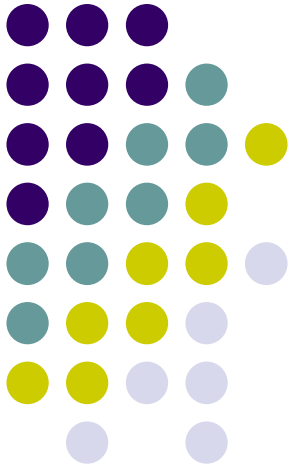
Two-photon process at Belle



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Institue of High Energy Physics, Beijing, China
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中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

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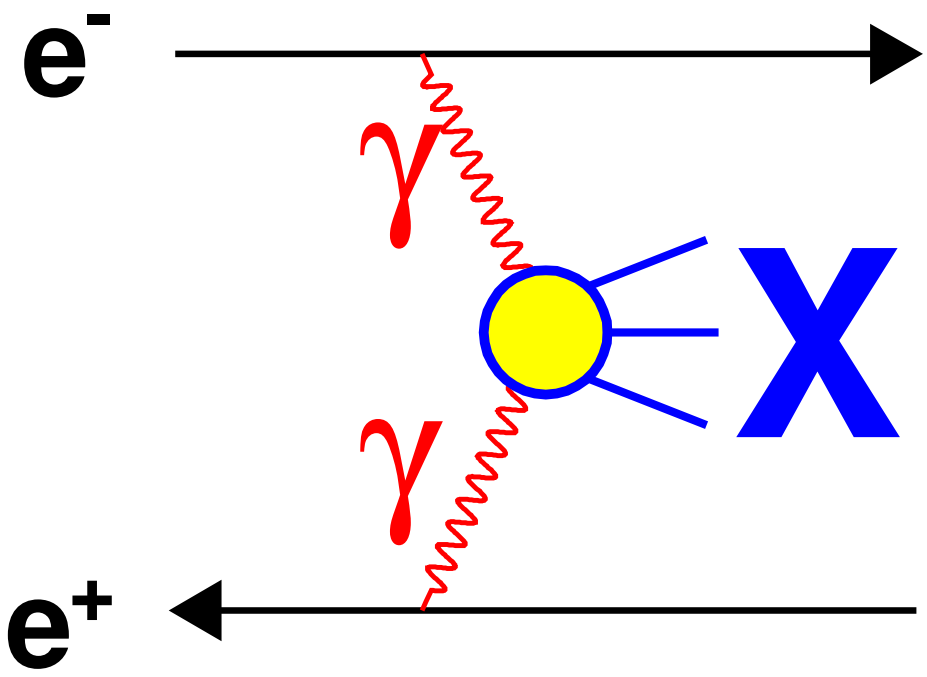


- No tag method
  - Beam particles escape to beam pipes
  - Small virtuality, almost real photons
- Apply tight transverse momentum cut to select exclusive two-photon events

Two-photon process

Differential cross section and invariant mass spectrum for $\gamma\gamma \to h h'$

$$\frac{d\sigma}{d|\cos\theta^*|} = \frac{\Delta Y - \Delta B}{\Delta W \Delta|\cos\theta^*| \varepsilon \frac{dL_{\gamma\gamma}}{dW} \int Ldt}$$

Luminosity function

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

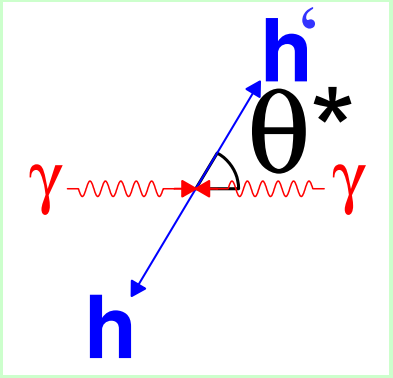
W=M($\gamma\gamma$)=M(X)

h h' = $\pi^+\pi^-$, K^+K^-, ppbar, KsKs

C=even, J≠1 resonances (↔C=odd in e^+e^-)

$$\Gamma_{\gamma\gamma}(R)Br(R \to X) = \frac{N_R m_R^2}{4(2J+1)\pi^2 \varepsilon \frac{dL_{\gamma\gamma}}{dW}(m_R) \int Ldt}$$

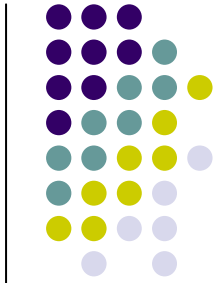
R = f_J, a_J, χ_{cJ}, $\eta_{c,\ldots}$



• $\gamma\gamma$ axis ≈ e^+e^- axis

For XYZ, see "XYZ particles at Belle" by Chengping Shen

Test of QCD predictions



- pQCD leading order calculation
  - $\sigma(\gamma\gamma \to h h')$ ~ W^{-n} $(W \to \infty)$
    - n = 6 for meson
    - n = 10 for baryon
  - $d\sigma / d|\cos\theta^*|$ ~ $\sin^{-4}\theta^*$
- Calculations for $\Gamma_{\gamma\gamma}$(R) for a resonance R

Contents

- $\gamma\ \gamma \rightarrow \pi^0 \pi^0$
- $\gamma\ \gamma \rightarrow \eta\ \pi^0$

