Study of ππ production in two-photon collisions at Belle

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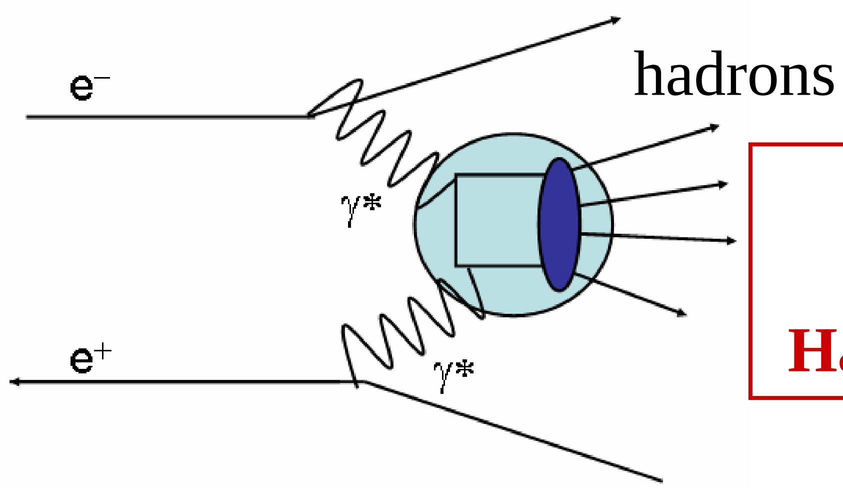
on behalf of **The Belle Collaboration**

Photon2007, 9 July, 2007, Paris

Motivation of two-photon physics



Resonance formation
or
Hard scattering with a quark line

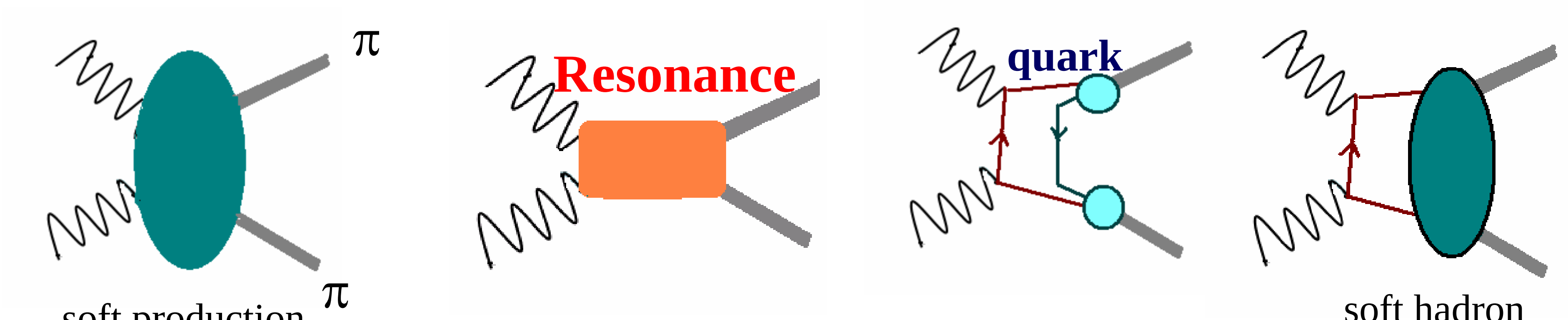
Hadron production from two quasi-real photons
($|q^2|<0.001\text{GeV}^2$, with no-tag condition)

Exclusive processes with $W_{\gamma\gamma}$=0.6 - 4.5 GeV at KEKB/Belle

Wide energy region --- Various physics aspects
can be studied simultaneously.

Light-quark resonances, Charmonia
Perturbative /Non-perturbative QCD,
Hadron production mechanism

General physics in $\gamma\gamma \rightarrow \pi^+\pi^-/\pi^0\pi^0$ final states



soft production of mesons

soft hadron exchange

$\pi^+\pi^-$ and $\pi^0\pi^0$:

Physics is almost the same, but gives independent information

Electromagnetic production as mesons: $\sigma(\pi^0\pi^0) \ll \sigma(\pi^+\pi^-)$

Resonances (I=0, $J^{PC}=0^{++}$) decaying via strong interaction:

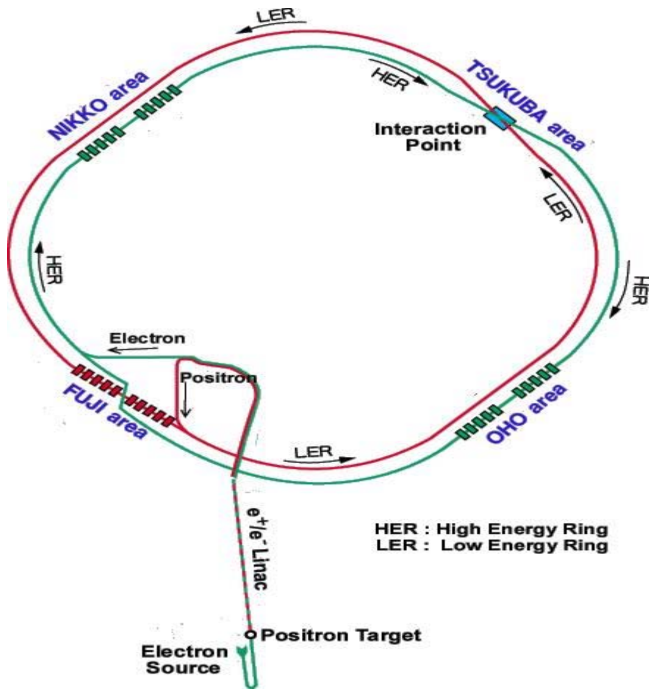
$$\sigma(\pi^0\pi^0):\sigma(\pi^+\pi^-) = 1:2$$

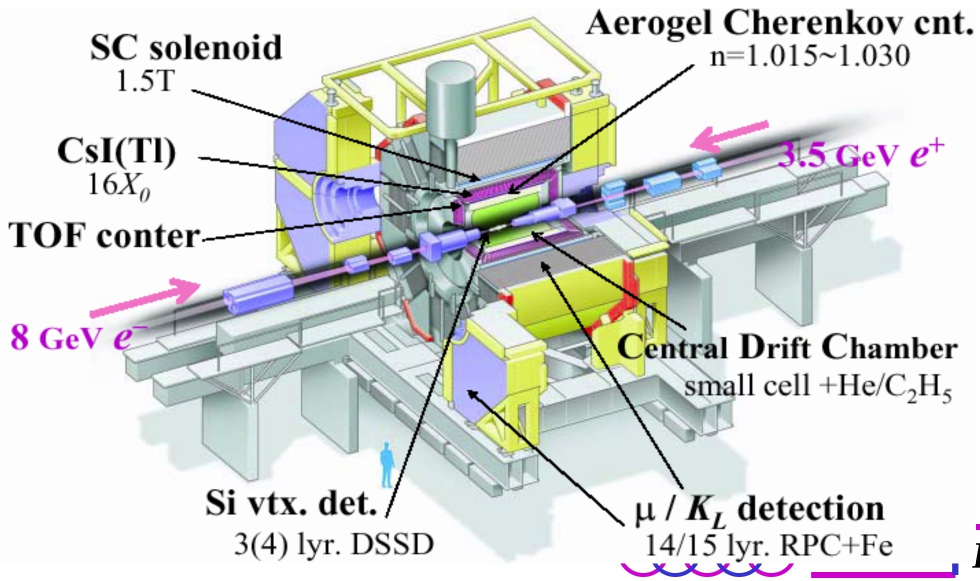
Test of QCD: $\sigma(\pi^0\pi^0)/\sigma(\pi^+\pi^-)$: ~0.03 (LO) – 0.5 (“handbag”)

c.m.-energy (W) and angular dependences must also be examined.

KEKB Accelerator and Belle Detector

- Asymmetric $e^- e^+$ collider
  8 GeV e- (HER) x 3.5 GeV e+ (LER)
  $\sqrt{s}$=10.58 GeV ⇔ $\Upsilon(4S)$
  Beam crossing angle: 22mrad
- Continuous injection
- Luminosity
  L_{max}=1.71x10^{34} cm^{-2}s^{-1}
  $\int$ Ldt ~ 710 fb^{-1}





High momentum/energy resolutions
CDC+Solenoid, CsI
Vertex measurement – Si strips
Particle identification
TOF, Si-aerogel, CDC-dE/dx,
RPC for K_L/muon

Results of $\gamma\gamma \rightarrow \pi^+\pi^-$

Belle Collaboration

W = 0.8 – 1.5 GeV Phys. Rev. D **75**, 051101(R) (2007)
arXiv:0704.3538[hep-ex],
to appear in J. Phys. Soc. Jpn. (2007)

W = 2.4 – 4.1 GeV Phys. Lett. B **615**, 39 (2005)

$f_0(980)$ in $\gamma\gamma \to \pi^+\pi^-$

$f_0(980)$ 85.9fb^{-1}

– is an ordinary $q\bar{q}$ meson?

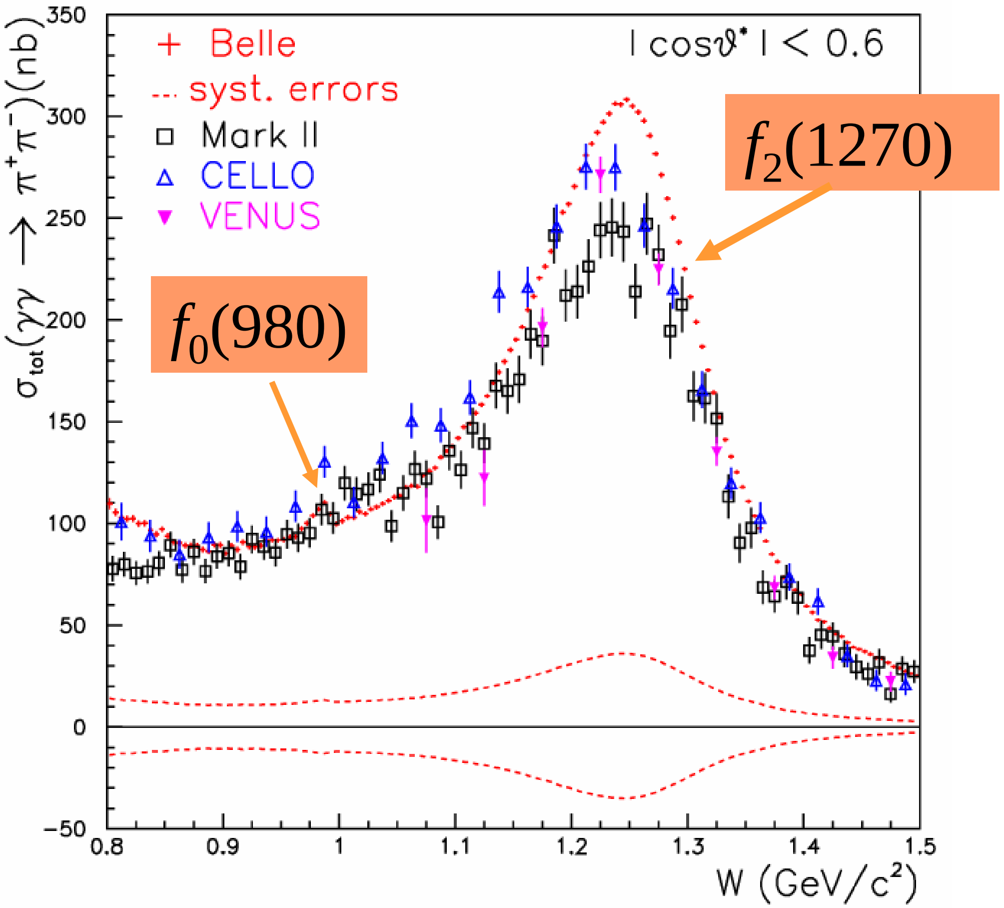
- an exotic state?
- some special theory needed?

Its two-photon coupling is a crucial key.

