Univerza v Ljubljani

THE UNIVERSITY OF TOKYO

# Flavour Physics at B-factories and Hadron Colliders

## Part 3+4: Experiments

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# Contents

# Principle of measurement

Principle of measurement:

- Produce pairs of B mesons, moving in the lab system
- Find events with B meson decay of a certain type (usually B -> $f_{CP}$ - CP eigenstate)
- Measure time difference between this decay and the decay of the associated B ($f_{tag}$) (from the flight path difference)
- Determine the flavour of the associated B (B or anti-B)
- Measure the asymmetry in time evolution for B and anti-B

Restrict for the time being to B meson production at Y(4s)

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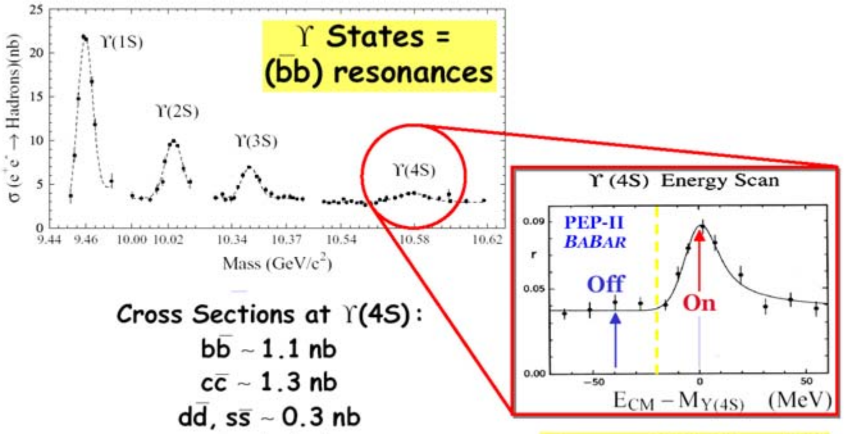
# B meson production at Y(4s)



**Cross Sections at ϒ(4S):**

$b\bar{b} \sim 1.1$ nb

$c\bar{c} \sim 1.3$ nb

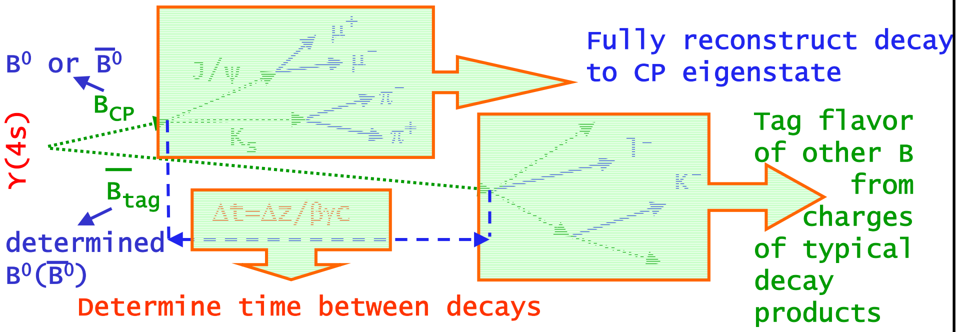
$d\bar{d}, s\bar{s} \sim 0.3$ nb

$u\bar{u} \sim 1.4$ nb

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$

$L = 1$ state

# Principle of measurement



$B^0$ or $\overline{B}^0$

$B_{CP}$

$\Upsilon(4s)$

$\overline{B}_{tag}$

determined $B^0(\overline{B}^0)$

Fully reconstruct decay to CP eigenstate

Tag flavor of other B from charges of typical decay products

Determine time between decays

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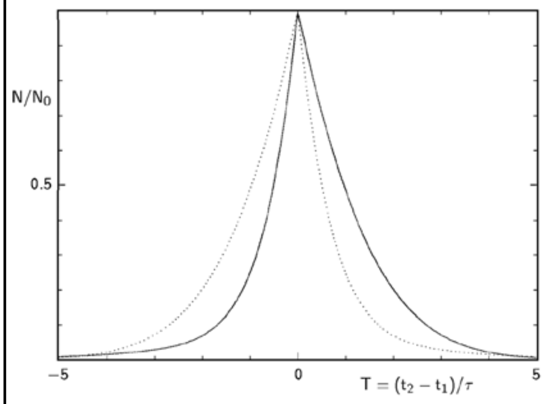
# Experimental considerations

What kind of vertex resolution do we need to measure the asymmetry?

$$P(B^0(\overline{B}^0) \to f_{CP}, t) = e^{-\Gamma t}\left(1 \mp \sin(2\phi_1)\sin(\Delta m t)\right)$$



Want to distinguish the decay rate of B (dotted) from the decay rate of anti-B (full).

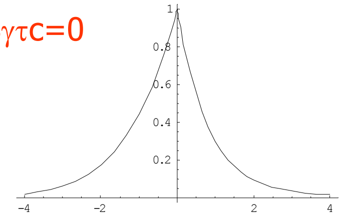
-> the two curves should not be smeared too much

Integrals are equal, time information mandatory! (true at Υ(4s), but not for incoherent production)

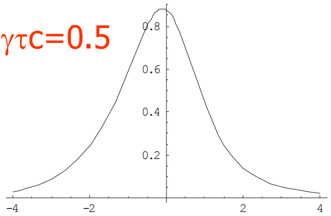
## Experimental considerations

B decay rate vs t for different vertex resolutions in units of typical B flight length $\sigma(z)/\beta\gamma\tau c$

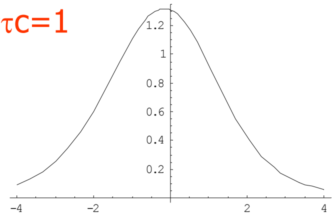
$\sigma(z)/\beta\gamma\tau c=0$



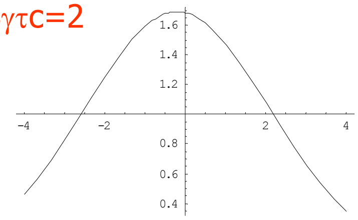
$\sigma(z)/\beta\gamma\tau c=0.5$



$\sigma(z)/\beta\gamma\tau c=1$



$\sigma(z)/\beta\gamma\tau c=2$



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## Experimental considerations

Since there are no pure samples of B and anti-B tags, what is really measured is the probability that the tagging B is a B or an anti-B.

Denote with x: variable between –1 (tag=anti-B) and +1 (tag=B) and the probability that the tag is wrong with w(x)

Probability density function for an event with t and x is

$$f\left(t,x,A\right)dxdt = e^{-\Gamma t}\left[1+q\left(x\right)A\sin\Delta mt\right]n(x)dxdt$$

with A=CP asymmetry (e.g. $\sin 2\phi_1$), $q(x)=1-2w$

Taking into account the finite vertex resolution, we arrive at

$$f\left(t,x,A,\sigma_t\right)dxdt = \left[\int \frac{1}{\sqrt{2\pi}\sigma_t}e^{-\frac{1}{2}\left(\frac{t-t'}{\sigma_t}\right)^2} e^{-\Gamma|t'|}\left[1+q\left(x\right)A\sin\Delta mt'\right]n(x)dt'\right]dxdt$$

## Experimental considerations

This can be rewritten as

$$f\left(t,x,A,\sigma\right)dxdt = \left[E\left(t\right) + Aq\left(x\right)S\left(t\right)\right]n(x)dxdt$$

$$E\left(t\right) = \int \frac{1}{\sqrt{2\pi\sigma_t}}e^{-\frac{1}{2}\left(\frac{t-t'}{\sigma_t}\right)^2} e^{-\Gamma|t'|}dt',$$

$$S\left(t\right) = \int \frac{1}{\sqrt{2\pi\sigma_t}}e^{-\frac{1}{2}\left(\frac{t-t'}{\sigma_t}\right)^2} e^{-\Gamma|t'|}\sin\Delta m t' dt'.$$

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## Experimental considerations

The log-likelihood function is a sum over all reconstructed and tagged events

$$\ln\mathcal{L} = \ln\prod_{i=1}^{N} f\left(t_i,x_i,A,\sigma_t\right) = \sum_{i=1}^{N}\ln f\left(t_i,x_i,A,\sigma_t\right)$$

$$\begin{aligned}\ln\prod_{i=1}^{N} f\left(t_i,x_i,A,\sigma_t\right) &= \sum_{i=1}^{N}\ln\left[\left(1+Aq\left(x\right)S\left(t\right)/E\left(t\right)\right)E\left(t\right)n(x)\right]\\ &= \sum_{i=1}^{N}\ln\left(1+Aq\left(x\right)S\left(t\right)/E\left(t\right)\right)+C\,.\end{aligned}$$

$$\Rightarrow \quad \ln\mathcal{L}' = \sum_{i=1}^{N}\ln\left(1+A\frac{qS}{E}\right)$$

## Experimental considerations

Error on the asymmetry parameter A can be evaluated in the standard way:

$$\frac{1}{\sigma_A^2} = N \int_{-1}^{1} \int_{-\infty}^{\infty} \frac{1}{f} \left( \frac{\partial f}{\partial A} \right)^2 n(x) dt dx$$

$$\sigma_A \approx \frac{\sigma_0}{\sqrt{N} \sqrt{\langle q^2 \rangle}} \, ,$$

Use f(t,x,A,$\sigma_t$) to get $\sigma_A$

$$\left\langle q^2 \right\rangle \equiv \int_{-1}^{1} q^2 (x) \, n(x) dx$$

$$\sigma_0 \equiv \frac{1}{\sqrt{\int_{-\infty}^{\infty} \frac{\left(\frac{S(t)}{E(t)}\right)^2}{\left[1+A\frac{S(t)}{E(t)}\right]} E(t) \, dt}} \, .$$

