Measurement of $\gamma\gamma^* \to \pi^0$ Transition Form Factor at Belle

Sadaharu Uehara (KEK)

The Belle Collaboration

Meson TFF Workshop, 29-30 May, 2012

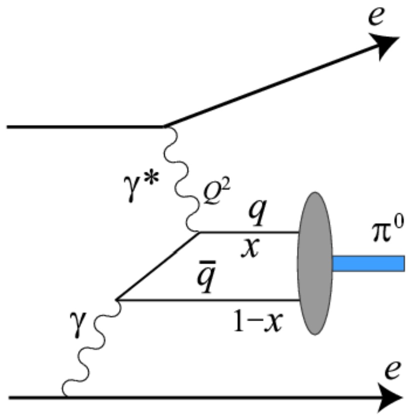
MESON2012, 31 May – 5 June, 2012

Jagiellonian University, Kraków

π^0 Transition Form Factor

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

Coupling of neutral pion with two photons
Good test for QCD at high Q^2



Single-tag π^0 production in two-photon process with a large-Q^2 and a small-Q^2 photon

Theoretically calculated from pion distribution amplitude and decay constant

$$F(Q^2) = \frac{\sqrt{2} f_\pi}{3} \int T_H(x, Q^2, \mu) \phi_\pi(x, \mu) dx$$

Measurement:

$|F(Q^2)|^2 = |F(Q^2,0)|^2 = (\mathbf{d\sigma/dQ^2})/(2A(Q^2))$ A(Q^2) is calculated by QED

$|F(0,0)|^2 = 64\pi\Gamma_{\gamma\gamma}/\{(4\pi\alpha)^2 m_R^3\}$

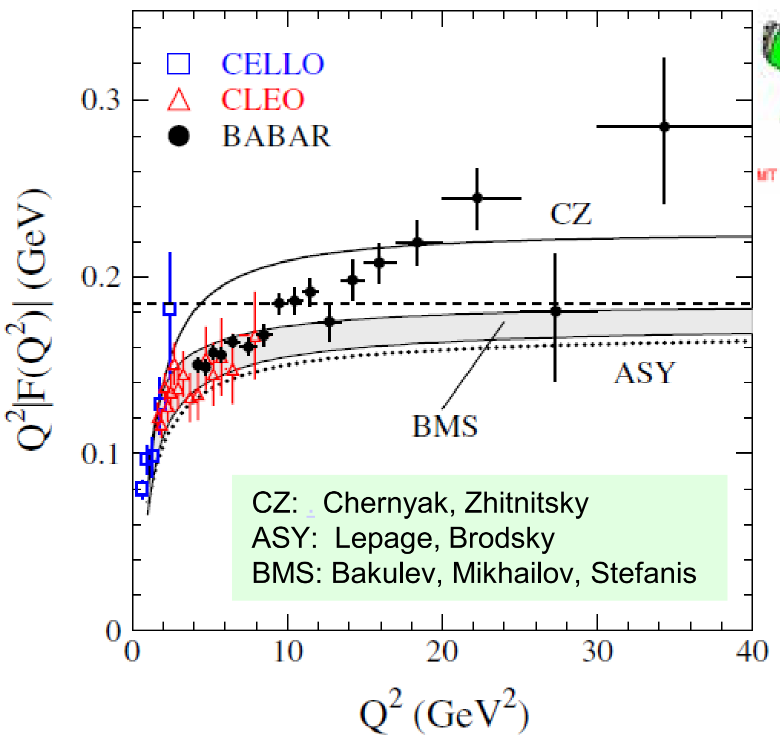
Detects e (tag side) and π^0

$Q^2 = 2EE'(1 - \cos\theta)$ from energy and polar angle of the tagged electron

BaBar’s Measurement

π^0 transition form factor (TFF) measured by BaBar is larger than the asymptotic pQCD prediction above Q^2>10GeV^2

BaBar, PRD 80, 052009 (2009) **442 fb^{-1}**



Below Q^2<8GeV^2, the BaBar result supports the CLEO result.

η and η' TFFs from BaBar
PRD 84, 052001(2011)
are consistent with QCD predictions.

Explanation within standard QCD calculations is difficult.

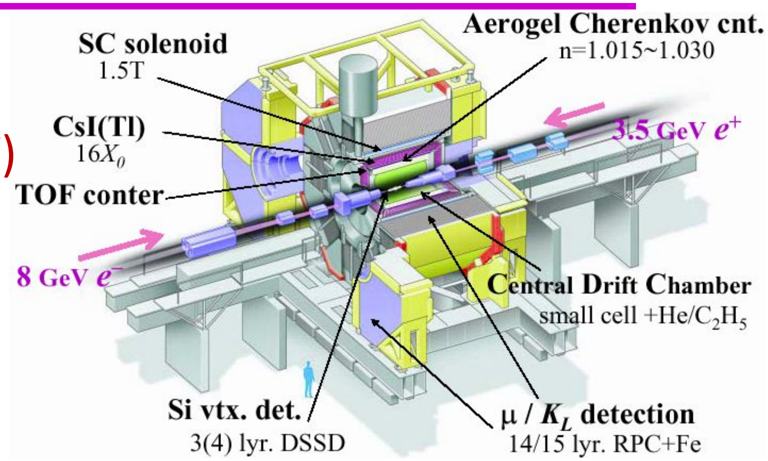
Measurement of π^0 TFF at Belle

KEKB accelerator and **Belle detector**

Asymmetric for beam energy (e^+: 3.5 GeV, e^-: 8 GeV)

for kinematic coverage of

e^+-tag(**p-tag**) and e^--tag(**e-tag**)



Available Triggers:

HiE && $\overline{\textbf{Bhabha}}$**(-veto)**

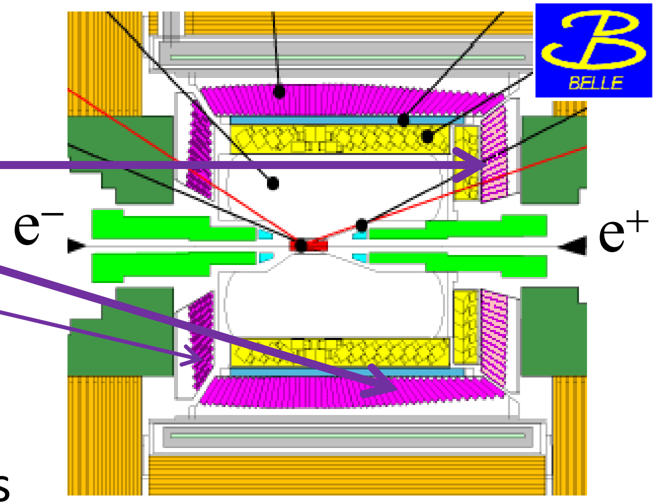
by ECL (electromagnetic calorimeter system)

HiE --- E(Forward+Barrel) > 1.15 GeV

Forward ECL

Barrel ECL

(Backward ECL)



Bhabha-veto logic kills a part of the acceptance

Significant loss of efficiency for some angular patterns

in contrast to BaBar, where a special salvaging logic was prepared.

Int. Luminosity :759 fb^{-1} (Larger than BaBar's)

Selection Criteria for Signal Events

- Triggered by HiE or CsIBB(≡Bhabha prescaled by factor 50)
- **1 good track** only, **Electron-ID** $E/p>0.8$, $p_e > 1.0$ GeV/c in lab. system
- **2 Photons from π^0** $E_{\gamma i}>0.2$GeV, $E_{\gamma\gamma} \equiv E_{\gamma 1} + E_{\gamma 2} > 1.0$ GeV

  No big energy asymmetry: $|E_{\gamma 1}-E_{\gamma 2}|/E_{\gamma\gamma} <0.8$

  Polar-angle difference: $\Delta\theta \equiv |\theta_{\gamma 1} - \theta_{\gamma 2}| > \frac{0.18\ [\text{rad}\cdot\text{GeV}]}{E_{\gamma\gamma}}$

  To reject large background from Radiative Bhabha (e)eγ process

- Polar- angle of the electron and the two photons

  $-0.6235 < \cos\theta < +0.9481$ and **Bhabha Mask cut**

- **e-charge vs. p_z direction correlation**

  $-Q_{tag}\,(p_z{}^*{}_e + p_z{}^*{}_{\gamma\gamma}) > 0$ (* --- e^+e^-c.m.s.)

- **3-body kinematical cut for π^0 energy $E^*_{\gamma\gamma}$**

  Energy-momentum conservation using direction of $\mathbf{p}_{\gamma\gamma}$, and $m_{\gamma\gamma} = m_{\pi 0}$

  $0.85 < (\mathbf{E}_{ratio} \equiv E^*{}_{\gamma\gamma}{}^{measured}/E^*{}_{\gamma\gamma}{}^{expected}) < 1.1$

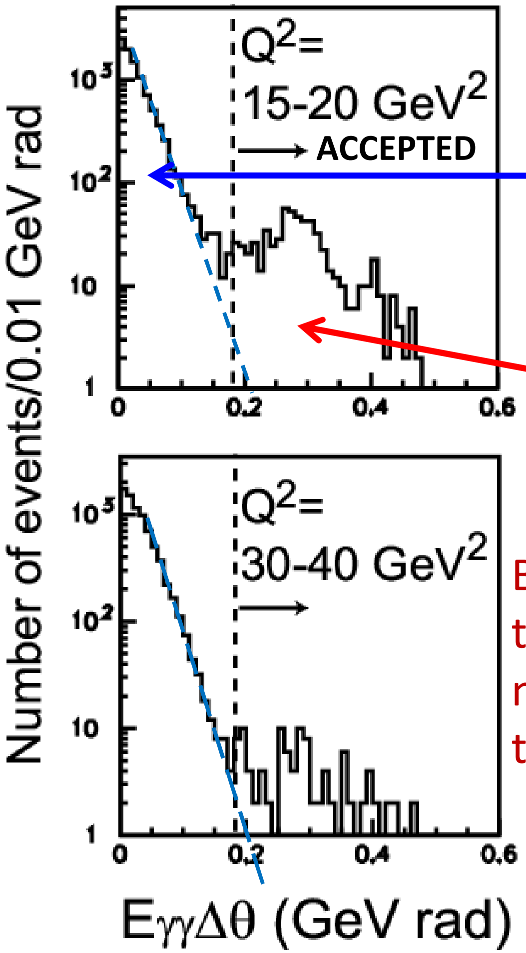
- Bhabha-background rejection, Acollinearity angle(e, γγ) < 177° in e^+e^- c.m. frame
- **Good balances in azimuthal angle and p_t** between e and π^0

  Acoplanarity angle(e, γγ) < 0.1 rad, $|\Sigma \mathbf{p}_t|<0.2$ GeV/c

Background rejection and signal enhancement

$\Delta\theta$: Polar-angle difference of $\gamma\gamma$
is used to reject 2 clusters from $\gamma \to ee$

π^0-mass region only

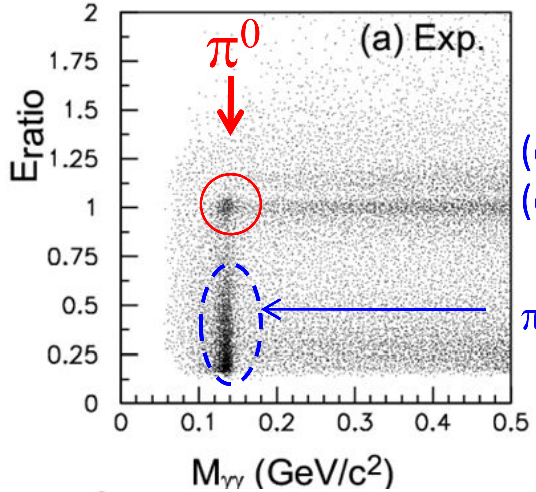


Background from (e)eγ with a conversion

π^0 Signal

Backgrounds from the conversion is negligibly small after the cut.

