# High Intensity Frontier in Particle Physics (part 2/2)

**Peter Križan**

***University of Ljubljana and J. Stefan Institute***

**Doctoral studies, Specialized Seminar on Experimental Physics**

# Contents of this course

- Lecture 1: Introduction, experimental methods, detectors, data analysis
- Lecture 2: Intensity frontier experiments

# Contents

- Physics case for B factories / Super B factories
- Accellerator
- Detector

# A little bit of history...

**CP violation:** difference in the properties of particles and their anti-particles – first observed in 1964 in the decays of neutral kaons.

**M. Kobayashi and T. Maskawa (1973):** CP violation in the Standard model – related to the weak interaction quark transition matrix

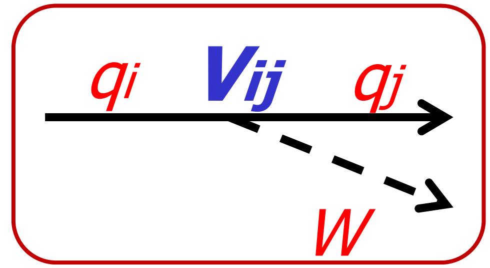
Their theory was formulated at a time when three quarks were known – and they requested the existence of three more!

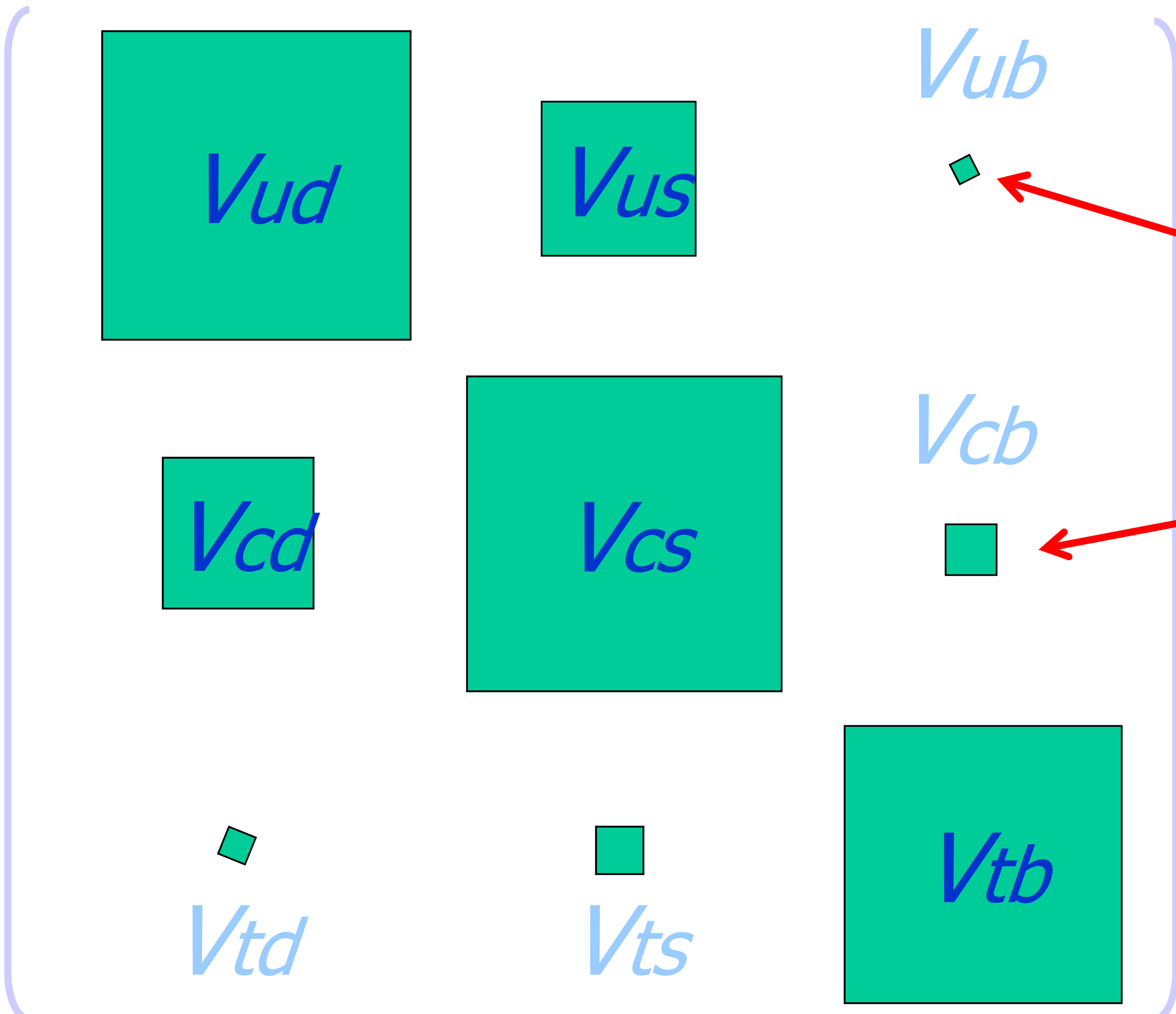
The last missing quark was found in 1994.

... and in 2001 two experiments – Belle and BaBar at two powerfull accelerators (B factories) - have further investigated CP violation and have indeed proven that it is tightly connected to the quark transition matrix

# CKM - Cabibbo-Kobayashi-Maskawa (quark transition) matrix:

almost real and diagonal, but not completely!




Amplitude for the b → u transition

Amplitude for the b → c transition

CKM: unitary matrix

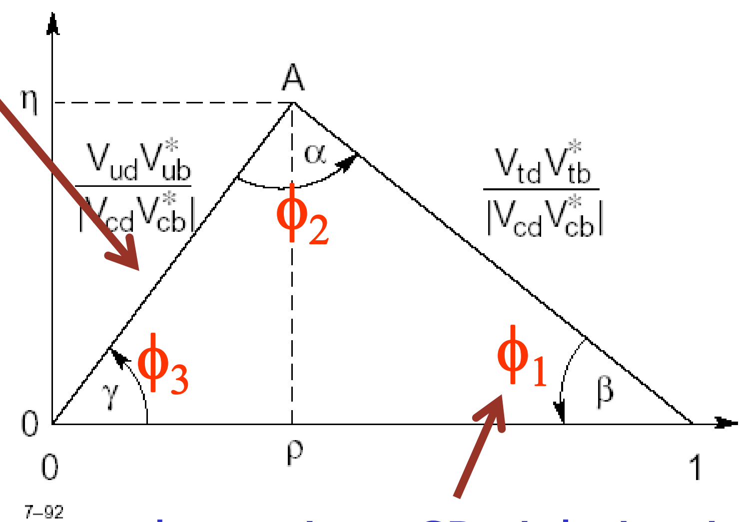
# CKM matrix: determines charged weak interaction of quarks

Wolfenstein parametrisation: expand the CKM matrix in the parameter $\lambda$ (=$\sin\theta_c$=0.22)

A, $\rho$ and $\eta$: all of order one

$$V = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

determines probability of b→u transitions



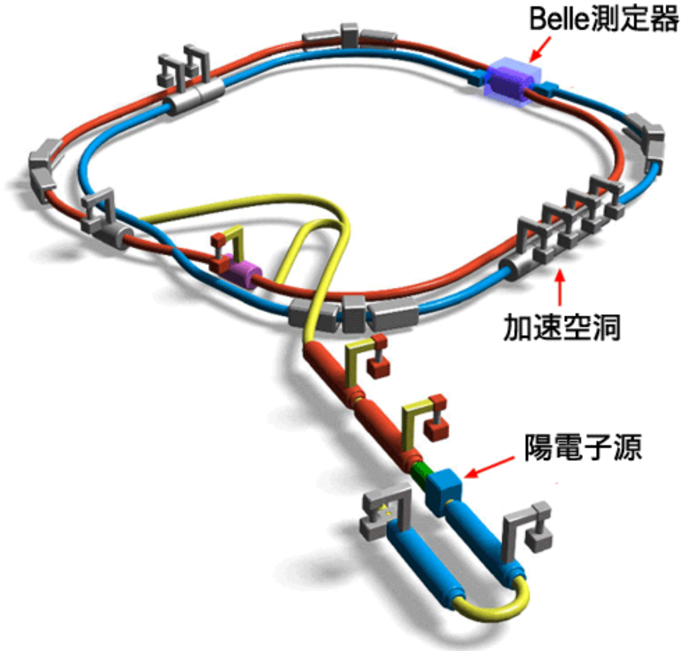

determines CP violation in B→J/ψ $K_S$ decays

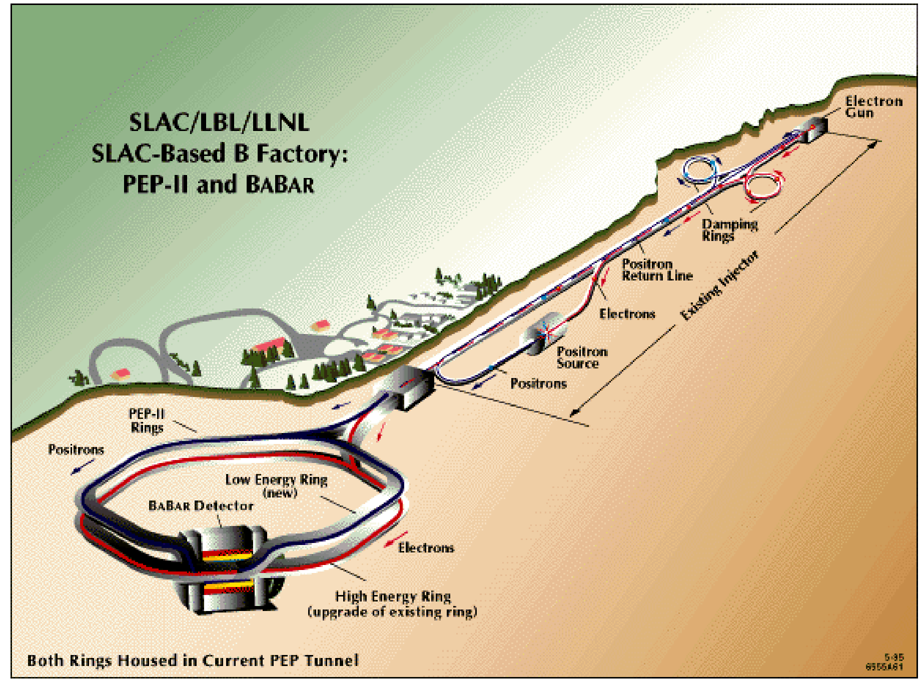
Unitarity condition:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

Goal: measure sides and angles in several different ways, check consistency →

# Asymmetric B factories




$\sqrt{s}=10.58$ GeV

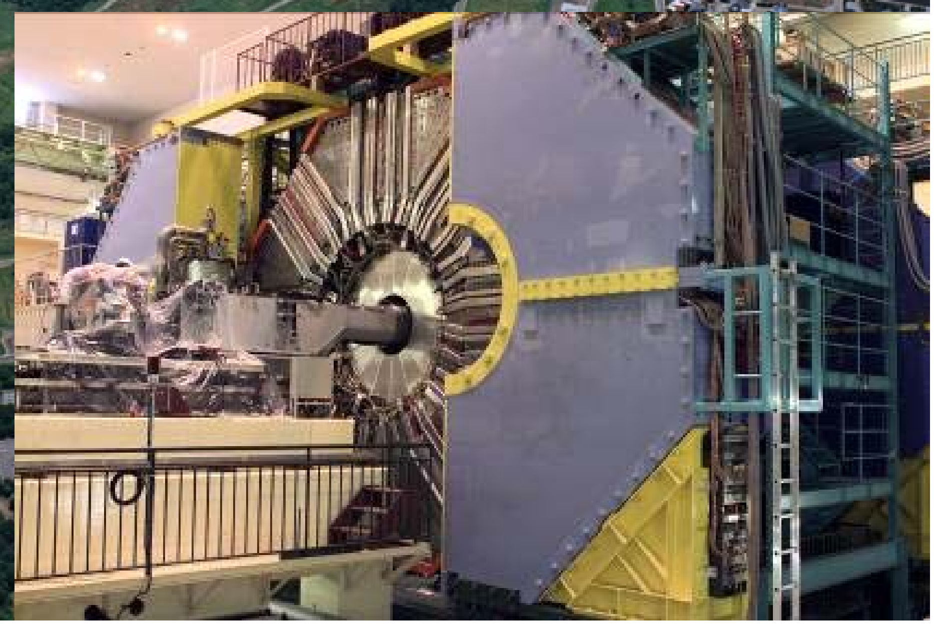
$e^+ \longrightarrow \Upsilon(4s) \longleftarrow e^-$

$\Upsilon(4s) \to B \, \bar{B}$

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

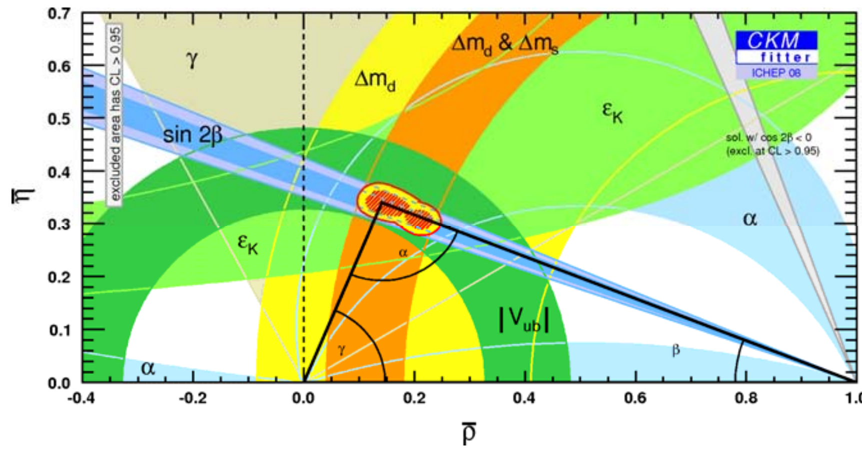
| | | | |
|---|---|---|---|
| BaBar | $p(e^-)=9$ GeV | $p(e^+)=3.1$ GeV | $\beta\gamma=0.56$ |
| Belle | $p(e^-)=8$ GeV | $p(e^+)=3.5$ GeV | $\beta\gamma=0.42$ |

# KEKB and Belle

# KM's bold idea verified by experiment

Relations between parameters as expected in the Standard model →

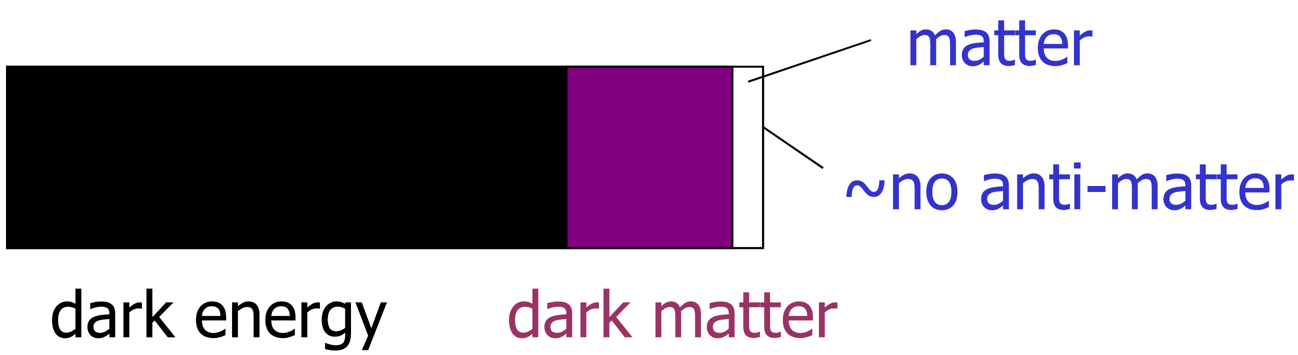



Nobel prize 2008!

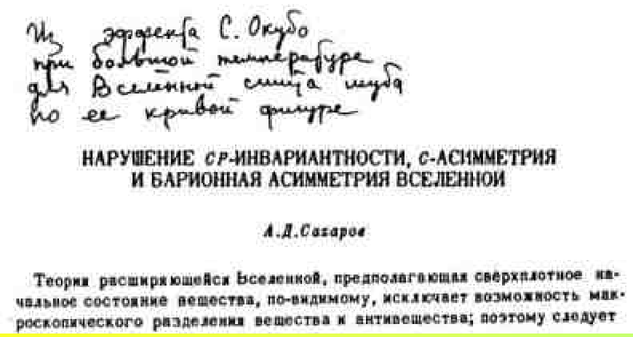
→ With essential experimental confirmations by BaBar and Belle! (explicitly noted in the Nobel Prize citation)

# The KM scheme is now part of the Standard Model of Particle Physics

- However, the CP violation of the KM mechanism is too small to account for the asymmetry between matter and anti-matter in the Universe (falls short by 10 orders of magnitude !)
- SM does not contain the fourth fundamental interaction, gravitation
- Most of the Universe is made of stuff we do not understand...



# Are we done ? (Didn't the B factories accomplish their mission, recognized by the 2008 Nobel Prize in Physics ?)

Из эффекта С. Окубо
при большой температуре
для Вселенной сшита шуба
по ее кривой фигуре

НАРУШЕНИЕ *CP*-ИНВАРИАНТНОСТИ, *C*-АСИММЕТРИЯ
И БАРИОННАЯ АСИММЕТРИЯ ВСЕЛЕННОЙ

*А.Д.Сахаров*

Теория расширяющейся Вселенной, предполагающая сверхплотное начальное состояние вещества, по-видимому, исключает возможность макроскопического разделения вещества и антивещества; поэтому следует

Matter - anti-matter asymmetry of the Universe: KM (Kobayashi-Maskawa) mechanism still short by 10 orders of magnitude !!!

# Two frontiers

Two complementary approaches to study shortcomings of the Standard Model and to search for the so far unobserved processes and particles (so called New Physics, NP). These are the **energy frontier** and the **intensity frontier** .

**Energy frontier :** direct search for production of unknown particles at the highest achievable energies.

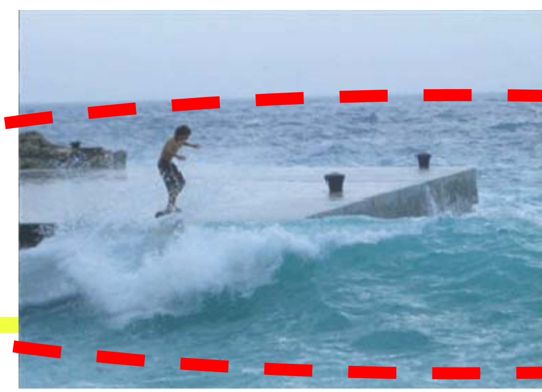
**Intensity frontier :** search for rare processes, deviations between theory predictions and experiments with the ultimate precision.

→for this kind of studies, one has to investigate a very large number of reactions events → need accelerators with ultimate **intensity** (= luminosity)

# Comparison of **energy** /**intensity** frontiers

To observe a large ship far away one can either use **strong binoculars** or observe **carefully the direction and the speed of waves** produced by the vessel.

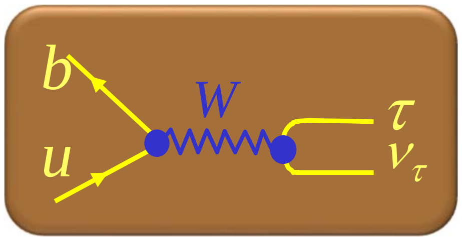
**Energy frontier (LHC)**



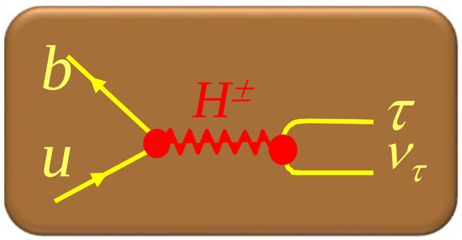
**Luminosity frontier (Belle and Belle II)**

# An example: Hunting the charged Higgs in the decay $B^- \to \tau^- \nu_\tau$

In addition to the Standard Model Higgs – as discovered at the LHC - in New Physics (e.g., in supersymmetric theories) there could also be a charged Higgs.




The rare decay $B^- \to \tau^- \nu_\tau$ is in SM mediated by the W boson

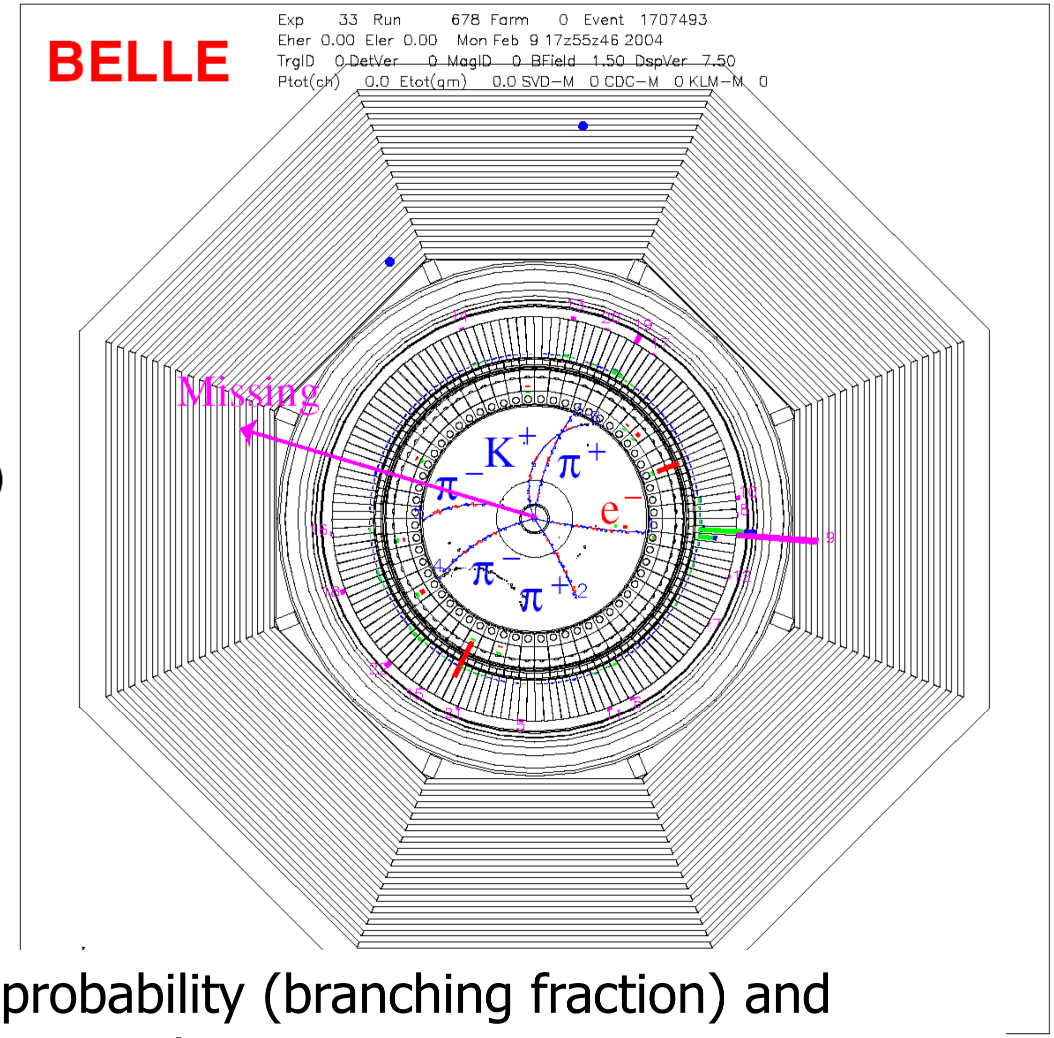



In some supersymmetric extensions it can also proceed via a charged Higgs

The charged Higgs would influence the decay of a B meson to a tau lepton and its neutrino, and modify the probability for this decay.

# Missing Energy Decays: $B^- \rightarrow \tau^- \nu_\tau$

$$B^+ \to D^0\pi^+$$
$$(\to K\pi^-\pi^+\pi^-)$$
$$B^- \to \tau(\to e\nu\bar{\nu})\nu$$

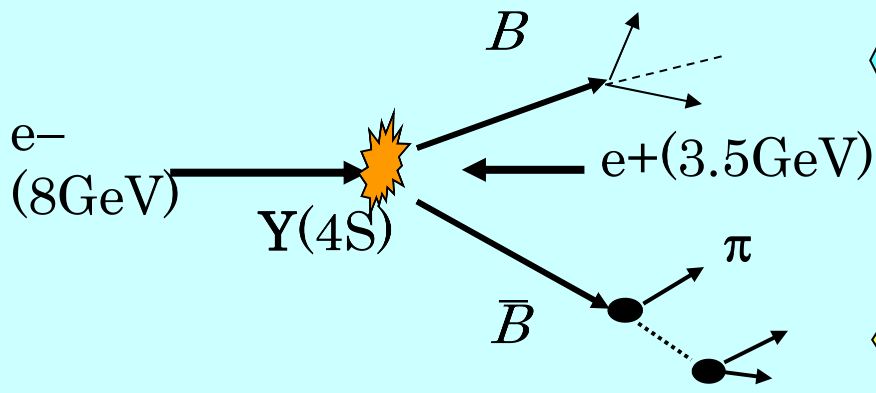



By measuring the decay probability (branching fraction) and comparing it to the SM expectation:

→ Properties of the charged Higgs (e.g. its mass)

# Full Reconstruction Method

- Fully reconstruct one of the B's to
  - Tag B flavor/charge
  - Determine B momentum
  - Exclude decay products of one B from further analysis




Decays of interest
$B \to X_u\, l\, \nu$,
$B \to K\, \nu\, \nu$
$B \to D\tau\nu$, $\tau\nu$

full reconstruction
$B \to D\pi$ etc. (0.1~0.3%)

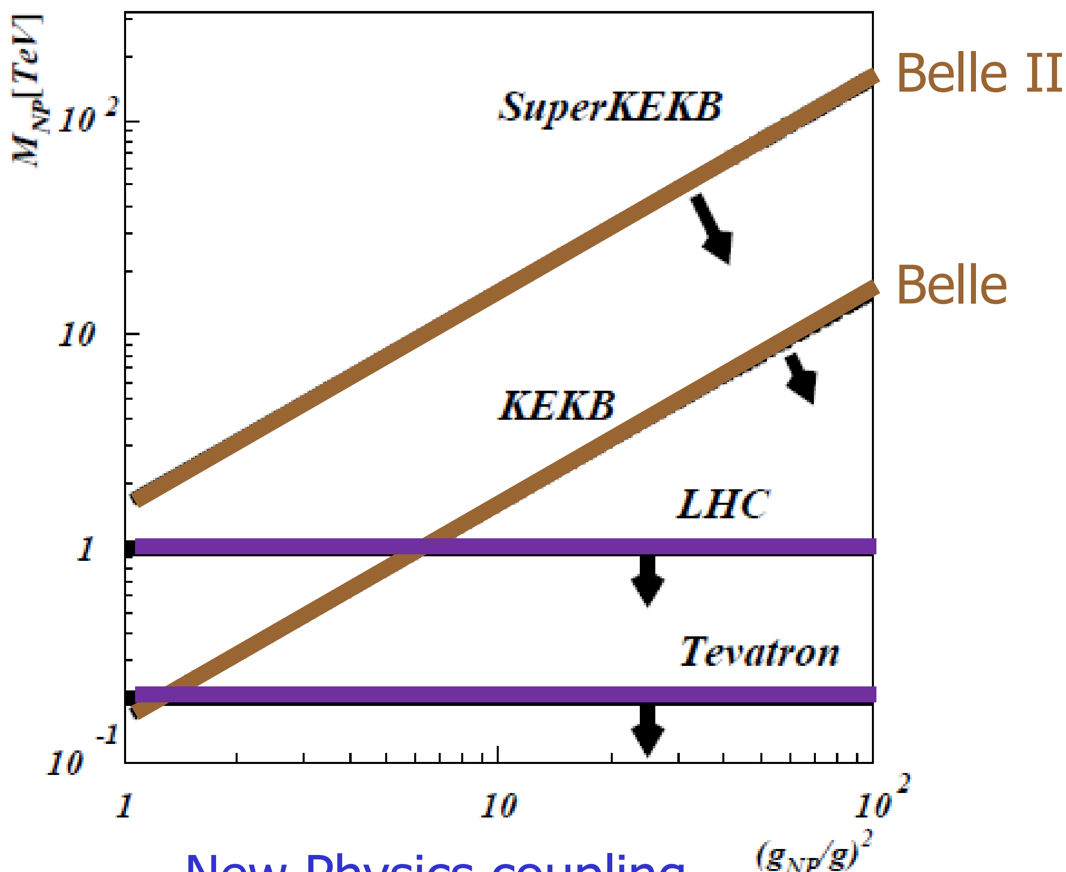
→ Offline B meson beam!

Powerful tool for B decays with neutrinos

# New Physics reach

**energy frontier** vs. **intensity frontier**

New Physics mass scale (TeV)



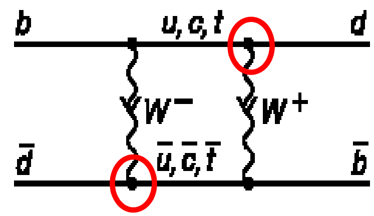

New Physics coupling

# Super B Factory Motivation 2

- Lessons from history: the top quark

<u>Physics of top quark</u>

| | |
|---|---|
| First estimate of mass: BB mixing | → ARGUS |
| Direct production, Mass, width etc. | → CDF/D0 |
| Off-diagonal couplings, phase | → BaBar/Belle |




$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Even before that: prediction of charm quark from the GIM mechanism, and its mass from $K^0$ mixing

# Physics at a Super B Factory

- There is a good chance to see new phenomena;
  - **CPV in B decays from the new physics (non KM).**
  - **Lepton flavor violations in $\tau$ decays.**
- They will help to diagnose (if found) or constrain (if not found) new physics models.
- $B \rightarrow \tau\nu$, $D\tau\nu$ can probe the charged Higgs in large $\tan\beta$ region.
- **Physics motivation is independent of LHC**.
  - If LHC finds NP, precision flavour physics is compulsory.
  - If LHC finds no NP, high statistics B/$\tau$ decays would be a unique way to search for the >TeV scale physics (=TeV scale in case of MFV).

Physics reach with 50 ab$^{-1}$:

- Physics at Super B Factory (Belle II authors + guests) hep-ex arXiv:1002.5012

# Components of an experimental apparatus (‘spectrometer’)

- Tracking and vertexing systems
- Particle identification devices
- Calorimeters (measurement of energy)

# Spectrometer design: what do we want to measure? B factories: Time evolution in the B system

An arbitrary linear combination of the neutral B-meson flavor eigenstates

$$a\left|B^0\right\rangle + b\left|\overline{B}^0\right\rangle$$

with a=a(t) and b=b(t), is governed by a time-dependent Schroedinger equation

$$i\frac{d}{dt}\begin{pmatrix} a \\ b \end{pmatrix} = H\begin{pmatrix} a \\ b \end{pmatrix} = (M - \frac{i}{2}\Gamma)\begin{pmatrix} a \\ b \end{pmatrix}$$

M and $\Gamma$ are 2x2 Hermitian matrices. CPT invariance → $H_{11}=H_{22}$

$$M = \begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix}, \Gamma = \begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}$$

diagonalize, solve →

# Time evolution of B's

Time evolution in the $B^0$ in $\overline{B}^0$ basis:

$$\left|B^0_{phys}(t)\right\rangle = g_+(t)\left|B^0\right\rangle + (q/p)g_-(t)\left|\overline{B}^0\right\rangle$$
$$\left|\overline{B}^0_{phys}(t)\right\rangle = (p/q)g_-(t)\left|B^0\right\rangle + g_+(t)\left|\overline{B}^0\right\rangle$$

with

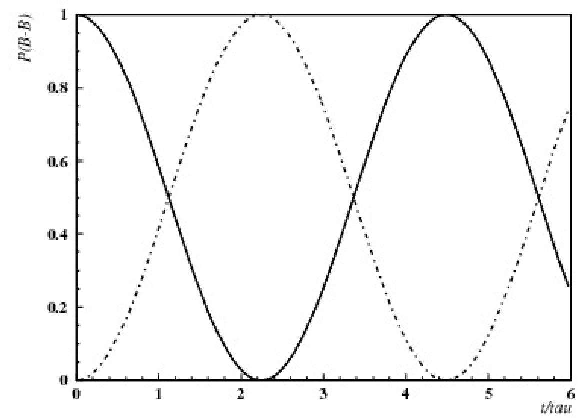
$$g_+(t) = e^{-iMt}e^{-\Gamma t/2}\cos(\Delta m t/2)$$
$$g_-(t) = e^{-iMt}e^{-\Gamma t/2} i\sin(\Delta m t/2)$$

$M = (M_H+M_L)/2$

If B mesons were stable ($\Gamma=0$), the time evolution would look like:

$$g_+(t) = e^{-iMt} \cos(\Delta m t / 2)$$

$$g_-(t) = e^{-iMt} i \sin(\Delta m t / 2)$$




→Probability that a B turns into its anti-particle

→beat in classical mechanics

$$\left| \langle \overline{B}^0 | B^0_{phys}(t) \rangle \right|^2 = |q/p|^2 |g_-(t)|^2 = |q/p|^2 \sin^2(\Delta m t / 2)$$

→Probability that a B remains a B

$$\left| \langle B^0 | B^0_{phys}(t) \rangle \right|^2 = |g_+(t)|^2 = \cos^2(\Delta m t / 2)$$

→Expressions familiar from quantum mechanics of a two level system, neutrino mixing etc

# CP violation: decay rate difference

Decay rate asymmetry:

$$a_{f_{CP}} = \frac{P(\overline{B}^0 \to f_{CP}, t) - P(B^0 \to f_{CP}, t)}{P(\overline{B}^0 \to f_{CP}, t) + P(B^0 \to f_{CP}, t)}$$

Decay rate:

$$P(B^0 \to f_{CP}, t) \propto \left| \left\langle f_{CP} \middle| H \middle| B^0_{phys}(t) \right\rangle \right|^2$$

Decay amplitudes vs time:

$$\left\langle f_{CP} \middle| H \middle| B^0_{phys}(t) \right\rangle = g_+(t) \left\langle f_{CP} \middle| H \middle| B^0 \right\rangle + (q/p) g_-(t) \left\langle f_{CP} \middle| H \middle| \overline{B}^0 \right\rangle$$

$$= g_+(t) A_{f_{CP}} + (q/p) g_-(t) \overline{A}_{f_{CP}}$$

$$\left\langle f_{CP} \middle| H \middle| \overline{B}^0_{phys}(t) \right\rangle = (p/q) g_-(t) \left\langle f_{CP} \middle| H \middle| B^0 \right\rangle + g_+(t) \left\langle f_{CP} \middle| H \middle| \overline{B}^0 \right\rangle$$

$$= (p/q) g_-(t) A_{f_{CP}} + g_+(t) \overline{A}_{f_{CP}}$$

$$a_{f_{CP}} = \frac{P(\overline{B}^0 \to f_{CP}, t) - P(B^0 \to f_{CP}, t)}{P(\overline{B}^0 \to f_{CP}, t) + P(B^0 \to f_{CP}, t)} =$$

CP violation: asymmetry in time evolution of B and anti-B

$$= \frac{\left|(p/q) g_-(t) A_{f_{CP}} + g_+(t) \overline{A}_{f_{CP}}\right|^2 - \left|g_+(t) A_{f_{CP}} + (q/p) g_-(t) \overline{A}_{f_{CP}}\right|^2}{\left|(p/q) g_-(t) A_{f_{CP}} + g_+(t) \overline{A}_{f_{CP}}\right|^2 + \left|g_+(t) A_{f_{CP}} + (q/p) g_-(t) \overline{A}_{f_{CP}}\right|^2} =$$

$$= \frac{(1 - |\lambda_{f_{CP}}|^2)\cos(\Delta m t) - 2\,\mathrm{Im}(\lambda_{f_{CP}})\sin(\Delta m t)}{1 + |\lambda_{f_{CP}}|^2}$$

$$= C\cos(\Delta m t) + S\sin(\Delta m t)$$

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

Non-zero effect if $\mathrm{Im}(\lambda) \neq 0$, even if $|\lambda| = 1$

If $|\lambda| = 1$ →

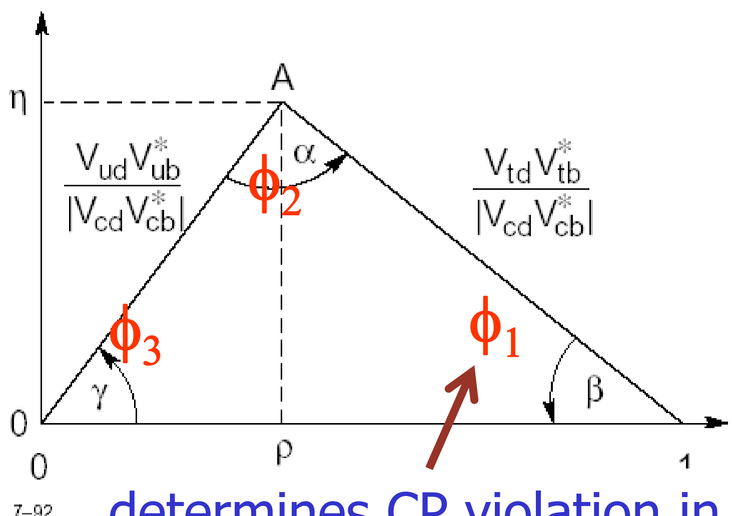
$$\boxed{a_{f_{CP}} = -\mathrm{Im}(\lambda)\sin(\Delta m t)}$$

Detailed derivation → backup slides

# CP violation: related to the angles of the unitarity triangle

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

Im(λ) = sin2$\phi_1$ in B→J/ψ $K_S$ decays!

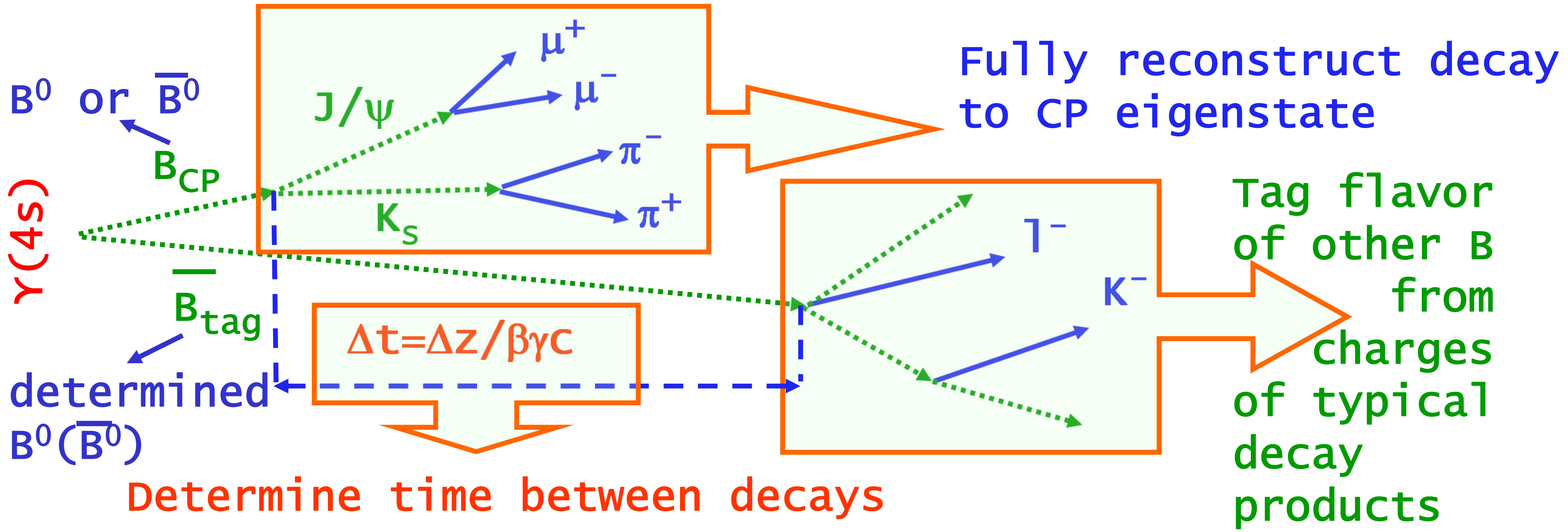



determines CP violation in B→J/ψ $K_S$ decays

Unitarity condition:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

# Typical measurement

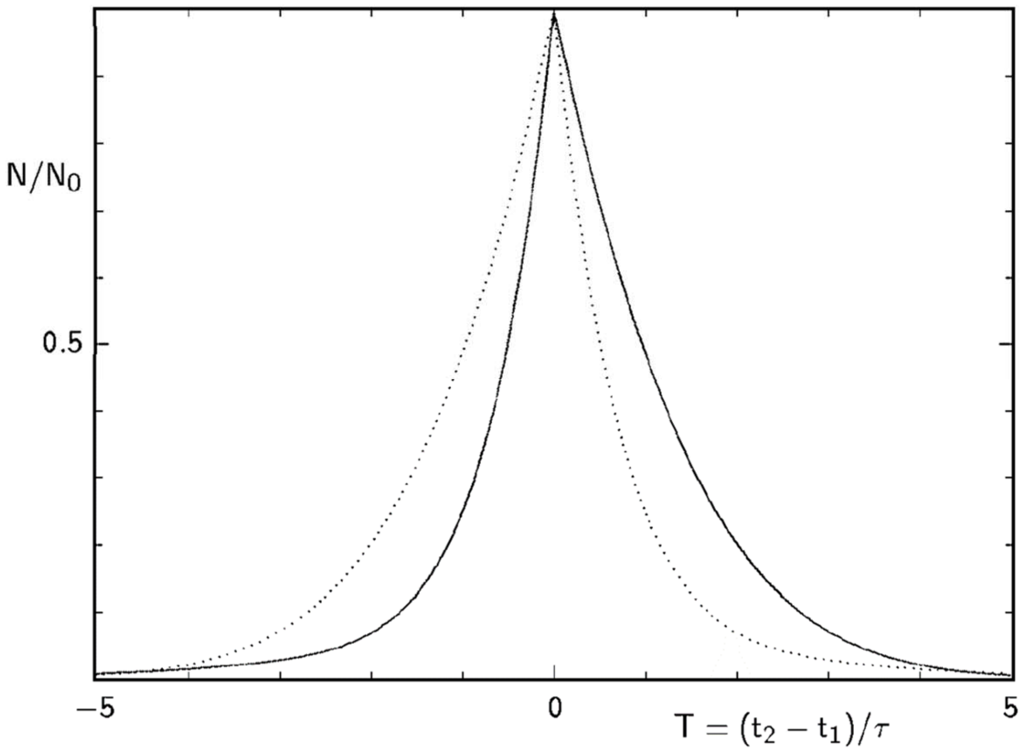


# Experimental considerations

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

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

We are measuring this parameter




T = time difference of the two decays

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

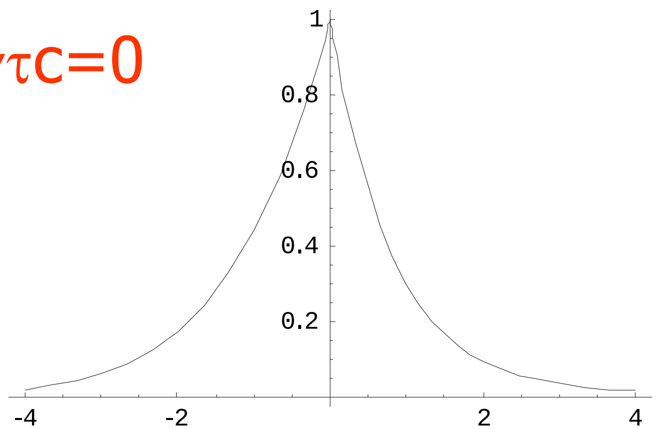
-> the two curves should not be smeared too much

Integrals are equal, time information mandatory!