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## Experimental considerations

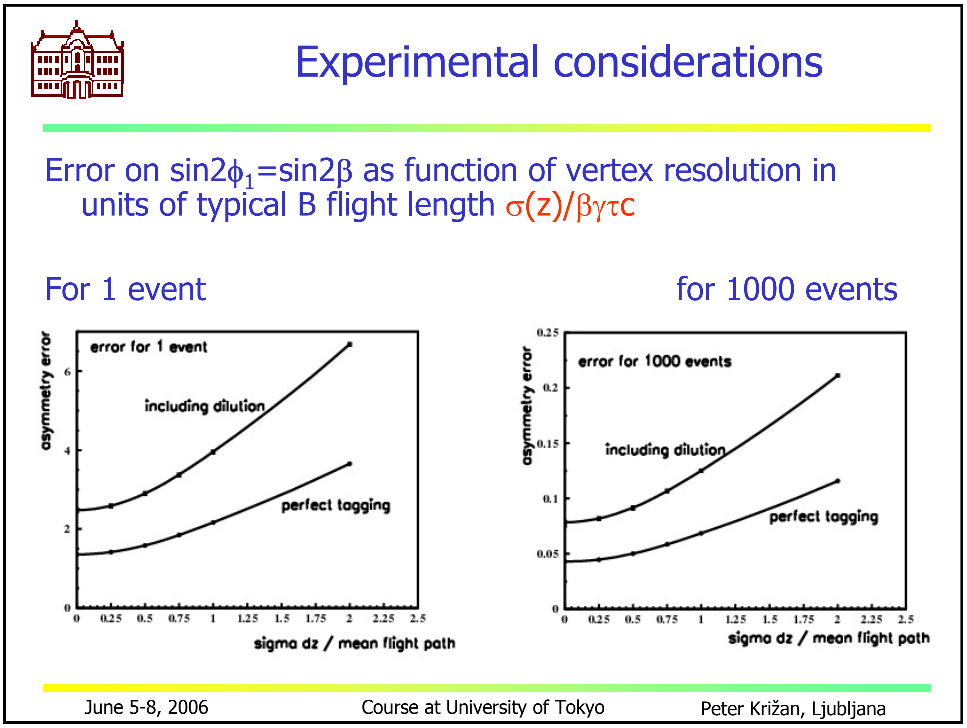
Final expression for the asymmetry error (error on sin2$\phi_1$) as a function of vertex resolution and wrong tag probability

$$\sigma_A(A, \Delta m/\Gamma, \sigma_t, N, w) = \frac{\sigma_0(A, \Delta m/\Gamma, \sigma_t)}{\sqrt{N}\sqrt{\epsilon}(1-2w).}$$

N: number of reconstructed events,

$\varepsilon$: tagging efficiency

w: wrong tag probability

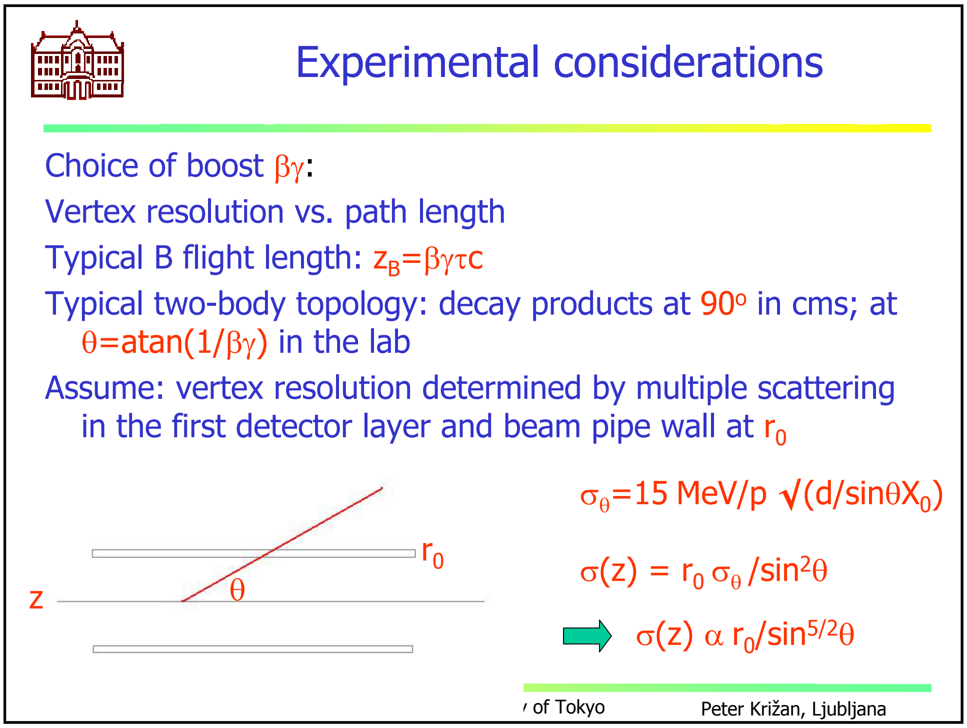


## Experimental considerations

Error on $\sin 2\phi_1 = \sin 2\beta$ as function of vertex resolution in units of typical B flight length $\sigma(z)/\beta\gamma\tau c$

For 1 event

for 1000 events



## Experimental considerations

Choice of boost $\beta\gamma$:

Vertex resolution vs. path length

Typical B flight length: $z_B = \beta\gamma\tau c$

Typical two-body topology: decay products at $90^o$ in cms; at $\theta = \mathrm{atan}(1/\beta\gamma)$ in the lab

Assume: vertex resolution determined by multiple scattering in the first detector layer and beam pipe wall at $r_0$

$$\sigma_\theta = 15\ \mathrm{MeV}/p\ \sqrt{(d/\sin\theta X_0)}$$

$$\sigma(z) = r_0\, \sigma_\theta / \sin^2\theta$$

$$\Rightarrow \sigma(z)\ \alpha\ r_0/\sin^{5/2}\theta$$

# Experimental considerations

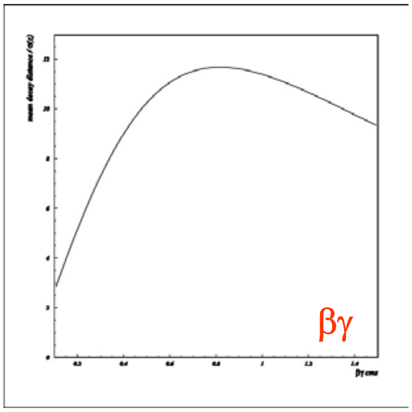
Choice of boost βγ:

Vertex resolution in units of typical B flight length

Boost around βγ=0.8 seems optimal

However....

βγτc/σ(z)



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# Experimental considerations

Which boost...

Arguments for a smaller boost:

- Larger boost -> smaller acceptance ->
- Larger boost -> it becomes hard to damp the betatron oscillations of the low energy beam: less synchrotron radiation at fixed ring radius (same as the high energy beam)

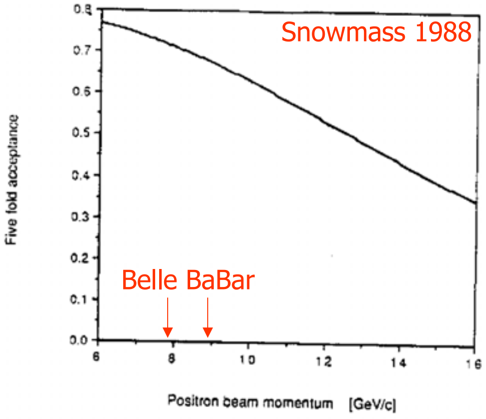
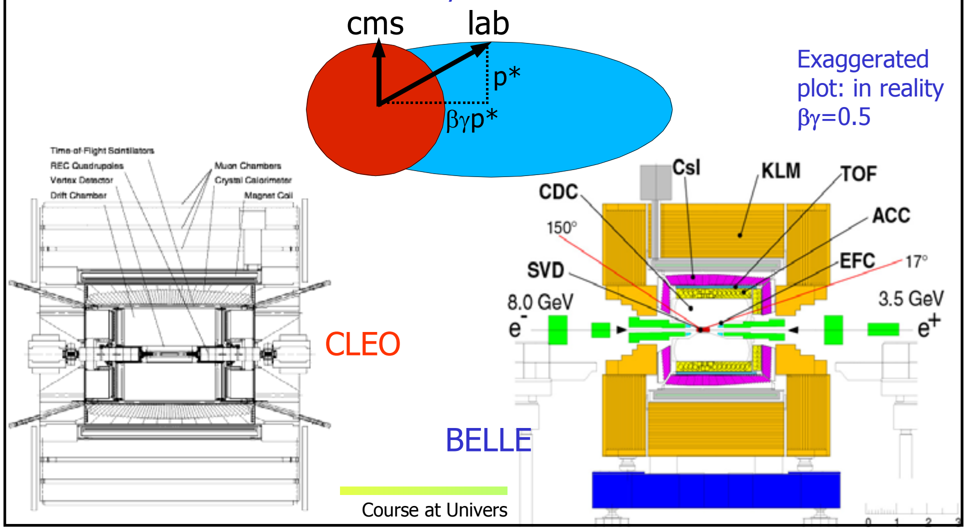


**Figure 4.** The acceptance of a detector covering $|\cos\theta_{lab}| < 0.95$ for five uncorrelated particles as a function of the energy of the more energetic beam in an asymmetric collider at the $\Upsilon(4S)$.

# Experimental considerations

Detector form: symmetric for symmetric energy beams; extended in the boost direction for an asymmetric collider.



