Two-photon Physics at Belle

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Belle Collaboration

PacificSpin2019, Miyazaki,
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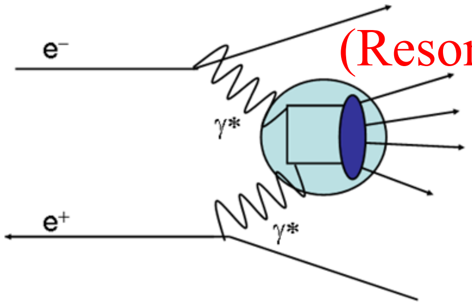
Two-photon Physics at e^+e^- collider



Hadronic system with Q = 0 , **C = +,**

Real two-photon collisions:

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

(With **virtual photon collisions, J^P=1$^+$** is possible.)

Determination of J^P by partial wave analysis (PWA)

Resonance formation:

$\Gamma\gamma\gamma$**:** proportional to the production cross section of the resonance

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

Decay properties

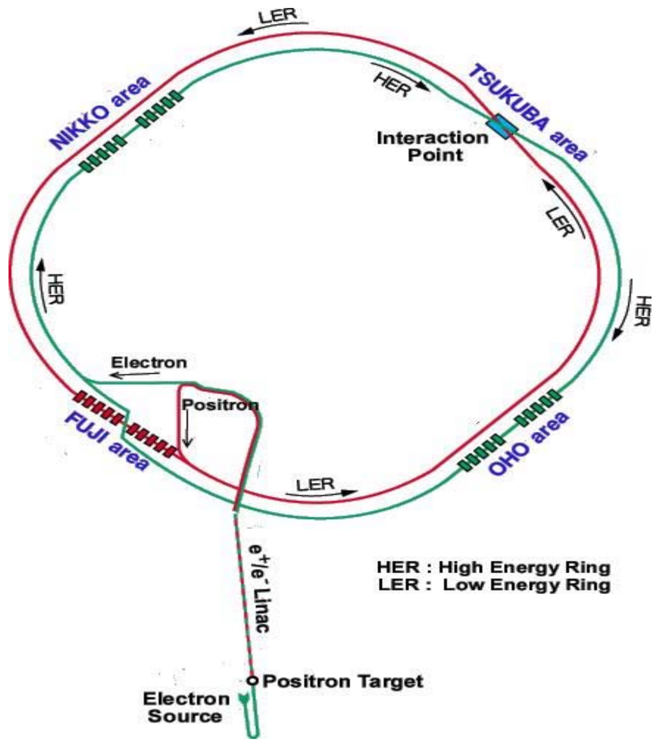
New resonances

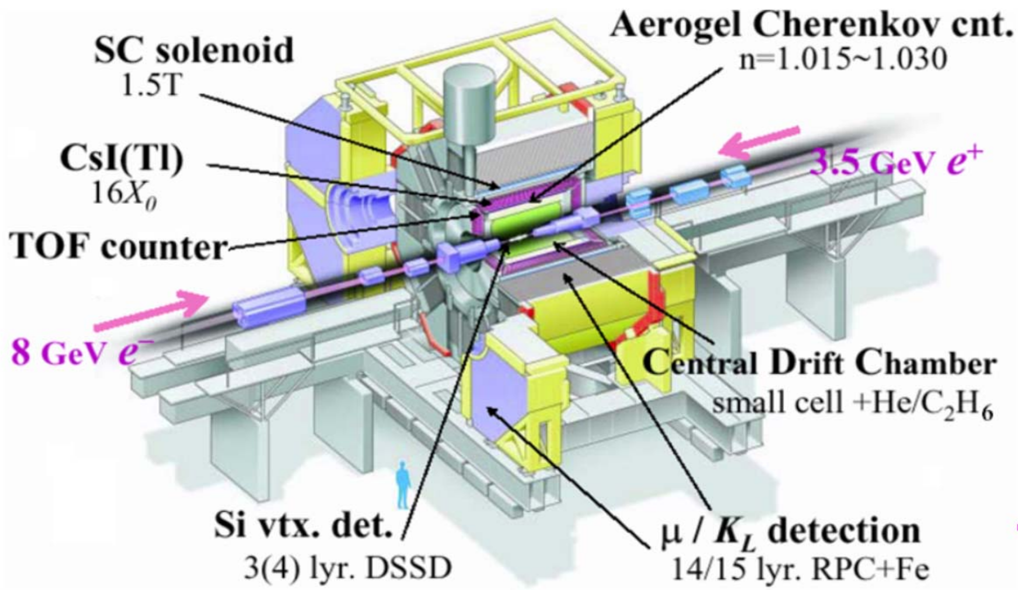
Test of QCD, Form factors

Use of **highly virtual photon γ*** is precious.

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
  - $L_{max}=2.1 \times 10^{34}\ cm^{-2}s^{-1}$
  - $\int Ldt \sim 1040\ fb^{-1}$ (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 results 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
$\phi J/\psi$	4.2-5.0	825	PRL 104, 112004	2010
$\omega J/\psi$	3.9-4.2	694	PRL 104, 092001	2010
$\omega\omega/\phi\phi/\omega\phi$	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, $f_0(980)$, $f_2(1270)$, $f_2'(1525)$

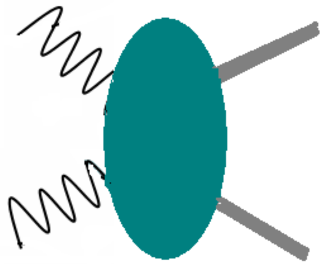
Summarized by M.Masuda

QCD test with meson-pair production

at the high-energy region

Meson-pair production and QCD

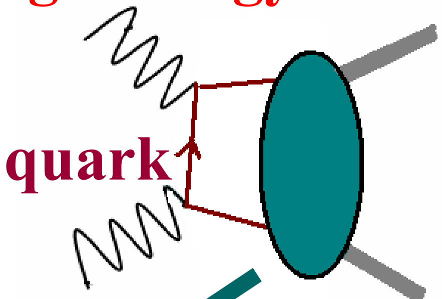
Low energy



Meson

Meson

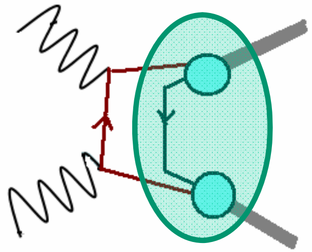
High energy



Meson

Meson

High energy



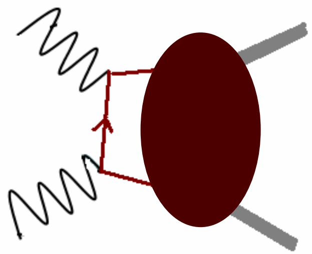
Brodsky and Lepage

Perturbative QCD approach

for exclusive meson production

Works with refined form factors

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



Kroll, Diehl and Vogt

Handbag model

with soft hadron exchange

Predict

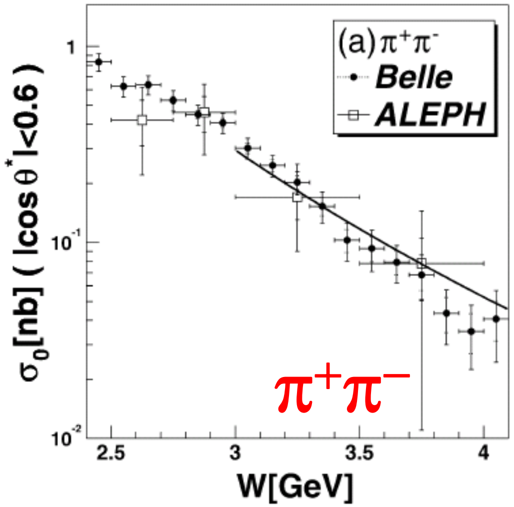
Meson scattering-angle distribution,
Energy -dependence
Cross section ratios under SU(3) sym.

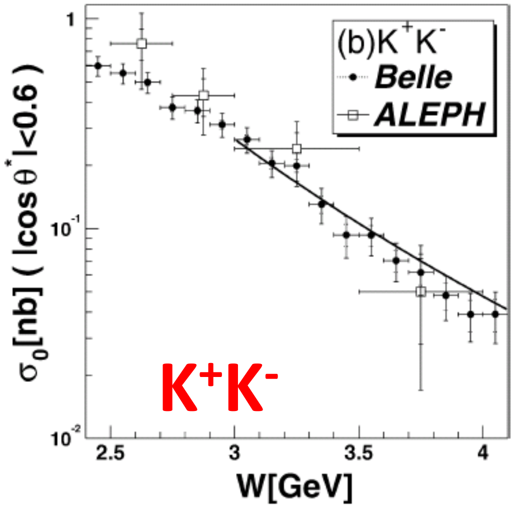
M.Diehl, P.Kroll, and C. Vogt, PLB 532, 99 (2002)
M.Diehl, P.Kroll, PLB 683, 165 (2010)

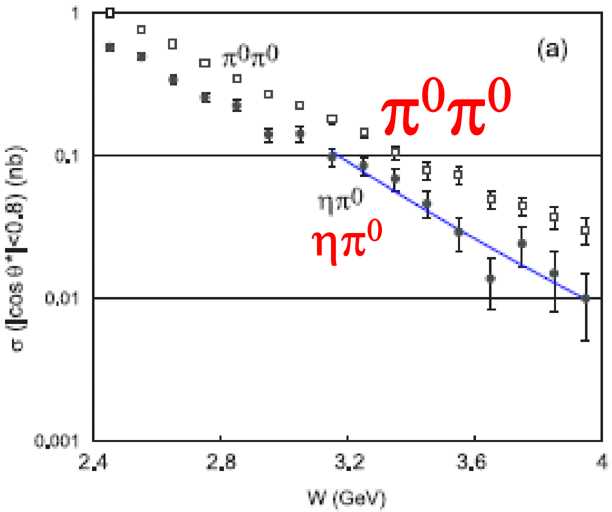
W-dependences at high energies

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

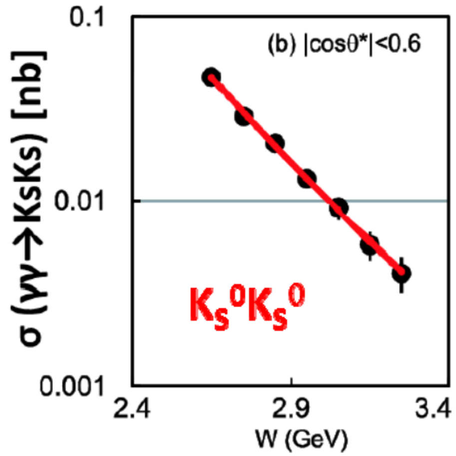
$\sigma(W) \sim W^{-n}$ **expected**

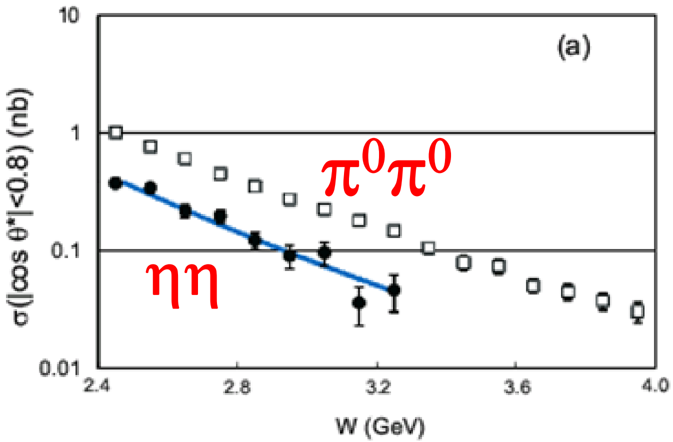






Fitted slope parameter **n**, e.g. for 2.5 – 4 GeV, are different among the reactions.





