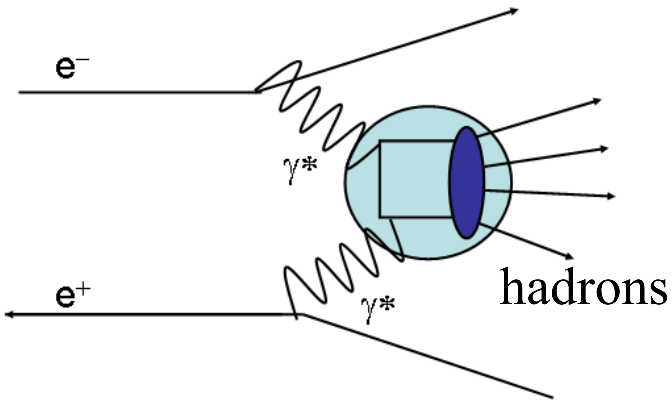
Measurements of $\gamma\gamma^* \to \pi^0$ transition form factor at Belle

S.Uehara (KEK)
Belle

QCD and Fragmentation

RIKEN, Wako, Nov. 9-11, 2012

Two-Photon Collisions and QCD/Hadron Physics



Hadron production from collisions of virtual or quasi-real photons

- Perturbative/Non-perturbative QCD
- Hadron/Photon form factors
- Resonances

Wide energy region and various physics aspects can be studied simultaneously.

Incident photon -- dominated by quasi-real photon

$$\mathbf{Q^2} \equiv |q^2| \lesssim 0.001\,\mathrm{GeV}^2$$

Zero-tag: Measurement of two real photon collisions

Single-tag: Collisions of a Real and a Virtual photons

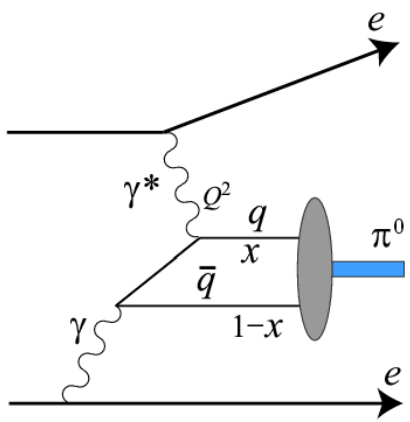
“$\gamma\gamma \to$ meson pair” measurements from Belle

Process	Reference	Int.Lum. (fb^{-1})	$\gamma\gamma$ c.m. Energy (GeV)	Physics covered: Light Mesons	QCD	Char-monia
$\pi^+\pi^-$	PLB 615, 39 (2005) PRD 75, 051101(R) (2007) J. Phys. Soc. Jpn. 76, 074102 (2007)	87.7 85.9 85.9	2.4 - 4.1 0.8 - 1.5 0.8 – 1.5	 √ √	√	√
K^+K^-	EPJC 32, 323 (2003) PLB 615, 39 (2005)	67 87.7	1.4 – 2.4 2.4 – 4.1	√	 √	 √
$\pi^0\pi^0$	PRD 78, 052004 (2008) PRD 79, 052009 (2009)	95 223	0.6 – 4.0 0.6 – 4.0	√ √	 √	 √
$K^0_SK^0_S$	PLB 651, 15 (2007)	397.1	2.4 – 4.0		√	√
$\eta\pi^0$	PRD 80, 032001 (2009)	223	0.84 – 4.0	√	√	
$\eta\eta$	PRD 82, 114031 (2010)	393	1.1 – 4.0	√	√	√
$\omega\omega, \omega\phi, \phi\phi$	PRL 108,232001(2012)	870	~2 – 4.0	√	√	√

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 photons

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

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

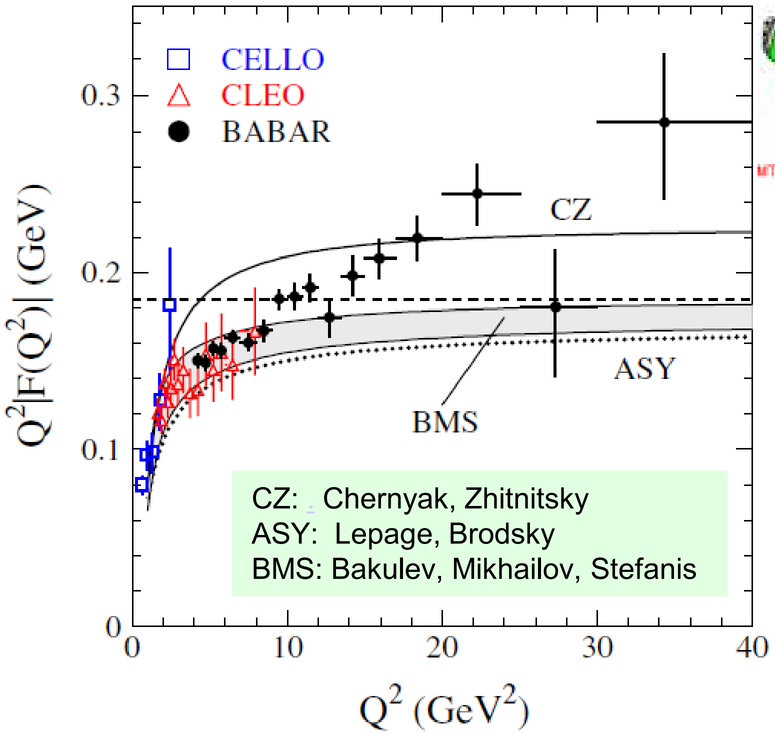
Detects e (tag side) and π^0

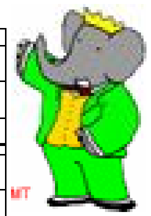
$Q^2 = 2EE'(1 - \cos\theta)$ from energy and polar angle of the tagged electron

BaBar's Measurement

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

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



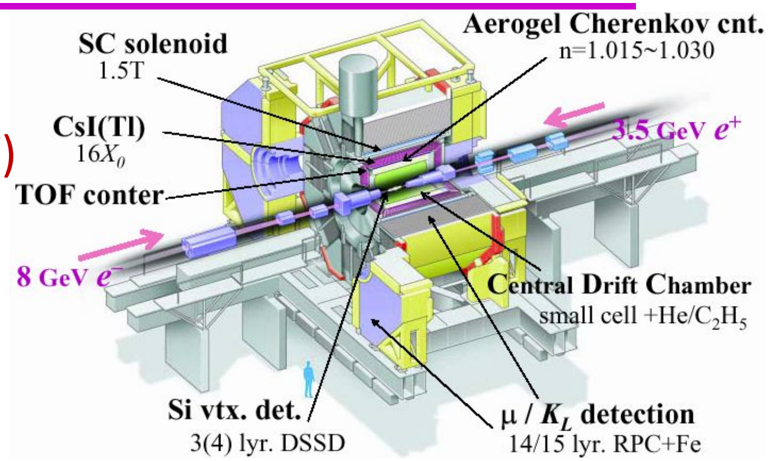


Below $Q^2 < 8 GeV^2$, the BaBar result supports the CLEO result.

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 && $\overline{\text{Bhabha}}$(-veto)

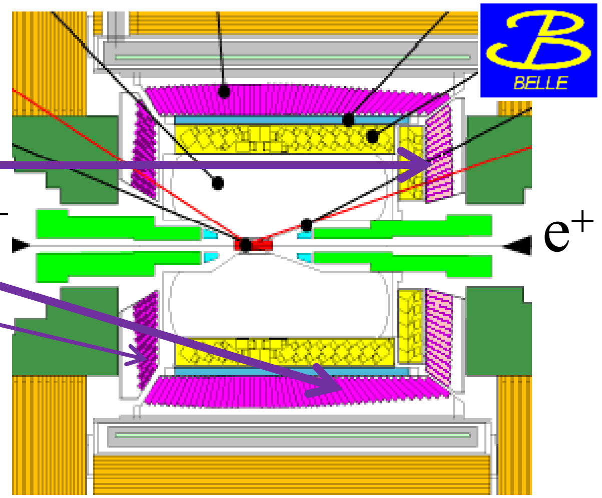
by ECL (electromagnetic calorimeter system)

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

  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 $m_{\gamma\gamma} = m_{\pi 0}$

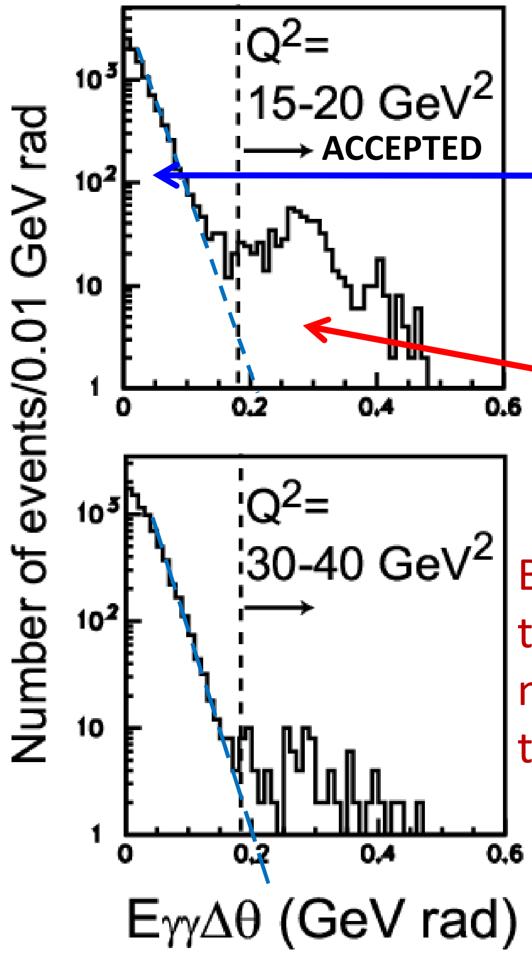
  $0.85 < (\mathbf{E}_{\mathbf{ratio}} \equiv E^{*\,measured}_{\gamma\gamma} / E^{*\,expected}_{\gamma\gamma}) < 1.1$
- Bhabha-background rejection, Acollinearity angle(e, γγ) < 177° in e^+e^- c.m. frame
- **Good balances in azimuthal angle and p_t** between e and π^0

  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

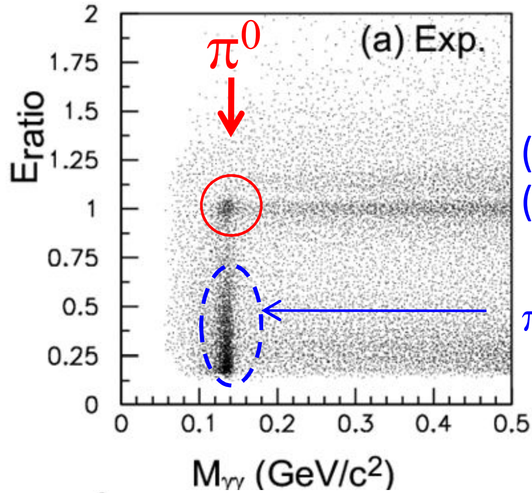


Background
from (e)eγ
with a conversion

π^0 Signal

Backgrounds from the conversion is negligibly small after the cut.

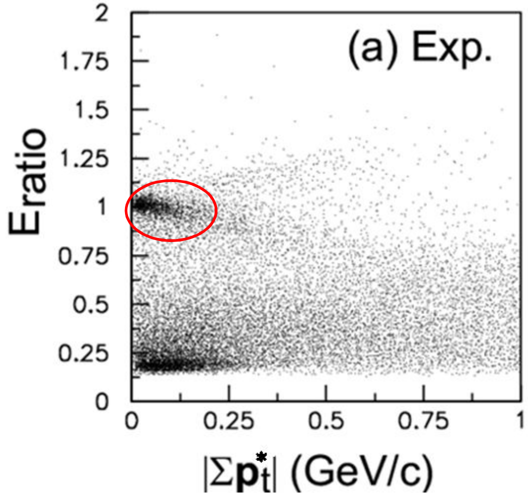
$E_{ratio} \equiv E^*_{\gamma\gamma}{}^{measured} / E^*_{\gamma\gamma}{}^{expected}$



π^0

(e)eγ
(e)eγγ

π^0X background



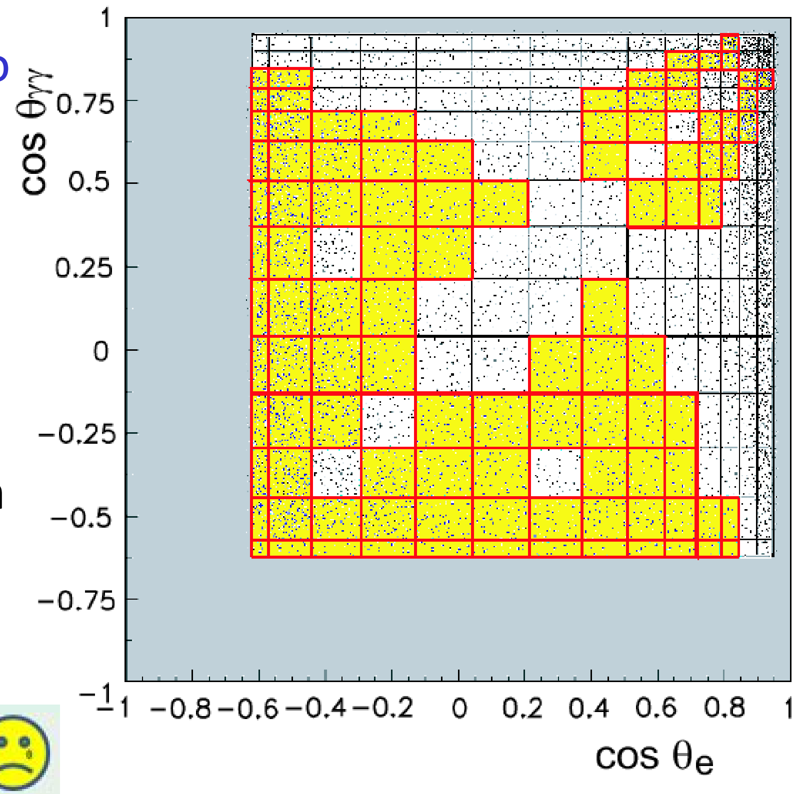
○ Signal

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

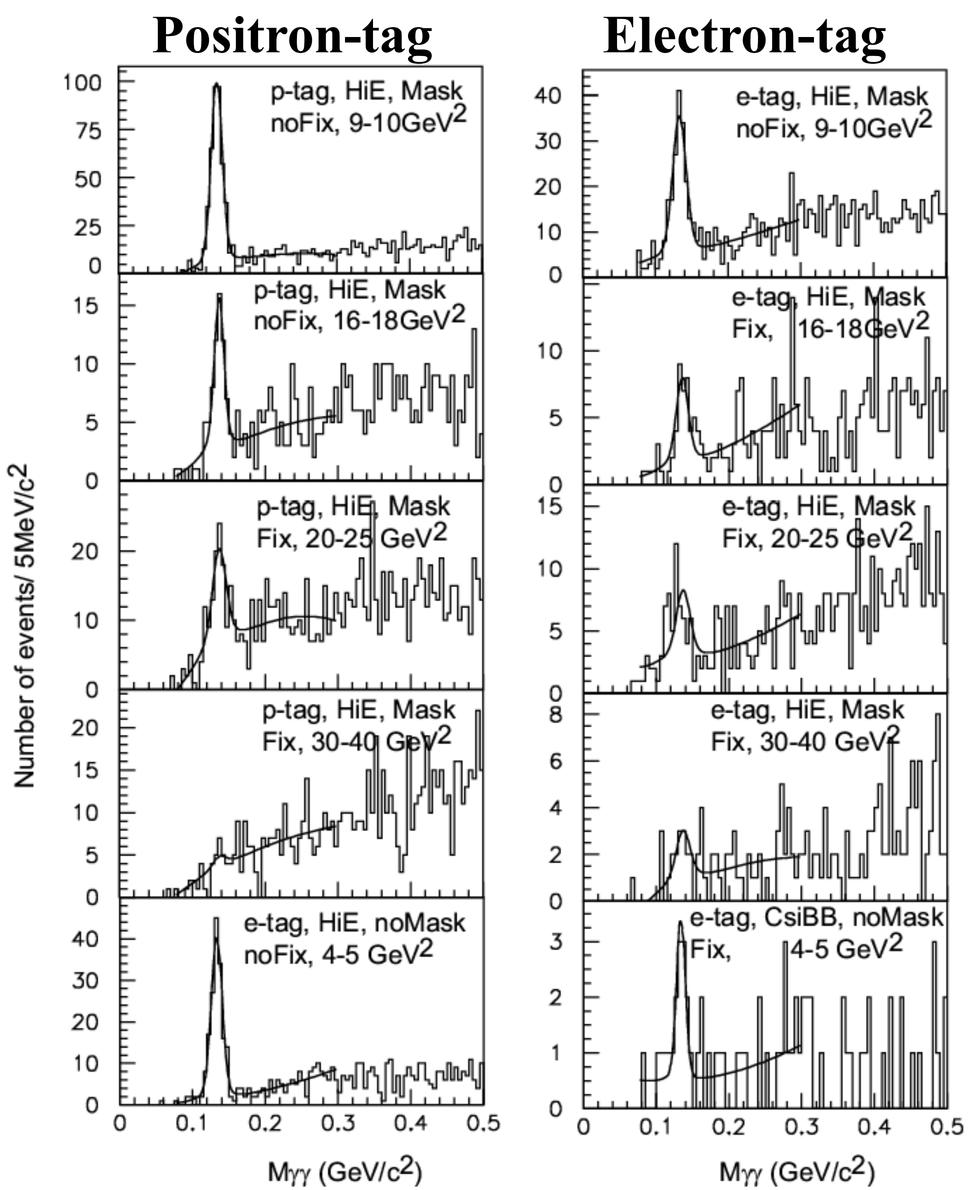
Nevent(HiE) + 50*Nevent(CsIBB)

