Studies of $\gamma\gamma \to p\overline{p}$ Production at Belle

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(for the Belle collaboration)

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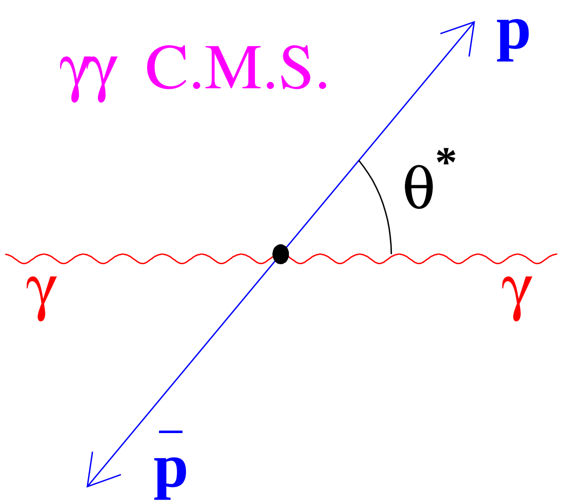
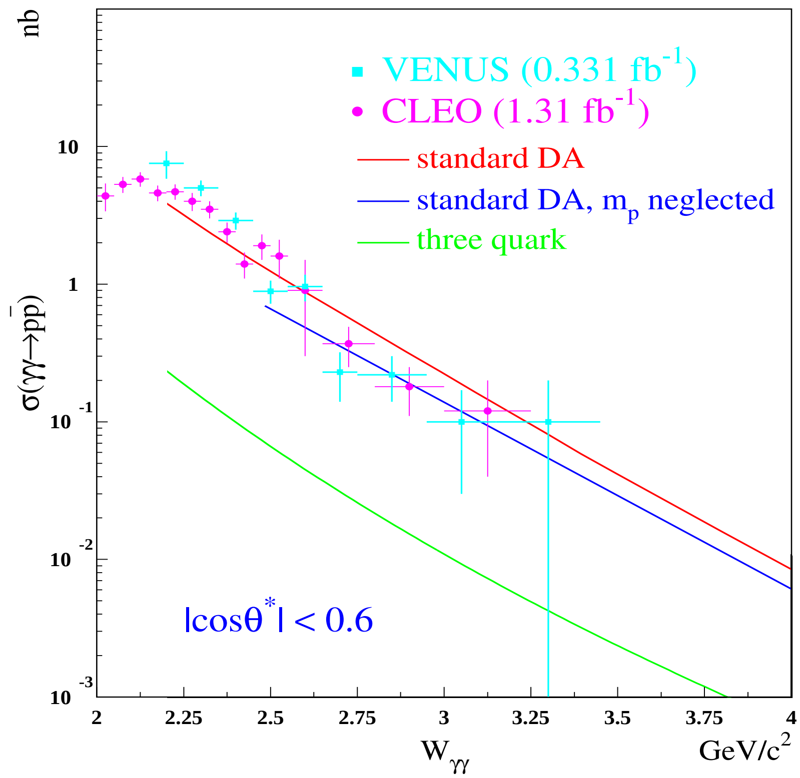
CONTENTS

1. Introduction

$$e^+e^- \rightarrow e^+e^- \boxed{\gamma\gamma} \hookrightarrow p\overline{p}$$

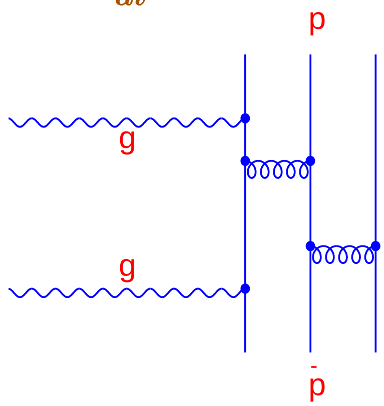




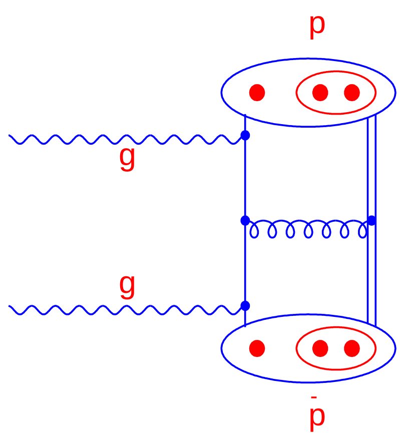
- The production of $\gamma\gamma \rightarrow p\overline{p}$ is one of the most interesting cases to study QCD. Such events can be produced in great abundance by high luminosity e^+e^- colliders experimentally, and several pQCD predictions have calculated the case $\gamma\gamma \rightarrow p\overline{p}$.
- Defining $W_{\gamma\gamma}$ as the two-photon invariant mass, the cross section for $\gamma\gamma \rightarrow p\overline{p}$ is a function of $W_{\gamma\gamma}$.
- Previous measurements for $\sigma_{\gamma\gamma\rightarrow p\overline{p}}(W_{\gamma\gamma})$ have exhibited a better agreement in scale with that predicted by the diquark model.
- However, the mechanism for hadron production based on QCD is not well understood for the full range of energy. Better statistics are expected in both lower and higher energies for the exploration from nonperturbative to perturbative region.

- Theoretical framework for $\sigma_{\gamma\gamma\to p\bar{p}}(W_{\gamma\gamma})$ developed by Brodsky and Lepage [Phys. Rev. D 22 (1980)2157], the dimensional counting rules, has given $\boxed{(d\sigma/dt)_{AB\to CD} \propto s^{2-n} f(t/s)}$ where n is the total number of constituents of the initial and final states.

  - **three-quark model** (Farrar et al.) [Nucl. Phys. B 259 (1985) 702] gives $n = 8$ and $\frac{d\sigma_{\gamma\gamma\to p\bar{p}}}{dt} \propto s^{-6}$



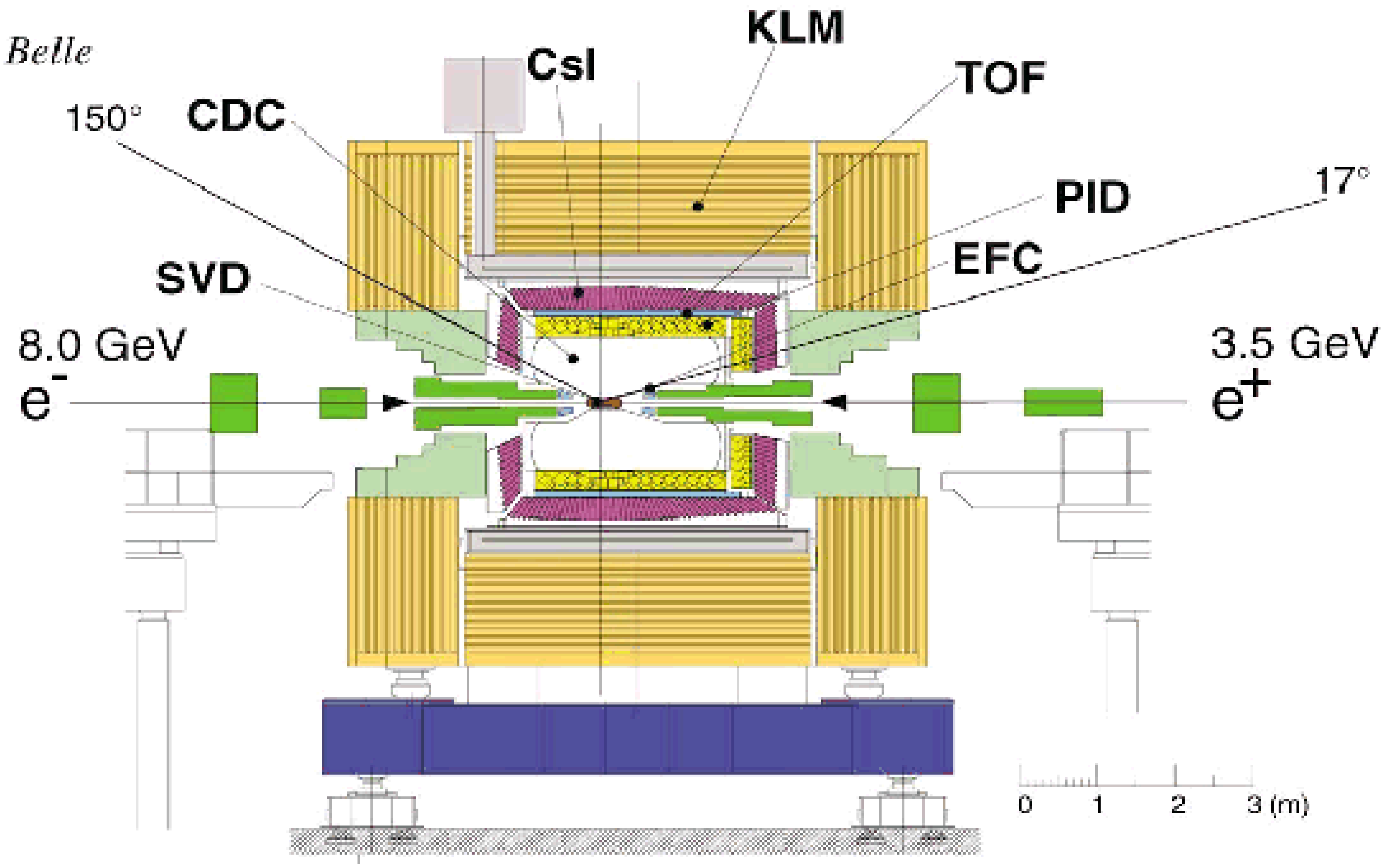
  - **diquark model** (Kroll et al.) [Phys. Lett. B 316 (1993) 546] gives $n = 6$ and $\frac{d\sigma_{\gamma\gamma\to p\bar{p}}}{dt} \propto s^{-4}|F|^2$,
    s^{-6} behavior is recovered with a diquark form factor of $F \to \frac{f(\theta)}{s}$



