Measurement of Hadronic Cross Section with ISR/Two-Photon Events at Belle

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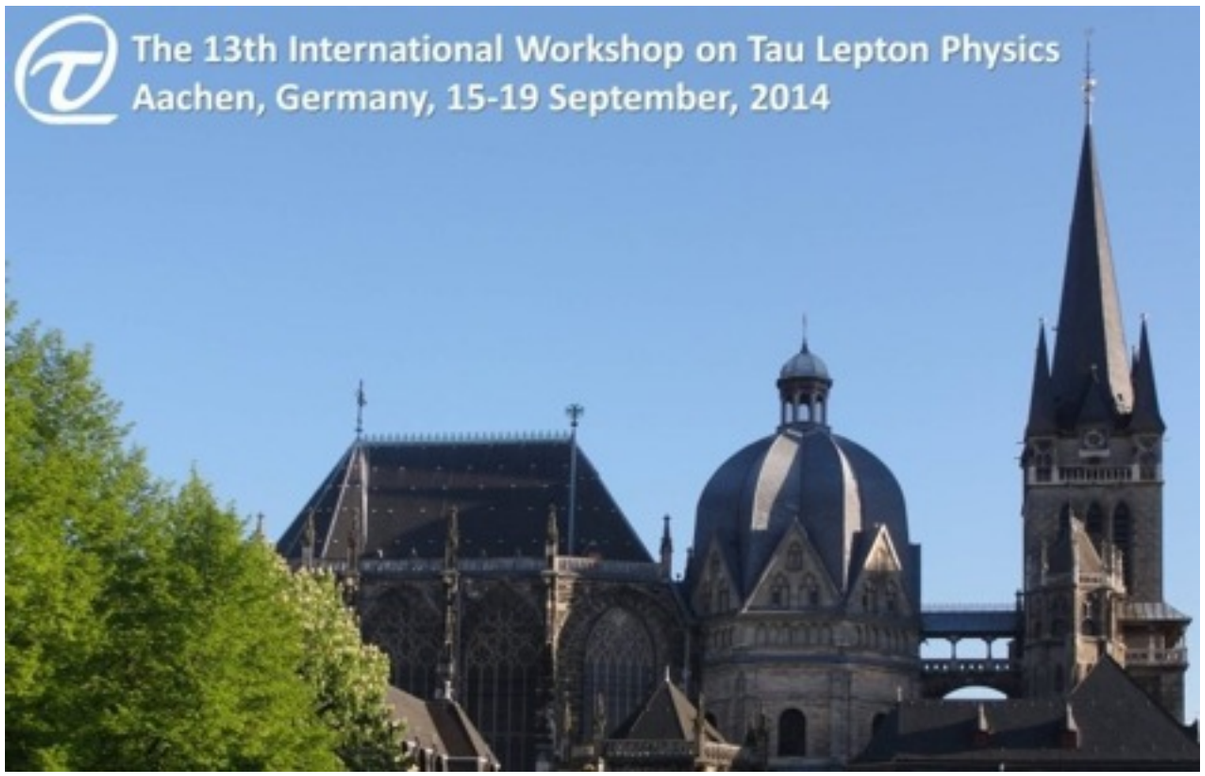
Tau2014 @ RWTH Aachen University



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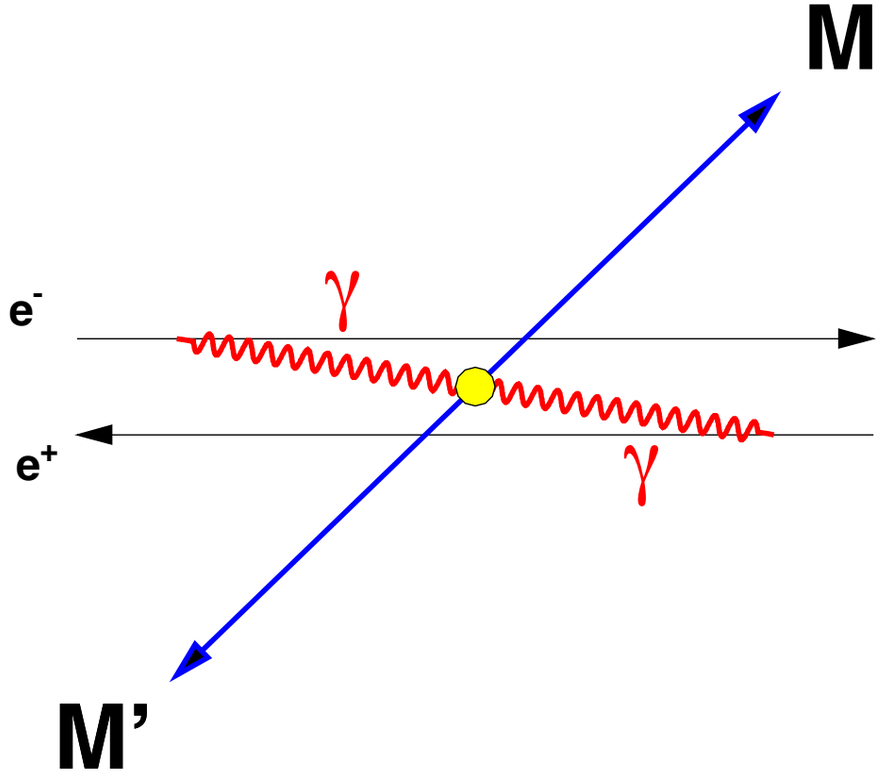
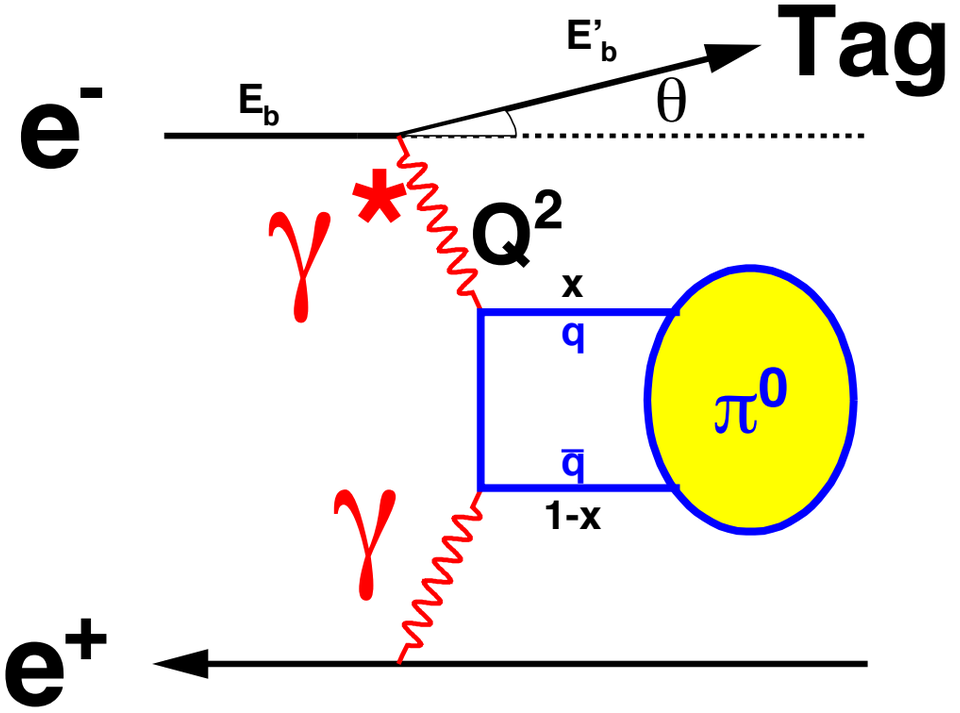
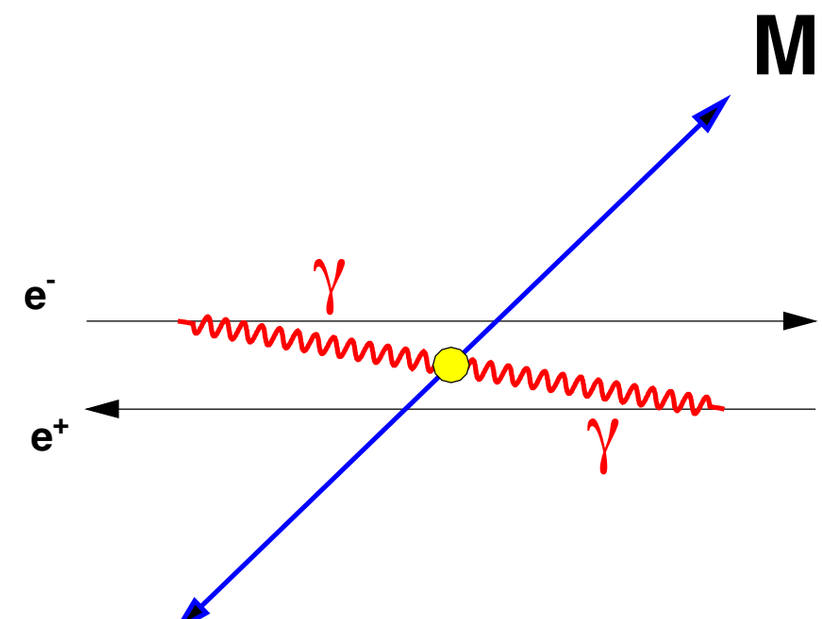
Two-Photon Process





Two-Photon Process by real photons — No-tag method

- Collision by two quasi-real photons
  - Virtuality of the photon: $Q^2 = 4E_b E' \sin^2 \frac{\theta_e}{2}$
  - $Q^2 \sim 0$ for both photons:
    - $e^+ e^-$ escape to beam pipe. Must not be detected
    - $\left|\sum_i \vec{p}_t(M_i)\right| \sim 0$ for detected final state particles
- $W = (M(\gamma\gamma))$ spectrum
- Final state of $J^{PC} = 0^{?+}, 2^{?+}, 3^{++}, \ldots$. C=+ resonance study.
- $\frac{d\sigma}{d|\cos\theta^*|} = \frac{\Delta N}{\Delta W \Delta|\cos\theta^*| \frac{dL_{\gamma\gamma}}{dW} \epsilon(W, |\cos\theta^*|) \int \mathcal{L} dt}$



