New Physics Searches in Flavour Physics: Introduction and Experimental Methods

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Contents

- Flavor physics: introduction, with a little bit of history
- Flavor physics at B factories: CP violation
- Flavor physics at B factories: rare decays and searches for NP effects
- Super B factory
- Flavor physics at hadron machines: history, LHCb and LHCb upgrade

Flavour physics

Flavour physics

… is about

- quarks

and

- their weak transitions and mixing
- CP violation

... and about searches for processes beyond the Standard Model

Contents, part 1

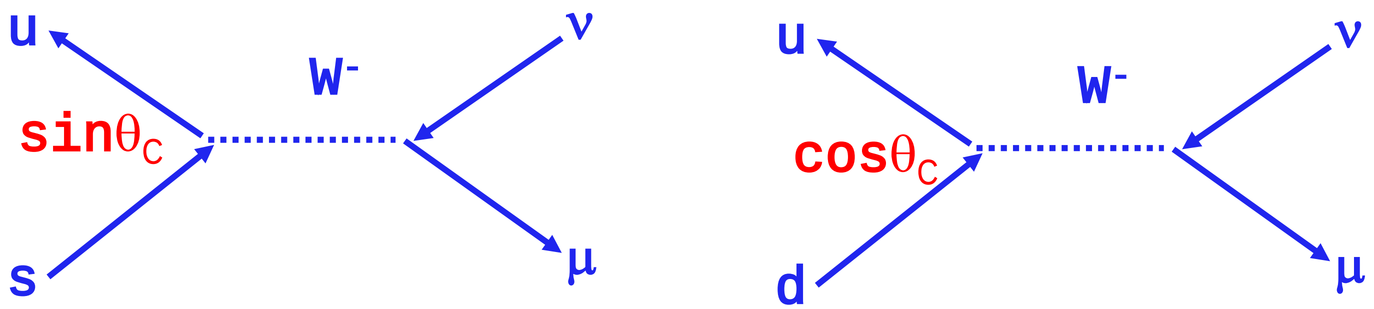
- **Flavor physics: introduction, with a little bit of history**
- **Flavor physics at B factories: CP violation**
- Flavor physics at B factories: rare decays and searches for NP effects
- Super B factory
- Flavor physics at hadron machines: history, LHCb and LHCb upgrade

Flavour physics - origins

Discovery of strange particles K and Λ (readily produced in pairs just like pions and protons – strong interaction, slow decay – weak interaction)

Difference in $K^- \to \mu^- \nu$ and $\pi^- \to \mu^- \nu$ decay rates:

→ u quark couples to d $\cos\theta_C$ + s $\sin\theta_C$ (N. Cabbibo, 1963)



$\sin\theta_C = 0.22$

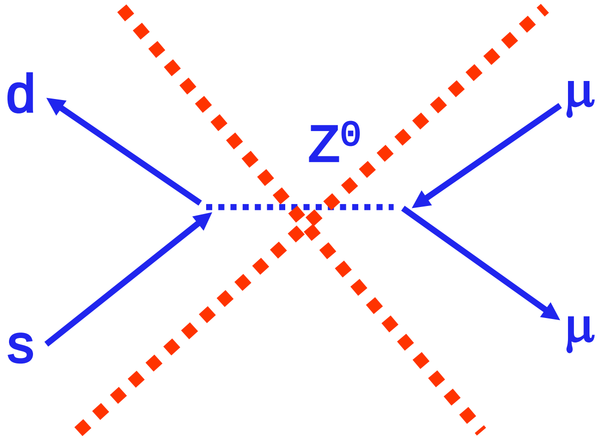
Flavour physics - origins

The smallness of $K_L \to \mu^+\mu^-$ (neutral current transition s→d) vs. $K^- \to \mu^- \nu$ (charged current s→u) by many orders of magnitude: can be solved if there is one more quark (c) – c quark couples to $-d \sin\theta_C + s \cos\theta_C$

Glashow-Iliopoulos-Maiani (GIM) mechanism forbids flavor changing neutral current (FCNC) transitions at tree level

From a measurement of the K^0 – anti-K^0 mixing frequency $\Delta m_K = m(K_L) - m(K_S)$ we can estimate the charm quark mass

forbidden



→c quark discovered in 1974!

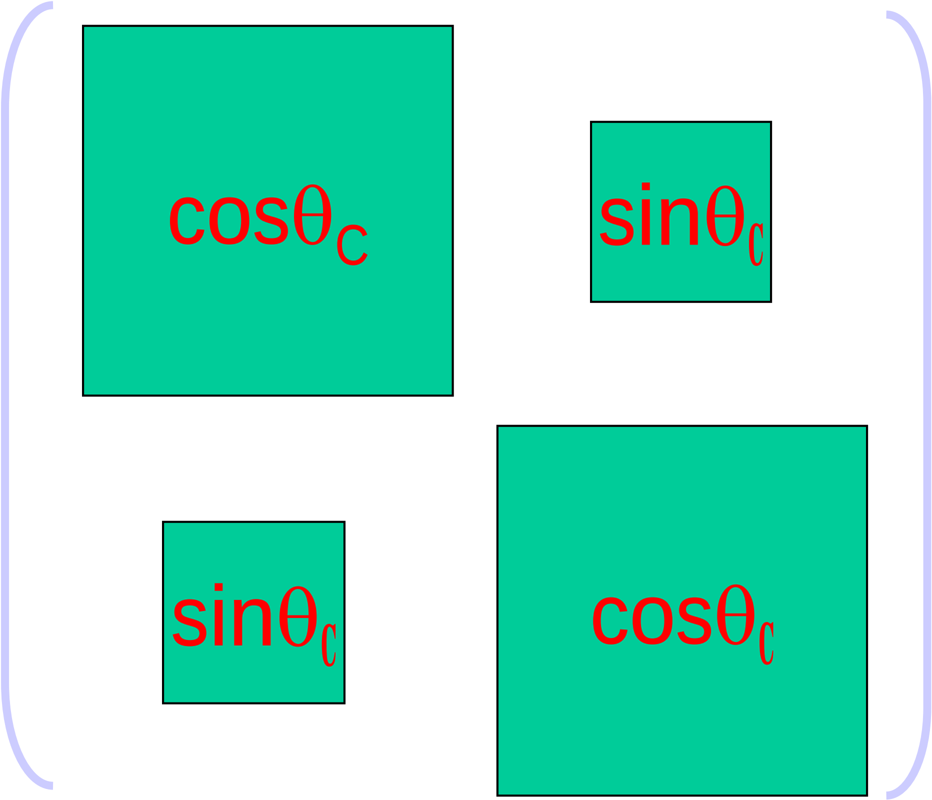
u and c

couple in weak interactions to

rotated d and s

u turns into d (probability $\cos^2\theta_C$)

u turns into s (probability $\sin^2\theta_C$)



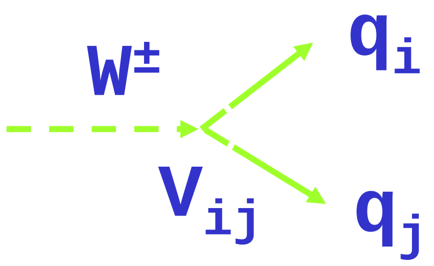
$\sin\theta_C = 0.22$

Flavour physics and CP violaton

Discovery of CP violation in $K_L \to \pi^+ \pi^-$ decays (Fitch, Cronin, 1964)

Kobayashi and Maskawa (1973): to accommodate CP violation into the Standard Model, need three quark generations, six quarks

Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix



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

Flavour physics and CP violaton

Kobayashi and Maskawa (1973): to accommodate CP violation into the Standard Model, need three quark generations, six quarks (at the time when only u, d, and s were known!)

The missing quarks were found, one by one, in 1974, in 1977, and in 1994.

How to test the CP violation part of their theory?

Nature was kind, made sure there is enough mixing in the B meson system

CP Violation

Fundamental quantity: distinguishes matter from anti-matter.

A bit of history:

- First seen in K decays in 1964
- Kobayashi and Maskawa propose in 1973 a mechanism to fit it into the Standard Model
- Discovery of a large B-anti-B mixing at ARGUS in 1987 indicated that the effect could be large in B decays (I.Bigi and T.Sanda)
- Many experiments were proposed to measure CP violation in B decays, some general purpose experiments tried to do it
- Measured in the B system in 2001 by the two dedicated spectrometers Belle and BaBar at asymmetric e^+e^- colliders - B factories

What happens in the B meson system?

Why is it interesting? Need at least one more system to understand the mechanism of CP violation.

Kaon system: not easy to understand what is going on at the quark level (light quark bound system, large dimensions).

B has a heavy quark, a smaller system, and is easier for interpreting the experimental results.

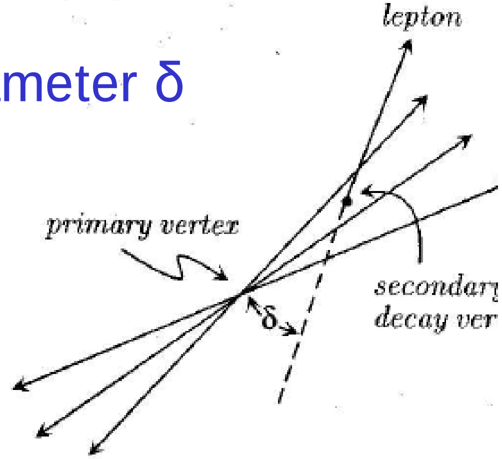
First B meson studies were carried out in 1970s at e^+e^- colliders with c.m.s. energies ~20GeV, considerably above threshold (~2x5.3GeV)

B meson decays: mainly through a $b \rightarrow c$ transition, with a relative strength of V_{cb}