Prediction of $\Gamma_{\gamma\gamma}$:

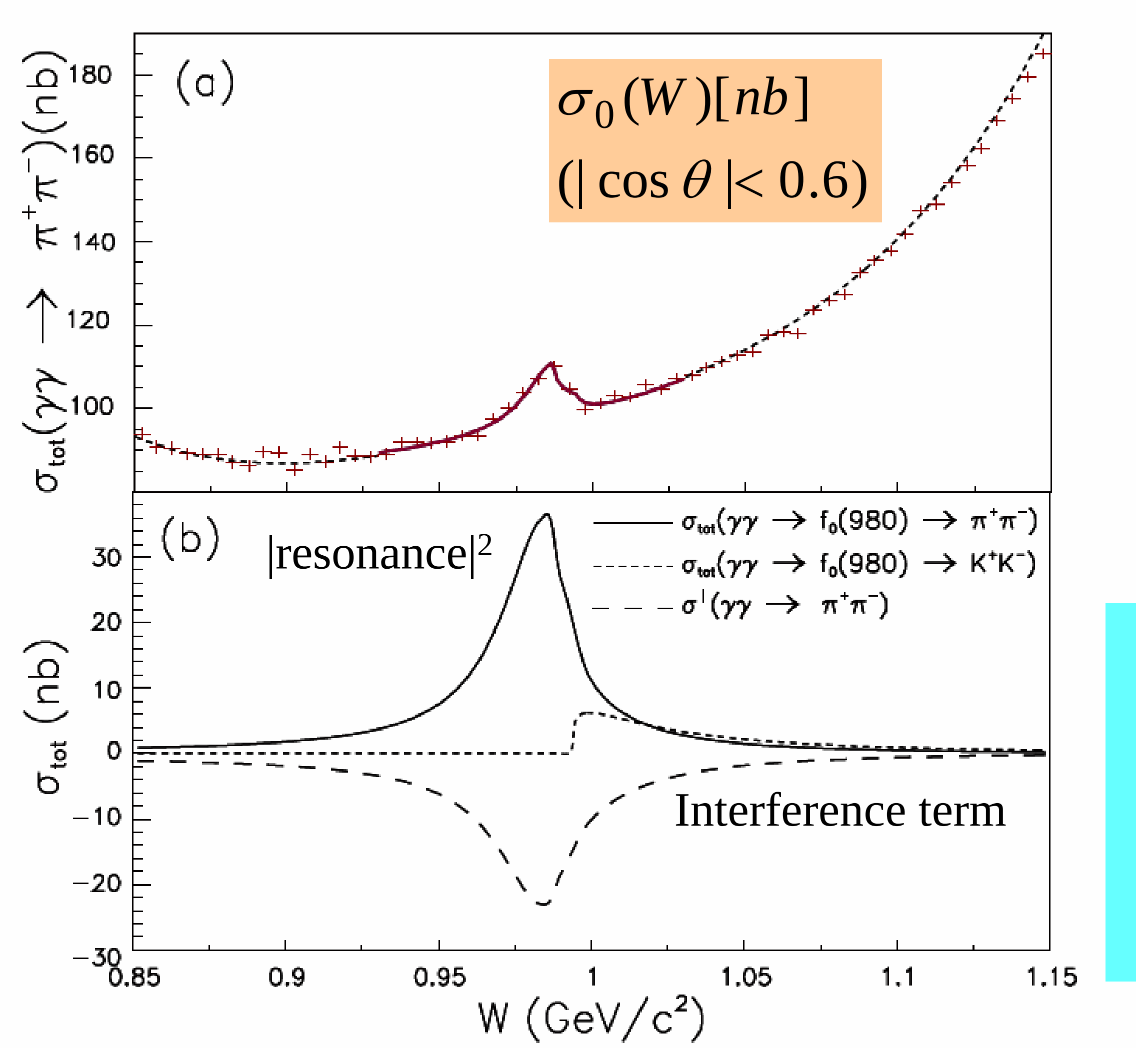
$u\bar{u}$, $d\bar{d}$	--- 1.3 – 1.8 keV
$s\bar{s}$	--- 0.3 – 0.5 keV
$K\bar{K}$ molecule	--- 0.2 – 0.6 keV

π/μ separation:
by comparing energy deposit in the CsI calorimeter between data and MC



$f_0(980)$ appears as a small but statistically significant peak.

Fit to the $f_0(980)$ line shape



$f_0(980) \to \pi^+\pi^-$

$M =$	$985.6^{+1.2+1.1}_{-1.5-1.6}$	**MeV/c²**
$\Gamma_{\pi^+\pi^-} =$	$34.2^{+13.9+8.8}_{-11.8-2.5}$	**MeV**
$\Gamma_{\gamma\gamma} =$	$205^{+95+147}_{-83-117}$	**eV**

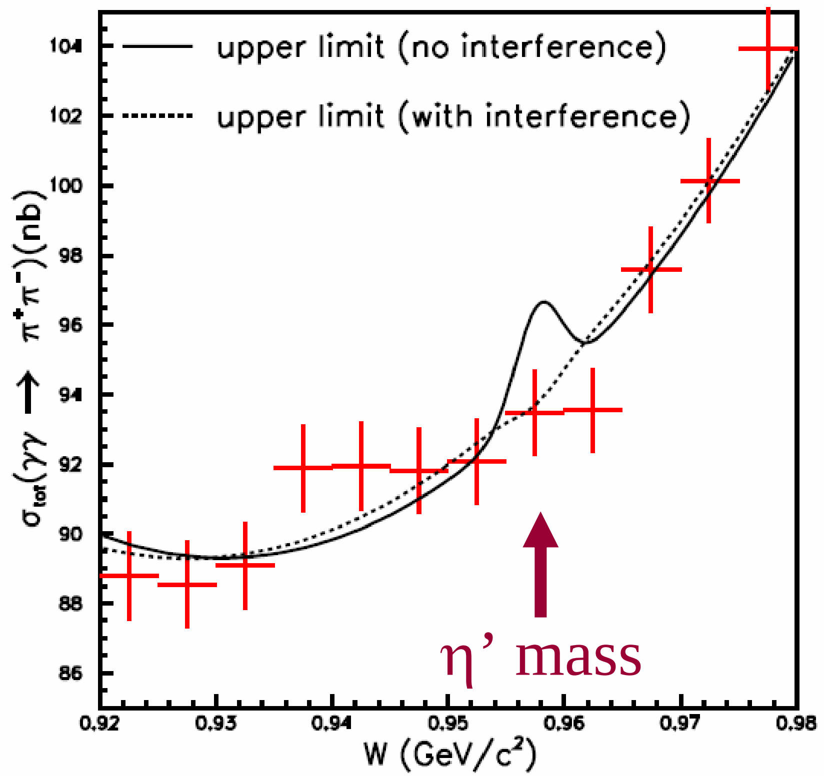
New upper limit for *Br* ($\eta' \to \pi^+\pi^-$)

No $\eta' \to \pi^+\pi^-$ enhancement is seen near 958MeV/c^2

This is a $\not{P}$ and $\not{CP}$ mode;

previous upper limit:

Br ($\eta' \to \pi^+\pi^-$) < 0.02 (HBC (1969))



New upper limit for

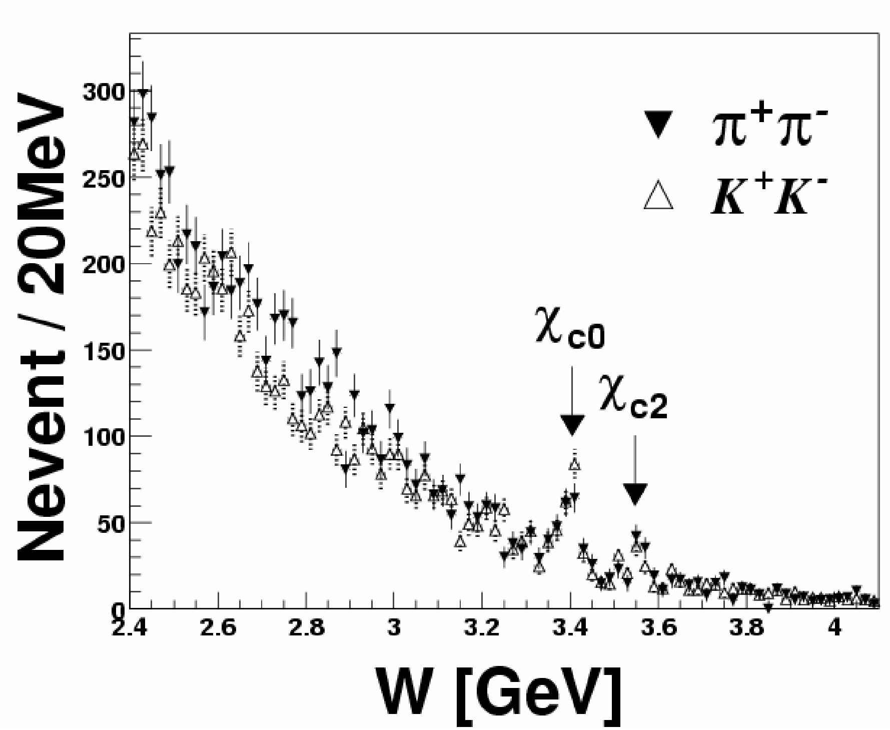
$Br(\eta' \to \pi^+\pi^-) < 2.8 \times 10^{-3}$

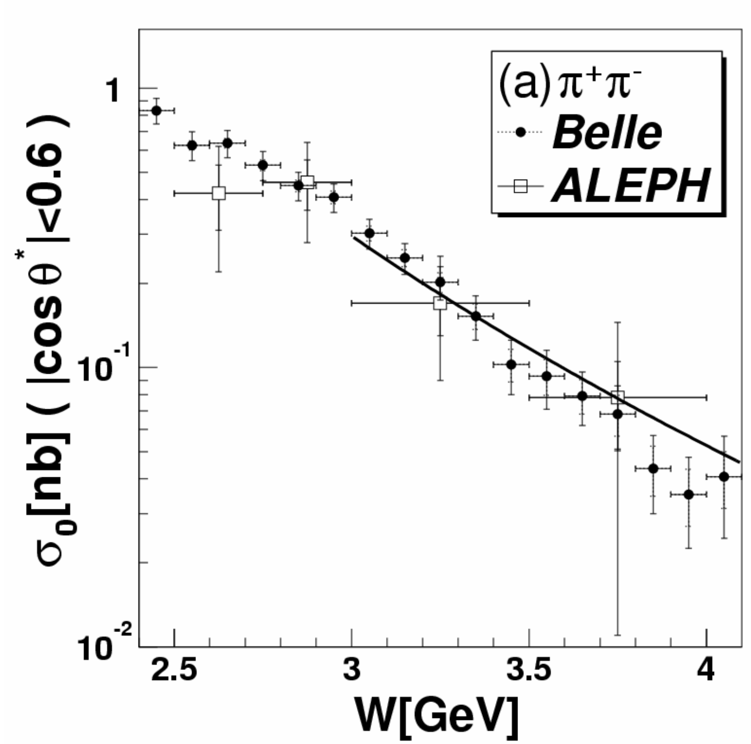
(interference with the non-resonant process allowed)

$< 3.3 \times 10^{-4}$ (no interference)

$\pi^+\pi^-$ measurements at high energies

PLB 615, 39 (2005)





Two-photon measurements of $\Gamma_{\gamma\gamma}(\chi_{cJ})Br$ (eV)

$\Gamma_{\gamma\gamma}Br(\chi_{c0}\to\pi^+\pi^-)$ 15.1 ± 2.1 ± 2.3 $\Gamma_{\gamma\gamma}Br(\chi_{c0}\to K^+K^-)$ 14.3 ± 1.6 ± 2.3

$\Gamma_{\gamma\gamma}Br(\chi_{c2}\to\pi^+\pi^-)$ 0.76 ± 0.14 ± 0.11 $\Gamma_{\gamma\gamma}Br(\chi_{c2}\to K^+K^-)$ 0.44 ± 0.76 ± 0.14