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

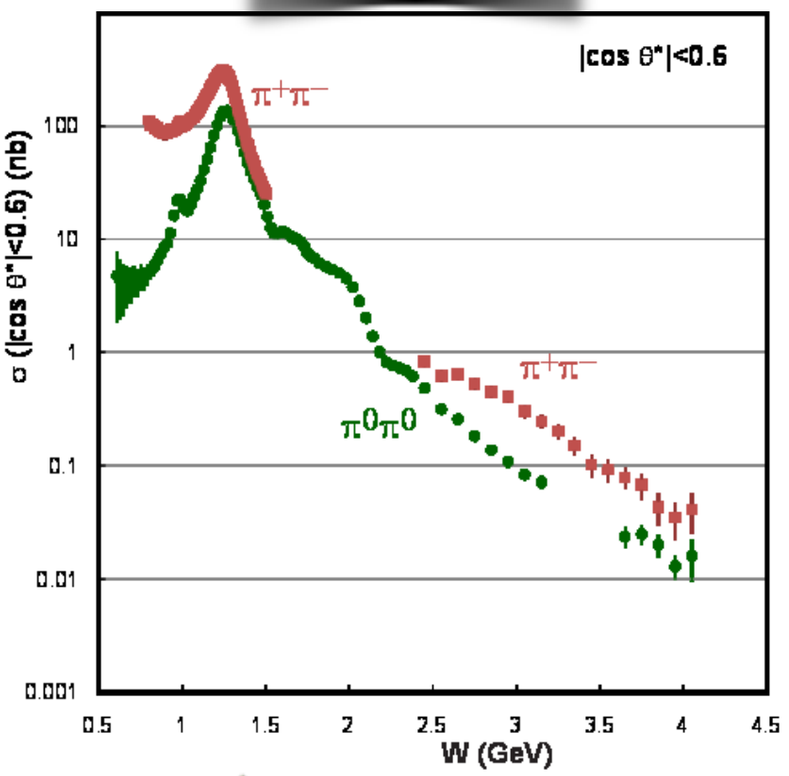
θ^*: Scattering angle in $\gamma\gamma$ system. ε: Efficiency

Cross section measurements of hadron pair production in no-tag two-photon processes

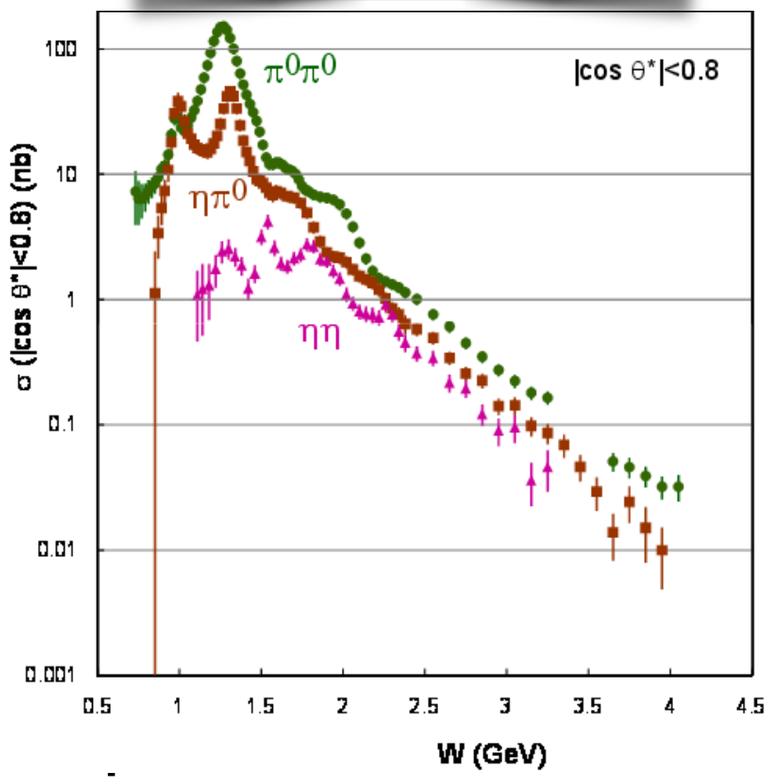
	GeV	< $\lvert\cos\theta^*\rvert$	fb-1	reference	year
$\pi^+\pi^-$	2.4 - 4.1	0.6	88	PLB15, 39	2005
	0.8 -1.5	0.6	86	PRD75, 051101	2007
				JPhySocJpn76, 074102	2007
K^+K^-	1.4 - 2.4	0.6	67	EPJC32, 323	2003
	2.4 - 4.1	0.6	88	PLB15, 39	2005
KsKs	2.4 - 4.0	0.6	398	PLB651, 15	2007
	1.05 - 4.0	0.8	972	PTEP2013, 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

Cross Sections

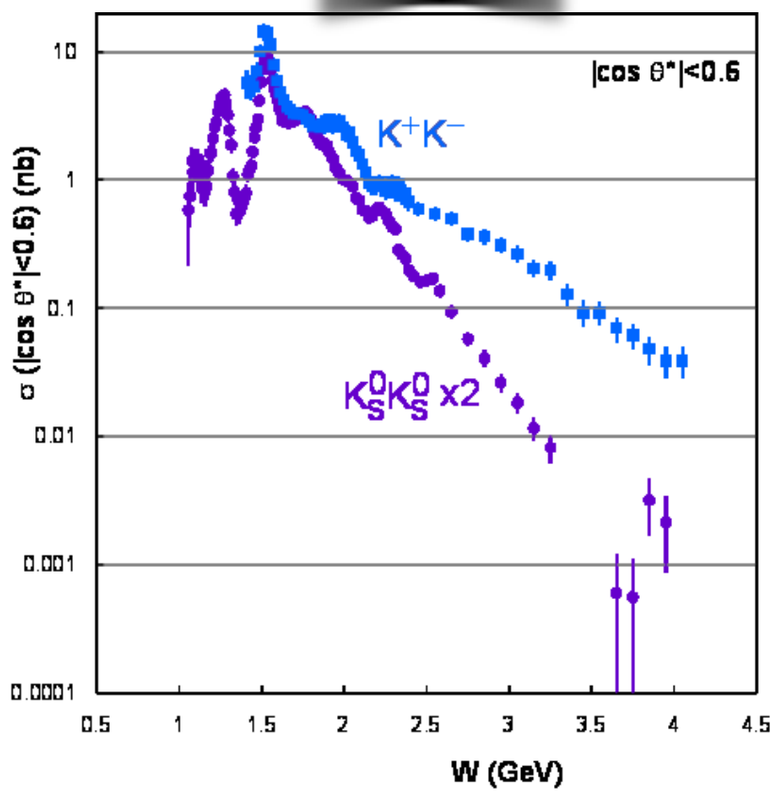
$\pi\ \pi$



neutral



KK



- Lower energy region
  - Partial Wave Analysis for overlapped resonances
- Higher energy region
  - Evaluation of QCD calculation

Light Meson Study using Partial Wave Analysis

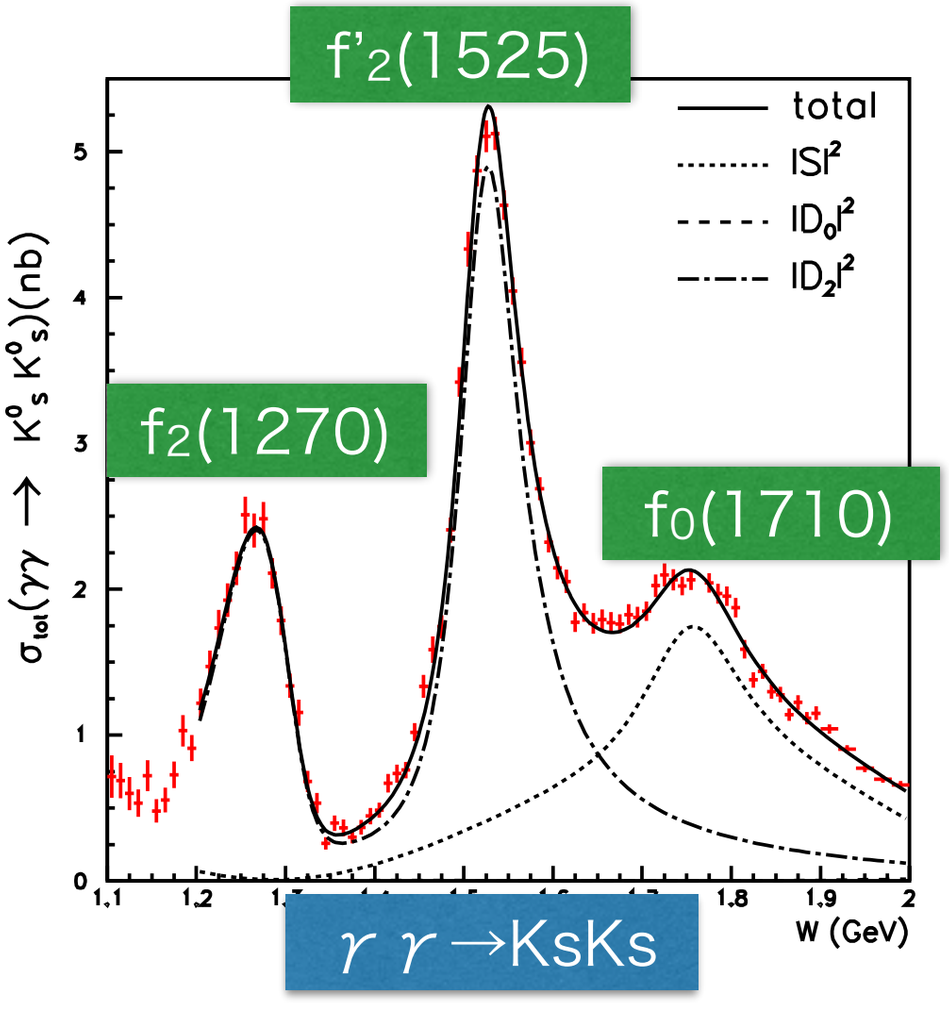
$$\frac{d\sigma}{4\pi d|\cos\theta^*|}(\gamma\gamma \to MM') = |SY_0^0 + D_0Y_2^0 + G_0Y_4^0|^2 + |D_2Y_2^2 + G_2Y_4^2|^2$$

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

- Y_J^m: spherical harmonics: angular dep.
- S, D, G: W dep. of each wave;
  Breit-Wigner + Non-resonant component

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

Resonance	Mass (MeV/c^2)	Width (MeV)	$\Gamma_{\gamma\gamma}$ (eV)
$f_2'(1525)$	$1525.3^{+1.2+3.7}_{-1.4-2.1}$	$82.9^{+2.1+3.1}_{-2.2-2.0}$	$48^{+67+108}_{-8-12}/\mathcal{B}(K\bar{K})$
$f_0(1710)$	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}	$145\pm12^{+27}_{-34}$	$3.2^{+0.5+1.3}_{-0.4-2.2}/\mathcal{B}(K\bar{K})$
$f_0(2500)$	$2539\pm14^{+38}_{-14}$	$274^{+77+126}_{-61-163}$	$40^{+9+17}_{-7-40}/\mathcal{B}(K\bar{K})$