Exaggerated plot: in reality $\beta\gamma=0.5$

# How many events?

Rough estimate:

Need ~1000 reconstructed B-> $J/\psi\ K_S$ decays with $J/\psi$ -> ee or $\mu\mu$, and $K_S$-> $\pi^+\pi^-$

½ of Y(4s) decays are $B^0$ anti-$B^0$ (but 2 per decay)

BR(B-> $J/\psi\ K^0$)=8.4 $10^{-4}$

BR($J/\psi$ -> ee or $\mu\mu$)=11.8%

½ of $K^0$ are $K_S$, BR($K_S$-> $\pi^+\pi^-$)=69%

Reconstruction effiency ~ 0.2 (signal side: 4 tracks, vertex, tag side pid and vertex)

N(Y(4s)) = 1000 / (½ * ½ * 2 * 8.4 $10^{-4}$ * 0.118 * 0.69 * 0.2) =
= 140 M

# How to produce 140 M BB pairs?

Want to produce 140 M pairs in two years
Assume effective time available for running is $10^7$ s per year.
-> need a rate of 140 $10^6$ / (2 $10^7$ s) = 7 Hz

Observed rate of events = Cross section x Luminosity

$$\frac{dN}{dt}=L\sigma$$

Cross section for Υ(4s) production: 1.1 nb = 1.1 $10^{-33}$ $\mathrm{cm}^2$

-> Accelerator figure of merit luminosity has to be

$$L = 6.5\ /\mathrm{nb/s} = 6.5\ 10^{33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

This is much more than any other accelerator achieved before!

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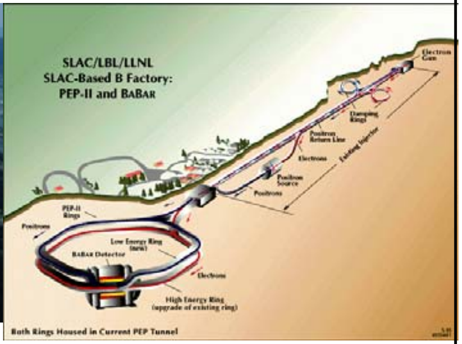
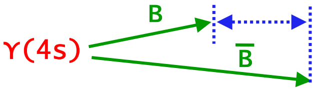
# Colliders: asymmetric B factories



$\sqrt{s}=10.58$ GeV

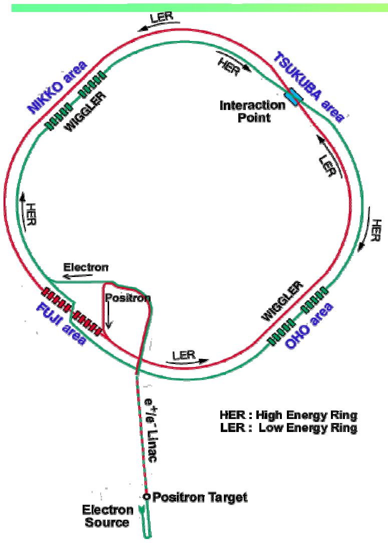
$$e^+ \rightarrow \Upsilon(4s) \leftarrow e^-$$

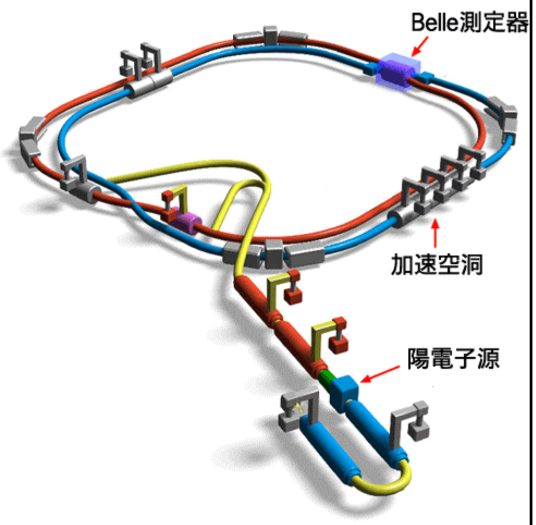


$\Delta z \sim c\beta\gamma\tau_B \sim 200\mu m$

| | | | |
|---|---|---|---|
| BaBar | $p(e^-)=9$ GeV | $p(e^+)=3.1$ GeV | $\beta\gamma=0.56$ |
| Belle | $p(e^-)=8$ GeV | $p(e^+)=3.5$ GeV | $\beta\gamma=0.42$ |

# Accelerator complex: KEK-B





# Accelerator performace

Observed rate of events = Cross section x Luminosity

$$\frac{dN}{dt} = L\sigma$$

Accelerator figures of merit: luminosity ***L***

and integrated luminosity $$L_{\text{int}} = \int L(t)dt$$

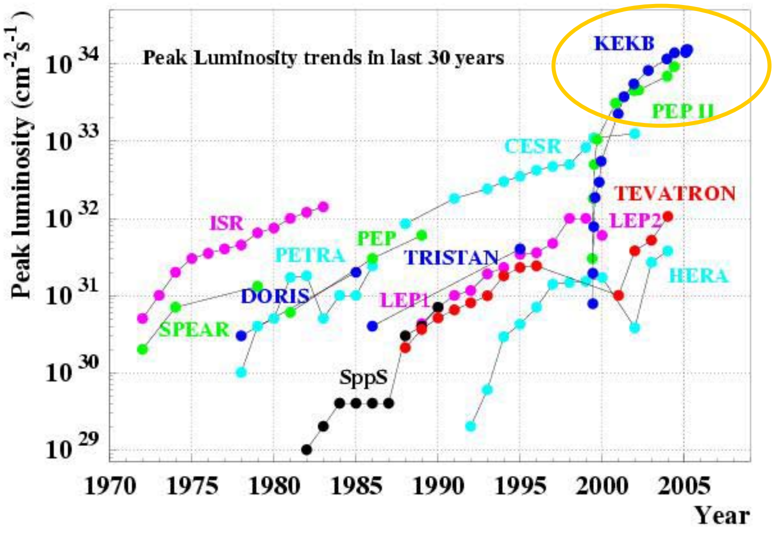
Records:

$L_{peak}$ = **16.27/nb/sec (Dec 19, 2005)** (=$1.627 \times 10^{34}$ $s^{-1}cm^{-2}$)

$L_{int}$= **603.852/fb (June 4, 2006)**

>600 M BB pairs

## Accelerator performance



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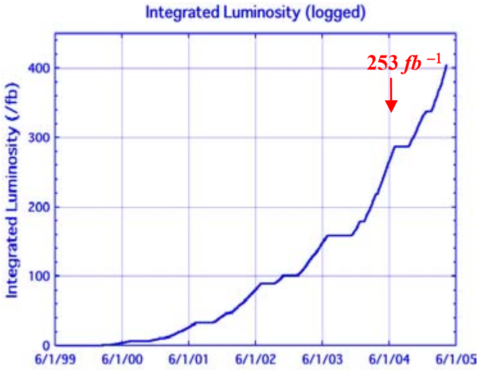
## Accelerator performance until autumn 2004

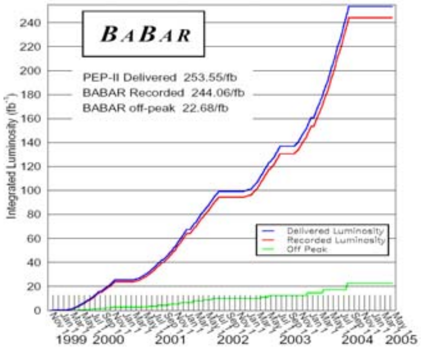
**3.5 GeV on 8.0 GeV**
**$\gamma\,\beta = 0.425$**



$\int L(t)dt =$ **434 *fb*$^{-1}$ on May 18**

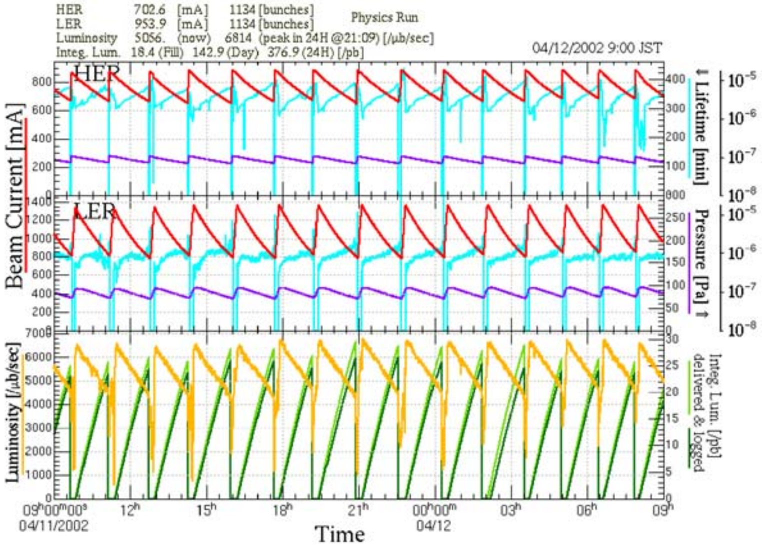
**$L_{peak}$ (max) = 1.58 x 10$^{34}$ cm$^{-2}$ s$^{-1}$**

