Gamma gamma physics at Belle

Sadaharu Uehara (KEK)

PHIPSI13

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Sapienza University of Rome

KEKB Accelerator and Belle Detector

- Asymmetric $e^- e^+$ collider

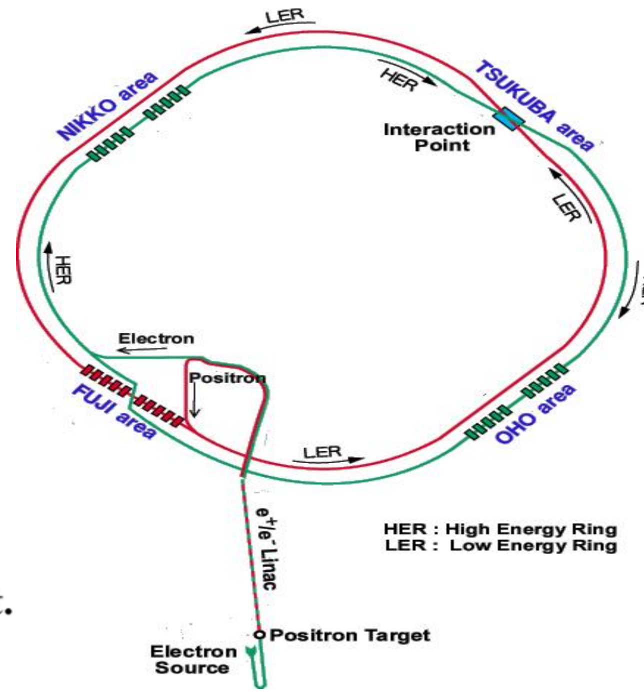
  8 GeV e^- (HER) x 3.5 GeV e^+ (LER)

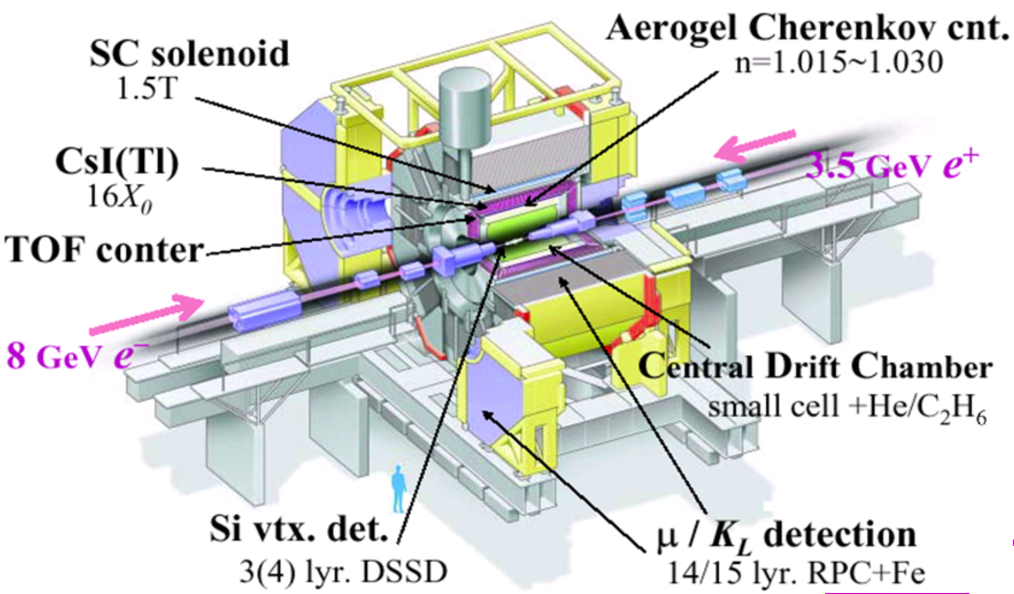
  $\sqrt{s}$=10.58 GeV ⇔ $\Upsilon(4S)$

  Beam crossing angle: 22mrad
- Continuous injection
- Luminosity

  L_{max}=2.1x10^{34} cm^{-2}s^{-1}

  $\int$ Ldt ~ 1040 fb^{-1}





High momentum/energy resolutions

CDC+Solenoid, CsI

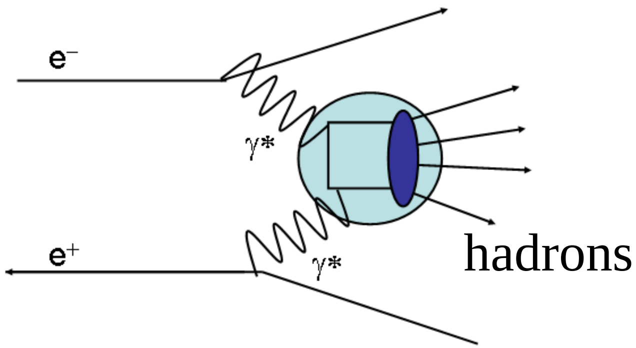
Vertex measurement – Si strips

Particle identification

TOF, Si-aerogel, CDC-dE/dx,

RPC for K_L/muon

Two-Photon Collisions and Hadron/QCD Physics



Hadron production from collisions of virtual or quasi-real photons

- Perturbative/Non-perturbative QCD
- Resonances
- Hadron/photon form factors

Single resonance formation in $\gamma\gamma^{(*)}$ collisions

Zero-tag with p_t-balance requirement for the hadron system

$Q^2 << W^2$ ($\gamma\gamma$ c.m. energy), **$Q^2 << E_{QCD}^2$** (Energy scale of QCD)

Measurement of $\Gamma\gamma\gamma$ $B(\rightarrow$ final state)

Single-tag process (Q^2 dependence in $\gamma\gamma*$ collisions)

Measurement of transition form factor

$\gamma\gamma \rightarrow K^0_S K^0_S$

The first measurement of the differential cross section in

W = 1.05 – 2.4 GeV with 972 fb^{-1} Belle data

W: c.m. energy of $\gamma\gamma$ collisions

arXiv:1307.7457[hep-ex], submitted to PTEP
(Progress of Theoretical and Experimental Physics)

Study of **resonances** including

exotic candidates (e.g. glueball state)

This process is dominated by resonances in W < ~ 2.4 GeV

W > 2.4 GeV -- Update of the previous Belle publication

(W.T.Chen et al., PLB651, 15 (2007), 397.6fb^{-1})

QCD study – Angular and W dependences

Charmonia: Partial decay widths for χ_{c0} and χ_{c2}

Search for χ_{c0}**(2P)** etc., which is to be 3.80 – 3.93 GeV

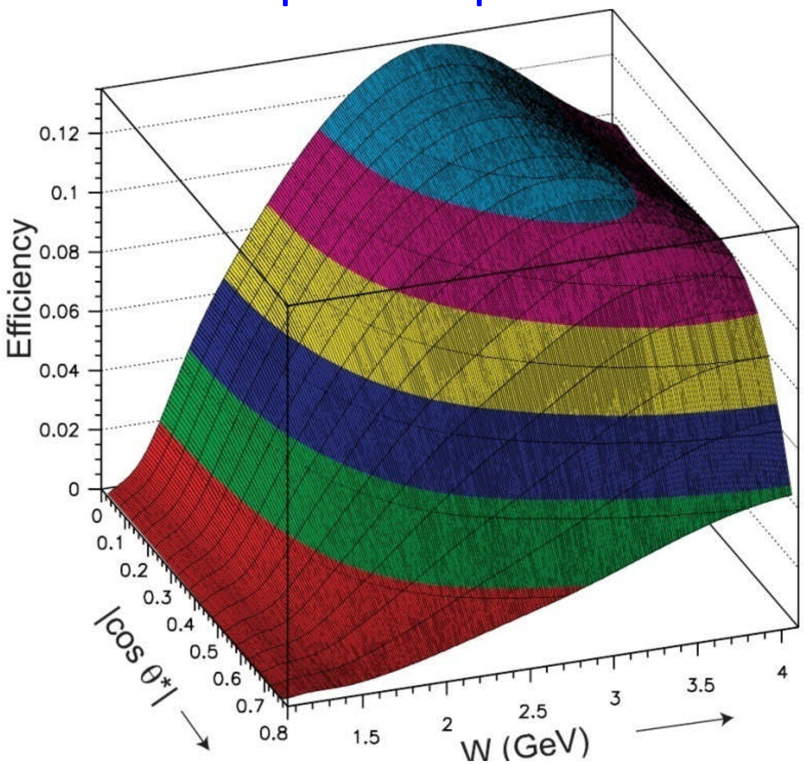
Cross section integrated over the angle

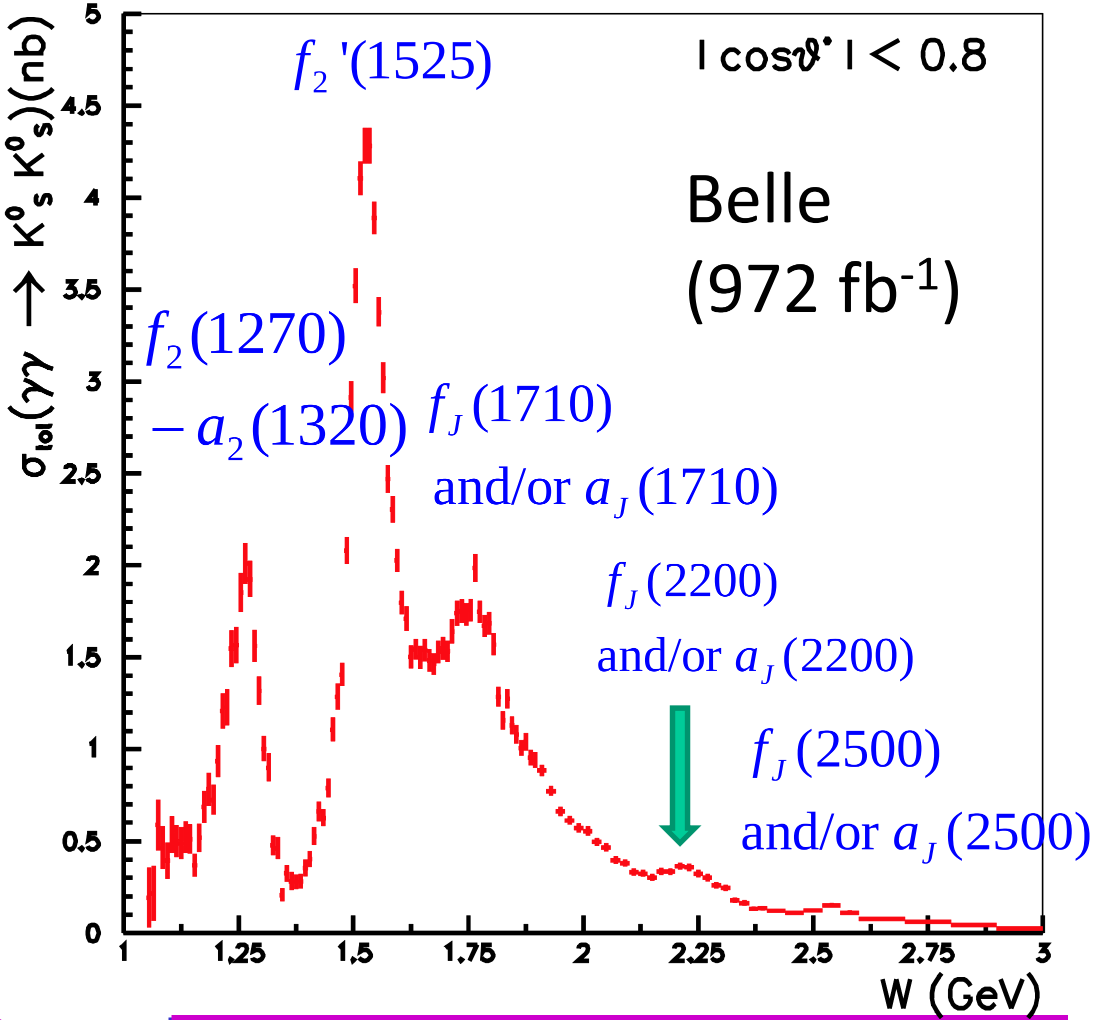
Five resonance-like peaks visible below 3 GeV

W and angular dependence of the efficiency

Covering W = 1.05 – 4.0 GeV

|cos θ*|<0.8





Formula for differential cross section

- At low energy (W < 3 GeV)

$$\frac{d\sigma}{d\Omega} = \left| S Y_0^{\ 0} + D_0 Y_2^{\ 0} + G_0 Y_4^{\ 0} \right|^2 + \left| D_2 Y_2^{\ 2} + G_2 Y_4^{\ 2} \right|^2$$