... At medium Q^2 a diquark acts as a quasi-elementary constituent bound by non-perturbative forces whereas at large Q^2 it resembles more and more two quarks kept collinear through the exchange of a hard gluon. ... With the diquarks, we have taken into account non-perturbative effects allowing us to apply this model at medium energies where the pure quark scheme fails. ...

(adapted from Anselmino et al. [Int. J. Mod. Phys. A 4 (1989) 5213])

2. Belle Detector



Detector	Type	Configuration	Performance
CDC	small cell drift chamber	$8.3 \leq r \leq 86.3\ cm$ $-77 \leq z \leq 160\ cm$ $17° \leq \theta \leq 150°$	$\sigma_{r\phi} = 130\ \mu m$ $\sigma_z = 200 \sim 1400\ \mu m$ $\sigma_{p_t}/p_t = 0.3\% \sqrt{p_t^2 + 1}$ $\sigma_{dE/dx} = 6\%$
ACC	silica aerogel	$17° \leq \theta \leq 127°$	K/π separation: $1.2 < p < 3.5\ GeV/c$
TOF	scintillator	$r = 120\ cm$, $3m$ long $34° \leq \theta \leq 120°$	$\sigma_t = 100\ ps$ K/π separation: up to $1.2\ GeV/c$
ECL	CsI	$17° \leq \theta \leq 150°$ $125 \leq r \leq 162\ cm$ (Barr.) $z = -102, +196\ cm$ (End.)	$\sigma_E/E = 1.3\%/\sqrt{E(GeV)}$ $\sigma_{pos} = 0.5\ cm/\sqrt{E(GeV)}$

3. Data and Monte Carlo Samples

- **Data:** **Low Multi. data corresponding to $L_{int.} = 88.96\ fb^{-1}$ taken at Belle**
- **MC samples:**

channel	$\gamma\gamma \to p\bar{p}$	$\gamma\gamma \to \pi^+\pi^-$	$\gamma\gamma \to \mu^+\mu^-$	$\gamma\gamma \to e^+e^-$
$N_{generated}$	4000000	8456711	6000000	6058800
$L_{int.}$	/	$\sim 3\ fb^{-1}$	$\sim 3\ fb^{-1}$	$\sim 3\ fb^{-1}$
$W_{\gamma\gamma}$ (GeV/c^2) range	$2.0 \sim 4.0$	$0.5 \sim 2.41$	$0.5 \sim 10.58$	$0.5 \sim 10.58$
$W_{\gamma\gamma}$ distribution	flat	model calculations [ref.]	model calculations [ref.]	model calculations [ref.]
$\cos\theta^*$ range	$-1 \sim +1$	$-1 \sim +1$	$-1 \sim +1$	$-1 \sim +1$
$\cos\theta^*$ distribution	flat	model calculations [ref.]	model calculations [ref.]	model calculations [ref.]

[ref.] V.M.Budnev et al., Phys. Rep. 15 (1974) 182.

- $\gamma\gamma \to K^+K^-$: Corresponding to each $W_{\gamma\gamma}$ bin of the $\gamma\gamma \to p\bar{p}$ sample, we are generating the same number of $\gamma\gamma \to K^+K^-$ events with that of $\gamma\gamma \to p\bar{p}$. The generation of a $\gamma\gamma \to K^+K^-$ sample with $N_{generated} = 4000000$ in total for $1.2 < W_{\gamma\gamma} < 3.7\ GeV/c^2$ is in process.

4. Event Selection

(1) two and only two tracks with opposite sign, each with $p_t > 0.4\ GeV/c$

(2) $p_t^{event} < 0.2\ GeV/c$

$$p_t^{event} \equiv |\vec{p}_{t,1} + \vec{p}_{t,2}|$$

(3) $E_{cal}/p < 0.9$ for the positive charged track

(4) $N_{ph.e.}^{ACC} < 2$ for both tracks

(5) $\chi_p^2(dE/dx) < 4$ for both tracks

$$\chi_p(dE/dx) \equiv \frac{(dE/dx)_{mea.} - (dE/dx)_{exp.}}{\sigma(dE/dx)}$$

(6) both tracks reach TOF counters

(7) $\chi_p^2(TOF) < 4$ for both tracks

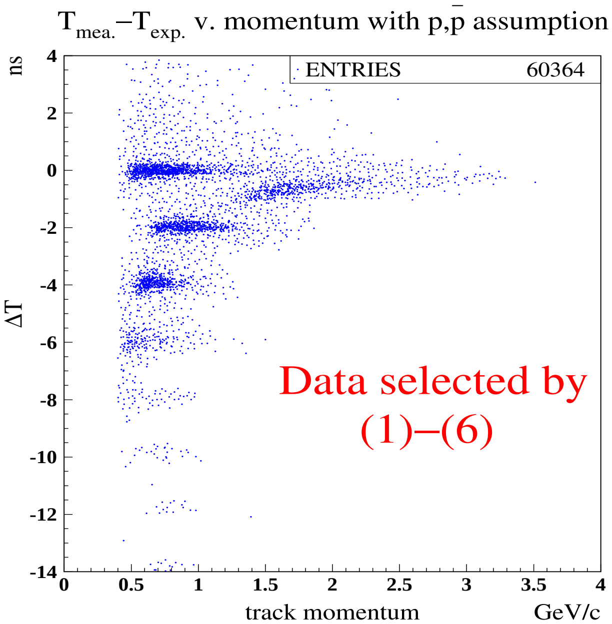
$$\chi_p(TOF) \equiv \frac{T_{mea.} - T_{exp.}}{\sigma(TOF)}$$

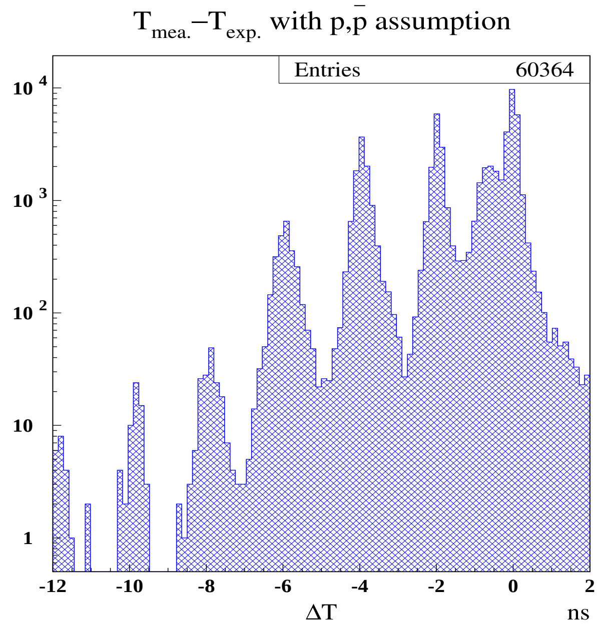
(8) $\lambda_p(\text{normalized likelihood}) > 0.98$ for both tracks

$$\lambda_p \equiv \frac{L_p}{L_p + L_K + L_\pi + L_\mu + L_e}$$

$$L_i \equiv e^{-\frac{1}{2}[\chi_i^2(dE/dx) + \chi_i^2(TOF)]}$$

- **Correction of $T_{mea.}$ due to mismatch in TOF for $\gamma\gamma \to p\overline{p}$**





$$\Longrightarrow \boxed{T^{cor.}_{mea.} \equiv T_{mea.} + \frac{n}{508.9\,M\mathrm{Hz}}}$$