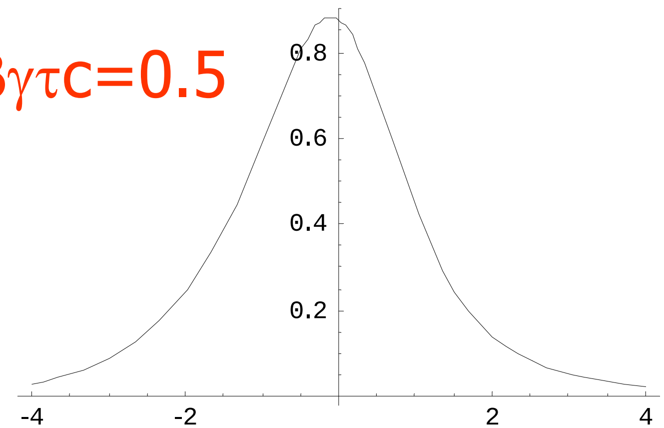
# Experimental considerations

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

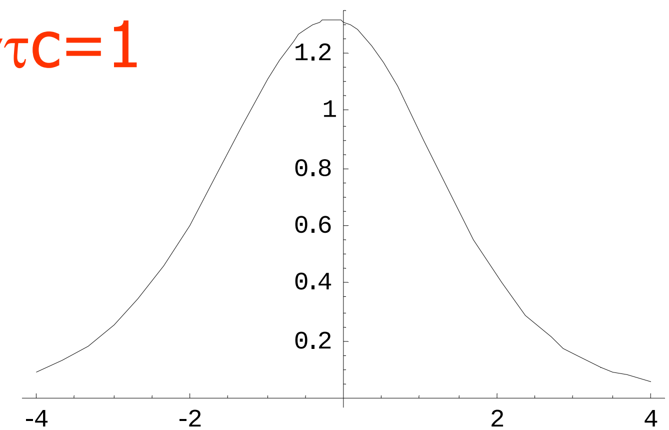
$\sigma(z)/\beta\gamma\tau c=0$



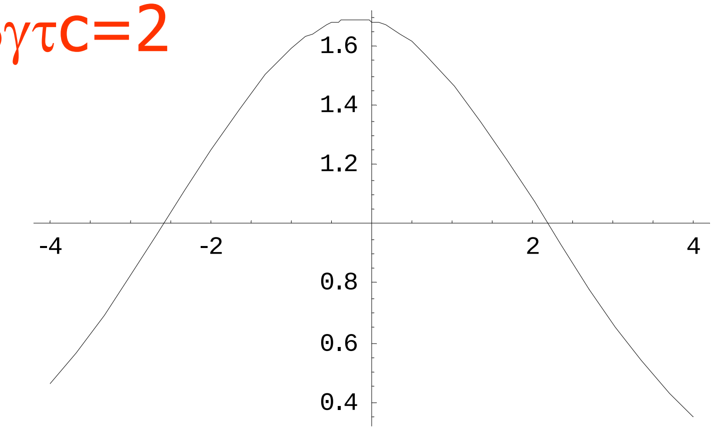

$\sigma(z)/\beta\gamma\tau c=0.5$




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




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

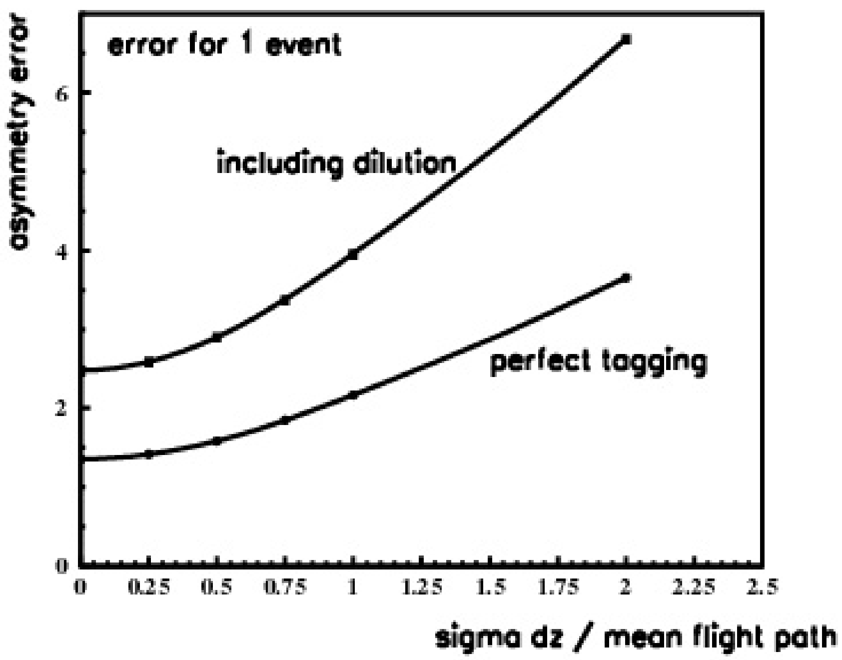



Measured distribution: convolution of P(t) and the resolution function (e.g., a Gaussian with $\sigma = \sigma(z)/\beta\gamma\tau c$)

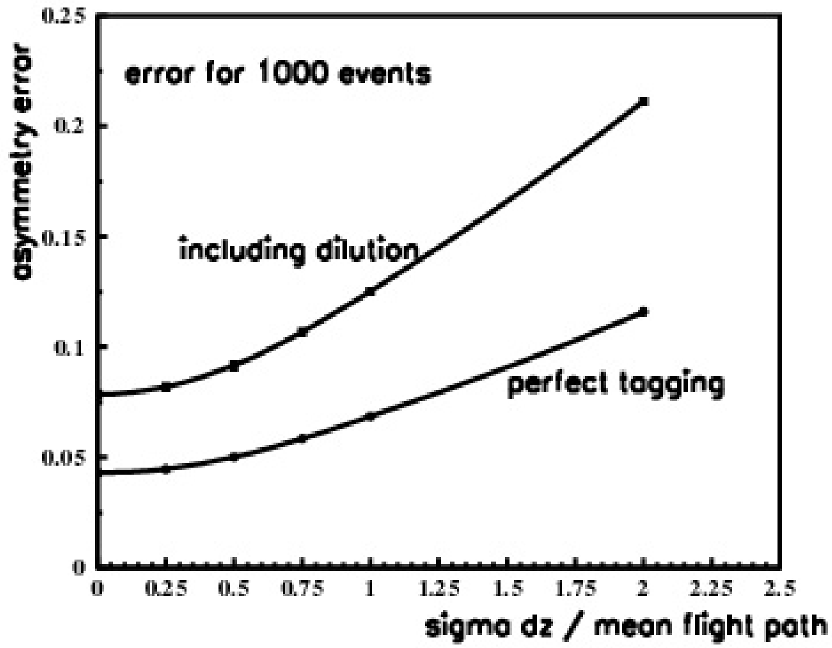
# Experimental considerations

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

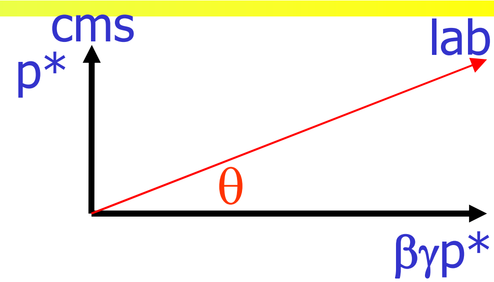
For 1 event




for 1000 events



# Experimental considerations



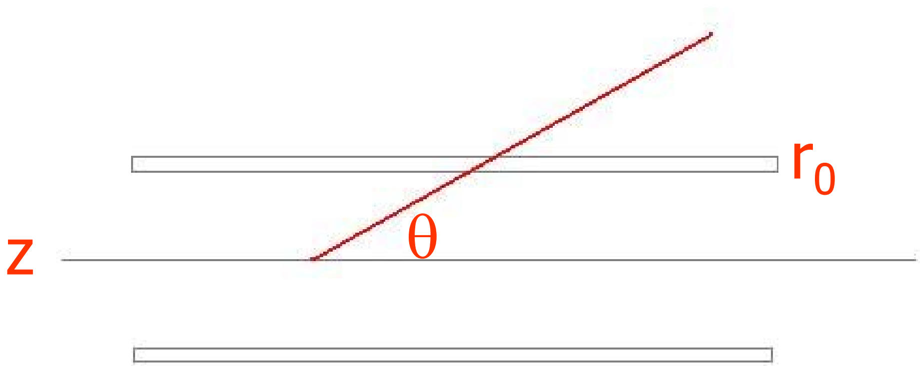

Choice of boost $\beta\gamma$:

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 $r_0$




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

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

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

# Experimental considerations

Choice of boost $\beta\gamma$:

Maximize the ratio between the average flight path $\beta\gamma\tau c$ and the vertex resolution $\sigma(z)$

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

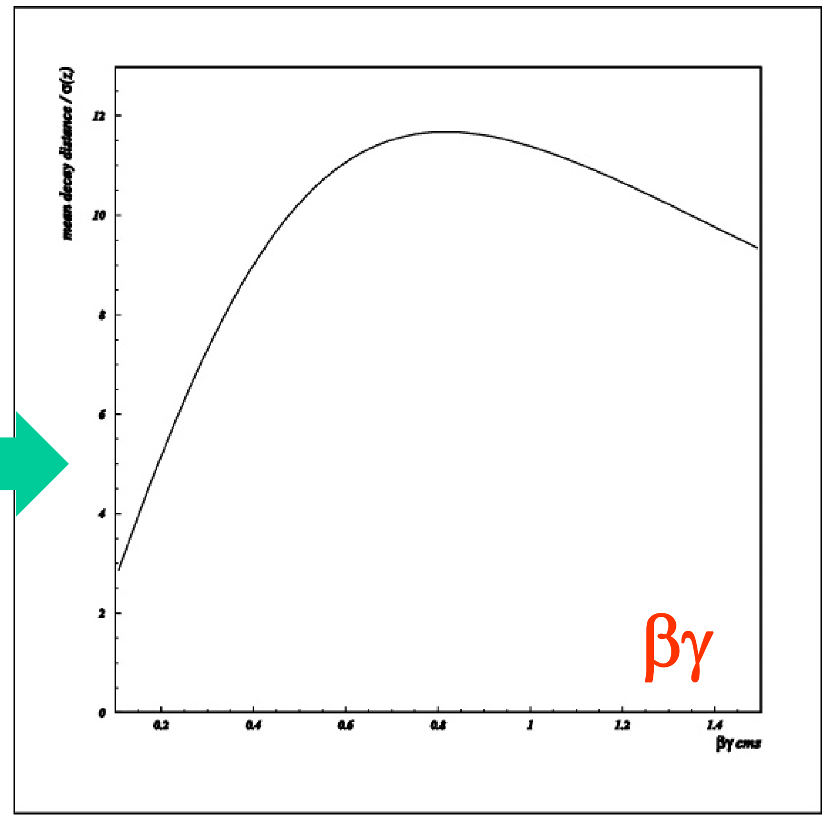
$\theta = \mathrm{atan}(1/\beta\gamma)$

$\beta\gamma\tau c/\sigma(z)\ \alpha\ (1/r_0)\ \beta\gamma\tau c\ \sin^{5/2}\theta =$

$= (1/r_0)\ \beta\gamma\tau c\ \sin^{5/2}(\mathrm{atan}(1/\beta\gamma))$

Boost around $\beta\gamma=0.8$ seems optimal

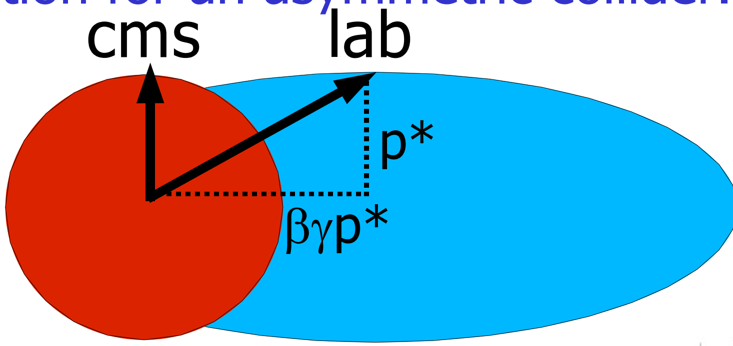
$\beta\gamma\tau c/\sigma(z)$



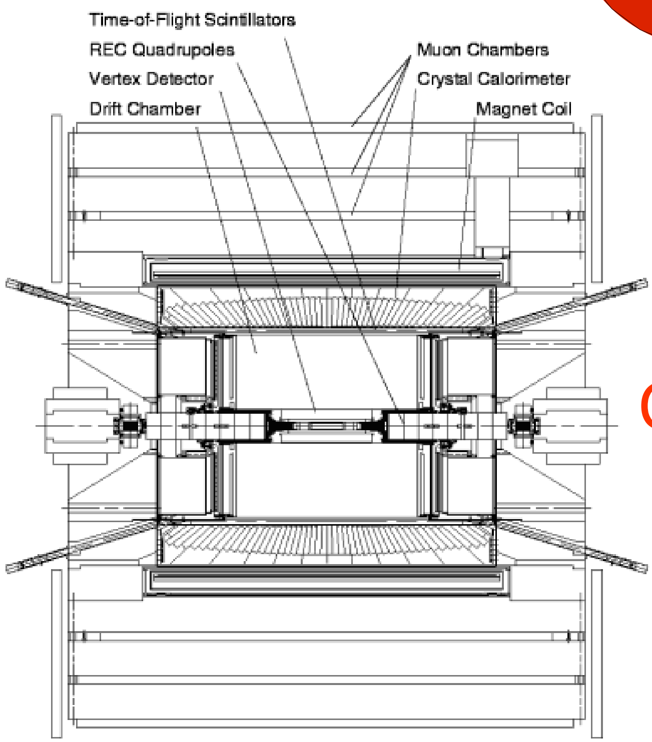

Not the whole story....

# Experimental considerations

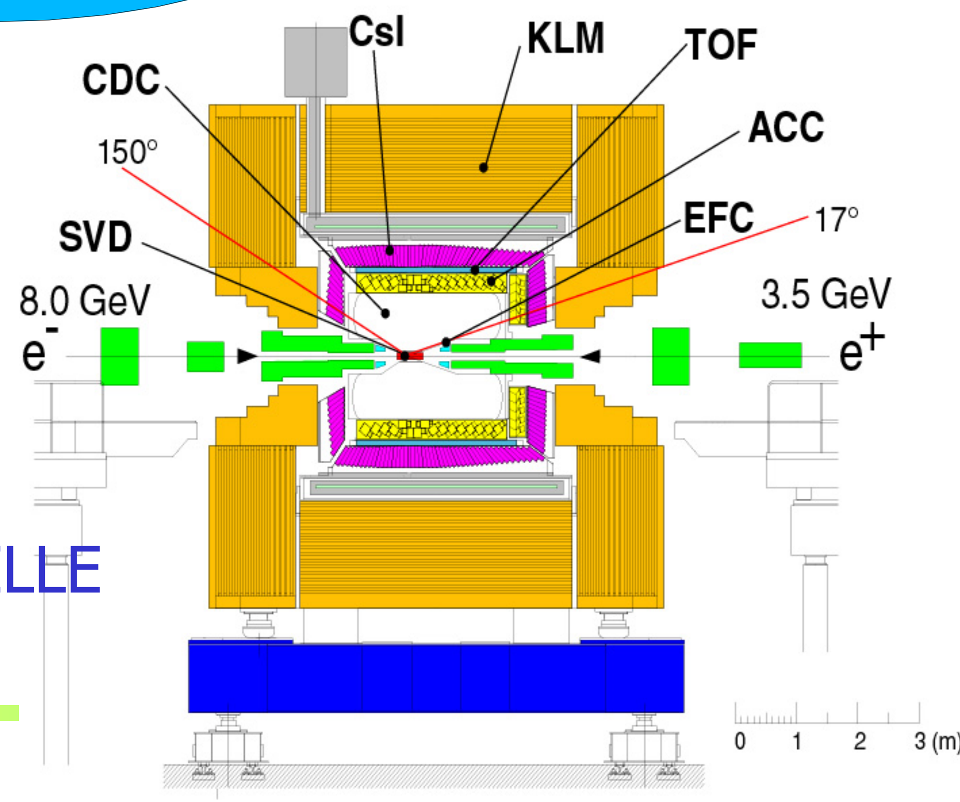
Detector form: symmetric for symmetric energy beams; extended in the boost direction for an asymmetric collider.




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




CLEO




BELLE

# Experimental considerations

Which boost...

Arguments for a smaller boost:

- Larger boost -> smaller acceptance

(particles escape in the boosted direction) ->

- 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)

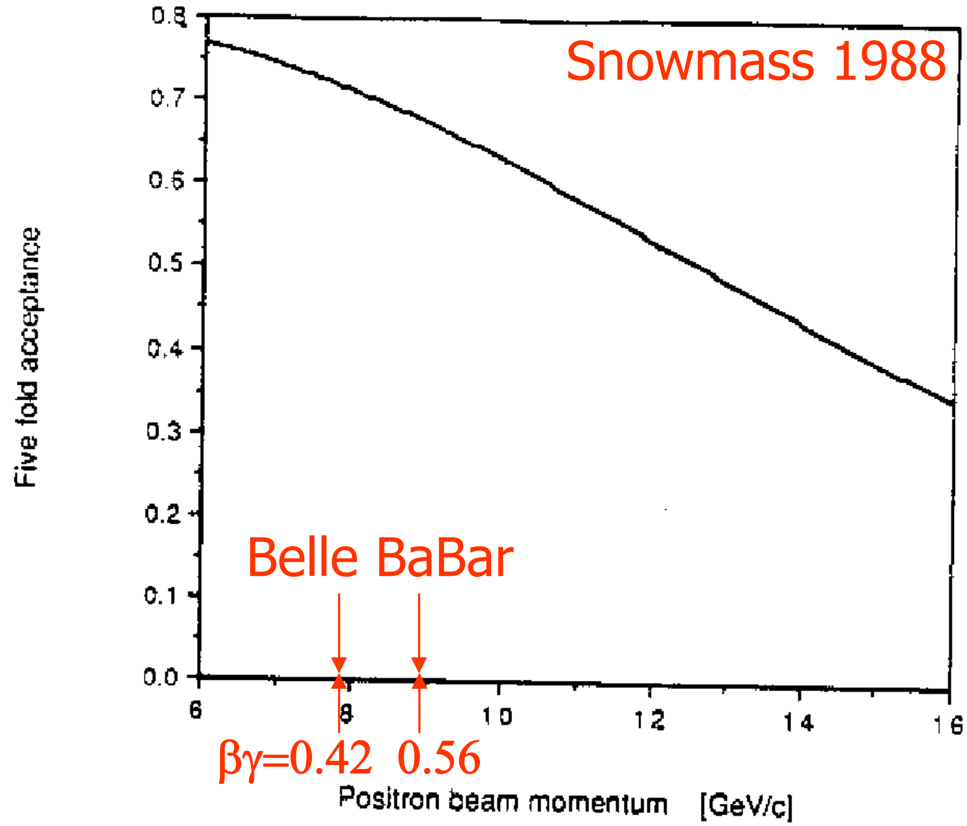
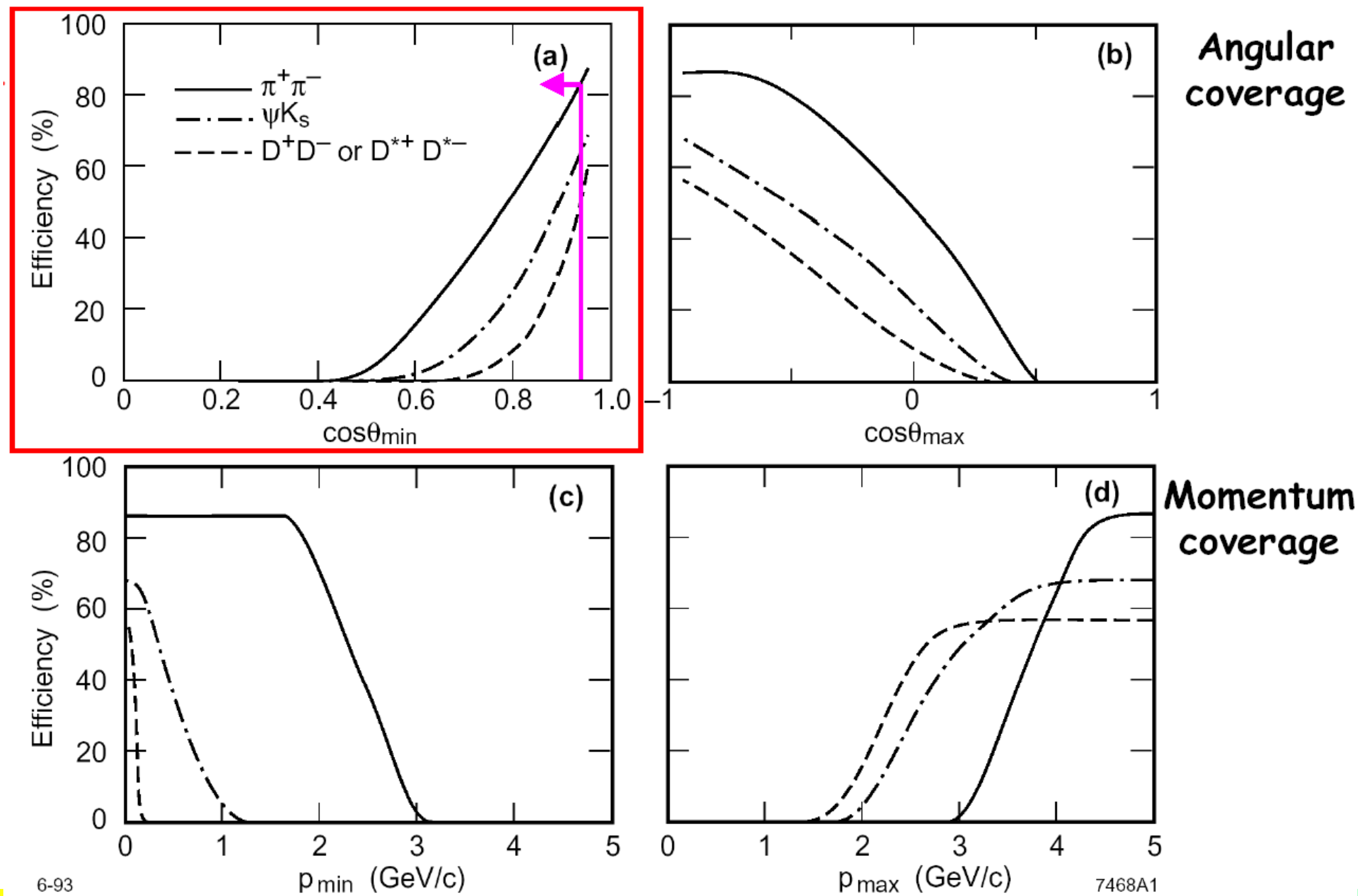



**Figure 4.** The acceptance of a detector covering $|\cos\theta_{lab}| < 0.95$ for five uncorrelated particles as a function of the energy of the more energetic beam in an asymmetric collider at the $\Upsilon(4S)$.

# Requirements: Geometric Acceptance



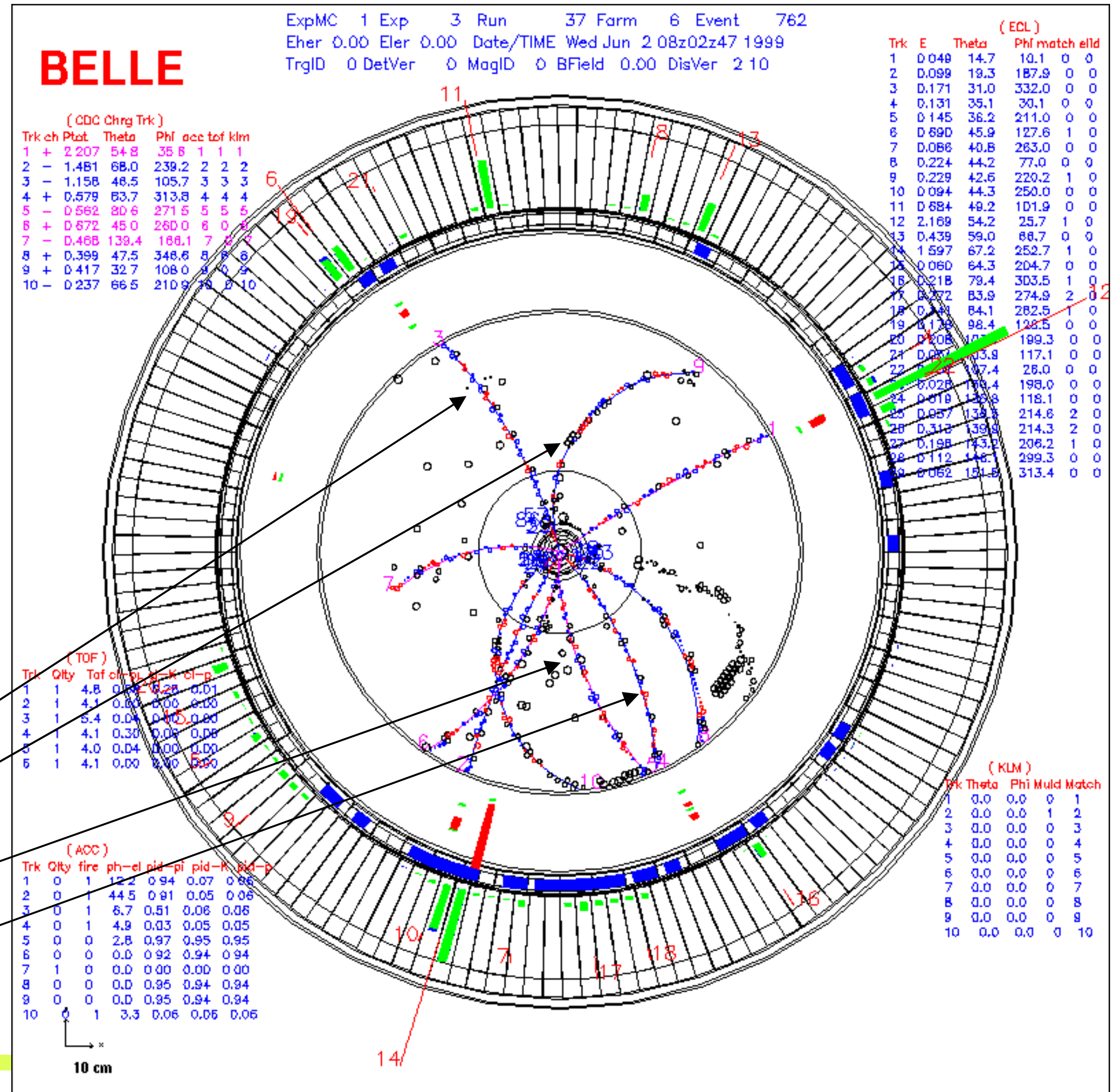
# How to understand what happened in a collision?

Illustration on an example:

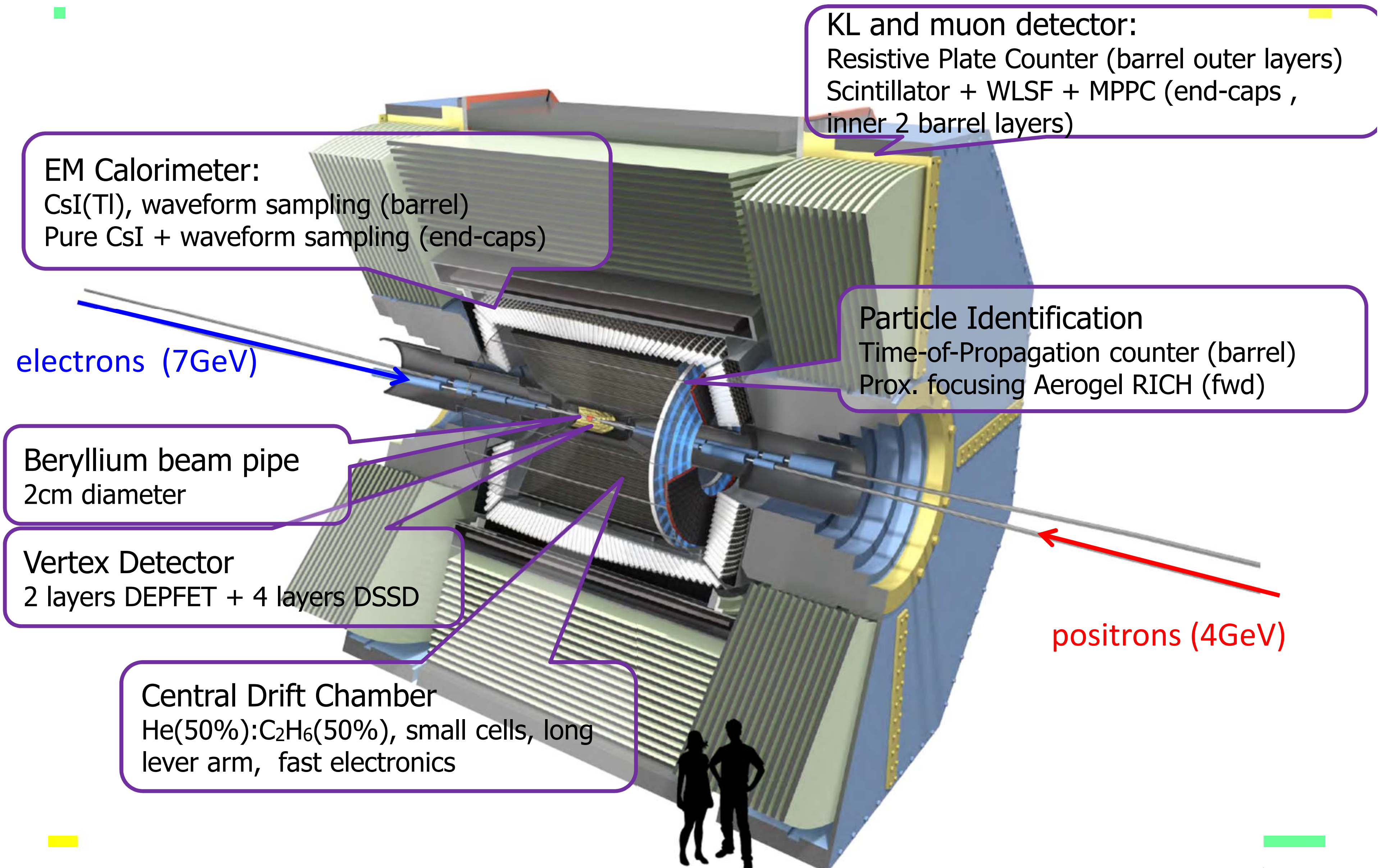
$B^0 \rightarrow K^0_S\, J/\psi$

$K^0_S \rightarrow \pi^- \pi^+$

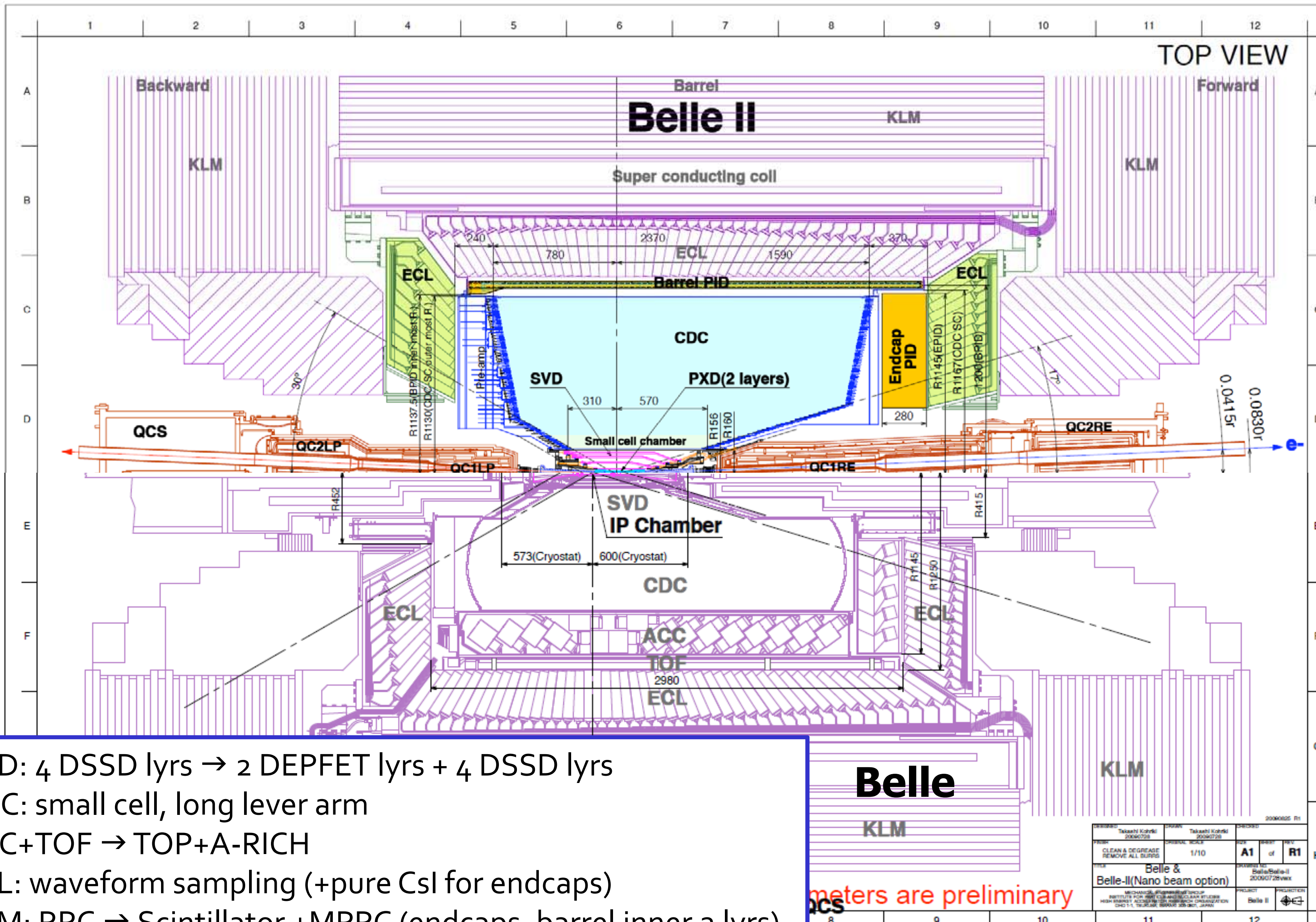
$J/\psi \rightarrow \mu^- \mu^+$



# Belle II Detector



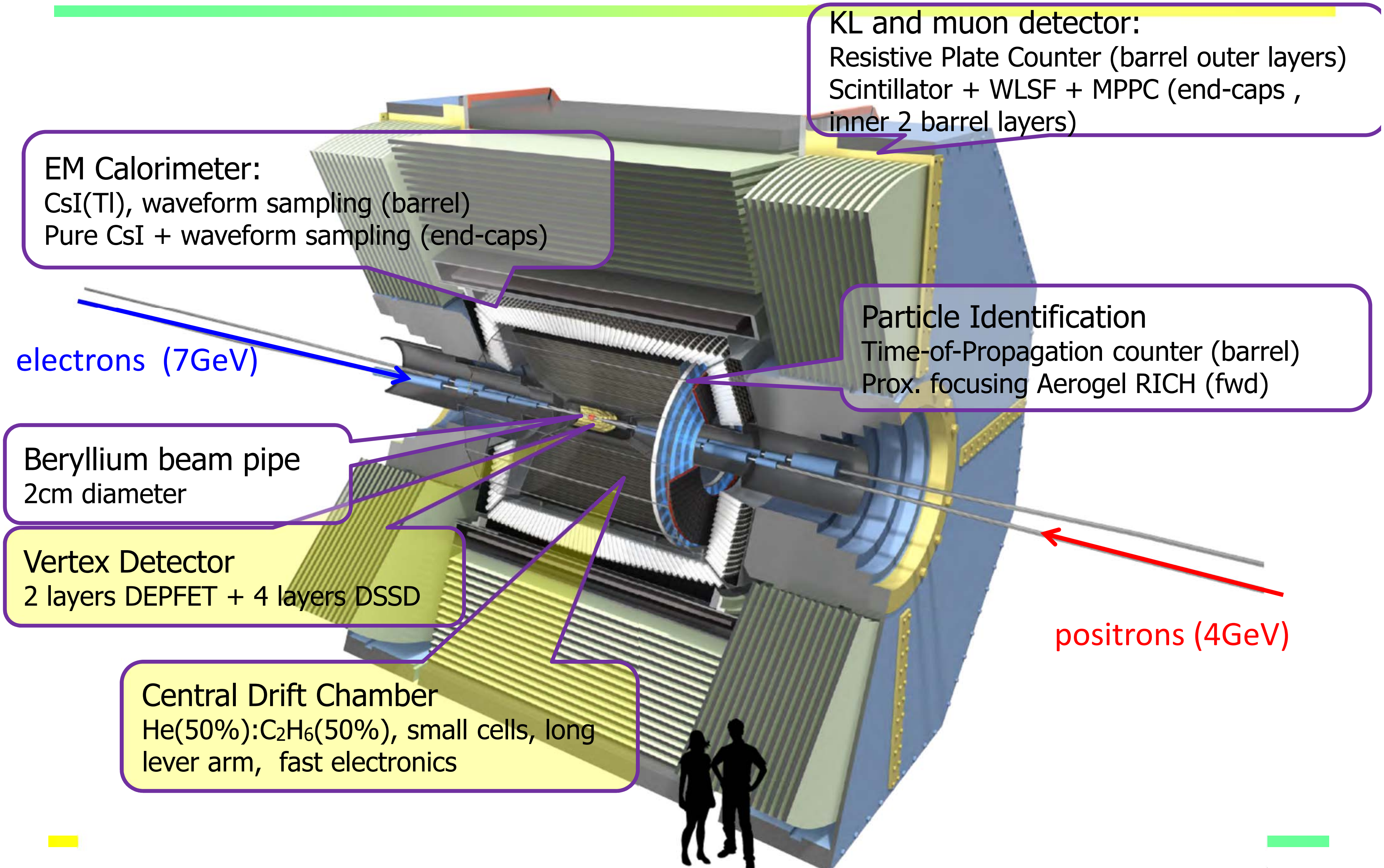
# Belle II Detector (in comparison with Belle)

