Studies of two-photon processes at Belle

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Outline

- $\gamma\gamma \rightarrow$ hadron-pair

  $K_S^0 K_S^0 \quad p\bar{p} \quad \Lambda\bar{\Lambda} \quad \Sigma^0\bar{\Sigma}^0$

- $\gamma\gamma \rightarrow$ charmonia resonances, η_c, χ_{c0} , χ_{c2}

  in $K_S^0 K_S^0 \quad p\bar{p} \quad \Lambda\bar{\Lambda} \quad \Sigma^0\bar{\Sigma}^0$

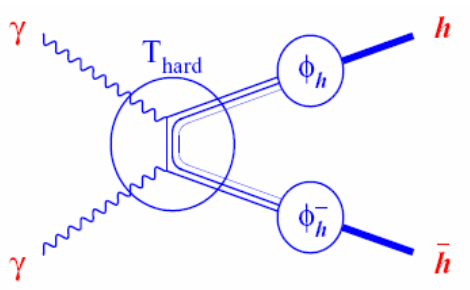
- $\gamma\gamma \rightarrow a_2(1320)$ and radially excited states

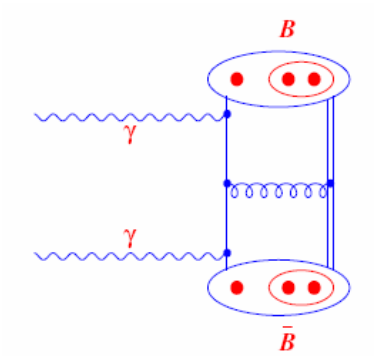
  in $\pi^+\pi^-\pi^0$ channel

Belle-Conf-0660 for $K_S^0 K_S^0$
PLB 621 (2005) 41 for $p\bar{p}$
Belle-Conf-0673 for $\Lambda\bar{\Lambda}$ $\Sigma^0\bar{\Sigma}^0$
Belle-Conf-0662 for $\pi^+\pi^-\pi^0$

Hadron-pair production in $\gamma\gamma$ interactions

pQCD hard-scattering



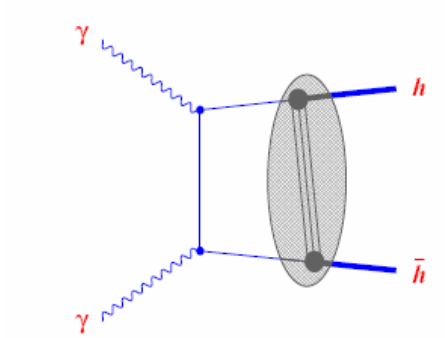


$$\frac{d\sigma(MM)}{d\,|\cos\theta^*|} \propto W_{\gamma\gamma}^{-6}\left\{\frac{F'(\theta^*)}{(1-\cos^2\theta^*)^2}+F''(\theta^*)\right\}$$

$$\frac{d\sigma(B\bar{B})}{d\,|\cos\theta^*|} \propto W_{\gamma\gamma}^{-10}\frac{F'(\theta^*)}{(1-\cos^2\theta^*)}$$

Brodsky Lepage PRD24(1981) 1808
Chernyak Zhitnitsky NP B246 (1984) 52
Farrar et al., NP B259(1985) 702
Kroll et al., PL B316(1993) 546
Berger et al., EPJC28(2003) 249

Handbag contribution



$$\frac{d\sigma(MM)}{d\,|\cos\theta^*|} \propto \frac{|R_{2M}(s)|^2}{s\ (1-\cos^2\theta^*)^2}$$

$$\frac{d\sigma(B\bar{B})}{d\,|\cos\theta^*|} \propto \frac{|R_{2M}(s)|^2\cos^2\theta^*+R_{eff}^2(s)}{s\ (1-\cos^2\theta^*)}$$

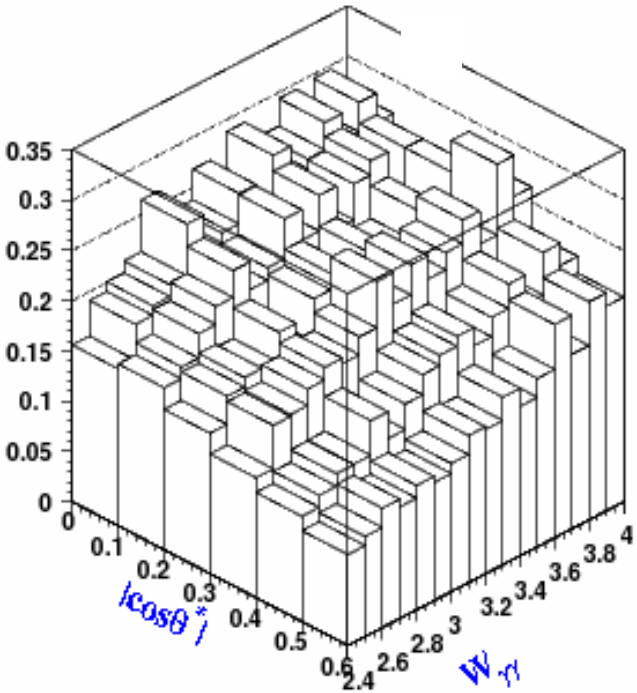
Diehl et al., PL B532(2002) 99,
EPJC26(2003) 567

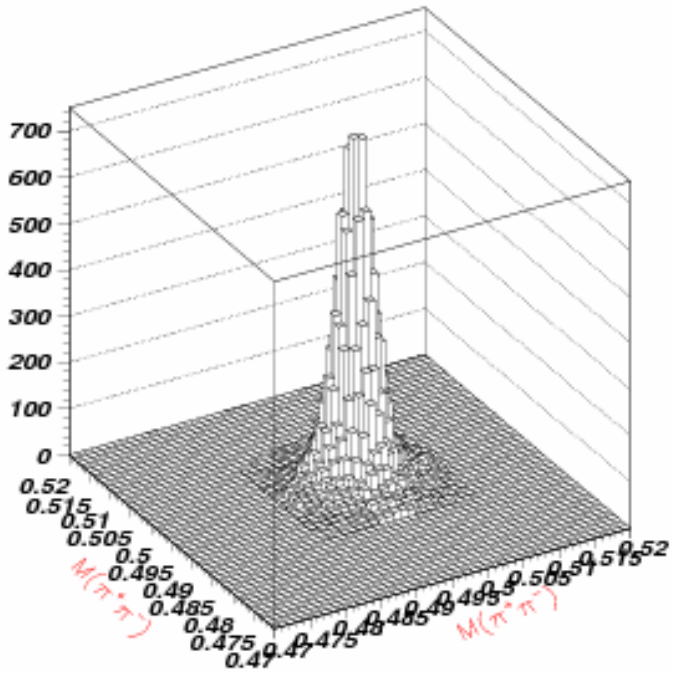
Selection of $\gamma\gamma \to K^0_S K^0_S$

- two-photon events of 4 tracks

  in tracking volume ($17^o<\theta<150^o$)
  of $p_T>300$ MeV
  from primary vertex ($|dr|<1cm$, $|dz|<5cm$)