**3.1 GeV on 9.0 GeV**
**$\gamma\,\beta = 0.56$**



**electrical accident halted machine on Oct. 11th (254 *fb*$^{-1}$) – restarted in April after SLAC/DOE safety review**

# Accelerator performance: Typical "Good Day" at KEKB in 2002



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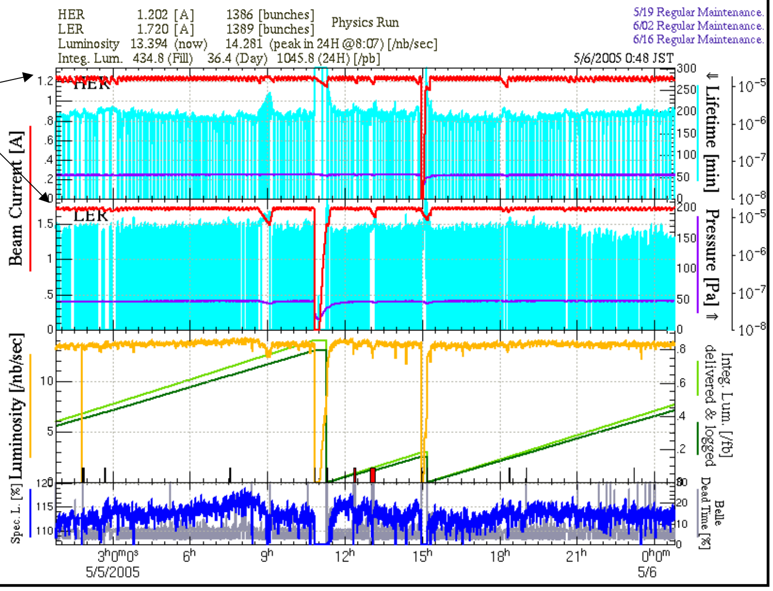
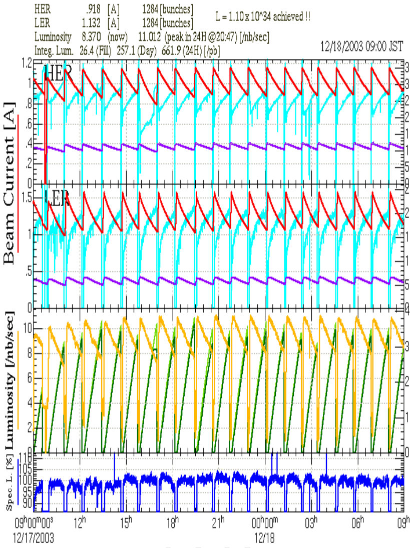
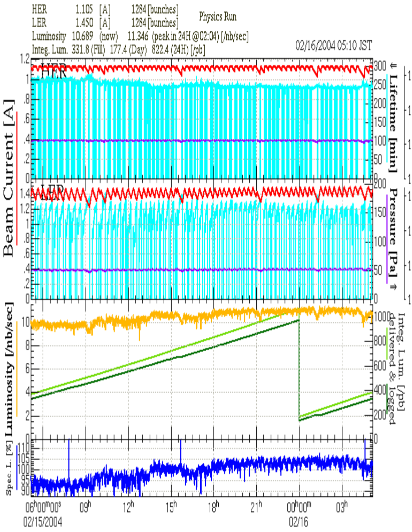
# Accelerator performance: just a day at KEKB in 2005

Continuous injection



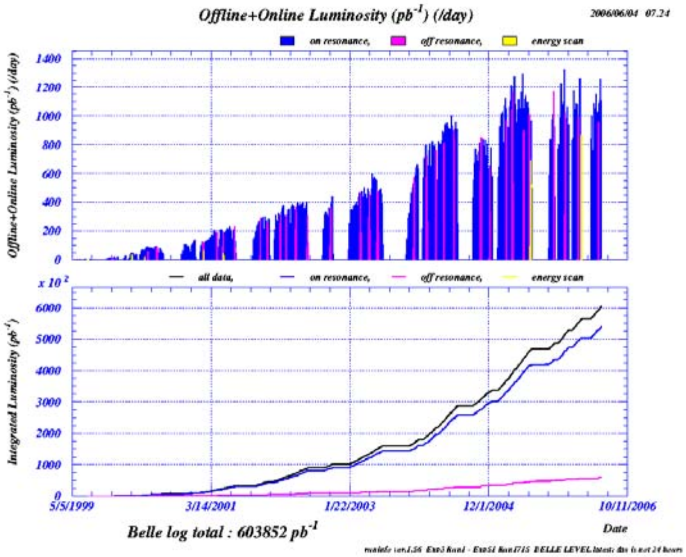
## *Normal injection* *Continuous injection*

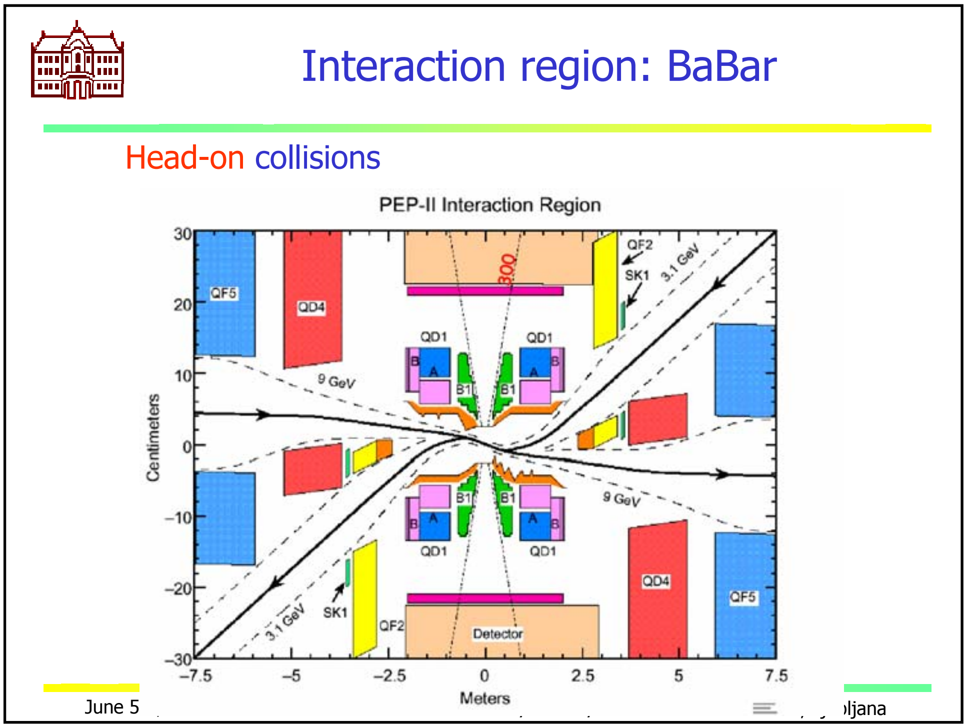




**661/pb/day** **→1182/pb/day**

## Accelerator performance: status as of this Sunday



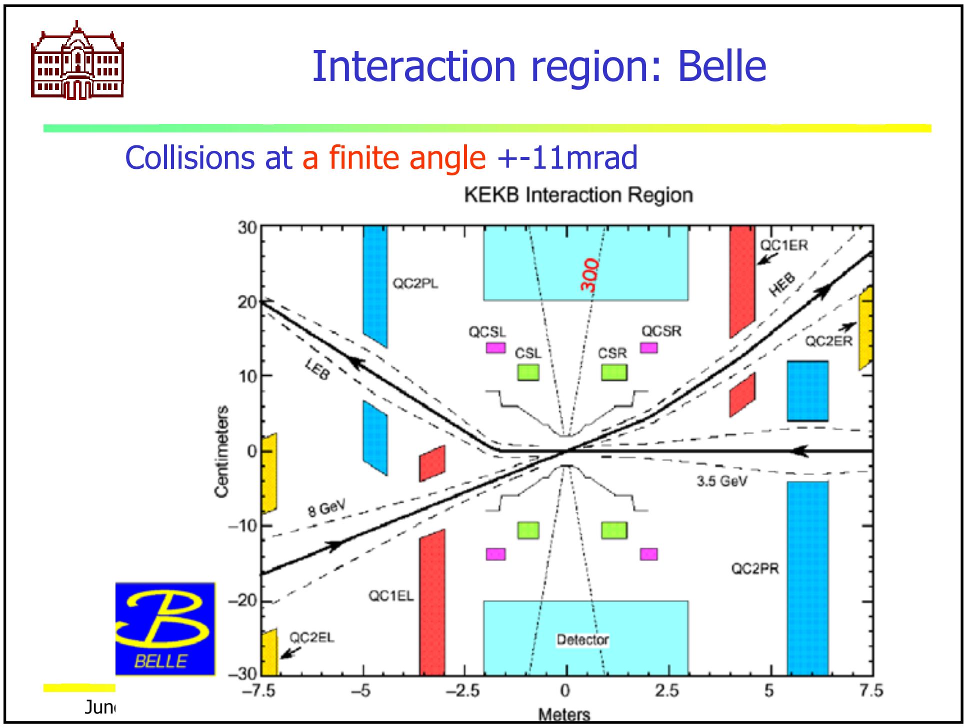


## Interaction region: BaBar

Head-on collisions

PEP-II Interaction Region

June 5 ljana



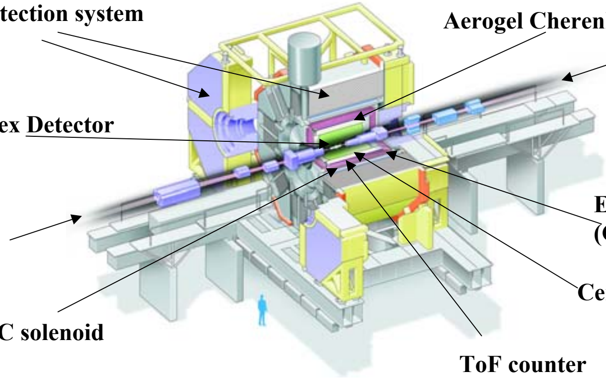
## Interaction region: Belle

Collisions at a finite angle +-11mrad

KEKB Interaction Region

Jun

# Belle spectrometer at KEK-B



μ and $K_L$ detection system

Aerogel Cherenkov Counter

3.5 GeV $e^+$

Silicon Vertex Detector

8 GeV $e^-$

Electromagnetic. Cal. (CsI crystals)