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	$2327\pm9\pm6$	$275\pm36\pm20$	$\begin{cases}22\pm3\pm6/\mathcal{B}\\161\pm22\pm48/\mathcal{B}\end{cases}$
$K^0_SK^0_S$	$f_2'(1525)$	$1525.3^{+1.2+3.7}_{-1.4-2.1}$	$82.9^{+2.1+3.1}_{-2.2-2.0}$	$48^{+67+108}_{-8-12}/\mathcal{B}(K\overline{K})$
	$f_0(1710)$	1750^{+6+29}_{-7-18}	139^{+11+96}_{-12-50}	$12^{+3+227}_{-2-8}/\mathcal{B}(K\overline{K})$
	$f_2(2200)$	2243^{+7+3}_{-6-29}	$145\pm12^{+27}_{-34}$	$3.2^{+0.5+1.3}_{-0.4-2.2}/\mathcal{B}(K\overline{K})$
	$f_0(2500)$	$2539\pm14^{+38}_{-14}$	$274^{+77+126}_{-61-163}$	$40^{+9+17}_{-7-40}/\mathcal{B}(K\overline{K})$
$\pi^0\pi^0$	$f_0(980)$	$982.2\pm1.0^{+8.1}_{-8.0}$		$286\pm17^{+211}_{-70}$
	$f_2(1270)$	fixed	fixed	
		$\mathcal{B}(f_2\to\gamma\gamma)=(1.57\pm0.01^{+1.39}_{-0.14})\times10^{-5}$		
	$f_0(Y)$	1470^{+6+72}_{-7-255}	90^{+2+50}_{-1-22}	$11^{+4+603}_{-2-7}/\mathcal{B}$
	$f_2(1950)$	2038^{+13}_{-11}	441^{+27}_{-25}	$54^{+23}_{-14}/\mathcal{B}$
	$f_4(2050)$	$1884^{+14+218}_{-13-25}$	$453\pm20^{+31}_{-129}$	$136^{+24+415}_{-22-91}$
$\eta\pi^0$	$a_0(980)$	$982.3^{+0.6+3.1}_{-0.7-4.7}$	$75.6\pm1.6^{+17.4}_{-10.0}$	$128^{+3+502}_{-2-43}/\mathcal{B}$
	$a_0(Y)$	$1316.8^{+0.7+24.7}_{-1.0-4.6}$	$65.0^{+2.1+99.1}_{-5.4-32.6}$	$432\pm6^{+1073}_{-256}/\mathcal{B}$
	$a_2(1320)$	fixed	fixed	$145^{+97}_{-34}/\mathcal{B}$
$\eta\eta$	$f_0(Y)$	$1262^{+51+82}_{-78-103}$	$484^{+246+246}_{-170-263}$	$121^{+133+169}_{-53-106}/\mathcal{B}$
	$f_2(1270)$	fixed	fixed	$11.5^{+1.8+4.5}_{-2.0-3.7}/\mathcal{B}$
	$f_2(X)$	$1737\pm9^{+198}_{-65}$	$228^{+21+234}_{-20-153}$	$5.2^{+0.9+37.3}_{-0.8-4.5}/\mathcal{B}$

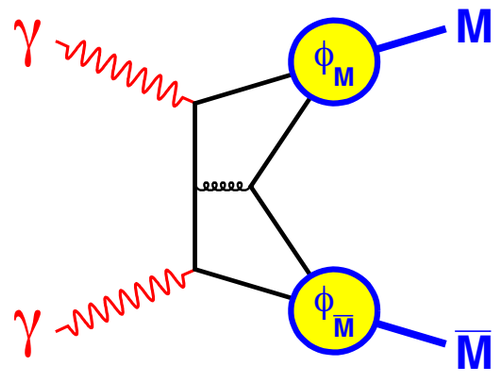
arxiv:1406.6311

QCD Calculation of Meson Pair Production

W>3 GeV: Resonance effect is small

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

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



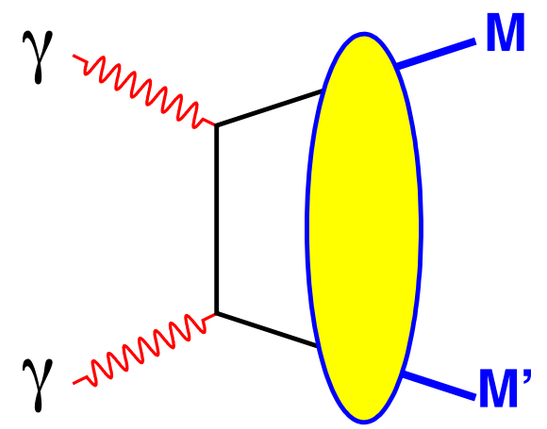
- For charged pair, $\sigma \sim f_M^4/W^6\sin^4\theta^*$, $d\sigma(K^+K^-)/d\sigma(\pi^+\pi^-)=2.3$

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))

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



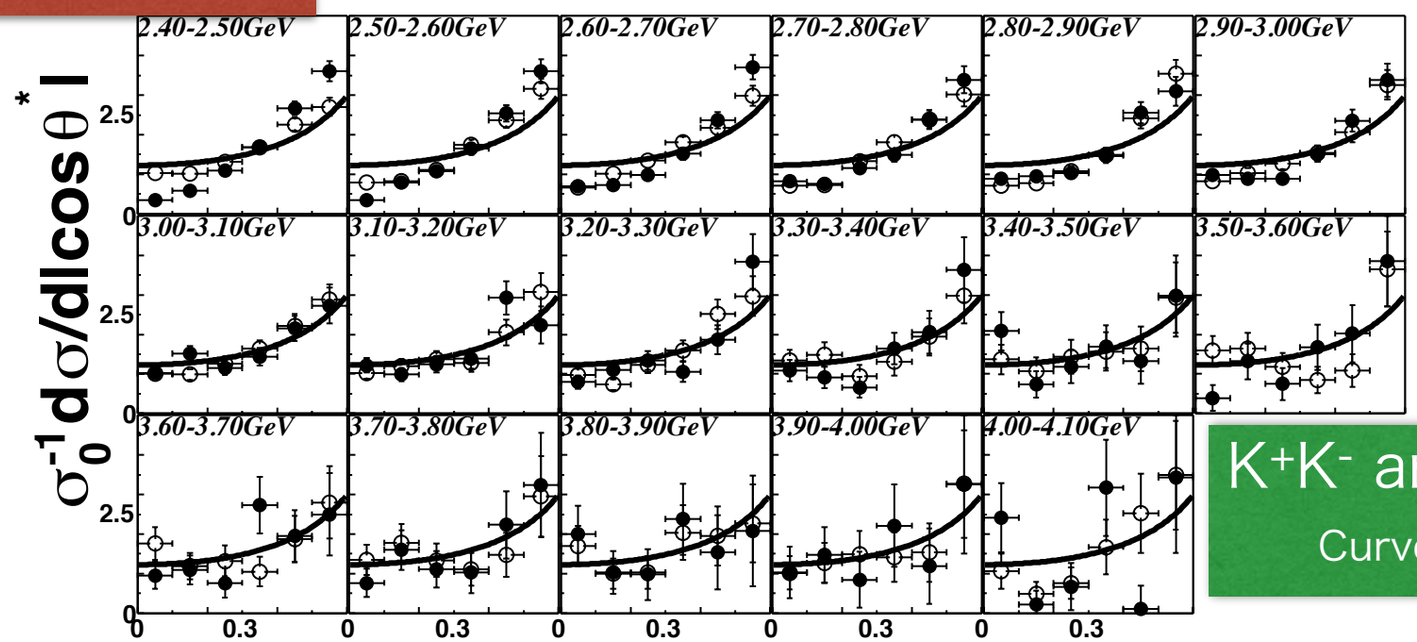
- Charge counting & flavor symmetry

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

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

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

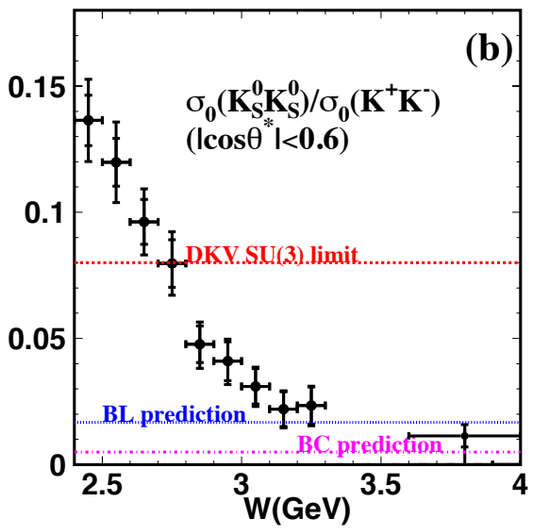
$\sigma_0 = \int \frac{d\sigma}{d|\cos\theta^*|} d|\cos\theta^*|$

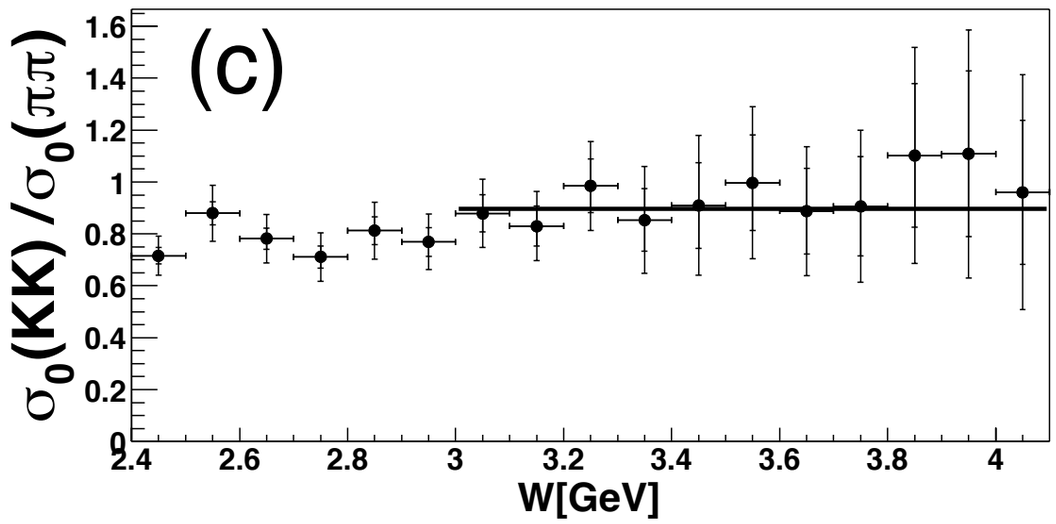
n for $\sigma_0 \sim W^{-n}$

Process	pQCD(BL)	pQCD(BC)	Bag(DKV)	Belle	W (GeV)	$<|\cos\theta^*|$
$\pi^+\pi-$	6	6		$7.9 \pm 0.4 \pm 1.5$	3.0 - 4.1	0.6
K^+K^-	6	6		$7.3 \pm 0.3 \pm 1.5$	3.0 - 4.1	0.6
$K_SK_S\dagger$	-	10		$10.5 \pm 0.6 \pm 0.5$	2.4 - 4.0	0.6
$K_SK_S\ddagger$	-	10		$11.0 \pm 0.4 \pm 0.4$	2.6 - 4.0	0.8
$\pi^0\pi^0$	-	10		$8.0 \pm 0.5 \pm 0.4$	3.1 - 4.1	0.8