- S, D_0, G_0, D_2 , G_2 Partial wave amplitudes

  J = L = 0, 2, 4 (even only) and total two-photon helicity = 0 or 2

  – give W dependence of each partial wave

    assuming resonance and continuum components

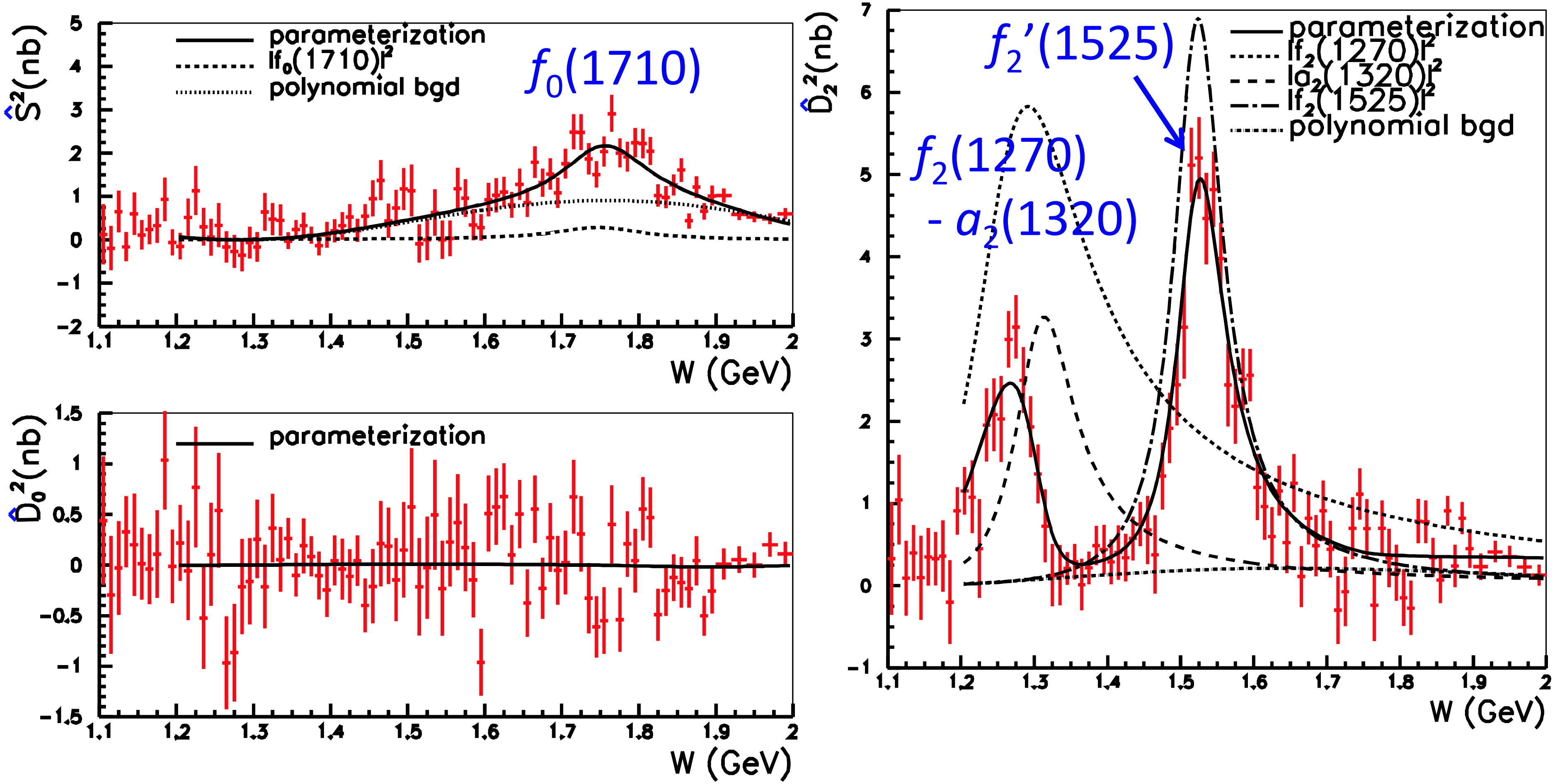
- $Y_J^{\ m}$: spherical harmonics
  – Each determines the angular dependence of the wave
  – But, not mutually independent

Fit with S and D waves for W < 2.0 GeV

Hat amplitudes

to visualize, model independent

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



Fit results for W < 2.0 GeV

f_2(1270) - a_2(1320) interference and f_2'(1525)

Parameter	Sol. H	Sol. L	H,L combined	Incoh. fit	PDG [23]
χ^2/ndf	375.09/387	375.22/387	–	406.6/388	–
$\phi_{a_2(1320)}$ (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($f_2'(1525)$) (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
$\Gamma_{\rm tot}(f_2'(1525))$ (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}
$\Gamma_{\gamma\gamma}\mathcal{B}(K\bar{K})(f_2'(1525))$ (eV)	113^{+25+43}_{-28-77}	$48 \pm 4^{+33}_{-10}$	$48^{+67+108}_{-8\ -12}$	79.1 ± 1.4	72 ± 7

Two solutions are found, and they are combined

- Destructive interference btw. f_2 (1270)and a_2 (1320) confirmed
- First attempt to include interference effect in measuring $\Gamma_{\gamma\gamma}B(K\bar{K})$of f_2'(1525).

Fit results for W < 2.0 GeV (cont.)

$f_J(1710)$

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}
$\Gamma_{\rm tot}(f_J)$ (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

Scalar rather than tensor! (in contrast to L3)

***f_0*(1710)** : $\Gamma_{\gamma\gamma}$>O(10 eV) *indicates not likely a pure glueball*

Fit Results for resonances in W>2.0 GeV

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

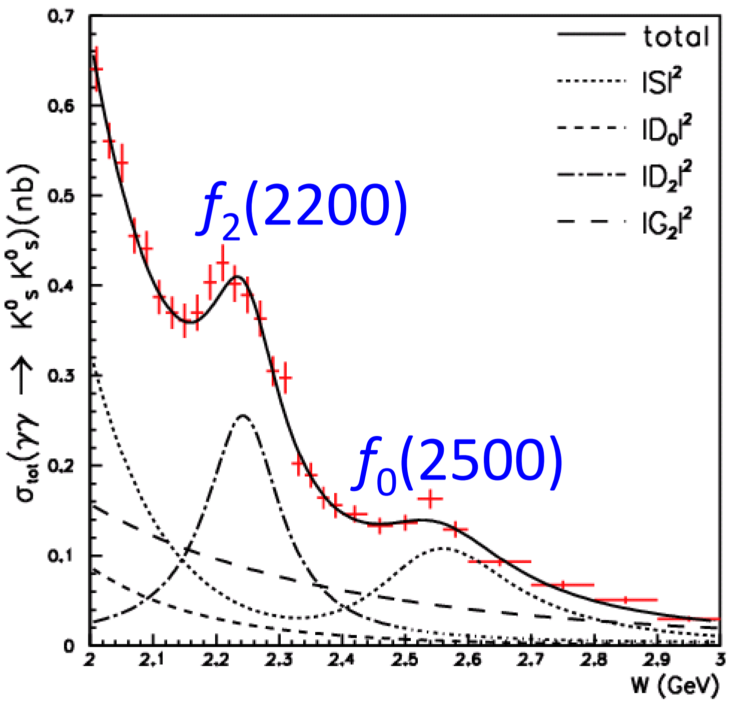
- The resonance parameters

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

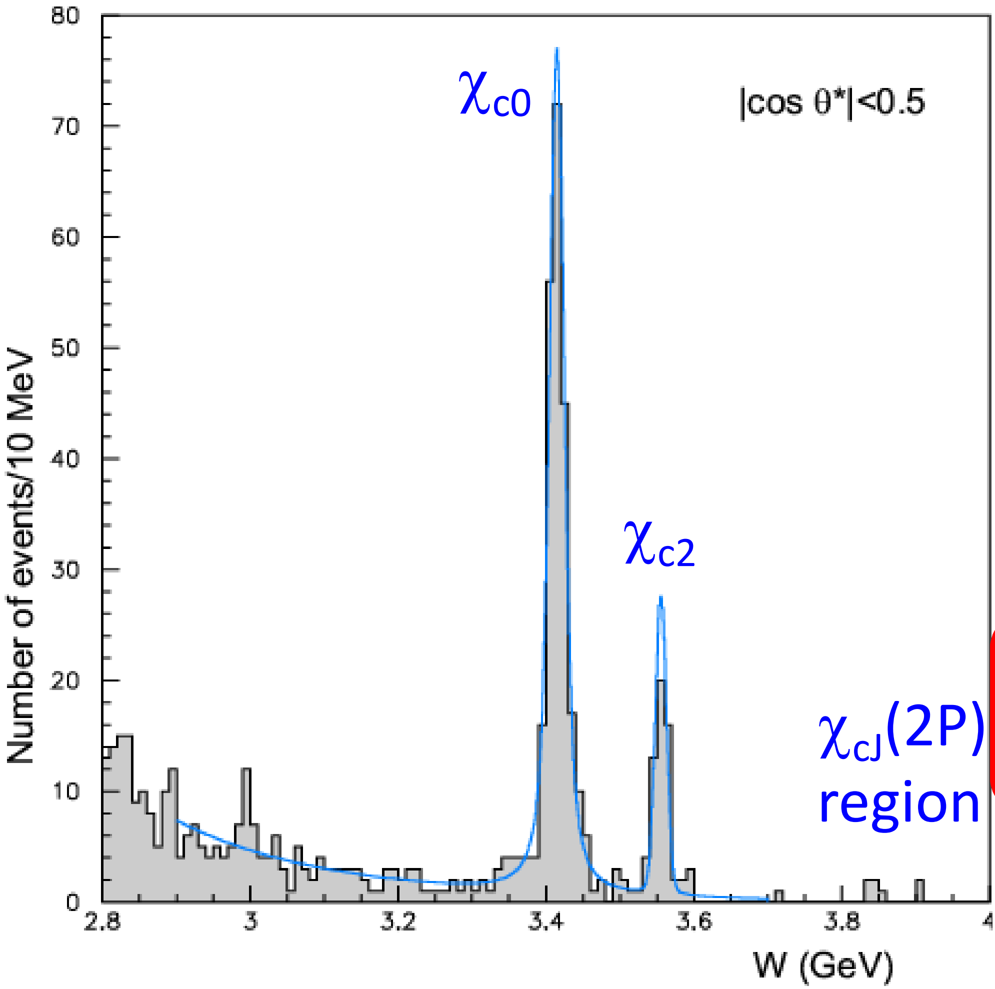
- Significances
  - 3.4σ for f_2(2200) over f_0(2200)
  - 4.3σ for f_0(2500) over f_2(2500)

  evaluated from min.($\Delta\chi^2$) for every sys. source

Fit



Charmonia χ_{c0} and χ_{c2}



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

QCD Studies: Angular dependence

Assume non-resonant effect **in 2.6 < W < 3.3 GeV ;**
we know there is a resonance near 2.5 GeV

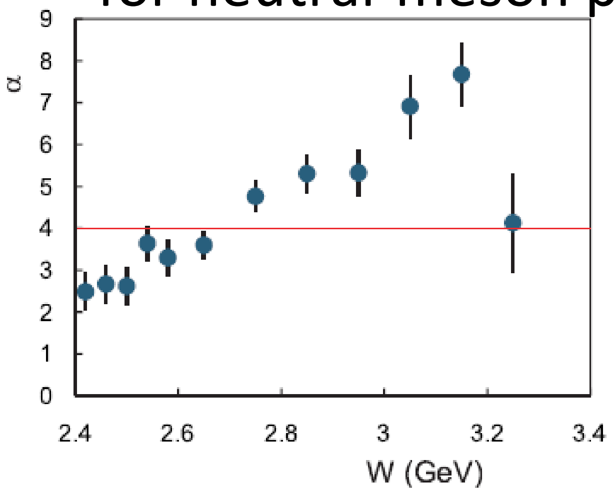
$d\sigma/d|\cos\theta^*| \propto$ **$1/\sin^{\alpha}\theta^*$**

Handbag: α = const. = 4

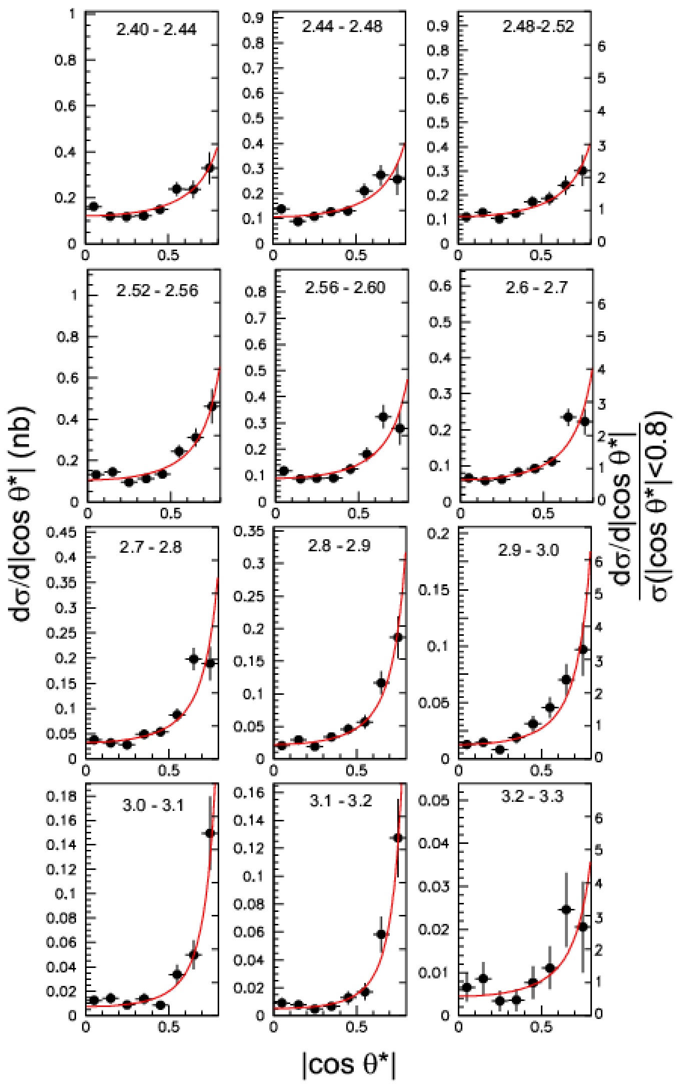
M.Diehl, P.Kroll, and C. Vogt, PLB 532, 99 (2002)
M.Diehl, P.Kroll, PLB 683, 165 (2010)

pQCD: α not const, depend on W

for neutral-meson pair



W= 2.4 – 3.3 GeV



No tendency is seen to converge to 4 at high energies

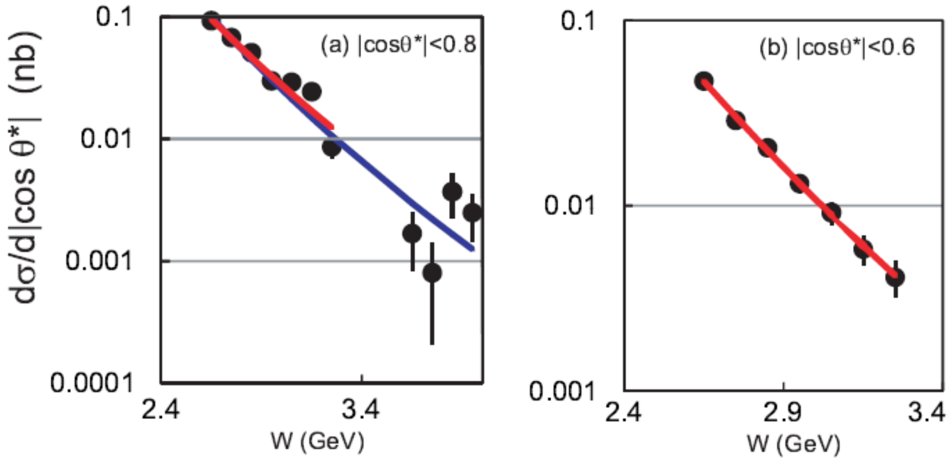
W-dependence

$\sigma \propto W^{-n}$ pQCD predictions

for charged-meson pair n = 6 ($\pi^+\pi^-$, K^+K^- etc.) = Dimensional counting rule

for neutral-meson pair n=10 ($K^0_S K^0_S$ etc.) by Chernyak

PLB 640, 246 (2006)
arXiv 1212.1304 [hep-ph]



