



# Study of $\gamma\gamma \rightarrow p\bar{p}$ Production at Belle

Chen-Cheng Kuo (Belle Collaboration)

*National Central University, Chung-Li, Taiwan*

**Nucleon 05**

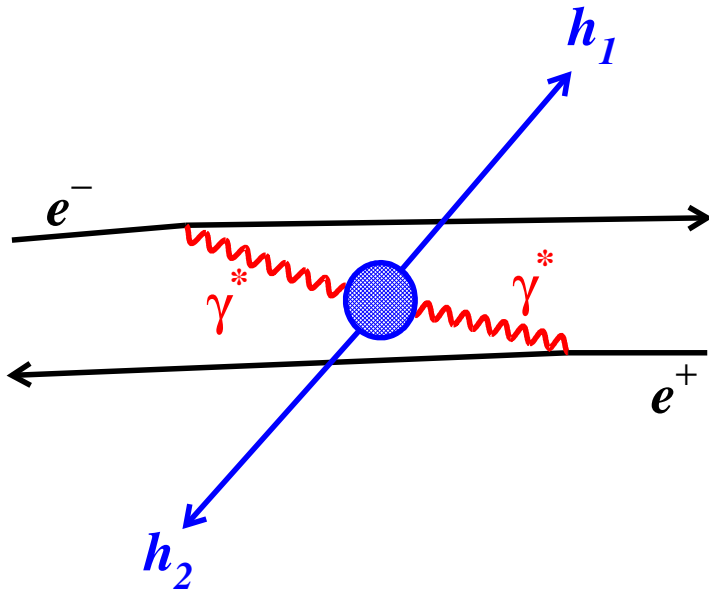
**October 12-14, 2005, Frascati, Italy**

# Outline

- ◆ Introduction and Theory
- ◆ Belle Detector
- ◆ Event Selection
- ◆ Cross Sections for  $\gamma\gamma \rightarrow p\bar{p}$
- ◆ Summary

# Hadron Pair Production from Collisions of two Quasi-Real Photons ( $\gamma\gamma \rightarrow h_1 h_2$ )

## Definitions and features:



- ◆  $W_{\gamma\gamma} \equiv$  invariant mass of  $h_1, h_2$
- ◆  $\theta^* \equiv$  c.m. scattering angle of hadrons with respect to  $\gamma\gamma$  axis

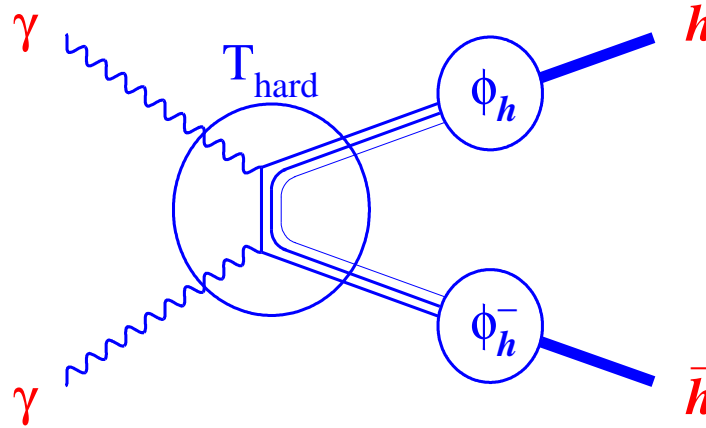
## ◆ KEKB:

- ▶  $\sqrt{s_{e^+e^-}} = 10.58$  GeV
- ▶ world highest luminosity ( $\sim 1.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ )
- ▶ abundant and clean  $\gamma\gamma$  events up to  $W_{\gamma\gamma} \sim 4.5$  GeV

## ◆ Test of theoretical predictions:

- ▶ pQCD framework
- ▶ pure quark picture
- ▶ quark-diquark model for baryons
- ▶ handbag model
- ▶ QCD sum rules
- ▶ resonance and pole dynamics

# PQCD Framework and Form Factor Models



- ◆ General theory of hard exclusive process in QCD:

$$\frac{d\sigma}{dt} \propto s^{2-n_c} f(\theta^*)$$

$$(\text{as } s \rightarrow \infty; s \equiv W_{\gamma\gamma}^2)$$

$$\text{if } n_c = 8, \text{ then } \sigma \propto W_{\gamma\gamma}^{-10}$$

[Chernyak et al.,  
JETPL 26 (1977) 594]

[Lepage and Brodsky,  
PR D22 (1980) 2157]

- ◆ Three-quark picture using proton wave function based on QCD sum rules:

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

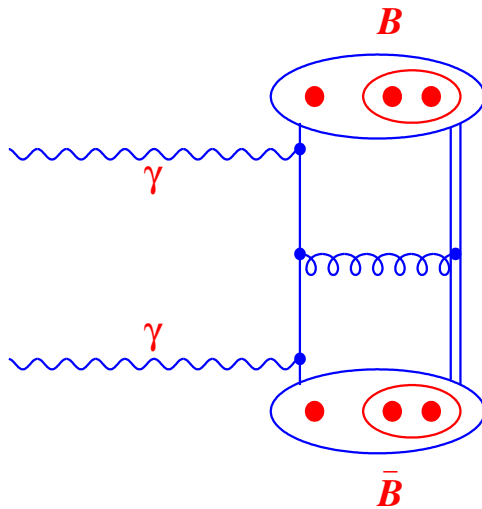
$\sim$  one order below the experimental cross sections

[Chernyak and Zhitnitsky,  
NP B246 (1984) 52]

[Farrar et al.,  
NP B259 (1985) 702]

## Models for moderately high energy:

◆ Baryons as quark-diquark systems:



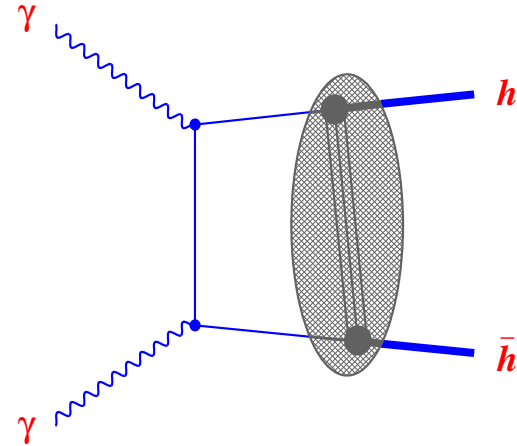
$$\frac{d\sigma(\gamma\gamma \rightarrow \mathcal{B}\bar{\mathcal{B}})}{d|\cos\theta^*|} \propto \frac{W_{\gamma\gamma}^{-6} |F_D|^2 T'(\theta^*)}{1 - \cos^2\theta^*}$$

$F_D \propto$  diquark form factors  
(if  $F_D \rightarrow 1/s$ , then  $\sigma \propto W_{\gamma\gamma}^{-10}$ )

[Kroll et al.,  
PL B316 (1993) 546]

[Berger et al.,  
EPJ C28 (2003) 249]

◆ Handbag contribution  
( $\gamma\gamma \rightarrow q\bar{q} \rightsquigarrow \mathcal{B}\bar{\mathcal{B}}$ ):

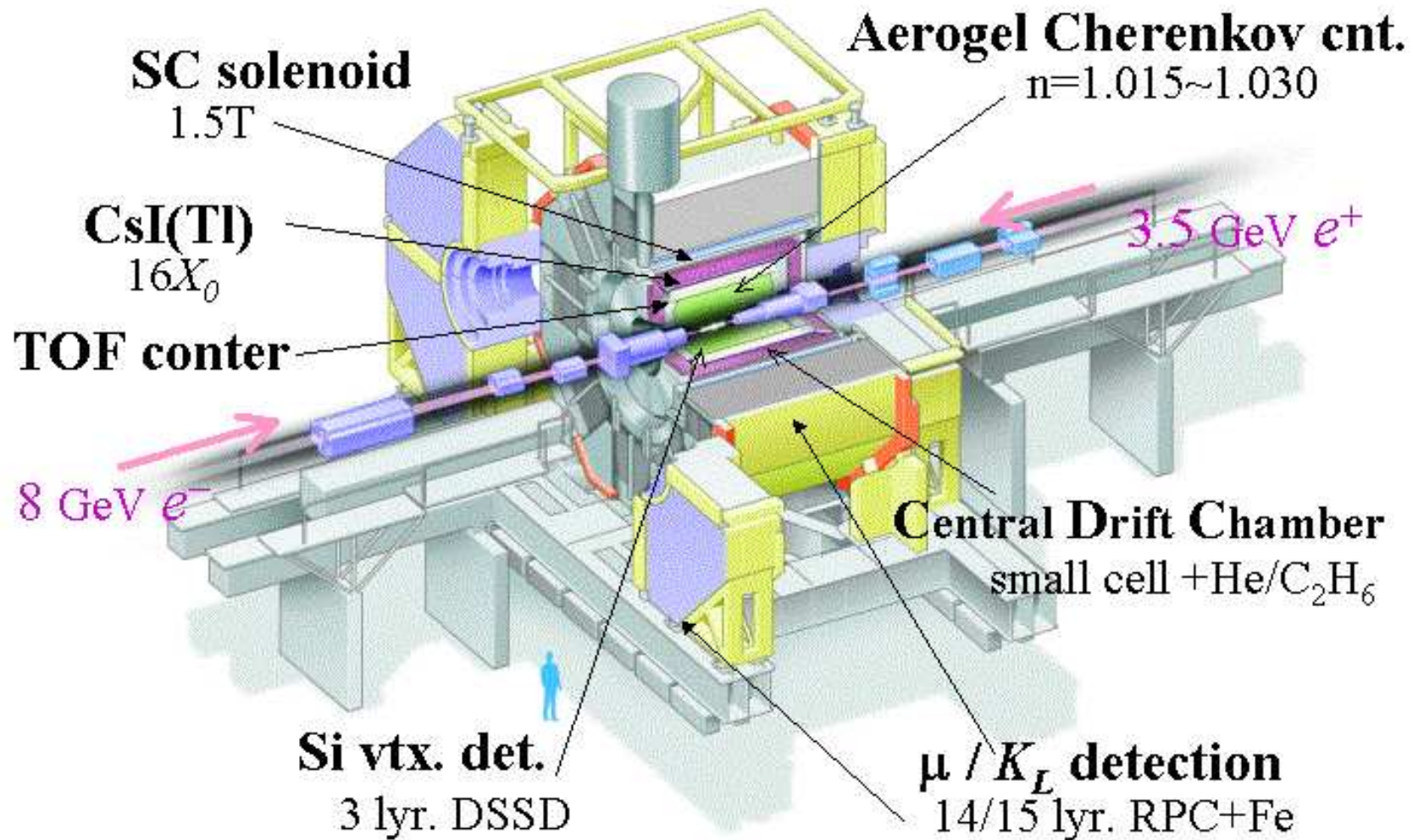


$$\frac{d\sigma(\gamma\gamma \rightarrow \mathcal{B}\bar{\mathcal{B}})}{d|\cos\theta^*|} \propto \frac{|R_V(s)|^2 \cos^2\theta^* + R_{eff}^2(s)}{s(1 - \cos^2\theta^*)}$$

$R$ 's: annihilation form factors  
(if  $R$ 's  $\propto s^{-2}$ , then  $\sigma \propto W_{\gamma\gamma}^{-10}$ )

[Diehl et al.,  
EPJ C26 (2003) 567]

# Belle Detector



# Event Selection Criteria

## ◆ Low Multi. (2-track) event selection:

- $\sum[|\vec{p}|] < 6 \text{ GeV}/c,$   
 $\sum[E_{\text{cal}}] < 6 \text{ GeV}$
- $M_{\text{inv}} < 4.5 \text{ GeV}/c^2,$   
 $M_{\text{miss}}^2 > 2 \text{ GeV}^2/c^4$
- $|\vec{p}_t| > 0.35 \text{ GeV}/c,$   
 $dr < 1 \text{ cm},$   
 $|dz| < 5 \text{ cm}$  for each track