σ_0 radio

Process	pQCD(BL)	pQCD(BC)	Bag(DKV)	Belle	W (GeV)	$<|\cos\theta^*|$
$K^+K^-/\pi^+\pi^-$	2.3	1.06		$0.89 \pm 0.04 \pm 0.15$	3.0 - 4.1	0.6
$K_SK_S/K^+K^-\dagger$		0.005	0.08	~ 0.13 to ~ 0.01	2.4 - 4.0	0.6
$\pi^0\pi^0/\pi^+\pi^-$		0.04-0.07	0.5	$0.32 \pm 0.03 \pm 0.06$	3.1 - 4.1	0.6





PRD86, 092007 (2012)

π^0 transition form factor

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

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

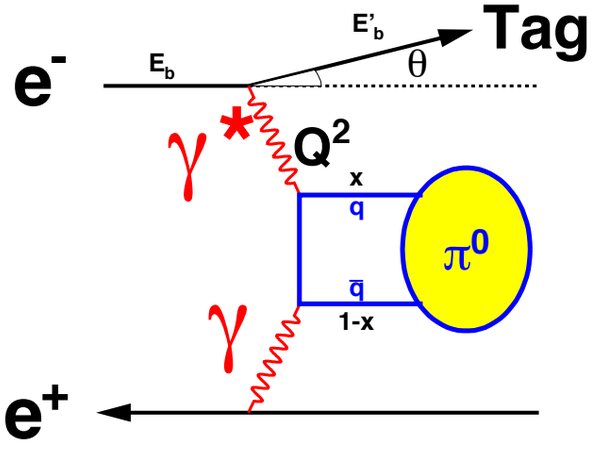
- Extraction from $d\sigma/dQ^2$

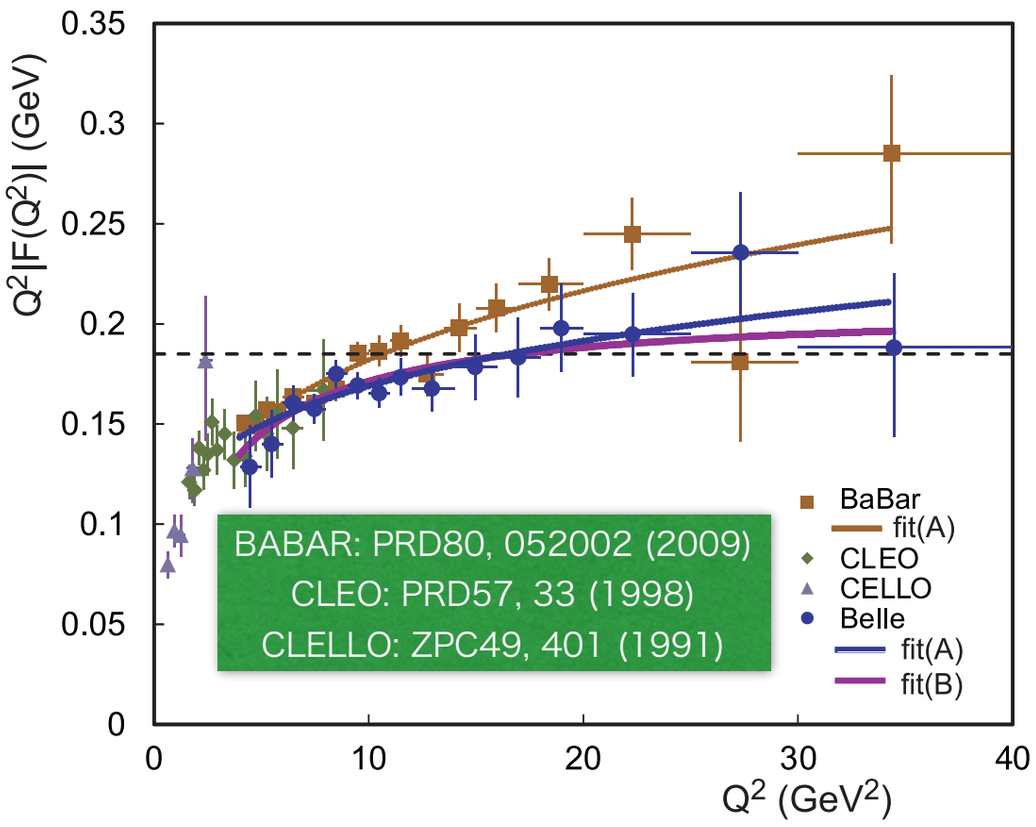
$$\frac{d\sigma}{dQ^2} = \frac{N(1 - r_b)}{\int L dt \epsilon \mathcal{B}(\pi^0 \to \gamma\gamma)(1 + \delta)\Delta Q^2}$$

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

ε	Efficiency
r	background fraction
δ	radiative correction

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





Asymptotically approaches

B=0.209 ± 0.016 GeV

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

Consistent with pQCD, 0.185 GeV

Rapid growth in BABAR data ($Q^2 > 9\text{GeV}^2$) not seen, but statistically not inconsistent each other.

ISR

Hadronic Cross Section measurements in ISR processes at Belle

$e^+e^- \to \gamma_{ISR} X$	range(GeV)	fb-1	reference	year
$\pi^+\pi^- \phi$	thre, 3.0	673	PRD80, 031101	2009
$\pi^+\pi^- J/\psi$	3.8, 5.5	548	PRL99, 182004	2007
	3.8, 5.5	967	PRL110, 252002	2013
$\pi^+\pi^- \psi(2S)$	thre, 5.5	673	PRL99, 142002	2007
	4.0, 5.5	980	Preliminary	
η J/ψ	3.8, 5.3	980	PRD87, 051101	2013
$K^+K^- J/\psi$	thre, 6.0	673	PRD77, 011105	2008
	thre, 6.0	980	PRD89, 072015	2014
KsKsJ/ψ	thre, 6.0	980	PRD89, 072015	2014
$D^+D^{(*)-}$	thre, 5.0	548	PRL98, 092001	2007
DDbar	thre, 5.0	673	PRD77, 011103	2008
$D^0D^-\pi^+$	4.0, 5.0	673	PRL100, 062001	2008
$D^0D^{*-}\pi^+$	thre, 5.2	695	PRD80, 091101	2009
$Ds^{(*)+}Ds^{(*)-}$	thre, 5.0	967	PRD83, 011101	2011
$\Lambda c^+ \Lambda c^-$	thre, 5.4	695	PRL101, 172001	2008