W range (GeV)	$\lvert\cos\theta^*\rvert$ range	n	note
2.6 – 4.0 (except 3.3 – 3.6)	< 0.8	$11.0 \pm 0.4 \pm 0.4$	
2.6 – 3.3	< 0.8	$10.0 \pm 0.5 \pm 0.4$	
2.6 – 3.3	< 0.6	$11.8 \pm 0.6 \pm 0.4$	
2.4 – 4.0 (except 3.3 – 3.6)	< 0.6	$10.5 \pm 0.6 \pm 0.5$	Belle 2007

Close to n=10, agree with pQCD prediction

"$\gamma\gamma \to$ meson pair" (six final states) from Belle

QCD Test in 2.4 – 4.1 GeV energy region

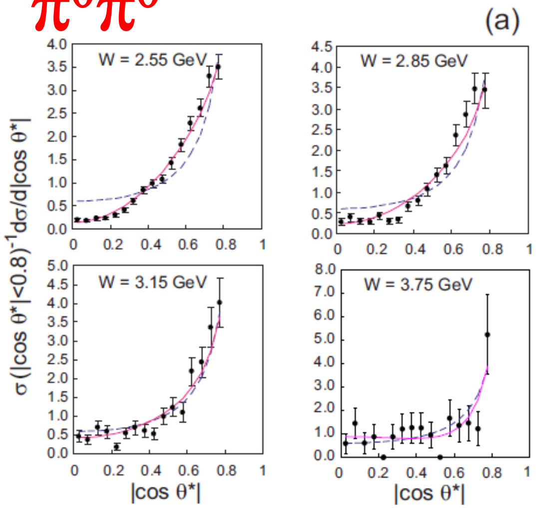
Process	Reference	Int.Lum. (fb^{-1})	$\gamma\gamma$ c.m. Energy (GeV)	Physics covered: Light Mesons	Physics covered: QCD	Physics covered: Char-monia
$\pi^+\pi^-$	●PLB 615, 39 (2005)	87.7	2.4 - 4.1		√	√
	PRD 75, 051101(R) (2007)	85.9	0.8 - 1.5	√		
	J. Phys. Soc. Jpn. 76, 074102 (2007)	85.9	0.8 – 1.5	√		
K^+K^-	EPJC 32, 323 (2003)	67	1.4 – 2.4	√		
	●PLB 615, 39 (2005)	87.7	2.4 – 4.1		√	√
$\pi^0\pi^0$	PRD 78, 052004 (2008)	95	0.6 – 4.0	√		
	●PRD 79, 052009 (2009)	223	0.6 – 4.0	√	√	√
$K^0_SK^0_S$	PLB 651, 15 (2007)	397.1	2.4 – 4.0		√	√
	arXiv:1307.7457[hep-ex] NEW	972	1.05 -- 4.0	√	√	√
$\eta\pi^0$	●PRD 80, 032001 (2009)	223	0.84 – 4.0	√	√	
$\eta\eta$	●PRD 82, 114031 (2010)	393	1.1 – 4.0	√	√	√

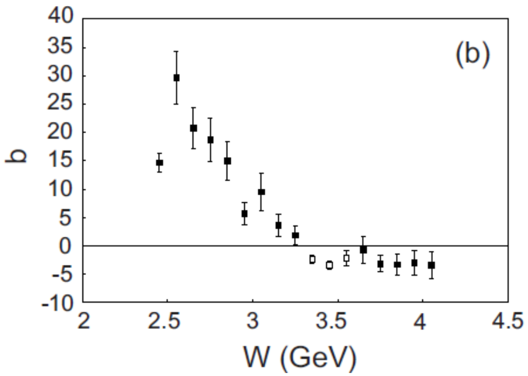
Differential cross section **$d\sigma/d|\cos\theta^*|$** for these reaction processes are measured.

Three kinds of QCD Studies for **2.4 – 4.1 GeV** Region

Angular dependence

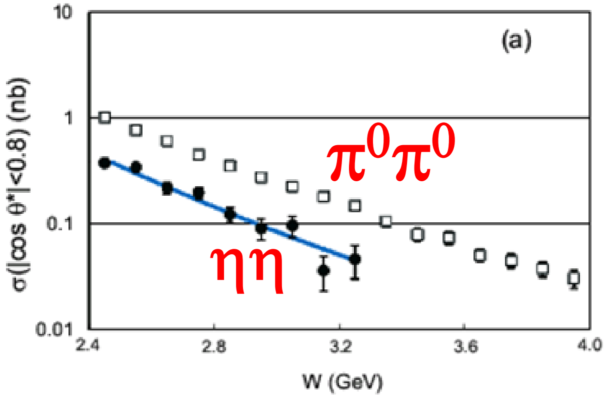
$\pi^0\pi^0$

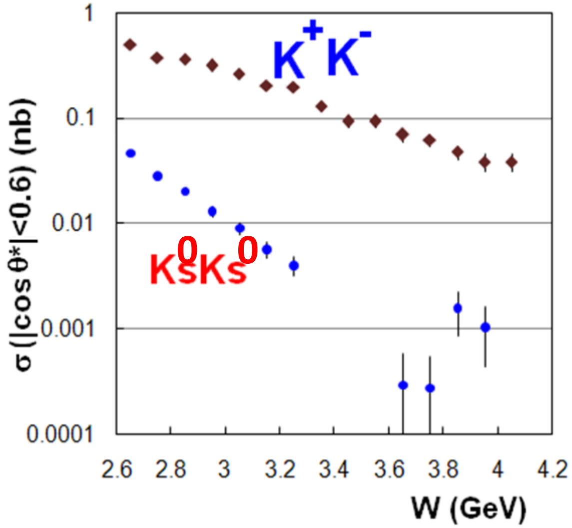




$d\sigma/d|\cos\theta^*| = a(\sin^{-4}\theta^* + b\cos^2\theta^*)$.

Energy dependence

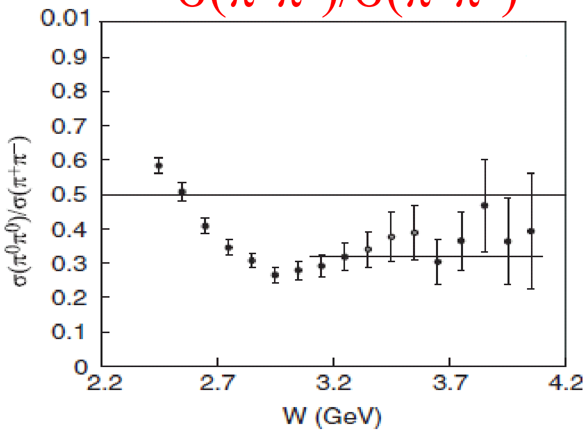




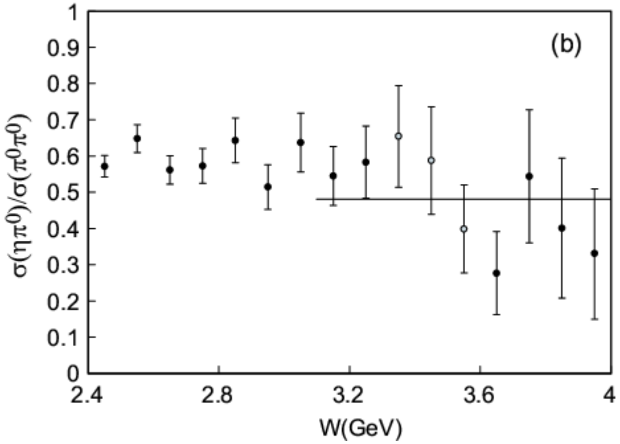
Difference of the slopes
$\sigma \sim W^{-n}$

Cross-section ratio

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



$\sigma(\eta\pi^0)/\sigma(\pi^0\pi^0)$



Summary of the six channels

mode	$\sin^{-4}\theta^*$	W [GeV]	$\lvert\cos\theta^*\rvert$
$\pi^+\pi^-$	Well matched	3.0 - 4.1	< 0.6
K^+K^-	Well matched	3.0 - 4.1	< 0.6
$K^0_S K^0_S$	$\sin^{-\alpha}\theta^*$ α= 3 - 8	2.6 – 3.3	< 0.8
$\pi^0\pi^0$	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 above 2.7 GeV	3.1 - 4.1	< 0.8
$\eta\eta$	Poor agreement Close to $\sin^{-6}\theta^*$ above 3.0 GeV	2.4 - 3.3	< 0.9

~ $\sin^{-4}\theta^*$ for charged meson pairs is predicted by pQCD

S.J.Brodsky, G.P.Lepage, PRD 24, 1808 (1981)

↑Angular dependence

↓Cross-section ratio

	$\sigma(\pi^0\pi^0) : \sigma(\eta\pi^0) : \sigma(\eta\eta)$
Theory (Brodsky and Lepage) η in SU(3) octet	$1 : 0.24\,R_f : 0.36\,R_f^2$
Theory $V_P = -18$ deg	$1 : 0.46R_f : 0.62\,R_f^2$
Belle	**1: (0.48±0.06) : (0.37±0.04)**

R_f: Squared form factor ratio of η/π^0

↓Slope parameter

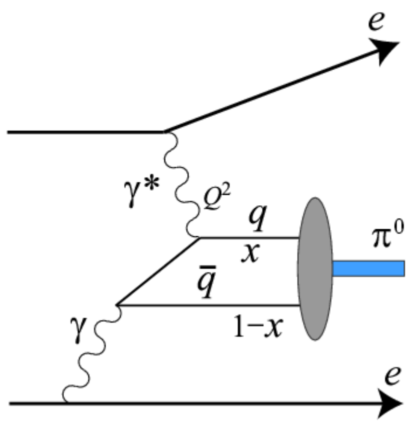
Process	n	W range (GeV)	$\lvert\cos\theta^*\rvert$ range
$\eta\eta$	$7.8 \pm 0.6 \pm 0.4$	2.4 – 3.3	< 0.8
$\eta\pi^0$	$10.5 \pm 1.2 \pm 0.5$	3.1 – 4.1	< 0.8
$\pi^0\pi^0$	$8.0 \pm 0.5 \pm 0.4$	3.1 – 4.1 (3.3 – 3.6 excluded)	< 0.8
$K^0_S K^0_S$	$11.0 \pm 0.4 \pm 0.4$	2.6 – 4.0 (3.3 – 3.6 excluded)	<0.8
$\pi^+\pi^-$	$7.9 \pm 0.4 \pm 1.5$	3.0 – 4.1	< 0.6
K^+K^-	$7.3 \pm 0.3 \pm 1.5$	3.0 – 4.1	< 0.6

$\sigma(K^+K^-)/\sigma(\pi^+\pi^-)$
$= 0.89 \pm 0.04$(stat.) ± 0.15(syst.)
$\sigma(\pi^0\pi^0)/\sigma(\pi^+\pi^-) = 0.32 \pm 0.03 \pm 0.05$,
$\sigma(K^0_S K^0_S)/\sigma(K^+K^-)$
changes ~ 0.10 to ~ 0.03

π^0 Transition Form Factor

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

Coupling of neutral pion with two photons
Good test for QCD at high Q^2



Single-tag π^0 production in two-photon process with a large-Q^2 and a small-Q^2 photon

Theoretically calculated from pion distribution amplitude and decay constant

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

Measurement:

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

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

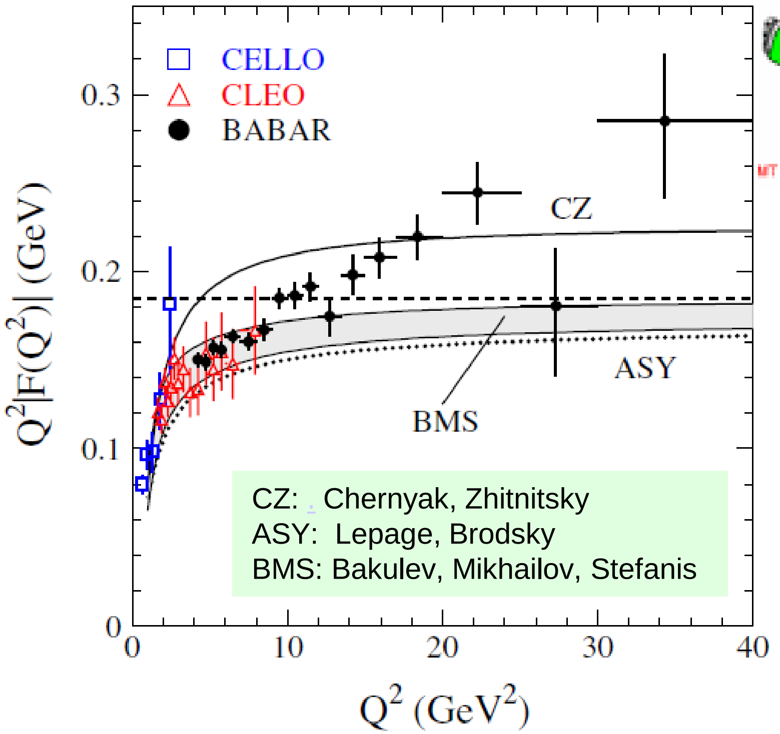
Detects e (tag side) and π^0

$Q^2 = 2EE'(1 - \cos\theta)$ from energy and polar angle of the tagged electron

BaBar's Measurement

π^0 transition form factor (TFF) measured by BaBar is larger than the asymptotic pQCD prediction above Q^2>10GeV^2

