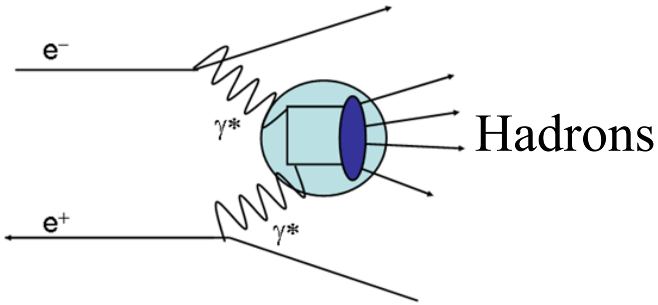
Study of mesonic states with two-photon processes at Belle

Sadaharu Uehara (KEK)

第5回クラスター階層領域研究会 (2020年9月24, 25日)

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



Hadronic system with

Total charge = 0 , **C = +,**

Real two-photon collisions dominate:

J^P= 0^+, 0^-, 2^+, 2^-, 3^+, … **(even)$^\pm$, (odd $\neq$1)$^+$**

With a virtual photon, J^P=1^+ is possible

The $\gamma\gamma$ **cross section is derived** using Equivalent Photon Approximation (luminosity function).

Single Resonance formation:

$\Gamma\gamma\gamma$: proportional to the production cross section

$\rightarrow$ reflecting **meson's internal structure**

Measurement of Decay properties, Search for new resonances, …

Hadron-pair production, Multi-hadron production:

Test of QCD/Hadron structure

Use of highly virtual photon γ* (Q^2 > 1 GeV)

$Q^2 = - q_1^2$: virtuality of a photon

Physics target in this talk

Study of mesonic states

with Single or two meson-production processes

$\gamma^{(*)}\gamma \rightarrow M$ ($\rightarrow$ decay)

$\gamma^{(*)}\gamma \rightarrow MM'$

We explore …

- Light meson spectroscopy and exotics (tetraquarks, glueballs etc.)
- Charmonium spectroscopy and exotics (XYZ)
- Meson properties
- Transition form factors, (G)VDM etc.
- Verification of (p)QCD through $q\bar{q}$-meson model

People contributing to these contents:

(**Present Belle Two-photon members only**, not covering the all):

Japan: Y. Watanabe, M.Masuda, Y. Teramoto, S. Uehara

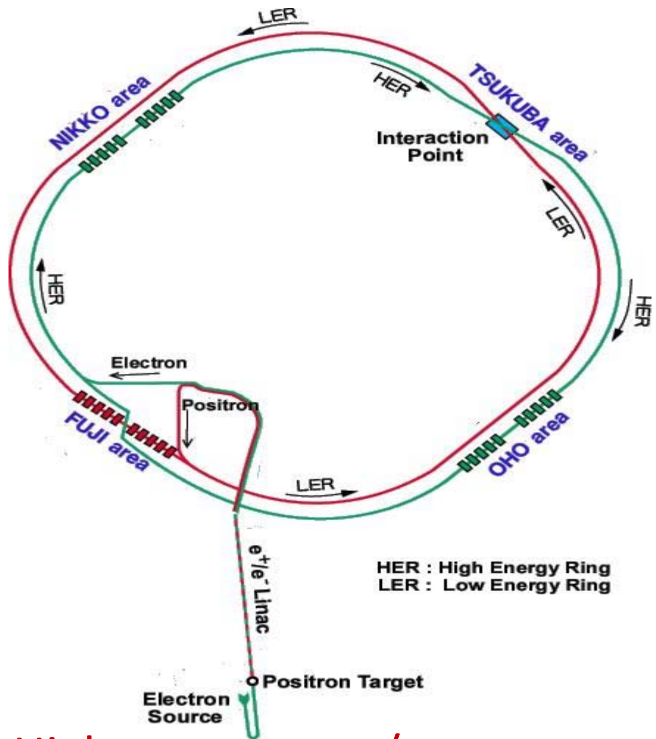
Taiwan: H. Nakazawa, A.Chen

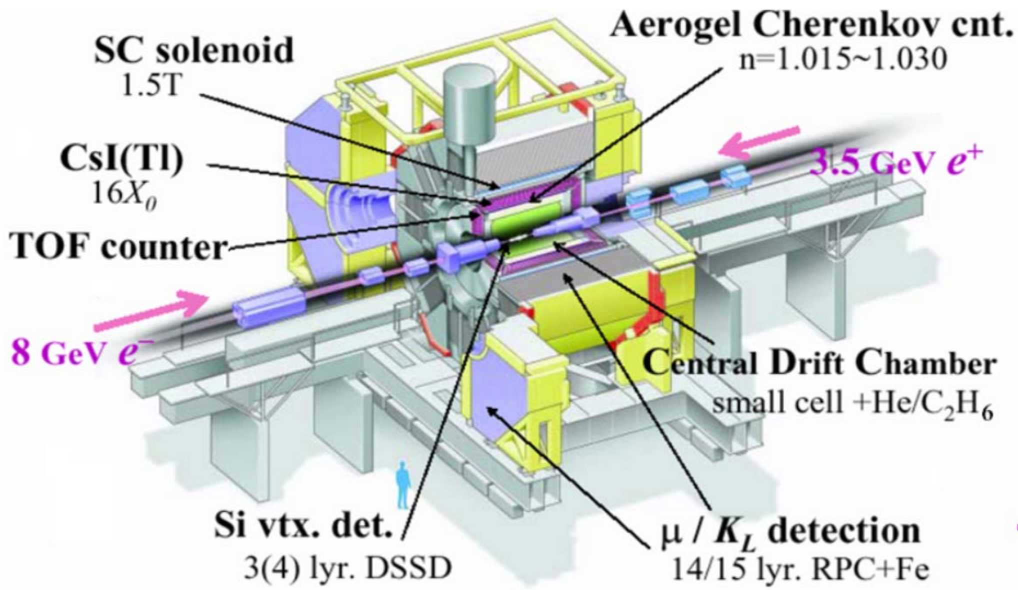
China: C.P. Shen, C.Z. Yuan

KEKB Accelerator and Belle Detector

- Asymmetric $e^- e^+$ collider
  8 GeV e^- (HER) x 3.5 GeV e^+ (LER)
  $\sqrt{s}$= around 10.58 GeV ⇔ $\Upsilon(4S)$
  Beam crossing angle: 22mrad

- World-highest Luminosity
  L_{max}=2.1x10^{34} $cm^{-2}s^{-1}$
  $\int$ Ldt ~ 1040 fb^{-1} (1999-2010)





High momentum/energy resolutions
CDC+Solenoid, CsI
Vertex measurement – Si strips
Particle identification
TOF, Aerogel, CDC-dE/dx,
RPC for K_L/muon

Two-photon result publications from Belle

process	W (GeV)	L (fb-1)	papers published by Belle	year
$\pi^0\pi^0$	0.6-4.0	95	PRD 78, 052004	2008
	0.6-4.0	223	PRD 79, 052009	2009
$\pi^+\pi^-$	0.8-1.5	86	PRD 75, 051101	2007
	0.8-1.5	86	JSPJ 76, 074102	2007
	2.4-4.1	88	PLB 615,39	2005
K^+K^-	1.4-2.4	67	EPJC 32, 323	2004
	2.4-4.1	88	PLB 615,39	2005
$K^0_SK^0_S$	2.4-4.0	398	PLB 651, 15	2007
	1.05-4.0	972	PTEP 2013, 123C01	2013
$\eta\eta$	1.1-3.8	393	PRD 82, 114031	2010
$\eta\pi^0$	0.84-4.0	223	PRD 80, 032001	2009
$4\pi/4K/2K2\pi$	2.4-4.1	395	EPJC 53, 1	2008
$\eta'\pi^+\pi^-$	1.4-3.4	673	PRD 86, 052002	2012
$\eta'\pi^+\pi^-, \eta_c(1S), \eta_c(2S)$	1.4-3.8	941	PRD 98, 072001	2018
D Dbar	3.7-4.3	395	PRL 96, 082003	2006
$\gamma J/\psi$	3.2-3.8	33	PLB 540,33	2002
$\varphi J/\psi$	4.2-5.0	825	PRL 104, 112004	2010
$\omega J/\psi$	3.9-4.2	694	PRL 104, 092001	2010
$\omega\omega/\varphi\varphi/\omega\varphi$	1.5-4.0	870	PRL 108, 232001	2012
ppbar	2.03-4.0	89	PLB 621,41	2005
ppbarK^+K^-	3.2-5.6	980	PRD 93, 112017	2016
π^0	0.6-4.0	759	PRD 86, 092007	2012
$\pi^0\pi^0$	0.5-2.1	759	PRD 93, 032003	2016
$K^0_SK^0_S$	1.0-2.6	759	PRD 97, 052003	2018

Pseudoscalars in No-tag

Vectors in No-tag

Baryons in No-tag

Peusoscalars in Single-tag

Fruitful achievements
by more than 15 processes

-Observation of $\chi_{c2}(2P)$, $X(4350)$, $X(3915)$, enhancements in VV

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

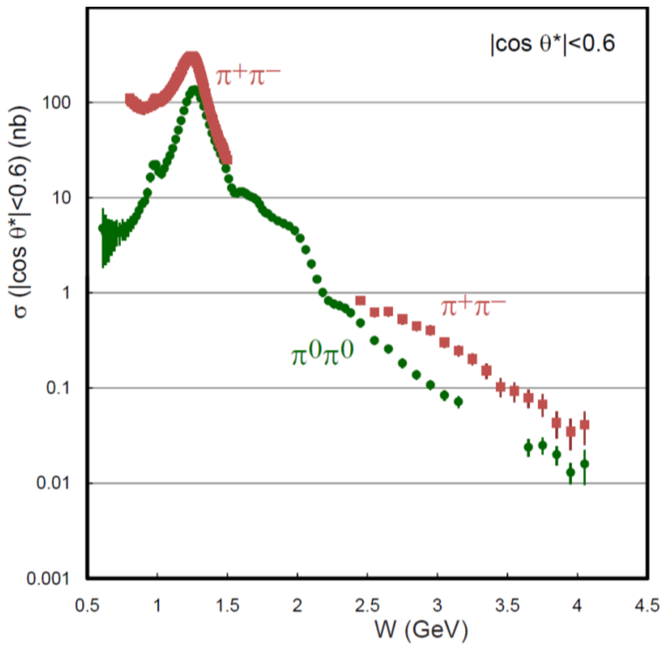
-Extraction of Transition Form Factors of π^0, $f_0(980)$, $f_2(1270)$, $f_2'(1525)$

Summarized by M.Masuda

The six 0⁻-meson-pair processes; in total ~20 peaks

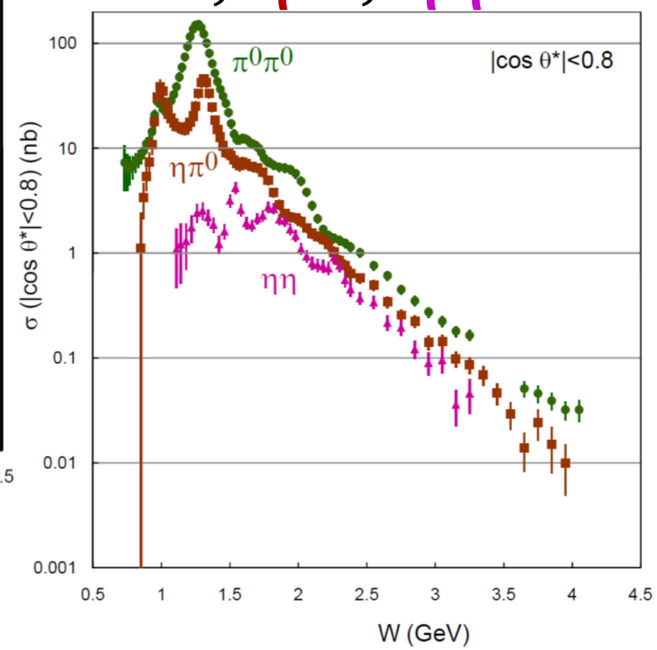
W<~2.5GeV: Dominated by resonance formation

Charged vs. Neutral ππ

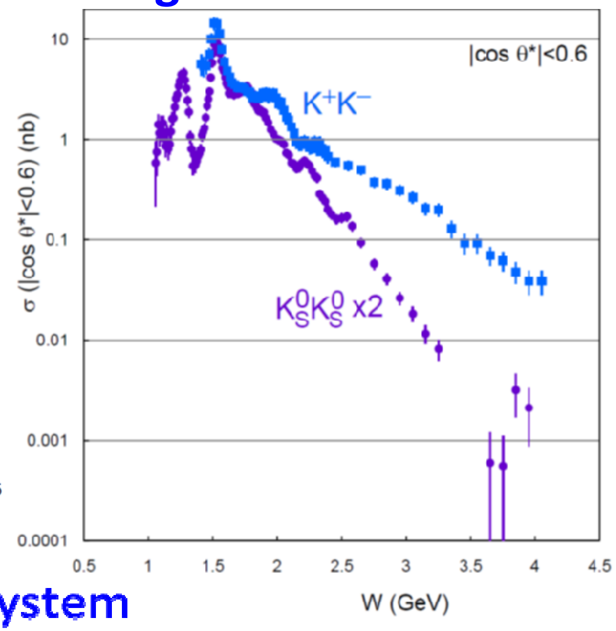


Neutral-pair processes

π⁰π⁰, ηπ⁰, ηη



Charged vs. Neutral $K\bar{K}$



Horizontal axis:

W -- γγ c.m. energy = invariant mass of the two-meson system

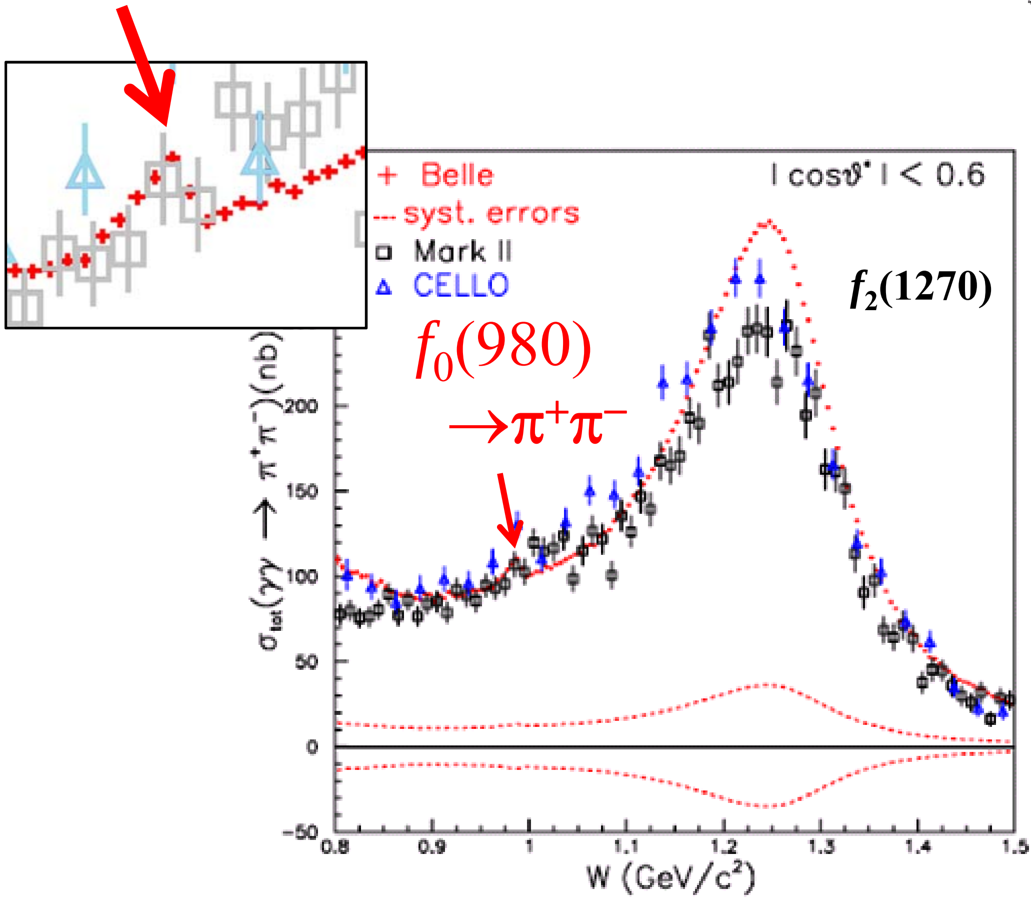
* Charmonium contributions are removed

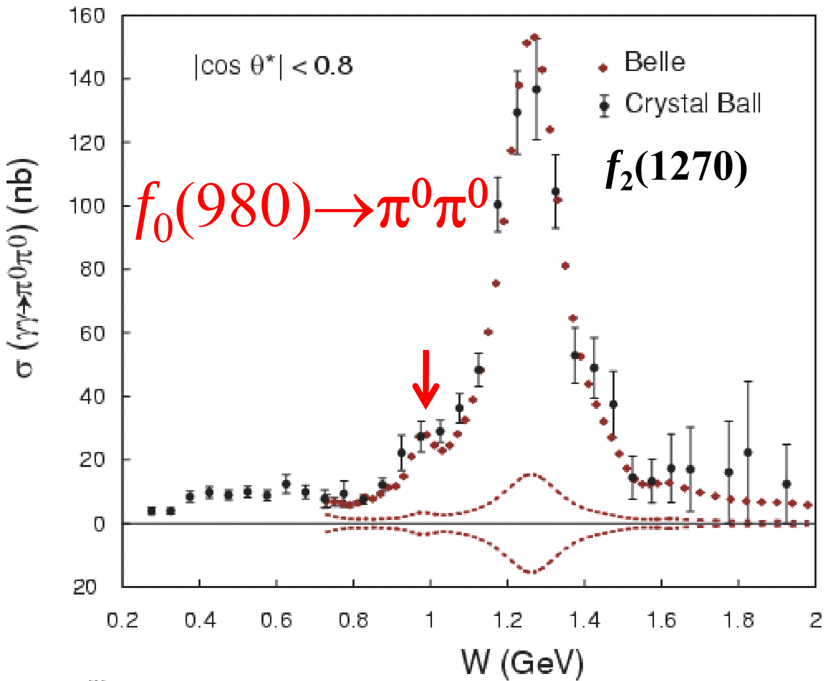
→ Study of Scalar resonances

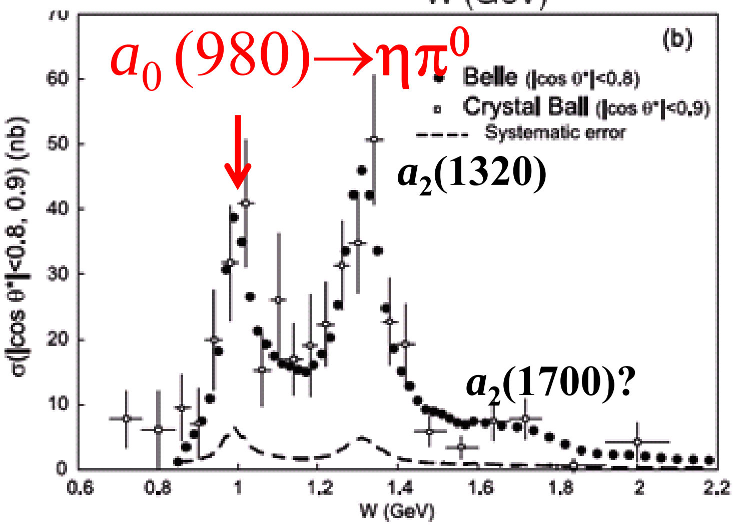
Confirmation of f_0(980) and a_0(980) formations

f_0(980) and a_0(980) : $K\bar{K}$ molecule component

Observed as a peak, very clearly in two-photon production, for the first time.



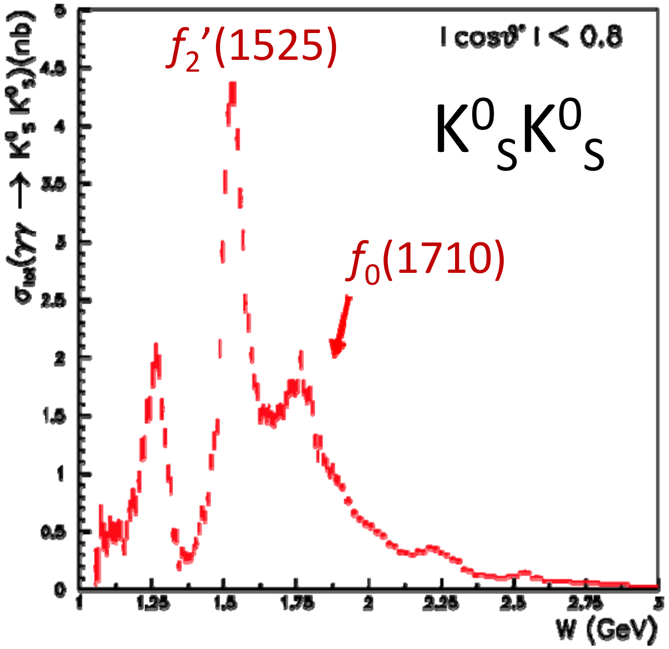


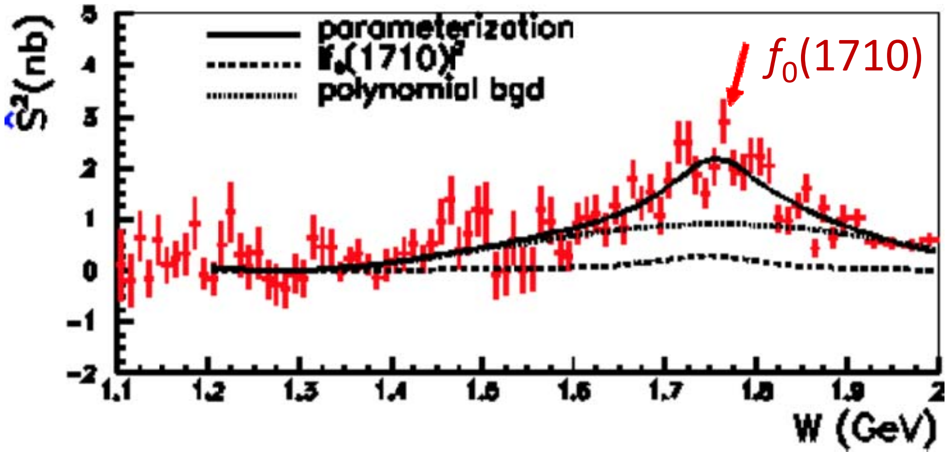


f_0(1710) formation in $K^0_S K^0_S$ and others

EPJ C (2014) 74:3026

A glueball candidate

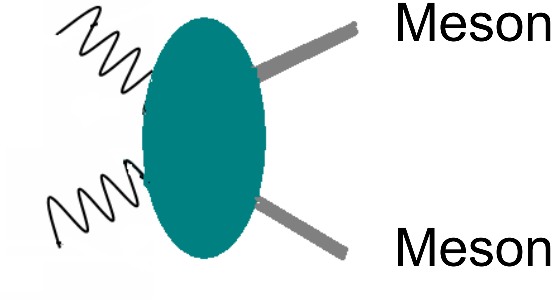




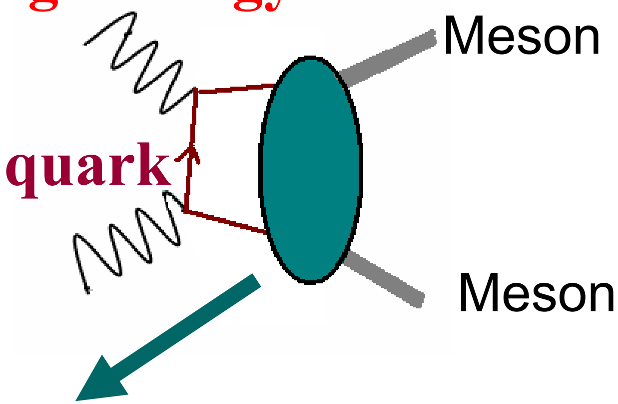
Mode	Resonance	Mass (MeV/c^2)	Width (MeV)	$\Gamma_{\gamma\gamma}$ (eV), $(J,\lambda)=\begin{cases}(2,2)\\(0,0)\end{cases}$
$\pi^+\pi^-$	$f_0(980)$	$985.6^{+1.2+1.1}_{-1.5-1.6}$	$34.2^{+13.9+8.8}_{-11.8-2.5}$	$205^{+95+147}_{-83-117}$
	$\eta'(958)$	$\mathcal{B}(\pi^+\pi^-)<2.9\times10^{-3}$ (with interference), 3.3×10^{-4} (without)		
K^+K^-	$f_2'(1525)$	$1518\pm1\pm3$	$82\pm2\pm3$	$28.2\pm2.4\pm5.8/\mathcal{B}$
	$f_J/f_0/a_2$	$1737\pm5\pm7$	$151\pm22\pm24$	$\begin{cases}10.3\pm2.1\pm2.3/\mathcal{B}\\76\pm15\pm17/\mathcal{B}\end{cases}$
	$f_2(2010)$	$1980\pm2\pm14$	$297\pm12\pm6$	$61\pm2\pm3/\mathcal{B}$
	f_J/f_2	$2327\pm9\pm6$	$275\pm36\pm20$	$\begin{cases}22\pm3\pm6/\mathcal{B}\\161\pm22\pm48/\mathcal{B}\end{cases}$
$K^0_S K^0_S$	$f_2'(1525)$	$1525.3^{+1.2+3.7}_{-1.4-2.1}$	$82.9^{+2.1+3.1}_{-2.2-2.0}$	$48^{+67+108}_{-8-12}/\mathcal{B}(K\overline{K})$
	$f_0(1710)$	1750^{+6+29}_{-7-18}	139^{+11+96}_{-12-50}	$12^{+3+227}_{-2-8}/\mathcal{B}(K\overline{K})$
	$f_2(2200)$	2243^{+7+3}_{-6-29}	$145\pm12^{+27}_{-34}$	$3.2^{+0.5+1.3}_{-0.4-2.2}/\mathcal{B}(K\overline{K})$
	$f_0(2500)$	$2539\pm14^{+38}_{-14}$	$274^{+77+126}_{-61-163}$	$40^{+9+17}_{-7-40}/\mathcal{B}(K\overline{K})$
$\pi^0\pi^0$	$f_0(980)$	$982.2\pm1.0^{+8.1}_{-8.0}$		$286\pm17^{+211}_{-70}$
	$f_2(1270)$	fixed	fixed	
		$\mathcal{B}(f_2\to\gamma\gamma)=(1.57\pm0.01^{+1.39}_{-0.14})\times10^{-5}$		
	$f_0(Y)$	1470^{+6+72}_{-7-255}	90^{+2+50}_{-1-22}	$11^{+4+603}_{-2-7}/\mathcal{B}$
	$f_2(1950)$	2038^{+13}_{-11}	441^{+27}_{-25}	$54^{+23}_{-14}/\mathcal{B}$
	$f_4(2050)$	$1884^{+14+218}_{-13-25}$	$453\pm20^{+31}_{-129}$	$136^{+24+415}_{-22-91}$
$\eta\pi^0$	$a_0(980)$	$982.3^{+0.6+3.1}_{-0.7-4.7}$	$75.6\pm1.6^{+17.4}_{-10.0}$	$128^{+3+502}_{-2-43}/\mathcal{B}$
	$a_0(Y)$	$1316.8^{+0.7+24.7}_{-1.0-4.6}$	$65.0^{+2.1+99.1}_{-5.4-32.6}$	$432\pm6^{+1073}_{-256}/\mathcal{B}$
	$a_2(1320)$	fixed	fixed	$145^{+97}_{-34}/\mathcal{B}$
$\eta\eta$	$f_0(Y)$	$1262^{+51+82}_{-78-103}$	$484^{+246+246}_{-170-263}$	$121^{+133+169}_{-53-106}/\mathcal{B}$
	$f_2(1270)$	fixed	fixed	$11.5^{+1.8+4.5}_{-2.0-3.7}/\mathcal{B}$
	$f_2(X)$	$1737\pm9^{+198}_{-65}$	$228^{+21+234}_{-20-153}$	$5.2^{+0.9+37.3}_{-0.8-4.5}/\mathcal{B}$