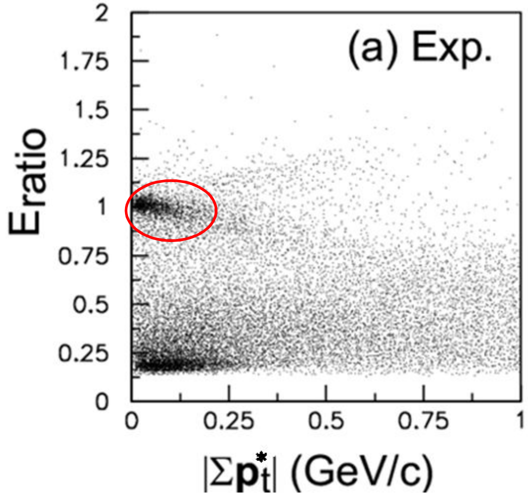
$E_{ratio} \equiv E^*_{\gamma\gamma}{}^{measured} / E^*_{\gamma\gamma}{}^{expected}$



(e)eγ
(e)e$\gamma\gamma$

π^0X background

◯ Signal

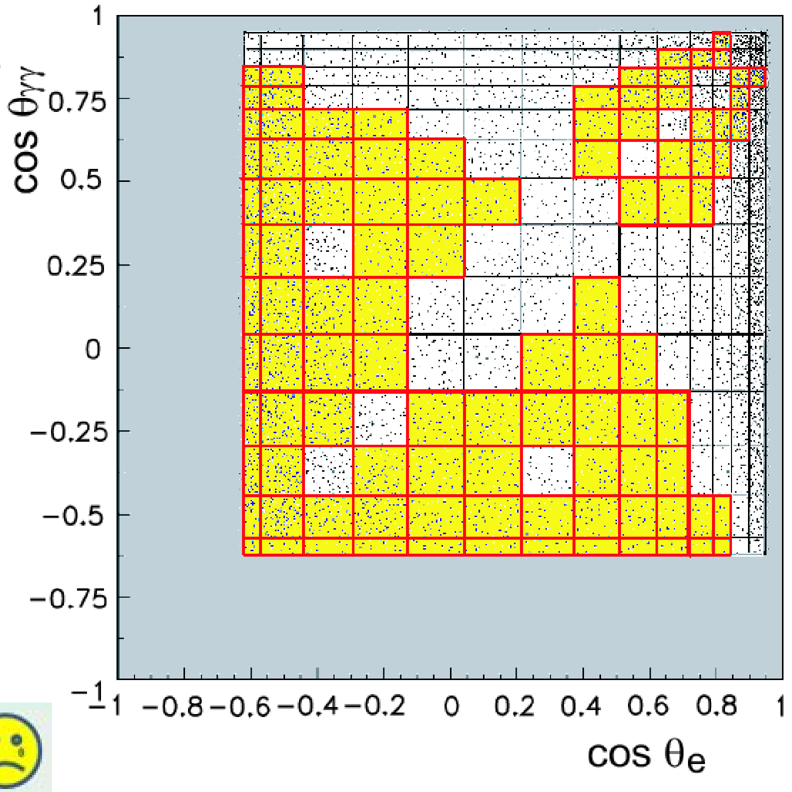


Concentration near $|\Sigma \mathbf{p}^*_t| = 0$

Bhabha Mask; Unbiased sample

Bhabha-Mask criteria (Yellow regions for selection)

masks low-efficiency regions due to Bhabha veto in ($\cos\theta_e$, $\cos\theta_{\gamma\gamma}$)
to reduce uncertainty from trigger inefficiency



Unbiased sample using CsIBB trigger (1/50)

Effects from the Bhabha-veto is compensated in

Nevent(HiE) + 50*Nevent(CsIBB)

≡"**Unbiased sample**"

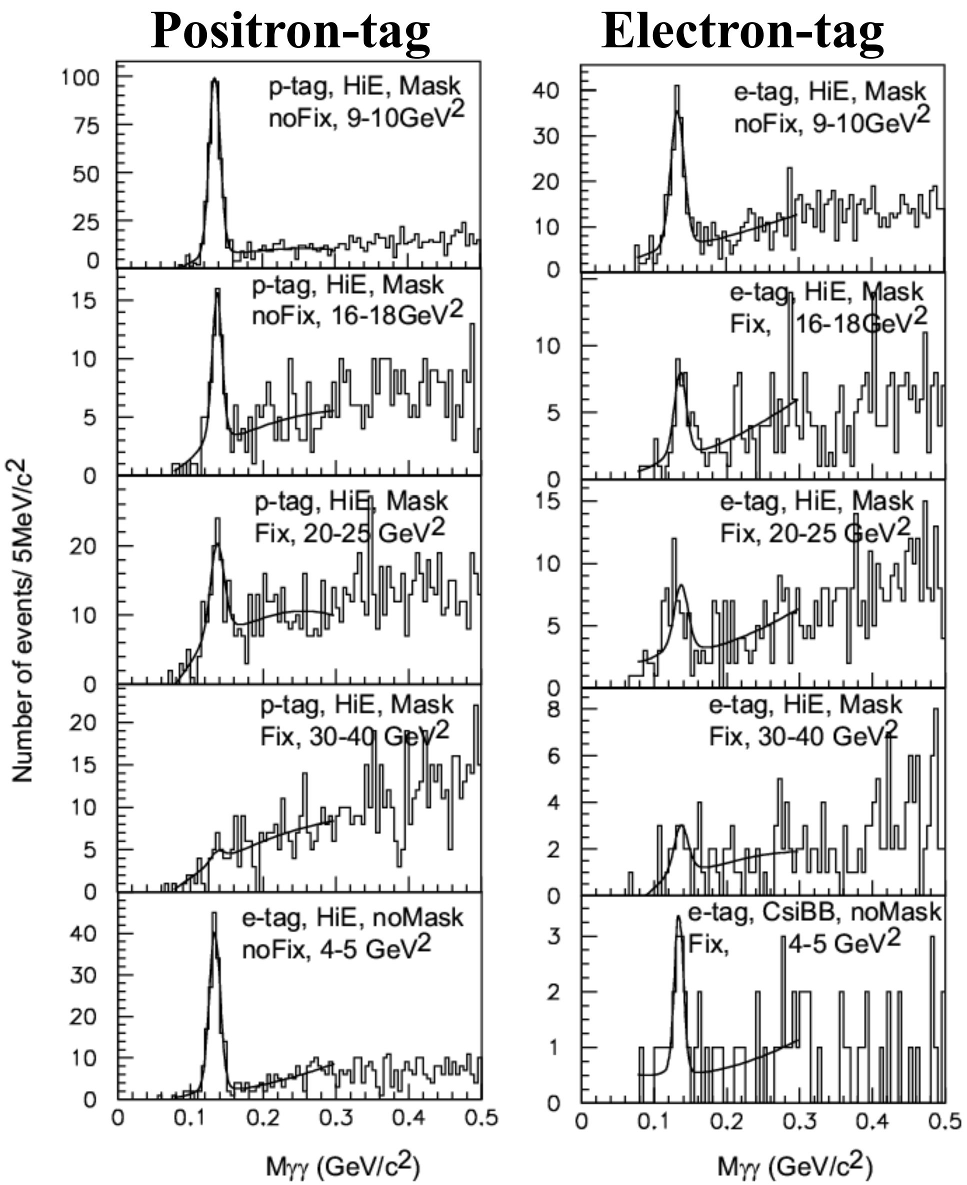
Statistically too small for the signal analysis

e-tag $4 < Q^2 < 6$ GeV^2 : HiE+50*CsIBB sample

other regions: HiE sample only

Extensively used for tuning and evaluation of the trigger simulator

Extraction of π^0 Yield

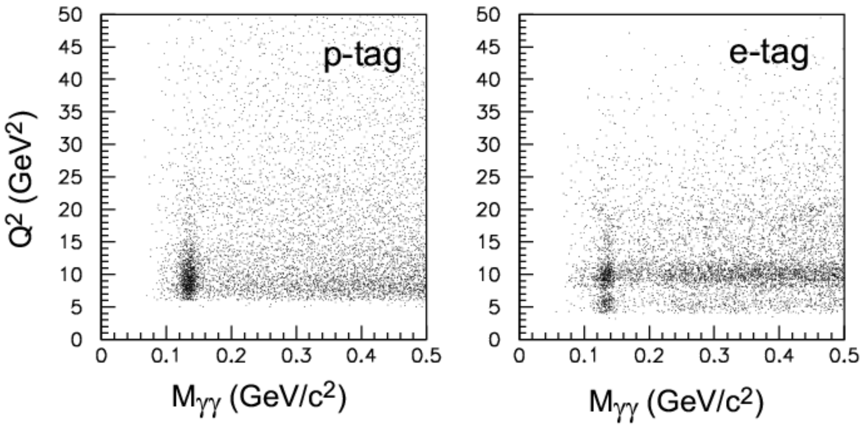


Fit $M_{\gamma\gamma}$ distribution by

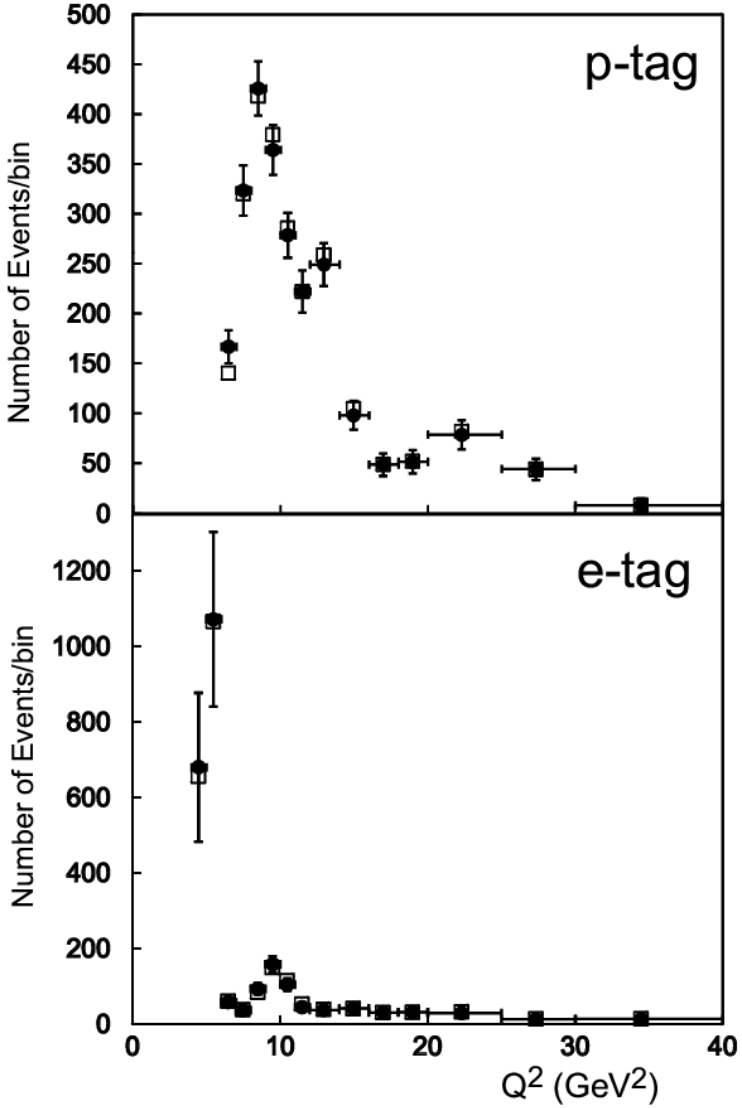
- Double Gaussian (for signal)
- + 2^{nd}-O^{rder} Polynomial (for background)
- in each Q^2 bin

π^0-mass resolution

- the narrower Gaussian component
  - 6 – 9 MeV (dependent on Q^2 = 4 – 40 GeV^2)
  - consistent between the exp. and MC
- the wider ~ 2.4 times larger than the narrower



Signal Yields ; Q^2 Unfolding



Q^2 – unfolding is applied
using inverted migration matrix
that takes into account the effects from:
- Detector resolution
- ISR at the tagged electron

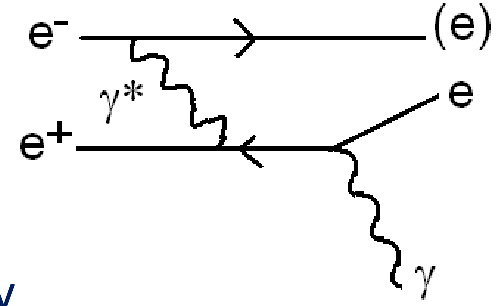
Signal yields
□ Before the unfolding
● After the unfolding

Calibration of Bhabha-veto Thresholds using Radiative-Bhabha (VC) Events

Bhabha-veto threshold is measured in real data

of **Virtual-Compton process of (e)eγ**

and is tuned in Trigger Simulator



MC generator **Rabhat** treats *t*-channel mass singularity

Comput. Phys. Commun. 55, 337 (1989)

VC process has a similar topology to the signal process

Require a single γ instead of π^0

Big cross section (~ O(1nb))

In **unbiased sample,** enough statistics available

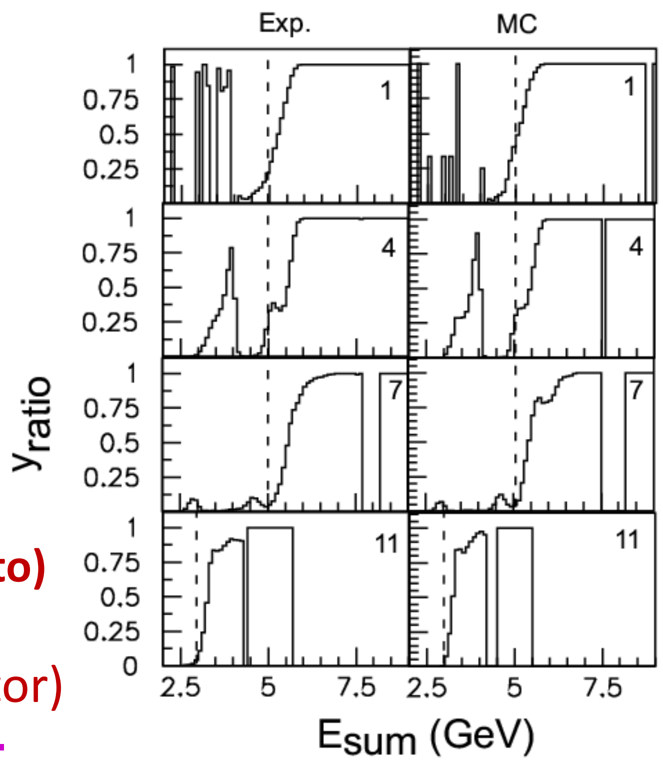
Bhabha-veto condition: ΣE(at least one of 11 patterns) > E_{thres}

$$y_{ratio} = \frac{50*N(CsiBB)}{N(HiE)+50*N(CsiBB)}$$

Trigger Efficiency for Bhabha (-veto)

as a function of energy deposit

→ tune MC (trigger simulator)



