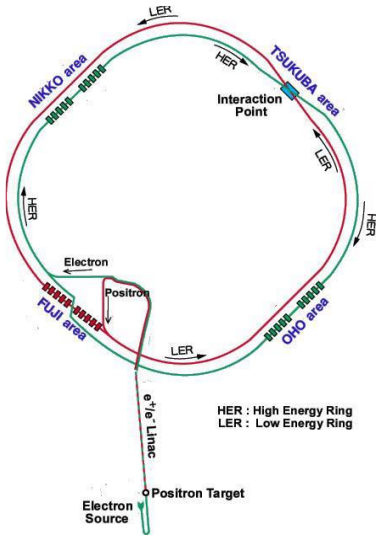
# Two-photon processes at Belle

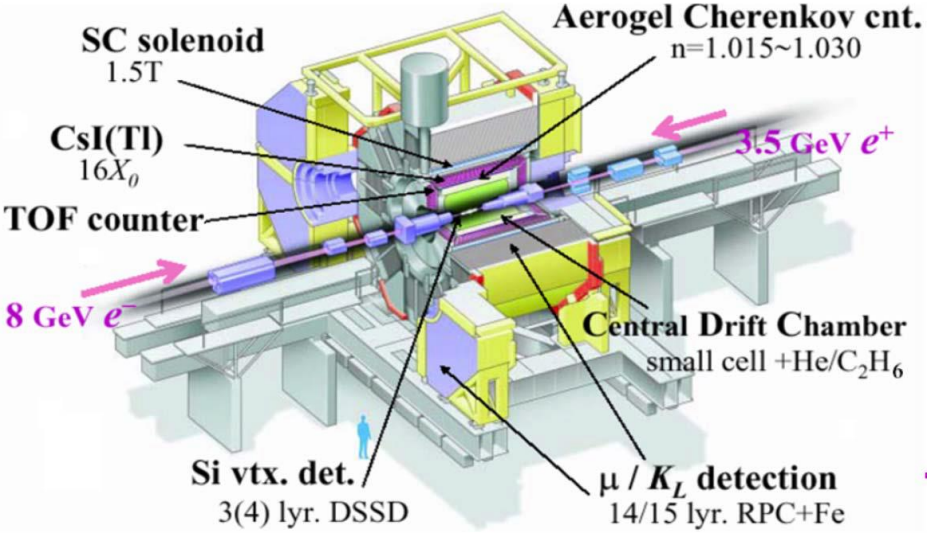

## Wenbiao Yan(USTC)

## On behalf of Belle Collaboration

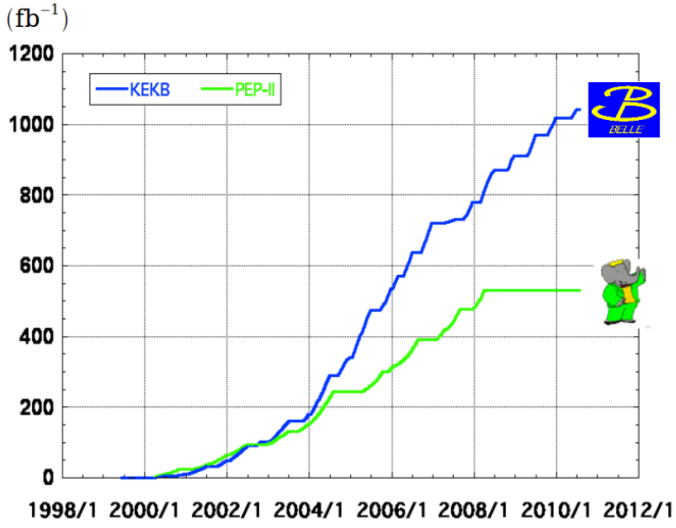


# KEKB accelerator & Belle Detector




- Asymmetric $e^+e^-$ collider
  - ✓ 8 GeV($e^-$); 3.5GeV($e^+$)
  - ✓ Around 10.58GeV ↔ Y(4S)
- World-highest luminosity
  - ✓ $L_{max}=2.1\times10^{34}cm^{-2}s^{-1}$

