The luminosity measurement at Belle detector

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Introduction: What is a luminosity?

The luminosity is a parameter which characterizes collider capability.

The idea of luminosity comes from a naive model.

If two clouds of solid particles with numbers N_1, N_2 collide each other the number of scattered particles are

$$N = \frac{N_1 * \sigma}{S} \cdot N_2,$$

where S – transverse area of the pack, for particles of radii R $\sigma = \pi(2R)^2$.

If collisions happen with frequency f one get a formula for the scattering rate

$$\frac{dN}{dt} = f \frac{N_1 * N_2}{S} \cdot \sigma,$$

Coefficient before σ is a **luminosity**.

For real collider with Gaussian spread of particles in beams the luminosity is

$$L = f\frac{N_1 * N_2}{4\pi\sigma_X\sigma_Y}$$

In reality accuracy of such calculation is not high because

- Vertical beam size is few microns – difficult to measure.
- Beam–beam alignment is not ideal.

In most cases one should to **measure** luminosity with some process with **known** cross section and

$$L = \frac{Rate}{\sigma_{vis}},$$

where σ_{vis} is a visible (effective) cross section which takes into account

- The process kinematics — that part is calculated by theory.
- The geometry and efficiency of the detection system — MC simulation.

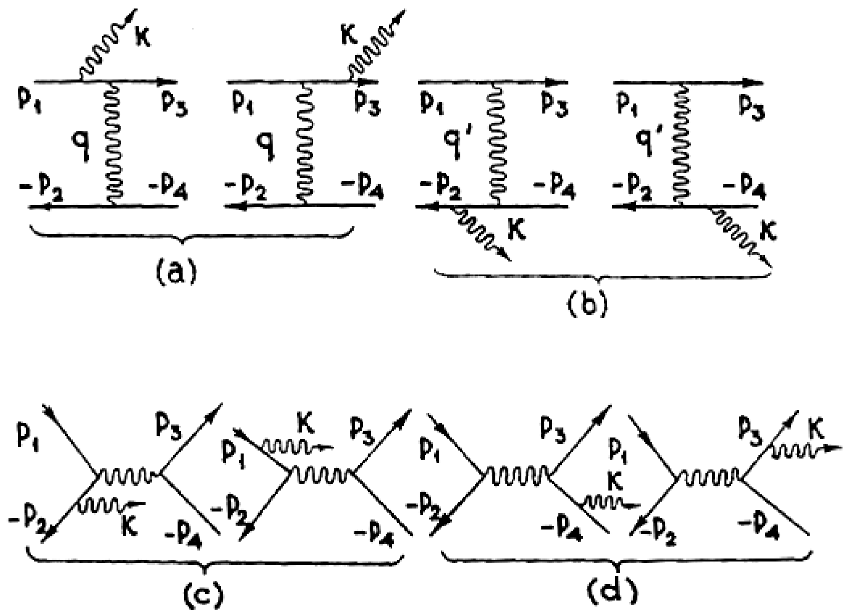
QED processes

In spite that QED calculations are developed for ∼50 there are not so many processes which cross section calculated with accuracy of few percents.

Processes used for luminosity measurements at e^+e^- colliders are:

- Single Bremsstrahlung (SBS) – $e^+e^- \rightarrow e + e\gamma$
- Bhabha Scattering – $e^+e^- \rightarrow e^+e^-$
- e^+e^- annihilation to $\gamma\gamma$
- e^+e^- annihilation to or $\mu^+\mu^-$

Single Bremsstrahlung – $e^+e^- \rightarrow e + e\gamma$



First order Feynman Diagrams for SBS process

Energy spectrum for SBS γ-quantum in the CM frame is described with formula

$$\frac{d\sigma}{dE_\gamma} = \frac{4\alpha r_e^2}{3E}\left(4\frac{E}{E_\gamma} + 3\frac{E_\gamma}{E} - 4\right)\left(\ln(4\gamma^2\frac{E - E_\gamma}{E_\gamma}) - \frac{1}{2}\right)$$

Cross section diverges when $E_\gamma \rightarrow 0$. So, one can tune SBS rate changing E_γ threshold.