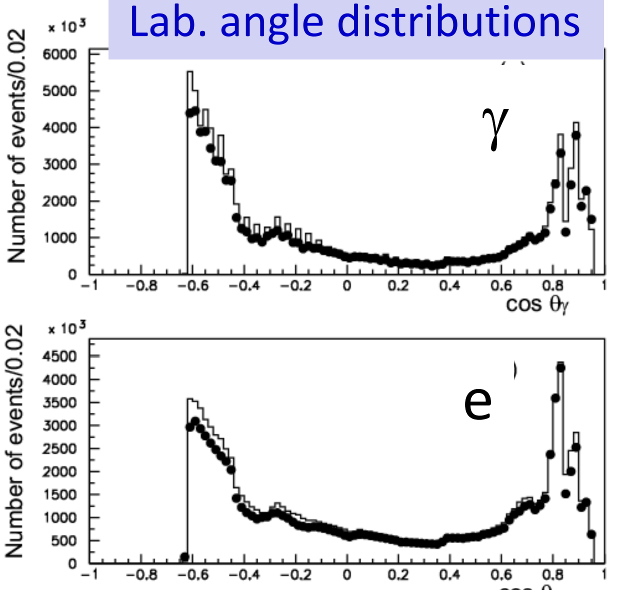
Comparisons in Radiative Bhabha (VC) samples

MC (Rabhat) is normalized by int. luminosity

For HiE (Bhabha-Masked) sample

Lowest order-only -- δ(rad.corr.)~ -6% (±4%) applied

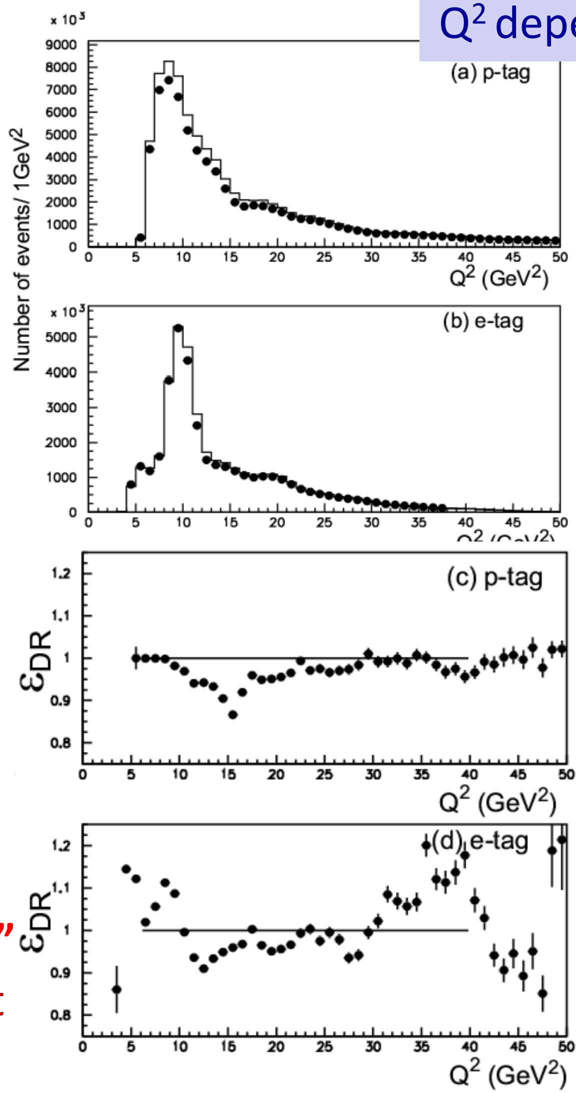
Lab. angle distributions

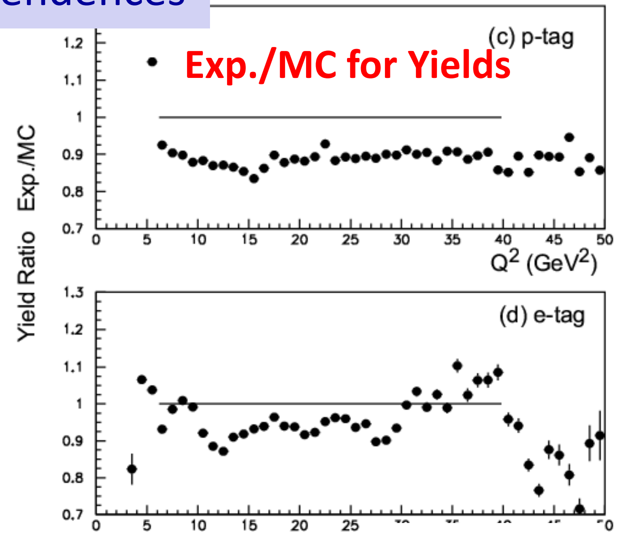


dots: Exp.
histograms: MC

cos θ

Q^2 dependences





Q^2 (GeV^2)

Horizontal line (=1): Expectation

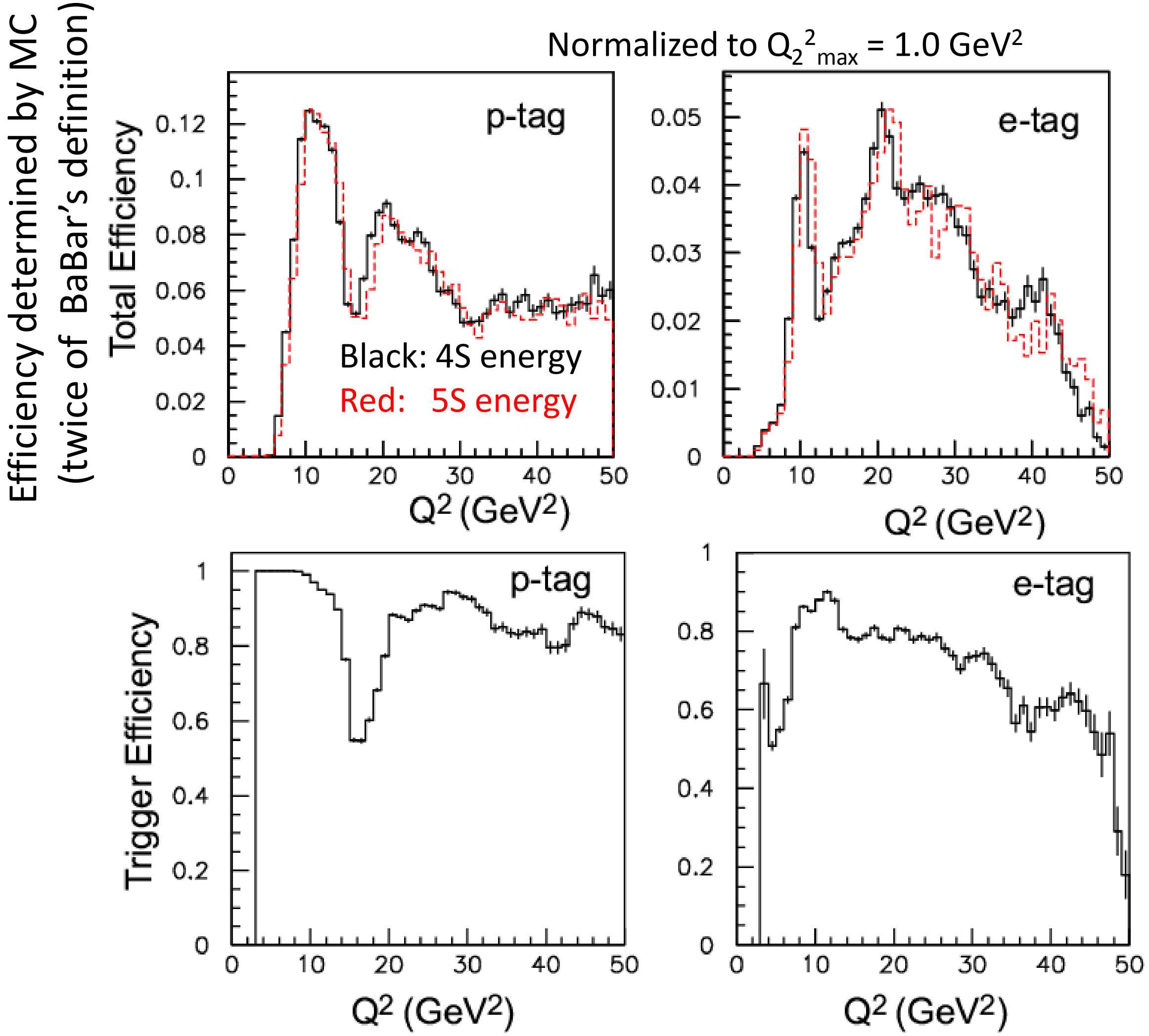
5-10% disagreement is explained by uncertainties in radiative correction and systematic uncertainty in the measurement

ε_{DR}:

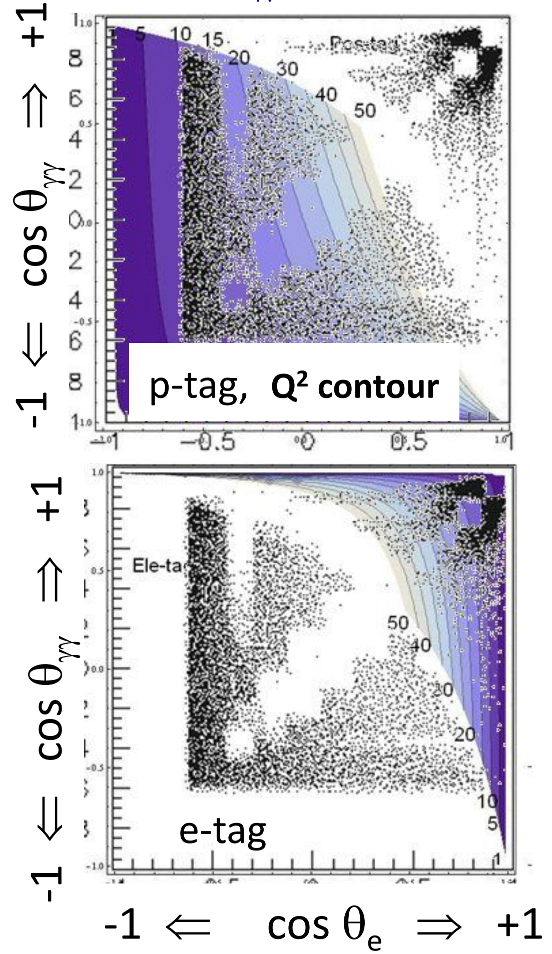
Exp./MC Ratio for Efficiency for "Bhabha-Mask" × "Bhabha-veto" →

shows a better agreement between Exp. and MC

Efficiency for the Signal Process



Up-down structures are reflection of Bhabha-mask and –veto correlated to Q^2 in ($\cos\theta_e$, $\cos\theta_{\gamma\gamma}$) plane

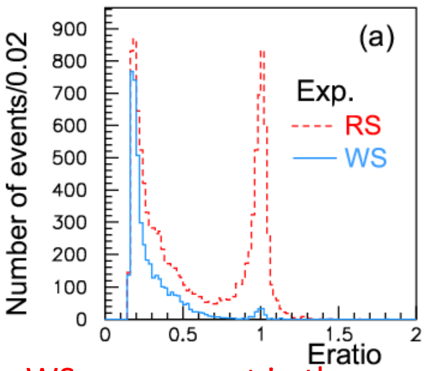


The trigger efficiency is defined for the acceptance after the selection

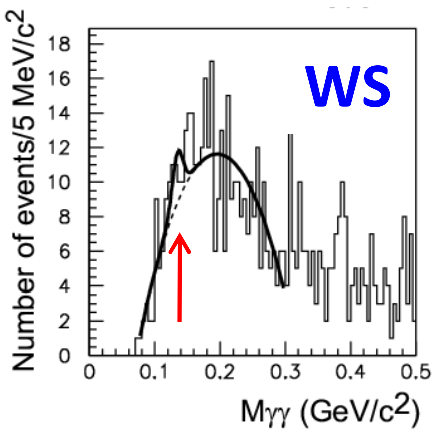
Peaking (π^0) Backgrounds

(e)eπ^0X --- Backgrounds peaking at the pion mass,
which leak near to (E_{ratio}=1, $|\Sigma p_t|$=0)

(1) Study of wrong-sign events (defined by the charge vs. *z*-direction correlation)



WS component in the signal region is very small



No π^0 is there (1.2 ± 0.9 events)

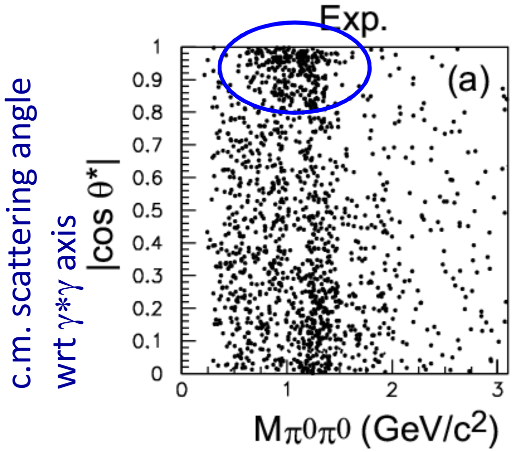
Backgrounds from e^+e^- annihilation and particle misidentification (of muon or hadron) are **negligibly small.**