## ◆ Non-exclusive background rejection:

- $p_t^*$ -balance:  
 $|\vec{p}_{t+}^* + \vec{p}_{t-}^*| < 0.2 \text{ GeV}$

## ◆ $p(\bar{p})$ identification ( $K^\pm, \pi^\pm, \mu^\pm, e^\pm$ rejection):

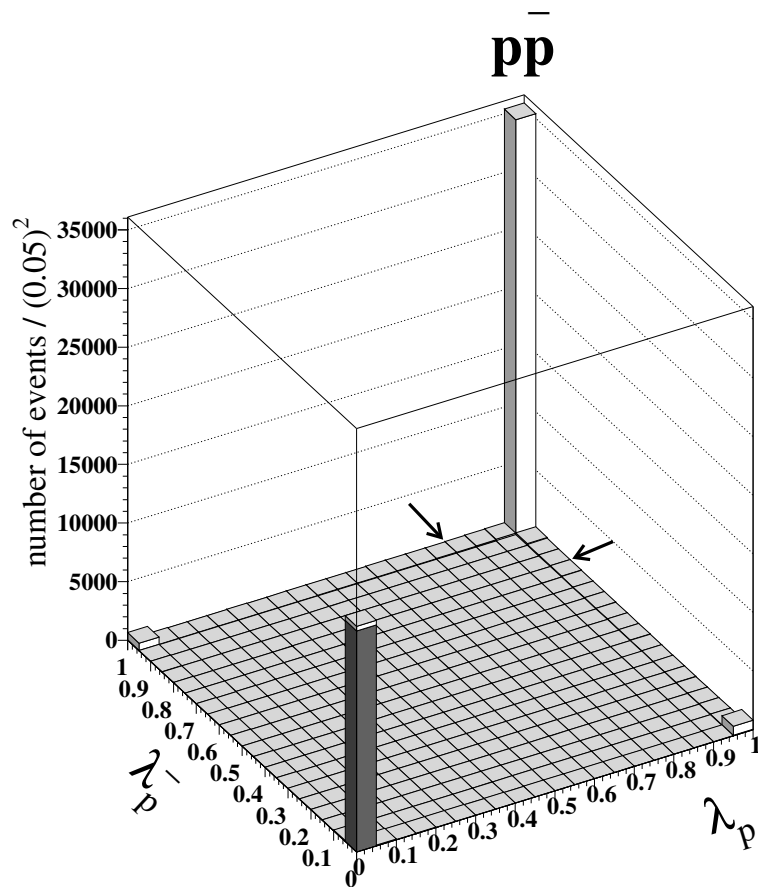
- $\frac{|\Delta(dE/dx)|}{\sigma_{dE/dx}} < 4$
- Normalized Likelihood:  
 $\lambda_{p(\bar{p})} \equiv \frac{L_p}{L_p + L_K + L_\pi + L_\mu + L_e}$   
 $> 0.8,$

where each  $L \equiv$

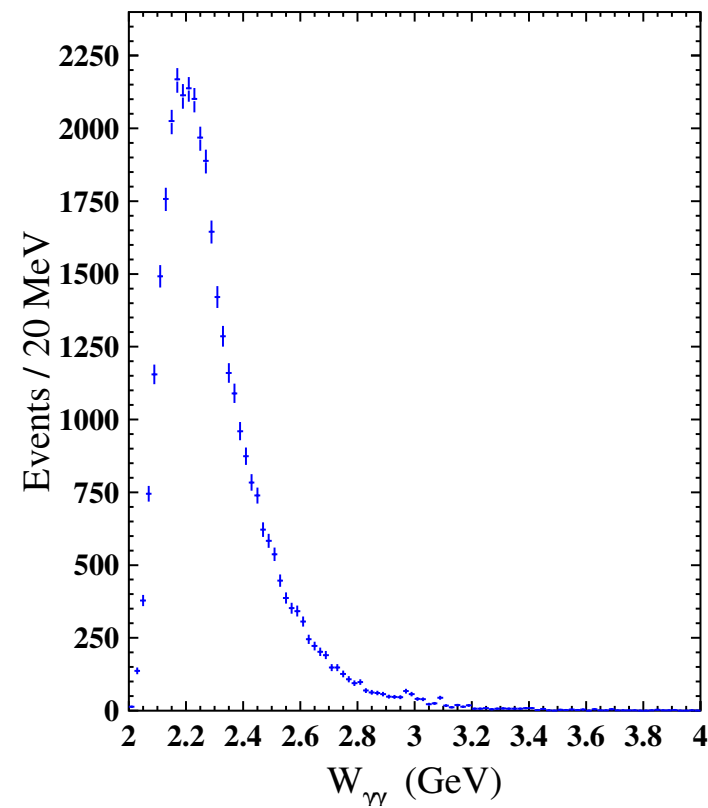
$$e^{-0.5\left[\left(\frac{\Delta(dE/dx)}{\sigma_{dE/dx}}\right)^2 + \left(\frac{\Delta T(\text{TOF})}{\sigma_T}\right)^2\right]}$$

- $\frac{E_{\text{cal}}}{|\vec{p}|} < 0.9$   
(only for  $p$  candidates)
- $N_{\text{ACC}} < 4$

- $p, \bar{p}$  identification by the Normalized Likelihood:



- Events versus  $W_{\gamma\gamma}$  after all selection criteria (36094 in total)





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<b>Group</b>	<b>Year</b>	<b><math>W_{\gamma\gamma}</math> (GeV)</b>	<b>Events</b>
TASSO	1983	2.0–3.1	72
JADE	1986	2.0–2.6	57
TPC/ $2\gamma$	1987	2.0–2.8	52
ARGUS	1989	2.0–2.9	60
CLEO	1994	2.0–3.25	484
VENUS	1997	2.2–3.3	311
OPAL	2003	2.15–3.95	163
L3	2003	2.1–4.5	938
Belle	2005	2.025–4.0	36094