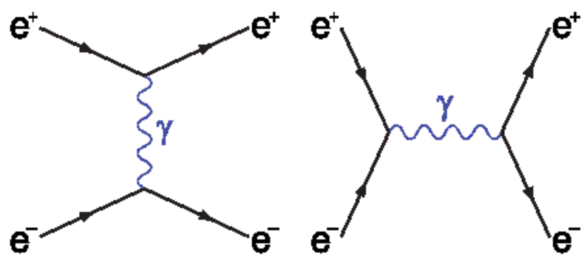
For KEKB energies $\sigma(E_\gamma > 100MeV) \sim 10^{-25}cm^2$.

This method was frequently used for luminosities $< 10^{32}$.

Its accuracy is limited with 3-5% level because $\sigma(SBS)$ depends on a transverse beam size.

Bhabha scattering – $e^+e^- \rightarrow e^+e^-$

First order Feynman Diagrams for Bhabha



In CM frame for beam energy E

the cross section of this process is

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{16 \cdot E^2} \cdot \left(\frac{3 + cos^2\theta}{1 - cos\theta}\right)^2$$

where θ is a scattering angle ($\theta_{e^-} = \pi - \theta_{e^+}$).

Cross section diverges when $\theta \rightarrow 0$. To calculate the Bhabha rate one should take into account the detector solid angle.

For Belle case Bhabha cross section change from

6 nb for $\theta > 50°$ – Barrel part

to 50 nb for $\theta > 16°$ – Endcaps

$1\ nb(nanobarn) = 10^{-9} \cdot 10^{-24} = 10^{-33} cm^2$

For accuracy better than 10% radiation corrections

for Bhabha diagrams should be calculated:

Some photons in the final state are possible,

number of diagrams increased dramatically.

e^+e^- annihilation to $\gamma\gamma$ or $\mu^+\mu^-$

Only annihilation diagram is possible.

The is no divergences for their cross section.

For Belle energies total cross sections are

$\sigma(e^+e^- \to \gamma\gamma) \simeq 6$ nb and

about 1 nb for barrel part.

$\sigma(e^+e^- \to \mu^+\mu^-) \approx 0.3\sigma(e^+e^- \to \gamma\gamma)$.

These processes usually used for

an integrated luminosity calculation.

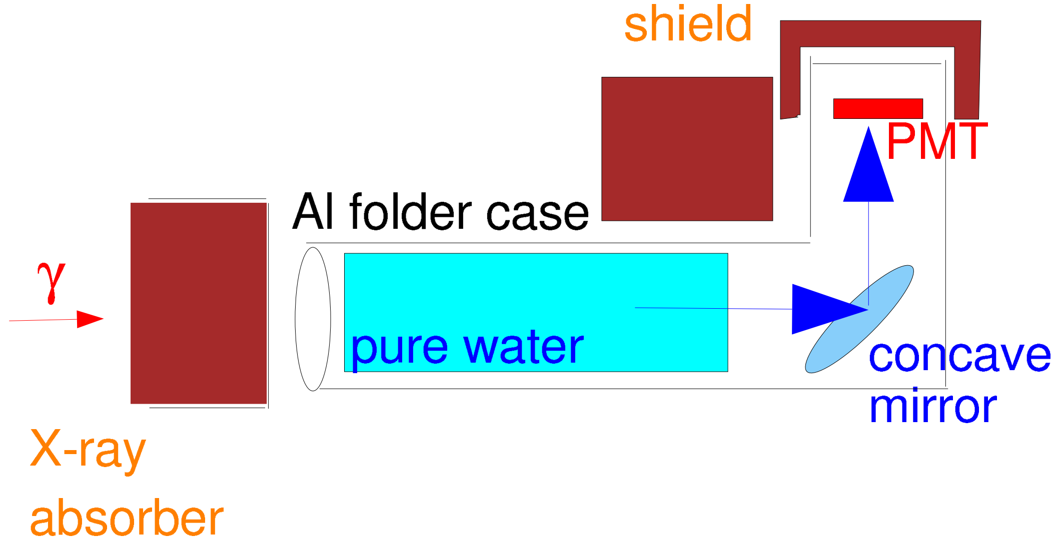
Online Luminosity

The on-line measurement used for collider tuning.

These measurements should be frequent enough and reasonably accurate.

Belle has 3 independent systems for online luminosity measurements.