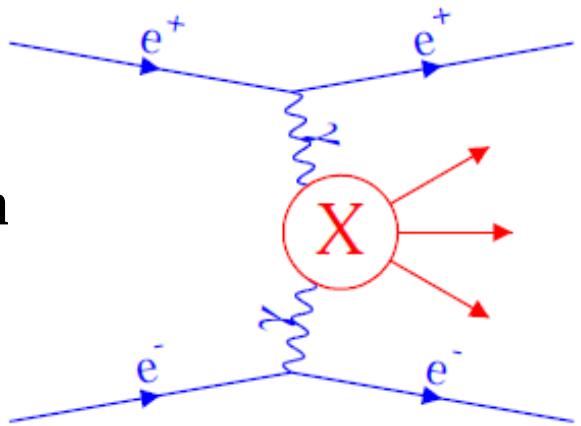


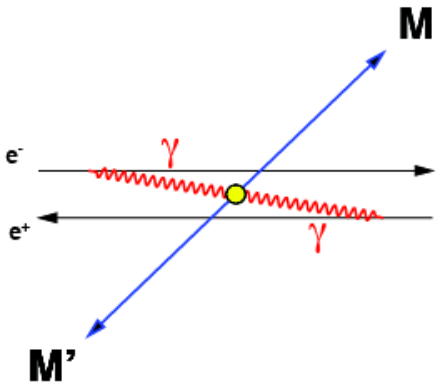

**> 1 ab$^{-1}$**
**On resonance:**
Υ(5S): 121 fb$^{-1}$
Υ(4S): 711 fb$^{-1}$
Υ(3S): 3 fb$^{-1}$
Υ(2S): 25 fb$^{-1}$
Υ(1S): 6 fb$^{-1}$
**Off reson./scan:**
~ 100 fb$^{-1}$

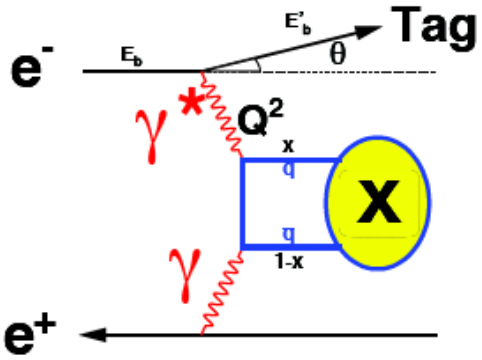
**~ 550 fb$^{-1}$**
**On resonance:**
Υ(4S): 433 fb$^{-1}$
Υ(3S): 30 fb$^{-1}$
Υ(2S): 14 fb$^{-1}$
**Off resonance:**
~ 54 fb$^{-1}$

# Two-photon process

- Reaction by virtual photon from $e^+$ & $e^-$ beam
  - ✓ Photon virtuality $Q^2 = 4E_b E_b' \sin^2 \frac{\theta_e}{2}$
  - ✓ Mass of hadronic system W
- Study of QCD calculation, Transition form factors (TFF), exotics search
- No-tag, single-tag and double-tag methods




- ☐ double-tag method
- ☐ $e^+$ and $e^-$ detected
- ☐ no belle results

$e^+$ & $e^-$ not detected  $e^+$ or $e^-$ detected

# Two-photon achievements at Belle

| | GeV | $\|\cos\theta^*\|$ < | $fb^{-1}$ | reference | year |
|---|---|---|---|---|---|
| $\gamma J/\psi$ | 3.2 - 3.8 | | 32.6 | PLB540, 33 | 2002 |
| $\pi^+\pi^-$ | 2.4 - 4.1 | 0.6 | 88 | PLB15, 39 | 2005 |
| | 0.8 -1.5 | 0.6 | 86 | PRD75, 051101 | 2007 |
| | | | | JPhySocJpn76, 074102 | 2007 |
| $K^+K^-$ | 1.4 - 2.4 | 0.6 | 67 | EPJC32, 323 | 2003 |
| | 2.4 - 4.1 | 0.6 | 88 | PLB15, 39 | 2005 |
| ppbar | 2.0 - 4.0 | 0.6 | 89 | PLB621, 41 | 2005 |
| 4 mesons | 2.75 - 3.75 | | 395 | EPJC53, 1 | 2006 |
| KsKs | 2.4 - 4.0 | 0.6 | 398 | PLB651, 15 | 2007 |
| | 1.05 - 4.0 | 0.8 | 972 | PTEP2013, 123C01 | 2013 |
| $\pi^0\pi^0$ | 0.6 - 4.0 | 0.8 | 95 | PRD78, 052004 | 2008 |
| | 0.6 - 4.1 | 0.8 | 223 | PRD79, 052009 | 2009 |
| $\eta\pi^0$ | 0.84 - 4.0 | 0.8 | 223 | PRD80, 032001 | 2009 |
| $\eta\eta$ | 1.096 - 3.8 | 1.0 | 393 | PRD82, 114031 | 2010 |
| $\omega J/\psi$ | 3.9 - 4.2 | | 694 | PRL104, 092001 | 2010 |
| $\phi J/\psi$ | 4.2 - 5.0 | | 825 | PRL104, 112004 | 2010 |
| $\omega\omega,\omega\phi,\phi\phi$ | thr - 4.0 | | 870 | PRL108, 232001 | 2012 |
| $\eta'\pi^+\pi^-$ | 1.4 - 3.4 | | 673 | PRD86, 052002 | 2012 |
| $\pi^0$ | $Q^2\in[4,40]GeV^2$ | | 759 | PRD86, 092007 | 2012 |
| $\pi^0\pi^0$ | $Q^2<30GeV^2$ | | 759 | PRD93, 032003 | 2016 |
| $ppbarK^+K^-$ | 3.2 - 5.6 | | 980 | PRD93, 112017 | 2016 |

