e^- (8 GeV)

continuous distribution of W; 0.8—4.5GeV

-**High integrated luminosity** (reached 1 ab^{-1})

statistics 2-3 orders of magnitude improved

-**Distinctive Triggers**

e.g. 1. $\gamma\gamma \rightarrow \pi^+\pi^-$

two charged tracks through CDC and TOF (o.a. >135°)

e.g. 2. $\gamma^*\gamma \rightarrow \pi^0\pi^0$

final state; 1-track of e^+ (e^-) and 4 γs

HIE (E_{tot} >1.15GeV & Bhabha-veto)

Clst4 (E>0.11GeV, Bhabha-veto not applied)

-**Sophisticated Event Selection**

Hadron ID by TOF, ACC, K/μ separation by KLM *etc.*

Two-photon process results at Belle

	W (GeV)	L (fb-1)	$Q^2(GeV^2)$	Reference	year
γJ/ψ	3.2-3.8	33		PLB 540,33	2002
K^+K^-	1.4-2.4	67		EPJC 32, 323	2004
$K^+K^-/\pi+\pi-$	2.4-4.1	88		PLB 615,39	2005
pp	2.03-4.0	89		PLB 621,341	2005
DD	3.7-4.3	395		PRL 96, 082003	2006
$\pi^+\pi^-$	0.8-1.5	86		PRD 75, 051101	2007
$\pi^+\pi^-$	0.8-1.5	86		JSPJ 76, 074102	2007
$K^0_SK^0_S$	2.4-4.0	398		PLB 651, 15	2007
4π/4K/2K2π	2.4-4.1	395		EPJC 53, 1	2008
$\pi^0\pi^0$	0.6-4.0	95		PRD 78, 052004	2008
$\pi^0\pi^0$	0.6-4.0	223		PRD 79, 052009	2009
$\eta\pi^0$	0.84-4.0	223		PRD 80, 032001	2009
φJ/ψ	4.2-5.0	825		PRL 104, 112004	2010
ωJ/ψ	3.9-4.2	694		PRL 104, 092001	2010
ηη	1.1-3.8	393		PRD 82, 114031	2010
ωω/φφ/ωφ	1.5-4.0	870		PRL 108, 232001	2012
π^0	0.6-4.0	759	4.0-40	PRD 86, 092007	2012
η'π+ π-	1.4-3.4	673		PRD 86, 052002	2012
$K^0_SK^0_S$	1.05-4.0	972		PTEP 2013, 123C01	2013
$\pi^0\pi^0$	0.5-2.1	759	3.0-30	PRD 93, 032003	2016
ppK^+K^-	3.2-5.6	980		PLB 615,39	2016

No-tag

Single-tag

No-tag

More than 15 processes

-Discovery of $\chi_{C2}(2P)$, $X(4350)$, $X(3915)$, enhancements in VV

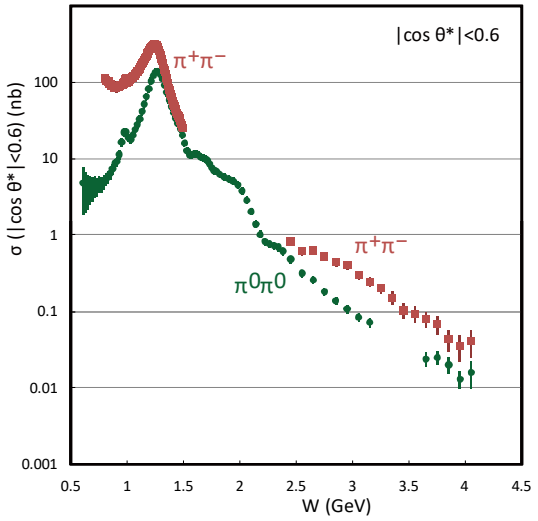
-Confirmation of $f_0(980)$, $a_0(980)$, $f_0(1710)$

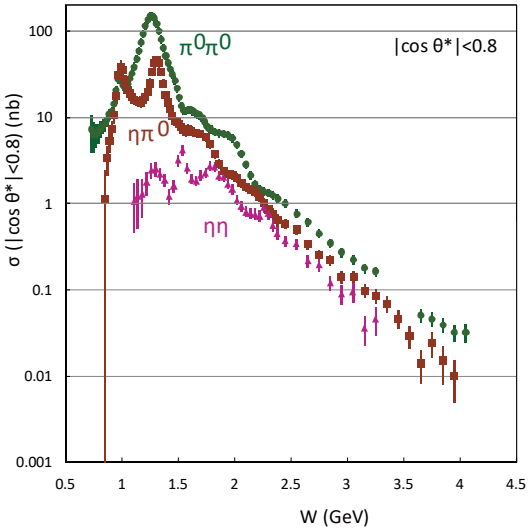
Six meson pair processes in no-tag

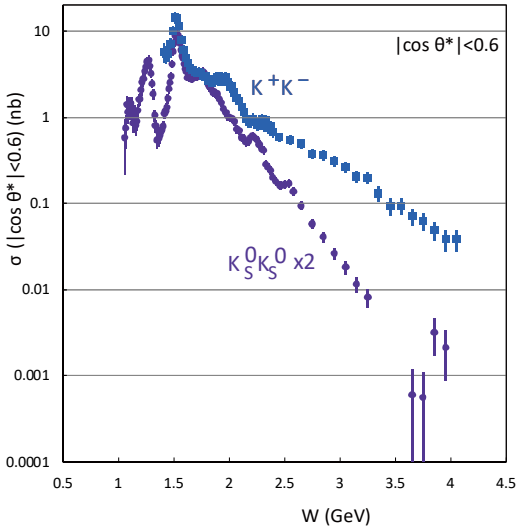
Charged and Neutral ππ

Three neutral-pair processes
$\pi^0\pi^0$, $\eta\pi^0$, $\eta\eta$

Charged and Neutral $K\bar{K}$







-High energy region (3 GeV $\lesssim$ W)

test of pQCD

charmonium(-like) states

-Low energy region (W $\lesssim$ 3 GeV) $(f_0(980), a_0(980), f_2(1270), a_2(1320), f_2'(1525) \ldots)$

Light meson spectroscopy

High energy regions for QCD test

Different predictions for W dependence of cross sections and cross sections ratios

- pQCD approach: Brodsky and Lepage PRD 24 1808 (1981)

$$\frac{d\sigma}{d|\cos\theta^*|} = 16\pi\alpha^2 \frac{|F_M(W^2)|^2}{W^2}\left\{\frac{(e_1-e_2)^4}{\sin^4\theta^*} + \frac{2e_1e_2(e_1-e_2)^2}{\sin^2\theta^*} g(\theta^*) + 2(e_1e_2)^2 g(\theta^*)\right\}$$

e.g. for charged meson pair, $d\sigma/d|\cos\theta^*| \propto 1/\sin^4\theta$

e.g. $\frac{\sigma(\gamma\gamma\to K^+K^-)}{\sigma(\gamma\gamma\to\pi^+\pi^-)} = (\frac{f_K}{f_\pi})^4 \cong 2.3$