B mesons: long lifetime

Isolate samples of high-p_T leptons (155 muons, 113 electrons) wrt thrust axis

Measure impact parameter δ wrt interaction point

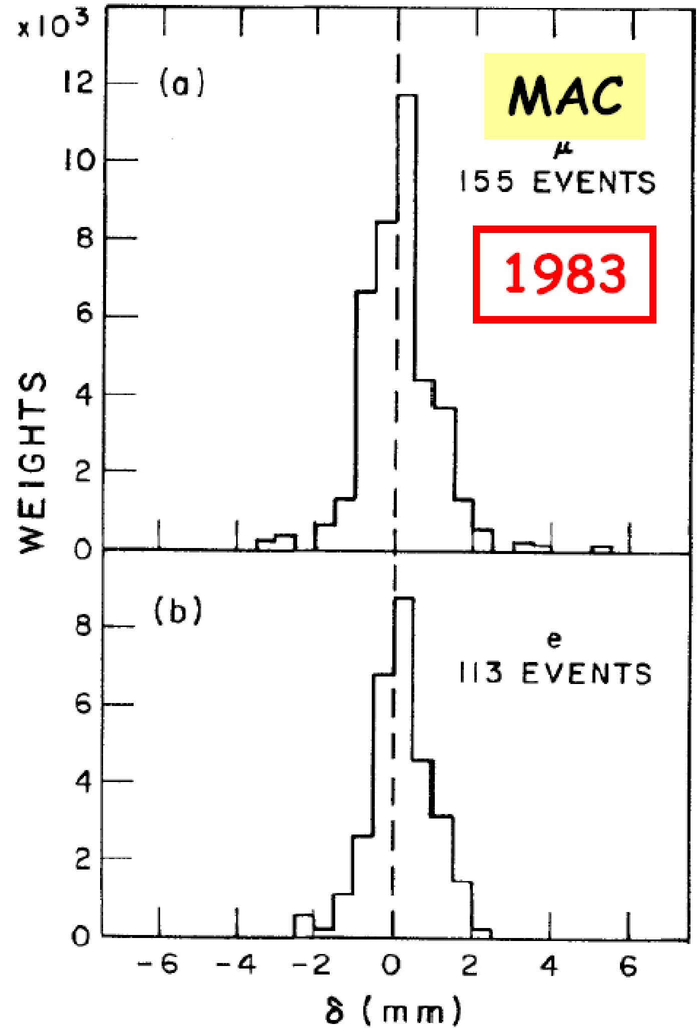


Lifetime implies: V_{cb} small

MAC: (1.8±0.6±0.4)ps

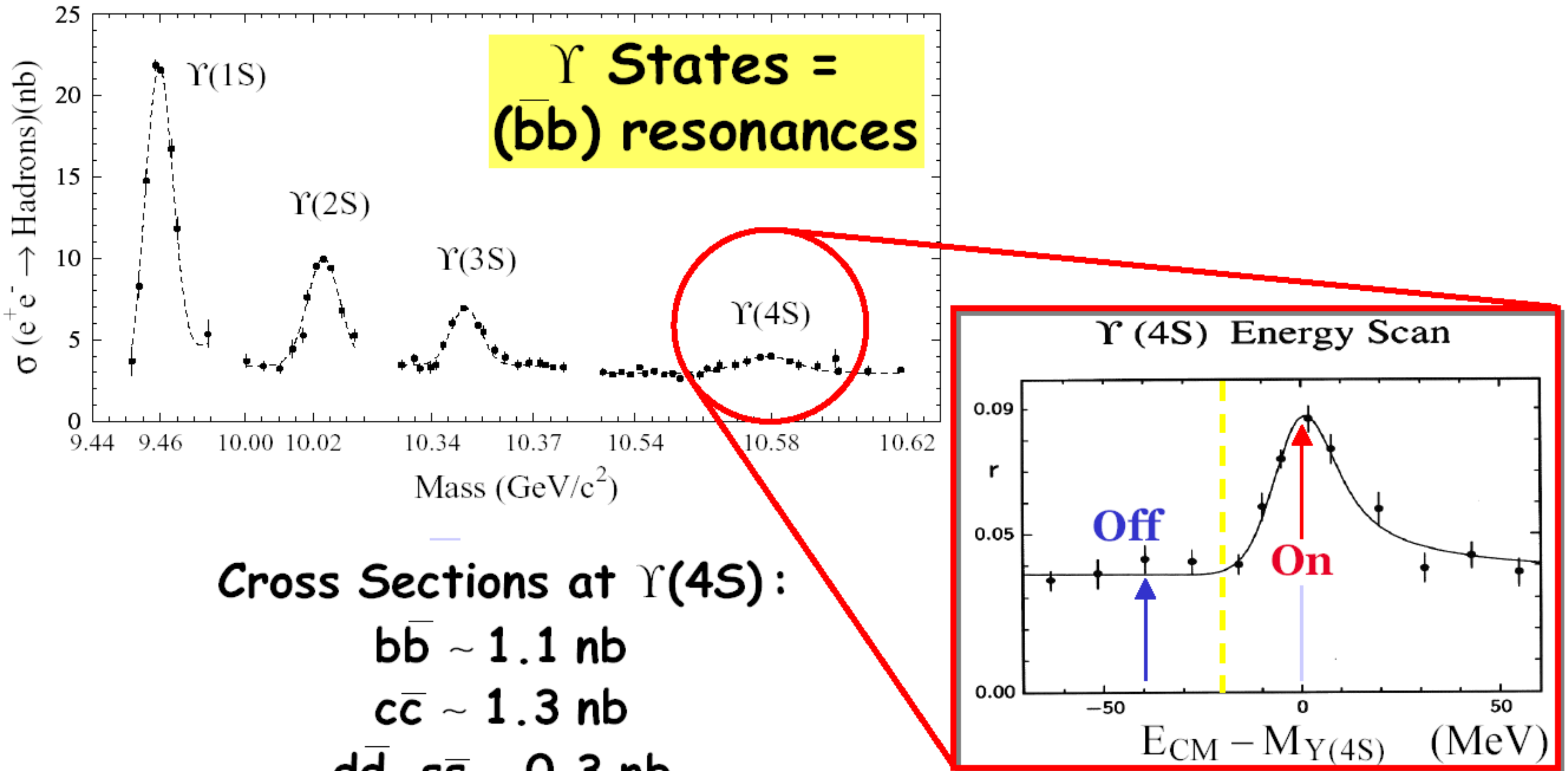
Mark II: (1.2±0.4±0.3)ps

Integrated luminosity at 29 GeV: 109 (92) pb^{-1}~3,500 bb pairs



MAC, PRL **51**, 1022 (1983)
MARK II, PRL **51**, 1316 (1983)

Systematic studies of B mesons: at Υ(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

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

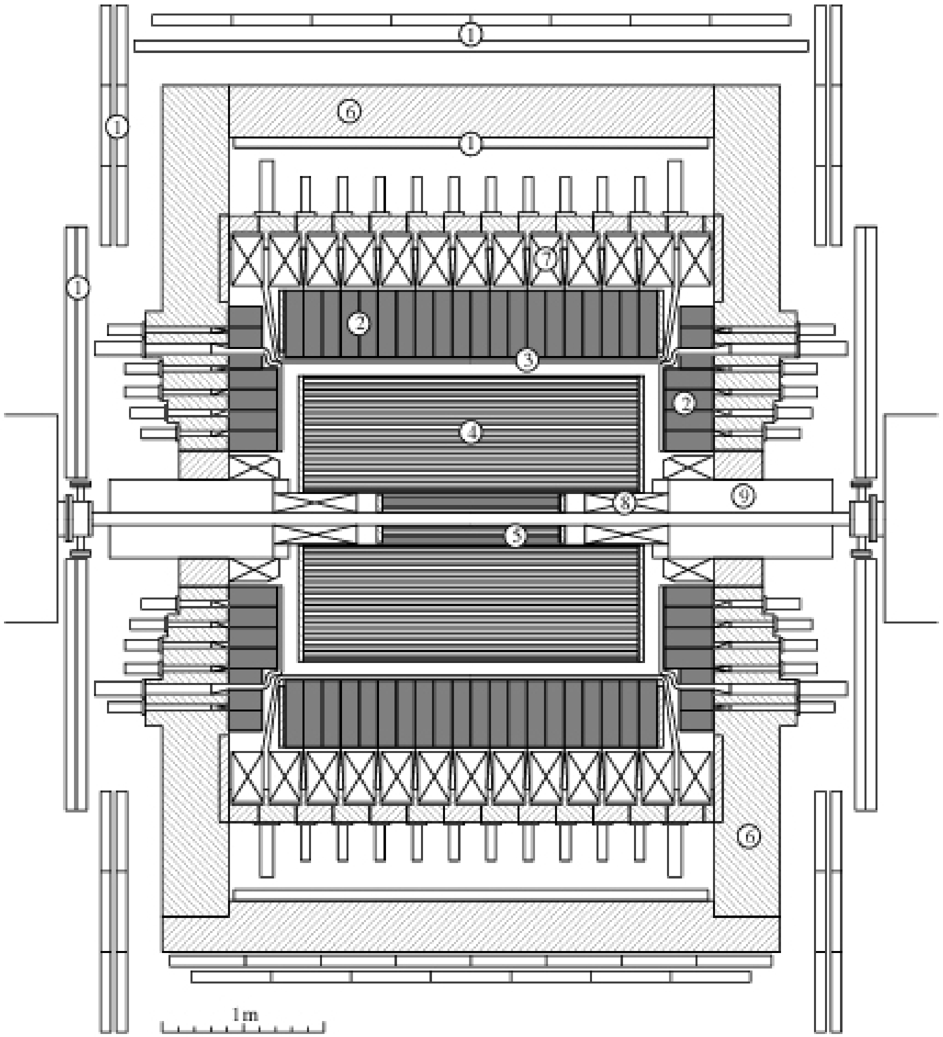
80s-90s: two very successful experiments:

•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).



Argus: part of the group in 1988

Mixing in the B^0 system

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

Produce: B and anti-B

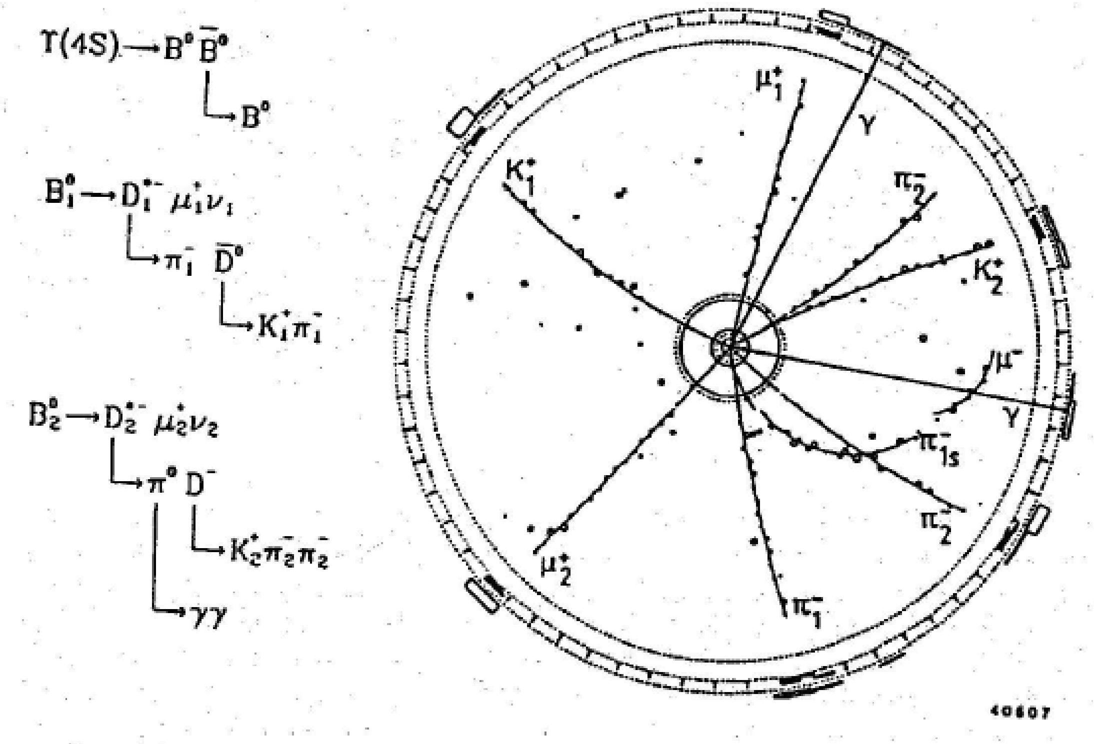
Detect: B and B

Reconstructed event

$$\chi_d = 0.17 \pm 0.05$$

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

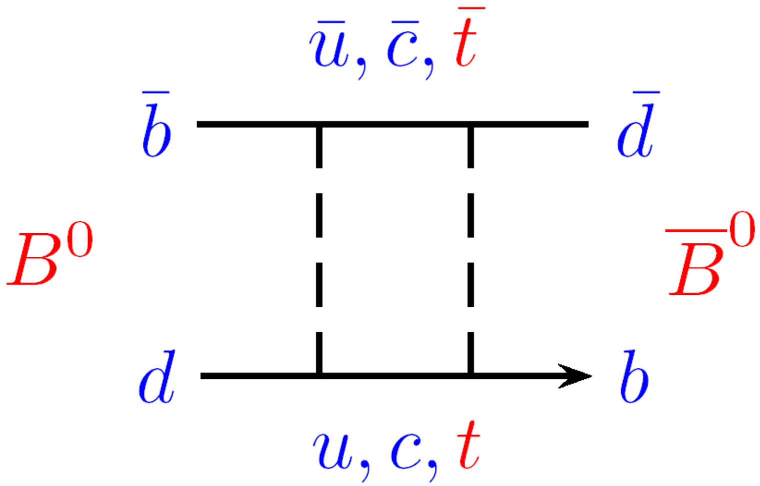
cited >1000 times.



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!

