Two-Photon Physics results from Belle and perspectives for Belle II

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PhiPsi2017 @ Mainz

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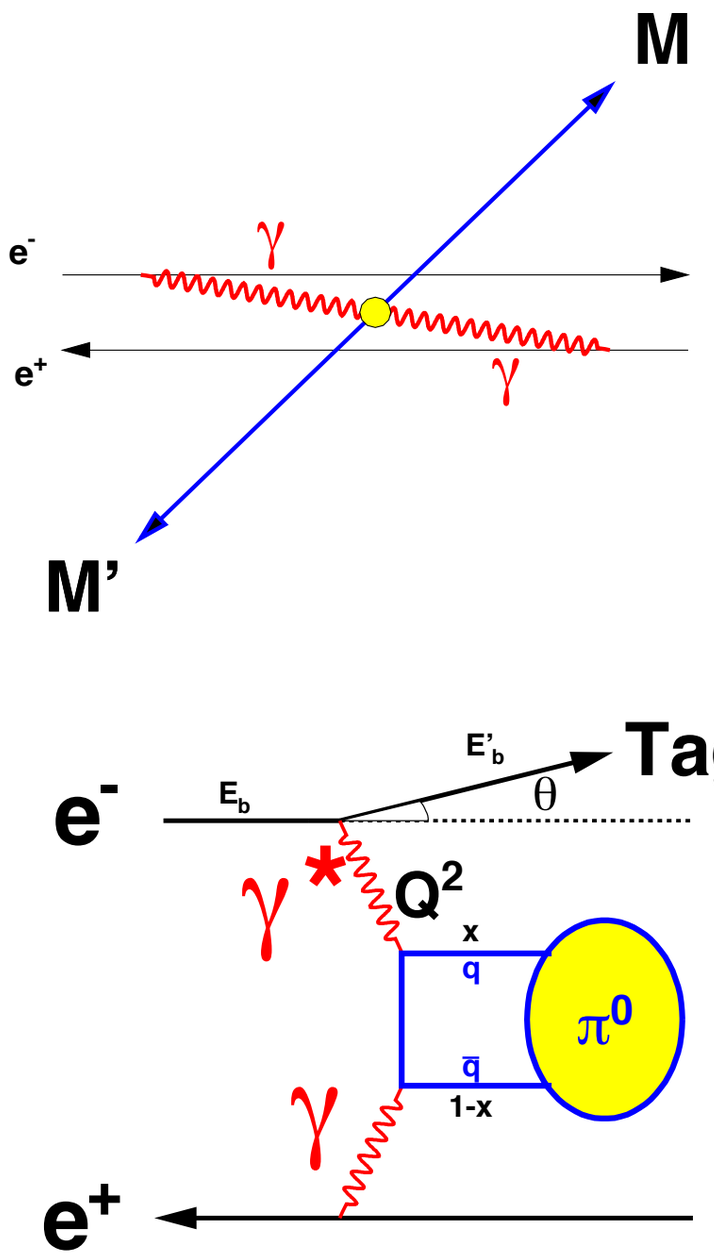
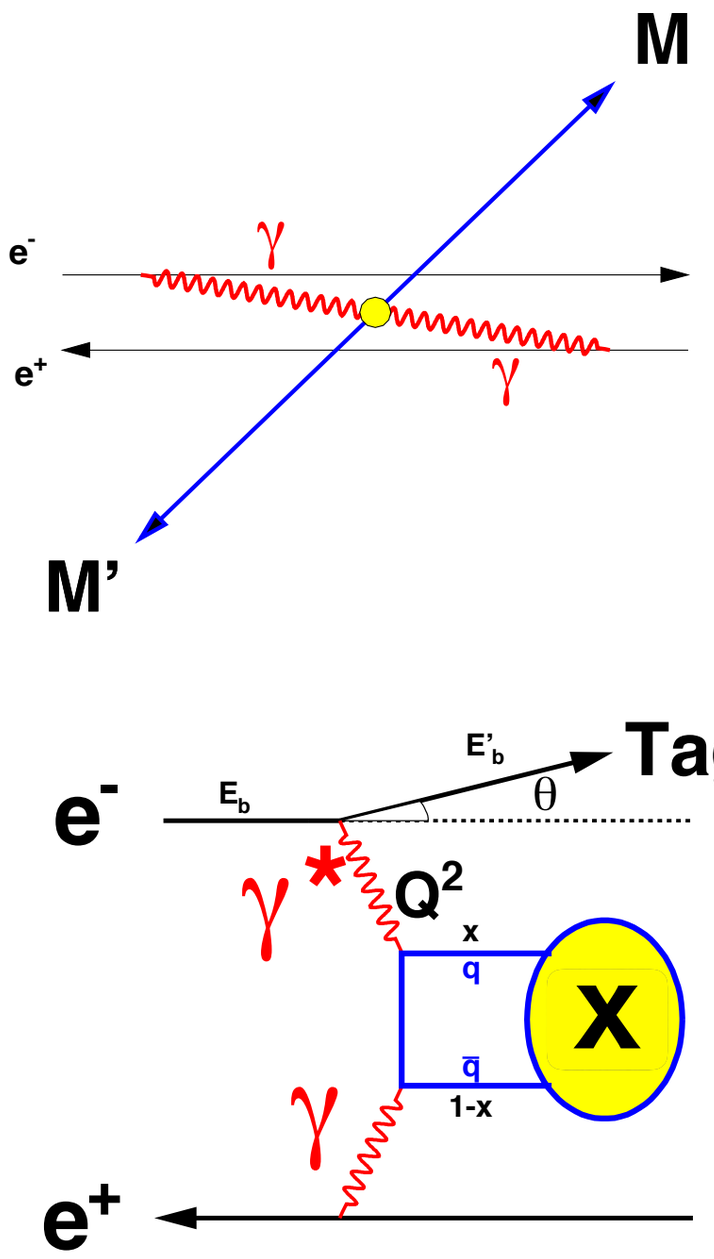


Two-Photon Process at Belle

- Reaction by virtual photons from each beam particle
- Beam particles do not annihilate
- Photon virtuality

$$Q^2 = 4E_b E' \sin^2 \frac{\theta_e}{2}$$

- W = M(**γγ**) = M(hadronic system)



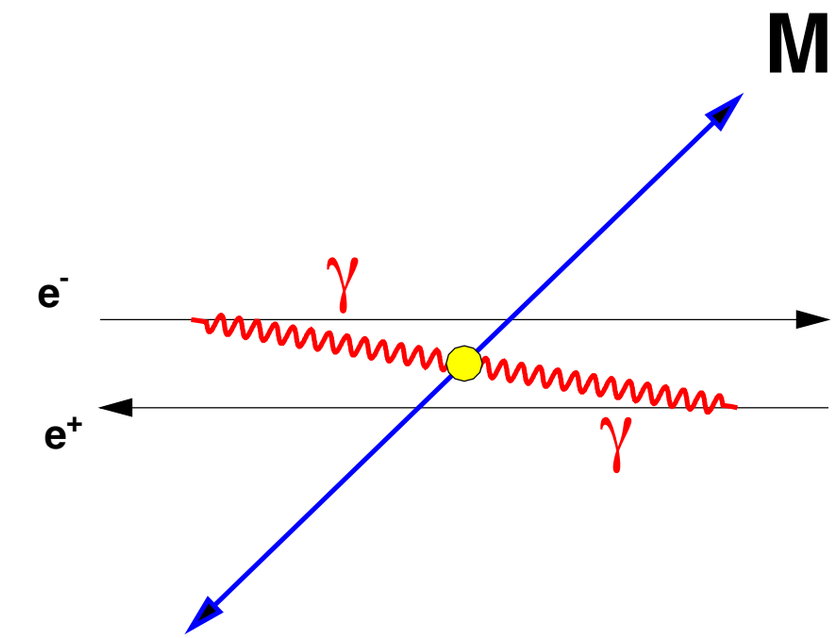
Two-Photon Measurements at Belle

	GeV	$\|\cos\theta^*\| <$	fb^{-1}	reference	year
γ J/ψ	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
ω J/ψ	3.9 - 4.2		694	PRL104, 092001	2010
ϕ J/ψ	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
π^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

Two-Photon Process by real photons

No-tag method

- Collision by two quasi-real photons
  - Dominant two-photon process.
    High Xsec compared with single-tag.
  - $e^+ e^-$ escape to beam pipe with small recoil angle.
    Must not be detected.
  - $\left|\sum_i \vec{p}_t(M_i)\right| \sim 0$ for detected final state particles
  - Translate the result to Xsec by real two-photons

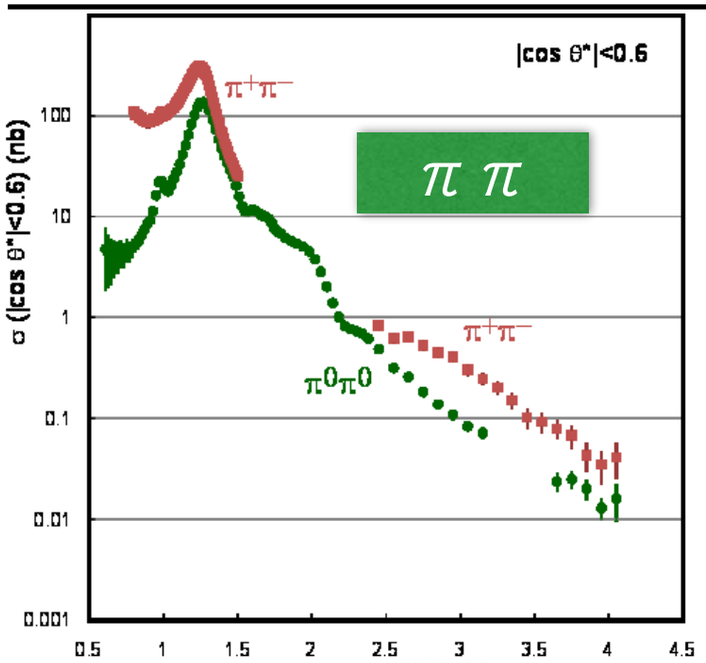


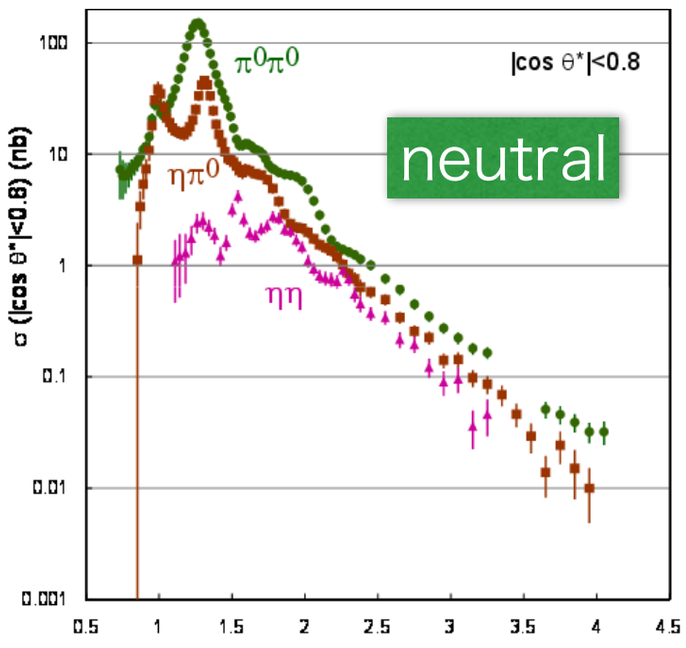
- W spectrum
- Final state of $J^{PC} = 0^{?+}, 2^{?+}, 3^{++}, \ldots$. **C=+ resonance study.**
- Hadron Pair production