- select K^0_S pair of $K^0_S \to \pi^+\pi^-$





$\gamma\gamma \to K^0_S K^0_S$ at $W_{\gamma\gamma}$ = 2.4 – 4.0 GeV

- $W_{\gamma\gamma}^{-n}$ dependence

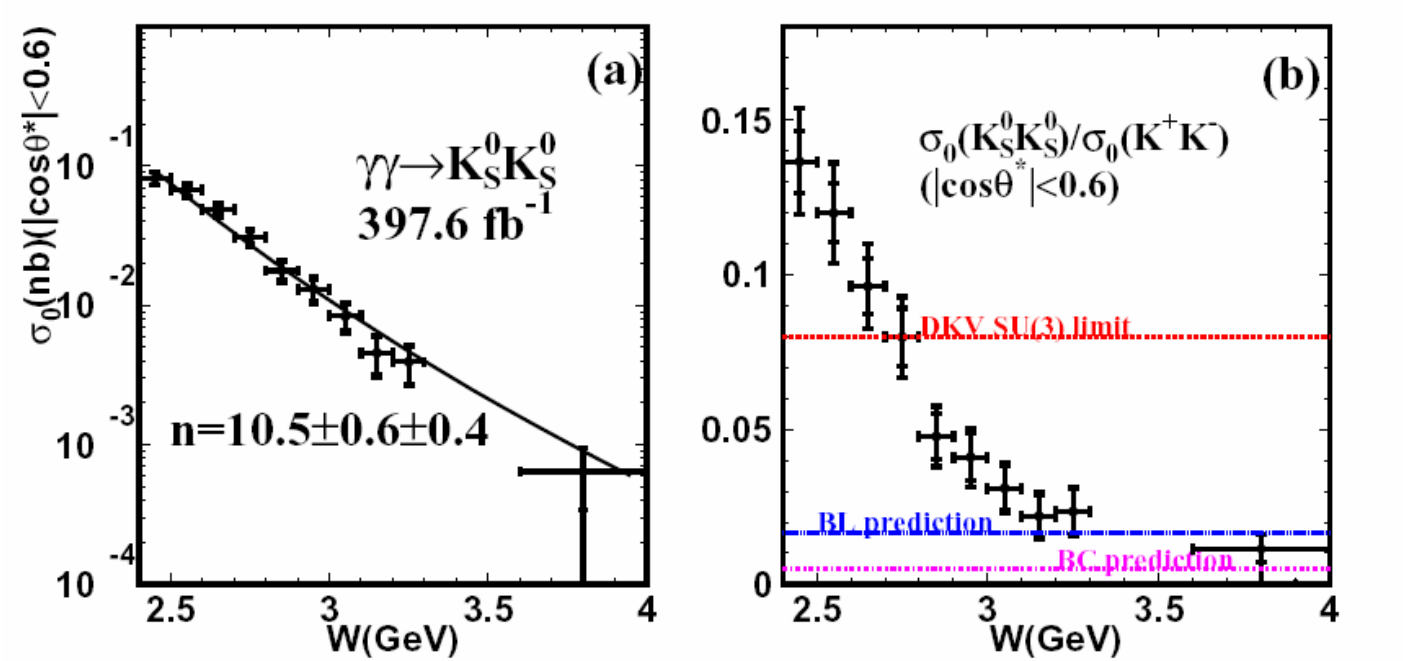
  n = 10.5 ± 0.6 ± 0.4

  (steeper than the $W_{\gamma\gamma}^{-6}$ prediction)

- Ratio to K+K-

$$\mathbf{r} = \frac{\sigma(\gamma\gamma \to K^0_S K^0_S)}{\sigma(\gamma\gamma \to K^+ K^-)}$$

0.13 (2.4 GeV) *to* **0.01** (4.0 GeV)

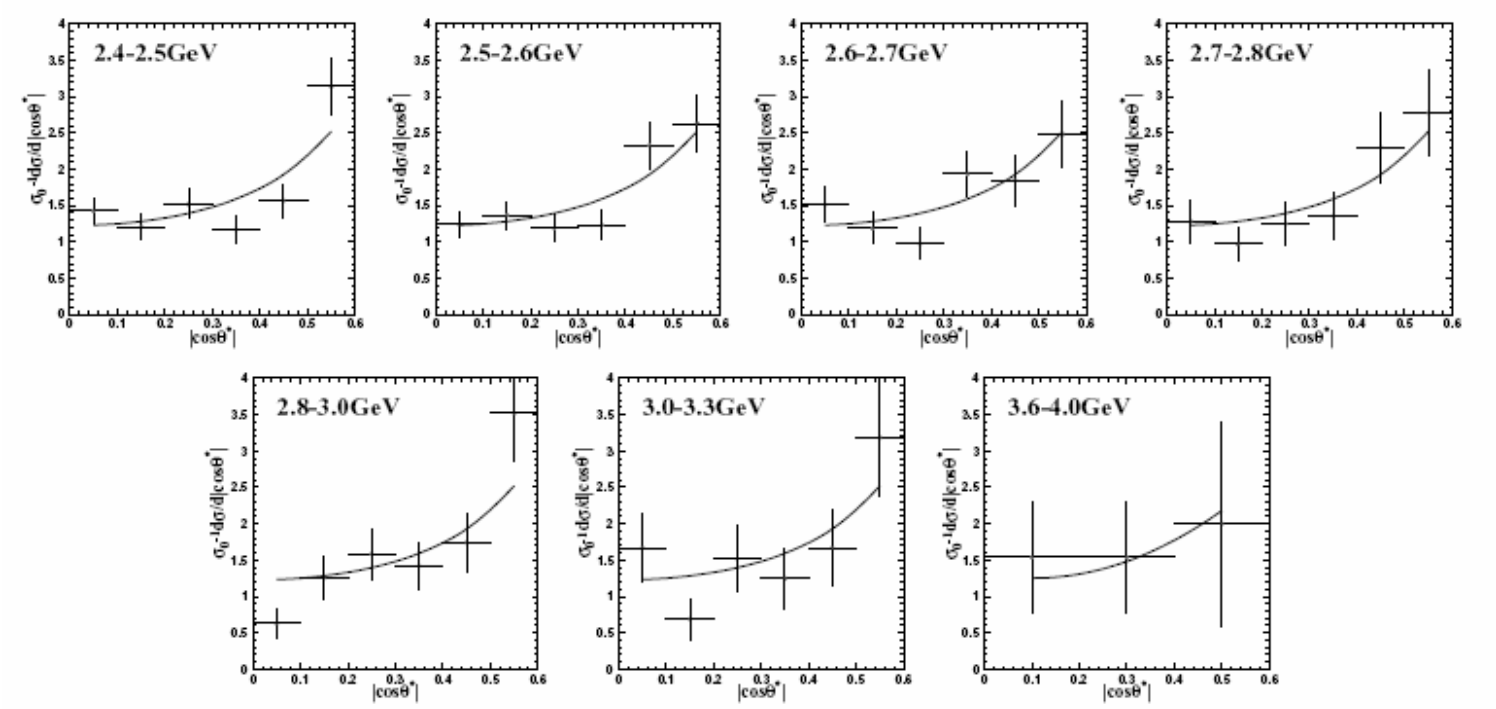


cf r ~ 0.08 Diehl et al., PLB532

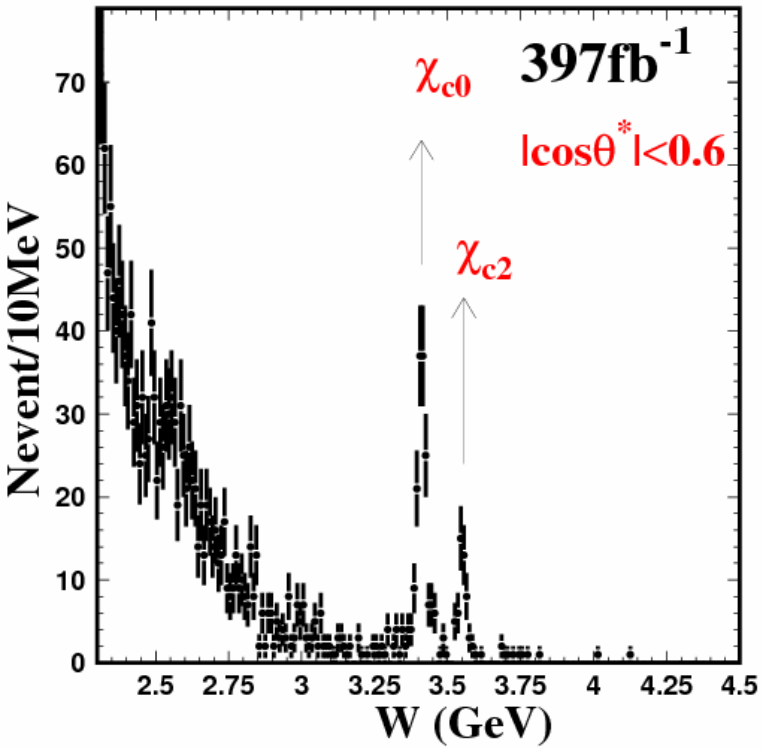
r ~ 0.017 Brodsky Lepage PRD24

$\gamma\gamma \to K^0_S K^0_S$ angular distribution

- cosθ* dependence in Wγγ intervals
- consists with the $\sin^{-4}\theta^*$ predictions