Systematic studies of B mesons at Υ(4s)

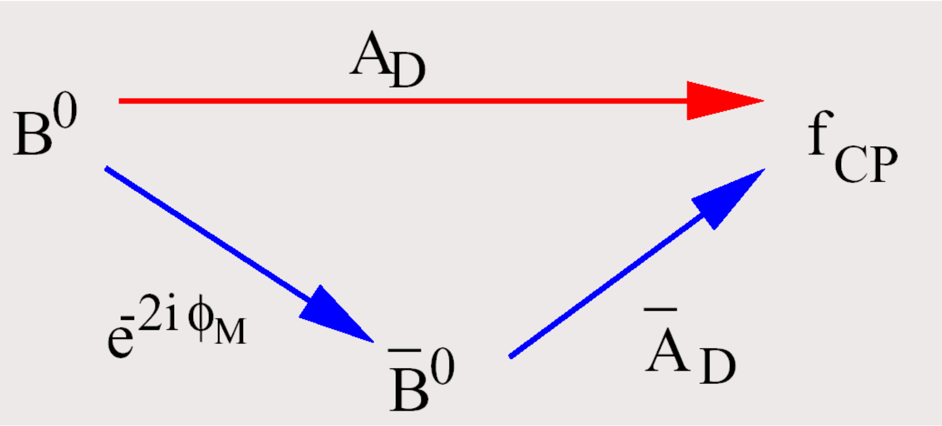
ARGUS and CLEO: In addition to mixing many important discoveries or properties of

- B mesons
- D mesons
- τ^- lepton
- and even a measurement of ν_τ mass.

CP violation in the B System

Large B mixing → expect sizeable CP violation (CPV) in the B system

CPV through interference between mixing and decay amplitudes



Directly related to CKM parameters in case of a single amplitude

Golden Channel: $B \rightarrow J/\psi K_S$

Soon recognized as the best way to study CP violation in the B meson system (I. Bigi and T. Sanda 1987)

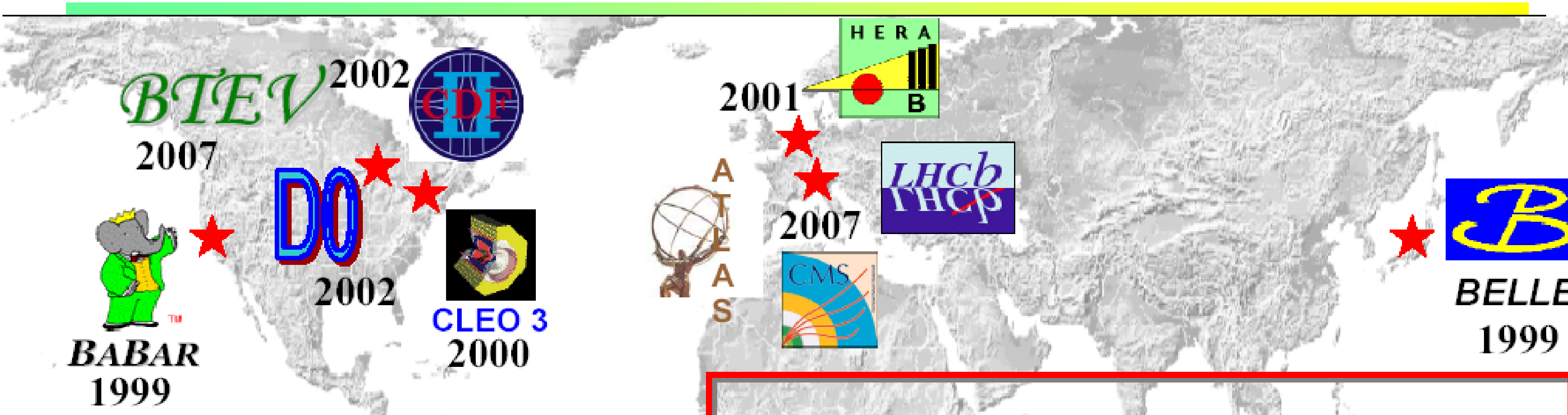
Theoretically clean way to one of the parameters ($\sin 2\phi_1$)

Use boosted BBbar system to measure the time evolution (P. Oddone)

Clear experimental signatures ($J/\psi \rightarrow \mu^+\mu^-$, e^+e^-, $K_S \rightarrow \pi^+\pi^-$)

Relatively large branching fractions for b->ccs ($\sim 10^{-3}$)

→ A lot of physicists were after this holy grail



Primary Goal

Precision measurements of **charged weak interactions** as a test of the **CKM** sector of the Standard Model and a probe of the origin of the ***CP*** **violation**

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 Γ 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

→ mass eigenstates B_L (light) and B_H (heavy) 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 by the M and Γ 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 Δm_B and $\Delta\Gamma_B$?

Δm_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 $\Delta\Gamma_B << \Delta m_B$

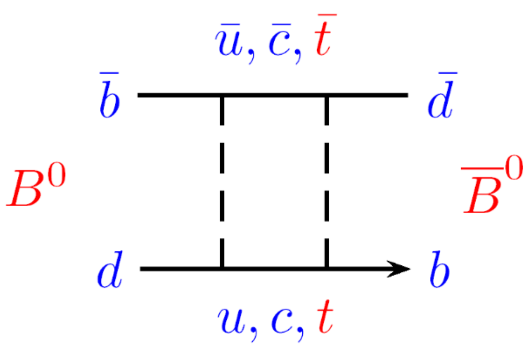
$$\Delta m_B = 2|M_{12}|$$

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

and

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

$\Delta m \propto$



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

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

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 $\exp(-iM_i t)$

→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

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

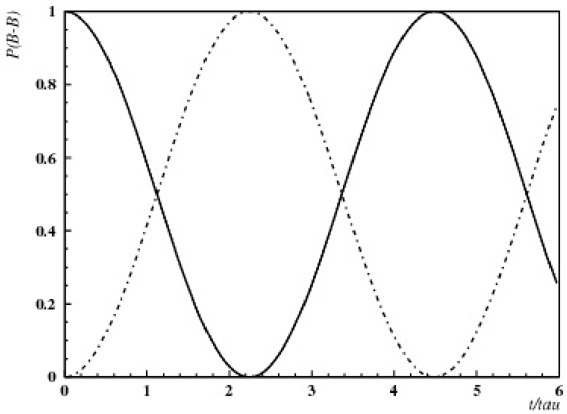
$$g_-(t) = e^{-iMt}e^{-\Gamma t/2} i\sin(\Delta m t/2)$$

$$M = (M_H + M_L)/2$$

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

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

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



→Probability that a B turns into its anti-particle →**beat**

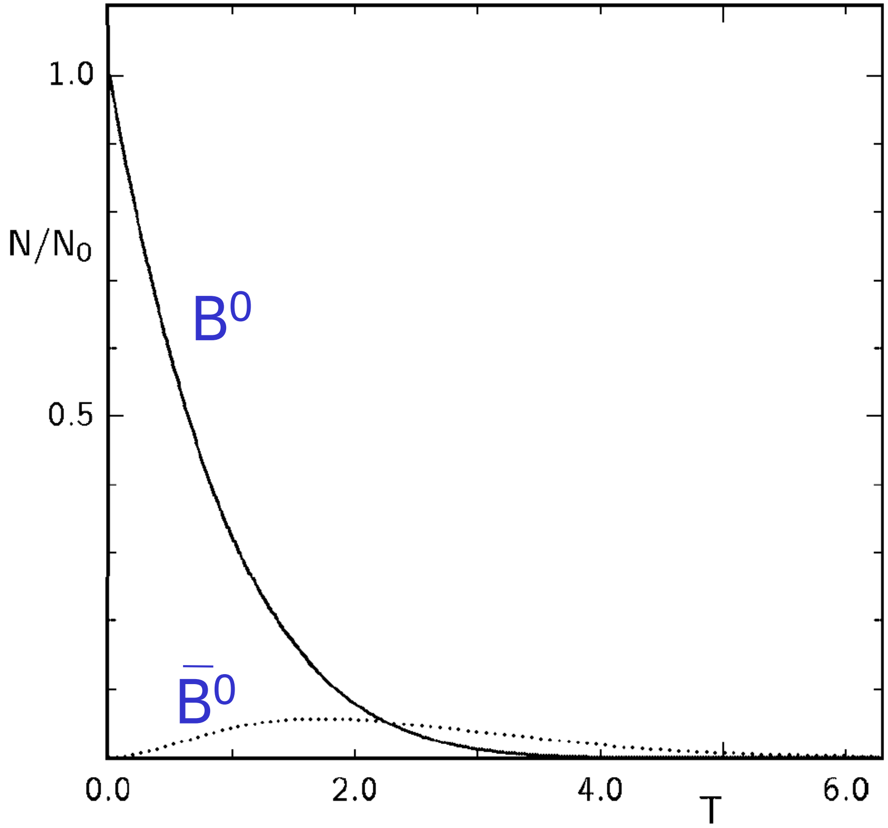
$$\left|\left\langle \overline{B}^0 \middle| B^0_{phys}(t)\right\rangle\right|^2 = |q/p|^2 |g_-(t)|^2 = |q/p|^2 \sin^2(\Delta m t/2)$$

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

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

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

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

Decay amplitude as a function of time:

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

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

… and similarly for the anti-B

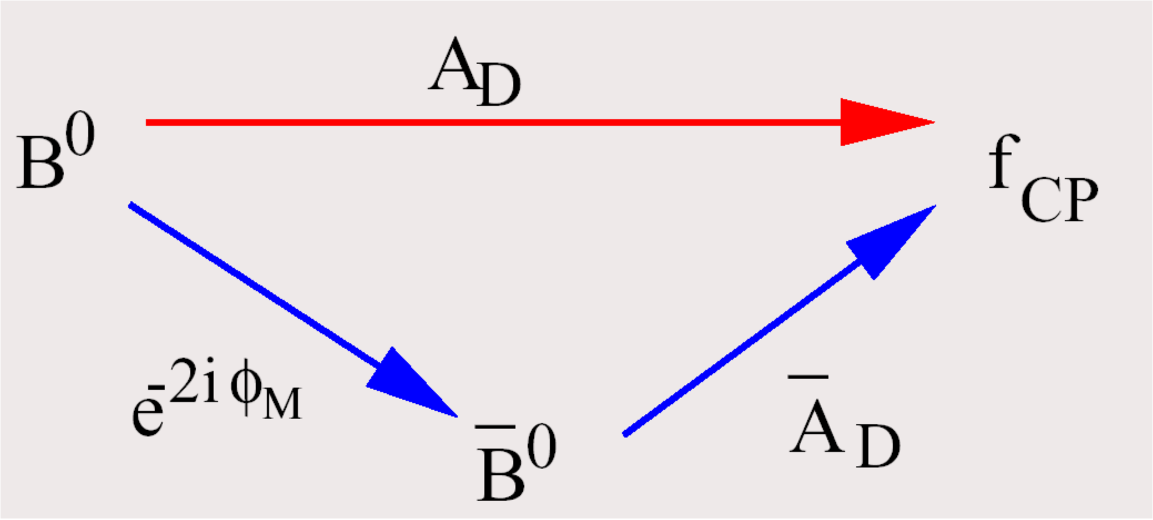
$$\lambda = \frac{q}{p} \frac{\overline{A}_f}{A_f}$$

Define a parameter λ

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 $\pi^+ \pi^-$



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:

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

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

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

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

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

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

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

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

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

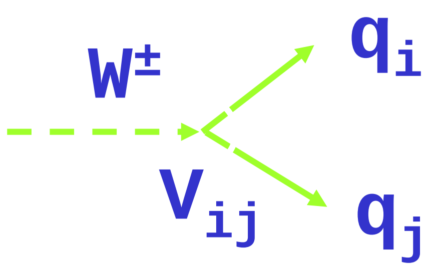
Non-zero effect if Im(λ) ≠ 0,
even if |λ| = 1

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

Detailed derivation → backup slides

CP violation in SM

CP violation: consequence of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix



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

CP violation is possible in this scheme if V_{CKM} is not a real matrix (i.e. has a non-trivial complex phase)