Zero Degree Luminosity Monitor



Counting rate about 10^6Hz.

Suffer from large synchrotron radiation and beam–gas background which depends on

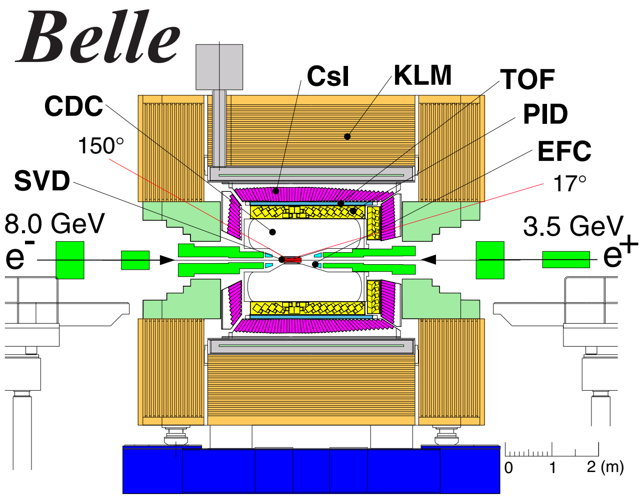
beam position. The accuracy 20–50%.

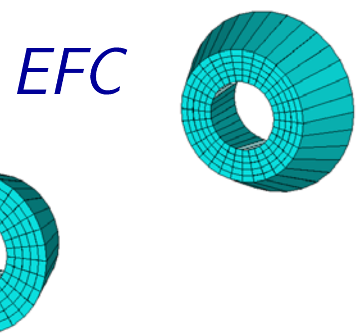
Used for separated bunch-to-bunch luminosities value (about 1500 independent items).

Extreme Forward Calorimeter (EFC)

EFC geometry:

- Two endcap BGO calorimeters cover the range of $6.2^\circ < \theta < 11.6^\circ$ in forward side and $163.1^\circ < \theta < 171.5^\circ$ in backward side.
- 160 crystals in each side with 5 layers in θ and 32 segment in ϕ.
- The typical cross section of a crystal is 2cm $\times$ 2cm with either 12.0(forward) or 10.5(backward) X_0 in length.





Uses back-to-back coincidence to select Bhabha events – 4 sectors each side.

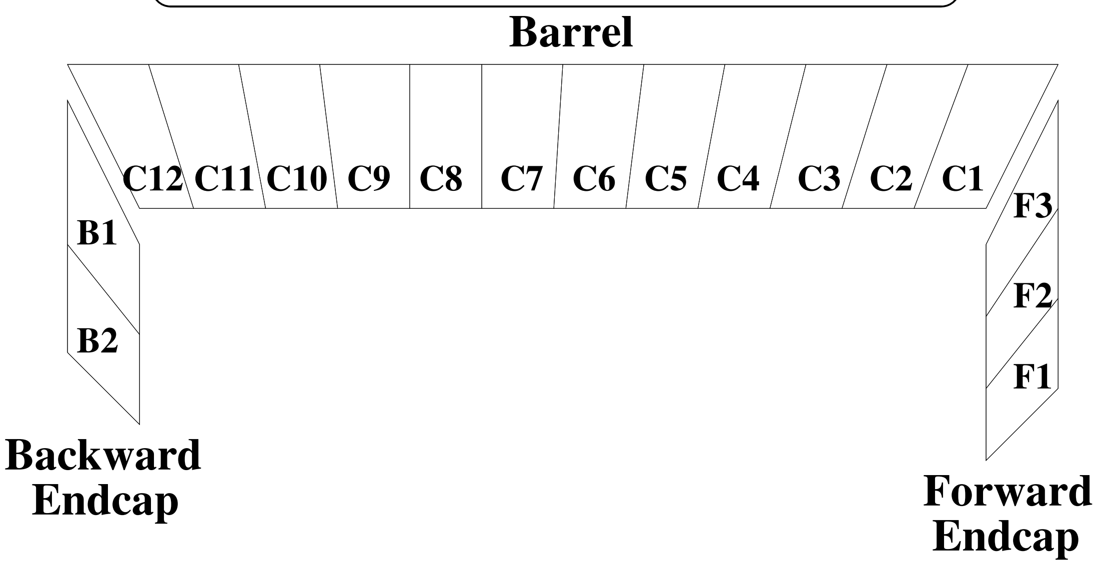
Counting rate about 1500 Hz. Fake coincidence is about 5%.