≡"**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

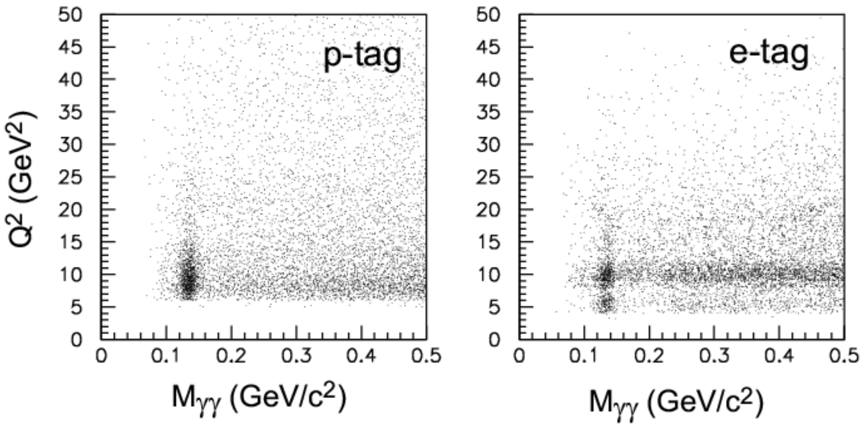


Fit Mγγ distribution by

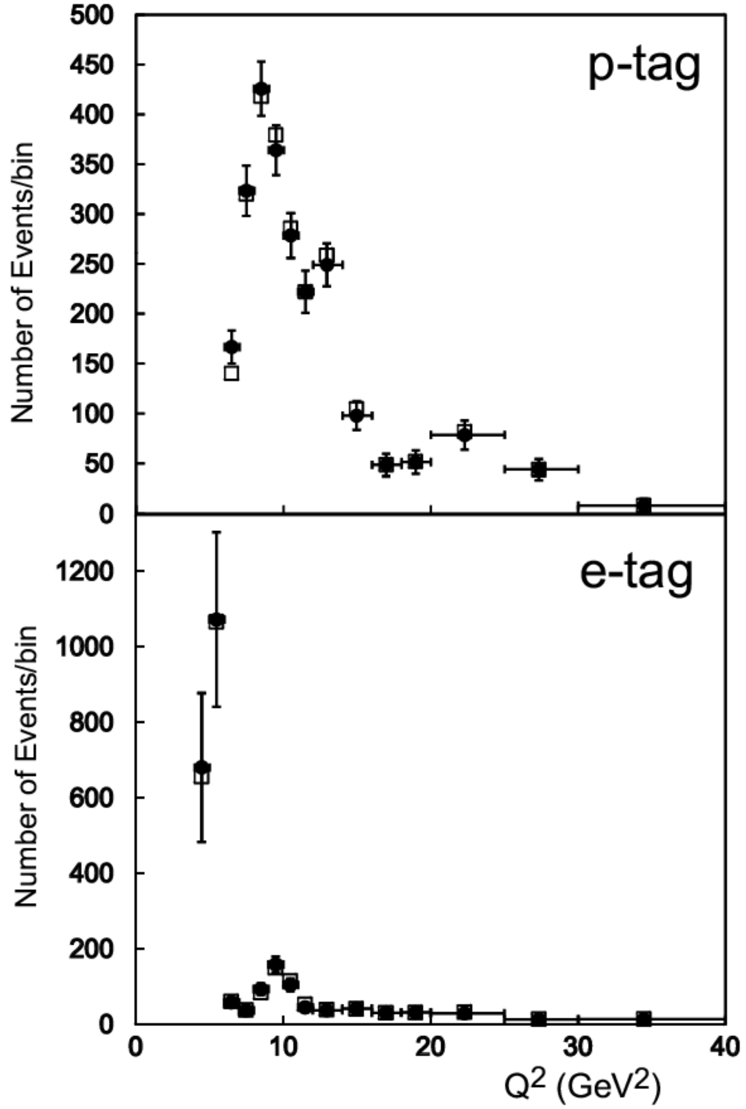
- Double Gaussian (for signal)
- \+ 2nd-Order Polynomial (for background)
- in each Q^2 bin

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

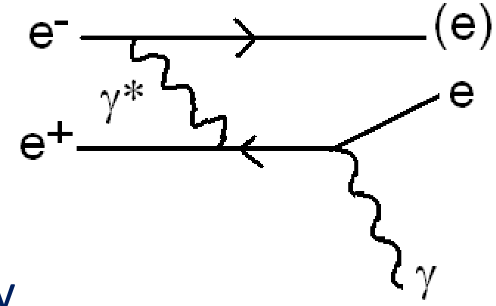
Signal yields
□ Before the unfolding
● After the unfolding

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 🙂

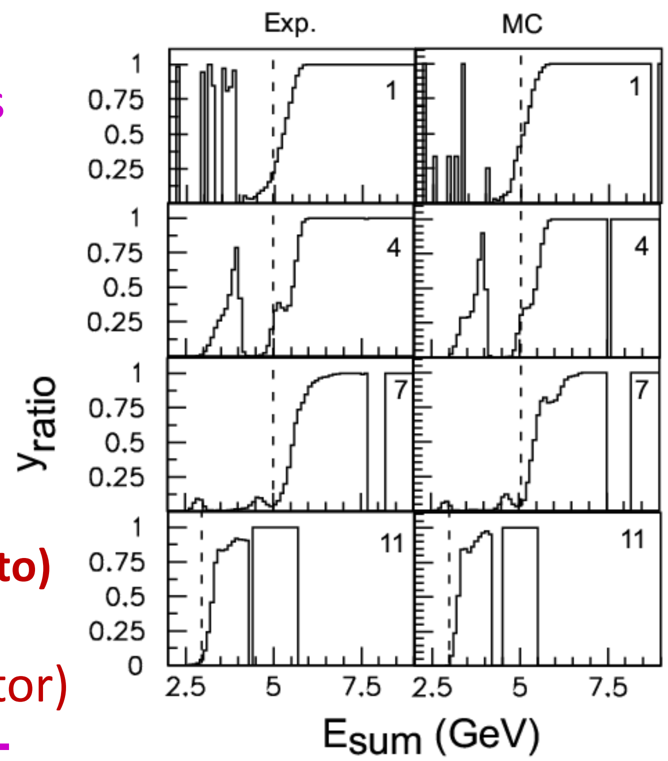
Bhabha-veto condition: ΣE(at least one of 11 patterns) > E_{thres}

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

Trigger Efficiency for Bhabha (-veto)

as a function of energy deposit

→ tune MC (trigger simulator)



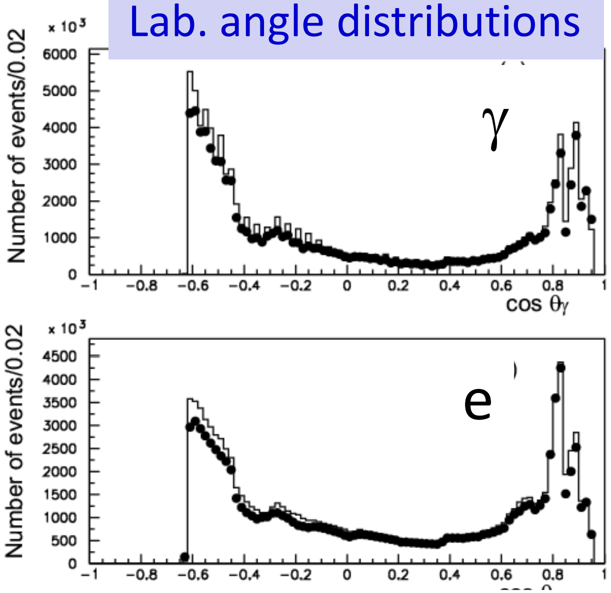
Comparisons in Radiative Bhabha (VC) samples

MC (Rabhat) is normalized by int. luminosity

For HiE (Bhabha-Masked) sample

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

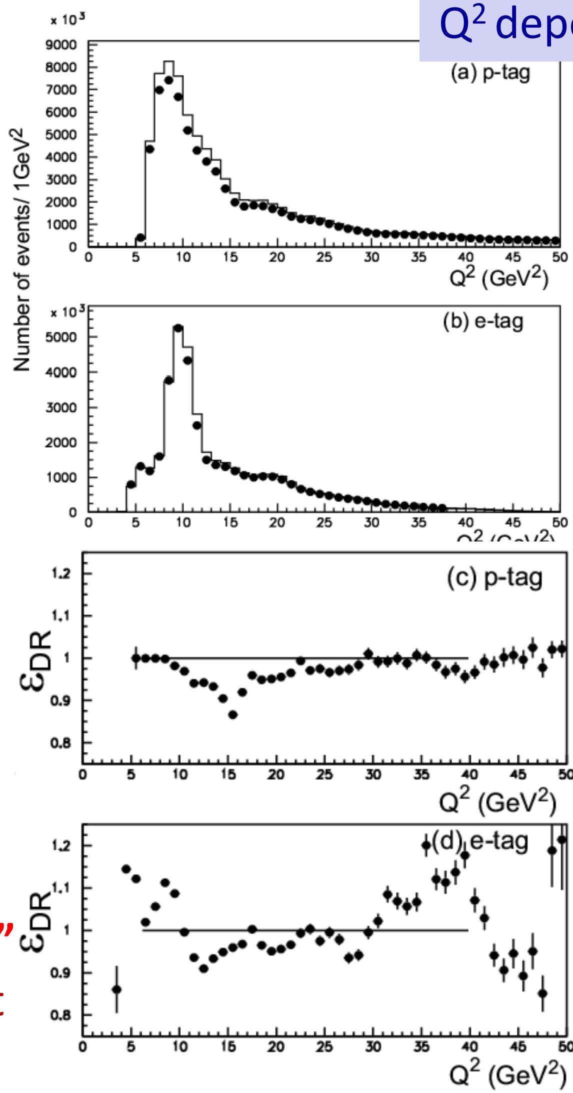
Lab. angle distributions

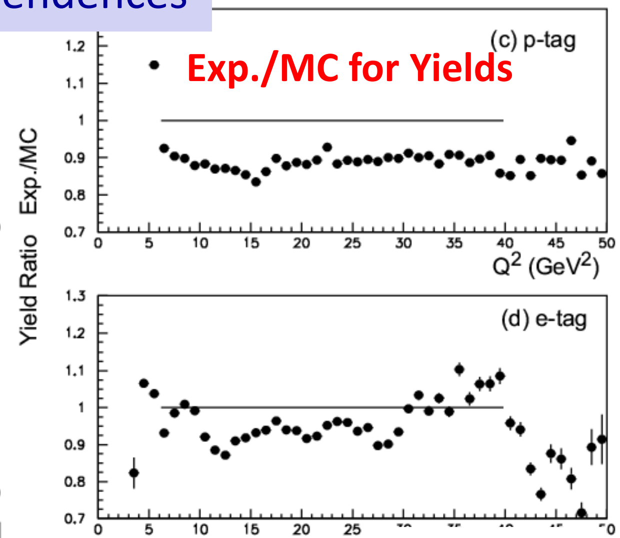


cos θ

dots: Exp.
histograms: MC

Q^2 dependences





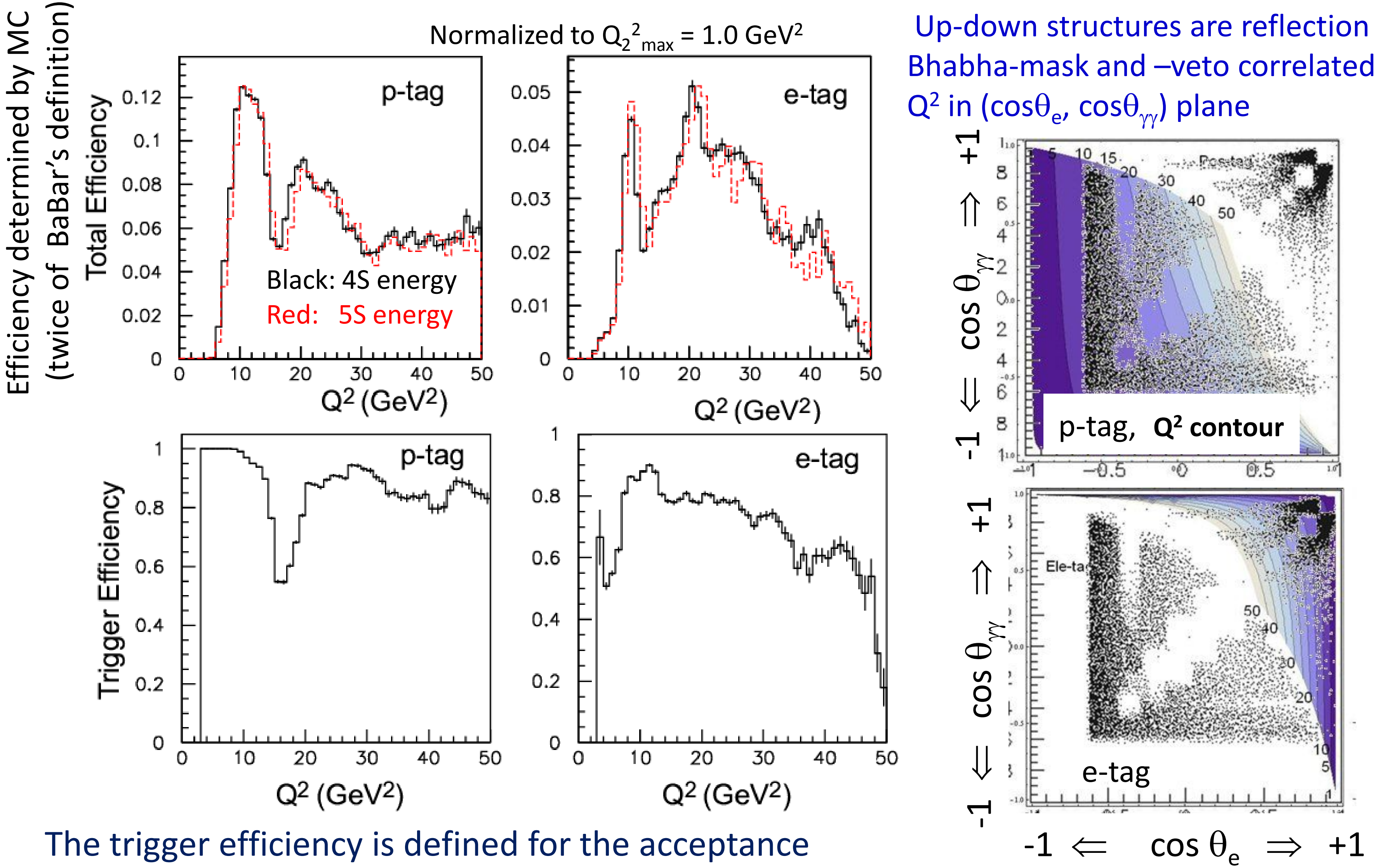
Q^2 (GeV^2)

ε_{DR}:
Exp./MC Ratio for Efficiency for "Bhabha-Mask" × "Bhabha-veto" →
shows a better agreement between Exp. and MC

Horizontal line (=1): Expectation

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

Efficiency for the Signal Process

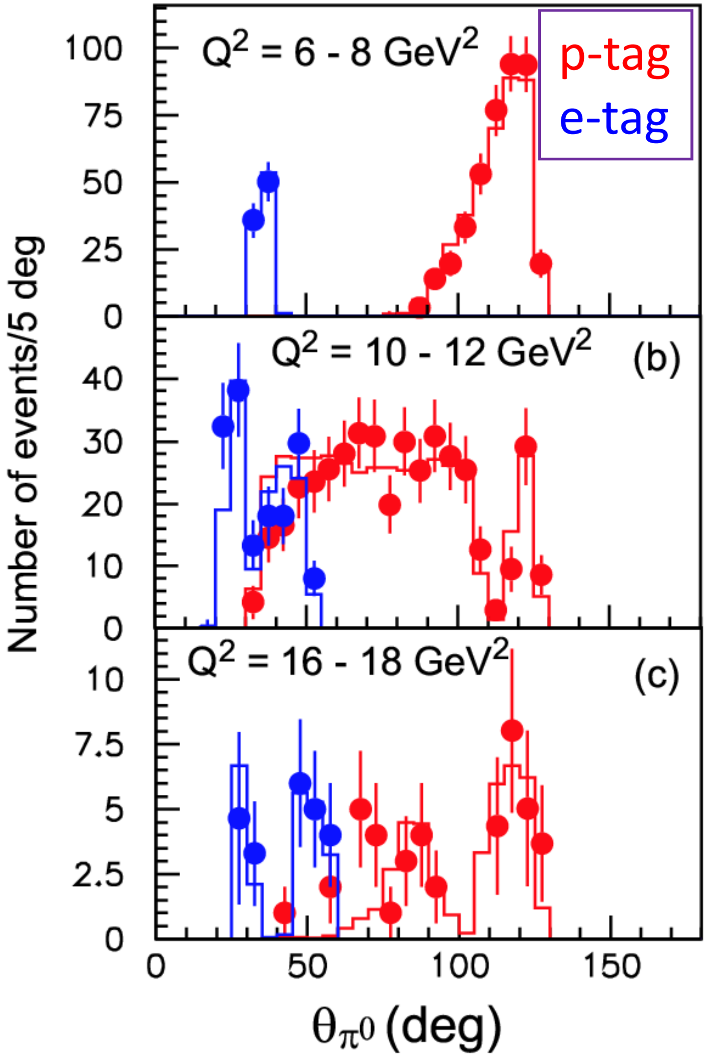


Up-down structures are reflection of Bhabha-mask and –veto correlated to Q^2 in ($\cos\theta_e$, $\cos\theta_{\gamma\gamma}$) plane

The trigger efficiency is defined for the acceptance after the selection

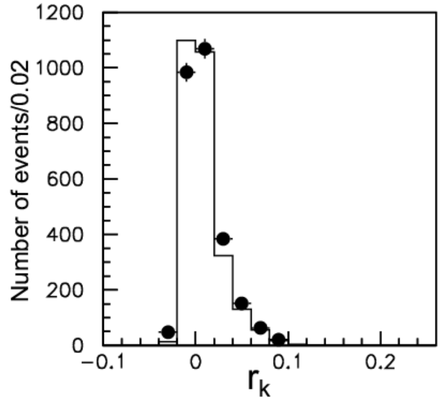
Checks of Signal Details with MC

π^0-polar-angle distribution

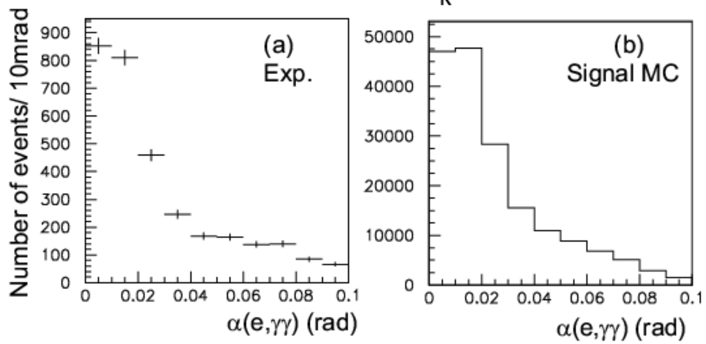


Radiative tails

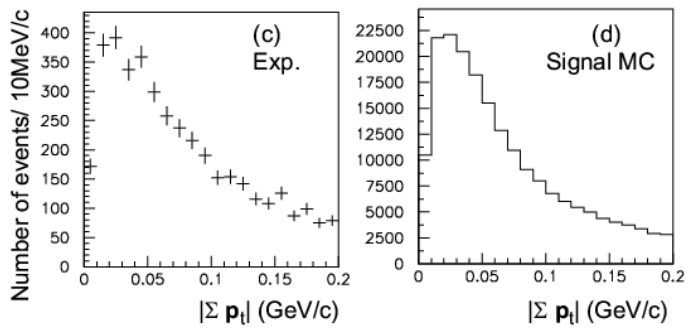
Radiative energy fraction



Acoplanarity angle for $e\pi^0$



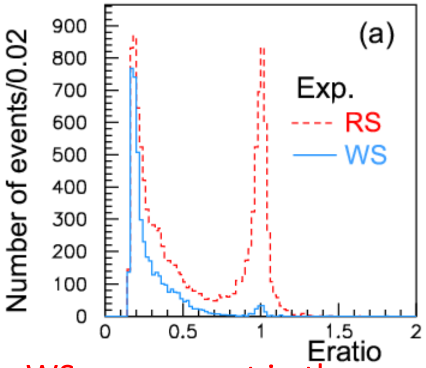
p_t-balance for $e\pi^0$



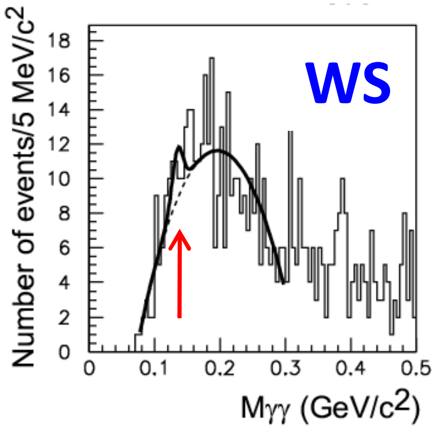
Peaking (π^0) Backgrounds

(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)