**The $d\sigma/d|\cos\theta^*|$ for some processes are measured**

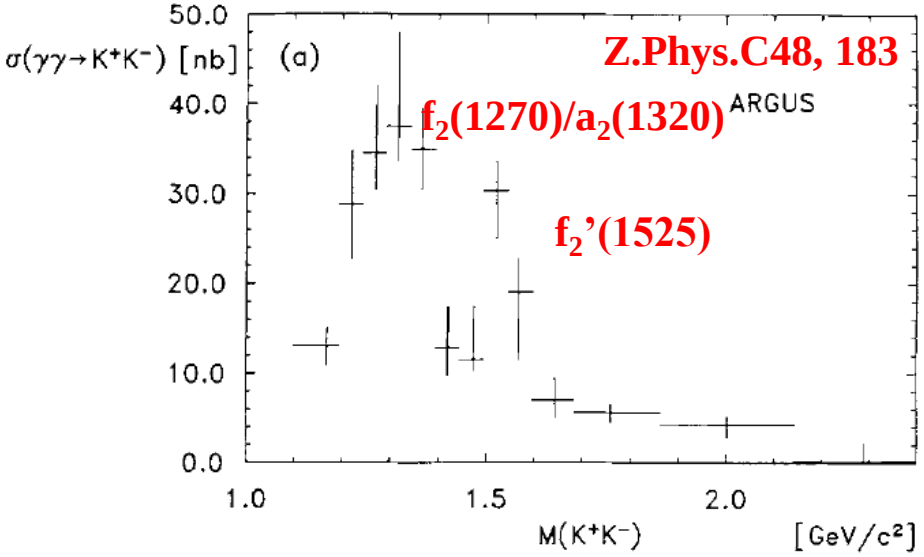
# Two-photon by real photon: no-tag

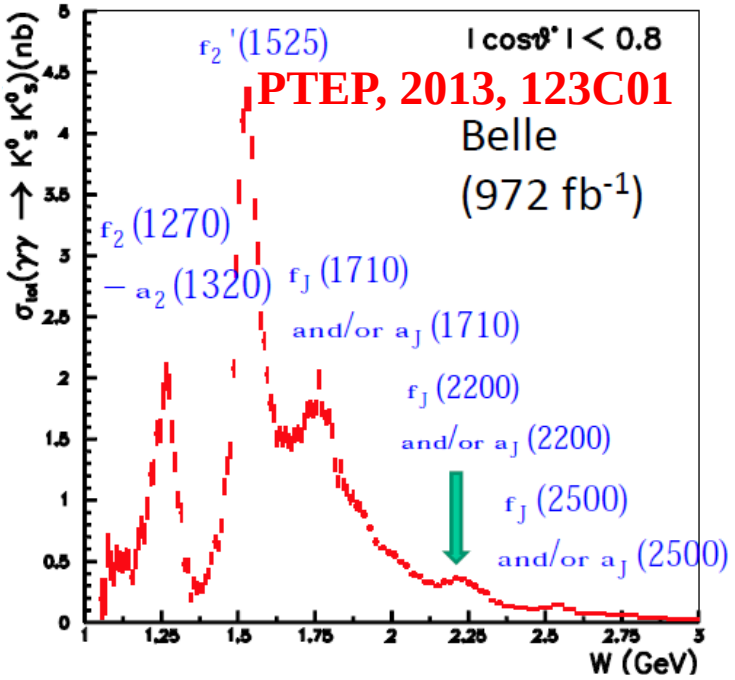
- **Collision by two-quasi-real photons**
- **For W < 3GeV, e.g. $\gamma\gamma \rightarrow K_s K_s$**

$$\frac{d\sigma}{4\pi d|\cos\theta^*|}(\gamma\gamma \rightarrow MM') = |SY_0^0 + D_0 Y_2^0 + G_0 Y_4^0|^2 + |D_2 Y_2^2 + G_2 Y_4^2|^2$$
$$= \hat{S}^2|Y_0^0|^2 + \hat{D}_0^2|Y_2^0|^2 + \hat{D}_2^2|Y_2^2|^2 + \hat{G}_0^2|Y_4^0|^2 + \hat{G}_2^2|Y_4^2|^2$$

- ✓ **two-photon spin-helicity (J, λ) have (0, 0), (2, 0), (2, ±2)**
- ✓ **S, $D_\lambda$, $G_\lambda$ for final hadronic systems**
- ✓ **$Y_J^m$ are spherical harmonics**
- ✓ **Angular dependence of cross section is governed by $Y_J^m$**
- ✓ **Energy dependence of cross section by partial wave**
- ✓ **Measure two-photon decay width $\Gamma_{\gamma\gamma}$ for studying nature of resonances**