- Improved pQCD approach: Benayoun and Chernyak, NPB 329,285(1990)

e.g. for neutral meson pair, $\sigma \propto W^{-10}$

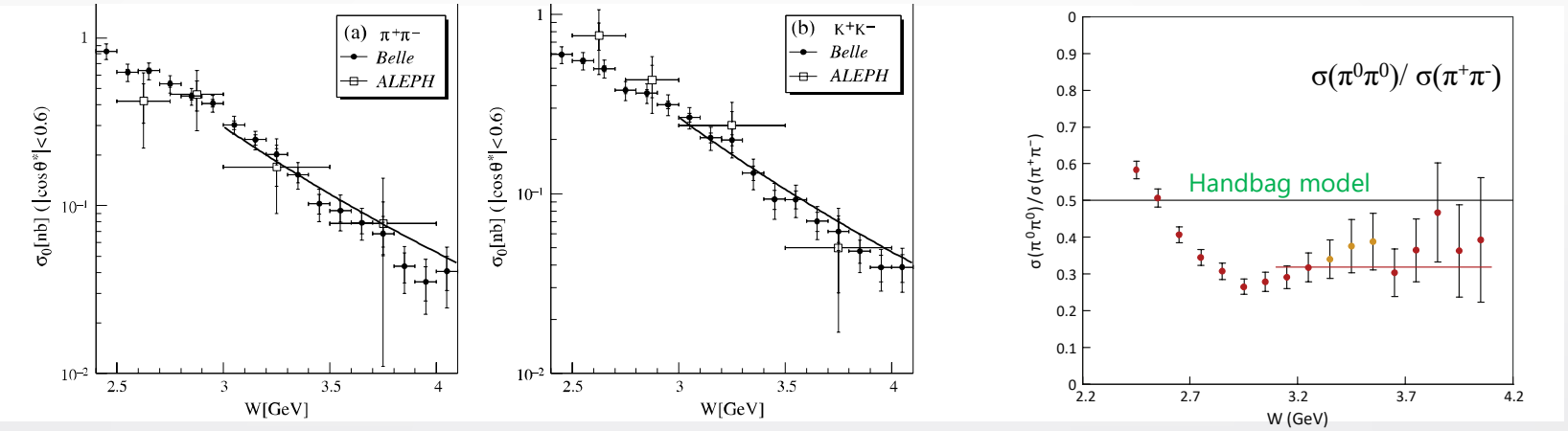
e.g. $\frac{\sigma(\gamma\gamma\to K^+K^-)}{\sigma(\gamma\gamma\to\pi^+\pi^-)} \cong 1.06$

- Handbag model : Diehl, Kroll *et.al.* PLB532,99(2002)

$$\frac{d\sigma}{d|\cos\theta^*|} = \frac{8\pi\alpha^2}{W^2}\frac{1}{\sin^4\theta}|R_{MM}(W^2)|^2$$

e.g. $\frac{\sigma(\gamma\gamma\to K^+K^-)}{\sigma(\gamma\gamma\to\pi^+\pi^-)} = 1$, $\frac{\sigma(\gamma\gamma\to\pi^0\pi^0)}{\sigma(\gamma\gamma\to\pi^+\pi^-)} \cong 0.5$

Slope parameters and cross section ratios



Process	n: slope parameter	W (GeV)	|cos θ*|	pQCD by BL	pQCD by BC	Handbag model by DKV
$\pi^+\pi^-$	7.9± 0.4± 1.5	3.0 - 4.1	< 0.6	6	6	
K^+K^-	7.3± 0.3± 1.5	3.0 - 4.1	< 0.6	6	6	
$K^0_S K^0_S$	10.5± 0.6± 0.5	2.4 - 4.0	< 0.6	6	10	
$\pi^0\pi^0$	8.0± 0.5± 0.4	3.1 - 4.1	< 0.8	6	10	
$\eta\pi^0$	10.5± 1.2± 0.5	3.1 - 4.1	< 0.8	6	10	
$\eta\eta$	7.8± 0.6± 0.4	2.4 – 3.3	< 0.8	6	10	
$p\bar{p}$	$12.4^{+2.4}_{-2.3}$	3.2 - 4.0	< 0.6	10		
Process	σ_0 ratio	W (GeV)	|cos θ*|	PRD24,1808	NPB329,285	PLB532,99
$K^+K^-/\pi^+\pi^-$	0.89± 0.04± 0.15	3.0 - 4.1	< 0.6	2.3	1.06	
$K^0_S K^0_S/K^+K^-$	~ 0.13 to ~ 0.01	2.4 - 4.0	< 0.6		0.005	0.08
$\pi^0\pi^0/\pi^+\pi^-$	0.32± 0.03± 0.06	3.1 - 4.1	< 0.6		0.04-0.07	0.5
$\eta\pi^0/\pi^0\pi^0$	0.48± 0.05± 0.04	3.1 - 4.0	< 0.8	$0.24R_f$ $(0.46R_f)$		
$\eta\eta/\pi^0\pi^0$	0.37± 0.02± 0.03	2.4 - 3.3	< 0.8	$0.36R_f^2$ $(0.62R_f^2)$		

$R_f = f_\eta^2/f_{\pi 0}^2$

Summarized by Nakazawa-san

Slope parameter n ($\sigma \sim W^{-n}$)

n measured 7 ~ 11

Not far from 6 or 10 (pQCD)

Cross section ratios

$\sigma(\pi^0\pi^0)/\sigma(\pi^+\pi^-)$ ~ constant

disagree with pQCD by BC

PWA for Light meson spectroscopy

- For W < 3.0 GeV , we assume that J $\leqq$ 4
  J; total spin = 0, 2, 4,
  L; orbital angular momentum =0 (S), 2(D), 4(G)
  λ; helicity = 0, 2

- Differential Cross section can be written:

$$\frac{d\sigma}{d\Omega} = \left|SY_0^0 + D_0Y_2^0 + G_0Y_4^0\right|^2 + \left|D_2Y_2^2 + G_2Y_4^2\right|^2$$