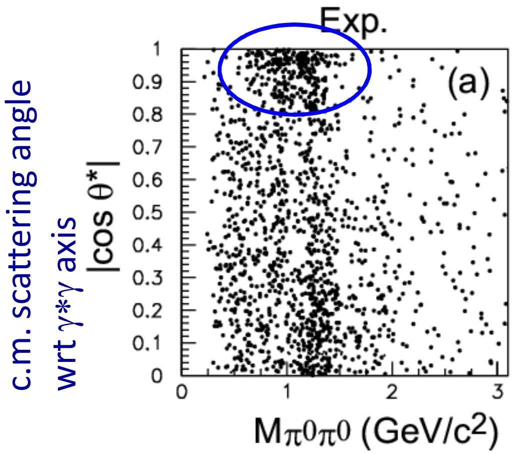
Backgrounds from e^+e^- annihilation and particle misidentification (of muon or hadron) are **negligibly small.**

(2) Background processes

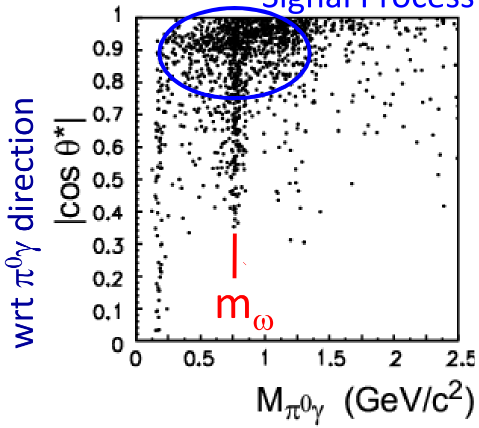
$\gamma\gamma^* \to \pi^0\pi^0$

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

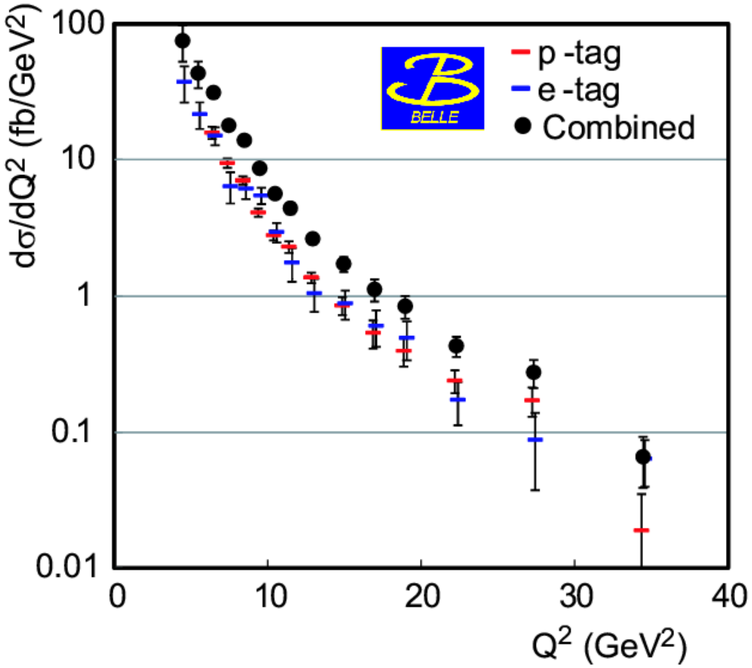
1 – 3% @ 12 – 40 GeV^2

Cross Section

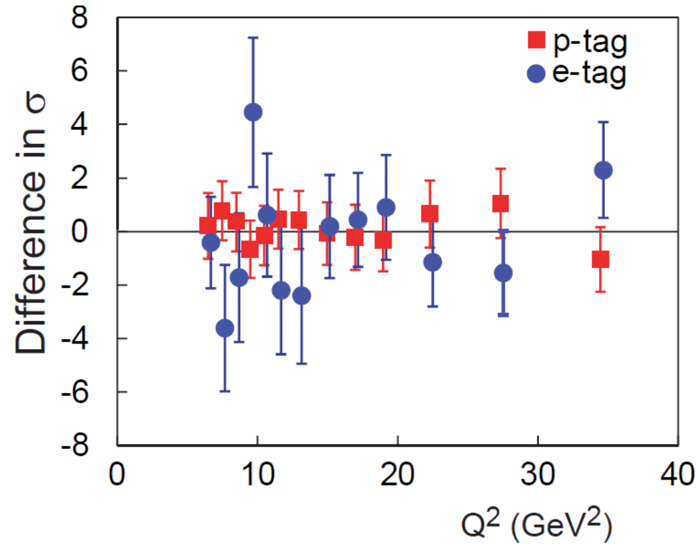
$$\frac{d\sigma}{dQ^2} = \frac{N\,(1-r_b)}{\int L dt \;\; eff \;\; B(\pi^0 \to \gamma\gamma)\,(1+\delta)\,\Delta Q^2}$$

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.



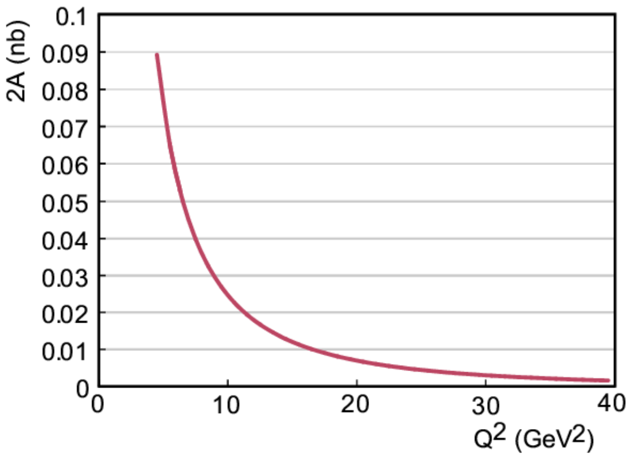
Q^2_{max} = 1.0 GeV^2 for the less-virtual photon
Corrected for $\sqrt{s}$ = 10.58 GeV

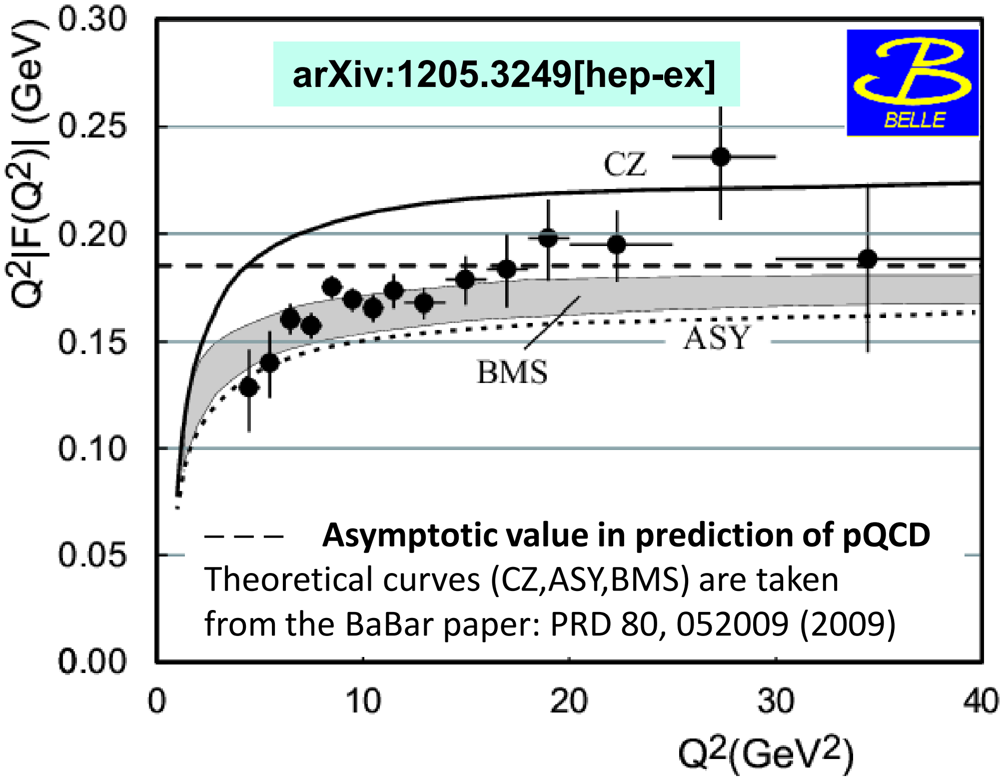


No systematic bias found between the p-tag and e-tag results.

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

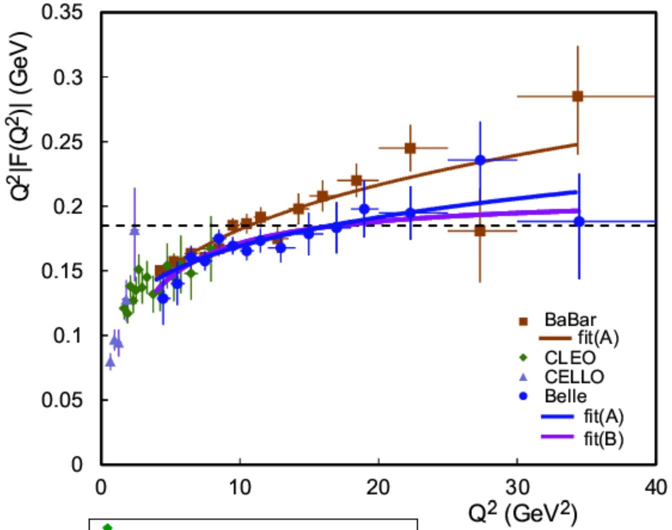
Peaking-background 1 – 4% **8 – 14% in total**

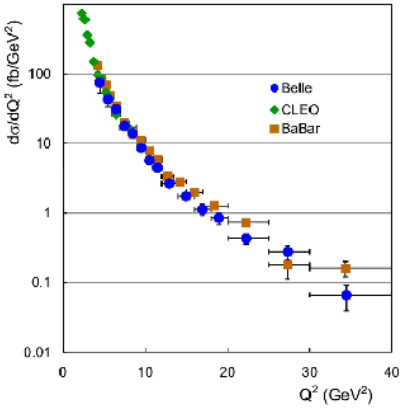
For Transition Form Factor:

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





No rapid growth above Q^2>9GeV^2 is seen in Belle result.

~ 2.3σ difference between Belle and BaBar in 9 – 20 GeV^2

Fit A (suggested by BaBar)

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

BaBar:

A = 0.182 ± 0.002 (± 0.004) GeV

β = 0.25 ± 0.02

Belle:

A = 0.169 ± 0.006 GeV

β= 0.18 ± 0.05

χ^2/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 ± 0.016 GeV

C = 2.2 ± 0.8 GeV^2

χ^2/ndf = 7.07/13

B is consistent with the QCD value (0.185GeV)

Summary

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

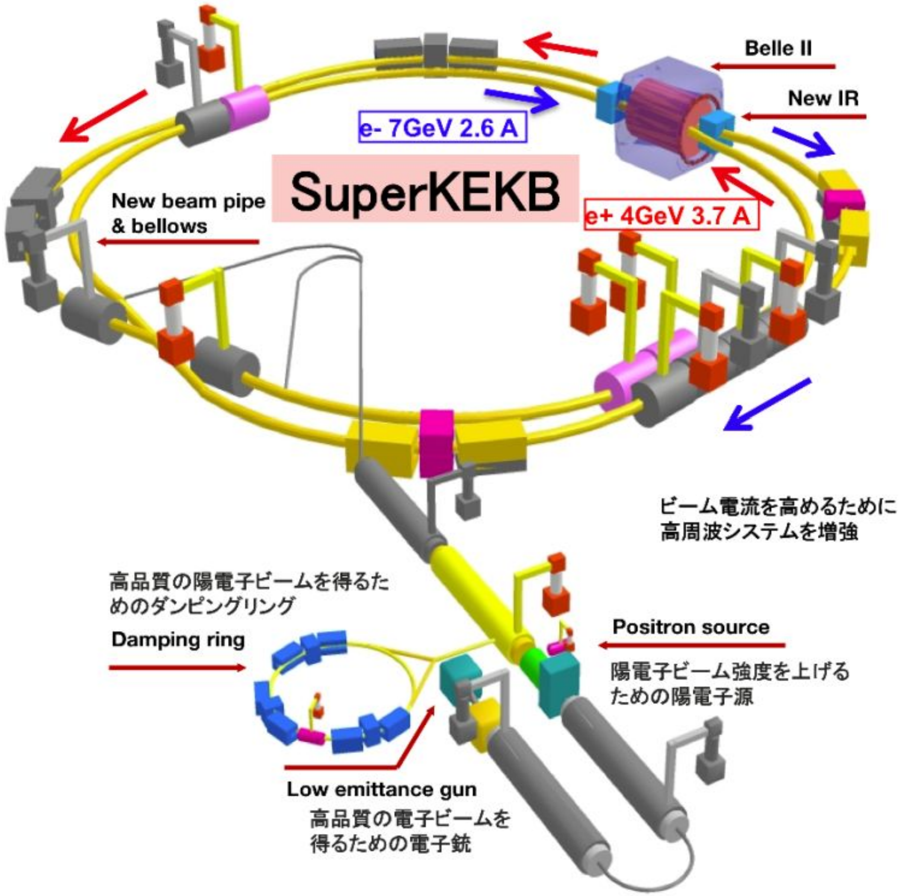
  There was a significant effect from Bhabha-veto, but the trigger simulator to estimate the signal efficiency is tuned, reliably,
  calibrating it using radiative Bhabha events.

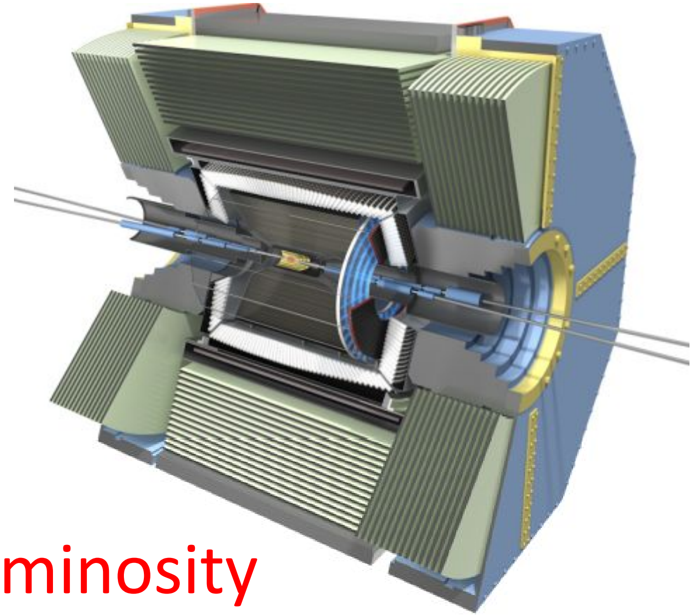
- No rapid growth of π^0 TFF is observed for the region Q^2>9GeV^2.

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

Belle
arXiv:1205.3249[hep-ex] (2012)
To appear in Phys. Rev. D

For future (SuperKEKB & Belle II)





Luminosity

"x40" → 8×10^{34} cm^{-2}s^{-1}

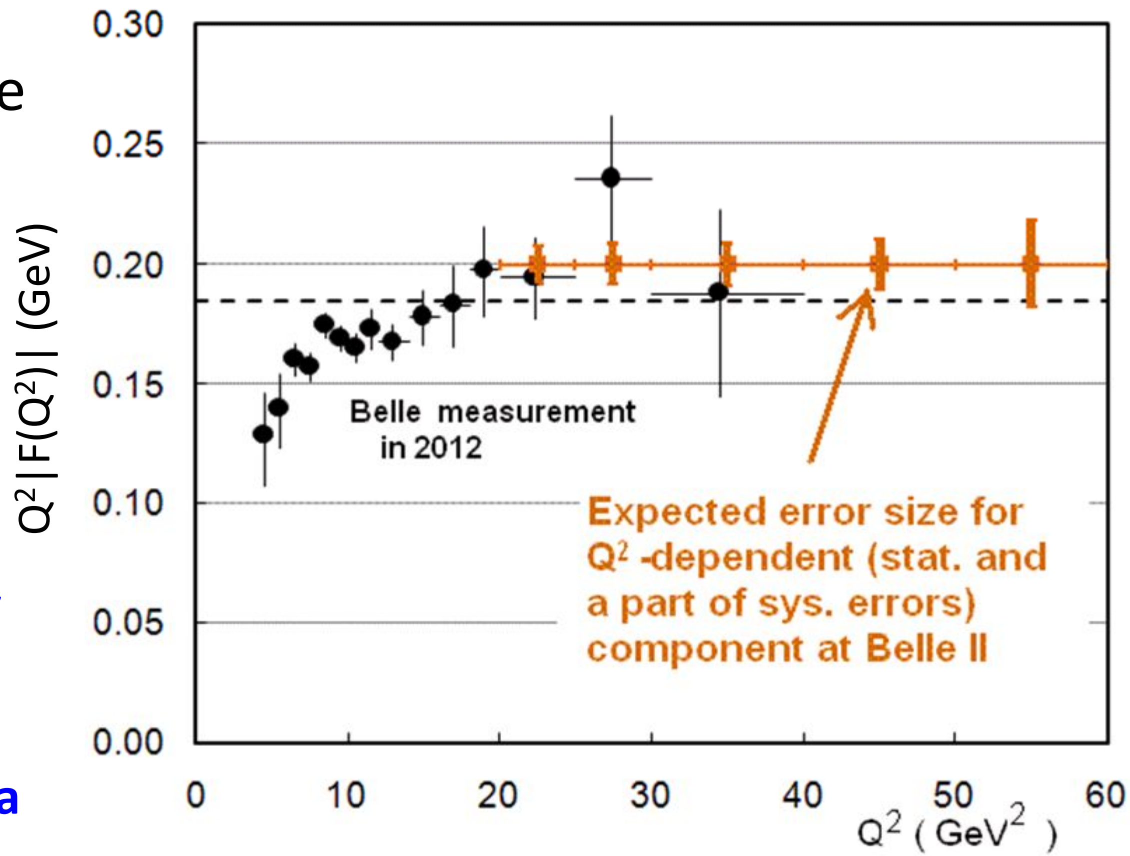
Target of

the integrated luminosity **50 ab^{-1}**

When 50ab^{-1} data at Belle II analyzed, …

Assumptions:

- Integrated luminosity 50 ab^{-1} (x 66)
- No large Bhabha-Veto inefficiency (x 2.5 @ high Q^2)
- Systematic errors from π^0-fit and trigger can be reduced
- Other systematics stay the same