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

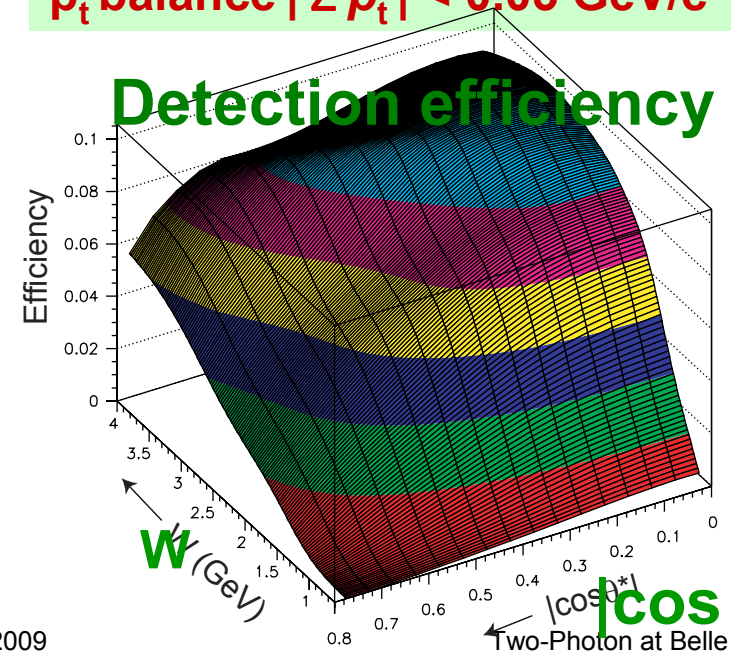
PRD78, 052004 95/fb

PRD79, 052009 223/fb

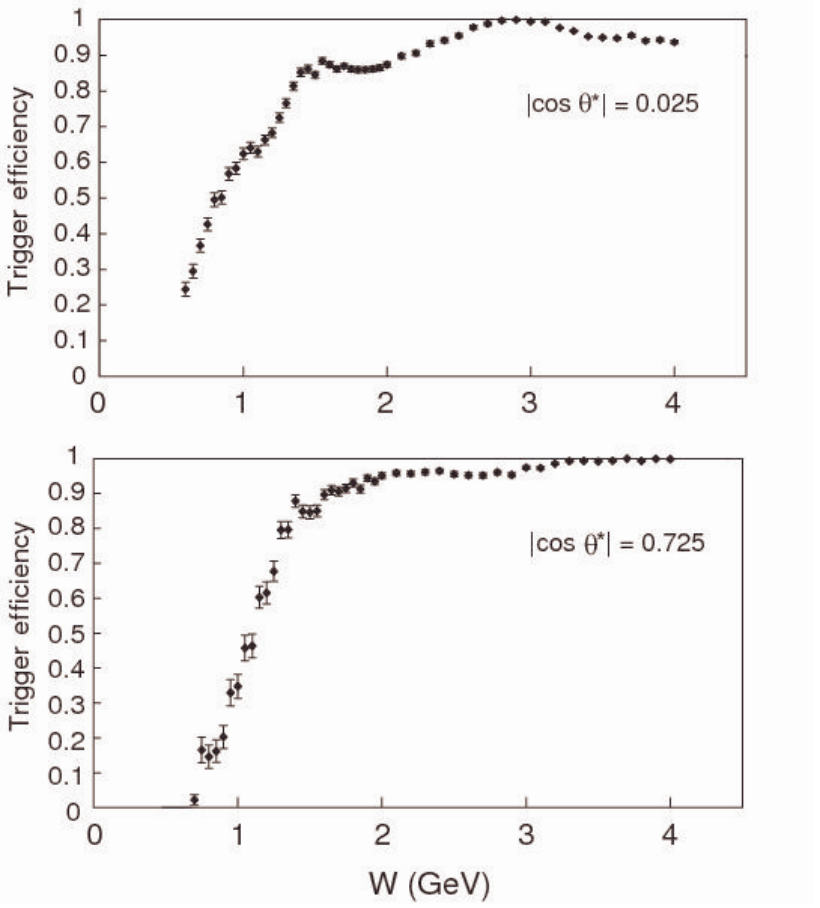
$|\cos\theta^*| < 0.8$

4 photons with E_γ>70 MeV
2 π^0 with p_t > 0.15 GeV/c
No track with p_t > 0.1 GeV/c
p_t balance $|\Sigma p_t| < 0.05$ GeV/c

Trigger by Calorimeter
Energy sum (>1.1GeV)
4 Cluster (>120 MeV)



Detection efficiency



Trigger efficiency

$|\cos\theta^*|$

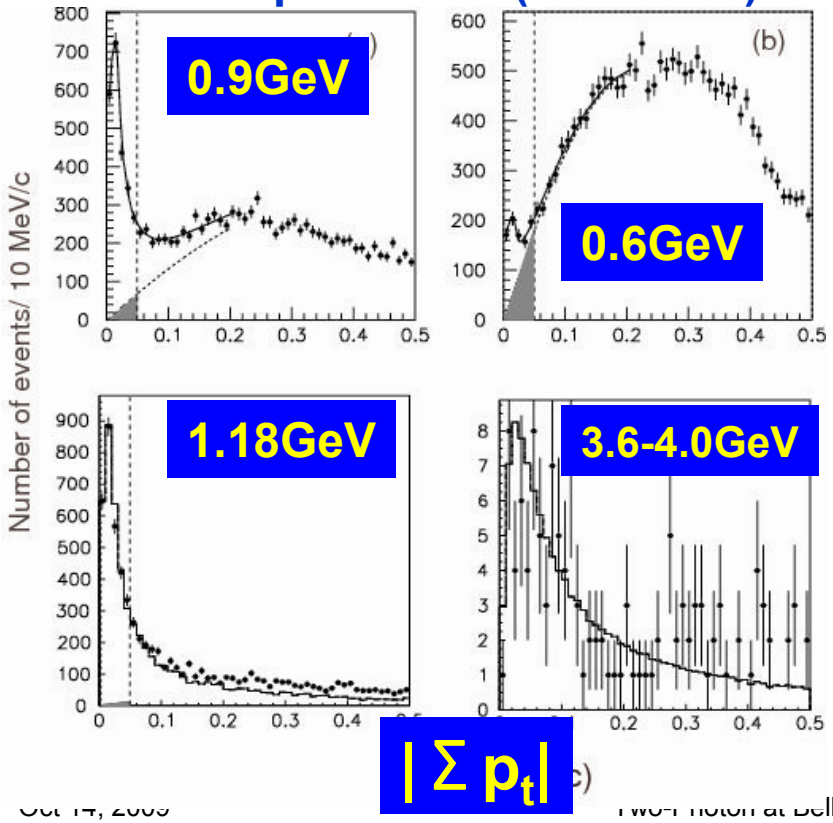
$\gamma\gamma \to \pi^0\pi^0$

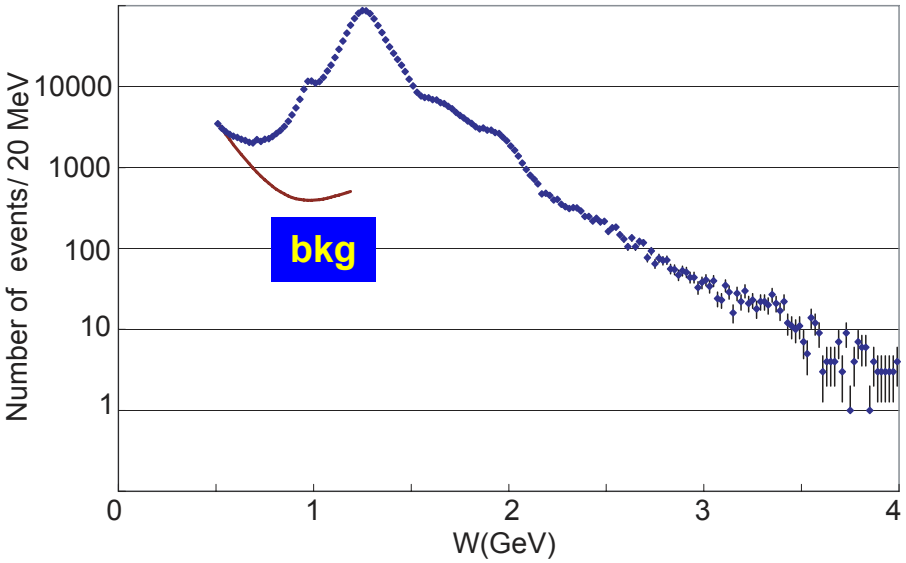
Background estimation using p_t-balance distribution

Fit to empirical shape

bkg: linear(x<0.05)+Pol2(other)

peak: Ax / ($x^{2.1}$+B+cx)