  - S, D_0, D_2, G_0, G_2 : Partial-Wave amplitude
  - Y_J^λ : spherical harmonics

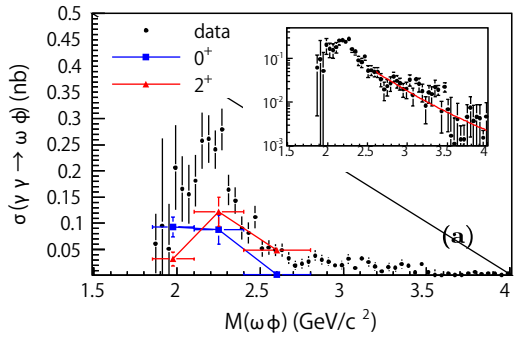
$$|Y_2^0|^2 = \frac{5}{16\pi}\left(3\cos^2\theta^* - 1\right)^2$$
$$|Y_2^2|^2 = \frac{15}{32\pi}\left(\cos^2\theta^* - 1\right)^2$$
$$|Y_4^0|^2 = \frac{9}{256\pi}\left(35\cos^4\theta^* - 30\cos^2\theta^* + 3\right)^2$$
$$|Y_4^2|^2 = \frac{45}{128\pi}\left(7\cos^2\theta^* - 1\right)^2\left(\cos^2\theta^* - 1\right)^2$$

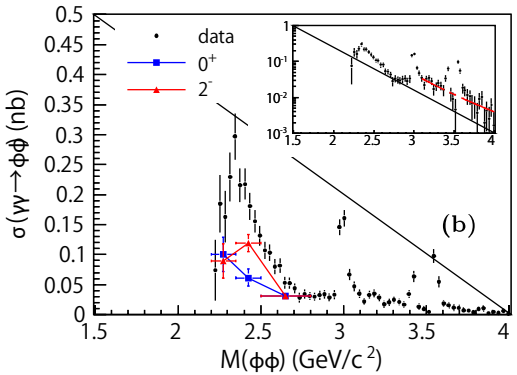
- Fundamental limitation
  e.g. Use a W dependence model for amplitude, BW, and continuum
  e.g. Convolute interference term in amplitudes

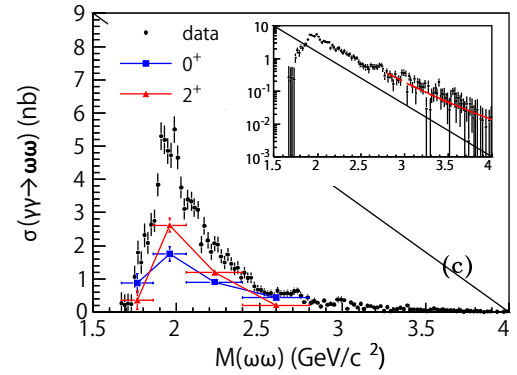
$$\frac{d\sigma}{d\Omega} = \hat{S}^2\left|Y_0^0\right|^2 + \hat{D}_0^2\left|Y_2^0\right|^2 + \hat{D}_2^2\left|Y_2^2\right|^2 + \hat{G}_0^2\left|Y_4^0\right|^2 + \hat{G}_2^2\left|Y_4^2\right|^2$$

Vector meson pair production

$\gamma\gamma \rightarrow \omega\varphi, \varphi\varphi, \omega\omega$







-Broad enhancement other than charmonia

M(ωφ) ~2.2 GeV/c^2 J^P ; 0^+ and 2^+

M(φφ) ~2.35 GeV/c^2 J^P ; 0^+ and 2^-

M(ωω) ~1.91 GeV/c^2 J^P ; 0^+ and 2^+

/ Zhang and Chen PRD 86, 116006 (2012)

predicted masses for molecular states 0^+

M(ωφ)~2.07±0.21 GeV

M(φφ)~2.18±0.29 GeV

M(ωω) ~1.97±0.17 GeV

/ Ebert et al. EPJC 60,273(2009)

tetraquark $ss\bar{s}\bar{s}$ M(φφ) ~2.2 GeV J^P 0^+

Slope parameter ($\sigma \sim 1/W^n$)

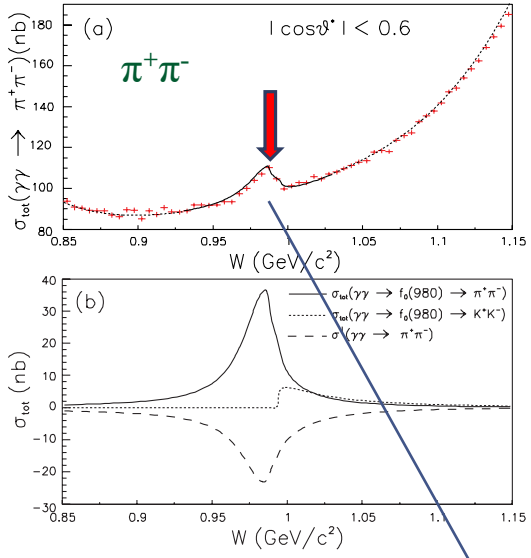
n=7.2±0.6 (ωφ)

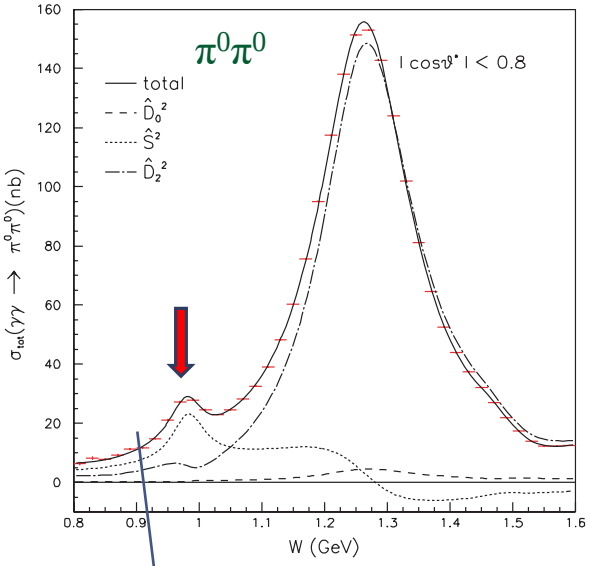
n=8.4±1.1 (φφ)

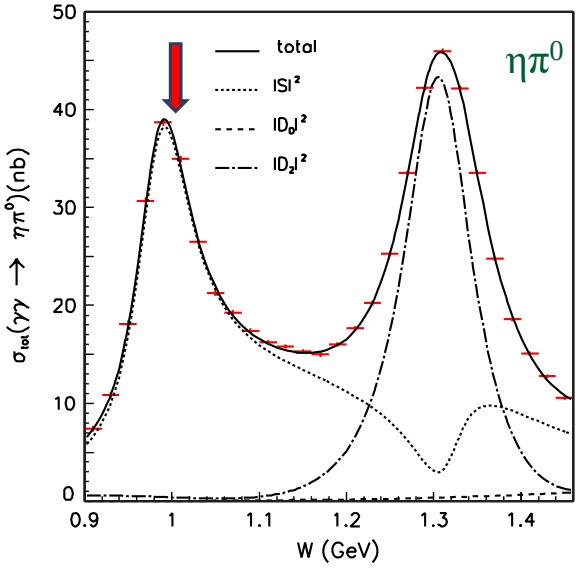
n=9.1±0.6 (ωω)

not far from pQCD by BC

Confirmation of $f_0(980)$ and $a_0(980)$ in $\gamma\gamma \to \pi^+\pi^-, \pi^0\pi^0, \eta\pi^0$