Q^2 > 60 GeV^2

Close to back-to-back topology of $e\pi^0$ in e^+e^- c.m. frame

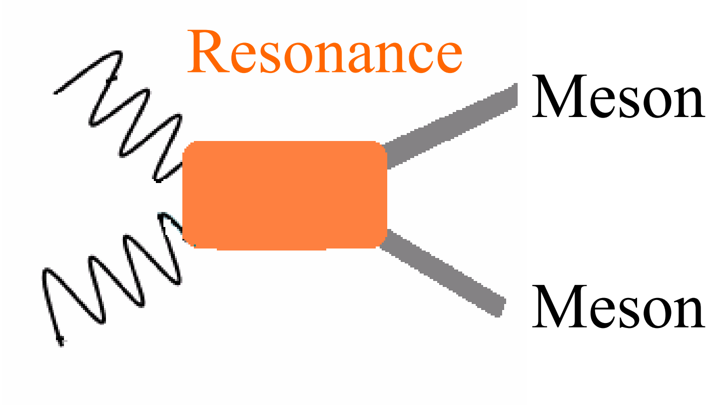
Huge background from Bhabha

Backup

Resonance production

Resonance production and quantum numbers

Resonance formation or **partial-waves**



$Q = 0$, **$C = +$,**

$J^P = 0^+, 0^-, 2^+, 2^-, 3^+, 4^+, 4^-, 5^+ \ldots.$

$(\text{even})^{\pm}$, $(\text{odd} \neq 1)^+$

Strict constraints for quantum numbers

Pseudoscalar-pair production: $J^P = (\text{even})^+$ only

$\Gamma\gamma\gamma$, two-photon partial decay width of the resonance,

from the cross-section measurement,

important information for the **meson's internal structure**

Decay properties

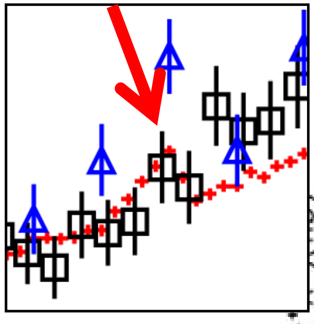
Searches/Discoveries of **new resonances, including *"XYZ"***

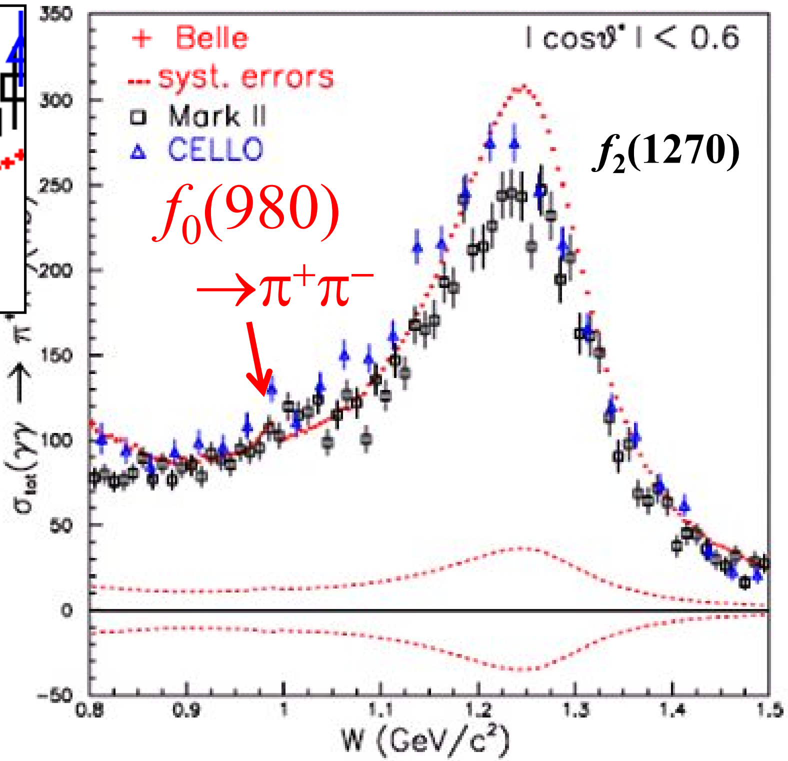
Confirmations of $f_0(980)$ and $a_0(980)$

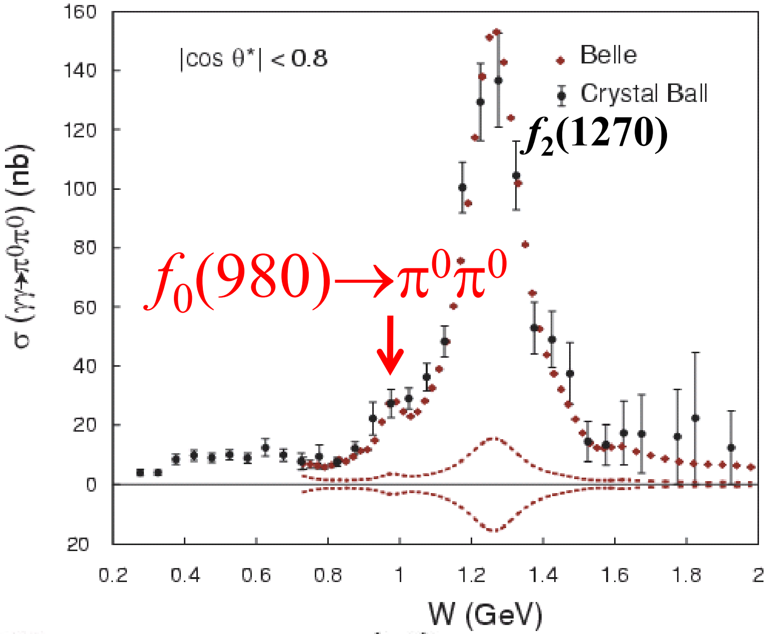
True nature of $f_0(980)$ **and** $a_0(980)$
is not clarified, well.

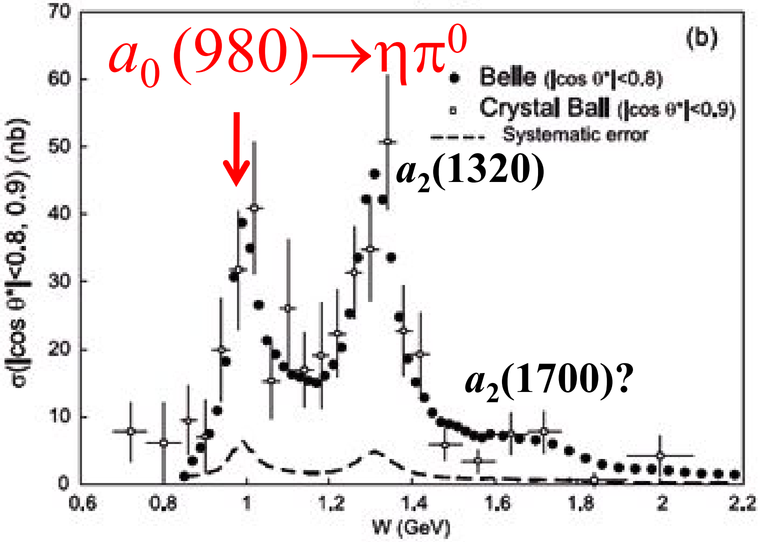
We observe them as a peak very clearly
in two-photon production for the first time

- Measurements of $\Gamma\gamma\gamma$



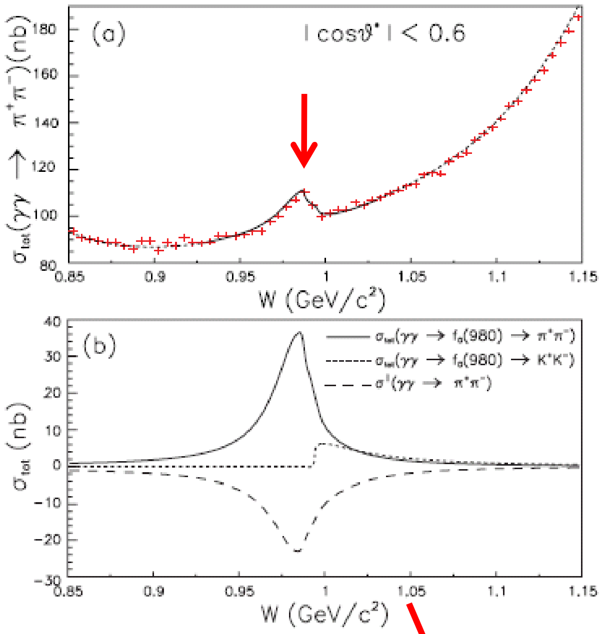


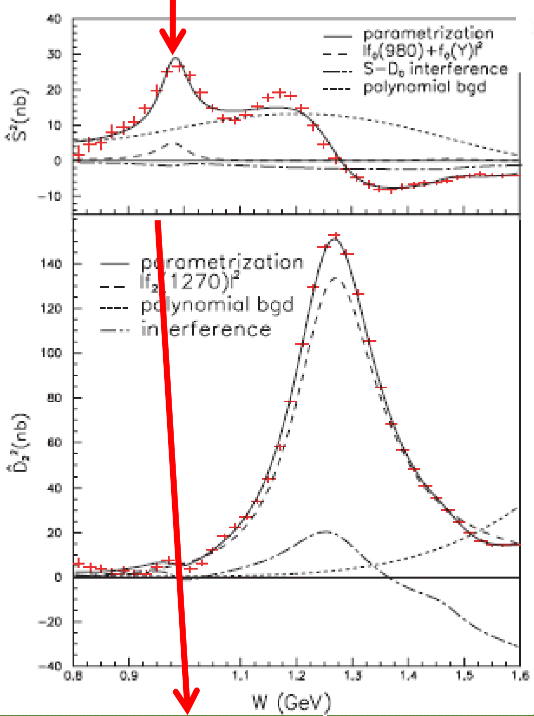




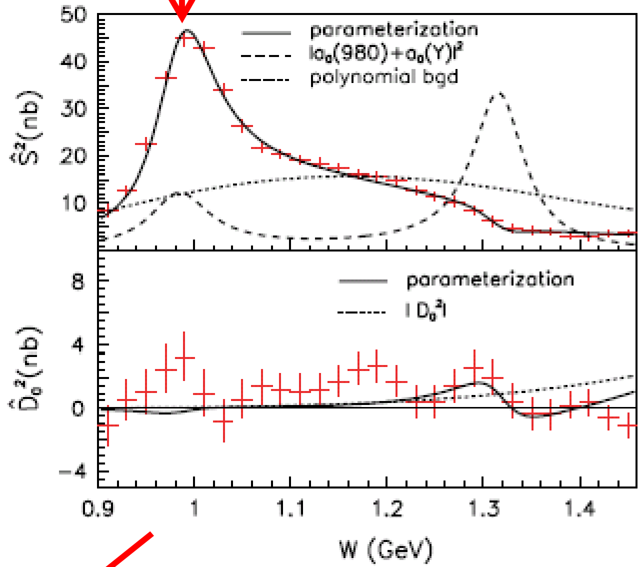
S.Uehara, Belle, Frag.2012, RIKEN, Nov.

Two-photon decay width of $f_0(980)$ and $a_0(980)$





$$\frac{d\sigma}{d\Omega} = \hat{S}^2 \left|Y_0^0\right|^2 + \hat{D}_0^2 \left|Y_2^0\right|^2 + \hat{D}_2^2 \left|Y_2^2\right|^2$$



Meson	$f_0(980)$	$f_0(980)$	$a_0(980)$
M[MeV/c^2]	$985.6^{+1.2+1.1}_{-1.5-1.6}$	$982.2 \pm 1.0^{+8.1}_{-8.0}$	$982.3^{+0.6+3.1}_{-0.7-4.7}$
$\Gamma_{\pi\pi/tot}$[MeV]	$51.3^{+20.9+13.2}_{-17.7-3.8}$	$66.9^{+13.9+8.8}_{-11.8-2.5}$	$75.6 \pm 1.6^{+17.4}_{-10.0}$
$\Gamma_{\gamma\gamma}$[eV]	$205^{+95+147}_{-83-117}$	$286 \pm 17^{+211}_{-70}$	$128^{+3+502}_{-2-43} / \mathcal{B}_{\pi^0\eta}$
Channel	$\gamma\gamma \to \pi^+\pi^-$	$\gamma\gamma \to \pi^0\pi^0$	$\gamma\gamma \to \pi^0\eta$
Reference	PRD75, 051101(2007)	PRD78, 052004(2008)	PRD80, 032001(2009)

Predictions

Model	$\Gamma_{\gamma\gamma}$ [eV]
*uu*bar,*dd*bar	1300 – 1800
*ss*bar	300 – 500
*KK*bar molecule	200 – 600
Four-quark	270

Summary of resonances seen in $\gamma\gamma \rightarrow MM'$

$f_0(980) \rightarrow \pi^+\pi^-, \pi^0\pi^0$ $a_0(980) \rightarrow \eta\pi^0$

The 1^3P_2 tensor-meson triplet $f_2(1270)$, $f'_2(1525)$, $a_2(1320)$

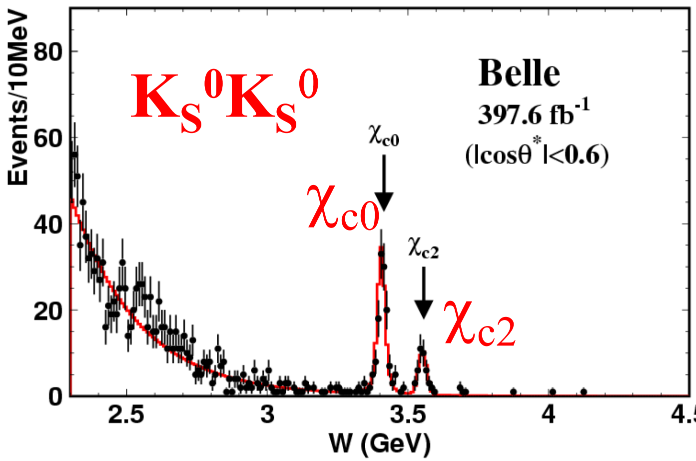
$f_0(Y) \rightarrow \pi^+\pi^-, \pi^0\pi^0, \eta\eta$ unidentified in 1.2 – 1.5 GeV

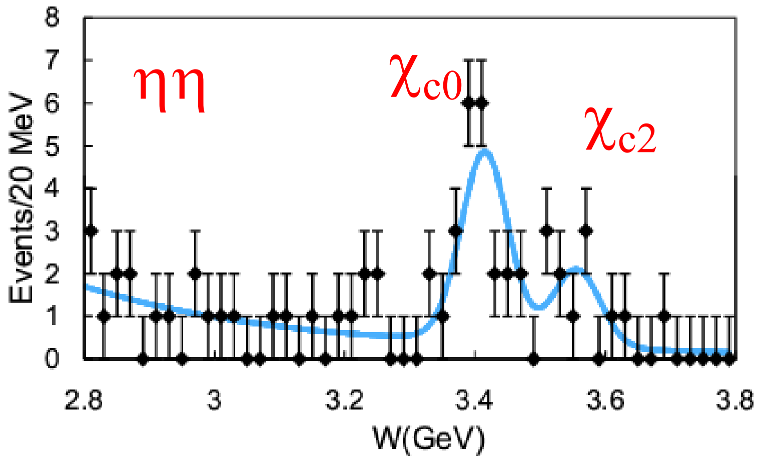
$a_0(Y) \rightarrow \eta\pi^0$ unidentified in 1.2 – 1.5 GeV

$f_2(X) \rightarrow \pi^0\pi^0, \eta\eta$ unidentified in 1.7 – 2.0 GeV

Signatures of $a_2(1700)$?, f_4, a_4, and/or others? seen in 1.7 – 2.3 GeV in $\pi^0\pi^0$, $\eta\pi^0$, $\eta\eta$ and K^+K^-

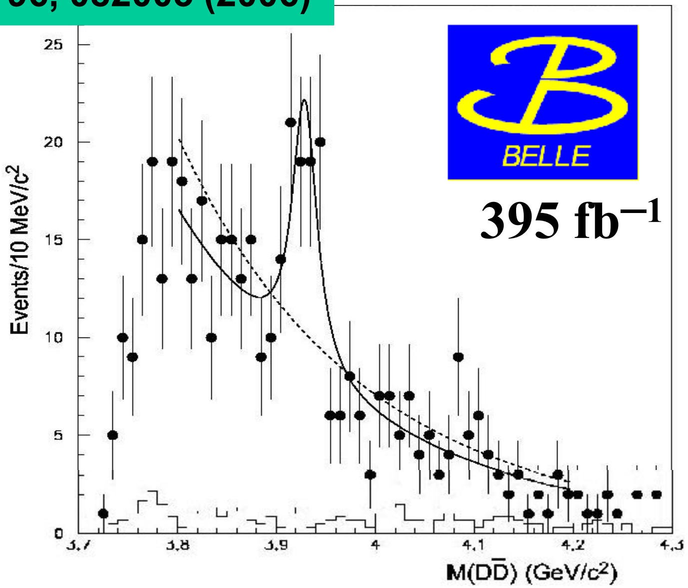
$\chi_{c0}, \chi_{c2} \rightarrow \pi^+\pi^-, K^+K^-, \pi^0\pi^0, K^0_SK^0_S, \eta\eta$

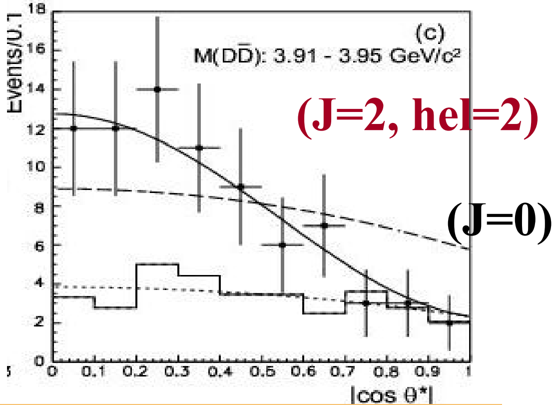




$\gamma\gamma \rightarrow Z(3930) \rightarrow D\bar{D}$ discovered /confirmed

PRL 96, 082003 (2006)

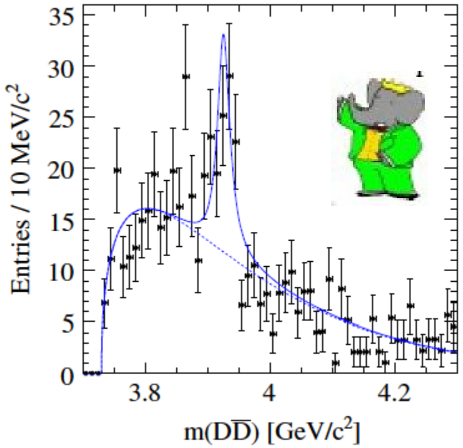


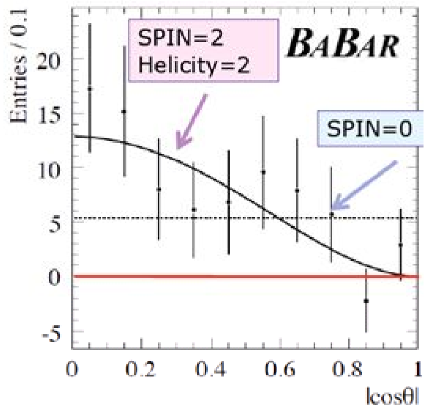


$m(3930)=3929\pm5\pm2$ MeV/c^2
$\Gamma(3930)=29\pm10\pm2$ MeV
$\Gamma_{\gamma\gamma}\cdot BF(Z(3930\rightarrow D\bar{D}))=0.18\pm0.05\pm0.03$ keV

BaBar, PRD 81, 092003 (2010)

384 fb^{-1}





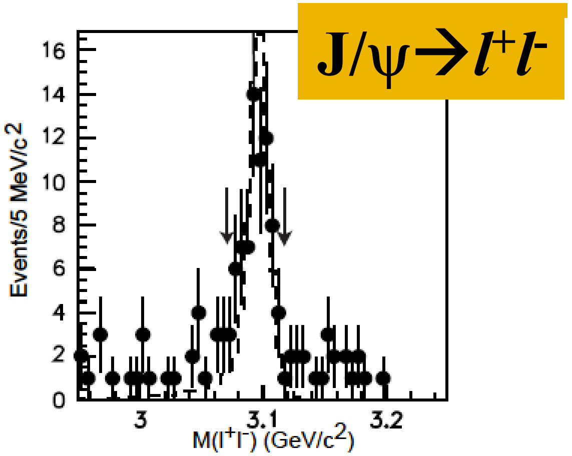
$m(3930)=3926.7\pm2.7\pm1.1$ MeV/c^2
$\Gamma(3930)=21.3\pm6.8\pm3.6$ MeV
$\Gamma_{\gamma\gamma}\cdot BF(Z(3930\rightarrow D\bar{D}))=0.24\pm0.05\pm0.04$ keV