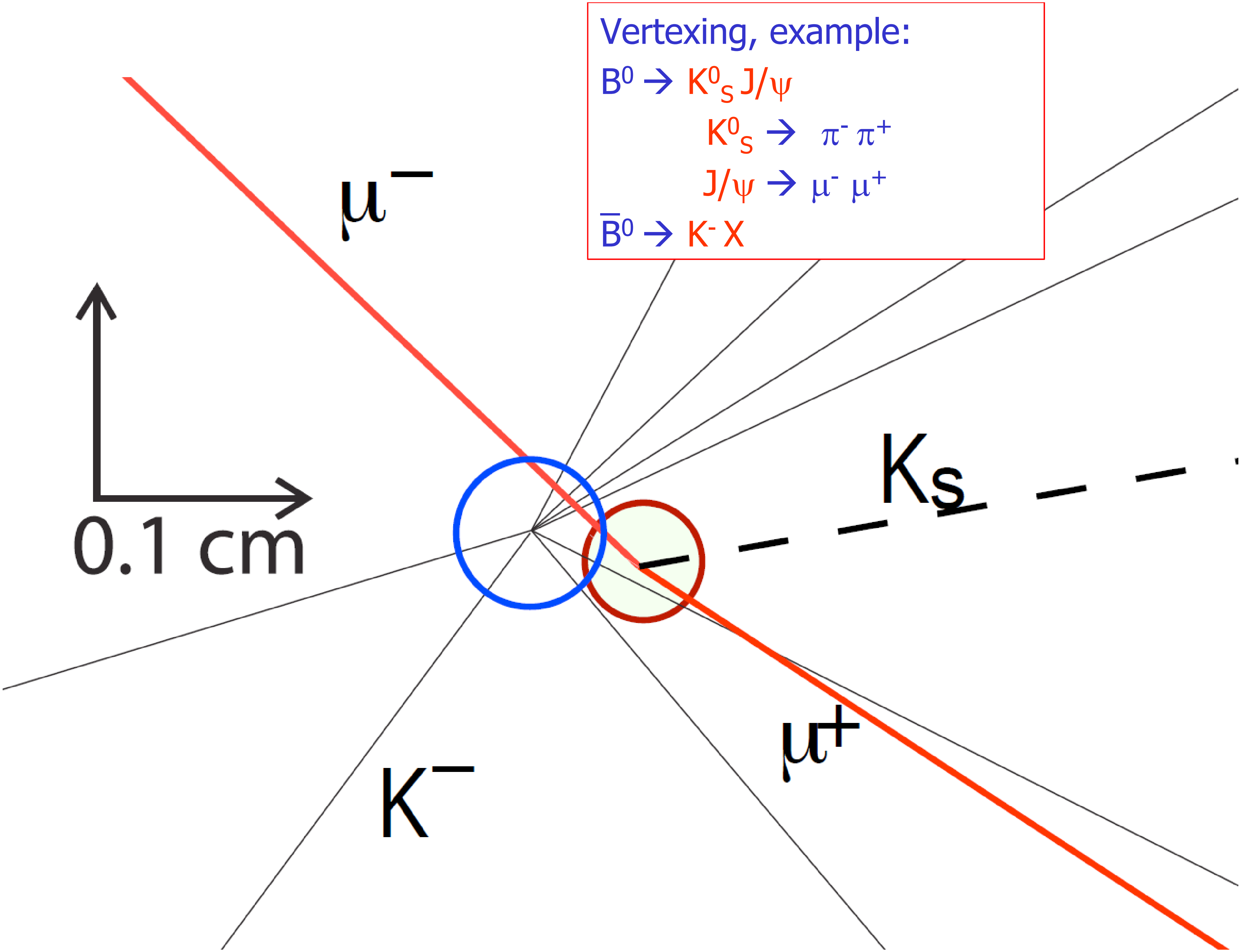



SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling (+pure CsI for endcaps)
KLM: RPC → Scintillator +MPPC (endcaps, barrel inner 2 lyrs)

meters are preliminary

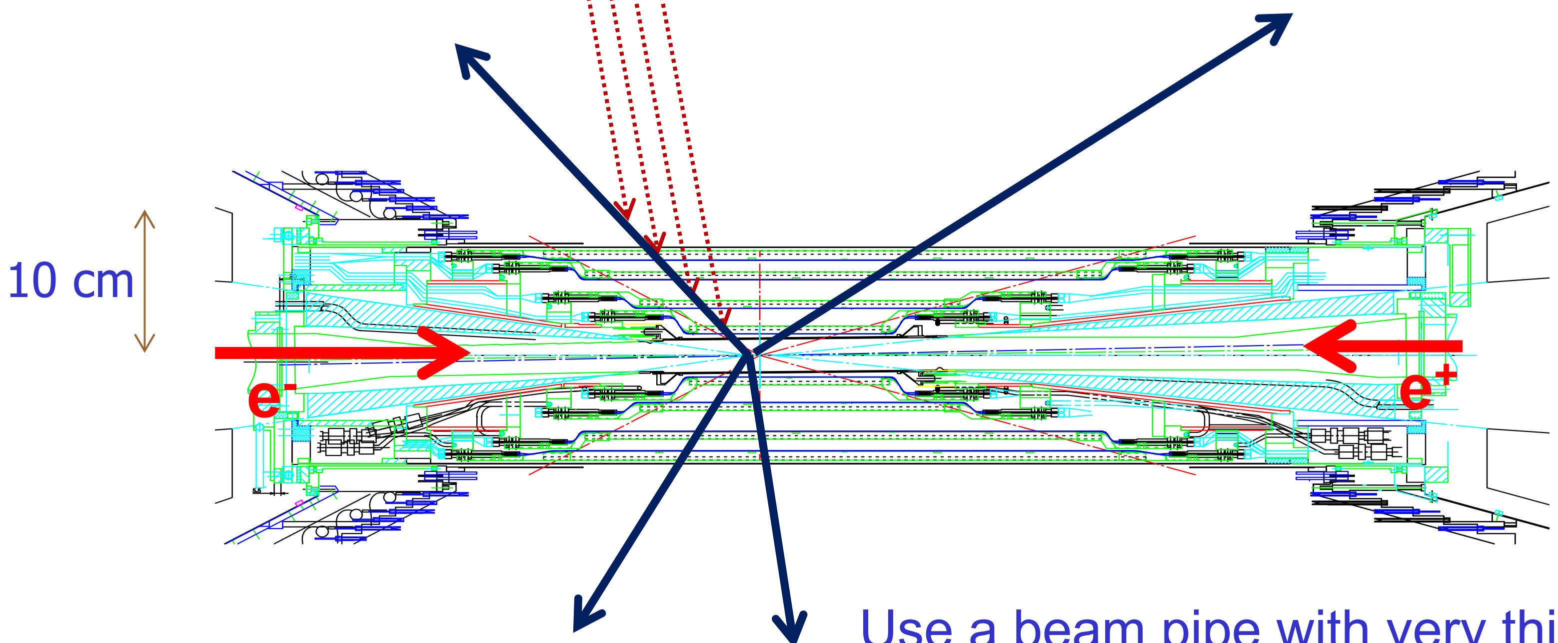
# Tracking and vertex systems in Belle II




Vertexing, example:
$B^0 \rightarrow K^0_S\, J/\psi$
$K^0_S \rightarrow \pi^- \pi^+$
$J/\psi \rightarrow \mu^- \mu^+$
$\bar{B}^0 \rightarrow K^- X$
$\mu^-$
0.1 cm
$K_S$
$\mu^+$
$K^-$

# Vertexing

Measure very accurately points on the track close to the interaction point




Use a beam pipe with very thin walls (and light material – long $X_0$) to reduce multiple scattering

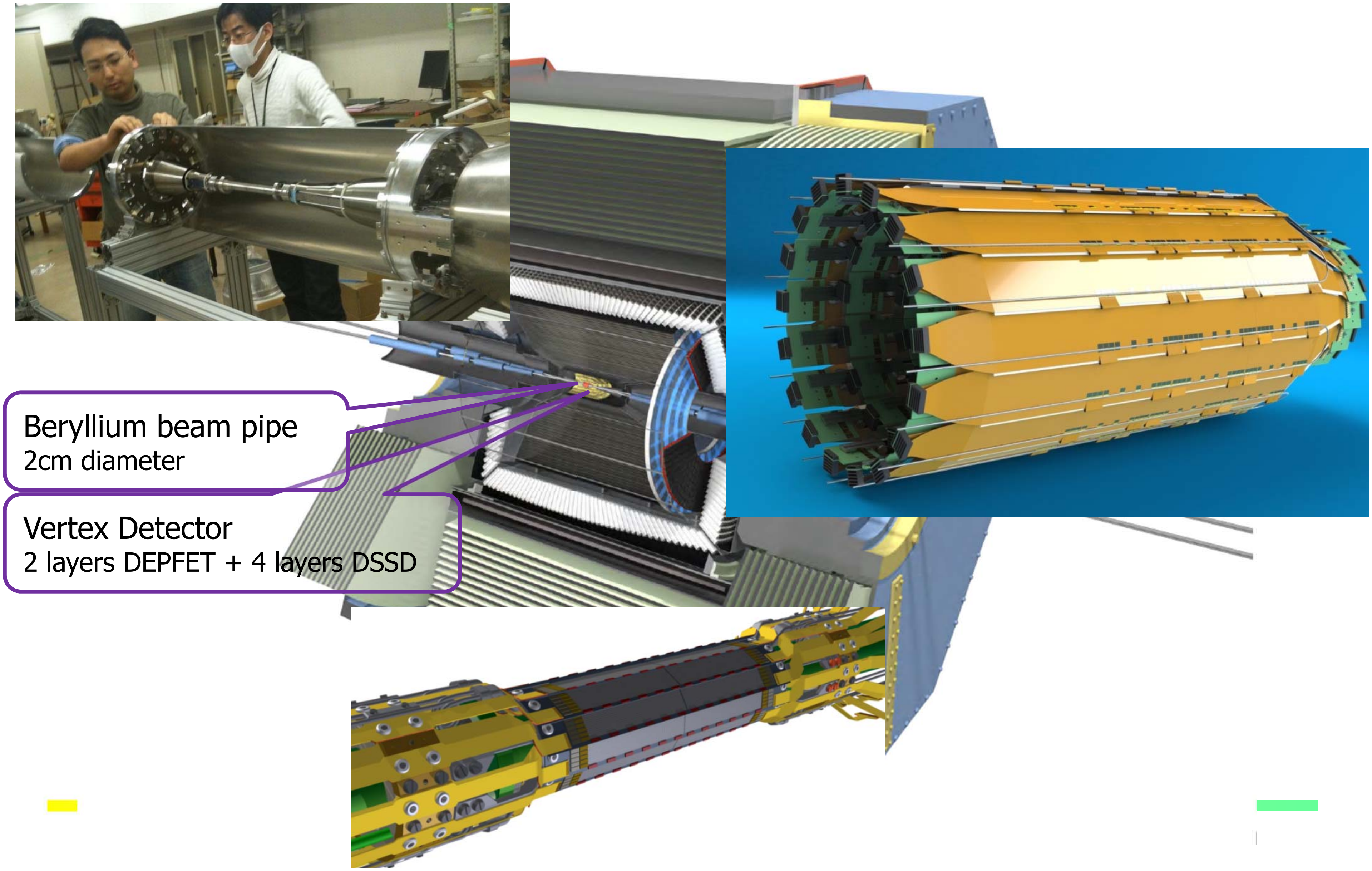
# 6. ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS

**Table 6.1** Abridged from `pdg.lbl.gov/AtomicNuclearProperties` by D. E. Groom (2007). See web pages for more detail about entries in this table including chemical formulae, and for several hundred other entries. Quantities in parentheses are for NTP (20° C and 1 atm), and square brackets indicate quantities evaluated at STP. Boiling points are at 1 atm. Refractive indices $n$ are evaluated at the sodium D line blend (589.2 nm); values $\gg$1 in brackets are for $(n-1)\times 10^6$ (gases).

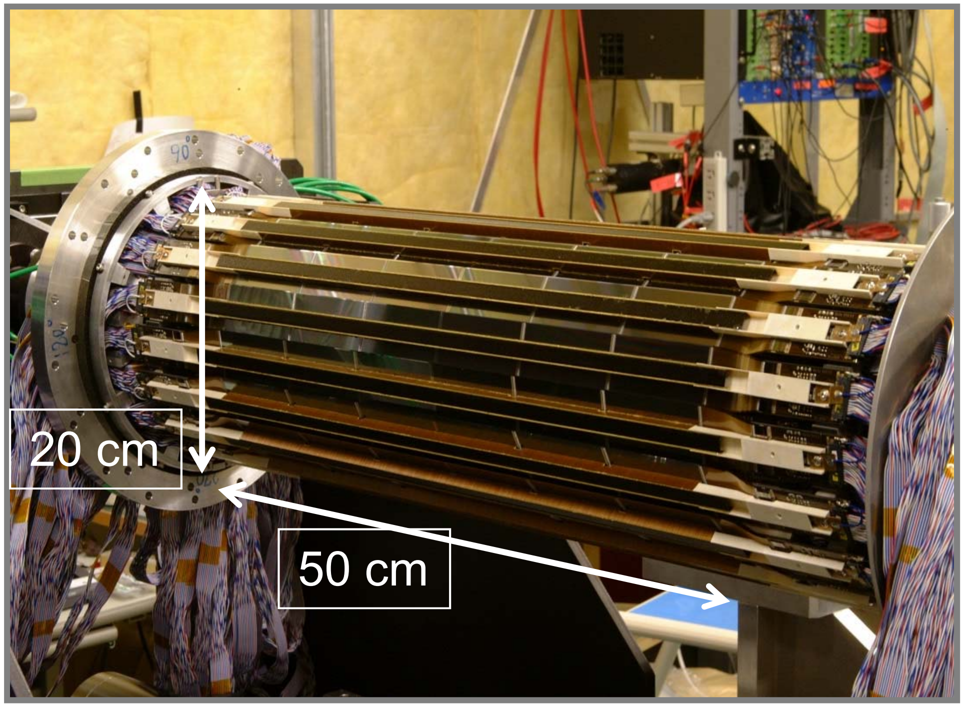
| Material | $Z$ | $A$ | $\langle Z/A \rangle$ | Nucl.coll. length $\lambda_T$ {g cm$^{-2}$} | Nucl.inter. length $\lambda_I$ {g cm$^{-2}$} | Rad.len. $X_0$ {g cm$^{-2}$} | $dE/dx\|_{\rm min}$ { MeV g$^{-1}$cm$^2$} | Density {g cm$^{-3}$} ({g$\ell^{-1}$}) | Melting point (K) | Boiling point (K) | Refract. index (@ Na D) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $H_2$ | 1 | 1.00794(7) | 0.99212 | 42.8 | 52.0 | 63.04 | (4.103) | 0.071(0.084) | 13.81 | 20.28 | 1.11[132.] |
| $D_2$ | 1 | 2.01410177803(8) | 0.49650 | 51.3 | 71.8 | 125.97 | (2.053) | 0.169(0.168) | 18.7 | 23.65 | 1.11[138.] |
| He | 2 | 4.002602(2) | 0.49967 | 51.8 | 71.0 | 94.32 | (1.937) | 0.125(0.166) | | 4.220 | 1.02[35.0] |
| Li | 3 | 6.941(2) | 0.43221 | 52.2 | 71.3 | 82.78 | 1.639 | 0.534 | 453.6 | 1615. | |
| Be | 4 | 9.012182(3) | 0.44384 | 55.3 | 77.8 | 65.19 | 1.595 | 1.848 | 1560. | 2744. | |
| C diamond | 6 | 12.0107(8) | 0.49955 | 59.2 | 85.8 | 42.70 | 1.725 | 3.520 | | | 2.42 |
| C graphite | 6 | 12.0107(8) | 0.49955 | 59.2 | 85.8 | 42.70 | 1.742 | 2.210 | | | |
| $N_2$ | 7 | 14.0067(2) | 0.49976 | 61.1 | 89.7 | 37.99 | (1.825) | 0.807(1.165) | 63.15 | 77.29 | 1.20[298.] |
| $O_2$ | 8 | 15.9994(3) | 0.50002 | 61.3 | 90.2 | 34.24 | (1.801) | 1.141(1.332) | 54.36 | 90.20 | 1.22[271.] |
| $F_2$ | 9 | 18.9984032(5) | 0.47372 | 65.0 | 97.4 | 32.93 | (1.676) | 1.507(1.580) | 53.53 | 85.03 | [195.] |
| Ne | 10 | 20.1797(6) | 0.49555 | 65.7 | 99.0 | 28.93 | (1.724) | 1.204(0.839) | 24.56 | 27.07 | 1.09[67.1] |
| Al | 13 | 26.9815386(8) | 0.48181 | 69.7 | 107.2 | 24.01 | 1.615 | 2.699 | 933.5 | 2792. | |
| Si | 14 | 28.0855(3) | 0.49848 | 70.2 | 108.4 | 21.82 | 1.664 | 2.329 | 1687. | 3538. | 3.95 |
| $Cl_2$ | 17 | 35.453(2) | 0.47951 | 73.8 | 115.7 | 19.28 | (1.630) | 1.574(2.980) | 171.6 | 239.1 | [773.] |
| Ar | 18 | 39.948(1) | 0.45059 | 75.7 | 119.7 | 19.55 | (1.519) | 1.396(1.662) | 83.81 | 87.26 | 1.23[281.] |
| Ti | 22 | 47.867(1) | 0.45961 | 78.8 | 126.2 | 16.16 | 1.477 | 4.540 | 1941. | 3560. | |
| Fe | 26 | 55.845(2) | 0.46557 | 81.7 | 132.1 | 13.84 | 1.451 | 7.874 | 1811. | 3134. | |
| Cu | 29 | 63.546(3) | 0.45636 | 84.2 | 137.3 | 12.86 | 1.403 | 8.960 | 1358. | 2835. | |
| Ge | 32 | 72.64(1) | 0.44053 | 86.9 | 143.0 | 12.25 | 1.370 | 5.323 | 1211. | 3106. | |
| Sn | 50 | 118.710(7) | 0.42119 | 98.2 | 166.7 | 8.82 | 1.263 | 7.310 | 505.1 | 2875. | |
| Xe | 54 | 131.293(6) | 0.41129 | 100.8 | 172.1 | 8.48 | (1.255) | 2.953(5.483) | 161.4 | 165.1 | 1.39[701.] |
| W | 74 | 183.84(1) | 0.40252 | 110.4 | 191.9 | 6.76 | 1.145 | 19.300 | 3695. | 5828. | |
| Pt | 78 | 195.084(9) | 0.39983 | 112.2 | 195.7 | 6.54 | 1.128 | 21.450 | 2042. | 4098. | |
| Au | 79 | 196.966569(4) | 0.40108 | 112.5 | 196.3 | 6.46 | 1.134 | 19.320 | 1337. | 3129. | |
| Pb | 82 | 207.2(1) | 0.39575 | 114.1 | 199.6 | 6.37 | 1.122 | 11.350 | 600.6 | 2022. | |
| U | 92 | [238.02891(3)] | 0.38651 | 118.6 | 209.0 | 6.00 | 1.081 | 18.950 | 1408. | 4404. | |
| Air (dry, 1 atm) | | | 0.49919 | 61.3 | 90.1 | 36.62 | (1.815) | (1.205) | | 78.80 | |
| Shielding concrete | | | 0.50274 | 65.1 | 97.5 | 26.57 | 1.711 | 2.300 | | | |
| Borosilicate glass (Pyrex) | | | 0.49707 | 64.6 | 96.5 | 28.17 | 1.696 | 2.230 | | | |

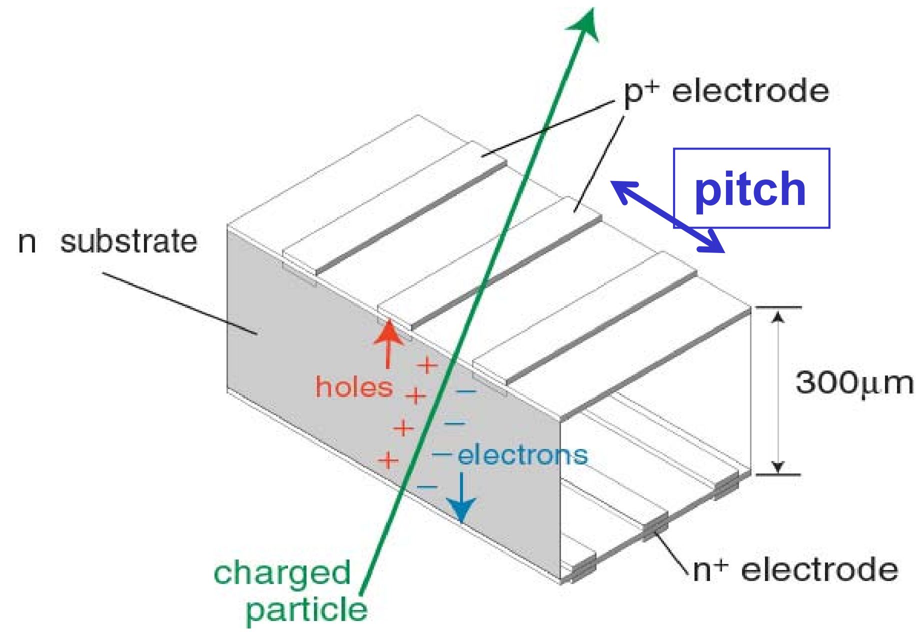
| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| W | 74 | 183.84(1) | 0.40252 | 110.4 | 191.9 | 6.76 | 1.145 | 19.300 | 3695. | 5828. | |
| Pt | 78 | 195.084(9) | 0.39983 | 112.2 | 195.7 | 6.54 | 1.128 | 21.450 | 2042. | 4098. | |
| Au | 79 | 196.966569(4) | 0.40108 | 112.5 | 196.3 | 6.46 | 1.134 | 19.320 | 1337. | 3129. | |
| Pb | 82 | 207.2(1) | 0.39575 | 114.1 | 199.6 | 6.37 | 1.122 | 11.350 | 600.6 | 2022. | |
| U | 92 | [238.02891(3)] | 0.38651 | 118.6 | 209.0 | 6.00 | 1.081 | 18.950 | 1408. | 4404. | |
| Air (dry, 1 atm) | | | 0.49919 | 61.3 | 90.1 | 36.62 | (1.815) | (1.205) | | 78.80 | |
| Shielding concrete | | | 0.50274 | 65.1 | 97.5 | 26.57 | 1.711 | 2.300 | | | |
| Borosilicate glass (Pyrex) | | | 0.49707 | 64.6 | 96.5 | 28.17 | 1.696 | 2.230 | | | |
| Lead glass | | | 0.42101 | 95.9 | 158.0 | 7.87 | 1.255 | 6.220 | | | |
| Standard rock | | | 0.50000 | 66.8 | 101.3 | 26.54 | 1.688 | 2.650 | | | |
| Methane ($CH_4$) | | | 0.62334 | 54.0 | 73.8 | 46.47 | (2.417) | (0.667) | 90.68 | 111.7 | [444.] |
| Ethane ($C_2H_6$) | | | 0.59861 | 55.0 | 75.9 | 45.66 | (2.304) | (1.263) | 90.36 | 184.5 | |
| Propane ($C_3H_8$) | | | 0.58962 | 55.3 | 76.7 | 45.37 | (2.262) | 0.493(1.868) | 85.52 | 231.0 | |
| Butane ($C_4H_{10}$) | | | 0.59497 | 55.5 | 77.1 | 45.23 | (2.278) | (2.489) | 134.9 | 272.6 | |
| Octane ($C_8H_{18}$) | | | 0.57778 | 55.8 | 77.8 | 45.00 | 2.123 | 0.703 | 214.4 | 398.8 | |
| Paraffin ($CH_3(CH_2)_{n\approx23}CH_3$) | | | 0.57275 | 56.0 | 78.3 | 44.85 | 2.088 | 0.930 | | | |
| Nylon (type 6, 6/6) | | | 0.54790 | 57.5 | 81.6 | 41.92 | 1.973 | 1.18 | | | |
| Polycarbonate (Lexan) | | | 0.52697 | 58.3 | 83.6 | 41.50 | 1.886 | 1.20 | | | |
| Polyethylene ($[CH_2CH_2]_n$) | | | 0.57034 | 56.1 | 78.5 | 44.77 | 2.079 | 0.89 | | | |
| Polyethylene terephthalate (Mylar) | | | 0.52037 | 58.9 | 84.9 | 39.95 | 1.848 | 1.40 | | | |
| Polyimide film (Kapton) | | | 0.51264 | 59.2 | 85.5 | 40.58 | 1.820 | 1.42 | | | |
| Polymethylmethacrylate (acrylic) | | | 0.53937 | 58.1 | 82.8 | 40.55 | 1.929 | 1.19 | | | 1.49 |
| Polypropylene | | | 0.55998 | 56.1 | 78.5 | 44.77 | 2.041 | 0.90 | | | |
| Polystyrene ($[C_6H_5CHCH_2]_n$) | | | 0.53768 | 57.5 | 81.7 | 43.79 | 1.936 | 1.06 | | | 1.59 |
| Polytetrafluoroethylene (Teflon) | | | 0.47992 | 63.5 | 94.4 | 34.84 | 1.671 | 2.20 | | | |
| Polyvinyltoluene | | | 0.54141 | 57.3 | 81.3 | 43.90 | 1.956 | 1.03 | | | 1.58 |
| Aluminum oxide (sapphire) | | | 0.49038 | 65.5 | 98.4 | 27.94 | 1.647 | 3.970 | 2327. | 3273. | 1.77 |
| Barium flouride ($BaF_2$) | | | 0.42207 | 90.8 | 149.0 | 9.91 | 1.303 | 4.893 | 1641. | 2533. | 1.47 |
| Bismuth germanate (BGO) | | | 0.42065 | 96.2 | 159.1 | 7.97 | 1.251 | 7.130 | 1317. | | 2.15 |
| Carbon dioxide gas ($CO_2$) | | | 0.49989 | 60.7 | 88.9 | 36.20 | 1.819 | (1.842) | | | [449.] |
| Solid carbon dioxide (dry ice) | | | 0.49989 | 60.7 | 88.9 | 36.20 | 1.787 | 1.563 | Sublimes at 194.7 K | | |
| Cesium iodide (CsI) | | | 0.41569 | 100.6 | 171.5 | 8.39 | 1.243 | 4.510 | 894.2 | 1553. | 1.79 |
| Lithium fluoride (LiF) | | | 0.46262 | 61.0 | 88.7 | 39.26 | 1.614 | 2.635 | 1121. | 1946. | 1.39 |
| Lithium hydride (LiH) | | | 0.50321 | 50.8 | 68.1 | 79.62 | 1.897 | 0.820 | 965. | | |
| Lead tungstate ($PbWO_4$) | | | 0.41315 | 100.6 | 168.3 | 7.39 | 1.229 | 8.300 | 1403. | | 2.20 |
| Silicon dioxide ($SiO_2$, fused quartz) | | | 0.49930 | 65.2 | 97.8 | 27.05 | 1.699 | 2.200 | 1986. | 3223. | 1.46 |
| Sodium chloride (NaCl) | | | 0.55509 | 71.2 | 110.1 | 21.91 | 1.847 | 2.170 | 1075. | 1738. | 1.54 |
| Sodium iodide (NaI) | | | 0.42697 | 93.1 | 154.6 | 9.49 | 1.305 | 3.667 | 933.2 | 1577. | 1.77 |
| Water ($H_2O$) | | | 0.55509 | 58.5 | 83.3 | 36.08 | 1.992 | 1.000(0.756) | 273.1 | 373.1 | 1.33 |
| Silica aerogel | | | 0.50093 | 65.0 | 97.3 | 27.25 | 1.740 | 0.200 | (0.03 $H_2O$, 0.97 $SiO_2$) | | |

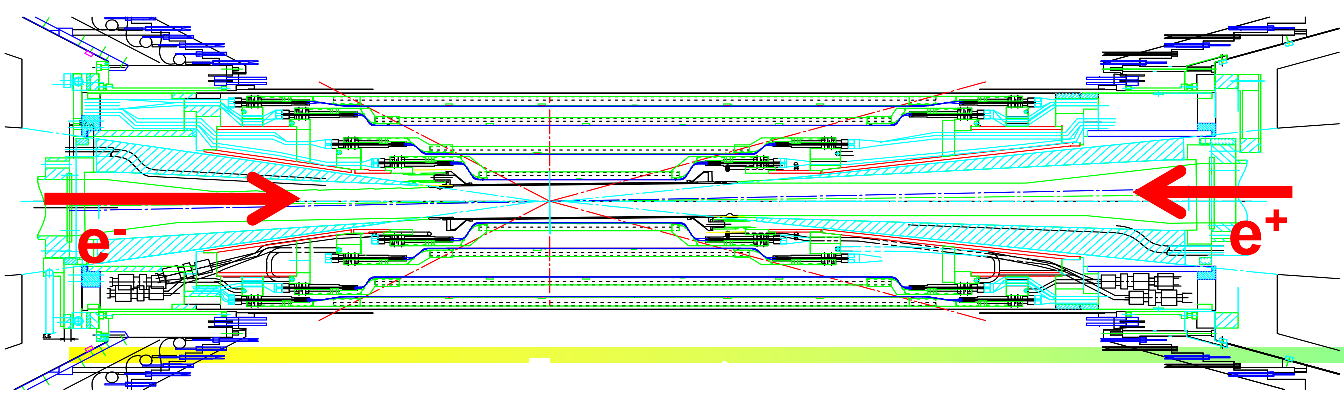
# Belle II Detector – vertex region



# Silicon vertex detector (SVD)




Two coordinates measured at the same time;

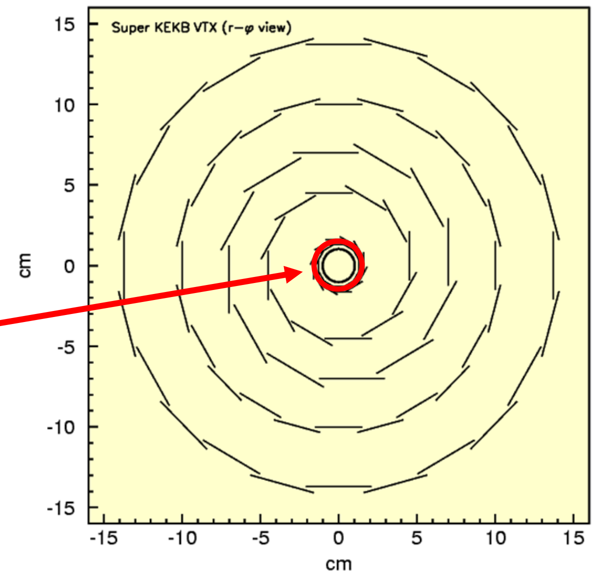
strip pitch: 50μm (75μm);

resolution 15μm (20μm).

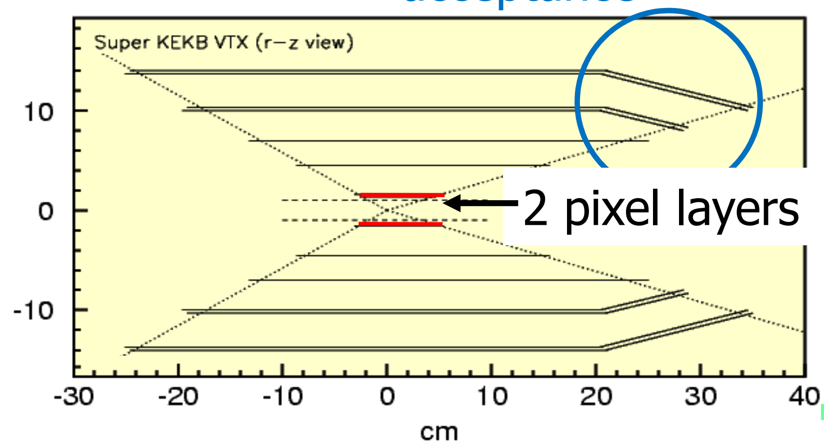
# Belle II Vertex detector SVD+PXD

- Sensors of the innermost layers:

  Normal double sided Si detector (DSSD) → DEPFET Pixel sensors
- Configuration: 4 layers → 6 layers (outer radius = 8cm→14cm)
  - More robust tracking
  - Higher Ks vertex reconstruction efficiency
- Inner radius: 1.5cm → 1.3cm
  - Better vertex resolution




Slant layer to keep the acceptance



# Pixel vertex detector PXD principle: DEPFET

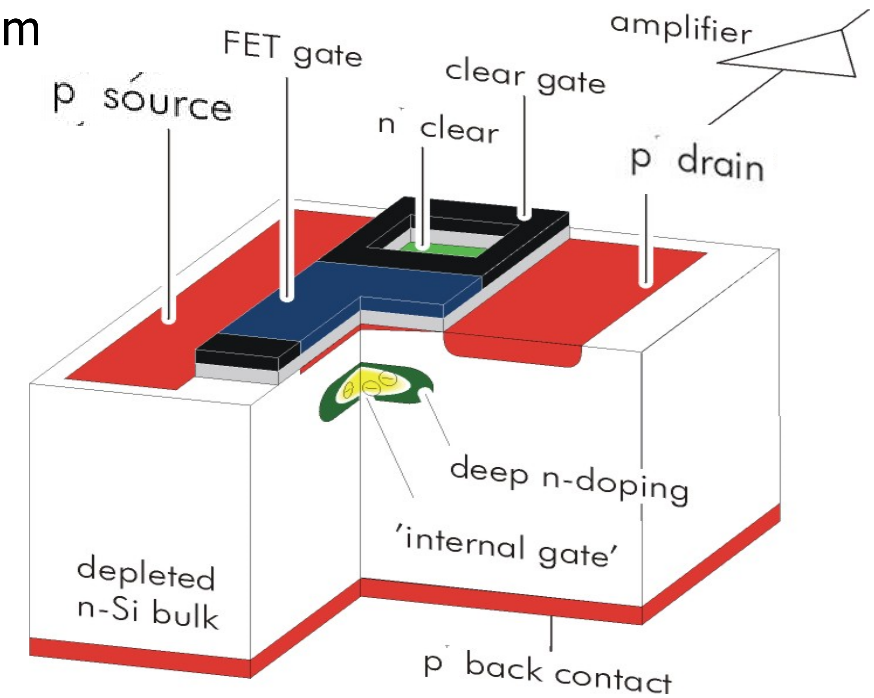
p-channel FET on a completely depleted bulk

A deep n-implant creates a potential minimum for electrons under the gate ("internal gate")

Signal electrons accumulate in the internal gate and modulate the transistor current ($g_q$ ~ 400 pA/$e^-$)

Accumulated charge can be removed by a clear contact ("reset")

Depleted p-channel FET




Fully depleted:
→ large signal, fast signal collection

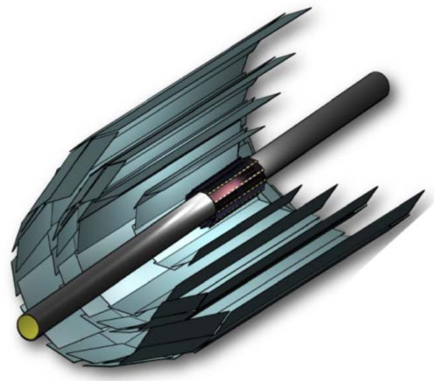
Low capacitance, internal amplification → low noise

Transistor on only during readout: low power

Complete clear → no reset noise

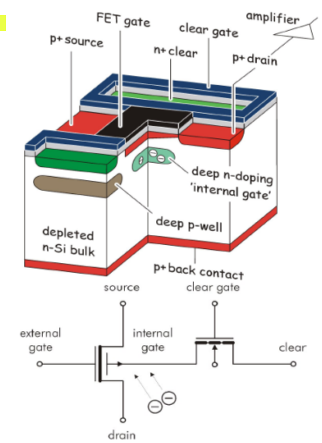
# Vertex Detector

DEPFET:
http://aldebaran.hll.mpg.de/twiki/bin/view/DEPFET/WebHome

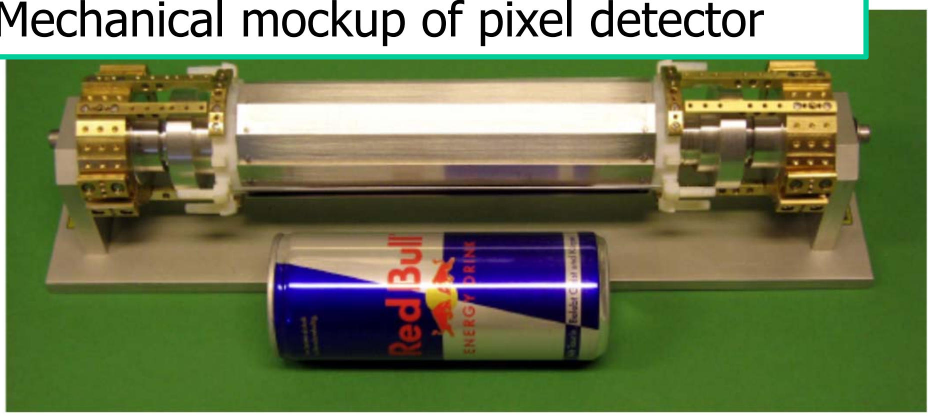


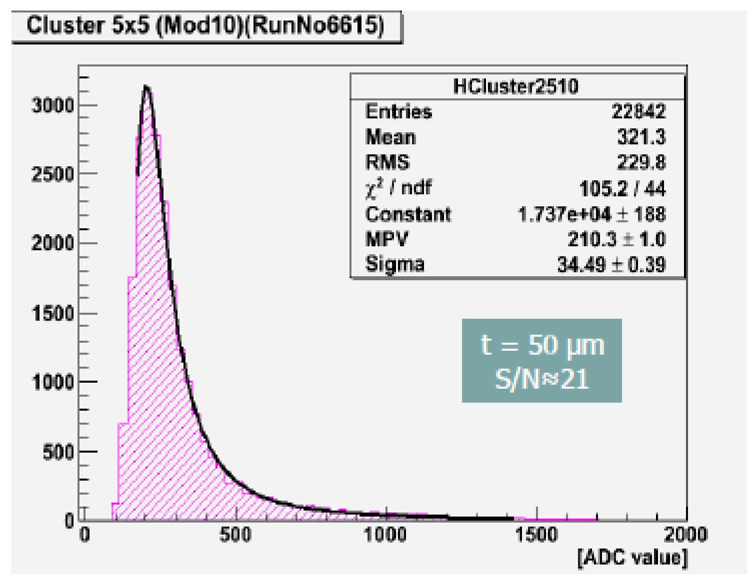
| | | |
|---|---|---|
| **Beam Pipe** | | **r = 10mm** |
| **DEPFET** | | |
| | **Layer 1** | **r = 14mm** |
| | **Layer 2** | **r = 22mm** |
| **DSSD** | | |
| | **Layer 3** | **r = 38mm** |
| | **Layer 4** | **r = 80mm** |
| | **Layer 5** | **r = 115mm** |
| | **Layer 6** | **r = 140mm** |

DEpleted P-channel FET




Mechanical mockup of pixel detector



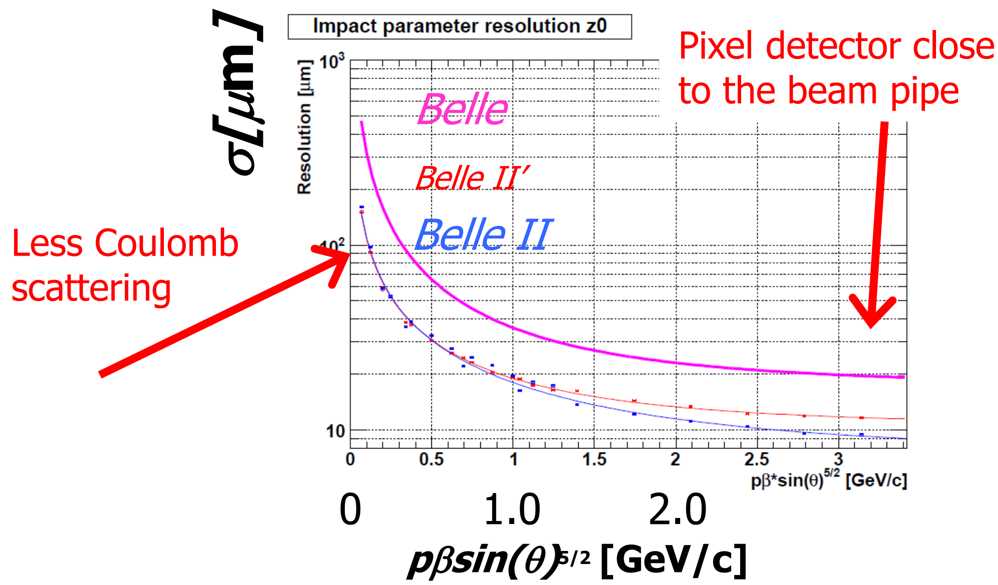

DEPFET pixel sensor

DEPFET sensor: very good S/N

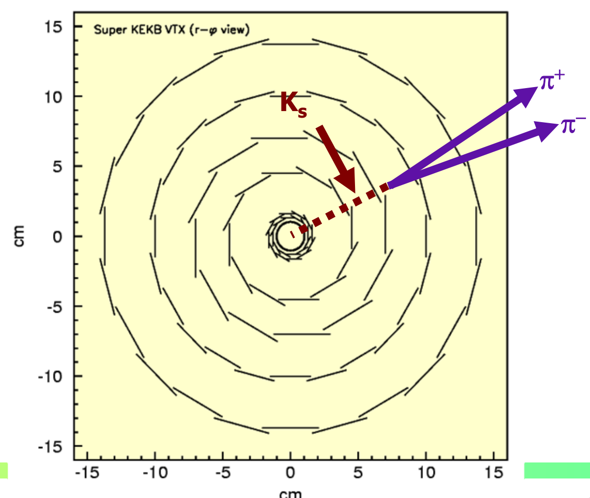
# Expected performance

$$\sigma = a + \frac{b}{p\beta \sin^{\nu}\theta}$$

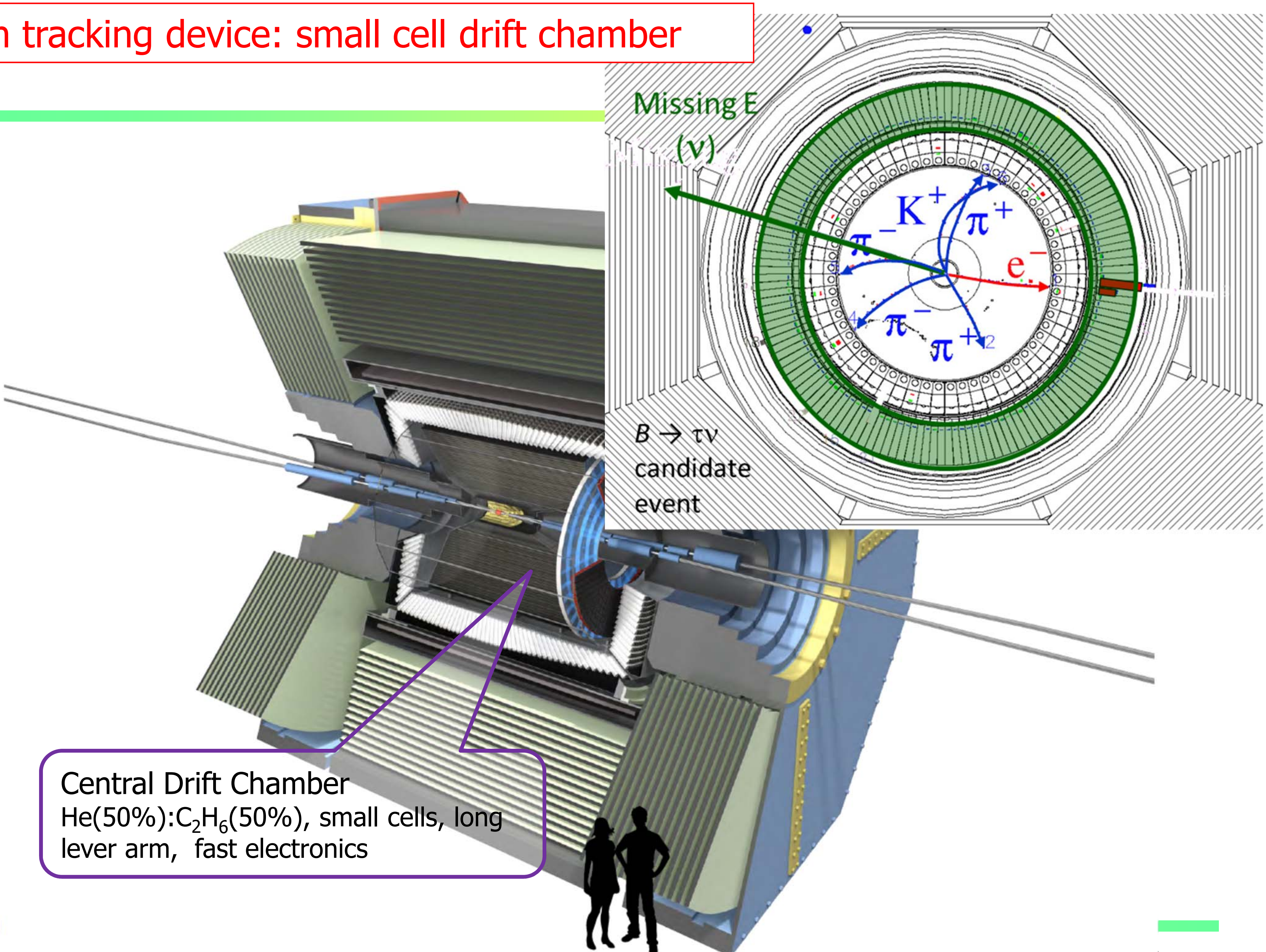
4 layers of silicons triop detectors → 2 layers of pixel detectors + 4 layers of silicons strip detectors: significant improvement in vertex resolution!