Cross sections for open charm processes

hep-ex1105.4975

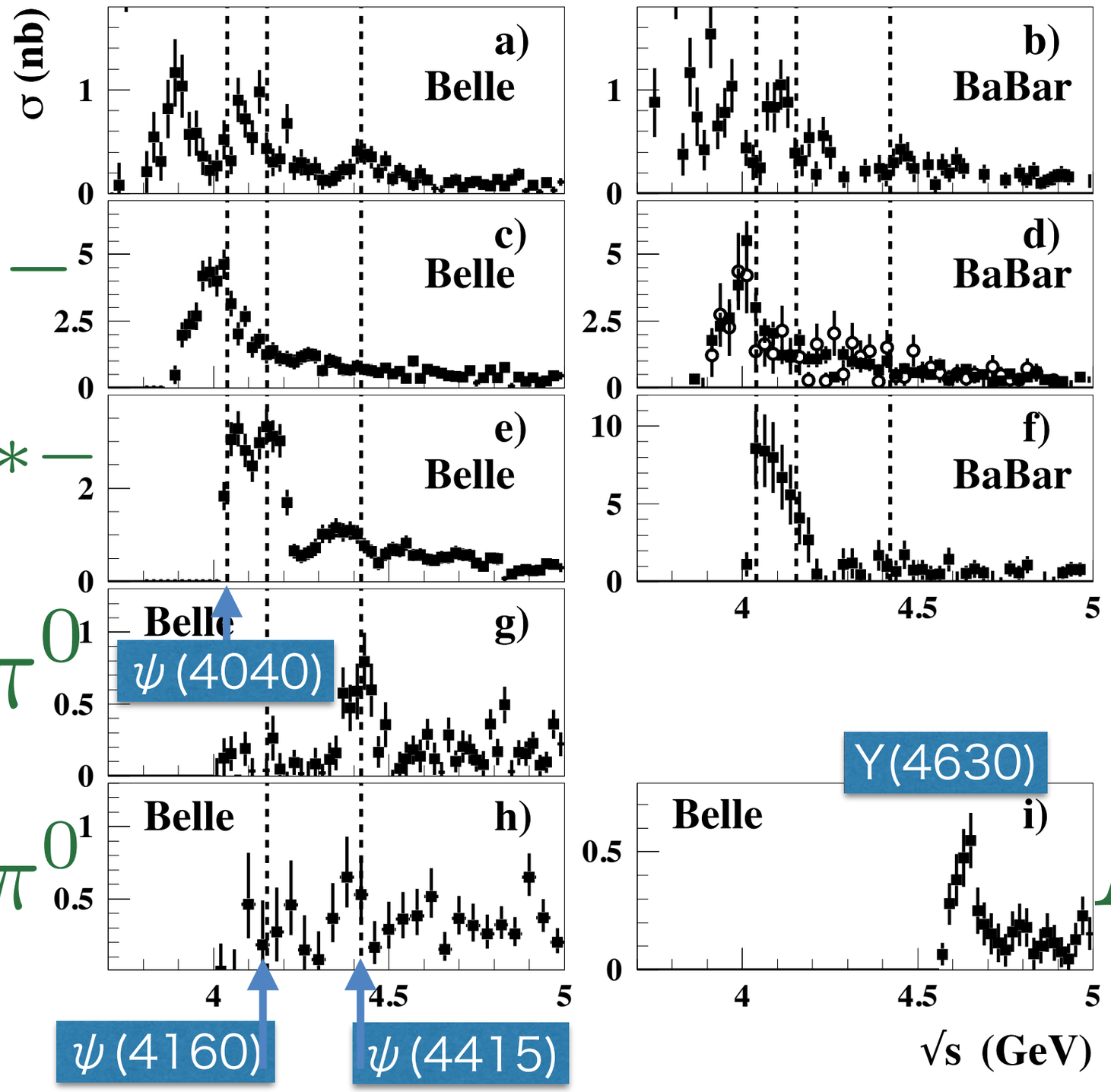
$D\overline{D}$

D^+D^{*-}

$D^{*+}D^{*-}$

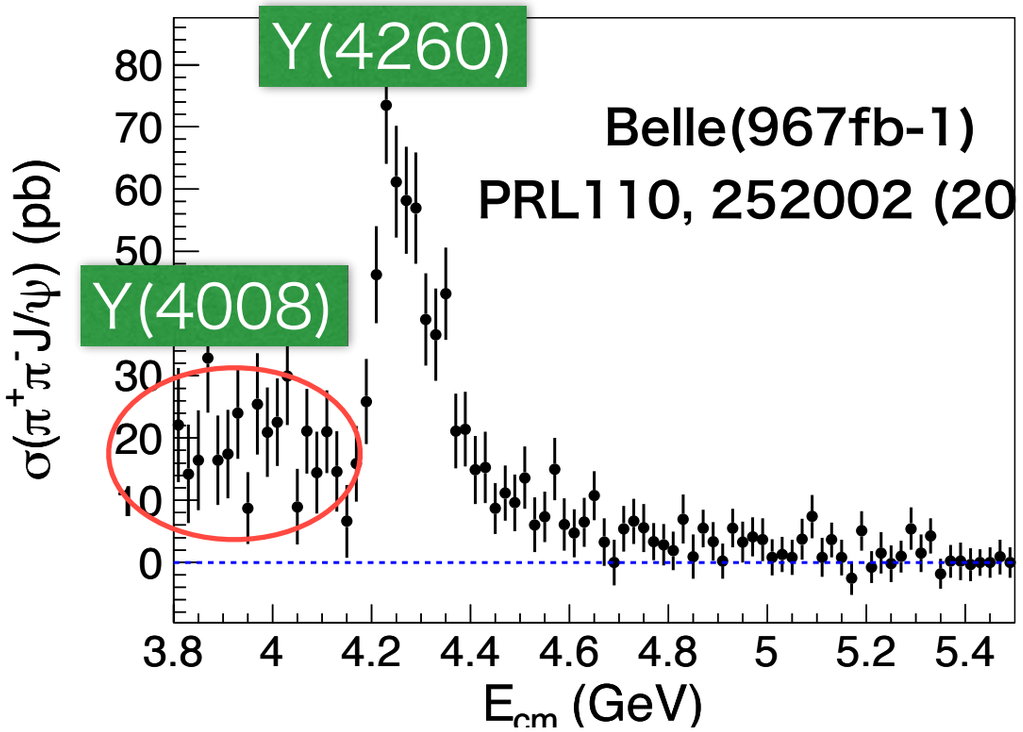
$D^0D^-\pi^0$

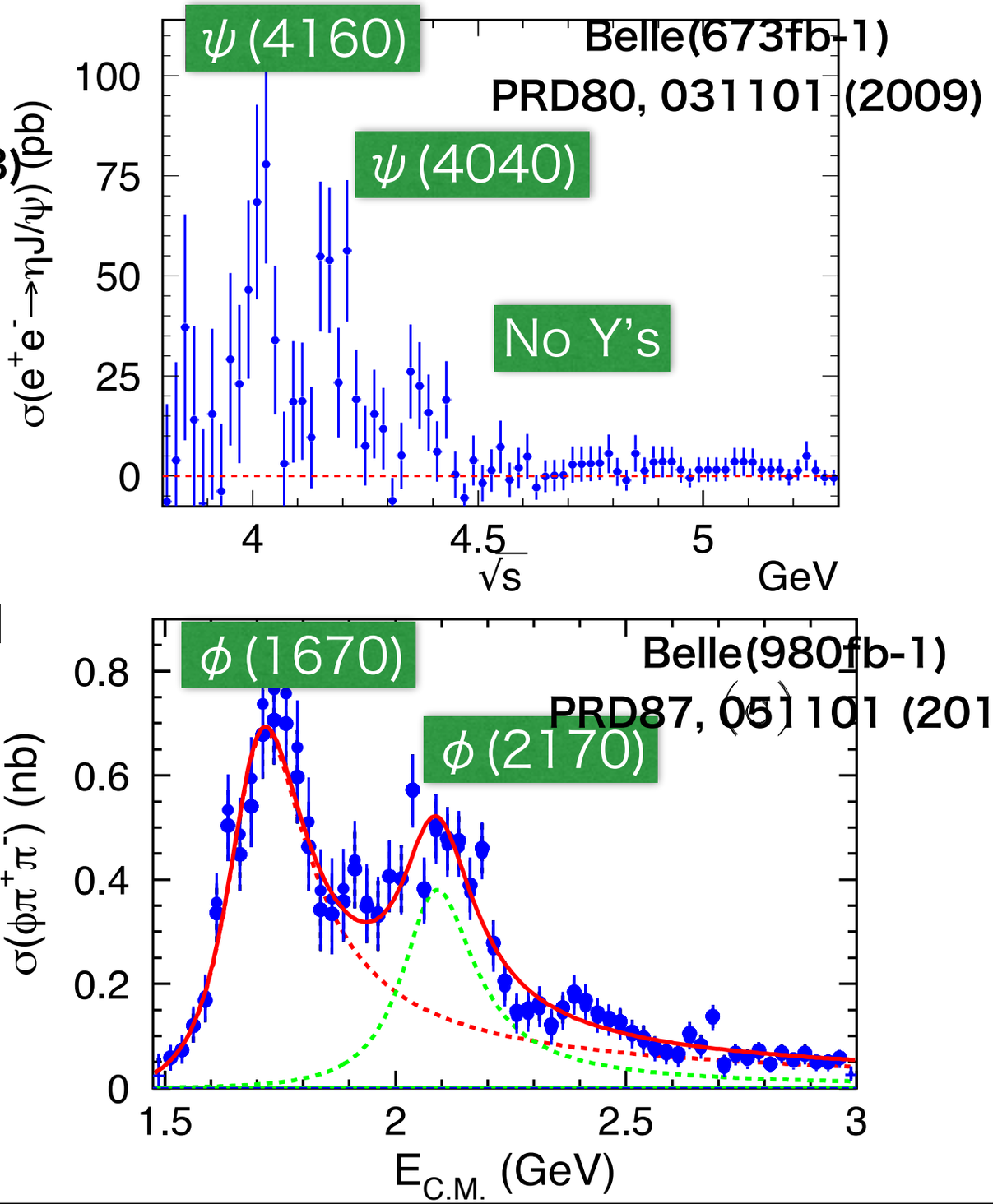
$D^0D^{*-}\pi^0$

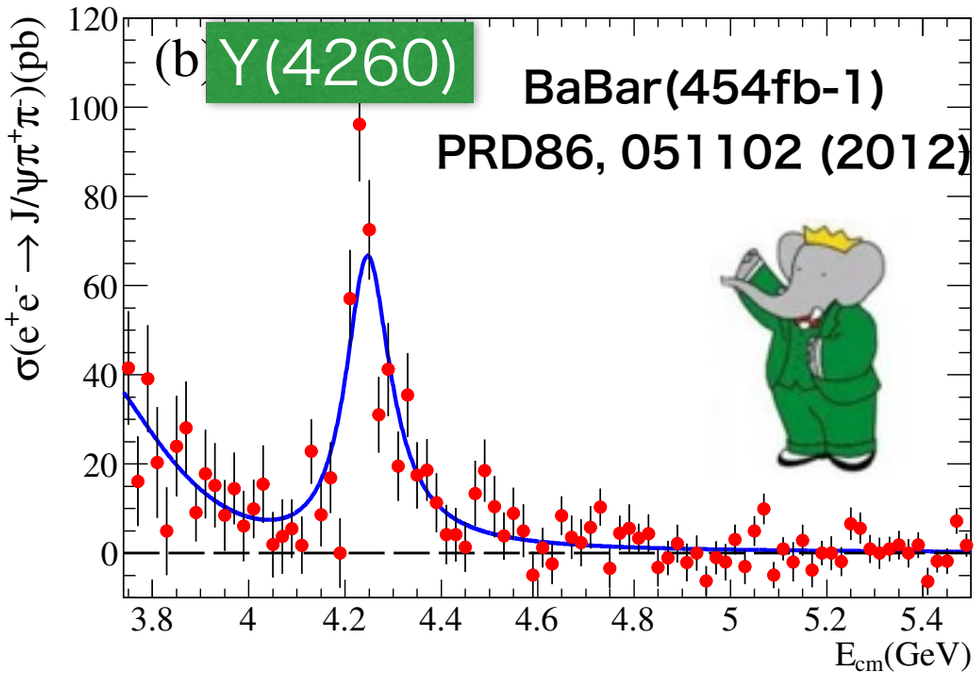


$\Lambda_c^+\Lambda_c^-$

Hidden Charm and Charmless modes



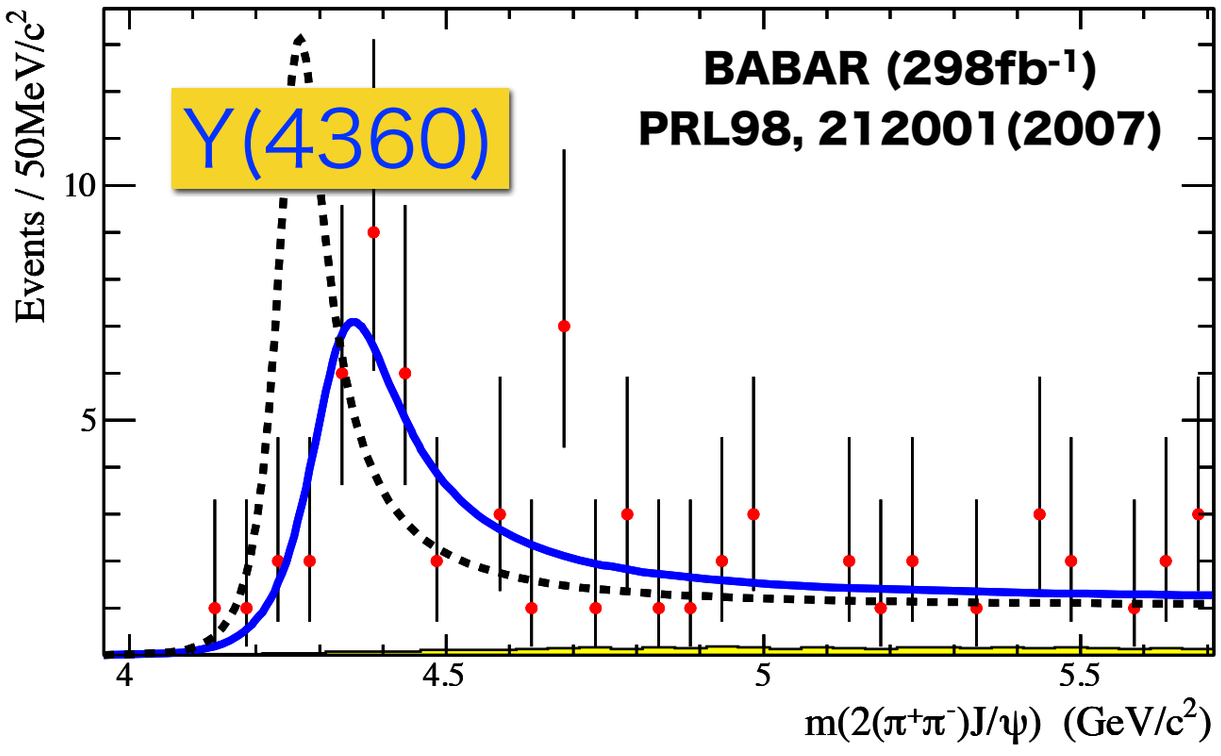


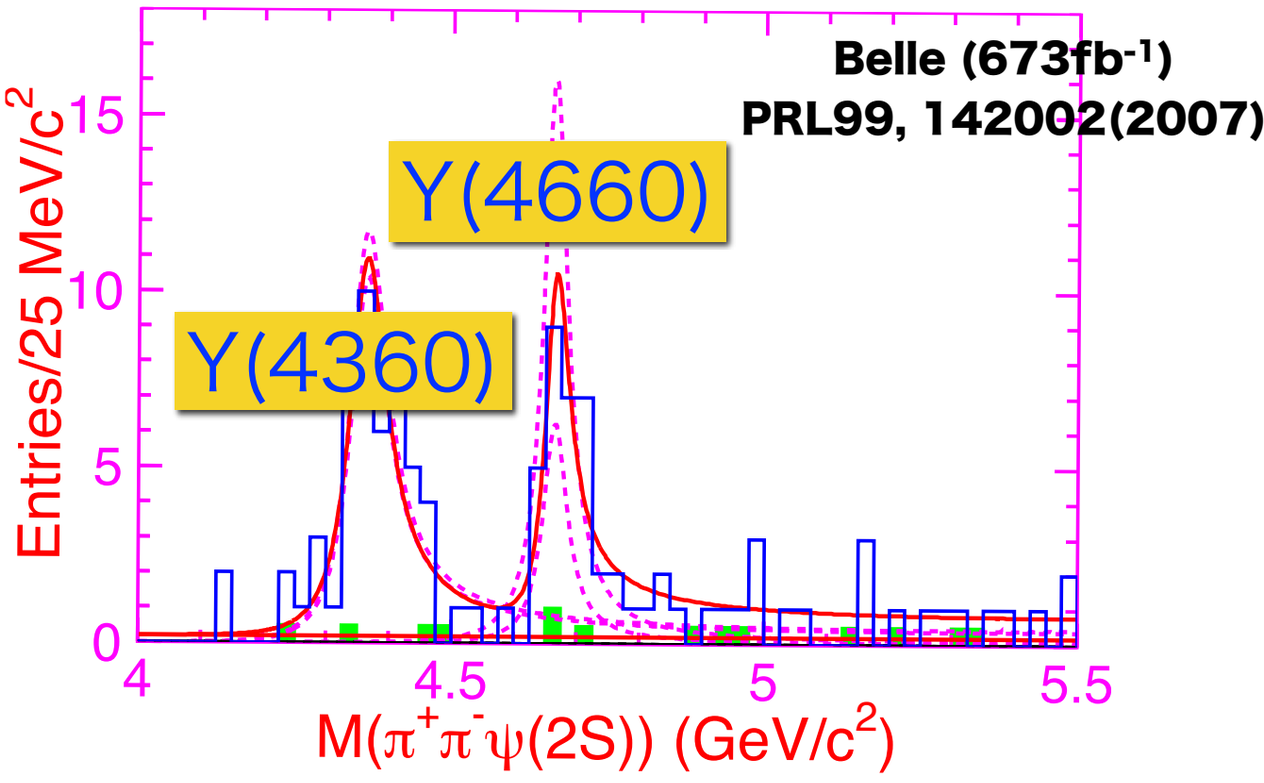


Preliminary

Updated $e^+e^- \to \pi^+\pi^-\psi(2S)$

Previous Measurements



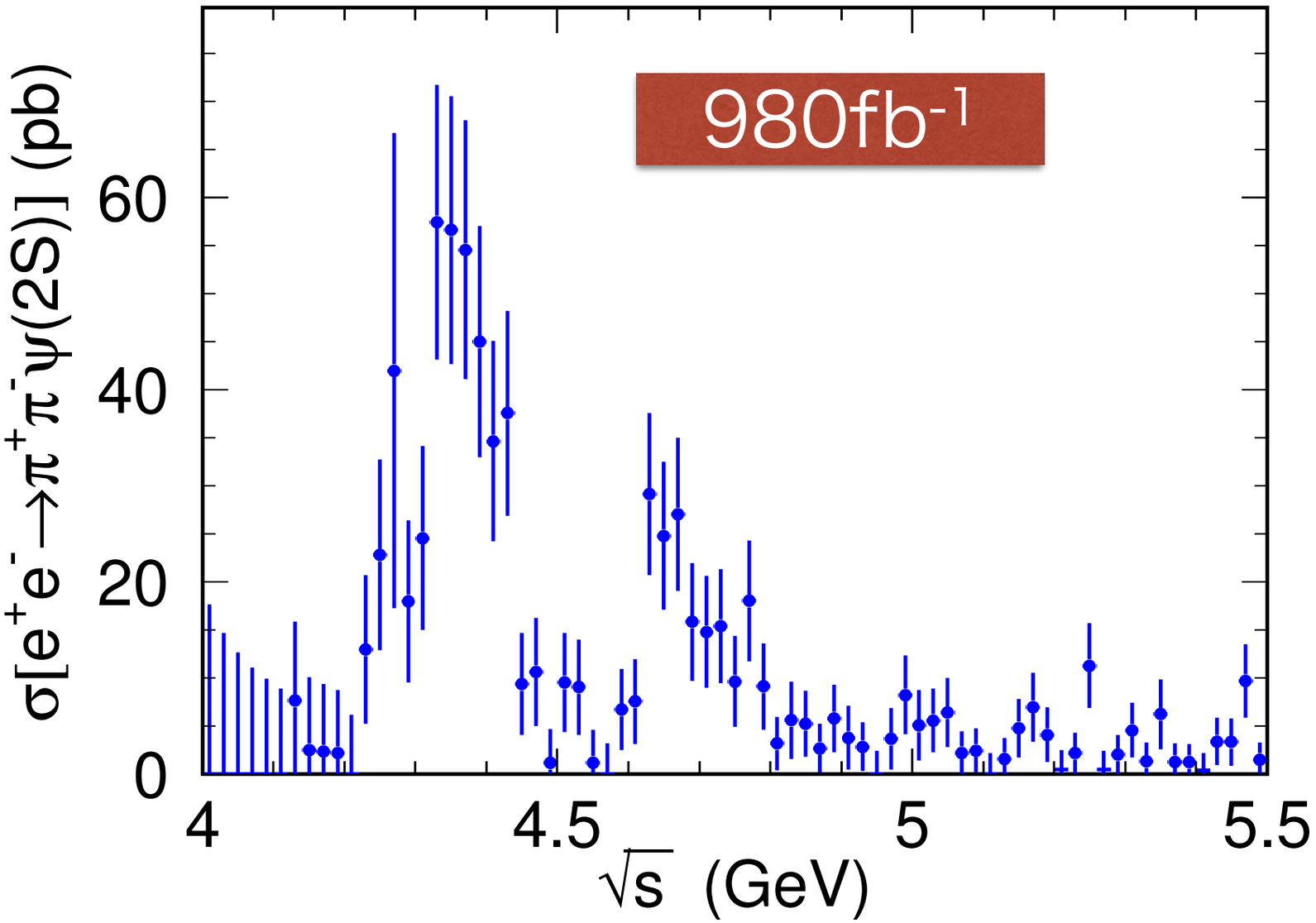


PDG2014

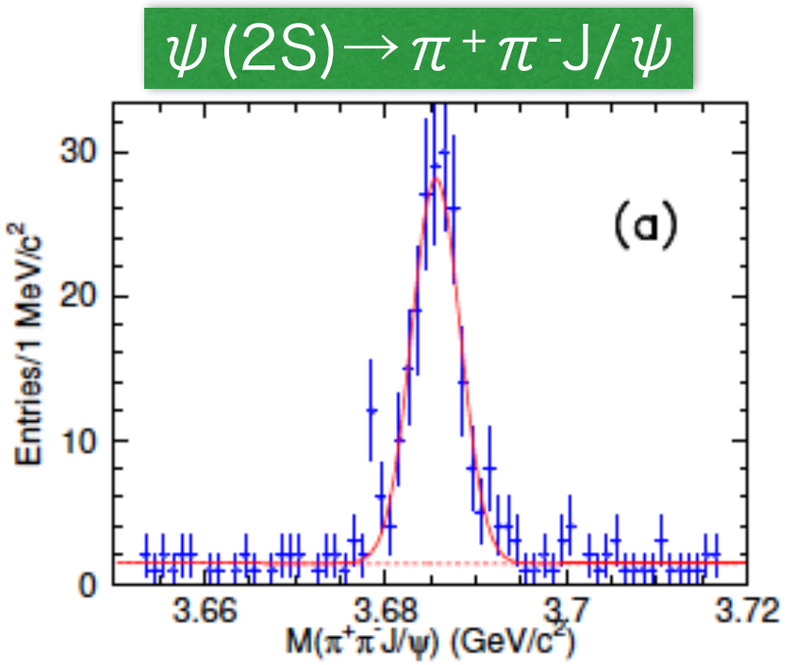
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0/2^{++}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [87] (3.2)	2009	NC!
$Y(4360)$	4361 ± 13	74 ± 18	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	BABAR [88] (np), Belle [89] (8.0)	2007	OK
$Z(4430)^+$	4458 ± 15	166^{+37}_{-32}	1^{+-}	$B^0 \to K^-(\pi^+ J/\psi)$	Belle [90,91,92](6.4), BaBar [93](2.4)	2007	OK
				$B^0 \to \psi(2S)\pi^- K^+$	LHCb [94](13.9)		
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle [95] (8.2)	2007	NC!
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	Belle [89] (5.8)	2007	NC!