BaBar, PRD 80, 052009 (2009) **442 fb^{-1}**

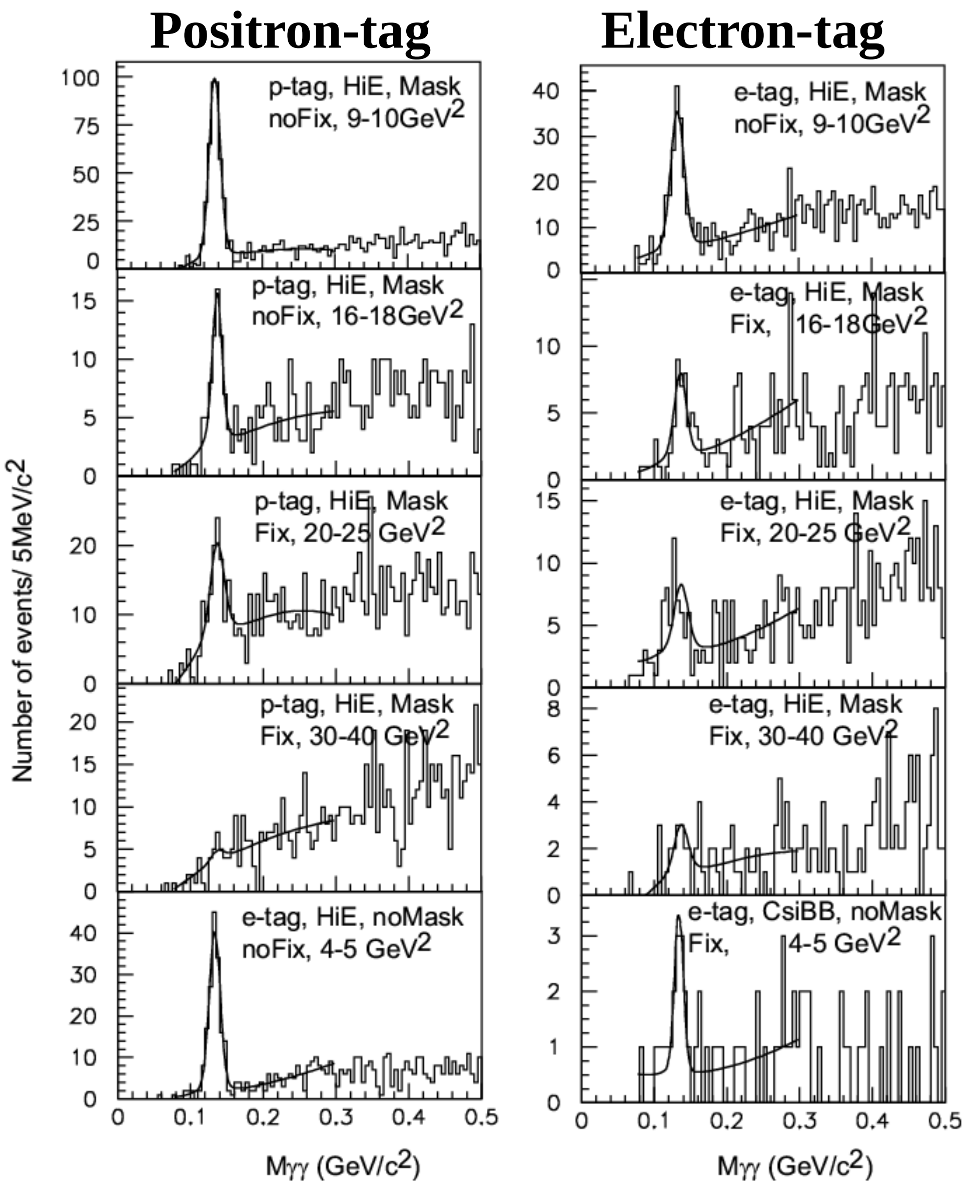


Below Q^2<8GeV^2, the BaBar result supports the CLEO result.

η and η' TFFs from BaBar **PRD 84, 052001(2011)** are consistent with pQCD predictions.

Explanation of this situation for the (π^0, η, η')-TFF's within standard QCD calculations is difficult.

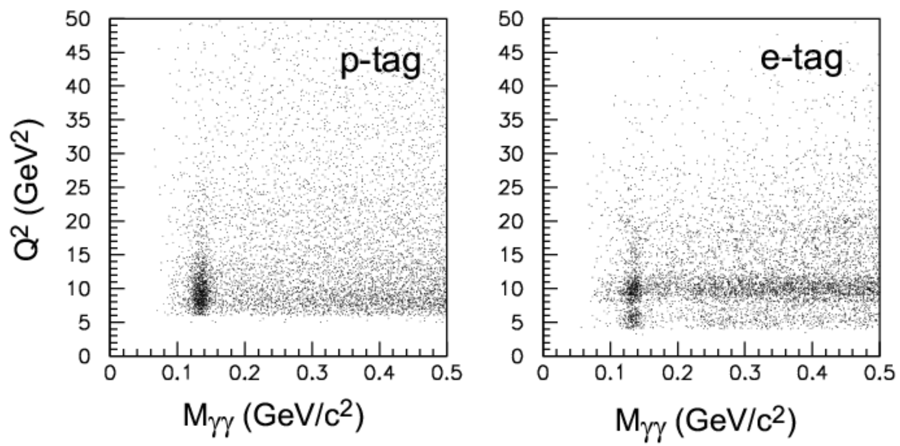
Belle measurement: Extraction of π^0 Yield



Int. Luminosity :759 fb^{-1}
(Larger than BaBar's)

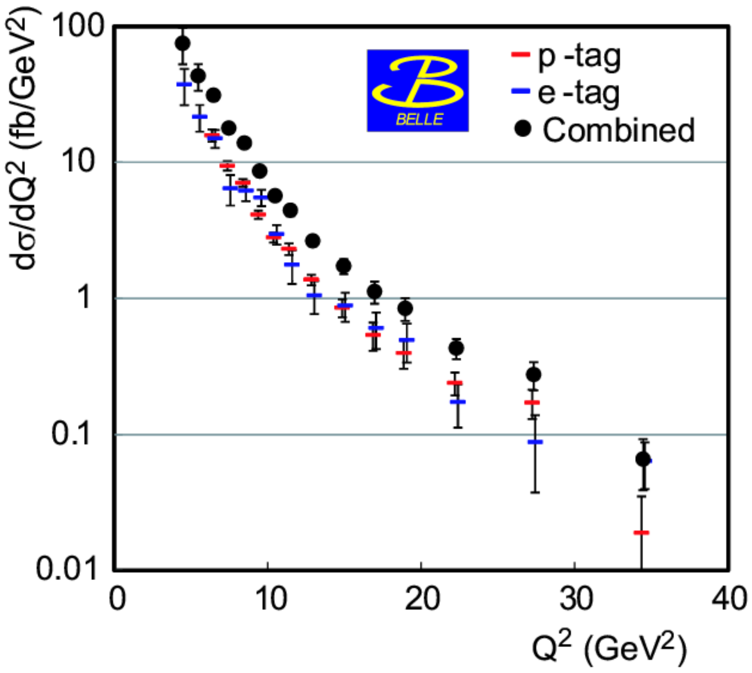
PRD 86, 092007 (2012)

Fit Mγγ distribution by
- Double Gaussian (for signal)
- \+ 2nd-Order Polynomial (for background)
- in each Q^2 bin



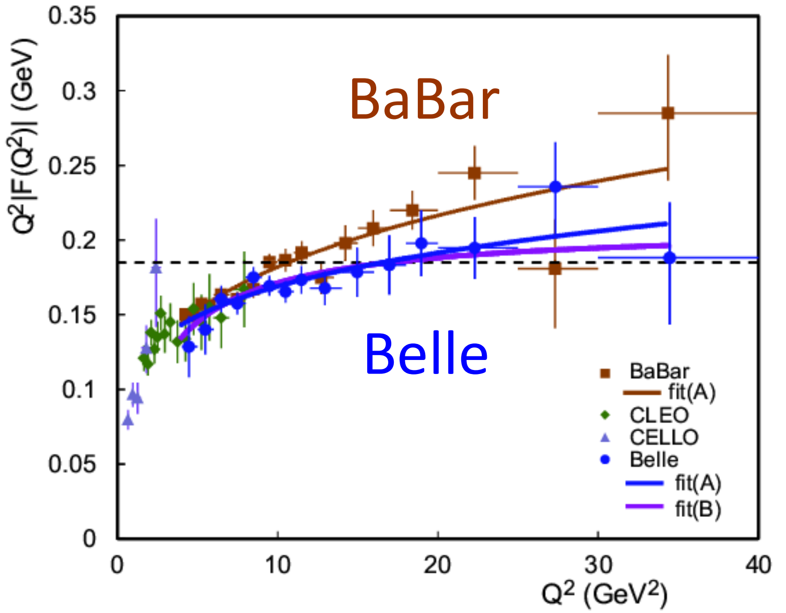
Belle result

The cross sections from p-tag and e-tag are evaluated, separately, and then combined.



Q^2_{max} = 1.0 GeV² for the less-virtual photon
Corrected for √s = 10.58 GeV

π^0 Transition Form Factor



No rapid growth above Q²>9GeV² is seen in Belle result.

~ 2.3σ difference between Belle and BaBar in 9 – 20 GeV²

Fit with an asymptotic parameter

$Q^2|F(Q^2)| = BQ^2/(Q^2+C)$ B = 0.209 ± 0.016 GeV

Consistent with the QCD value (0.185GeV)

Summary

- **$d\sigma/d|\cos\theta^*|$ of $\gamma\gamma \to K^0_S K^0_S$ is measured for the first time for $1.05 < W < 2.4$ GeV**

  - $f_2(1270)$ and $a_2(1320)$ interfere indeed destructively

  - $f_0(1710)$ is favored over $f_2(1710)$, $\Gamma_{\gamma\gamma} > O(10$ eV$)$ Not likely a pure glueball

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

- **QCD test using measurements of six processes of $\gamma\gamma \to$ *meson pair***

  ($\pi^+\pi^-$, K^+K^-, $\pi^0\pi^0$, $K^0_S K^0_S$, $\eta\pi^0$, $\eta\eta$, for W = 2.4 – 4.1 GeV)

  - W-dependence of $K^0_S K^0_S$, n ~10 predicted by pQCD, is confirmed

    $\pi^+\pi^-$, K^+K^- (n=6 predicted, n=7 – 8 measured)

  - Systematic QCD studies using W and angular dependences and cross section ratio of these exclusive processes are now possible

- **Measurement of $\gamma\gamma^* \to \pi^0$ transition form factor**

  - Steep increase in $Q^2 > \sim 9$ GeV^2 observed by BaBar is not seen by Belle

  - Belle result is consistent with the QCD asymptotic value backup

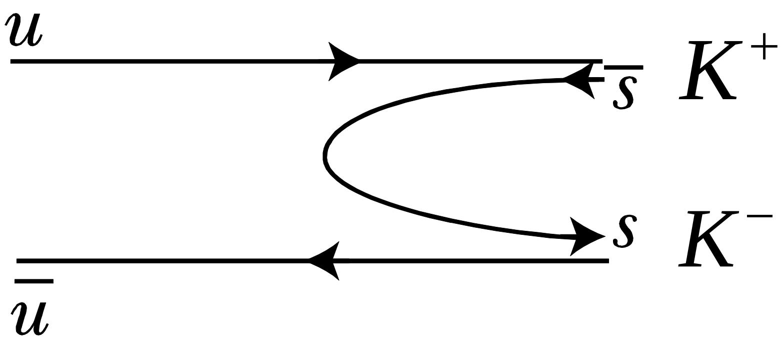
Nature of $\gamma\gamma \to R \to K^0_S K^0_S$

- $R = f_J$ or a_J (J = even)
- Destructive interference between f_J and a_J

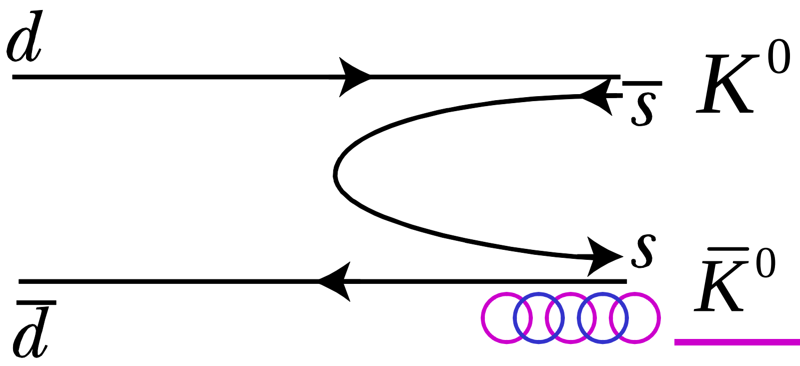
  $\left(\left|\phi_{a2} - \phi_{f2}\right| = 180^\circ\right)$

  – (D. Faiman, H.J. Lipkin and H.R. Rubinstein, PL 59B,269 (1975))

    based on OZI (Okubo-Zweig-Iizuka) rule and isospin



$$|u\bar{u}\rangle = \frac{1}{\sqrt{2}}\left(f_J + a_J\right)$$



$$|d\bar{d}\rangle = \frac{1}{\sqrt{2}}\left(f_J - a_J\right)$$

Selection Criteria

4 Pions from 2 Ks's

- L4 (filtering) brings non-negligible inefficiency
  (At least 1 track with pt > 0.3GeV, dr<1cm and |dz|< 4cm)
- Trigger restricted in bit#3(ff_t2oc, Trigger A)
  #27(loe_fs_o, Trigger B)
  #24(hadron_a=loe_sss_tc, Trigger C)
- LowMult – 4track (previous page)
- 4 charged pions $(L(K)/(L(K)+L(\pi))<0.8)$ with $|\Sigma \mathbf{p}_t|<0.2$ GeV/c
- No neutral pion candidate with $p_t>0.1$ GeV/c
- Just two Ks candidates with
  z-matching @vertex $|\Delta z| < p_K$[cm/GeV/c] + 1.6 cm
  $\pi\pi$ invariant mass@vertex $|M_{\pi\pi} - m_K|<20$ MeV/c^2
- Two $M_{\pi\pi}$ mass conditions: $|M_{K1} - M_{K2}|<10$ MeV/c^2
- Vertices off IP (only for W>2GeV) :
  $r_{vi} > (W - 2\text{GeV}) \times 0.1$ cm/GeV

Selection Criteria (continued)

The 2 Ks-vertex distances and tr.-momentum relations etc.