Meson-pair production and QCD

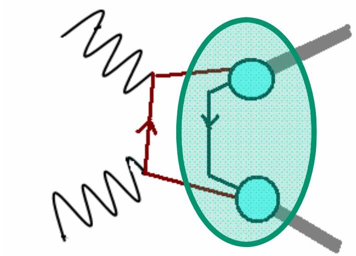
Low energy



High energy



High energy

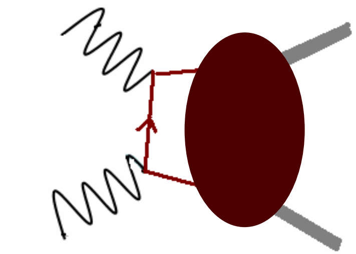


Perturbative QCD approach

for exclusive meson production

with hard scattering, distribution amp., form factor

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)

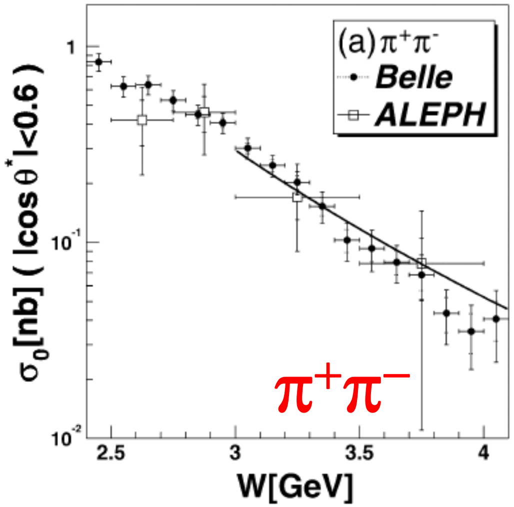
Predict

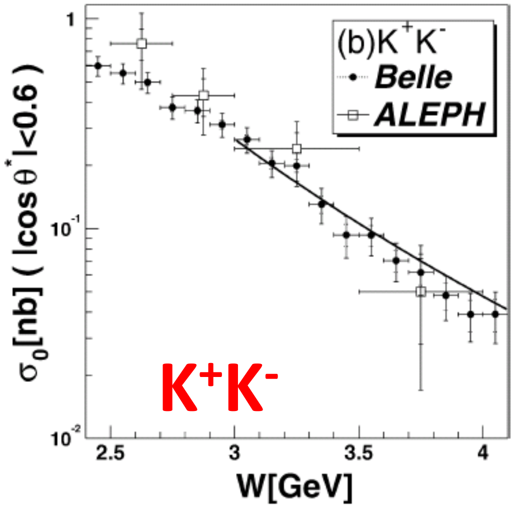
Meson scattering-angle distribution,
Energy -dependence
Cross section ratios under SU(3) sym.

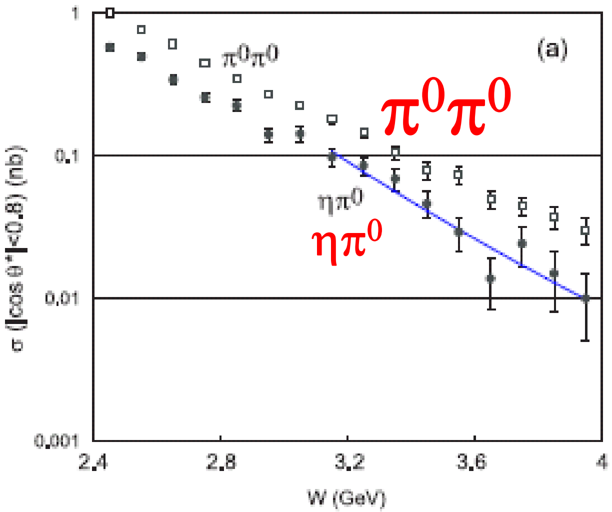
W-dependences at high energies

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

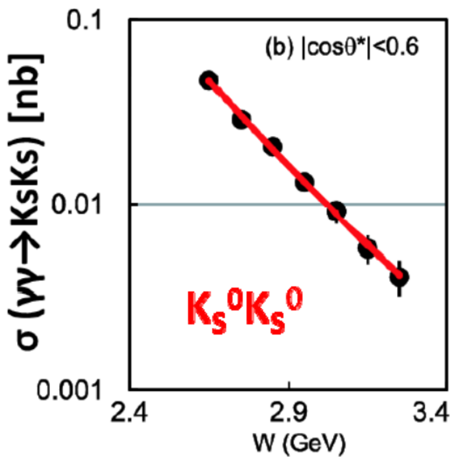
$\sigma(W) \sim W^{-n}$ expected

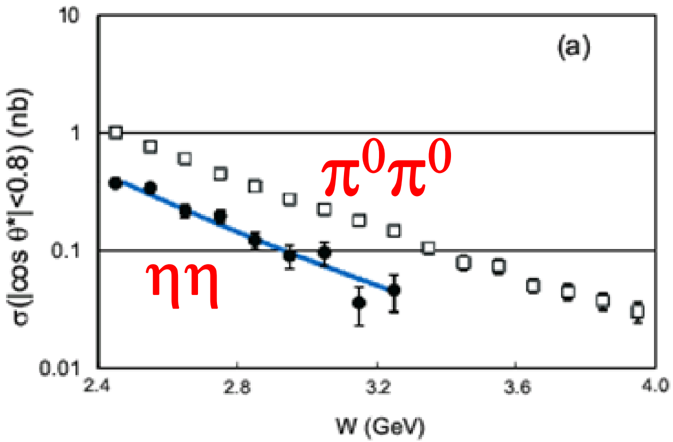






Fitted slope parameter **n**, for ~ 2.4 – 4 GeV, are different among the reactions.





Cross sections and their ratios

Process	n	W(GeV)	$\lvert\cos\theta^*\rvert$	BL	BC	DKV
$\pi^+\pi^-$	$7.9 \pm 0.4 \pm 1.5$	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	
K_SK_S	$11.0 \pm 0.4 \pm 0.4$	2.4 - 4.0†	< 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_SK_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.

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

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

measured with **a virtual photon** in the **Single-tag Mode**

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

$\sigma(W,Q^2) = \sigma_{TT} + \varepsilon\sigma_{LT}$ (**T**ransverse photon and **L**ongitudinal photon)

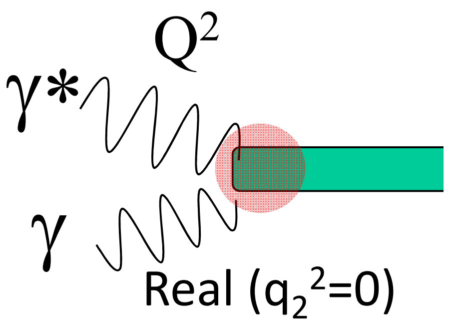
$\leftrightarrow$ Two real-photon collisions case : the No-tag mode,
where the contribution is only near $Q^2 = 0$, and $\sigma(W) = \sigma_{TT}$ only.

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

Proportional to the helicity amplitude of the resonance production

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

Produce Resonance with helicity λ;
defined along the γ^* direction



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

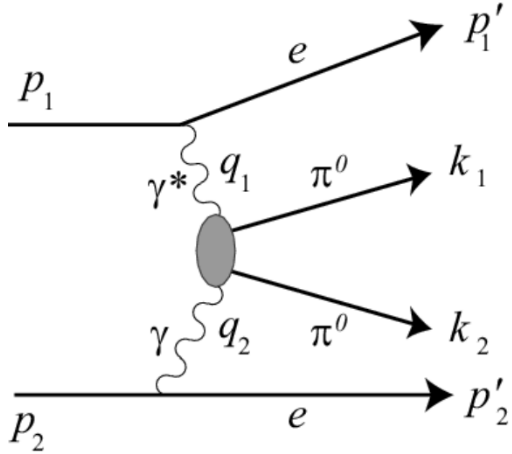
PRD 93, 032003 (2016)

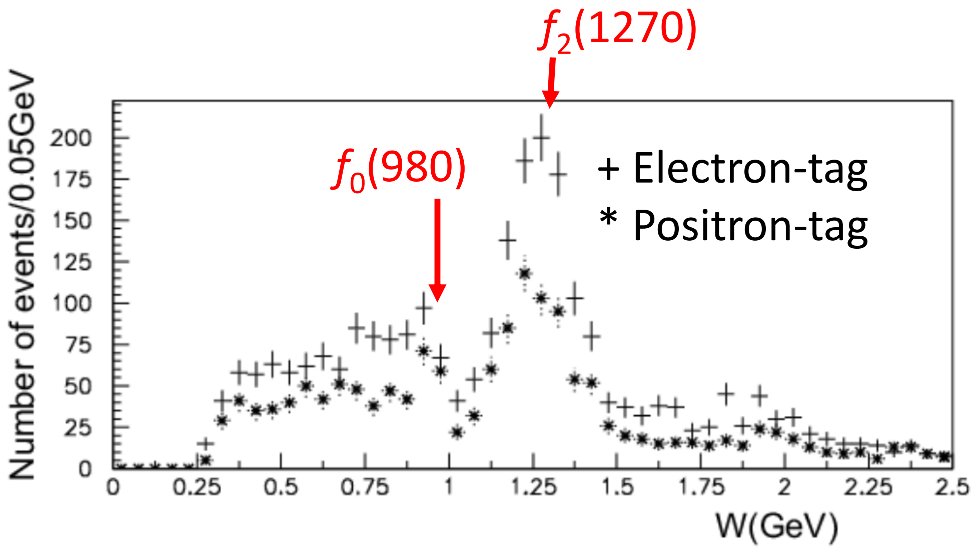
Physics motivations:

- Q^2 dependence of TFF for scalar and tensor mesons
  (This is the first measurement)

- Test of QCD of $q\bar{q}$ meson model

- Hadronic Light-by-Light contribution to g-2$|_\mu$
  for validation check of theoretical calculations



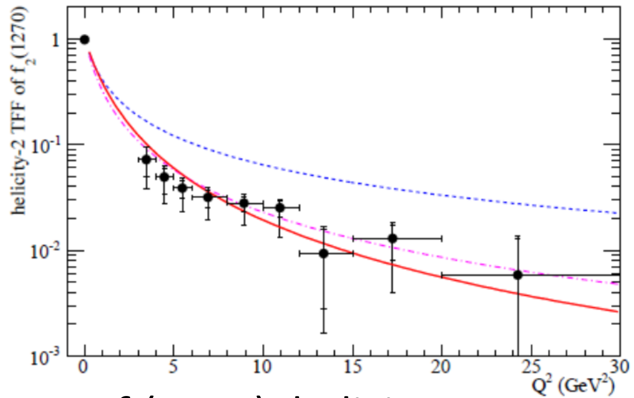


The f_0/f_2 ratio is larger than in the no-tag case.