Charmonium contributions are removed

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	$0.36R_f^2(0.62R_f^2)$‡		

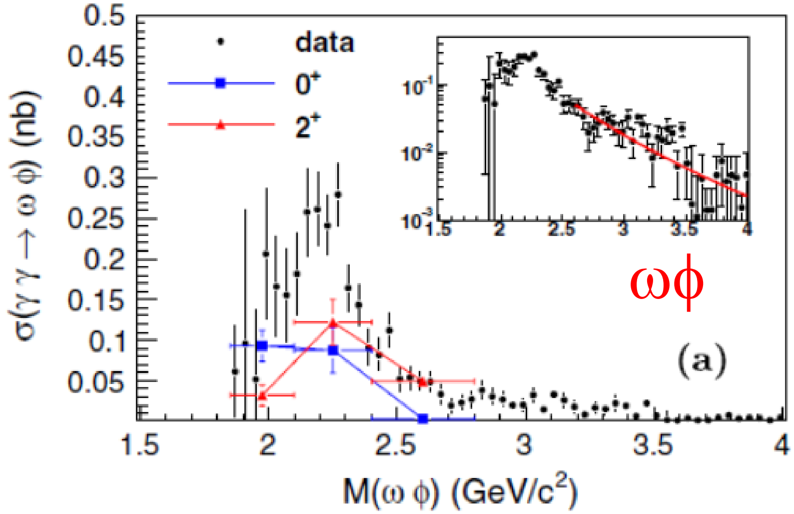
† Exclude χ_{cJ} region, 3.3 - 3.6 GeV.
‡ Assuming η is a member of SU(3) octet (superposition of octet and singlet with mixing angle of $\theta_p = -18°$).
R_f is a ratio of decay constants, $f_\eta^2/f_{\pi^0}^2$.

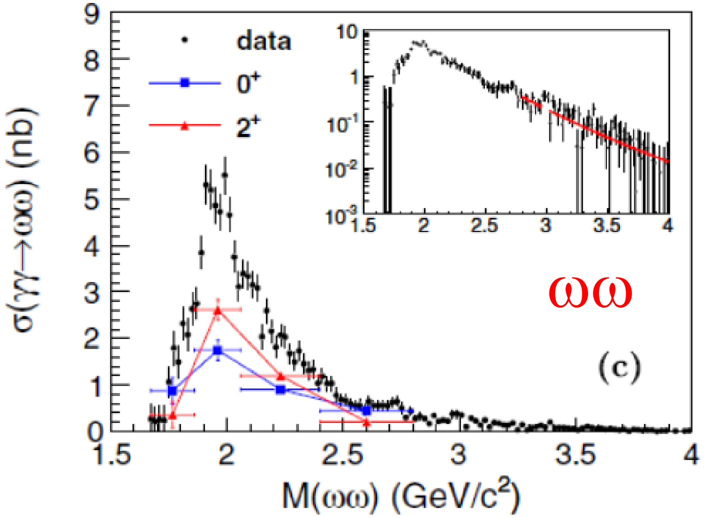
- n ranges 7 to 11. Close or not far from QCD prediction of 6 and 10.

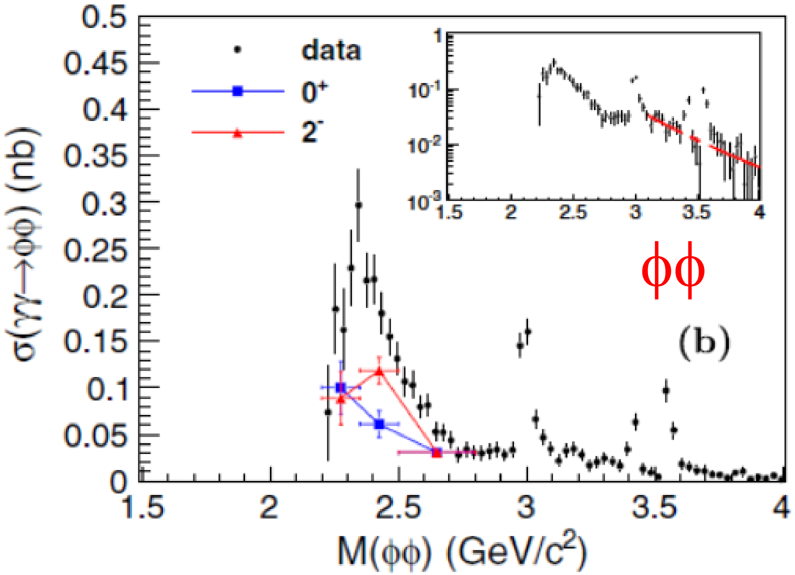
Summarized by H.Nakazawa and S.Uehara

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

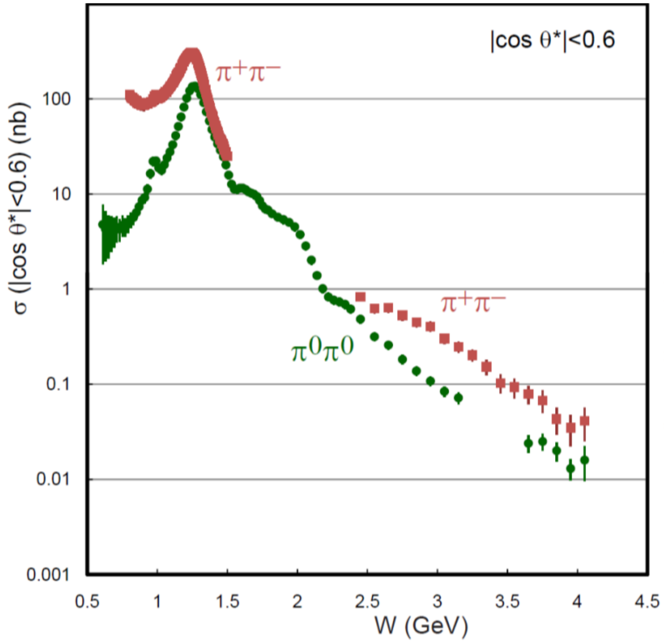
Light-meson spectroscopy

Scalar mesons in 0.9 - 2.0 GeV/c^2

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

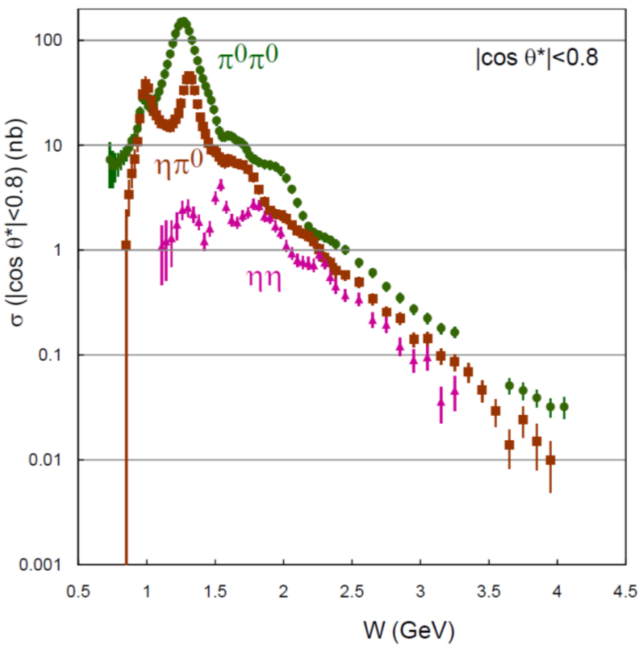
W<~2.5GeV: Dominated by resonance formation

Charged vs. Neutral $\pi\pi$

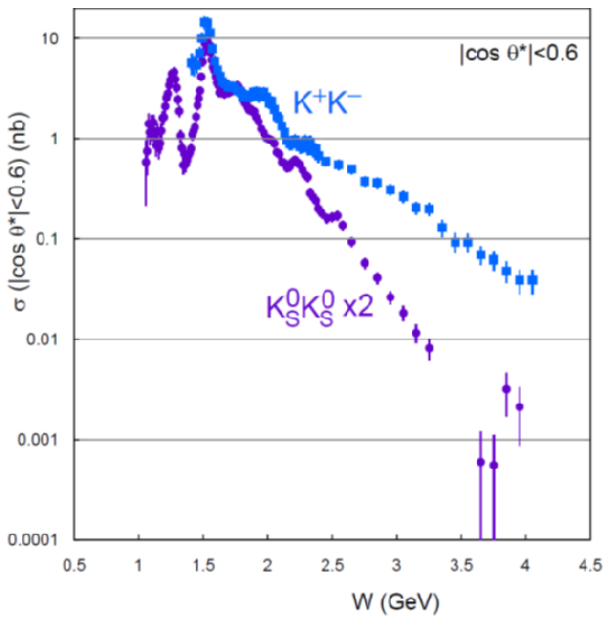


Three neutral-pair processes

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



Charged vs. Neutral KK

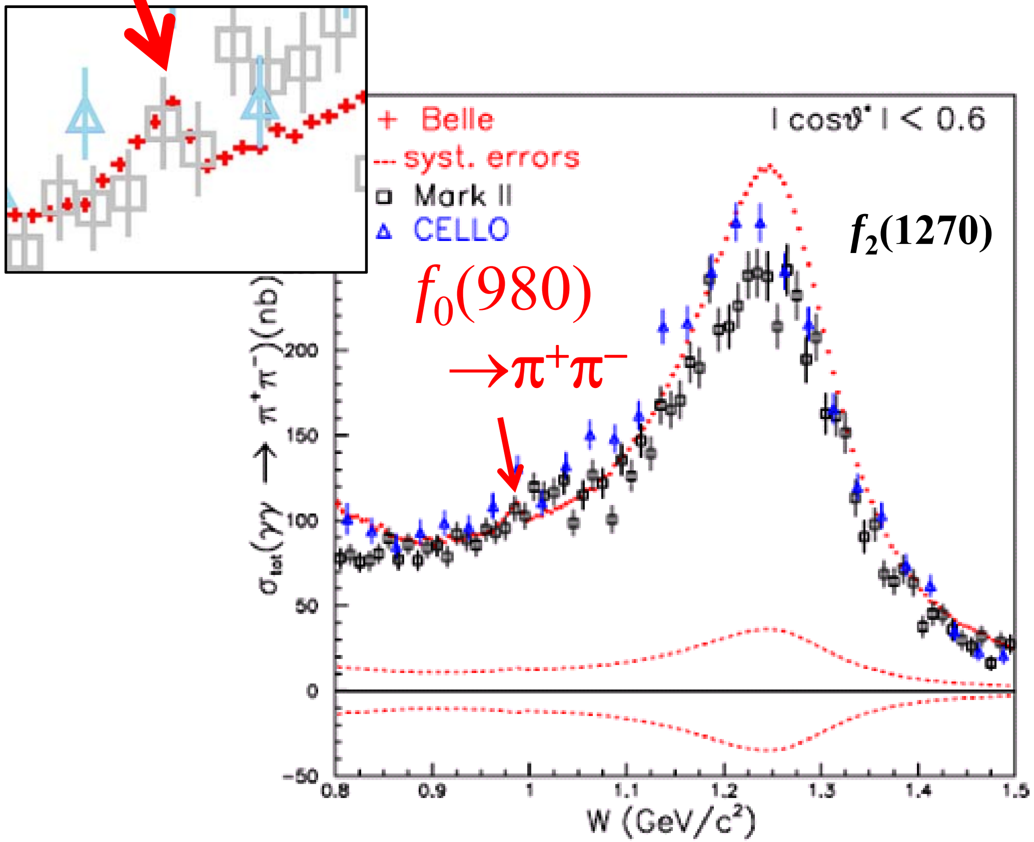


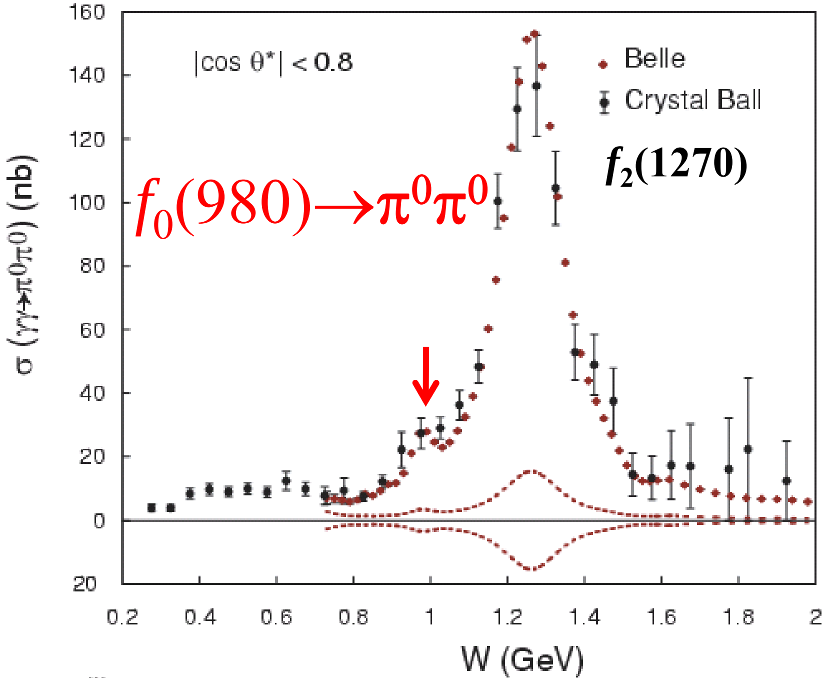
Horizontal axis:

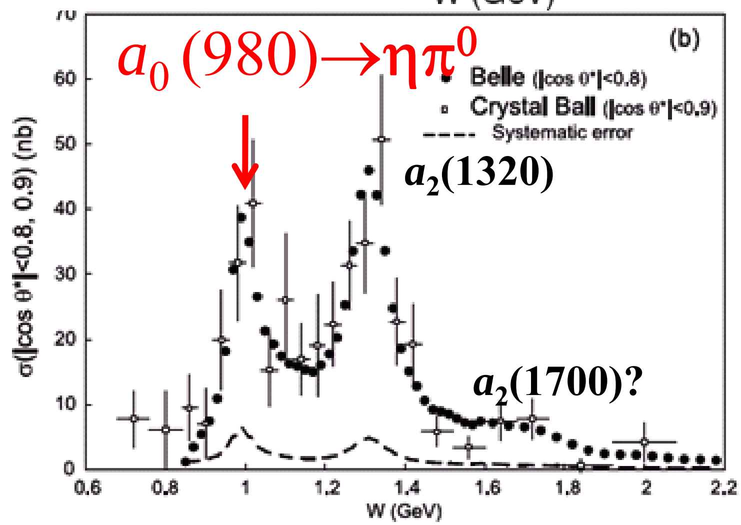
W -- $\gamma\gamma$ c.m. energy = invariant mass of the two-meson system

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

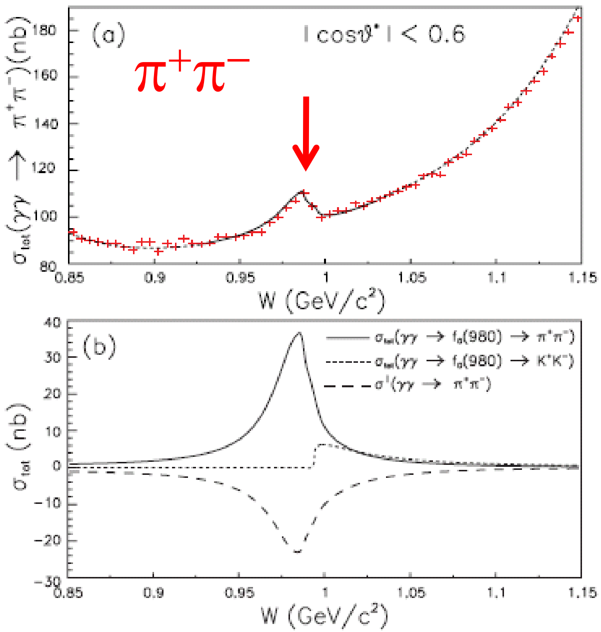
f_0(980) and a_0(980) :
Observed as a peak, very clearly in two-photon production, for the first time.

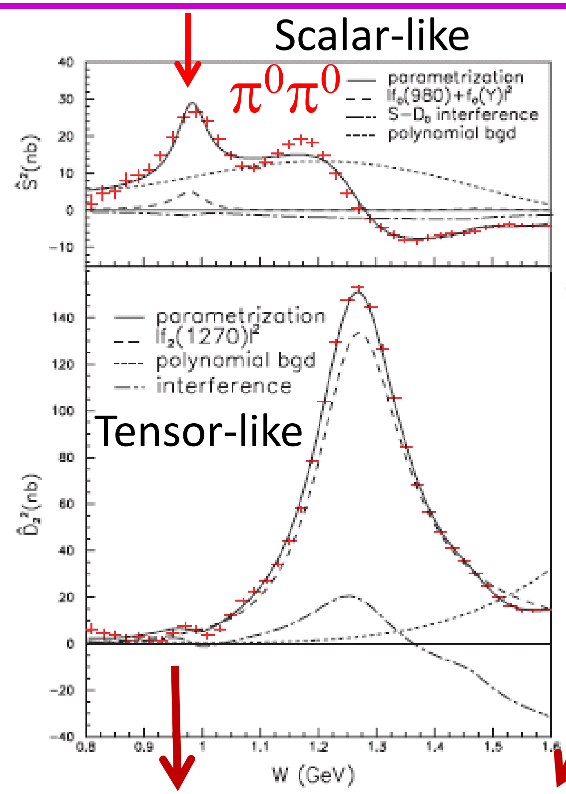


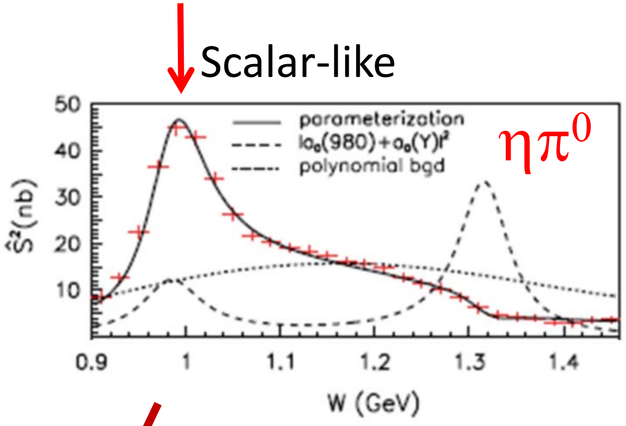




Two-photon decay width of $f_0(980)$ and $a_0(980)$







Meson	$f_0(980)$	$f_0(980)$	$a_0(980)$
M[MeV/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

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 $f_0(1100\text{-}1400) \to \pi\pi$ almost concealed by the huge $f_2(1270)$.
- Belle's $\pi^0\pi^0$ measurement reports $f_0(1470)$.

May be visible in the line shape.

$\rightarrow$ favorable to the narrow $\boldsymbol{f_0(1500)}$, but also consistent with $f_0(1370)$.

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

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

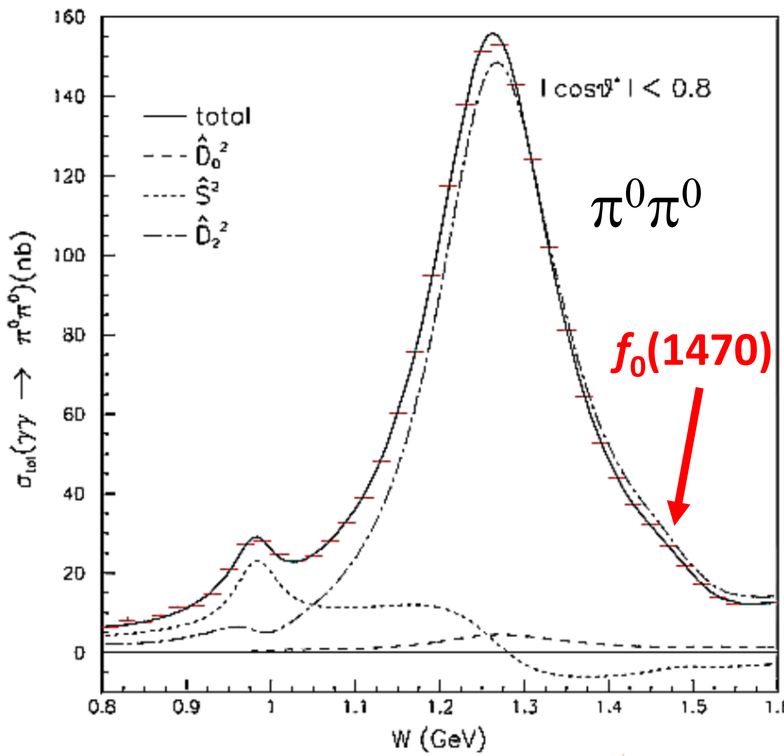
$f_0(1370)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\pi\pi$	seen	672
...		
$\gamma\gamma$	seen	685
...		

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

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

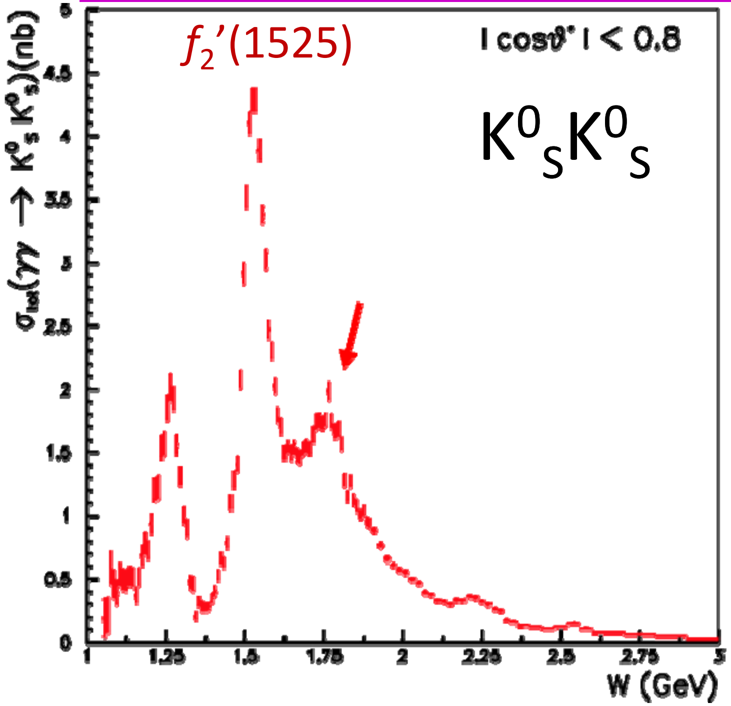
$f_0(1500)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor	p (MeV/c)
$\pi\pi$	(34.5±2.2) %	1.2	741
...			
$\gamma\gamma$	not seen		753

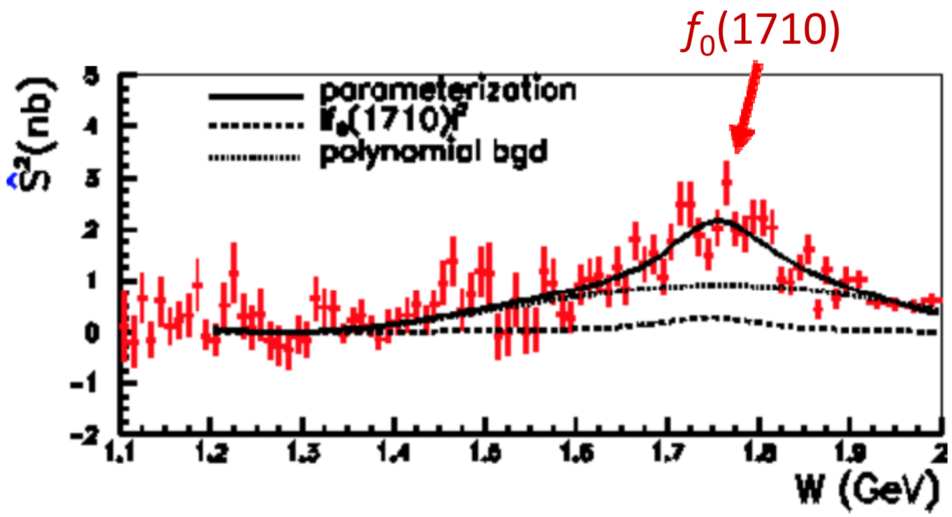
PDG2019 puts the opposite favor.