Larger detector volume → significant improvement in $K_S$ reconstruction efficiency



# Main tracking device: small cell drift chamber




Central Drift Chamber
$He(50\%):C_2H_6(50\%)$, small cells, long lever arm, fast electronics

# Search for unstable particles which decayed close to the production point

How do we reconstruct final states that decayed to two stable particles?

From the measured tracks calculate the invariant mass of the system (i= 1,2):

$$Mc^2 = \sqrt{(\sum E_i)^2 - (\sum \vec{p}_i)^2 c^2}$$

The candidates for the X→12 decay show up as a peak in the distribution on (mostly combinatorial) background.

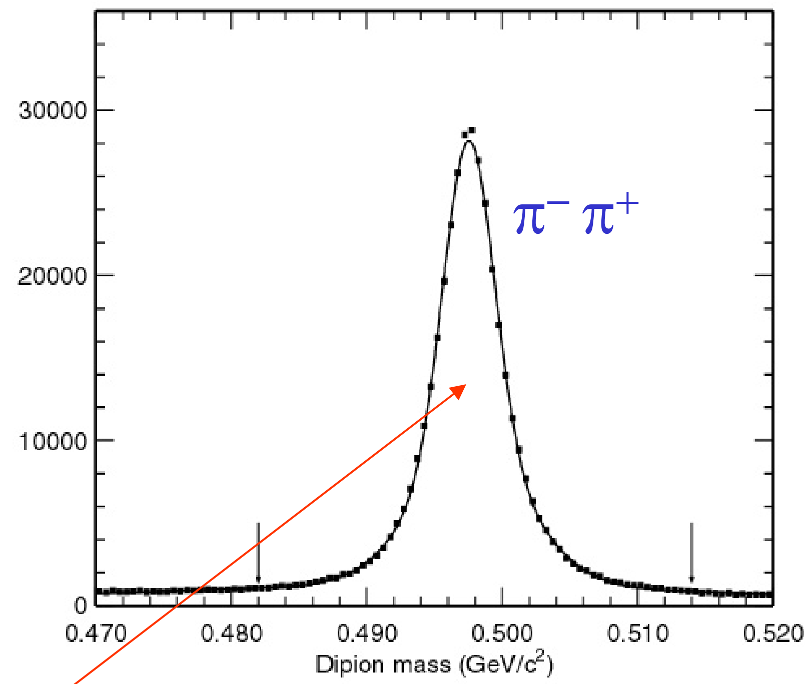
# How do we know it was precisely this reaction?

$B^0 \rightarrow K^0_S \, J/\psi$

$K^0_S \rightarrow \pi^- \pi^+$

$J/\psi \rightarrow \mu^- \mu^+$

detect

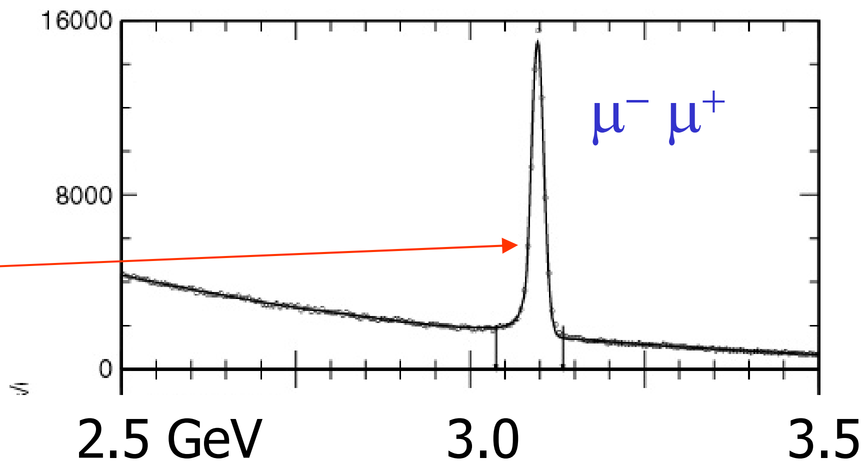



For $\pi^- \pi^+$ in $\mu^- \mu^+$ pairs we calculate the invariant mass:

$M^2c^4=(E_1+ E_2)^2- (p_1+ p_2)^2$

$Mc^2$ must be for $K^0_S$ close to 0.5 GeV,

for $J/\psi$ close to 3.1 GeV.




Rest in the histrogram: random coincidences (‘combinatorial background’)

# Invariant mass resolution – momentum resolution

The name of the game: have as little background under the peak as possible without loosing the events in the peak (=reduce background and have a narrow peak).

$$Mc^2 = \sqrt{(\sum E_i)^2 - (\sum \vec{p}_i)^2 c^2}$$

To understand the impact of momentum resolution, simplify the expression for the case where final state particles have a small mass compared to their momenta.

Example $J/\psi \rightarrow \mu^- \mu^+$

$M^2c^4 = (E_1 + E_2)^2 - (p_1 + p_2)^2 \rightarrow M^2c^4 = 2\, p_1\, p_2\, (1 - \cos\Theta_{12})$

# Resolution in invariant mass

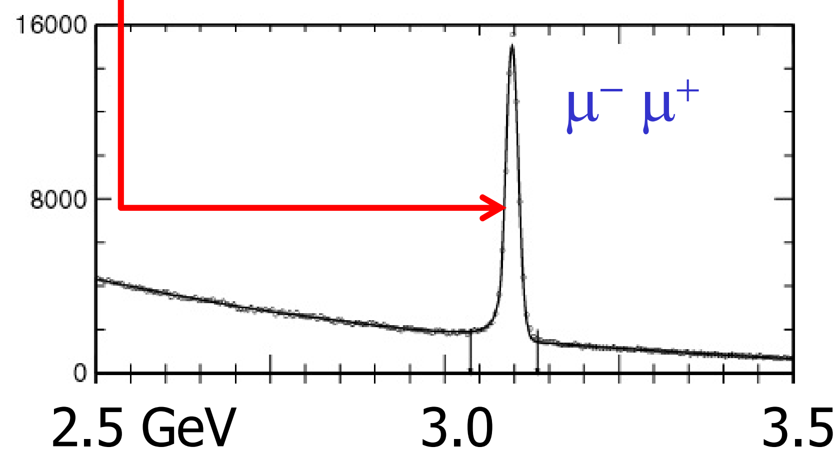
$B^0 \rightarrow K^0_S J/\psi$, $K^0_S \rightarrow \pi^- \pi^+$, $J/\psi \rightarrow \mu^- \mu^+$

$M^2c^4 = (E_1 + E_2)^2 - (p_1 + p_2)^2c^2 \rightarrow M^2c^4 = 2\, p_1\, p_2\, c^2\,(1 - \cos\Theta_{12})$

The $J/\psi$ peak should be narrow to minimize the contribution of random coincidences ('combinatorial background')

The required resolution in $Mc^2$: about 10 MeV.

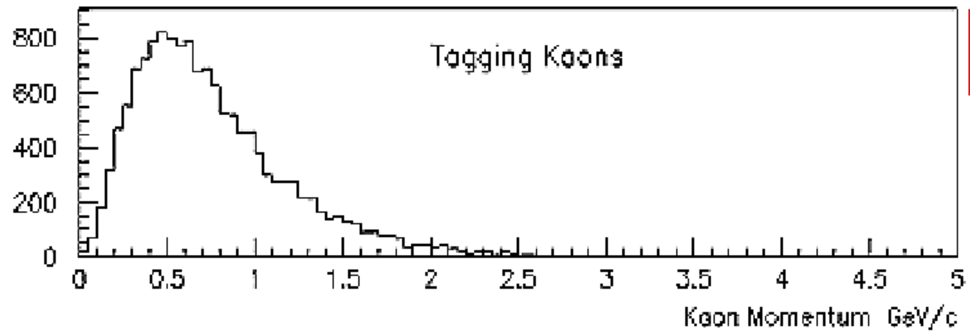
What is the corresponding momentum resolution?



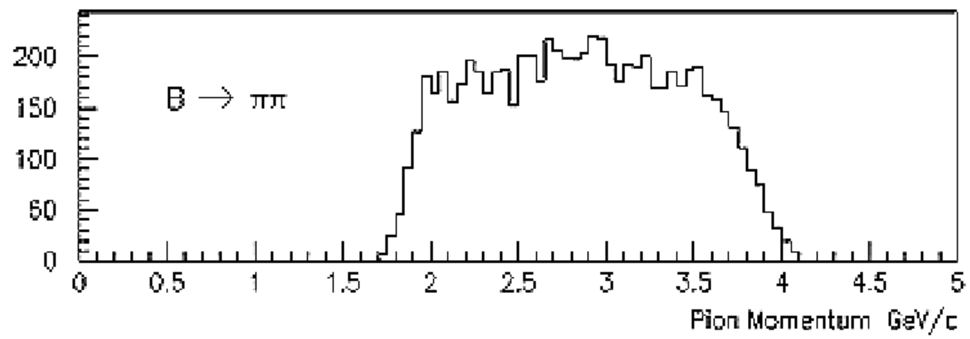

For simplicity assume $J/\psi$ is at rest $\rightarrow$
$\Theta_{12}=180^0$, $p_1=p_2=p=1.5$ GeV/c, $Mc^2=2pc$
$\rightarrow \sigma(Mc^2) = 2\,\sigma(pc)$ at $p=1.5$ GeV/c

$\rightarrow \sigma(p)/p = 10\text{ MeV}/2/1.5\text{GeV} = 0.3\%$

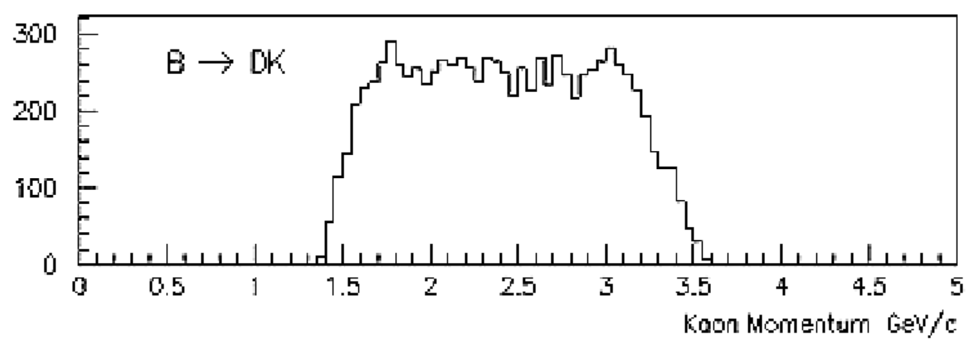
# Requirements: momentum spectrum




**Tagging Kaons**



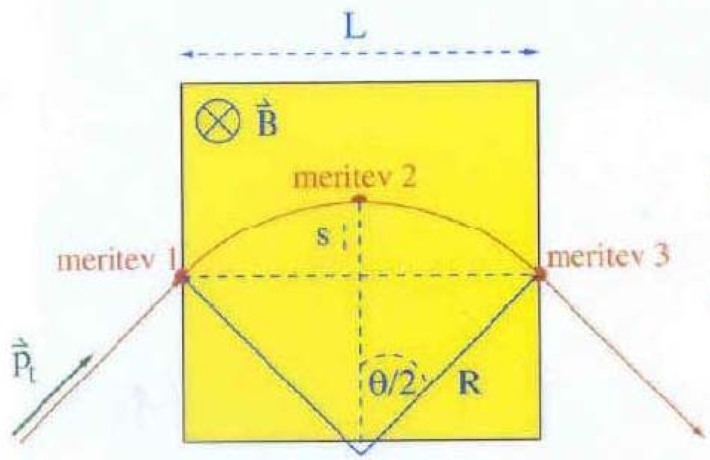

**B $\to \pi\pi$**




**B $\to$ DK**

## From raw data to summary data
### momentum measurement

Example of momentum determination:




$$p_t = q\,B\,R \Rightarrow R = \frac{p_t}{qB}$$

$$\sin\frac{\theta}{2} \approx \frac{\theta}{2} = \frac{L}{2R}$$

$$\cos\frac{\theta}{2} = \frac{R-s}{R} \Rightarrow s \approx R\frac{\theta^2}{8}$$

$$s = \frac{B\,L^2\,q}{8p_t}$$

if s determined by
3 measurement points:

$$s = x_2 - \frac{x_1 + x_3}{2}$$

$$\frac{\sigma(p_t)}{p_t} = \frac{\sigma(s)}{s} = \frac{\sqrt{\frac{3}{2}}\sigma(x) 8 p_t}{BL^2 q}$$

for N measurement points:

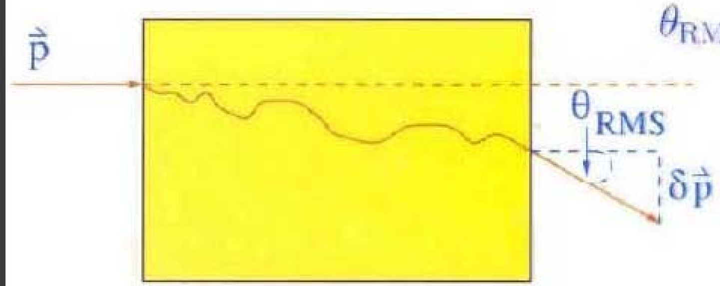
$$\frac{\sigma_{p_T}}{p_T} = \frac{\sigma_x p_T}{eBL^2}\sqrt{\frac{720}{N+4}}$$



http://www-f9.ijs.si/~krizan/sola/nddop/slides/anpod_1213.pdf

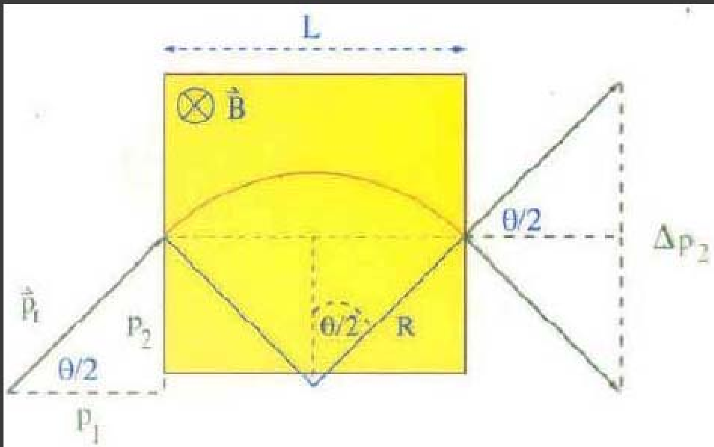
# From raw data to summary data
## momentum measurement

Multiple scattering:




$$\theta_{\mathrm{RMS}} \approx \frac{13.6\mathrm{MeV}}{cp\beta} \sqrt{\frac{L}{X_0}}[1 + 0.038 \ln \frac{L}{X_0}]$$

$$\delta p = p \sin \theta_{\mathrm{RMS}}$$




$$\Delta p_2 = 2p_t \sin\frac{\theta}{2} \approx p_t\theta$$

$$\frac{\sigma(p_t)}{p_t} = \frac{\sigma(\Delta p_2)}{\Delta p_2}$$

$$\frac{\sigma(p_t)}{p_t} \approx \frac{p_t \sin\theta_{\mathrm{RMS}}}{p_t\theta} \approx \frac{\theta_{\mathrm{RMS}}}{\theta}$$

$$\frac{\sigma(p_t)}{p_t} \approx \frac{13.6\ \mathrm{MeV}}{qB\sqrt{LX_0}}$$

http://www-f9.ijs.si/~krizan/sola/nddop/slides/anpod_1213.pdf

eB = 0.3 (B/T) (1/m) GeV/c

# Momentum resolution

Tracking system uncertainty

$$\frac{\sigma_{p_T}}{p_T} = \frac{\sigma_x p_T}{eBL^2}\sqrt{\frac{720}{N+4}}$$

eB = 0.3 (B/T) (1/m) GeV/c

$$\frac{\sigma_{p_T}}{p_T} = p_T \frac{0.1\times 10^{-3} m}{0.3(GeV/m)\times 1.5\times 1m^2}\sqrt{\frac{720}{54}} = \frac{p_T \times 0.0008}{GeV}$$

For B=1.5T, L = 1m, $\sigma_x$ = 0.1 mm

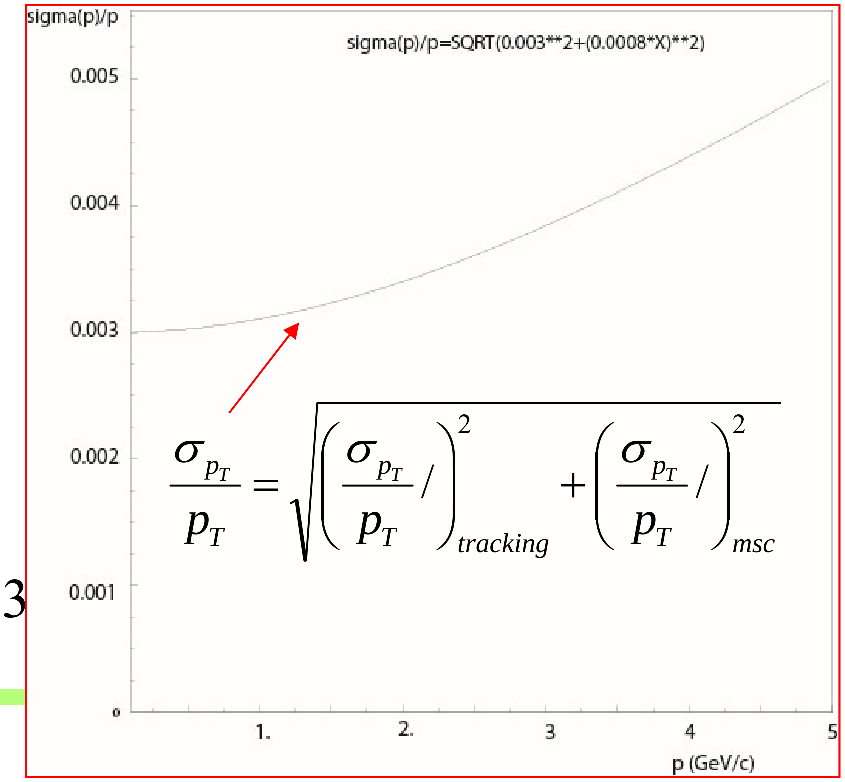
For $p_T$ = 1 GeV: $\sigma_{pT}/p_T$ = 0.08%

For $p_T$ = 2 GeV: $\sigma_{pT}/p_T$ = 0.16%

Uncertainty from multiple scattering

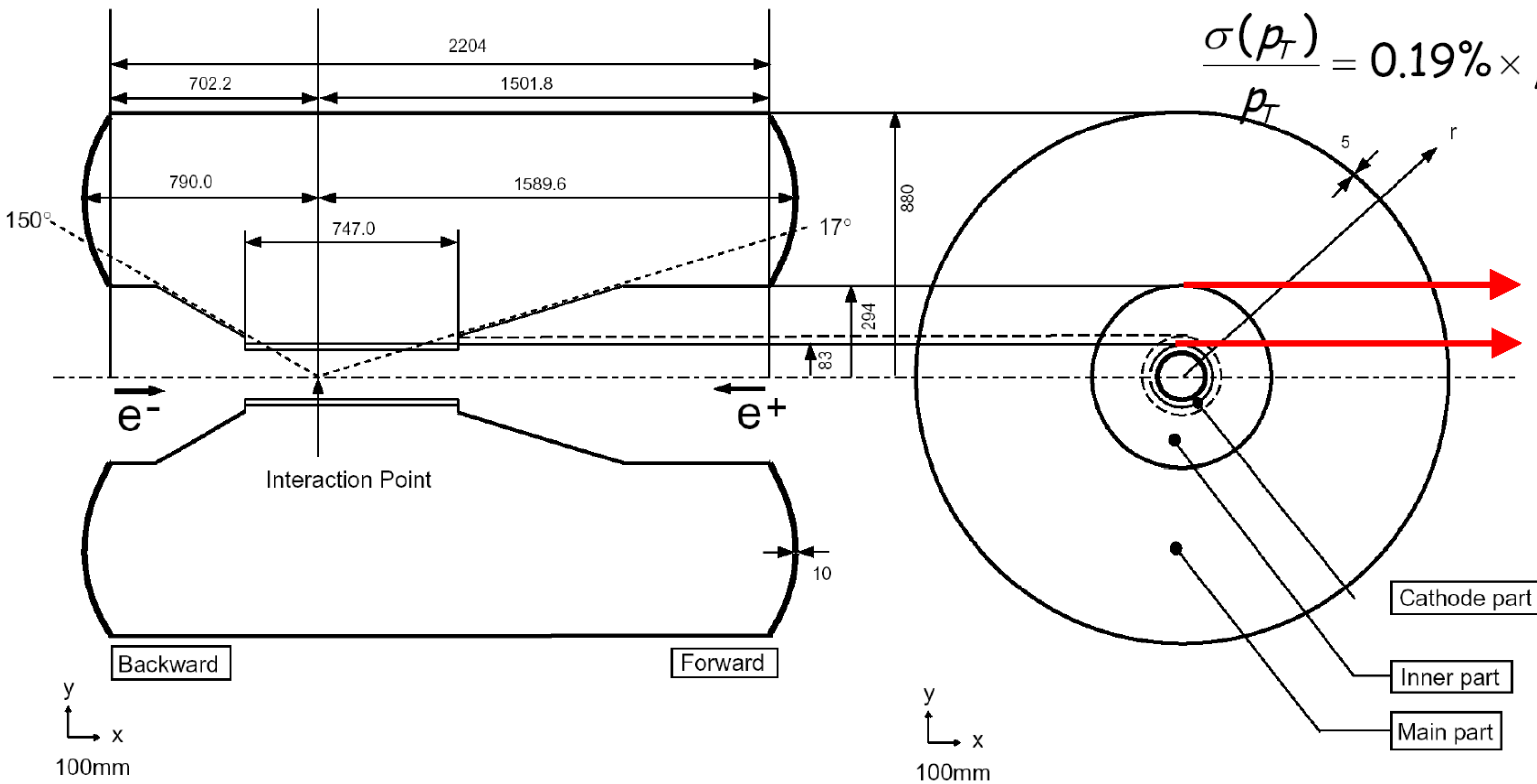
$$\frac{\sigma_{p_T}}{p_T} = \frac{13.6 MeV}{eB\sqrt{LX_0}}$$

$$\frac{\sigma_{p_T}}{p_T} = \frac{13.6 MeV}{0.3(GeV/m)\times 1.5\sqrt{1m\times 100m}} = 0.003$$



# Tracking: Belle central drift chamber

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

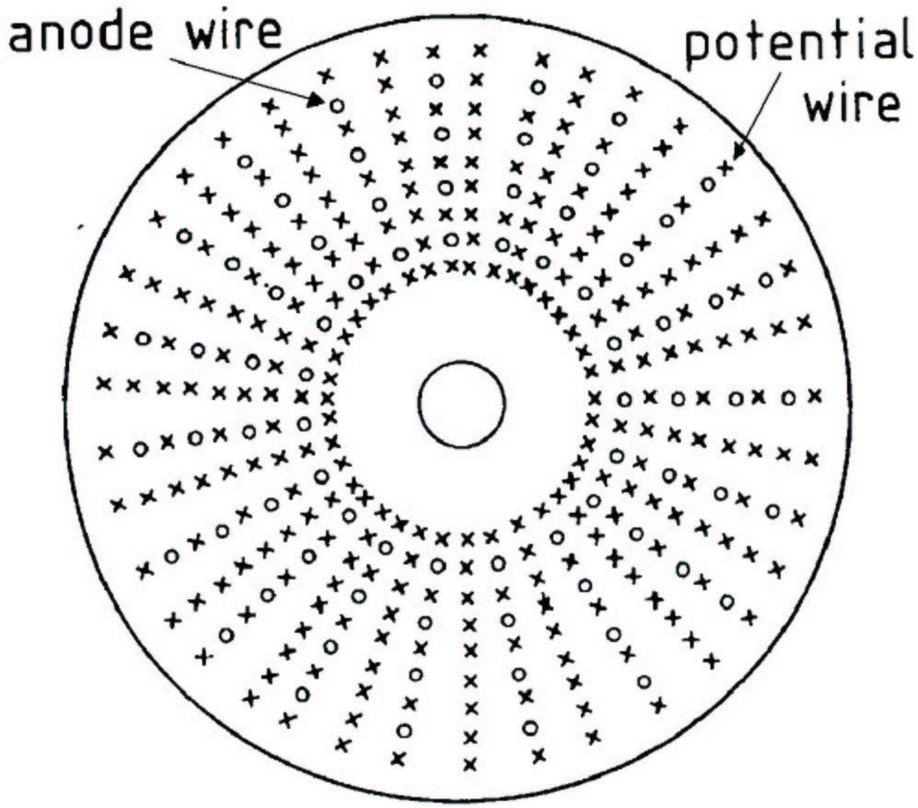


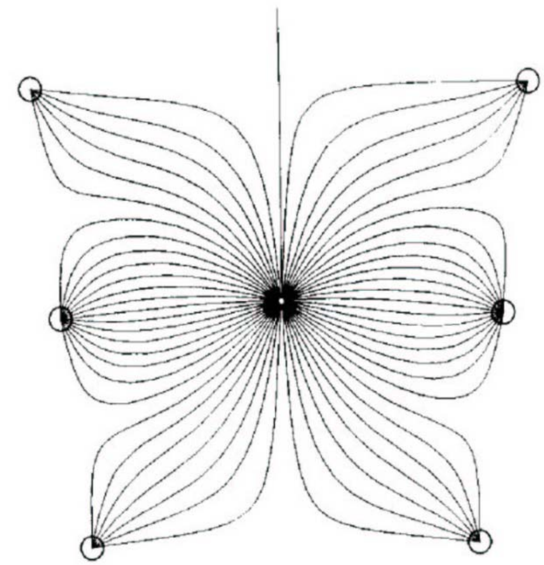

$$\frac{\sigma(p_T)}{p_T} = 0.19\% \times p_T \oplus \frac{0.30\%}{\beta}$$

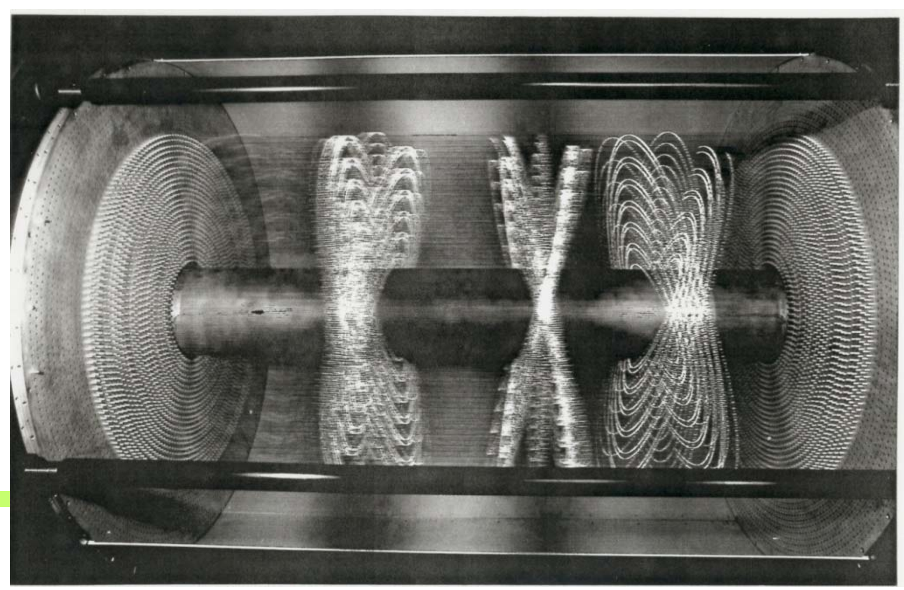
**15 layers: 8.8-22.4 cm radius**

# Drift chamber with small cells

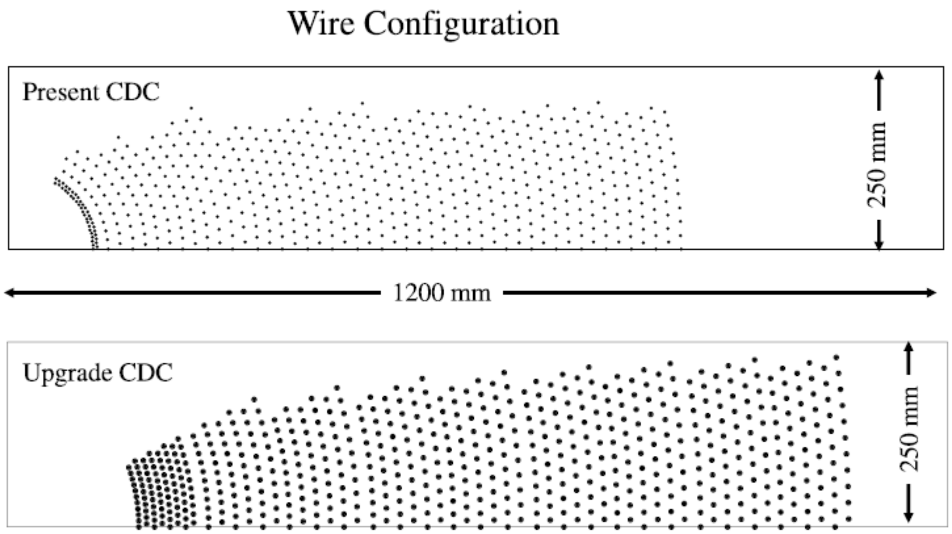
One big gas volume, small cells defined by the anode and field shaping (potential) wires

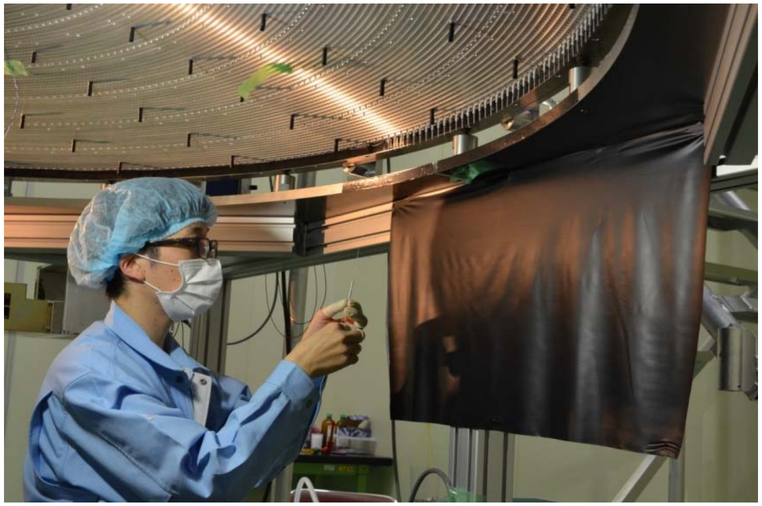




# Belle II CDC

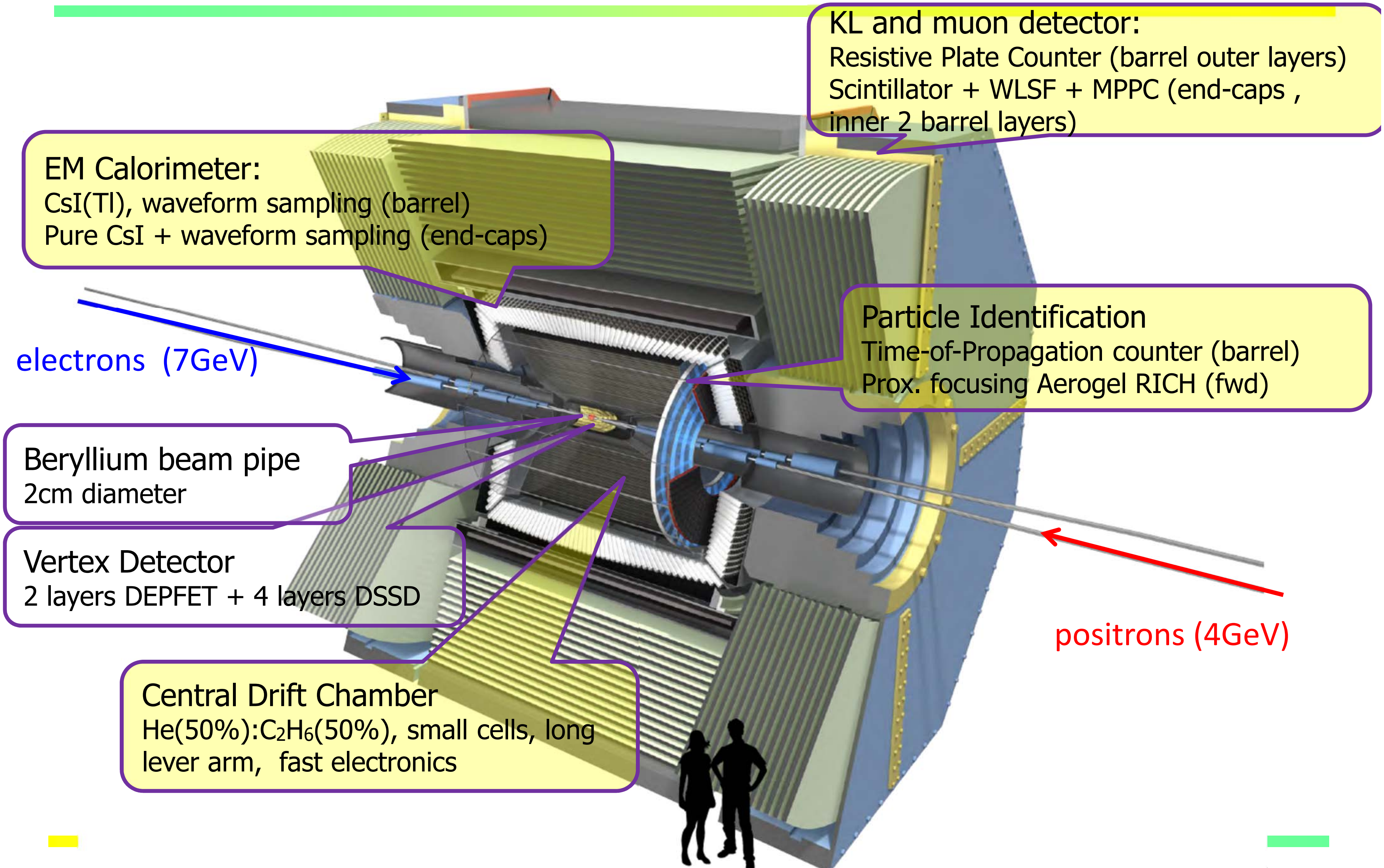


Wire stringing in a clean room

- thousands of wires,
- 1 year of work...

# Particle identification systems in Belle II



# Identification of charged particles

Particles are identified by their mass or by the way they interact.

**Determination of mass:** from the relation between momentum and velocity, $p=\gamma mv$.

Momentum known (radius of curvature in magnetic field)

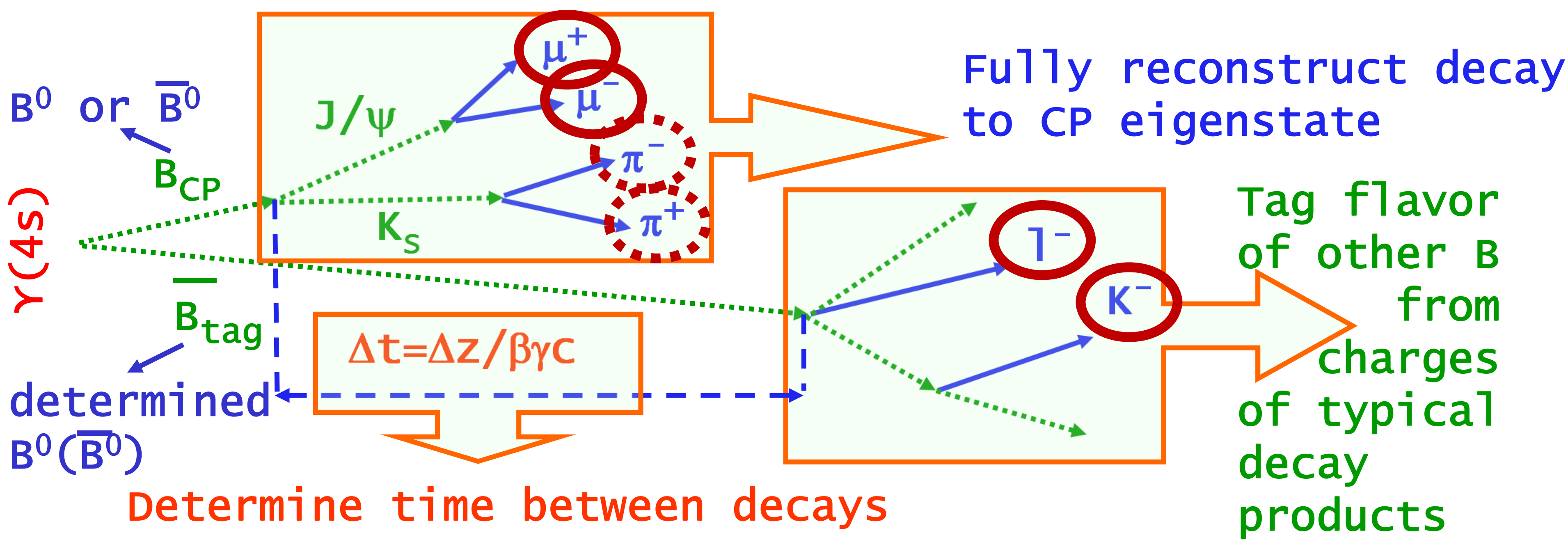
→Measure velocity:

- time of flight
- ionisation losses dE/dx
- Cherenkov angle
- transition radiation

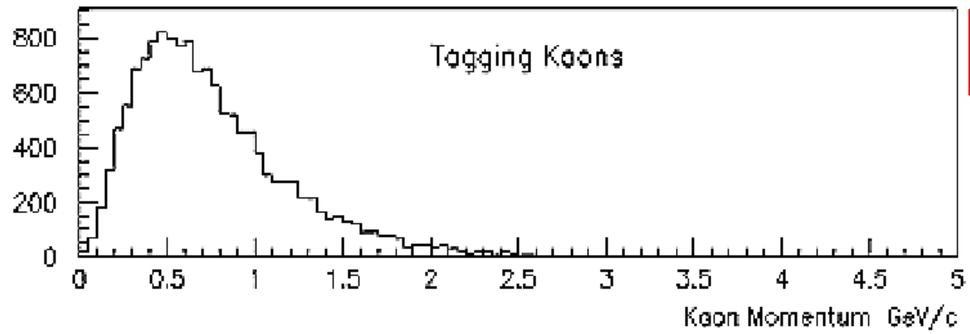
Mainly used for the identification of hadrons.