- Distance between the vertices in the $r\varphi$, dVr > +0.5 cm
  (dVr has a sign according to the relative momentum of the 2 Ks's)
- 3D distance dV > 0.7 cm OR 2D distance dVr > +0.3 cm
- Projected vertex distance on the relative momentum δv < 0.7 cm

$$\delta_V = |(\boldsymbol{r}_{V2} - \boldsymbol{r}_{V1}) \times (\boldsymbol{p}_{t2} - \boldsymbol{p}_{t1})| / |\boldsymbol{p}_{t2} - \boldsymbol{p}_{t1}| = |\boldsymbol{r}_{V2} - \boldsymbol{r}_{V1}| \sin \Delta\varphi$$

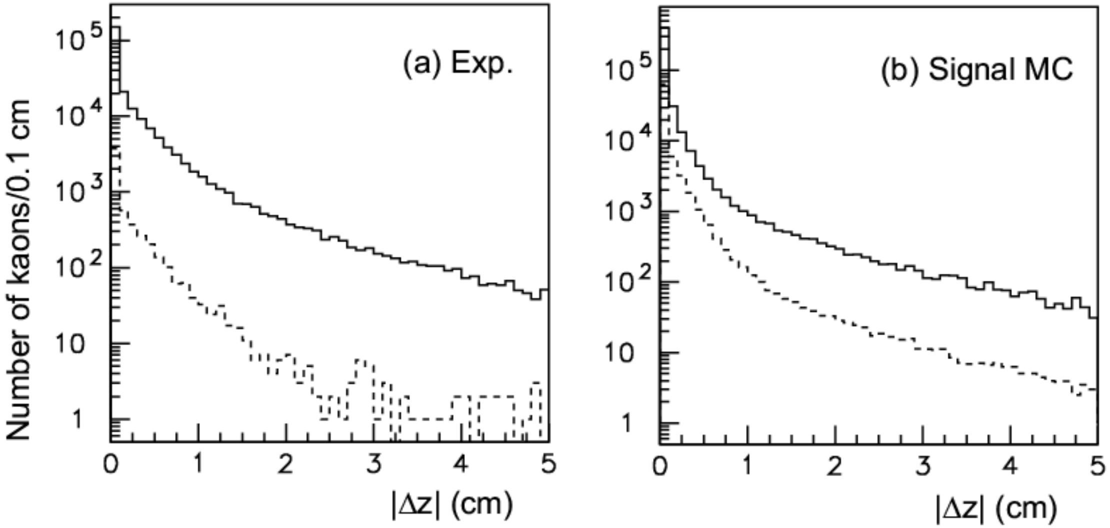
- $|\Sigma \mathbf{p}_t(Ks)| < 0.1$ GeV/c

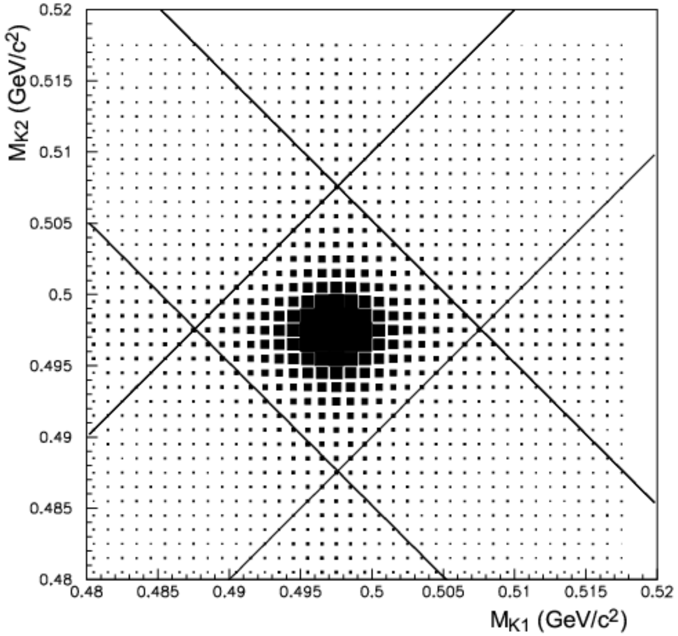
- Refined cut for the Ks mass
  $|\langle M_K \rangle - m_K| < 5$ MeV/c^2, $\langle M_K \rangle = (M_{K1} + M_{K2})/2$
- ECL total energy cut
  $E_{ECL} < E_{K1} + E_{K2} - 0.3$ GeV, E_{Ki} – Ks's total energy calculated from its lab. momentum

Ks Selection

Final KsKs mass-cut

z-matching @vertex





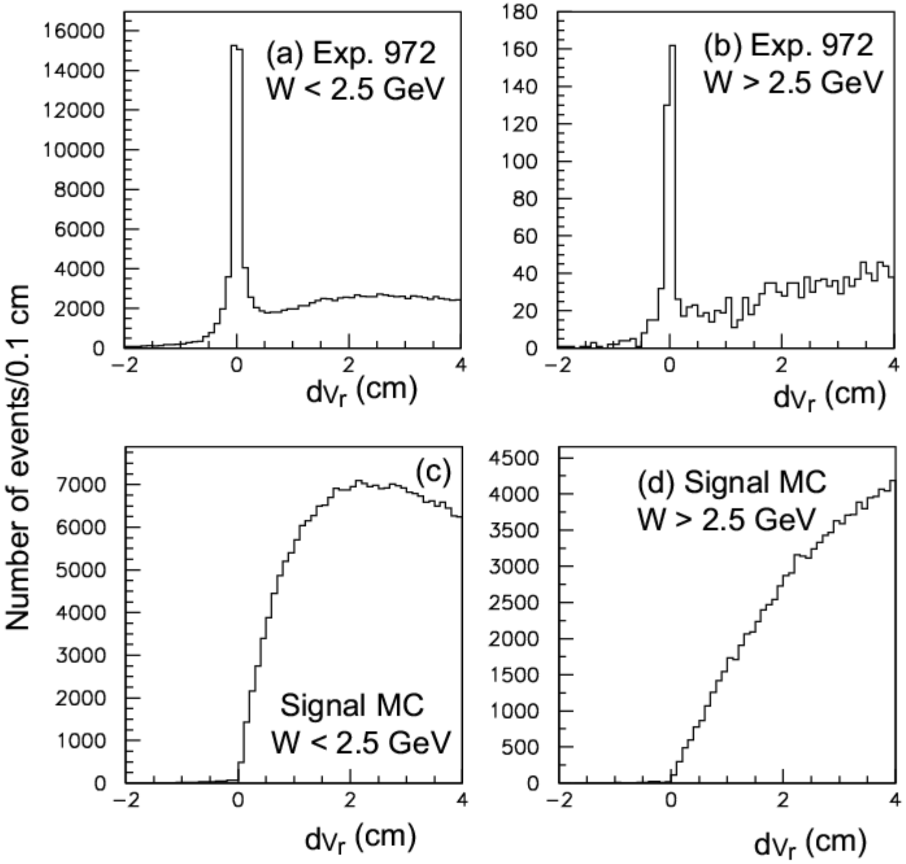
Solid : W<2.5 GeV
Dashed: W>2.5 GeV

Ks-mass vs Ks-mass

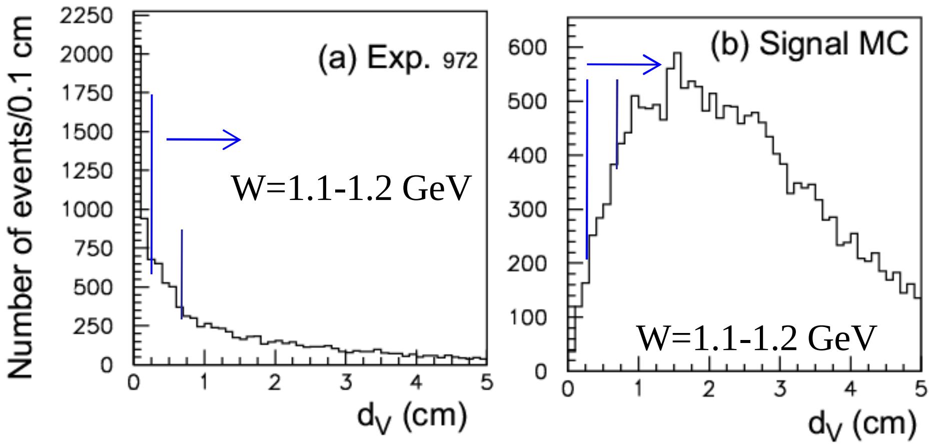
Cut lines for
[M(Ks1) + M(Ks2)]/2
and
|M(Ks1) – M(Ks2)|

Ks Ks vertex distances

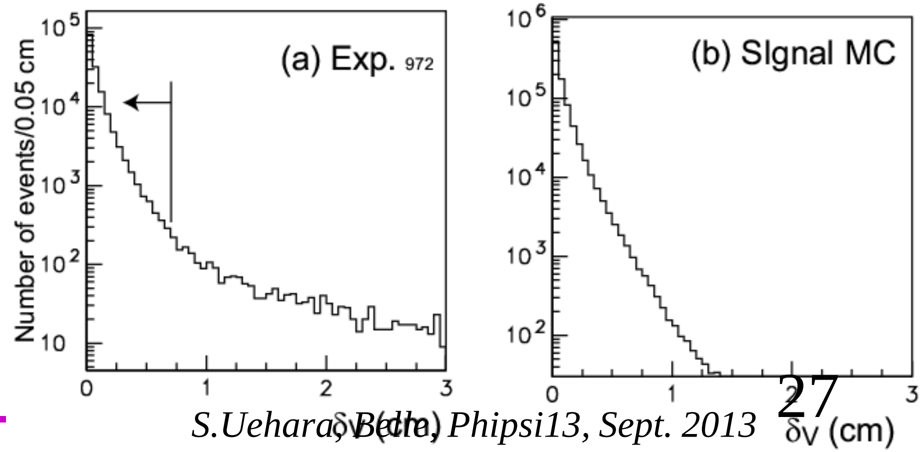
2D vertex distance



3D vertex distance



Tr. mometum diff. and vertex position diff. must be in parallel

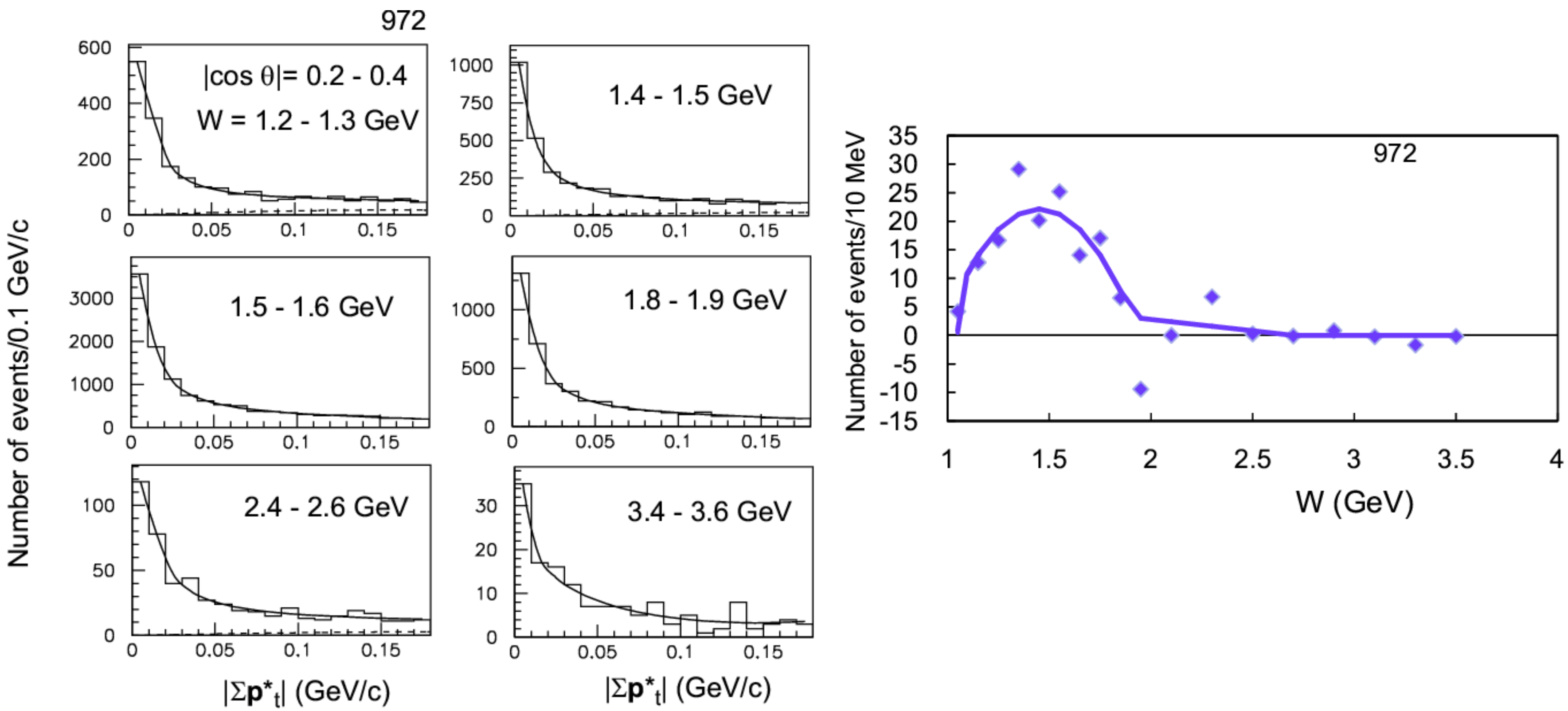


Sharp peaks near 0cm seen only in Exp.are from Direct 4π ($\pi^+\pi^-\pi^+\pi^-$) production backgrounds.