CP violation in SM

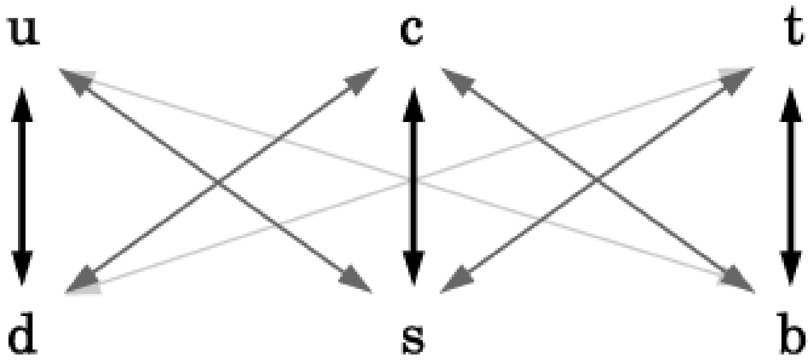
$$\mathcal{L} = V_{ij}\overline{U}_i\gamma^\mu(1-\gamma_5)D_jW_\mu + V_{ij}^*\overline{D}_i\gamma^\mu(1-\gamma_5)U_jW_\mu$$

c CP

$$\mathcal{L}_{CP} = V_{ij}\overline{D}_i\gamma^\mu(1-\gamma_5)U_jW_\mu + V_{ij}^*\overline{U}_i\gamma^\mu(1-\gamma_5)D_jW_\mu$$

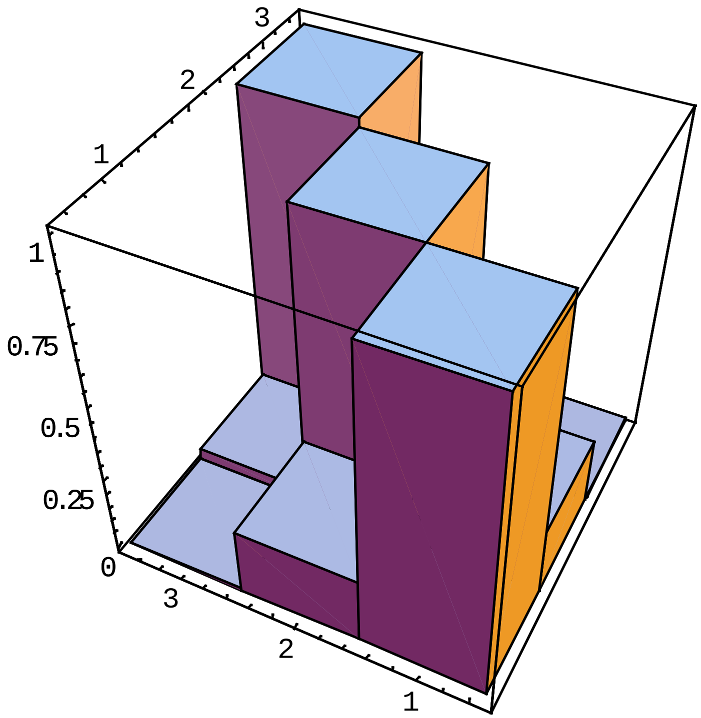
If $V_{ij}=V_{ij}^*$ ► $\mathcal{L}=\mathcal{L}_{CP}$ ► CP is conserved

CKM matrix

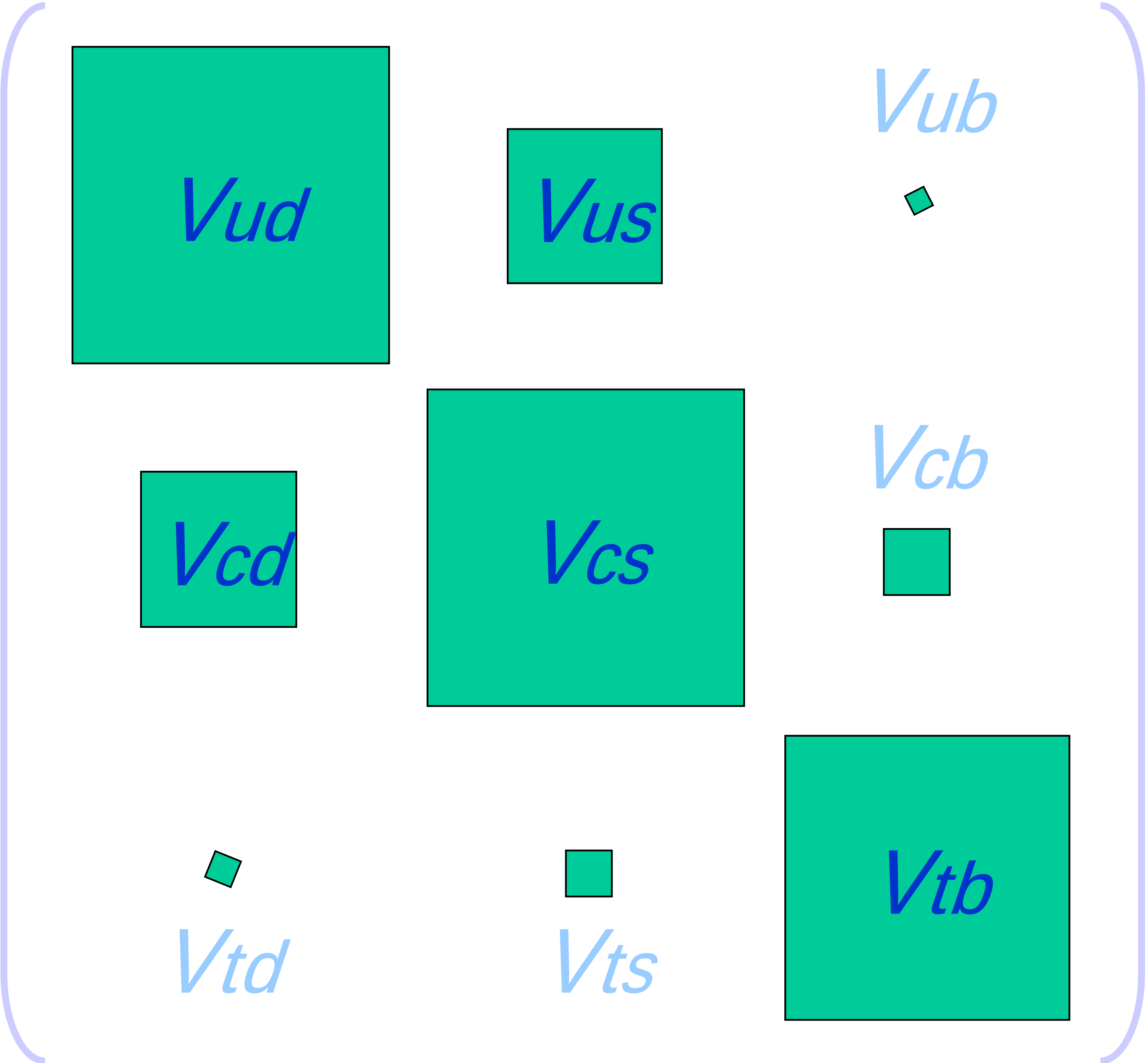


Transitions between members of the same family more probable (=thicker lines) than others

→CKM: almost a diagonal matrix, but not completely →



→CKM: almost real,
but not completely!



CKM matrix

Almost a real diagonal matrix, but not completely →

Wolfenstein parametrisation: expand in the parameter λ (=$\sin\theta_c$=0.22)

A, ρ and η: all of order one

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

Unitary relations

Rows and columns of the V matrix are orthogonal

Three examples: 1st+2nd, 2nd+3rd, 1st+3rd columns

$$V_{ud}V_{us}^{*}+V_{cd}V_{cs}^{*}+V_{td}V_{ts}^{*}=0,$$
$$V_{us}V_{ub}^{*}+V_{cs}V_{cb}^{*}+V_{ts}V_{tb}^{*}=0,$$
$$V_{ud}V_{ub}^{*}+V_{cd}V_{cb}^{*}+V_{td}V_{tb}^{*}=0.$$

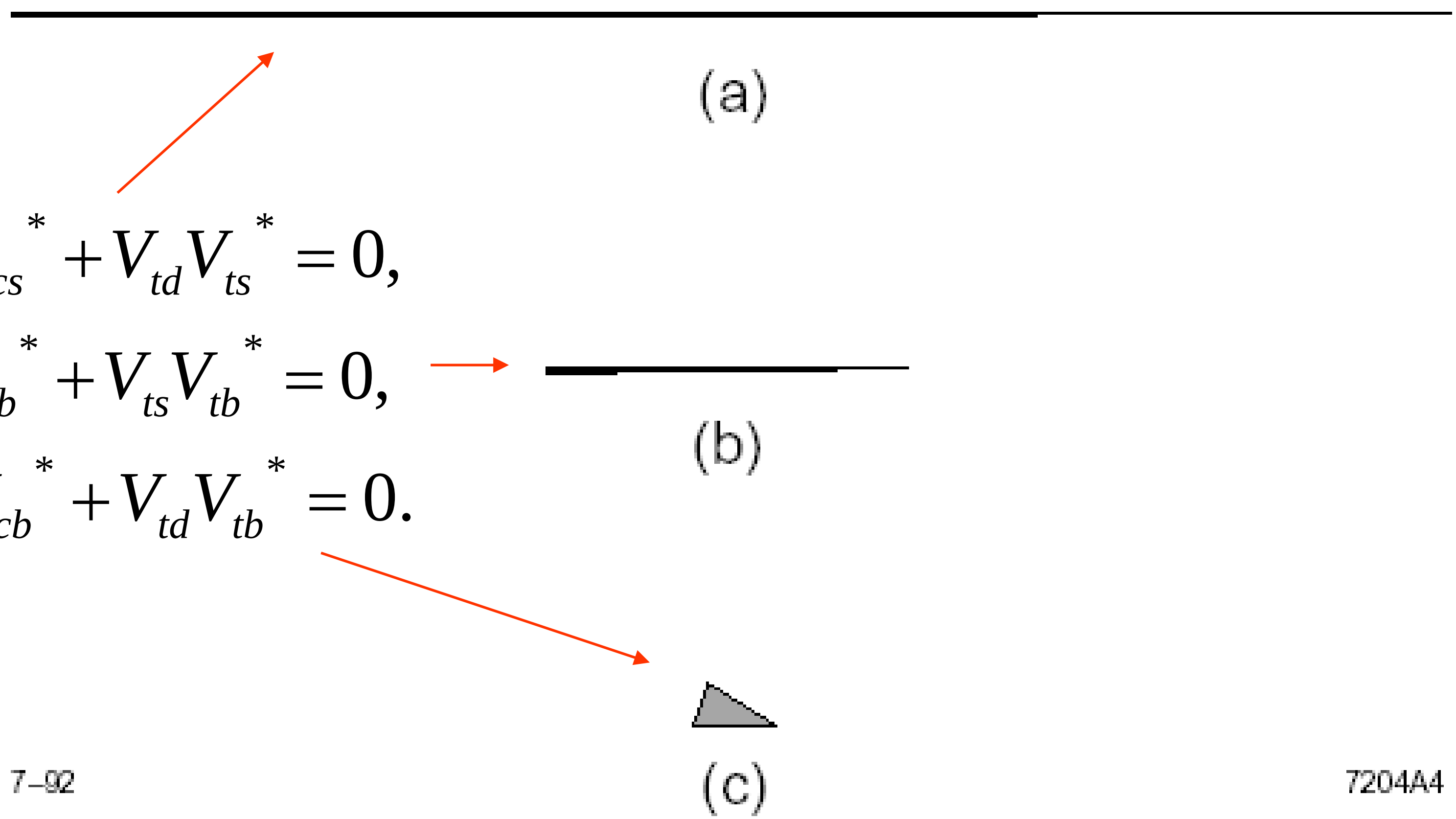
Geometrical representation: triangles in the complex plane.