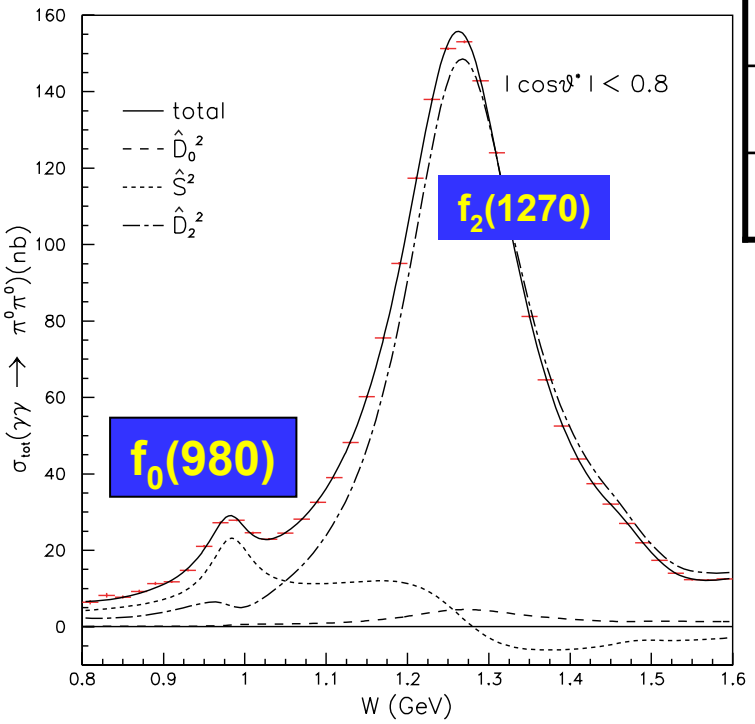
Subtraction for W < 1.2 GeV

No significant bkg for W > 1.2 GeV

$\gamma\gamma \to \pi^0\pi^0$: Partial Wave Analysis for $f_0(980)$ region

- Unfold mass resolution
- Efficiency correction

$$\frac{d\sigma}{4\pi d\,|\cos\theta^*|} = |SY_0^0 + D_0 Y_2^0|^2 + |D_2 Y_2^2|^2 = \hat{S}^2 |Y_0^0|^2 + \hat{D}_0^2 |Y_2^0|^2 + \hat{D}_2^2 |Y_2^2|^2$$



	$\pi^0\pi^0$	$\pi^+\pi^-$	PDG
M [MeV/c^2]	$982.2 \pm 1.0^{+8.1}_{-8.0}$	$985.6^{+1.2}_{-1.5}{}^{+1.1}_{-1.6}$	980 ± 10
$\Gamma_{\gamma\gamma}$[eV]	$286 \pm 17^{+211}_{-70}$	$205^{+95}_{-83}{}^{+147}_{-117}$	310^{+80}_{-110}

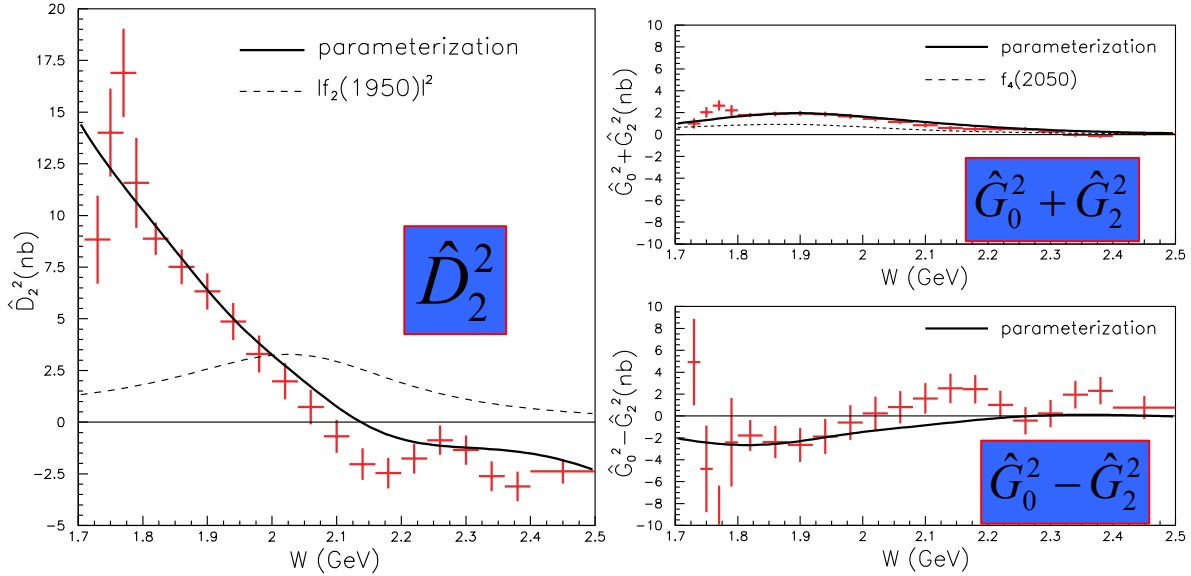
Model	$\Gamma_{\gamma\gamma}$[keV]
uubar,ddbar	1.3-1.8
ssbar	0.3-0.5
KKbar molecule	0.2-0.6
Four-quark	0.27

Consistent with $\pi^+\pi^-$ mode (PRD75,051101)
uubar, ddbar disfavored compared to other models

$\gamma\gamma \to \pi^0\pi^0$: $f_2(1950)$, $f_4(2050)$

$$\frac{d\sigma}{4\pi d\,|\cos\theta^*|} = |\,SY_0^0 + D_0Y_2^0 + G_0Y_4^0\,|^2 + |\,D_2Y_2^2 + G_2Y_4^2\,|^2$$

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



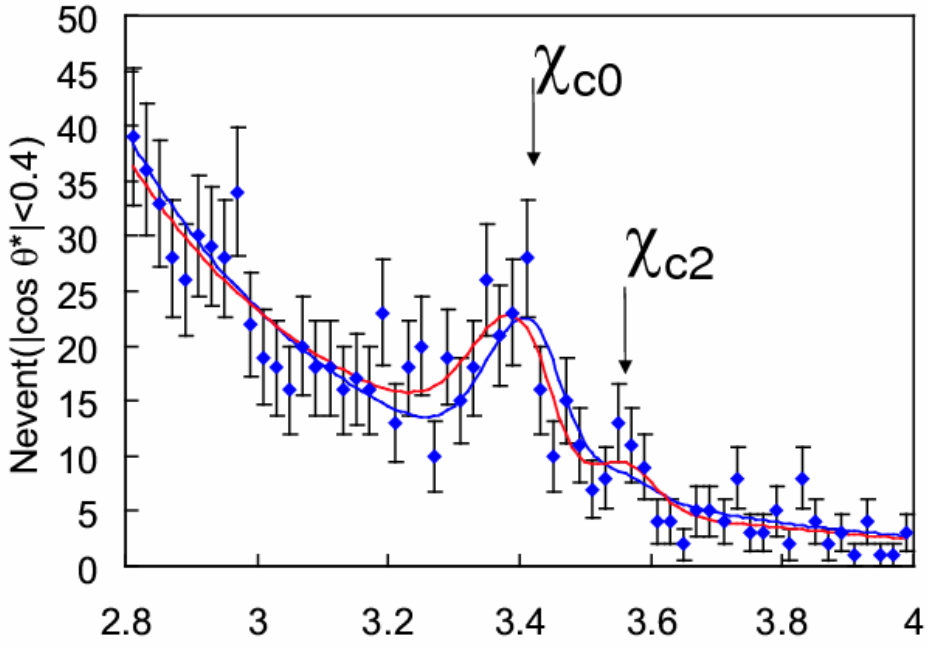
$M(f_4(2050))$	1885^{+14}_{-13} MeV/c^2
$\Gamma(f_4(2050))$	453±20 MeV
$\Gamma_{\gamma\gamma}B(\pi^0\pi^0)$	$7.7^{+1.2}_{-1.1}$ eV
$M(f_2(1950))$	2038^{+13}_{-11} MeV/c^2
$\Gamma(f_2(1950))$	441^{+27}_{-25} MeV
$\Gamma_{\gamma\gamma}B(\pi^0\pi^0)$	54^{+23}_{-14} eV