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

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





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

Parameter	Scalar hypothesis fit				Tensor fit	
$f_J(1710)$	fit-H	fit-L	H,L combined	PDG	fit-H	fit-L
χ^2/ndf	694.2/585	701.6/585	Two solutions of interference		796.3/585	831.5/585
Mass(f_J) (MeV/c^2)	1750^{+5+29}_{-6-18}	1749^{+5+31}_{-6-42}	1750^{+6+29}_{-7-18}	1720 ± 6	1750^{+6}_{-7}	1729^{+6}_{-7}
$\Gamma_{tot}(f_J)$ (MeV)	138^{+12+96}_{-11-50}	145^{+11+31}_{-10-54}	139^{+11+96}_{-12-50}	135 ± 6	132^{+12}_{-11}	150 ± 10
$\Gamma_{\gamma\gamma}\mathcal{B}(K\bar{K})_{f_J}$ (eV)	12^{+3+227}_{-2-8}	21^{+6+38}_{-4-26}	12^{+3+227}_{-2-8}	unknown	$2.1^{+0.5}_{-0.3}$	1.6 ± 0.2

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

Single-tag measurements of Scalar and Tensor meson TFFs

TFF: transition form factor

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

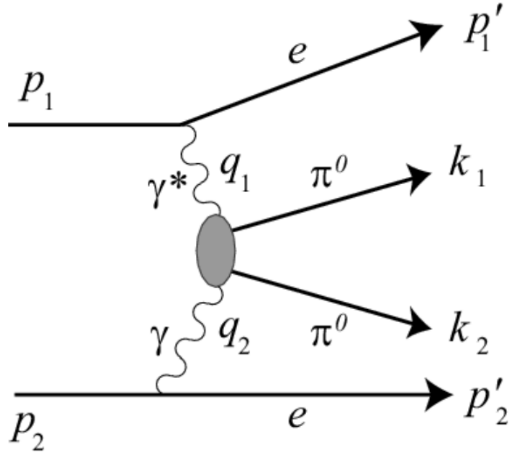
PRD 93, 032003 (2016)

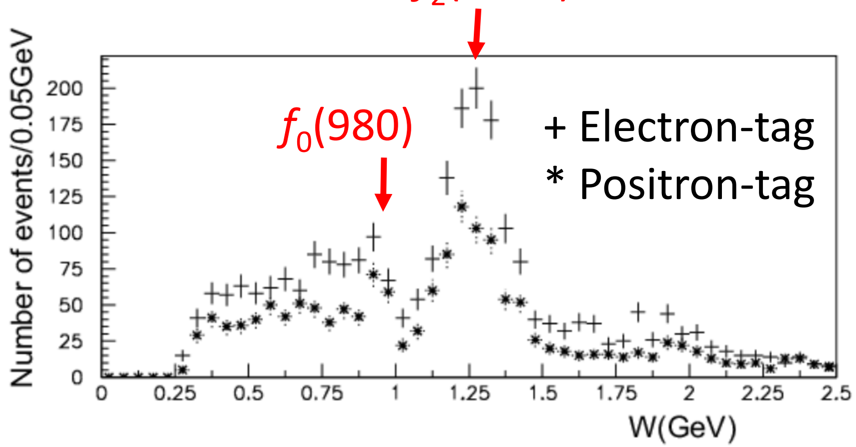
Physics motivations:

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

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

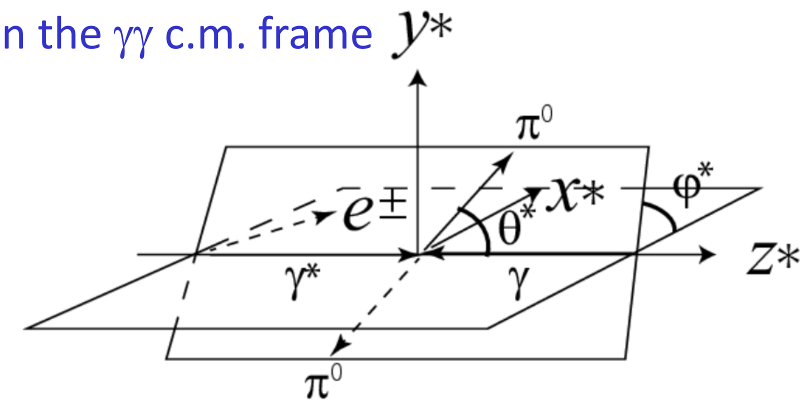
- Hadronic Light-by-Light contribution to g-2$|_\mu$
  for validation check of theoretical calculations





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

Definition of the scattering angles in the $\gamma\gamma$ c.m. frame



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.,

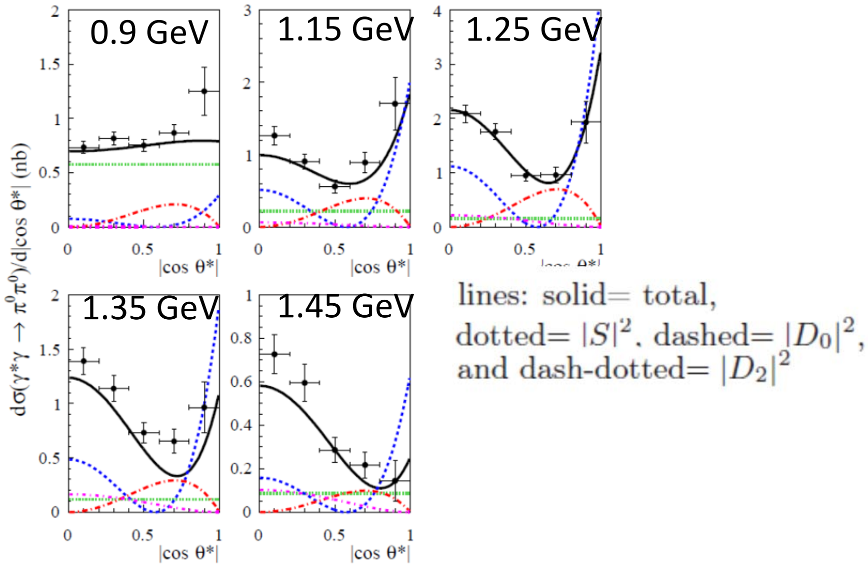
$M_{++} = S + D_0$,
$S = B_S(W) + A_{f0}(W)$
$D_0 = 4\pi\, [B_{D0}(W) + A_{f2}(W)\sqrt{r_{20}}]\; Y_2^0$
etc.

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

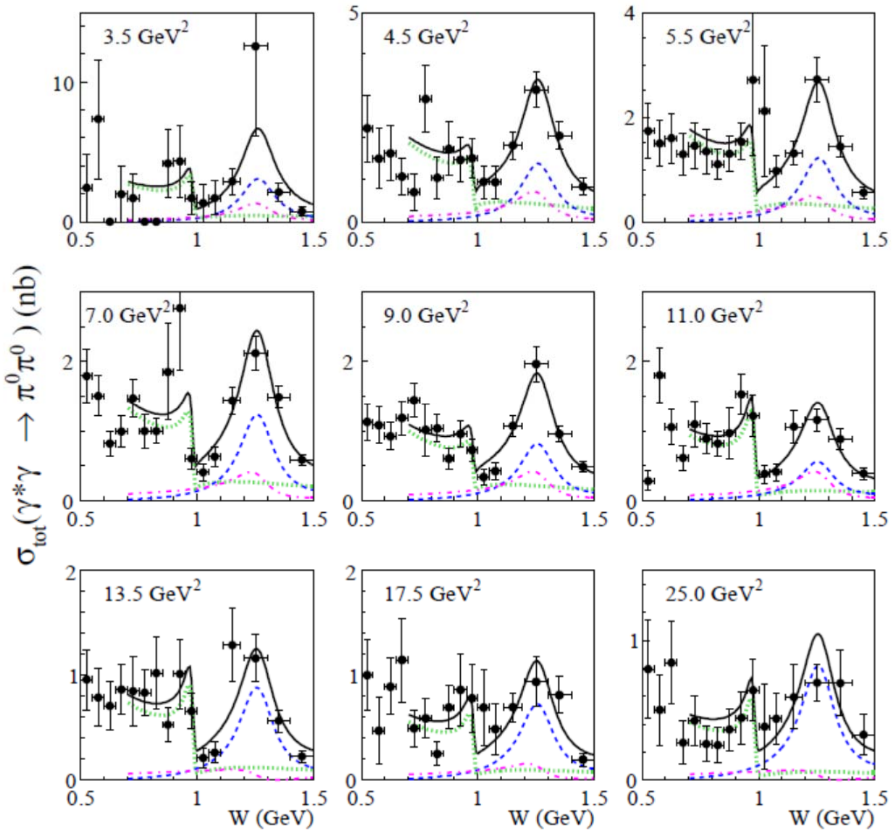
++, +-, 0+ --- Helicity state of the incident photons
S, D_0 etc. -- Partial-wave amplitude in $\pi^0\pi^0$ scattering
B, A_f -- Background and f-resonance components.
ε_0, ε_1 --- A spin-dependent flux factor ratio for the virtual-photons

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

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



W dependence for different Q^2 bins

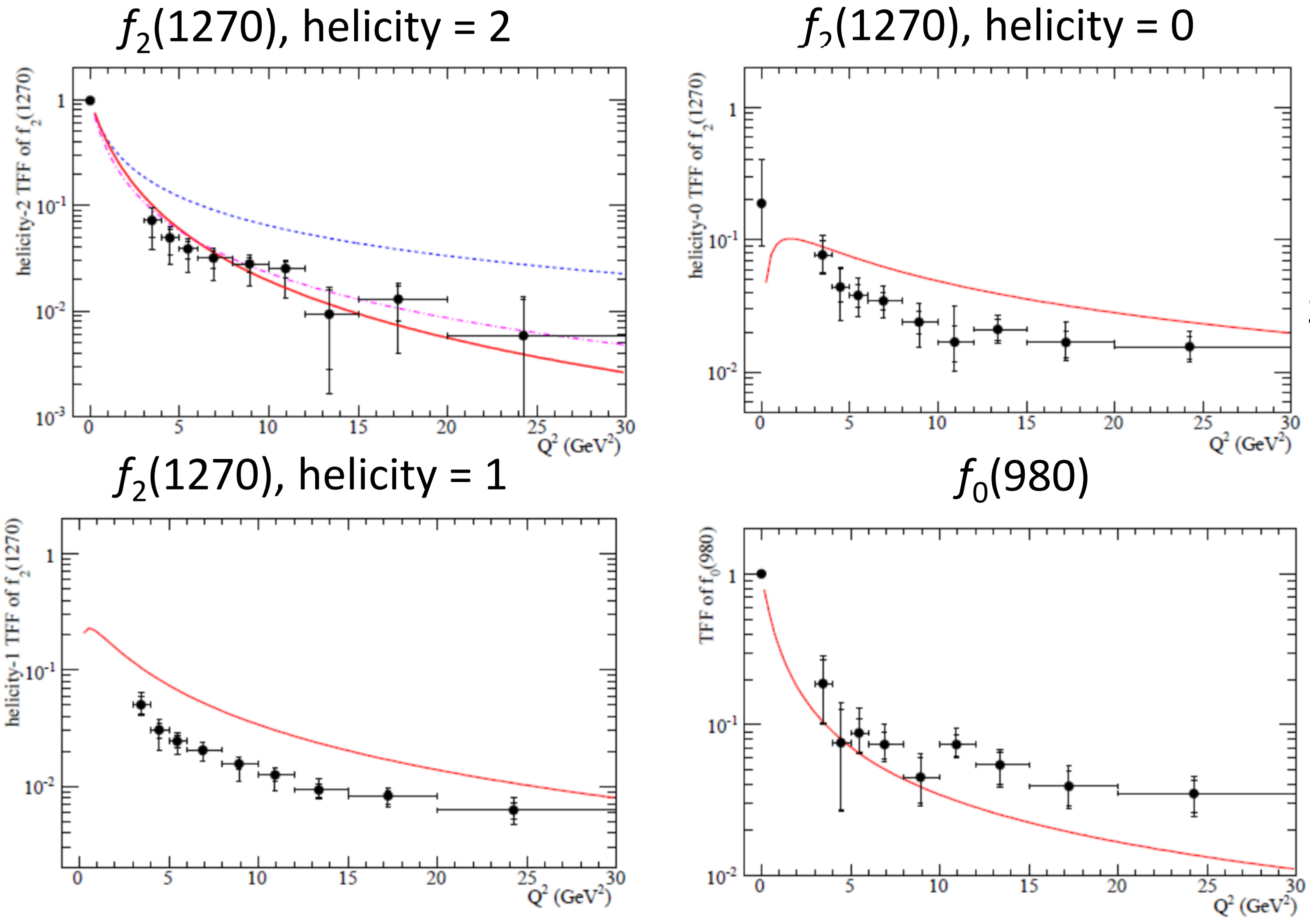


The curves are PWA fit constructed by parameterized resonant (f_0(980) and f_2(1270)) and continuum amplitudes.