(in order to minimize $\chi^2_p(TOF)$)

where **508.9 MHz** is

Beam Crossing Rate

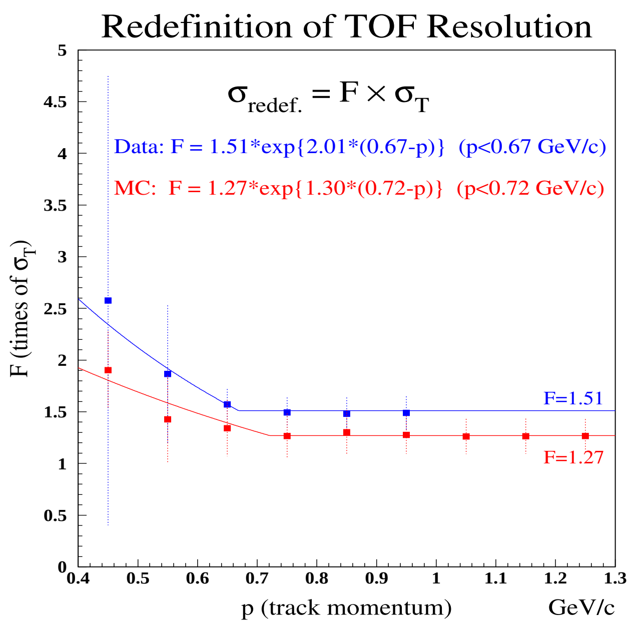
(RF Frequency)

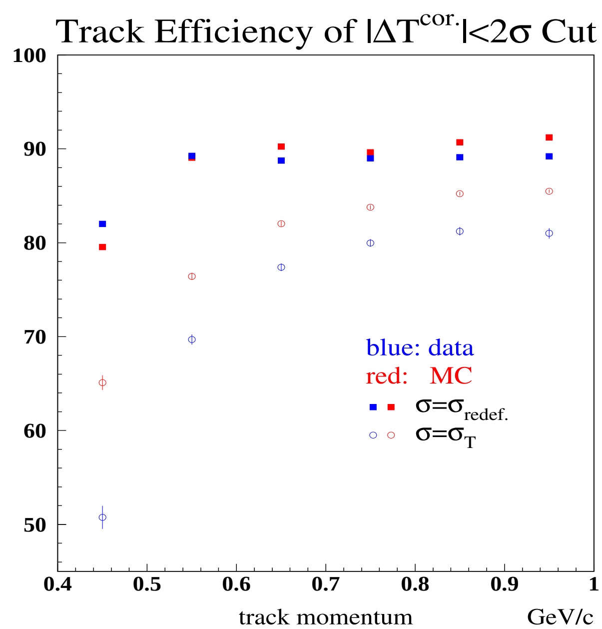
$n = 0,\ 1,\ 2,\ 3,\ \ldots$

$n_1 = n_2$ is required in condition (6) of event selection !

- **Redefinition of TOF resolution**

Since Belle $T0$-determination is optimized for typical hadron events where pions are dominant, $\sigma(TOF)$ of pions is assumed for most of the cases. However, for massive particles like $p, \overline{p}$ with $\beta < 0.8$, a much larger TOF resolution (relative to pions at the same momentum) is observed and it is β-dependent. We thus investigate $\chi_p(TOF)$ distributions, using Data and MC samples selected by conditions (1)-(6), separated in different momentum ranges.

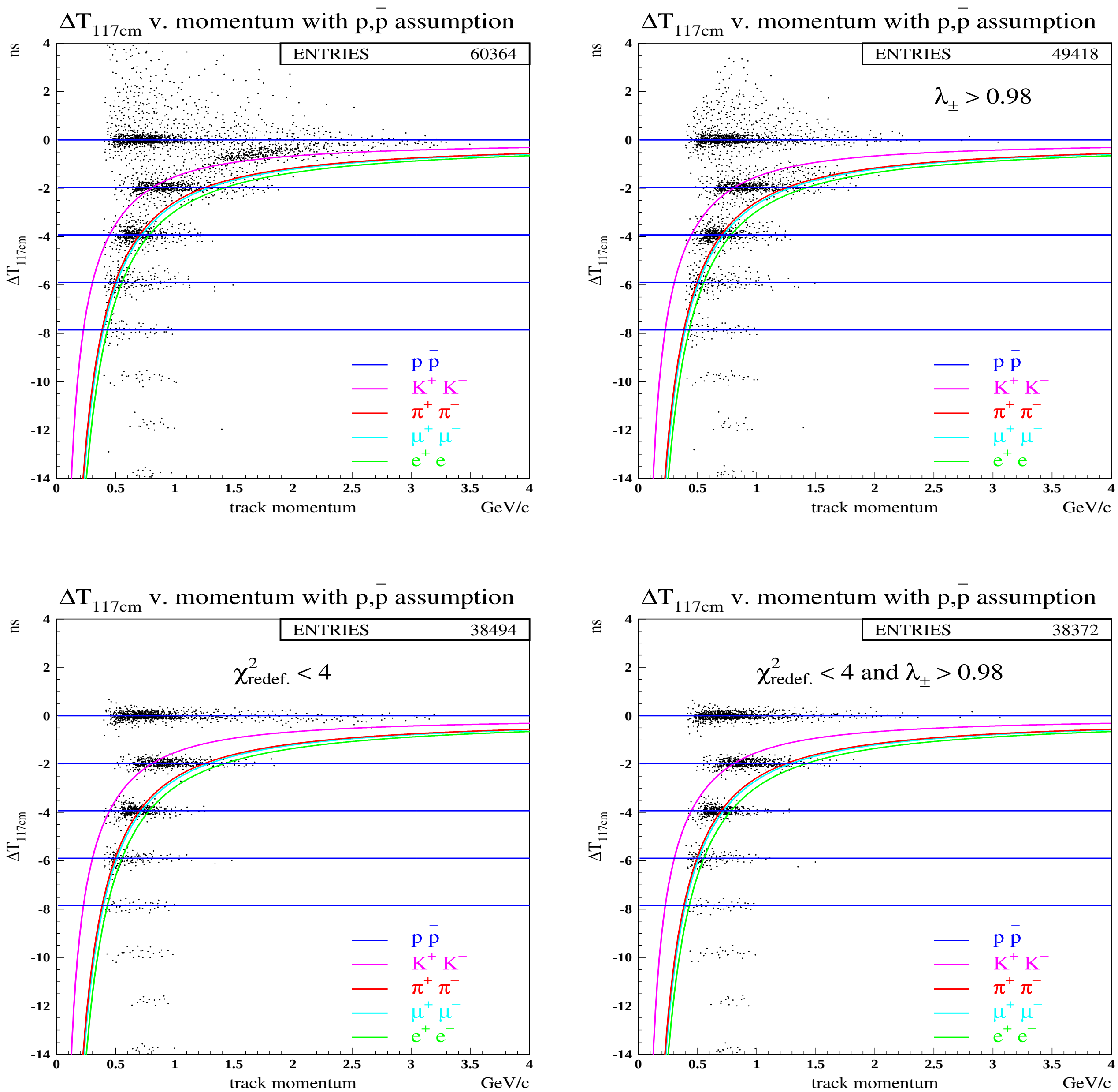




- $F \equiv$ resolution of $\chi_p(TOF)$ which is ideally equal to 1. However, F is larger than 1 in the realistic situation. TOF resolution is redefined as $\sigma_{redef.} = F \times \sigma(TOF)$.

- $\chi_p^2(TOF)$ is then replaced by $\chi^2_{redef.}$ in condition (7) of event selection, where $\chi_{redef.} \equiv \frac{T^{cor.}_{mea.} - T_{exp.}}{\sigma_{redef.}}$ with $p, \overline{p}$ assumption.

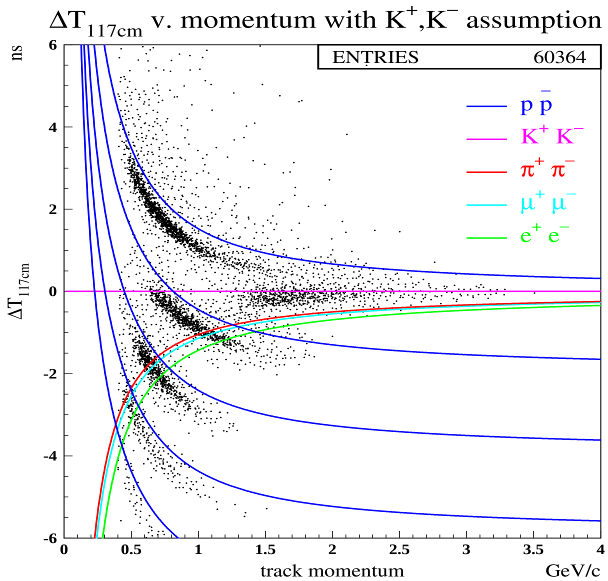
- $T_{exp.} = T_p$



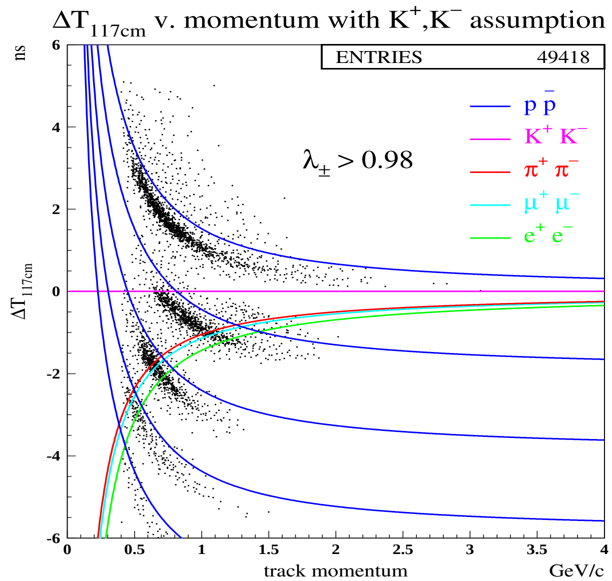
- $\Delta T_{117cm} \equiv (T_{mea.} - T_{exp.}) \times \frac{117cm}{l(\text{path length})}$ where 117 cm is corresponding to the radius of the inner wall of TOF