	Nominal	Fixed $f_4(2050)$	No $f_4(2050)$	No $f_2(1950)$
χ^2 (ndf)	323.2(311)	594.4(313)	1397.8(315)	2306.8(315)

Inclusion of both $f_2(1950)$ and $f_4(2040)$ gives much better χ^2

$\gamma\gamma \to \pi^0\pi^0$: χ_{cJ}

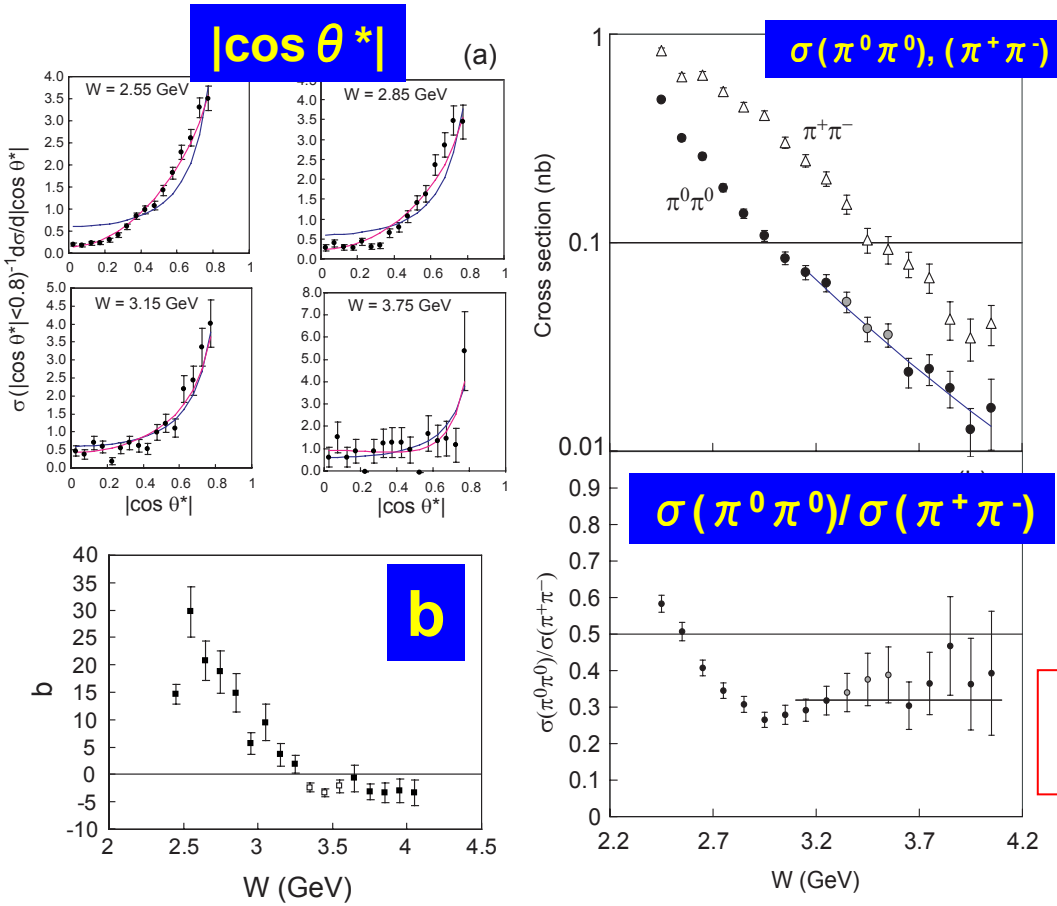
$$Y(W) = |\sqrt{\alpha k W^{-\beta}} + e^{i\phi}\sqrt{N_{\chi_{c0}}}BW_{\chi_{c0}}(W)|^2 + N_{\chi_{c2}}|BW_{\chi_{c2}}(W)|^2 + \alpha(1-k)W^{-\beta}$$



	$\Gamma_{\gamma\gamma}Br(\chi_{c0})$[eV]		$\Gamma_{\gamma\gamma}Br(\chi_{c2})$[eV]	
w/ interference	$9.7\pm1.5\pm1.2$	7.6σ	$0.18^{+015}_{-0.14}\pm0.08$	2.6σ
w/o interference	$9.9^{+5.8}_{-4.0}\pm1.6$	7.3σ	$0.48\pm0.18\pm0.07\pm0.14$	1.3σ
$\gamma\gamma \to \pi^+\pi^-$	$15.1\pm2.1\pm2.3$		$0.76\pm0.14\pm0.11$	

Consistent with Isospin invariance $2Br(\pi^0\pi^0)=Br(\pi^+\pi^-)$

$\gamma\gamma \to \pi^0\pi^0$: Higher region



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

pQCD prediction

$\sigma \sim W^{-n}$: n=6

$\sigma(\pi^0\pi^0)/\sigma(\pi^+\pi^-)$ = const.
- < 0.1: leading-order pQCD
- = 0.5 Isospin symmetry

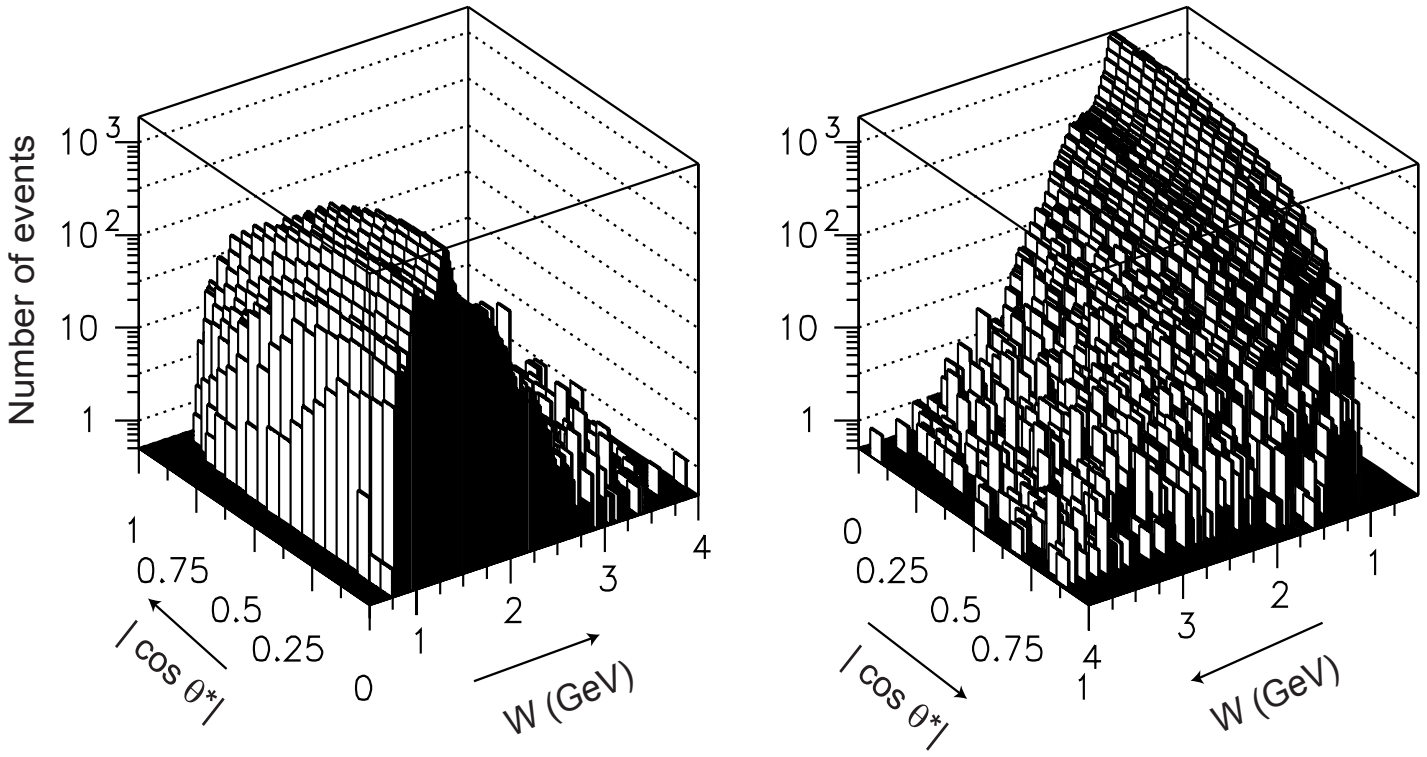
n = 6.9±0.6±0.7
$\sigma(\pi^0\pi^0)/\sigma(\pi^+\pi^-)$ =0.32±0.03±0.05