(2) Background processes

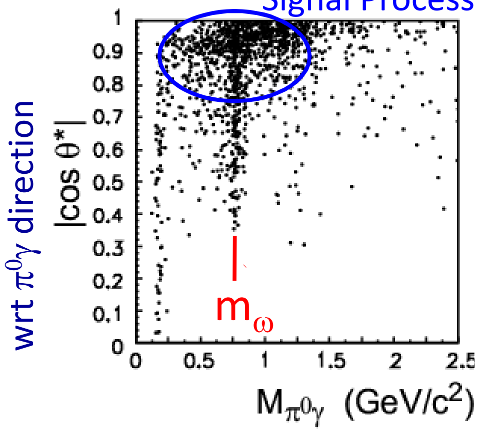
$\gamma\gamma^* \to \pi^0\pi^0$

ee→(e)e ρ^0/ω, $\rho^0/\omega \to \pi^0\gamma$

are **experimentally observed**



Noise from Signal Process



We build background MC's normalized to these observations

Background contamination estimated

$\pi^0\pi^0$: 2% uniformly for Q^2

$\pi^0\gamma$: 0.8% @ Q^2 < 12 GeV^2

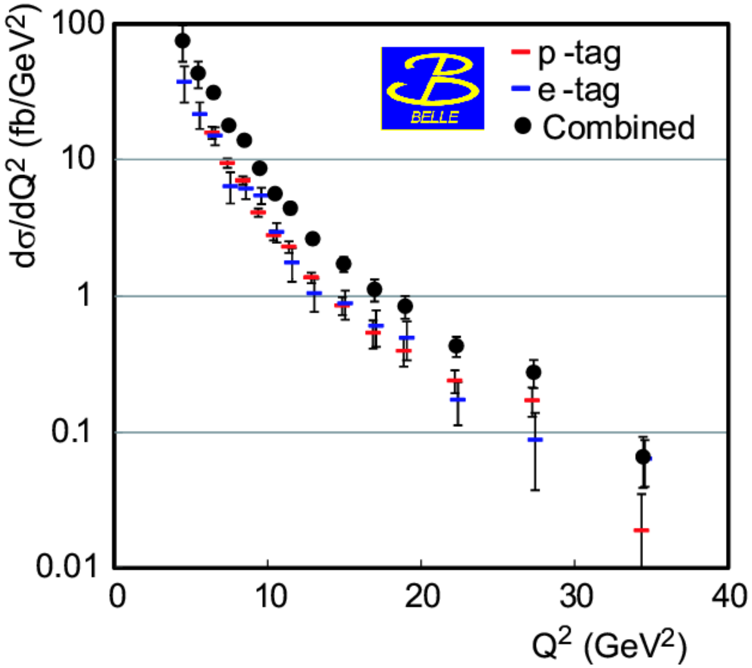
1 – 3% @ 12 – 40 GeV^2

Cross Section

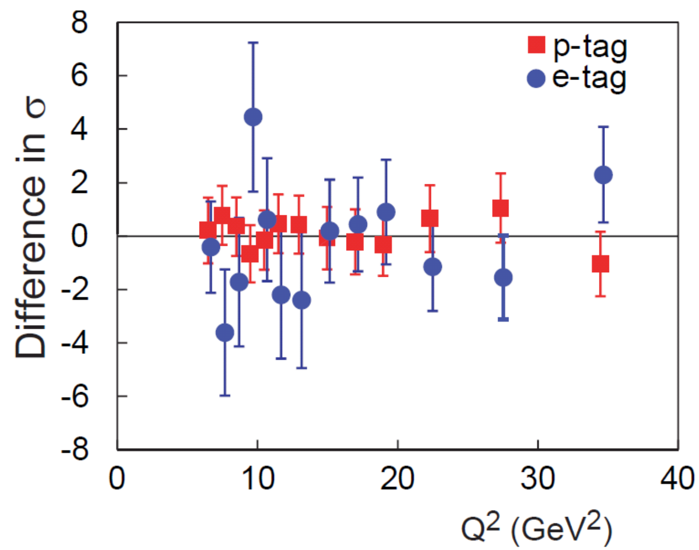
$$\frac{d\sigma}{dQ^2} = \frac{N\,(1-r_b)}{\int Ldt\ \ eff\ \ B(\pi^0 \rightarrow \gamma\gamma)\ (1+\delta)\ \Delta Q^2}$$

r_b: background fraction
eff -- signal selection efficiency
d : radiative correction = +2%

The cross sections from p-tag and e-tag are evaluated, separately, and then combined.



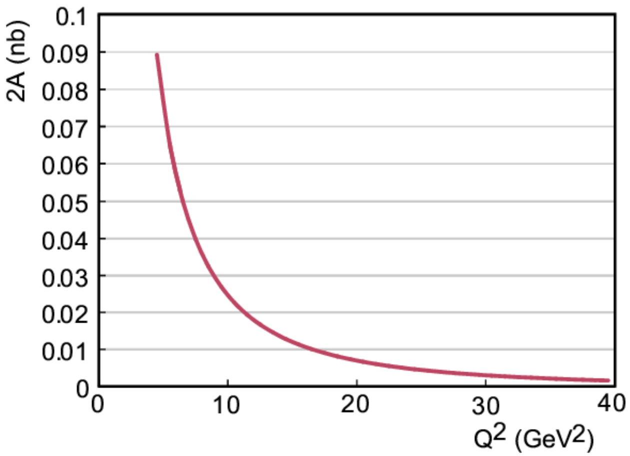
Q^2_{max} = 1.0 GeV² for the less-virtual photon
Corrected for √s = 10.58 GeV

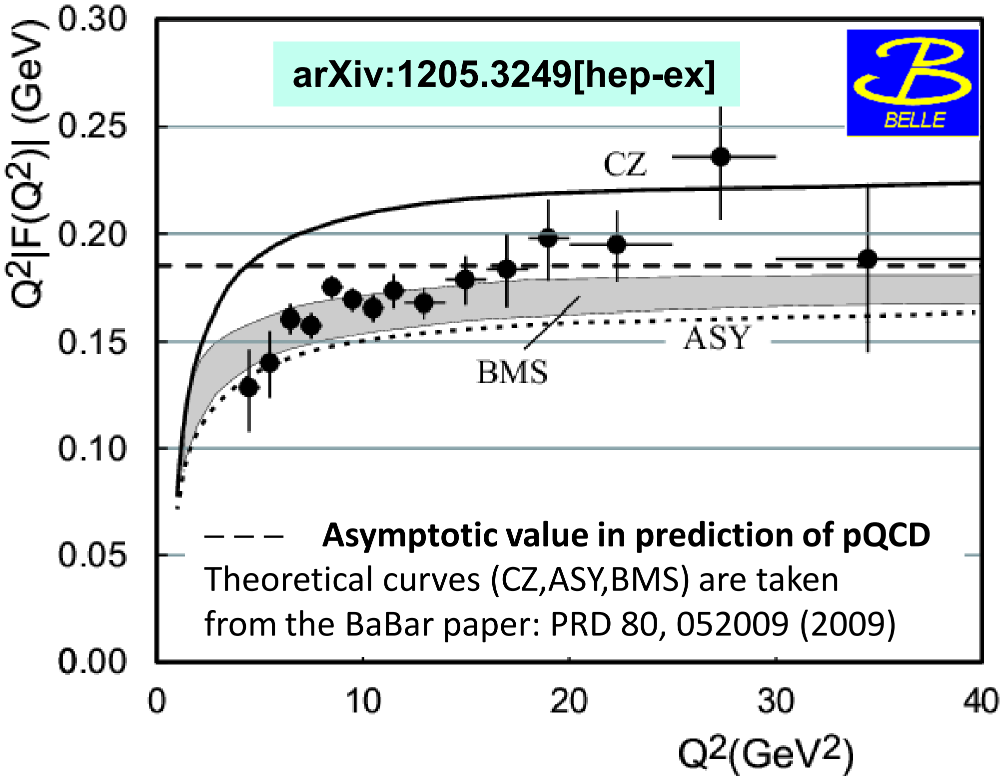


No systematic bias found between the p-tag and e-tag results.

Transition Form Factor

$$Q^2|F(Q^2)| = Q^2\sqrt{(d\sigma/dQ^2)/(2A(Q^2))}$$





Representative value $\overline{Q^2}$ is used for

Q^2 point that gives the cross section with the same size as the mean over the bin calculated using an approximated dependence, $d\sigma/dQ^2 \sim Q^{-7}$

Systematic Uncertainties

For Cross Section:

Q^2 independent:	Tracking	1%
	e-ID	1%
	$\gamma\gamma$ reconstruction	3%
	kinematical selection	2%
	geometrical selection	2%
	beam background	2%
	integrated luminosity	1.4%
	radiative correction	3%
	form-factor effect	1.0%

(subtotal 6%)

Q^2 dependent: Extraction of π^0-yield 5–10% estimated variation of fit (single Gauss + linear fit)

Trigger efficiency 2–12%

estimated by studies of trigger threshold & Rad.Bhabha events

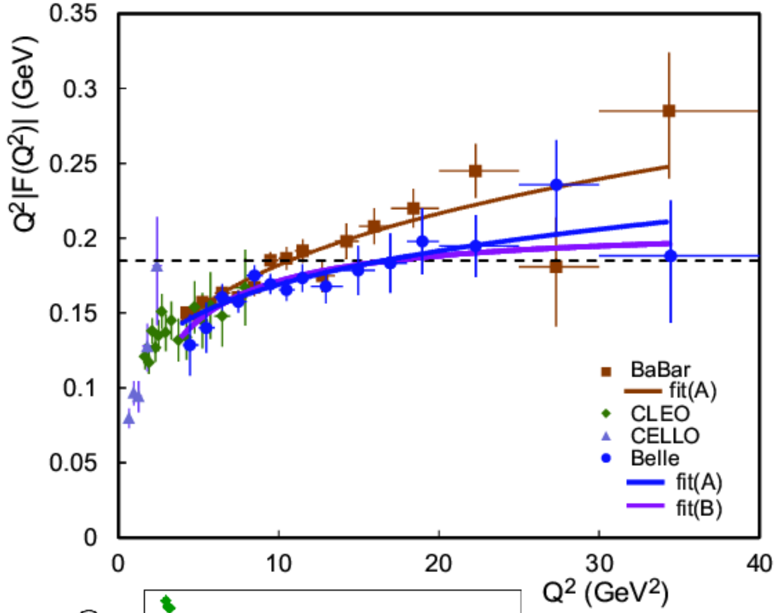
Peaking-background 1 – 4% 8 – 14% in total

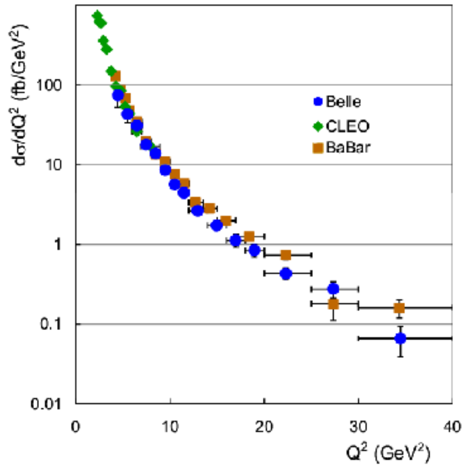
For Transition Form Factor:

Half of the above values, as $|F| \sim \sqrt{d\sigma/dQ^2}$

with **added by an** uncertainty of $2A(Q^2)$ -- 2% (form-factor effect for the low-Q^2photon)

Comparisons with Previous Measurements and Fits





Fit A (suggested by BaBar)

$Q^2|F(Q^2)| = A\,(Q^2/10\text{GeV}^2)^\beta$

BaBar: —

$A = 0.182 \pm 0.002\ (\pm 0.004)$ GeV

$\beta = 0.25 \pm 0.02$

Belle: —

$A = 0.169 \pm 0.006$ GeV

$\beta = 0.18 \pm 0.05$

$\chi^2/\text{ndf} = 6.90/13$ ~1.5σ difference from BaBar

Fit B (with an asymptotic parameter)

$Q^2|F(Q^2)| = BQ^2/(Q^2+C)$

Belle: —

$B = 0.209 \pm 0.016$ GeV

$C = 2.2 \pm 0.8\ \text{GeV}^2$

$\chi^2/\text{ndf} = 7.07/13$

B is consistent with the QCD value (0.185GeV)

No rapid growth above $Q^2 > 9\text{GeV}^2$ is seen in Belle result.

Summary

- The π^0 transition form factor is measured at Belle in the range, $4\ \mathrm{GeV}^2 \lesssim Q^2 \lesssim 40\ \mathrm{GeV}^2$.

  There was a significant effect from Bhabha-veto, but the trigger simulator to estimate the signal efficiency is tuned, reliably, calibrating it using radiative Bhabha events.