# $f_2(1270)$-$a_2(1320)$ interference @ $\gamma\gamma \to K\bar{K}$



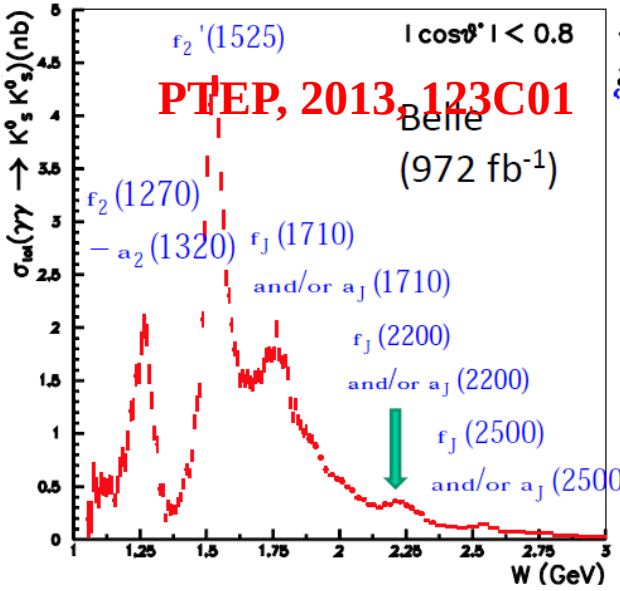



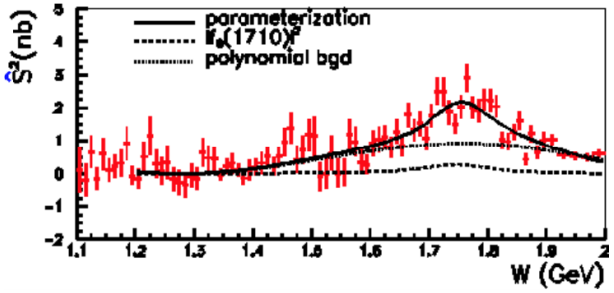

- **Constructive interference**
  - ✓ **$f_2(1270)+a_2(1320)$ in $K^+K^-$**
- **Destructive interference**
  - ✓ **$f_2(1270)$-$a_2(1320)$ in $K_sK_s$**
- **Due to a phase relation in isospin composition (PLB 59, 269)**

- **A fit in W @ (1.15, 1.65)GeV**
- **Phase difference between $f_2(1270)$ and $a_2(1320)$**

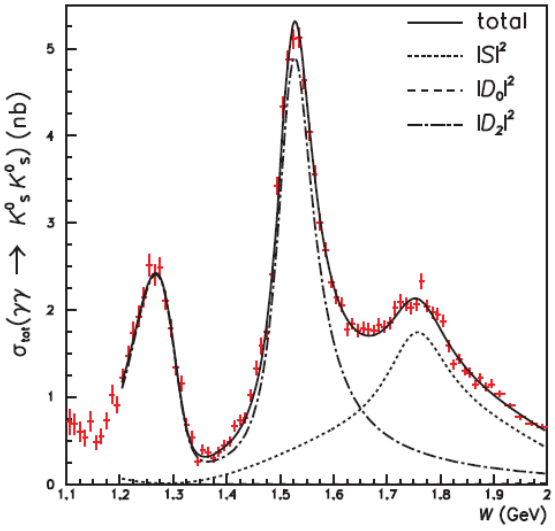
$$\left(172.6^{+6.0+12.2}_{-0.7-7.0}\right)^\circ$$

# $f_0(1710)$ formation in $K_sK_s$




- **Assume a signal resonance with J=0/2 , J=0 is favored.**




| | $f_0(1710)$ fit | | | | $f_2(1710)$ fit | |
|---|---|---|---|---|---|---|
| Parameter | fit-H | fit-L | H,L combined | PDG | fit-H | fit-L |
| $\chi^2/ndf$ | 694.2/585 | 701.6/585 | Two solutions of interference | | 796.3/585 | 831.5/585 |
| Mass($f_J$) (MeV/$c^2$) | $1750^{+5+29}_{-6-18}$ | $1749^{+5+31}_{-6-42}$ | $1750^{+6+29}_{-7-18}$ | $1720 \pm 6$ | $1750^{+6}_{-7}$ | $1729^{+6}_{-7}$ |
| $\Gamma_{tot}(f_J)$ (MeV) | $138^{+12+96}_{-11-50}$ | $145^{+11+31}_{-10-54}$ | $139^{+11+96}_{-12-50}$ | $135 \pm 6$ | $132^{+12}_{-11}$ | $150 \pm 10$ |
| $\Gamma_{\gamma\gamma}\mathcal{B}(K\bar{K})_{f_J}$ (eV) | $12^{+3+227}_{-2-8}$ | $21^{+6+38}_{-4-26}$ | $12^{+3+227}_{-2-8}$ | unknown | $2.1^{+0.5}_{-0.3}$ | $1.6 \pm 0.2$ |

- **$f_0(1710) \to K_sK_s$ is confirmed in two-photon process.**

# W-dependence of cross section

- **Study in high-W region @ no-tag method** — **PRD 24, 1808**, **NPB 329, 285**
  - ✓ **Good place to test QCD**
- **$\sigma \propto W^{-n}$: $W^{-6}$ for charged pair, $W^{-10}$ for neutral and $p\bar{p}$**