Central Drift Chamber

1.5T SC solenoid

ToF counter

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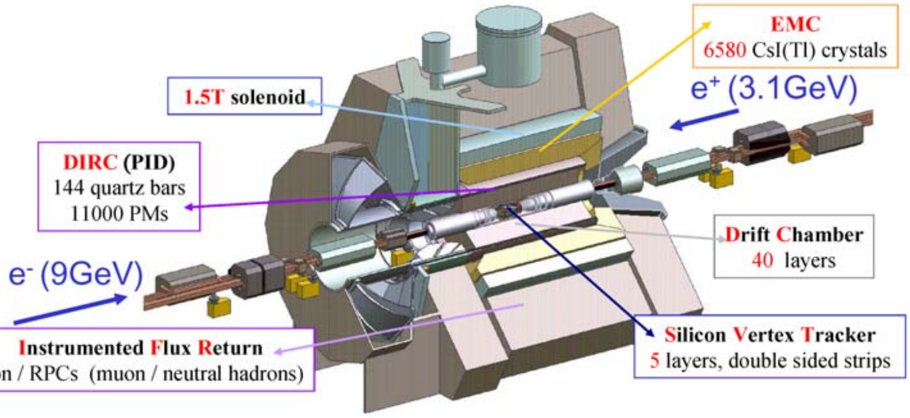
# BaBar spectrometer at PEP-II



**EMC**
6580 CsI(Tl) crystals

$e^+$ (3.1GeV)

**1.5T solenoid**

**DIRC (PID)**
144 quartz bars
11000 PMs

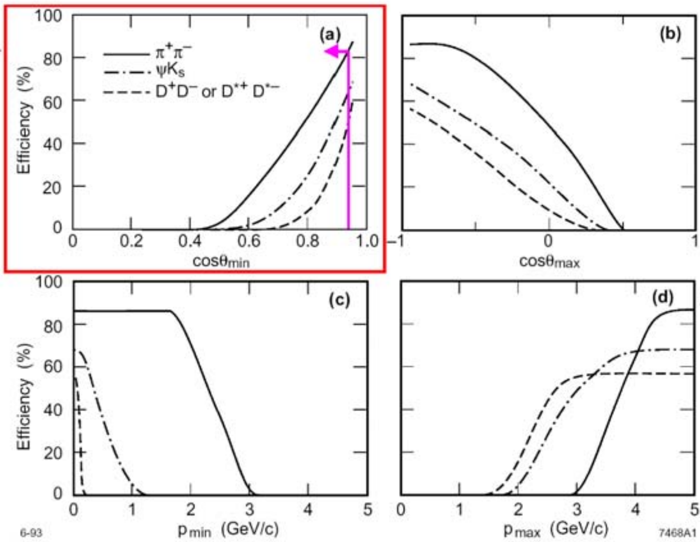
**Drift Chamber**
40 layers

$e^-$ (9GeV)

**Silicon Vertex Tracker**
5 layers, double sided strips

**Instrumented Flux Return**
iron / RPCs (muon / neutral hadrons)

## Requirements: Geometric Acceptance



Angular coverage

Momentum coverage

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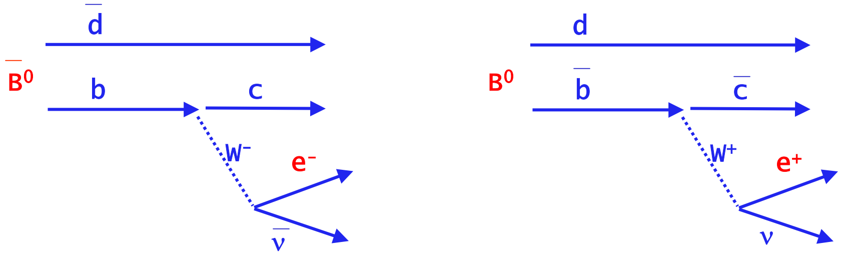
## Flavour tagging

Was it a B or an anti-B that decayed to the CP eigenstate?

Look at the decay products of the associated B

- Charge of high momentum lepton



## Flavour tagging

Was it a B or anti-B that decayed to the CP eigenstate?

Look at the decay products of the associated B
- Charge of high momentum lepton
- Charge of kaon
- Charge of 'slow pion' (from $D^*$->$D\pi$ decay)
- .....

Charge measured from curvature in magnetic field, need reliable particle identification

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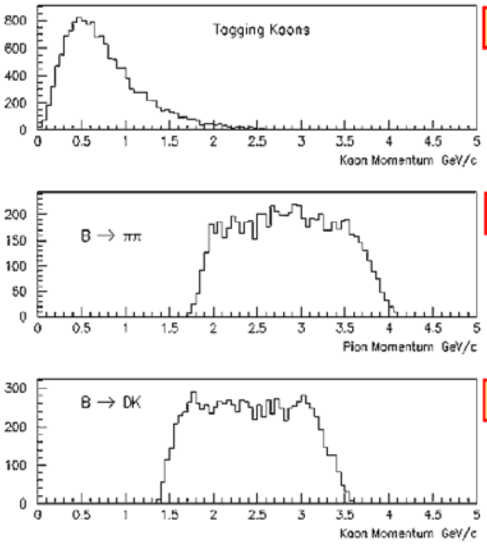
## Requirements: Particle Identification



**Tagging Kaons**

Relatively soft, ms dominated for tracking

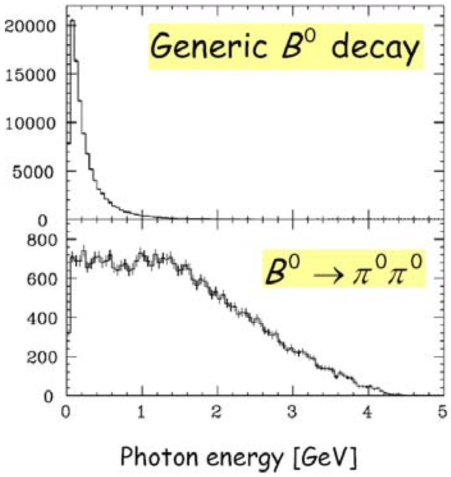
**B → ππ**

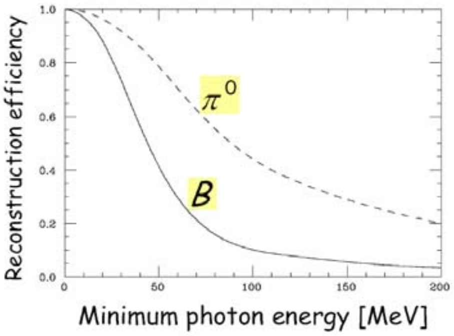
Requires dedicated PID

**B → DK**

Requires dedicated PID

## Requirements: Photons





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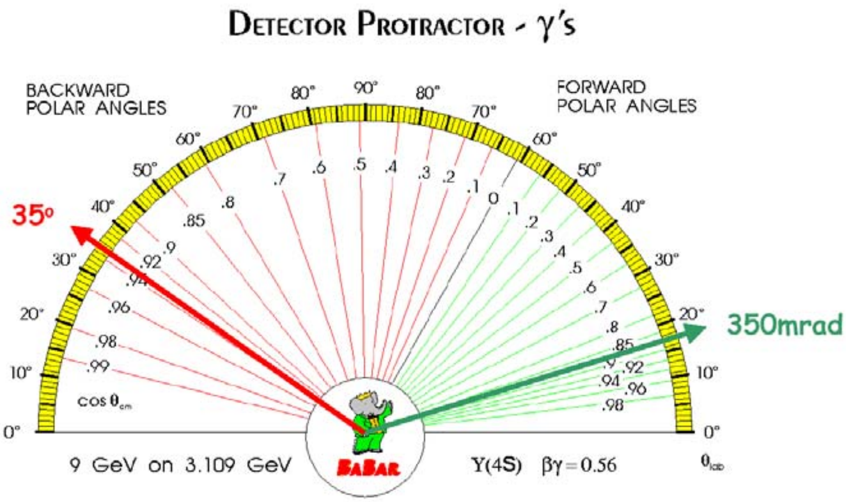
## Photons in the lab system



# Another requirement: measure both b-> c anti-c s CP=+1 and CP=-1 eigenstates

$$a_{f_{CP}} = -\mathrm{Im}(\lambda_{f_{CP}})\sin(\Delta m t)$$

$$\lambda_{f_{CP}} = \eta_{f_{CP}} \frac{q}{p} \frac{\overline{A}_{\overline{f}_{CP}}}{A_{f_{CP}}}$$

Asymmetry sign depends on the CP parity of the final state $f_{CP}$, $\eta_{\mathbf{fcp}}$=+-1

$J/\psi\ K_S\ (\pi^+\ \pi^-)$: CP=-1

- $J/\psi$: P=-1, C=-1 (vector particle $J^{PC}=1^{--}$): CP=+1
- $K_S$ (->$\pi^+\ \pi^-$): CP=+1, orbital ang. momentum of pions=0 -> $P(\pi^+\ \pi^-)=(\pi^-\ \pi^+)$, $C(\pi^-\ \pi^+)=(\pi^+\ \pi^-)$
- orbital ang. momentum between $J/\psi$ and $K_S$ l=1, $P=(-1)^1=-1$