Charmonia in $\gamma\gamma \to K^0_S K^0_S$



χ_{c0}, χ_{c2} resonance parameters

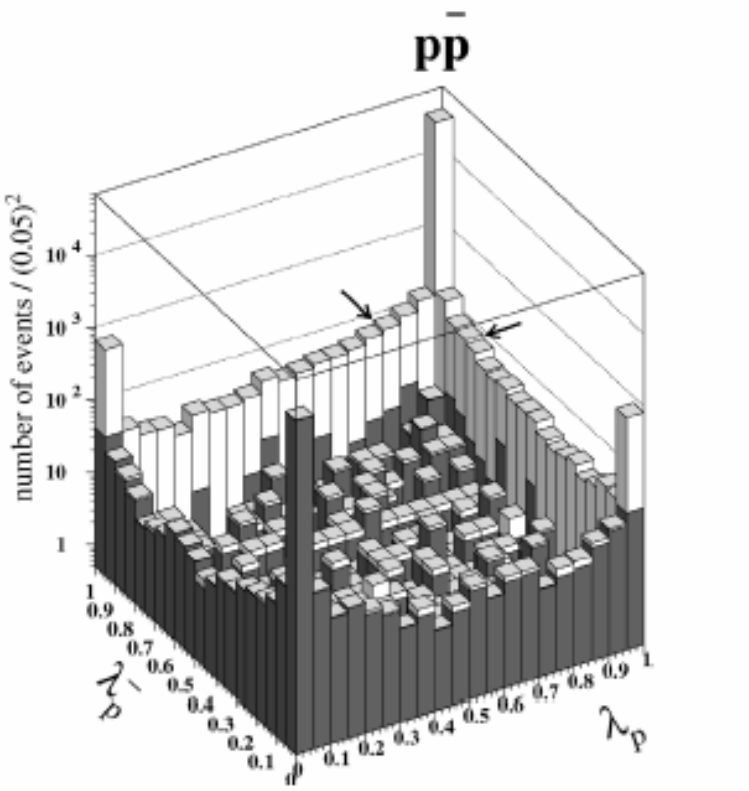
χ_{cJ}	$N_{\rm events}$	$\Gamma_{\gamma\gamma}B(K^0_S K^0_S)$[eV]
χ_{c0}	161 ± 14	$7.07 \pm 0.61 \pm 0.62$
χ_{c2}	44 ± 7	$0.30 \pm 0.05 \pm 0.03$

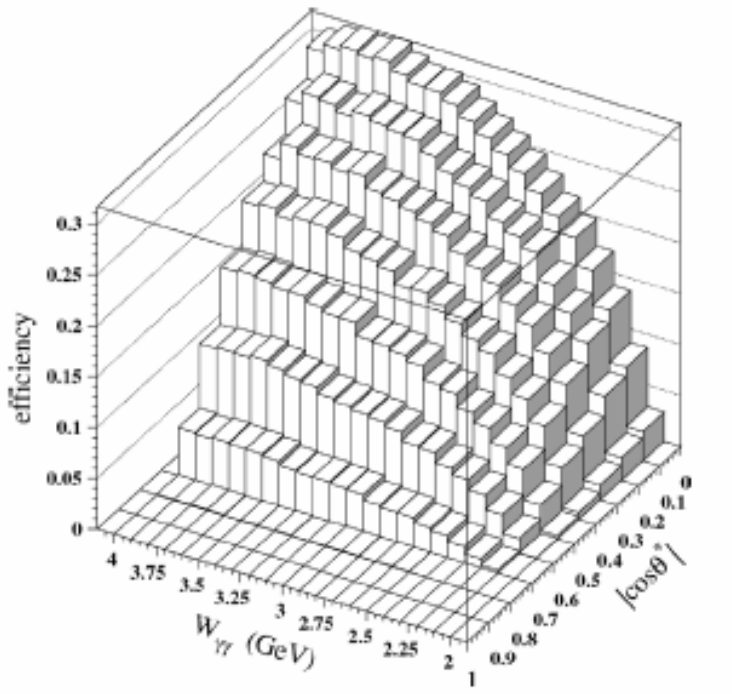
Branching ratio to K^+K^- channel

χ_{cJ}	$B(K^0_S K^0_S)/B(K^+K^-)$
χ_{c0}	$0.49 \pm 0.07 \pm 0.09$
χ_{c2}	$0.68 \pm 0.20 \pm 0.13$

Selection of $\gamma\gamma \to p\bar{p}$

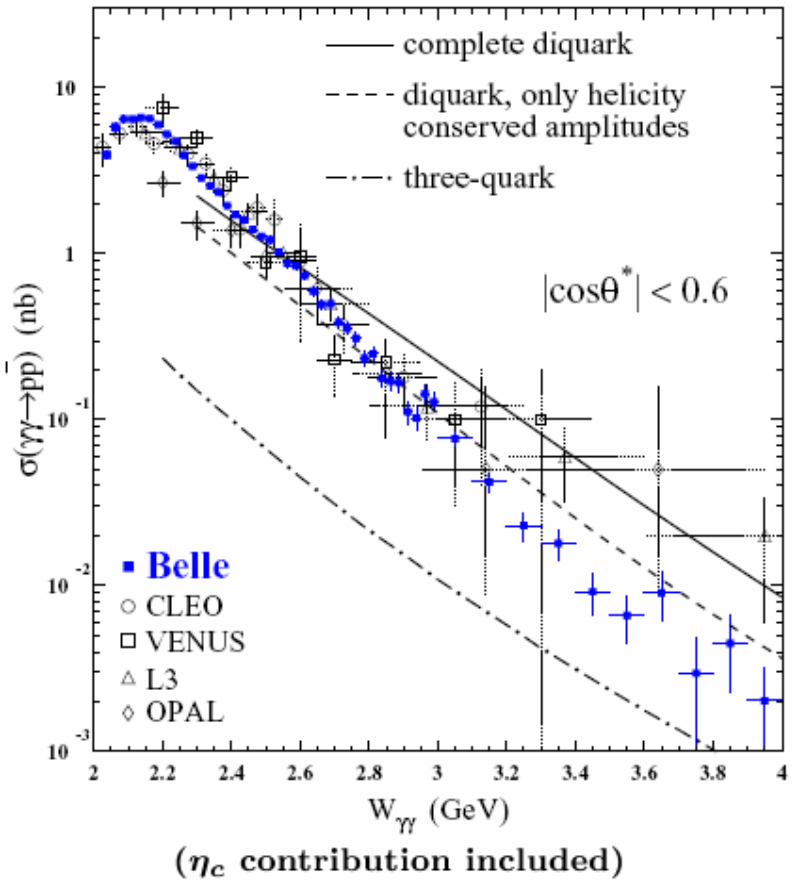
PLB 621 (2005) 41



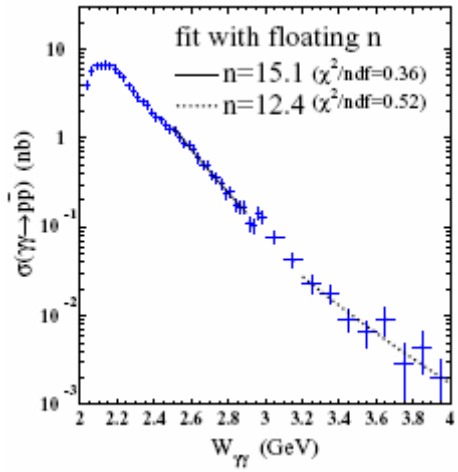


- Select proton by Tracking, Calorimeter, Cherenkov combined likelihood function
- Cross section in $W_{\gamma\gamma}$ and $\cos\theta^*$

$\gamma\gamma \to p\bar{p}$ cross section



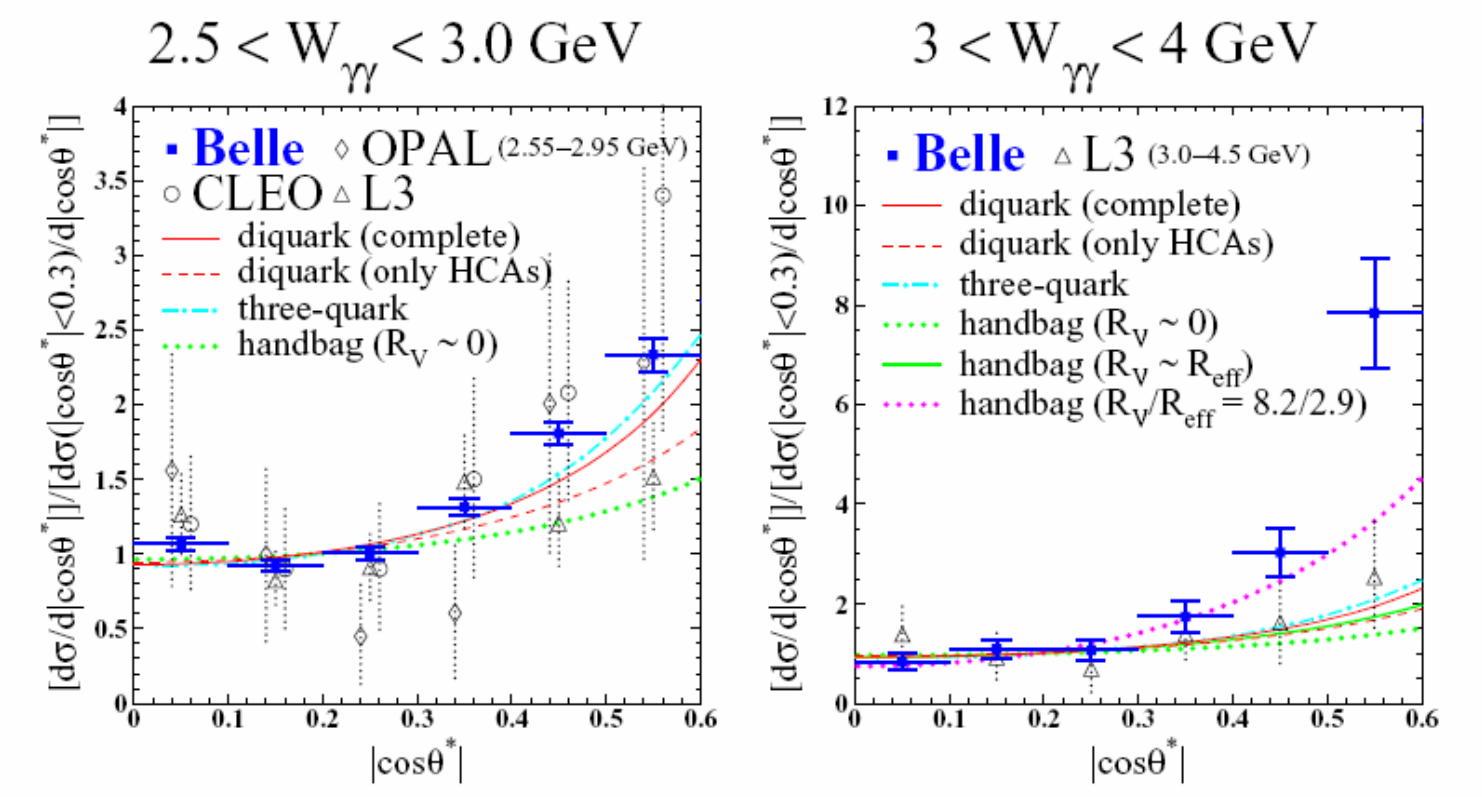
(η_c contribution included)