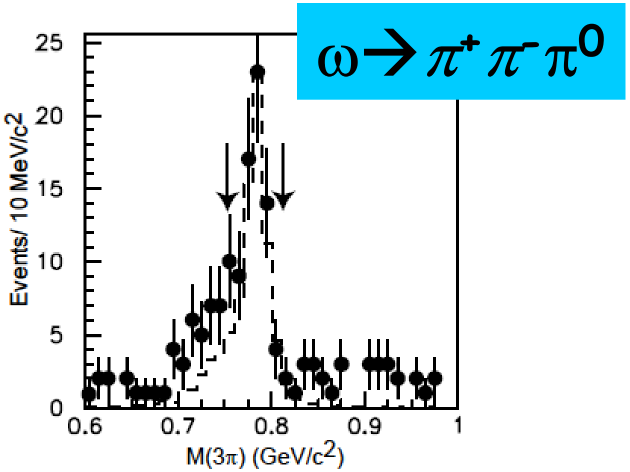
Belle and Babar results are consistent

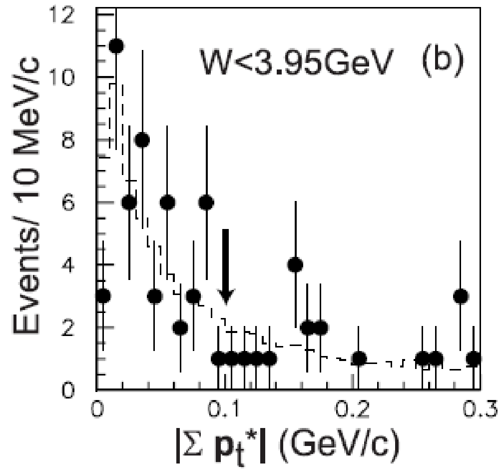
Confirms that Z(3930) = χ_{c2}(2P)

Peak in $\gamma\gamma \rightarrow \omega J/\psi$

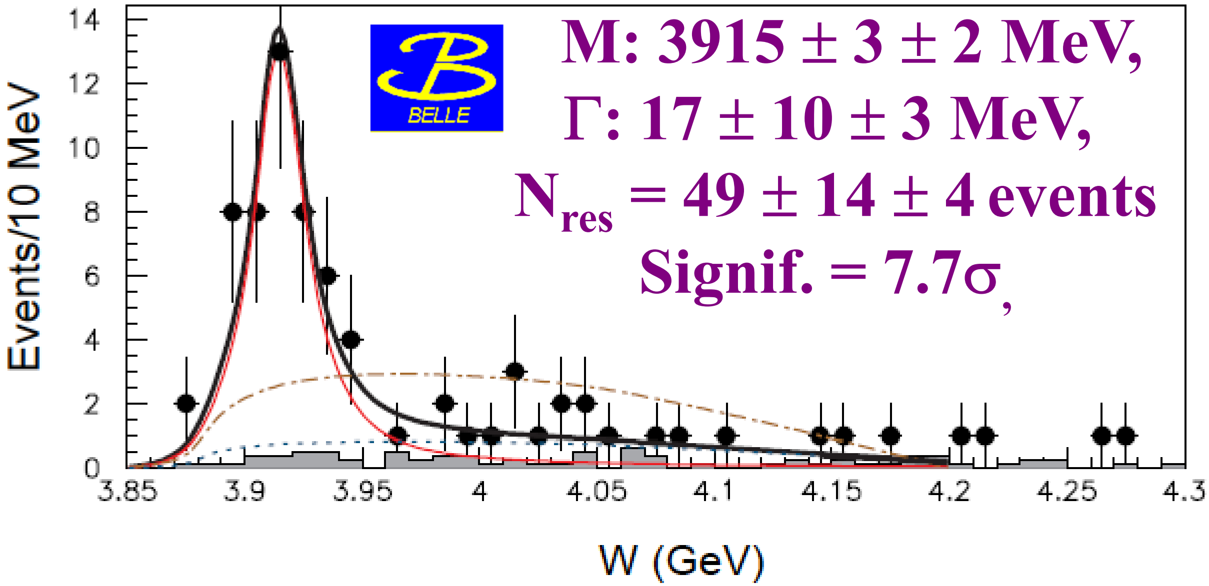
PRL 104, 092001 (2010)







694 fb^{-1}



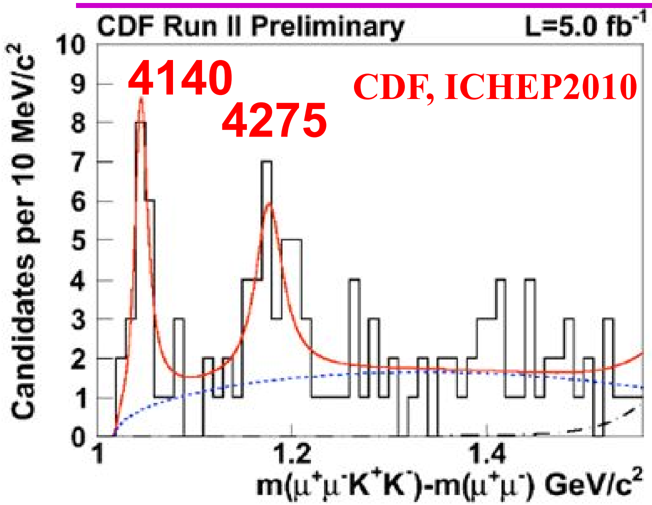
M: 3915 ± 3 ± 2 MeV,
Γ: 17 ± 10 ± 3 MeV,
N_{res} = 49 ± 14 ± 4 events
Signif. = 7.7σ,

Two-photon production of Y(3940) ? reported in B decay

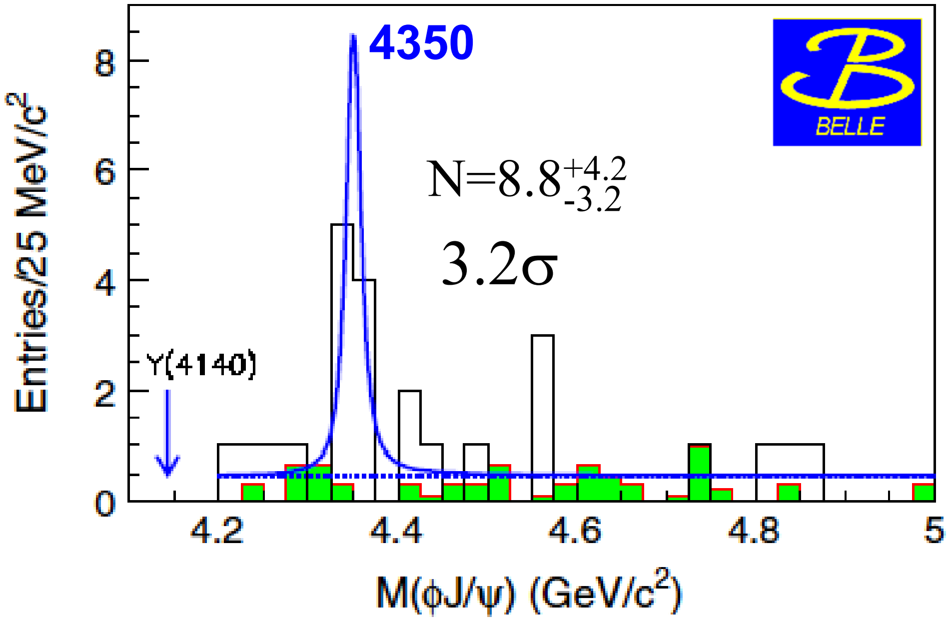
or

New decay mode of $Z(3930)/\chi_{c2}(2P)$?

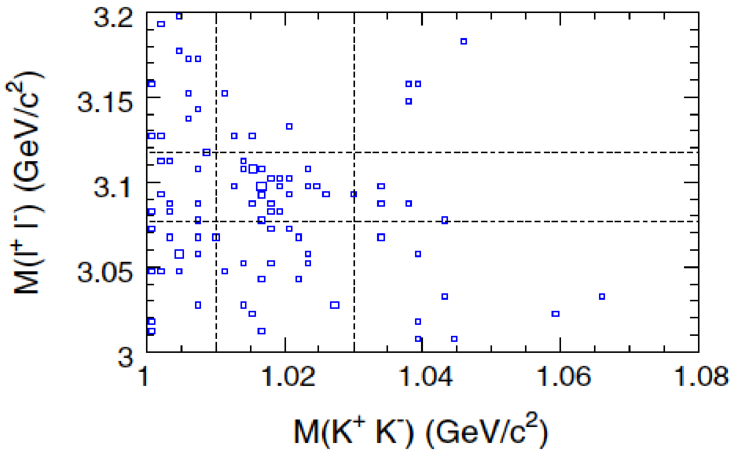
$\gamma\gamma \to \phi\, J/\psi$



PRL 104,112004 (2010)



Y(4140), reported by CDF in B-meson decays, is NOT seen in two-photon process by Belle.



Instead, a **new peak** is seen at around 4.35 GeV in the same process

$M = 4350.6\,^{+4.6}_{-5.1} \pm 0.7\ \mathrm{MeV}/c^2$

$\Gamma = 13\,^{+18}_{-9} \pm 4\ \mathrm{MeV}$

Summary

Many meson-pair production processes from two-photon collisions are studied at Belle.

- Cross sections in the 2 – 4 GeV region are compared with predictions based on QCD, systematically.
- Any comprehensive reproducibility by theoretical models is not obtained, yet.

  Further comparison with theories is now possible.
- Belle discovers/confirms several interesting meson states produced in two-photon fusion:

  $\Gamma\gamma\gamma$ for $f_0(980)$ and $a_0(980)$ are measured

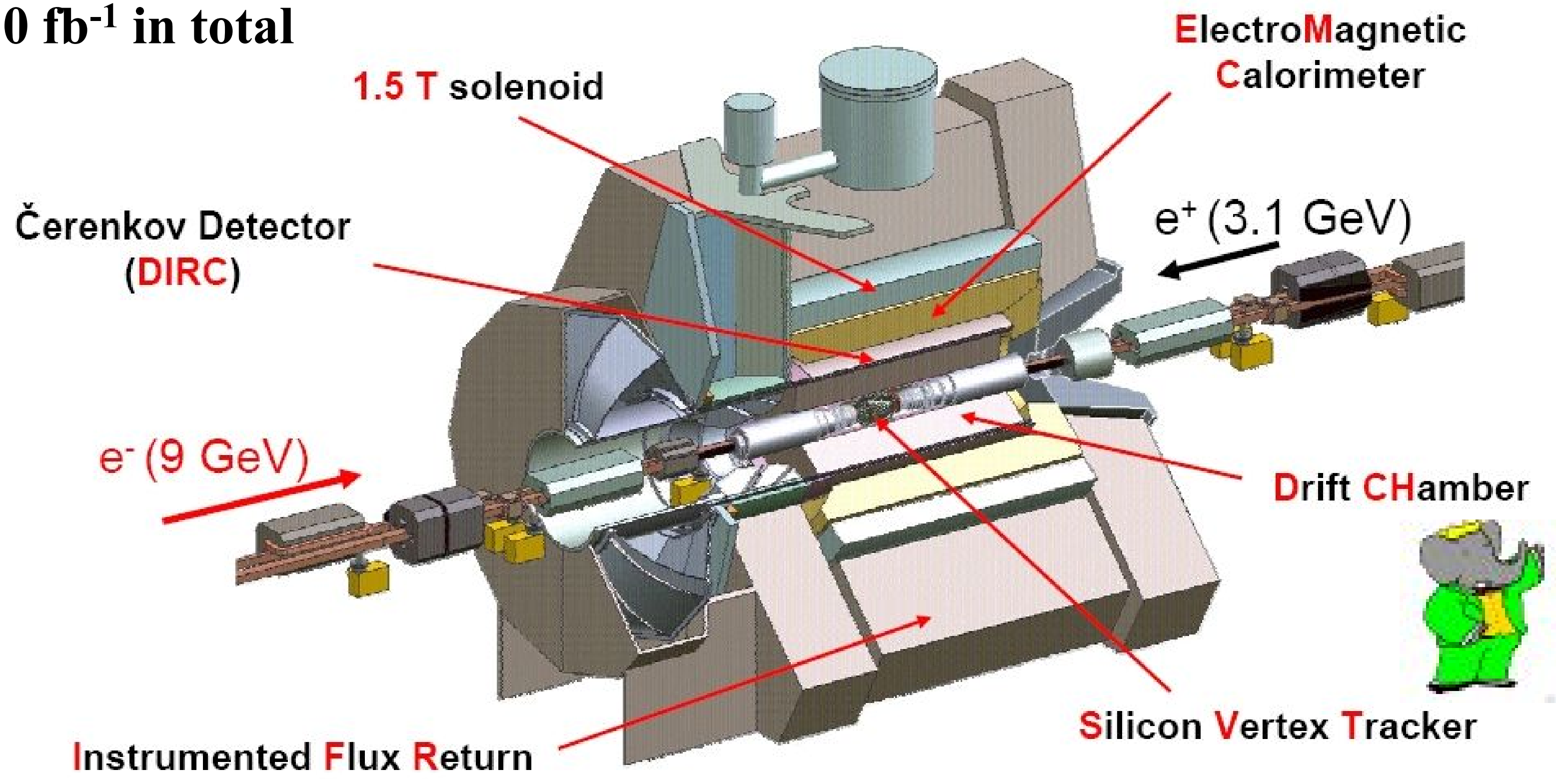
  New charmonium-like states are found

  Z(3930) = $\chi_{c2}(2P)$, X(3915)=Y(3940)?, X(4350)

BaBar at PEP-II

$e^+e^- \to \Upsilon(4S)$ and nearby continuum:
$E_{cms} \sim 10.6$ GeV

530 fb^{-1} in total



Experimental Analysis; $\gamma\gamma \to \eta\eta$

η(548MeV)$\to\gamma\gamma$ (Only 4 photons are visible in this process)

Triggered by ECL triggers (ΣE>1.1GeV or ≥4 clusters)

$\sqrt{s}$ = 9.4 – 11.0 GeV $\int L dt$=393 fb^{-1}

Selection of $\eta\eta$ signal events

-Just 4 γ's with Eγ>100 MeV, No π^0 candidate

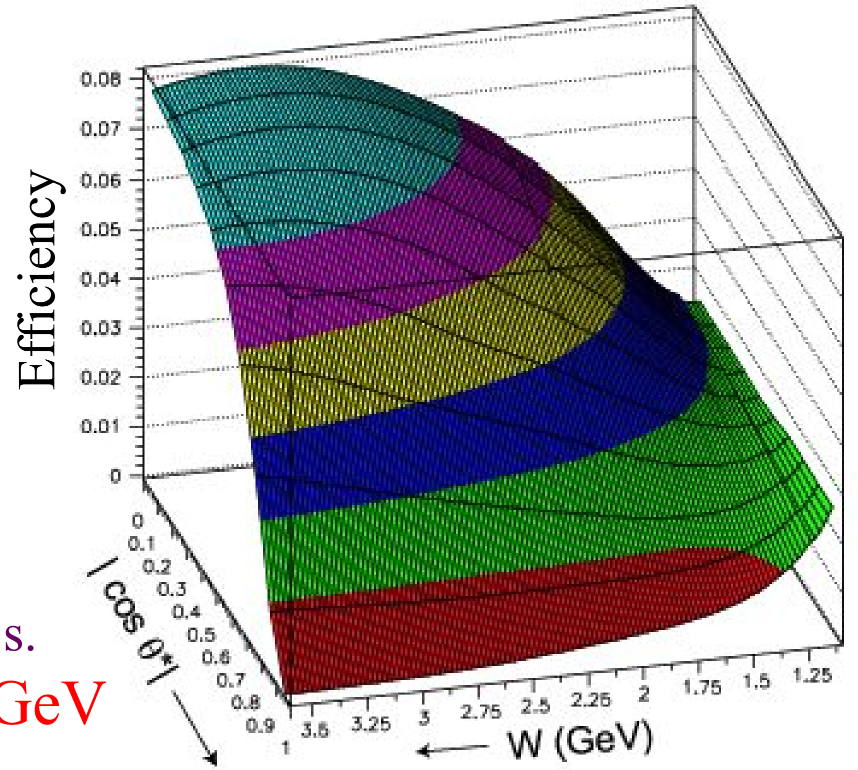
η reconstruction

-Two 2γ sets each satisfying

0.52<M$\gamma\gamma$<0.57GeV

- Apply energy correction for each η, scaling to the nominal mass

-p_t-balance <50 MeV/c



W: $\gamma\gamma$ energy in its c.m.s.

θ^*: scattering angle of the meson in the $\gamma\gamma$ c.m.s.

1.096GeV (mass threshold) < W < 3.8 GeV

$|\cos\theta^*|$ <0.9 or <1.0

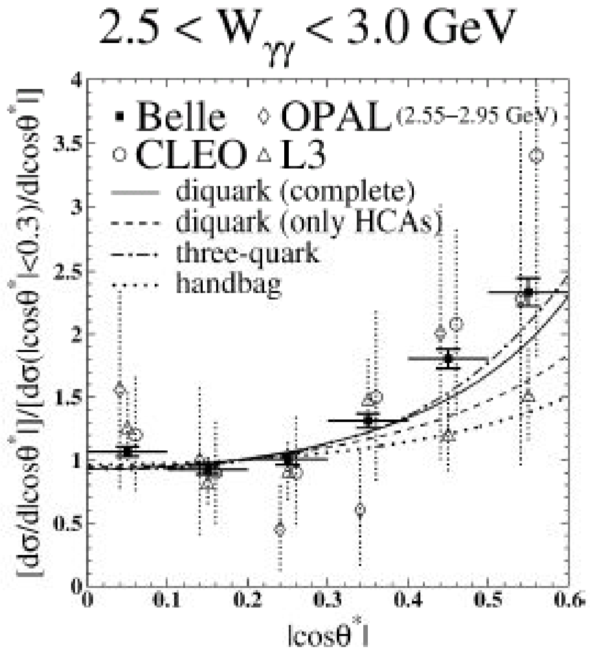
Baryon pair: $\gamma\gamma \to p\bar{p}$

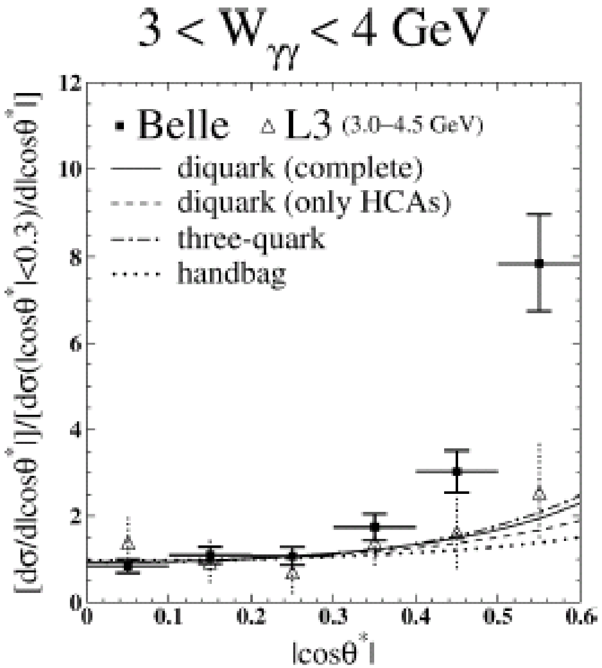
PLB 621, 41 (2005)

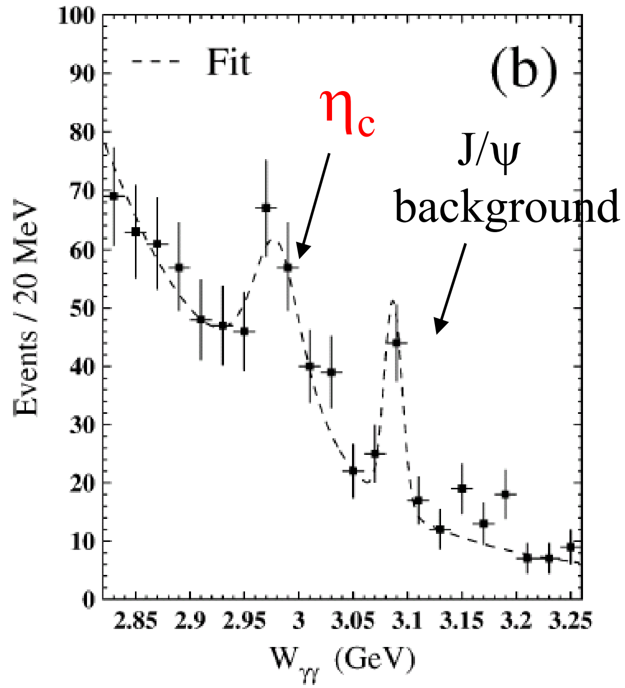
Baryon production mechanism

Couple with a single quark?.. or a diquark?