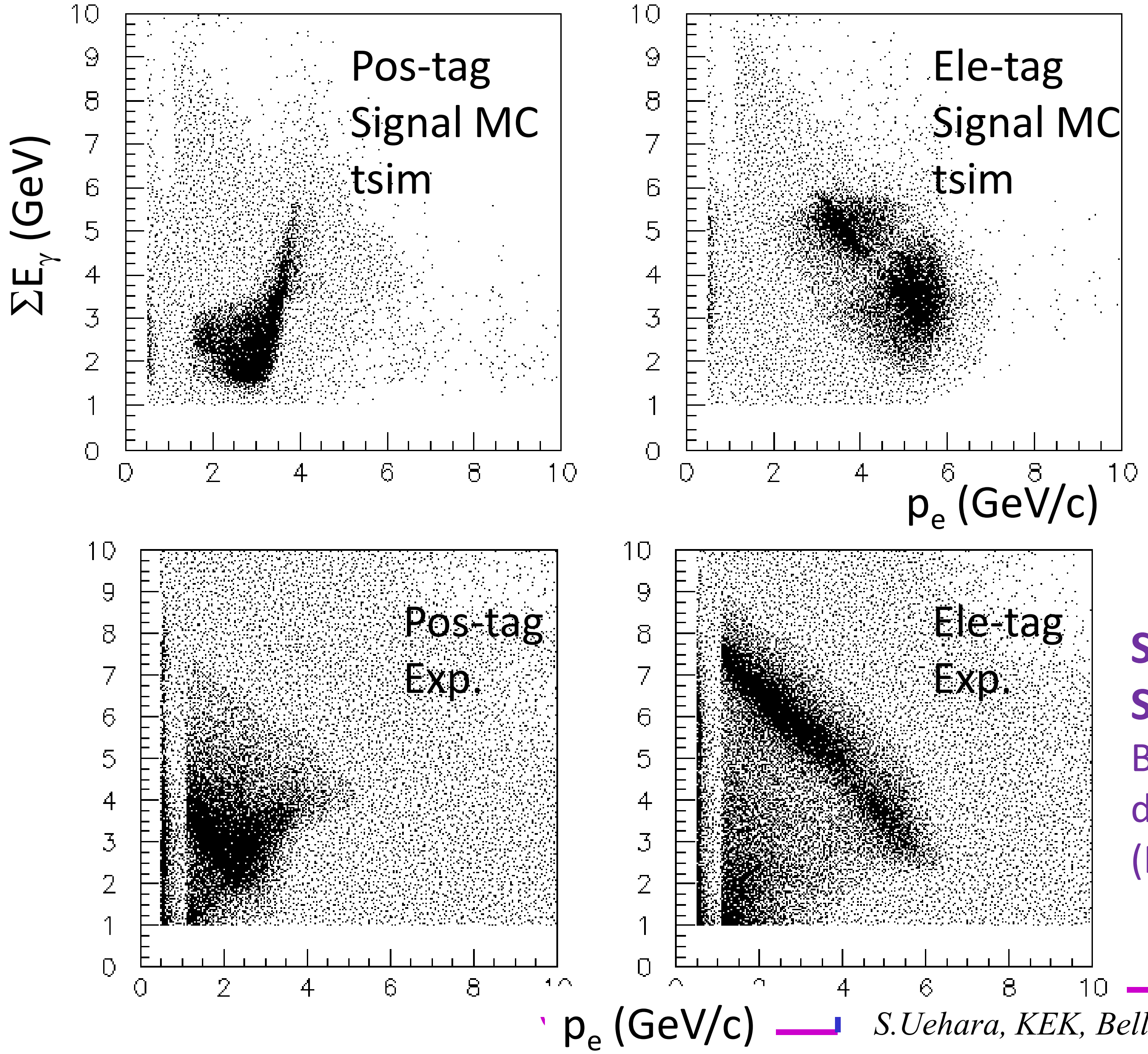
- No rapid growth of π^0 TFF is observed for the region $Q^2 > 9\mathrm{GeV}^2$.

- Phenomenological fits are applied for Q^2 dependence of π^0 TFF.

Belle
arXiv:1205.3249[hep-ex] (2012)
Submitted to Phys. Rev. D

Backup

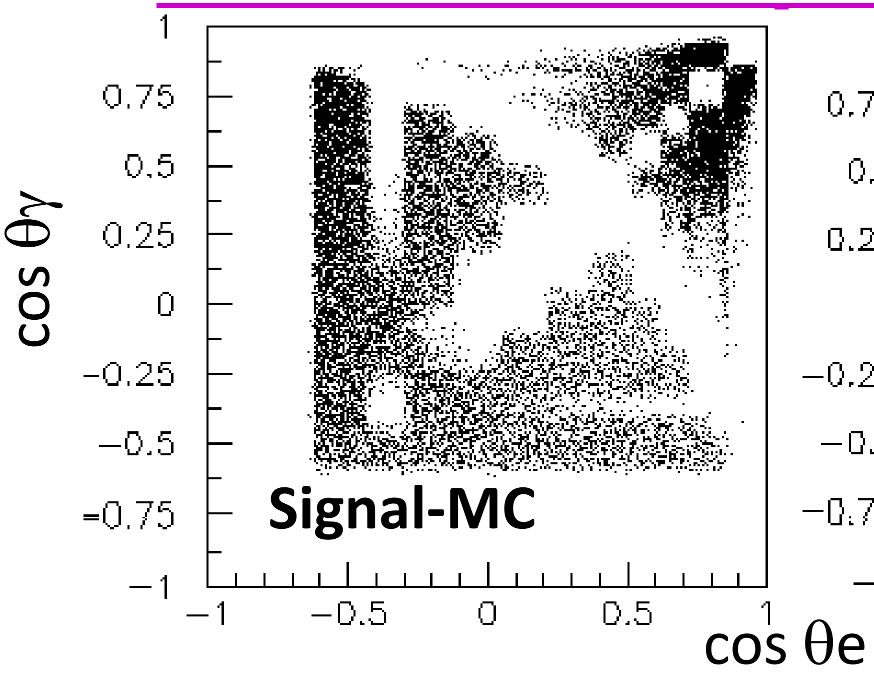
Energy-correlations in the skim file, $\Sigma E\gamma$ **> 1.0 GeV**

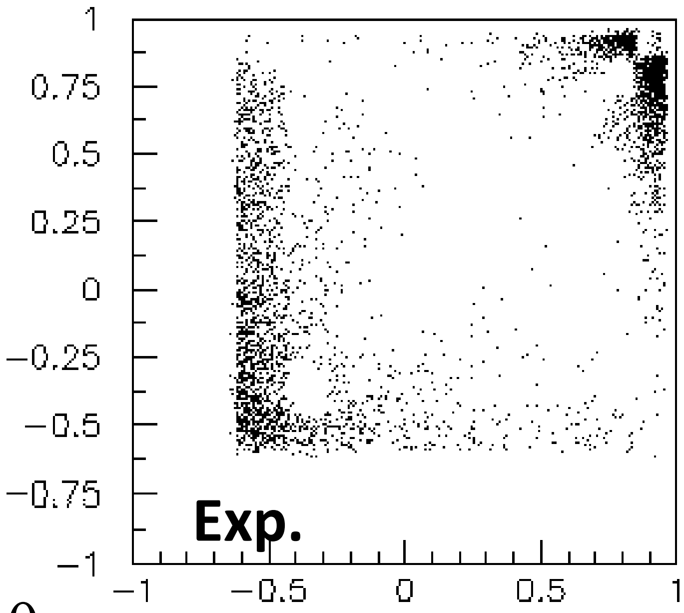


Similar distribution to Signal-MC.

But, the exp. events are dominated by backgrounds (Radiative Bhabha)

Effect of Bhabha-veto in angle correlation





Bhabha-mask is not applied

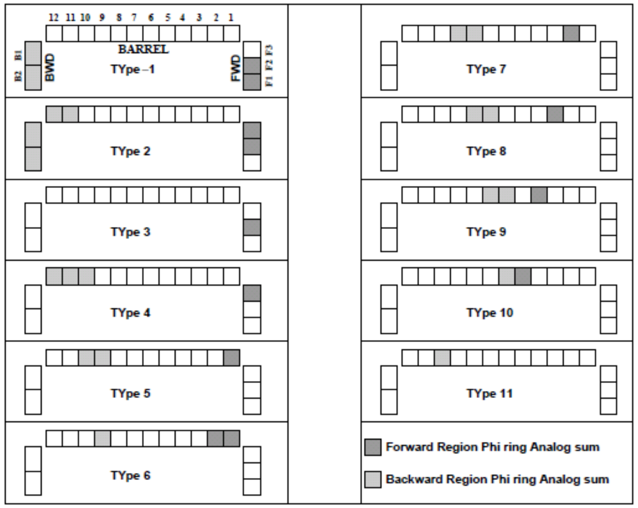
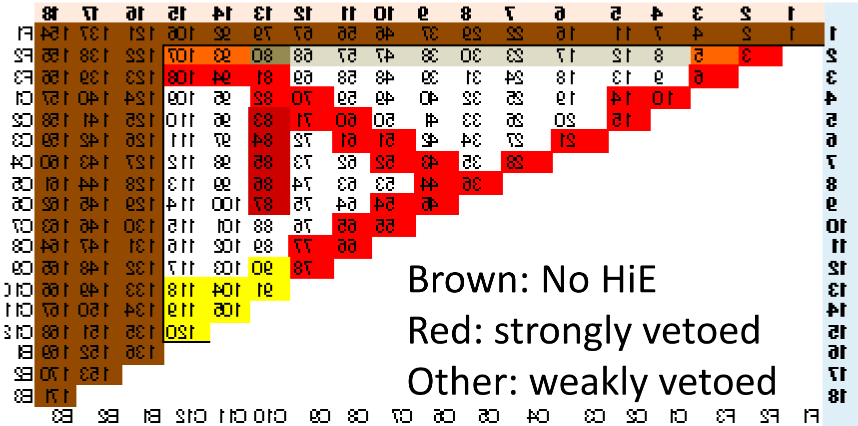


Fig. 4. Eleven types of Bhabha triggers based on each ϕ-ring sum.