$W_{\gamma\gamma}^{-n}$ dependence:

$W_{\gamma\gamma}$ (GeV)	n
2.5 - 2.9	$15.1^{+0.8}_{-1.1}$
3.2 - 4.0	$12.4^{+2.4}_{-2.3}$

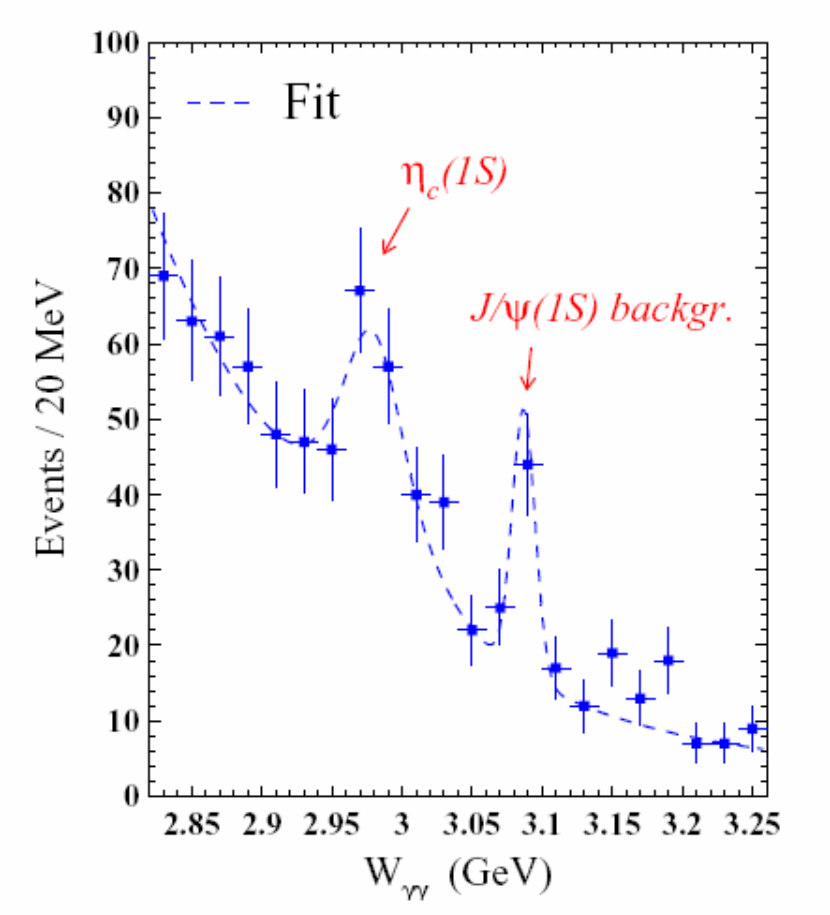
$\gamma\gamma \to p\bar{p}$ angular distribution



Consist with hard scattering amplitude $\propto 1/(1-\cos^2\theta^*)$

Higher rate in forward direction, than predicted

$\eta_c(1S)$ in $\gamma\gamma \to p\bar{p}$



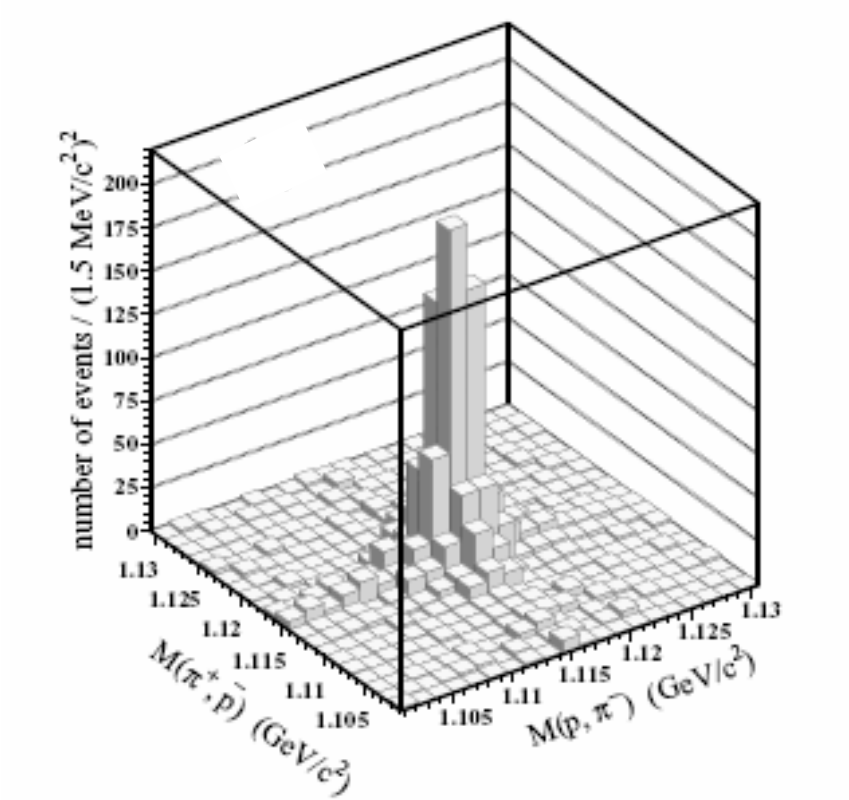
Two-photon radiative width

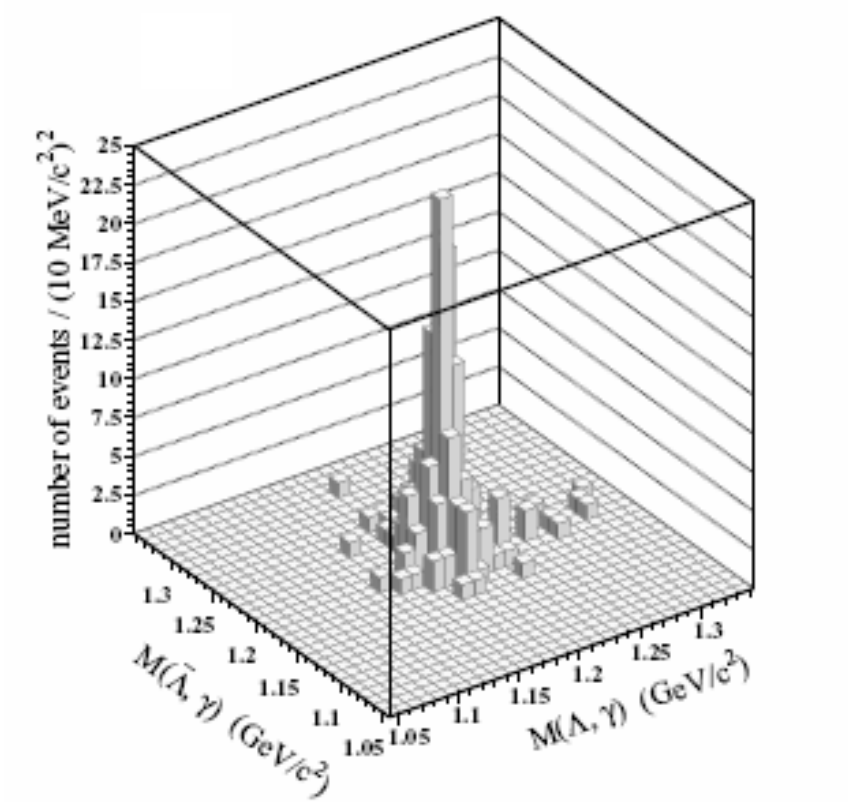
N_{η_c}	$\Gamma_{\gamma\gamma}(\eta_c)B(\eta_c \to p\bar{p})$[eV]
157 ± 33	$7.20 \pm 1.53^{+0.67}_{-0.75}$ (Belle)
	6.63 ± 1.55 (PDG*)