- colorful curves show the ideal formula of ΔT_{117cm} calculated for different particles: $T_{exp.} = T_p$ and $T_{mea.} = T_{K,\pi,\mu,e}$ with $T_i = \frac{m_i}{p\sqrt{1+\frac{p^2}{p^2+m_i^2}}} \times \frac{l}{c}$ for $i = p, K, \pi, \mu, e$

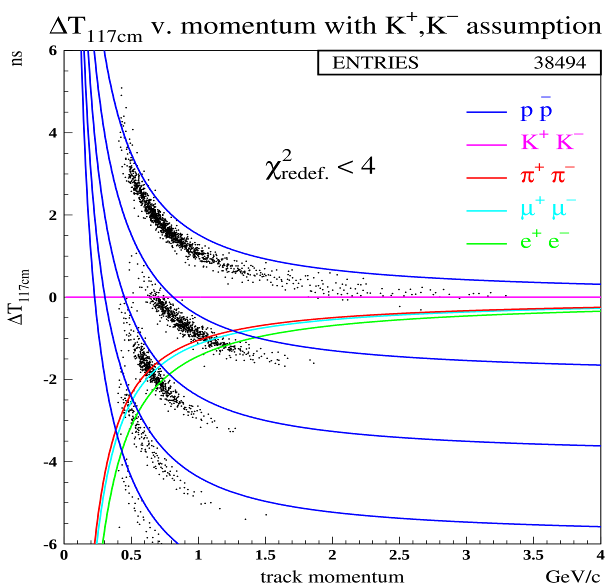
- $T_{exp.} = T_K$



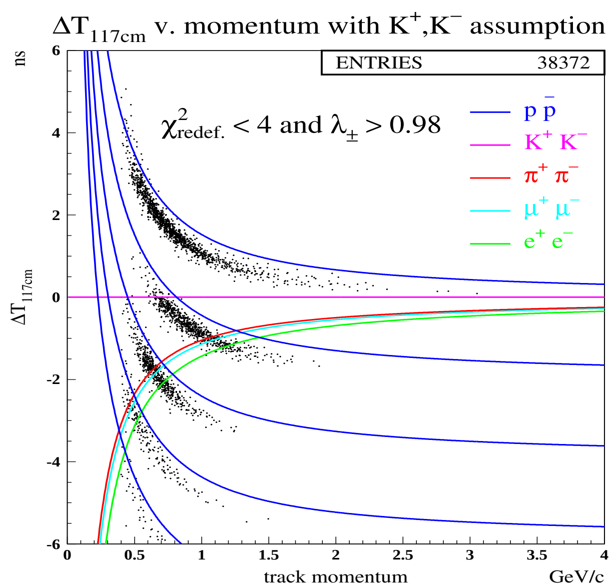
ΔT117cm v. momentum with K+,K− assumption
ENTRIES 60364
p p̄
K+ K−
π+ π−
μ+ μ−
e+ e−
ΔT117cm
ns
track momentum
GeV/c



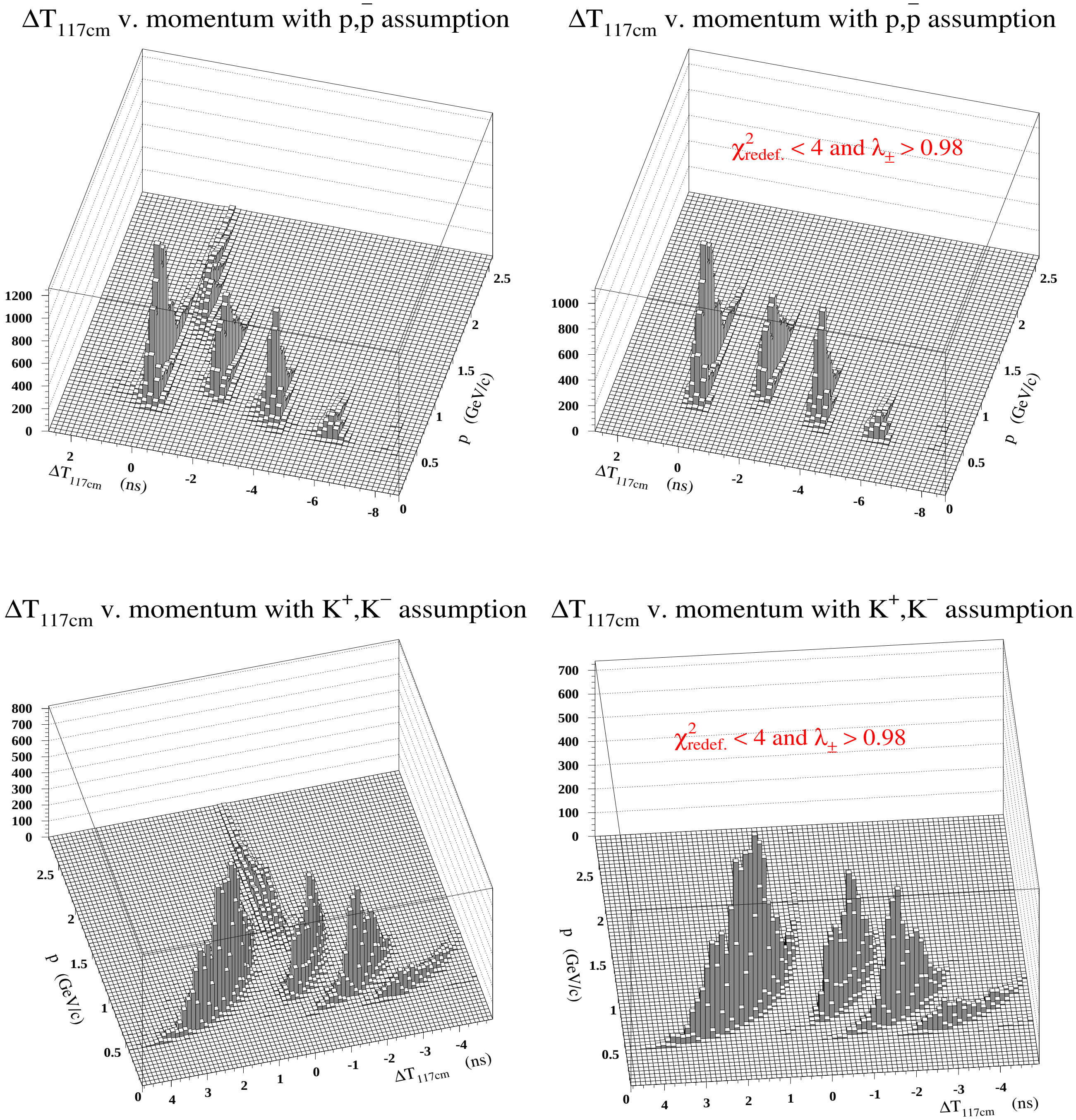
ΔT117cm v. momentum with K+,K− assumption
ENTRIES 49418
λ± > 0.98
p p̄
K+ K−
π+ π−
μ+ μ−
e+ e−
ΔT117cm
ns
track momentum
GeV/c