Preliminary results of $\gamma\gamma \to \pi^0\pi^0$

Selection of $\pi^0\pi^0$ candidates

Based on data with an integrated luminosity of 95 fb^{-1}

Only 4 photons are visible

- Triggered by Calorimeter triggers

- No reconstructed track with

p_t>0.1GeV/c, dr<5cm, |dz|<5cm

- 2 or more photons OR 1 or more π^0s

- Just 2 π^0s with E(decay product photon)>70MeV, p_t>0.15GeV/c

- Transverse-momentum (p_t)-balance of the two π^0's

$|\Sigma \mathbf{p}_t|<0.05$GeV/c

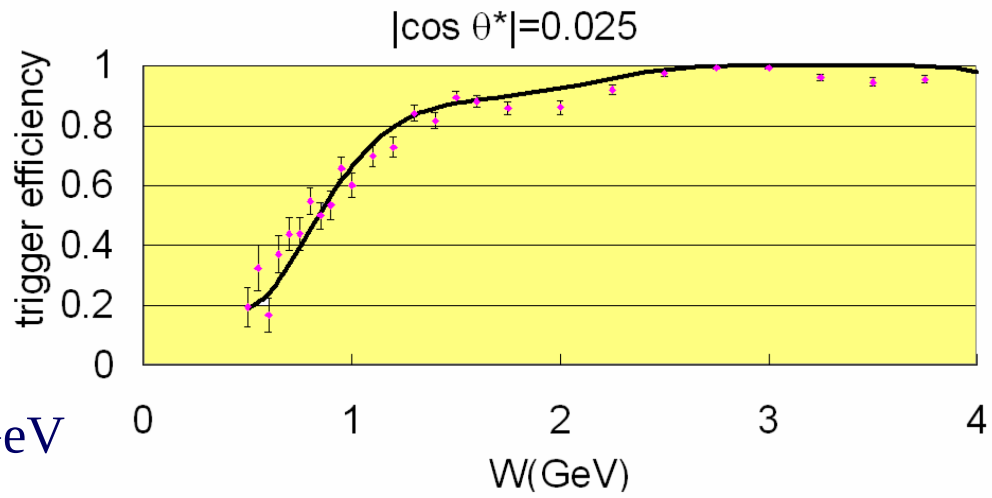
- Satisfying a rough trigger condition at offline:

N_gamma=4 or Esum_lab>1.25 GeV

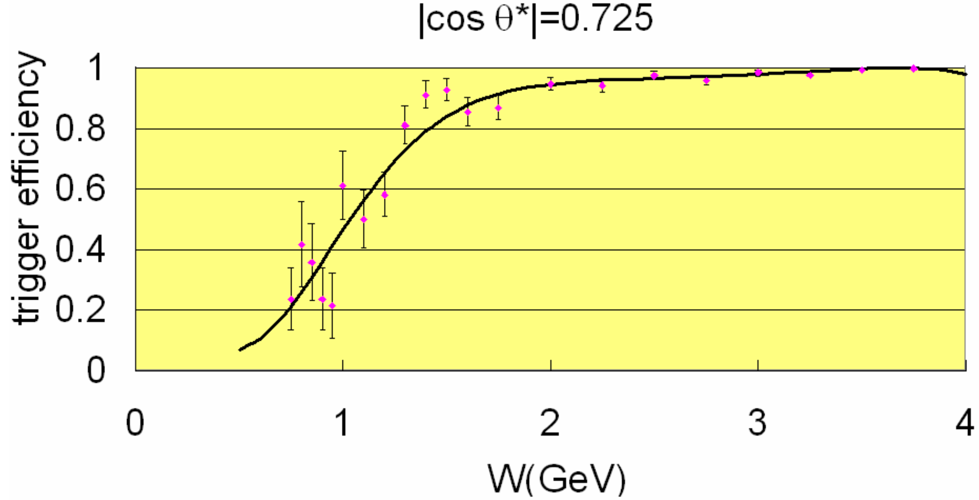
in the ECL-trigger region, $17<\theta_{lab}<128.7$deg

Trigger efficiency from the simulation

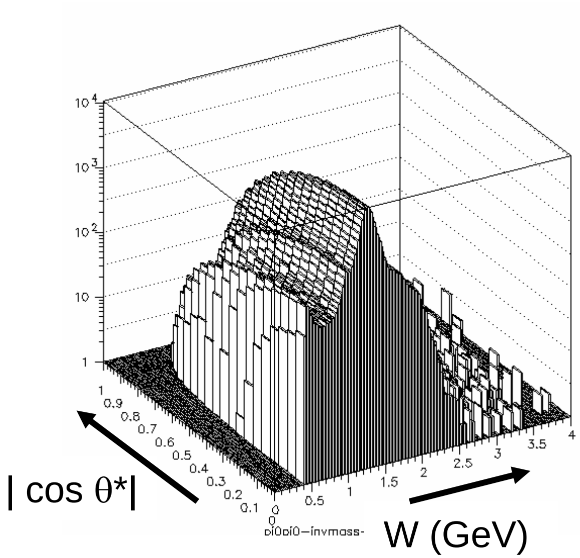
Trigger efficiency is determined
by the trigger simulator, tsim
after tunings of the energy thresholds
for
the total energy trigger (HiE) – 1.15 GeV
and for
counting number of clusters (Clst4)
- 110 MeV

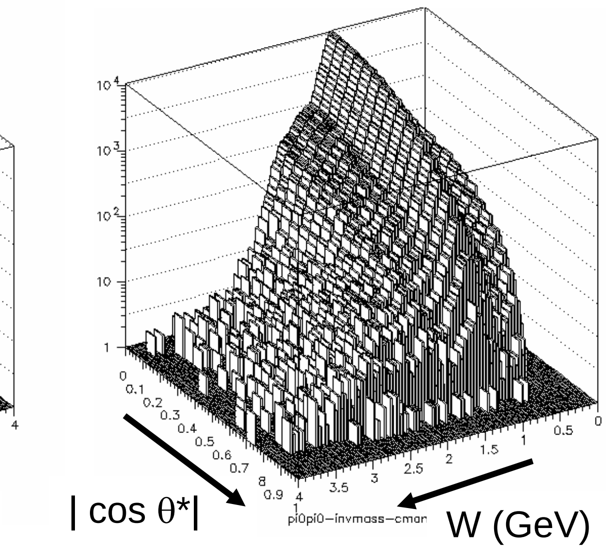


In each of 16 c.m. angular bins
$0.0 < |\cos\theta^*| < 0.8$,
Fitted by a two-dimensional
function of (W, $|\cos\theta^*|$)