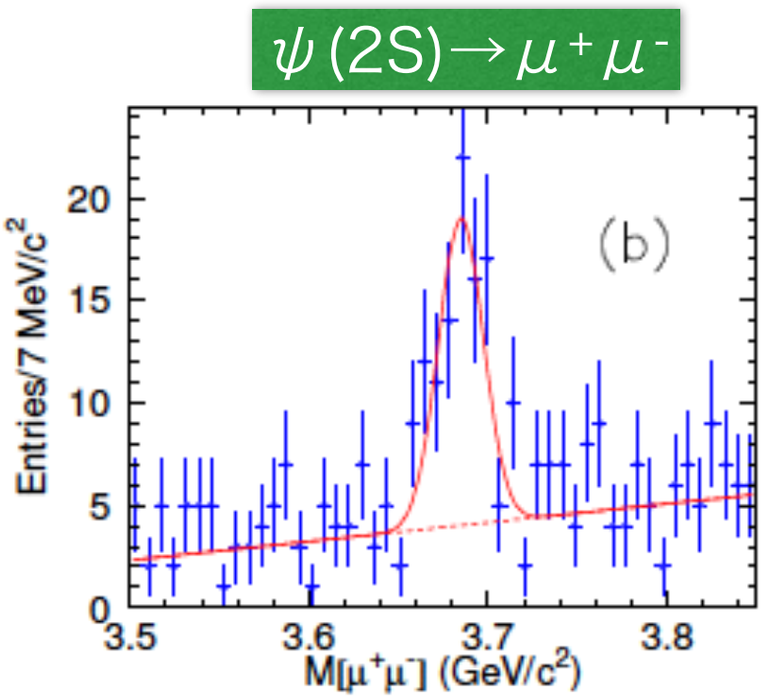
Preliminary

Updated $e^+e^- \to \pi^+\pi^-\psi(2S)$



4.8% systematic error not included

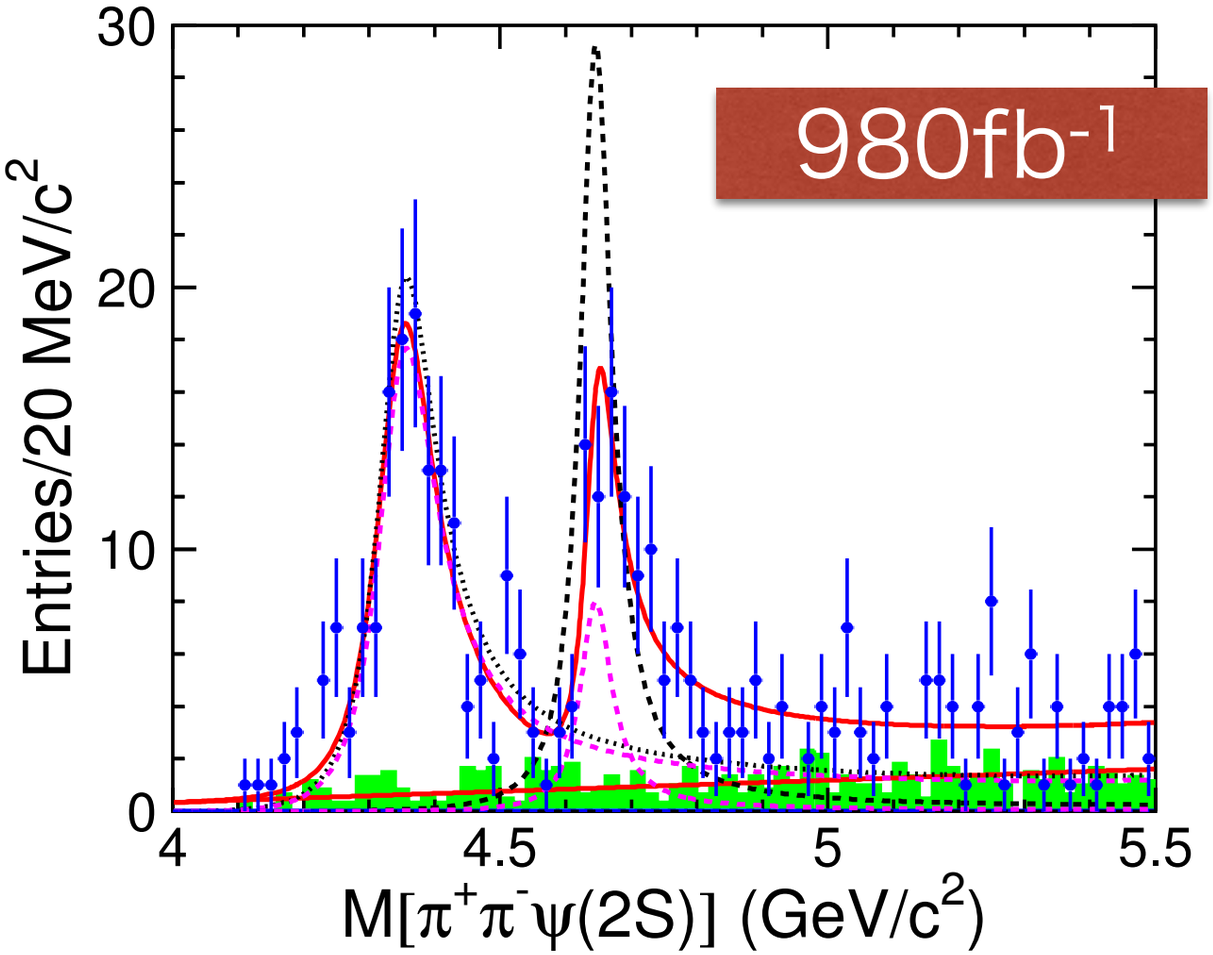




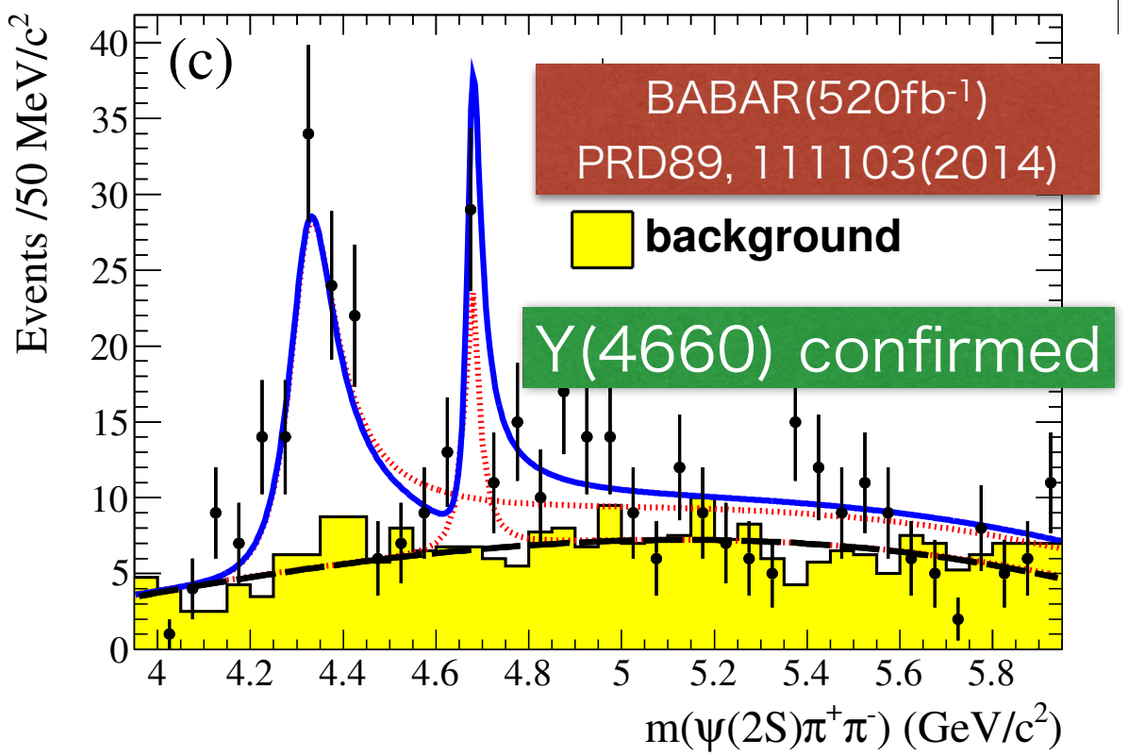
Preliminary

M($\pi^+\pi^-\psi(2S)$) fit

Simultaneous UML fit to $\pi^+\pi^-J/\psi$ and $\mu^+\mu^-$ modes



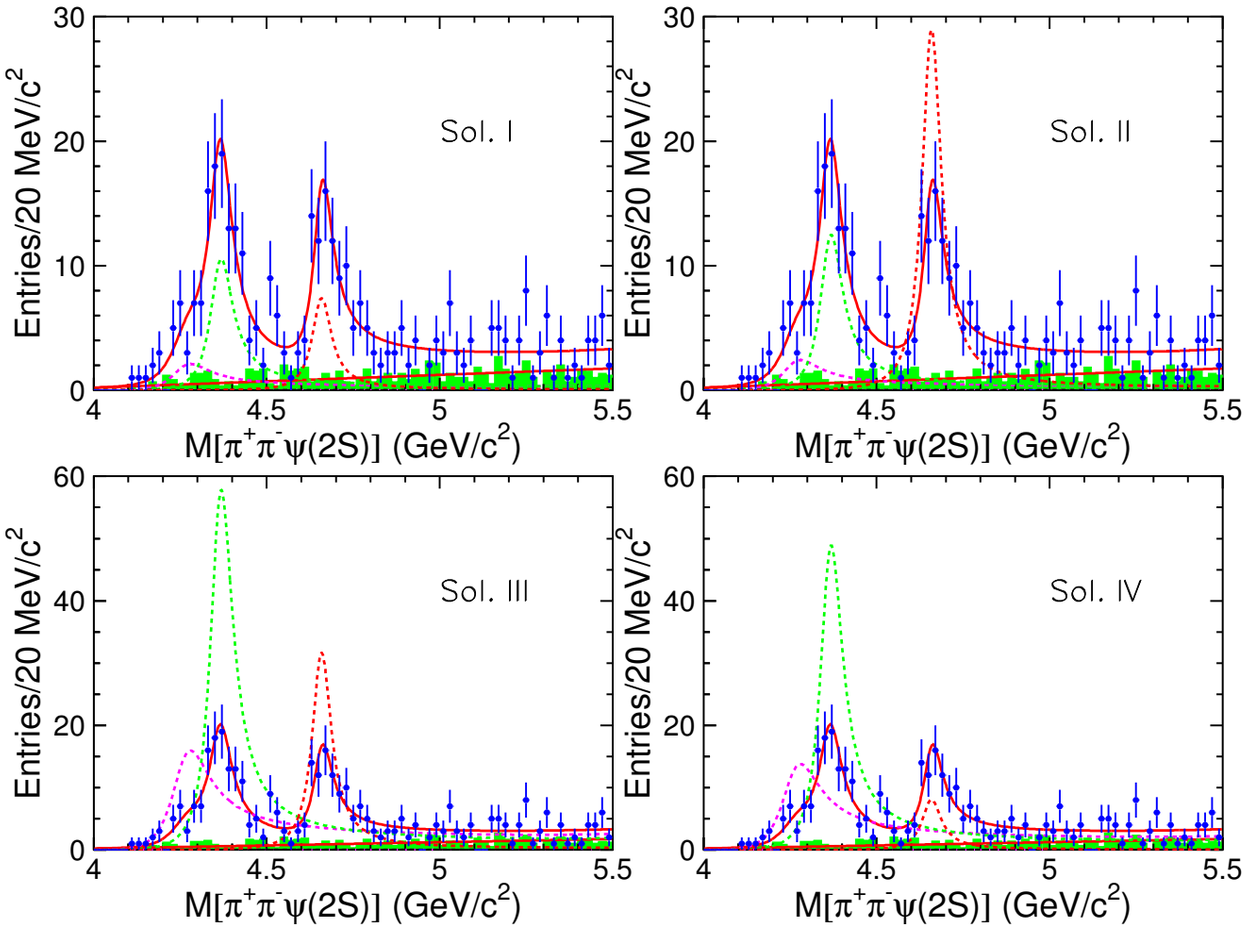
- Two solutions with χ^2/ndf=27.6/21
- No obvious signal above Y(4660)
- Some events accumulate at Y(4260)



			Solution I	Solution II
$Y(4360)$	M	MeV/c^2	$4346 \pm 6 \pm 2$	
	Γ	MeV	$111 \pm 10 \pm 7$	
	$\mathcal{B} \cdot \Gamma_{ee}$	eV	$10.6 \pm 0.6 \pm 0.7$	$9.2 \pm 0.8 \pm 0.7$
$Y(4660)$	M	MeV/c^2	$4644 \pm 12 \pm 8$	
	Γ	MeV	$59 \pm 12 \pm 2$	
	$\mathcal{B} \cdot \Gamma_{ee}$	eV	$6.8 \pm 1.6 \pm 0.7$	$1.8 \pm 0.3 \pm 0.1$
	ϕ	deg	$278 \pm 11 \pm 8$	$19 \pm 24 \pm 20$