If e^+e^- interaction point shifts 1 mm $\delta L/L \approx 1.5\%$

Electromagnetic Calorimeter

for Luminosity measurements

θ components of Bhabha trigger.



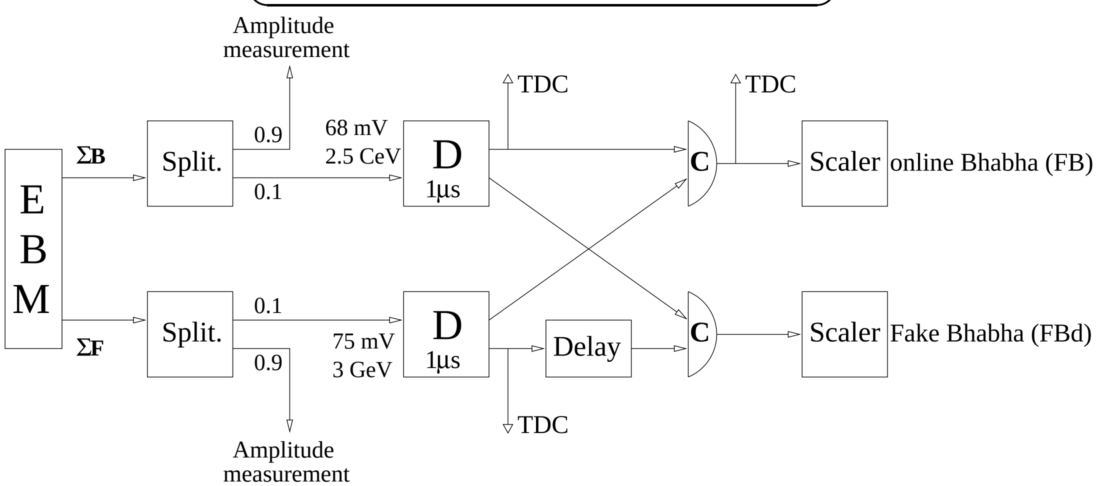
- Calorimeter (ECL) consists of 8736 crystals.
- The ECL trigger has about 600 cells (mainly 4x4 counters) with threshold 50–100 MeV
- The sums of signals are calculated for 17 rings in ϕ direction.
- Bhabha trigger – energy threshold for various ring combinations

At the beginning we use this signal for L mesurement, but

- Low L— cosmic background.
- Larger L— beam lost background.

ECL luminosity monitor

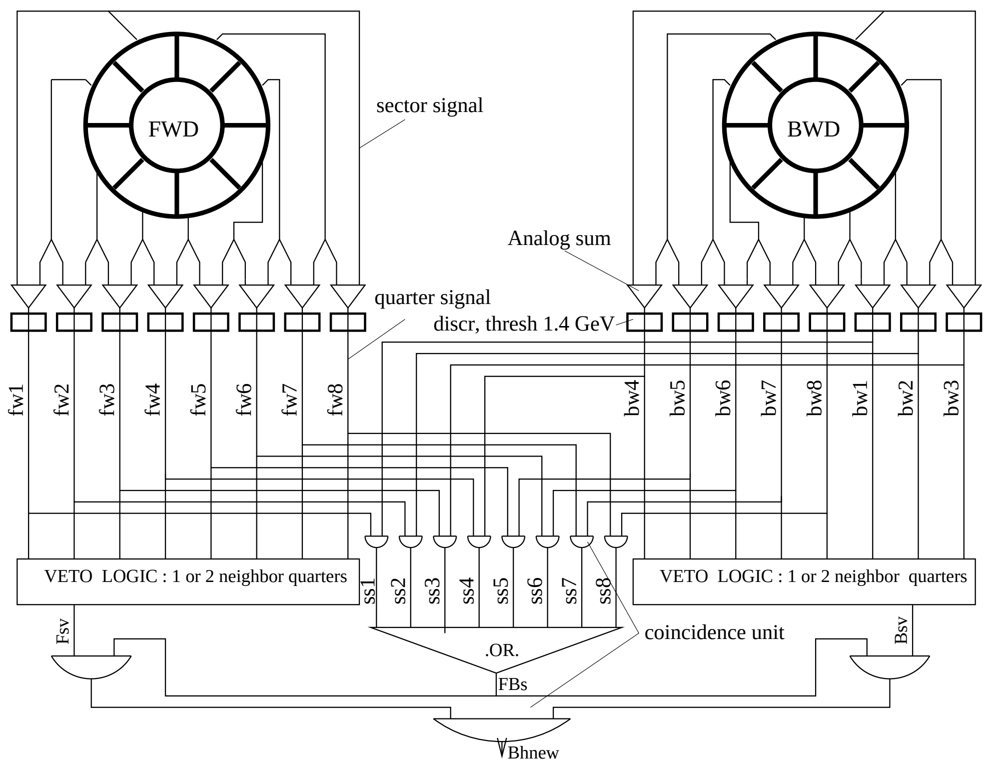
Old luminosity monitor.