**Identification through interaction:** electrons and muons

# Reminder: where do we need identification?

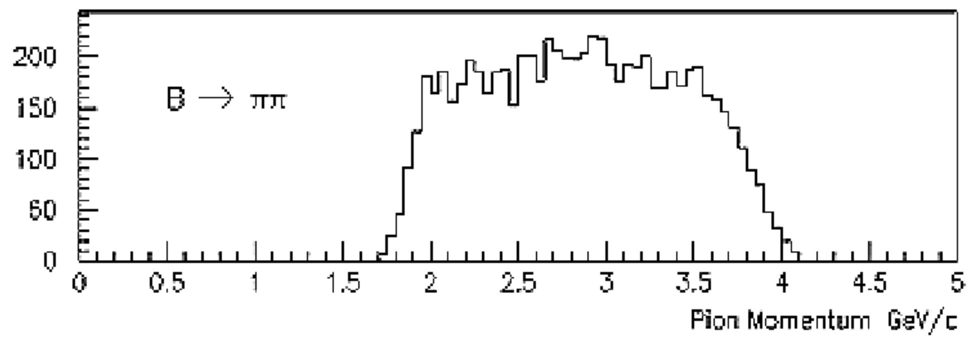


# Requirements: Particle Identification



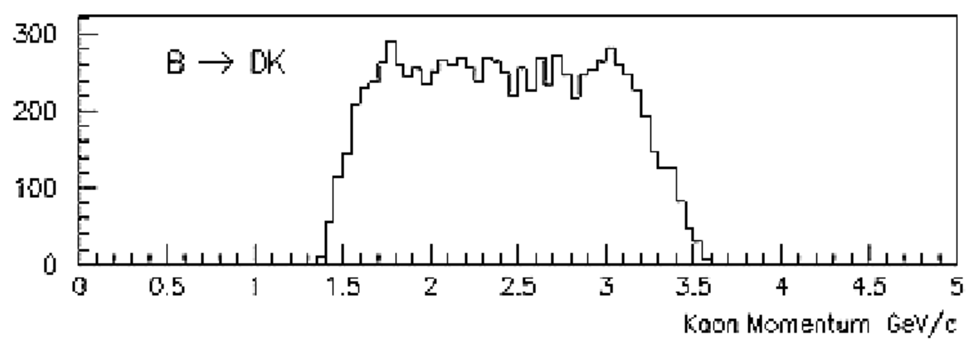

**Tagging Kaons**

Relatively soft, ms dominated for tracking




**B → ππ**

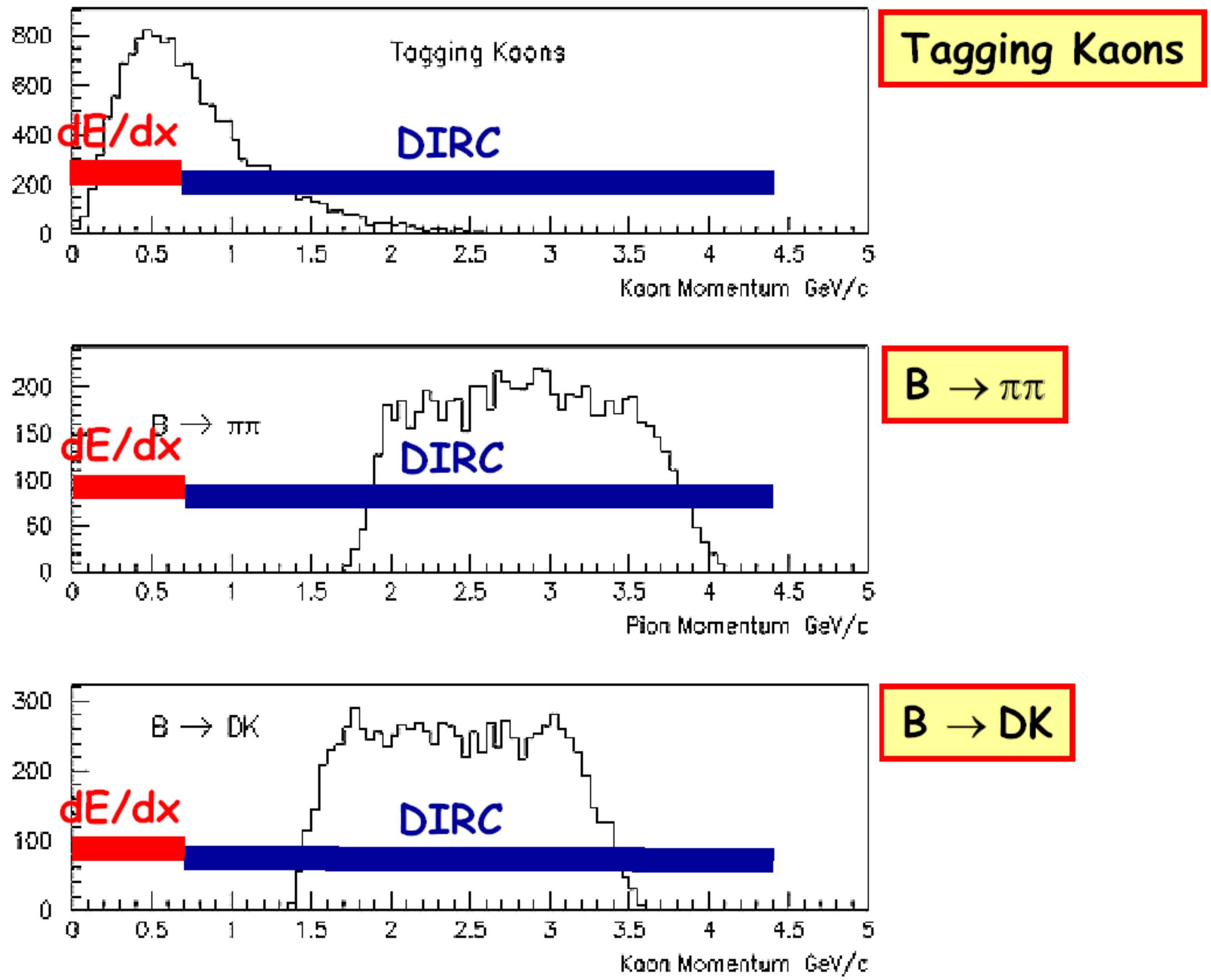
Requires dedicated PID



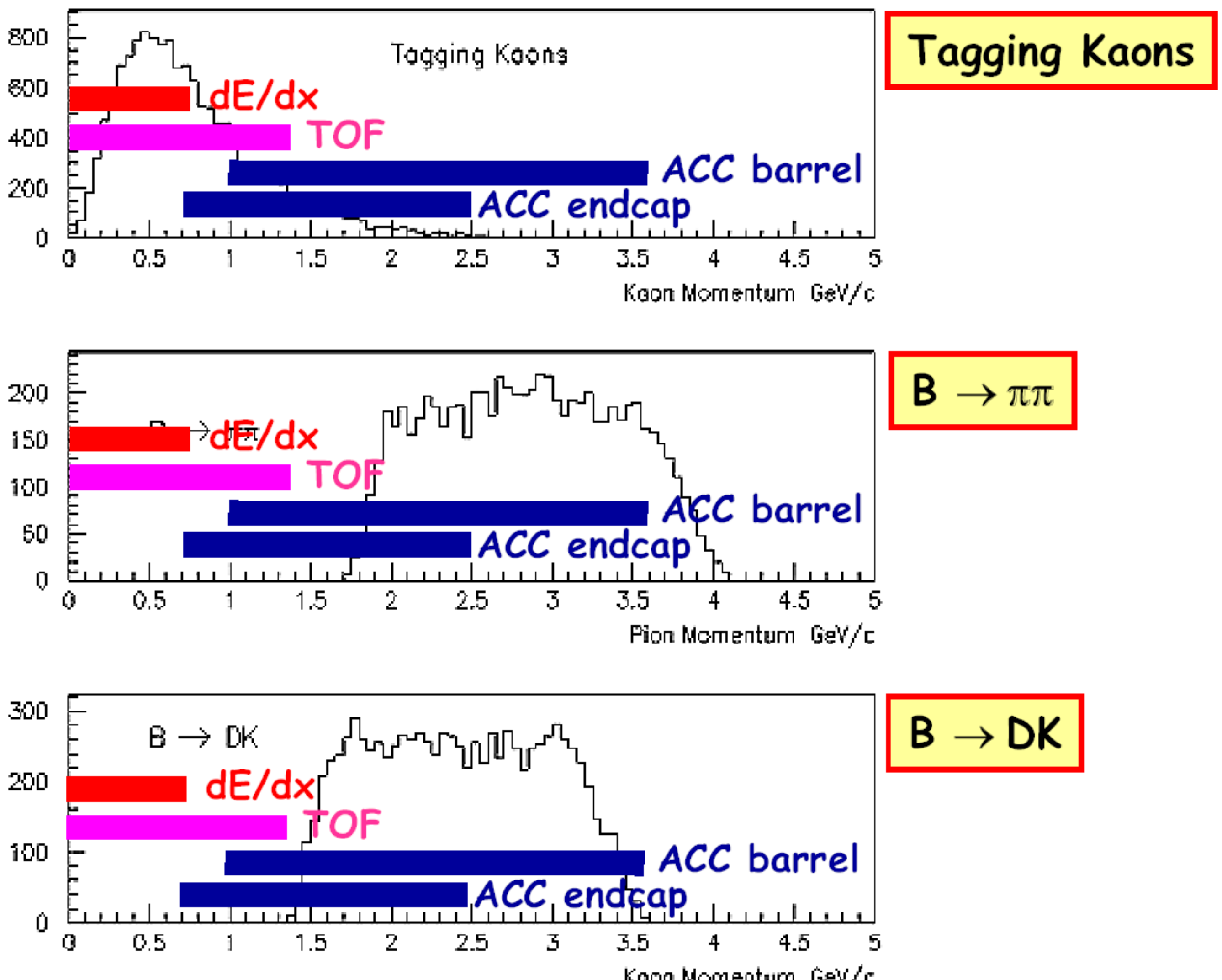

**B → DK**

Requires dedicated PID

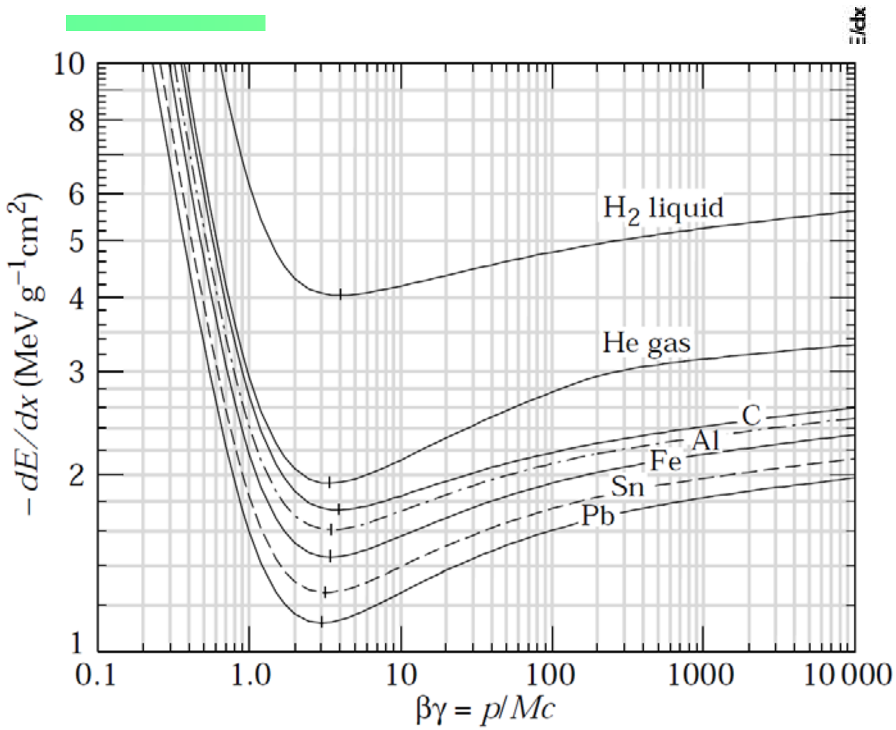
# PID coverage of kaon/pion spectra

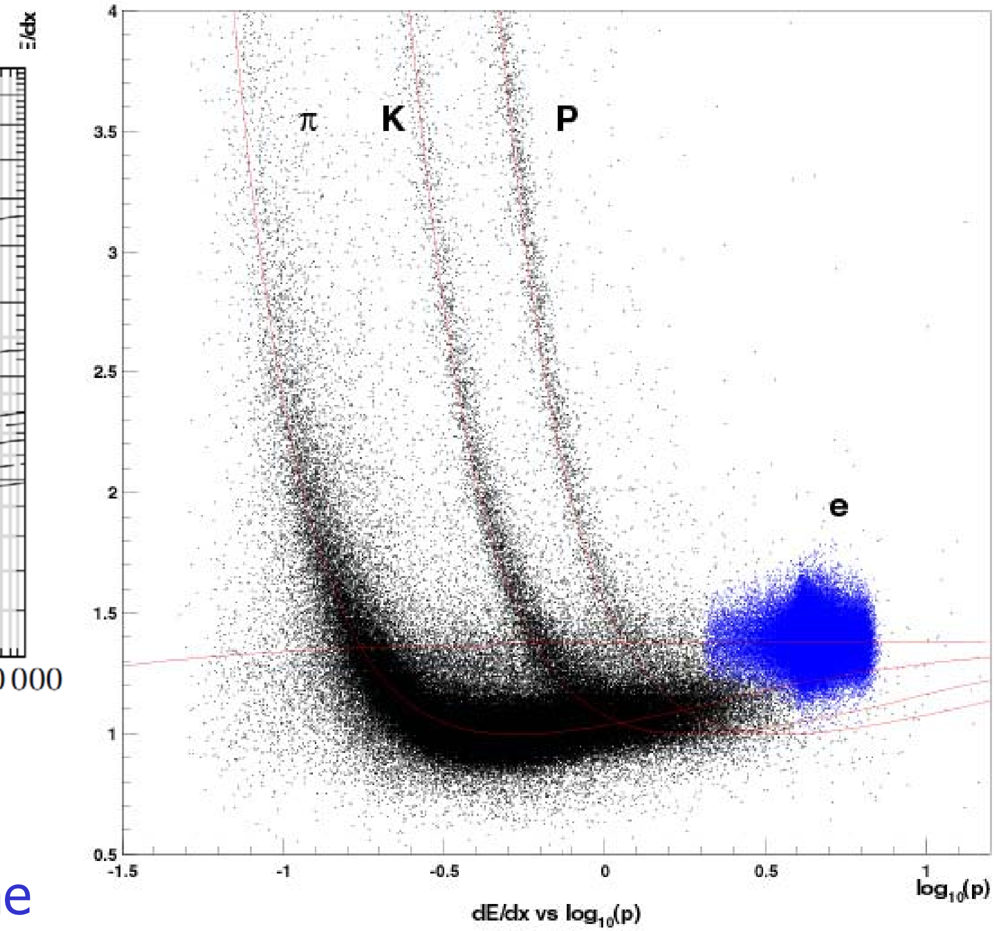


# PID coverage of kaon/pion spectra



# Identification with the dE/dx measurement



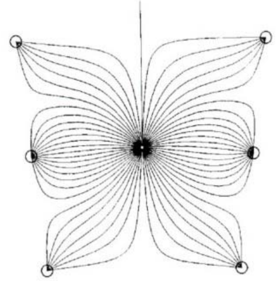

dE/dx is a function of velocity β

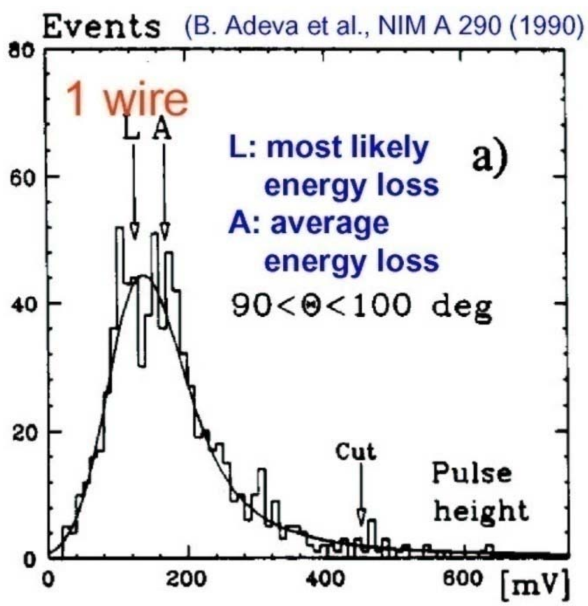
For particles with different mass the Bethe-Bloch curve gets displaced if plotted as a function of p

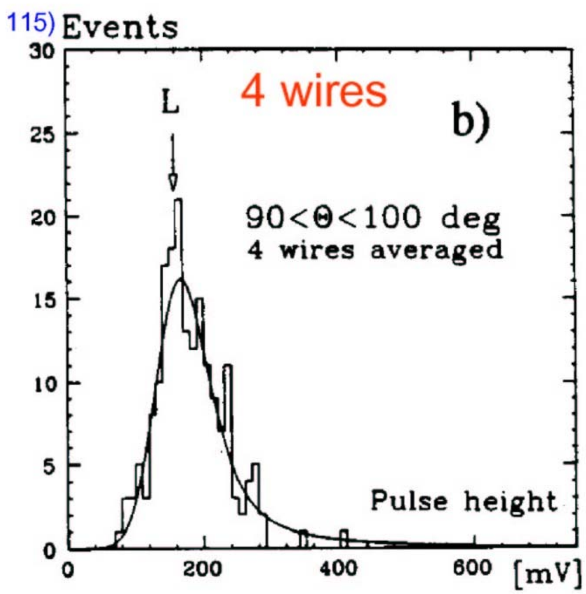
For good separation: resolution should be ~5%

# Identification with dE/dx measurement

Problem: long tails (Landau distribution, not Gaussian) of a single measurement (one drift chamber cell)






Measure in each of the 50 drift chamber layers – use truncated mean (discard 30% largest values – from the tail).

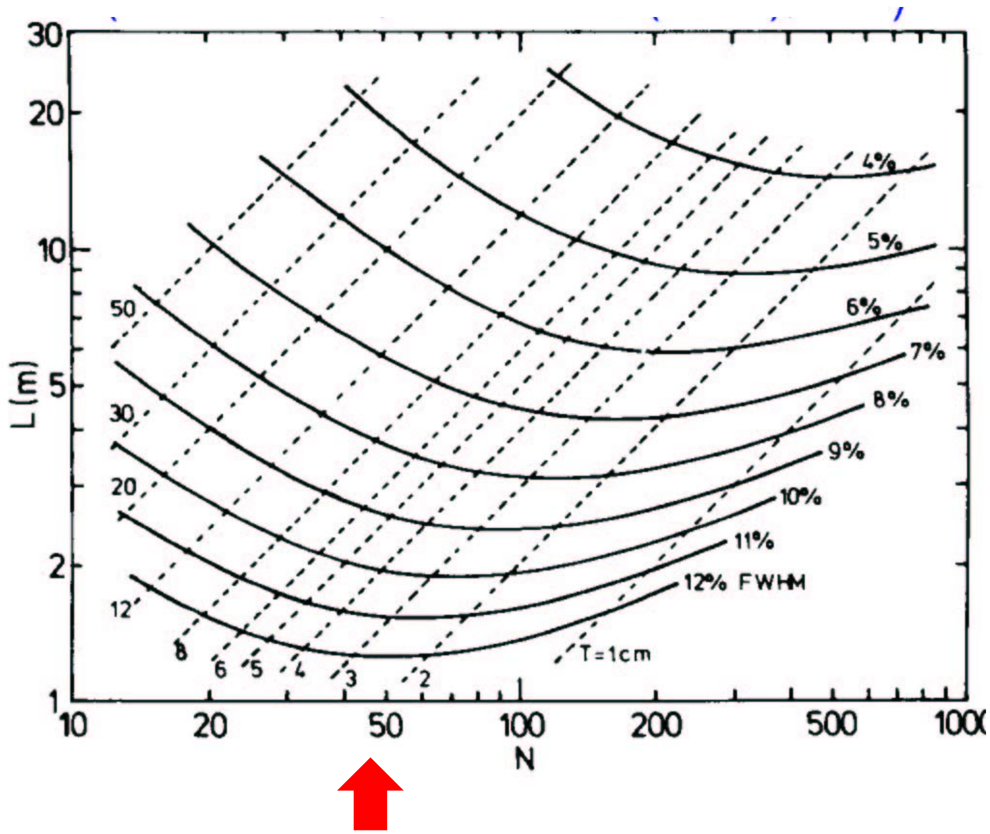
# Identification with dE/dx measurement

Optimisation of the counter: length L, number of samples N, resolution (FWHM)

If the distribution of individual measurements were Gaussian, only the total detector length L would be relevant.

Tails: eliminate the largest 30% values → the optimum depends also on the number of samples.

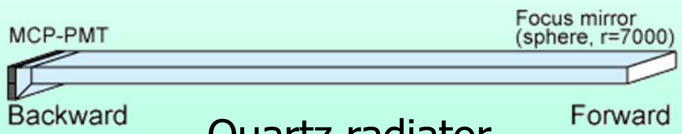
At about 1m path length: optimal number of samples: 50




FWHM: full width at half maximum = 2.35 sigma for a Gaussian distribution

# Cherenkov detectors

## Barrel PID: Time of Propagation Counter (TOP)



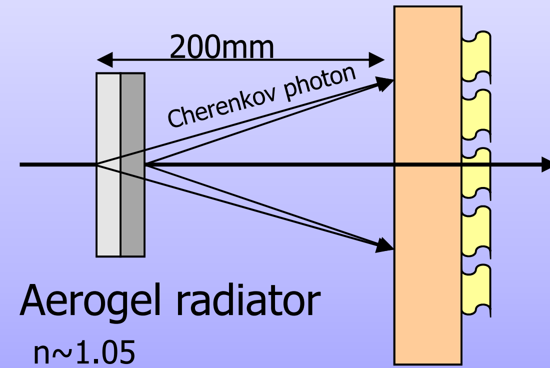

Quartz radiator

Focusing mirror

Small expansion block

Hamamatsu MCP-PMT (measure t, x and y)

## Endcap PID: Aerogel RICH (ARICH)

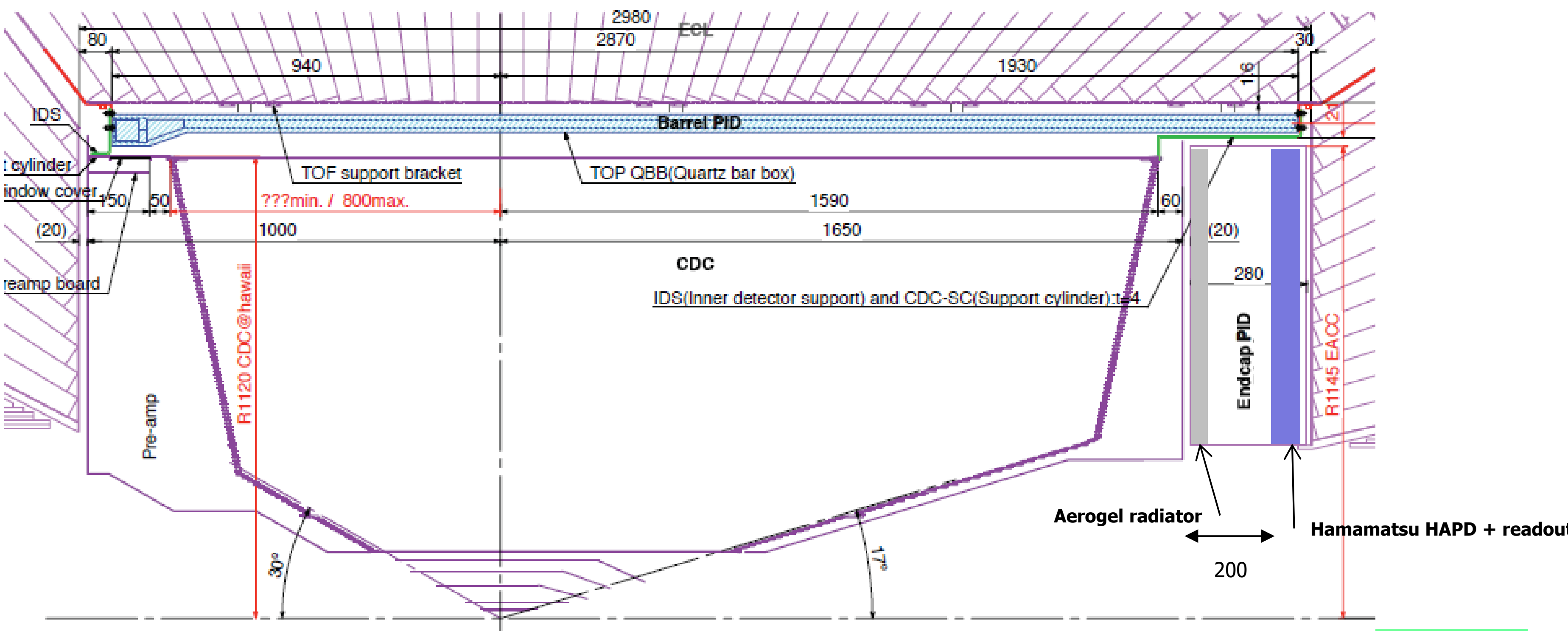



Aerogel radiator

n~1.05

Hamamatsu HAPD

+ new ASIC

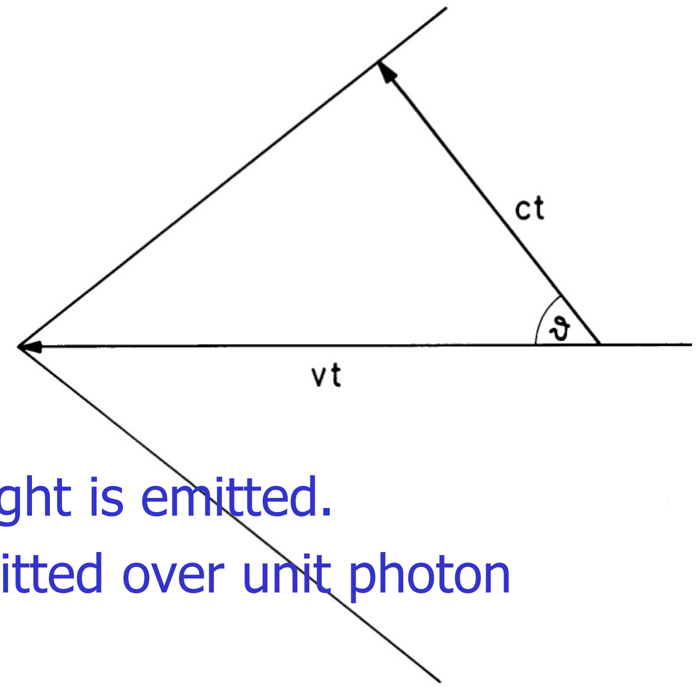



Peter Križan, Ljubljana

# Cherenkov radiation

A charged track with velocity $v=\beta c$ exceeding the speed of light $c/n$ in a medium with refractive index $n$ emits polarized light at a characteristic (Cherenkov) angle,

$$\cos\theta = c/nv = 1/\beta n$$




Two cases:

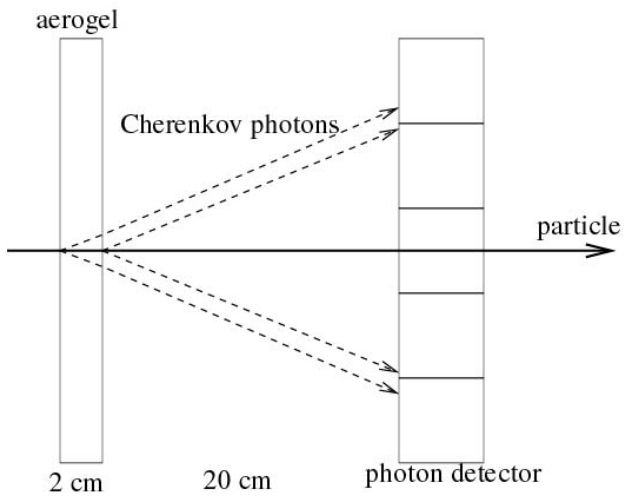
→ $\beta < \beta_t = 1/n$: below threshold no Cherenkov light is emitted.

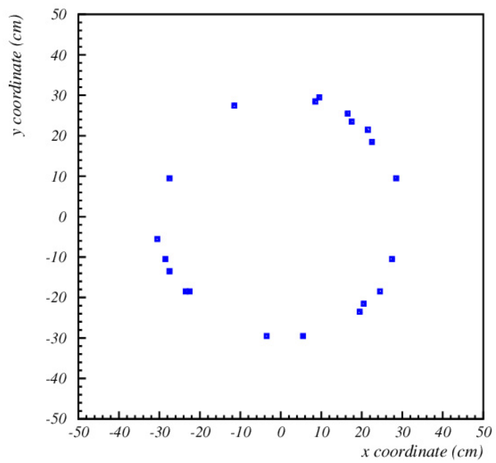
→ $\beta > \beta_t$ : the number of Cherenkov photons emitted over unit photon energy $E=h\nu$ in a radiator of length ***L***:

$$\boxed{\frac{dN}{dE} = \frac{\alpha}{\eta c} L \sin^2\theta = 370(cm)^{-1}(eV)^{-1} L \sin^2\theta}$$

→Few detected photons

# Measuring the Cherenkov angle



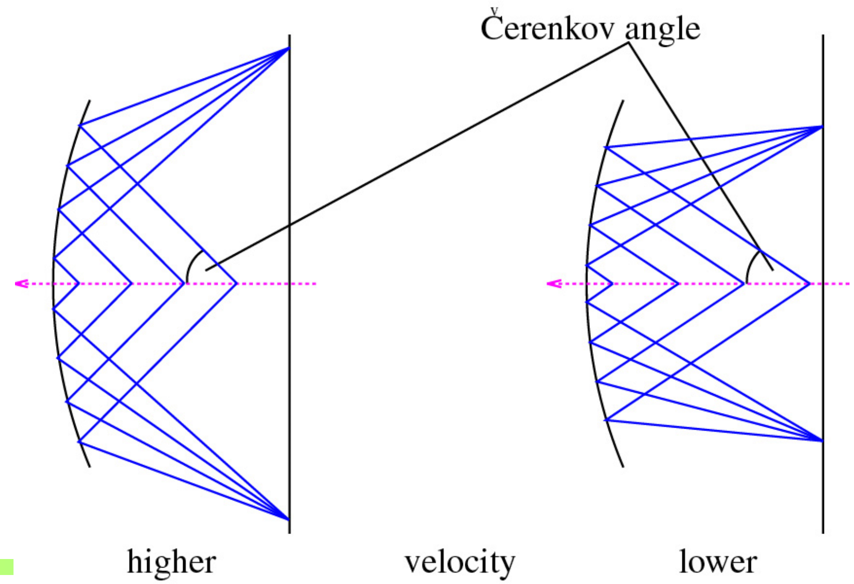

Idea: transform the direction into a coordinate → ring on the detection plane

→ Ring Imaging Cherenkov (RICH) counter

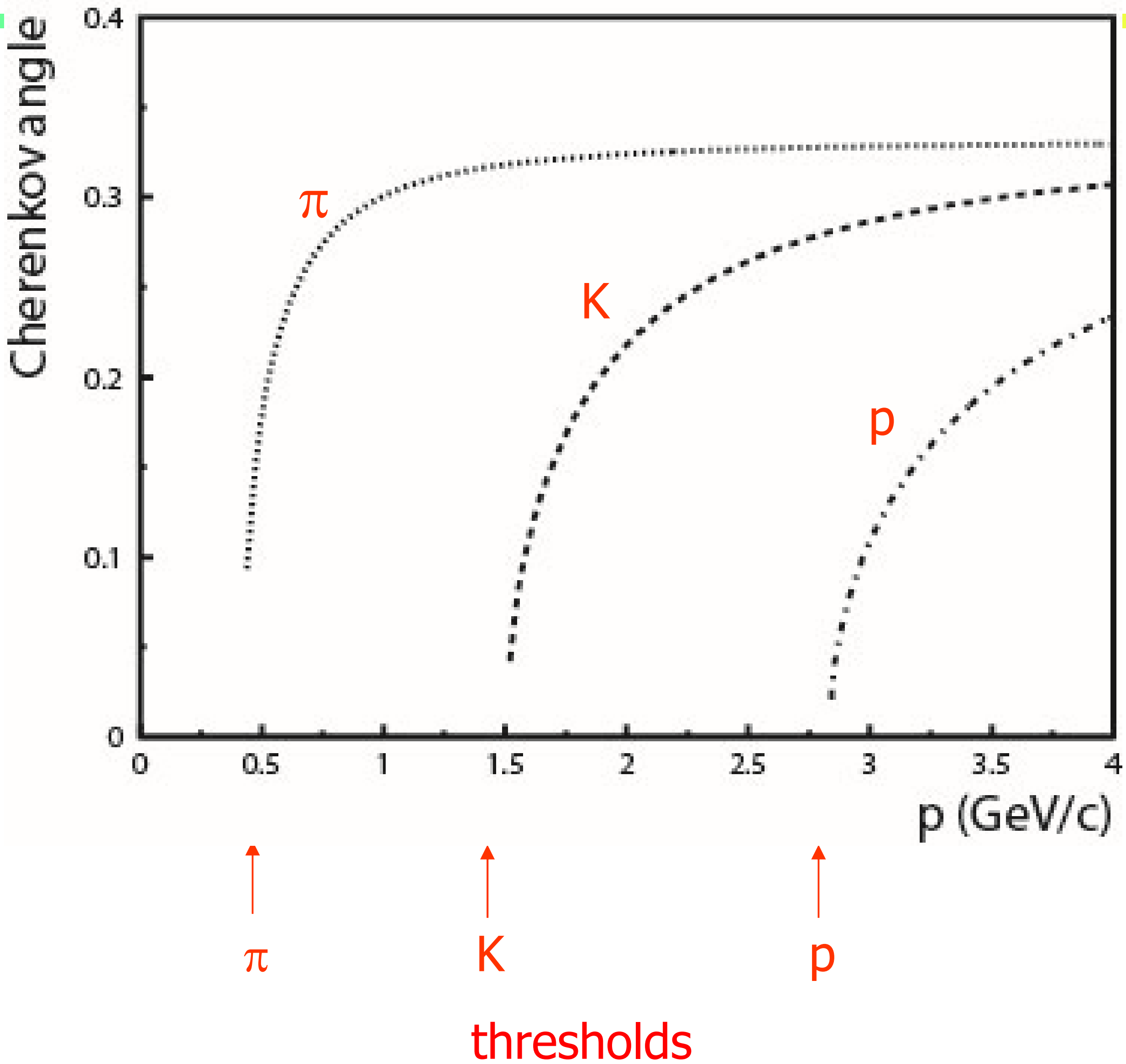
Proximity focusing RICH

RICH with a

focusing mirror

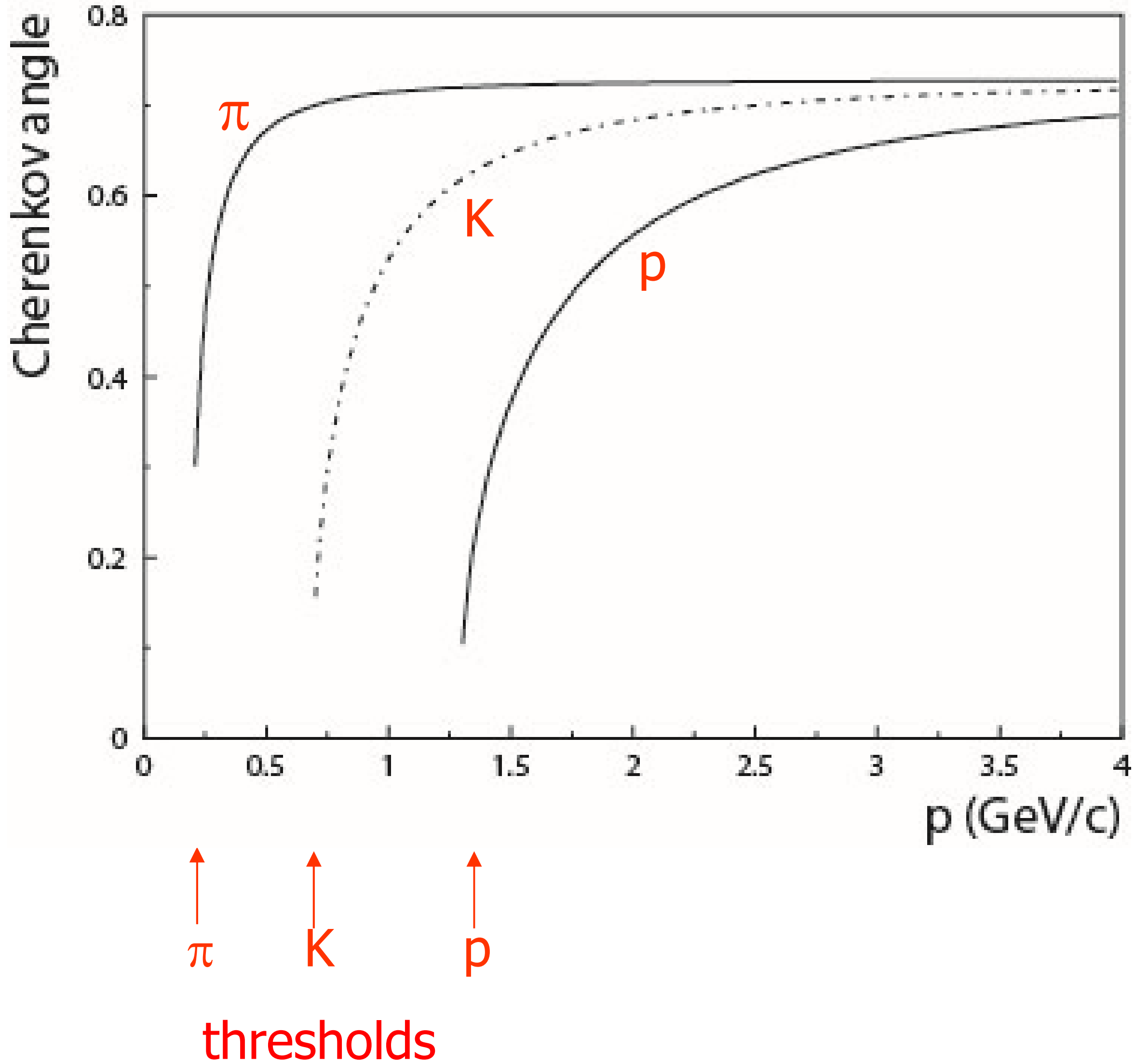


# Measuring Cherenkov angle




Radiator:
aerogel, n=1.06

# Measuring Cherenkov angle




Radiator:
quartz, n=1.46

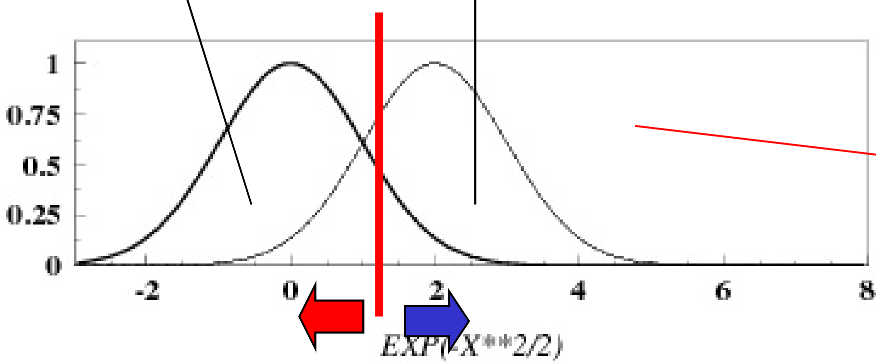
# Efficiency and purity in particle identification

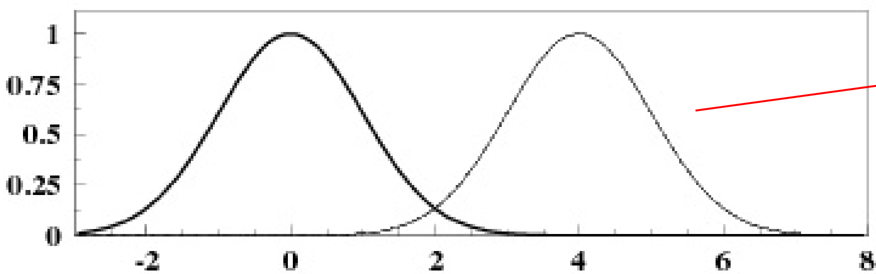
Efficiency and purity are tightly coupled!