Angular and W dependences, Cross-section size







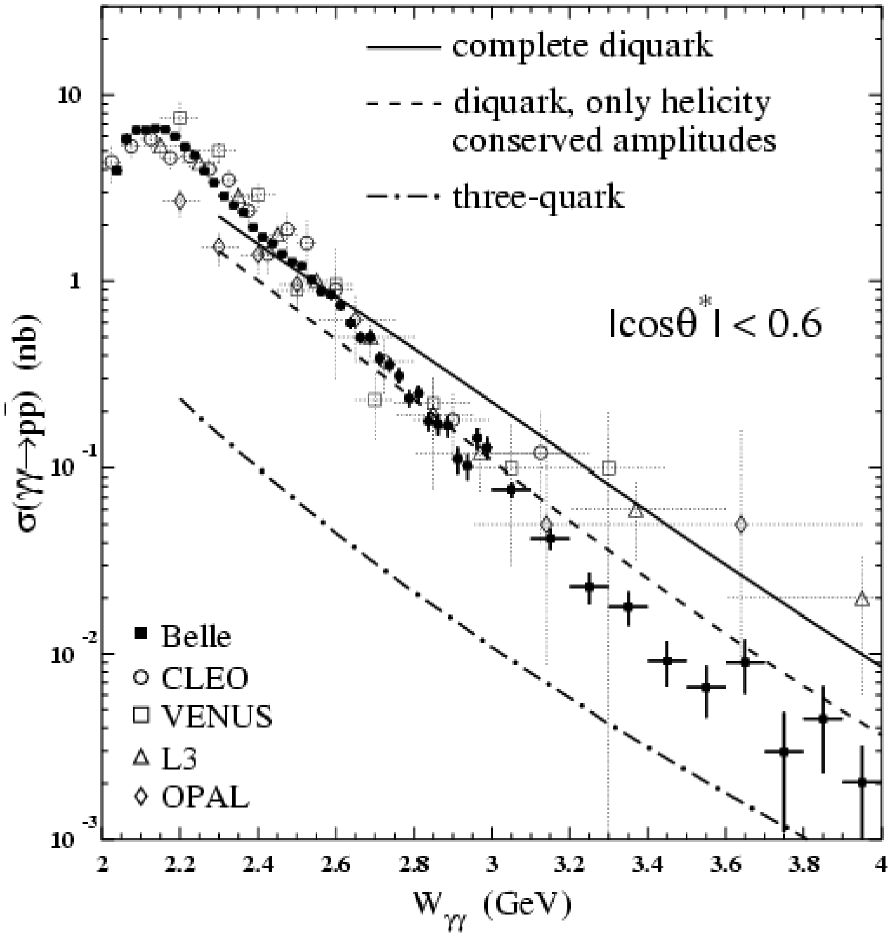
Model predictions are normalized for $|\cos\theta^*|<0.3$.

Agreement is not very good in W>3 GeV

η_c :observation in this proces

Subtract charmonium contributions

Cross sections; W dependence



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

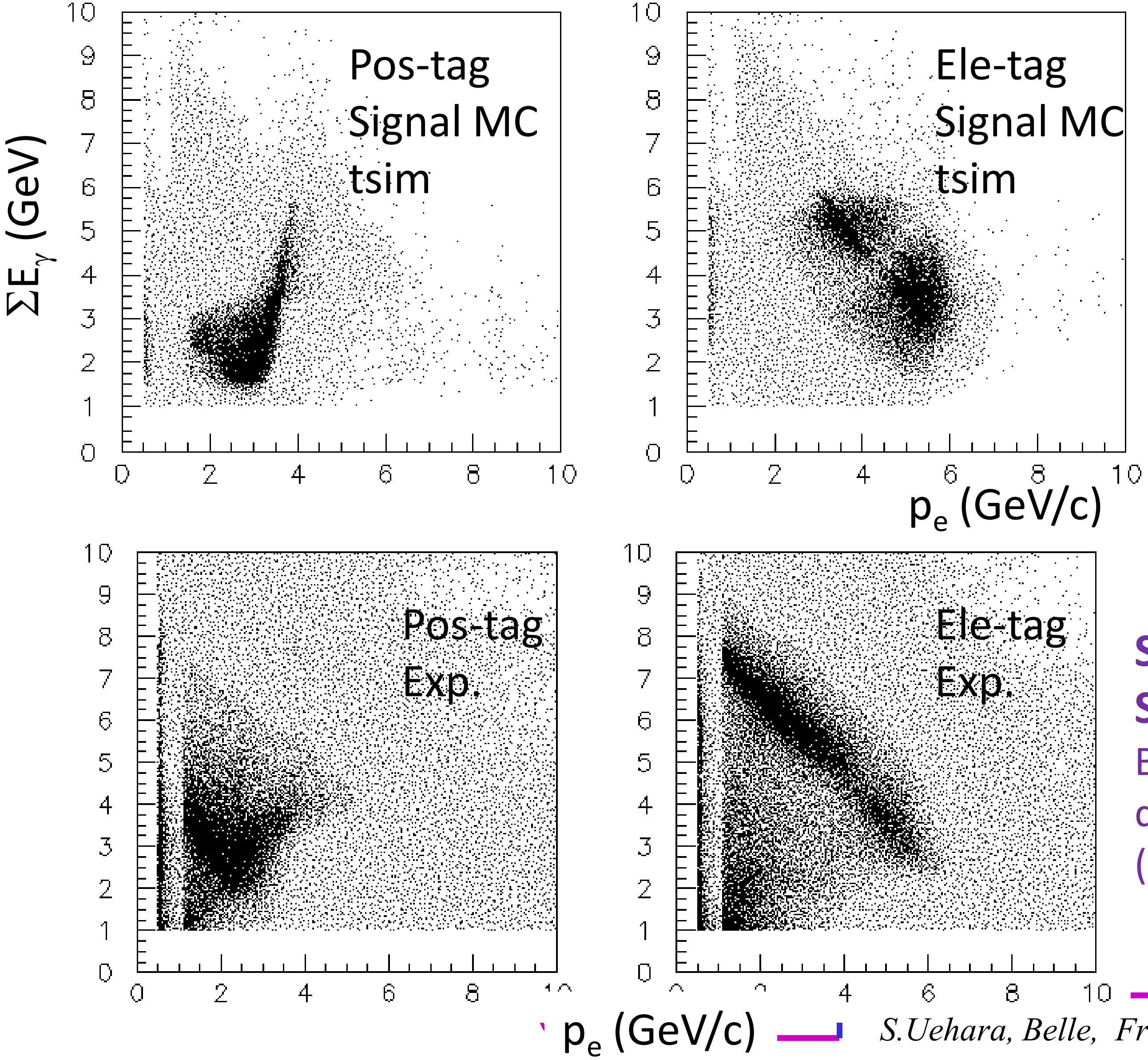
$n = 15.1 \pm^{0.8}_{1.1}$ @ 2.5 – 2.9 GeV

$n = 12.4 \pm^{2.4}_{2.3}$ @ 3.2 – 4.0 GeV

Might agree with a
QCD prediction n= 10
at some energy above 3.1 GeV

Slope – steeper than meson pairs

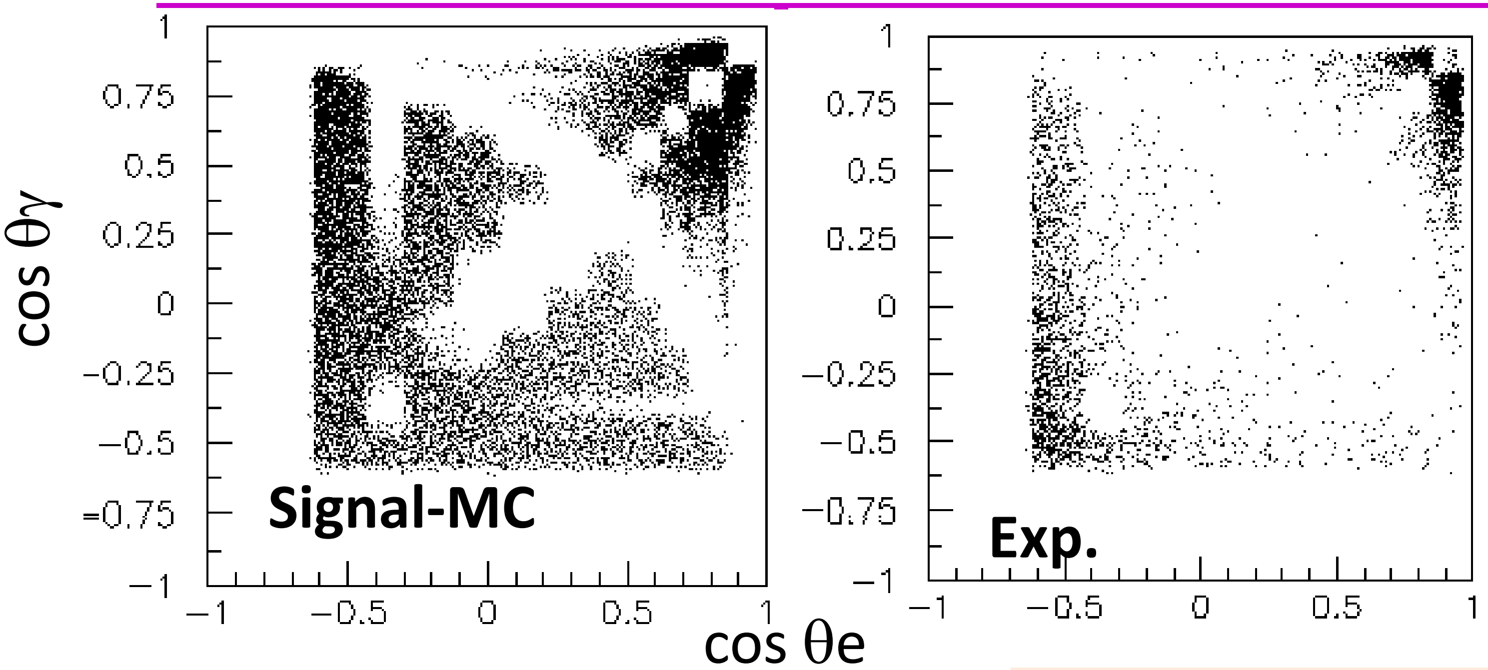
Energy-correlations in the skim file, $\Sigma E\gamma$ > 1.0 GeV



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

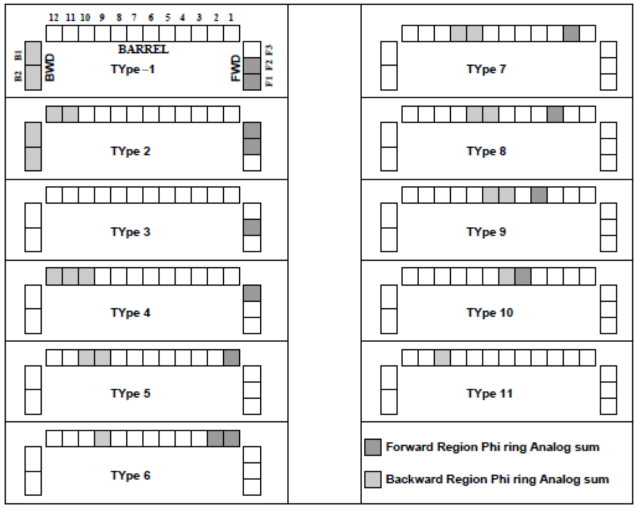
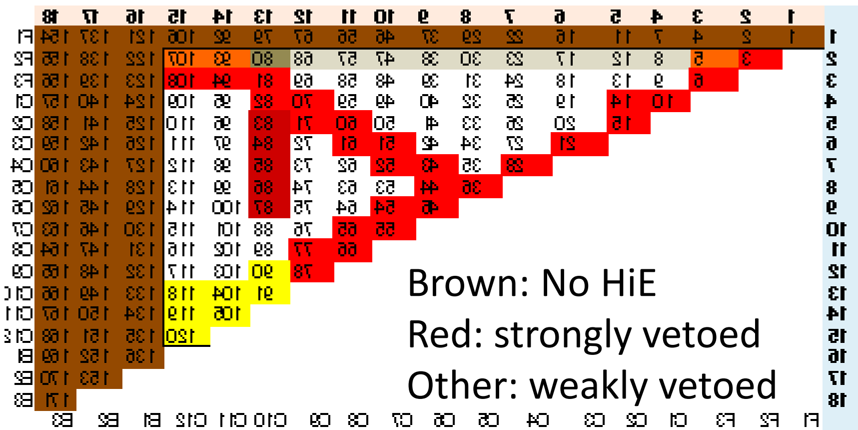


Fig. 4. Eleven types of Bhabha triggers based on each ϕ-ring sum.