Unitary triangles

$$V_{ud}V_{us}^{\ *} + V_{cd}V_{cs}^{\ *} + V_{td}V_{ts}^{\ *} = 0,$$

$$V_{us}V_{ub}^{\ *} + V_{cs}V_{cb}^{\ *} + V_{ts}V_{tb}^{\ *} = 0,$$

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



All triangles have the same area J/2 (about $4\text{x}10^{-5}$)

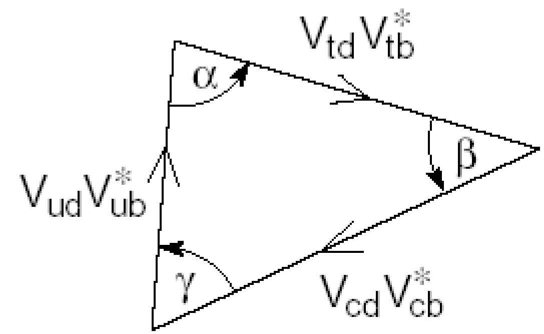
$$J = c_{12}c_{23}c_{13}^{2}s_{12}s_{23}s_{13}\sin\delta$$

Jarlskog invariant

Unitarity triangle

THE unitarity triangle:

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

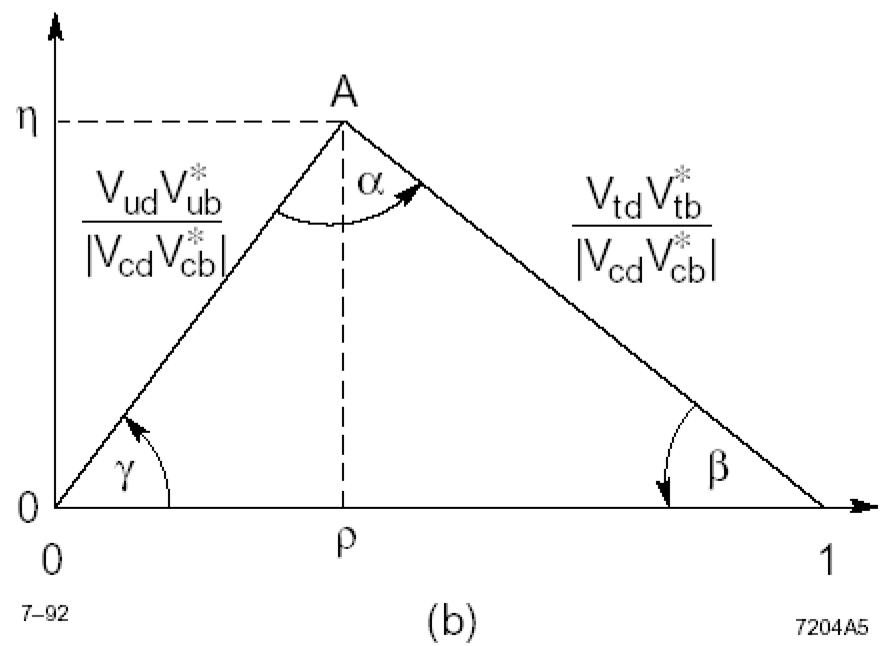


(a)

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

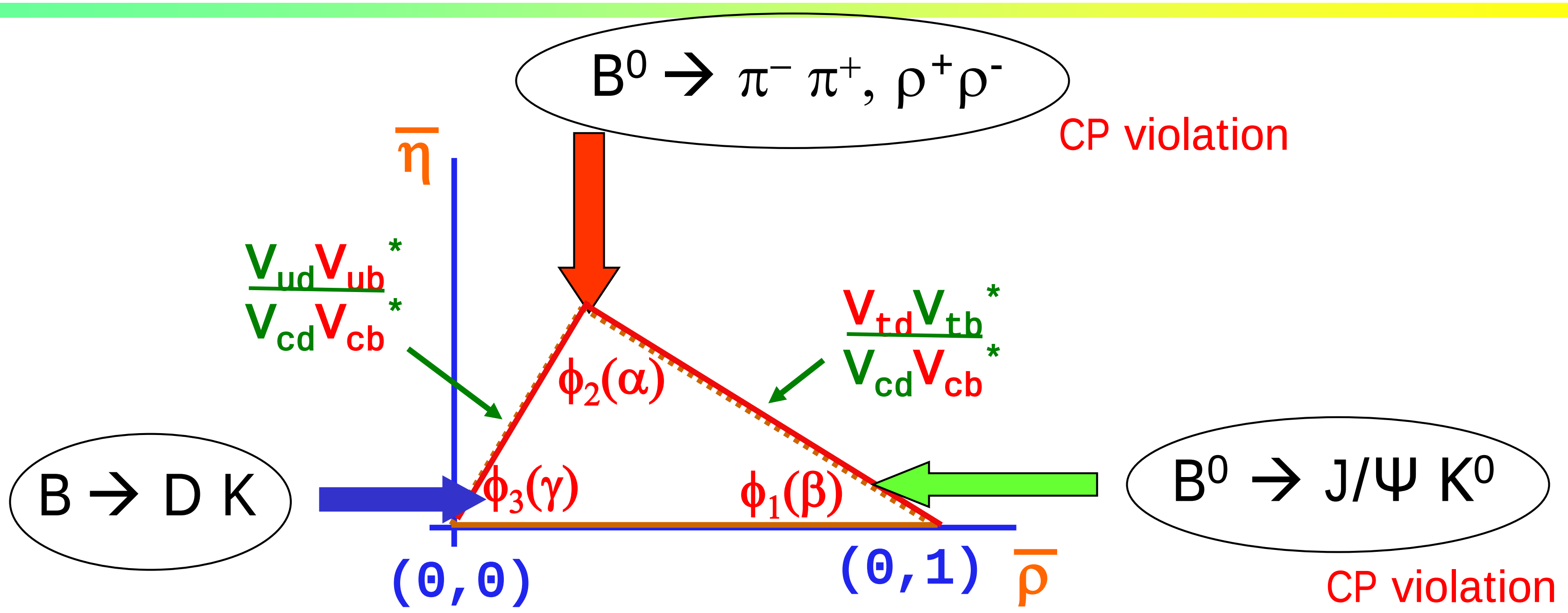
$$\beta \equiv \phi_1 \equiv \arg\left(\frac{V_{cd}V_{cb}^{\ *}}{V_{td}V_{tb}^{\ *}}\right)$$

$$\gamma \equiv \phi_3 \equiv \arg\left(\frac{V_{ud}V_{ub}^{\ *}}{V_{cd}V_{cb}^{\ *}}\right) \equiv \pi-\alpha-\beta$$



(b)

Unitarity triangle: measuring angles and sides

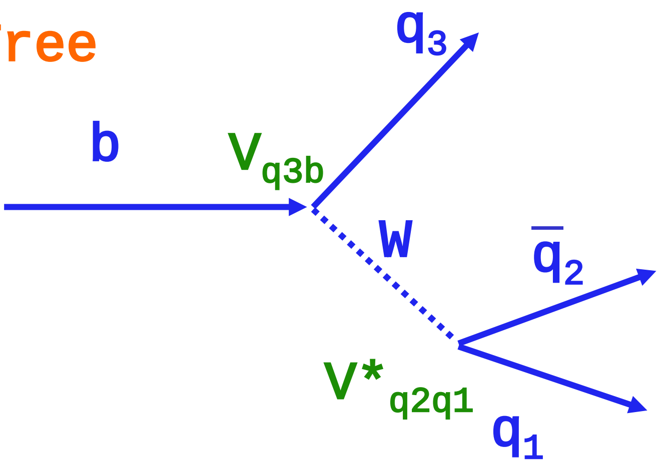


Consistency check of the unitarity triangle: precisely measure

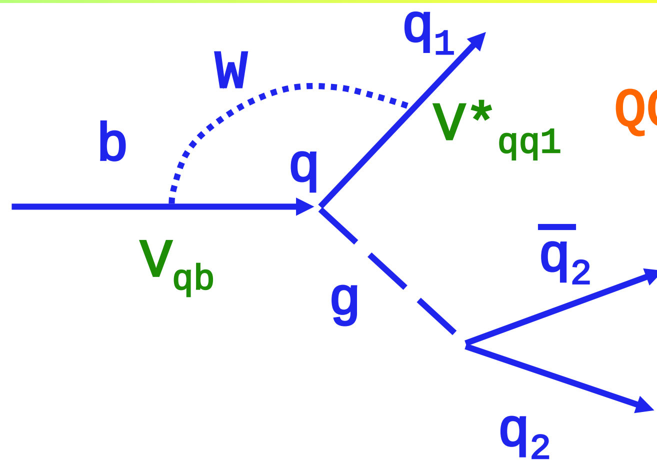
- angles (through CP violation)
- sides (b→u and b→c rates) and B mixing

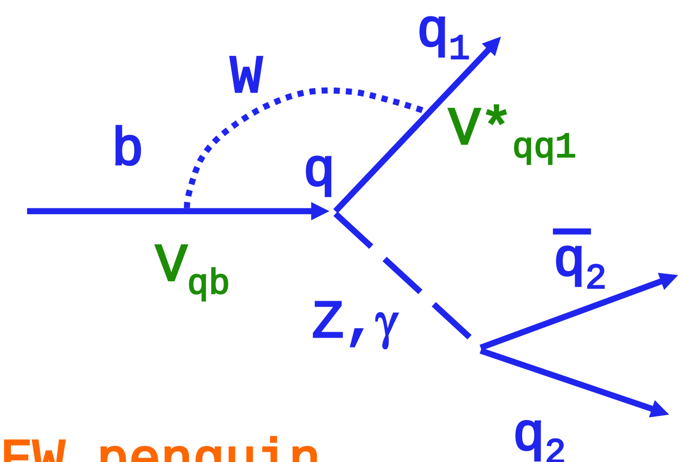
b decays

Tree



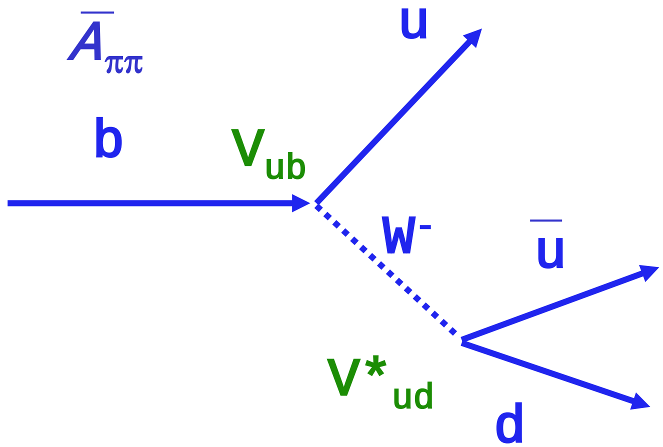
QCD penguin

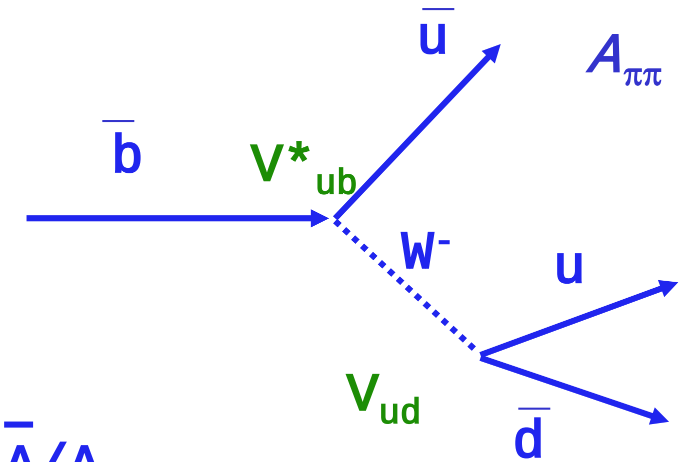




EW penguin

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





(q/p) $\bar{A}/A$

$$\lambda_{\pi\pi} = \eta_{\pi\pi} \left(\frac{V_{tb}^{*} V_{td}}{V_{tb} V_{td}^{*}} \right) \left(\frac{V_{ud}^{*} V_{ub}}{V_{ud} V_{ub}^{*}} \right)$$

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

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

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

How to measure CP violation?