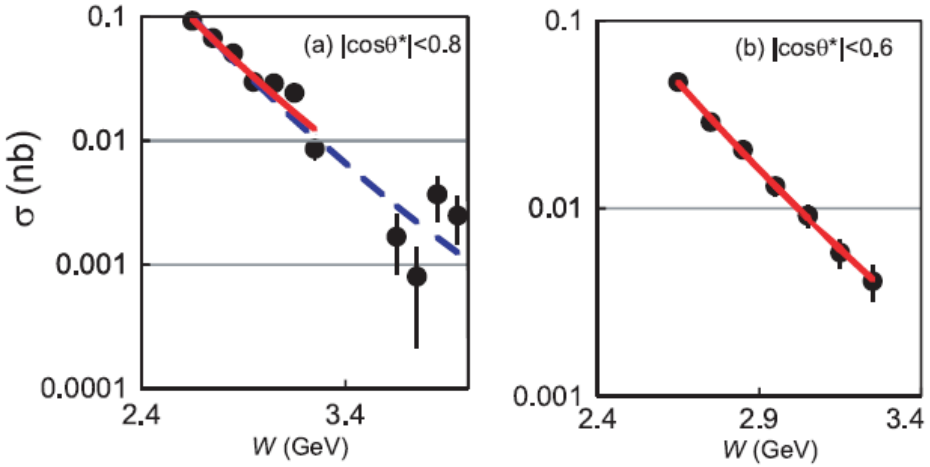
$$\frac{d\sigma}{d|\cos\theta^*|} = 16\pi\alpha^2 \frac{|F_M(W^2)|^2}{W^2}\left\{\frac{(e_1-e_2)^4}{\sin^4\theta^*} + \frac{2e_1e_2(e_1-e_2)^2}{\sin^2\theta^*}g(\theta^*) + 2e_1^2e_2^2g^2(\theta^*)\right\}$$

  - ✓ **$F_M$: meson form factor**
  - ✓ **$g(\theta^*)$: unknown, non-perturbative factor**

| | pQCD[2] | Belle | W(GeV) | $\lvert\cos\theta^*\rvert<$ |
|---|---|---|---|---|
| $\pi^+\pi^-$ | 6 | 7.9±0.4±1.5 | 3.0-4.1 | 0.6 |
| $K^+K^-$ | 6 | 7.3±0.3±1.5 | 3.0-4.1 | 0.6 |
| KsKs | 10 | 10.5±0.6±0.5 | 2.4-4.0 | 0.6 |
| KsKs | 10 | 11.0±0.4±0.4 | 2.6-4.0 | 0.8 |
| $\pi^0\pi^0$ | 10 | 8.0±0.5±0.4 | 3.1-4.1 | 0.8 |
| ppbar | 10 | 12.4+2.4-2.3 | 3.2-4.0 | 0.6 |

# $\gamma\gamma \to K_s K_s$

- **Study of $K_s K_s$ via fusion with low background level**

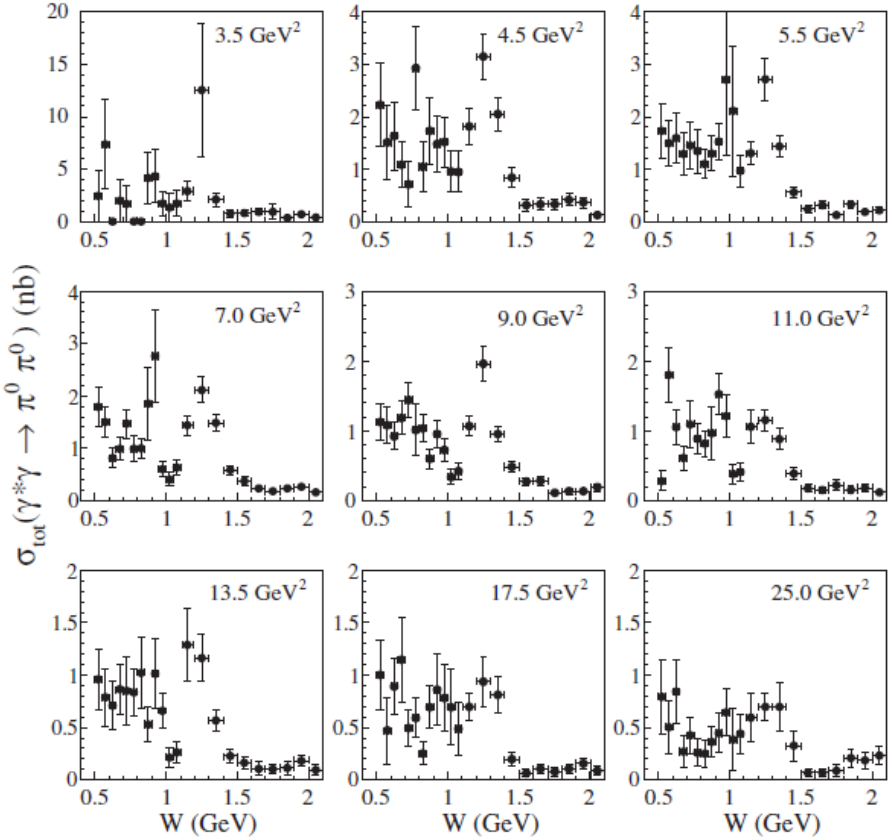



$$\sigma(|\cos\theta^*| < 0.8) = aW^{-n}$$

| $W$ range (GeV) | $\lvert\cos\theta^*\rvert$ range | $n$ | Note |
|---|---|---|---|
| 2.6–4.0 (excluding 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 (excluding 3.3–3.6) | $< 0.6$ | $10.5 \pm 0.6 \pm 0.5$ | Belle 2007 |