Bhabha-veto patterns in trigger



Brown: No HiE

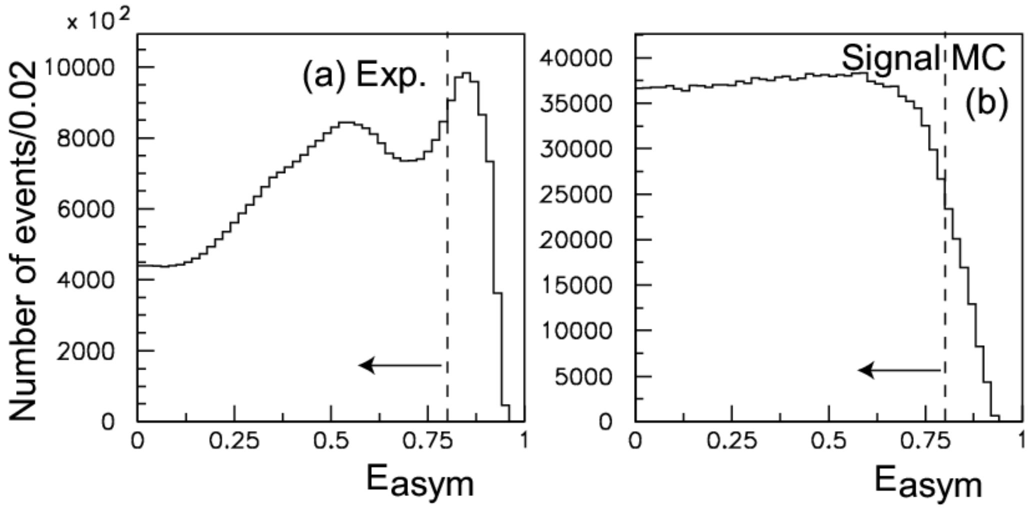
Red: strongly vetoed

Other: weakly vetoed

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

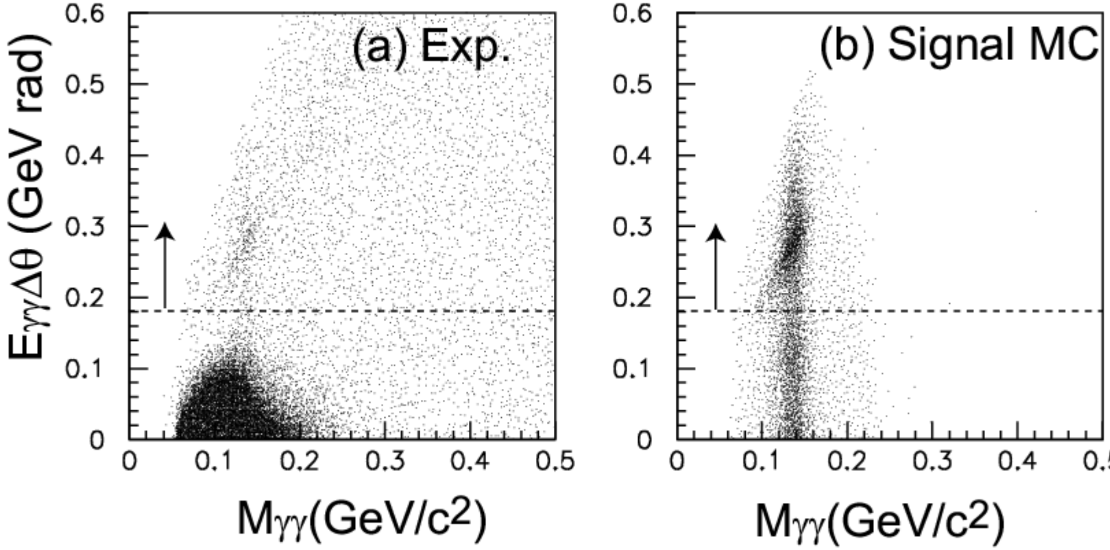
Energy asymmetry

to reject low-energy photon background



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

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

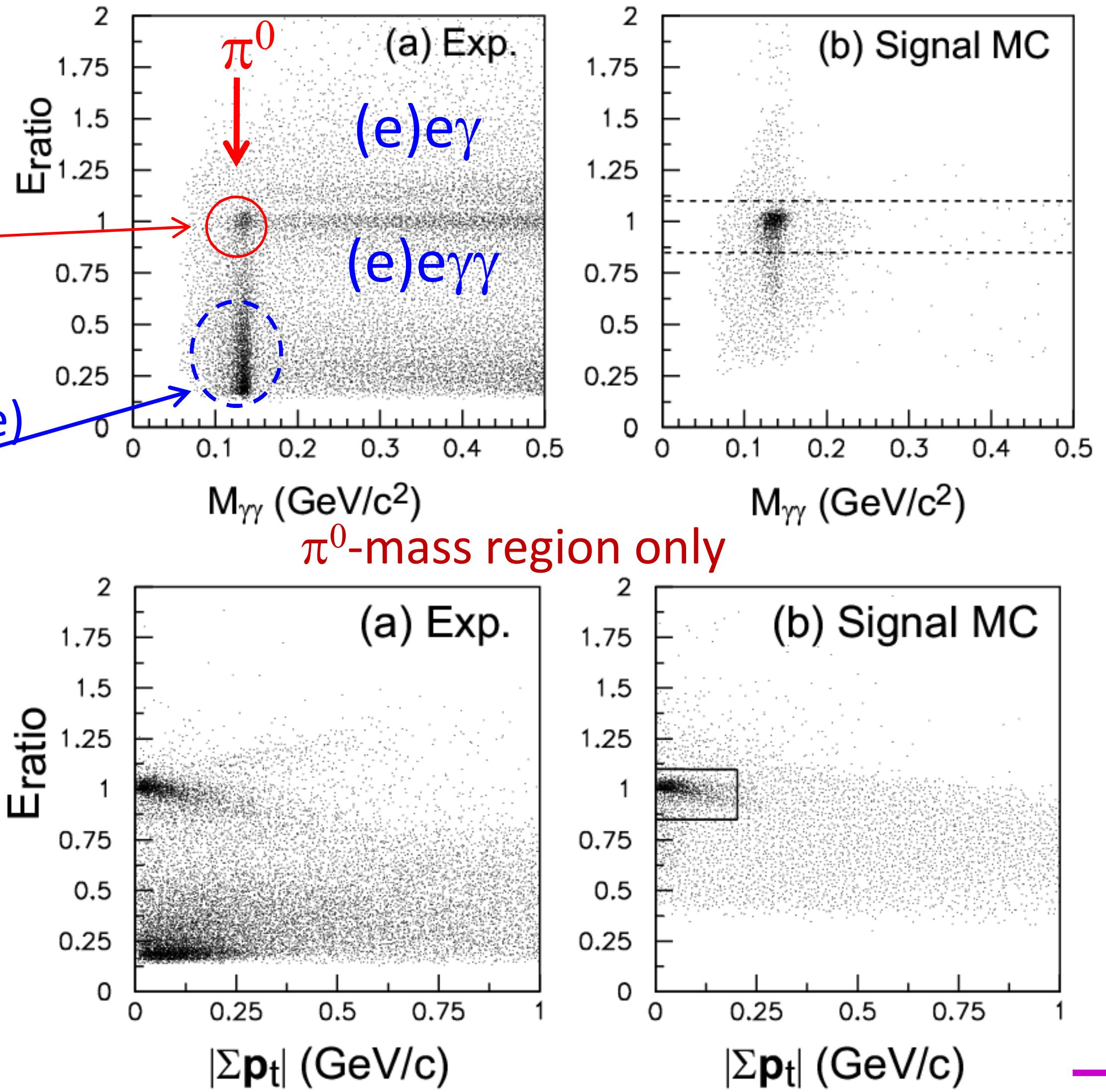


Kenematical Criteria

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

Signal

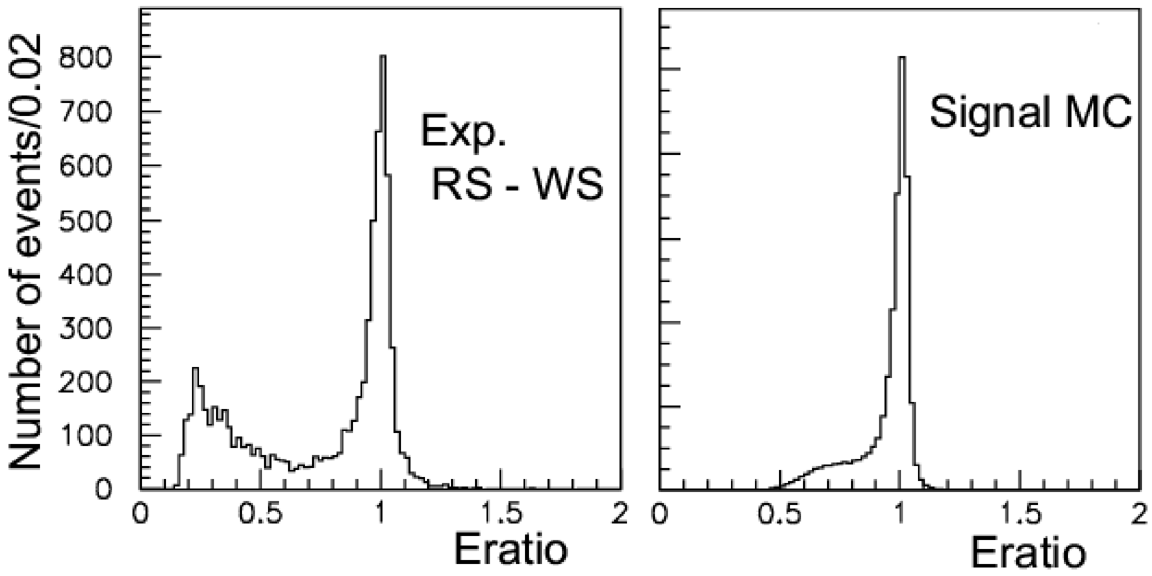
π^0X (non-exclusive) background



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

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

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

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

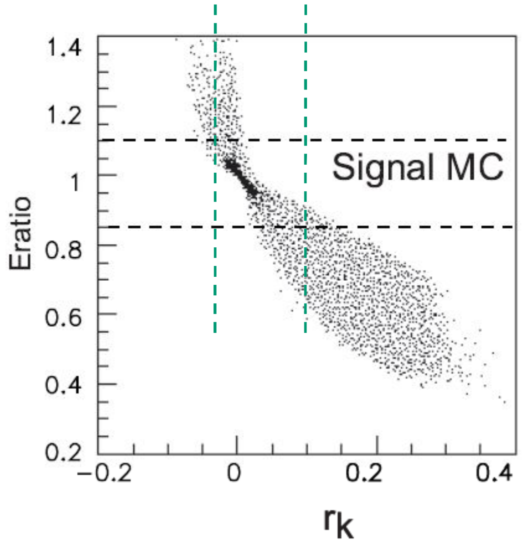
with the same scheme for the efficiency determination

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%.

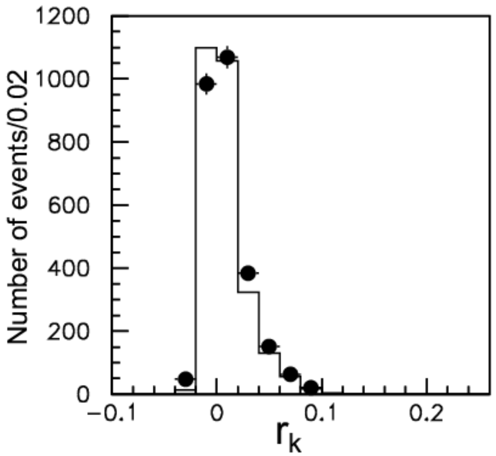
ISR and Radiative Correction

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.

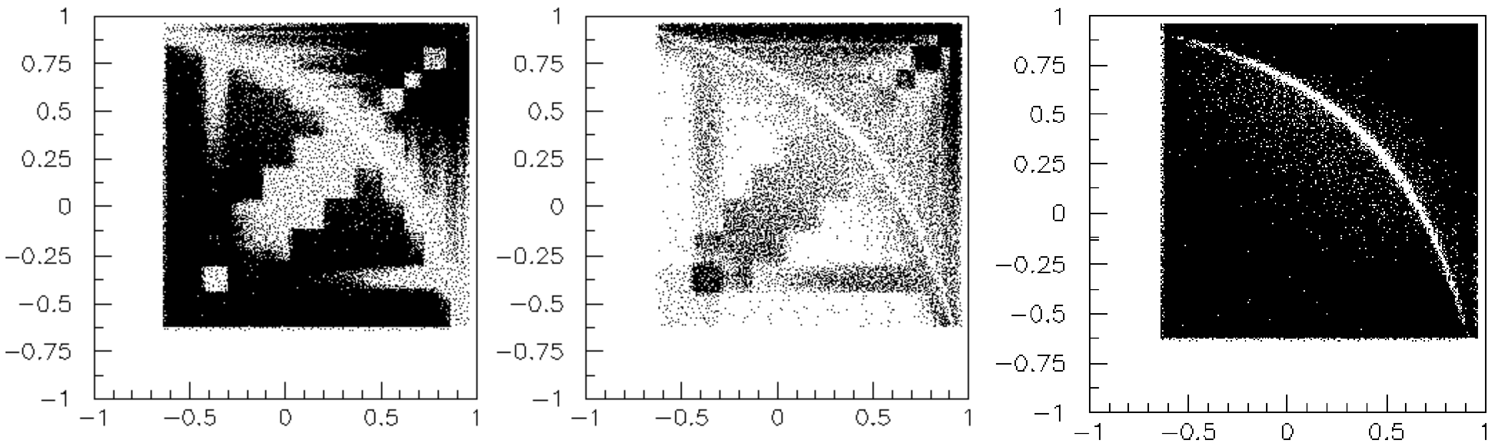
Study of Radiative Bhabha samples

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

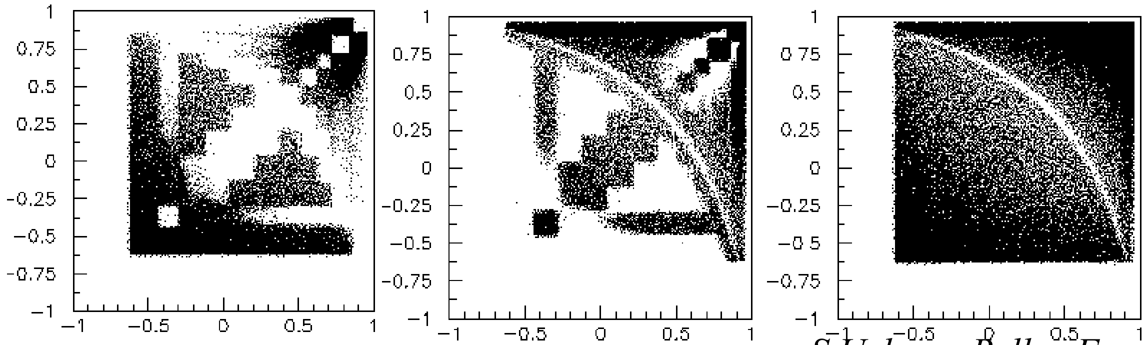


HiE

CsiBB

Unbiased: HiE + 50*CsiBB

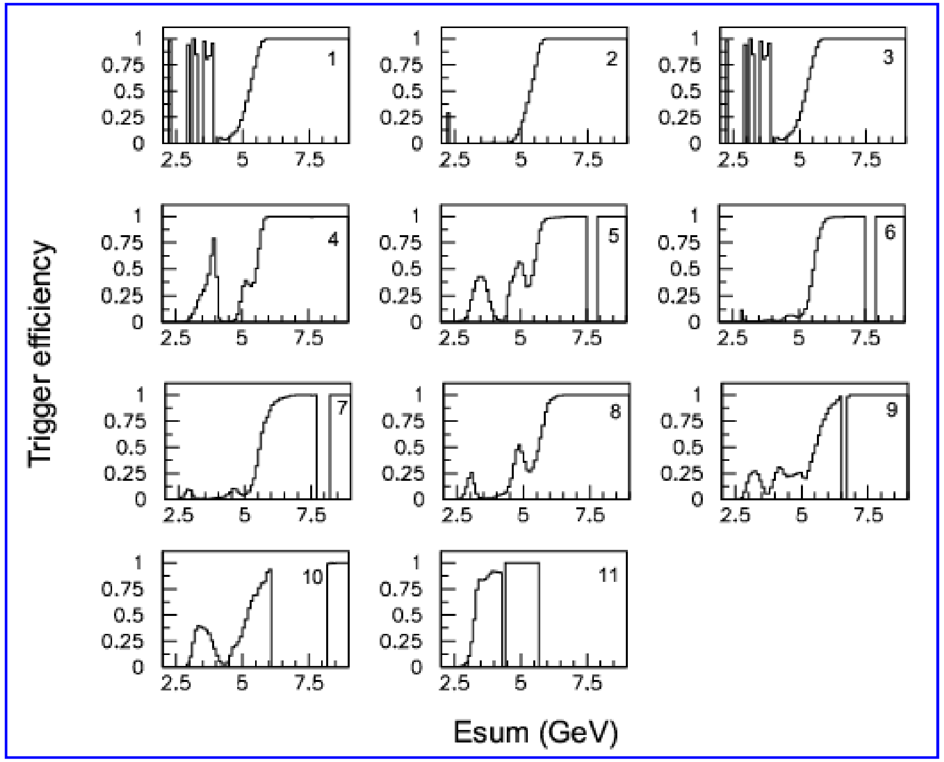
Veto-structure is compensated!



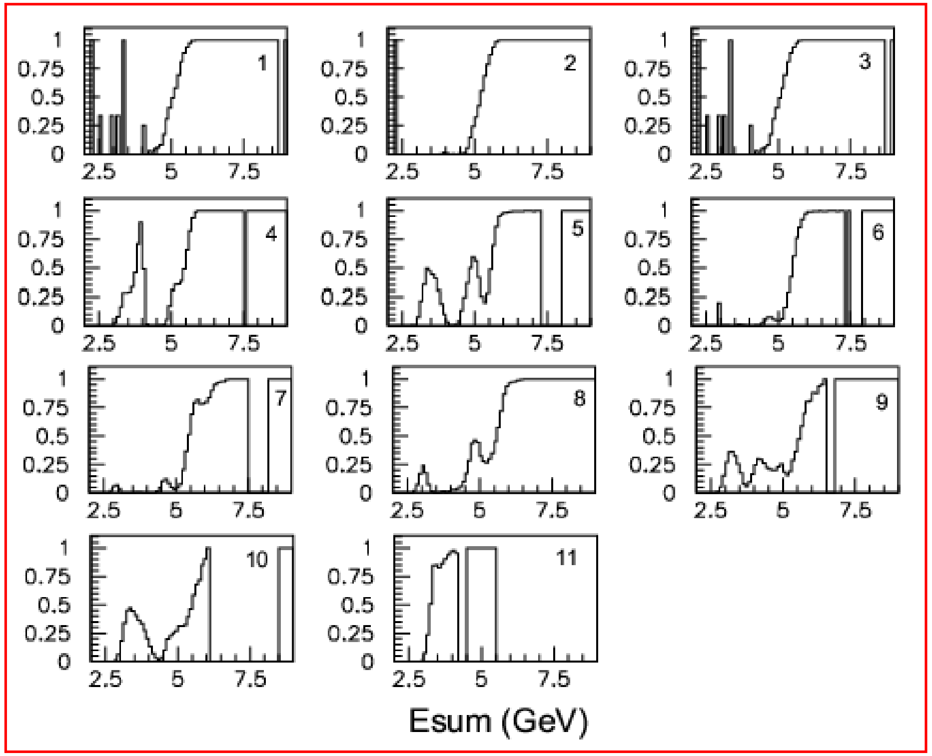
← **MC(Rabhat)**

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



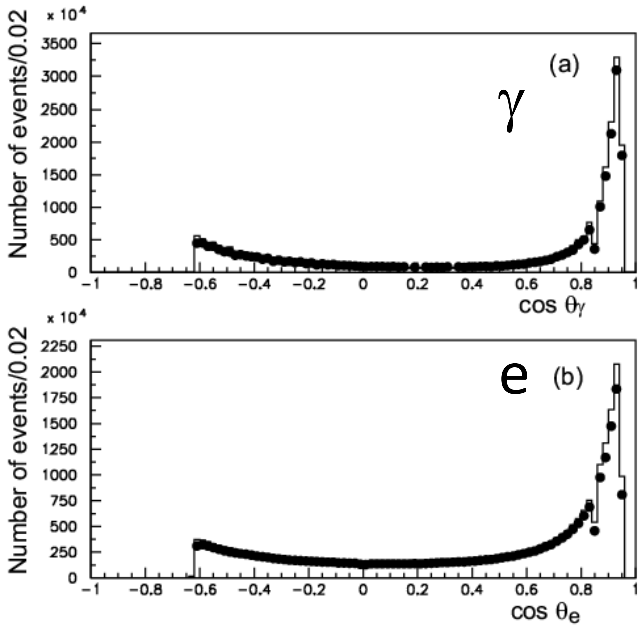
Tuned MC

Comparisons of Radiative Bhabha (VC) samples

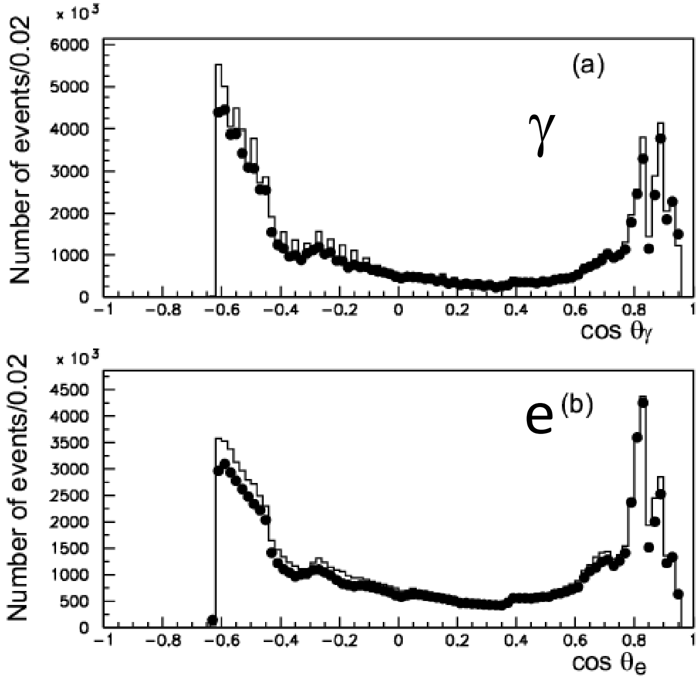
Dots: Exp.
Histograms: MC

Angular cos $\theta \in (-1, +1)$
distributions for γ and e

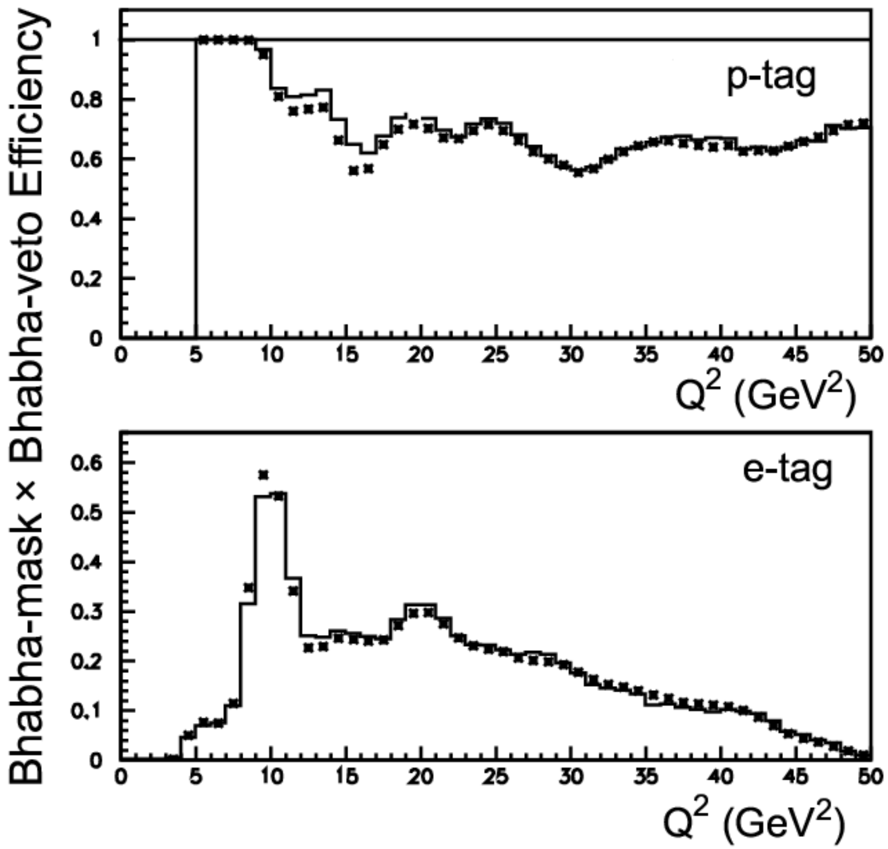
Unbiased



HiE (Bhabha-Masked)