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

Q^2 dependence of the TFFs

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



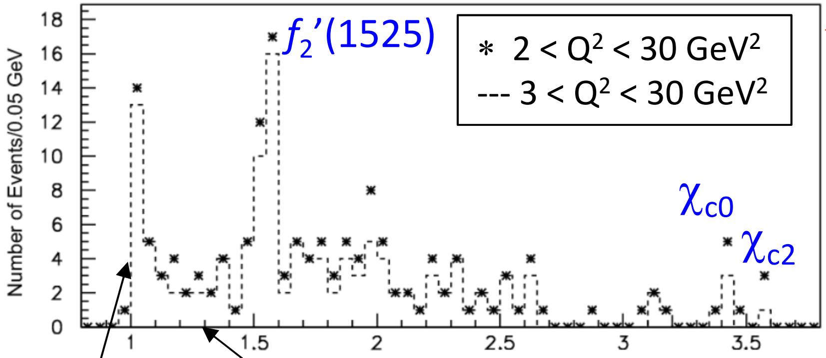
Shorter error bars : Statistical

Longer error bars : Statistical and systematic

Theoretical predictions:

- (solid red line) Schuler, Berends, van Gulik, a heavy quark approx. NPB 523, 423 (1998)
- (dotted blue line) Pascalutes, Pauk, Vanderhaeghen, saturated sum rule, PRD 85, 116001 (2012), η's
- (dashed red line) ibid., axial-vector mesons

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



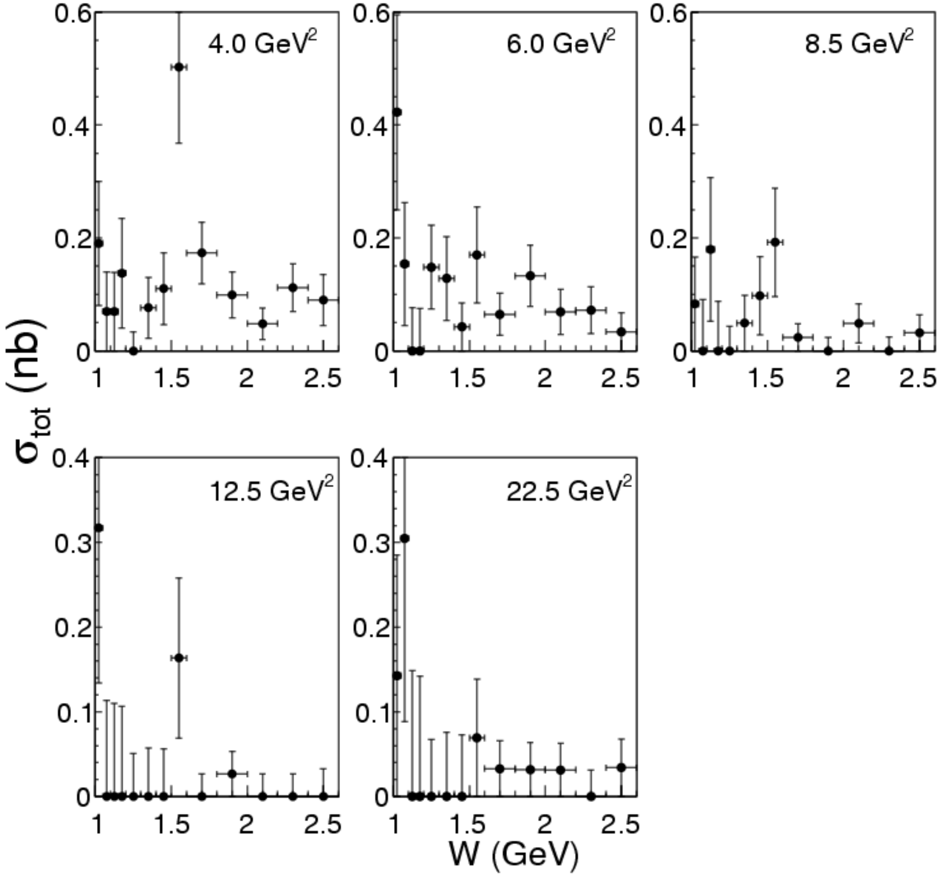
121 events W(GeV) **10 events**

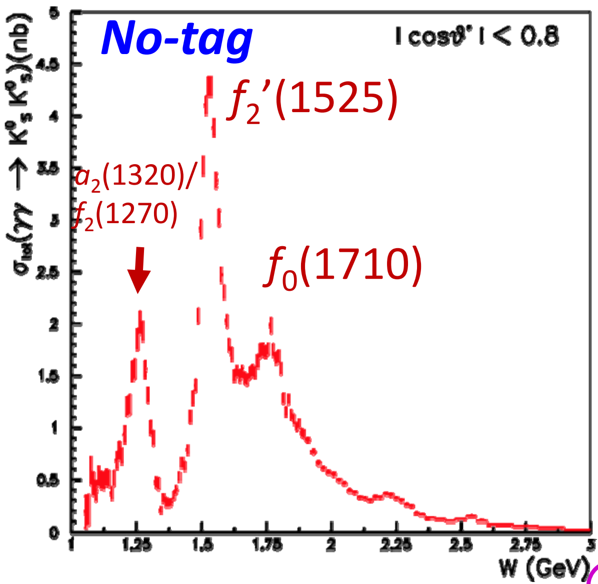
Threshold enhancement (including backgrounds)

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

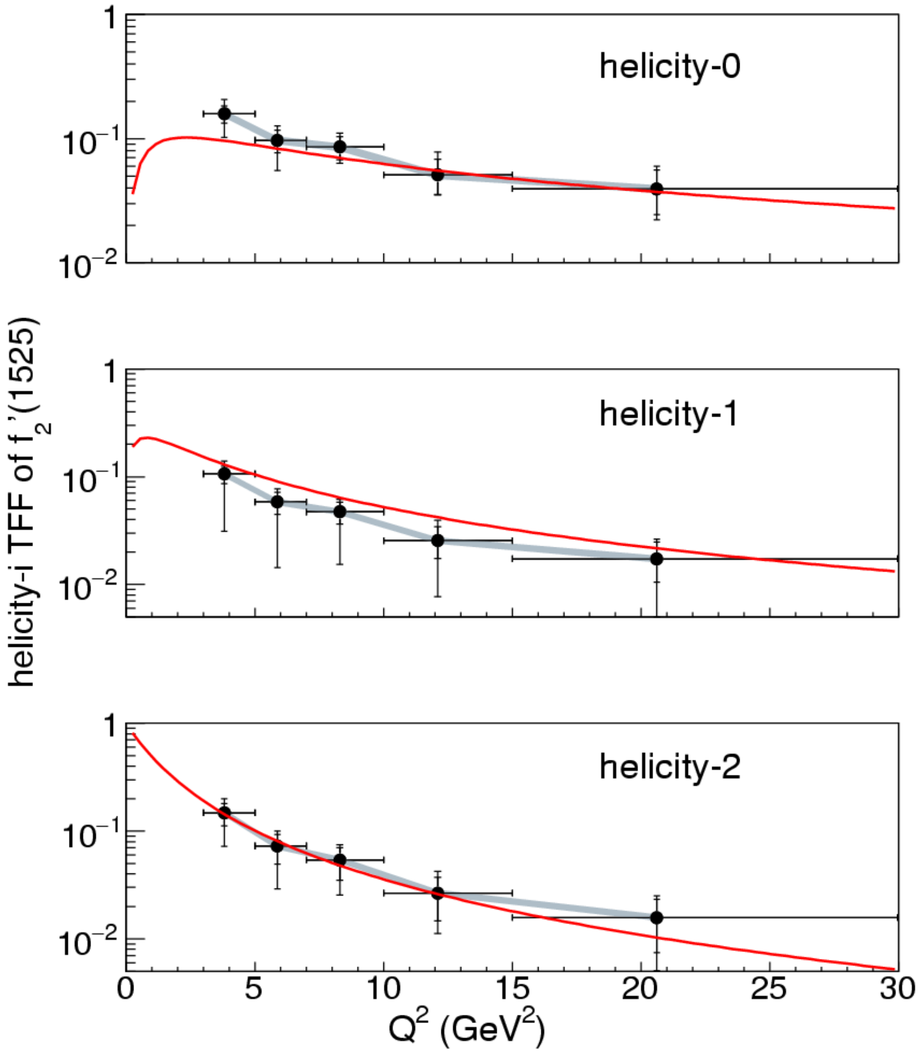
Single-tag

W-dependence for different Q^2 bins





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

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

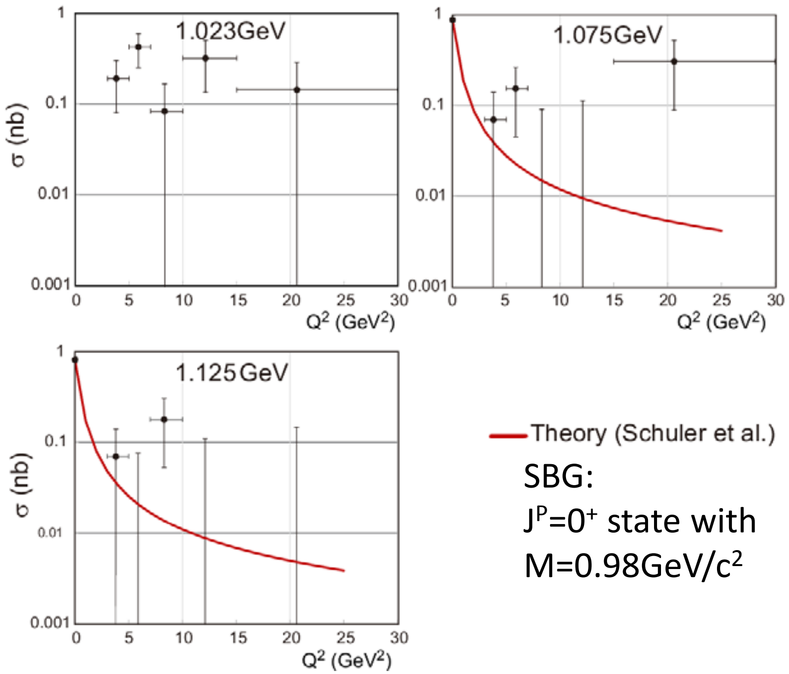
Fractions k_0 and k_1 are floated.

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

Threshold Enhancement, χ_{c0}, and χ_{c2}

The threshold enhancement exists at 0.99 -1.05GeV.

Q^2 dependence for the three lowest W bins

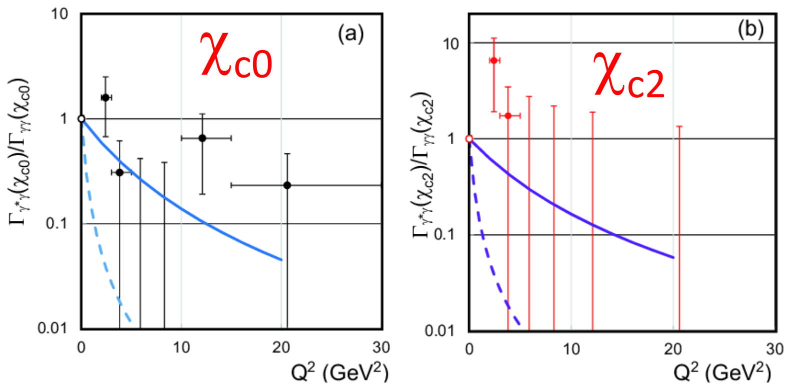


SBG:
$J^P=0^+$ state with $M=0.98\text{GeV}/c^2$

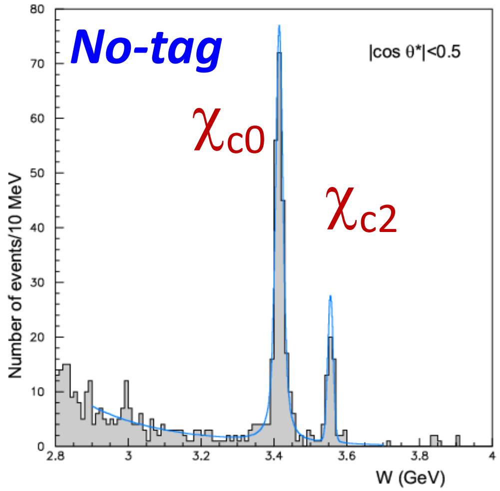
- Not inconsistent with SBG.
- The limited statistics currently preclude a conclusive interpretation.