Background Subtractions (1)

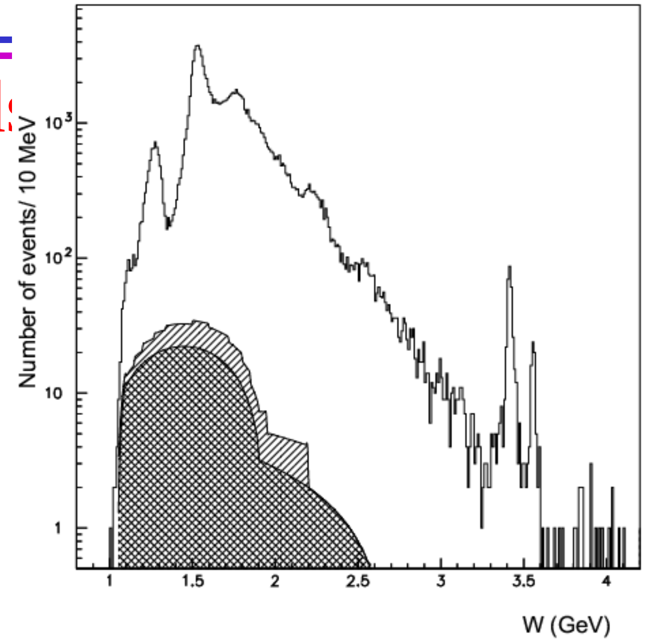
- Non-exclusive (KsKsX) backgrounds

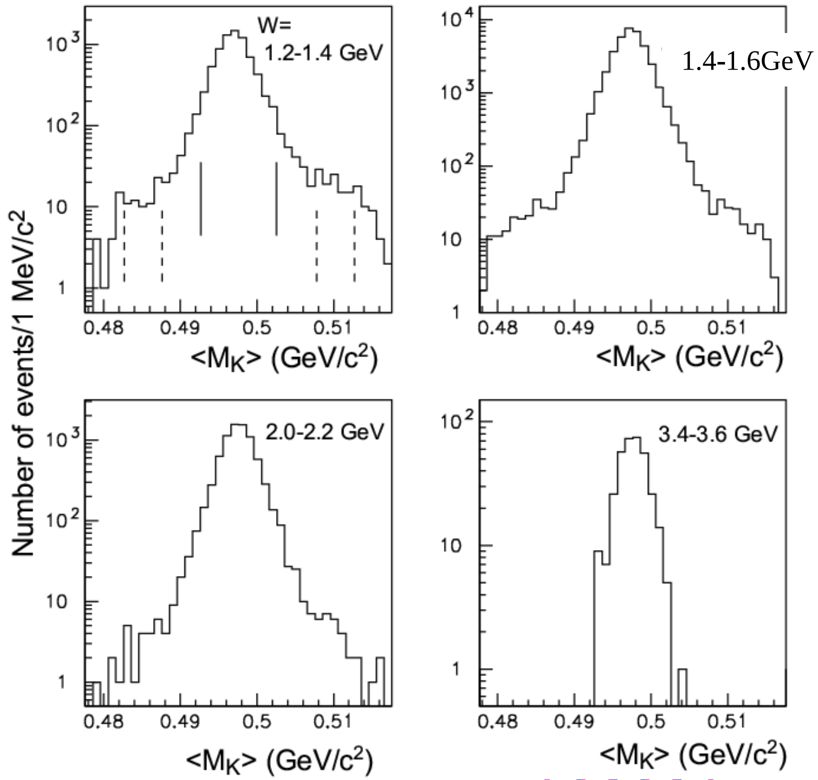
Estimated from a fit of $|\Sigma \mathbf{p}_t^*|$ distributions

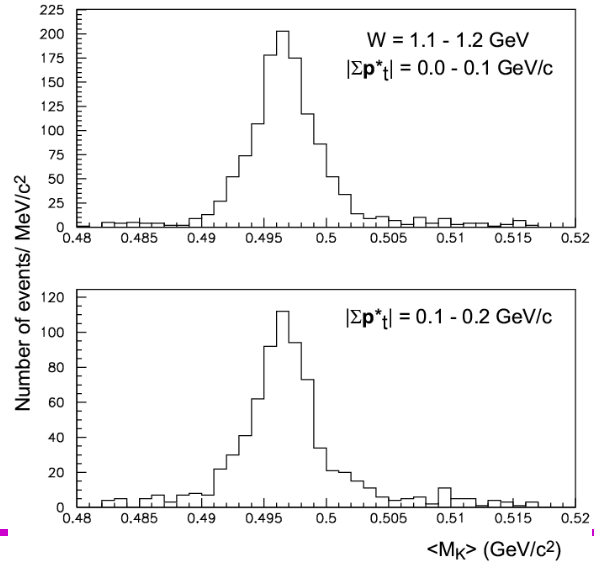


Background Subtractions (2)

- Non-Ks Ks(4π-process) backgrounds
  - Estimated from <M_K> sideband
  - Non-exclusive and non-Ks
    - --- very small (typically ~1% level)

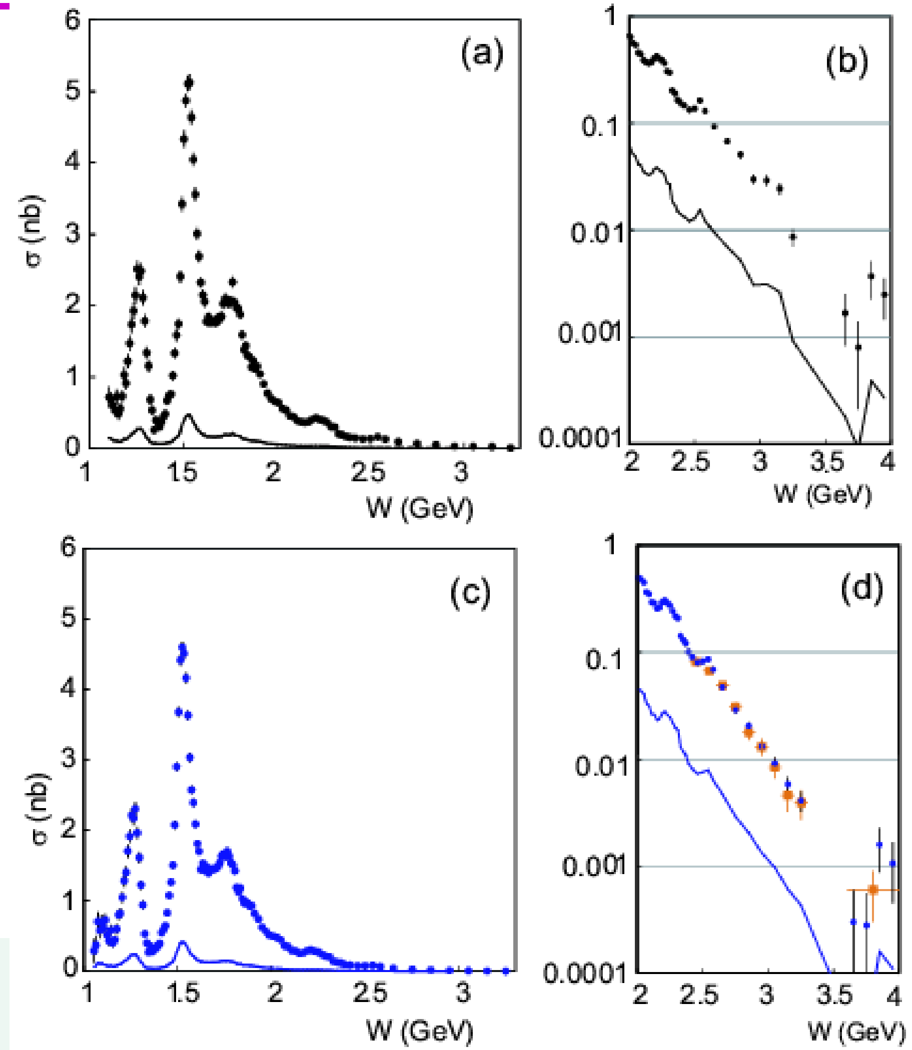






Cross section integrated over the angle

$$\int \frac{d\sigma}{d|\cos\theta^*|} \, d|\cos\theta^*|$$



Black --- $|\cos\theta^*|<0.8$
Blue --- $|\cos\theta^*|<0.6$
Orange --- $|\cos\theta^*|<0.6$ (previous, Belle 2007)

Systematic errors

Source	Uncertainty(%)
Tracking efficiency (for 4 tracks)	2
Beam background effect	1
Pion identification (for 4 tracks)	2
Non-exclusive and four-pion backgrounds	2 – 19
Geometrical coverage and fit uncertainty	4
$K_S^0 K \pi$ background subtraction	1 – 2
K_S^0-pair reconstruction	5 – 3
Trigger efficiency	5 – 7
$E_{\rm ECL}$ cut	1
Integrated luminosity and luminosity function	5 – 4
L4 efficiency	1 – 10
Total	9 – 25, typically 10

From correlation study of different Exp# settings in data and signal MC (→ Beam background effect)

A Half of the subtraction + 2% from pt-fit (quad.sum) (→ Non-exclusive and four-pion backgrounds)

Loose-cut sample (→ K_S^0-pair reconstruction)

Correlation of the two triggers (→ Trigger efficiency)

About 10% of the inefficiency (→ L4 efficiency)

Hat amplitudes

- We rewrite

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

- $\left|Y_J^{\ m}\right|^2$ are mutually independent

→ obtain "hat amplitudes":

$$\hat{S}^2, \hat{D}_0^{\ 2}, \hat{G}_0^{\ 2} \hat{D}_2^{\ 2}, \hat{D}_2^{\ 2} \text{ and } \hat{G}_2^{\ 2}$$

through fitting *dσ/dΩ*

- They contain interference terms
- Yet, they convey useful information on partial waves

W < 2 GeV : f_0(1710) assumption

- Parameterization

$$S = f_0(1710)e^{i\phi_{f0}} + B_S$$

$$D_0 = B_{D0}e^{i\phi_{D0}}$$

$$D_2 = f_2(1270) + a_2(1320)e^{i\phi_{a2}} + f_2'(1525)e^{i\phi_{f2'}} + B_{D2}e^{i\phi_{D2}}$$

$$B_L = \beta^{2L+1}(aW'^2 + bW' + c) \text{ (bgd amplitude)}$$

$$\beta = \sqrt{1 - \frac{4m_K^2}{W^2}}, \quad W' = W - W_{\text{th}}$$

- Fix param. of f_2(1270) and a_2(1320). Free f_2'(1525)
- Then fit $d\sigma/d\Omega$ (20 free param.)
- phases in D_2 are relative to f_2(1270)

Systematic uncertainties

+ σ and -σ

Source	Fit-H						Fit-L					
	Mass (MeV/c^2)		Γ_{tot} (MeV)		$\Gamma_{\gamma\gamma}\mathcal{B}(KK)$ (eV)		Mass (MeV/c^2)		Γ_{tot} (MeV)		$\Gamma_{\gamma\gamma}\mathcal{B}(KK)$ (eV)	
W-range	21	0	0	−15	0	−1	16	0	5	−13	6	−4
W bias	2	−2	6	−5	2	−1	4	0	2	−7	2	−4
Efficiency	8	−4	25	−30	209	0	11	−5	0	−28	2	−12
Overall normalization	4	−2	9	−11	1	−2	7	−2	4	−16	5	−8
$\cos\theta^*$ bias	0	−1	3	−1	1	0	4	0	2	−7	2	−4
B_S	5	−7	84	−9	87	−2	7	0	26	−3	35	−2
B_{D0}	0	0	1	0	0	0	1	0	0	−2	0	−1
B_{D2}	1	0	0	−1	0	0	11	−37	4	−11	1	−2
Mass($f_2(1270)$)	3	−1	6	−6	1	−1	3	0	0	−4	2	−3
$\Gamma_{\mathrm{tot}}(f_2(1270))$	0	0	1	0	0	0	2	−2	5	−4	4	−2
$\mathcal{B}(\gamma\gamma)(f_2(1270))$	7	0	12	−18	2	−4	6	−1	0	−17	5	−10
r_R	0	0	0	0	0	0	1	−1	1	0	1	0
Mass($a_2(1320)$)	1	0	0	−2	0	0	2	0	0	−2	0	−1
$\Gamma_{\mathrm{tot}}(a_2(1320))$	2	−2	7	−5	2	−1	3	0	2	−9	3	−6
$\mathcal{B}(\gamma\gamma)(a_2(1320))$	1	−1	2	0	1	0	2	0	0	−2	0	−1
Mass($f_2'(1525)$)	2	−2	1	0	1	0	1	−1	3	−4	3	−3
$\Gamma_{\mathrm{tot}}(f_2'(155))$	2	−2	4	−3	2	−1	4	0	0	−4	0	−2
$\mathcal{B}(\gamma\gamma)(f_2'(1525))$	14	0	0	−24	0	−4	14	−18	14	−27	9	−12
$\phi_{f_2'(1525)}$	4	−15	33	−12	22	−3	4	−5	0	−17	3	−11
$\phi_{a_2(1320)}$	4	−1	5	−8	1	−2	3	0	0	−4	0	−2
Total	29	−18	96	−50	227	−8	31	−42	31	−54	38	−26

Resonances in M=1.7 – 2.4 GeV (from PDG2012)

Parameter	$f_0(1710)$	$a_2(1700)$	$f_2(1810)$
Mass (MeV/c^2)	1720 ± 6	1732 ± 16	1815 ± 12
Γ_{tot} (MeV)	135 ± 8	194 ± 40	197 ± 22
$f_J/a_J \to K\bar{K}$	seen	seen	unknown
$f_J/a_J \to \gamma\gamma$	unknown	unknown	seen

Parameter	$f_0(2200)$	$f_2(2300)$	$f_4(2300)$
Mass (MeV/c^2)	2189 ± 13	2297 ± 28	~ 2300
Γ_{tot} (MeV)	238 ± 50	149 ± 41	250 ± 80
$f_J \to K\bar{K}$	seen	seen	seen
$f_J \to \gamma\gamma$	unknown	seen	unknown

$f_J(2220)$ $I^G(J^{PC}) = 0^+(2^{++}$ or $4^{++})$

OMITTED FROM SUMMARY TABLE

Needs confirmation. See our mini-review in the 2004 edition of this *Review*, PDG 04.