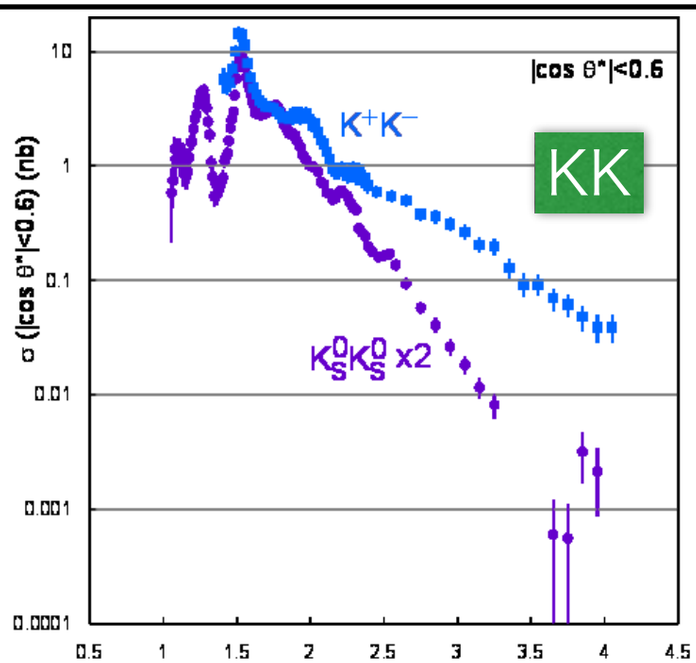
$$\frac{d\sigma}{d|\cos\theta^*|} = \frac{\Delta N}{\Delta W \Delta|\cos\theta^*| \frac{dL_{\gamma\gamma}}{dW} \epsilon(W, |\cos\theta^*|) \int \mathcal{L} dt}$$

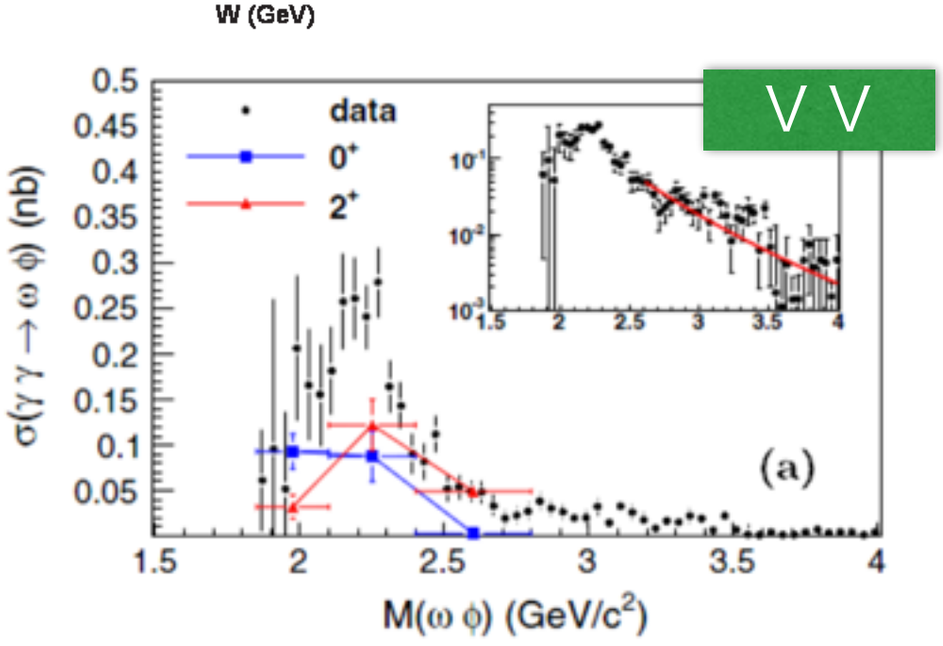
$$\sigma(e^+e^- \to e^+e^- X) = \int \sigma(\gamma\gamma \to X; W) \frac{dL_{\gamma\gamma}}{dW} dW$$

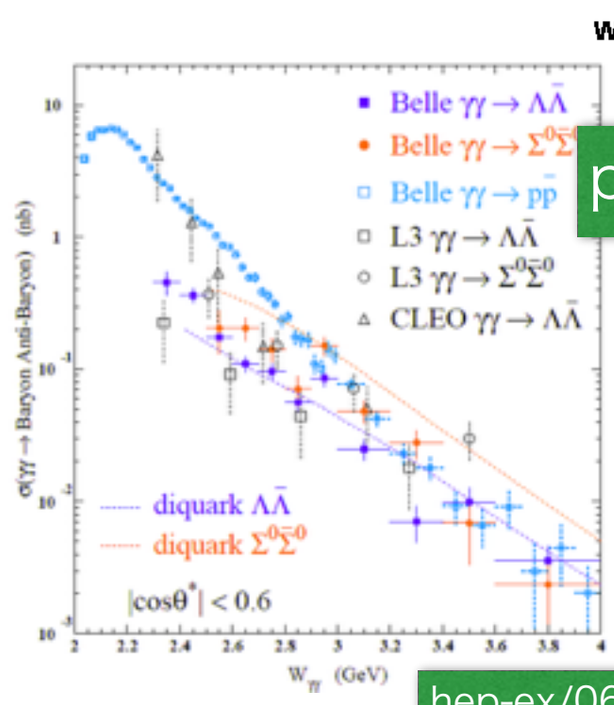
Cross Sections for hadron pair production in no-tag measurements











hep-ex/0609048 (Unpublished)

Wide W region can be measured at once

Light Meson Study using Partial Wave Analysis

No-tag measurements in lower W region (W<3GeV)

$$\frac{d\sigma}{4\pi d|\cos\theta^*|}(\gamma\gamma \to MM') = |SY_0^0 + D_0Y_2^0 + G_0Y_4^0|^2 + |D_2Y_2^2 + G_2Y_4^2|^2$$

$$= \hat{S}^2|Y_0^0|^2 + \hat{D}_0^2|Y_2^0|^2 + \hat{D}_2^2|Y_2^2|^2 + \hat{G}_0^2|Y_4^0|^2 + \hat{G}_2^2|Y_4^2|^2$$

- Two-photon spin-helicity state (J, λ) = (0, 0), (2, 0), (2, ±2)
- S, Dλ, Gλ waves for final hadronic systems
  - S, Dλ, Gλ have W dependence;

Breit-Wigner + Non-resonant component

$$A(f_0) = \sqrt{\frac{8\pi m_{f_0}}{W}} \frac{\sqrt{\Gamma_{f_0}\Gamma_{\gamma\gamma}(f_0)\mathcal{B}(K\bar{K})}}{m_{f_0}^2 - W^2 - im_{f_0}\Gamma_{f_0}}$$

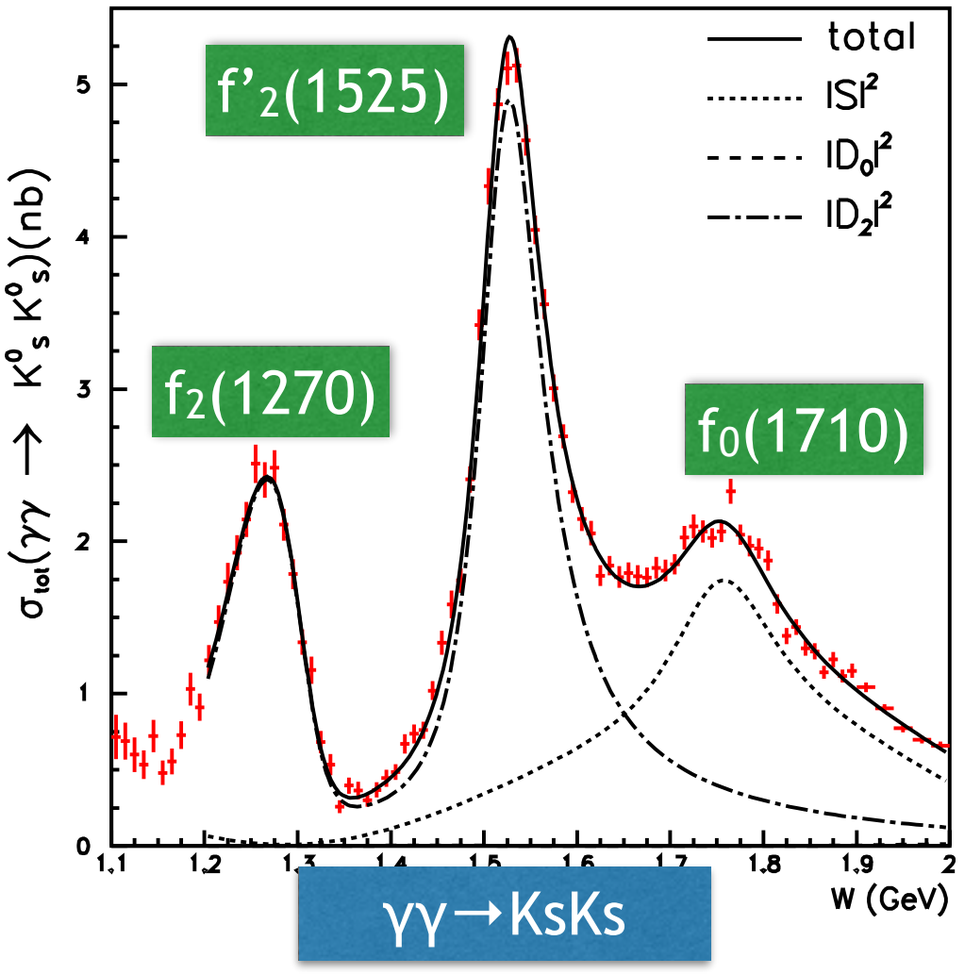
- Two-photon decay width $\boldsymbol{\Gamma_{\gamma\gamma}}$
  - Useful to study the nature of the resonance

    glueballs, four quark states, ...