- Bhabha rate about 300 Hz.
- Problem: Injection background is large.

ECL luminosity monitor–2

New luminosity monitor for continuous injection.

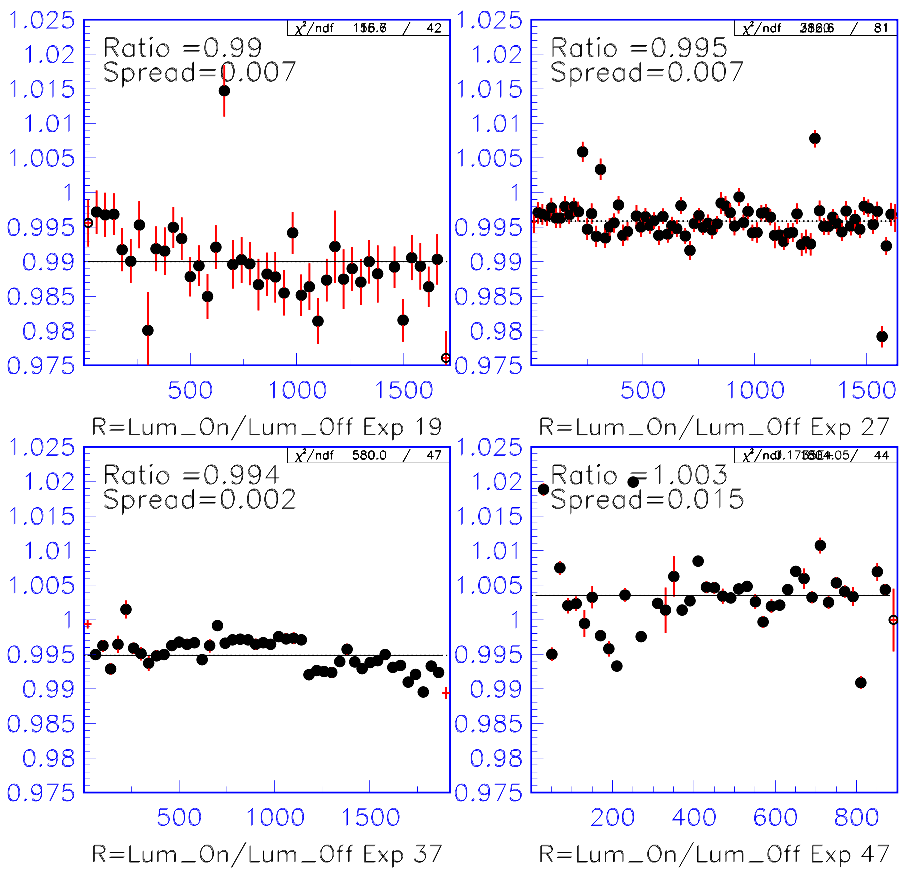


Advantage

- Few Hz rate of injection background.
- Threshold 1.4 GeV → 500 Hz of Bhabha rate.

ECL luminosity monitor stability

History of R=Lum_OnLine/Lum_OffLine for 2001–2005



The comparison of the online and offline luminosity.

Sum of 20 runs per bin. The errors are statistical.