Significant b term contribution
Cross section ratio slightly smaller than Isospin symmetry

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

PRD80, 032001 (2009). 223/fb
a_J resonances (Isospin=1)
$|\cos\theta^*| < 0.8$

4 photons with E_γ>100 MeV
$\Sigma E < 5.7$ GeV
π^0 with $p_t > 0.15$ GeV/c
η : $0.51 < M(\gamma\gamma) < 0.57$ MeV
No track with $p_t > 0.1$ GeV/c
$|\Sigma p_t| < 0.05$ GeV/c
E_γ scaled with $M(\eta) / M(\gamma\gamma)$

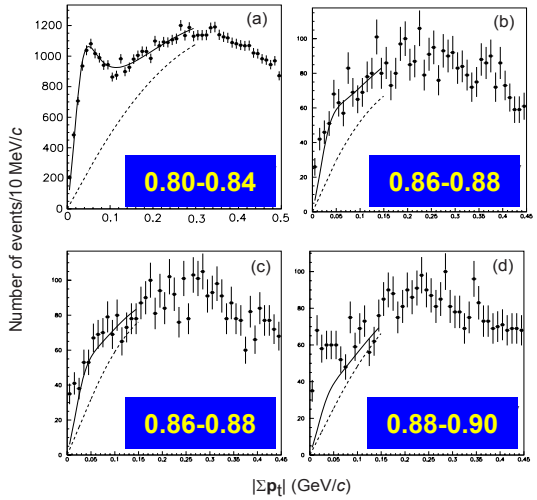


~0.3 M events

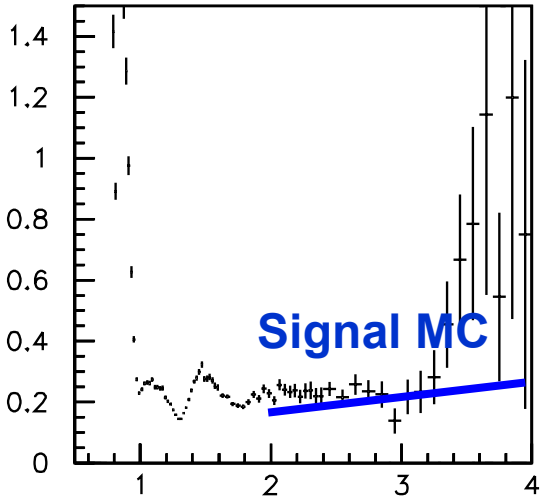
$\gamma\gamma \to \eta\pi^0$: Bkg subtraction

Bkg = $\eta' \to \eta\pi^0\pi^0$ (0.8-0.9GeV) + other p_t unbalanced bkg (0.8-4.0 GeV)