$J/\psi\ K_L(3\pi)$: CP=+1

Opposite parity to $J/\psi\ K_S\ (\pi^+\ \pi^-)$, because $K_L(3\pi)$ has CP=-1

**-> need $K_L$ detection**

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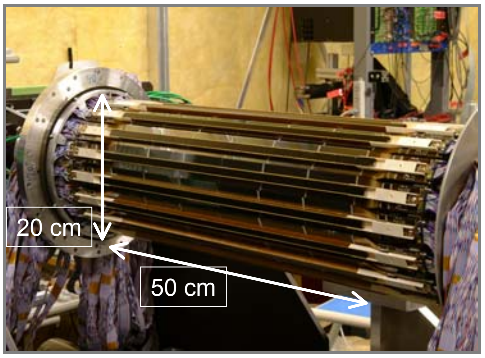
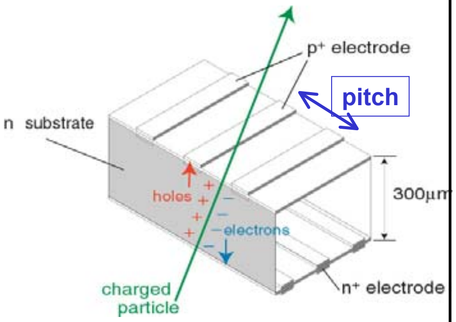
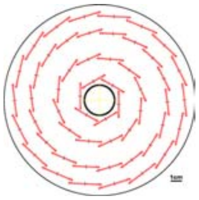
# Silicon vertex detector (SVD)

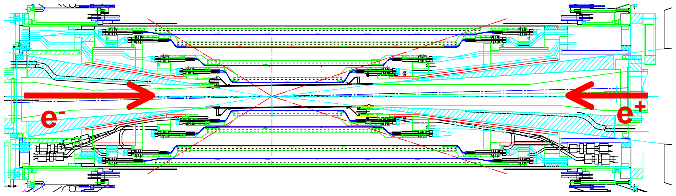




Two coordinates measured at the same time; strip pitch: 50 µm (75 µm); resolution about 15 µm (20 µm).

## Silicon vertex detector (SVD)



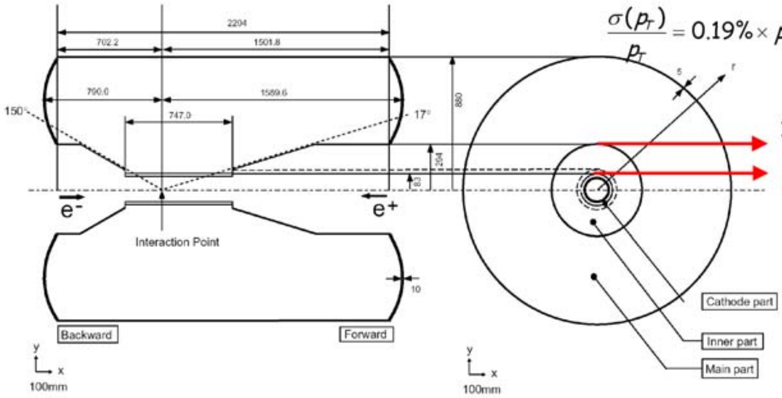


4 layers

covering polar angle from 17 to 150 degrees

## Tracking: Belle central drift chamber

- 50 layers of wires (8400 cells) in 1.5 Tesla magnetic field
- Helium:Ethane 50:50 gas, Al field wires, CF inner wall with cathodes, and preamp only on endplates
- Particle identification from ionization loss (5.6-7% resolution)



$$\frac{\sigma(p_T)}{p_T} = 0.19\% \times p_T \oplus \frac{0.30\%}{\beta}$$

15 layers: 8.8-22.4 cm radius

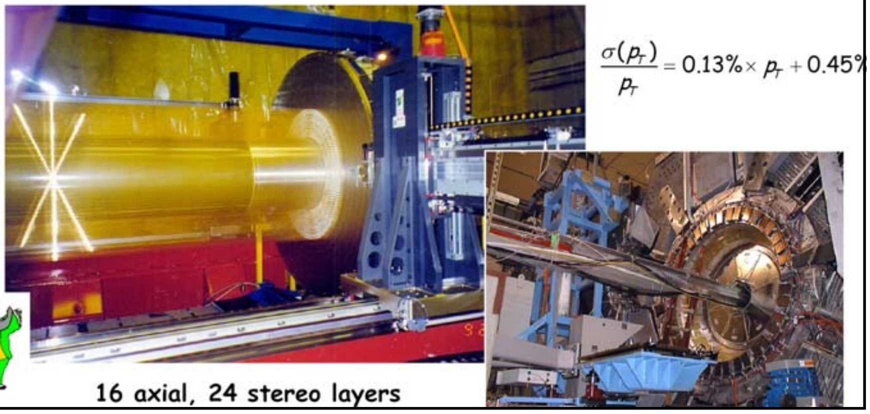
## Tracking: BaBar drift chamber

40 layers of wires (7104 cells) in 1.5 Tesla magnetic field

Helium:Isobutane 80:20 gas, Al field wires, Beryllium inner wall, and all readout electronics mounted on rear endplate

Particle identification from ionization loss (7% resolution)

$$\frac{\sigma(p_T)}{p_T} = 0.13\% \times p_T + 0.45$$



16 axial, 24 stereo layers

---

## Identification

Hadrons ($\pi$, K, p):
- Time-of-flight (TOF)
- dE/dx in a large drift chamber
- Cherenkov counters

$K_L$: chambers in the instrumented magnet yoke

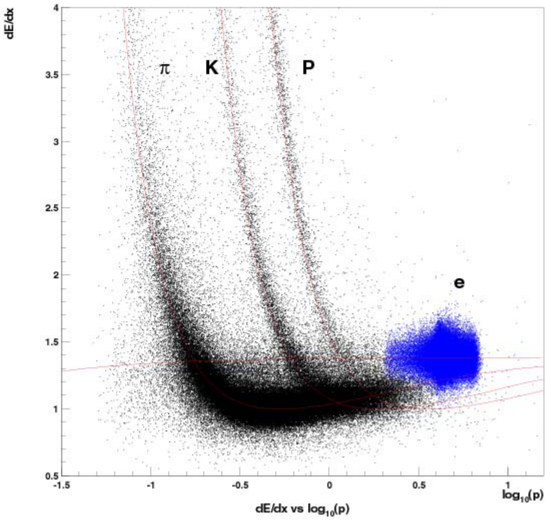
Electrons: electromagnetic calorimeter

Muon: chambers in the instrumented magnet yoke

## Identification with dE/dx measurement

dE/dx performance in a large drift chamber.

Essential for hadron identification at low momenta.



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## Cherenkov counters

Essential part of particle identification systems.

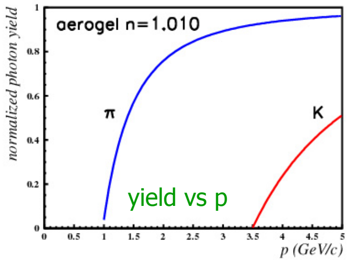
Cherenkov relation: **cosθ = c/nv = 1/βn**

Threshold counters --> count photons to separate particles below and above threshold; for $\beta < \beta_t = 1/n$ (below threshold) no Čerenkov light is emitted

Ring Imaging (RICH) --> measure Čerenkov angle and count photons

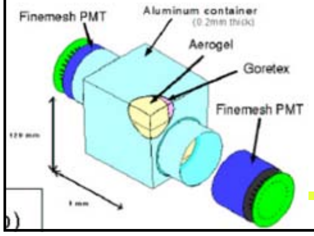
## Belle ACC (aerogel Cherenkov counter): threshold Čerenkov counter

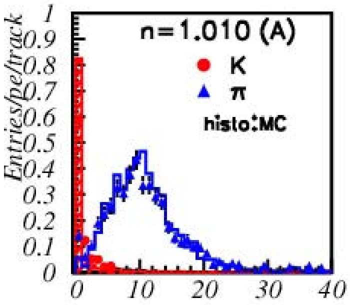
K (below thr.) vs. π (above thr.): adjust n



measured for 2 GeV < p < 3.5 GeV expected, measured ph. yield

Detector unit: a block of aerogel and two fine-mesh PMTs





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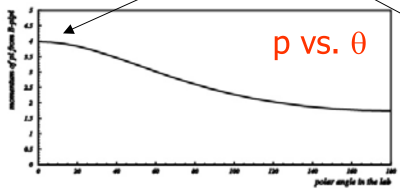
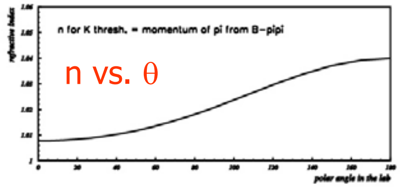
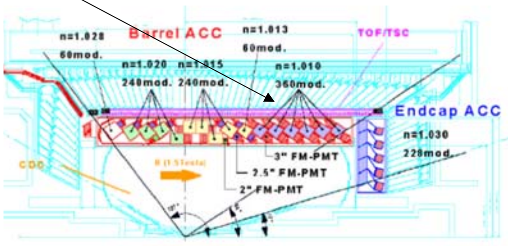
## Belle ACC (aerogel Cherenkov counter): threshold Cherenkov counter

K (below thr.) vs. π (above thr.): adjust n for a given angle kinematic region (more energetic particles fly in the 'forward region')



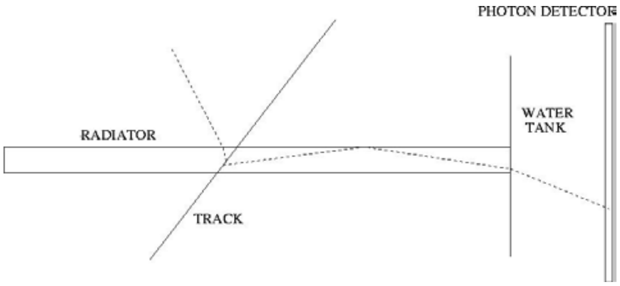




# DIRC: Detector of Internally Reflected Cherekov photons

Use Cherenkov relation $\cos\theta = c/nv = 1/\beta n$ to determine velocity from angle of emission

DIRC: a special kind of RICH (Ring Imaging Cherenkov counter) where Čerenkov photons trapped in a solid radiator (e.q. quartz) are propagated along the radiator bar to the side, and detected as they exit and traverse a gap.