	$f_0(980)$	$f_0(980)$
Mass (MeV/c²)	$985.6^{+1.2+1.1}_{-1.5-1.6}$	$982.2^{+1.0+8.1}_{-1.0-8.0}$
$\Gamma_{\pi\pi}$ (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)	$205^{+195+147}_{-183-117}$	$286^{+17+211}_{-17-70}$

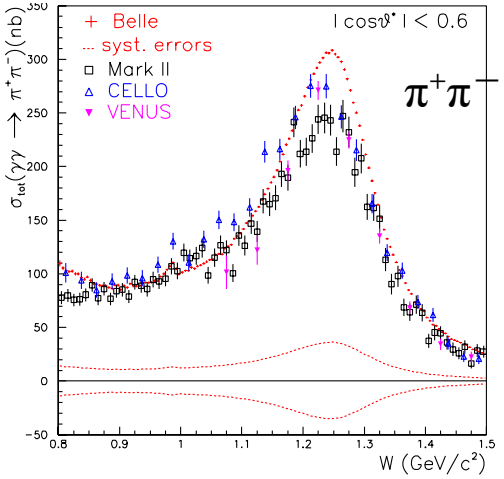
	$a_0(980)$
Mass (MeV/c²)	$982.3^{+0.6+3.1}_{-0.7-4.7}$
Γ_{tot} (MeV)	$75.6^{+1.6+17.4}_{-1.6-10.0}$
Br $\Gamma_{\gamma\gamma}$ (eV)	128^{+3+502}_{-2-43}

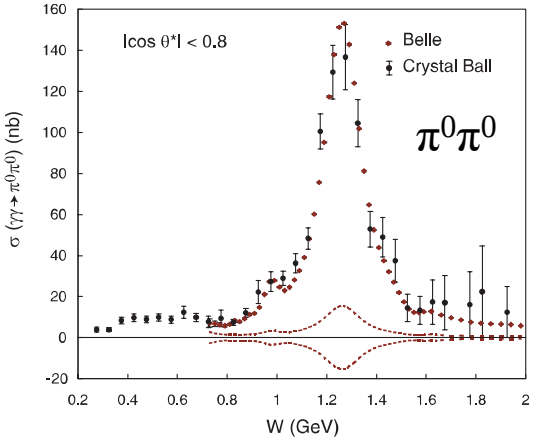
Predictions for $f_0(980)$

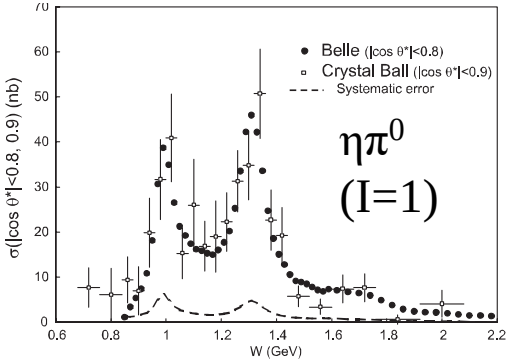
Model	$\Gamma_{\gamma\gamma}$ [eV]
*uu*bar,*dd*bar	1300 – 1800
*ss*bar	300 – 500
*KK*bar molecule	200 – 600
Four-quark	270

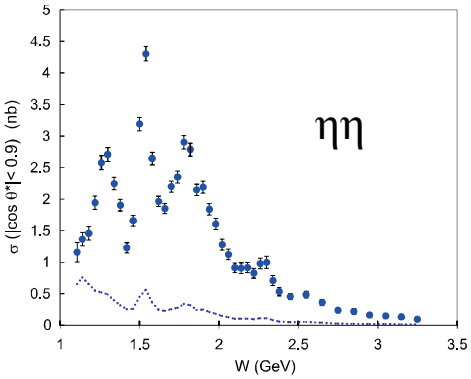
Not ordinary qqbar picture favored but not conclusive.

Tensor mesons $f_2(1270)$, $a_2(1320)$, $f_2'(1525)$







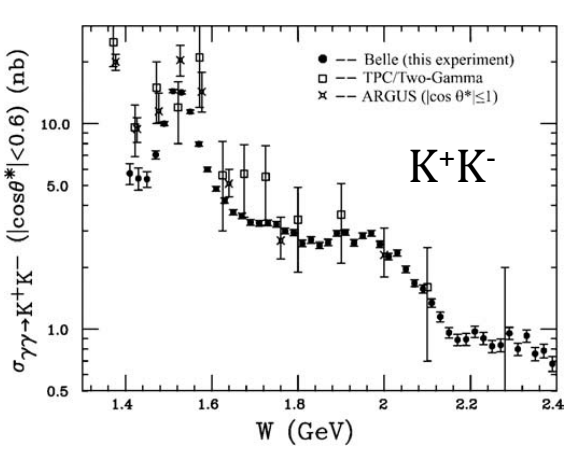


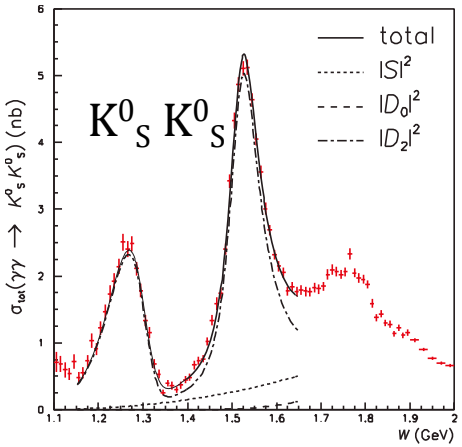
-$f_2(1270)$
Seen in $\pi^+\pi^-$, $\pi^0\pi^0$, $\eta\eta$

-$a_2(1320)$
Largest peak in $\eta\pi^0$

-$f_2'(1525)$
Largest peak in $\eta\eta$, $K^0_S K^0_S$
$\sim$ almost pure $s\bar{s}$

Interference bewteen $f_2(1270)$ and $a_2(1320)$ in KK





$$S = B_S$$
$$D_0 = B_{D0}e^{i\phi_{BD0}}$$
$$D_2 = A_{f_2(1270)} + A_{a_2(1320)}e^{i\phi_{a2}} + A_{f_2'(1525)}e^{i\phi_{f2p}} + B_{D2}e^{i\phi_{BD2}}$$