Light Meson Study using Partial Wave Analysis

No-tag measurements in lower W region (W<3GeV)

- Abundant data in this region but too many parameters.
- Needs more data.



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	$2327\pm9\pm6$	$275\pm36\pm20$	$\begin{cases}22\pm3\pm6/\mathcal{B}\\161\pm22\pm48/\mathcal{B}\end{cases}$
$K^0_SK^0_S$	$f_2'(1525)$	$1525.3^{+1.2+3.7}_{-1.4-2.1}$	$82.9^{+2.1+3.1}_{-2.2-2.0}$	$48^{+67+108}_{-8-12}/\mathcal{B}(K\bar{K})$
	$f_0(1710)$	1750^{+6+29}_{-7-18}	139^{+11+96}_{-12-50}	$12^{+3+227}_{-2-8}/\mathcal{B}(K\bar{K})$
	$f_2(2200)$	2243^{+7+3}_{-6-29}	$145\pm12^{+27}_{-34}$	$3.2^{+0.5+1.3}_{-0.4-2.2}/\mathcal{B}(K\bar{K})$
	$f_0(2500)$	$2539\pm14^{+38}_{-14}$	$274^{+77+126}_{-61-163}$	$40^{+9+17}_{-7-40}/\mathcal{B}(K\bar{K})$
$\pi^0\pi^0$	$f_0(980)$	$982.2\pm1.0^{+8.1}_{-8.0}$		$286\pm17^{+211}_{-70}$
	$f_2(1270)$	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	$11.5^{+1.8+4.5}_{-2.0-3.7}/\mathcal{B}$
	$f_2(X)$	$1737\pm9^{+198}_{-65}$	$228^{+21+234}_{-20-153}$	$5.2^{+0.9+37.3}_{-0.8-4.5}/\mathcal{B}$

W-dependence of Xsec, $\sigma_0 \propto W^{-n}$

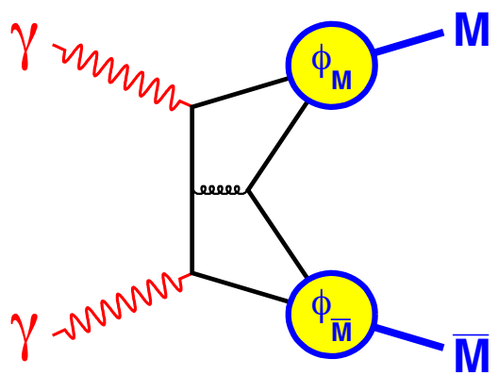
No-tag measurements in higher W region

- Resonance effects small above 3.0 GeV
  - Good place to study (p)QCD
- pQCD prediction

$$\mathcal{M}_{\lambda_1\lambda_2}(W^2,\theta^*) = \int_0^1\int_0^1 dxdy\phi_M(x,Q_x)\phi_{M'}(y,Q_y)T_{\lambda_1\lambda_2}(x,y,\theta^*)$$ PRD24, 1808

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

F_M	Meson form factor. ~1/W^2 at leading term
ϕ_M	Meson distribution amplitude (DA)
$T_{\lambda 1 \lambda 2}$	Hard Scattering amplitude for
$g(\theta^*)$	Only unknown, non-perturbative factor



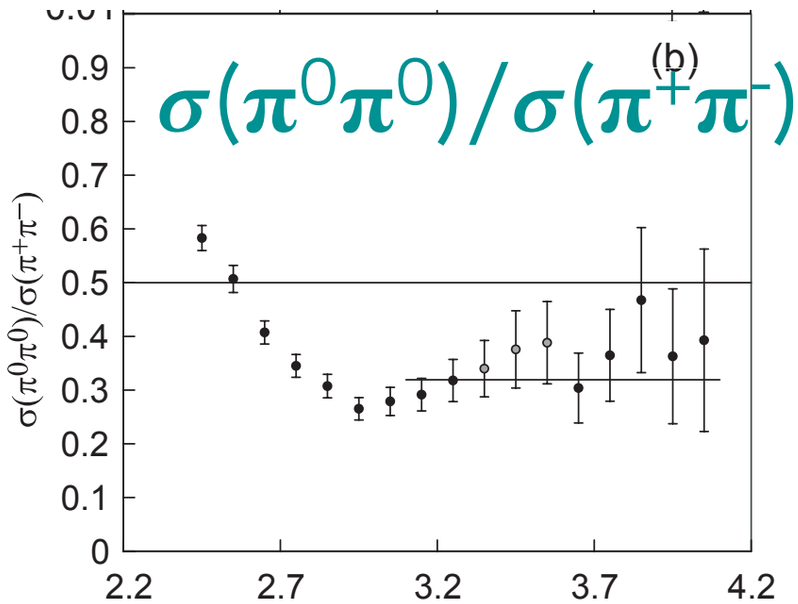
- $\sigma \sim W^{-6}$ for charged pair, $\sigma \sim W^{-10}$ for neutral and ppbar
- At which energy is enough high to apply pQCD?

W-dependence of Xsec, $\sigma_0 \propto W^{-n}$

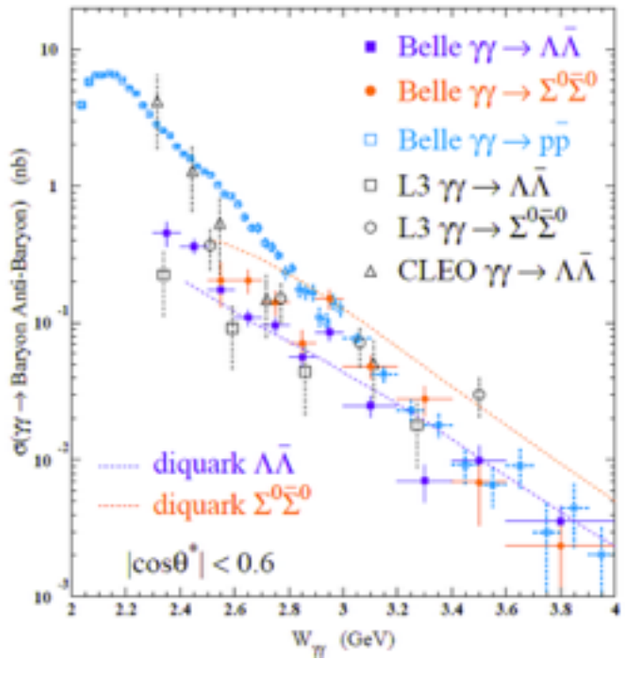
No-tag measurements in higher W region

	pQCD[2]	Belle	W(GeV)	$\|\cos\theta^*\|<$
$\pi^+\pi^-$	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

pQCD: PRD24,1808(1981), NPB329,285(1990)

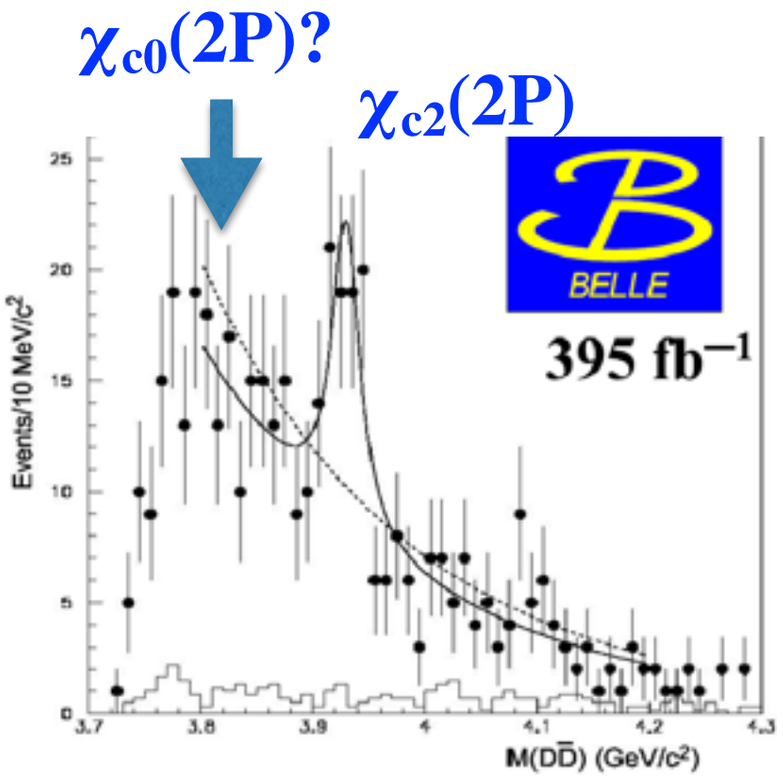


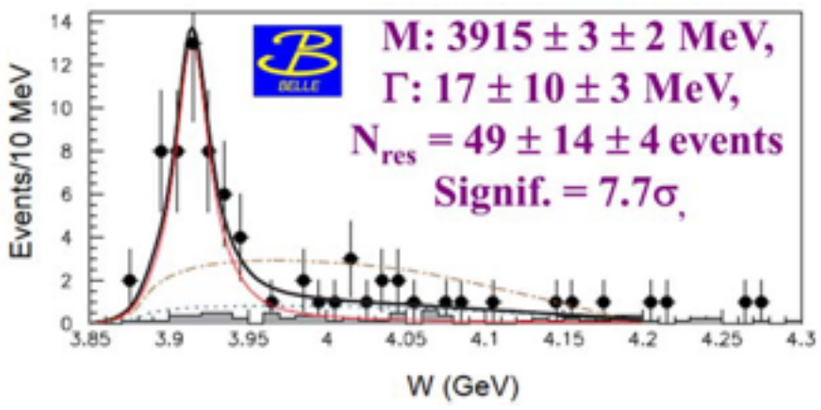
- $\sigma(\pi^0\pi^0)/\sigma(\pi^+\pi^-)$~constant. Disagree with pQCD.
- $\sigma(\Lambda\Lambda)/\sigma$(ppbar)~1. Possible for different quark charge?
- At Belle W<4.0. At Belle II, as large W as possible, but e+e- annihilation bkg significant
- Neutral modes relatively clean, but low Xsec