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# Determination of Differential Cross Sections

$$\frac{d\sigma_{\gamma\gamma \rightarrow p\bar{p}}(W_{\gamma\gamma})}{d|\cos\theta^*|} = \frac{\Delta N (1-f)}{\epsilon L_{\text{int}} \frac{dL_{\gamma\gamma}}{dW_{\gamma\gamma}} \Delta W_{\gamma\gamma} \Delta|\cos\theta^*|}$$

$$\sigma_{\gamma\gamma \rightarrow p\bar{p}}(W_{\gamma\gamma}) = \sum \frac{d\sigma_{\gamma\gamma \rightarrow p\bar{p}}(W_{\gamma\gamma})}{d|\cos\theta^*|} \Delta|\cos\theta^*|$$

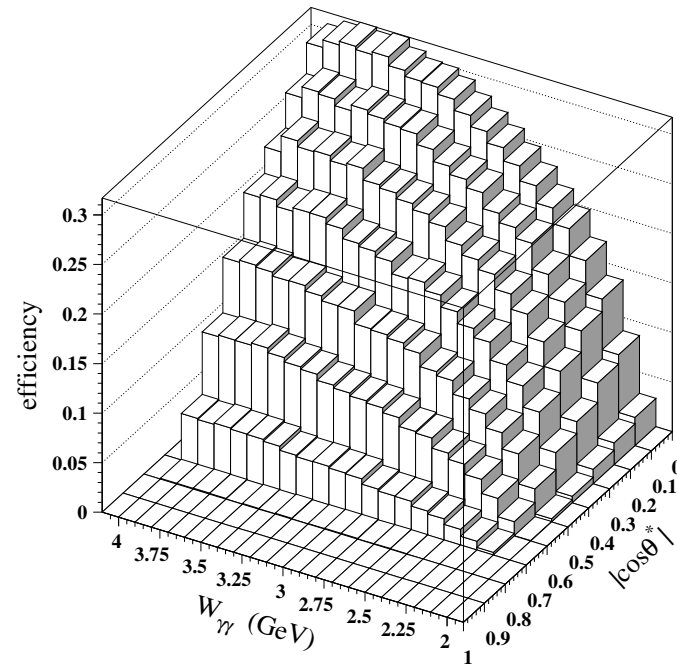
$L_{\text{int}}$ : integrated luminosity ( $\sim 89 \text{ fb}^{-1}$ )     $\epsilon$ : efficiency: up to 32%

$\frac{dL_{\gamma\gamma}}{dW_{\gamma\gamma}}$ : luminosity function, defined by

$$\begin{aligned} & \sigma_{e^+e^- \rightarrow e^+e^-p\bar{p}} \\ &= \int \sigma_{\gamma\gamma \rightarrow p\bar{p}}(W_{\gamma\gamma}) \frac{dL_{\gamma\gamma}(W_{\gamma\gamma})}{dW_{\gamma\gamma}} dW_{\gamma\gamma} \end{aligned}$$

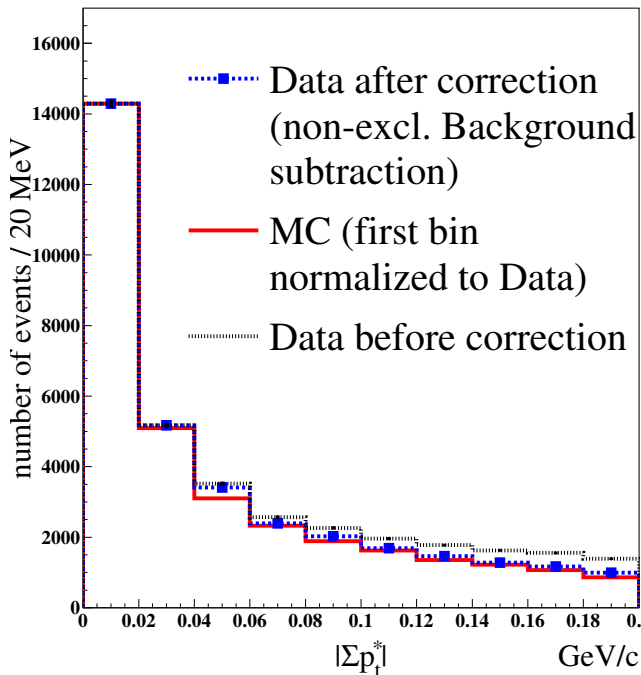
$\Delta N, \Delta W_{\gamma\gamma}, \Delta|\cos\theta^*|$ : number of events in each 2-dimensional bin and the bin widths

$f$ : fraction of residual background in the data



# Corrections and Systematic Errors

- ◆ Residual non-exclusive ( $p\bar{p}\pi^0$ ) background subtraction ( $W_{\gamma\gamma} = 2-4$  GeV):  
 $f_n = 5 \pm 2\% - 17 \pm 8\%$