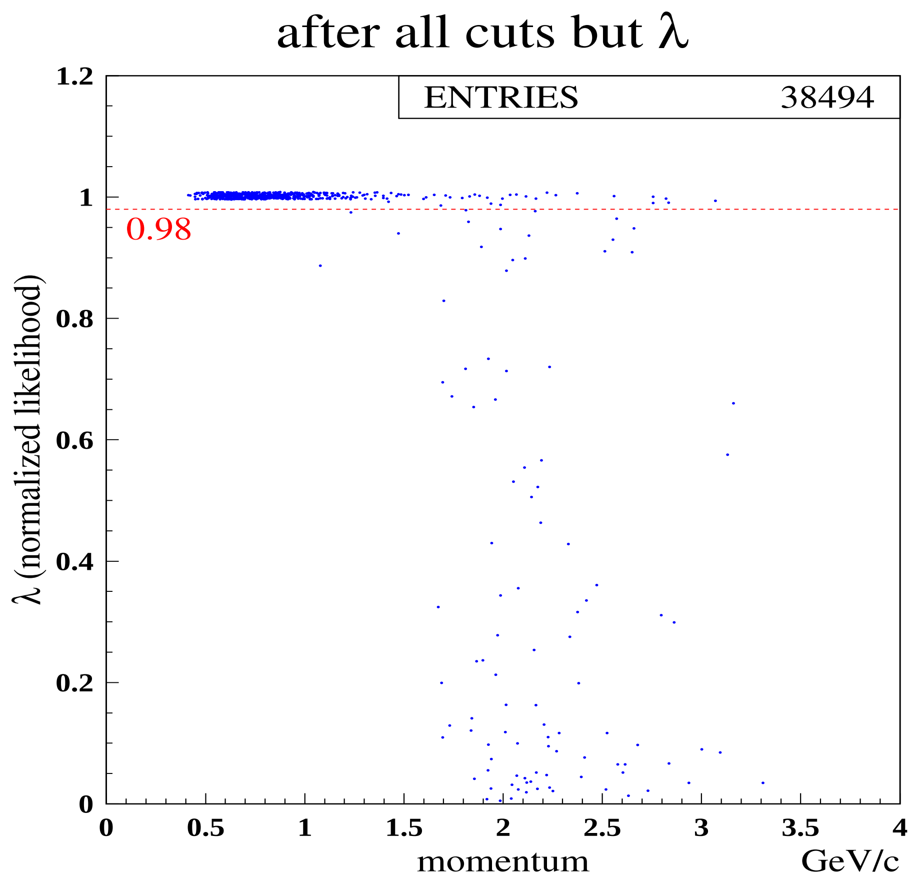


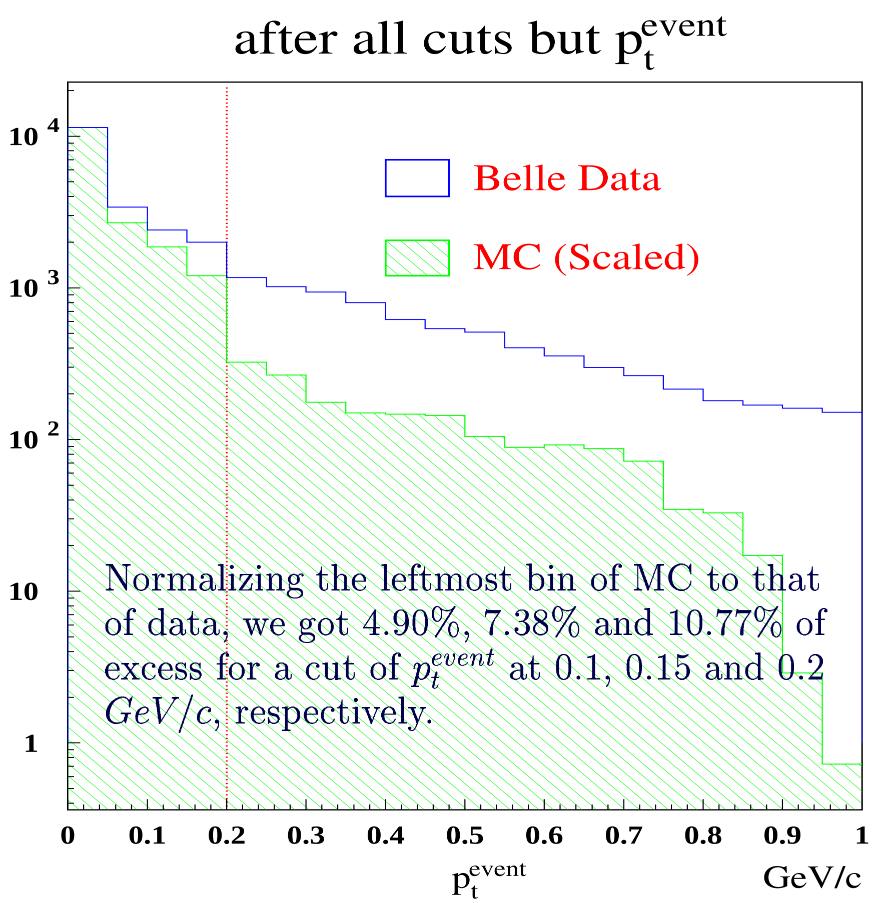
ΔT117cm v. momentum with K+,K− assumption
ENTRIES 38494
χ2redef. < 4
p p̄
K+ K−
π+ π−
μ+ μ−
e+ e−
ΔT117cm
ns
track momentum
GeV/c



ΔT117cm v. momentum with K+,K− assumption
ENTRIES 38372
χ2redef. < 4 and λ± > 0.98
p p̄
K+ K−
π+ π−
μ+ μ−
e+ e−
ΔT117cm
ns
track momentum
GeV/c

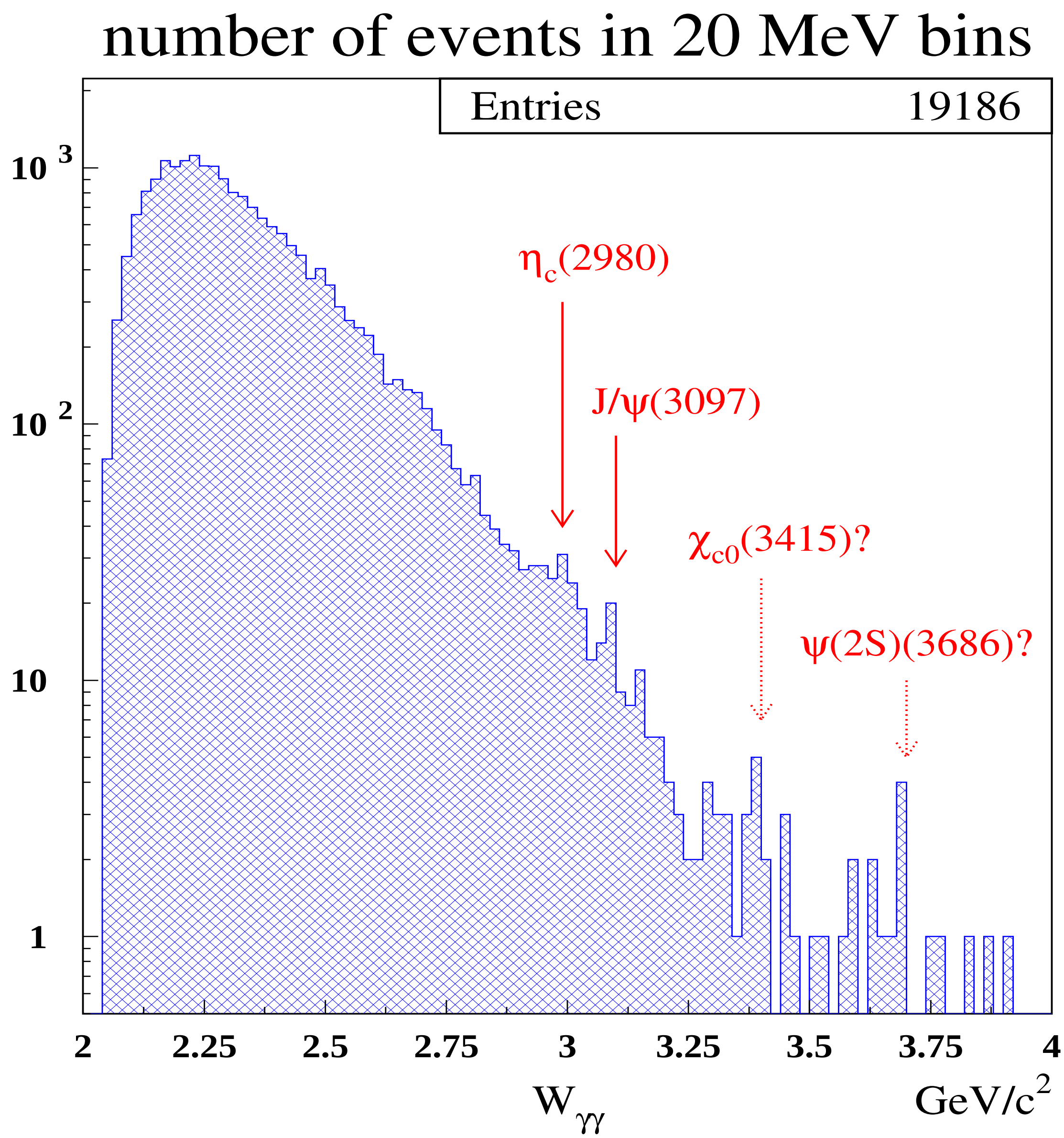

ΔT117cm v. momentum with p,p̄ assumption
ΔT117cm v. momentum with p,p̄ assumption
χ²redef. < 4 and λ± > 0.98
ΔT117cm v. momentum with K+,K− assumption
ΔT117cm v. momentum with K+,K− assumption
χ²redef. < 4 and λ± > 0.98
ΔT117cm (ns)
p (GeV/c)


after all cuts but λ
ENTRIES 38494
0.98
λ (normalized likelihood)
1.2
1
0.8
0.6
0.4
0.2
0
0 0.5 1 1.5 2 2.5 3 3.5 4
momentum
GeV/c