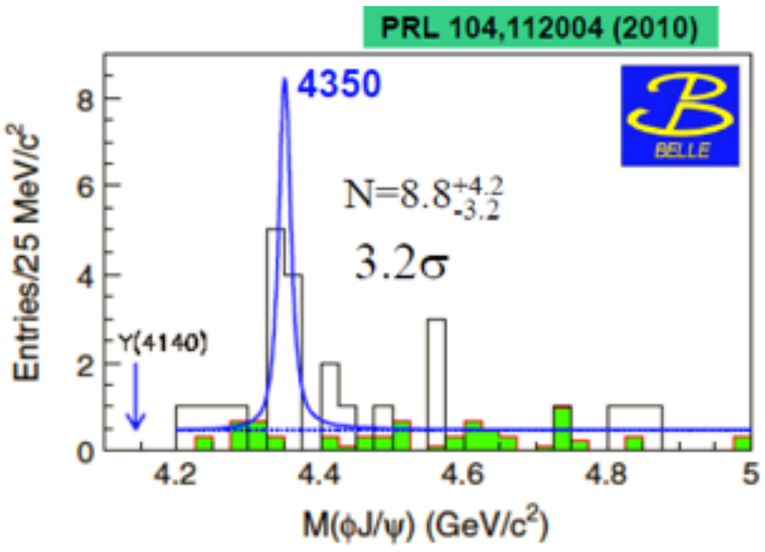


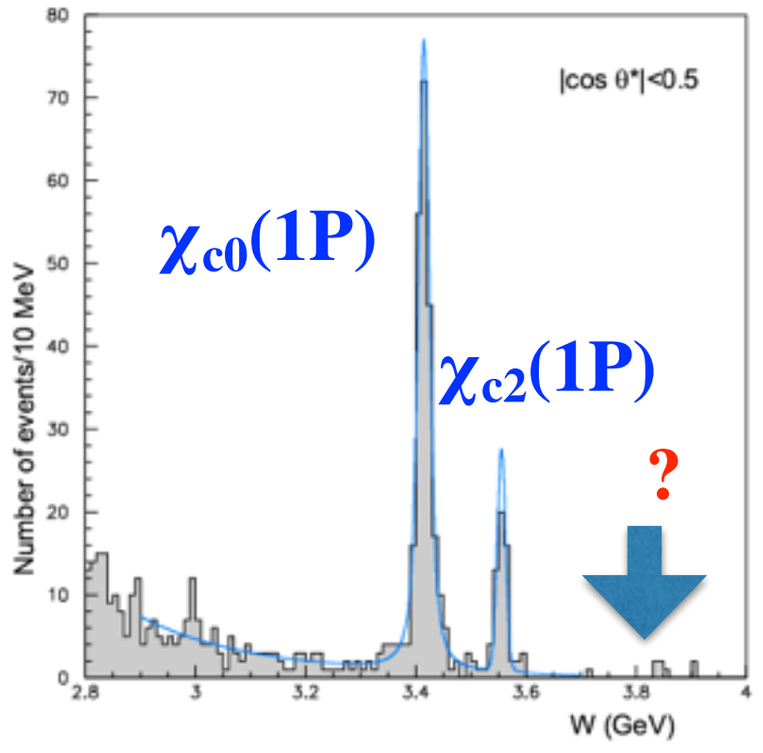
charmonia and XYZ

- X(3915) and X(4350) found, but nature unknown
- X(3915) is no longer $\chi_{c0}(2P)$. Where is it?
- $\chi_{c2}(2P)$ -> DD* -> DDX should be treated carefully





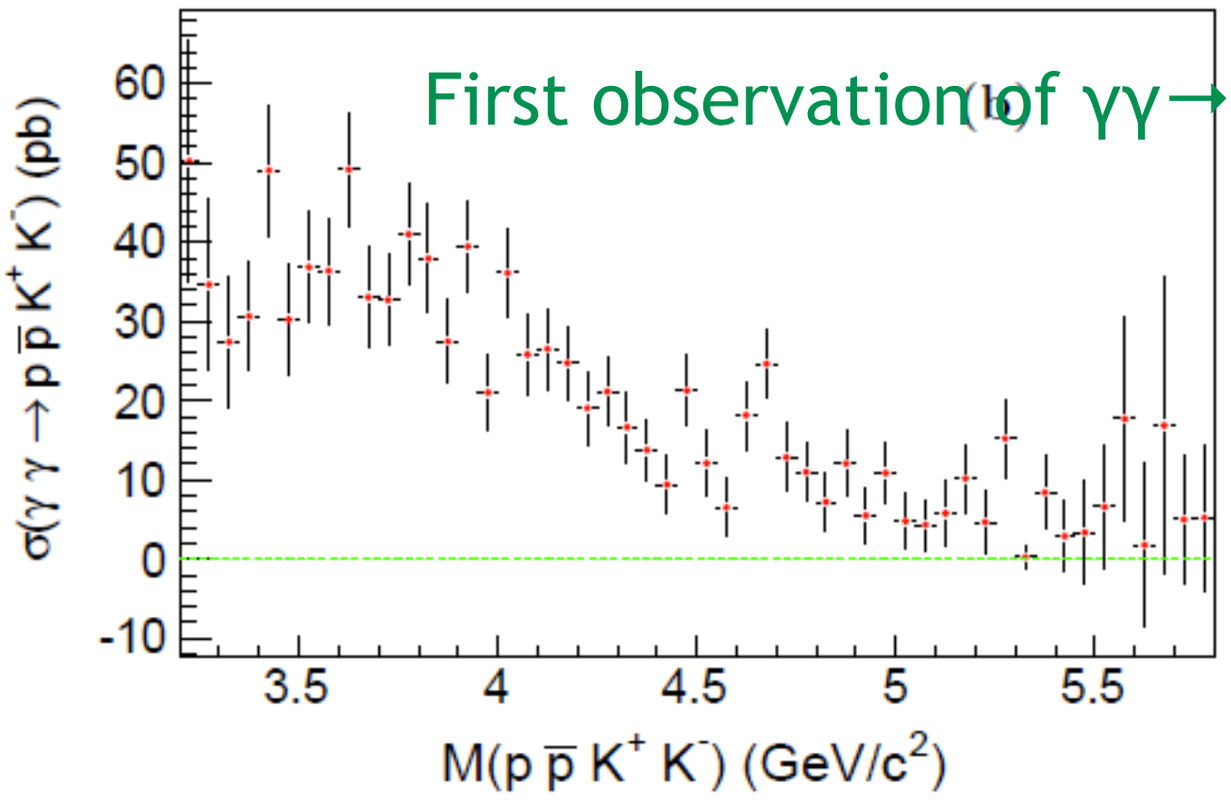




PRD 93, 1120137(2016)

Search for exotic baryons in γγ→pp K+K-

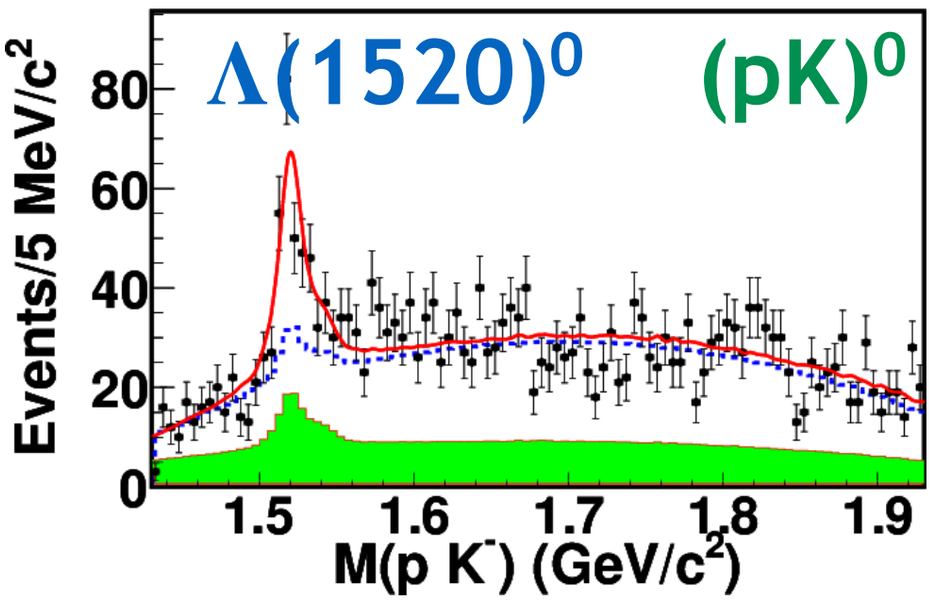
- Search for $X^+ \to \phi$ p
  - Pc(4380, 4450)$^+$ → J/Ψ p [LHCb: PRL115,072001(2015)]
- Search for Θ(1540)^0→pK$^-$ and Θ(1540)$^{++}$→p K$^+$
  - First pentaquark "evidence" Θ(1540)$^+$ → n K+ [LEPS: PRL91,012002(2003)]