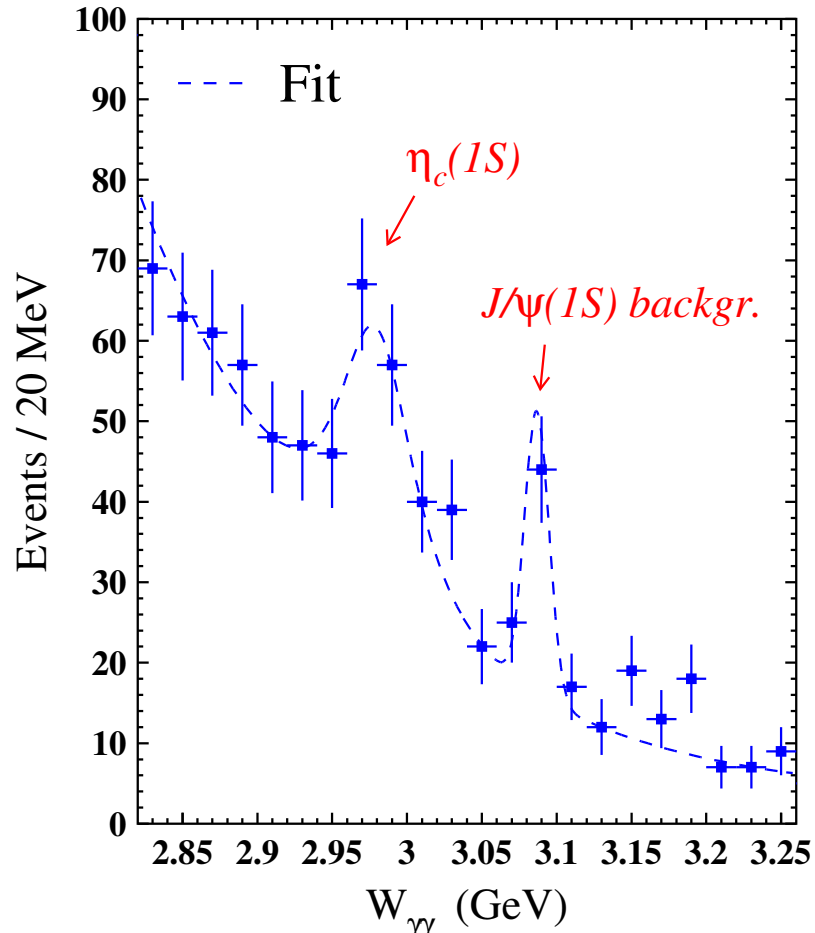
- ◆ Residual  $K^+K^-$  background subtraction ( $W_{\gamma\gamma} = 3.2-4.0$  GeV):  
 $f_m = 0.8 \pm 0.3\% - 7.7 \pm 0.8\%$

- ◆ Subtraction of excess due to radiative return  $J/\psi$  background ( $W_{\gamma\gamma} \sim 3.1$  GeV):  
a total number of  $\sim 31 \pm 8$  events subtracted

◆ Systematic error: Total 7–14%

Source	Sys. error (%)
Integrated luminosity ( $L_{\text{int}}$ )	1.4
Luminosity function ( $dL_{\gamma\gamma}/dW_{\gamma\gamma}$ )	3–5
Trigger efficiency ( $\sim 83\%$ – $95\%$ )	5
PID efficiency ( $\sim 92\%$ down to $78\%$ )	1–6
MC statistics	1–3
Residual $K^+K^-$ subtraction ( $f_m$ )	0–1
Residual $p\bar{p}\pi^0$ subtraction ( $f_n$ )	2–12
$ \Sigma p_t^* $ effect	2–3
$J/\psi$ subtraction ( $W_{\gamma\gamma} = 3.0$ – $3.1$ GeV)	8
Radiative return background	1

# First Observation of $\gamma\gamma \rightarrow \eta_c(1S) \rightarrow p\bar{p}$



- **Statistical Significance**

$$\equiv \sqrt{-2 \ln(L_0/L_S)} = 5.3\sigma$$

- $\Gamma_{\gamma\gamma}(\eta_c) \times B(\eta_c \rightarrow p\bar{p})$

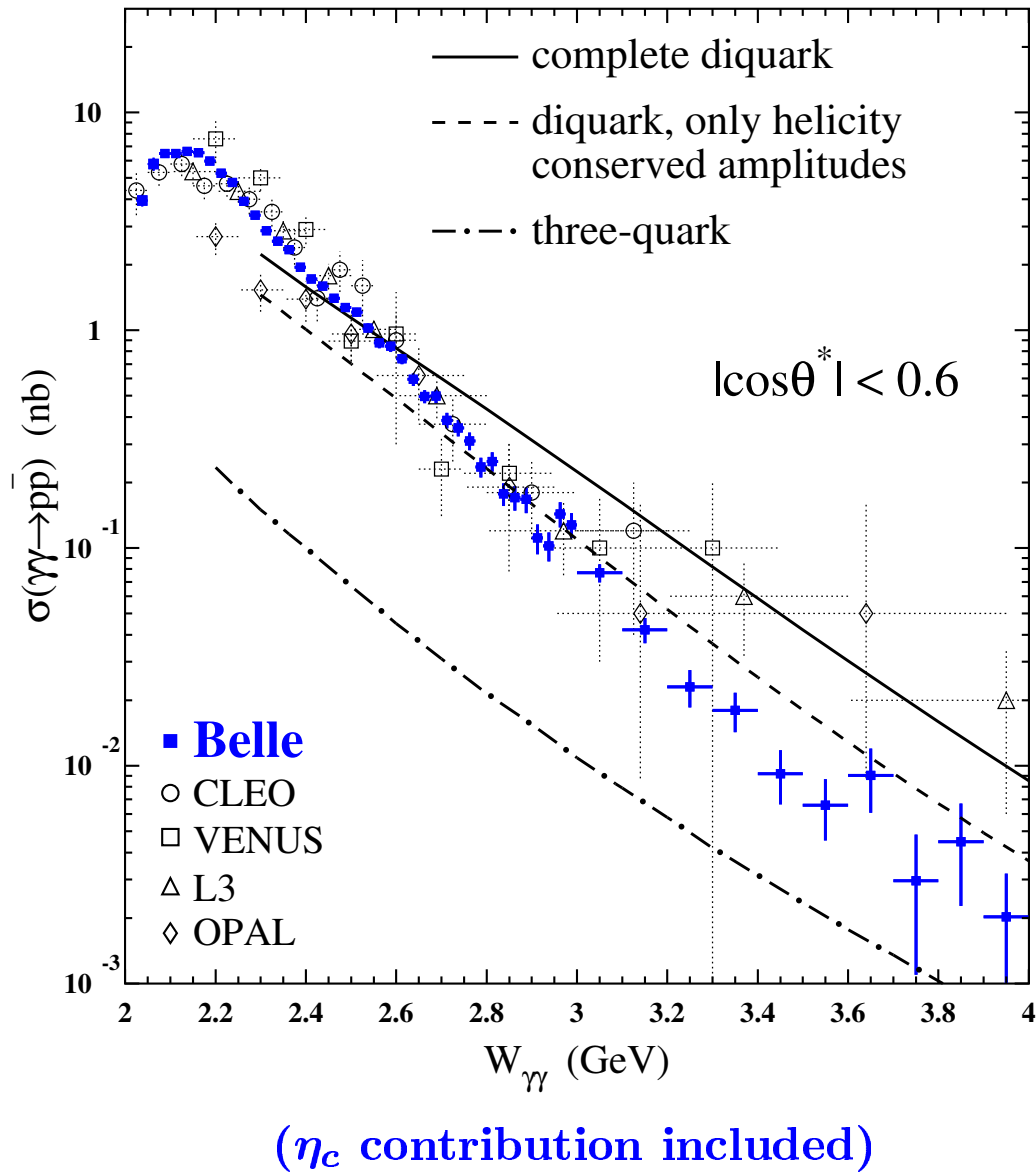
$$= \frac{N_{\eta_c} m_{\eta_c}^2}{4\pi^2 \epsilon L_{\text{int}} \frac{dL_{\gamma\gamma}}{dW_{\gamma\gamma}}}$$