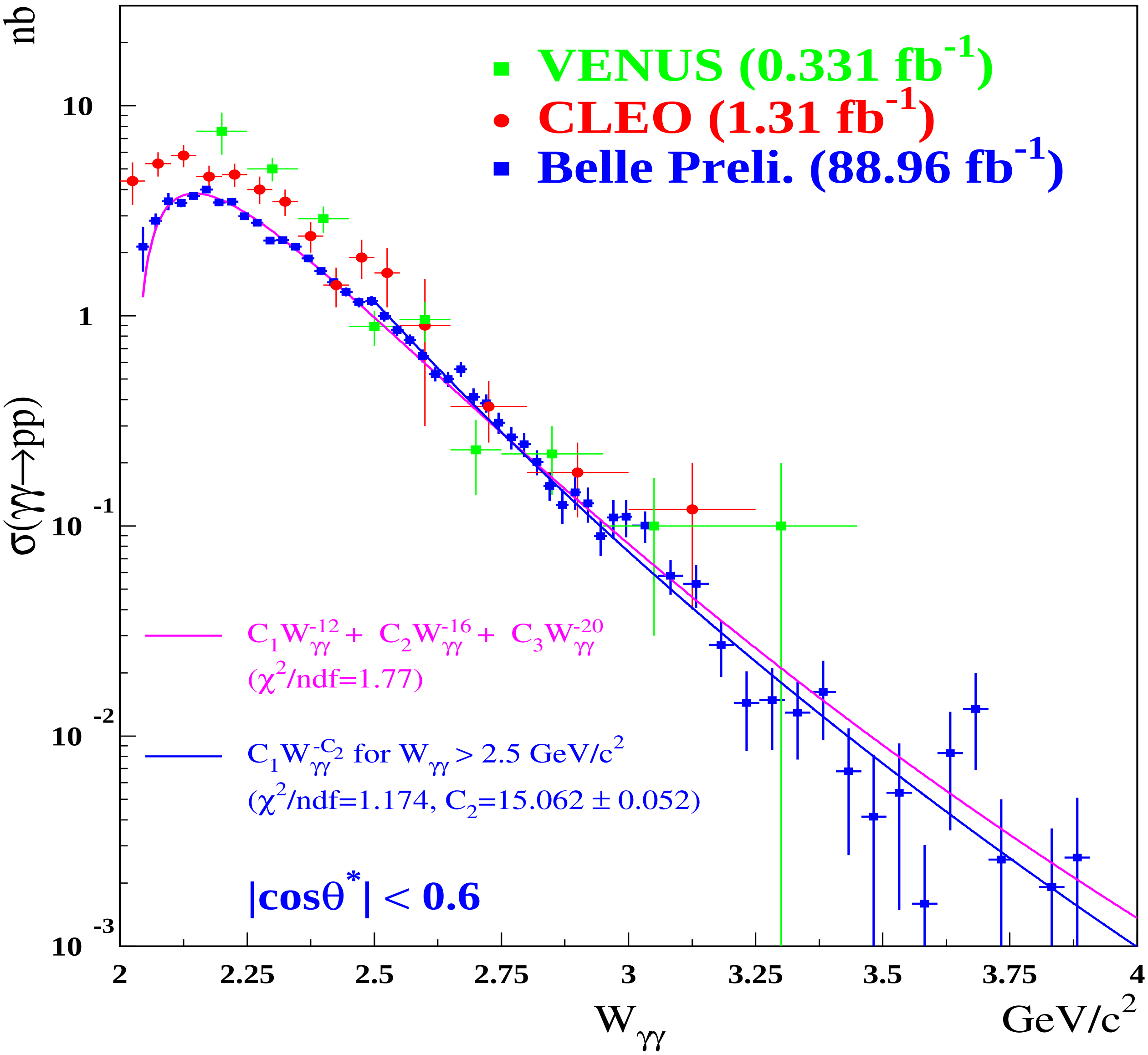

after all cuts but p_t^{event}
Belle Data
MC (Scaled)
Normalizing the leftmost bin of MC to that of data, we got 4.90%, 7.38% and 10.77% of excess for a cut of p_t^{event} at 0.1, 0.15 and 0.2 GeV/c, respectively.
10^4
10^3
10^2
10
1
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
p_t^{event}
GeV/c

- **Number of exclusive $\gamma\gamma \to p\bar{p}$ events selected from the 88.96 fb^{-1} data**

  - 19186 events are selected.
  - Charmonium states appear in the $W_{\gamma\gamma}$ spectrum (spin 0: *two-photon*; spin 1: *quasi-compton scattering*).
  - From MC studies, none of events from $\gamma\gamma \to \pi^+\pi^-$, $\mu^+\mu^-$, e^+e^- samples survives. The contamination from them ($< 0.5\%$) is thus negligible in our data.



5. Measurement of Cross Sections for $\gamma\gamma \to p\bar{p}$

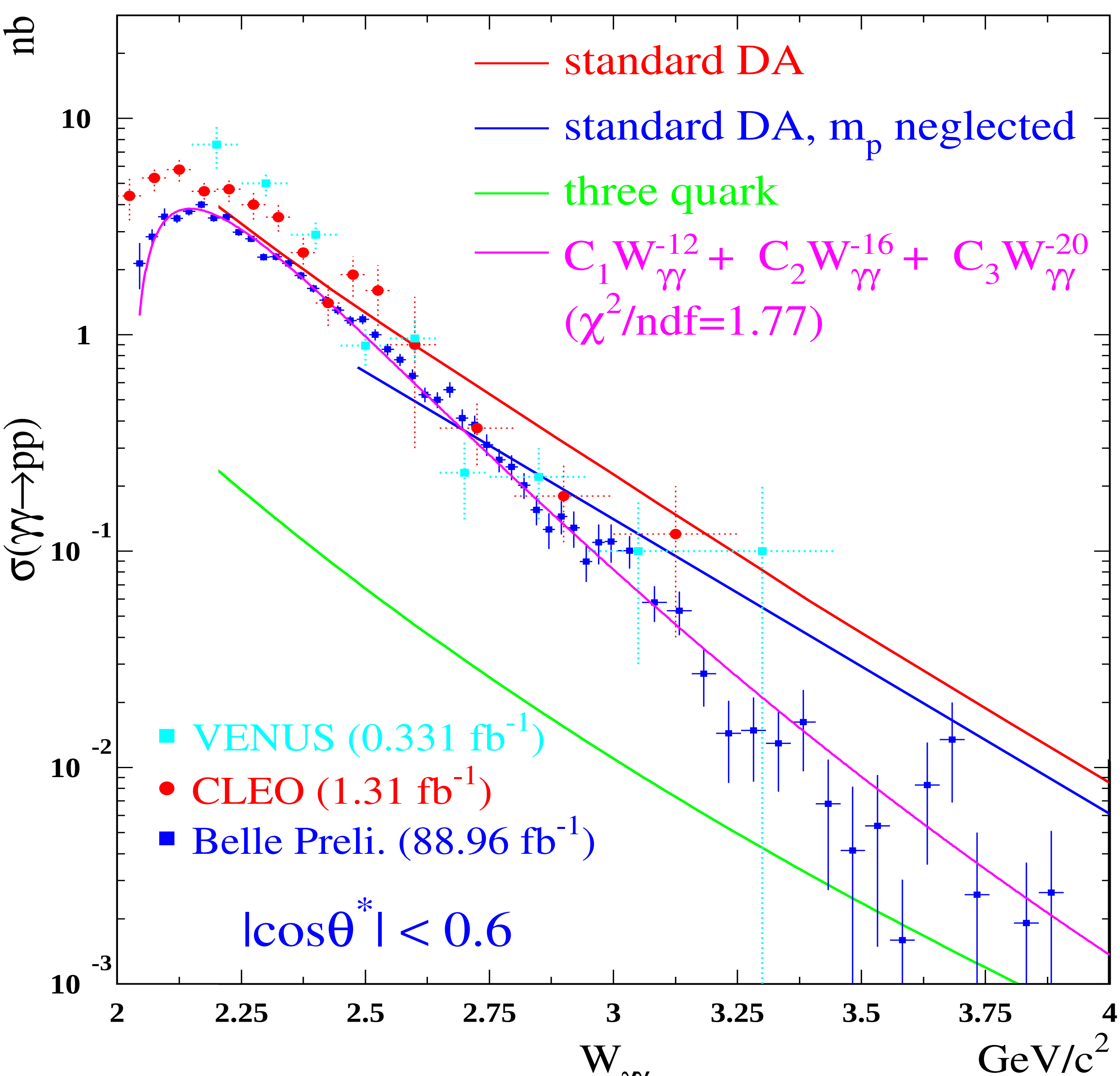


$$\frac{N_{bin}}{\mathcal{E}_{bin}} = L_{int.} \cdot \frac{d\mathcal{L}_{\gamma\gamma}}{dW_{\gamma\gamma}} \cdot \boxed{\frac{d\sigma_{\gamma\gamma\to p\bar{p}}}{d\cos\theta^*}} \cdot \Delta\cos\theta^* \cdot \Delta W_{\gamma\gamma}$$

$$\sigma_{\gamma\gamma\to p\bar{p}}(W_{\gamma\gamma}) = \sum_{|\cos\theta^*|<0.6} \frac{d\sigma_{\gamma\gamma\to p\bar{p}}}{d\cos\theta^*} \cdot \Delta\cos\theta^*$$