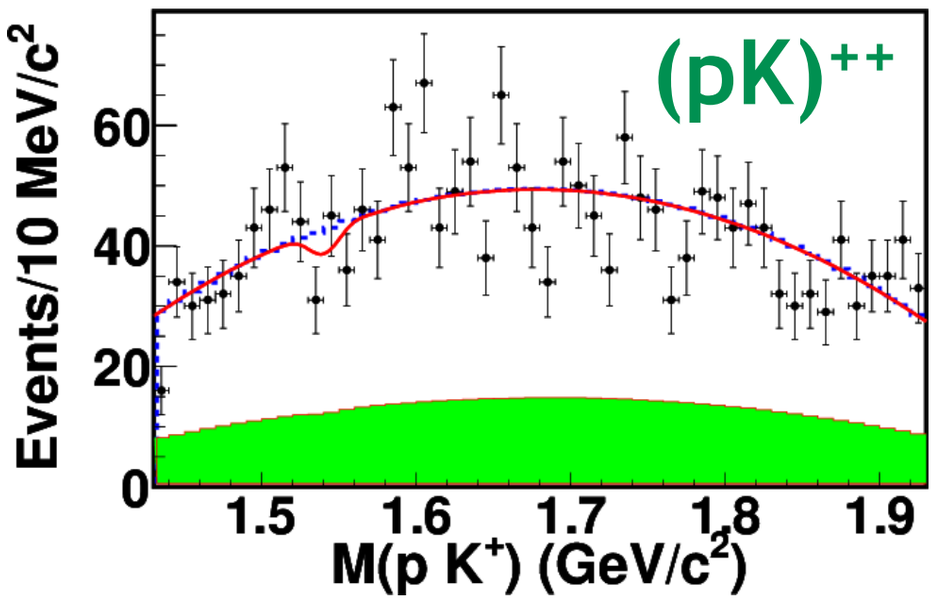


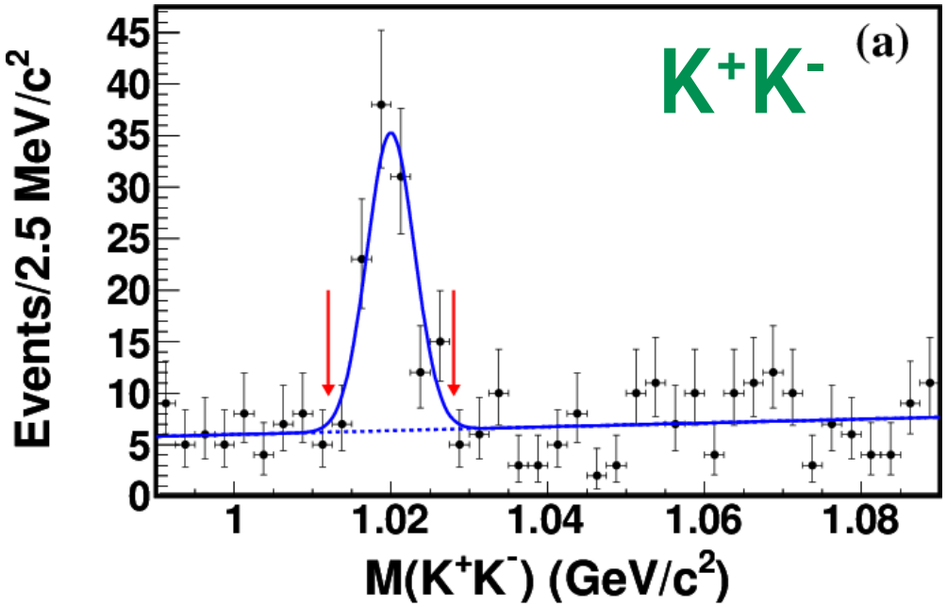
First observation of γγ→pp K+K-

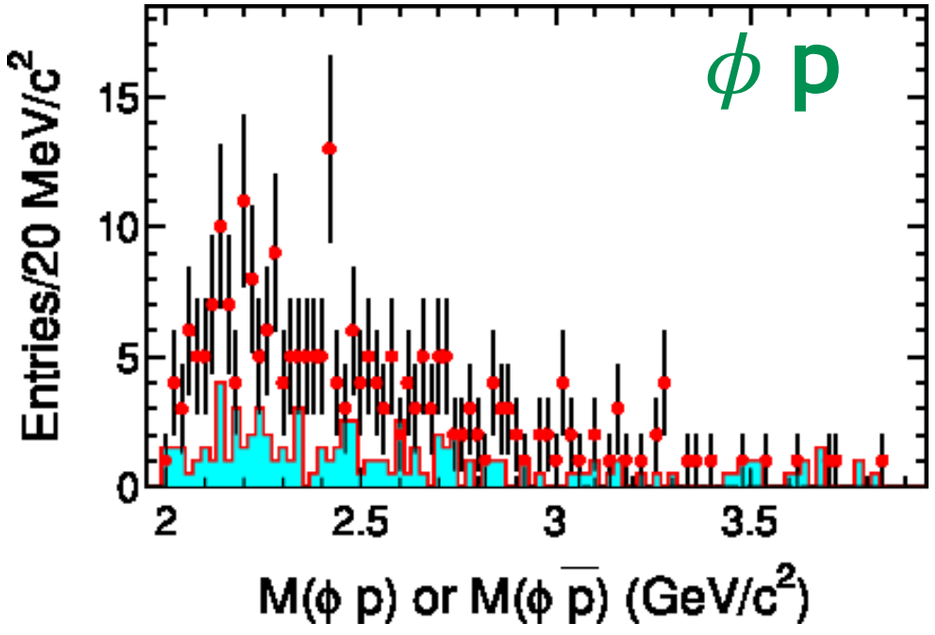
PRD 93, 1120137(2016)

Search for exotic baryons in γγ→*pp* K+K-









- No evidence of ssbar partner of Pc(4380, 4450)⁺ seen

π^0 transition form factor

PRD86, 092007 (2012)

Single-tag measurement

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

pQCD: Agaev et.al. PRD22, 2157 (1980)

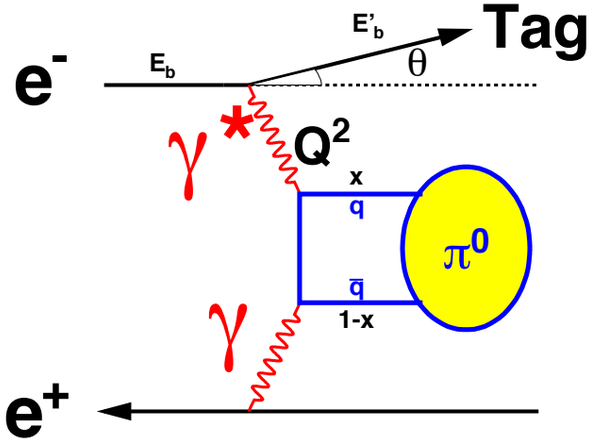
- Extraction from $d\sigma/dQ^2$

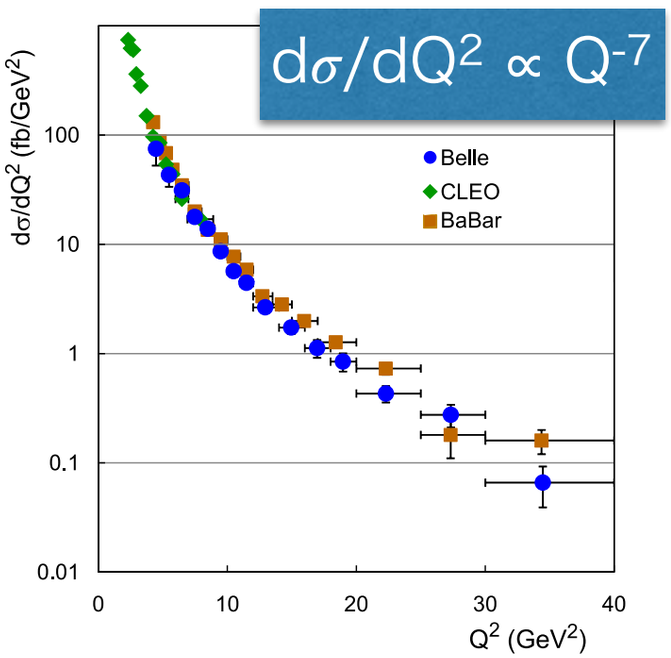
$$\frac{d\sigma}{dQ^2} = \frac{N(1-r_b)}{\int Ldt\epsilon\mathcal{B}(\pi^0\to\gamma\gamma)(1+\delta)\Delta Q^2}$$

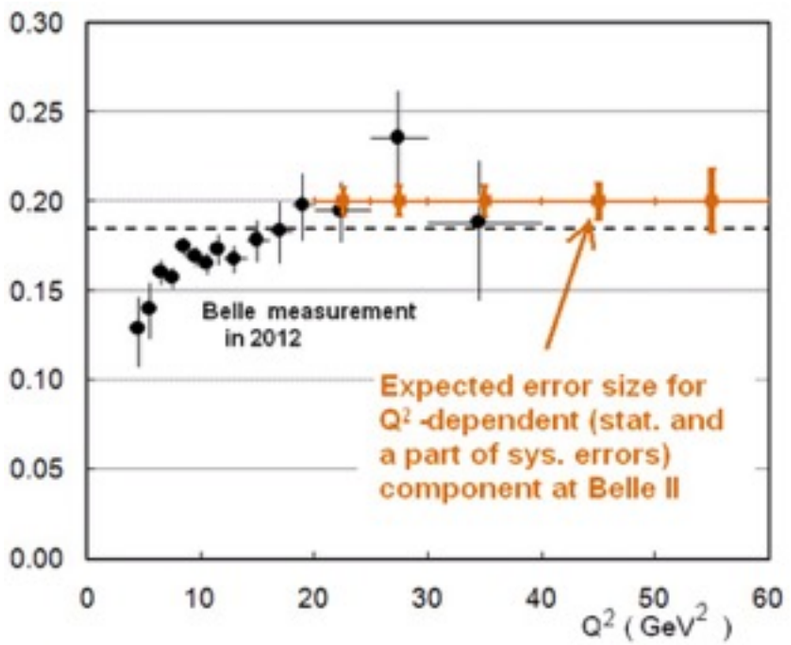
ε	Efficiency
r_b	background fraction
δ	radiative correction

$$Q^2|F(Q^2)| = Q^2\sqrt{(d\sigma/dQ^2)/(2A(Q^2))}$$

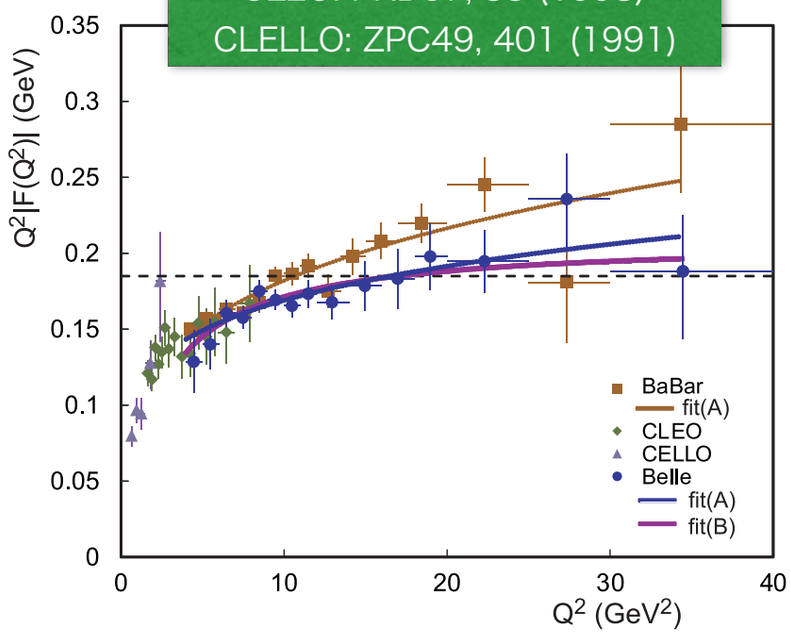
2A(Q²) from QED Brodsky et.al. PRD4, 1532(1971)