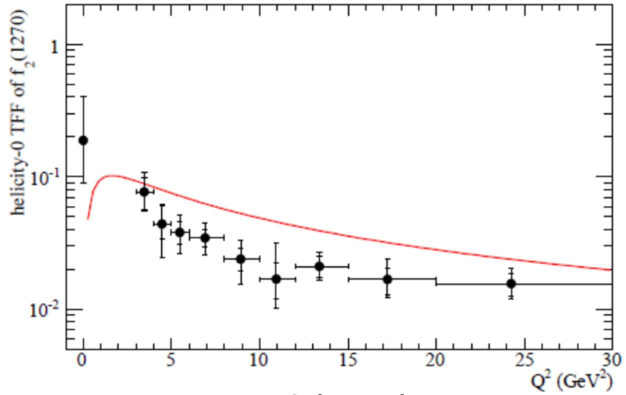
Q^2 dependence of the TFFs

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

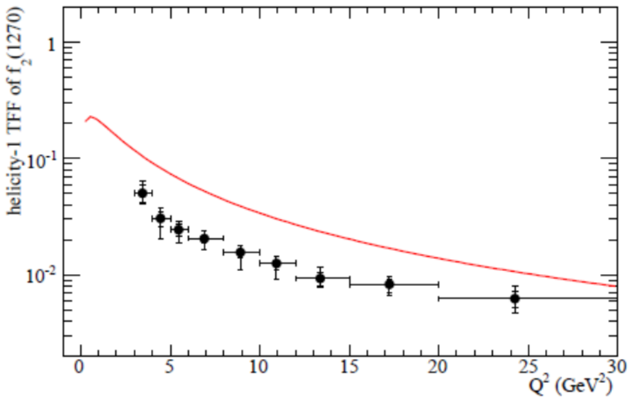
$f_2(1270)$, helicity = 2



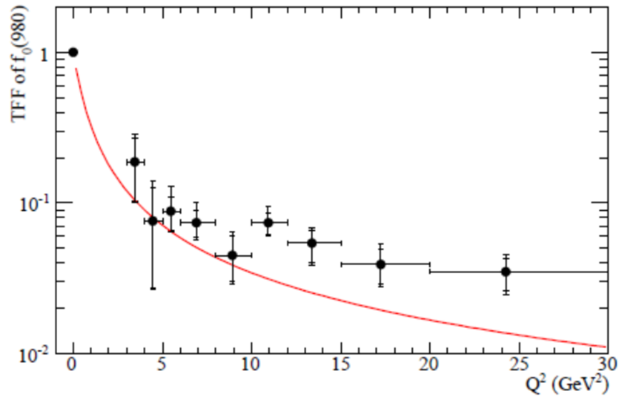
$f_2(1270)$, helicity = 0



$f_2(1270)$, helicity = 1



$f_0(980)$



Shorter error bars : Statistical

Longer error bars : Statistical and systematic

Theoretical predictions:

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

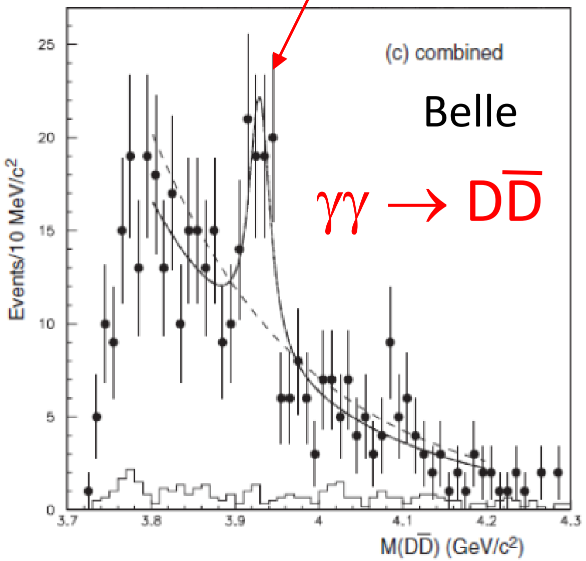
Pascalutes, Pauk, Vanderhaeghen, saturated sum rule, PRD 85, 116001 (2012), η's

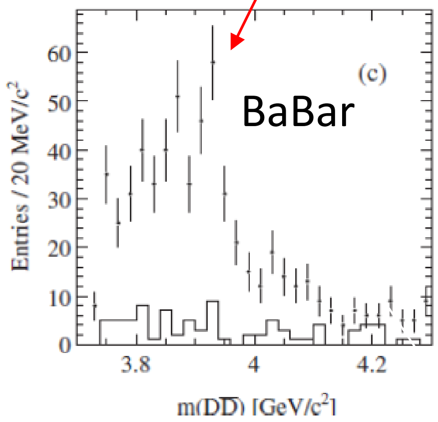
ibid., axial-vector mesons

Charmonium(-like) states

χ_{c2}**(3930)** is discovered by Belle and confirmed by BaBar,

so far seen in the $D\bar{D}$ decay mode only.

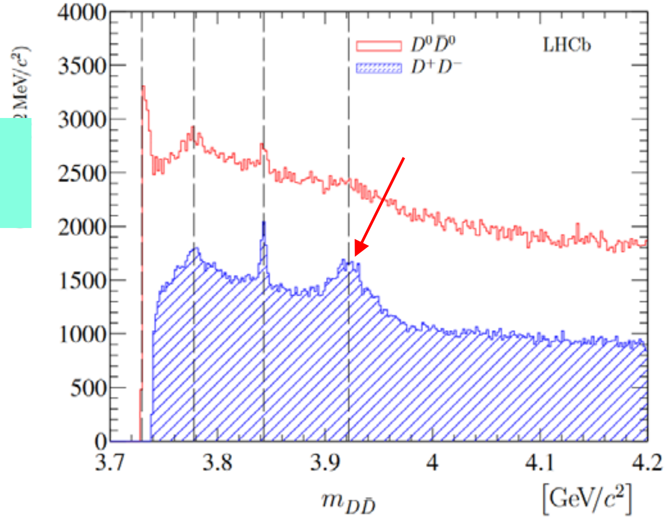




Belle: PRL 96, 082003 (2006)
BaBar: PRD 81, 092003 (2010)

Recently confirmed also at LHCb

LHCb: JHEP 07 (2019) 035

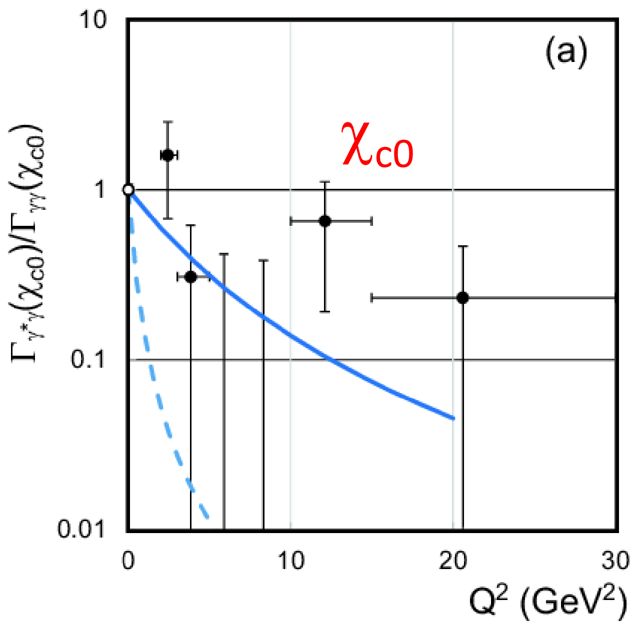


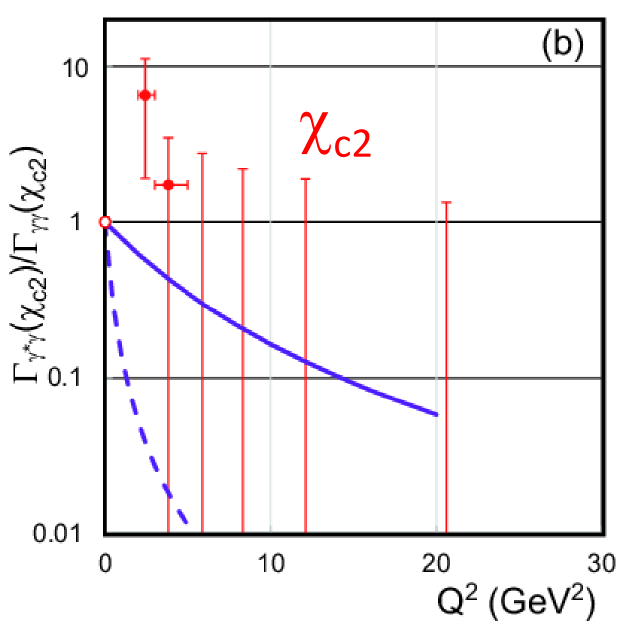
Consistent with the radial-excited 2P charmonium state.

χ_{c0} and χ_{c2} production with high-Q^2 photons

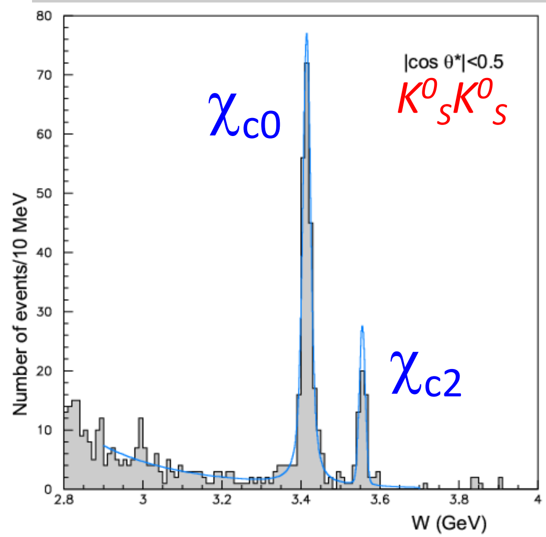
$\gamma^*\gamma \to \chi_{cJ} \to K^0_S K^0_S$

Belle, PRD 92, 052003 (2018)





Normalized by the
↓ No-tag measurements



PTEP 2013, 123C01 (2013)

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

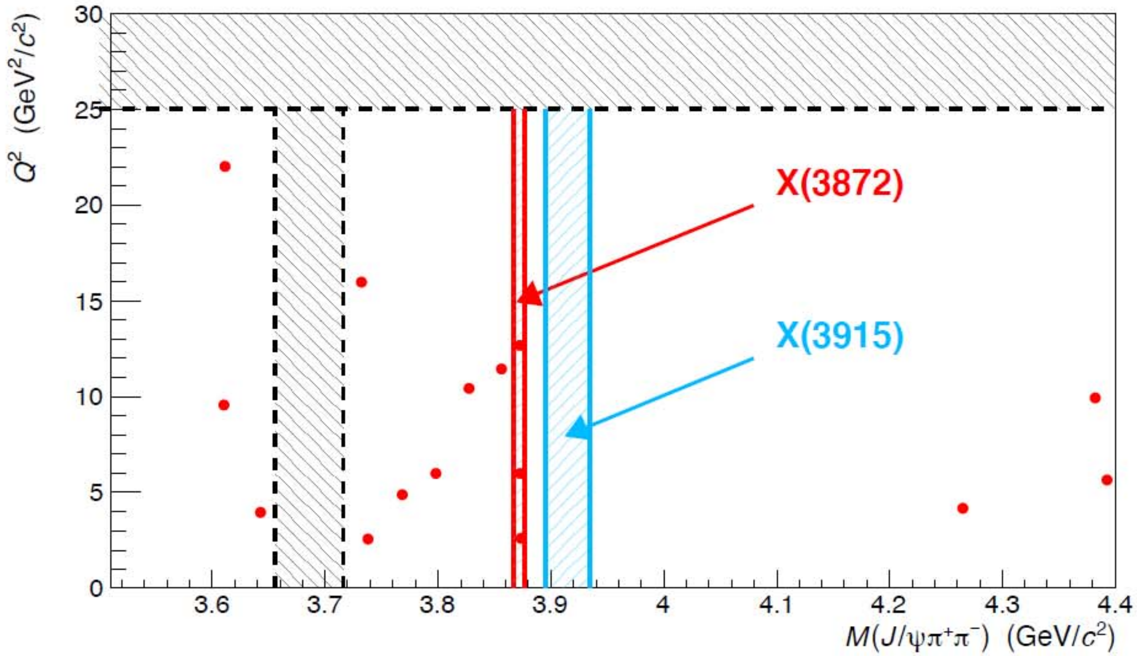
Consistent with Q^2 dependence of the charmonium mass scale,
$\sim 1/(Q^2+M(c\bar{c})^2)$

X(3872) search in single-tag with $J/\psi\pi^+\pi^-$ final state

$\gamma^*\gamma \to X(3872) \to J/\psi\ \pi^+\pi^-$

J^{PC} of X(3872) is 1^{++}. Production Allowed in single tag mode.

$D\bar{D}^*$ molecule candidate



2007.05696 (2020)

submitted to PRL

- $2.9^{+2.2}_{-2.0}\pm0.1$ events (3.2σ) found
- No events for X(3915)

Theoretical expectation (roughly):

$d\sigma/dQ^2 \sim Q^2/(1+Q^2/M^2)^c$

Summary

Highlights of Two-photon physics results from Belle
for meson/exotic spectroscopy and structure studies

- Comprehensive light-meson spectroscopy:
  observation of scalar states
- Systematic QCD test with many meson-pair production processes

- First measurement of scalar & tensor-meson TFFs

- Discovery/observations of new charmonium(like) states

- Charmonium and X(3872) production through high-Q^2 photons

Backup

No-tag and Single-tag measurements

Experimental features

No-tag (No electron observed)

$\gamma\gamma \to$ hadron(s) (quasi-real two-photon collisions)

Relatively large cross section

A p_t-balanced hadron system observed

C-odd ($\gamma^* \to$ hadron(s)) contamination is very small, in general.