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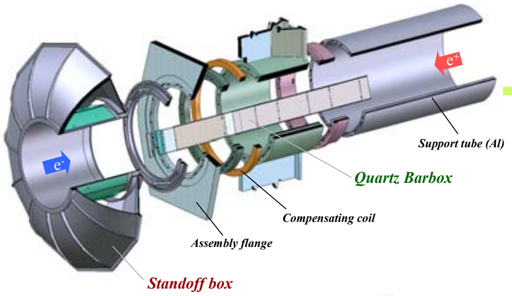
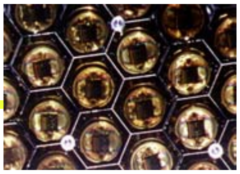
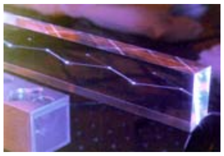
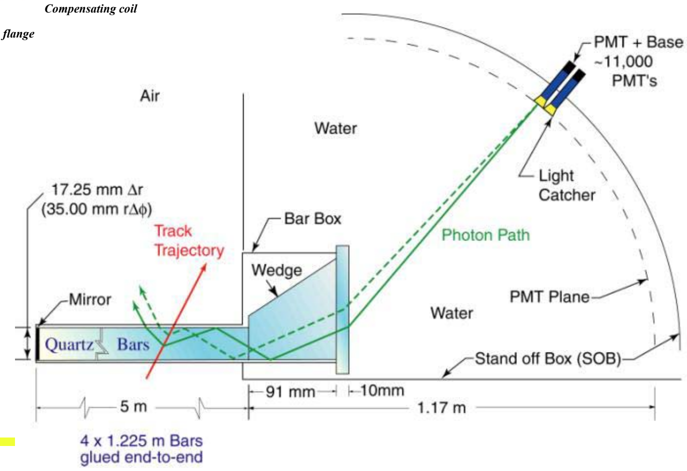
# DIRC



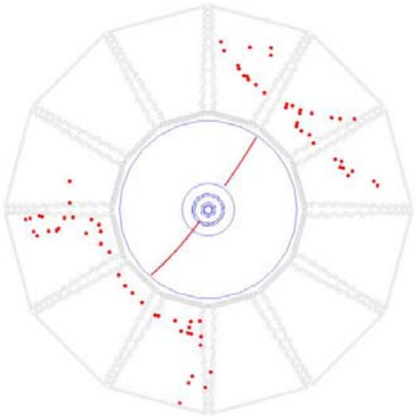






## DIRC event

Babar DIRC: a Bhabha event $e^+ e^- \rightarrow e^+ e^-$



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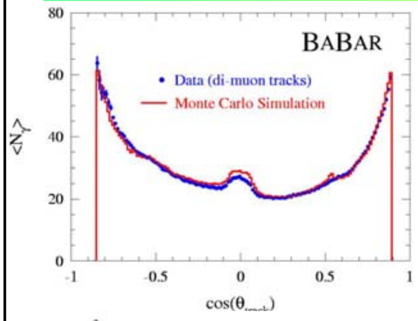
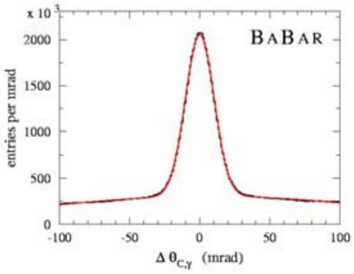
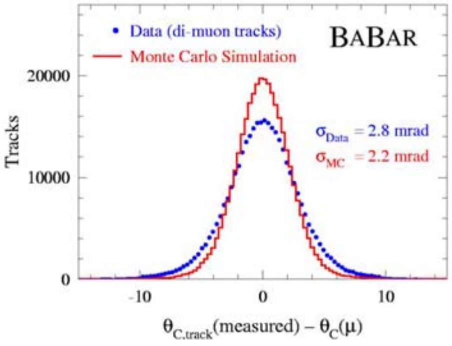
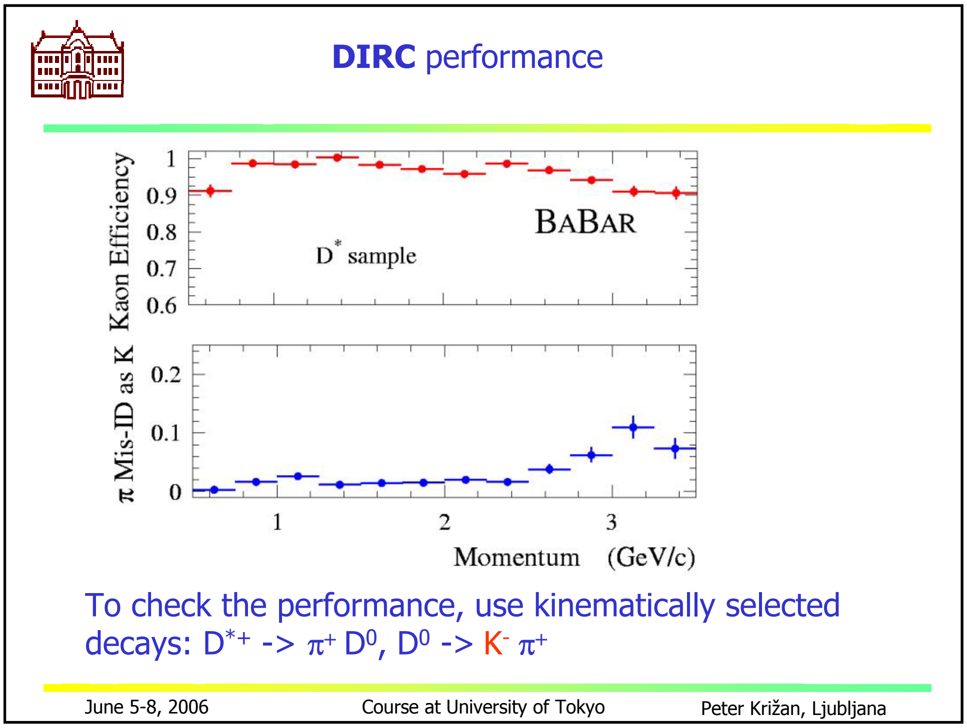
## DIRC performance





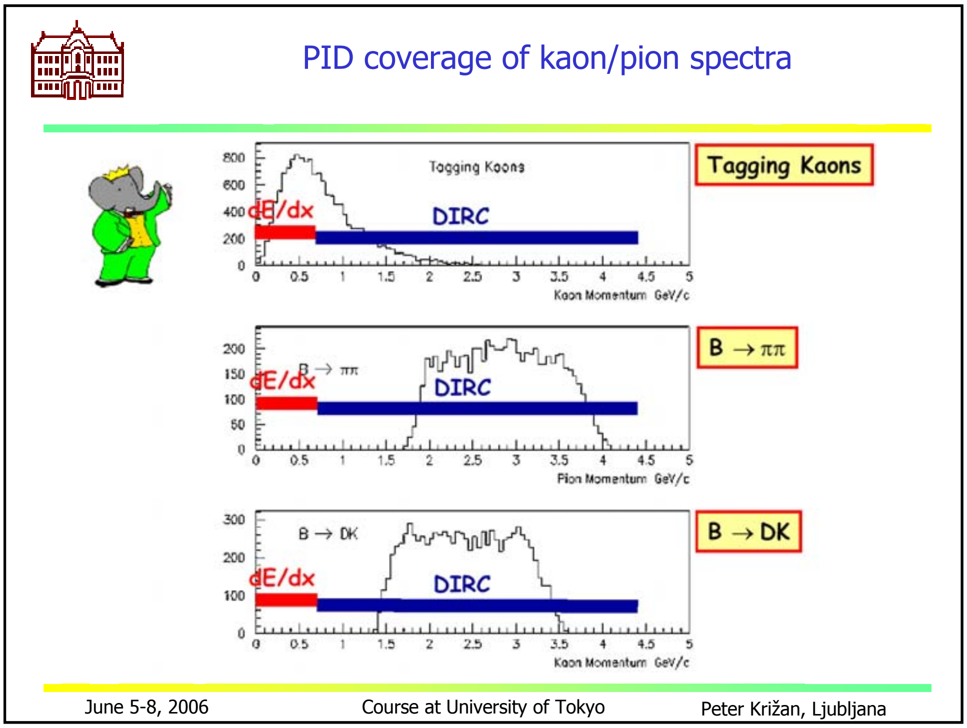
Performance





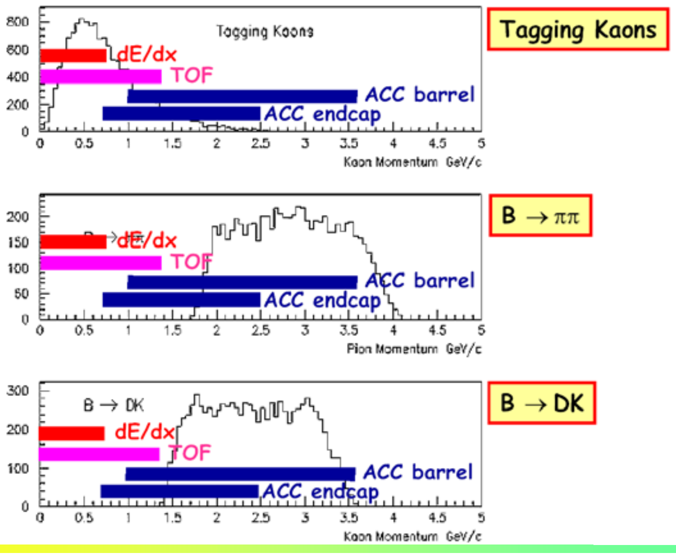
## **DIRC** performance

To check the performance, use kinematically selected decays: $D^{*+} \to \pi^+ D^0$, $D^0 \to K^- \pi^+$