Comparison of Bhabha Mask*Veto efficiency for Radiative Bhabha events

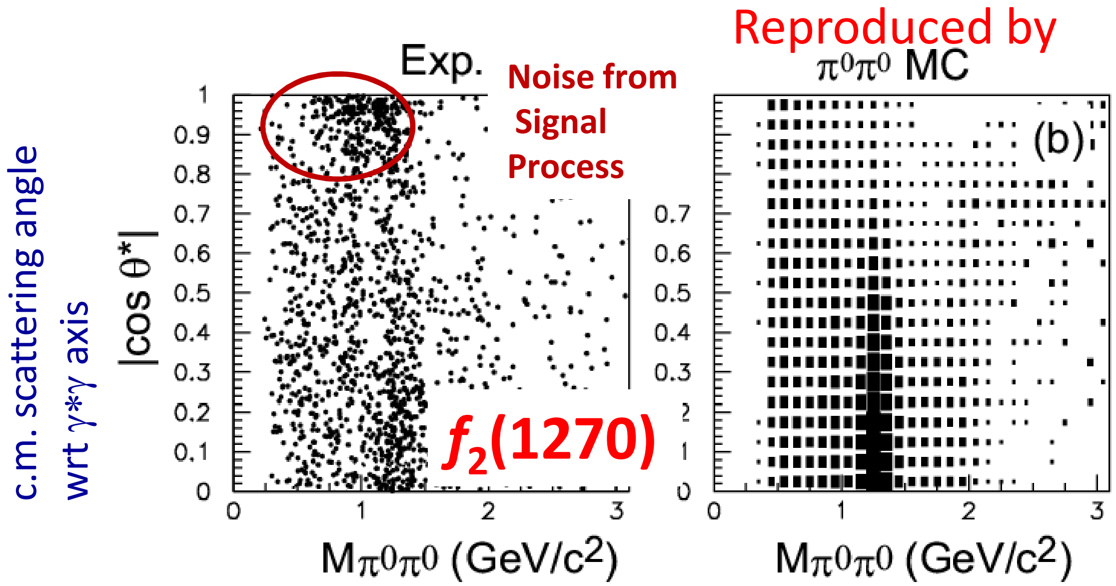


Asterisk: Exp.
Histogram: MC

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

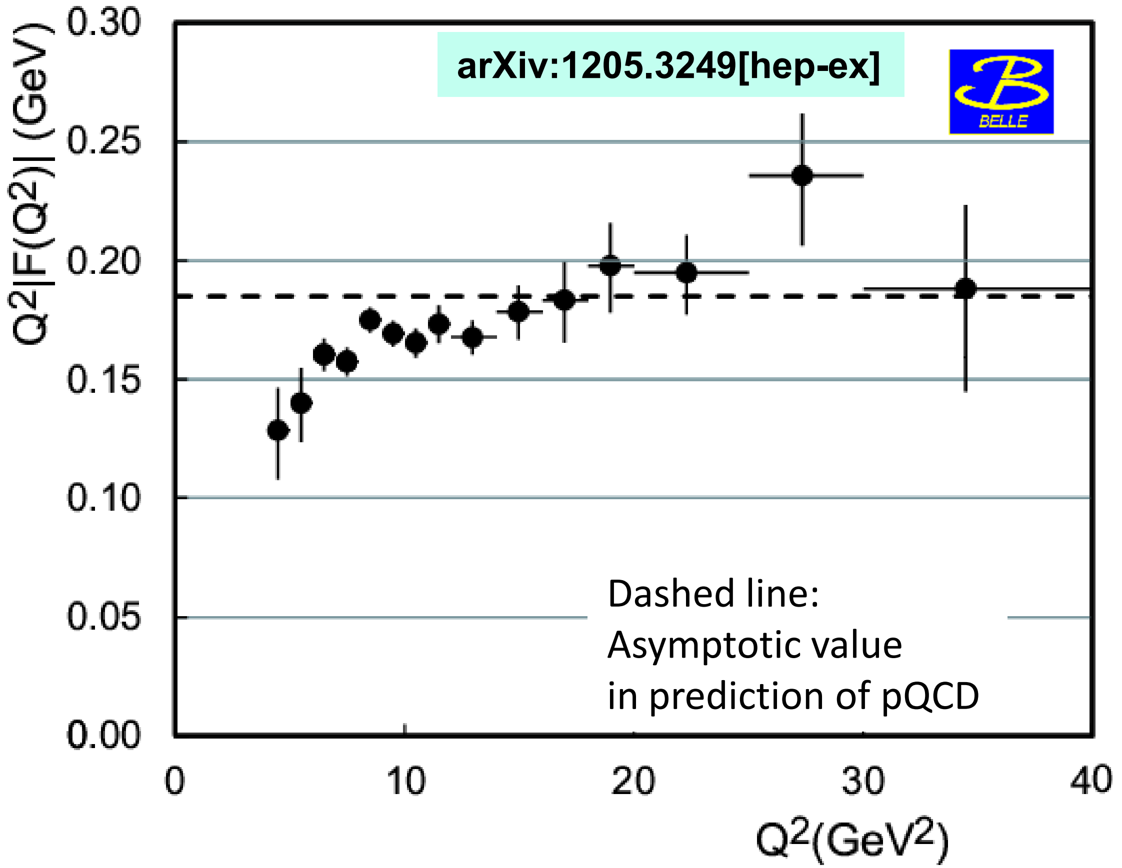
$\pi^0\pi^0$ background MC

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

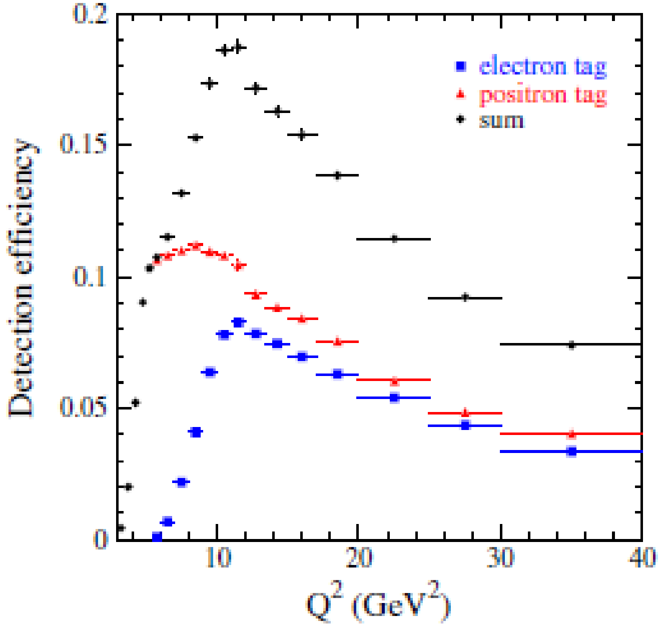


FIG. 4 (color online). The detection efficiency as a function of the momentum transfer squared for events with a tagged electron (squares), a tagged positron (triangles), and their sum (circles).

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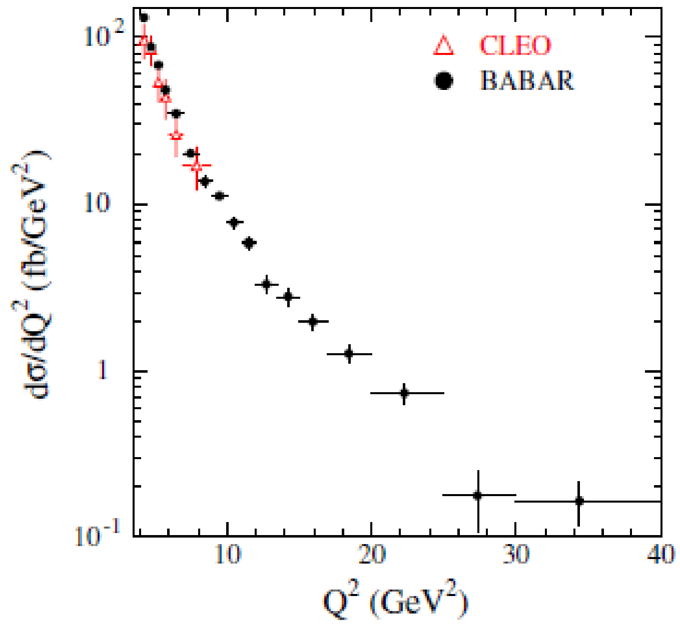
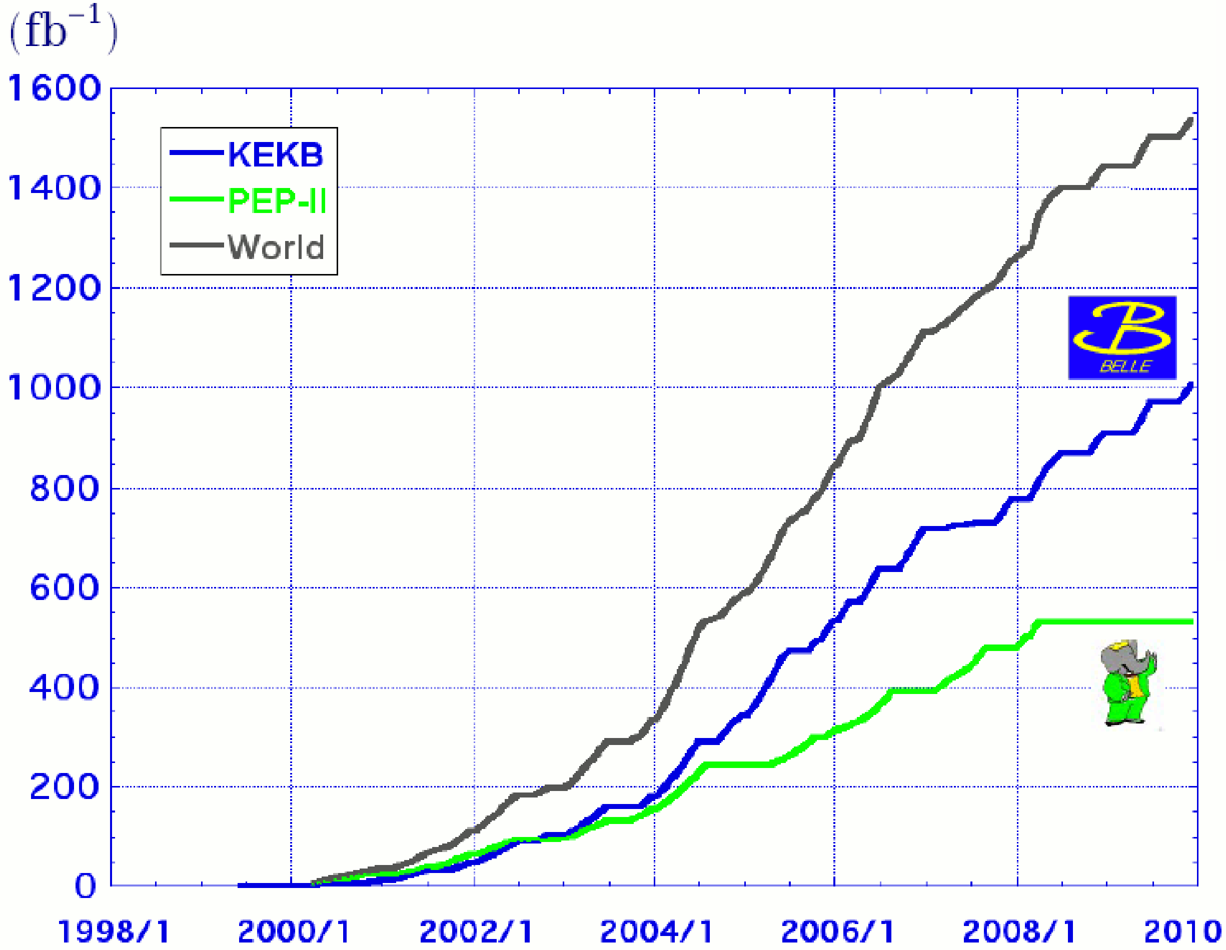


FIG. 21 (color online). The $e^+e^- \to e^+e^-\pi^0$ differential cross section obtained in this experiment compared to that from the CLEO experiment [12].

Integrated luminosities and beam energies

Luminosity at B factories



> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 24 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

~ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

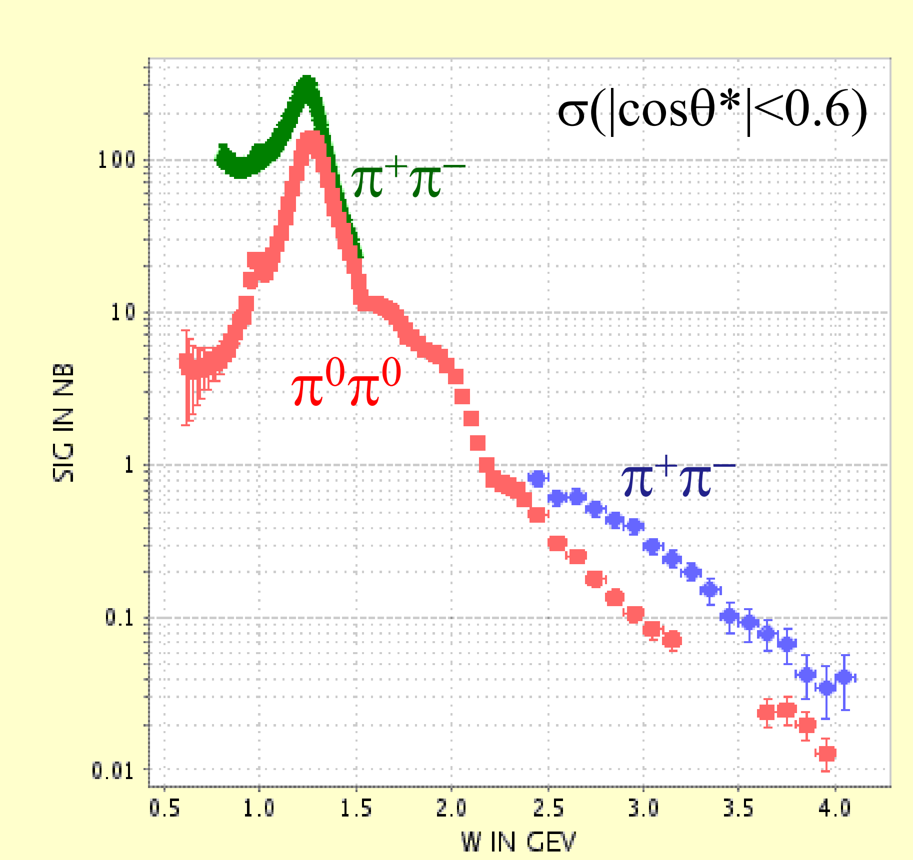
$\Upsilon(3S)$: 30 fb^{-1}

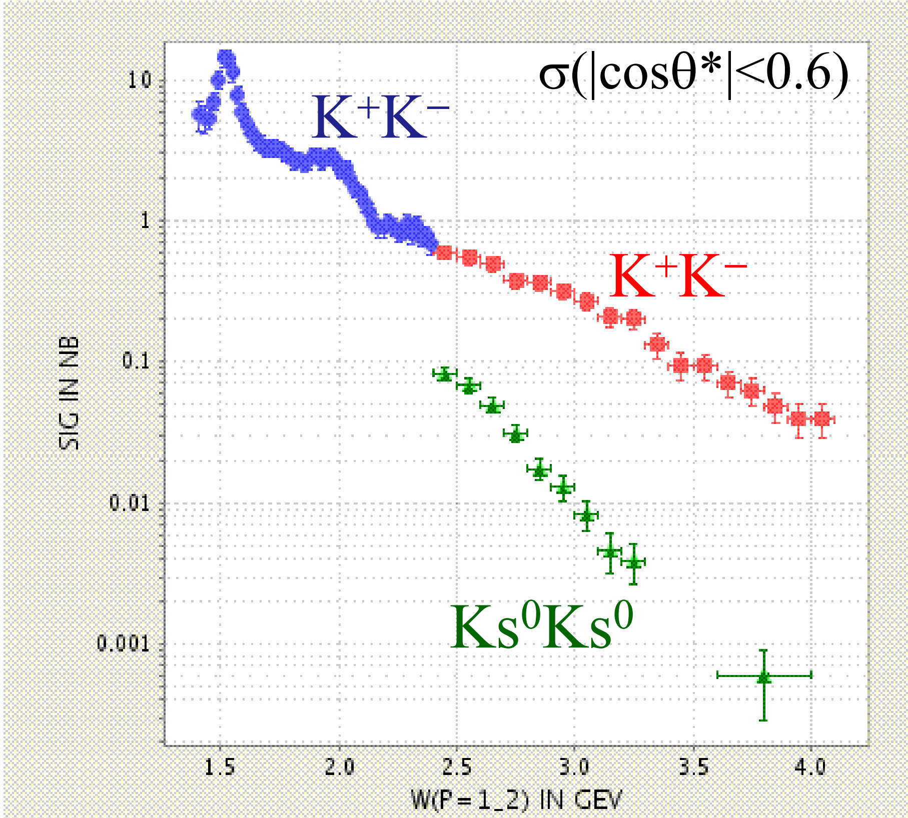
$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

~ 54 fb^{-1}

Cross sections integrated over angle

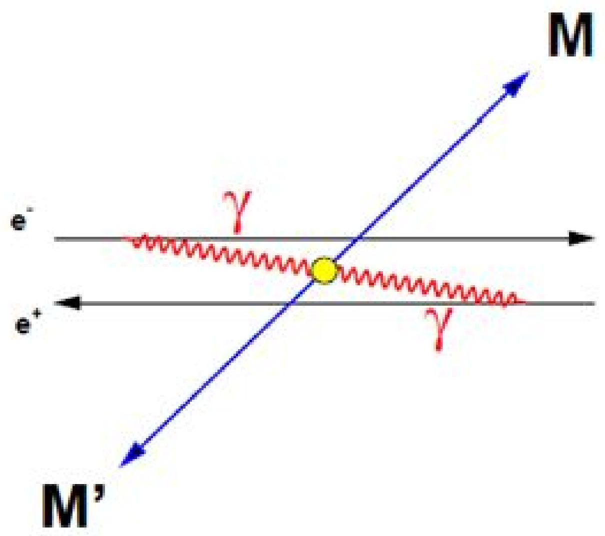




♠Those for $\eta\pi^0$ and $\eta\eta$ are shown in other slides

Zero-tag measurement

- e^+e^- escape down beam pipe at small recoil angles.
- Reactions involve small virtuality photons with $\left|\sum_i \vec{p_t}(M_i)\right| \sim 0$.
- $$\frac{d\sigma}{d|\cos\theta^*|} = \frac{\Delta N}{\Delta W \Delta|\cos\theta^*| \frac{dL_{\gamma\gamma}}{dW} \text{ effi} \int \mathcal{L}dt},$$
  $\frac{dL_{\gamma\gamma}}{dW}$: Luminosity Function
- For a resonance R, two-photon decay width $\Gamma_{\gamma\gamma}$ is measured from
  $$\sigma(W) = 8\pi(2J+1)\frac{\Gamma_{\gamma\gamma}(R)\Gamma_R \mathcal{B}(R\to\text{final states})}{(W^2-M_R^2)^2+M_R^2\Gamma_R^2}$$



$$W = M(\gamma\gamma) = M(\text{Mesons})$$