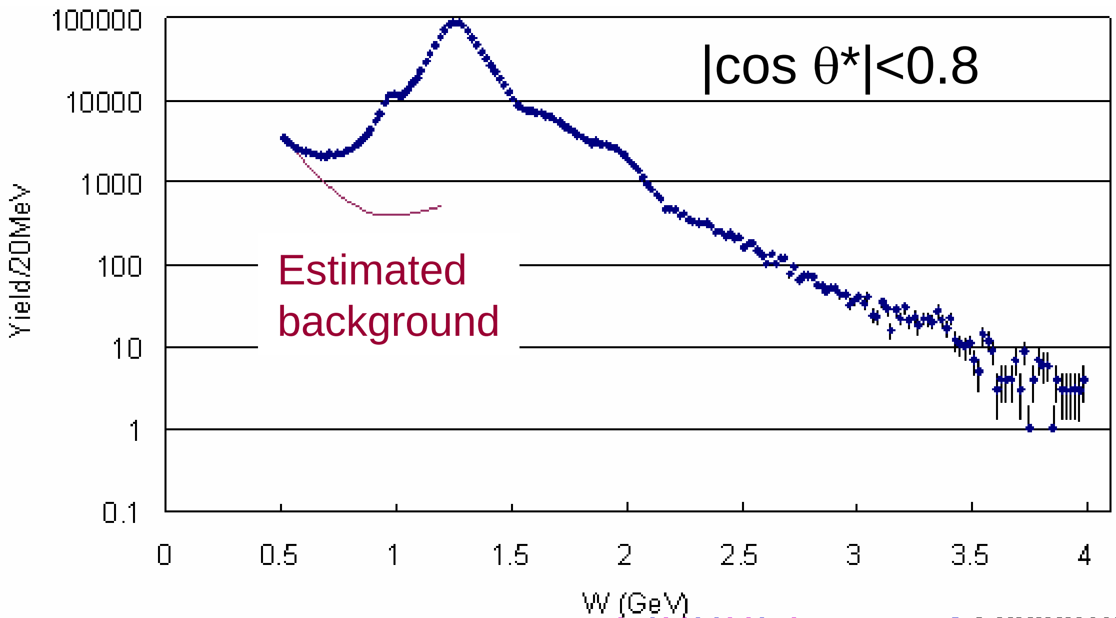
Raw-event distribution of $\pi^0\pi^0$

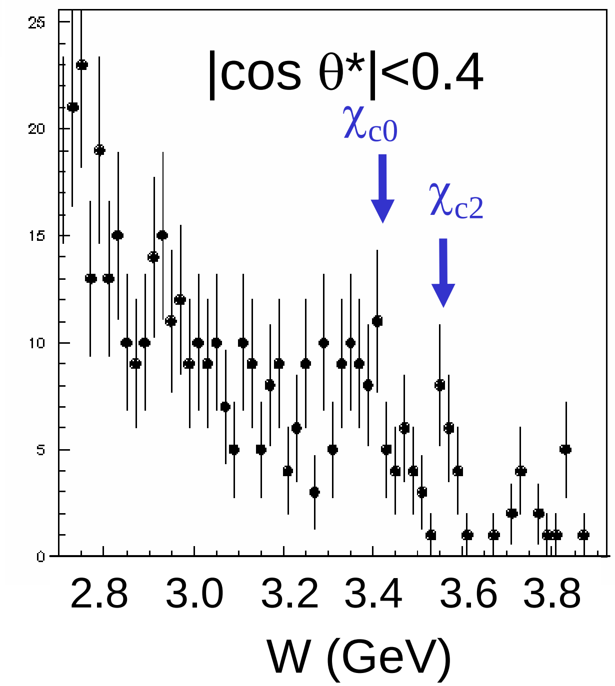




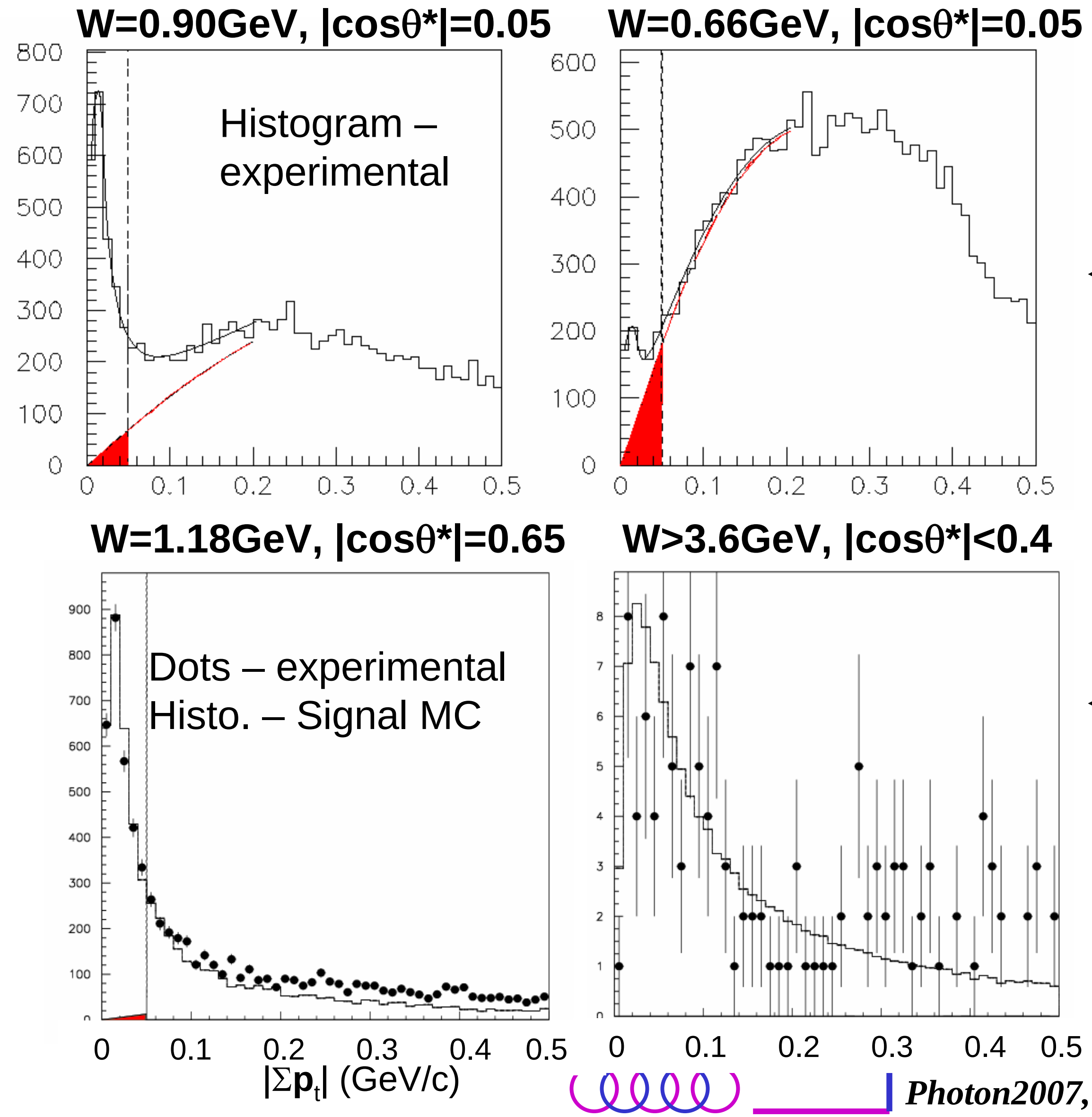
$W = M(\pi^0\pi^0)$

About 1.26M events (before the background subtraction)





p_t-balance distributions and backgrounds



p_t-unbalanced backgrounds are seen in W<1.2 GeV

← Low-energy beam-background photons

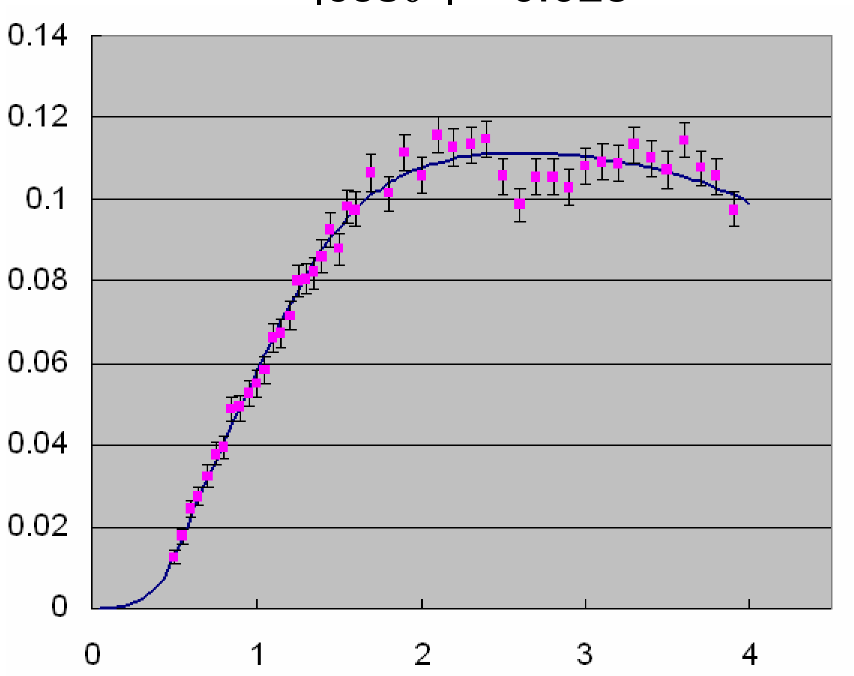
← Intermediate or Higher energies

Non-exclusive process sources not significantly seen

Detector acceptance not including trigger

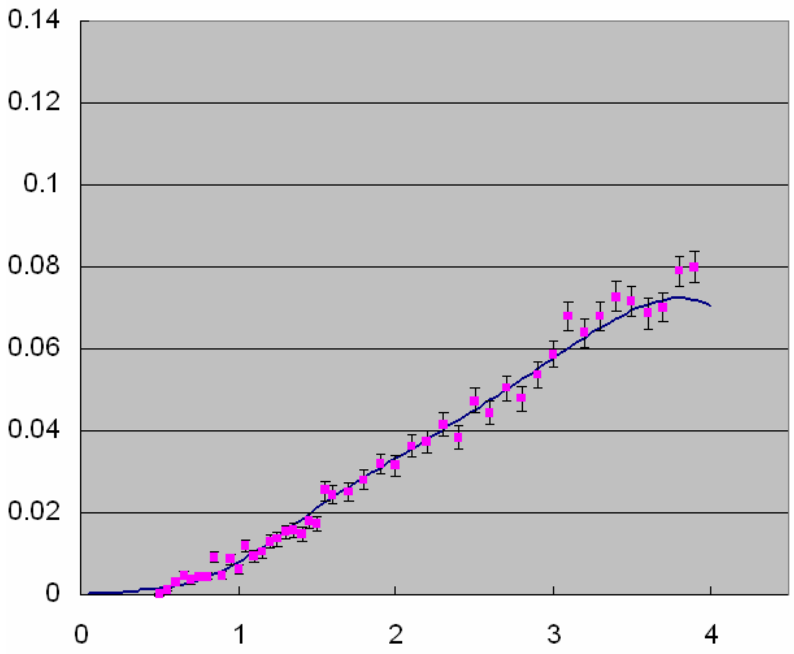
Calculated from signal MC simulation and fitted by a smooth function

|cosθ*| = 0.025



W (GeV)

|cosθ*| = 0.725



W (GeV)

Around 11% at maximum, typically 5 %

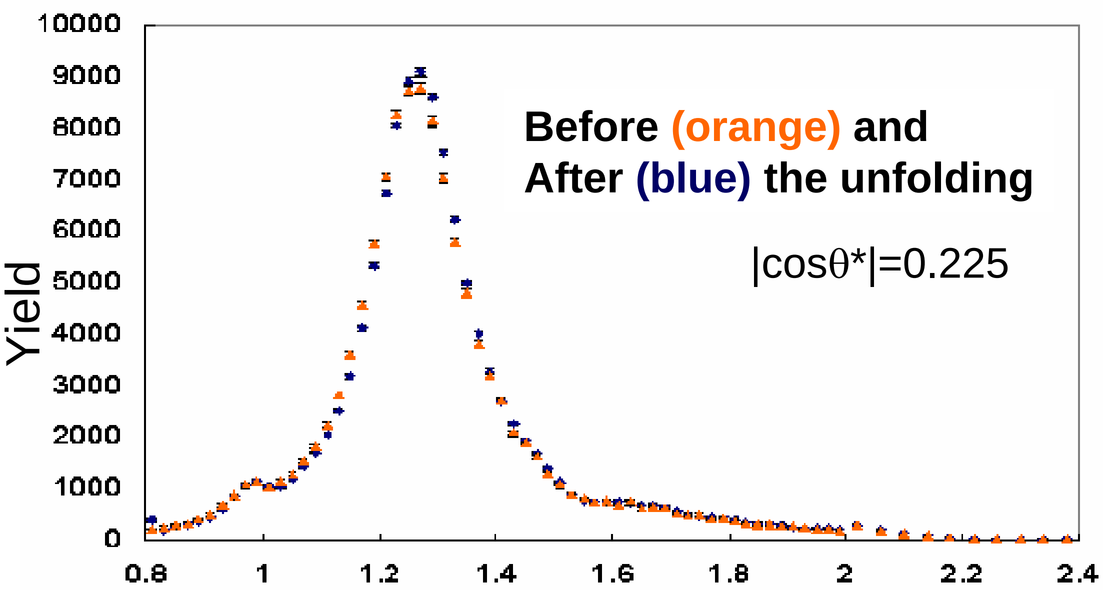
Large angular dependence due to geometrical condition of the detector

Overall efficiency = Acceptance ∗ trigger efficiency

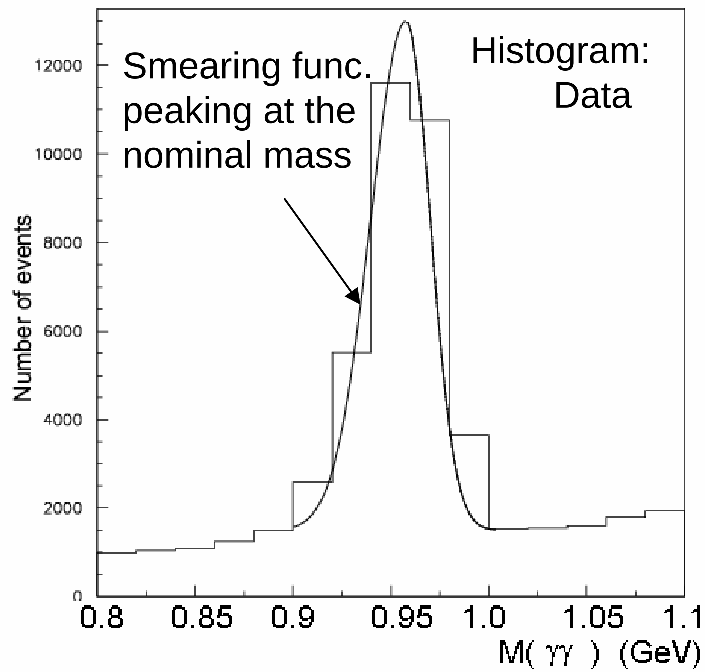
Invariant-mass resolution and Unfolding

W resolution --- ~ 1.4% ×W, almost independently of W (from signal MC)
Apply Unfolding to the experimental W distribution (in each angle region) for the smearing effect in the W direction using an asymmetric Gaussian (1.3% higher side and 1.9 % lower side).

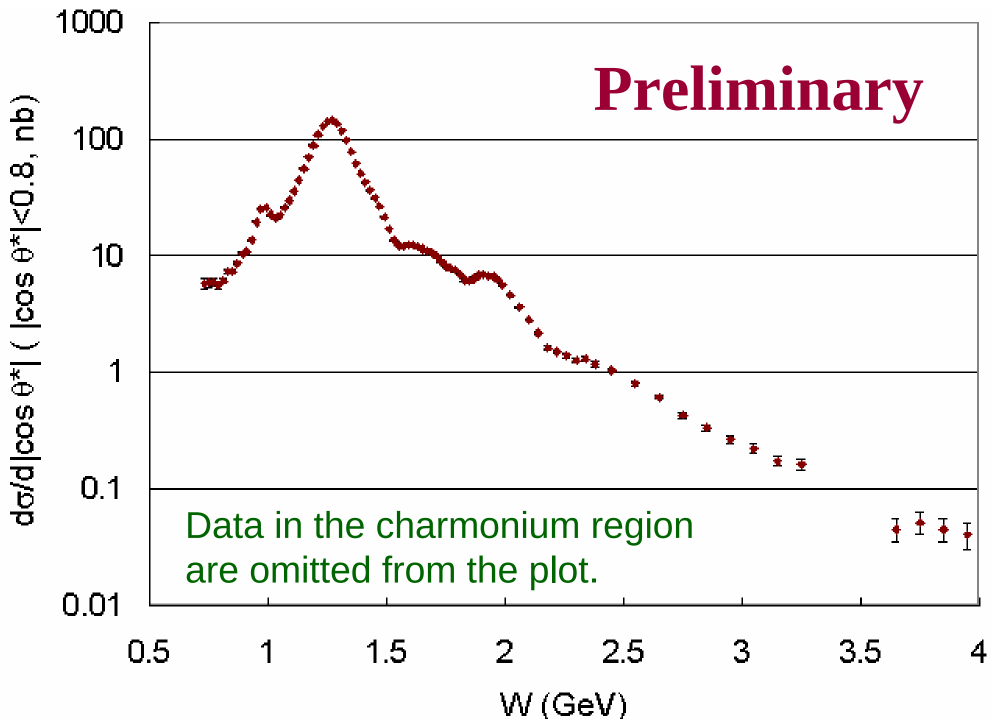
Unfolding is applied in 0.9 GeV < W < 2.4 GeV.
Wider bin-widths than the resolution are used in the other W regions.