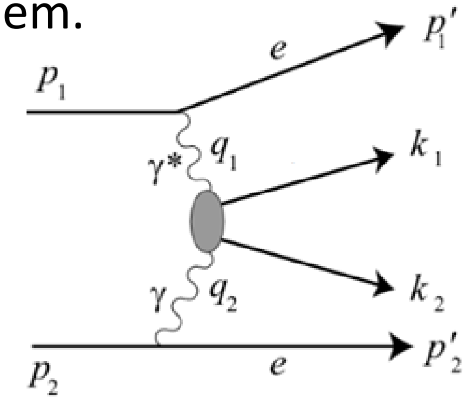
Single-tag (only one electron observed)

$\gamma^*\gamma \to$ hadron(s) (virtual-photon & quasi-real-photon collisions)

Relatively small cross section

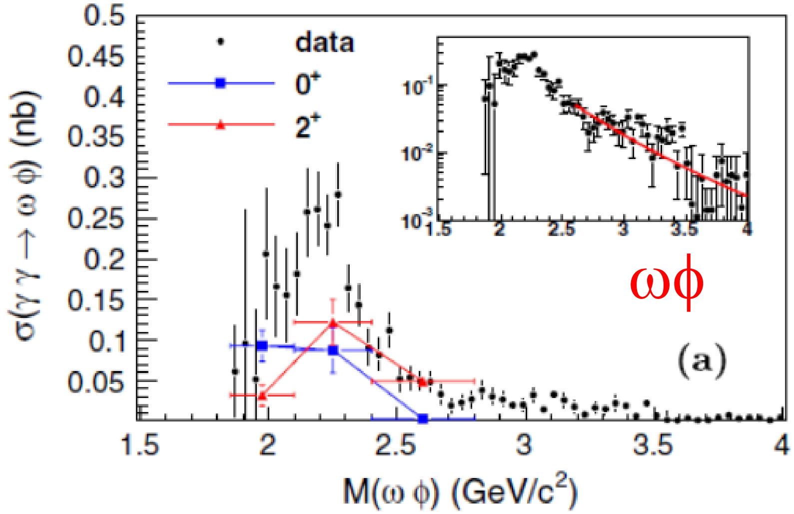
p_t-balance between a tag-electron and the hadron system

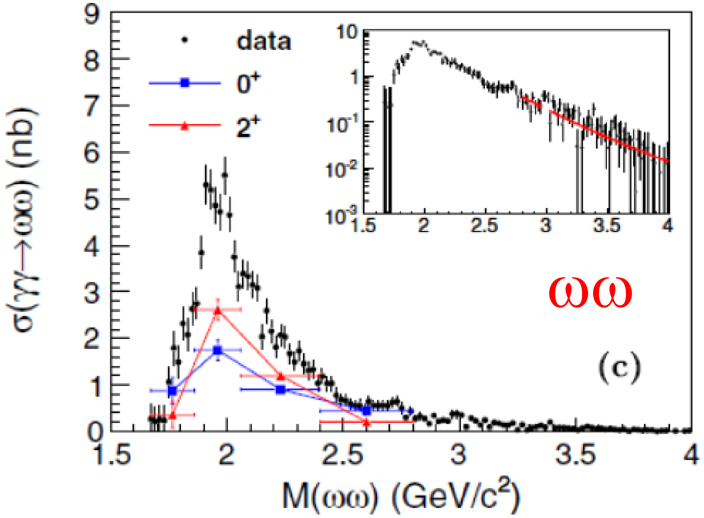
C-odd ($\gamma^* \to$ hadron(s)) contamination sometimes problem.

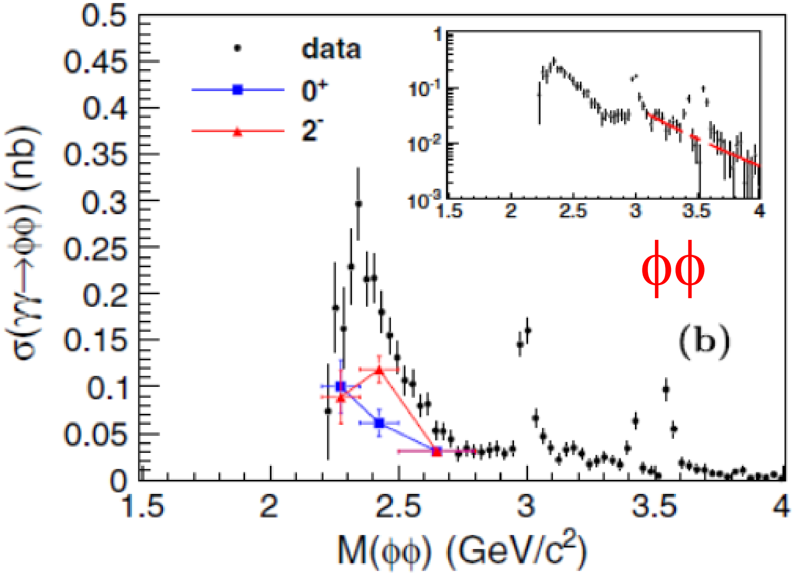


$\gamma\gamma \rightarrow$ Vector-meson pair

Belle, PRL 108, 232001 (2012)







The large cross-section size for $\omega\phi$ cannot be well explained by a theory.

Slope parameters for high W:

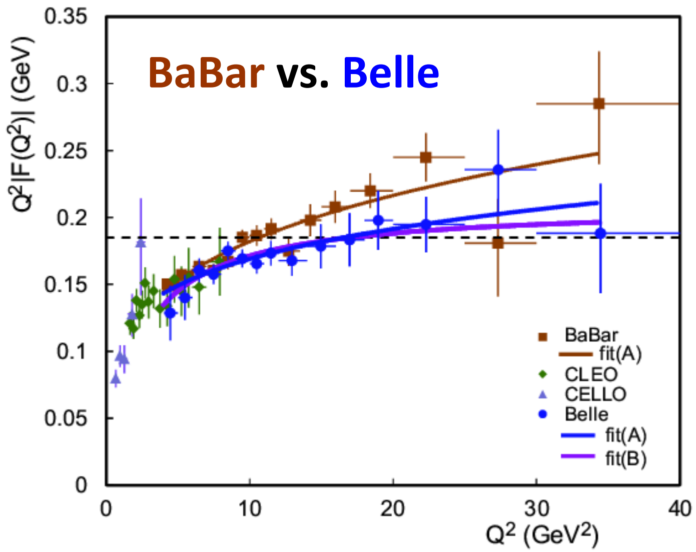
n=7.2 $\pm$ 0.6 ($\omega\phi$)
8.4 $\pm$ 1.1 ($\phi\phi$)
9.1 $\pm$ 0.6 ($\omega\omega$)
Similar values with $\pi^0\pi^0$.

Single-tag, TFF for π^0 at high Q^2

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

The BaBar and Belle results are close to or above the QCD asymptotic limit at high Q^2.

BaBar, PRD 80, 052002 (2009) **Belle, PRD 86, 092007 (2012)**

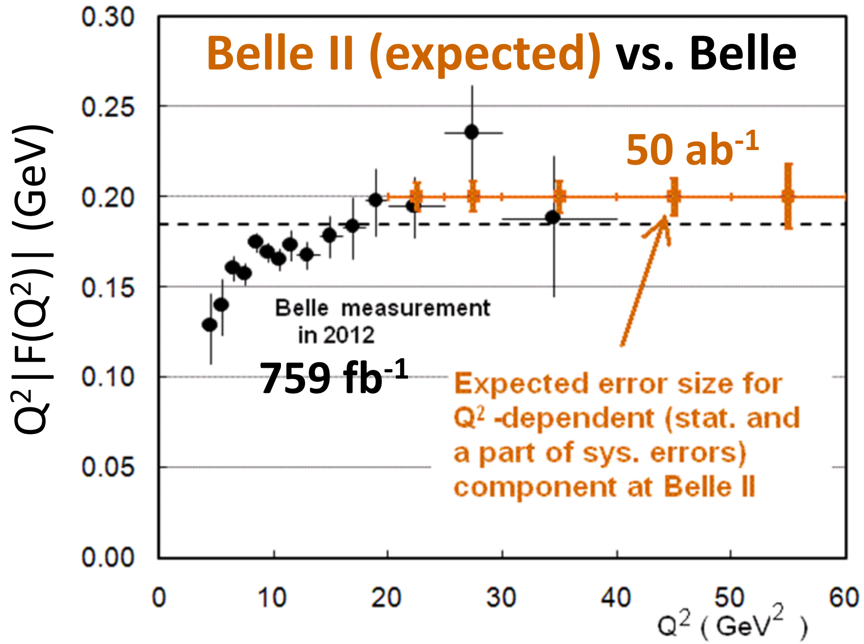


More precise and more data points at higher Q^2 are desired.

Errors for π^0-TFF measurement in the high Q^2 region at Belle II are estimated, for

- Integrated luminosity 50 ab^{-1}

  (x 66 of the Belle analysis)
- reduced systematic errors from π^0-mass fit and trigger efficiency



Q^2 > 60 GeV^2
Huge background will come from Bhabha

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, 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.

We determine each component as well as the relative phase by a fit.

++, +-, 0+ --- Helicity state of the incident photons

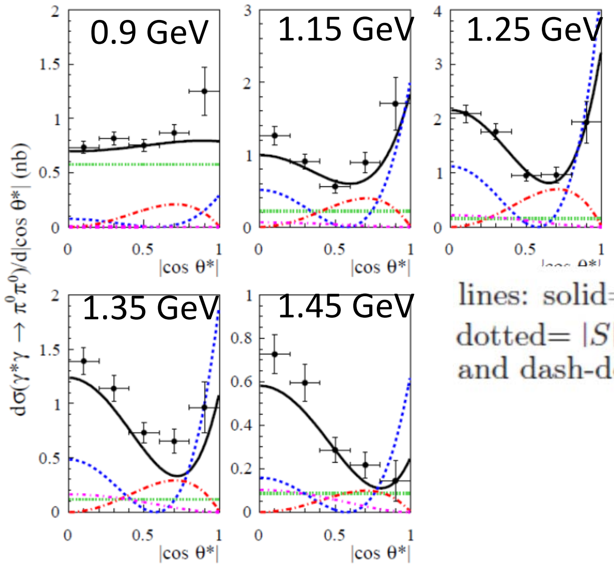
S, D_0 etc. -- Partial-wave amplitude in $\pi^0\pi^0$ scattering

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

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

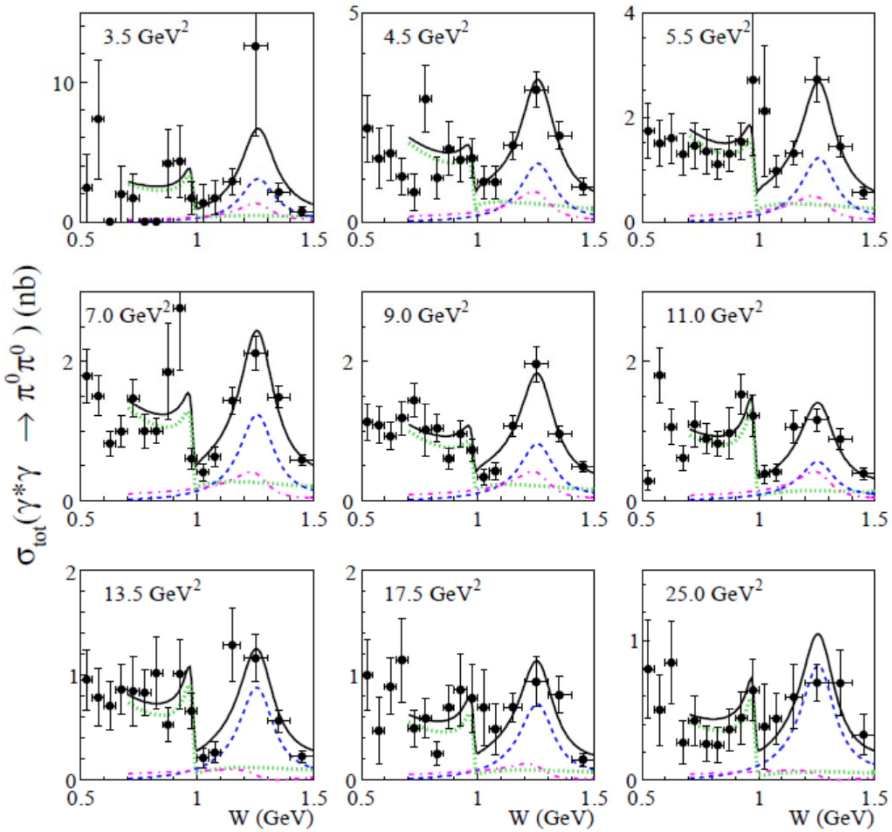
$\gamma^*\gamma \to \pi^0\pi^0$:Cross-section results and fit

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



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

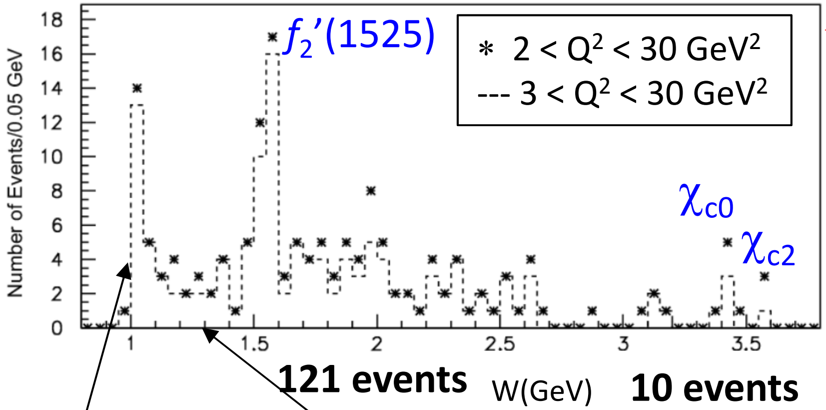
W dependence for different Q^2 bins



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

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

How about in the $K^0_S K^0_S$ process?