- **Close to n=10, agreement with pQCD**

# $\gamma\gamma^* \rightarrow 2\pi^0$

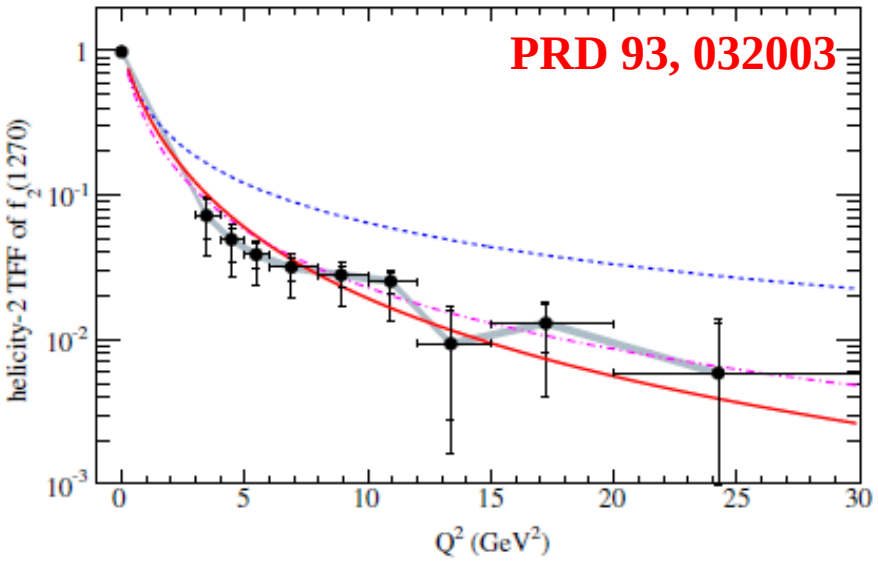


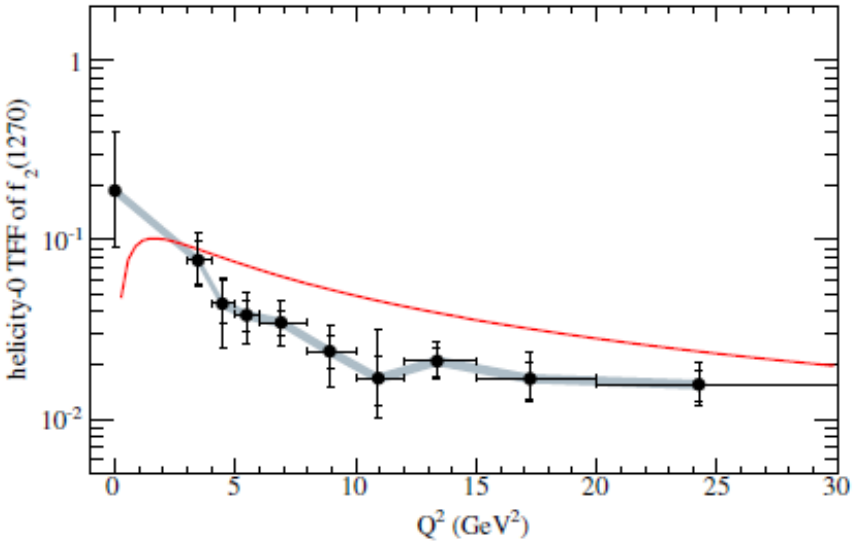

- **Integrated cross section in $Q^2$ bins**
- **$f_0(980)$ & $f_2(1270)$ are evident**
- **Partial-wave amplitudes analysis**
  - ✓ **For W < 1.5GeV, S & D wave**

$$t_0 = |SY_0^0 + D_0 Y_2^0|^2 + |D_2 Y_2^2|^2 + 2\epsilon_0 |D_1 Y_2^1|^2,$$
$$t_1 = 2\epsilon_1 \Re((D_2^* |Y_2^2| - S^* Y_0^0 - D_0^* Y_2^0) D_1 |Y_2^1|),$$
$$t_2 = -2\epsilon_0 \Re(D_2^* |Y_2^2| (SY_0^0 + D_0 Y_2^0)),$$