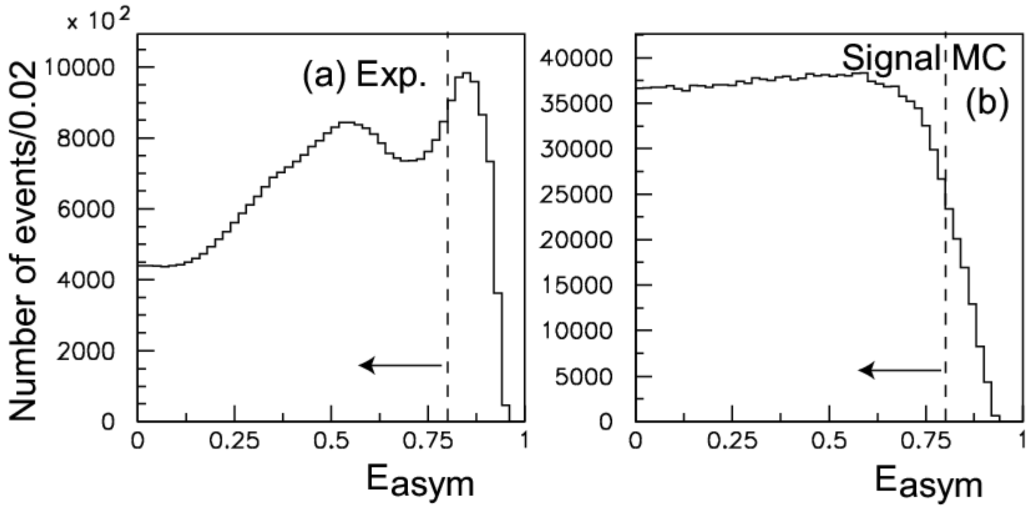
Bhabha-veto patterns in trigger



$\gamma\gamma$ from π^0 and from backgrounds

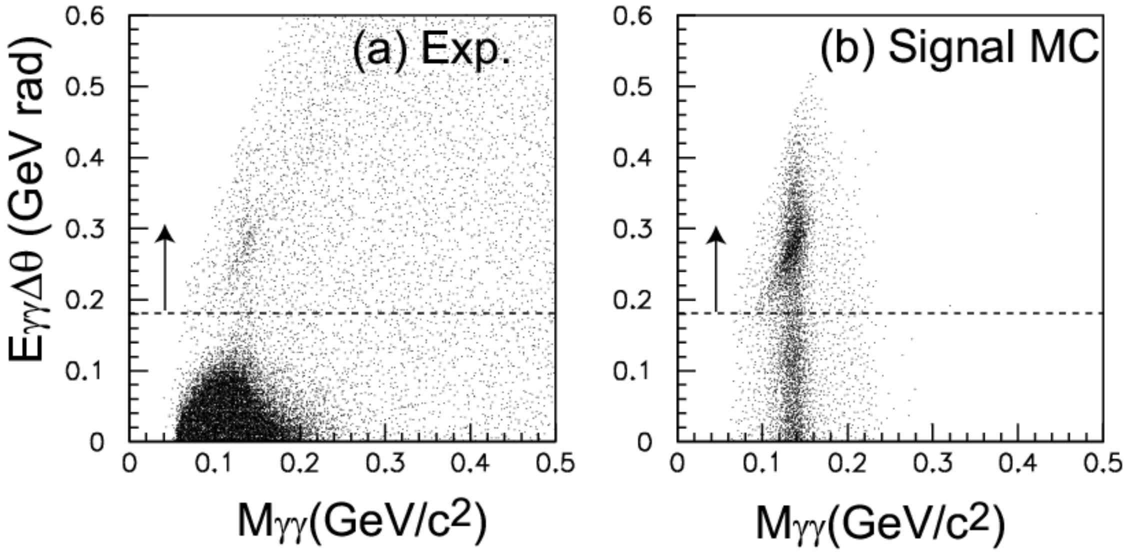
Energy asymmetry

to reject low-energy photon background



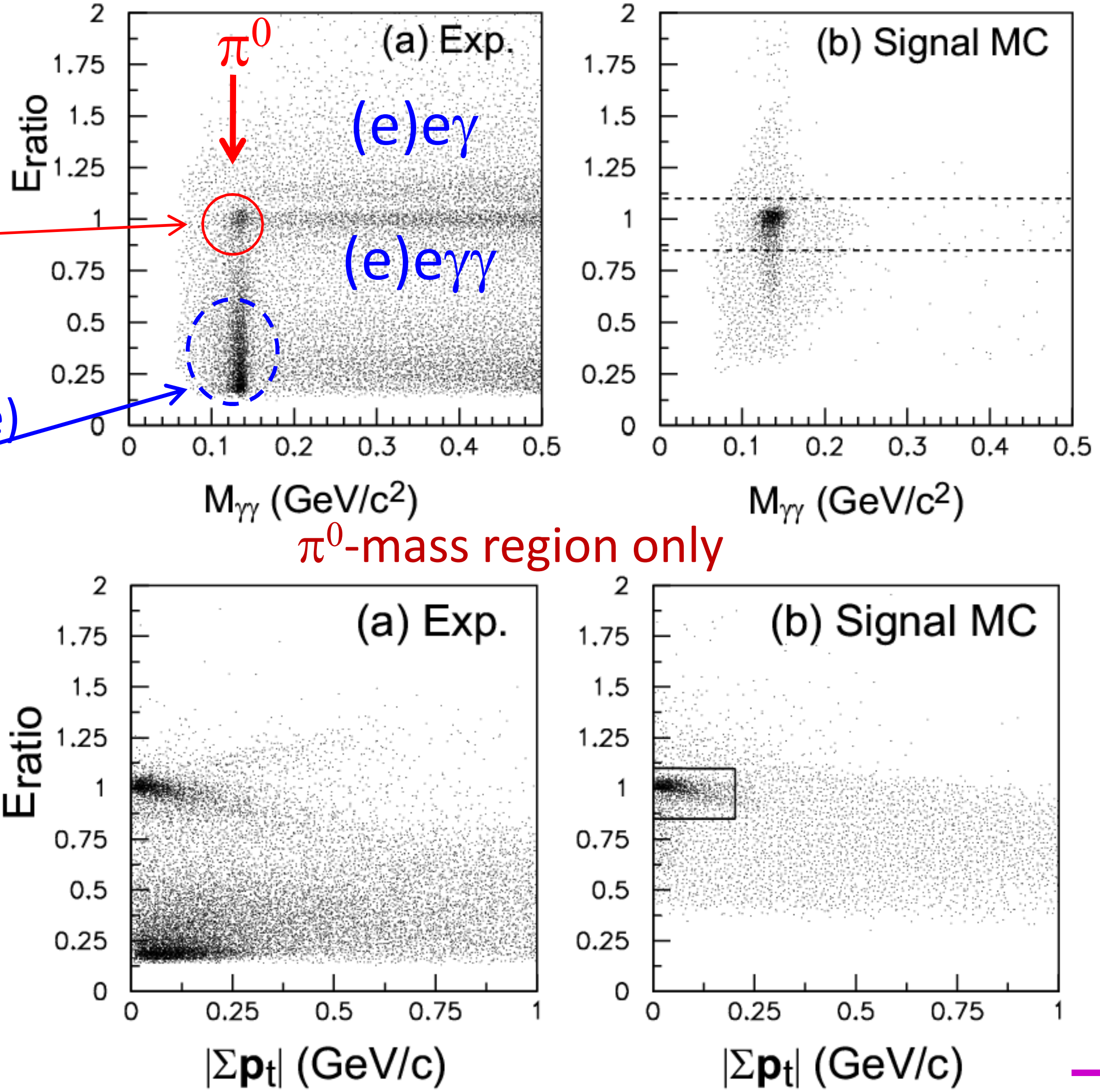
$\Delta\theta$ –Polar-angle difference of $\gamma\gamma$

Used to reject 2 clusters from $\gamma\to ee$



Kenematical Criteria

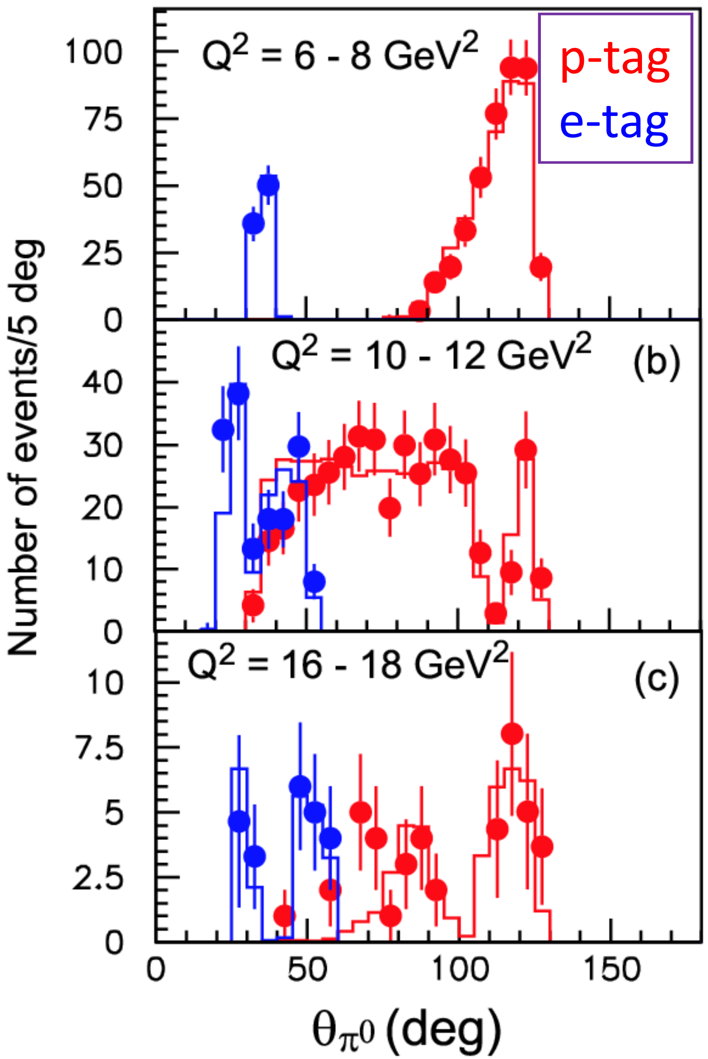
$E_{ratio} \equiv E^*_{\gamma\gamma}{}^{measured} / E^*_{\gamma\gamma}{}^{expected}$



Concentration near $\Sigma \mathbf{p}_t = 0$

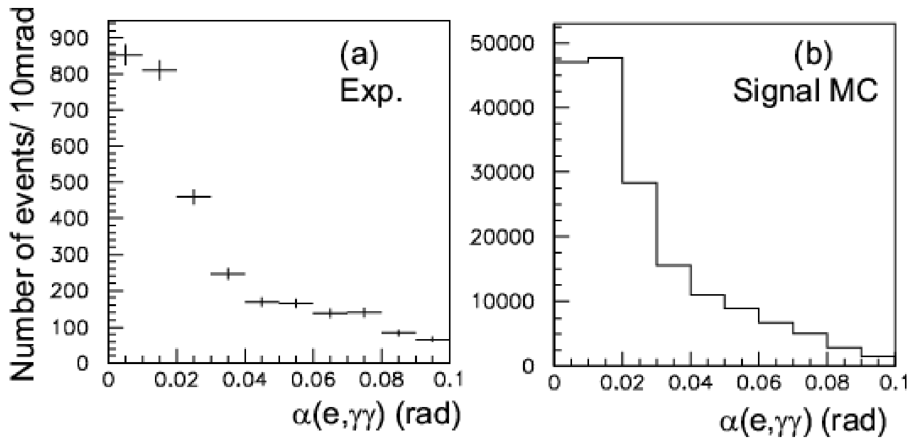
Checks of Signal Details

π^0-angle distribution

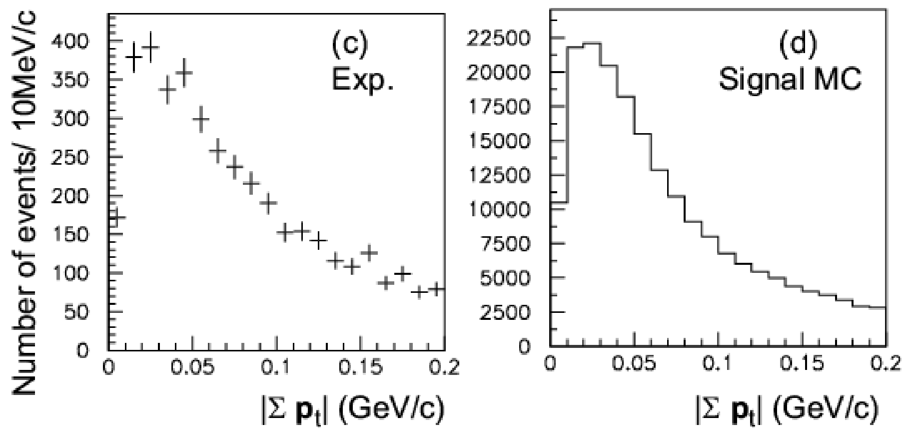


Radiative tails

Acoplanarity angle

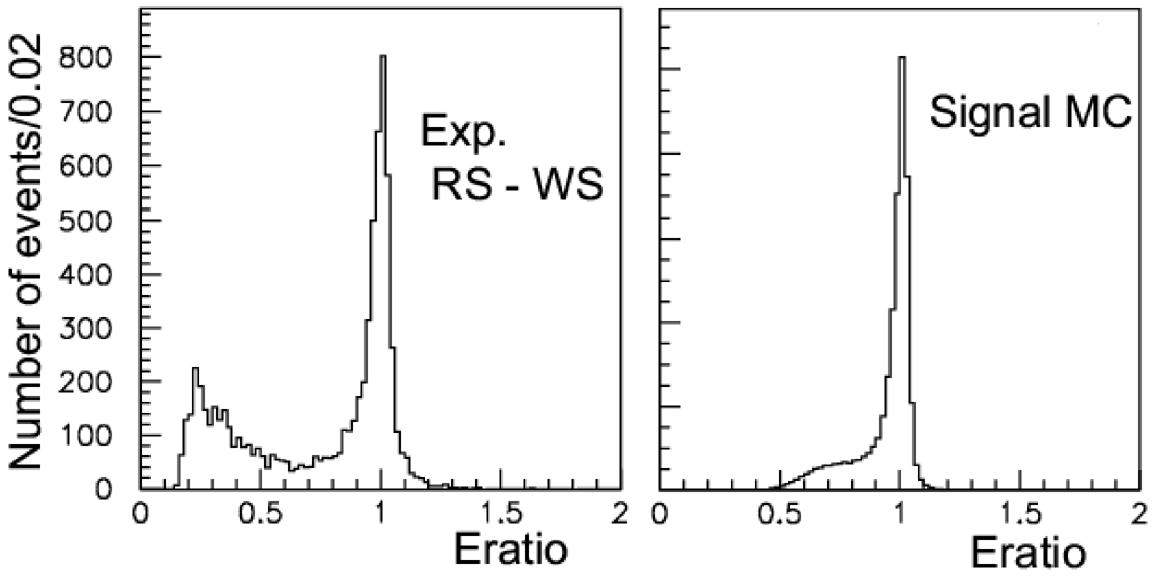


p_t-balance



E_{ratio} tail

Study of **wrong-sign events** defined by the charge vs direction relation.



The tail around E_{ratio}~0.75 is consistent with the expected radiative tail of the signal process.

$M_{\gamma\gamma}$ Fit

Double Gaussian(for signal)+ 2nd-Order Polynomial (background)

$$f(x) \sim a + bx + cx^2 + \frac{A}{\sqrt{2\pi}\sigma}\{re^{-\frac{(x-m)^2}{2\sigma^2}} + \frac{1-r}{k}e^{-\frac{\{x-(m+\Delta m)\}^2}{2(k\sigma)^2}}\}$$

Conversion factor for $|F(Q^2)|$: $2A(Q^2)$

Use the cross section formula by
"Brodsky-Kinoshita-Terazawa" (PRD 4, 1532(1971))

Not using EPA --- not trivial **CLEO, PRD57, 33(1998)**

EPA – Equivalent Photon Approximation

Assume being factorized as

$\sigma_{ee} \sim \int \sigma_{\gamma\gamma}(Q_1^2, Q_2^2)\, N_\gamma(Q_1^2)\, N_\gamma(Q_2^2)$ (we do not assume this)

We assume only the form factors is factorized

$\sigma_{ee} \sim \int a(Q_1^2, Q_2^2)\,|F(Q_1^2, Q_2^2)|^2$, and

$F(Q_1^2, Q_2^2) = F(0, 0)\, f(Q_1^2)\, f(Q_2^2)$, $f(0) = 1$

Furthermore,

we assume $f(Q^2) = 1/(1+Q^2/m_\rho^2)$ when $Q^2<m_\rho^2$

But, $f(Q^2)$ is unknown for $Q^2 > m_\rho^2$ (what we measure)

Define as $F(Q^2) \equiv F(Q^2, 0) = F(0, Q^2) = F(0, 0)\, f(Q^2)$

Conversion factor for $|F(Q^2)|$ (cont.)