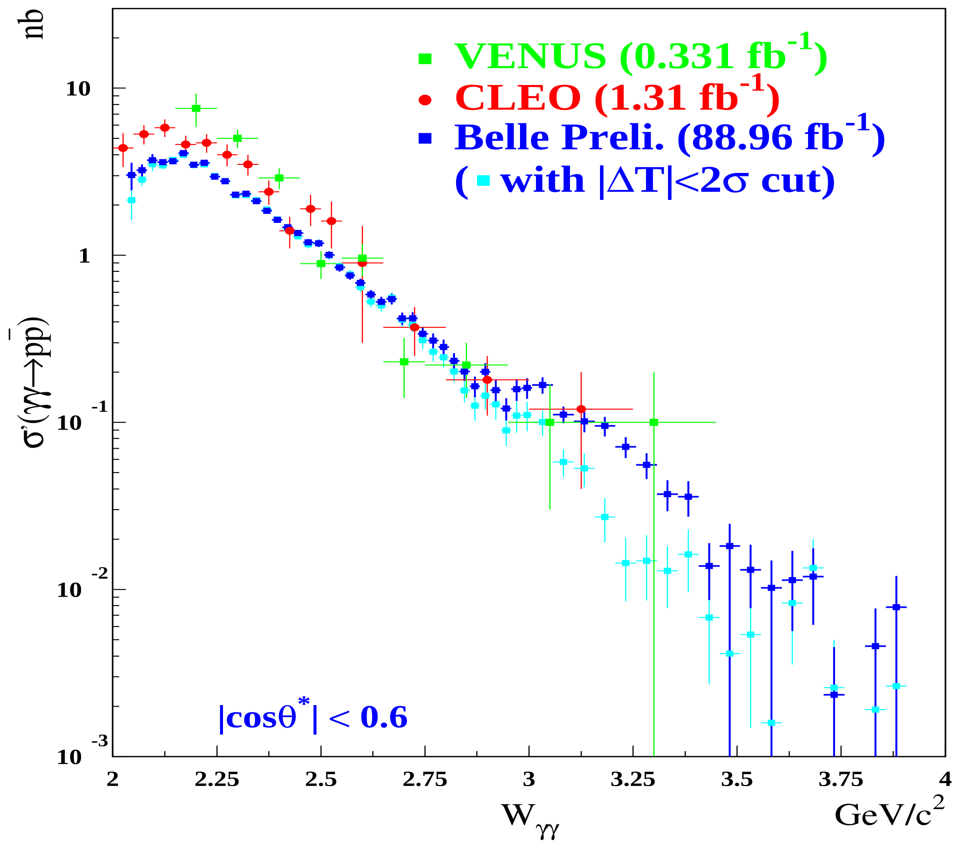
- $\Delta\cos\theta^* = 0.1$, $\Delta W_{\gamma\gamma} = 0.25$ or $0.5\ GeV/c^2$
- $\frac{d\mathcal{L}_{\gamma\gamma}}{dW_{\gamma\gamma}}$: ***Luminosity Function*** at each $W_{\gamma\gamma}$ bin

† only statistical errors (including MC statistics for Belle data) are shown

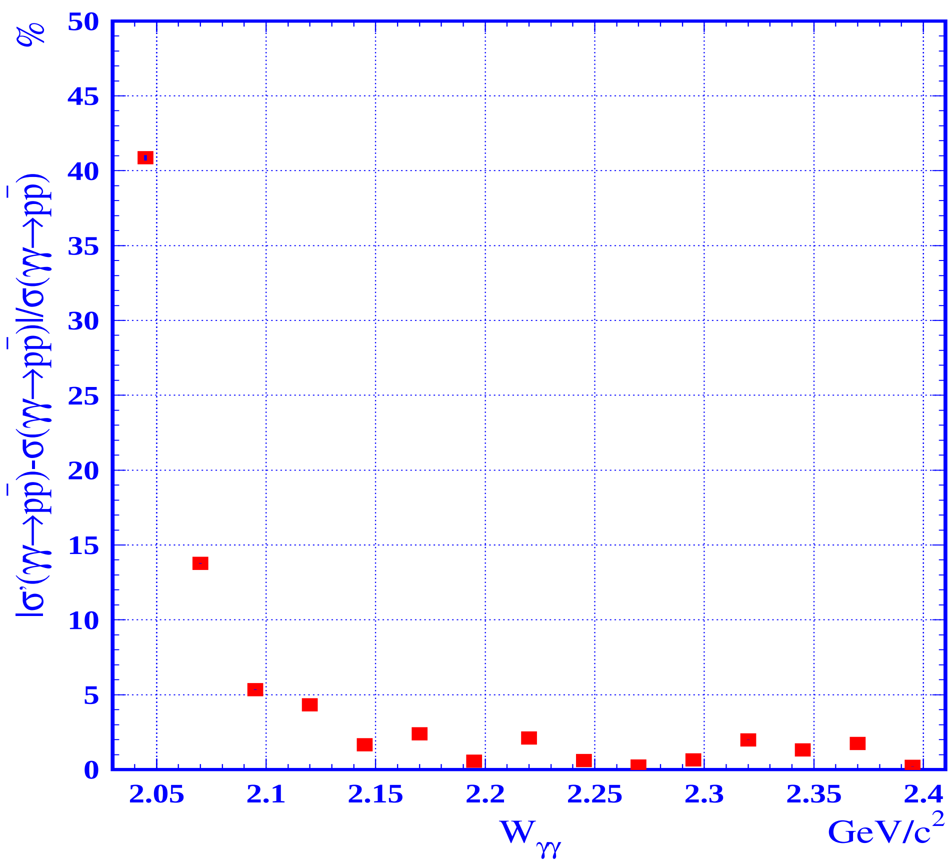


nb
10
1
10^{-1}
10^{-2}
10^{-3}
$\sigma(\gamma\gamma\rightarrow p\bar{p})$
2
2.25
2.5
2.75
3
3.25
3.5
3.75
4
$W_{\gamma\gamma}$
GeV/c^2
standard DA
standard DA, m_p neglected
three quark
$C_1W_{\gamma\gamma}^{-12} + C_2W_{\gamma\gamma}^{-16} + C_3W_{\gamma\gamma}^{-20}$
(χ^2/ndf=1.77)
VENUS (0.331 fb^{-1})
CLEO (1.31 fb^{-1})
Belle Preli. (88.96 fb^{-1})
$|\cos\theta^*| < 0.6$

- If condition (7) is not applied (namely, using conditions (1)-(6) and (8): $\lambda_p > 0.98$), the measured $\sigma'_{\gamma\gamma\to p\bar{p}}(W_{\gamma\gamma})$ is obtained as follows:



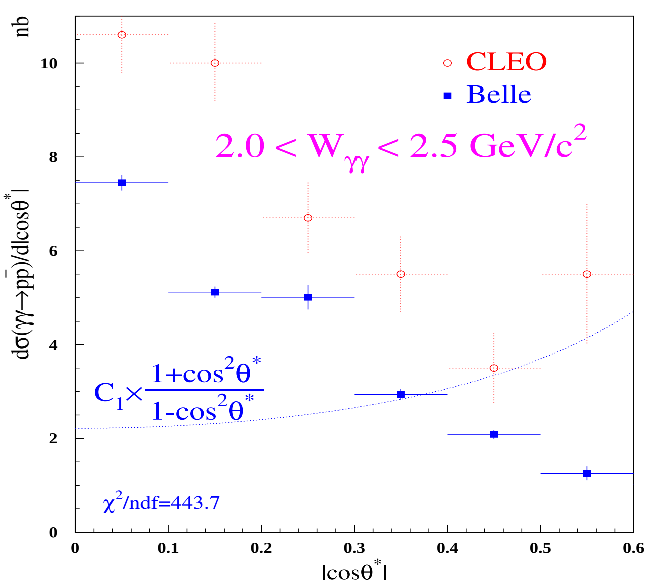
Systematic Error at Low Energy due to |ΔT|<2σ Cut