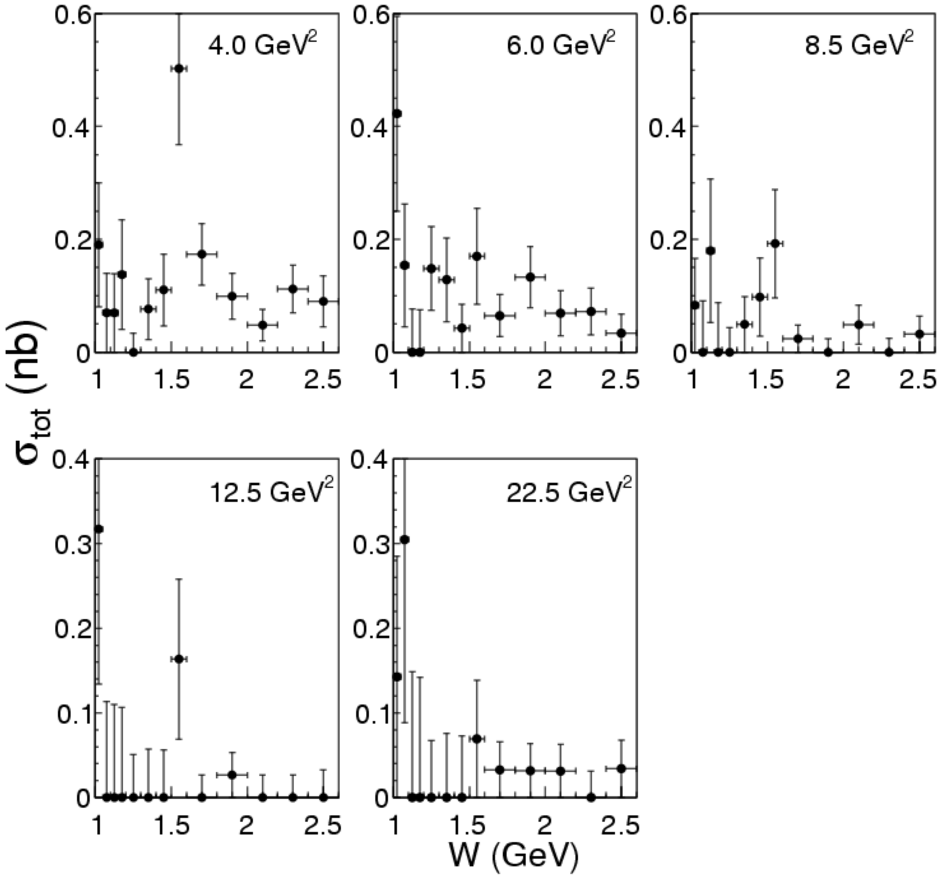


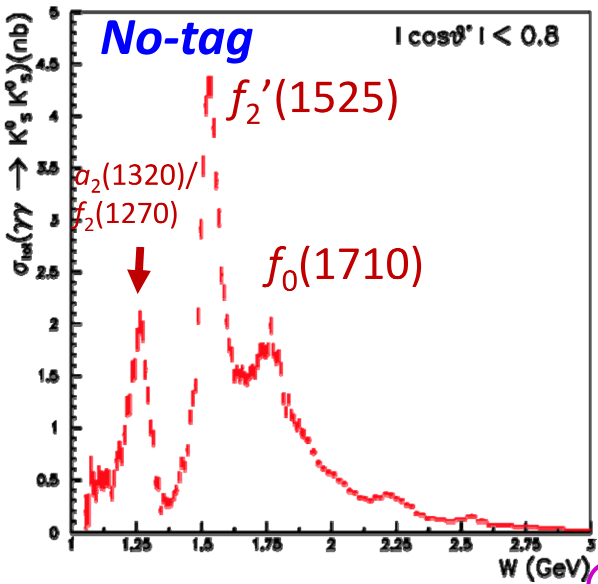
Single-tag

Threshold enhancement (including backgrounds)

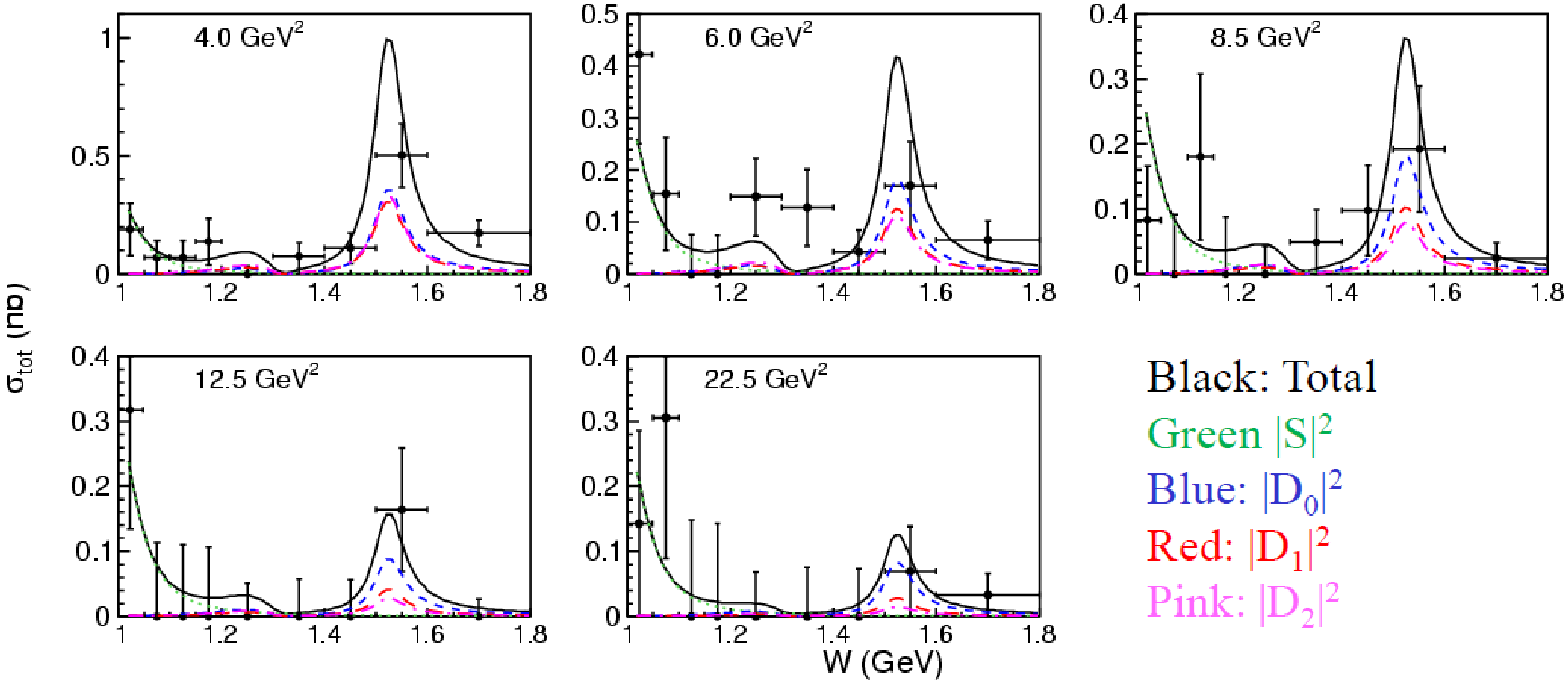
No $a_2(1320)/f_2(1270)$ seen

W-dependence for different Q^2 bins





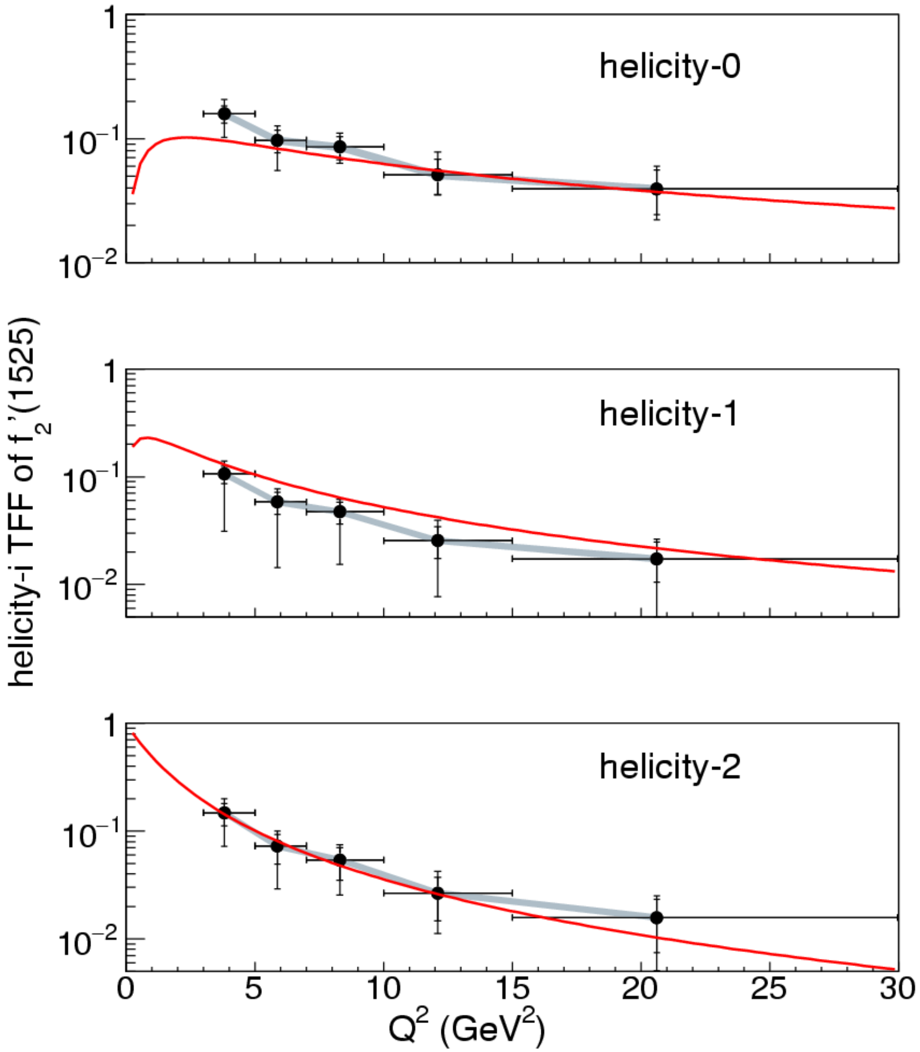
Fit results in W (Q^2) and angles



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).

$\gamma^*\gamma \to K^0_S K^0_S$: $f'_2(1525)$ TFF



Shaded areas; overall systematic

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

The Q^2 dependence of each helicity fraction is assumed as:

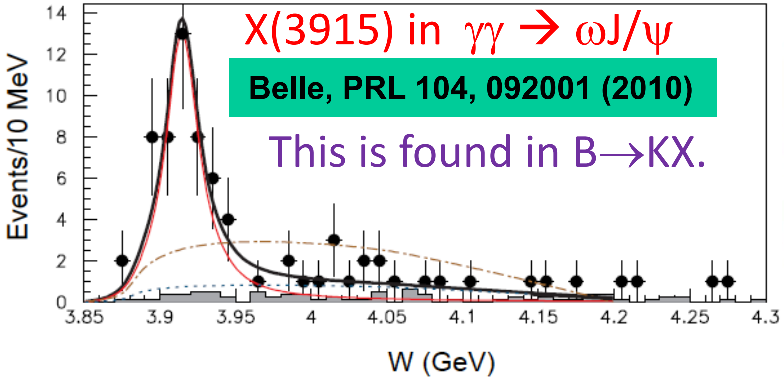
$$r_{0fp} : r_{1fp} : r_{2fp} = k_0 Q^2 : k_1 \sqrt{Q^2} : 1$$

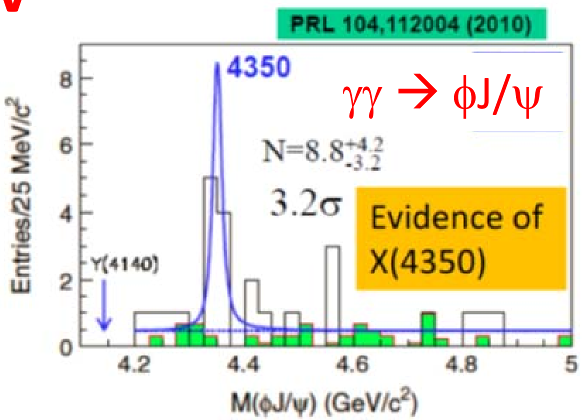
Fractions k_0 and k_1 are floated.