Selection of $\gamma\gamma \to \Lambda\overline{\Lambda}$, $\Sigma^0\overline{\Sigma}^0$

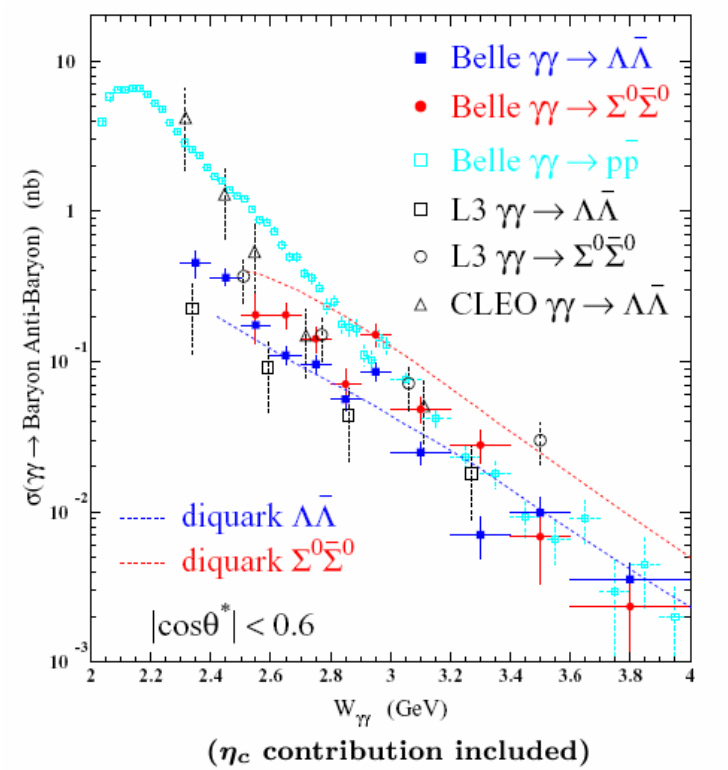
Belle-Conf-0673

- Select $\Lambda \to p\pi^-$
- Select $\Sigma^0 \to \Lambda\gamma$

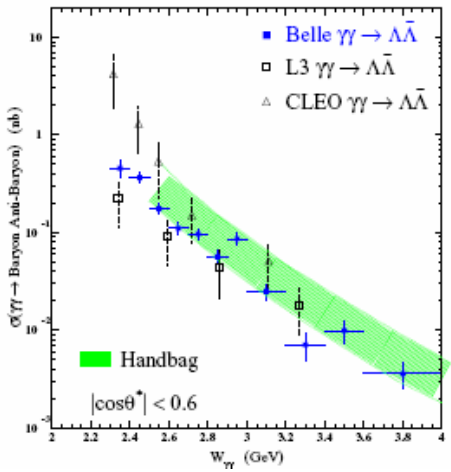


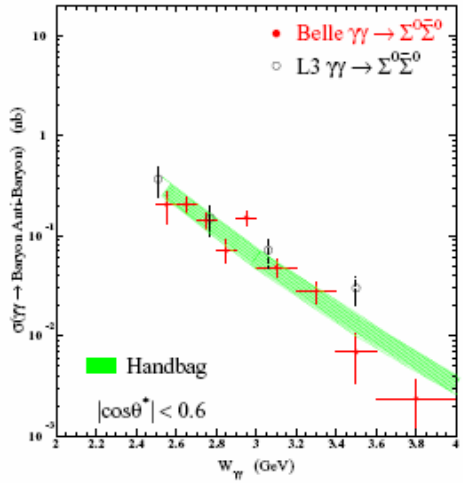


$\gamma\gamma \to \Lambda\bar{\Lambda}$, $\Sigma^0\bar{\Sigma}^0$ cross section

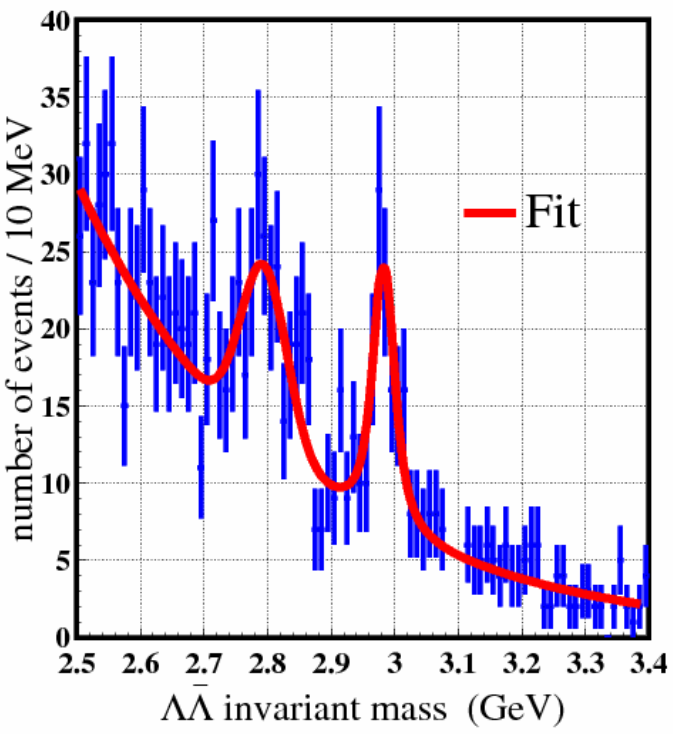


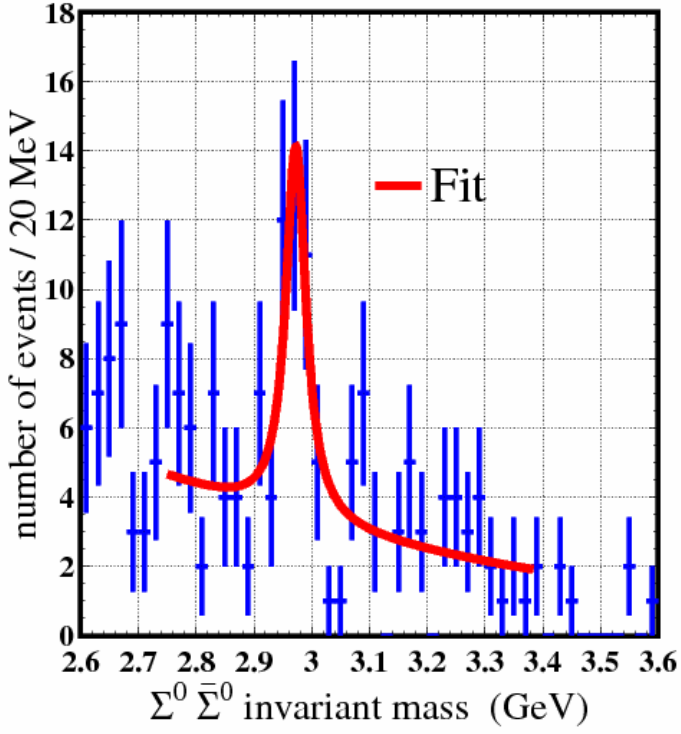
- Comparison with $p\bar{p}$
- And theories
  di-quark: Berger et al., EPJC28
  Handbag: Diehl et al., EPJC26





$\eta_c(1S)$ in $\gamma\gamma \to \Lambda\bar{\Lambda}$, $\Sigma^0\bar{\Sigma}^0$





- two-photon width

$\eta_c \to x\bar{x}$	$N_{\rm events}$	$\Gamma_{\gamma\gamma} \times B(x\bar{x})$[eV]
$\Lambda\bar{\Lambda}$	$101.2 \pm 16.4^{+1.2}_{-3.0}$	$6.21 \pm 1.01^{+0.49}_{-0.52}$
$\Sigma^0\bar{\Sigma}^0$	$36.1 \pm 9.2^{+0.0}_{-1.2}$	$9.80 \pm 2.50^{+0.98}_{-1.03}$