Offline Luminosity

beginlarge Processes of $e^+e^- \rightarrow e^+e^-$ and $e^+e^- \rightarrow \gamma\gamma$ are chosen.

Event selection criteria (CM frame).

Description	e^+e^-	$\gamma\gamma$
Frame for cuts	CM frame	CM frame
# of charged tracks	≥ 2	< 2
# of ECL clusters	≥ 2	≥ 2
Track momentum	2 tracks > 2.645GeV	
Cluster max. energy	> 2.0GeV	> 2.0GeV
Sum of ECL energy	> 4.0GeV	> 4.0GeV
Acollinearity $\delta\psi$	for two tracks $< 10^\circ$	for two clusters $< 10^\circ$
$acos(-(\vec{p1} \cdot \vec{p2})/\lvert\vec{p1}\rvert/\lvert\vec{p2}\rvert)$	of opposite charge	1st and 2nd highest
Additional cuts for:	charged tracks	clusters
	$P_t > 0.1$GeV	$\Delta\phi < 2.3^\circ$
	$\lvert dr\rvert < 2$cm, $\lvert dz\rvert < 4$cm	
Barrel selection	for two tracks	for two clusters
Polar angle θ(CM)	$46.7^\circ - 145.7^\circ$	$46.7^\circ - 145.7^\circ$

Acepatnce calulations

The detector acceptance is restricted to the barrel part only.

To obtain an integrated luminosity one calculate number of Bhabha ($\gamma\gamma$) event for some period, apply some efficiency corrections and divide it by σ_{vis} from MC calculation.

Generators for Monte Carlo Simulation.

Parameters	BKJ for Bhabha	BHLUMI for Bhabha	BKJ for $\gamma\gamma$
QED correction	α^3 0 or 1 rad.γ	α^4 many rad. γ	α^3 0 or 1 rad.γ
Accuracy	1–2% Theoretical estimation	1.3% CLEO estimation	1.3% CLEO estimation
σ_{vis}	6.90±.03	6.93±.02	0.970±.003

Accuracy of the luminosity measurements

Statistic errors

For 1 hour run Belle collects about 50 pb^{-1} resulting stat.errors are

.7% — for Bhabha and 1.7% — for $e^+e^- \to\gamma\gamma$.

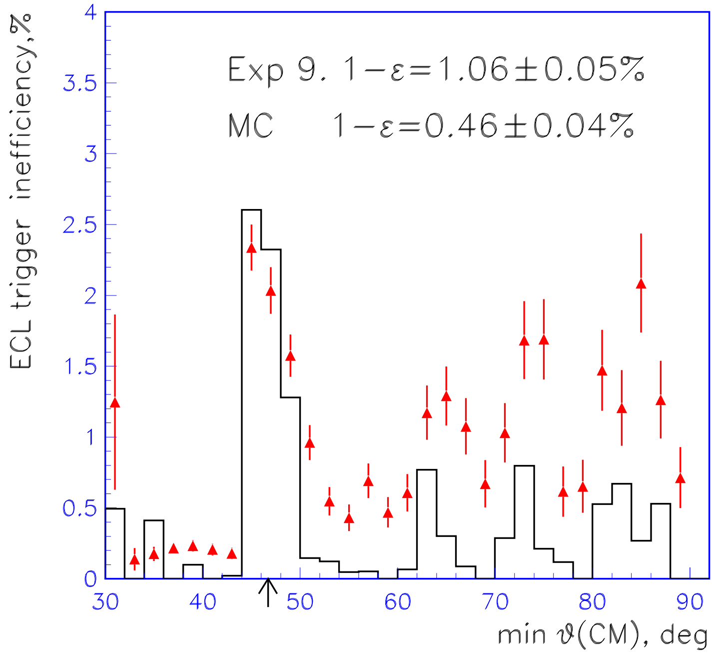
In most cases it negligible.