- Principle of measurement
- Experimental considerations
- Babar and Belle spectrometers

Principle of measurement

Principle of measurement:

•Produce pairs of B mesons, moving in the lab system

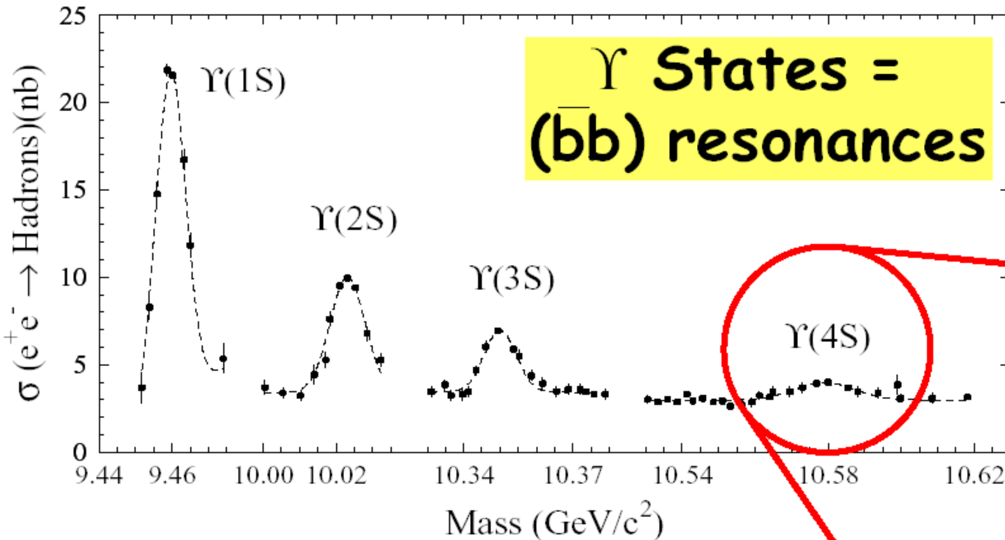
•Find events with B meson decay of a certain type (usually $B \rightarrow f_{CP}$ - CP eigenstate)

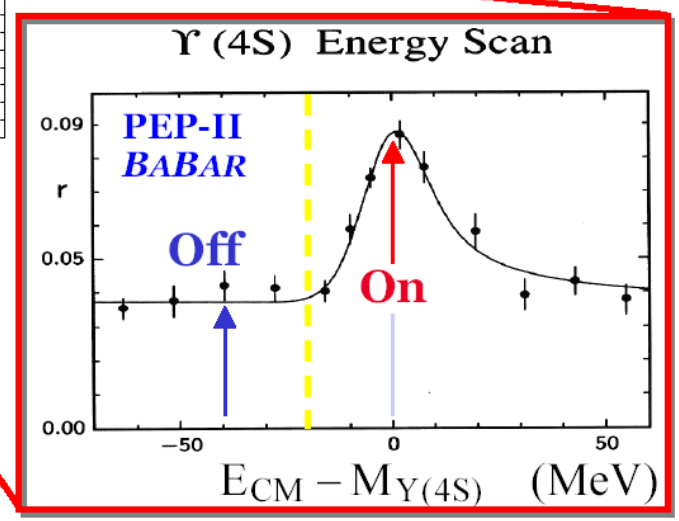
•Measure time difference between this decay and the decay of the associated B (f_{tag}) (from the flight path difference)

•Determine the flavour of the associated B (B or anti-B)

•Measure the asymmetry in time evolution for B and anti-B

B meson production at Υ(4s)





Cross Sections at Υ(4S):

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

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

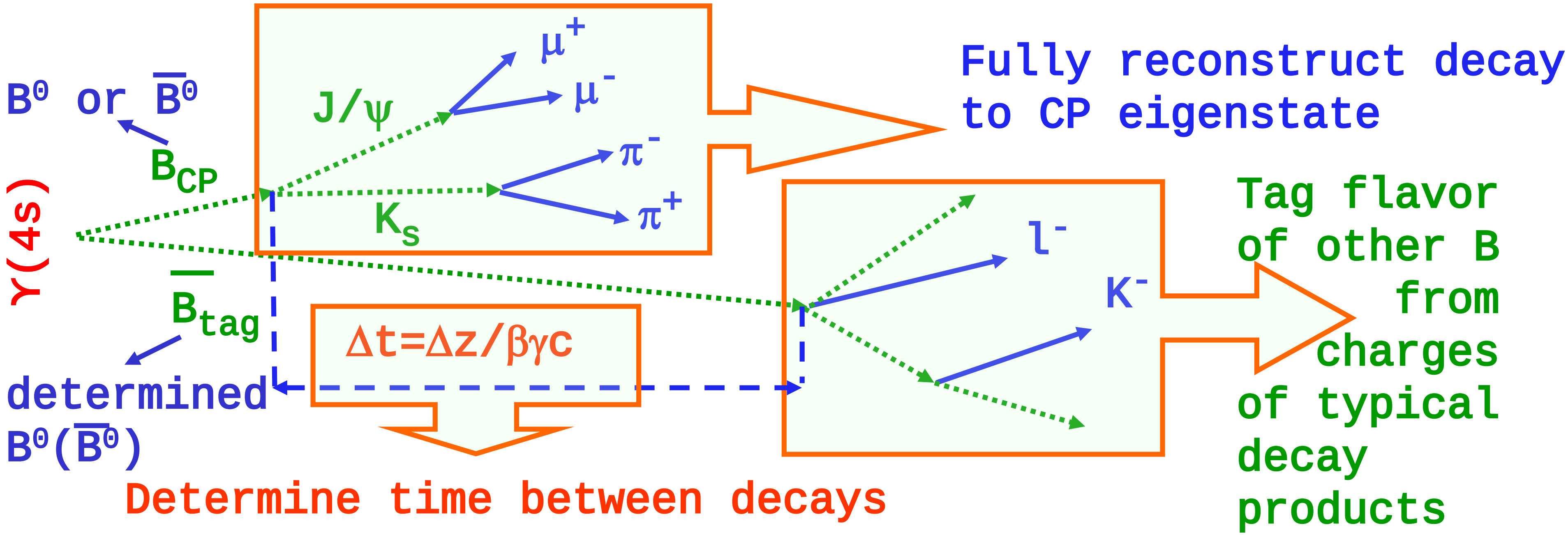
$d\bar{d}, s\bar{s} \sim 0.3$ nb

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

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

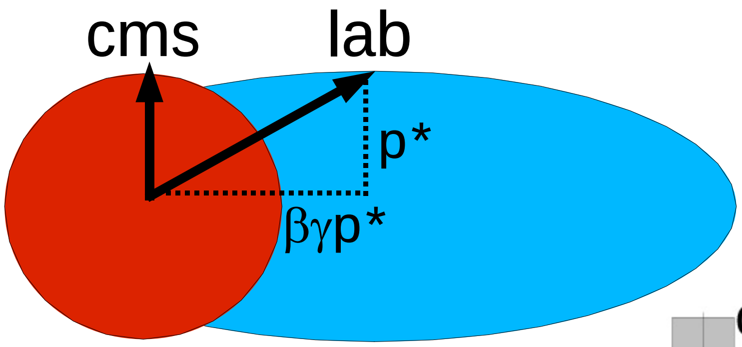
$L = 1$ state

Principle of measurement

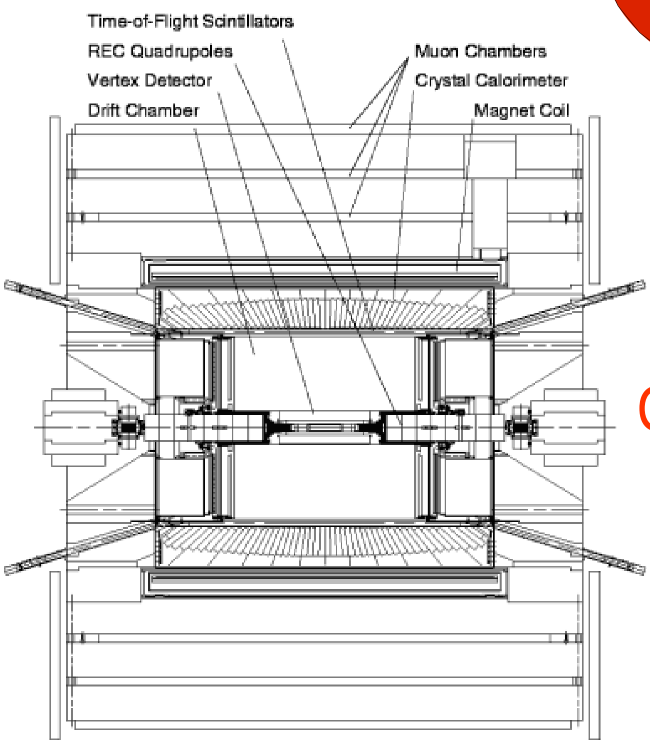


Experimental considerations

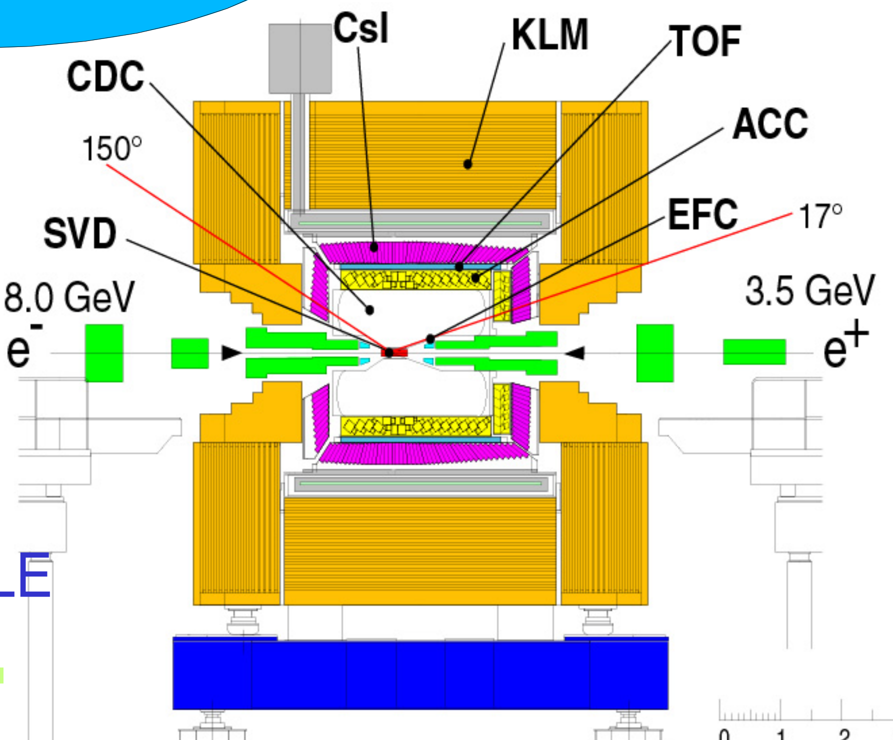
Detector form: symmetric for symmetric energy beams; slightly extended in the boost direction for an asymmetric collider.



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



CLEO



BELLE

How many events?