$|\Sigma p_t|$



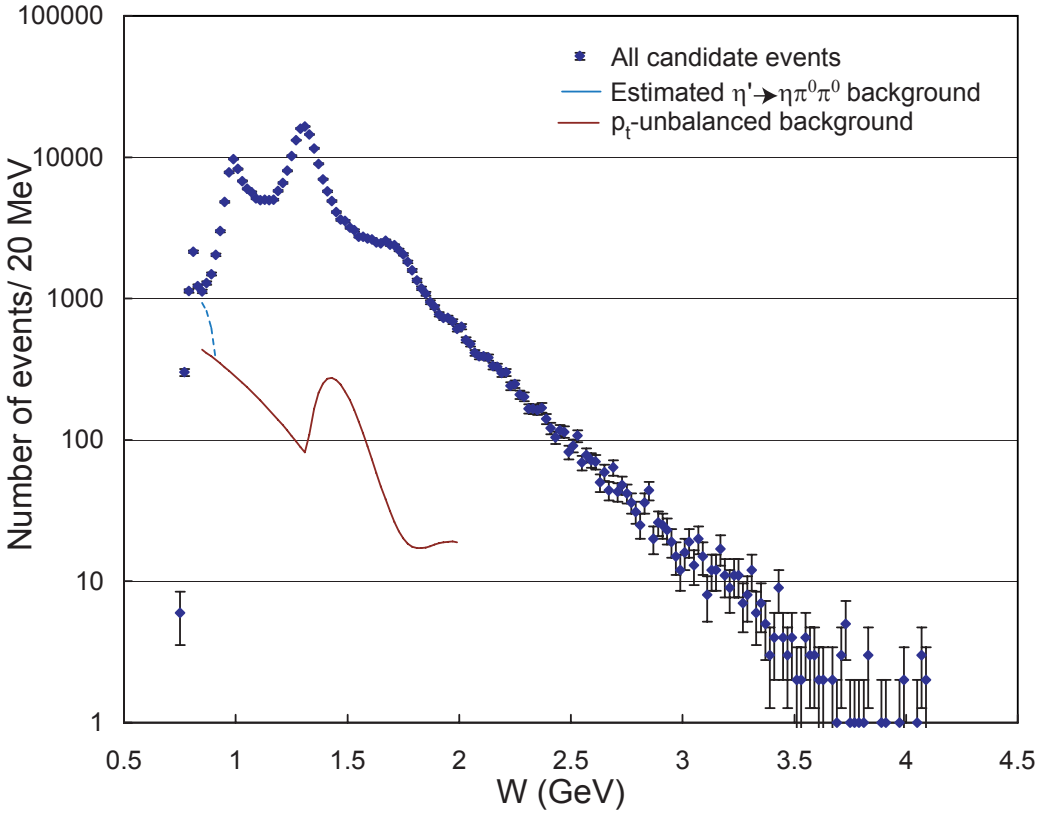
R



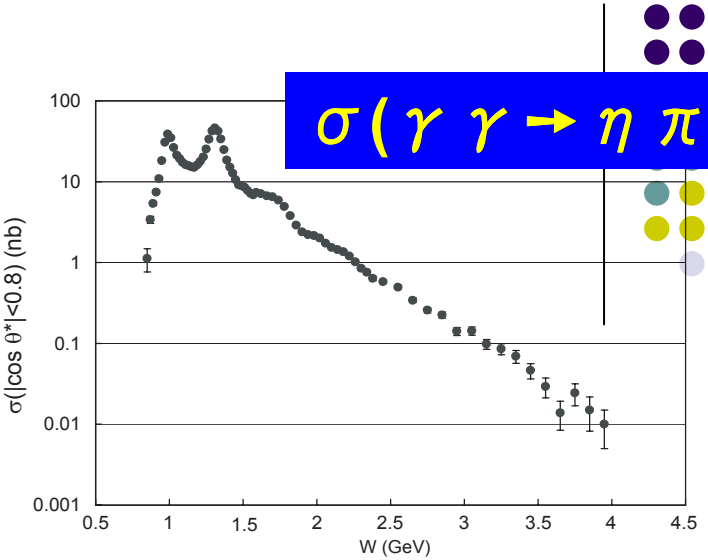
$\eta' \to \eta\pi^0\pi^0$
- One π^0 missed
- Peaks 0.05 GeV/c in p_t balance
- Estimated in 0.84-0.90 GeV assuming no signal in 0.80-0.84 GeV

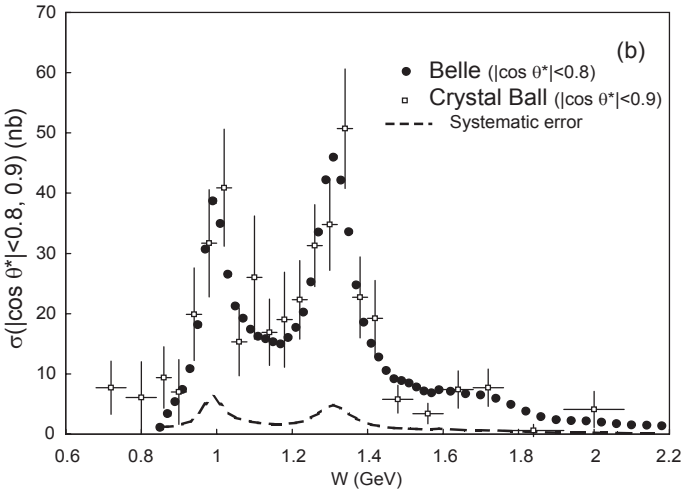
Other p_t unbalanced bkg
- W<2.0GeV
  - linear($|\Sigma p_t|$<0.05)+Pol2(other)
- W>3.3 GeV
  - Estimated by comparing $R = Y(0.15 < |\Sigma p_t| < 0.20) / Y(0 < |\Sigma p_t| < 0.05)$ between data and signal MC

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



$\sigma(\gamma\gamma \to \eta\pi^0)$



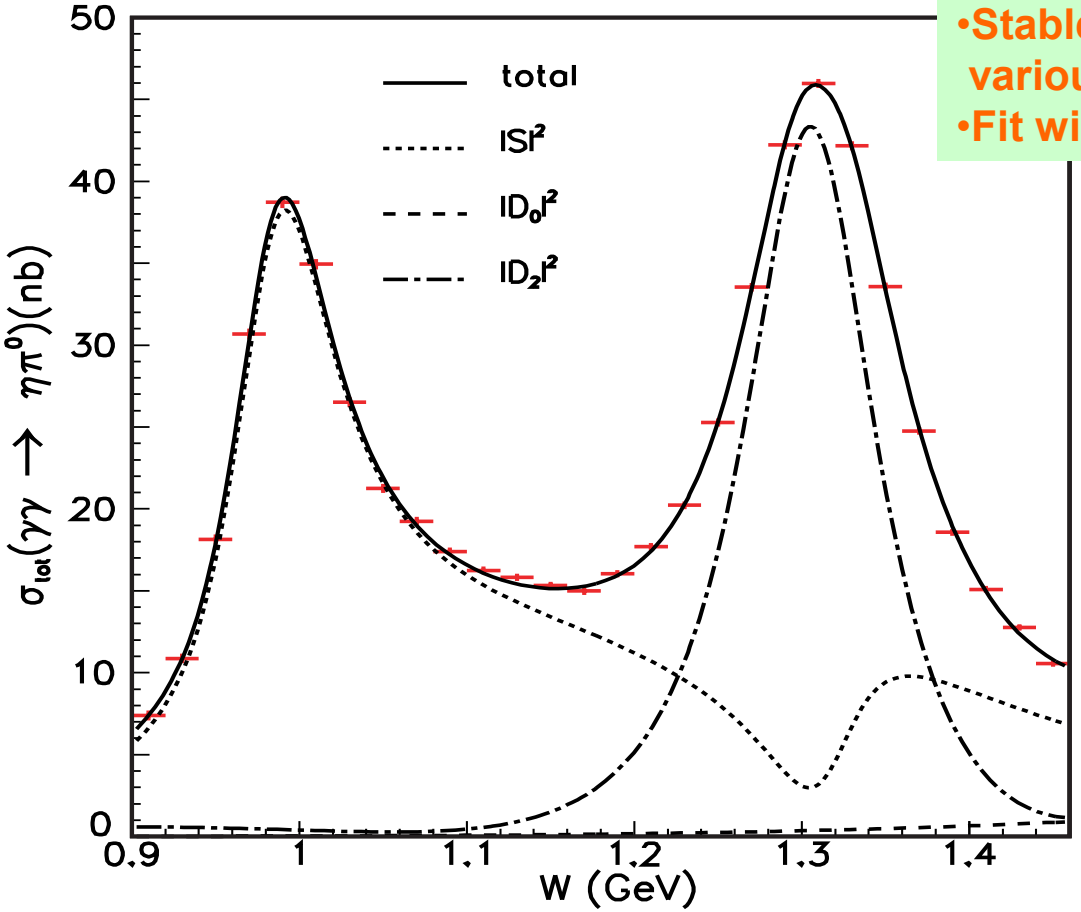


- **Unfolding between 0.9 and 2.4 GeV**
- **Consistent with Crystal Ball measurement (PRD33, 1847 (1986))**
- **$a_0(980)$, $a_2(1320)$, $a_2(1700)$ seen**

$\gamma\gamma \to \eta\pi^0$:

Partial Wave Analysis in 0.9 < W < 1.5 GeV

$$\frac{d\sigma}{4\pi d\,|\cos\theta^*|} = |SY_0^0 + D_0 Y_2^0|^2 + |D_2 Y_2^2|^2 = \hat{S}^2 |Y_0^0|^2 + \hat{D}_0^2 |Y_2^0|^2 + \hat{D}_2^2 |Y_2^2|^2$$