Systematic errors

- Correction to MC
  - ECL inefficiency: is 1% mostly due to Bhabha trigger.
  - CDC inefficiency: usually 0.5%. Sometimes track reconstruction fails.
  - Effect of material in front of ECL: MC description of the detector isn't perfect: Essential for online monitor.
  - Background from other physical processes: Rather small.
  - Instabilities of KEKB, electronics etc

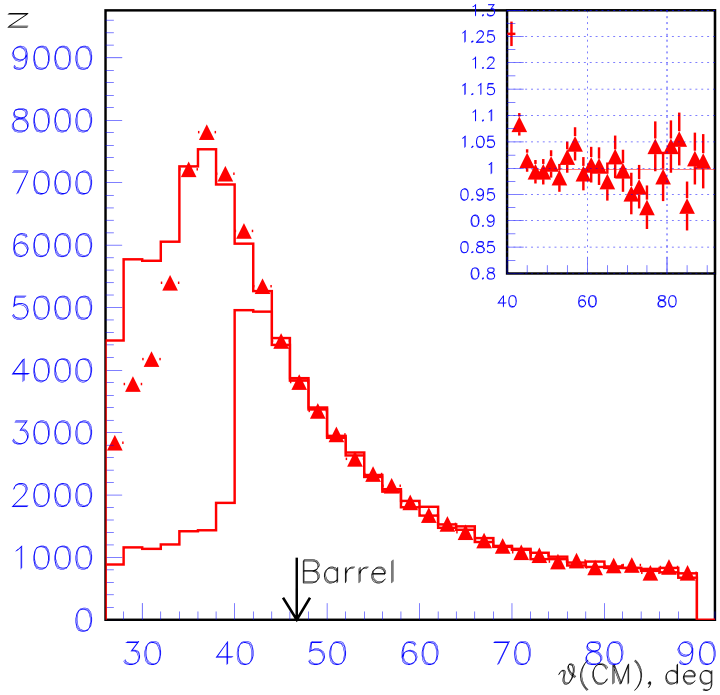
Accuracy of the MC simulation

Inefficiency of ECL trigger versus $\theta = min(\theta_{e^+}, \theta_{e^-})$ in CM frame



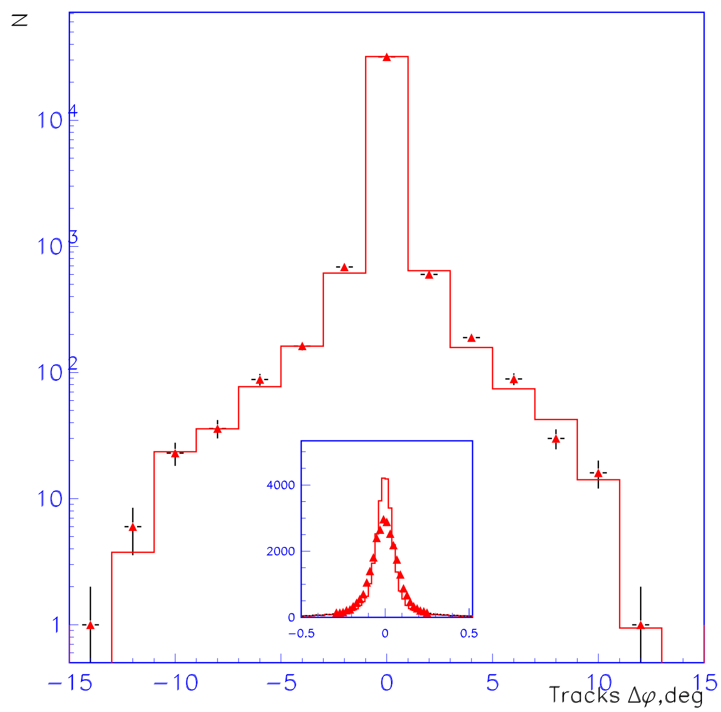
The arrow – for the cut position for luminosity.

Bhabha events. Comparison with MC.



θ=min($\theta_{e^+}, \theta_{e^-}$)(CM). Points - exp, hist - MC.

Insertion: Ratio of exp. spectrum to MC one.