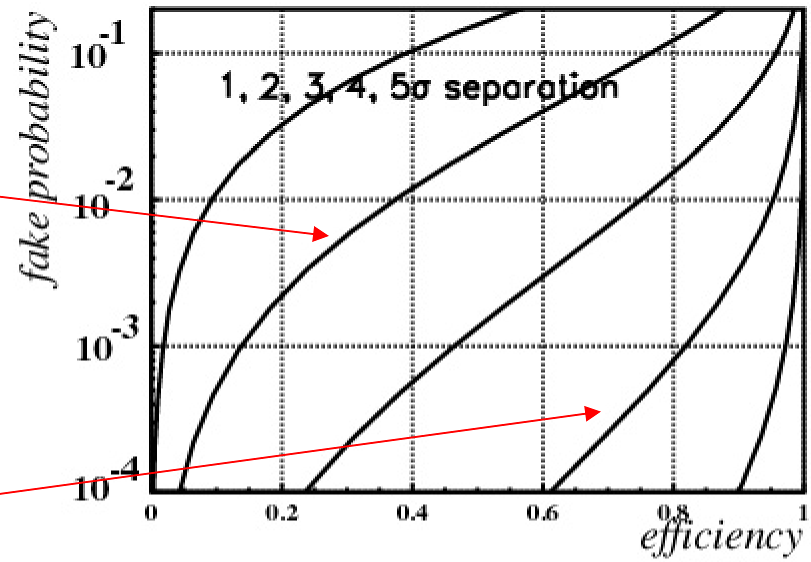
Two examples:

particle type 1 type 2

eff. vs fake probability

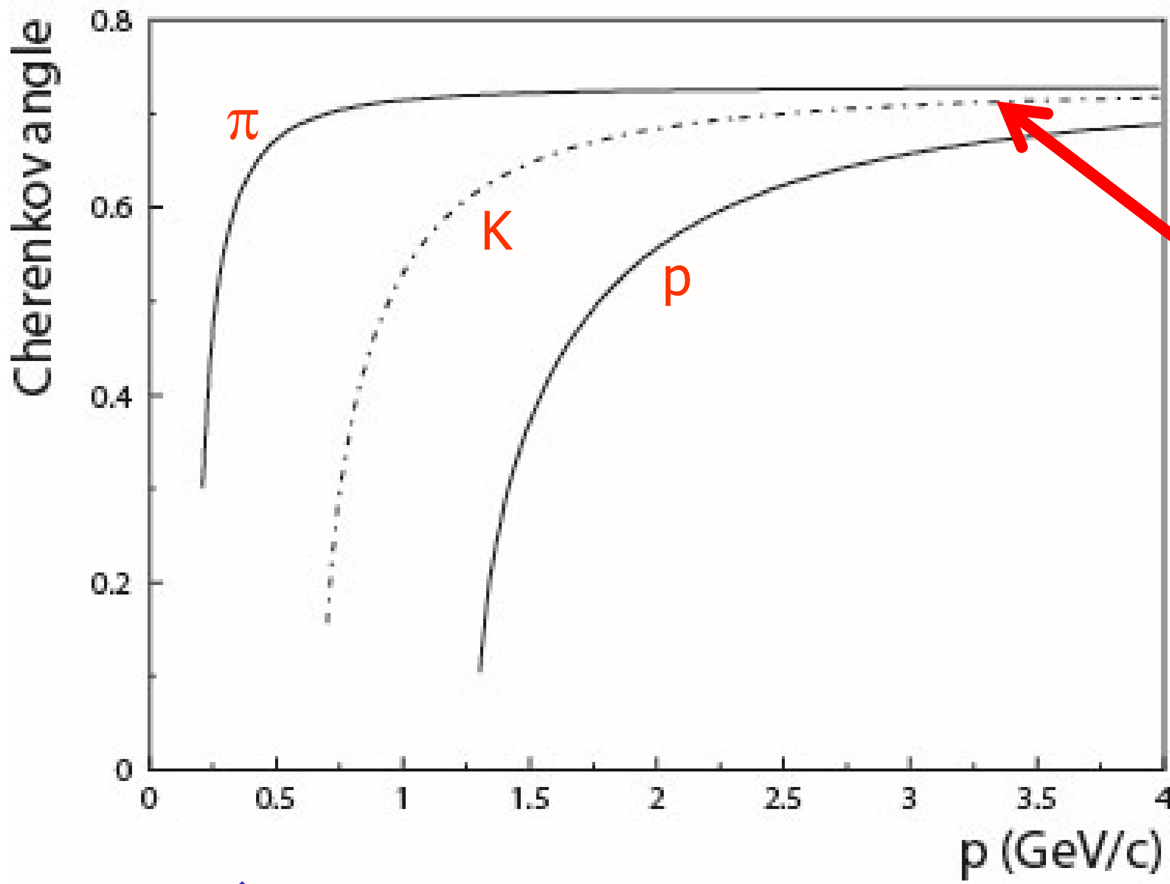



- any discriminating variable, e.g. Cherenkov angle

# Measuring Cherenkov angle



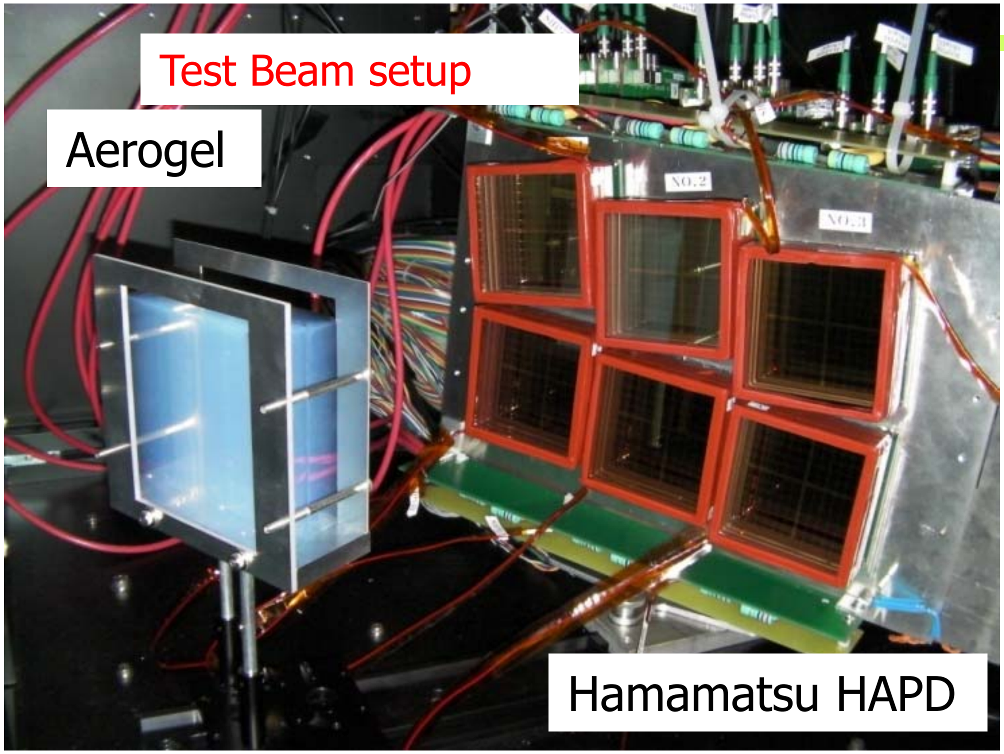

Radiator: quartz, n=1.06

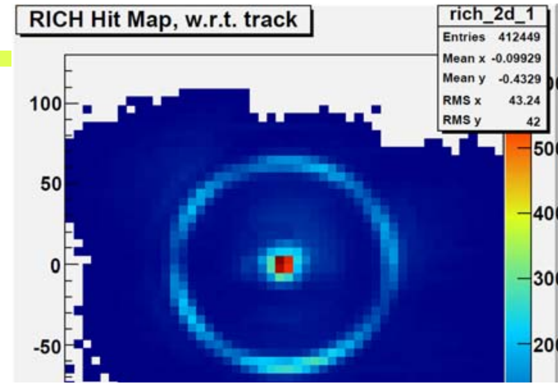
K/π overlap

**$P_{min}$** for K/π separation

**$P_{max}$** for K/π separation

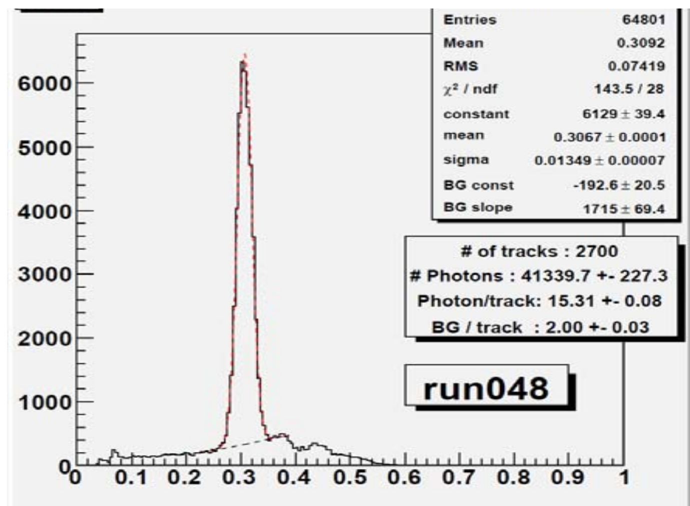
# Aerogel RICH (endcap PID): larger particle momenta



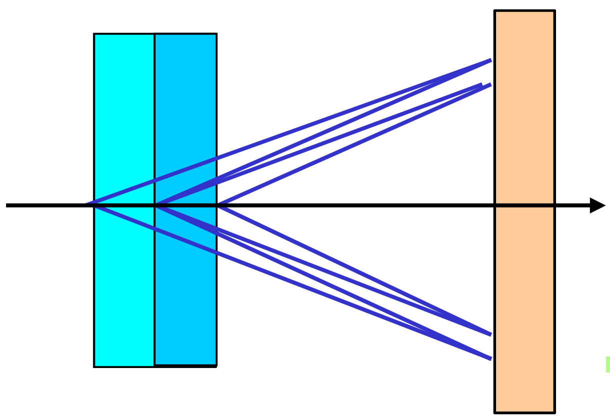

Clear Cherenkov image observed

Cherenkov angle distribution




RICH with a novel "focusing" radiator – a two layer radiator

Employ multiple layers with different refractive indices→ Cherenkov images from individual layers overlap on the photon detector.



**6.6 σ π/K at 4GeV/c !**

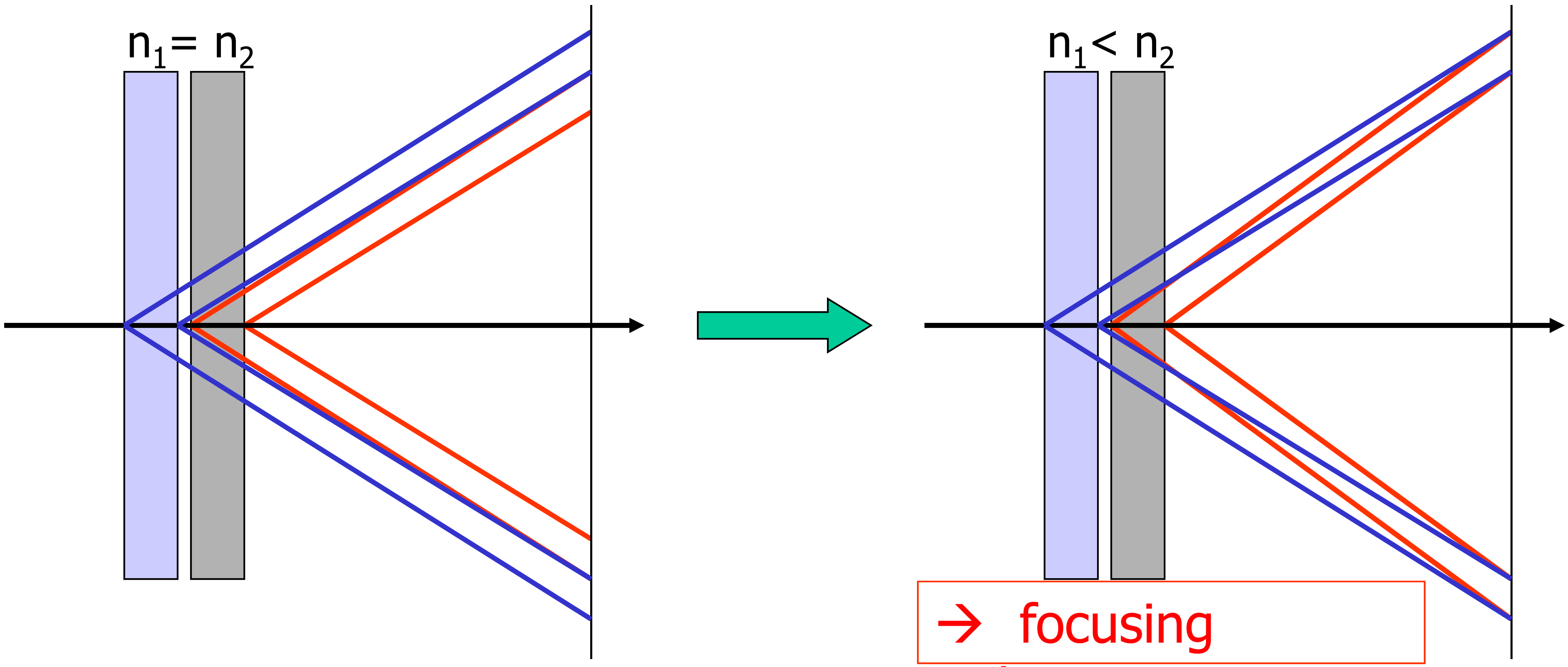
Peter Križan, Ljubljana

# Radiator with multiple refractive indices

How to increase the number of photons without degrading the resolution?

→ stack two tiles with different refractive indices: "focusing" configuration

normal



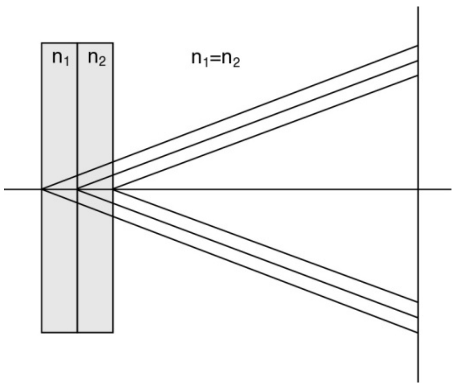

→ focusing

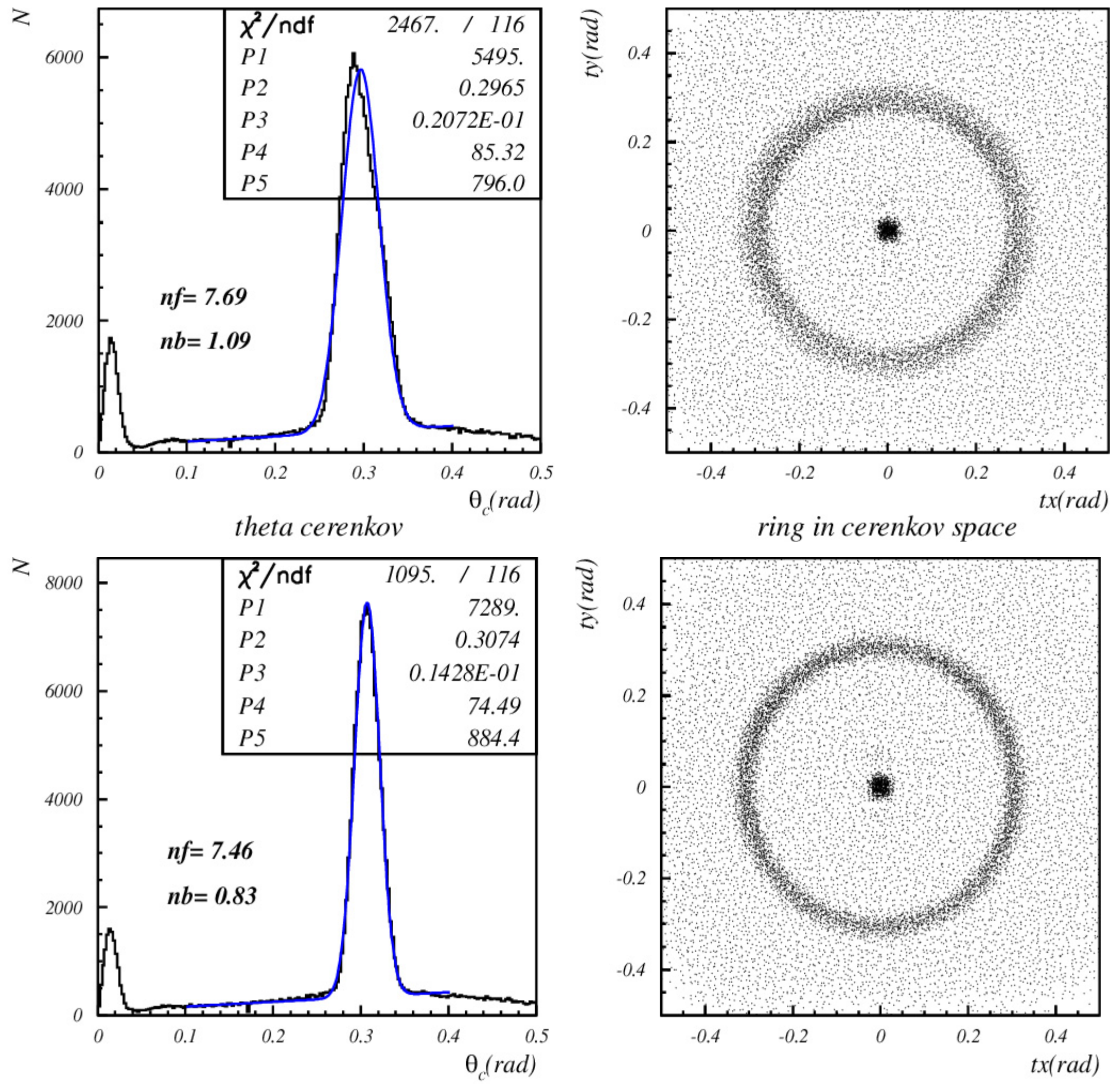
Such a configuration is only possible with aerogel (a form of $Si_xO_y$) – material with a tunable refractive index between 1.01 and 1.13.

# Focusing configuration – data

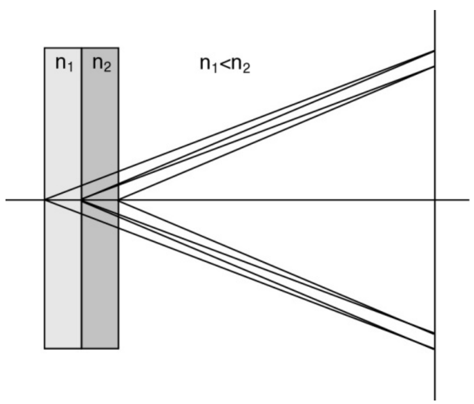
Increases the number of photons without degrading the resolution

## 4cm aerogel single index




## 2+2cm aerogel




→NIM A548 (2005) 383

# Cherenkov detectors

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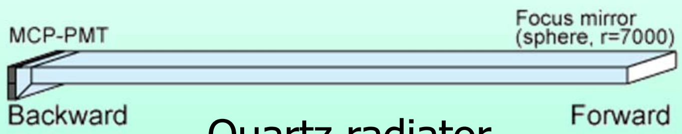


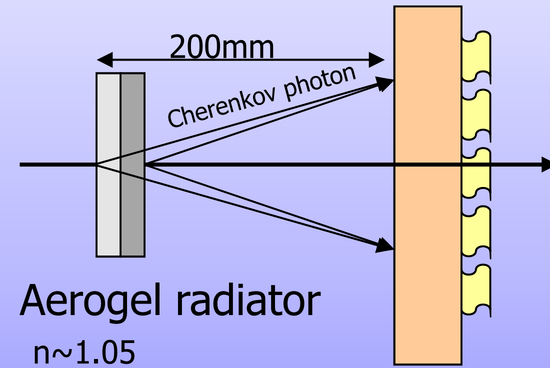

Quartz radiator

Focusing mirror

Small expansion block

Hamamatsu MCP-PMT (measure t, x and y)

## Endcap PID: Aerogel RICH (ARICH)

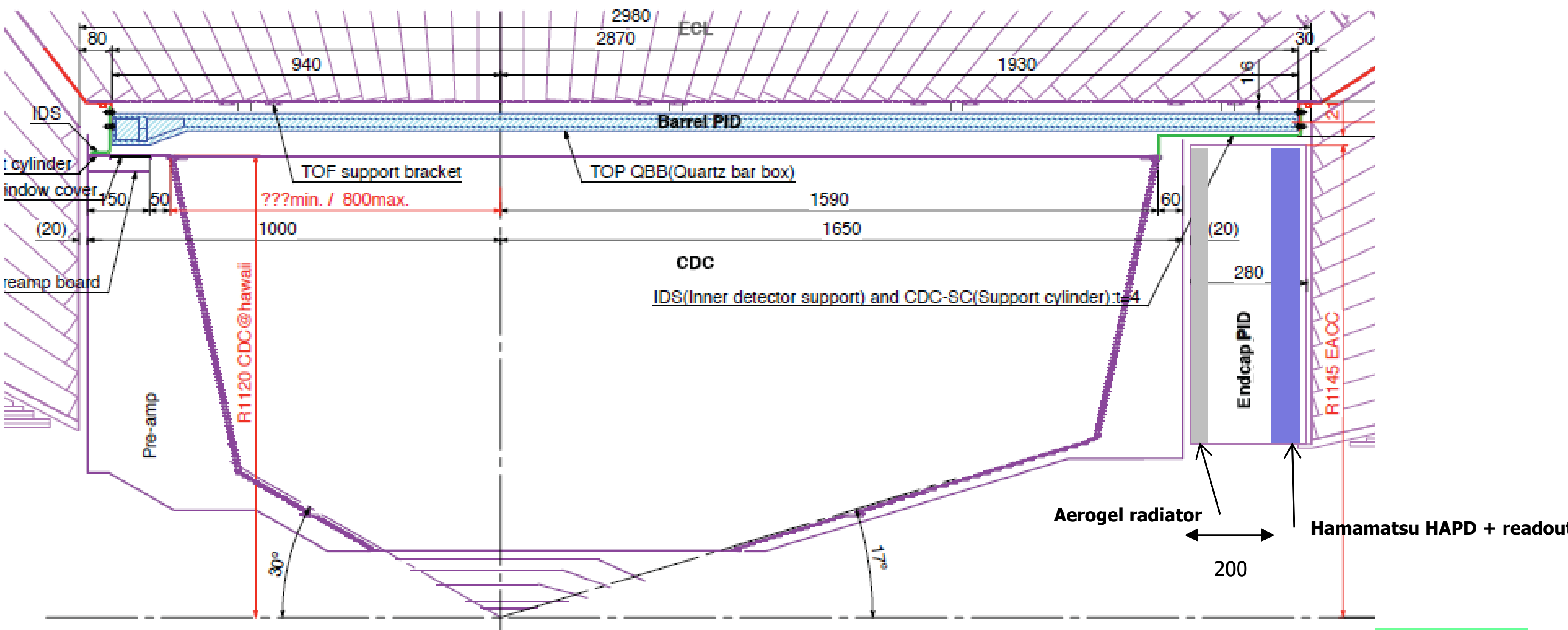



Aerogel radiator

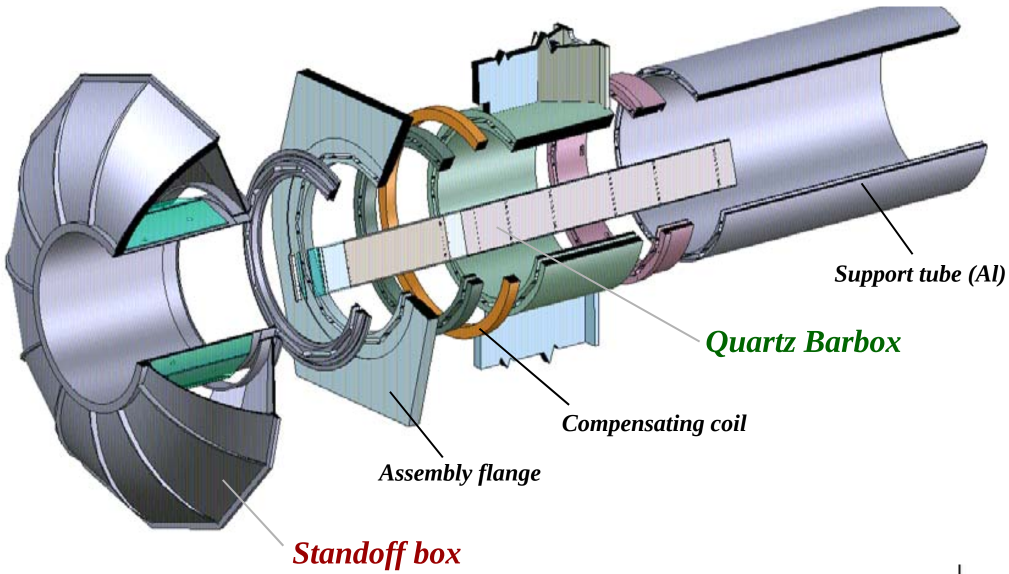
n~1.05

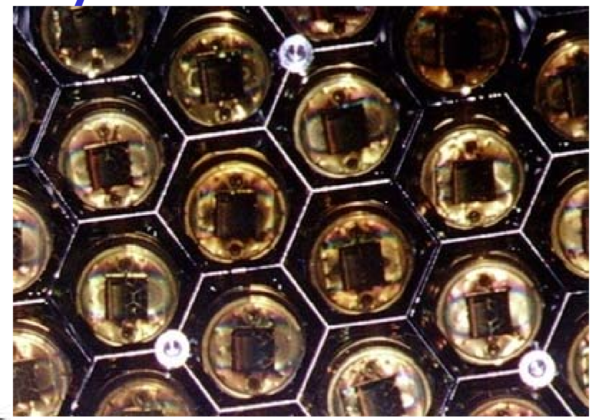
Hamamatsu HAPD

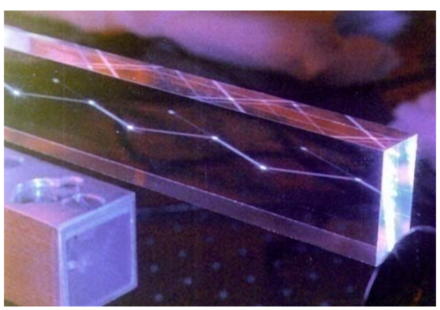
+ new ASIC

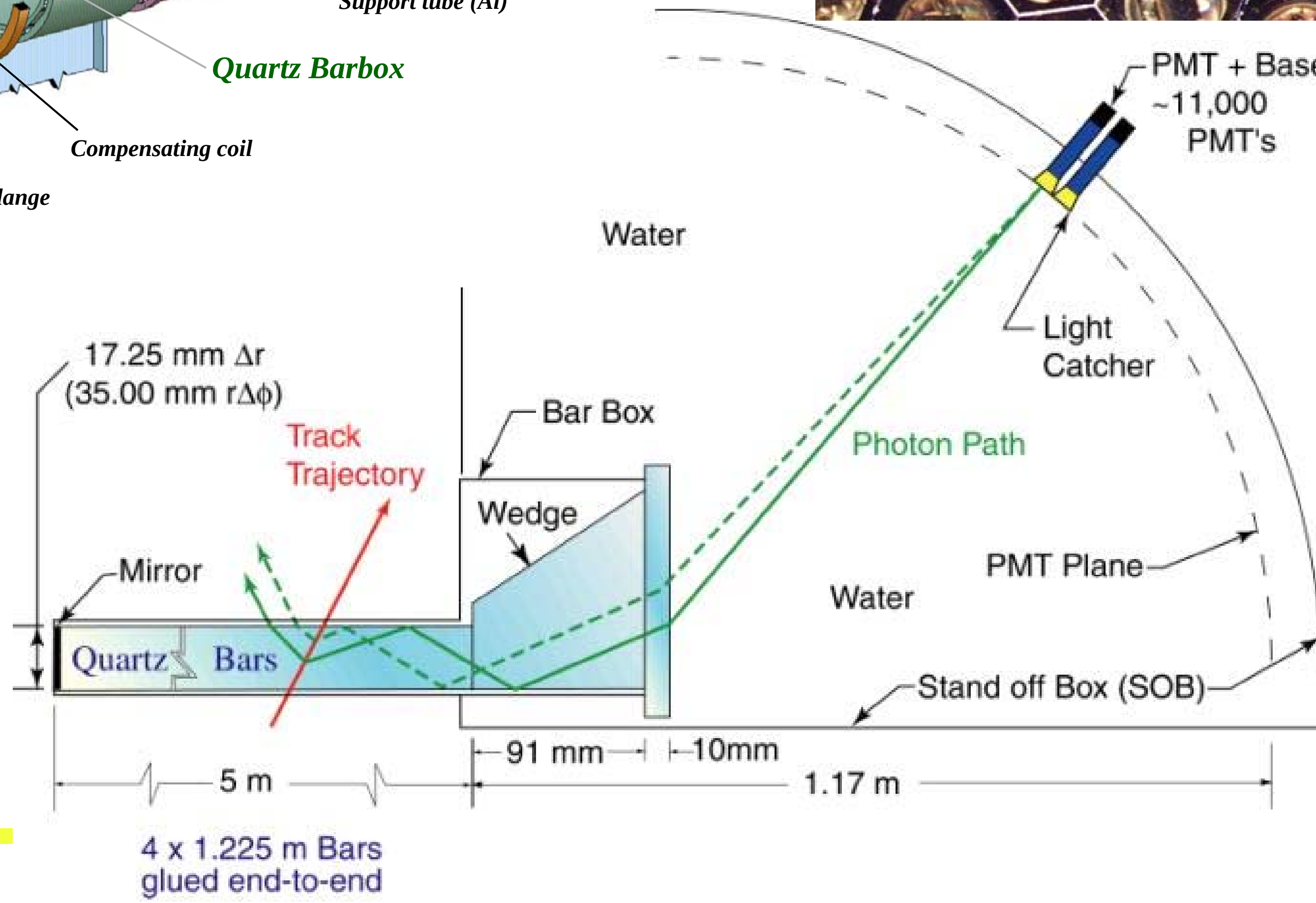


# DIRC (@BaBar) - detector of internally reflected Cherenkov light

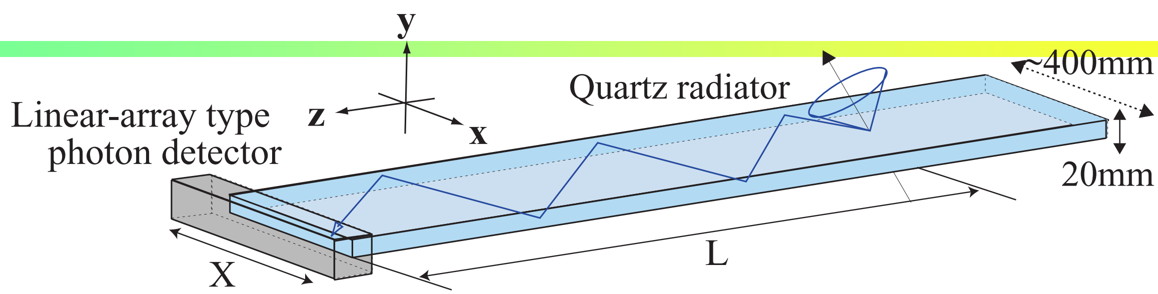


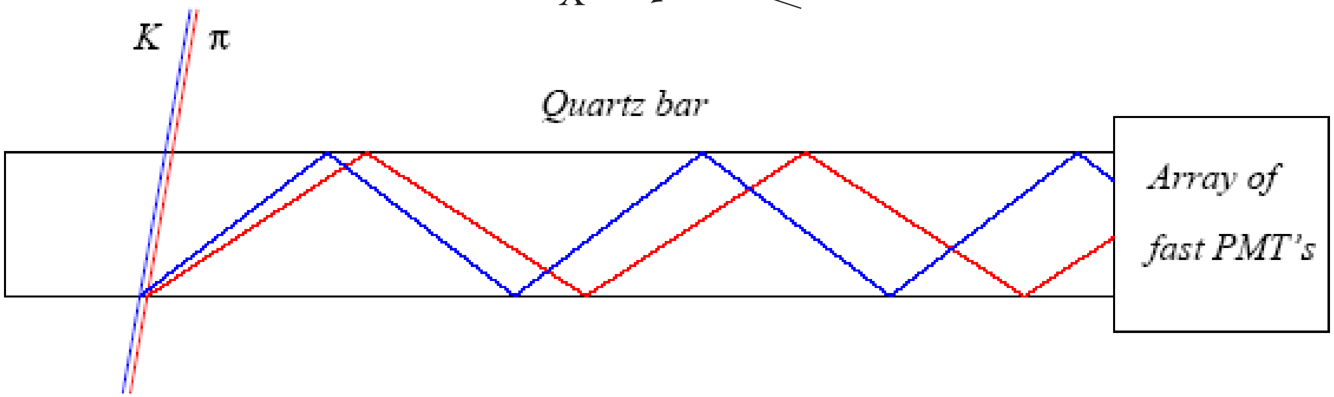



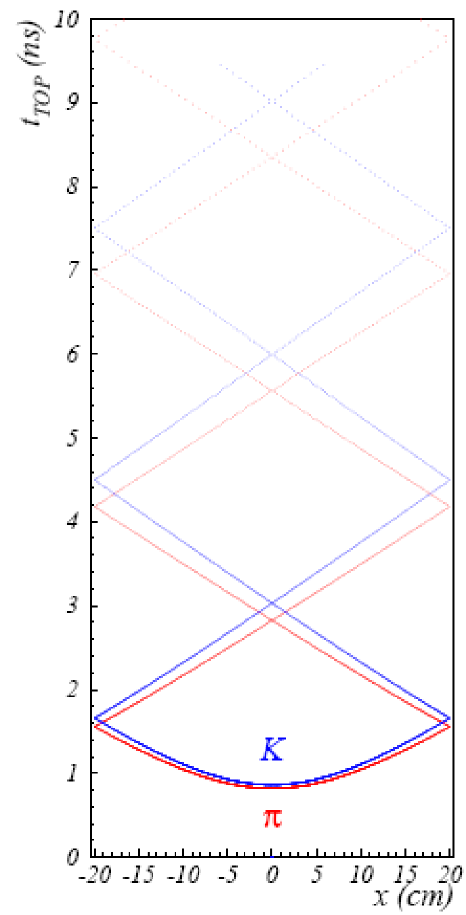




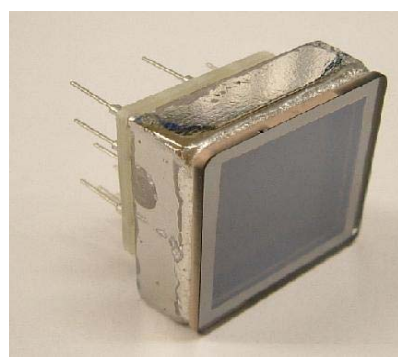
# Belle II Barrel PID: Time of propagation (TOP) counter



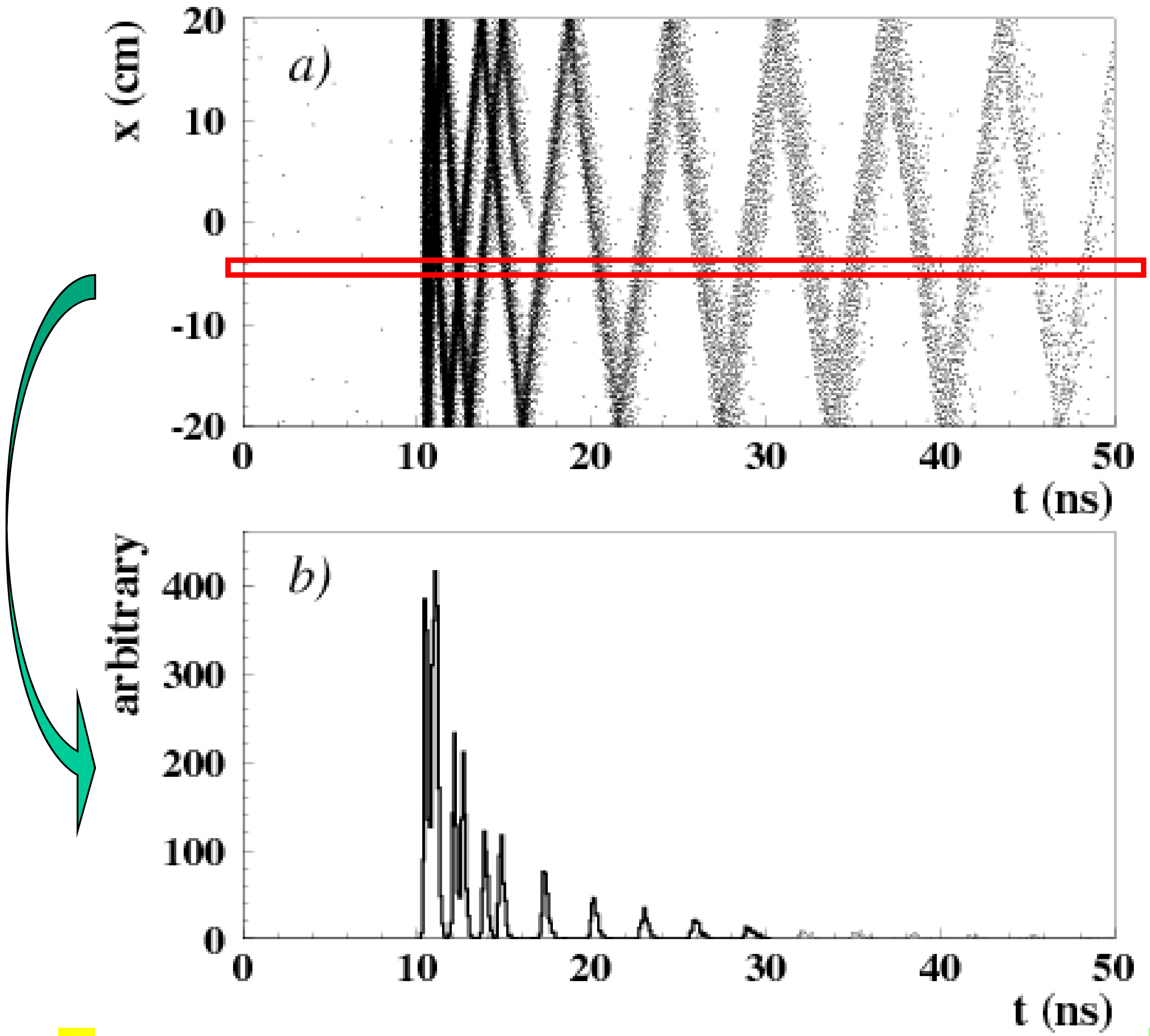




- Cherenkov ring imaging with precise time measurement.
- Device uses internal reflection of Cerenkov ring images from quartz like the BaBar DIRC.
- Reconstruct Cherenkov angle from two hit coordinates and the time of propagation of the photon
  - Quartz radiator (2cm)
  - Photon detector (MCP-PMT)
    - Excellent time resolution ~ 40 ps
    - Single photon sensitivity in 1.5