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

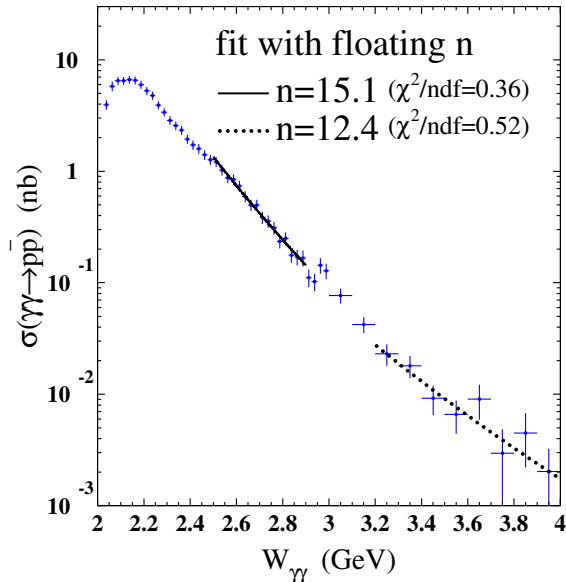
\*  $\frac{\Gamma_i \Gamma_f}{\Gamma_{\text{tot}}^2}$  (in  $p\bar{p} \rightarrow \eta_c \rightarrow \gamma\gamma$ )  $\times \Gamma_{\text{tot}}$

[FNAL E835 (2003) etc.]

# Measured Cross Sections for $\gamma\gamma \rightarrow p\bar{p}$



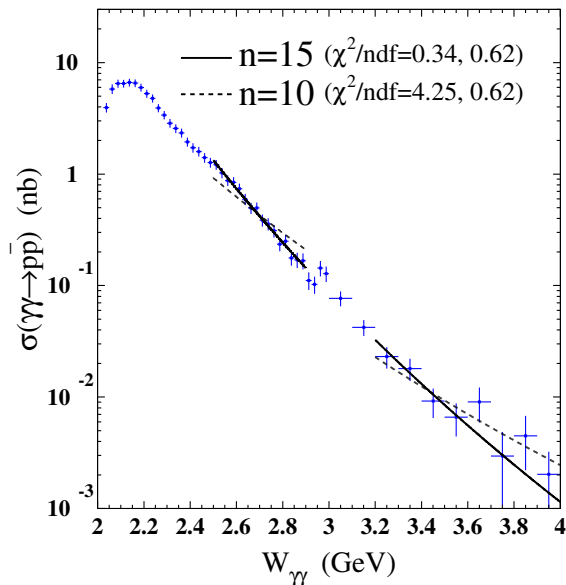
# $W_{\gamma\gamma}^{-n}$ Dependence of $\sigma_{\gamma\gamma \rightarrow p\bar{p}}(W_{\gamma\gamma})$