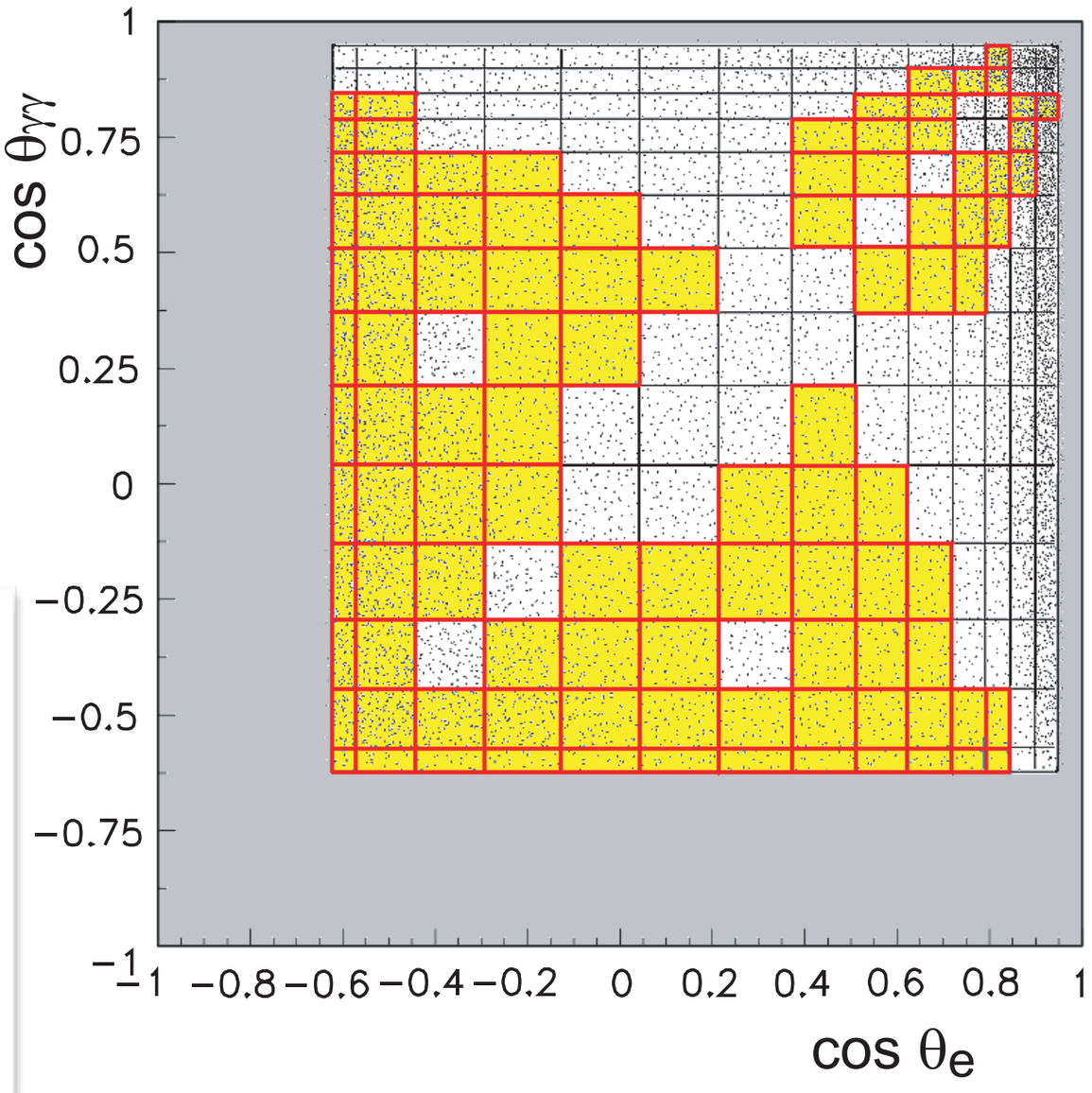


BABAR: PRD80, 052002 (2009)
CLEO: PRD57, 33 (1998)
CLELLO: ZPC49, 401 (1991)



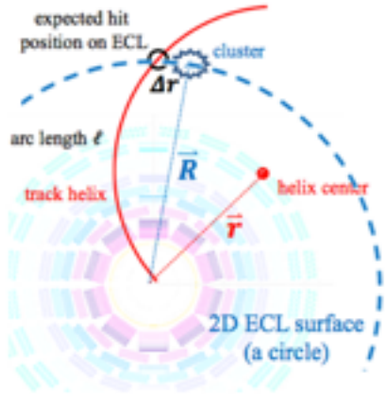
Trigger at Belle II

- At Belle Bhabha trigger caused event loss
- At Belle II more sophisticated trigger
  - Matching between sub trigger components
  - PID at trigger Level: E/p, muon hit. ..
  - benefit to Lowmultipicity events



Trigger Level Analysis

- 2D tracker output from TRGCDC:
  - center of track helix: $\vec{r} = (r, \phi)$
  - p_t
  - Track is extrapolated as a circle/helix inside ECL.
- Output from TRGECL:
  - cluster position on ECL: $\vec{R} = (x, y) = (R, \theta)$ (Cluster position is with **15cm** depth to the inner surface.)
  - Deposit Energy



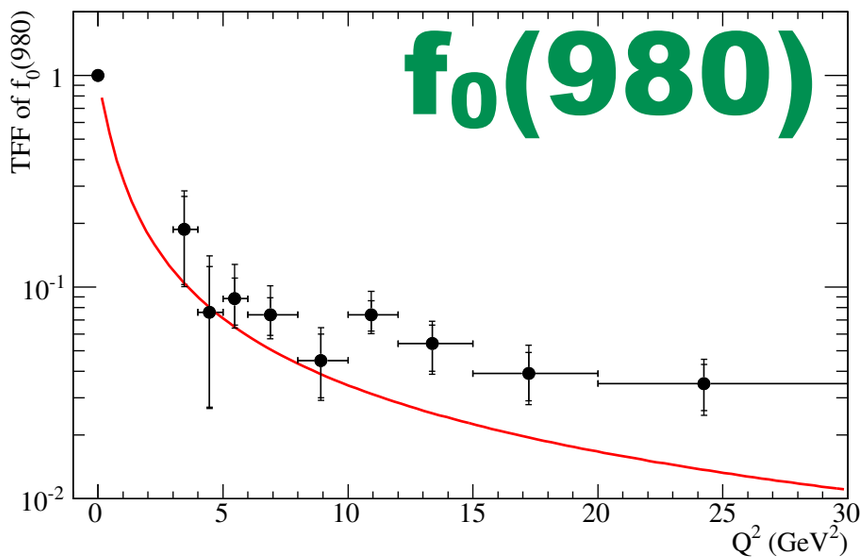
- Solve the expect hit position for a track on ECL:
  - $\overrightarrow{R'} = (x', y') = (R, \theta')$, where $\theta' = \cos^{-1}(R/2r) + \phi$ or $\phi - \cos^{-1}(R/2r)$
- $\Delta r \equiv |\vec{R} - \overrightarrow{R'}|$: the deviation between cluster position and expected hit position.

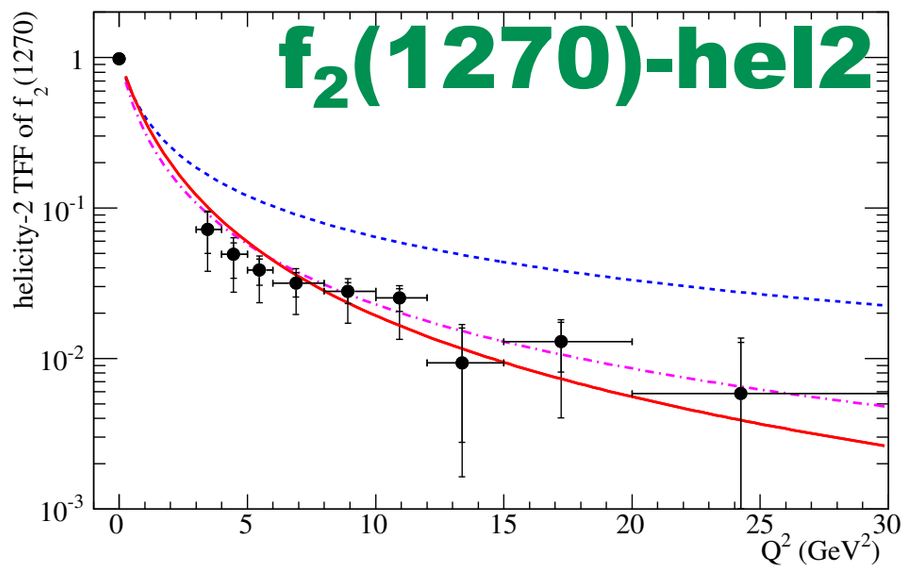
PRD93, 032003 (2016)

transition form factors for $f_0(980)$ and $f_2(1270)$

Single-tag measurement

- $\gamma^* \gamma \to \pi^0\pi^0$, PWA with Q^2
- spin-1 particle, helicity-1 component allowed in single-tag
- f2(1270) TFF for helicity-0, 1, 2 separately for the first time
  - large helicity-0 and non-zero helicity-1 components seen
- Spin-1 has not measured yet. χ_{c1} TFF is useful to test LbL sum rules (1705.01179)





Summary

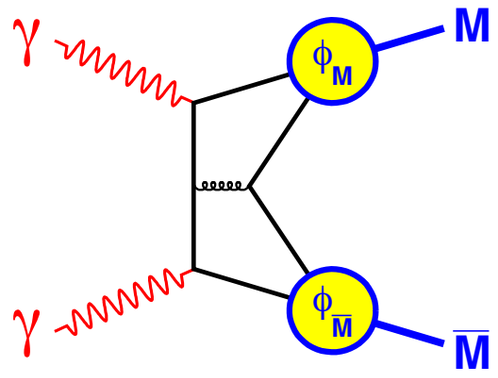
- Belle has measured various two-photon processes
  - Mainly using no-tag method, a few with single-tag method
  - Light resonance, ccbar and XYZ, and (p)QCD have been studied by the data
  - Challenges to go higher W and Q^2 at Belle II