$c = F(0, 0) \rightarrow F(Q_1^2, Q_2^2) = c\, f(Q_1^2)\, f(Q_2^2) = c\, f(Q_1^2)/(1+Q_2^2/m_\rho^2)$

-- factorization assumption

Assume some values for c and $f(Q_1^2)$

$\rightarrow d\sigma/dQ_1^2 = A(Q_1^2)\, c^2\, |f(Q_1^2)|^2$ (by BKT formula)

conversion factor $A(Q^2)$ is determined by the calculation

- Single-tag measurement $d\sigma/dQ^2$

Factor 2 : Ele-tag + Pos-tag

$(d\sigma/dQ^2)/2A(Q^2) = c^2\, |f(Q^2)|^2 = c^2\, |f(Q^2)|^2\, |f(0)|^2$

$= |F(Q^2, 0)|^2 = |F(Q^2)|^2$

with the same scheme for the efficiency determination

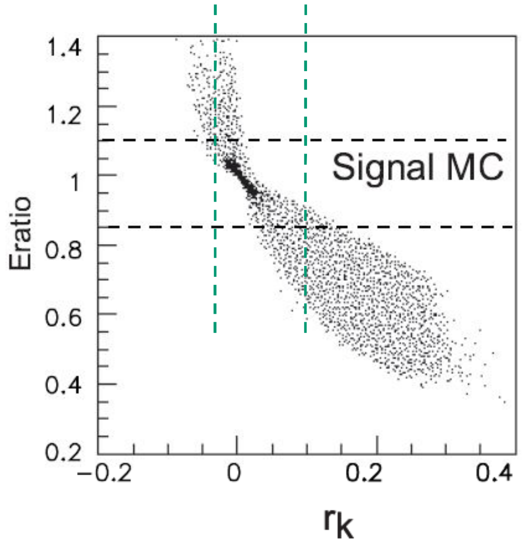
and event generation → Signal MC

Calculation of $A(Q^2)$ coincides BaBar's calculation with the same BKT and the same $f(Q_2^2)$ within 0.1%.

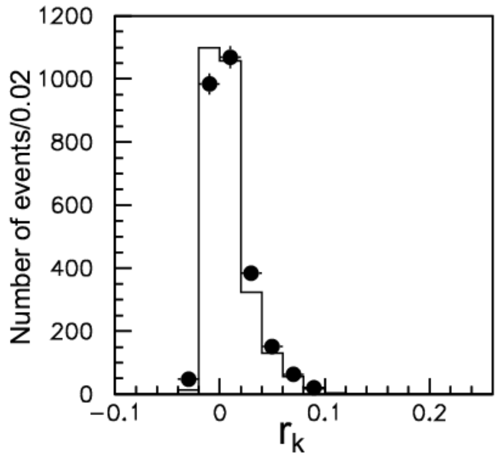
ISR and Radiative Correction

***r_k* ---** Energy fraction of the ISR photon
wrt. the beam energy

The r_k range for the signals is constrained by **E_{ratio} cut**
which roughly corresponds to $-0.03 < r_k < 0.10$



MC event generation includes the ISR effect
by exponentiation technique for ***r_k* < 0.25**



r_k distribution is consistent
between the data and the signal MC,
The selected events are contained in r_k<0.10

Radiative correction for cross section

$1+\delta = 1.02$ (definition: $\sigma_{LO+NLO} = \sigma_{LO}(1+\delta)$,
including +0.03 hadron-loop in vacuum polarization.
with small Q^2 dependence (~1% effect).

Our cross section and TFF are converted to those for the LO.

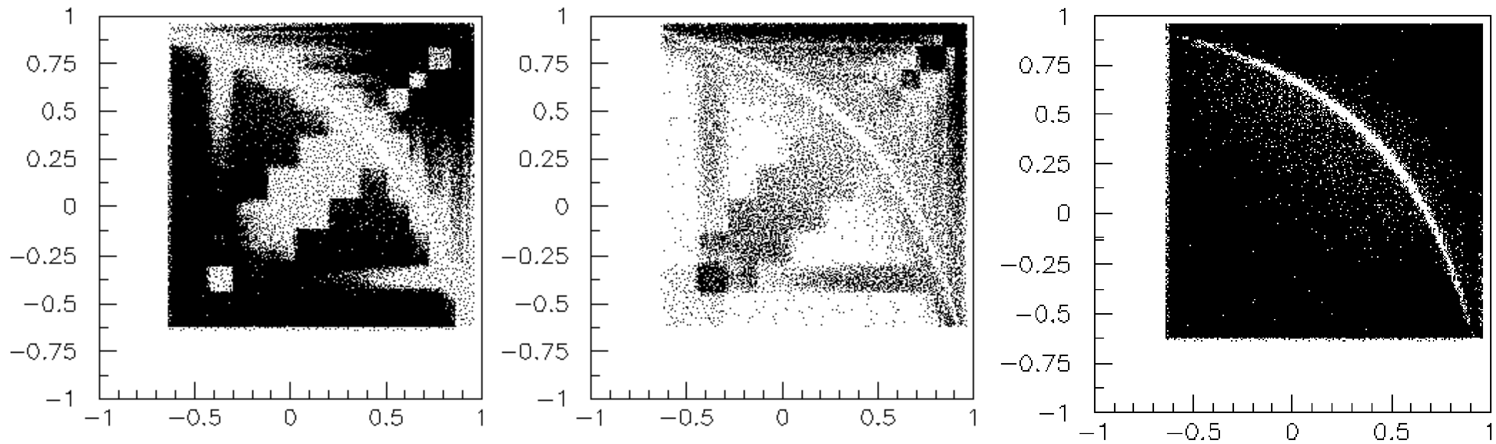
Study of Radiative Bhabha samples

Experimental (e)eγ sample with the similar topology to (e)eπ^0

10,000 times larger statistics (but physics is different…)

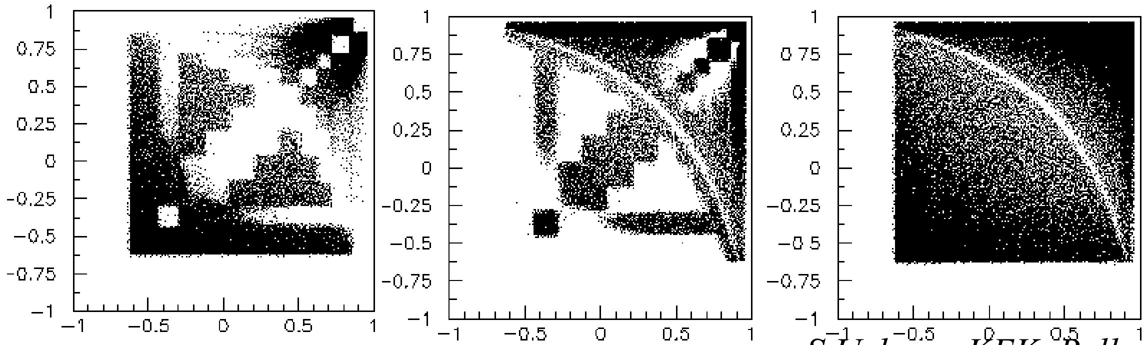
Angle-angle (cos θ_γ vs. cos θ_e) Bhabha-Veto pattern in Exp.data

Exp. Data



HiE CsiBB **Unbiased: HiE + 50*CsiBB**

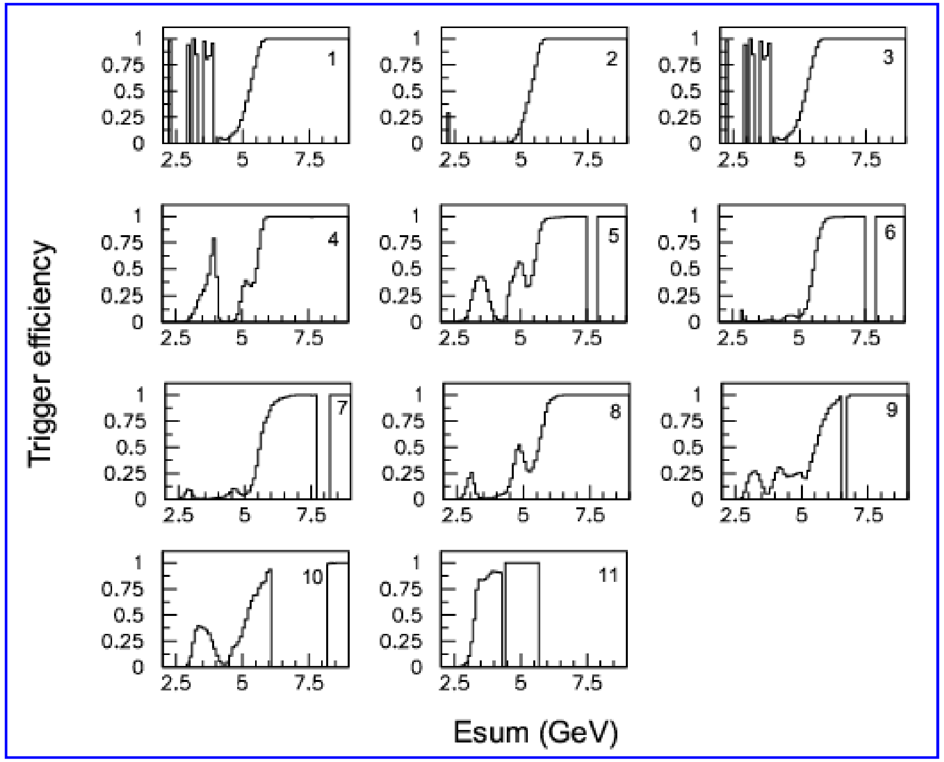
Veto-structure is compensated!



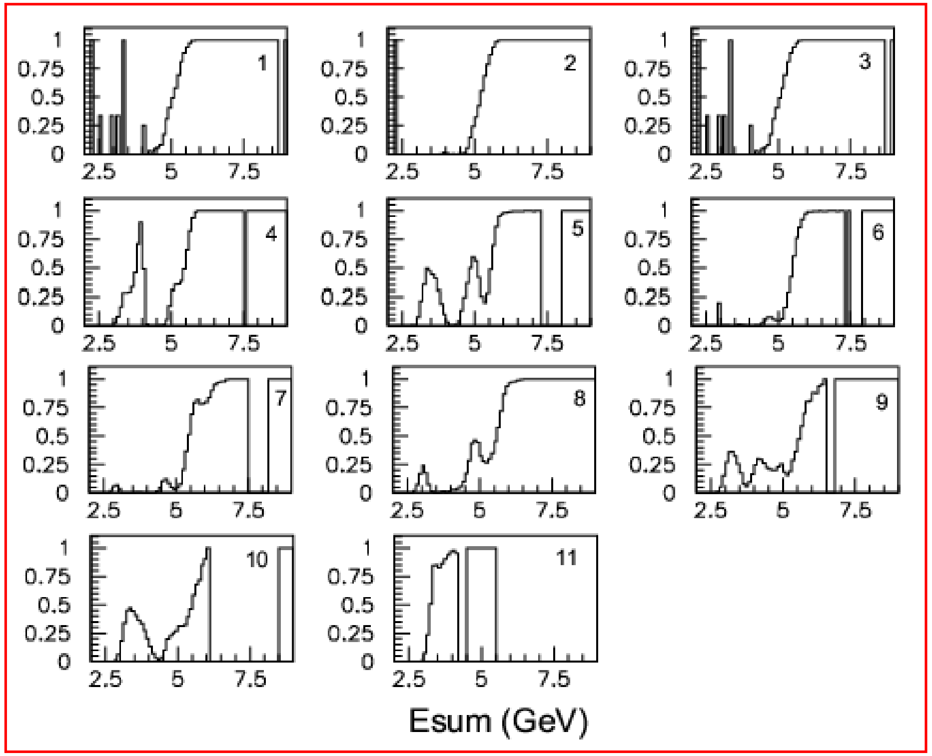
← **MC(Rabhat)**

Tuning of Bhabha-veto thresholds

Looking at N(HiE)/N(Unbiased) as a function of E-deposit in Each ECL-Bhabha trigger segment