- branching ratio to $p\bar{p}$

$$\frac{B(\Lambda\bar{\Lambda})}{B(p\bar{p})} \sim 0.86 \pm 0.26$$

$$\frac{B(\Sigma^0\bar{\Sigma}^0)}{B(p\bar{p})} \sim 1.36 \pm 0.49$$

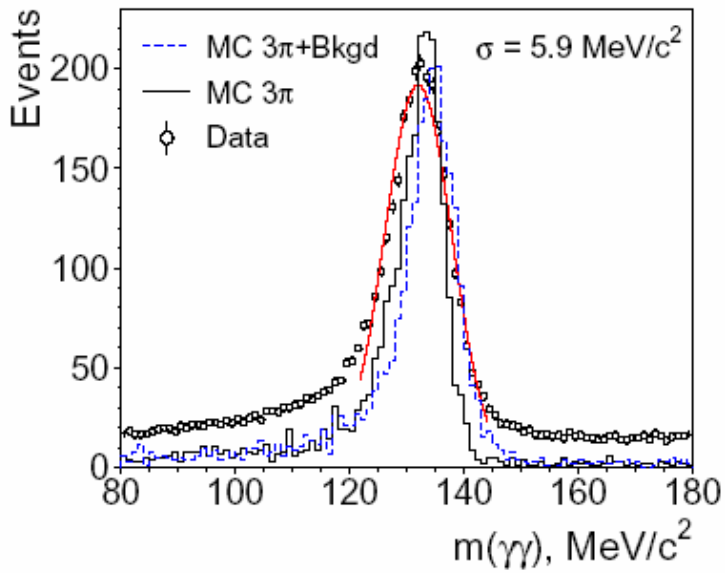
Tensor mesons in $\gamma\gamma \rightarrow \pi^+\pi^-\pi^0$

Belle-Conf-662

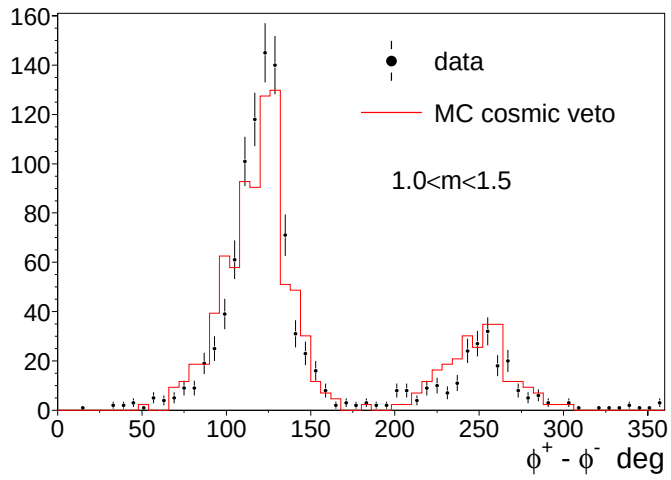
$\gamma\gamma \rightarrow \pi^+\pi^-\pi^0$ is an ideal study for ***$a_2(1320)$ & beyond***

- Exclusive $\pi^+\pi^-\pi^0$
  two final state photons for π^0, two charged π^+,π^-
- Trigger is highly redundant
  by two-track >135° and Ecal > 1GeV

π^0 reconstructed of two photons



two-track trigger distribution



Interference of multiple resonances

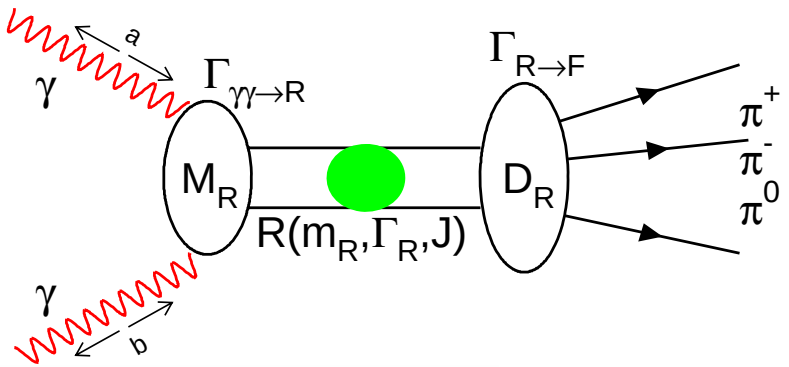
$\gamma\gamma$ cross section

by VDM luminosity function

interference in decay amplitudes

of R → Iπ, I → ππ

Spin coupling, J, J_z (helicity 0 or 2)



$$d\sigma_{\gamma\gamma} = 2\pi(2J+1)\Gamma_{\gamma\gamma}\sum_{J_z} R_{J_z}\left|\sqrt{\frac{m_0}{s}}\mathrm{BW}_0\sum_I D_0^{J_z}(I)\right.$$

$$\left.+\alpha_1 e^{i\phi_1}\sqrt{\frac{m_1}{s}}\mathrm{BW}_1\sum_I D_1^{J_z}(I)+\alpha_2 e^{i\phi_2}\sqrt{\frac{m_2}{s}}\mathrm{BW}_2\sum_I D_2^{J_z}(I)+..\right|^2 d\mathrm{Lips}(3\pi)$$

Multi-Res *coupling amp α, phase φ*

$$\sum D_i^{J_z}(I) = \mathrm{BW}(\rho^+)T^{J_z}(\rho^+,\pi)+\mathrm{BW}(\rho^-)T^{J_z}(\rho^-,\pi)+\xi_i e^{i\psi_i}\mathrm{BW}(f_2)T^{J_z}(f_2,\pi)$$

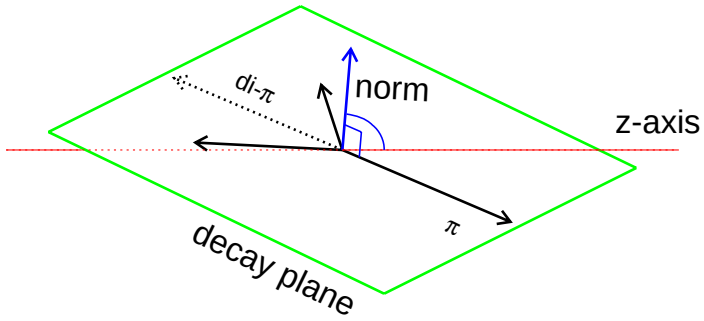
Decay modes

$$T^{J_z}(I,\pi) = 32\pi^2\left(m_R\Gamma_R\, m_{2\pi}\Gamma_{2\pi}\frac{\sqrt{s\, s_{2\pi}}}{p_{2\pi}\, p_\pi}\right)^{1/2}\sum_m C^{J,J_z}_{L,J_z-m,l,m}Y_L^{J_z-m}(\theta_{2\pi},\phi_{2\pi})Y_l^m(\theta_\pi,\phi_\pi)$$