Assuming that all the events near the χ_{c0} (χ_{c2}) mass are purely from the charmonium decays.

Backgrounds are estimated <1 event in total.



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



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

Physics at luminosity frontier
Belle to Belle II

1999-2010 2018-

with x50 larger statistics

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

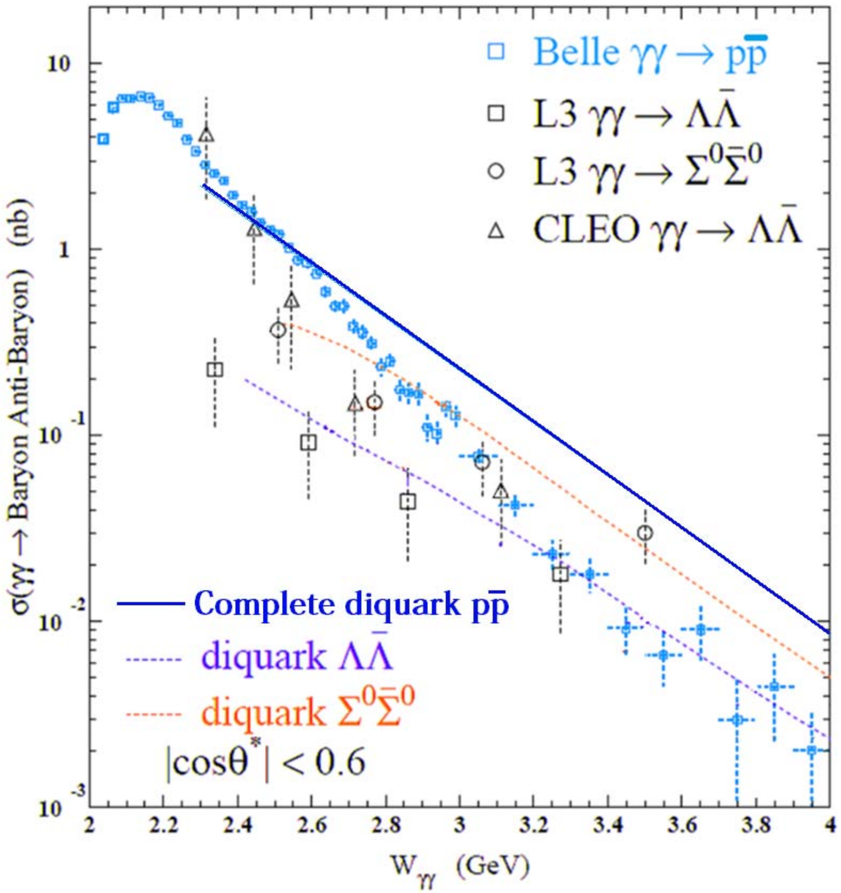
Baryon-pair production processes are statistically limited due to a large n for $\sigma \propto W^{-n}$

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

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.

Charmonium(-like) states

χ_{c2}(2P) is discovered by Belle, but so far seen in $\gamma\gamma \rightarrow D\bar{D}$ only.

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

Search for $\chi_{c2}(2P) \rightarrow D\bar{D}^*$

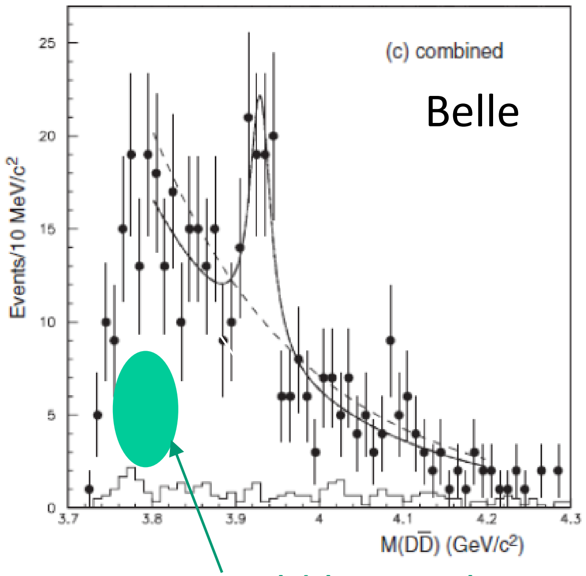
another important decay mode

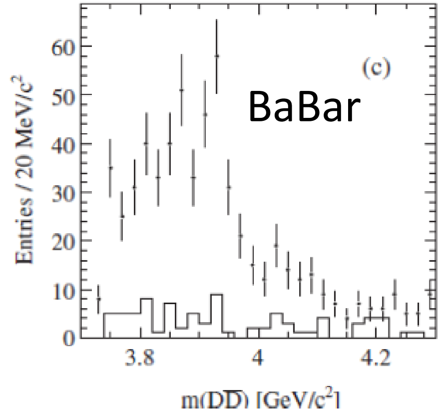
Difficulty: Low-p_t soft π detection

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

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

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





$M(D\bar{D}) \approx M(D\bar{D}^*) - 0.14\ \mathrm{GeV}/c^2$

D-meson pair with the **the different charges →**

an identification of $D\bar{D}^*$ even without tagging the soft pion

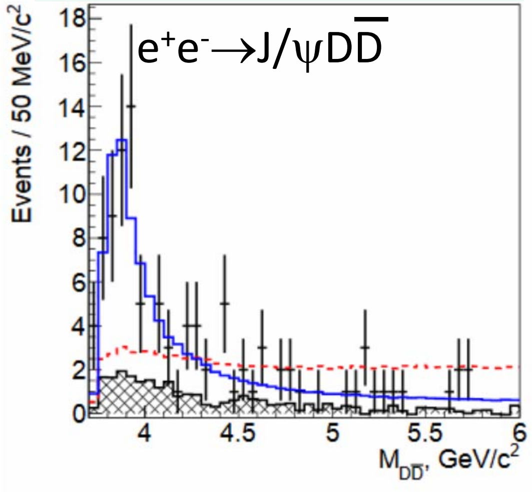
Possible with ~5 ab^{-1} data.

Search for the other or new states

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

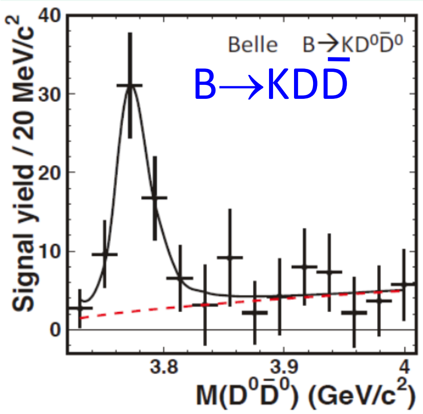
Double-charmonium production: χ_{c0}(2P) is at 3.8-3.9GeV and somewhat broad?

Belle, PRD 95, 112003 (2017)



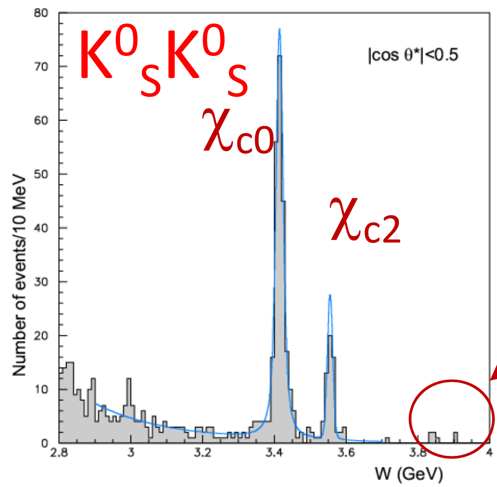
No signature in B decay

Belle, PRL 100, 092001 (2008)



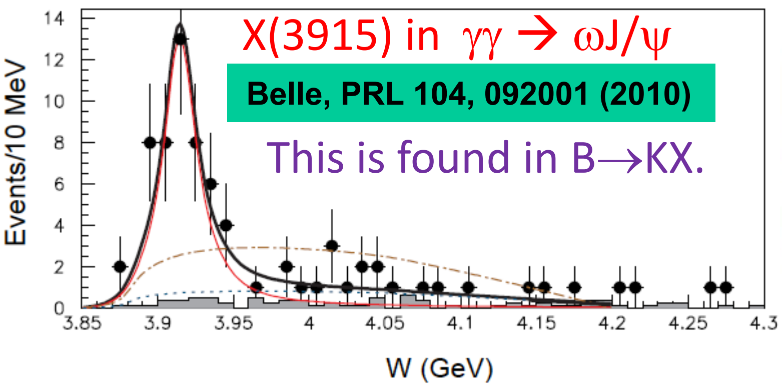
Two-photon processes:

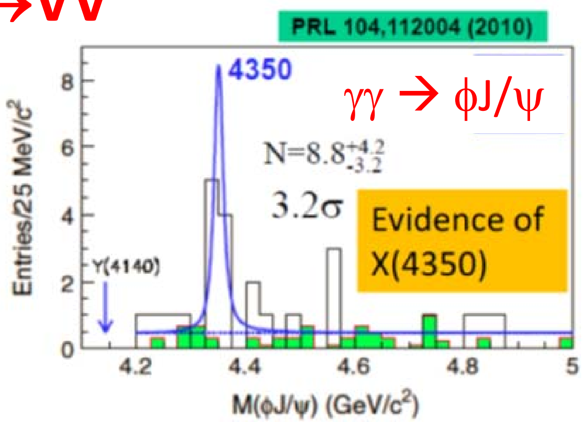
Elimination of χ_{c2}(2P) → $D\bar{D}^*$ is needed.



Something be here ?
at 3.8 – 4.0GeV

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





Candidates of exotic state

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

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.

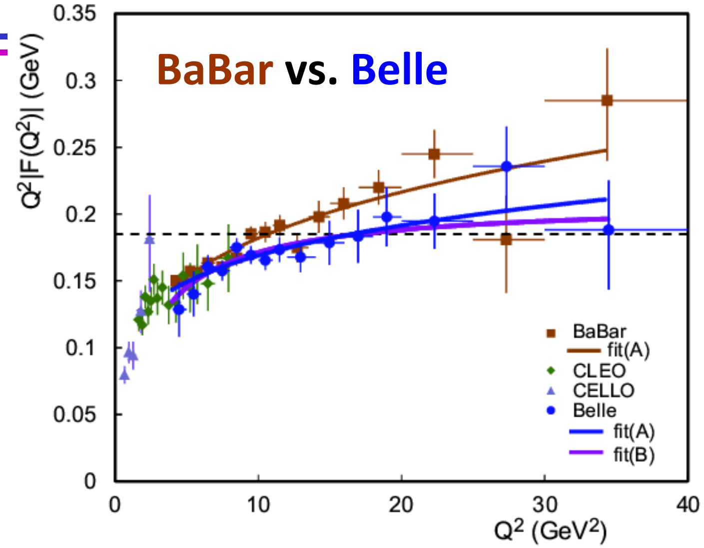
BaBar, PRD 80, 052002 (2009) **Belle, PRD 86, 092007 (2012)**

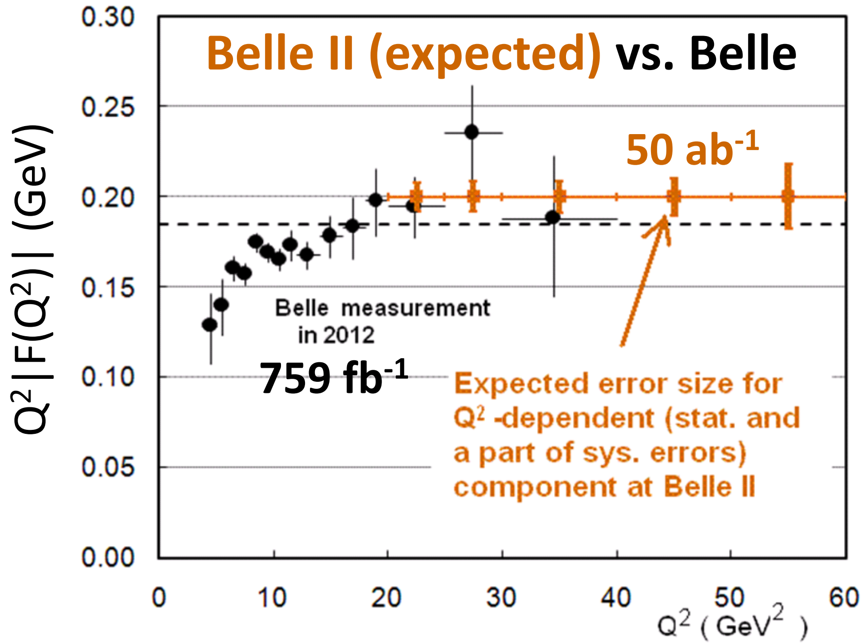
More precise and more data points at higher Q^2 are desired.