Rough estimate:

Need ~1000 reconstructed B-> J/ψ K_S decays with J/ψ -> 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/ψ K^0)=$8.4\ 10^{-4}$

BR(J/ψ -> 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 * 2 * 8.4 10^{-4} * 0.118 * ½ * 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

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

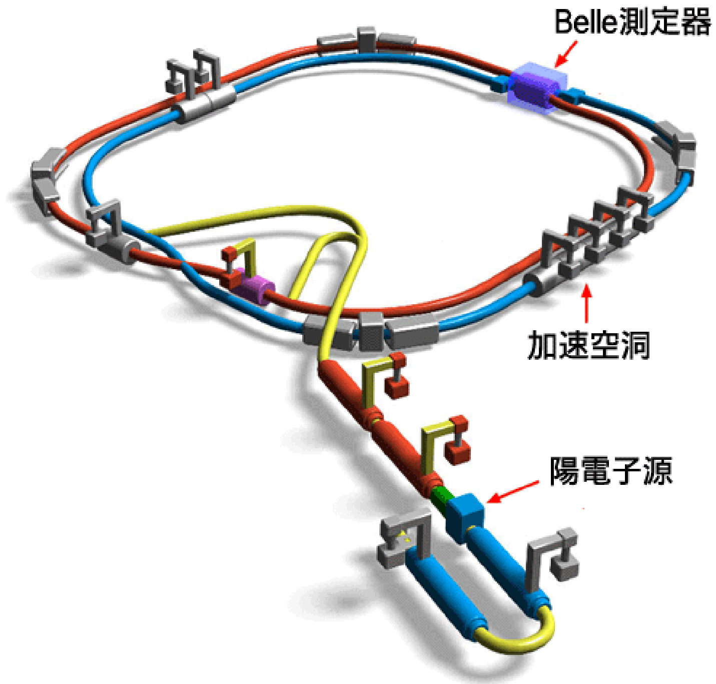
Cross section for Υ(4s) production: 1.1 nb = 1.1 10^{-33} cm^2

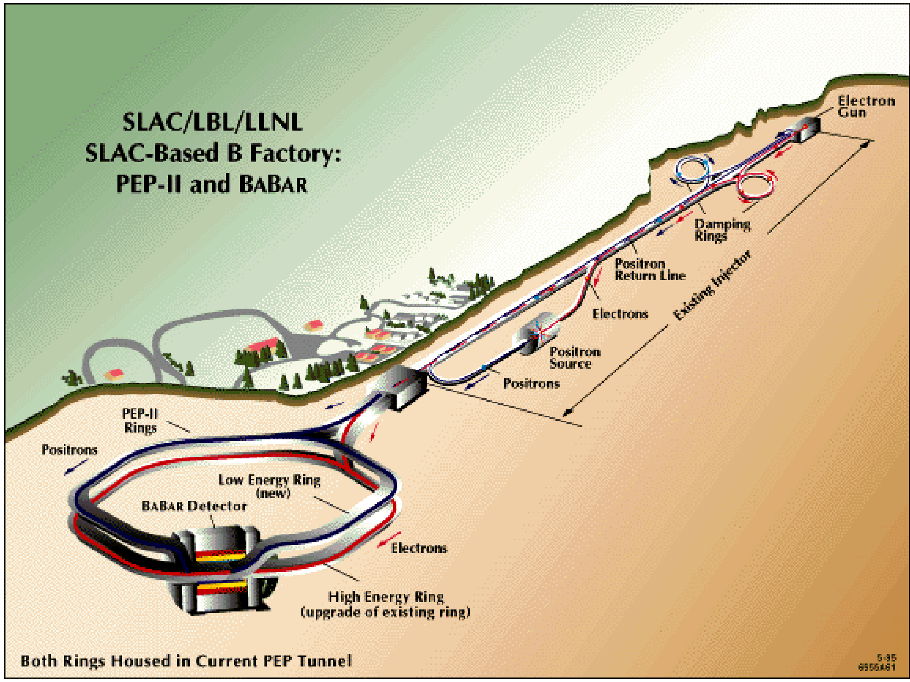
→ Accelerator figure of merit - luminosity - has to be

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

This is much more than any other accelerator achieved before!

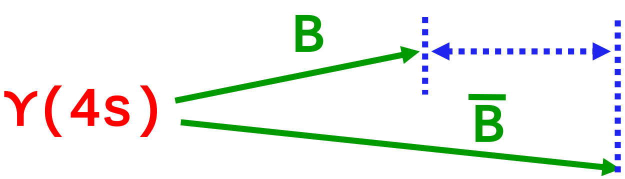
Colliders: asymmetric B factories





$\sqrt{s}=10.58$ GeV

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



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

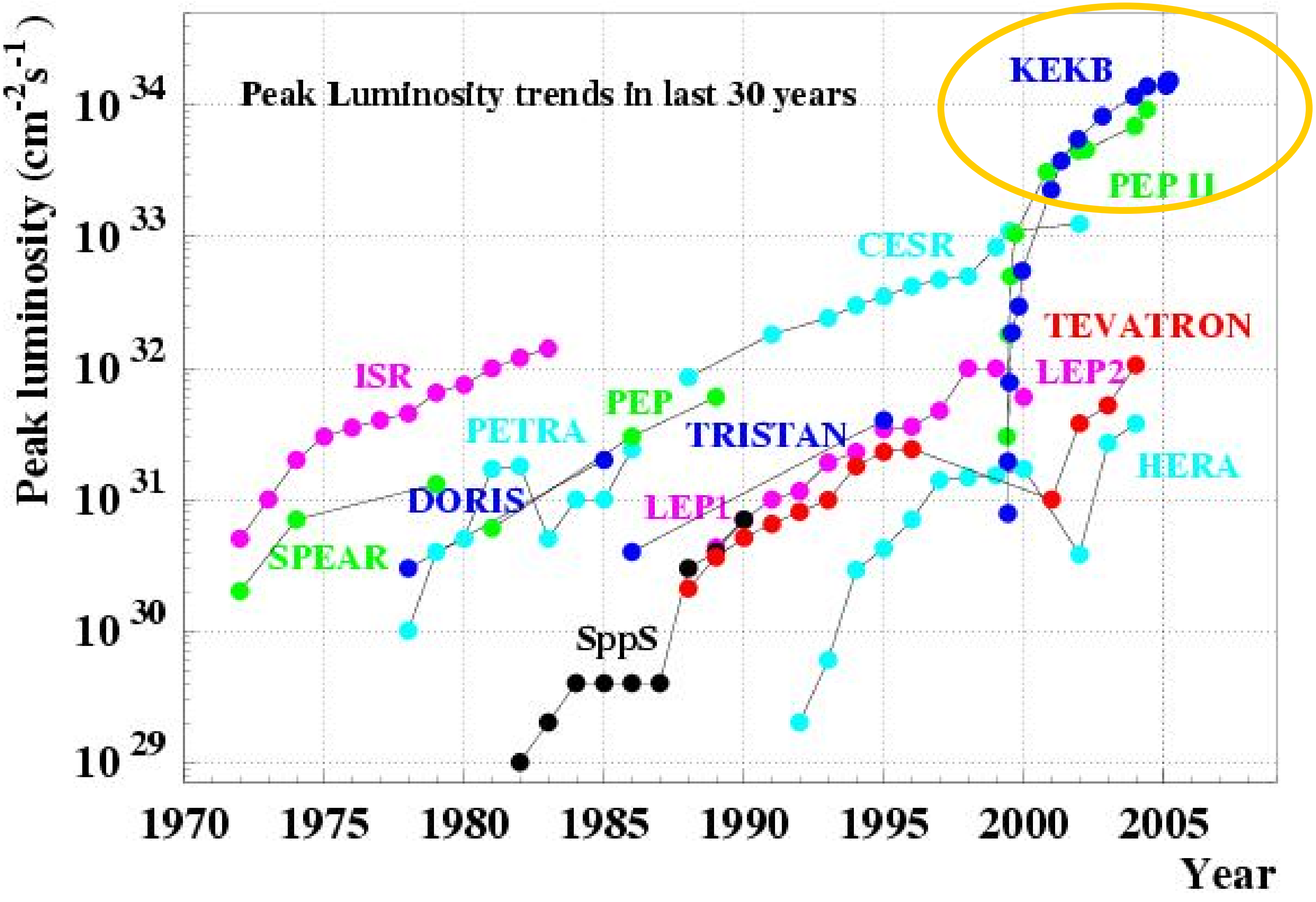
BaBar $p(e^-)=9$ GeV $p(e^+)=3.1$ GeV $\beta\gamma=0.56$

Belle $p(e^-)=8$ GeV $p(e^+)=3.5$ GeV $\beta\gamma=0.42$

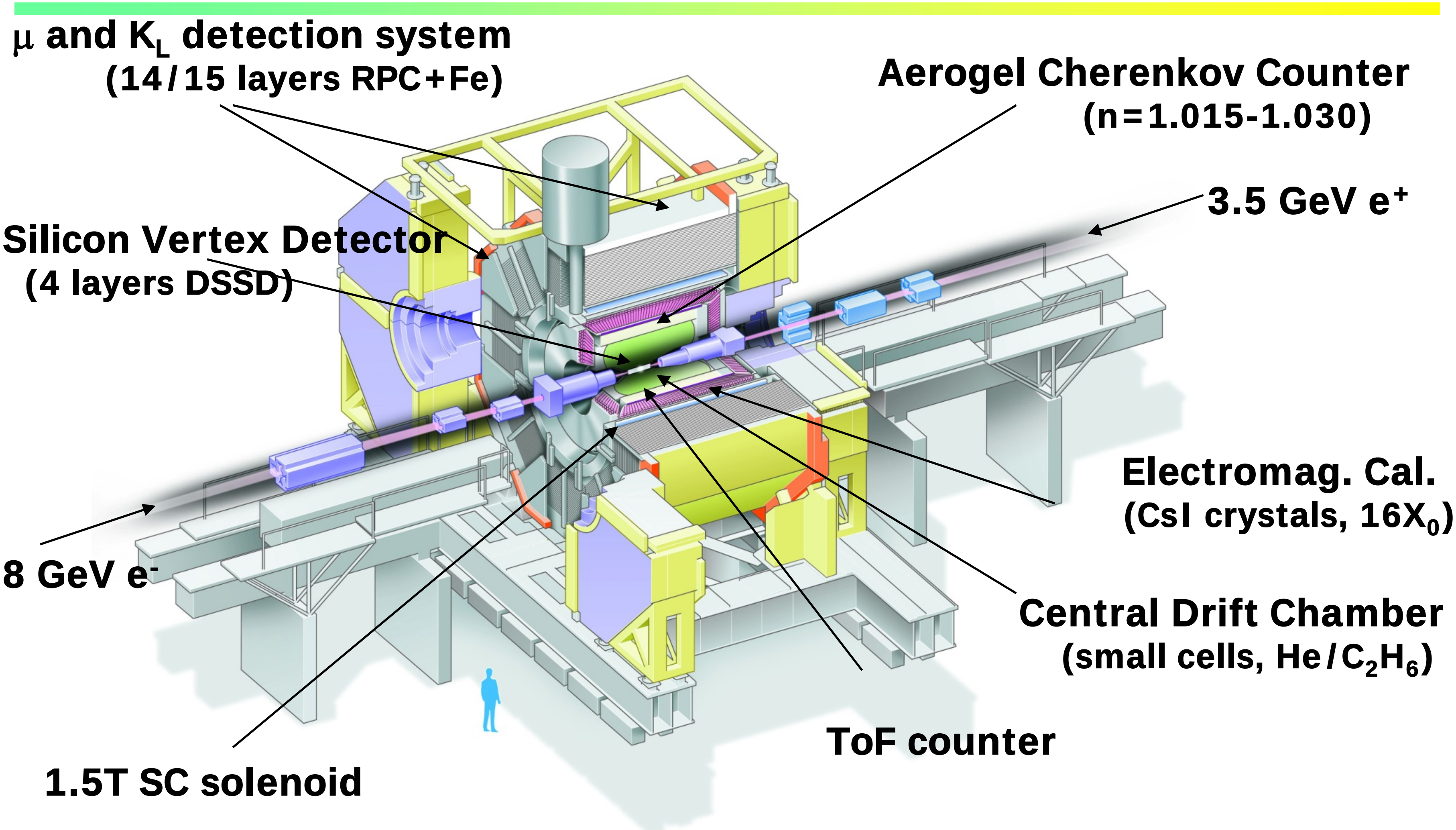
KEKB records: L_{peak} = 17/nb/sec (=1.7×10^{34} $s^{-1}cm^{-2}$)