# TOP image



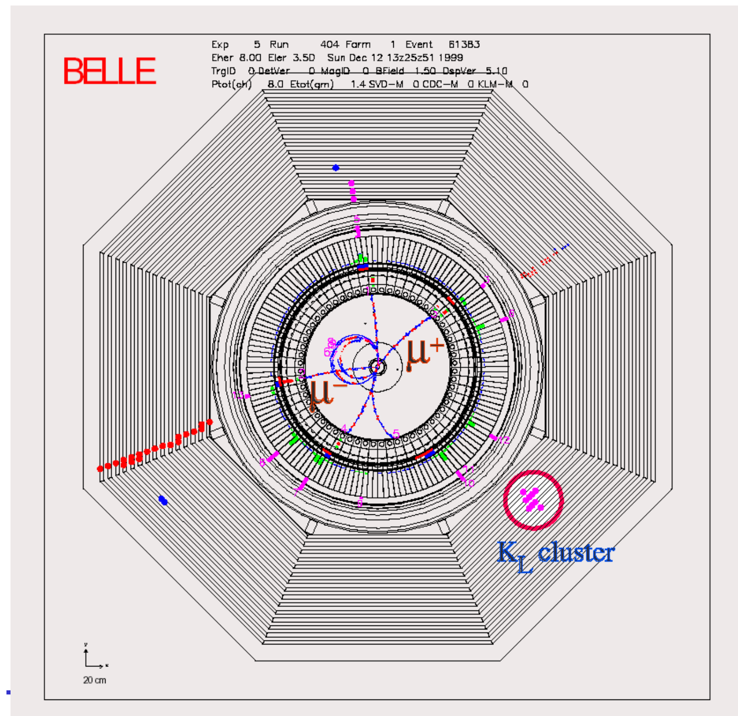

Pattern in the coordinate-time space ('ring') of a pion hitting a quartz bar with ~80 MAPMT channels

Time distribution of signals recorded by one of the PMT channels: different for π and K (~shifted in time)

# 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.




→ Put the detector outside the magnet coil, and integrate into the return yoke

Some numbers: 3.9 interaction lengths (iron)

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 → identification of muons above ~600 MeV

# Muon and $K_L$ detector

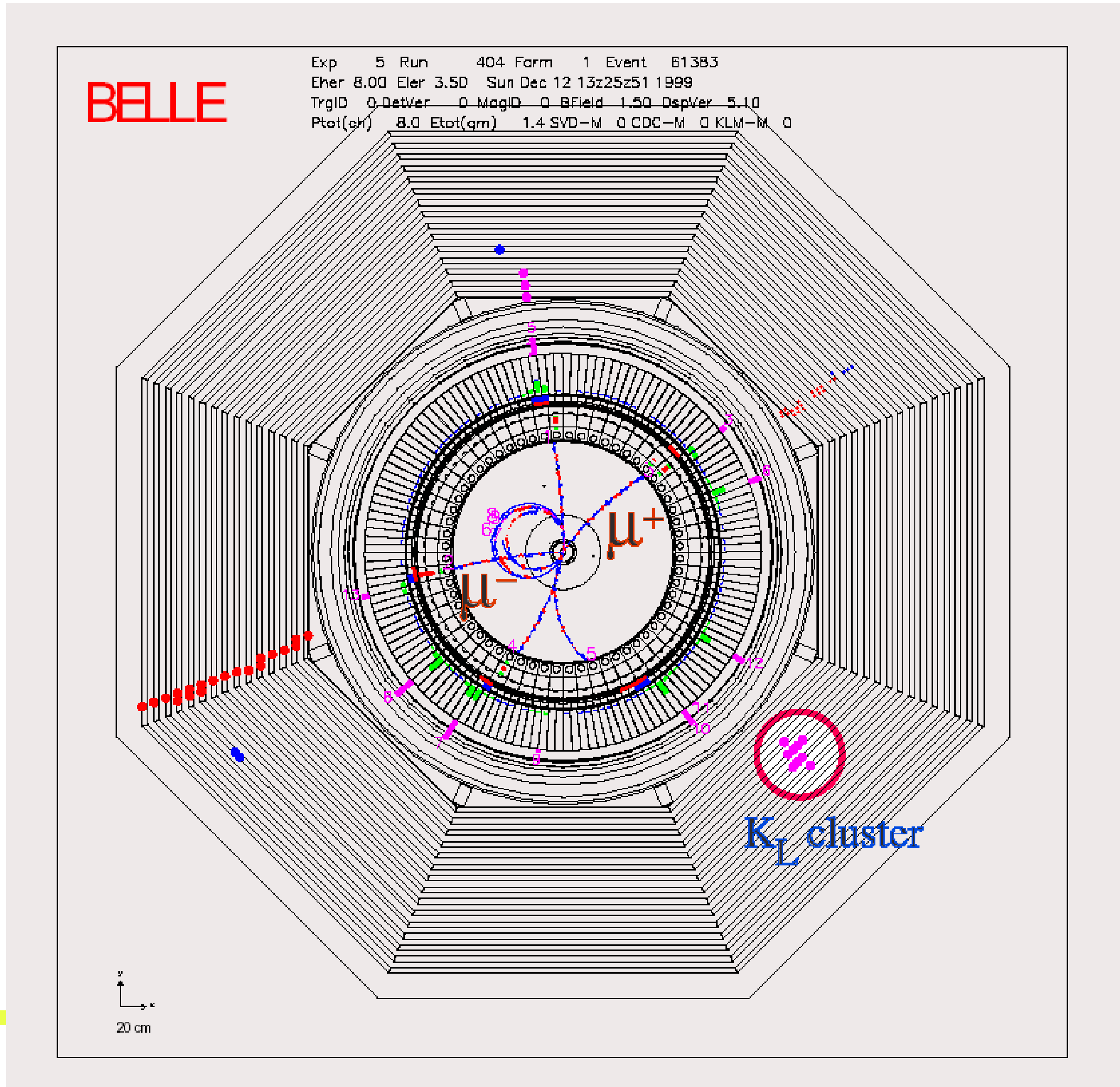
**Example:**

**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

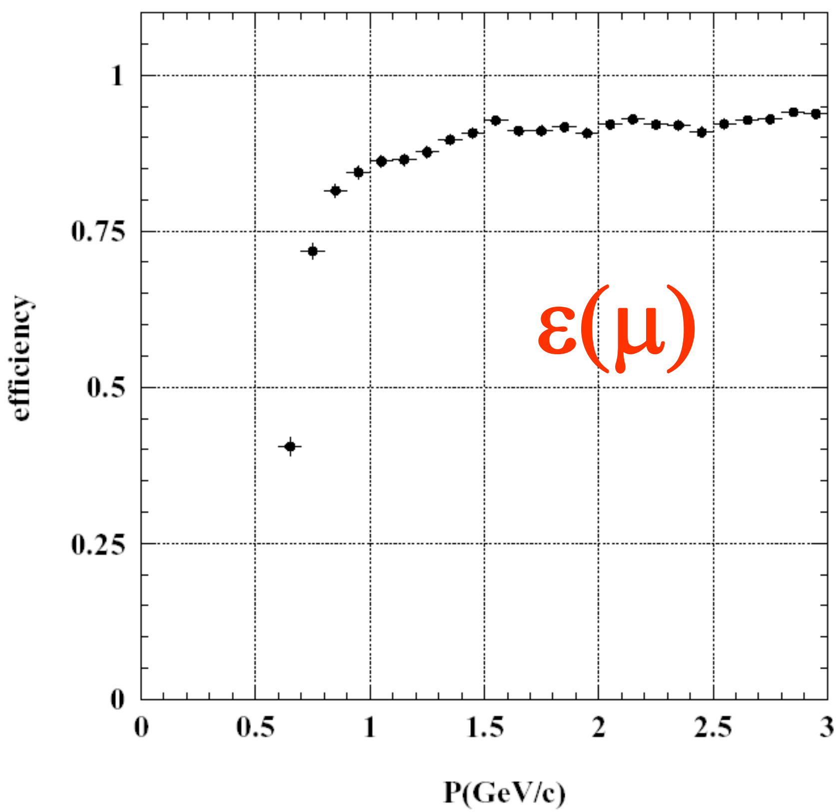



Fig. 109. Muon detection efficiency vs. momentum in KLM.

fake probability

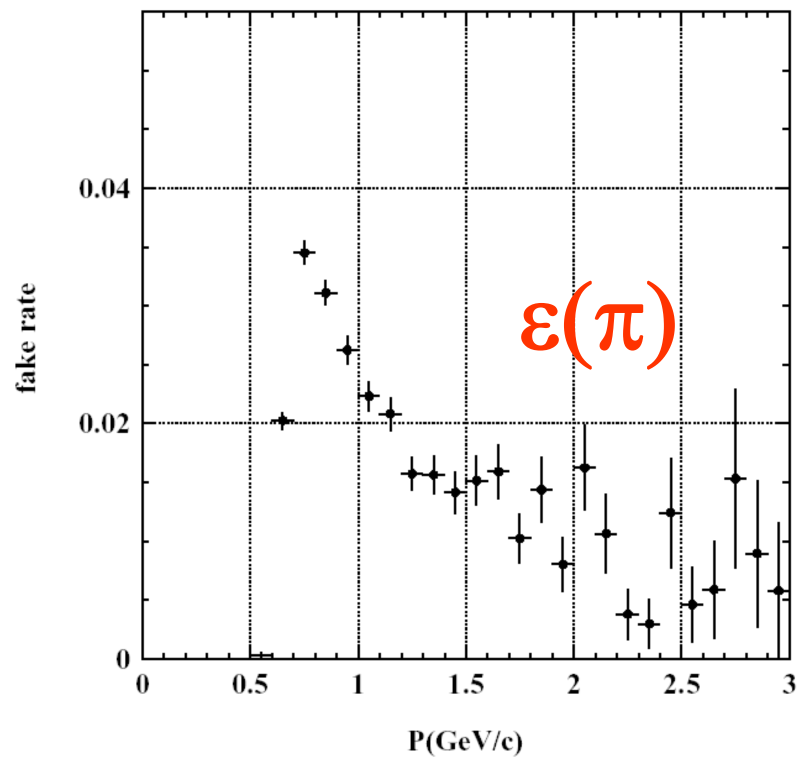



Fig. 110. Fake rate vs. momentum in KLM.

# 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)

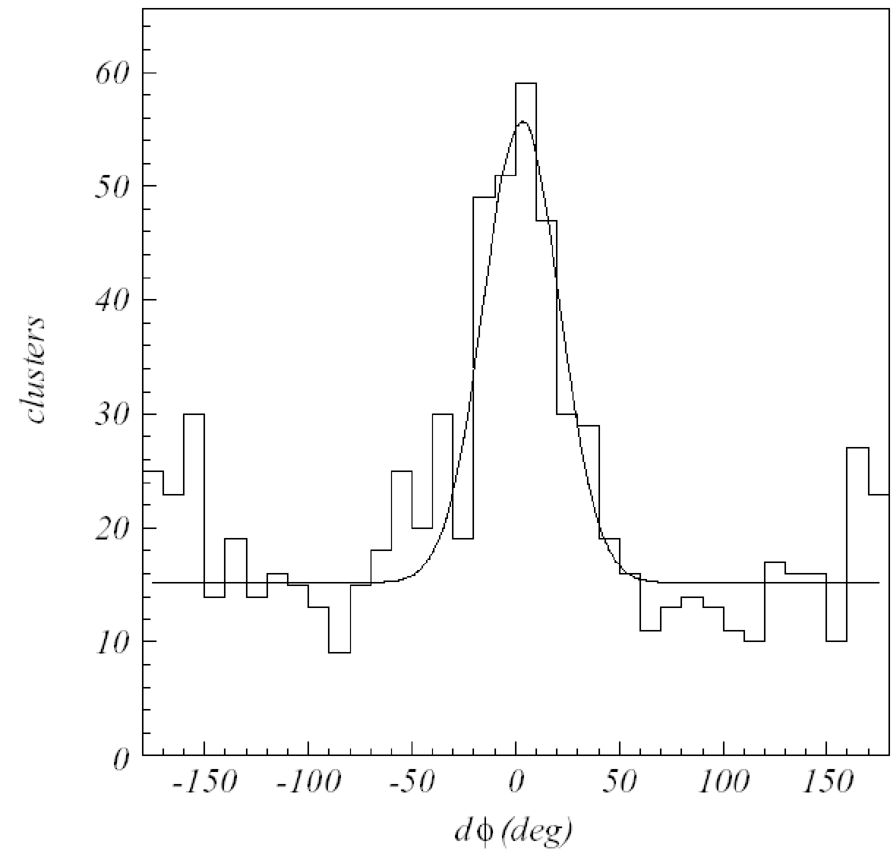
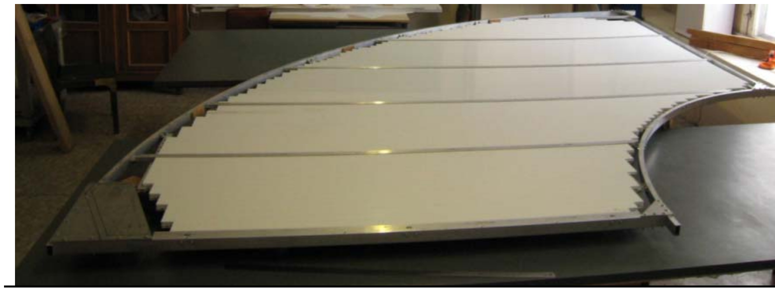
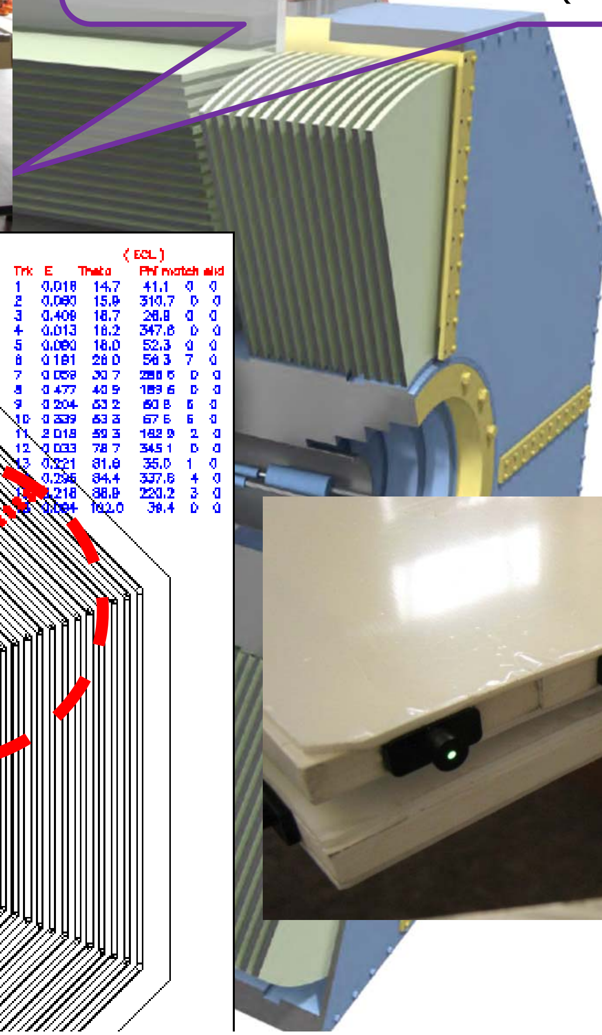


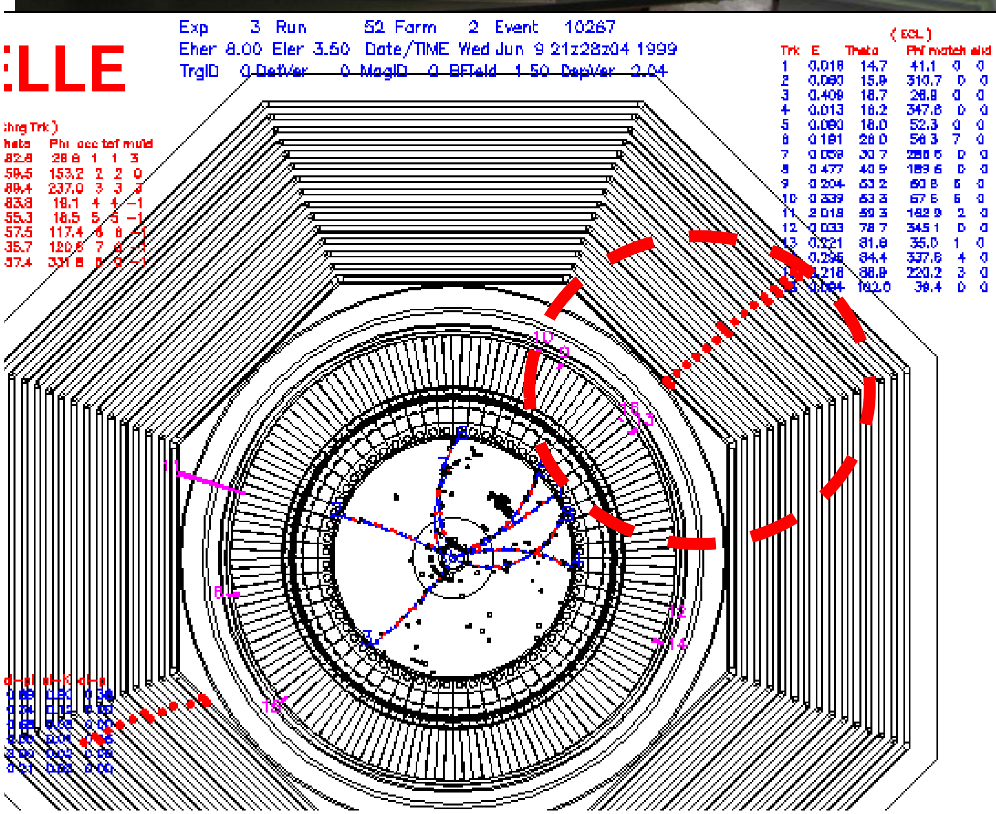

Fig. 107. Difference between the neutral cluster and the direction of missing momentum in KLM.

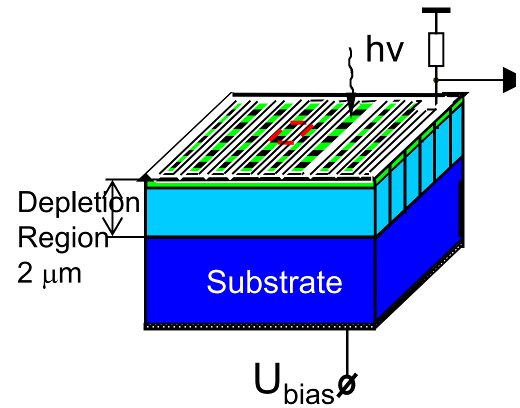
Belle II, detection of muons and $K_L$s: Parts of the present RPC system have to be replaced to handle higher backgrounds (mainly from neutrons).

$K_L$ and muon detector:
Resistive Plate Counter (barrel)
Scintillator + WLSF + MPPC (end-caps + barrel 2 inner layers)







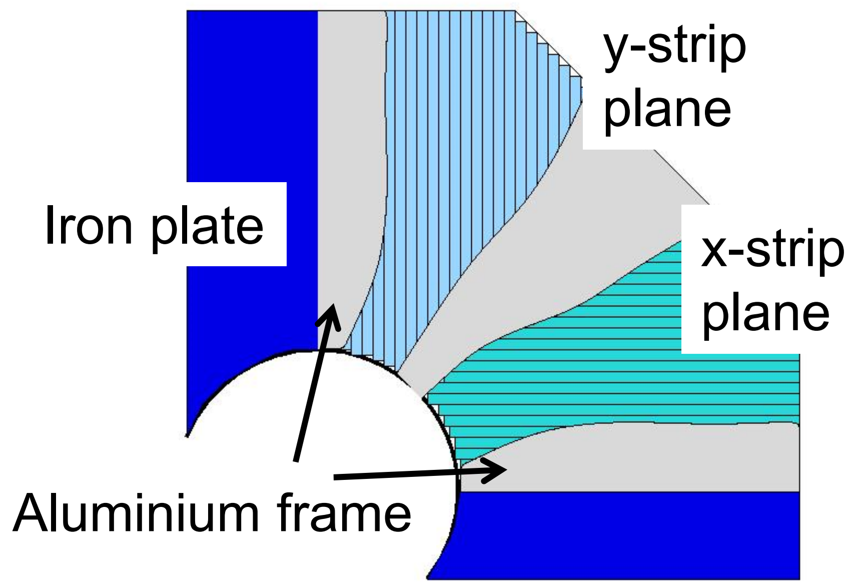


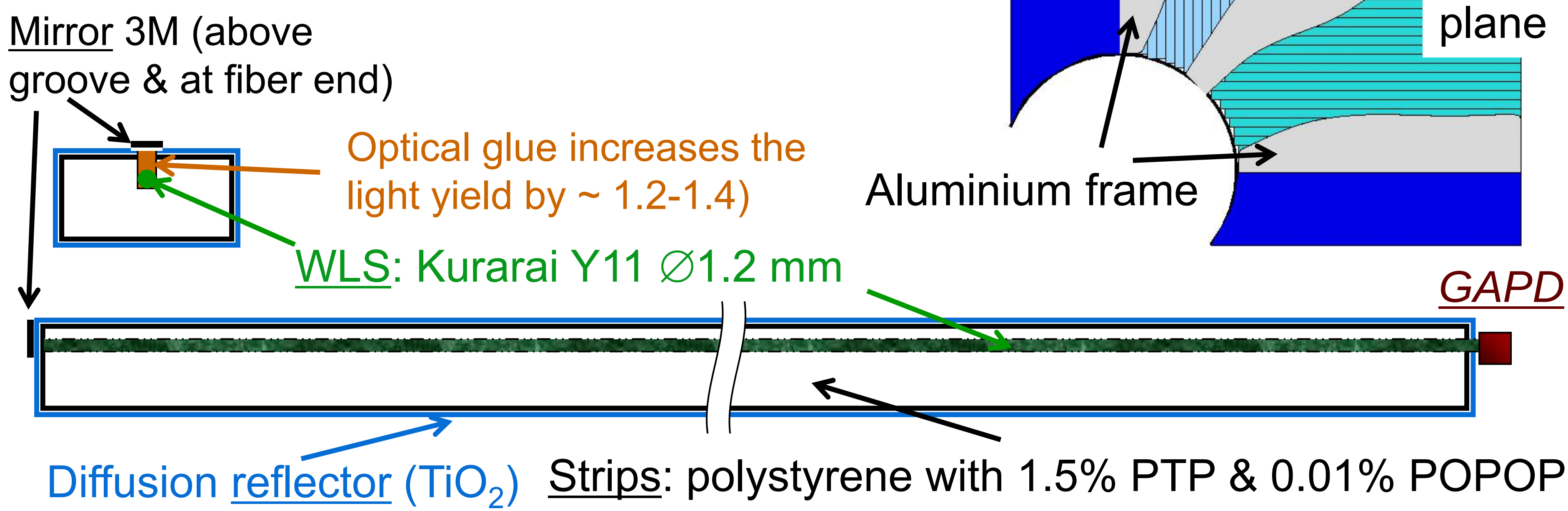

ljana

# Muon detection system upgrade in the endcaps

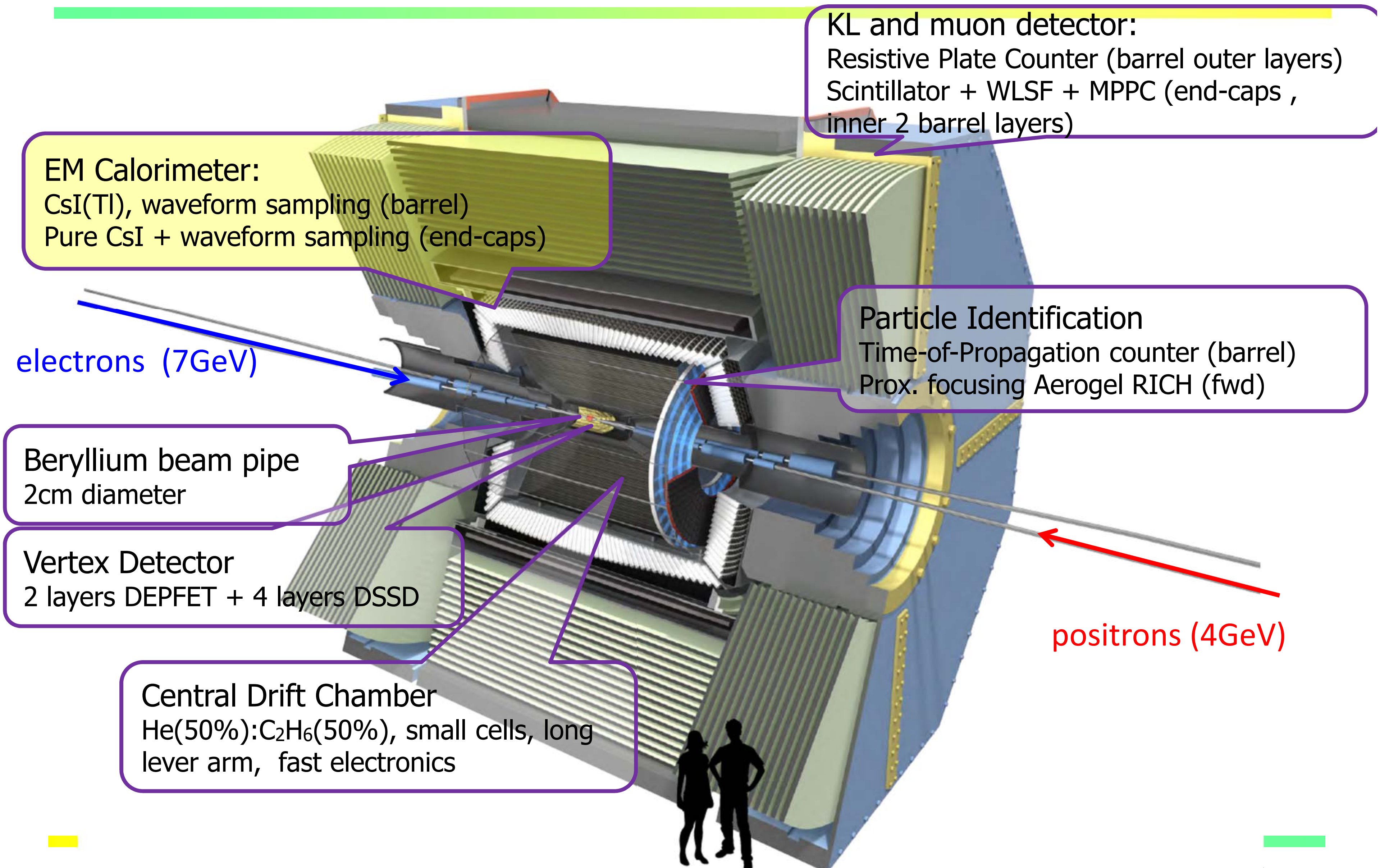
Scintillator-based KLM (endcap and two layers in the barrel part)

- Two independent (x and y) layers in one superlayer made of orthogonal strips with WLS read out
- Photo-detector = avalanche photodiode in Geiger mode (SiPM)
- ~120 strips in one 90º sector (max L=280cm, w=25mm)
- ~30000 read out channels
- Geometrical acceptance > 99%

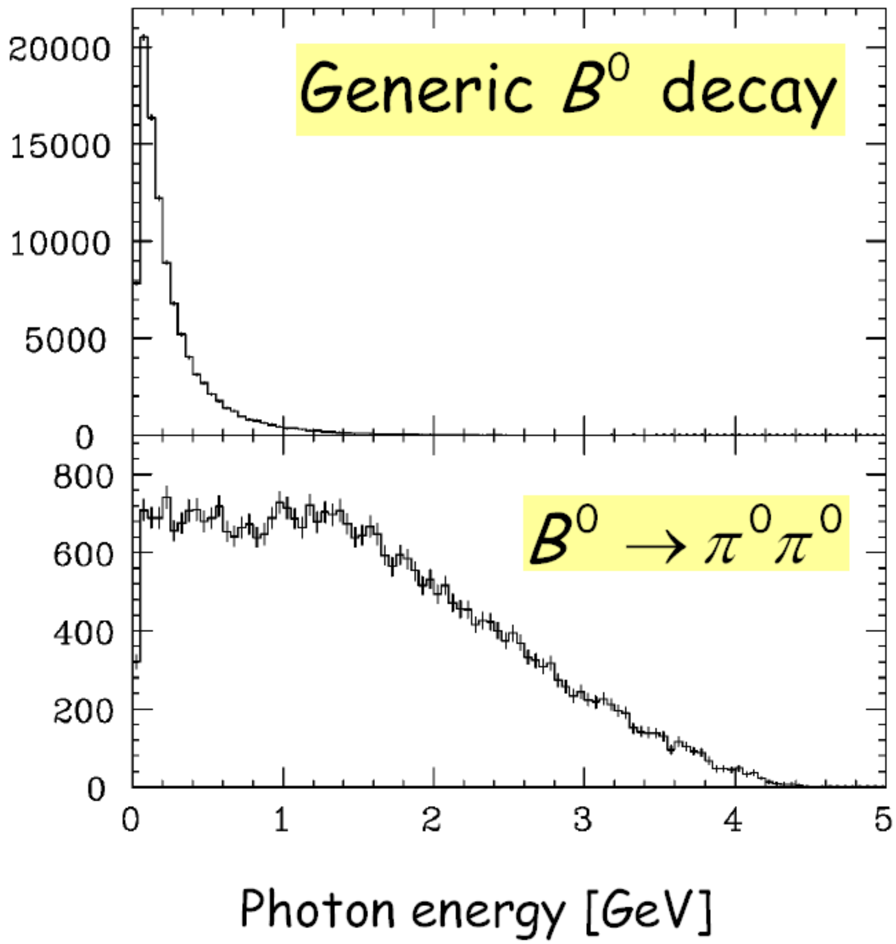


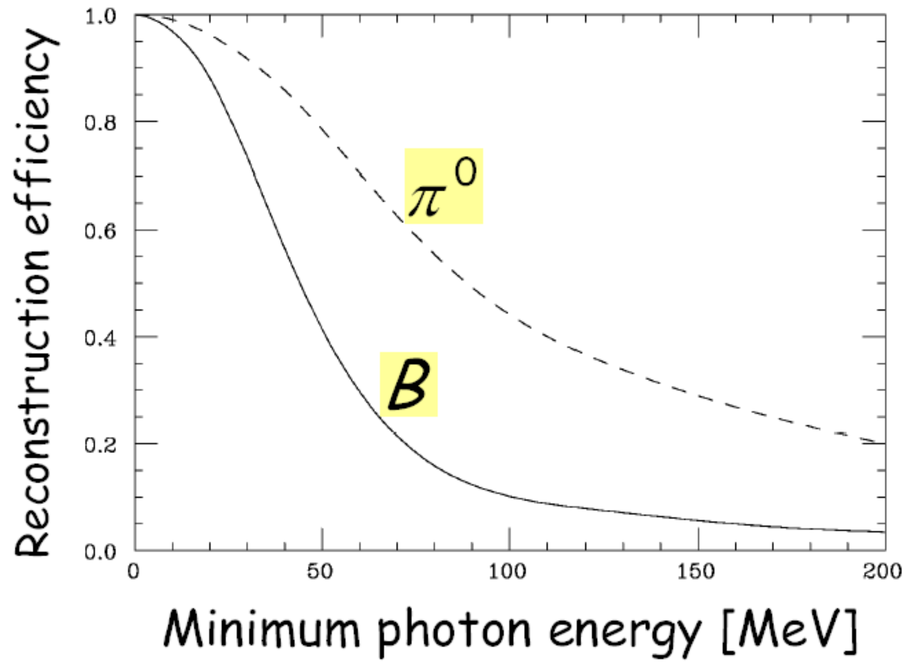



# Calorimetry in Belle II

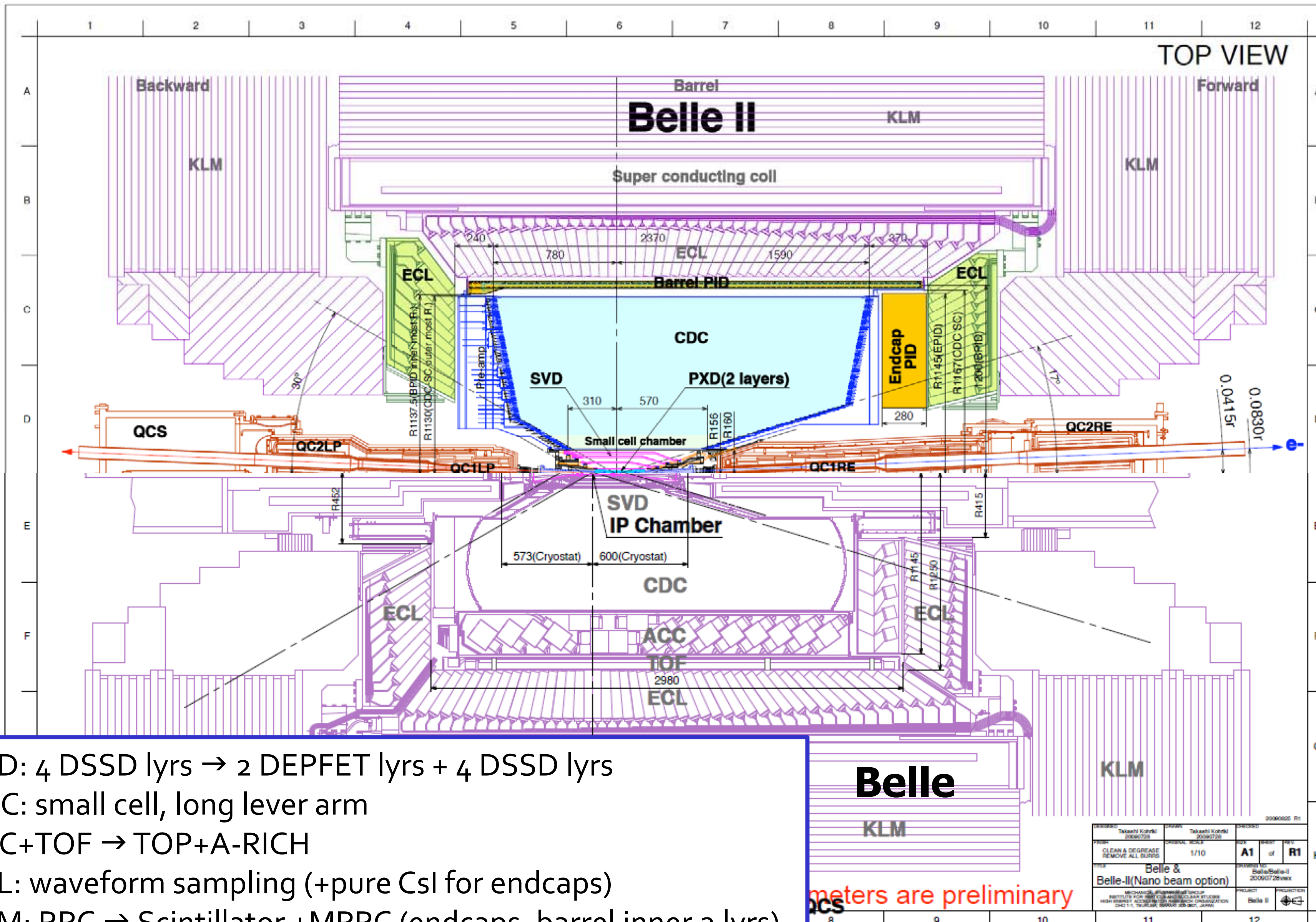


# Requirements: Photons



# Belle II Detector (in comparison with Belle)



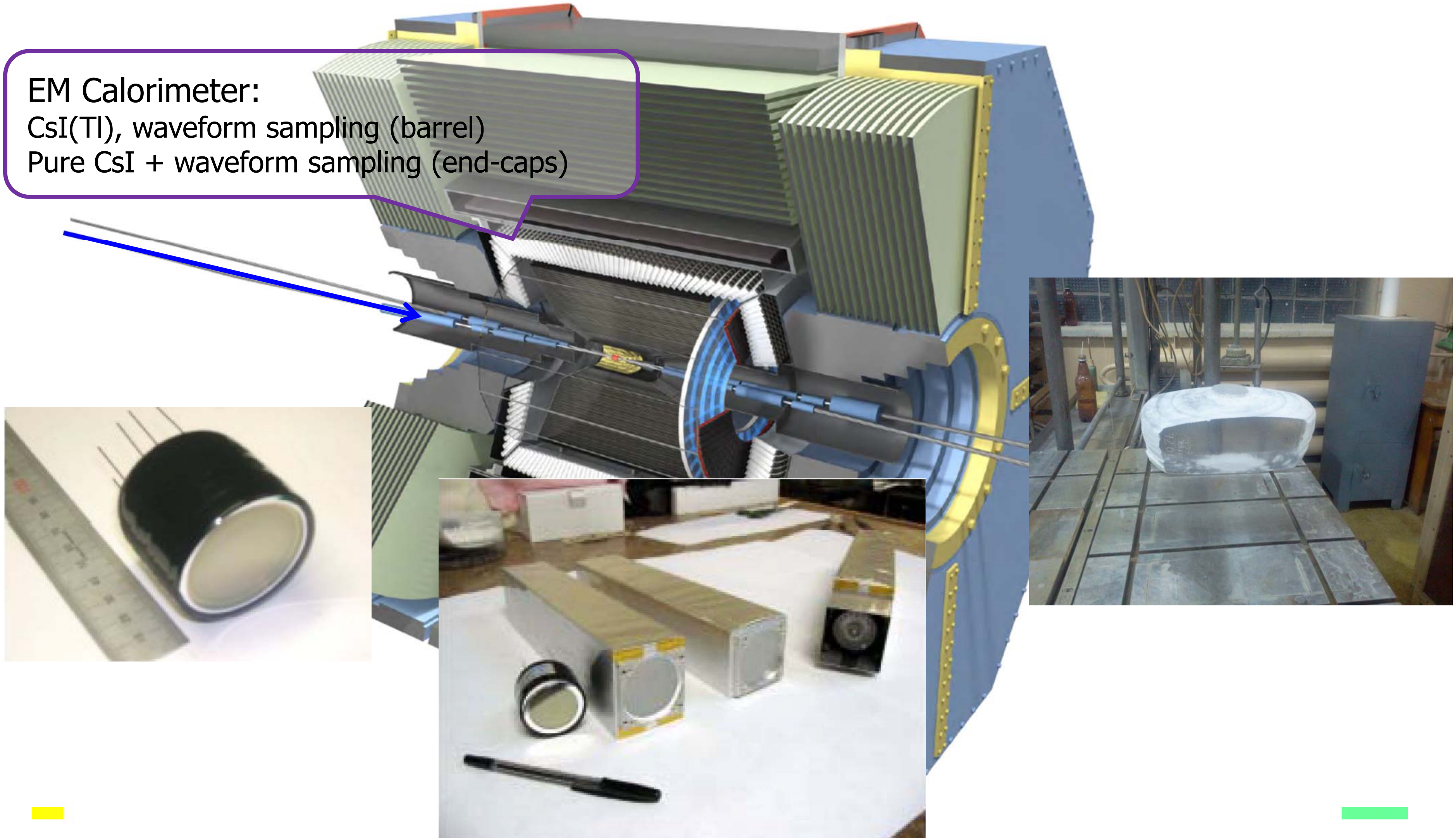

SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling (+pure CsI for endcaps)
KLM: RPC → Scintillator +MPPC (endcaps, barrel inner 2 lyrs)

# Comparison of Inorganic Scintillators

| Scintillator material | Density (g/cm³) | Radiation length | Refractive index | Wavelength at peak | Decay time | Light yield (Y/MeV) |
|---|---|---|---|---|---|---|
| NaI (Tl) | 3.67 | 2.59 cm | 1.78 | 410 nm | 230 ns | 4.1 x$10^4$ |
| CsI (Tl) | 4.51 | 1.86 cm | 1.85 | 550 nm | 800–6000 ns | 6.6 x$10^4$ |
| CsI (Na) | 4.51 | 1.86 cm | 1.80 | 420 nm | 630 ns | 4.0 x$10^4$ |
| $LaBr_3$ (Ce) | 5.3 | 1.88 cm | 1.9 | 358 nm | 35 ns | 6.1 x$10^4$ |
| $Bi_4Si_3O_{12}$ BSO | 6.8 | 1.15 cm | 2.06 | 480 nm | 100 ns | 0.2 x$10^4$ |
| $Bi_4Ge_3O_{12}$ BGO | 7.1 | 1.12 cm | 2.15 | 480 nm | 300 ns | 0.9 x$10^4$ |
| $CdWO_4$ | 7.9 | 1.1 cm | 2.25 | 495 nm | 5000 ns | 2.0 x$10^4$ |
| $YAlO_3$ (Ce) YAP | 5.5 | 2.9 cm | 1.94 | 350 nm | 30 ns | 2.1 x$10^4$ |
| $Lu_3Al_5O_7$ (Ce) LuAG | 7.4 | 1.4 cm | 1.84 | 420 nm | 40 ns | 2.6 x$10^4$ |
| $Gd_2SiO_5$ (Ce) GSO | 6.7 | 1.4 cm | 1.87 | 440 nm | 60 ns | 0.8 x$10^4$ |
| $PbWO_4$ | 8.3 | 0.89 cm | 1.82 | 425 nm | 25 ns | 0.05 x$10^4$ |

EM calorimeter: upgrade needed because of higher rates (barrel: electronics, endcap: electronics and CsI(Tl) → pure CsI), and radiation load (endcap: CsI(Tl) → pure CsI)

EM Calorimeter:
CsI(Tl), waveform sampling (barrel)
Pure CsI + waveform sampling (end-caps)



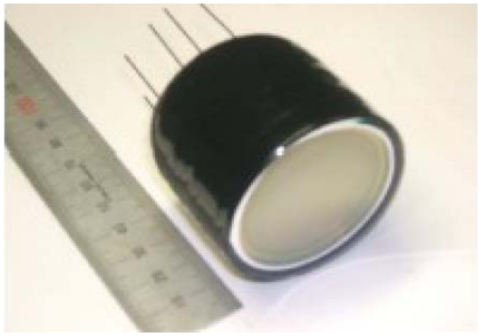
EM calorimeter: upgrade needed because of

•higher rates (barrel: electronics, endcap: electronics and CsI(Tl) → pure CsI), and

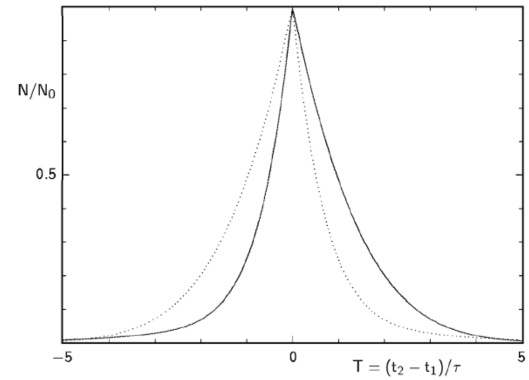
•radiation load (endcap: CsI(Tl) → pure CsI)

Pure CsI is faster, but has a smaller light yield...