Parameter χ^2/ndf	Solution H 375.09/387	Solution L 375.22/387	H, L combined –	Incoherent fit 406.6/388	PDG –
$\varphi_{a_2(1320)}$ (deg.)	$178.1^{+1.7+6.7}_{-1.3-12.5}$	$172.6^{+1.3+6.7}_{-1.0-3.1}$	$172.6^{+6.0+12.2}_{-0.7-7.0}$	$173.6^{+1.3}_{-1.4}$	–
Mass (MeV/c^2)	$1526.1^{+0.9+2.9}_{-1.0-2.8}$	$1524.3^{+1.0+1.6}_{-0.9-1.1}$	$1525.3^{+1.2+3.7}_{-1.4-2.1}$	1530.7 ± 0.4	1525 ± 5
Γ_{tot} (MeV)	$83.4^{+1.9+2.0}_{-1.7-3.4}$	$81.8^{+2.3+4.4}_{-2.0-0.9}$	$82.9^{+2.1+3.3}_{-2.2-2.0}$	82.7 ± 1.4	73^{+6}_{-5}
$\Gamma_{\gamma\gamma}$ B($\bar{K}K$) (eV)	113^{+25+43}_{-28-77}	$48 \pm 4^{+33}_{-10}$	$48^{+67+108}_{-8-12}$	79.1 ± 1.4	72 ± 7

In K^+K^-
Peak ~1.3GeV > $f_2'(1525)$

In $K^0_S K^0_S$
Peak ~1.3GeV < $f_2'(1525)$

PWA fit the phase φ_{a2}
consistent with 180°

(First analysis to include non-resonant amplitude.)

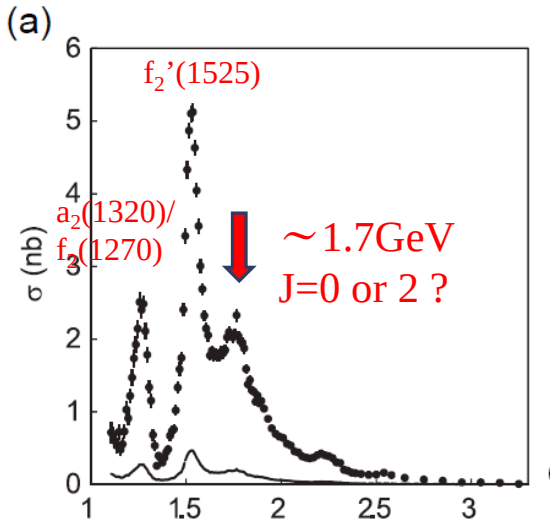
consistent with

$$f_2 = \frac{1}{2}|u\bar{u}+d\bar{d}>$$
$$a_2 = \frac{1}{2}|u\bar{u}-d\bar{d}>$$

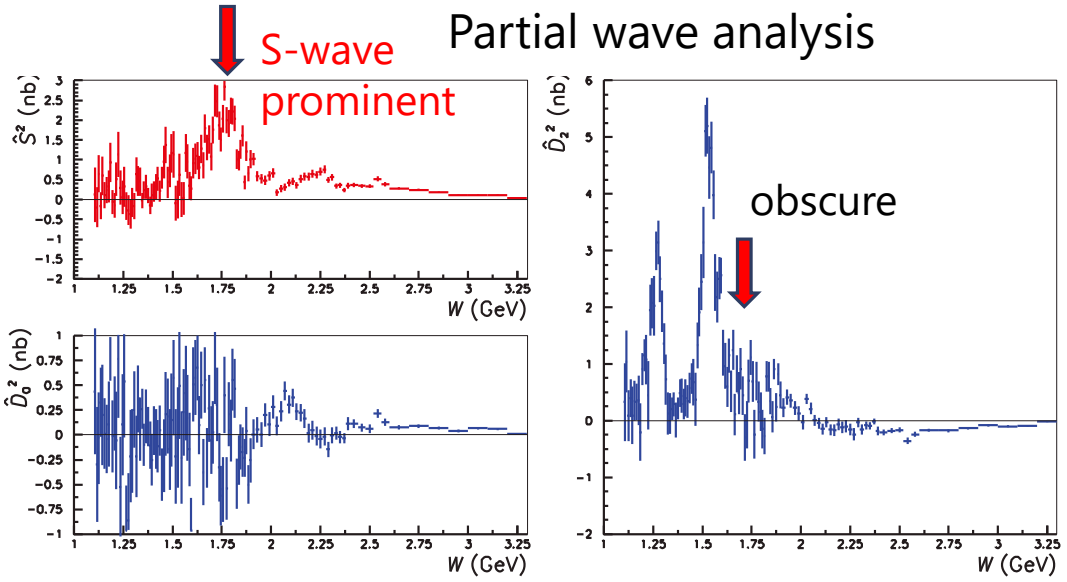
Confirmation of $f_0(1710)$ in $K^0_S K^0_S$

$f_J(1710)$ suggested

Integrated cross section



Partial wave analysis



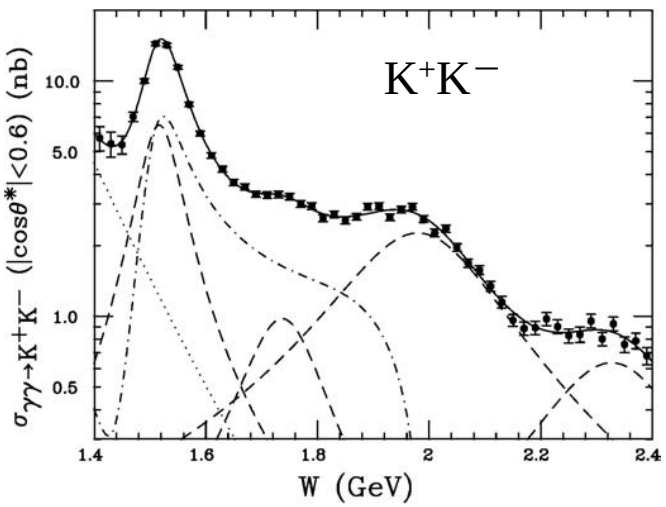
Parameter	$f_0(1710)$ fit				$f_2(1710)$ fit	
	fit-H	fit-L	H,L combined	PDG	fit-H	fit-L
χ^2/ndf	694.2/585	701.6/585	–	–	796.3/585	831.5/585
Mass(f_J) (MeV/c^2)	1750^{+5+29}_{-6-18}	1749^{+5+31}_{-6-42}	1750^{+6+29}_{-7-18}	1720 ± 6	1750^{+6}_{-7}	1729^{+6}_{-7}
$\Gamma_{tot}(f_J)$ (MeV)	138^{+12+96}_{-11-50}	145^{+11+31}_{-10-54}	139^{+11+96}_{-12-50}	135 ± 6	132^{+12}_{-11}	150 ± 10
$\Gamma_{\gamma\gamma}B(K\bar{K})_{f_J}$ (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