Experimental sample of $\eta' \to \gamma\gamma$



Cross sections of $\gamma\gamma \rightarrow \pi^0\pi^0$



Obtain first
$d\sigma/d|\cos\theta^*|$ in each $\Delta|\cos\theta^*|=0.05$ bin
Then, accumulate them over the angle

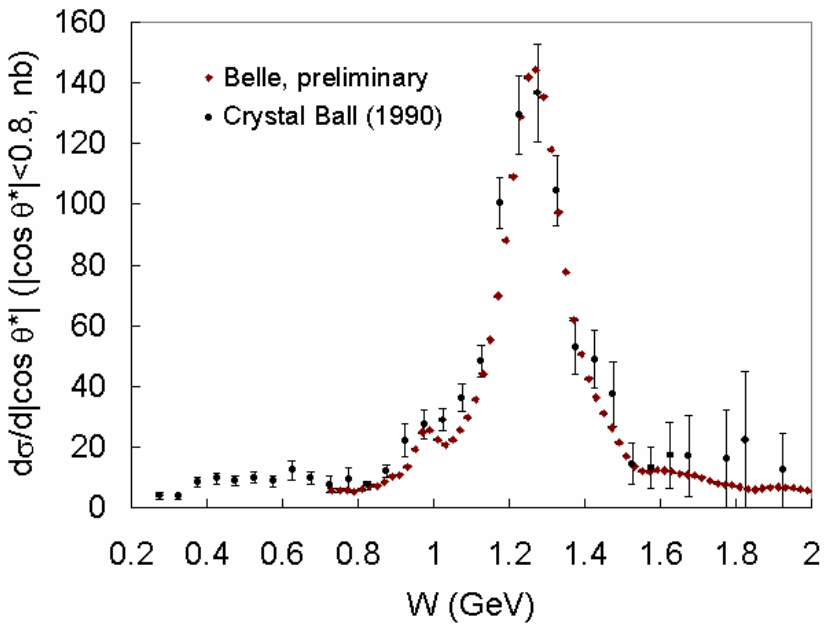
Important note:
After the Unfolding, different data bins and errors are no longer independent of each other.

Comparison with Crystal Ball at DORIS II (1990)

They are consistent.

Belle has ~10^3 times more data.

Statistical errors only.



Systematic-error sources

-Trigger efficiency --- 4% @ W > ~ 1.1 GeV (HiE)
5% - 30% @ W< ~1.1 GeV (Clst4)

-π^0 reconstruction efficiency --- 6%

-Acceptance (dominated by pt-balance cut) - - 3% - 5%

- Background subtraction --- 20% of the subtraction component
3% in High W where no subtraction applied.

-Luminosity function --- 4% - 5%

Total	55% - 10%	@ W<~1.05GeV
	~9%	@ 1.05GeV<W<~2.7GeV
	10% - 11%	@ W>~2.7GeV

Differential cross section (Angular dependence)

$\gamma\gamma \rightarrow \pi^0\pi^0$

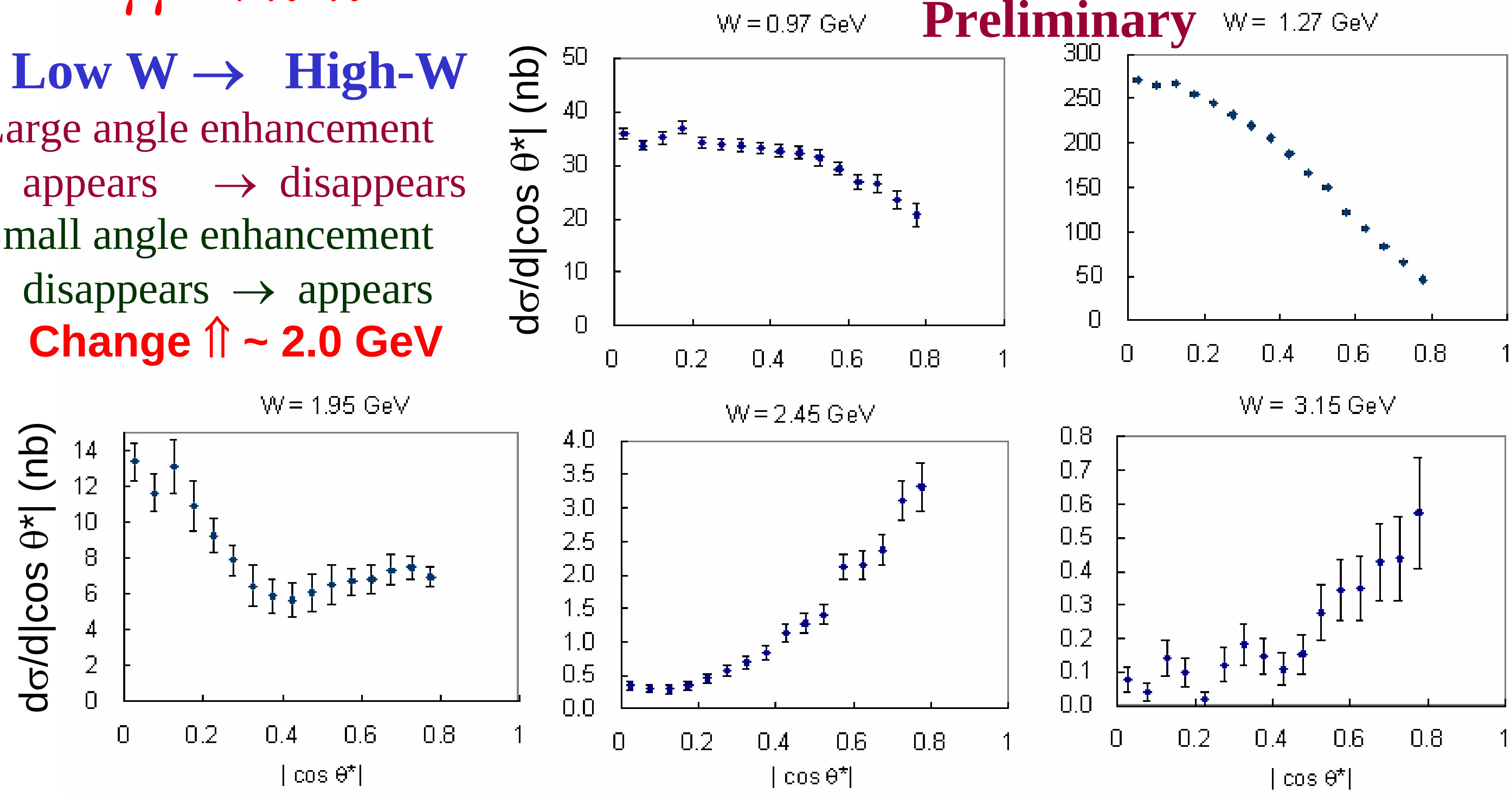
Low W → High-W

Large angle enhancement
appears → disappears

Small angle enhancement
disappears → appears

Change ⇑ ~ 2.0 GeV

Preliminary



Resonant structures

Resonances:

Clearly seen: $f_0(980)$, $f_2(1270)$, ~1.65 GeV, ~1.95 GeV

Hints with a lower significance : ~1.45 GeV, χ_{c0}, χ_{c2}

Sizes of the charmonia

$\Gamma\gamma\gamma(\chi_{c0})B(\chi_{c0}\to\pi^0\pi^0)$:

$8.4 \pm 2.2 \pm 0.8$ eV (4.5σ)

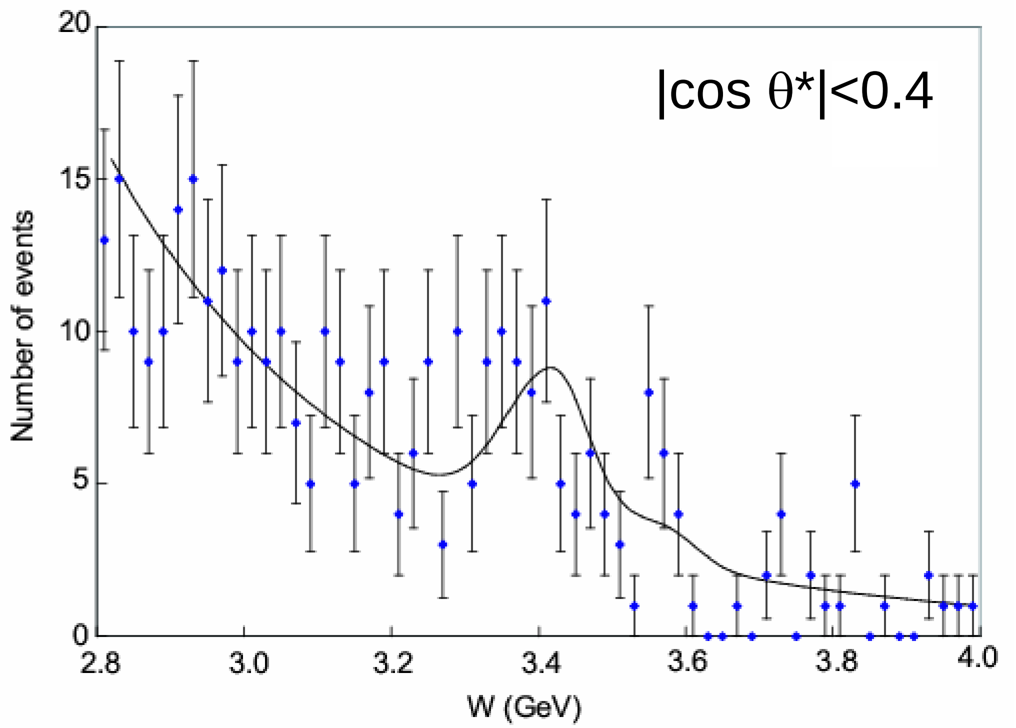
$\Gamma\gamma\gamma(\chi_{c2})B(\chi_{c2}\to\pi^0\pi^0)$:

$0.29 \pm 0.23 \pm 0.03$ eV (1.4σ)