**PRD 93, 032003**

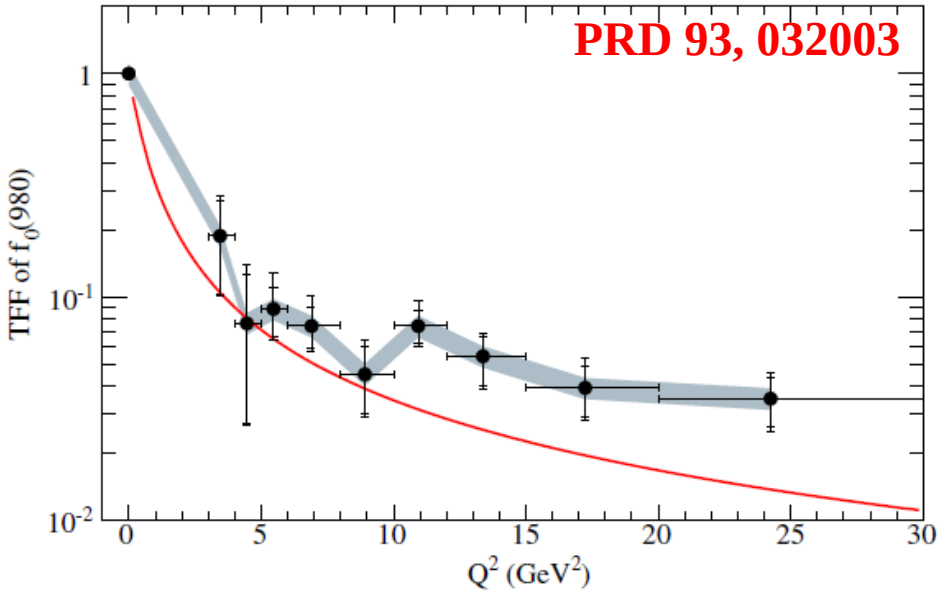
# $f_2(1270)$ TFF



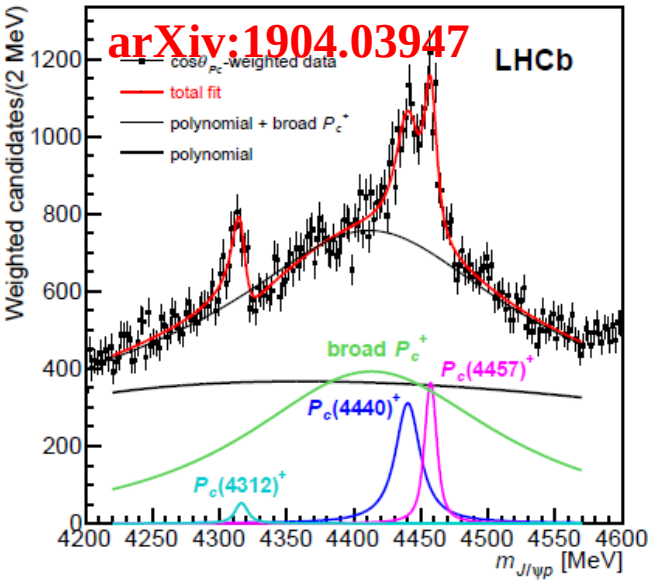

- The $f_2(1270)$ TFF for helicity-0,1,2 are studied for the first time.
  - ✓ Solid: NPB 523, 423; (dot-) dashed: Eqs in PRD85, 116001
  - ✓ The predictions agrees well with $f_2(1270)$ helicity-2 data
  - ✓ Large helicity-0 and non-zero helicity-1 components seen
  - ✓ The predictions is a factor of 1.5-2 larger than measured helicity-0/1 data.

# $f_0(980)$ TFF




- The $Q^2$ dependence of $f_0(980)$ TFF
- The prediction NPB 523, 423 agrees well with data up to $Q^2 = 10$ $GeV^2$, but has steeper $Q^2$ dependence for $Q^2 > 10GeV^2$