fitted $n$	range of $W_{\gamma\gamma}$ (GeV)
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$15.1^{+0.8}_{-1.1}$	2.5–2.9
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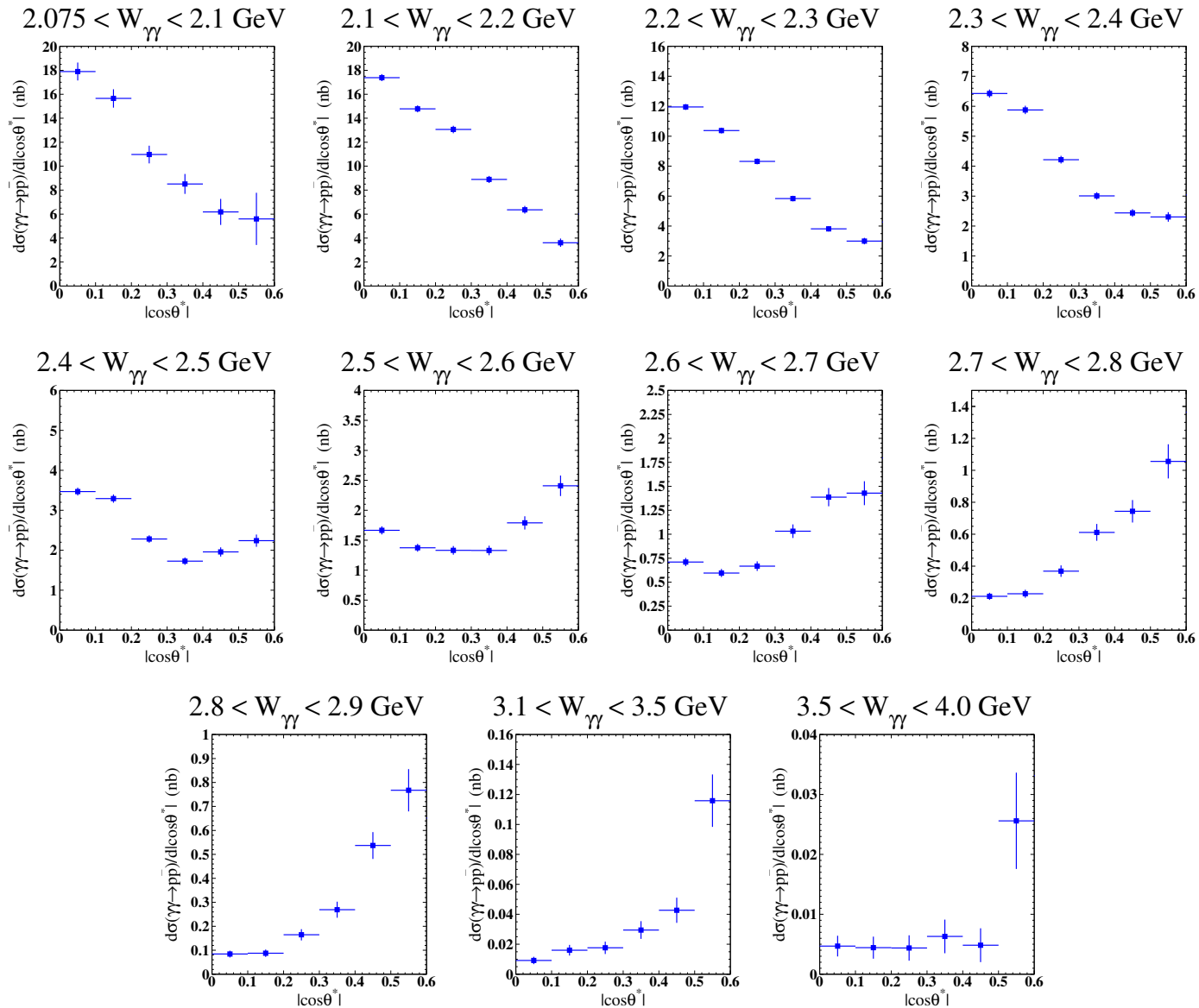
$12.4^{+2.4}_{-2.3}$	3.2–4.0
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◆ Steeper fall in  $W_{\gamma\gamma}$  than pQCD  $n = 10$  ( $n = 10$  not rejected for  $W_{\gamma\gamma} > 3.2$  GeV)

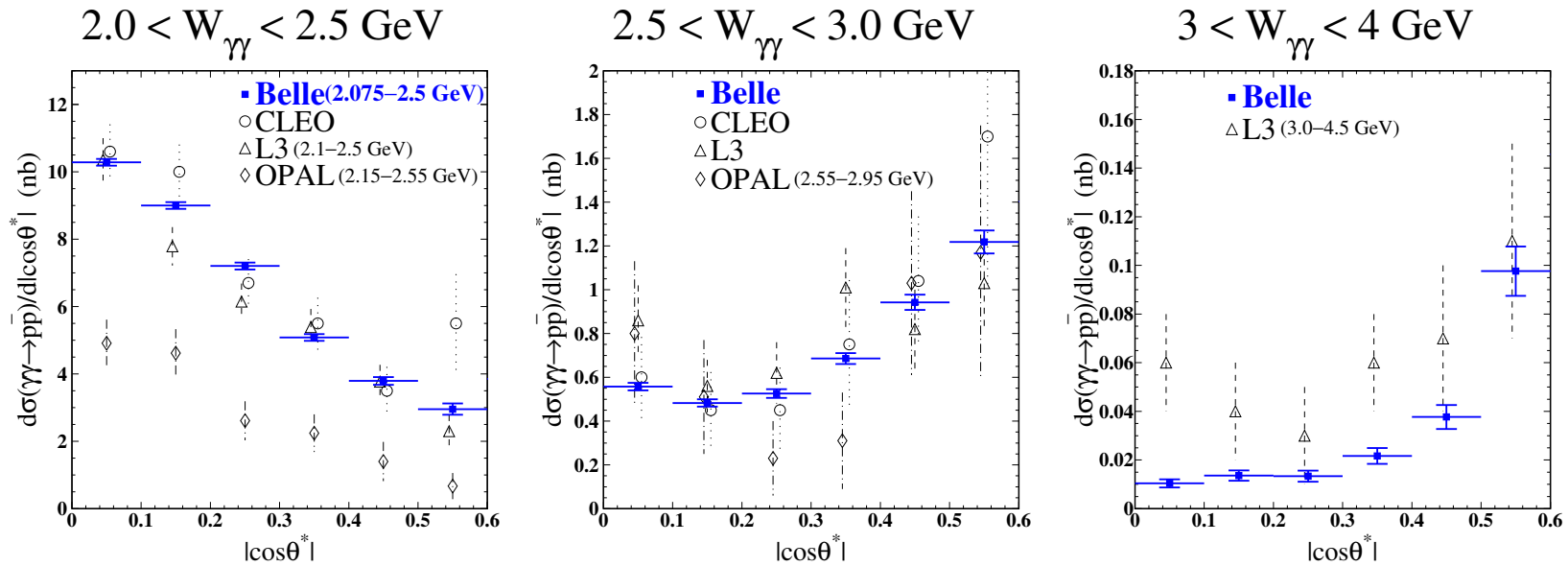
◆ Decreasing  $n$  in  $W_{\gamma\gamma}$  (indication of a transition to asymptotic predictions)