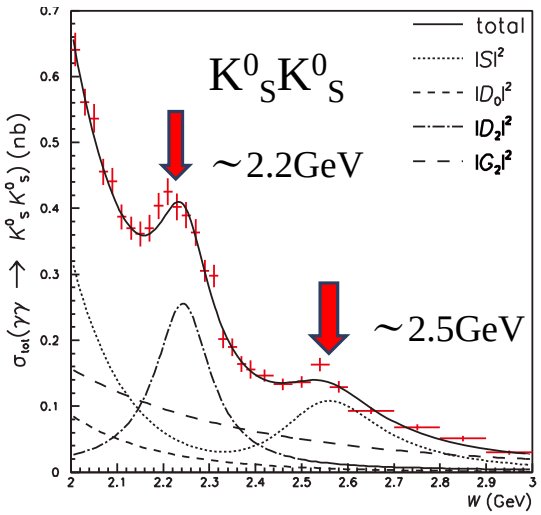
- J=0 is favored over J=2. (7.9σ)
- parameters extracted for $f_0(1710)$.
- still candidate for glueball.

Brünner and Rebhan
PRL. 115, 131601 (2015)

2.2-2.6 GeV in $K^0_S K^0_S$ and K^+K^-

$f_J(2220)$ with narrow width suggested





PWA in $K^0_S K^0_S$

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

Extracted parameters

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

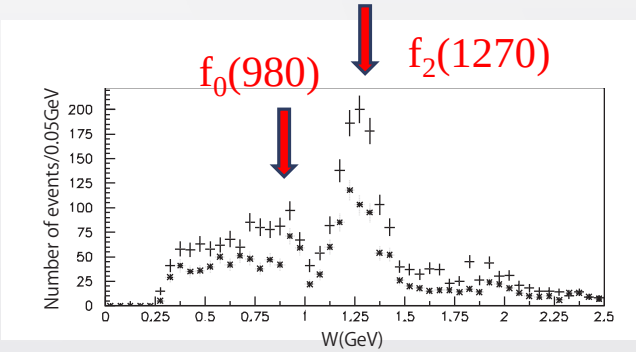
in $K^0_S K^0_S$
- 3.4σ for $f_2(2200)$ over $f_0(2200)$
  ; not narrow
- 4.3σ for $f_0(2500)$ over $f_2(2500)$
  ; may be the heaviest light-quark scalar observed experimentally

Single-tag $\pi^0\pi^0$ production

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

Physics Motivations:

- TFF measurement of $f_0(980)$ and $f_2(1270)$
- test QCD-based theoretical predictions
- provide information for the hadronic light-by-light contribution



Partial-Wave amplitude : *S*, D_0, D_1, and D_2, contribute (W < 1.5GeV)
Differential cross section for $\gamma^*\gamma \to \pi^0\pi^0$ is given by I.F. Ginzburg et al, EPJC 18, 731 (2001).

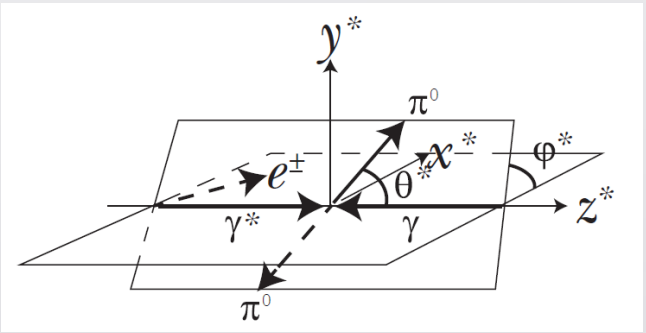
$$\frac{d\sigma}{d\Omega} = \sum_{n=0}^{2} t_n \cos n\varphi^*$$

$$t_0 = \left|SY_0^0 + D_0Y_2^0\right|^2 + \left|D_2Y_2^2\right|^2 + 2\varepsilon_0\left|D_1Y_2^1\right|^2$$

$$t_1 = 2\varepsilon_1\,\Re\left(D_2\left|Y_2^2\right| - SY_0^0 - D_0Y_2^0\right)D_1^*\left|Y_2^1\right|$$

$$t_2 = -2\varepsilon_0\,\Re(D_2^*\left|Y_2^2\right|\,(SY_0^0 + D_0Y_2^0))$$

ε_0, ε_1 variables depending on $\dfrac{p_1\cdot p_2}{q_1\cdot q_2}$



Parameterization of amplitudes

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

Partial-wave amplitudes S D_0 D_1 and D_2

$$S = A_{f_0(980)}e^{i\phi_{f0}} + B_S e^{i\phi_{BS}}$$

$$D_i = \underbrace{\sqrt{r_i(Q^2)}}_{\text{fraction ratio}} A_{f_2(1270)}e^{i\phi_{f2Di}} + B_{Di}e^{i\phi_{BDi}} \quad (i = 0,1,2)$$

$$\sum_{i=0}^{2} r_i = 1$$

where $r_i(Q^2)$ is fraction of $f_2(1270)$ contribution in D_i wave

$$A_{f_0(980)} = F_{f0}(Q^2)\sqrt{1+\frac{Q^2}{M_{f0}^2}}\sqrt{\frac{8\pi\beta_\pi}{W}}\frac{g_{f0\gamma\gamma}g_{f0\pi\pi}}{16\sqrt{3}\pi}\frac{1}{D_{f0}}$$

$$A_{f_2(1270)} = F_{f2}(Q^2)\sqrt{1+\frac{Q^2}{M_{f2}^2}}\sqrt{\frac{8\pi(2J+1)M_{f2}}{W}}\frac{\sqrt{\Gamma_{tot}(W)\Gamma_{\gamma\gamma}(W)B(\pi^0\pi^0)}}{M_{f2}^2 - W^2 - iM_{f2}\Gamma_{tot}(W)}$$