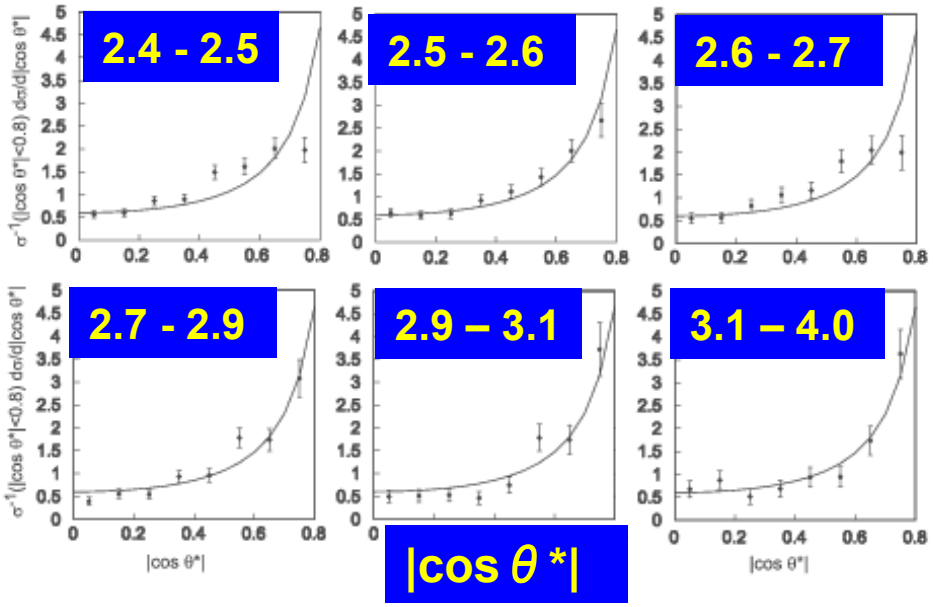
- Stable solution for $a_2(1700)$ not found in various fits. -> concentrate on W<1.5 GeV
- Fit with $a_0(980)$, $a_2(1320)$ and $a_0(Y)$

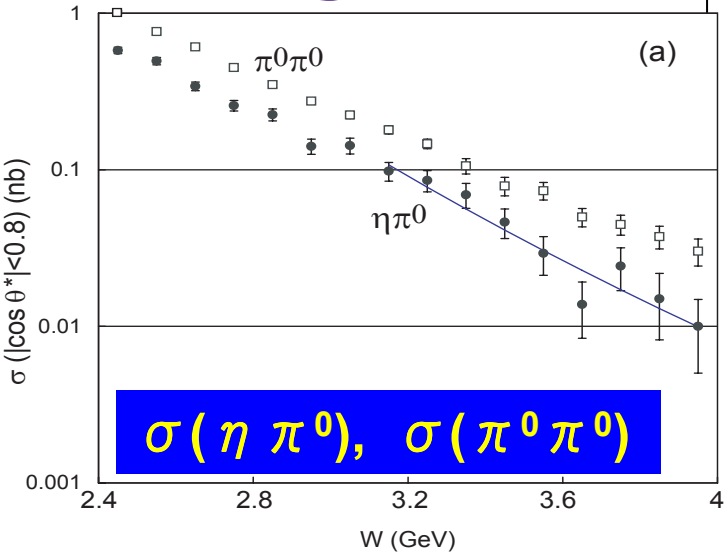
a_0 (980)	
M [MeV/c²]	$982.3^{+0.6}_{-0.7}{}^{+3.1}_{-4.7}$
Γ [MeV]	$75.6 \pm 1.6^{+17.4}_{-10.0}$
$\Gamma_{\gamma\gamma}$ [eV]	$128^{+3}_{-2}{}^{+502}_{-43}$
a_0 (Y)	
M [MeV/c²]	$1316.8^{+0.7}_{-1.0}{}^{+24.7}_{-4.6}$
Γ [MeV]	$65.0^{+2.1}_{-5.4}{}^{+99.1}_{-32.6}$
$\Gamma_{\gamma\gamma}$ [eV]	$432 \pm 6^{+1073}_{-256}$

	Nominal	M(a_0(Y)) = M(a_0(1450))	No a_0(Y)
χ^2 (ndf)	597.6/429	704.5/430	753.6/433

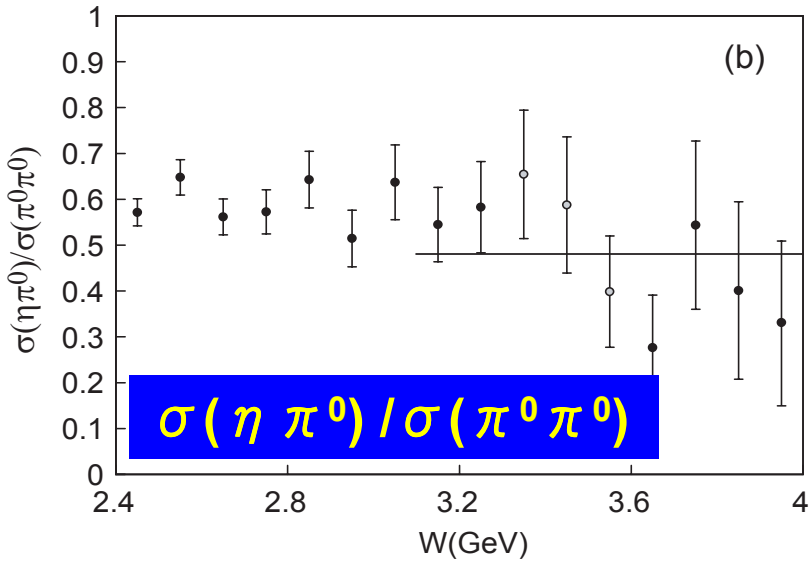
For $a_0(Y)$, nominal $a_0(1450)$ and contribution from $a_2(1320)$ disfavored

$\gamma\gamma \to \eta\pi^0$: Higher region

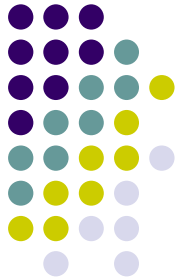




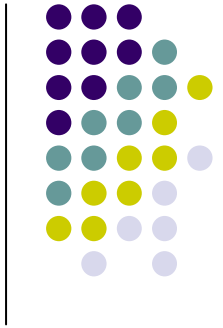
- Comparison with pQCD prediction
  $\sin^{-4}\theta^*$ in agreement for W>2.7 GeV
- W^{-n} dependence of σ
  n = 10.5±1.2±0.5
  consistent with KsKs (10.5±0.6±0.5)
- $\sigma(\eta\pi^0) / \sigma(\pi^0\pi^0)$ = 0.48 ±0.05±0.04
- Not conclusive due to large error



Summary



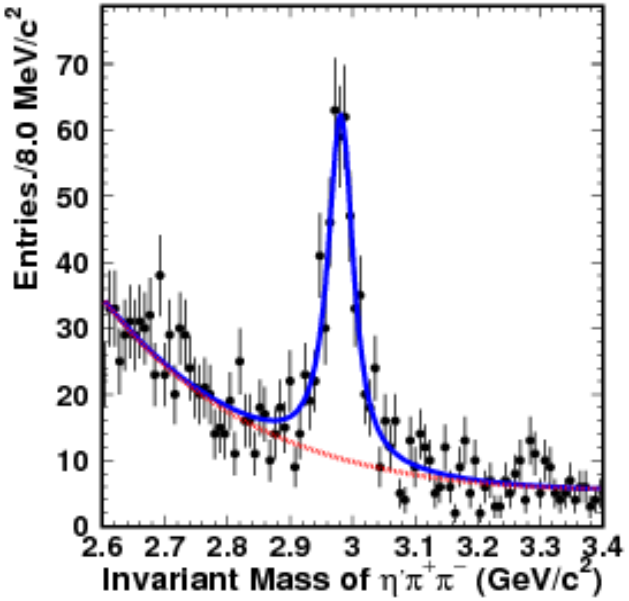
- **Belle has studied pure neutral final states $\pi^0\pi^0$ and $\eta\,\pi^0$ in two-photon process**
  - **Light quark resonances are studied by Partial Wave Analysis**
  - χ_{cJ} mesons are measured in $\pi^0\pi^0$ final states
  - Differential cross section and cross section are compared with QCD predictions