QCD Calculation of Meson Pair Production

W>3 GeV: Resonance effect is small

pQCD by BL(Brodsky and Lepage, PRD24, 1808)

$$\mathcal{M}_{\lambda_1\lambda_2}(W^2,\theta^*) = \int_0^1\int_0^1 dxdy\phi_M(x,Q_x)\phi_{M'}(y,Q_y)T_{\lambda_1\lambda_2}(x,y,\theta^*)$$



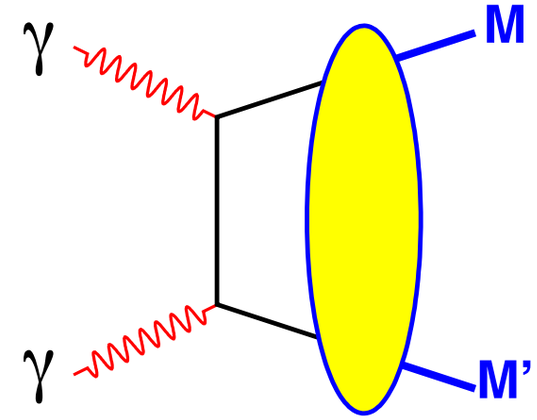
- For charged pair, $\sigma \sim f_M^4/W^6\sin^4\theta^*$, $d\sigma(K^+K^-)/d\sigma(\pi^+\pi^-)=2.3$

Improved by BC (Benayoun and Chernyak, NPB329, 285 (1990))

- SU(3) symmetry breaking $d\sigma(K^+K^-)/d\sigma(\pi^+\pi^-)=1.06$
- For neutral pair, $\sigma \sim 1/W^{10}$ Chernyak, 0912.0623

Handbag Model by DKV(Diehl, Kroll et.al. PLB532, 99 (2002))

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



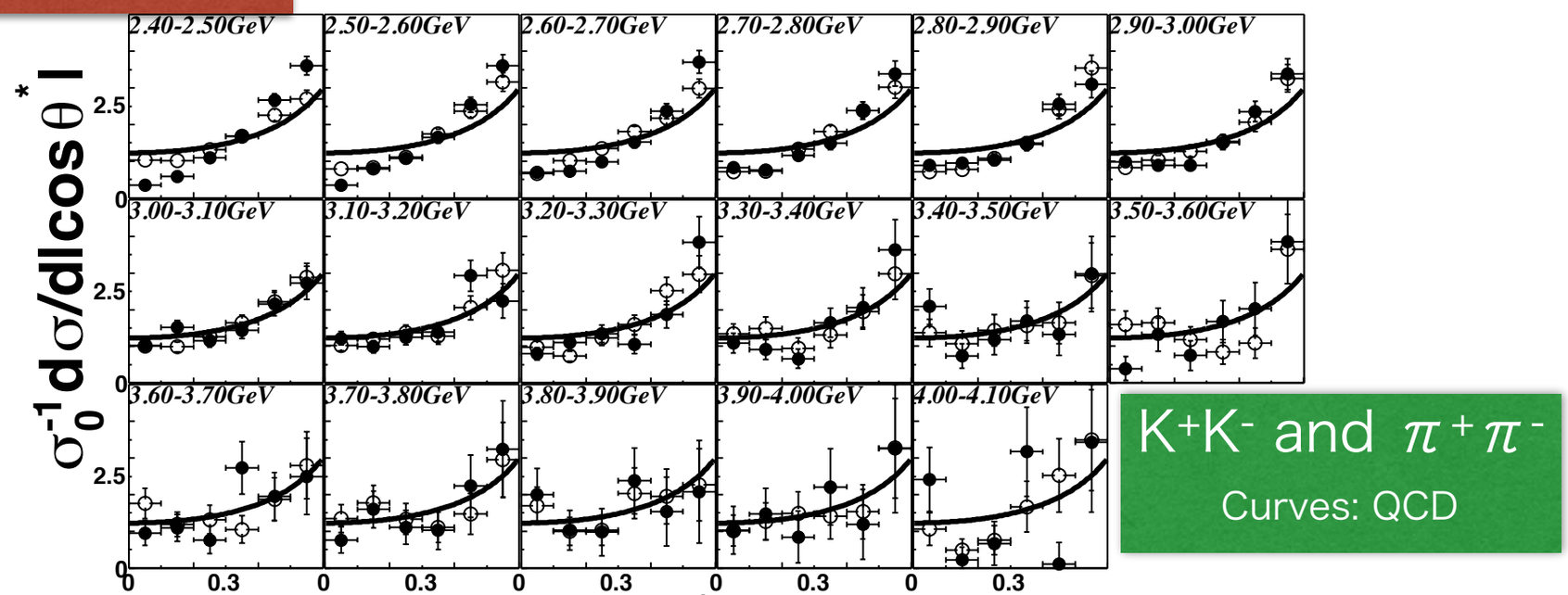
- Charge counting & flavor symmetry

$$\sigma(K_SK_S)/\sigma(K^+K^-) = 2/25$$

$$\sigma(\pi^0\pi^0)/\sigma(\pi^+\pi^-) = 0.5$$

Angular Dependence

2.4 GeV →



K^+K^- and $\pi^+\pi^-$

Curves: QCD

mode	$1/\sin^4\theta^*$	energy range	$\lvert\cos\theta^*\rvert$ range
$\pi^+\pi^-$	Match well.	3.0 - 4.1	< 0.6
K^+K^-	Match well.	3.0 - 4.1	< 0.6
$K^0_S K^0_S$	α varies from 4–8 for $1/\sin^\alpha\theta^*$	2.6 - 3.3	< 0.8
$\pi^0\pi^0$	$1/\sin^4\theta^* + b\cos\theta^*$ better. Approaches $1/\sin^4\theta^*$ 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. $1/\sin^6\theta^*$ better above 3.0 GeV.	2.4 - 3.3	< 0.9

† χ_{cJ} region, 3.3 - 3.6 GeV is excluded.

Cross section and their ratio

Process	n of $\sigma \sim W^{-n}$	W (GeV)	$\lvert\cos\theta^*\rvert$	PRD24,1808	NPB329, 285	PLB532, 99
$\pi^+\pi^-$	$7.9 \pm 0.4 \pm 1.5$	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	
$K^0_S K^0_S$ #	$10.5 \pm 0.6 \pm 0.5$	2.4 - 4.0†	< 0.6	-	10	
$K^0_S K^0_S$ ##	$11.0 \pm 0.4 \pm 0.4$	2.6 - 4.0†	< 0.8	-	10	
$\pi^0\pi^0$	$8.0 \pm 0.5 \pm 0.4$	3.1 - 4.1†	< 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)	$\lvert\cos\theta^*\rvert$	PRD24,1808	NPB329, 285	PLB532, 99
$K^+K^-/\pi^+\pi^-$	$0.89 \pm 0.04 \pm 0.15$	3.0 - 4.1	< 0.6	2.3	1.06	
$K^0_S K^0_S / K^+K^-$ #	~ 0.13 to ~ 0.01	2.4 - 4.0	< 0.6†		0.005	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	$0.36R_f^2(0.62R_f^2)$‡		

† χ_{cJ} region, 3.3 – 3.6 GeV is excluded.

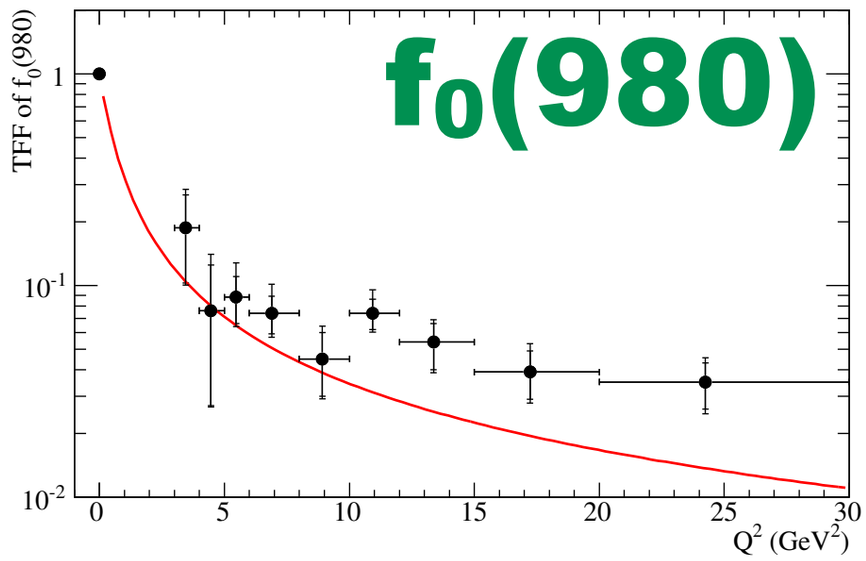
‡ η meson as a pure $SU(3)$ octet (mixture of octet and singlet with $\theta_p = -18°$), $R_f = f_\eta^2/f_{\pi^0}^2$.