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

Search for the other or new states

New resonant peaks in $\gamma\gamma \to VV$





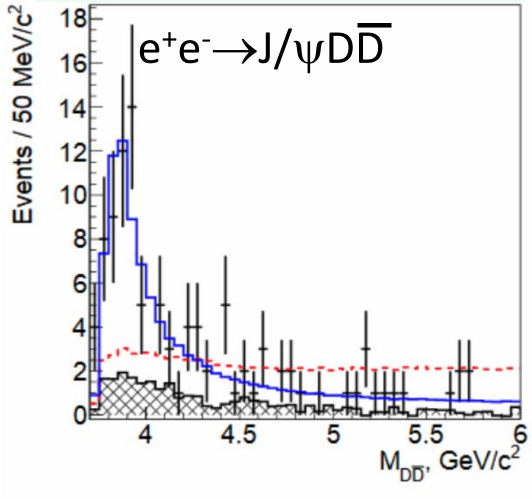
Candidates of exotic state

How about in PP? $\pi^0\eta_c$, $\eta\eta_c$ etc.

χ_{c0}(2P) , expected also to have a large coupling to $D\bar{D}$.

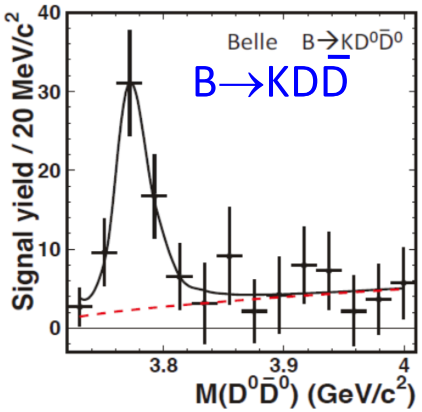
Double-charmonium production: χ_{c0}(2P) is at 3.8-3.9GeV and somewhat broad?

Belle, PRD 95, 112003 (2017)



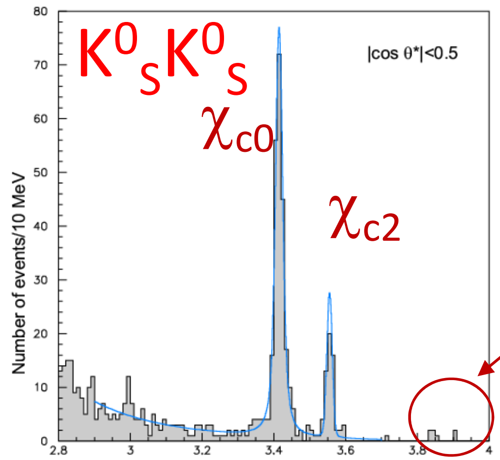
No signature in B decay

Belle, PRL 100, 092001 (2008)



Two-photon processes (No-tag):

PTEP 2013 123C01



Something be here ?
at 3.8 – 4.0GeV

High W, the luminosity frontier, 3-4 GeV region

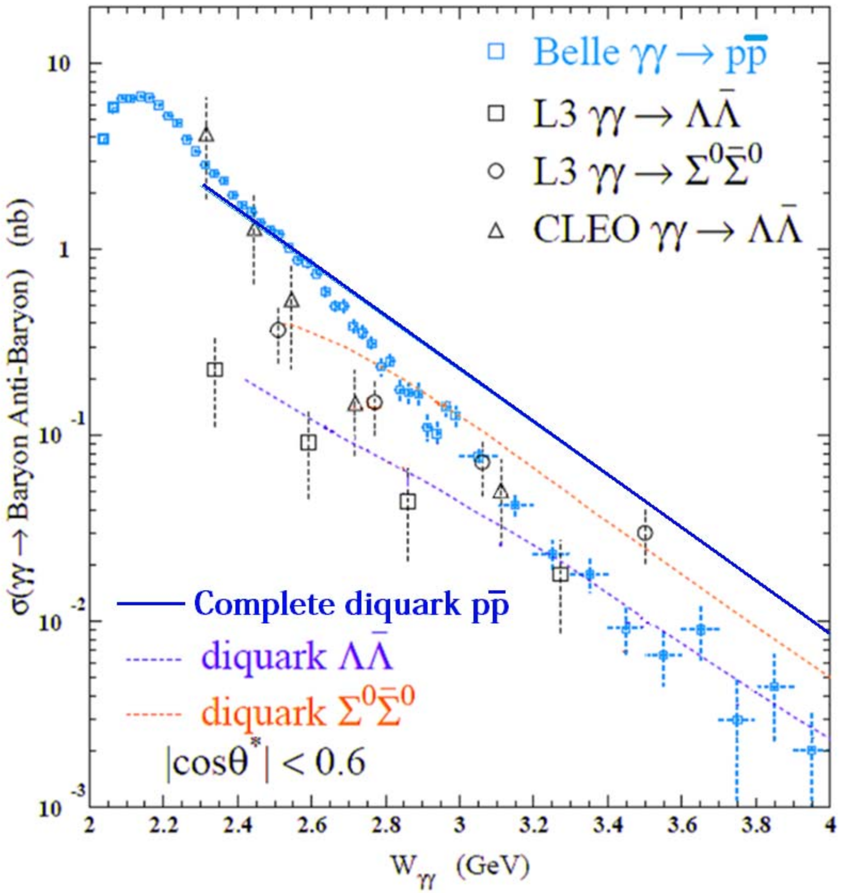
Baryon-pair production processes are statistically limited due to a large n for $\sigma \propto W^{-n}$

$\gamma\gamma \to p\bar{p}$

Belle, PLB 621, 41 (2005)

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

Might agree with a QCD prediction n= 10



Hyperon (Λ, Σ) pairs, Δ pairs etc.

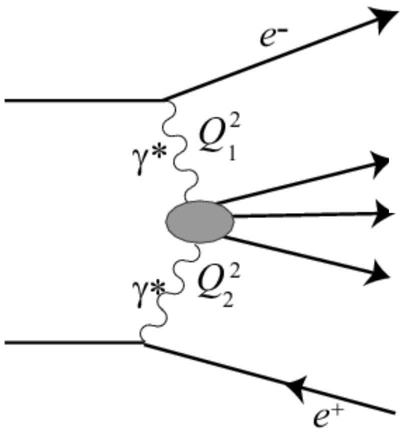
also should be interesting at Belle II

$\sigma(\Lambda\bar{\Lambda})$: $\sigma(\Sigma^0\bar{\Sigma}^0)$: $\sigma(p\bar{p}) \approx 1 : 1 : 1$ at high W !?

uds and uud

to solve possible diquark combinations.

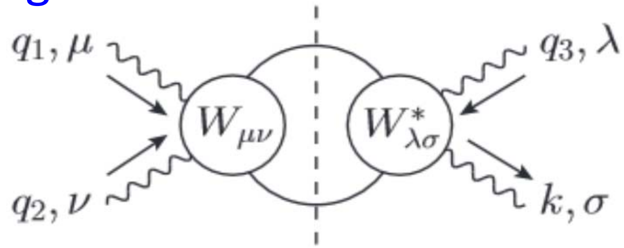
Double-tag processes



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

Hadrons

Validation test for theoretical calculation of Hadronic Light-by-Light contribution to muon g-2



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

Test of QCD by $\gamma^*\gamma^* \rightarrow \pi^0$

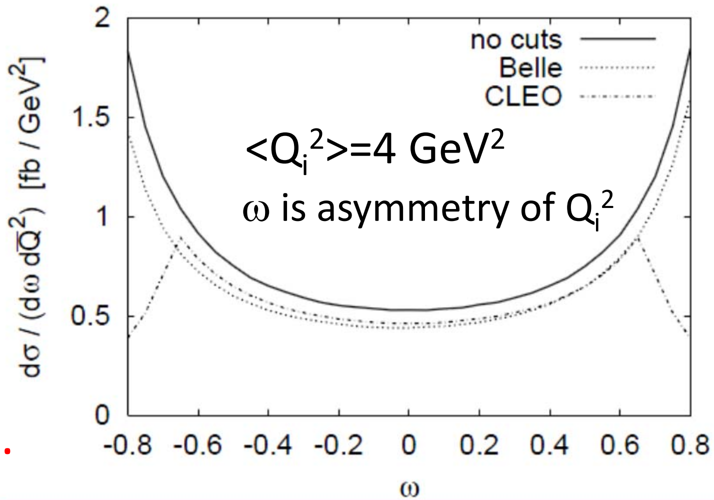
with $Q_1^2 \sim Q_2^2$

Dependence on Distribution Amplitude is small

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

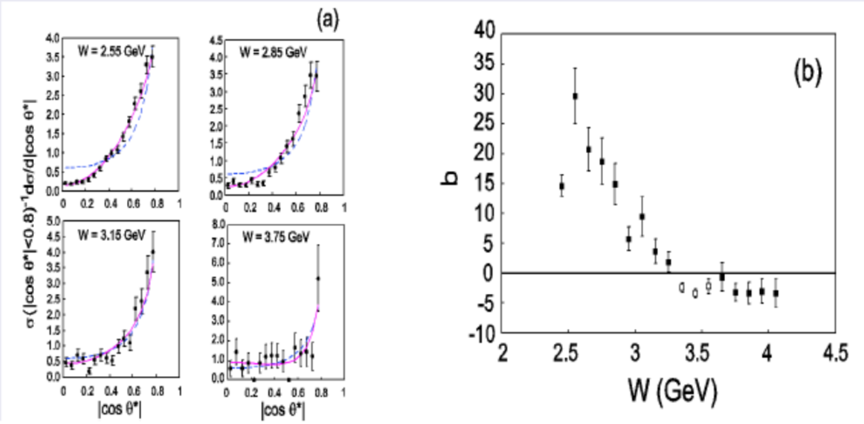
M. Diehl, et al., Eur. Phys. J. C 22, 439 (2001)

These measurements are feasible at Belle II.



Angular dependence

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



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

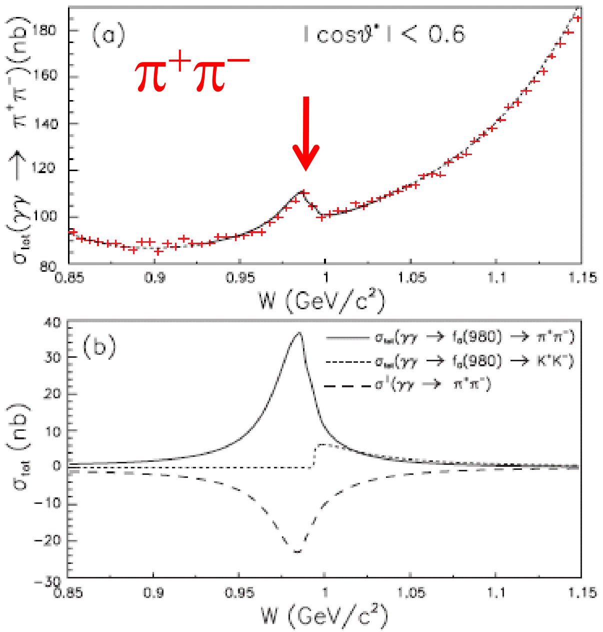
- Fit to $\sin^{-4}\theta^* + b\cos\theta^*$
- b becomes constant above 3.2 GeV.