Back up

$\gamma\gamma \to \eta'\pi^+\pi^-$

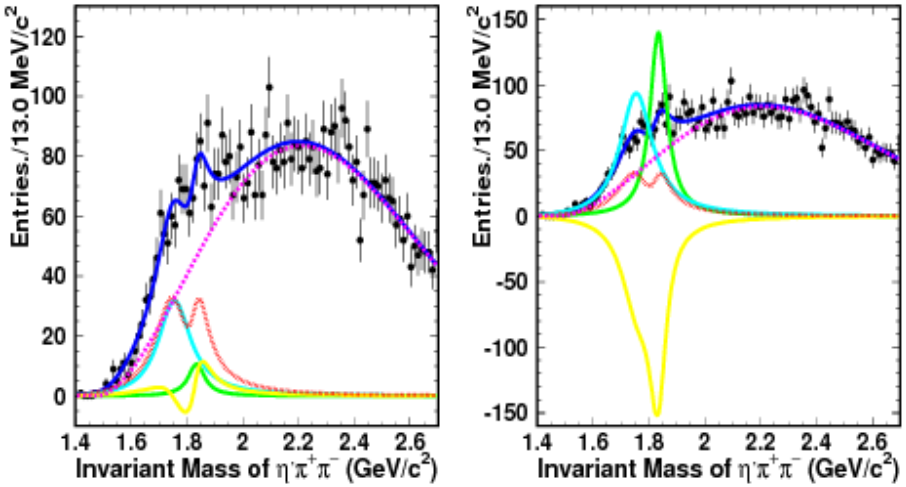
- Search for X(1835)
  - found in $J/\Psi \to \gamma X(1835)$, $X(1835) \to \eta'\pi^+\pi^-$ by BES (PRL95, 262001 (2005))
- Measurement of $\eta(1760)$
- Measurement of η_c



Preliminary

Parameters	This	PDG08
Y	$456^{+39}_{-38} \pm 55$	
M	$2981.9 \pm 1.8 \pm 1.4$	2980.3 ± 1.2
Γ	$36.2^{+5.3}_{-4.4} \pm 2.6$	26.7 ± 3
$\Gamma_{\gamma\gamma} \cdot \mathcal{B}$	$52.1 \pm 4.3 \pm 6.3$	194 ± 97
$\mathcal{B}$	$0.72 \pm 0.10 \pm 0.22$	2.7 ± 1.1

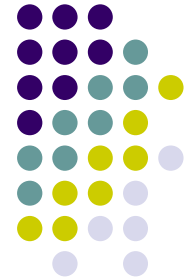
$\gamma\gamma \to \eta'\pi^+\pi^-$



- Coherent sum of η(1760) and X(1835)
- Improved Crystal Ball function for threshold effect
- 2 solutions are found
- No significant evidence of X(1835)
- η(1760) alone gives 6σ

Preliminary

Parameters	One resonance	*Two resonances with interference*		PDG08
		Solution I	Solution II	
X(1835)				
M	*1833.7 (fixed)*			$1833.7 \pm 6.1 \pm 2.7$
Γ	*67.7 (fixed)*			$67.7 \pm 20.3 \pm 7.7$
Y		$86^{+62}_{-45} \pm 33$	$1142^{+656}_{-429} \pm 434$	
Y_{90}		< 265	< 3960	
$\Gamma_{\gamma\gamma}\mathcal{B}$		$4.3^{+3.1}_{-2.3} \pm 1.6$	$56^{+27}_{-21} \pm 21$	
$(\Gamma_{\gamma\gamma}\mathcal{B})_{90}$		< 13.3	< 194	
$\eta(1760)$				
M	$1773 \pm 17 \pm 11$	$1752^{+20}_{-22} \pm 11$		1756 ± 9
Γ	$198^{+30}_{-32} \pm 30$	$138^{+31}_{-29} \pm 30$		96 ± 70
Y	$629^{+160}_{-147} \pm 82$	$478^{+259}_{-204} \pm 62$	$1406^{+760}_{-587} \pm 183$	
$\Gamma_{\gamma\gamma}\mathcal{B}$	$35.2^{+9.0}_{-8.2} \pm 4.6$	$26^{+16}_{-11} \pm 3$	$75^{+41}_{-31} \pm 10$	
ϕ		$(25 \pm 38)^o$	$(133 \pm 10)^o$	



Parameter	This work	$a_0(1450)$ (PDG)	Unit
Mass	$1316.8^{+0.7+24.7}_{-1.0-4.6}$	1474 ± 19	MeV/c^2
$\Gamma_{\rm tot}$	$65.0^{+2.1+99.1}_{-5.4-32.6}$	265 ± 13	MeV
$\Gamma_{\gamma\gamma}\mathcal{B}(\eta\pi^0)$	$432 \pm 6^{+1073}_{-256}$	unknown	eV

Resonance	Parameter	Nominal	$M(a_0(Y))$ fixed	No $a_0(Y)$	Unit
$a_0(980)$	Mass	$982.3^{+0.6}_{-0.7}$	$982.3^{+0.8}_{-0.7}$	982.3 ± 0.6	MeV/c^2
	$\Gamma_{\rm tot}$	75.6 ± 1.6	$76.9^{+1.0}_{-1.3}$	$75.6^{+1.4}_{-1.3}$	MeV
	$\Gamma_{\gamma\gamma}\mathcal{B}(\eta\pi^0)$	128^{+3}_{-2}	558^{+52}_{-44}	642 ± 8	eV
$a_0(Y)$	Mass	$1316.8^{+0.7}_{-1.0}$	1474.0 (fixed)	-	MeV/c^2
	$\Gamma_{\rm tot}$	$65.0^{+2.1}_{-5.4}$	251^{+25}_{-33}	-	MeV
	$\Gamma_{\gamma\gamma}\mathcal{B}(\eta\pi^0)$	432 ± 6	$(11.0^{+4.4}_{-3.3}) \times 10^3$	0 (fixed)	eV
χ^2/ndf		$597.6/429 = 1.39$	$704.5/430 = 1.65$	$753.6/433 = 1.74$	

Parameter	This work	PDG	Unit
Mass	$982.3^{+0.6+3.1}_{-0.7-4.7}$	984.7 ± 1.2	MeV/c^2
$\Gamma_{\rm tot}$	$75.6 \pm 1.6^{+17.4}_{-10.0}$	50–100	MeV
$\Gamma_{\gamma\gamma}\mathcal{B}(\eta\pi^0)$	128^{+3+502}_{-2-43}	240^{+80}_{-70}	eV