$f_J(2220)$ MASS

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

$f_J(2220)$ WIDTH

VALUE (MeV)	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
23^{+8}_{-7} OUR AVERAGE					

Fitting the region W > 2 GeV

- Parameterization

$$i-wave = B.W.e^{i\phi_i} + B_i$$

$$B_i = b_i \left(\frac{W}{W0} \right)^{-c_i} e^{i\phi_i}$$

(assume power behavior

for non-resonant background:

i = S, D_0, D_2 and G_2; (we assume G_0=0))

B.W.= f_J(2200) and/or f_J(2500) with J=0, 2 and 4

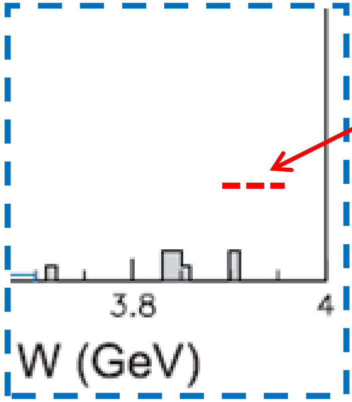
- Then fit *dσ/dΩ* (typically 16 free parameters)

Fit results for 13 assumptions

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

S.Uehara, Belle, Phipsi13, Sept. 2013

Upper limit for $\chi_{c2}(2P) \rightarrow KsKs$



$\chi_{c2}(2P)$ $I^G(J^{PC}) = 0^+(2^{++})$

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

$\chi_{c2}(2P)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\gamma\gamma$	seen	1964
$D\overline{D}$	seen	615
D^+D^-	seen	600
$D^0\overline{D}^0$	seen	615

We use a counting method
No knowledge for $\chi_{c0}(2P)$

$$\Gamma_{\gamma\gamma}(\chi_{c2}(2P))\mathcal{B}(\chi_{c2}(2P) \rightarrow K^0_S K^0_S) < 0.064 \text{ eV}$$

2 events in $M \pm 2\Gamma$

90% CL UL, 1σ of syst.err. shifted

$N^{UL} = 5.32$ for 90%CL
without assuming interference
Poisson(μ=5.32; n<=2) = 0.10

$\Gamma_{\gamma\gamma}(\chi_{c2}(2P))$ is not known, but conjectured to be around 500 eV

Upper limit for X(3915)→KsKs

PDG2013 X(3915) = χ_{c0}(2P)

Same counting as that in χ_{c2}(2P)

2 events in M ± 2Γ

N^{UL} = 5.32 for 90%CL
without assuming interference

Same method, the same events
Almost same M and Γ
Spin and angular distribution are different.

$\chi_{c0}(2P)$
was $X(3915)$

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

$\chi_{c0}(2P)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
3918.4± 1.9 OUR AVERAGE				
[3917.5 ± 2.7 MeV OUR 2012 AVERAGE]				
3919.4± 2.2± 1.6	59 ± 10	LEES 12AD	BABR	$e^+e^- \to e^+e^-\omega J/\psi$
$3919.1^{+3.8}_{-3.4}\pm 2.0$		DEL-AMO-SA...10B	BABR	$B \to \omega J/\psi K$
3915 ± 3 ± 2	49 ± 15	UEHARA 10	BELL	10.6 $e^+e^- \to e^+e^-\omega J/\psi$
3943 ±11 ±13	58 ± 11	[1] CHOI 05	BELL	$B \to \omega J/\psi K$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$3914.6^{+3.8}_{-3.4}\pm 2.0$		[1] AUBERT 08W	BABR	Superseded by DEL-AMO-SANCHEZ 10B

[1] $\omega J/\psi$ threshold enhancement fitted as an S-wave Breit-Wigner resonance.

$\chi_{c0}(2P)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
20± 5 OUR AVERAGE Error includes scale factor of 1.1. [27 ± 10 MeV OUR 2012 AVERAGE Scale factor = 1.4]				
13± 6± 3	59 ± 10	LEES 12AD	BABR	$e^+e^- \to e^+e^-\omega J/\psi$
$31^{+10}_{-8}\pm 5$		DEL-AMO-SA...10B	BABR	$B \to \omega J/\psi K$
17±10± 3	49 ± 15	UEHARA 10	BELL	10.6 $e^+e^- \to e^+e^-\omega J/\psi$
87±22±26	58 ± 11	[2] CHOI 05	BELL	$B \to \omega J/\psi K$
• • • We do not use the following data for averages, fits, limits, etc. • • •				

$$\Gamma_{\gamma\gamma}(\chi_{c0}(2P))\mathcal{B}(\chi_{c0}(2P) \to K^0_S K^0_S) < 0.49 \text{ eV}$$

90% CL UL, 1σ of syst.err. shifted

Upper limit for $\eta_c \to K_S K_S$

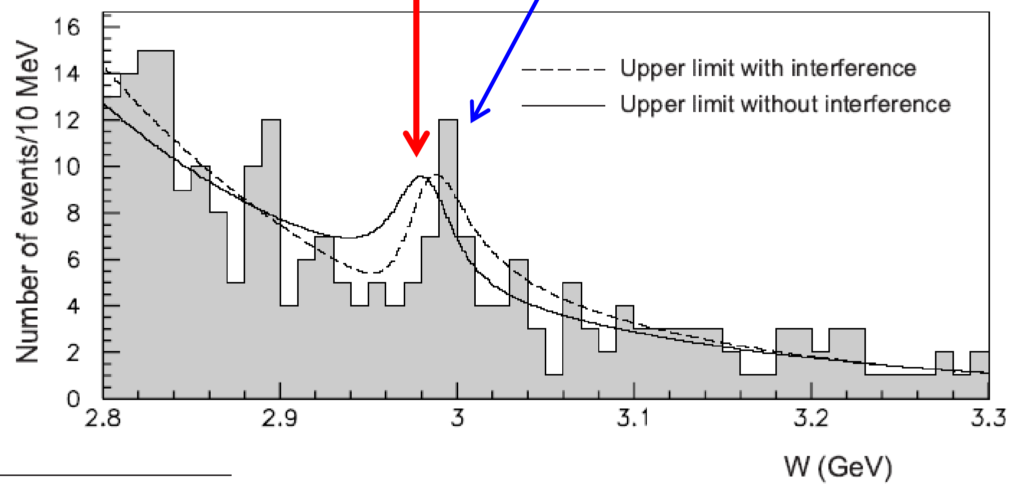
P and CP violating process

(PDG2012 BF < 4.2×10^{-4})

Fit function

$$Y(W) = |\sqrt{\alpha k W^{-\beta}} + e^{i\phi}\sqrt{N}\ \ \mathrm{BW}\ (W)|^2 + \alpha(1-k)W^{-\beta}$$

Fluctuation ?
of 1 –2 σ



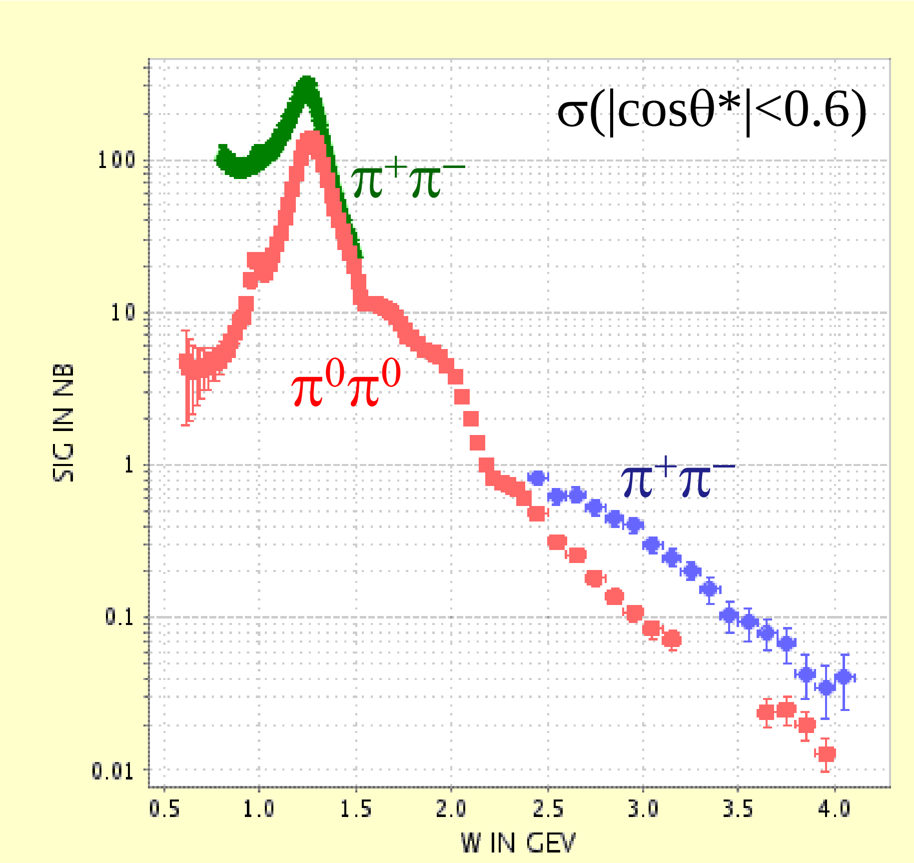
N^{UL} = 15 (= 85) for 90%CL
without (with) interference
k=0 (0<k≤1)

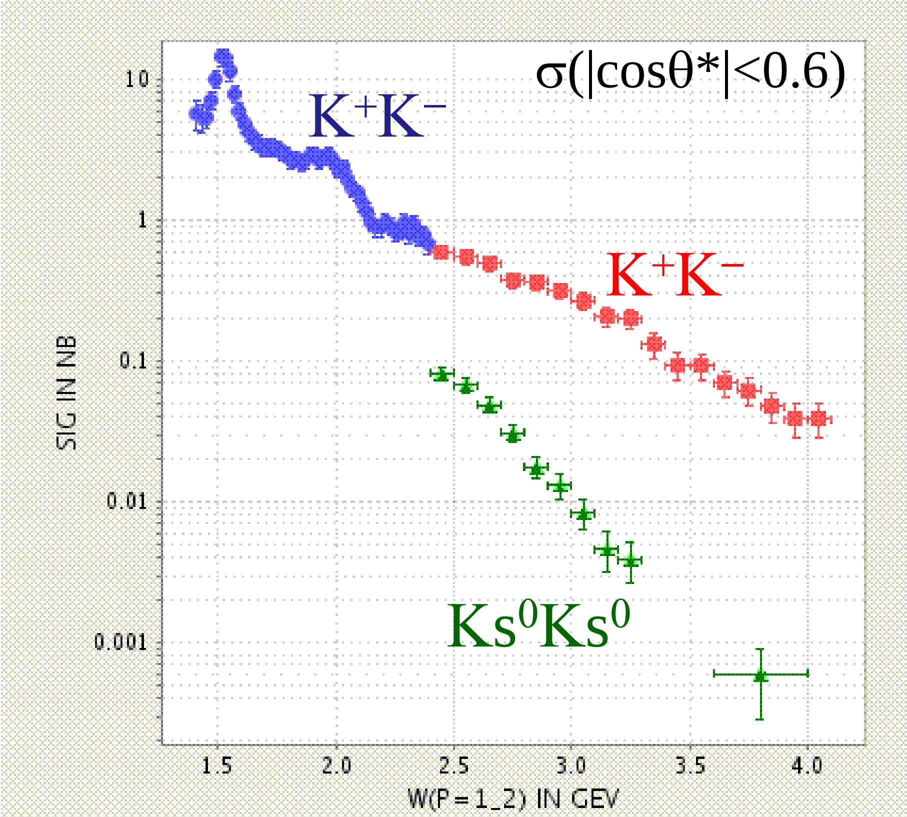
k cannot be determined by the fit

Interference	$\Gamma_{\gamma\gamma}\mathcal{B}(\eta_c)$	$\mathcal{B}(\eta_c \to K_S^0 K_S^0)$	
Without	< 0.29 eV	$< 5.6\times10^{-5}$	90% CL
With	< 1.6 eV	$< 3.2\times10^{-4}$	90% CL

90% CL: UL $\Delta(2\ln L) = (1.64)^2$
floating the other parameters
1σ of syst.err. shifted
→World severest upper limits

Cross sections integrated over angle

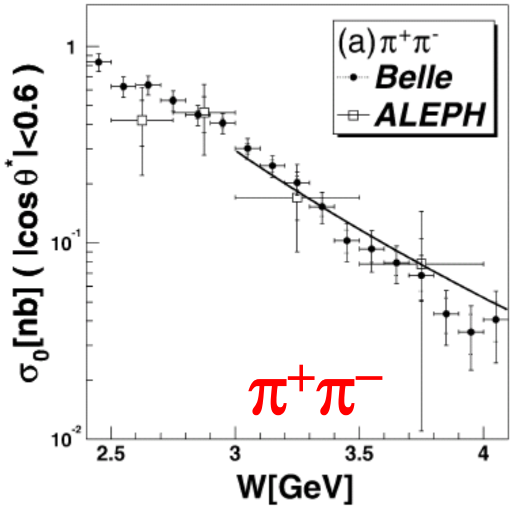


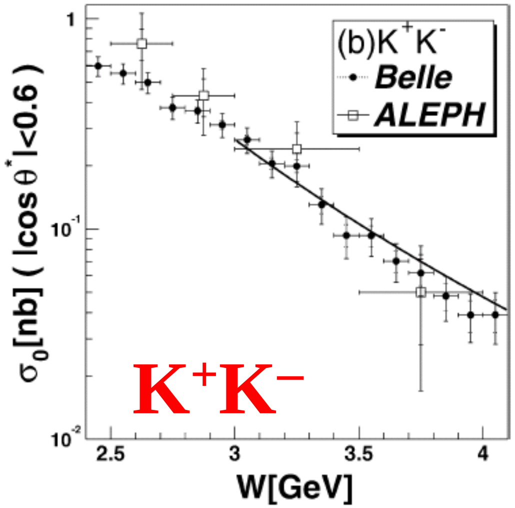


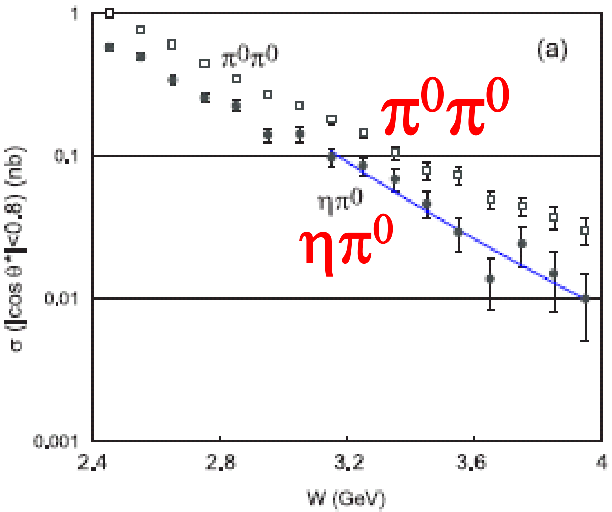
♠Those for $\eta\pi^0$ and $\eta\eta$ are shown in other slides