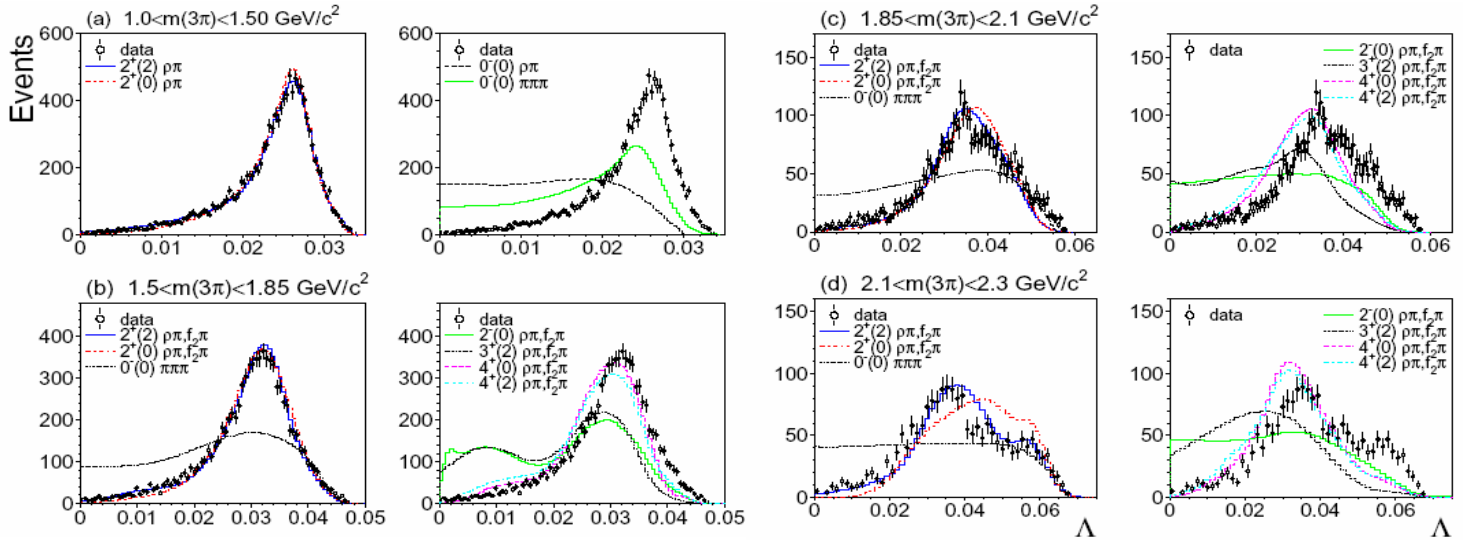
Spin-Parity

Spin-parity by the norm of 3π decay plane

$$\Lambda = \left| \frac{\vec{p}(\pi^+) \times \vec{p}(\pi^-)}{Q} \right|^2$$



$m(3\pi)$ range (GeV/c^2)		1.0-1.5	1.5-1.85	1.85-2.1	2.1-2.3
MC resonance mass (MeV/c^2)		1318	1750	1950	2140
width (MeV/c^2)		105	250	250	250
Decay modes, J^P(helicity)		χ^2/ndf			
$\rho\pi + f_2\pi^0$	$2^+(0)$	-	1.9	1.5	3.4
$\rho\pi + f_2\pi^0$	$2^+(2)$	-	1.0	1.4	1.4
$\rho\pi + f_2\pi^0$	$2^-(0)$	-	37	12	9.4
$\rho\pi + f_2\pi^0$	$3^+(2)$	-	44	17	15
$\rho\pi + f_2\pi^0$	$4^+(0)$	-	6.1	5.1	5.2
$\rho\pi + f_2\pi^0$	$4^+(2)$	-	6.9	6.0	5.0



Neural Network to select tensor events

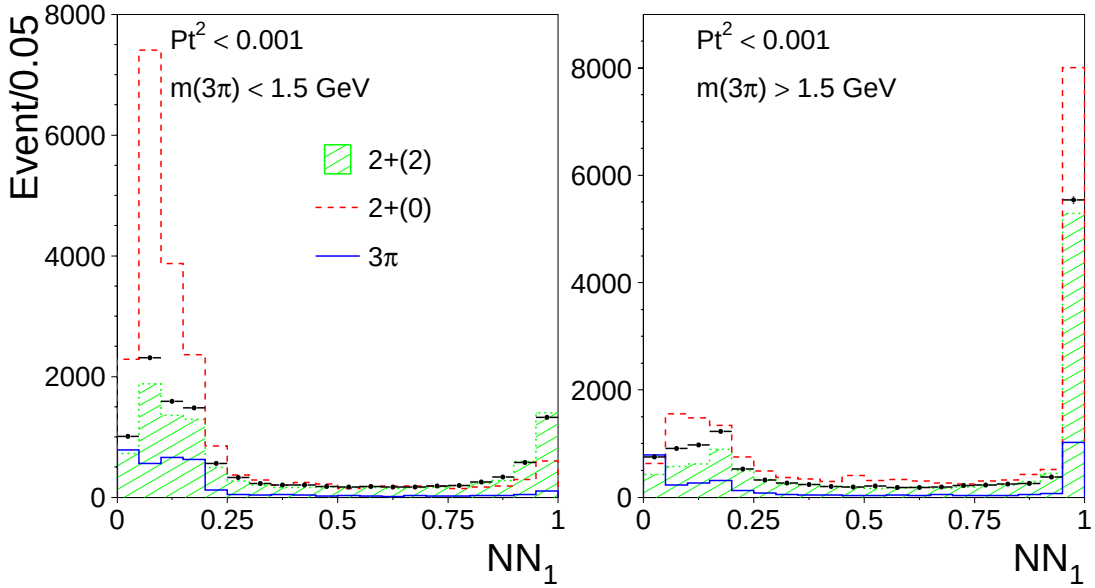
- Feed-forward Neural Network

  7 variables (di-π masses, $\pi\gamma$ opening angles, norm of decay plane)

  3 waves: 2+(2), 2+(0) , ph.space

- Test output : $NN(2)=NN_2(1-NN_0)(1-NN_{3\pi})$

- Data follow $2^+(2)$
- Cut on NN >2
  to suppress ph.space



Helicity state of tensor events

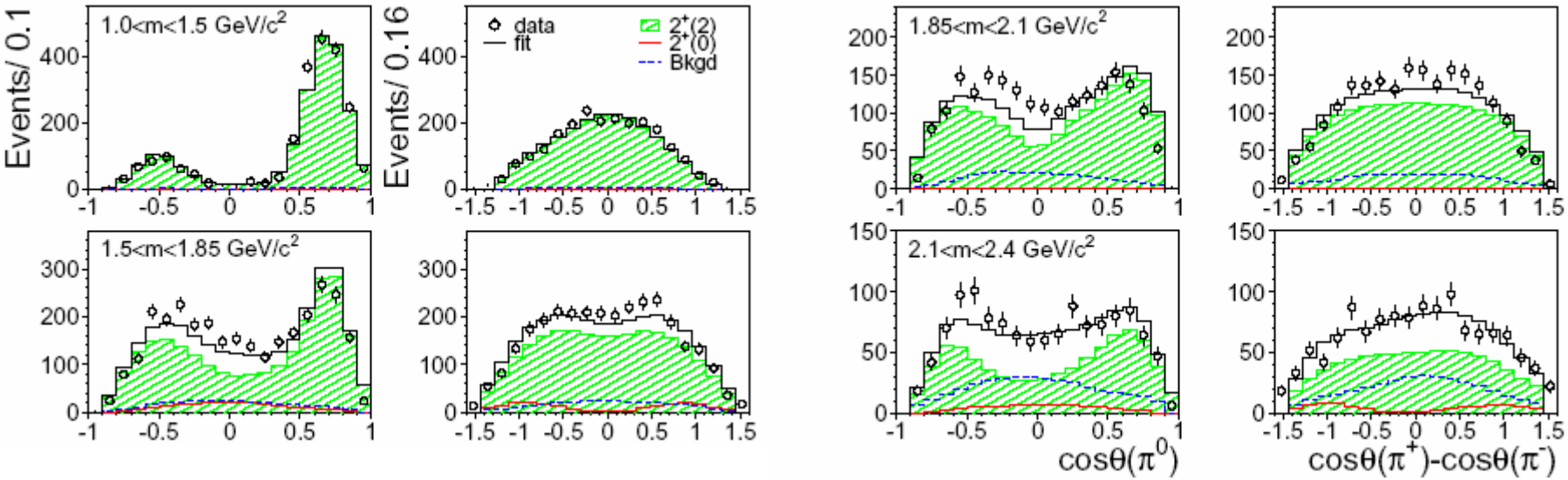
Final sample

$p^2_T(3\pi) < 0.0005$ GeV^2

$E\gamma > 180$ MeV

NN > 0.2

$m(3\pi)$ mass range	background (fixed) %	Helicity-2 %	χ^2/ndf
$1.0 - 1.5$ GeV/c^2	0.8	$100 \pm 2 \pm 5$	1.2
$1.5 - 1.85$ GeV/c^2	10	$95 \pm 2 \pm 5$	2.8
$1.85 - 2.1$ GeV/c^2	13	$100 \pm 2 \pm 5$	3.8
$2.1 - 2.4$ GeV/c^2	30	$82 \pm 2 \pm 5$	1.1

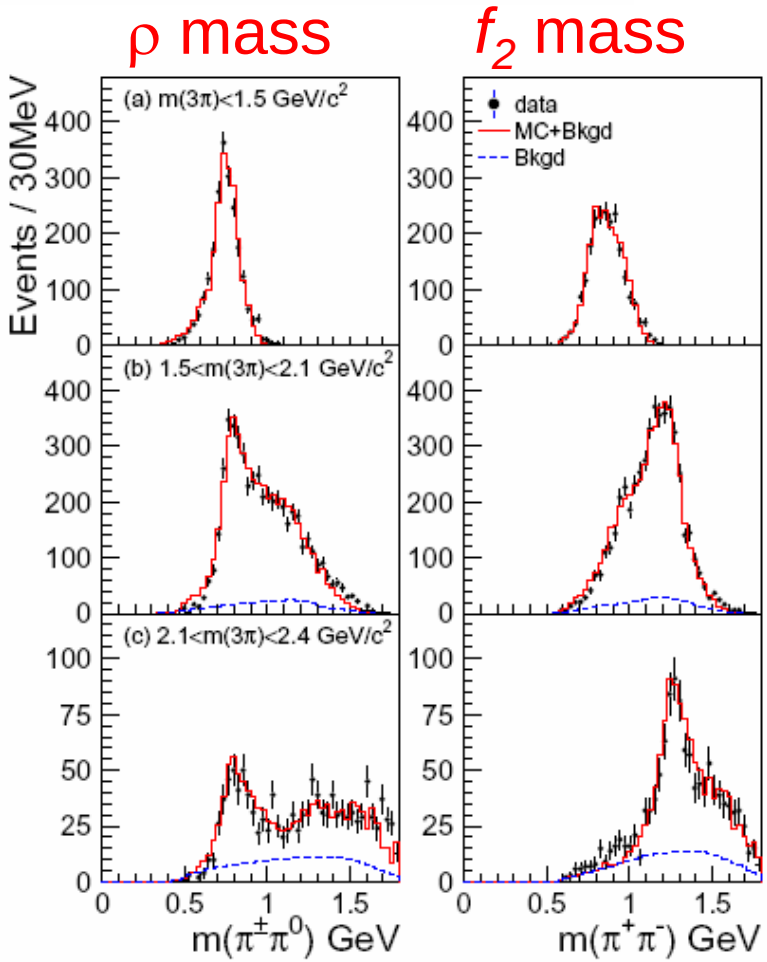


Decay modes: $\rho\pi$, $f_2\pi$

$$\sum_I D_i^{J_z}(I) = \mathrm{BW}(\rho^+)T^{J_z}(\rho^+,\pi) + \mathrm{BW}(\rho^-)T^{J_z}(\rho^-,\pi) + \xi_i e^{i\psi_i}\mathrm{BW}(f_2)T^{J_z}(f_2,\pi)$$