# Search for exotic baryons in $\gamma\gamma \to p\bar{p}K^+K^-$



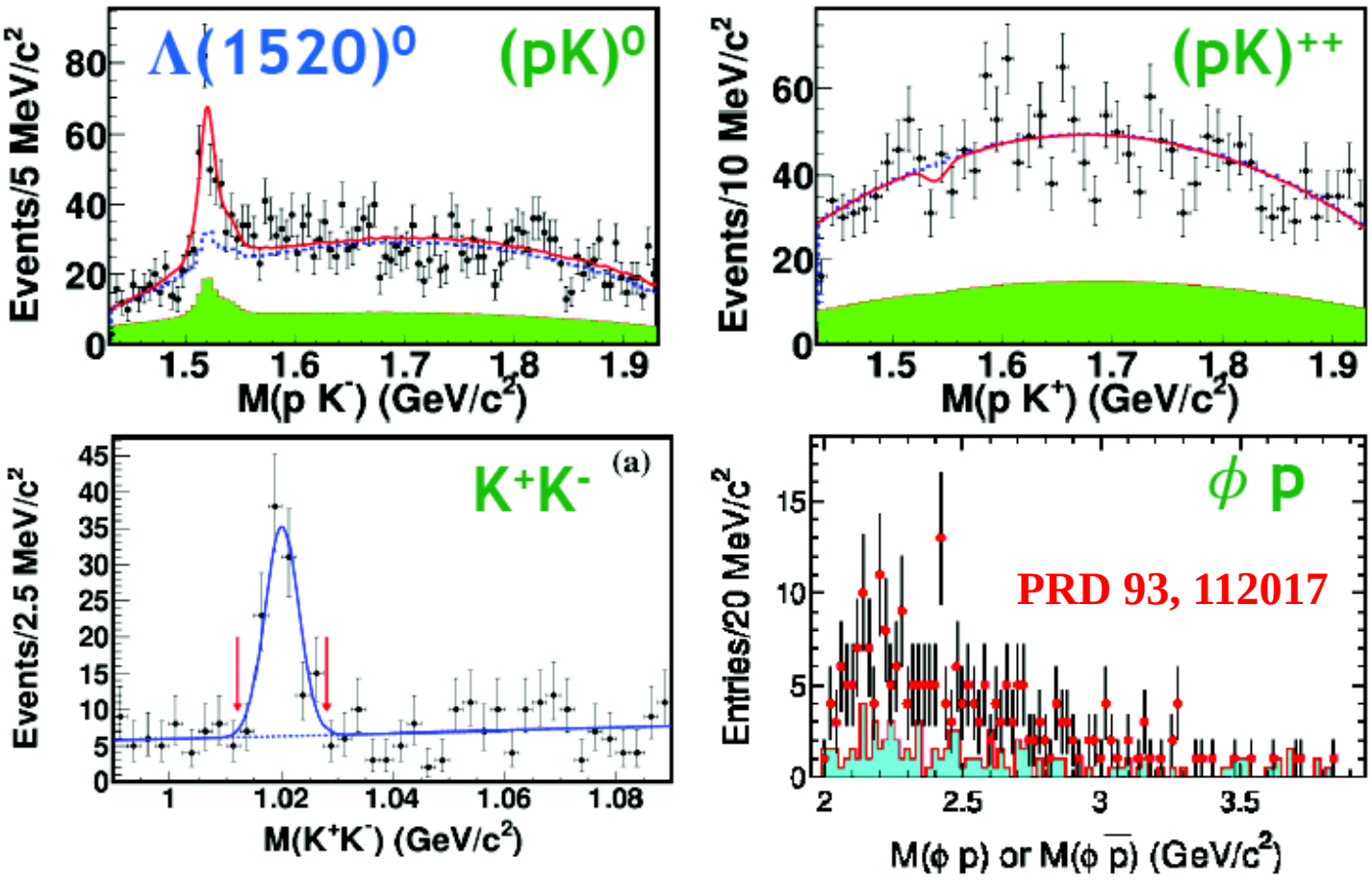

| Group | Reaction | Mass (MeV) | Width (MeV) | $\sigma$'s[a] |
|---|---|---|---|---|
| LEPS | $\gamma C \to K^+K^-X$ | $1540 \pm 10$ | $<25$ | 4.6 |
| DIANA | $K^+Xe \to K^0pX$ | $1539 \pm 2$ | $<9$ | 4.4 |
| CLAS | $\gamma d \to K^+K^-p(n)$ | $1542 \pm 5$ | $<21$ | $5.2 \pm 0.6$[b] |
| SAPHIR | $\gamma d \to K^+K^0(n)$ | $1540 \pm 6$ | $<25$ | 4.8 |
| ITEP | $\nu A \to K^0pX$ | $1533 \pm 5$ | $< 20$ | 6.7 |
| CLAS | $\gamma p \to \pi^+K^+K^-(n)$ | $1555 \pm 10$ | $<26$ | 7.8 |
| HERMES | $e^+d \to K^0pX$ | $1526 \pm 3$ | $13 \pm 9$ | $\sim$5 |
| ZEUS | $e^+p \to e^+K^0pX$ | $1522 \pm 3$ | $8 \pm 4$ | $\sim$5 |
| COSY-TOF | $pp \to K^0p\Sigma^+$ | $1530 \pm 5$ | $<18$ | 4–6 |
| SVD | $pA \to K^0pX$ | $1526 \pm 5$ | $<24$ | 5.6 |

**Θ(1540) -> pK or nK**

**$P_c(4312)$ -> p J/ψ: uudcc̄**

- **Search for exotic baryons by pϕ (uudss̄) and pK channels**
- **Search in Belle via $\gamma\gamma \to p\bar{p}K^+K^-$**

# Search for exotic baryons in $\gamma\gamma \to p\bar{p}K^+K^-$




- No evidence for $s\bar{s}$ partner of $P_c(4312)$

# Summary and outlook

- **Belle has performed many two-photon process**
  - ✓ **Most of analyses with no-tag method**
  - ✓ **Few analyses with single-tag method**
- **Playground to**
  - ✓ **Investigate particle nature by $\Gamma_{\gamma\gamma} \times$BR**
  - ✓ **Understand QCD**
  - ✓ **Transition form factors**
  - ✓ **Search for exotics hadron**
- **Improved are expected with Belle II data by integrated luminosity, higher W & $Q^2$.**

**See Prof. Boris Shwartz's talk at June 5**