W-dependences at high energies

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



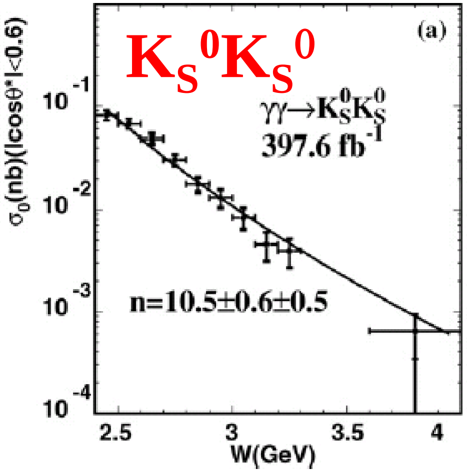


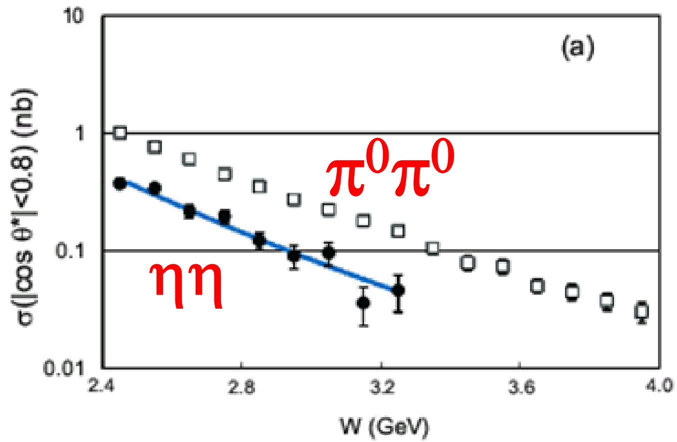


Fitted and reproduced

Slope parameter **n** different

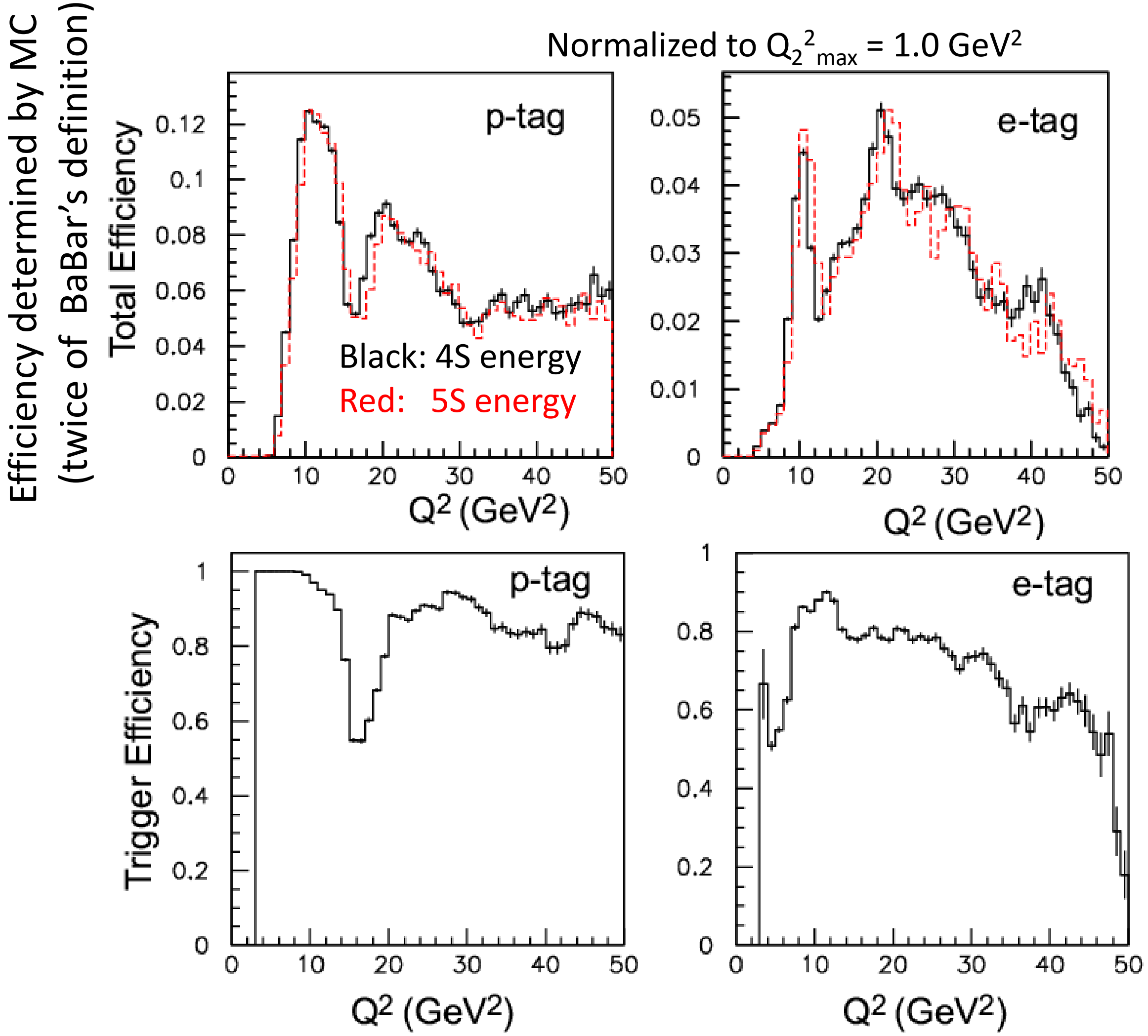
among the reactions





Charmonium contributions
not included/removed

Efficiency for the Signal Process at **Belle**

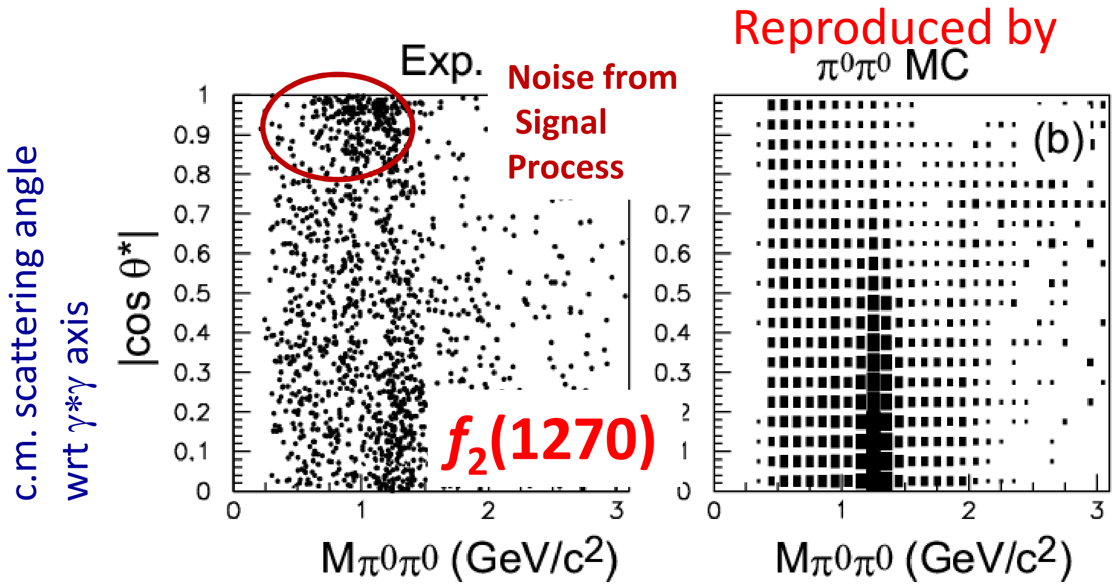


Up-down structures in the efficiencies are due to Bhabha-veto trigger condition correlated in the ($\cos\theta_e$, $\cos\theta_{\gamma\gamma}$) plane

The trigger efficiency is defined for the acceptance after the selection

$\pi^0\pi^0$ background MC

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



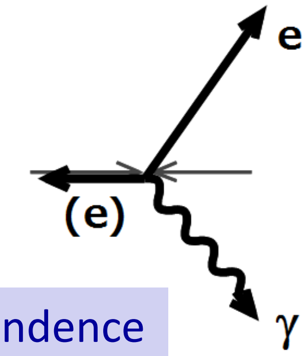
Background contamination in signal is estimated by the **$\pi^0\pi^0$ background MC** which is normalized to the observation, **as 2%**

Calibrations using Radiative-Bhabha (VC) Events

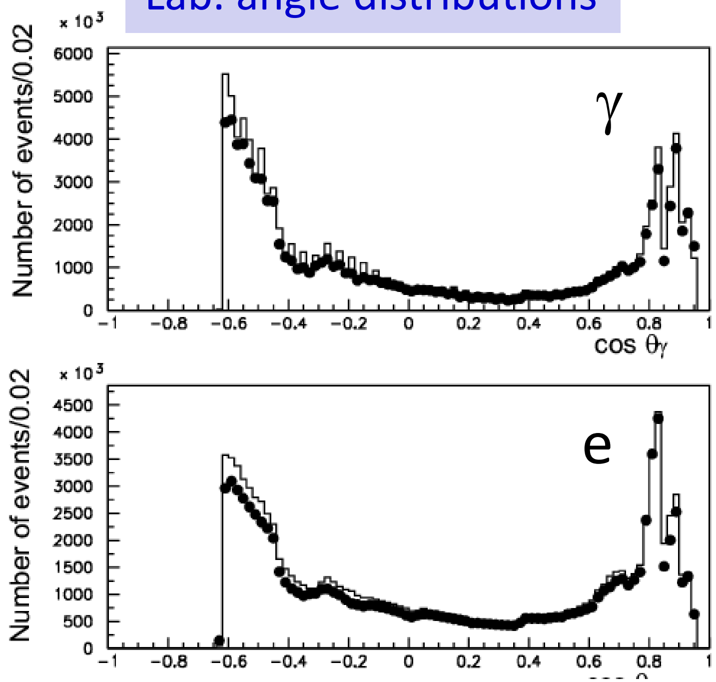
Bhabha-veto threshold is measured in real data

of **Virtual-Compton process of (e)eγ**

and is tuned in Trigger Simulator

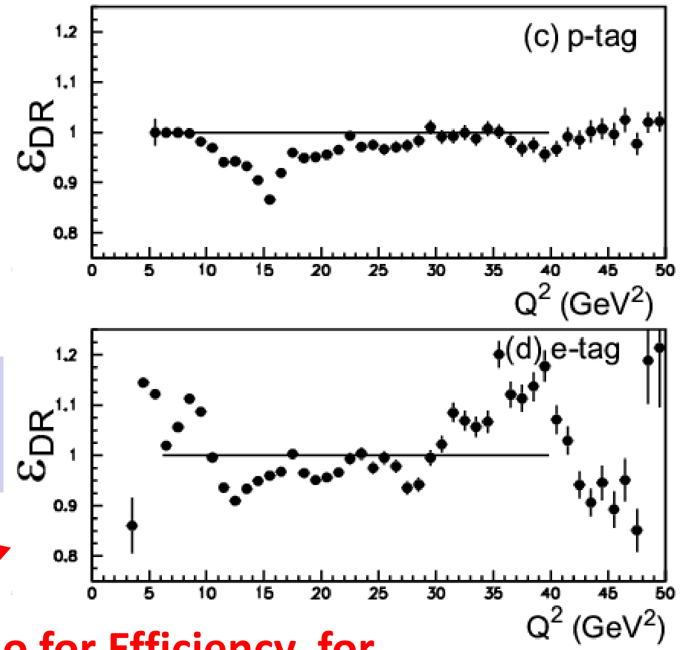


Lab. angle distributions



cos θ

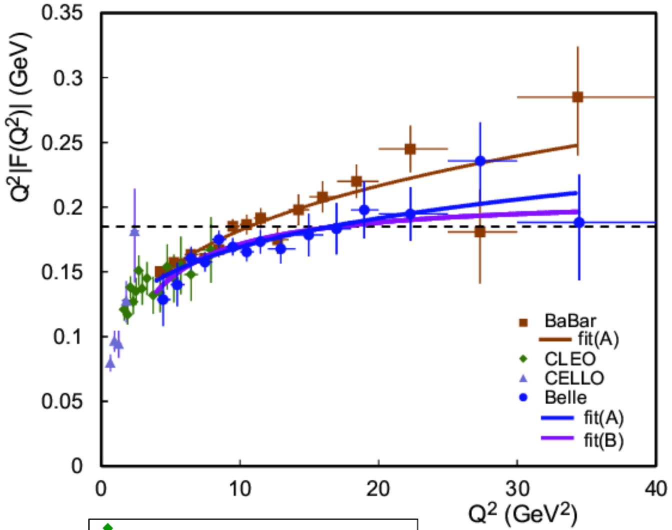
Q^2 dependence

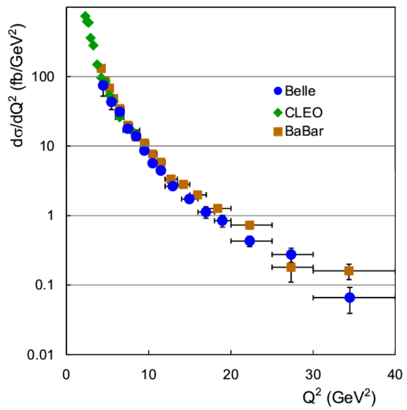


dots: Exp.
histograms: MC

ε_{DR}:
Exp./MC Ratio for Efficiency for "Bhabha-Mask" × "Bhabha-veto"

Comparisons with Previous Measurements and Fits





No rapid growth above Q^2>9GeV^2 is seen in Belle result.

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

Fit A **(suggested by BaBar)**

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

BaBar:

$A = 0.182 \pm 0.002 (\pm 0.004)$ GeV

$\beta = 0.25 \pm 0.02$

Belle:

$A = 0.169 \pm 0.006$ GeV

$\beta = 0.18 \pm 0.05$

χ^2/ndf = 6.90/13 ~1.5σ difference from BaBar

Fit B **(with an asymptotic parameter)**

$Q^2|F(Q^2)| = BQ^2/(Q^2+C)$

Belle:

$B = 0.209 \pm 0.016$ GeV

$C = 2.2 \pm 0.8$ GeV^2

χ^2/ndf = 7.07/13

B is consistent with the QCD value (0.185GeV)