## PID coverage of kaon/pion spectra

# PID coverage of kaon/pion spectra



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# Calorimetry Design

**Requirements**

•Best possible energy and position resolution: 11 photons per Y(4S) event; 50% below 200 MeV in energy

•Acceptance down to lowest possible energies and over large solid angle

•Electron identification down to low momentum

**Constraints**

•Cost of raw materials and growth of crystals

•Operation inside magnetic field

•Background sensitivity

**Implementation**

Thallium-doped Cesium-Iodide crystals with 2 photodiodes per crystal

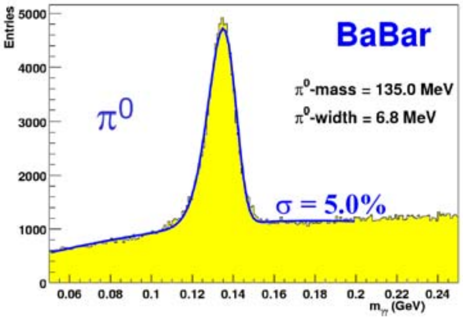
Thin structural cage to minimize material between and in front of crystals

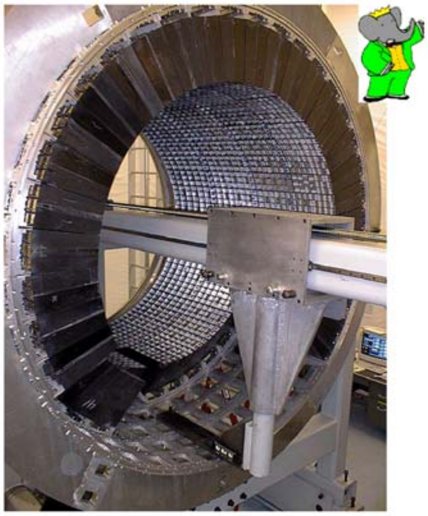
# Calorimetry: BaBar

6580 CsI(Tl) crystals with photodiode readout

About 18 $X_0$, inside solenoid

$$\frac{\sigma(E)}{E} = \frac{(2.32 \pm 0.03 \pm 0.3)\%}{\sqrt[4]{E}} \oplus (1.85 \pm 0.07 \pm 0.1)\%$$





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# Muon and $K_L$ detector

**Separate muons from hadrons (pions and kaons):** exploit the fact that muons interact only e.m., while hadrons interact strongly → need a few interaction lengths (about 10x radiation length in iron, 20x in CsI)

**Detect $K_L$ interaction (cluster):** again need a few interaction lengths.

Some numbers: 3.9 interaction lengths (iron) + 0.8 interaction length (CsI)

Interaction length: iron 132 g/cm$^2$, CsI 167 g/cm$^2$

$(dE/dx)_{min}$: iron 1.45 MeV/(g/cm$^2$), CsI 1.24 MeV/(g/cm$^2$)

→ $\Delta E_{min}$ = (0.36+0.11) GeV = 0.47 GeV → reliable identification of muon above ~600 MeV

# Muon and $K_L$ detector

**Up to 21 layers of resistive-plate chambers (RPCs) between iron plates of flux return**

**Bakelite RPCs at BABAR**

**Glass RPCs at Belle**

(better choice)

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# Muon and $K_L$ detector

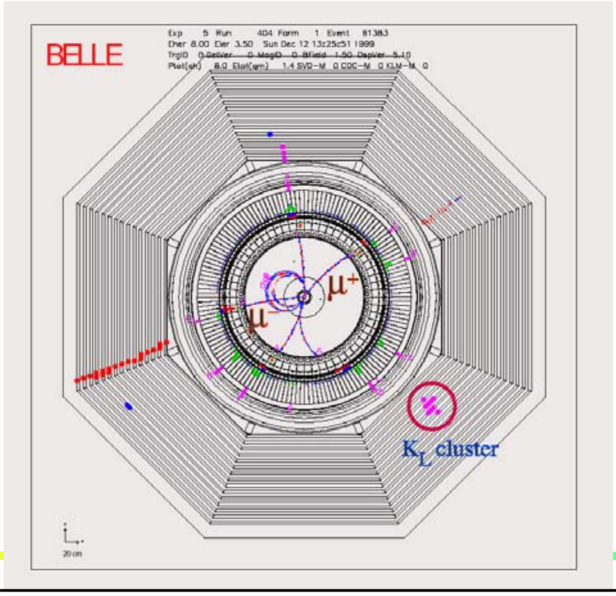
**Example:**

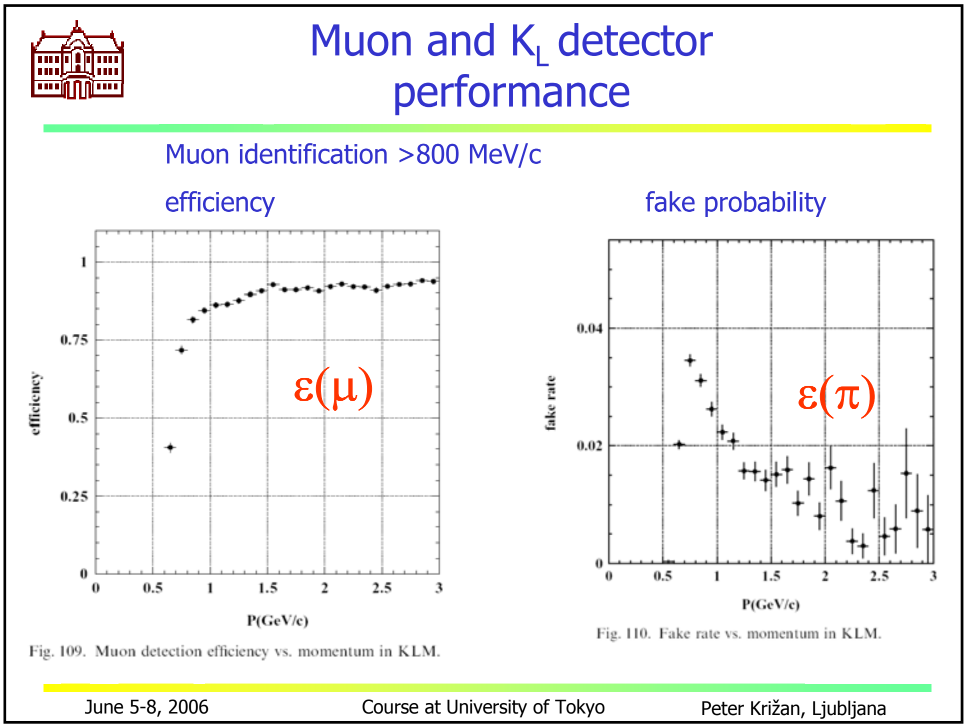
**event with**

**•two muons and a**

**•$K_L$**

**and a pion that partly penetrated**





# Muon and $K_L$ detector performance

Muon identification >800 MeV/c

efficiency

fake probability

Fig. 109. Muon detection efficiency vs. momentum in KLM.

Fig. 110. Fake rate vs. momentum in KLM.

June 5-8, 2006 Course at University of Tokyo Peter Križan, Ljubljana

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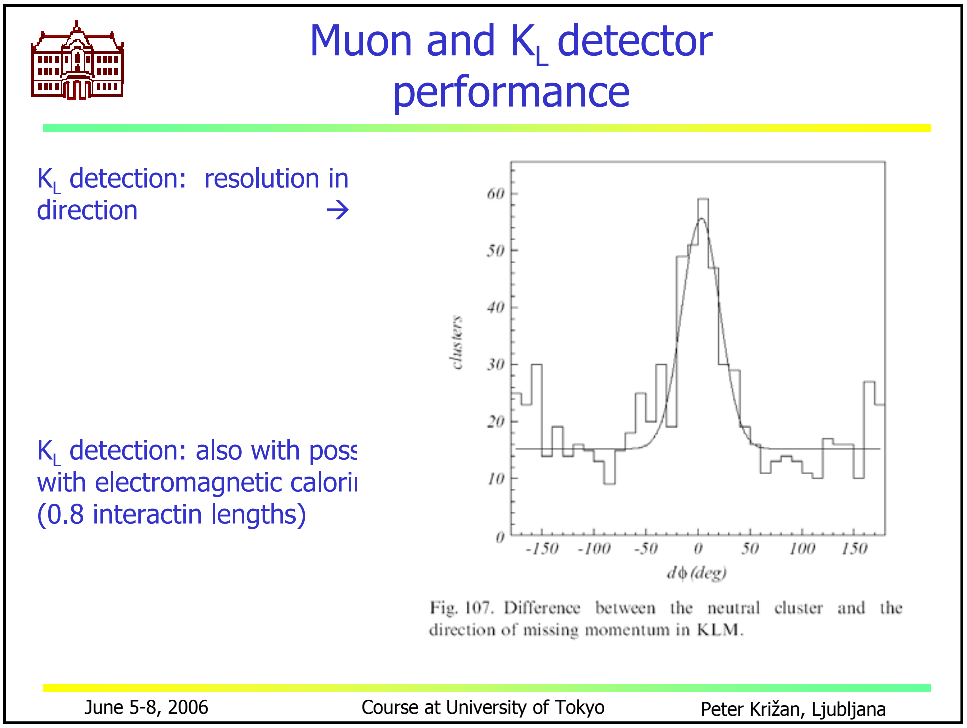

# Muon and $K_L$ detector performance

$K_L$ detection: resolution in direction →

$K_L$ detection: also with poss with electromagnetic calori (0.8 interactin lengths)

Fig. 107. Difference between the neutral cluster and the direction of missing momentum in KLM.

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