Preliminary

$M(\pi^+\pi^-\psi(2S))$ fit with Y(4260)



- Coherent sum of 3 BWs
- 4 solutions with χ^2/ndf=24.8/19
- Significance of Y(4260) is 2.1 σ.
  - Not significant but effect is large

$Y(4260)$	M	4259(fix)	MeV/c^2
	Γ	134(fix)	MeV
$Y(4360)$	M	4363 ± 8	MeV/c^2
	Γ	80 ± 16	MeV
$Y(4660)$	M	4657 ± 9	MeV/c^2
	Γ	68 ± 11	MeV

		Solution I	Solution II	Solution III	Solution IV
$\mathcal{B} \cdot \Gamma_{ee}(Y(4260))$	eV	1.4 ± 0.6	1.6 ± 0.7	10.7 ± 1.4	9.3 ± 1.3
$\mathcal{B} \cdot \Gamma_{ee}(Y(4360))$	eV	3.9 ± 1.0	4.6 ± 1.3	21.5 ± 3.7	18.2 ± 2.9
$\mathcal{B} \cdot \Gamma_{ee}(Y(4660))$	eV	2.0 ± 0.4	7.7 ± 0.9	8.4 ± 1.1	2.1 ± 0.4
ϕ_1	deg	309 ± 26	300 ± 28	131 ± 5	140 ± 5
ϕ_2	deg	25 ± 22	243 ± 14	329 ± 9	111 ± 26

Summary

- Cross sections in two-photon processes, $\gamma\gamma \to \pi^+\pi^-$, K^+K^-, $\pi^0\pi^0$, $\eta\pi^0$, $\eta\eta$, and $e^+e^- \to e^+e^-\pi^0$ have been measured
  - Measured cross sections (W dependence and angular dependence) are compared with QCD calculations
- π^0 transition form factor measured in single-tag two-photon events is consistent with pQCD prediction
- Update of $e^+e^- \to \pi^+\pi^-\psi(2S)$ is ongoing. Inclusion of Y(4260) in the fit is tested
- Hadronic cross sections for e+e- $\to \gamma_{ISR}$ X are measured in various processes
  - Conventional and exotic states are observed

Backup

Hadronic Cross Section in ISR processes

$e^+e^- \to \gamma_{ISR}X$:
Mass spectrum of 1^{--} final state X at a fixed beam energy experiment

$$\sigma(e^+e^- \to D\bar{D}) = \frac{dN/dm}{\epsilon_{\rm tot} dL/dm}$$

dN/dm	mass spectrum
ε	total efficiency
dL/dm	Diffential ISR Luminosity

Tagged: Better background reduction

Untagged: Better statistics. Missing Mass Cut

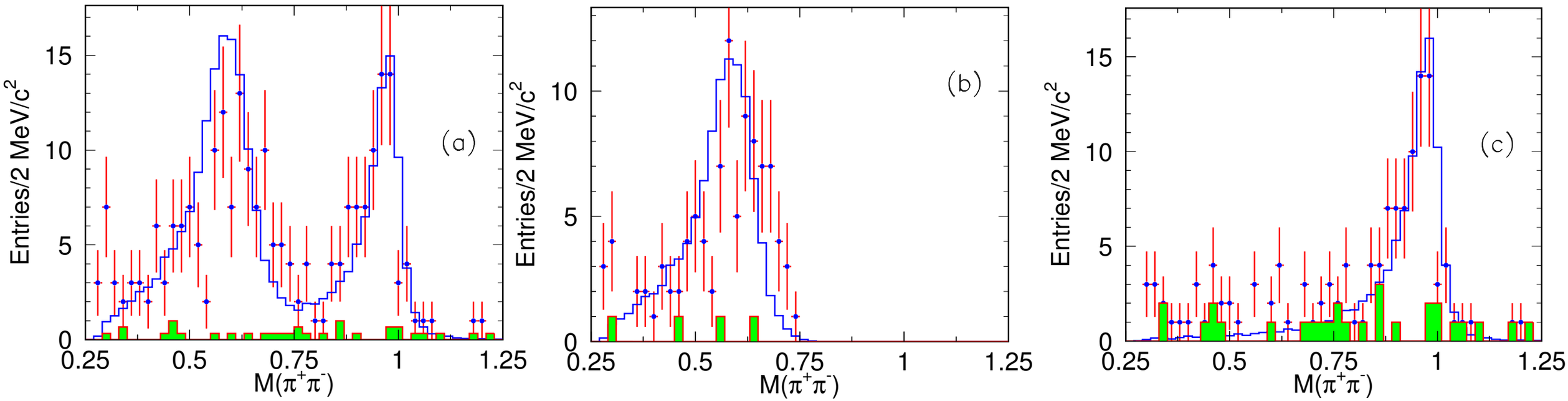
$$\frac{dL}{dm} = \begin{cases} \frac{\alpha}{\pi x}\left((2-2x+x^2)\ln\frac{1+\cos\theta_0}{1-\cos\theta_0} - x^2\cos\theta_0\right)\frac{2m\mathcal{L}_{\rm int}}{E^2_{\rm c.m.}} & \text{tagged} \\ \frac{\alpha}{\pi x}(2-2x+x^2)(\ln\frac{s}{m_e^2}-1)\frac{2m\mathcal{L}_{\rm int}}{E^2_{\rm c.m.}} & \text{untagged} \end{cases}$$

Preliminary

M($\pi^+\pi^-$) distribution in $\psi(2S)\pi^+\pi^-$

Y(4360) region

Y(4660) region



$f_0(500)$?

$f_0(980)$

BABAR ok

Cross section and their ratio

Process	n of σ~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

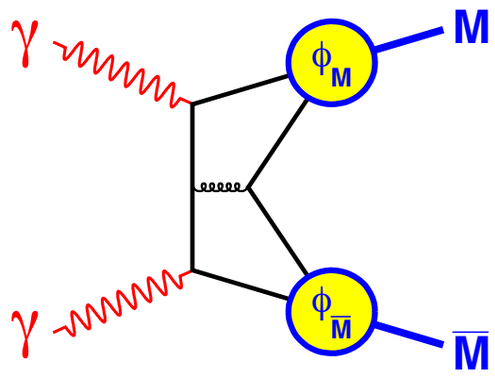
\#\# PTEP2013, 123C01

Meson Pair Production in pQCD

$$\mathcal{M}_{\lambda_1\lambda_2}(W^2,\theta^*) = \int_0^1\int_0^1 dxdy\phi_M(x,Q_x)\phi_{M'}(y,Q_y)T_{\lambda_1\lambda_2}(x,y,\theta^*)$$ 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	Meson form factor. ~1/W
ϕ	Meson distribution amplitude (DA)
T	Hard Scattering amplitude for
g(θ^*)	Only unknown, non-perturbative factc



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

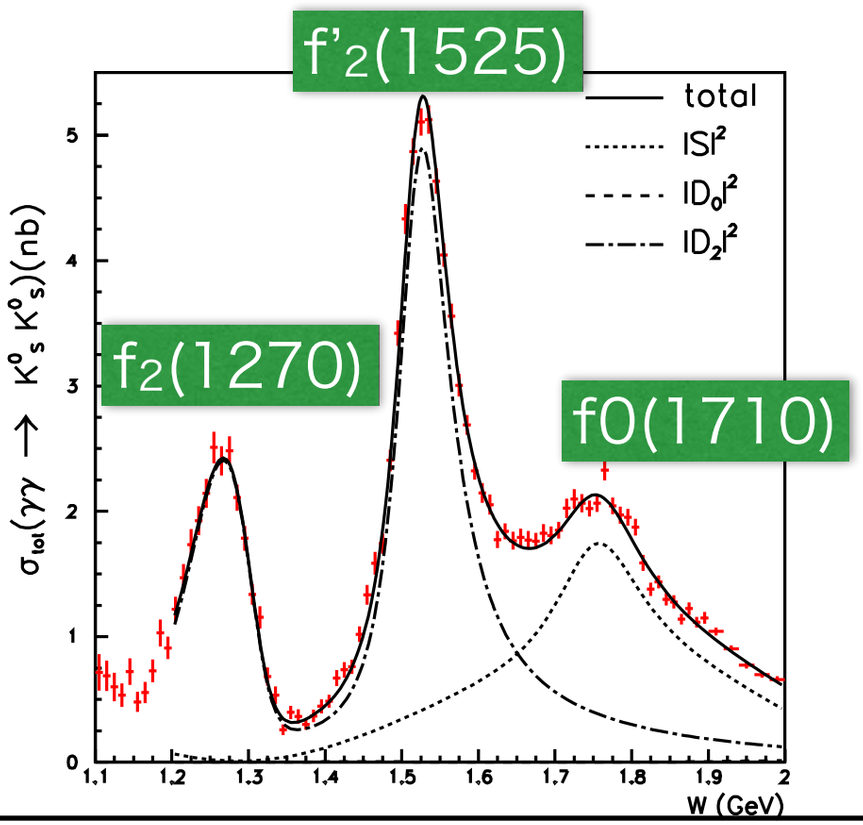
Light Meson Study using Partial Wave Analysis

$$\frac{d\sigma}{4\pi d|\cos\theta^*|}(\gamma\gamma \to MM') = |SY_0^0 + D_0Y_2^0 + G_0Y_4^0|^2 + |D_2Y_2^2 + G_2Y_4^2|^2$$
$$= \hat{S}^2|Y_0^0|^2 + \hat{D}_0^2|Y_2^0|^2 + \hat{D}_2^2|Y_2^2|^2 + \hat{G}_0^2|Y_4^0|^2 + \hat{G}_2^2|Y_4^2|^2$$

- S, D, G have W dependence;
  Breit-Wigner + Non-resonant component

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

- Y_J^m; spherical harmonics



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	$2327\pm9\pm6$	$275\pm36\pm20$	$\begin{cases}22\pm3\pm6/\mathcal{B}\\161\pm22\pm48/\mathcal{B}\end{cases}$
$K_S^0K_S^0$	$f_2'(1525)$	$1525.3^{+1.2+3.7}_{-1.4-2.1}$	$82.9^{+2.1+3.1}_{-2.2-2.0}$	$48^{+67+108}_{-8-12}/\mathcal{B}(K\bar{K})$
	$f_0(1710)$	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	$11.5^{+1.8+4.5}_{-2.0-3.7}/\mathcal{B}$
	$f_2(X)$	$1737\pm9^{+198}_{-65}$	$228^{+21+234}_{-20-153}$	$5.2^{+0.9+37.3}_{-0.8-4.5}/\mathcal{B}$

Single-tag cross section

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

$$\text{PhotonVirtuality}: Q^2 = 4E_bE'\sin^2\frac{\theta_e}{2}$$

ε	Efficiency
r	background fraction
δ	radiative correction