→replace photodiodes with a special kind of PMT (photopentode) that can be operated in magnetic field

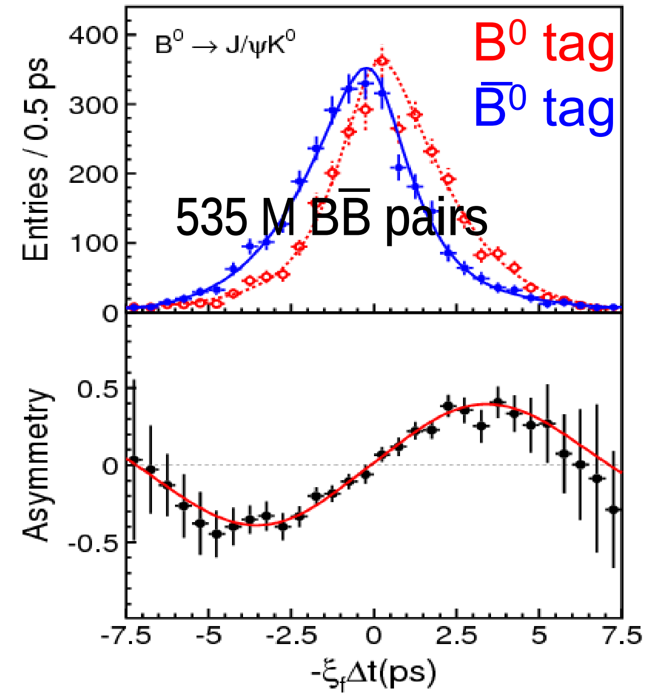


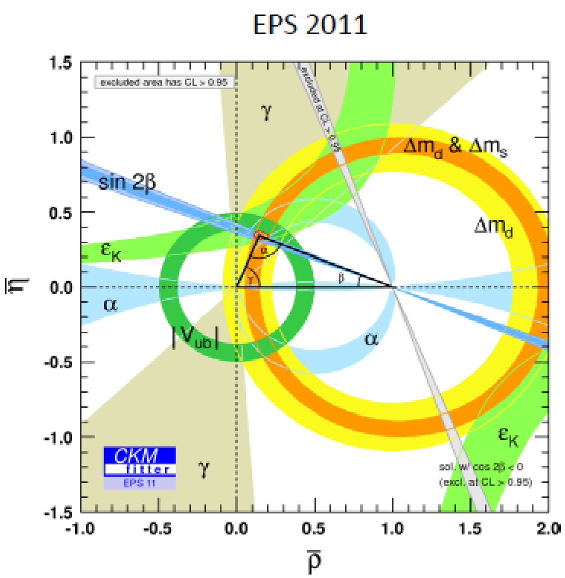
# B factories main result: CP violation in the B system




CP violation in B system: from the discovery (2001) to a precision measurement

$\sin 2\phi_1 / \sin 2\beta$ from $b \rightarrow c\bar{c}s$



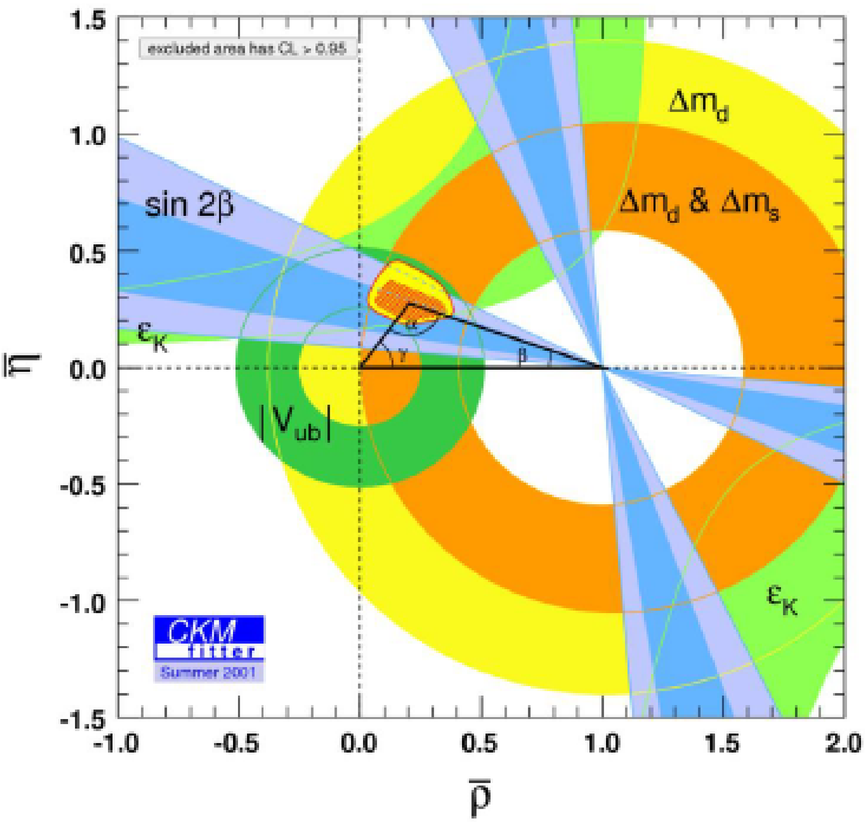




Constraints from measurements of angles and sides of the unitarity triangle → Remarkable agreement

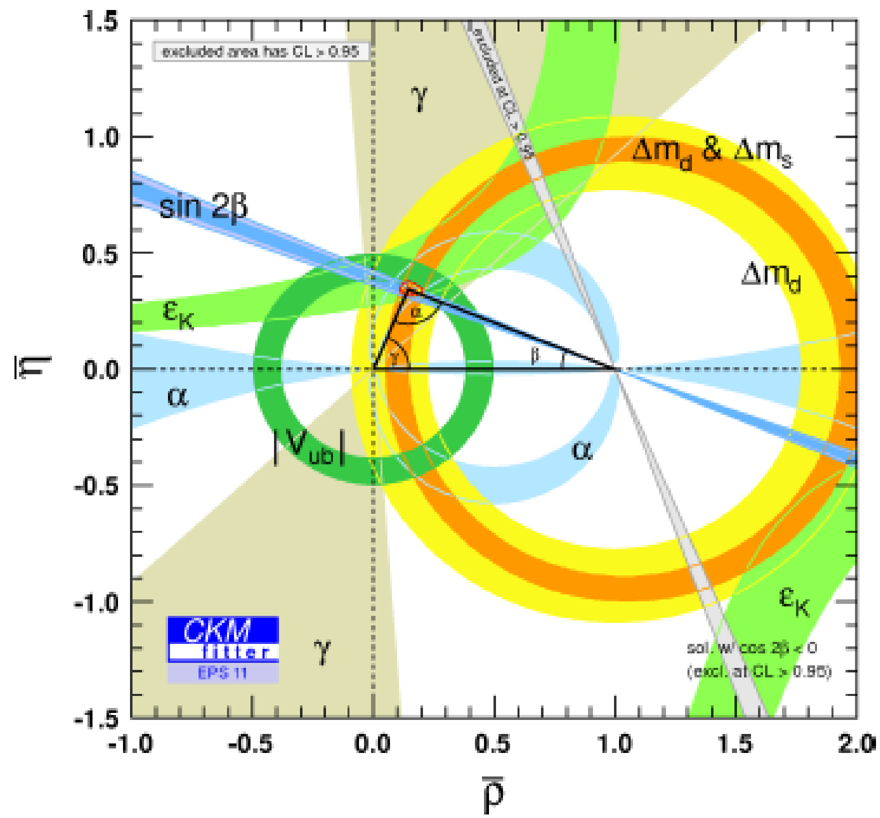
# Unitarity triangle – 2011 vs 2001

CP violation in the B system: from the discovery (2001) to a precision measurement (2011).

EPS 2001




EPS 2011

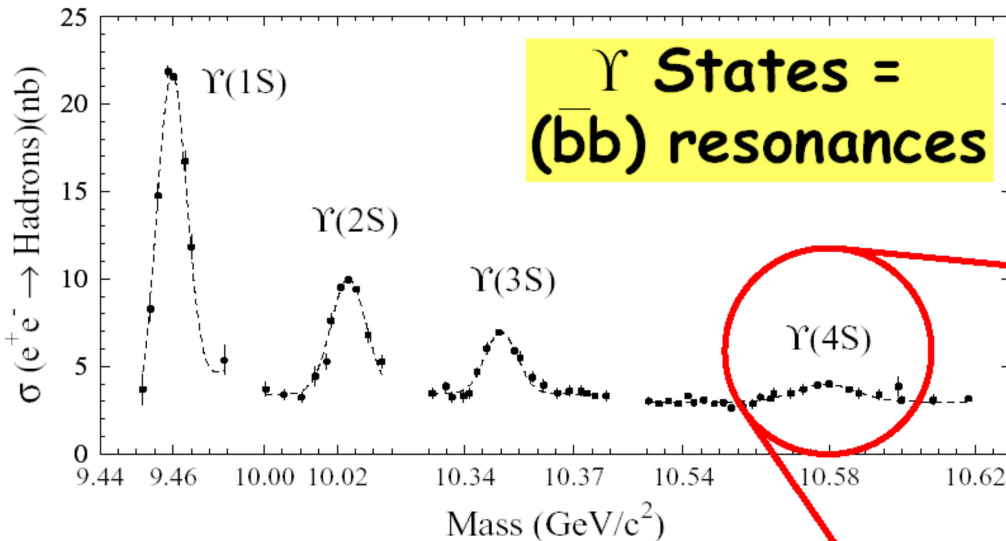


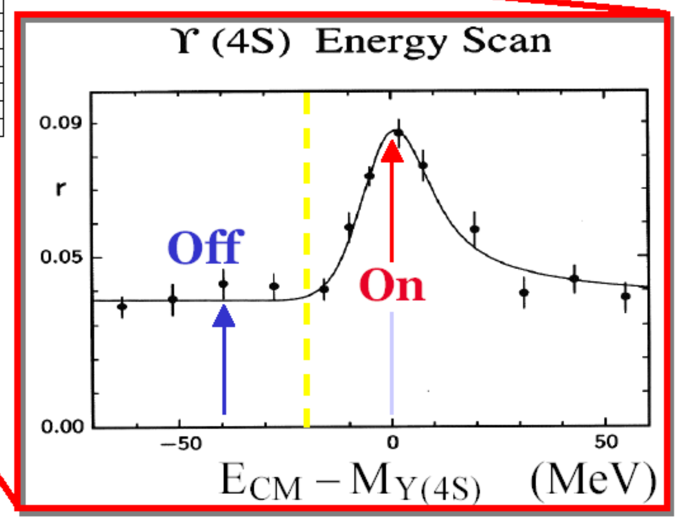
# B factories: a success story

- Measurements of CKM matrix elements and angles of the unitarity triangle
- Observation of direct CP violation in B decays
- Measurements of rare decay modes (e.g., $B \rightarrow \tau\nu$, $D\tau\nu$)
- $b \rightarrow s$ transitions: probe for new sources of CPV and constraints from the $b \rightarrow s\gamma$ branching fraction
- Forward-backward asymmetry ($A_{FB}$) in $b \rightarrow sl^+l^-$ has become a powerfull tool to search for physics beyond SM.
- Observation of D mixing
- Searches for rare $\tau$ decays
- Observation of new hadrons

# More slides...

# Systematic studies of B mesons: at $\Upsilon$(4s)




**Cross Sections at $\Upsilon$(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

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

$L = 1$ state

# Systematic studies of B mesons at $\Upsilon(4s)$

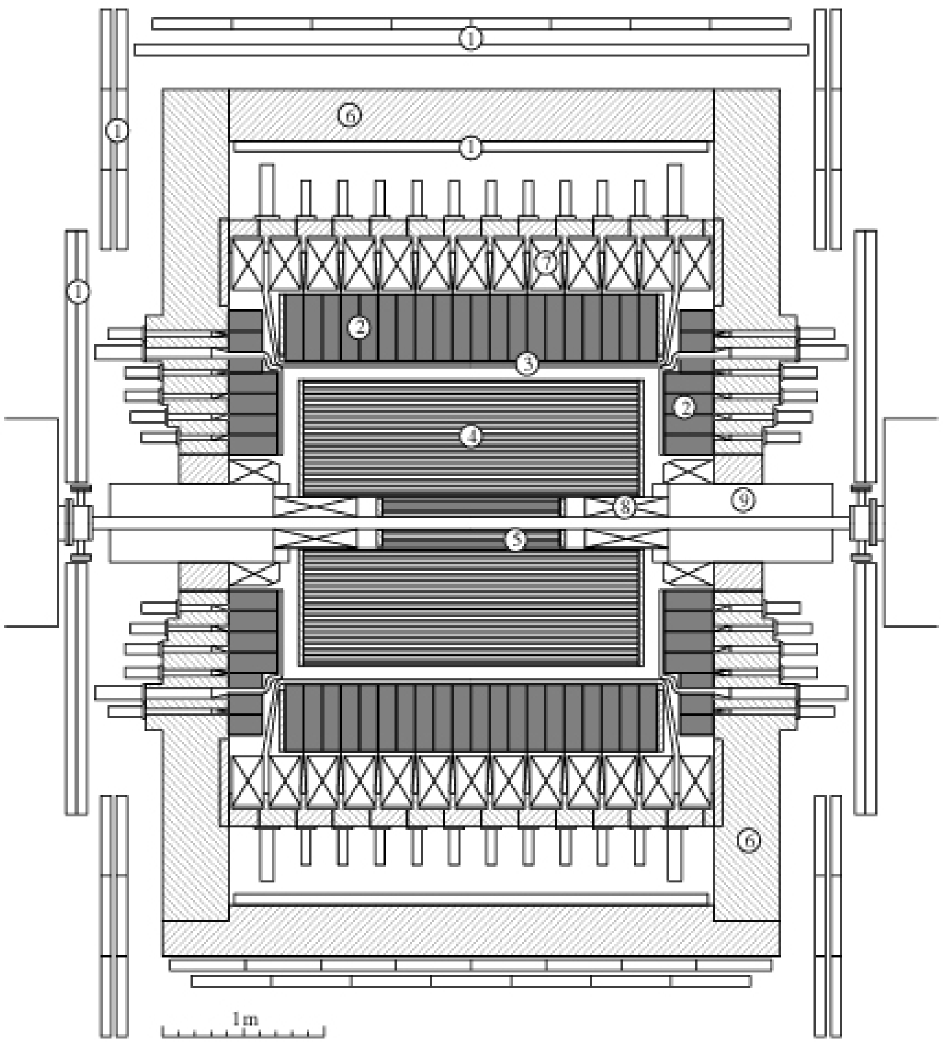
80s-90s: two very successful experiments:

•ARGUS at DORIS (DESY)

•CLEO at CESR (Cornell)

Magnetic spectrometers at $e^+e^-$ colliders (5.3GeV+5.3GeV beams)

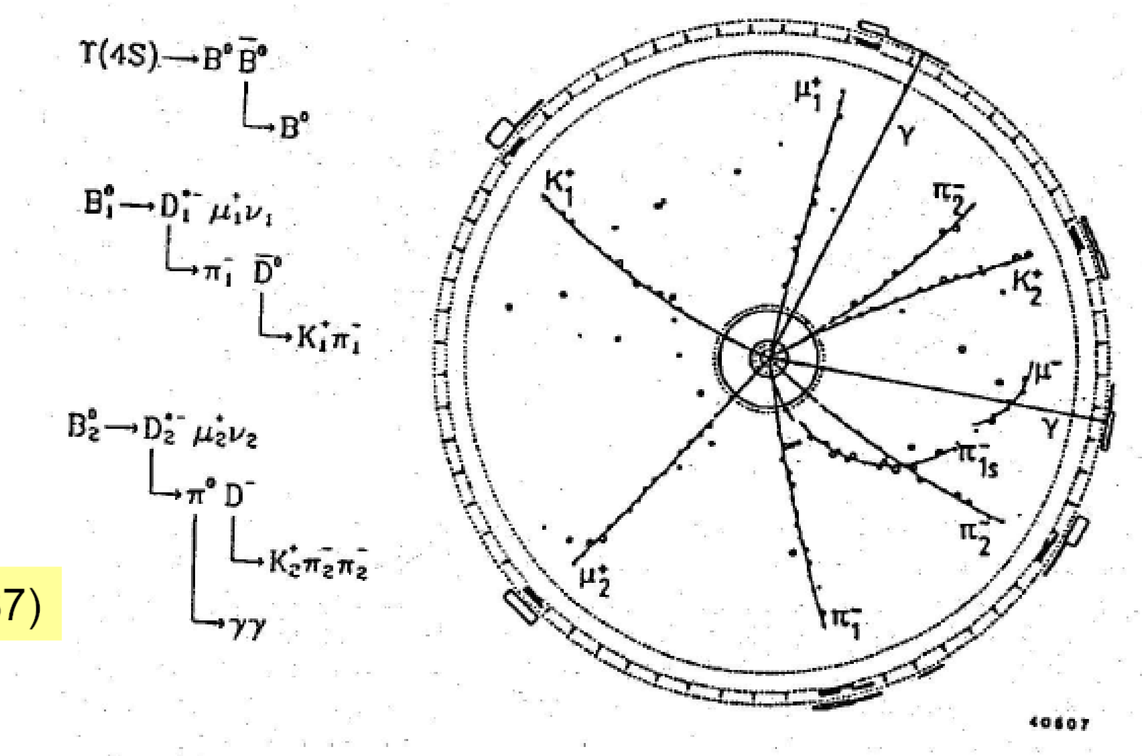
Large solid angle, excellent tracking and good particle identification (TOF, dE/dx, EM calorimeter, muon chambers).



# Mixing in the $B^0$ system

1987: ARGUS discovers BB mixing: $B^0$ turns into anti-$B^0$

Reconstructed event




$\chi_d = 0.17 \pm 0.05$

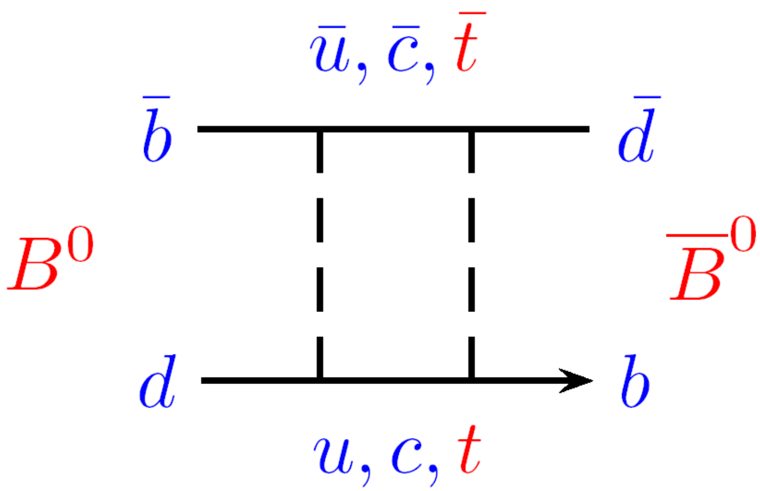
ARGUS, PL B **192**, 245 (1987)

cited >1000 times.

Time-integrated mixing rate: 25 like sign, 270 opposite sign dilepton events

Integrated Y(4S) luminosity 1983-87: 103 $pb^{-1}$ ~110,000 B pairs

# Mixing in the $B^0$ system




$$\Delta m \propto$$

$$|V_{tb}^* \, V_{td}|^2 m_t^2 \;\propto\; \lambda^6 m_t^2$$

$$|V_{cb}^* \, V_{cd}|^2 m_c^2 \;\propto\; \lambda^6 m_c^2$$

Large mixing rate → high top mass (in the Standard Model)

The top quark has only been discovered seven years later!

# Time evolution in the B system

An arbitrary linear combination of the neutral B-meson flavor eigenstates

$$a\left|B^0\right\rangle + b\left|\overline{B}^0\right\rangle$$

is governed by a time-dependent Schroedinger equation

$$i\frac{d}{dt}\begin{pmatrix} a \\ b \end{pmatrix} = H\begin{pmatrix} a \\ b \end{pmatrix} = (M - \frac{i}{2}\Gamma)\begin{pmatrix} a \\ b \end{pmatrix}$$

M and $\Gamma$ are 2x2 Hermitian matrices. CPT invariance →$H_{11}=H_{22}$

$$M = \begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix}, \Gamma = \begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}$$

diagonalize →

# Time evolution in the B system

The light $B_L$ and heavy $B_H$ mass eigenstates with eigenvalues $m_H, \Gamma_H, m_L, \Gamma_L$ are given by

$$\left| B_L \right\rangle = p \left| B^0 \right\rangle + q \left| \overline{B}^0 \right\rangle$$

$$\left| B_H \right\rangle = p \left| B^0 \right\rangle - q \left| \overline{B}^0 \right\rangle$$

With the eigenvalue differences

$$\Delta m_B = m_H - m_L, \Delta\Gamma_B = \Gamma_H - \Gamma_L$$

They are determined from the M and $\Gamma$ matrix elements

$$(\Delta m_B)^2 - \frac{1}{4}(\Delta\Gamma_B)^2 = 4(\left|M_{12}\right|^2 - \frac{1}{4}\left|\Gamma_{12}\right|^2)$$

$$\Delta m_B \Delta\Gamma_B = 4\,\mathrm{Re}(M_{12}\Gamma_{12}^*)$$

The ratio p/q is

$$\frac{q}{p} = -\frac{\Delta m_B - \frac{i}{2}\Delta\Gamma_B}{2(M_{12} - \frac{i}{2}\Gamma_{12})} = -\frac{2(M_{12}{}^* - \frac{i}{2}\Gamma_{12}{}^*)}{\Delta m_B - \frac{i}{2}\Delta\Gamma_B}$$

What do we know about $\Delta m_B$ and $\Delta\Gamma_B$?

$\Delta m_B$=(0.502+-0.007) ps$^{-1}$ well measured

→ $\Delta m_B/\Gamma_B = x_d$ =0.771+-0.012

$\Delta\Gamma_B/\Gamma_B$ not measured, expected O(0.01), due to decays common to B and anti-B - O(0.001).

→ **$\Delta\Gamma_B << \Delta m_B$**

Since $\Delta\Gamma_B << \Delta m_B$

$$\Delta m_B = 2|M_{12}|$$

$$\Delta\Gamma_B = 2\,\mathrm{Re}(M_{12}\Gamma_{12}^*)/|M_{12}|$$

and

$$\frac{q}{p} = -\frac{|M_{12}|}{M_{12}}$$

= a phase factor

or to the next order

$$\frac{q}{p} = -\frac{|M_{12}|}{M_{12}}\left[1 - \frac{1}{2}\mathrm{Im}\left(\frac{\Gamma_{12}}{M_{12}}\right)\right]$$

$B^0$ and $\overline{B}^0$ can be written as an admixture of the states $B_H$ and $B_L$

$$\left| B^0 \right\rangle = \frac{1}{2p}\left( \left| B_L \right\rangle + \left| B_H \right\rangle \right)$$

$$\left| \overline{B}^0 \right\rangle = \frac{1}{2q}\left( \left| B_L \right\rangle - \left| B_H \right\rangle \right)$$

# Time evolution

Any B state can then be written as an admixture of the states $B_H$ and $B_L$, and the amplitudes of this admixture evolve in time

$$a_H(t) = a_H(0) e^{-iM_H t} e^{-\Gamma_H t/2}$$

$$a_L(t) = a_L(0) e^{-iM_L t} e^{-\Gamma_L t/2}$$

A $B^0$ state created at t=0 (denoted by $B^0_{phys}$) has

$a_H(0) = a_L(0) = 1/(2p)$;

an anti-B at t=0 (anti-$B^0_{phys}$) has

$a_H(0) = -a_L(0) = 1/(2q)$

At a later time t, the two coefficients are not equal any more because of the difference in phase factors exp(-iMt)

→initial $B^0$ becomes a linear combination of B and anti-B

→mixing

# Time evolution of B's

Time evolution can also be written in the $B^0$ in $\overline{B}^0$ basis:

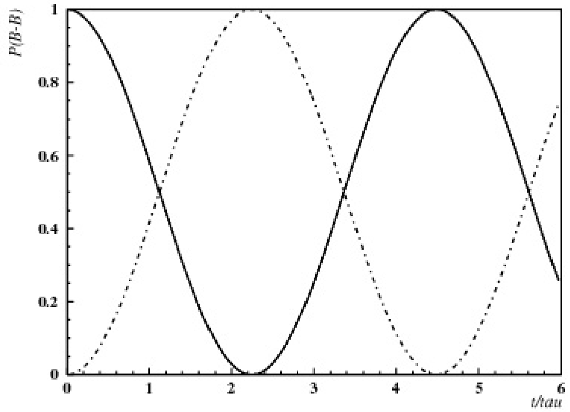
$$\left|B^0_{phys}(t)\right\rangle = g_+(t)\left|B^0\right\rangle + (q/p)g_-(t)\left|\overline{B}^0\right\rangle$$
$$\left|\overline{B}^0_{phys}(t)\right\rangle = (p/q)g_-(t)\left|B^0\right\rangle + g_+(t)\left|\overline{B}^0\right\rangle$$

with
$$g_+(t) = e^{-iMt}e^{-\Gamma t/2}\cos(\Delta m t/2)$$
$$g_-(t) = e^{-iMt}e^{-\Gamma t/2}i\sin(\Delta m t/2)$$

$M = (M_H+M_L)/2$

If B mesons were stable ($\Gamma=0$), the time evolution would look like:

$$g_+(t) = e^{-iMt}\cos(\Delta m t/2)$$
$$g_-(t) = e^{-iMt}\, i\sin(\Delta m t/2)$$




→Probability that a B turns into its anti-particle

→beat in classical mechanics

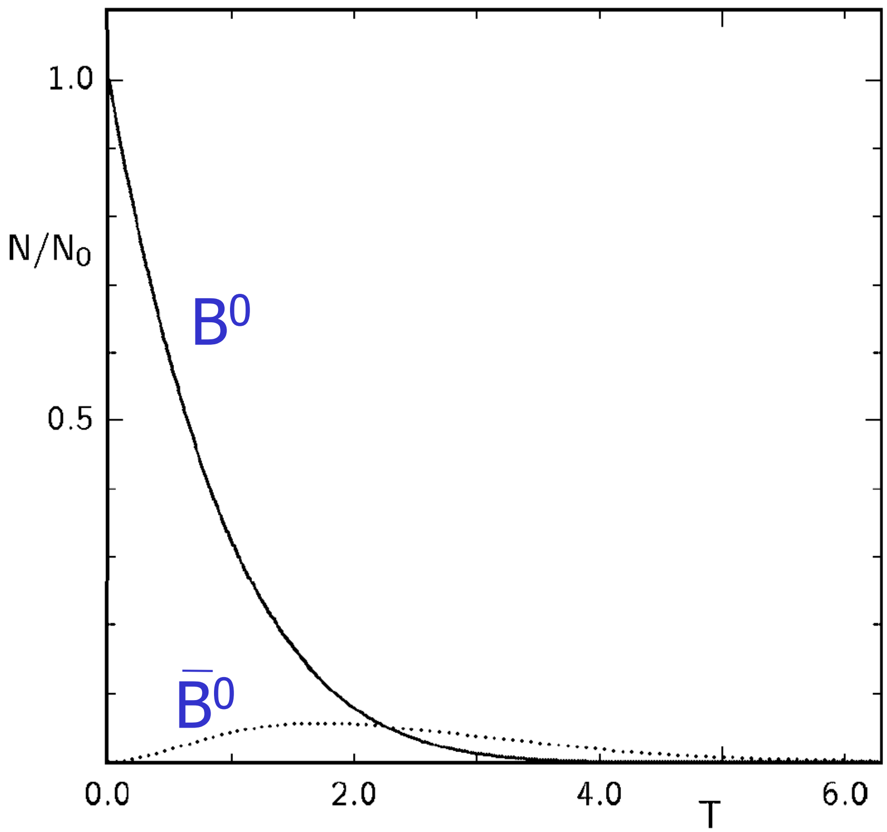
$$\left|\left\langle \overline{B}^0 \middle| B^0_{phys}(t)\right\rangle\right|^2 = |q/p|^2 |g_-(t)|^2 = |q/p|^2 \sin^2(\Delta m t/2)$$

→Probability that a B remains a B

$$\left|\left\langle B^0 \middle| B^0_{phys}(t)\right\rangle\right|^2 = |g_+(t)|^2 = \cos^2(\Delta m t/2)$$

→Expressions familiar from quantum mechanics of a two level system

# B mesons of course do decay →




$B^0$ at t=0

Evolution in time

- Full line: $B^0$
- dotted: $B^0$

T: in units of $\tau=1/\Gamma$

# Decay probability

Decay probability $$P(B^0 \to f,t) \propto \left| \langle f | H | B^0_{phys}(t) \rangle \right|^2$$

Decay amplitudes of B and anti-B to the same final state ***f***

$$A_f = \langle f | H | B^0 \rangle$$

$$\overline{A}_f = \langle f | H | \overline{B}^0 \rangle$$

Decay amplitude as a function of time:

$$\langle f | H | B^0_{phys}(t) \rangle = g_+(t) \langle f | H | B^0 \rangle + (q/p) g_-(t) \langle f | H | \overline{B}^0 \rangle$$

$$= g_+(t) A_f + (q/p) g_-(t) \overline{A}_f$$

... and similarly for the anti-B

# CP violation: three types

Decay amplitudes of B and anti-B to the same final state ***f***

$$A_f = \langle f | H | B^0 \rangle$$

$$\bar{A}_f = \langle f | H | \bar{B}^0 \rangle$$

Define a parameter λ

$$\lambda = \frac{q}{p} \frac{\bar{A}_f}{A_f}$$

Three types of CP violation (CPV):

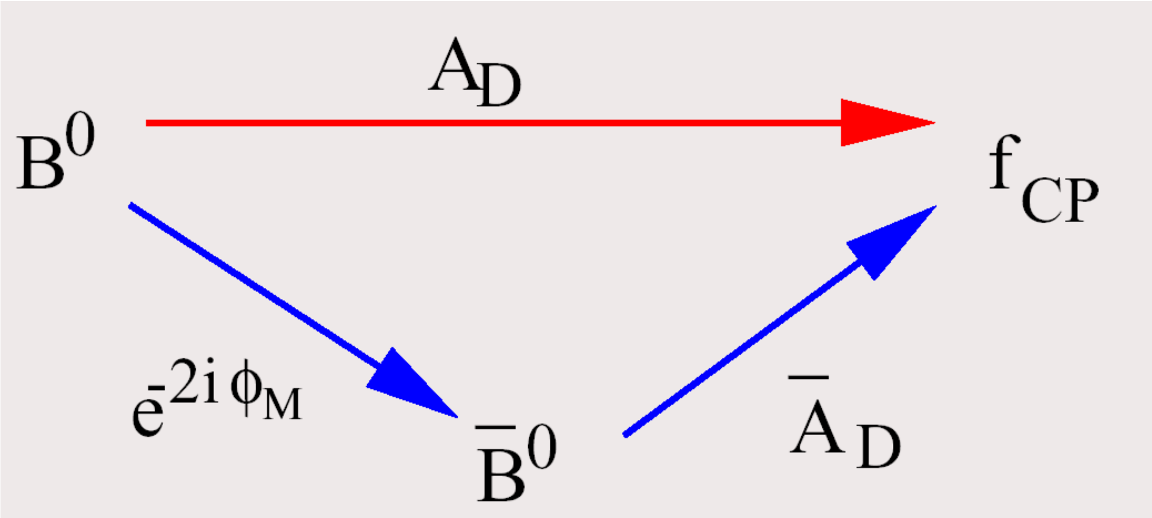
$$\left.\begin{array}{l} \cancel{CP} \text{ in decay: } |\bar{A}/A| \neq 1 \\ \\ \cancel{CP} \text{ in mixing: } |q/p| \neq 1 \end{array}\right\} |\lambda| \neq 1$$

$\cancel{CP}$ in interference between mixing and decay: even if $|\lambda| = 1$ if only $\mathrm{Im}(\lambda) \neq 0$

# CP violation in the interference between decays with and without mixing

CP violation in the interference between mixing and decay to a state accessible in both $B^0$ and anti-$B^0$ decays

For example: a CP eigenstate $f_{CP}$ like $\pi^+ \pi^-$




$$\lambda = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

**We can get CP violation if $\mathrm{Im}(\lambda) \neq 0$, even if $|\lambda| = 1$**

# CP violation in the interference between decays with and without mixing

Decay rate asymmetry:

$$a_{f_{CP}} = \frac{P(\overline{B}^0 \to f_{CP}, t) - P(B^0 \to f_{CP}, t)}{P(\overline{B}^0 \to f_{CP}, t) + P(B^0 \to f_{CP}, t)}$$

Decay rate:

$$P(B^0 \to f_{CP}, t) \propto \left| \left\langle f_{CP} \middle| H \middle| B^0_{phys}(t) \right\rangle \right|^2$$

Decay amplitudes vs time:

$$\left\langle f_{CP} \middle| H \middle| B^0_{phys}(t) \right\rangle = g_+(t) \left\langle f_{CP} \middle| H \middle| B^0 \right\rangle + (q/p) g_-(t) \left\langle f_{CP} \middle| H \middle| \overline{B}^0 \right\rangle$$

$$= g_+(t) A_{f_{CP}} + (q/p) g_-(t) \overline{A}_{f_{CP}}$$

$$\left\langle f_{CP} \middle| H \middle| \overline{B}^0_{phys}(t) \right\rangle = (p/q) g_-(t) \left\langle f_{CP} \middle| H \middle| B^0 \right\rangle + g_+(t) \left\langle f_{CP} \middle| H \middle| \overline{B}^0 \right\rangle$$

$$= (p/q) g_-(t) A_{f_{CP}} + g_+(t) \overline{A}_{f_{CP}}$$

$$a_{f_{CP}} = \frac{P(\overline{B}^0 \to f_{CP}, t) - P(B^0 \to f_{CP}, t)}{P(\overline{B}^0 \to f_{CP}, t) + P(B^0 \to f_{CP}, t)} =$$

$$= \frac{\left|(p/q) g_-(t) A_{f_{CP}} + g_+(t) \overline{A}_{f_{CP}}\right|^2 - \left|g_+(t) A_{f_{CP}} + (q/p) g_-(t) \overline{A}_{f_{CP}}\right|^2}{\left|(p/q) g_-(t) A_{f_{CP}} + g_+(t) \overline{A}_{f_{CP}}\right|^2 + \left|g_+(t) A_{f_{CP}} + (q/p) g_-(t) \overline{A}_{f_{CP}}\right|^2} =$$

$$= \frac{(1 - |\lambda_{f_{CP}}|^2)\cos(\Delta m t) - 2\,\mathrm{Im}(\lambda_{f_{CP}})\sin(\Delta m t)}{1 + |\lambda_{f_{CP}}|^2}$$

$$= C\cos(\Delta m t) + S\sin(\Delta m t)$$

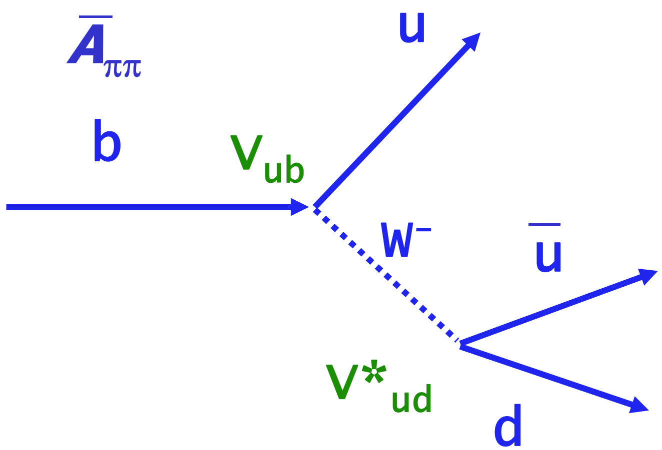
$$\lambda = \frac{q}{p}\frac{\overline{A}_f}{A_f}$$

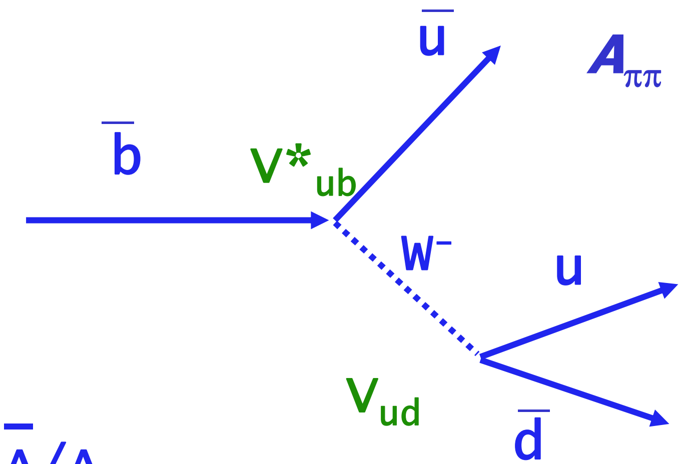
**Non-zero effect if Im(λ) ≠ 0,**
**even if |λ| = 1**

**If |λ| = 1 →** $$\boxed{a_{f_{CP}} = -\mathrm{Im}(\lambda)\sin(\Delta m t)}$$

Detailed derivation → backup slides

# Decay asymmetry predictions – example $\pi^+ \pi^-$




$$\lambda_{\pi\pi} = \eta_{\pi\pi} \overbrace{\boxed{\left(\frac{V_{tb}^{*} V_{td}}{V_{tb} V_{td}^{*}}\right)}}^{(q/p)} \overbrace{\boxed{\left(\frac{V_{ud}^{*} V_{ub}}{V_{ud} V_{ub}^{*}}\right)}}^{\bar{A}/A}$$

$$\mathrm{Im}(\lambda_{\pi\pi}) = \sin 2\phi_2$$

$$\alpha \equiv \phi_2 \equiv \arg\left(\frac{V_{td} V_{tb}^{*}}{V_{ud} V_{ub}^{*}}\right)$$

N.B.: for simplicity we have neglected possible penguin amplitudes (which is wrong as we shall see later, when we will do it properly).

# Decay asymmetry predictions – example $J/\psi K_S$

$b \to c\bar{c}s$: Take into account that we measure the $\pi^+\pi^-$ component of $K_S$ – also need the $(q/p)_K$ for the K system

$$\lambda_{\psi Ks} = \eta_{\psi Ks} \underbrace{\left(\frac{V_{tb}^{*}V_{td}}{V_{tb}V_{td}^{*}}\right)}_{(q/p)_B} \underbrace{\left(\frac{V_{cs}^{*}V_{cb}}{V_{cs}V_{cb}^{*}}\right)}_{\bar{A}/A} \underbrace{\left(\frac{V_{cd}^{*}V_{cs}}{V_{cd}V_{cs}^{*}}\right)}_{(q/p)_K} =$$

$$= \eta_{\psi Ks} \left(\frac{V_{tb}^{*}V_{td}}{V_{tb}V_{td}^{*}}\right)\left(\frac{V_{cb}}{V_{cb}^{*}}\frac{V_{cd}^{*}}{V_{cd}}\right)$$

$$\mathrm{Im}(\lambda_{\psi Ks}) = \sin 2\phi_1$$

$$\beta \equiv \phi_1 \equiv \arg\left(\frac{V_{cd}V_{cb}^{*}}{V_{td}V_{tb}^{*}}\right)$$

$p_t$~1 GeV/c

B=1.5 T
L~1m
N~50
$X_0$~$2.9\cdot10^5$ cm

estimate:

$\sigma_{pt}/p_t$ ~
$\sqrt{[(8\cdot10^{-3})^2+(0.6\cdot10^{-3})^2]}$
3 $\quad$ $p_t^2$

measured:

$\sigma_{pt}/p_t$ ~
$\sqrt{[(3\cdot10^{-3})^2 p_t^2+(3\cdot10^{-3})^2]}$

how to measure?
→ calibration!