$$F(0) = 1$$

TFF of $f_0(980)$; $F_{f0}(Q^2)$

TFF of helicity-i $f_2(1270)$; $\sqrt{r_i(Q^2)}F_{f2}(Q^2)$

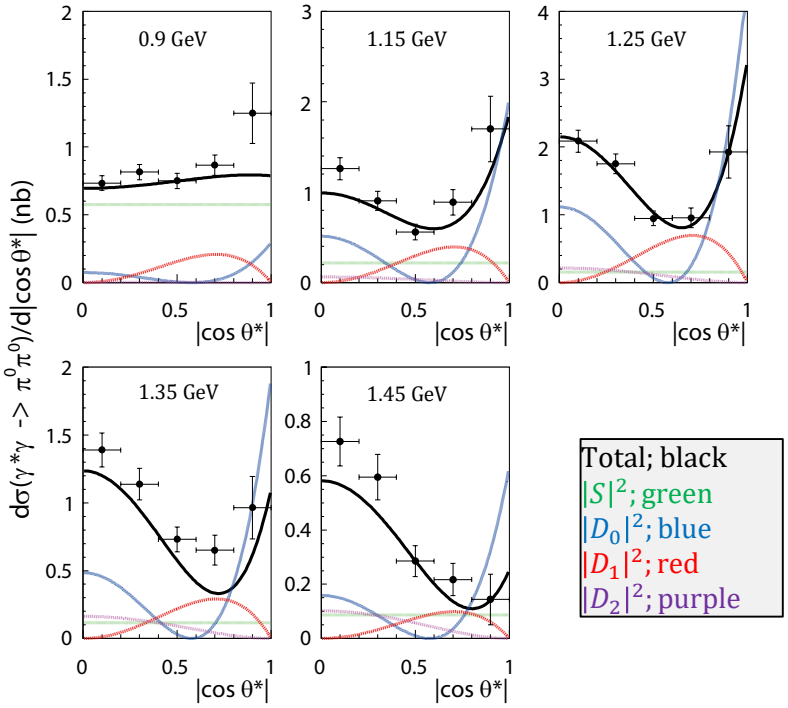
Float parameters ; $r_i(Q^2)$, $F_{f0}(Q^2)$, $F_{f2}(Q^2)$, B_S, B_{Di}, ϕ_{f0}, ϕ_{f2Di}…

Parameters of $f_0(980)$ and $f_2(1270)$ such as masses, fractions width ..,are given.

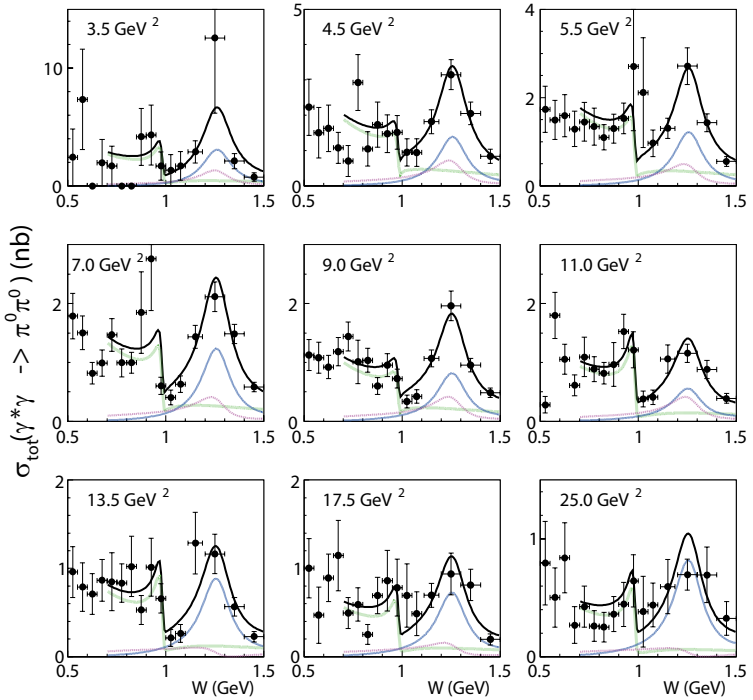
Cross section and fit

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

$d\sigma/d|\cos\theta^*|$ in five W bins



σ in nine Q^2 bins



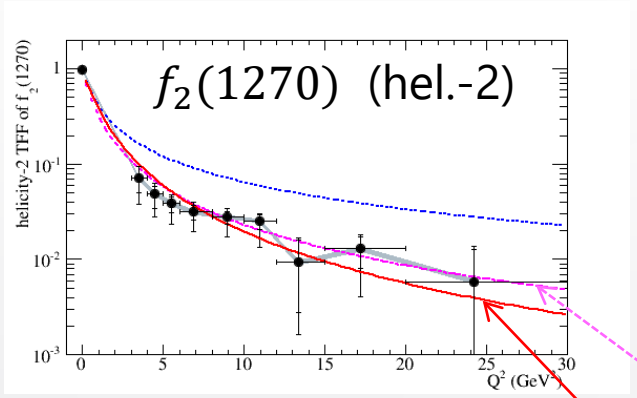
W∼$f_0(980)$ dominted by $|S|^2$

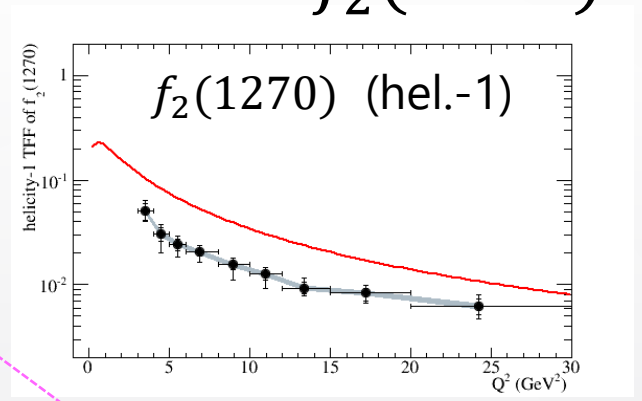
W∼$f_2(1270)$ has $|D_0|^2$, $|D_1|^2$, $|D_2|^2$

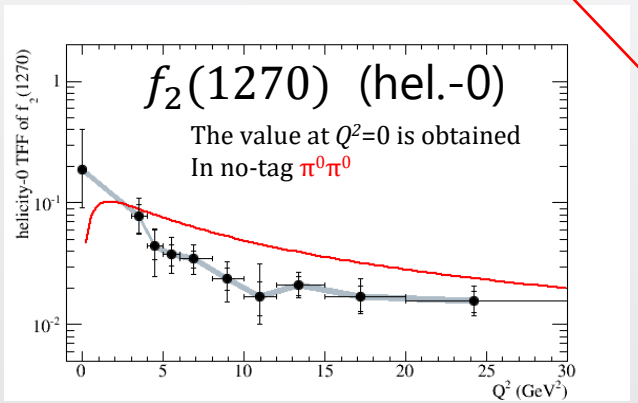
Q^2 dependence of $f_2(1270)$: helicity $2 \to 0$ dominance with Q^2