Experimental Rad.Bhabha sample



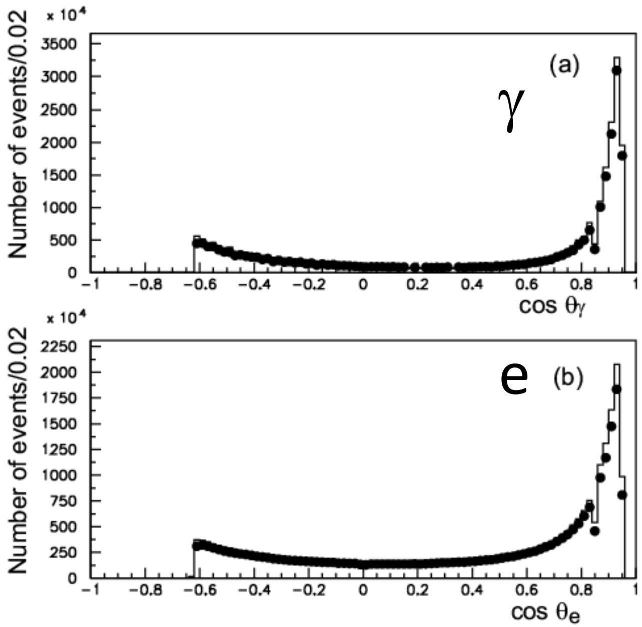
Tuned MC

Comparisons of Radiative Bhabha (VC) samples

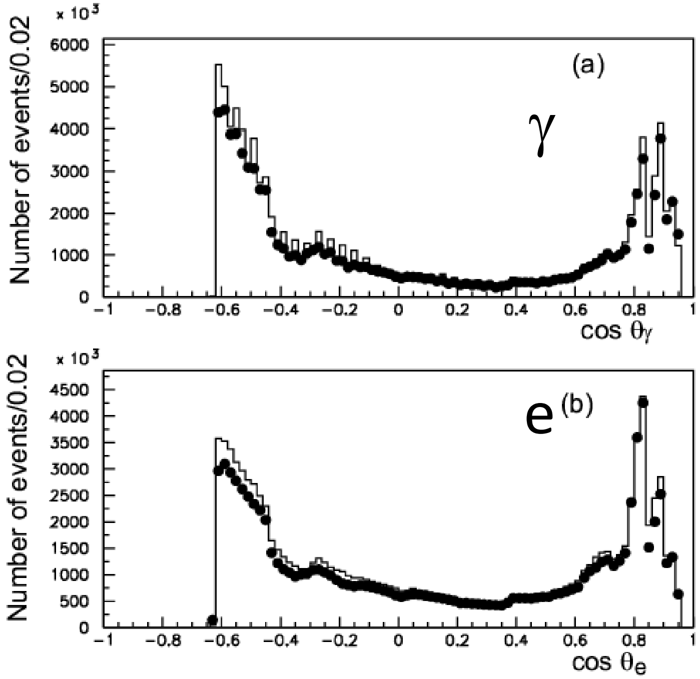
Dots: Exp.
Histograms: MC

Angular cos θ ∈(-1 ,+1)
distributions for γ and e

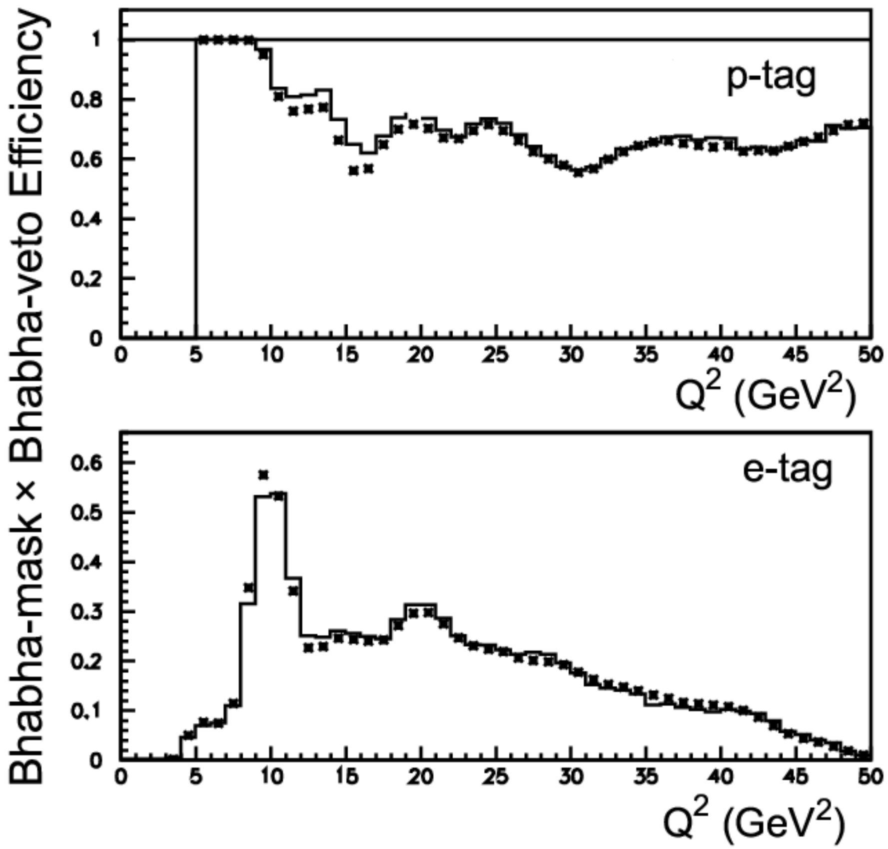
Unbiased



HiE (Bhabha-Masked)



Comparison of Bhabha Mask*Veto efficiency for Radiative Bhabha events

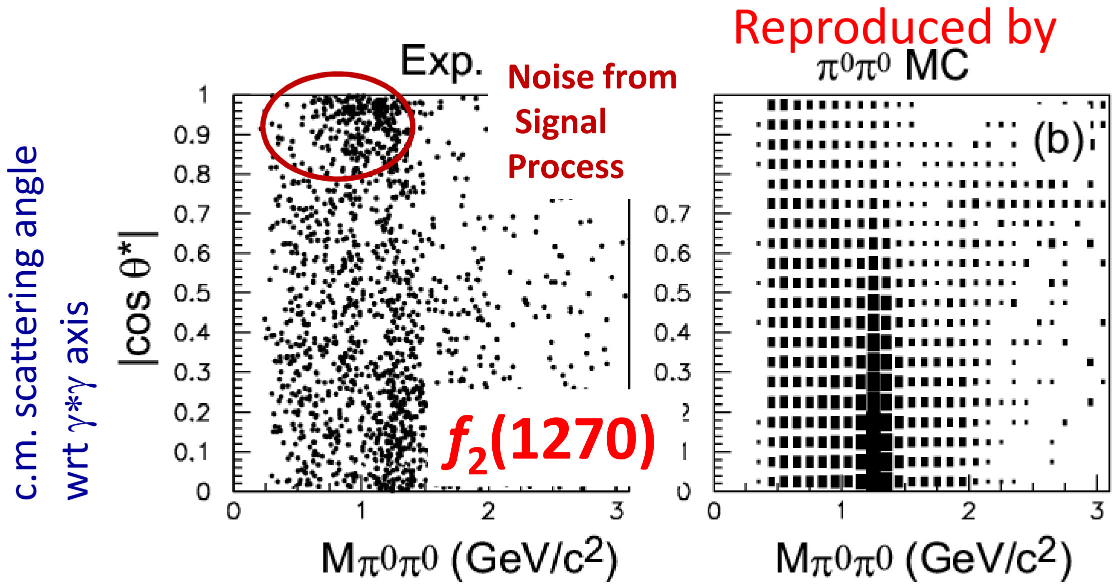


Asterisk: Exp.
Histogram: MC

Bhabha mask*veto efficiency from MC is confident
Within 5 – 12% error depending on Q^2

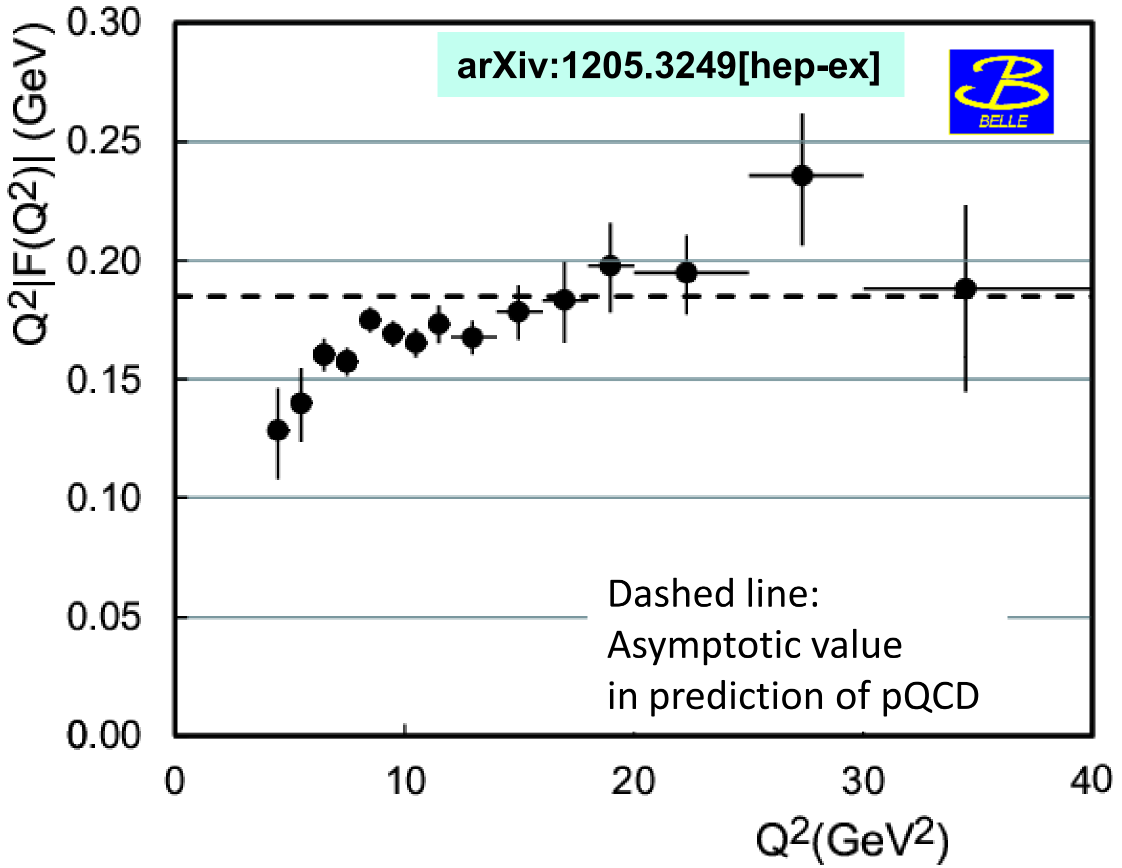
$\pi^0\pi^0$ background MC

Experimentally identified $\gamma\gamma^* \to \pi^0\pi^0$



Background contamination in signal is estimated by the $\pi^0\pi^0$ **background MC** which is normalized to the observation, **as 2%**

Transition Form Factor



Representative value $\overline{Q}^2$ is used for each Q^2 bin

Q^2 point that gives the cross section with the same size as the mean over the bin calculated using an approximated dependence, $d\sigma/dQ^2 \sim Q^{-7}$

BaBar's Efficiency and Cross section

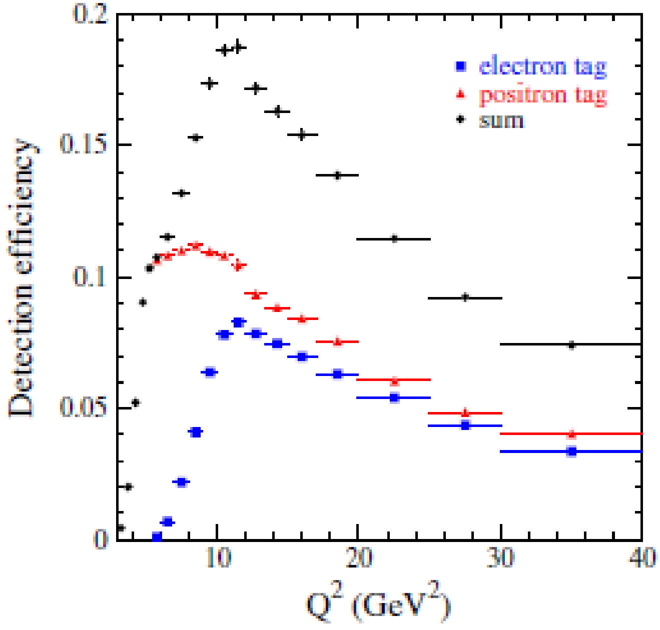


FIG. 4 (color online). The detection efficiency as a function of the momentum transfer squared for events with a tagged electron (squares), a tagged positron (triangles), and their sum (circles).

BaBar, PRD 80, 052009 (2009)

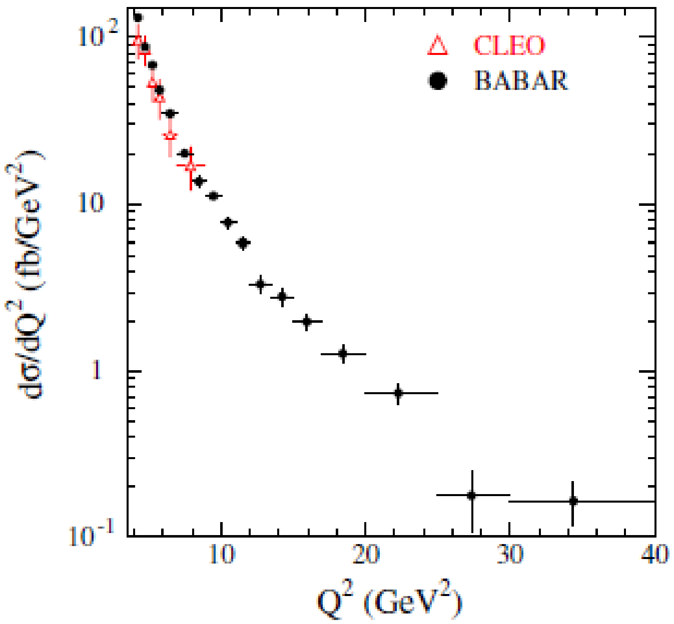


FIG. 21 (color online). The $e^+e^- \to e^+e^-\pi^0$ differential cross section obtained in this experiment compared to that from the CLEO experiment [12].