Fit with MC for ξ_i ψ_i

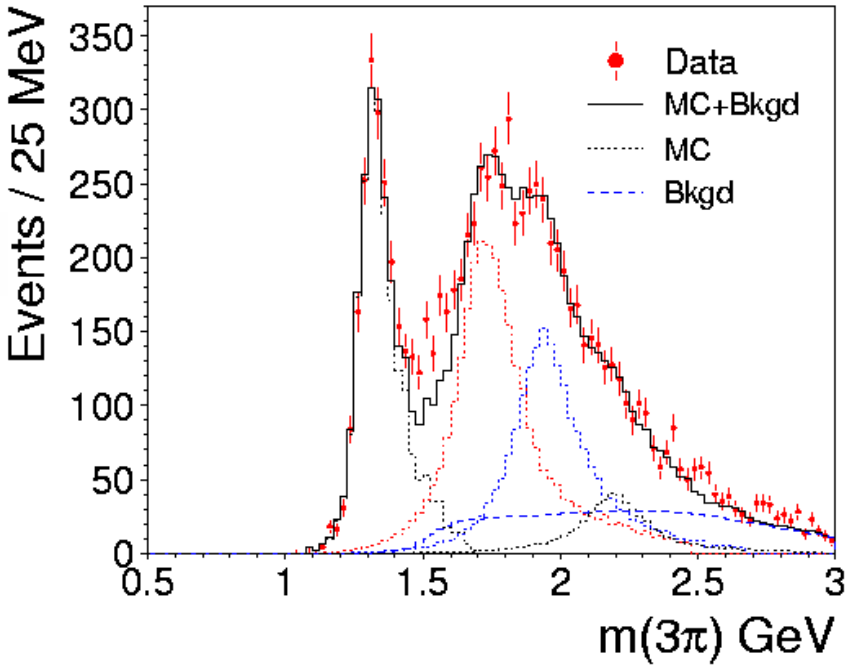
	amplitude (ξ's)	phase (ψ's) deg.
$a_2(1700)$	$0.92 \pm 0.10 \pm 0.08$	$151 \pm 4 \pm 12$
$BW(1950)$	$0.91 \pm 0.10 \pm 0.12$	$149 \pm 4 \pm 20$
$BW(2140)$	$1.0 \pm 0.20 \pm 0.30$	$145 \pm 10 \pm 30$



3π mass fit to 4 independent resonances

Background from $p_t^2(3\pi)$ estimation

χ^2 /ndf(1-2.4GeV)= 2.3



a_2(1320) of full MC apply PDG values

$$\Gamma_{\gamma\gamma}(a_2(1320)) = 0.99 \pm 0.03 \pm 0.11 \text{ keV}.$$

Two-photon radiative width
Consistent with world average

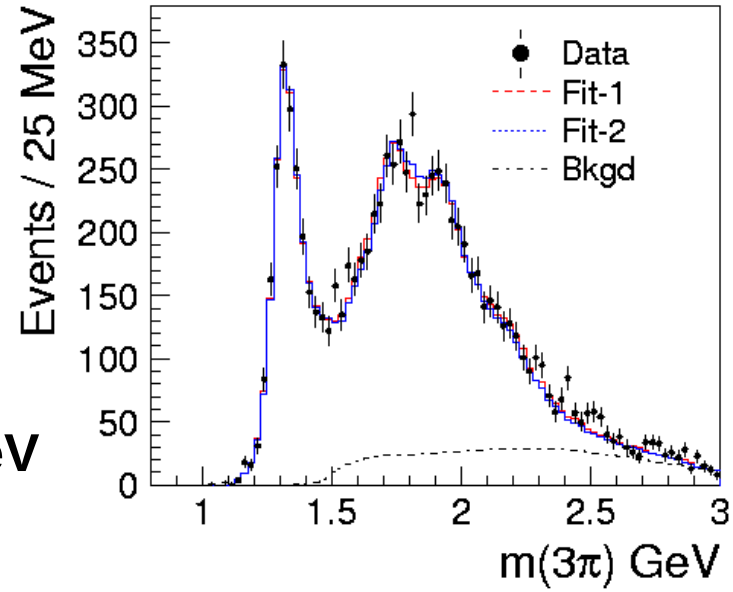
$\Gamma_{\gamma\gamma}(a_2(1700))\text{Br}(3\pi)$ = 0.34±0.01 keV

Consistent with L3 measurement

	Events(fit)	mass (MeV/c^2)	width (MeV/c^2)	$\Gamma_{\gamma\gamma} \cdot \text{Br}(\rho\pi, f_2\pi)$ (keV)
$a_2(1700)$	3048	$1699 \pm 6 \pm 8$	$253 \pm 10 \pm 10$	$0.343 \pm 0.009 \pm 0.040$
$BW(1950)$	1997	$1942 \pm 8 \pm 8$	$249 \pm 14 \pm 10$	$0.196 \pm 0.007 \pm 0.020$
$BW(2140)$	530	$2180 \pm 20 \pm 8$	$270 \pm 50 \pm 10$	$0.050 \pm 0.005 \pm 0.005$

3π mass fit to 4 Tensors w. interference

- A fit obtained every half-period in phase
- Two fits with radially excited amplitudes <1
  six fits obtained with amplitude>1



(Fit-1) χ^2/50 bins (1.0-2.4 GeV) = 0.92
(Fit-2) χ^2/50 bins (1.0-2.4 GeV) = 0.93

$\Gamma_{\gamma\gamma}(a_2(1700))B(3\pi) = 0.10 \pm 0.02 \pm 0.02$ keV
derived from amplitude

Fit-1	mass MeV/c^2	width MeV/c^2	amplitude (α's)	phase (ϕ's) deg.
$a_2(1700)$	$1769 \pm 10 \pm 8$	$270 \pm 7 \pm 10$	$0.371 \pm 0.022 \pm 0.040$	$154 \pm 6 \pm 12$
$BW(1950)$	$1948 \pm 4 \pm 8$	$291 \pm 6 \pm 10$	$0.613 \pm 0.019 \pm 0.050$	$143 \pm 5 \pm 12$
$BW(2140)$	$2146 \pm 12 \pm 8$	$358 \pm 26 \pm 10$	$0.401 \pm 0.026 \pm 0.040$	$139 \pm 4 \pm 12$
Fit-2	mass MeV/c^2	width MeV/c^2	amplitude (α's)	phase (ϕ's) deg.
$a_2(1700)$	$1758 \pm 13 \pm 8$	$269 \pm 10 \pm 10$	$0.365 \pm 0.027 \pm 0.040$	$221 \pm 7 \pm 12$
$BW(1950)$	$1949 \pm 6 \pm 8$	$324 \pm 14 \pm 10$	$0.713 \pm 0.030 \pm 0.050$	$220 \pm 6 \pm 12$
$BW(2140)$	$2161 \pm 17 \pm 8$	$342 \pm 22 \pm 10$	$0.438 \pm 0.032 \pm 0.040$	$221 \pm 6 \pm 12$

Summary

Belle has high statistics for two-photon analysis

➔ $\gamma\gamma$ ➔ **hadron-pair** show steeper $W_{\gamma\gamma}$ then predictions

➔ χ_{c0}, χ_{c2} observed in $\gamma\gamma \to K^0_S K^0_S$

➔ η_c observed in $\gamma\gamma \to p\bar{p}$, $\Lambda\bar{\Lambda}$, $\Sigma\bar{\Sigma}^0$

➔ $\gamma\gamma \to \pi^+\pi^-\pi^0$ is dominated by Tensor Helicity 2 wave

➔ $a_2(1320)$, $a_2(1700)$ is consistent with PDG

higher radially excited states observed

at 1950, 2140 MeV