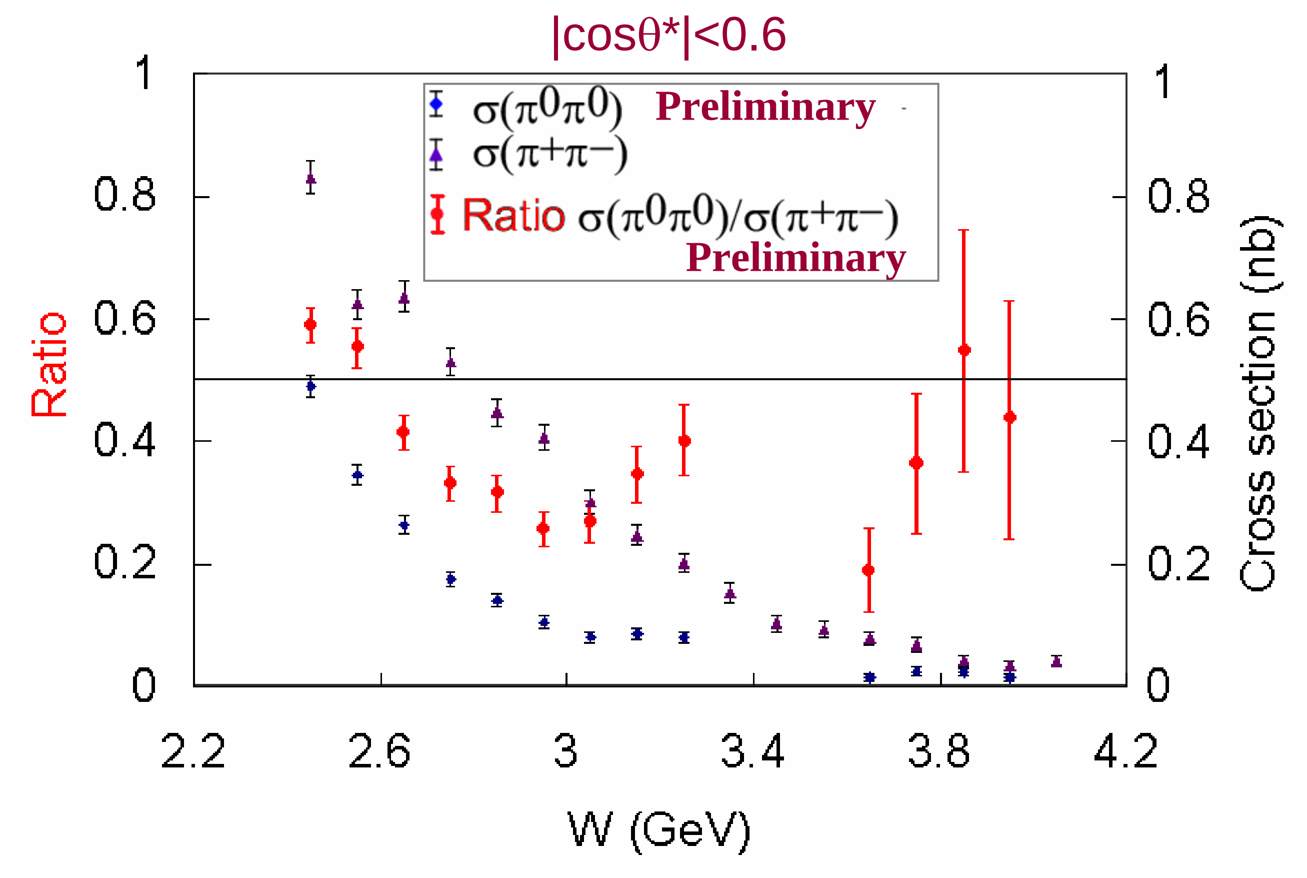
Upper limit < 0.75 eV (90%CL)

Preliminary

The central values are consistent with the expectations from isospin invariance between the $\pi^+\pi^-/\pi^0\pi^0$ decays



Cross section ratio $\sigma(\pi^0\pi^0)/\sigma(\pi^+\pi^-)$



Error bars are statistical only.

Systematic errors: About 10% at each measurement point, except $\pi^+\pi^-$ above the charmonium masses (~25%).

Charmonium region is omitted from the plot.

The ratio is 0.3 – 0.4 at W>2.7 GeV

Conclusion of $\pi^+\pi^-$ measurement

- We measure the process $\gamma\gamma \to \pi^+\pi^-$ with 85.9 fb^{-1} data.

- The differential cross sections are obtained in 0.8 GeV < W < 1.5 GeV and $|\cos\theta^*|<0.6$ in the $\gamma\gamma$ c.m. frame.
  (# We separately published before for the region 2.4 GeV<W<4.1GeV)

- We confirm small but statistically significant peak from $f_0(980)$.

- New upper limit for P and CP violating process $\eta' \to \pi^+\pi^-$ is obtained.

Summary for $\pi^0\pi^0$ measurement

- We measure the process $\gamma\gamma \to \pi^0\pi^0$ with $95 fb^{-1}$ data.

- Preliminary results of the differential cross sections are obtained in 0.6 GeV $< W < 4.0$ GeV and $|\cos\theta^*| < 0.8$ in the $\gamma\gamma$ c.m. frame.

- Several resonant structures are seen, including a statistically significant peak from $f_0(980)$.

- Behavior of the angular dependence (forward- and/or large-angle enhancements) changes drastically at around W= 2.0 GeV.

- The cross section ratio $\sigma(\pi^0\pi^0)/\sigma(\pi^+\pi^-)$ in 3 GeV region is obtained.

BACKUP slides

Measurements of two-photon processes at Belle

$\gamma\gamma \to \chi_{c2} \to \gamma J/\psi$ PLB 540, 33(2002)

$\gamma\gamma \to (f_2'(1525)\text{etc.} \to) K^+K^-$ (1.4 - 2.4 GeV) EPJC 32, 323 (2003)

$\gamma\gamma \to (\chi_{c0},\chi_{c2} \to) \pi^+\pi^-, K^+K^-$ (2.4 - 4.1 GeV) PLB 615, 39 (2005)

$\gamma\gamma \to (\eta_c \to) p\bar{p}$ (2.025 - 4.0 GeV) PLB 621, 41 (2005)

$\gamma\gamma \to \chi_{c2}' \to D\bar{D}$ PRL 96, 082003 (2006)

$\gamma\gamma \to (f_0(980)\text{etc.} \to) \pi^+\pi^-$ (0.8 - 1.5 GeV) PRD 75, 051101(R) (2007), arXiv:0704.3538[hep-ex], to appear in Jour. Phys. Soc. Jpn. (2007)

$\gamma\gamma \to (\chi_{c0},\chi_{c2} \to) K^+K^-$ (2.4 - 4.0 GeV) hep-ex/0609042v2, submitted to PLB

$\gamma\gamma \to (\eta_c,\chi_{c0},\chi_{c2} \to) \pi^+\pi^-\pi^+\pi^-, K^+K^-\pi^+\pi^-, K^+K^-K^+K^-$ arXiv:0706.3955[hep-ex], submitted to EPJC

$\gamma\gamma \to a_2\text{'s} \to \pi^+\pi^-\pi^0$ (1.2 - 3.0 GeV) hep-ex/0610022

$\gamma\gamma \to (\eta_c \to) \Lambda\bar{\Lambda}, \Sigma^0\bar{\Sigma}^0$ (2.3-4.0 GeV) hep-ex/0609048

Reactions at KEKB/Belle

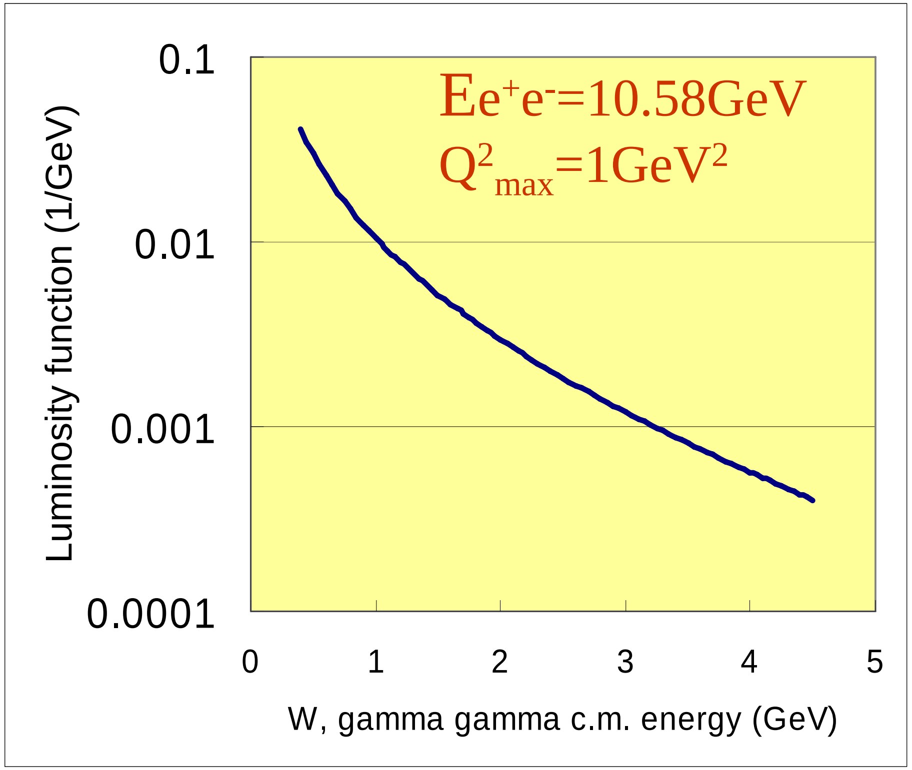
The cross sections observable there

$e^+e^- \to \Upsilon(4S) \to B\bar{B}$	--- 1.1 nb
$e^+e^- \to q\bar{q}$ (uds)	--- 2.1 nb
$e^+e^- \to c\bar{c}$	--- 1.2 nb
$e^+e^- \to \tau^+\tau^-$	--- 0.9 nb
$\gamma\gamma \to$ hadrons ($W_{\gamma\gamma}$>0.8GeV)	--- ~1 nb

(within the acceptance)

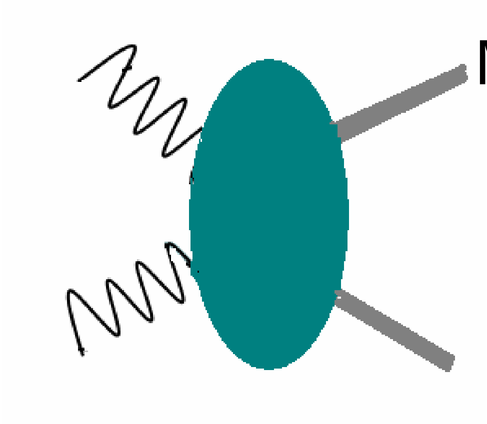
Luminosity Function
for quasi-real $\gamma\gamma$ collisions

$$d\sigma_{(\text{in ee})} = \sigma_{(\text{in }\gamma\gamma)} L\gamma\gamma(W)\, dW$$



Calculated with equivalent-photon approximation

Two-meson exclusive final states



C = + resonances: Peak structure in the invariant mass distribution

Test of QCD: c.m.-energy (W) dependence and
angular dependence in high energies

General Analysis strategy

Invariant-mass of hadron pair = W (c.m. energy of $\gamma\gamma$)

Quasi-real two-photon collisions with final state fully reconstructed

--- strict transverse momentum balance is required

($|\Sigma \mathbf{p}_t|$ <50 - 200 MeV/c)