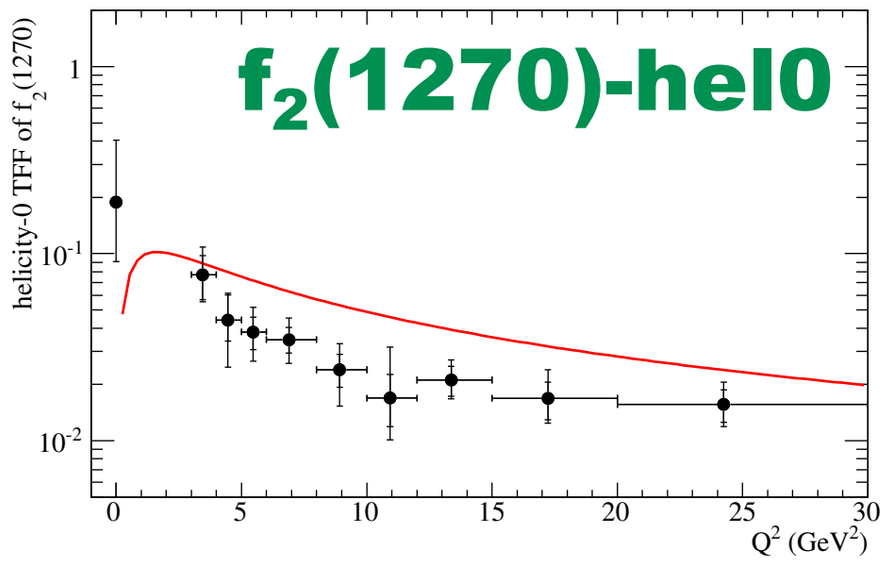
\# PLB651, 15

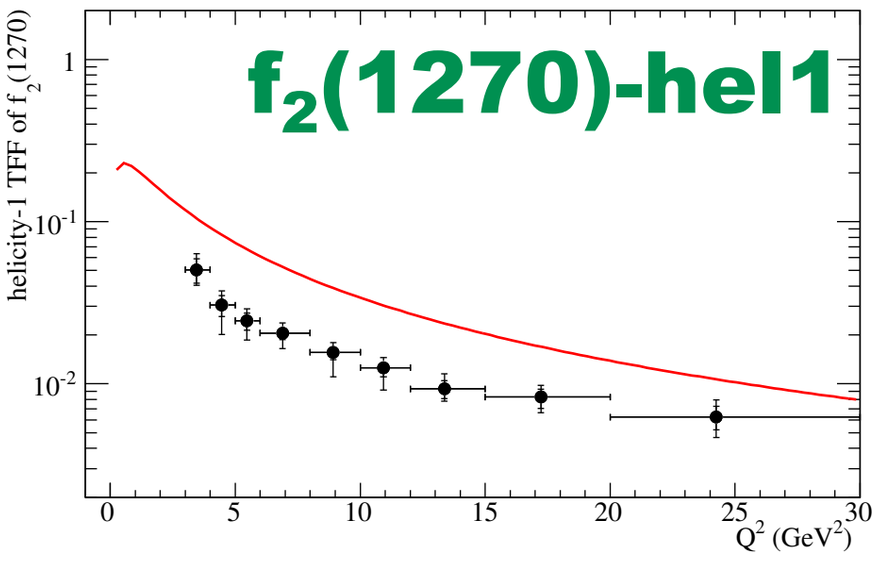
\#\# PTEP2013, 123C01

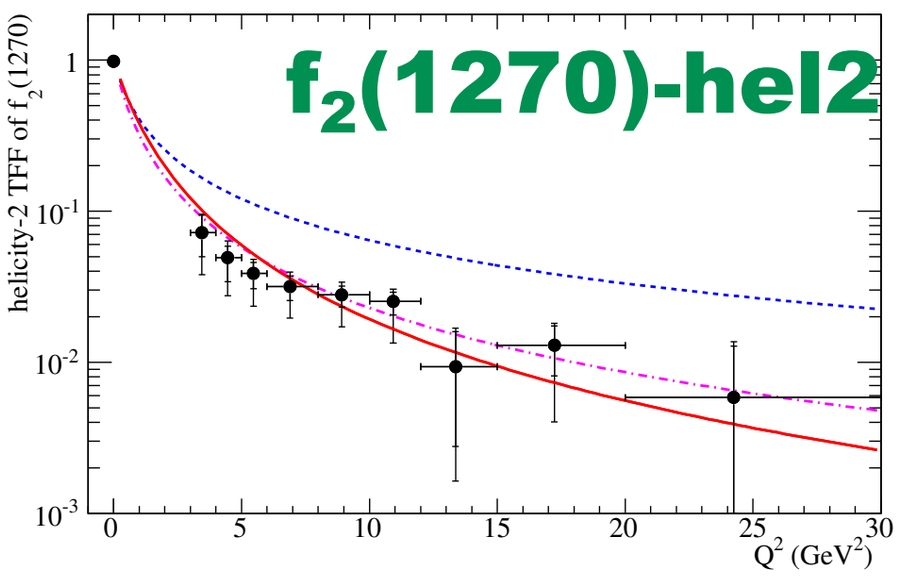
transition form factors for $f_0(980)$ and $f_2(1270)$

Single-tag measurement

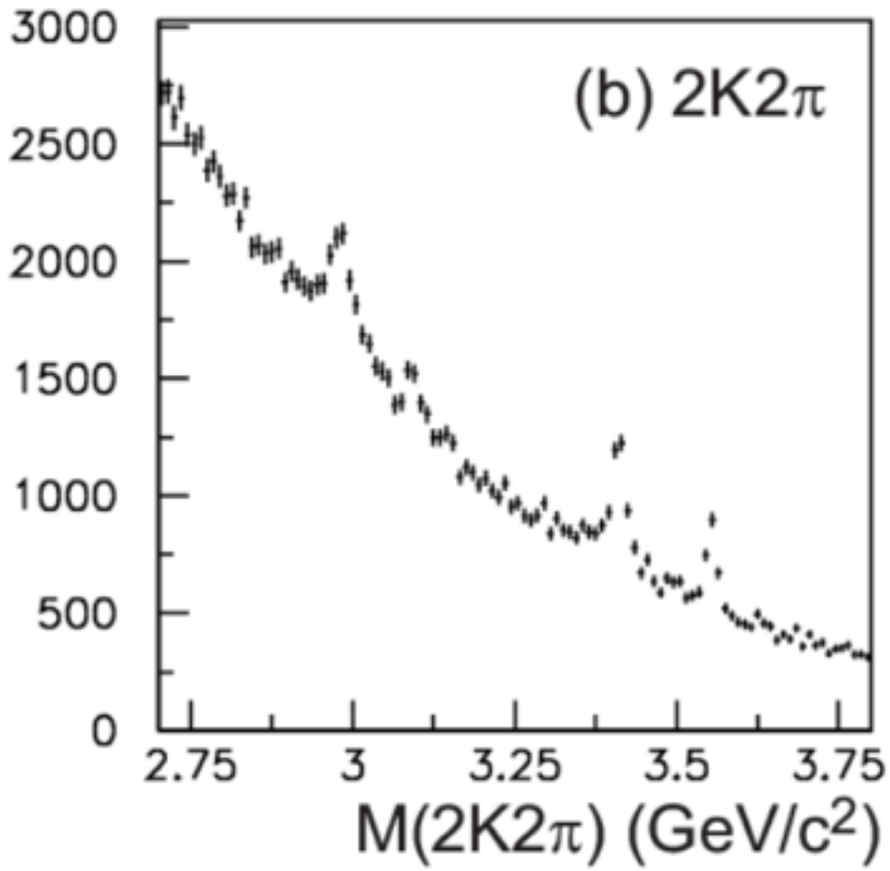




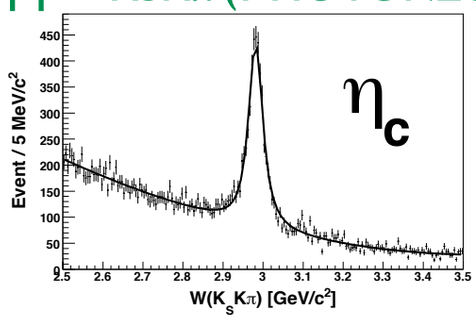


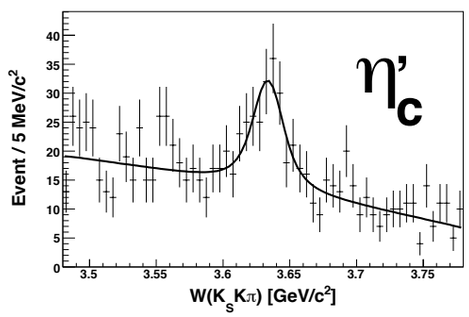


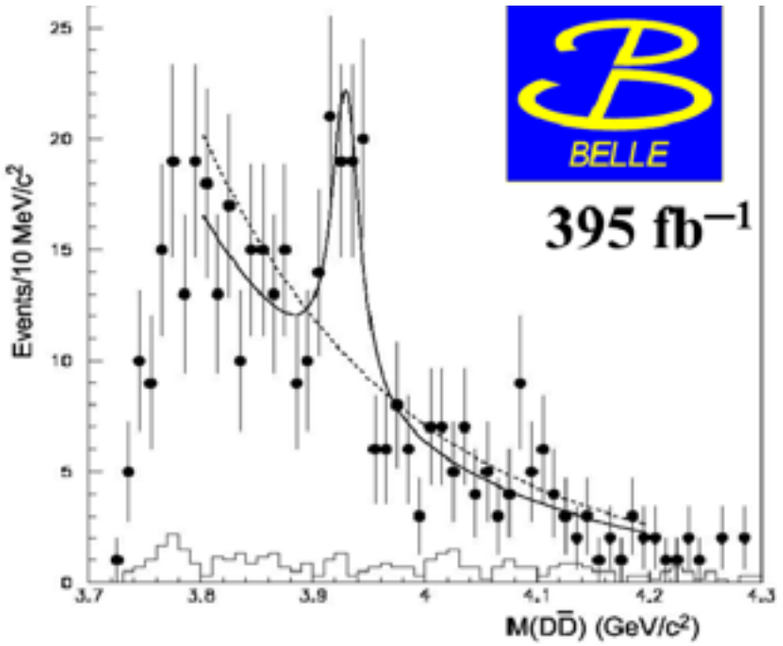
charmonia and XYZ

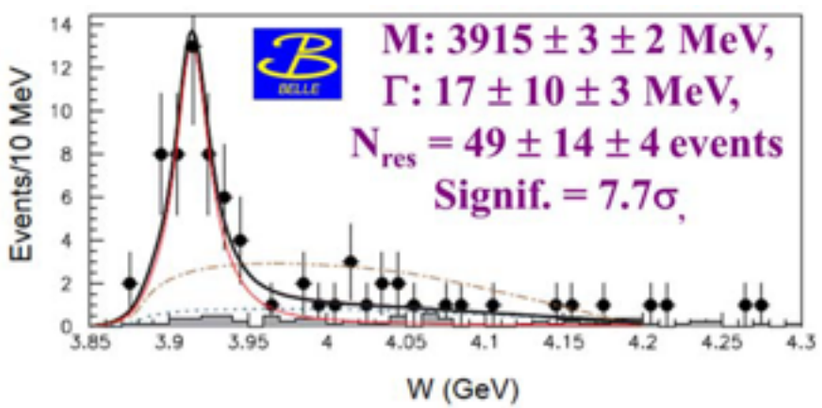


γγ→KsKπ(PHOTON2007)









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