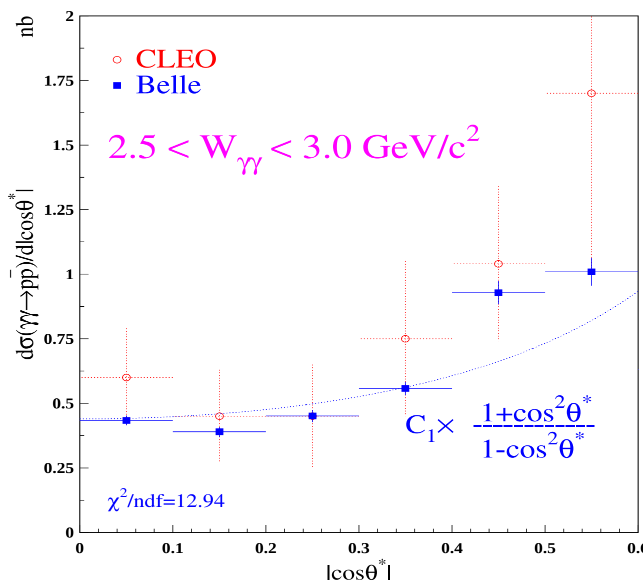


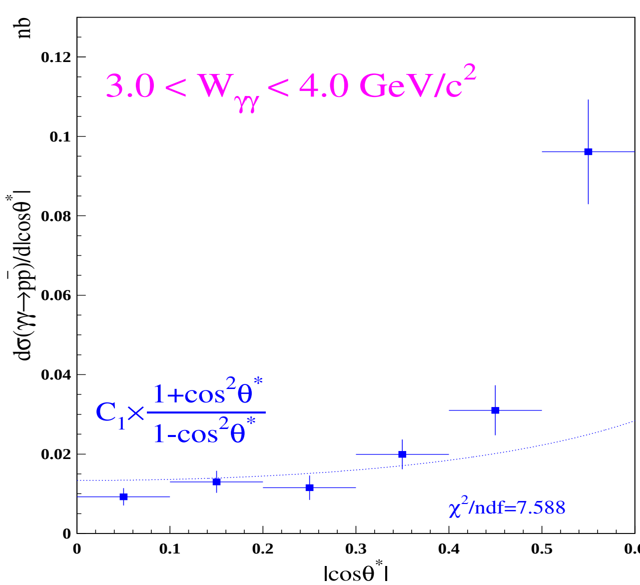
6. Differential Cross Sections in $|\cos\theta^*|$

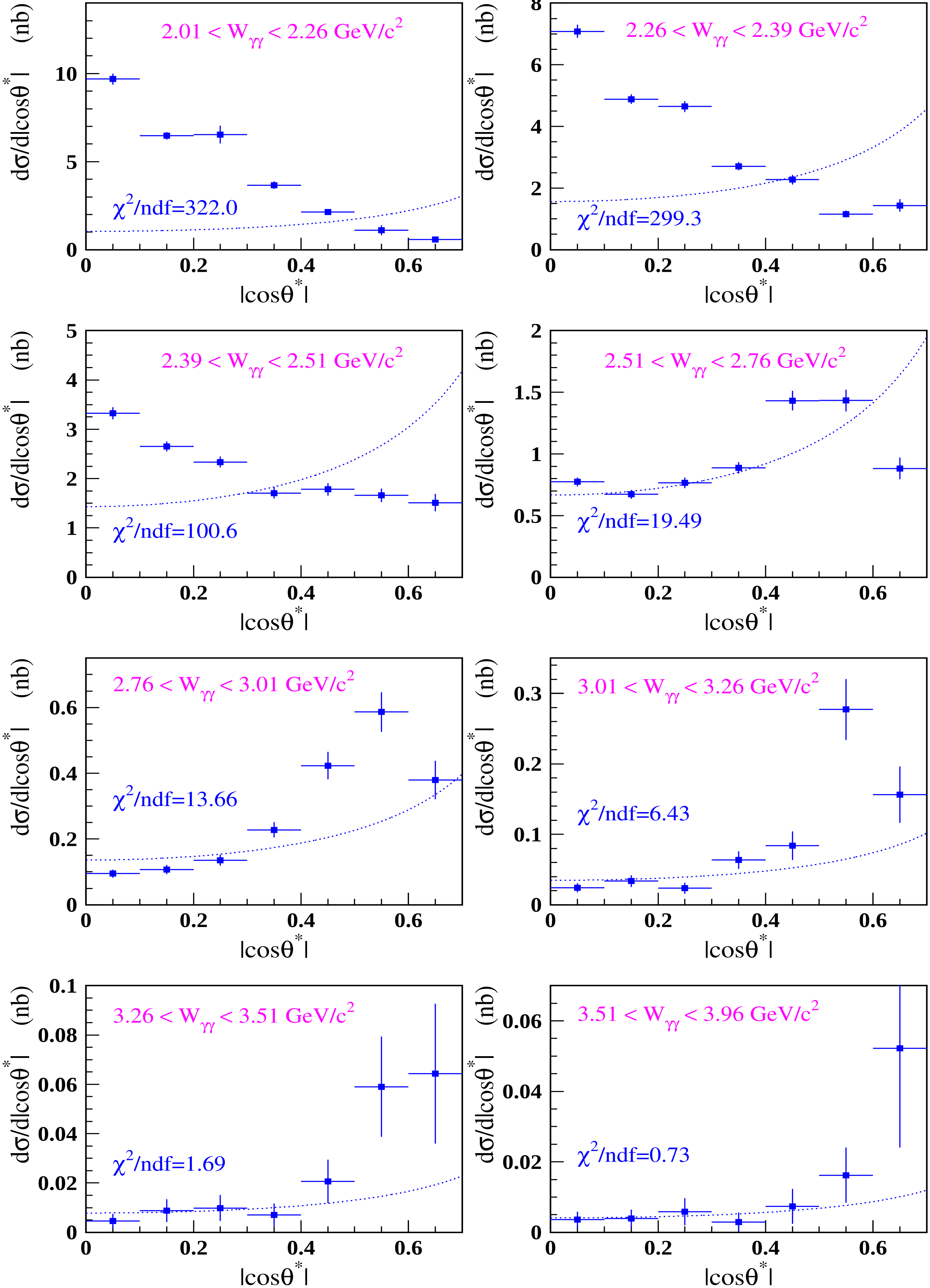
- Due to statistics, the differential cross sections are averaged in each $W_{\gamma\gamma}$ range $\left[\frac{d\sigma_{\gamma\gamma\to p\bar{p}}}{d\cos\theta^*}\right]_{average} \equiv \frac{\sum\left(\frac{d\sigma_{\gamma\gamma\to p\bar{p}}}{d\cos\theta^*}\cdot\Delta W_{\gamma\gamma}\right)}{\sum \Delta W_{\gamma\gamma}}$, respectively.

- The differential cross sections as a function of $\cos\theta^*$ are fitted with the curve $\frac{d\sigma}{d\Omega} \propto \frac{1+\cos^2\theta^*}{1-\cos^2\theta^*}$ which is referred as **point-like proton** prediction calculated by simple QED rules (Budnev et al.) [Phys. Rep. 15 (1974) 182], neglecting the proton mass and taking into account only scalar diquarks, so that $q, \bar{q}$ and hence $p, \bar{p}$ have to be in opposite helicity states (Anselmino et al.) [Int. J. Mod. Phys. A 4 (1989) 5213]. This is the same result as in the **pure quark** picture (Farrar et al.) [Nucl. Phys. B 259 (1985) 702].









- fitted with $C_1 \times \frac{1+\cos^2\theta^*}{1-\cos^2\theta^*}$ shown by blue curves

7. Summary

19186 $\gamma\gamma \to p\bar{p}$ candidates in total are selected from the $\mathbf{88.96}\ fb^{-1}$ Belle data

- $\sigma_{\gamma\gamma\to p\bar{p}}(W_{\gamma\gamma})$ **from 2 to 4 GeV/c^2**
  - falls as $W_{\gamma\gamma}^{-15}$ for $W_{\gamma\gamma} > 2.5\ GeV/c^2$
  - different from $W_{\gamma\gamma}^{-10}$ (dimensional counting rules)
  - **steeper fall** could imply **nonperturbative** processes at lower energy
- $\frac{d\sigma_{\gamma\gamma\to p\bar{p}}}{d\cos\theta^*}$ **in** $|\cos\theta^*|$ **up to** $|\cos\theta^*| = 0.7$
  - the **higher** the $W_{\gamma\gamma}$, the **better** the **agreement** of $|\cos\theta^*|$ distribution with **pQCD** predictions ($\sim \frac{1+\cos^2\theta^*}{1-\cos^2\theta^*}$)
  - for $2.5 < W_{\gamma\gamma} < 3\ GeV/c^2$:
    much **inconsistency** implies that **pQCD** is **incomplete**
  - for $W_{\gamma\gamma} < 2.5\ GeV/c^2$:
    the $|\cos\theta^*|$ distribution exhibits a completely different trend where **pQCD** predictions **fail**