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

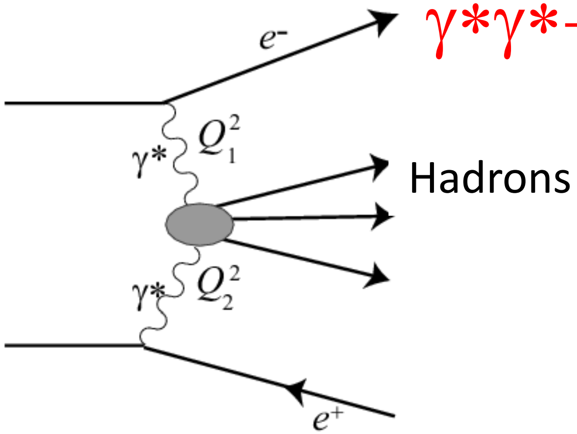
- Integrated luminosity 50 ab^{-1} (x 66 of the Belle analysis)
- reduced systematic errors from π^0-mass fit and trigger efficiency

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



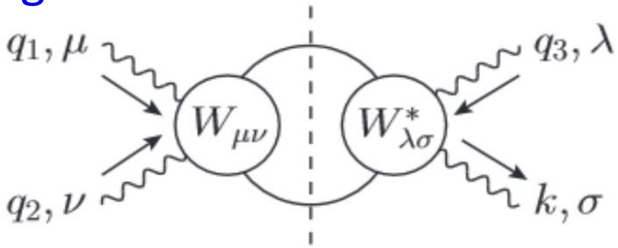


Double-tag processes



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

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

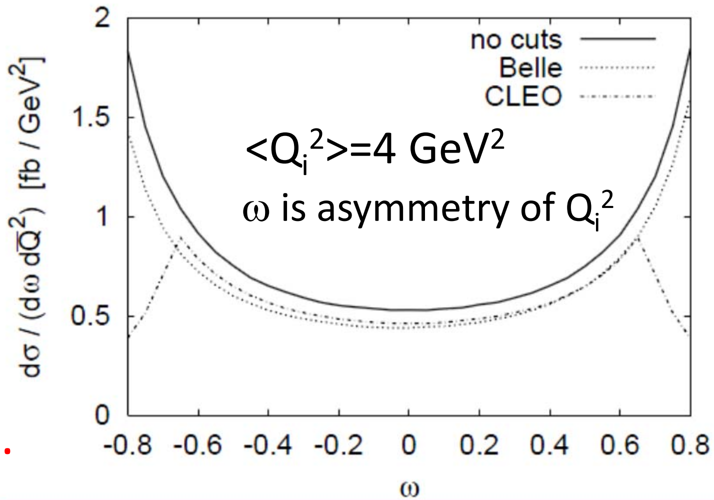
with $Q_1^2 \sim Q_2^2$

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.



Summary

Highlights of Two-photon physics results from Belle

for spin-dependent structures of hadrons and spectroscopy

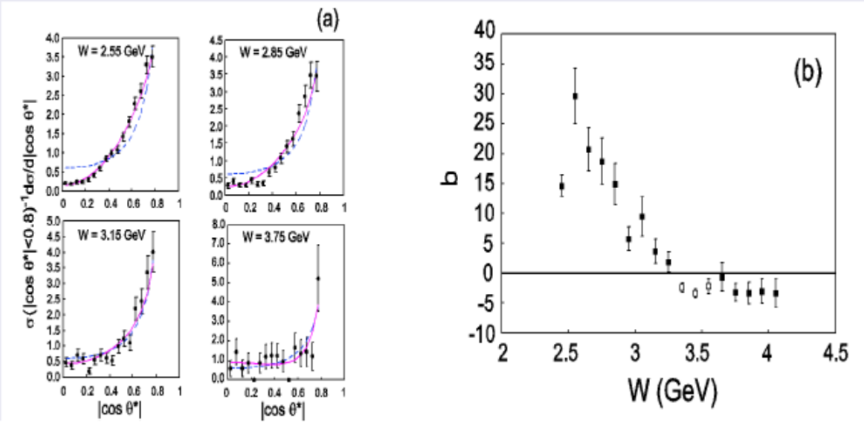
- Systematic QCD test with many meson (and baryon)-pair processes @ 2.5 – 4 GeV
- Comprehensive light-meson spectroscopy: Observation of scalar states
- Discovery/observations of new charmonium(like) states, $\chi_{c2}(2P)$, X(3915) etc.
- Studies related to glueball, tetraquark etc. exotic hadrons
- First measurement of scalar and tensor-meson Transition Form Factors

Exploration for the luminosity frontier continues to Belle II, SuperKEKB.

Backup

Angular dependence

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



$d\sigma/d|\cos\theta^*| \propto \sin^{-4}\theta^*$ is predicted by $q\bar{q}$-meson model and perturbative QCD

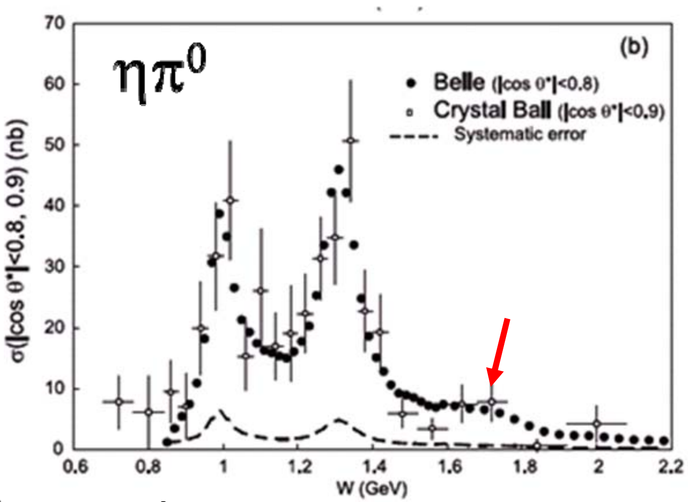
- Fit to $\sin^{-4}\theta^* + b\cos\theta^*$
- b becomes constant above 3.2 GeV.

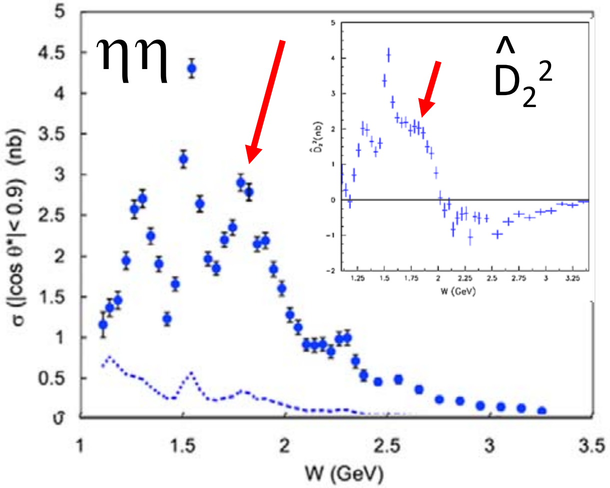
mode	α in $\sin^{-\alpha}\theta^*$	GeV	$\lvert\cos\theta^*\rvert$
$K_S K_S$	3 – 8	2.6 - 3.3	< 0.8
$\pi^+\pi^-$	Good agreement with 4	3.0 - 4.1	< 0.6
K^+K^-	Good agreement with 4	3.0 - 4.1	< 0.6
$\pi^0\pi^0$	Better agreement with $\sin^{-4}\theta^* + b\cos\theta^*$ Approaches $\sin^{-4}\theta^*$ above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

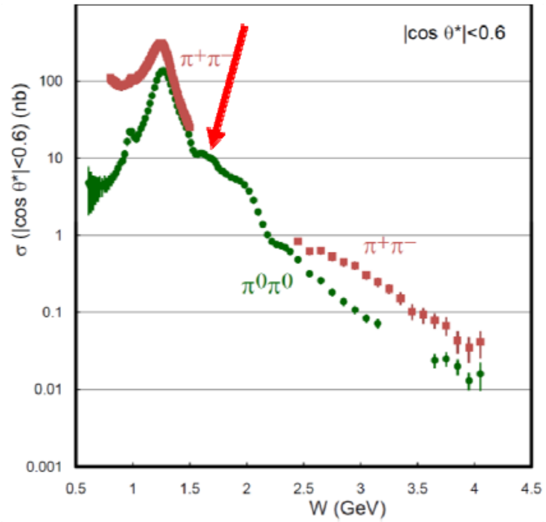
Exclude † χ_{cJ} region, 3.3 - 3.6 GeV

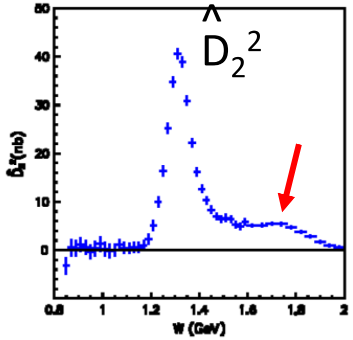
Summarized by H.Nakazawa Hadron2013

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.

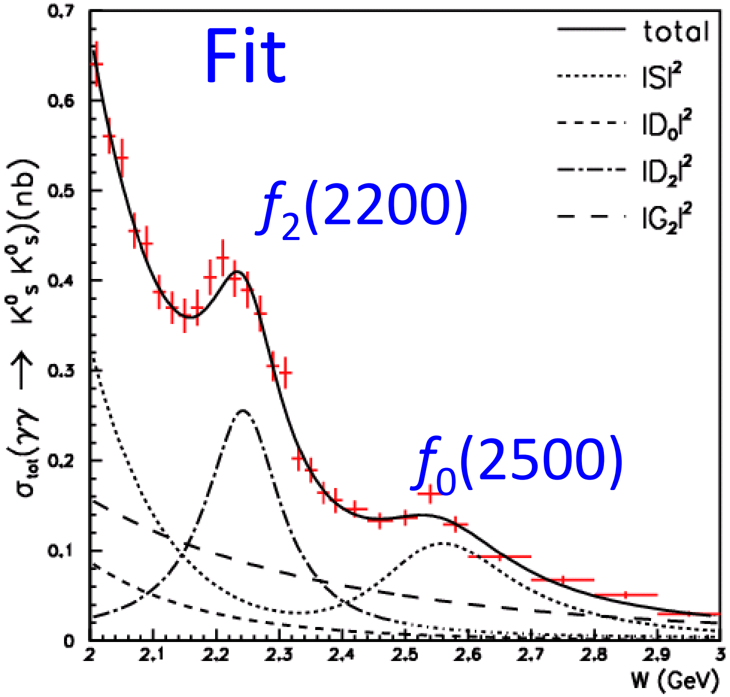
Fit Results for resonances in $K^0_S K^0_S$

$f_2(2200)$-$f_0(2500)$ 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}	$2539 \pm 14^{+38}_{-14}$
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 $f_2(2500)$

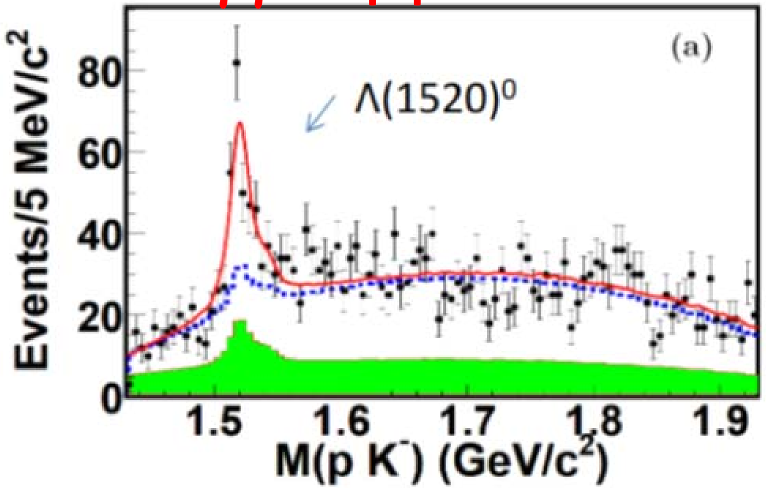


- There can be an only wide state around 2240 MeV.
- Narrow appearances in previous measurements may be due to an interference effect and/or statistical fluctuation.
- A high-mass state at 2.5 GeV may be the heaviest light-quark scalar meson so far found.