# Variation of the Angular Distribution in $W_{\gamma\gamma}$



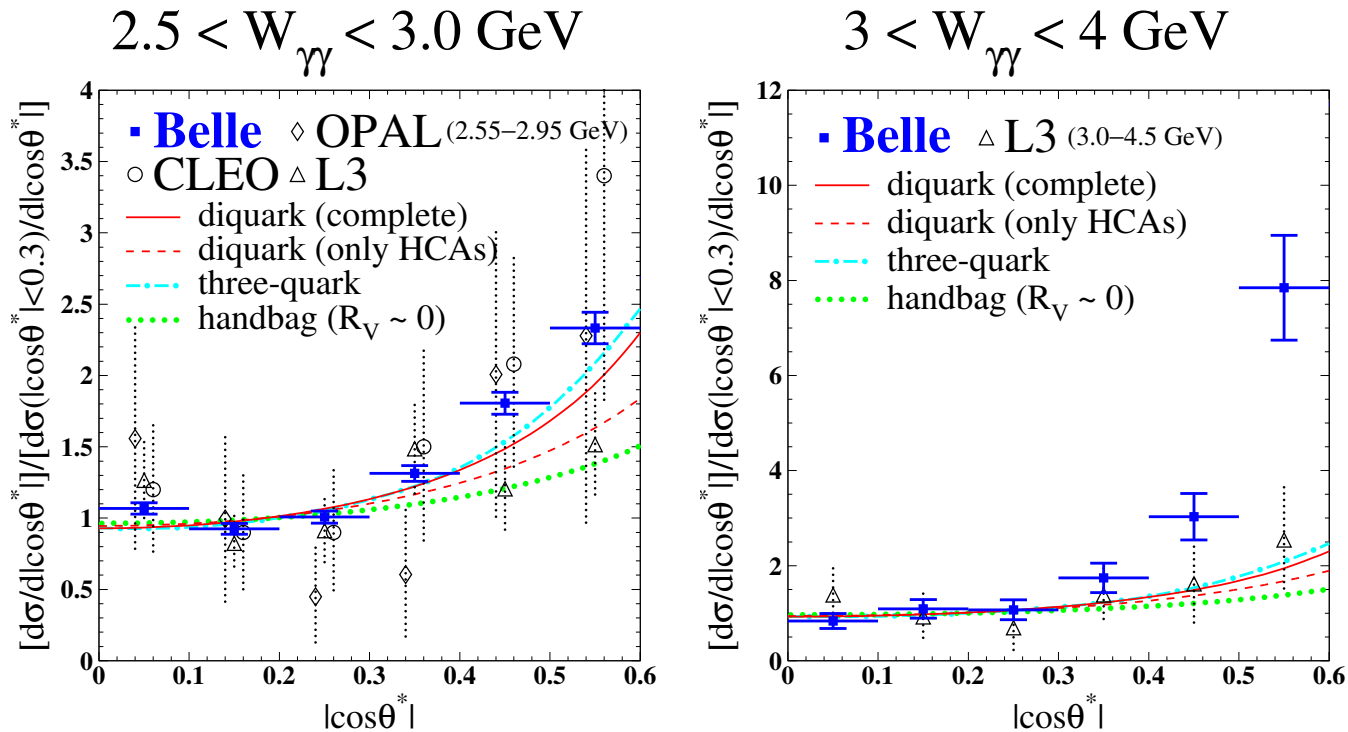


# Angular Distribution in 3 $W_{\gamma\gamma}$ -Ranges



- ◆  $W_{\gamma\gamma} = 2.0-2.5$  GeV: enhancement at large-angle (small- $|\cos\theta^*|$ )
- ◆  $W_{\gamma\gamma} = 2.5-3.0$  GeV: enhancement at small-angle (large- $|\cos\theta^*|$ ), beginning of the transition from a descending to an ascending trend
- ◆  $W_{\gamma\gamma} = 3.0-4.0$  GeV: enhancement at small-angle (large- $|\cos\theta^*|$ ), steeper enhancement for  $|\cos\theta^*| \sim 0.5-0.6$

# Angular Distribution at Higher Energies and Predictions



- ◆ Ascending trend is a general feature of pQCD due to the hard scattering amplitude:  $\frac{d\sigma}{d|\cos\theta^*|} \propto \frac{1}{tu} \propto \frac{1}{1-\cos^2\theta^*}$
- ◆ Handbag contribution with  $R_V^p$  neglected:  $\frac{d\sigma}{d|\cos\theta^*|} \propto \frac{1}{1-\cos^2\theta^*}$
- ◆ Steeper enhancement of data at higher  $|\cos\theta^*|$  must be explained

# Summary

- ◆ Measurement of  $\sigma_{\gamma\gamma \rightarrow p\bar{p}}(W_{\gamma\gamma})$  and  $\frac{d\sigma}{d|\cos\theta^*|}$ 
  - ▶  $W_{\gamma\gamma} = 2.025\text{--}4.0$  GeV,  $|\cos\theta^*| < 0.6$  ( $\sim 36000$  events selected)
  - ▶ systematic uncertainty: 7%–14%
  - ▶ first observation of  $\gamma\gamma \rightarrow \eta_c \rightarrow p\bar{p}$ ,  $\Gamma_{\gamma\gamma}(\eta_c) \times B(\eta_c \rightarrow p\bar{p})$  determined
- ◆ Fitting of  $\sigma_{\gamma\gamma \rightarrow p\bar{p}}(W_{\gamma\gamma})$  to  $W_{\gamma\gamma}^{-n}$ 
  - ▶ steeper fall but decreasing  $n$  in  $W_{\gamma\gamma}$  ( $n \sim 15 \pm 1 \rightarrow 12 \pm 2$ )
  - ▶ asymptotically approaching  $n=10$  predictions
- ◆  $\frac{d\sigma}{d|\cos\theta^*|}$  in  $|\cos\theta^*|$ 
  - ▶ ascending trend (general pQCD feature) from  $W_{\gamma\gamma} \sim 2.5$  GeV up
  - ▶ steeper enhancement around  $|\cos\theta^*| \sim 0.5\text{--}0.6$  at higher measured-energies (not explained by current models)
- ◆ Measurement of  $\gamma\gamma \rightarrow p\bar{p}$  is important for the test of QCD and form factor models.

For Detail: PL B621 (2005) 41