This gives efficient background rejection

Selection of $\pi^+\pi^-$ candidates

Based on data with an integrated luminosity of $85.9 fb^{-1}$

- Two charged tracks (oppositely charged)

with $p_t > 0.3$ GeV/c, $-0.47 < \cos\theta_{lab} < +0.82$

- $|\Sigma \boldsymbol{p}_t^*|$ (in e+e- c.m.s) < 0.1 GeV/c
- π/K, π/p separations

using TOF, Aerogel-Cherenkov and *dE/dx*

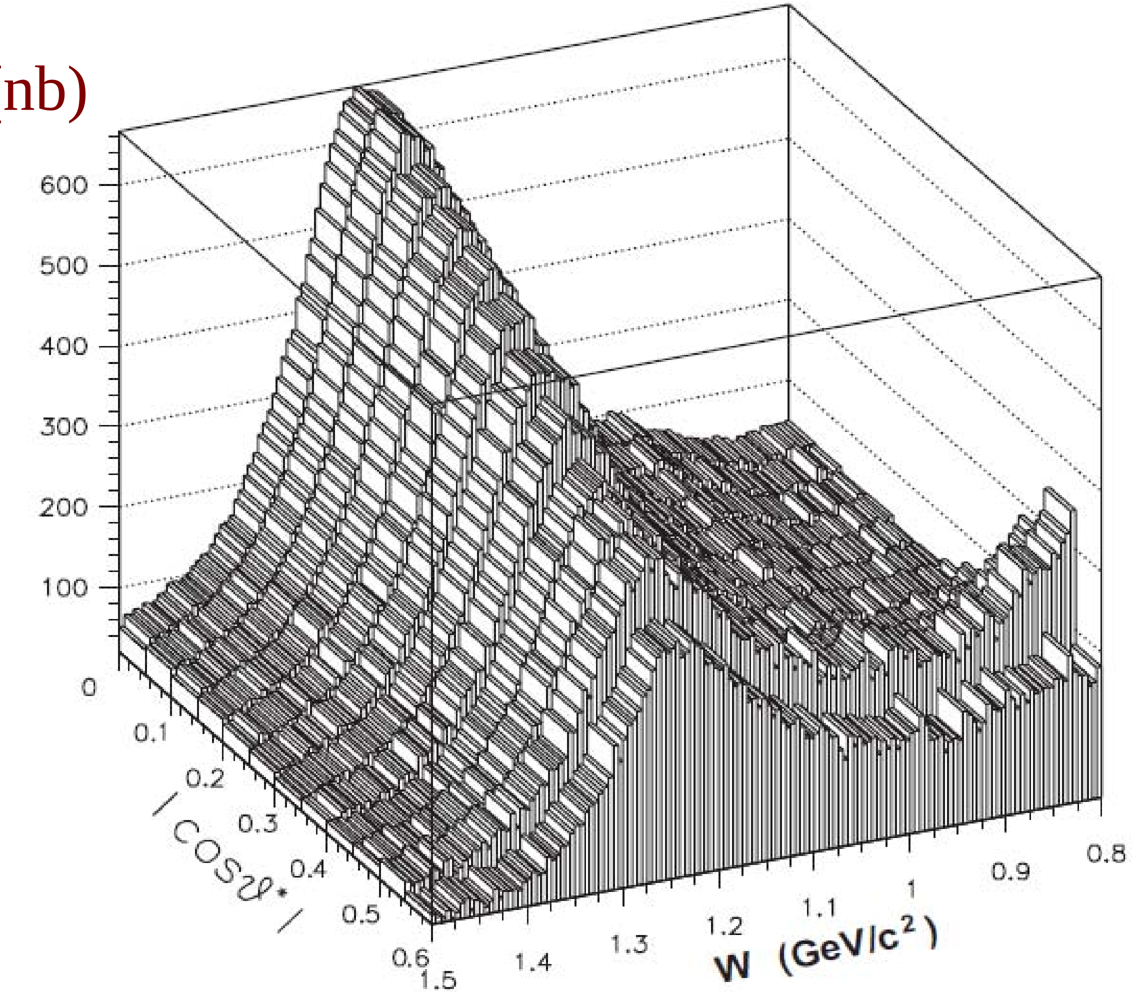
- Muon background subtraction

with fitting the energy-deposit distribution on ECL

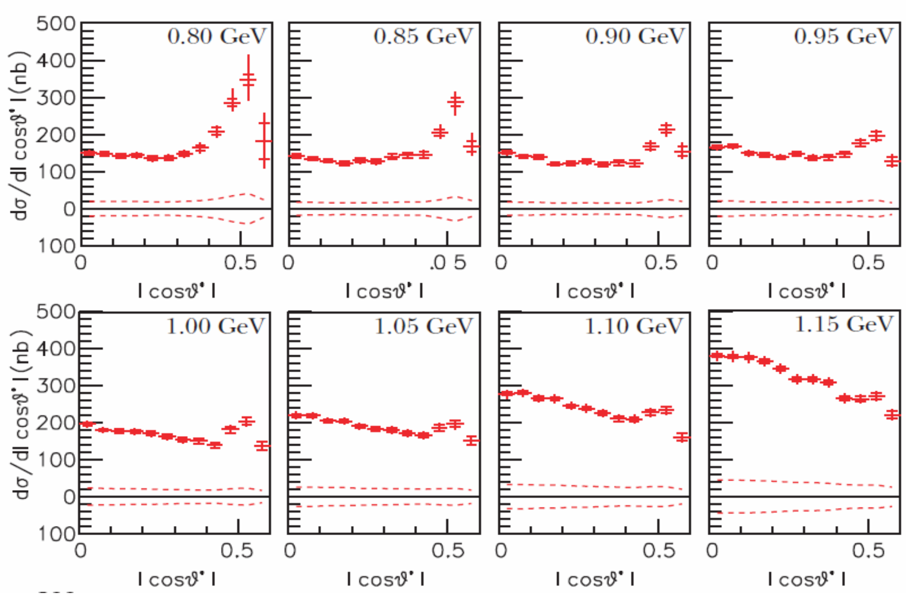
KLM (muon detector with iron filter) cannot be available in these low energies

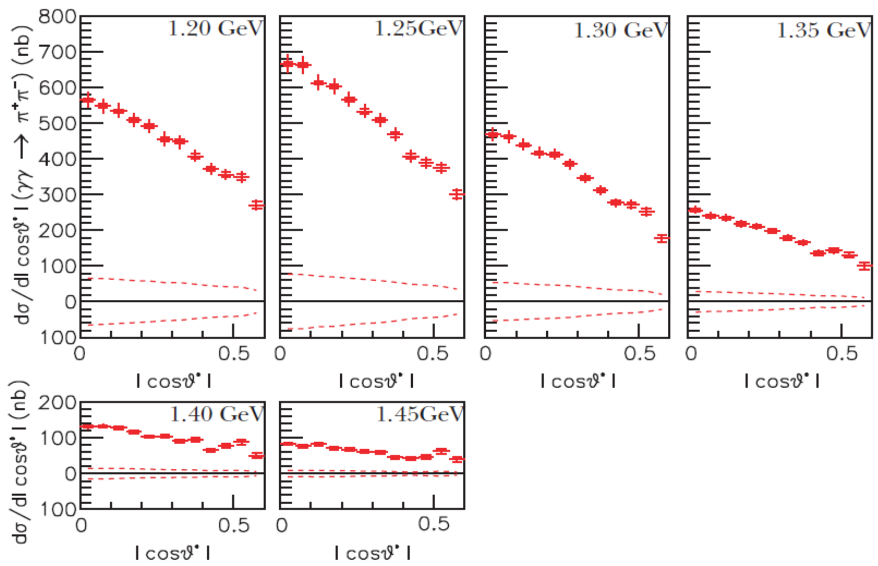
Differential cross section

$d\sigma/d|\cos\theta^*|$ (nb)



Angular dependences at some energy points





Red dashed lines ---
Size of point-to-point systematic error

Systematic structure near |cos θ*|=0.45-0.55
could be due to a measurement bias

Fitting formula for $f_0(980)$

$$\sigma = \left| \frac{\sqrt{4.8\pi\beta_\pi}}{W} \mathcal{F}^{f_0} e^{i\varphi} + \sqrt{\sigma_0^{\rm BG}} \right|^2 + \sigma^{\rm BG} - \sigma_0^{\rm BG}, \quad (1)$$

where the factor 4.8 includes the fiducial angular acceptance $|\cos\theta^*| < 0.6$, $\beta_X = \sqrt{1 - \frac{4M_X{}^2}{W^2}}$ is the velocity of the particles X with mass M_X in the two-body final states, $\mathcal{F}^{f_0}$ is the amplitude of the $f_0(980)$ meson, which interferes with the helicity-0-background amplitude $\sqrt{\sigma_0^{\rm BG}}$ with relative phase φ, and $\sigma^{\rm BG}$ is the total background cross section. The amplitude $\mathcal{F}^{f_0}$ can be written as

$$\mathcal{F}^{f_0} = \frac{g_{f_0\gamma\gamma} g_{f_0\pi\pi}}{16\pi} \cdot \frac{1}{D_{f_0}}, \quad (2)$$

where g_{f_0XX} is related to the partial width of the $f_0(980)$ meson via $\Gamma_{XX}(f_0) = \frac{\beta_X g_{f_0XX}^2}{16\pi M_{f_0}}$. The factor D_{f_0} is given as follows [16]:

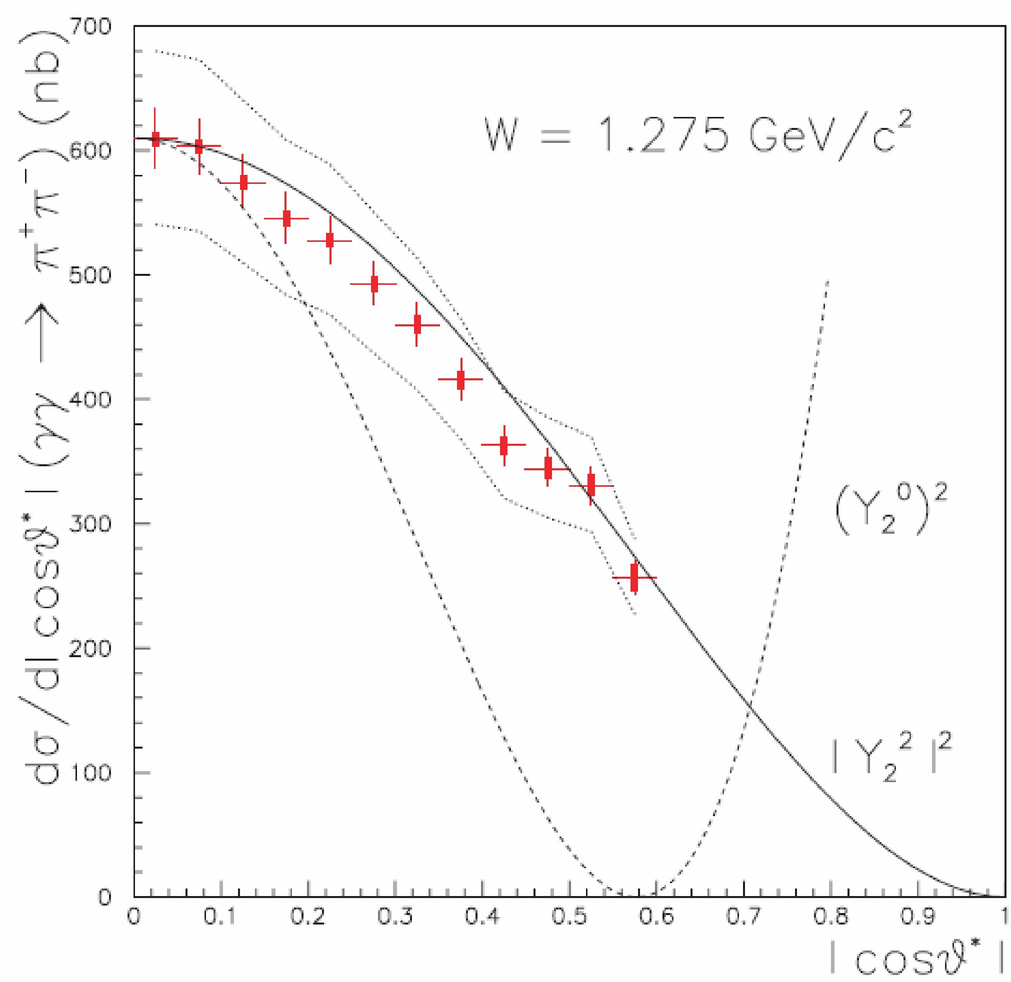
$$D_{f_0}(W) = M_{f_0}^2 - W^2 + \Re\Pi_\pi^{f_0}(M_{f_0}) - \Pi_\pi^{f_0}(W) + \Re\Pi_K^{f_0}(M_{f_0}) - \Pi_K^{f_0}(W),$$

where for $X = \pi$ or K,

$$\Pi_X^{f_0}(W) = \frac{\beta_X g_{f_0XX}^2}{16\pi} \left[i + \frac{1}{\pi} \ln \frac{1-\beta_X}{1+\beta_X} \right]. \quad (3)$$

The factor β_K is real in the region $W \geq 2M_K$ and becomes imaginary for $W < 2M_K$. The mass difference between $K^\pm$ and K^0 $(\overline{K^0})$ is included by using $\beta_K = \frac{1}{2}(\beta_{K^\pm} + \beta_{K^0})$.