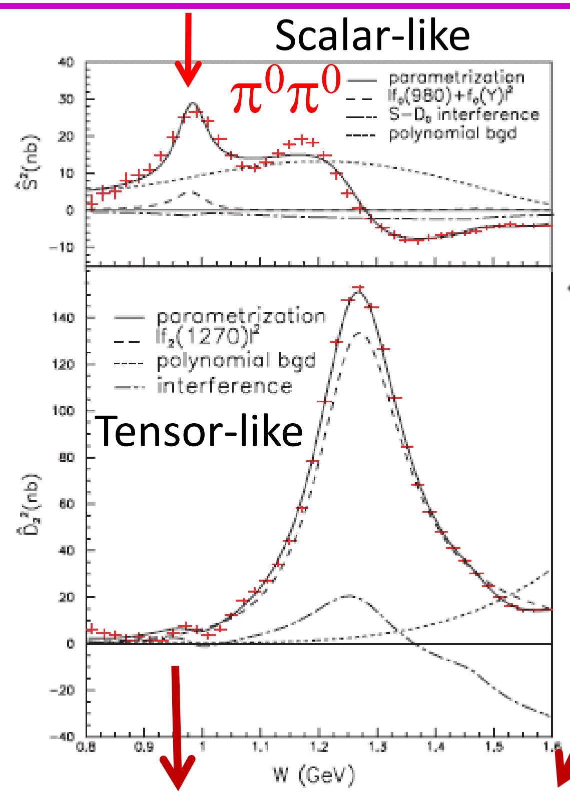
mode	α in $\sin^{-\alpha}\theta^*$	GeV	$\lvert\cos\theta^*\rvert$
$K_S K_S$	3 – 8	2.6 - 3.3	< 0.8
$\pi^+\pi^-$	Good agreement with 4	3.0 - 4.1	< 0.6
K^+K^-	Good agreement with 4	3.0 - 4.1	< 0.6
$\pi^0\pi^0$	Better agreement with $\sin^{-4}\theta^* + b\cos\theta^*$ Approaches $\sin^{-4}\theta^*$ above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

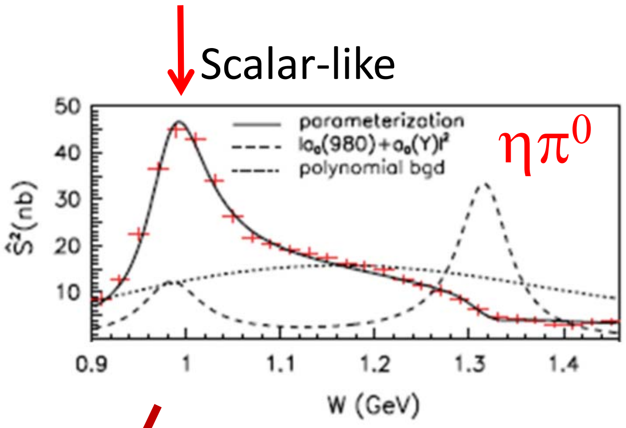
Exclude † χ_{cJ} region, 3.3 - 3.6 GeV

Summarized by H.Nakazawa Hadron2013

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 $f_0(980)$

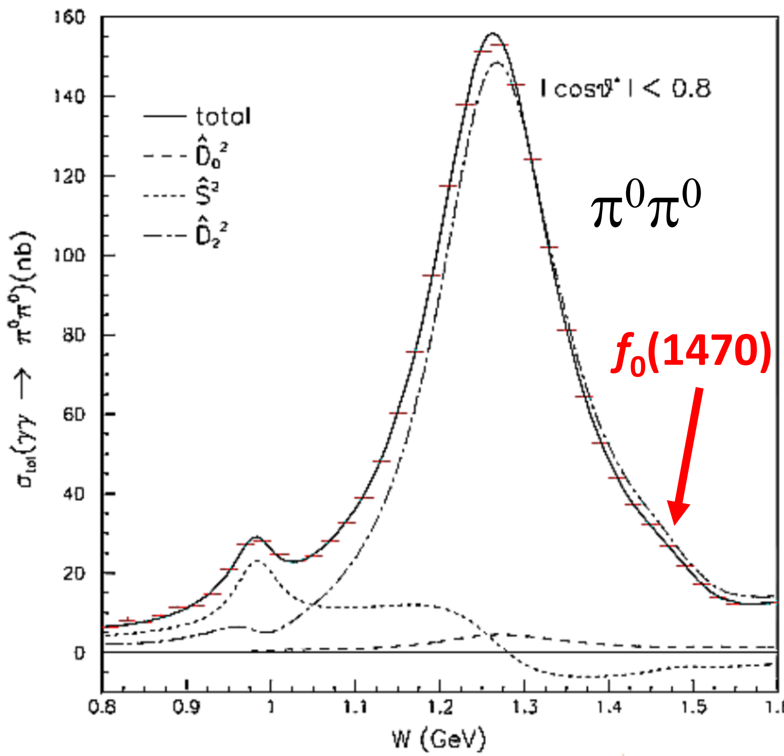
Model	$\Gamma_{\gamma\gamma}$ [eV]
uubar,*ddbar*	1300 – 1800
ssbar	300 – 500
KKbar molecule	200 – 600
Four-quark	270

Scalars in the 1.2 – 1.8 GeV region

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

  May be visible in the line shape.

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



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

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
...		
$\gamma\gamma$	seen	685
...		

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

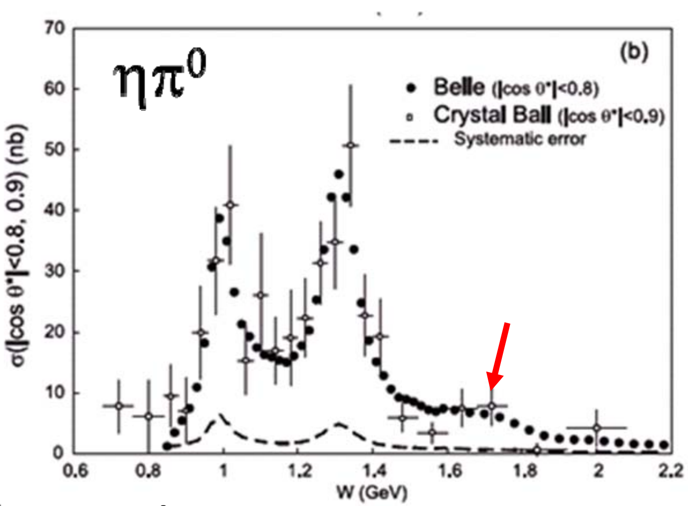
Mass $m = 1506 \pm 6$ MeV (S = 1.4)
Full width $\Gamma = 112 \pm 9$ MeV

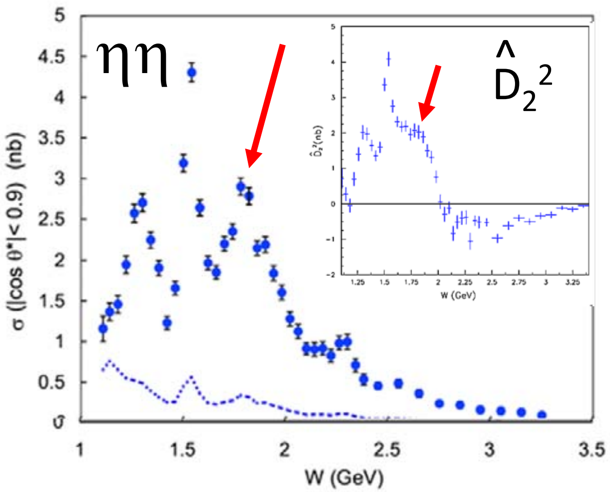
$f_0(1500)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor	p (MeV/c)
$\pi\pi$	(34.5±2.2) %	1.2	741
...			
$\gamma\gamma$	not seen		753

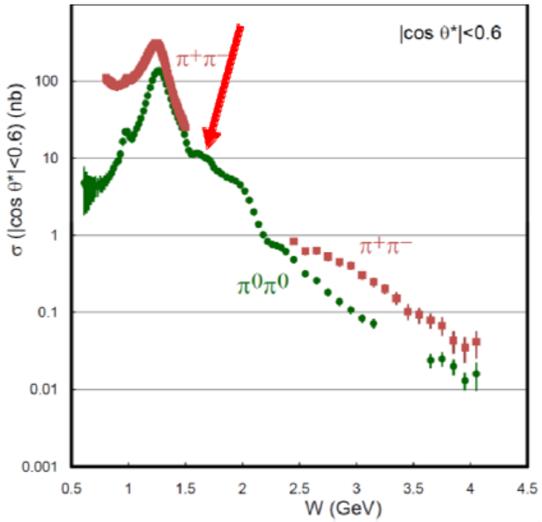
PDG2019 puts the opposite favor.

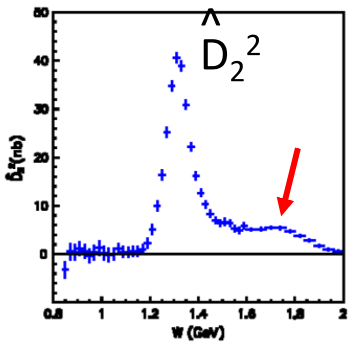
Parameter	Belle ($\pi^0\pi^0$)	Crystal Ball	Unit
Mass	1470^{+6+72}_{-7-255}	1250	MeV/c^2
Γ_{tot}	90^{+2+50}_{-1-22}	268 ± 70	MeV
$\Gamma_{\gamma\gamma}\mathcal{B}(\pi^0\pi^0)$	11^{+4+603}_{-2-7}	430 ± 80	eV

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) → $\rho^0\pi^0$ → $\pi^+\pi^-\pi^0$ is confirmed by previous two-photon measurements.
- a_2(1700) → $\eta\pi^0$ seen in our data, but no definite parameters obtained.
- f_2(1810)→ $\eta\eta$ 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.

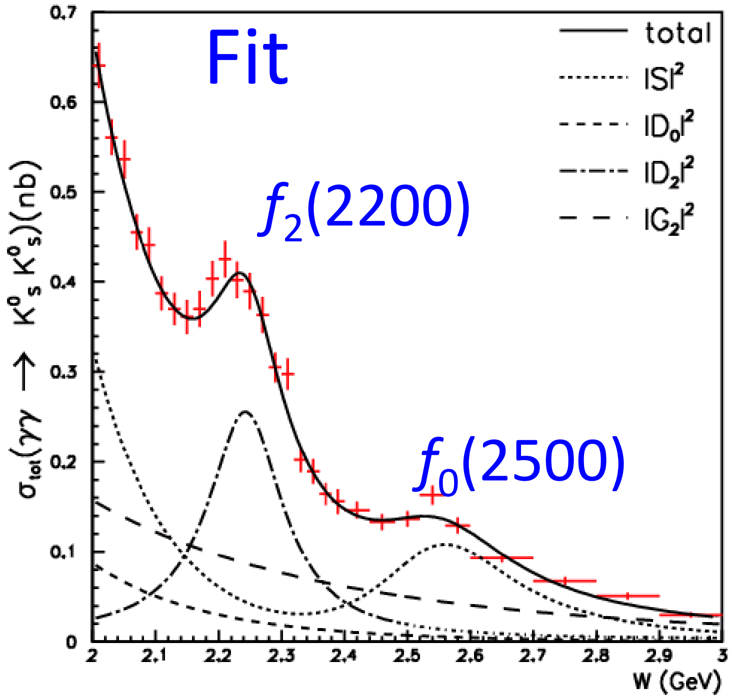
Fit Results for resonances in $K^0_S K^0_S$

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

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

Significances

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

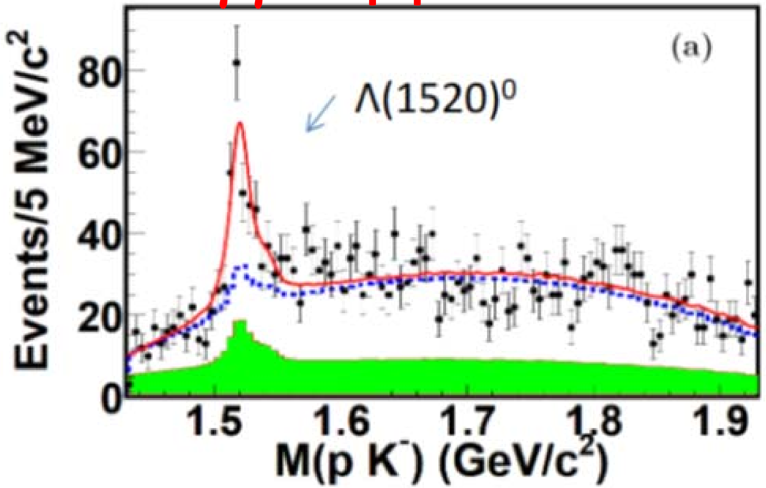


- There can be an only wide state around 2240 MeV.
- Narrow appearances in previous measurements may be due to an interference effect and/or statistical fluctuation.
- A high-mass state at 2.5 GeV may be the heaviest light-quark scalar meson so far found.

Search for exotic baryons (Pentaquarks)

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

PRD 93, 112017(2016)

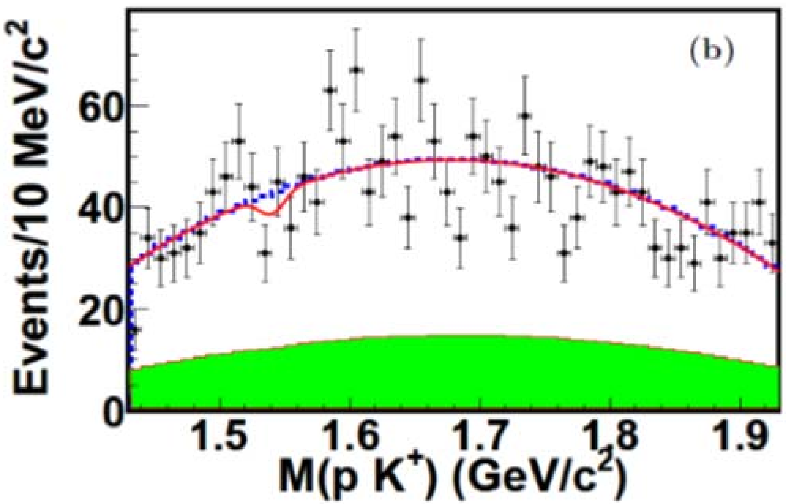


Simultaneous fit: $\Lambda(1520)^0$ and $\Theta(1540)^0$ signal are included.

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