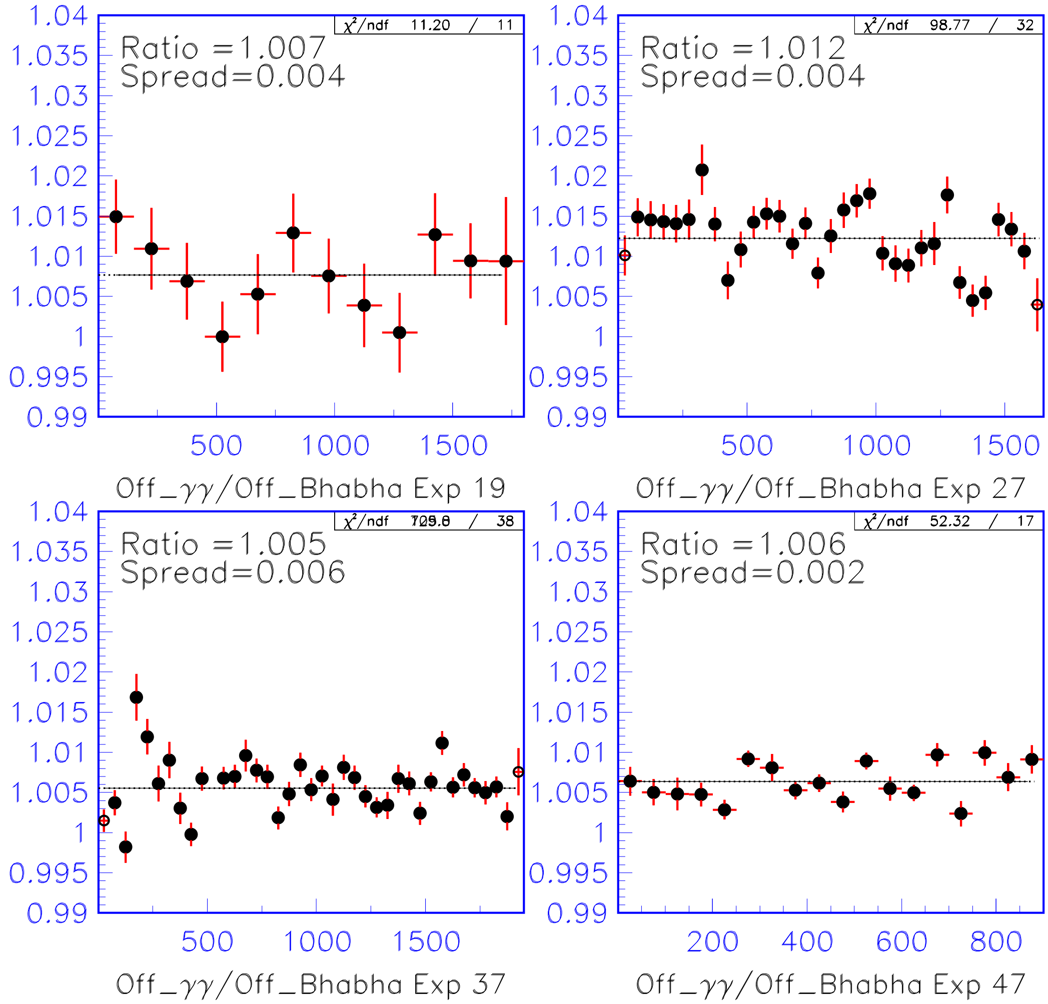


Tracks $\Delta\phi = \phi(e^-) - \phi(e^+)$.

Insertion: $\Delta\phi$ for the central bin.

Long-term stability

Ratio of luminosity values with Bhabha and $\gamma\gamma$.



Sum of 50 runs per bin. The errors are statistical.

Conclusions

- The online of the KEKB collider is measured online with stat. accuracy 1–2% for 10 sec. Long-term stability is about 1-2% in average.

  Some degradation of CsI crystals is observed – about drop 1% for season.

  Background conditions becomes harder with increasing of KEKB luminosity.

- The offline luminosity is measured with Bhabha events in the barrel part of the Belle. The systematic error is 1.5%.

Online Luminosity

Belle detector exploits 3 independent systems for online luminosity measurements.

Table 1: Belle systems for online luminosity control.

	ZDLM	EFC	ECL
Process	Single Bremsstrahlung	Bhabha	Bhabha and $\gamma\gamma$
Rate at $10^{34}\text{cm}^{-2} \cdot s^{-1}$	10^6–10^7 Hz	1500 Hz	500 Hz
Limiting factors for accuracy	Calibration of orbit dependence	Dependence of Z(vertex) position	Statistical error Beam lost
Beam background	30%	-5%	less 1%
Usage	Bunch2bunch luminosity	Cross check	Main monitor