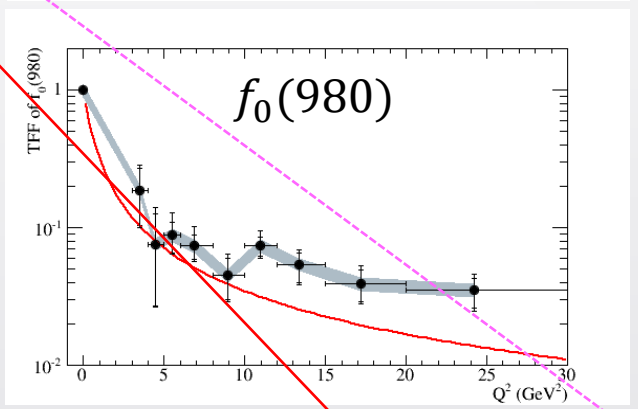
Brown, *et al.* 10.1007/JHEP06 (2016) 039 Achasov, *et al.*JETP Lett. 102 (2015) 571

Transition form factors of $f_2(1270)$ and $f_0(980)$









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

References

[1] Schuler, *et al.* NPB 523, 423 (1998).
Based on application of heavy quark approximation to light quarks

[2] Pascalutsa, *et al.* PRD 85, 116001 (2012).
Based on sum rules

- shows large contribution for the $f_2(1270)$ hel.-0 component, and small but non-zero contribution for the $f_2(1270)$ hel.-1 component.
- hel.-2 TFF of $f_2(1270)$ agrees with the prediction of Ref.[1] and one of Ref. [2].
- hel.-0 and 1 TFF of $f_2(1270)$, 1.5 – 2 smaller than the prediction of Ref.[1].
- TFF of $f_0(980)$: agree well with the prediction of Ref.[1] for $Q^2 < 10$ GeV^2
  less steeper Q^2 dependence for $Q^2 > 10$ GeV^2

Future prospects
no-tag and single-tag at Belle and Belle II

No-tag

-light mesons; $\rho^0\rho^0$, $\rho^+\rho^-$

-Charmonia; $\chi_{c2}(2P)$, X(3915), X(4350)

Single-tag

- $\gamma^* \gamma \to \pi^0$ Q^2 up to 60 GeV^2 expected

  Assumptions:

  - Integrated luminosity of 50ab-1 (x66)
  - No large Bhabha-Veto inefficiency
  - systematic errors from π^0 fit and trigger can be reduced
  - Other systematics stay the same

- $\gamma^* \gamma \to K^0_S K^0_S$

  About 200 events at Belle are under analysis

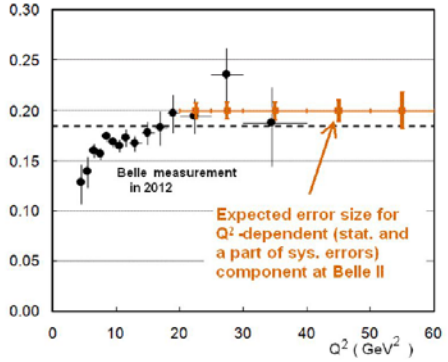
  More than 10k events expected for Belle II

- $\gamma^* \gamma \to \rho^0\rho^0 \to 4\pi^0$

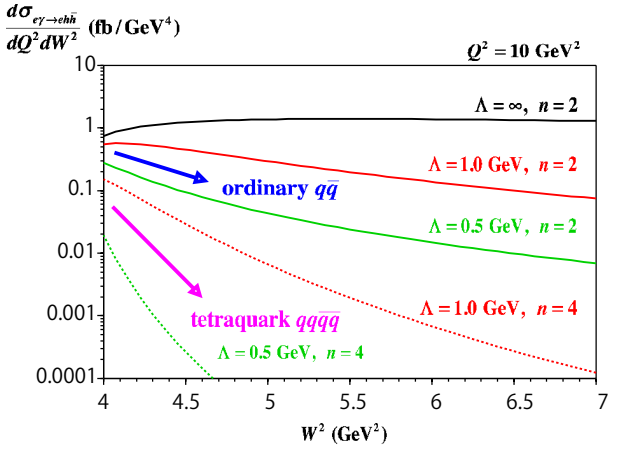
  5M events expected in no-tag, while ~ a few thousand events expected single-tag (at Belle)

- X(3872)?

Stat. error estimation for π^0 TFF by Uehara-san



Kawamura and Kumano PRD 89, 054007 (2014)



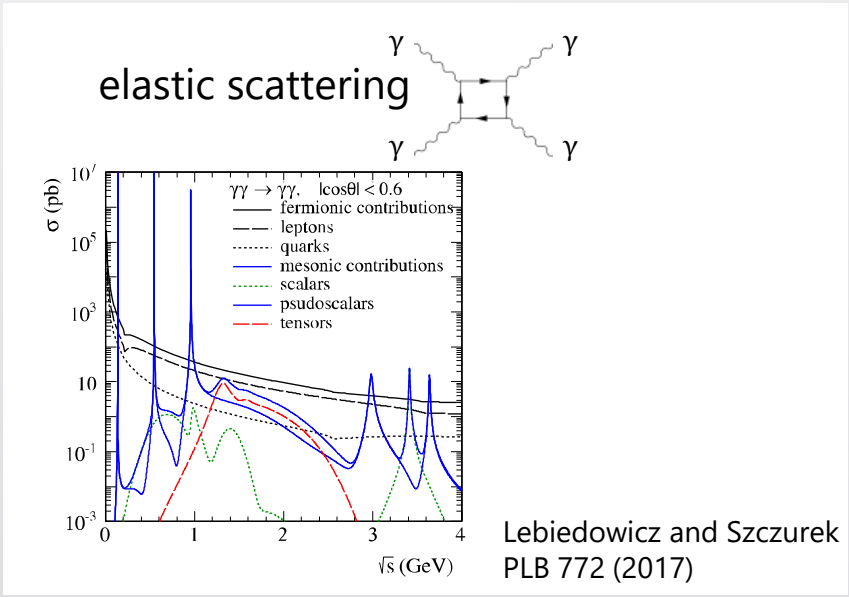
Future prospects; double-tag and light-by-light at Belle II

Double-tag $\gamma^* \gamma^* \rightarrow X$
hadronic Light-by-Light contribution
for muon g-2 theoretical calculation.

$$a_\mu^{\mathrm{SM}} = a_\mu^{QED} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{Had}}$$

Partial waves for $\gamma^* \gamma^* \rightarrow \pi^+ \pi^-, \pi^0 \pi^0$
could be input
Colangelo,et al. PLB 738, 6 (2014).

Elastic scattering $\gamma\gamma \rightarrow \gamma\gamma$
- resonances observed only at π^0, η, η'
- non-resonance region measured in Pb-Pb
  Nature Physics 13 (2017) 852
- cross section predicted by
  Lebiedowicz and Szczurek PLB 772 (2017)
- can be used to search for exotic particle
- may be seen near η_c
  double-radiation Bhabha process



Lebiedowicz and Szczurek
PLB 772 (2017)