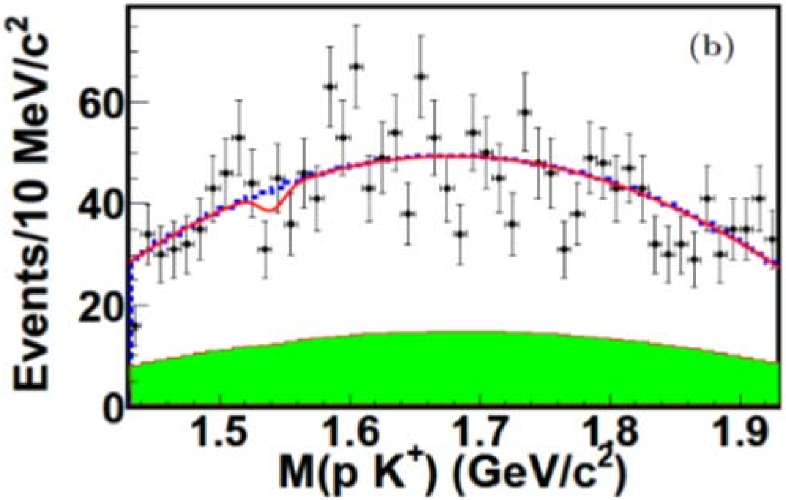
Search for exotic baryons (Pentaquarks)

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

PRD 93, 112017(2016)



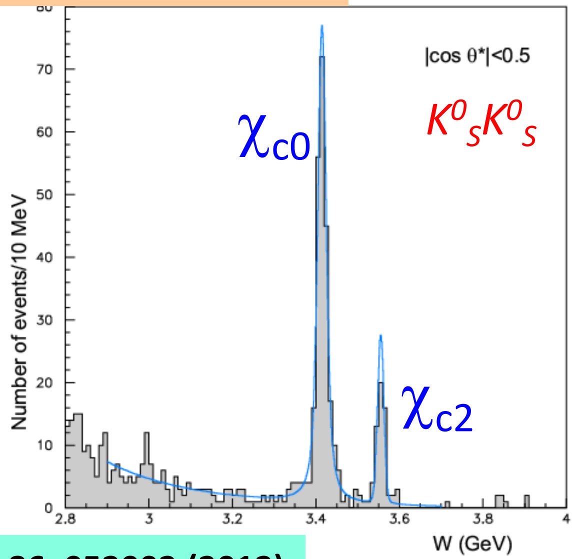
Simultaneous fit: $\Lambda(1520)^0$ and $\Theta(1540)^0$ signal are included.
The shaded histogram: $\sum Pt^*$ sideband
288 ± 48 $\Lambda(1520)^0$ events, 8.6σ
22 ± 34 $\Theta(1540)^0$ events, 1.4σ



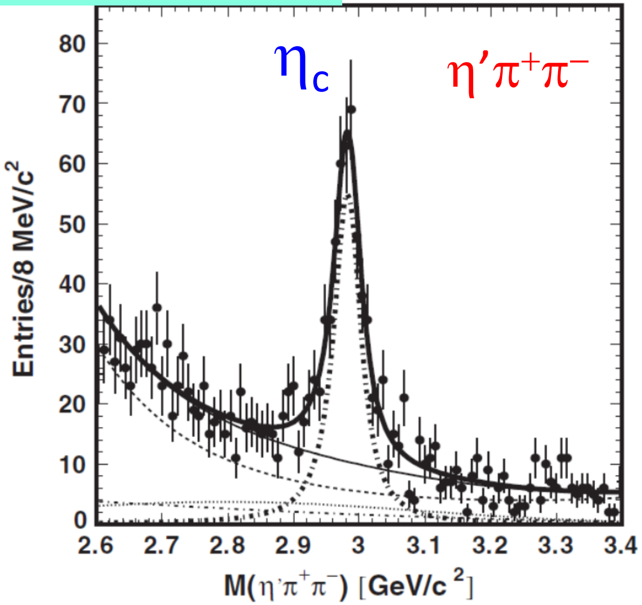
Similar simultaneous fit: $\Theta(1540)^{++}$ signal
Solid line: the simultaneous fit
The dotted curve: background estimate
The shaded histogram: $\sum Pt^*$ sideband
-16 ± 34 $\Theta(1540)^{++}$ events

Most beautiful charmonium signals

PTEP 2013, 123C01 (2013)



PRD 86, 052002 (2012)



Yield

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

* Interference between χ_{c0} and continuum

Product of two-photon decay width and B($K^0_S K^0_S$)

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

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

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

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)

$\rightarrow$ 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

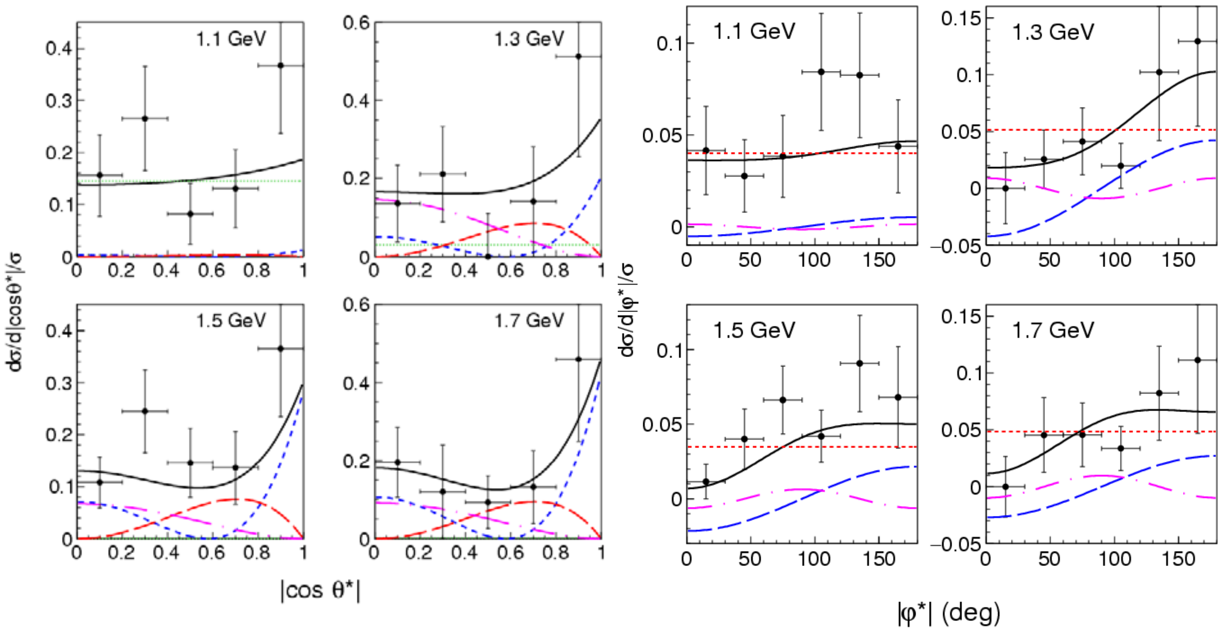
Angular dependence and the PWA fit

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



We regard this as the angular dependence at $\langle Q^2 \rangle = 6.5$ GeV^2

Fit:

Black: total

Red: t_0

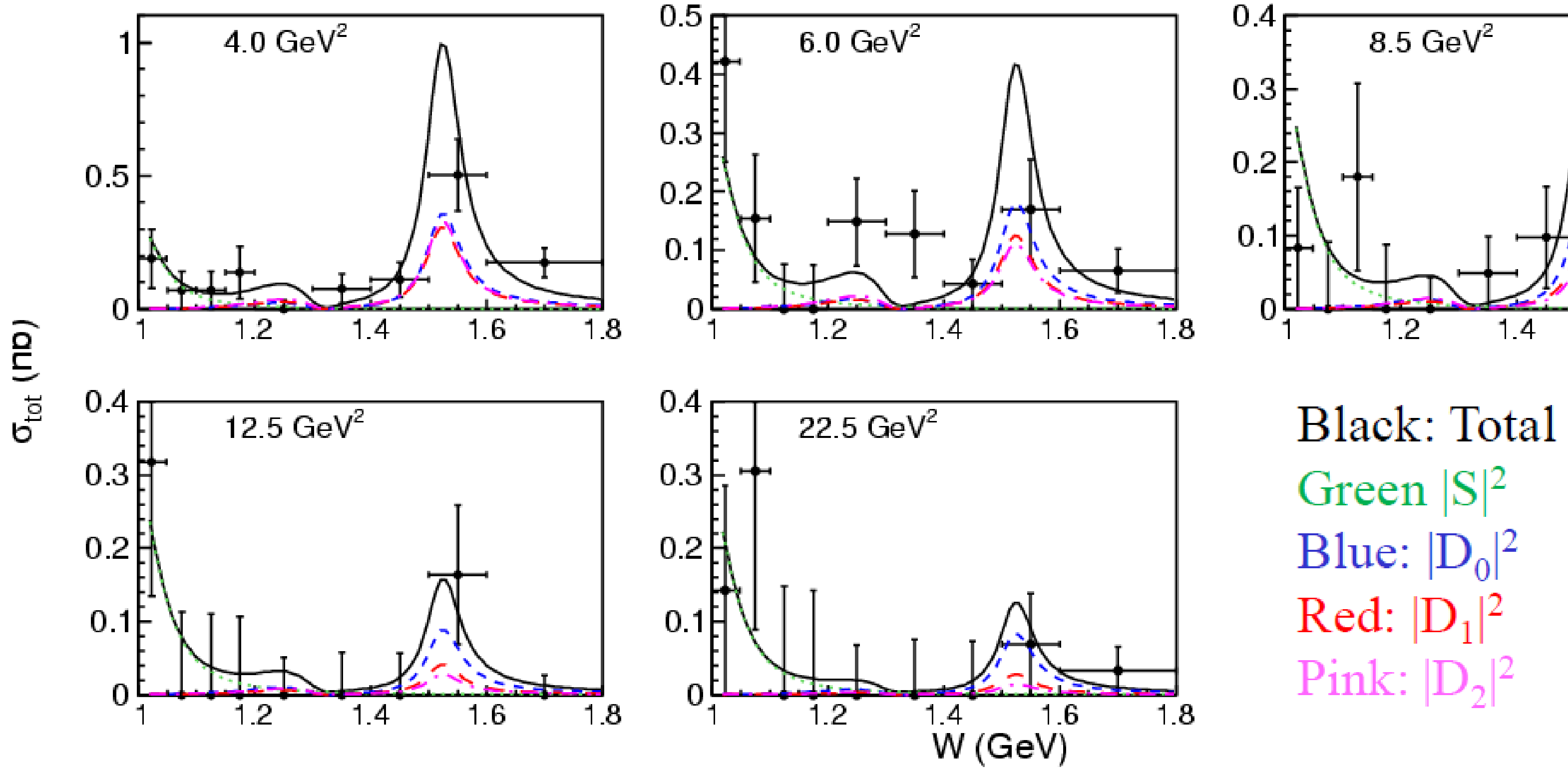
Blue: $t_1 \cos\varphi^*$

Magenta: $t_2 \cos 2\varphi^*$

Originally two-dimensional data are used.

Forward enhancement is from the λ=0 component

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).