Angular dependence in $f_2(1270)$ region

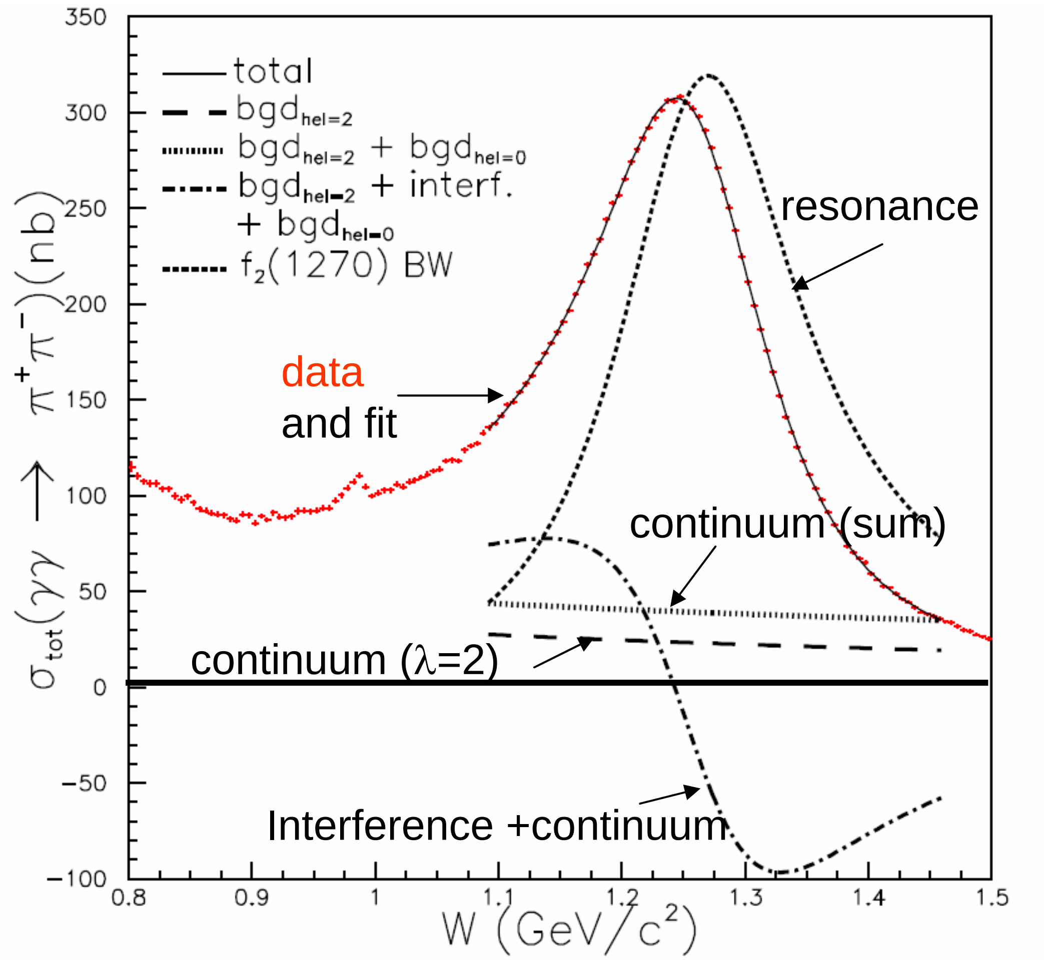


Close to $|Y_2^2|^2$

Consistent with
pure J=2 and λ=2

But, mathematically
the partial waves cannot be fully separated taking into account the interference between J=0 and 2.

Fit to f_2(1270) line shape



Components:

f_2 (1270) resonance

Smooth continuum:

Interfering component (l=2)

No-interfering component (I=0)

This is for consistency check: Known mass and width of f_2(1270) (PDG2006) are used.

The continuum and relative phase parameters were floated.

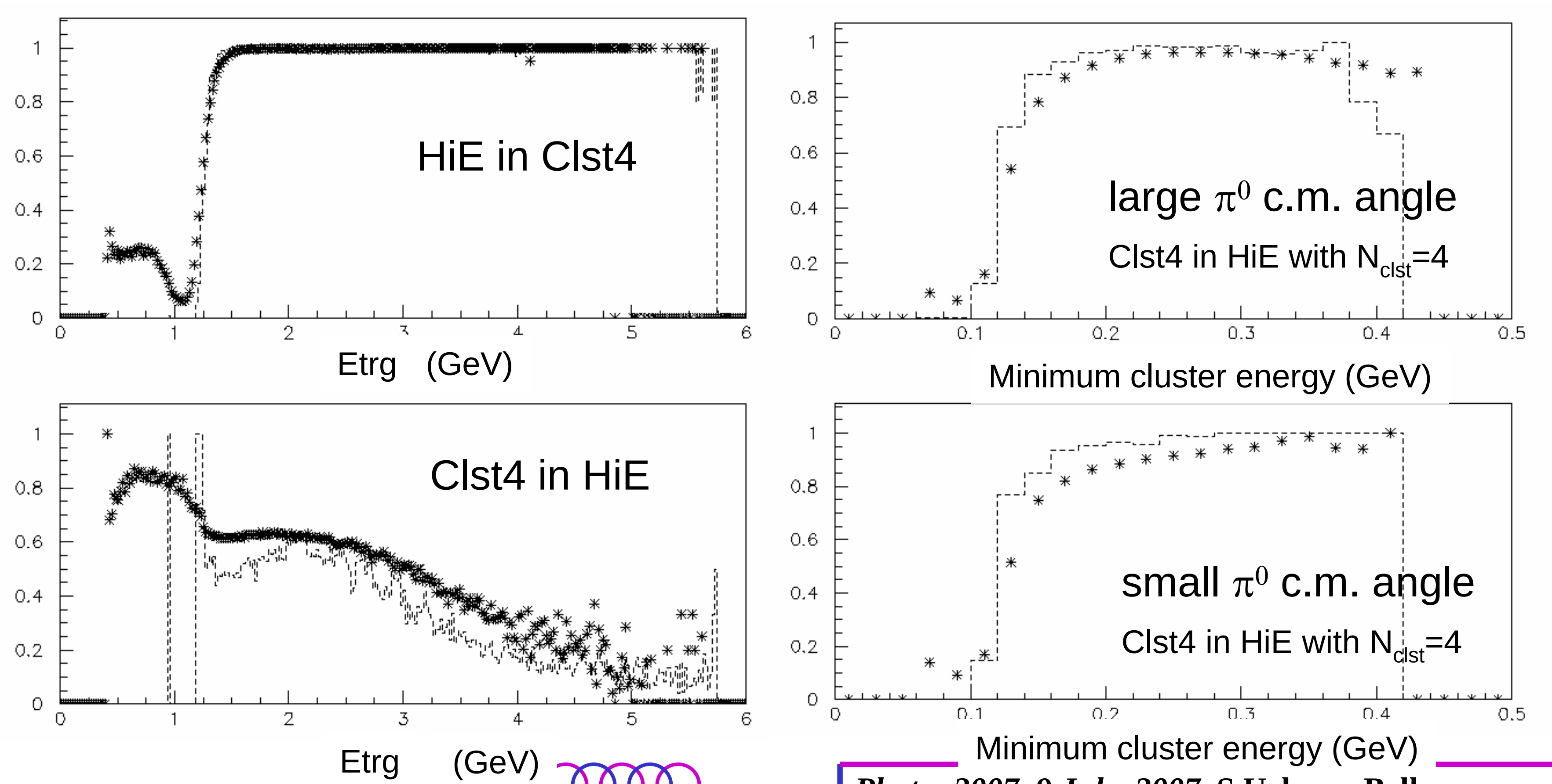
Trigger efficiency study

Correlation between the two triggers:

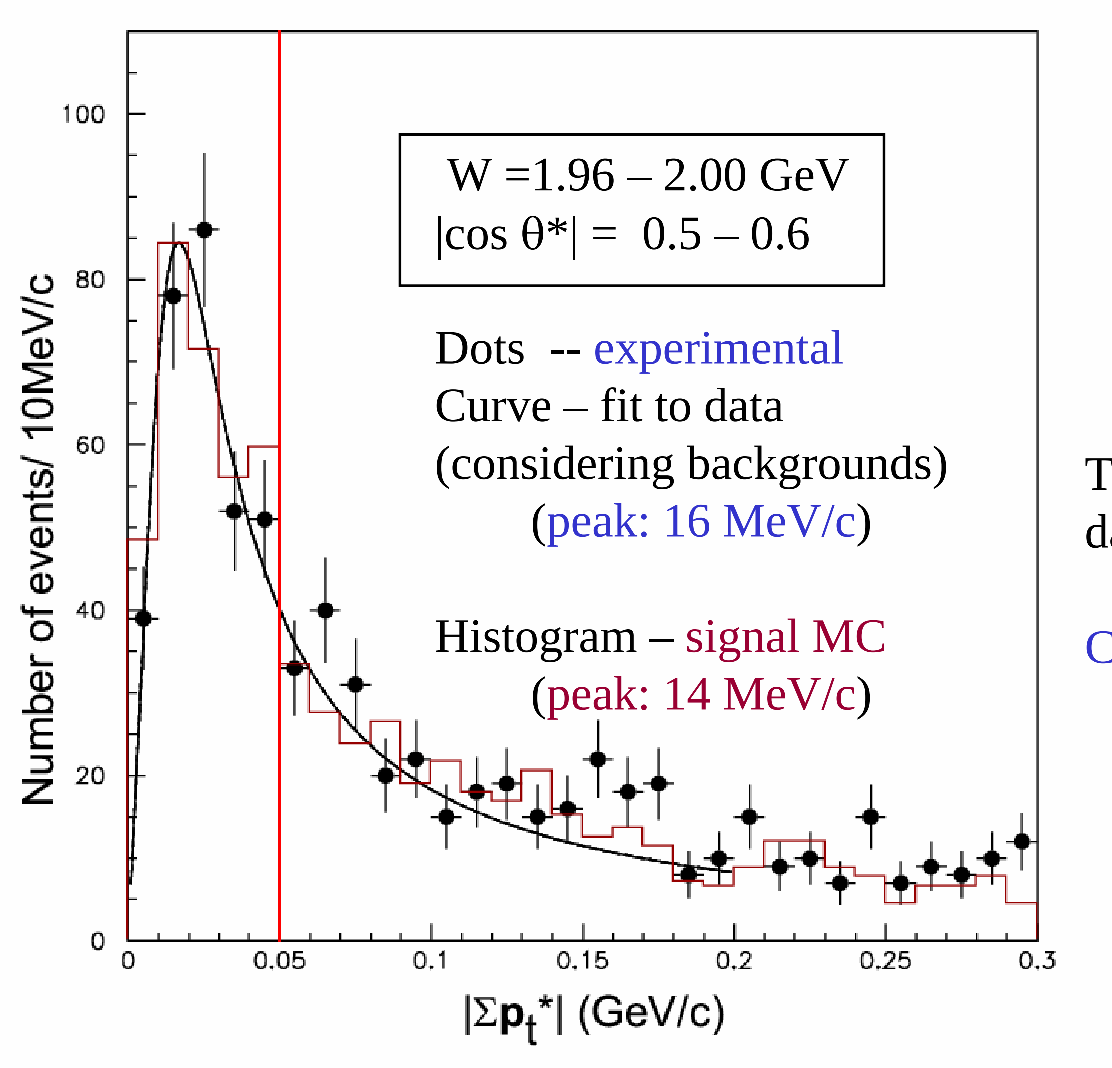
HiE (Etot_trg>1.15GeV), Clst4 (>=4 clusters each with >110MeV)

(The thresholds have been tuned.)

* -- data, dashed histogram – trigger simulator (tsim)



p_t-balance resolution and correction to efficiency



the pt-balance cut

Efficiency is affected by p_t-balance resolution.

The resolution in the experimental data is by ~15% worse than the MC.

Correction factor: 5% - 10%, depending on W and |cos θ*|