L_{int}= 852/fb → ~900 M BB pairs

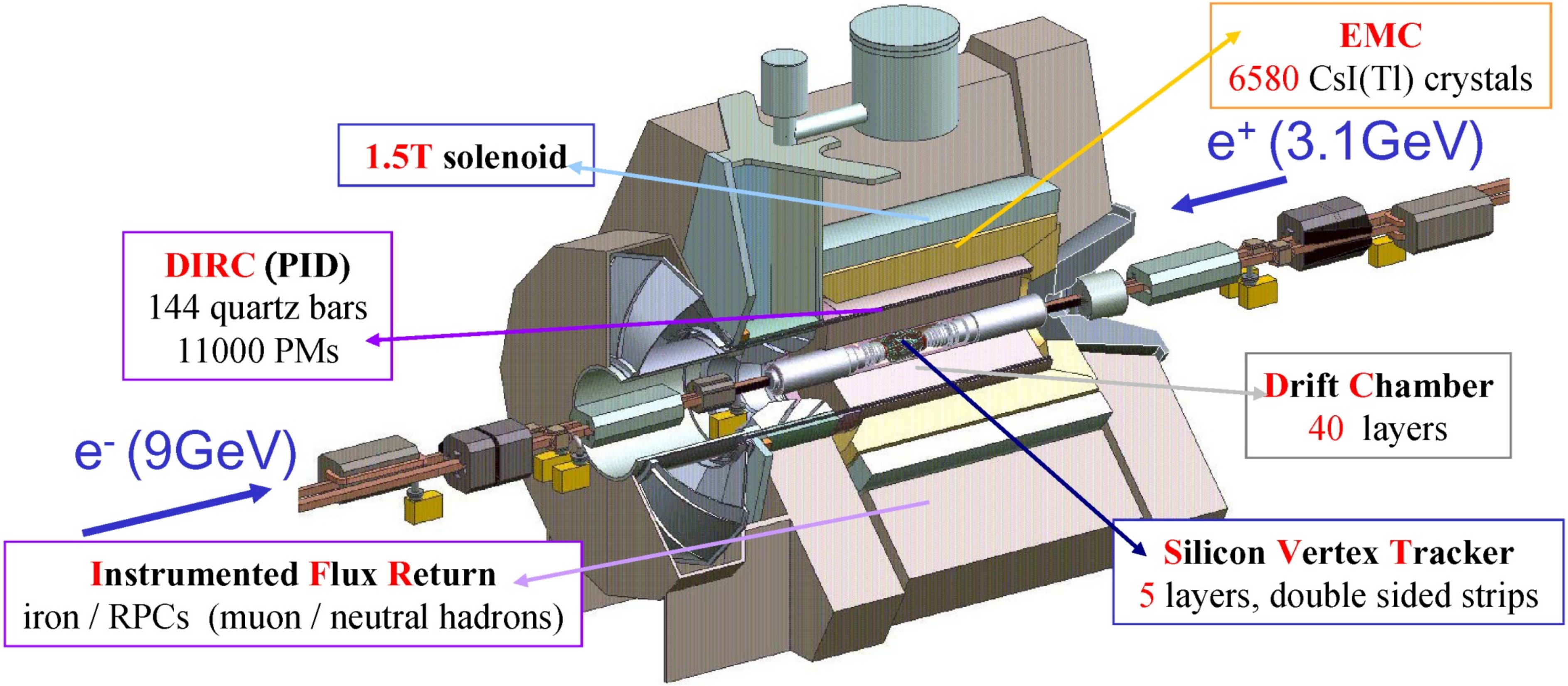
Accelerator performance



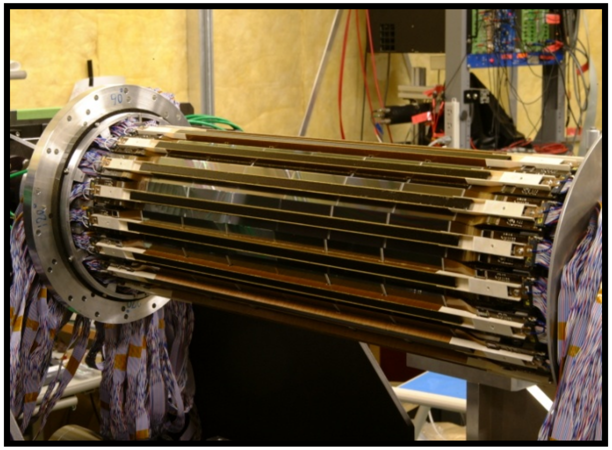
Belle spectrometer at KEK-B

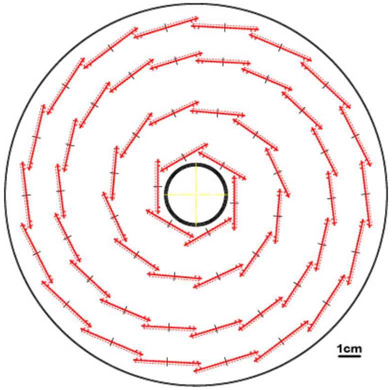


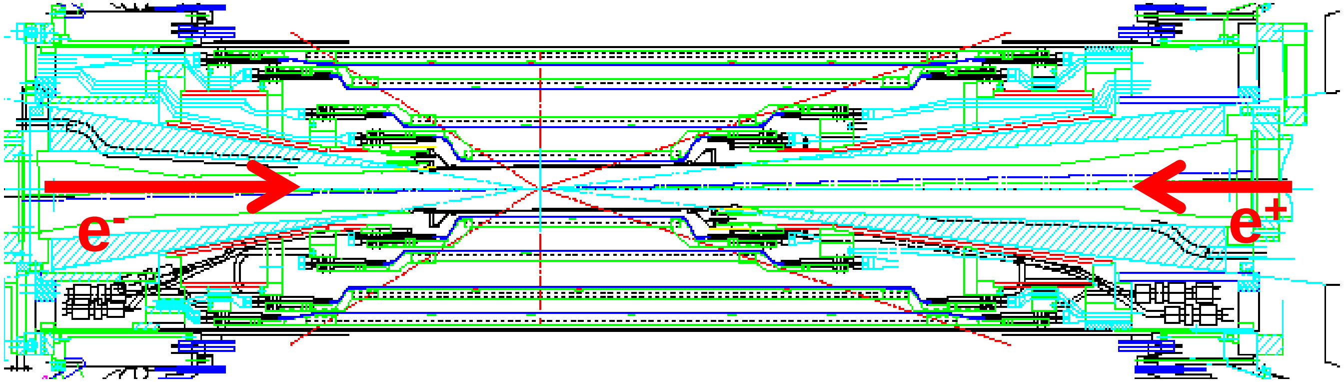
BaBar spectrometer at PEP-II



Silicon vertex detector (SVD)







4 layers

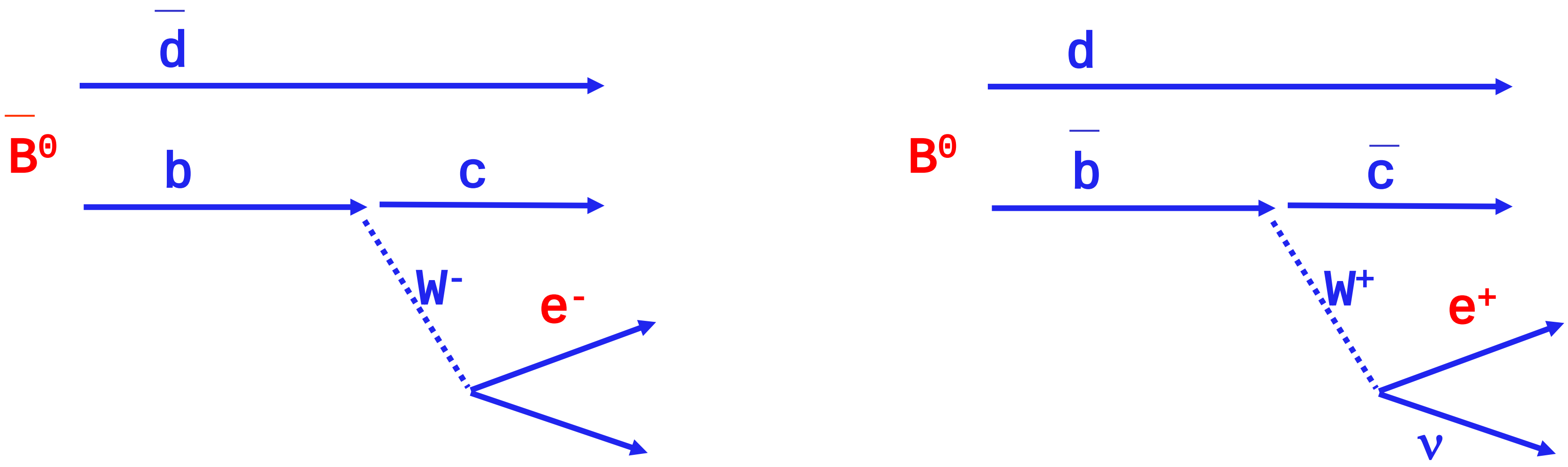
covering polar angle from 17 to 150 degrees

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 $D^{*+} \rightarrow D^0 \pi^+$ and $D^{*-} \rightarrow D^0 \pi^-$ decays)
- .....

Charge measured from curvature in magnetic field,

→ need reliable particle identification

Identification

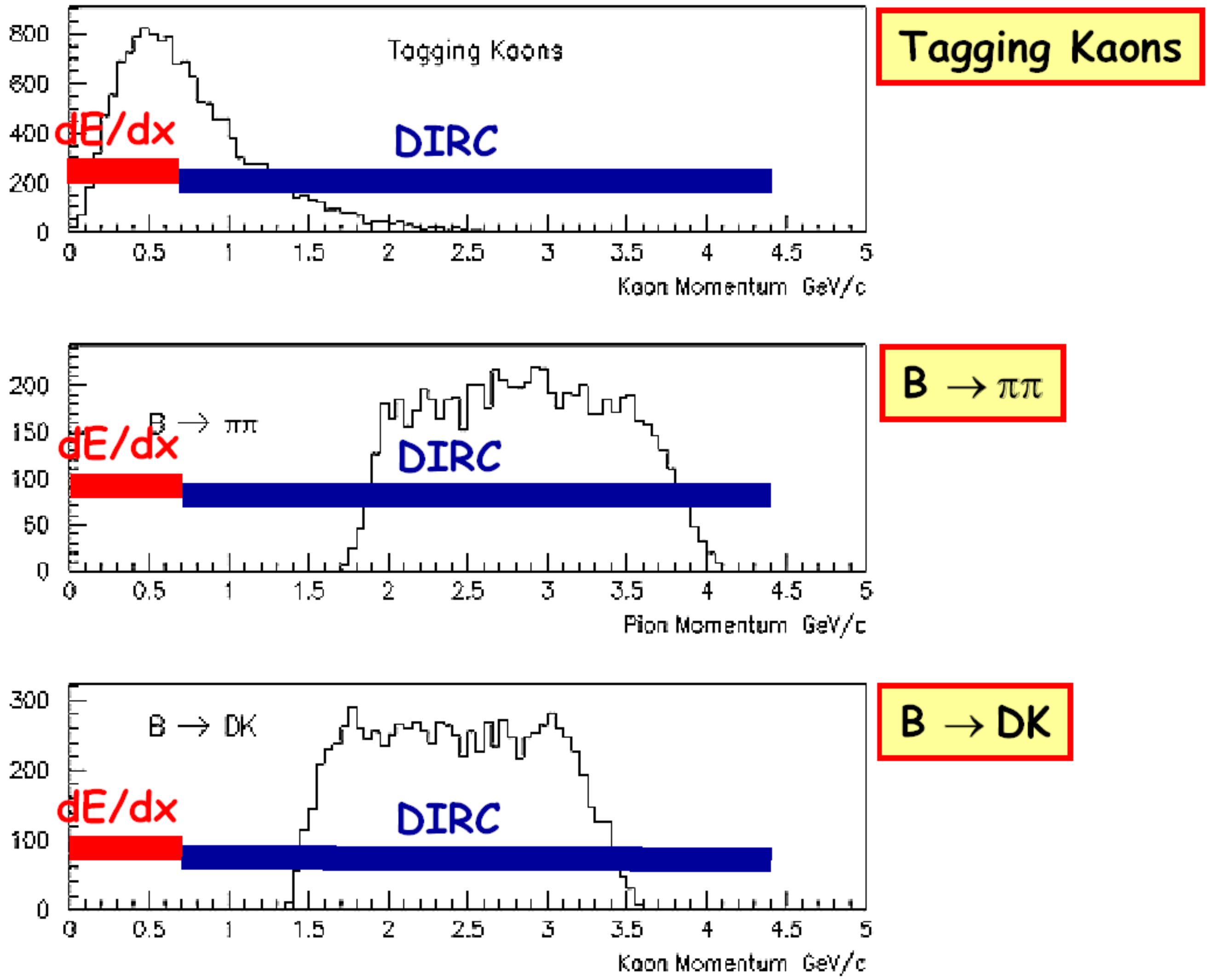
Hadrons (π, K, p):

- Time-of-flight (TOF)
- dE/dx in a large drift chamber
- Cherenkov counters

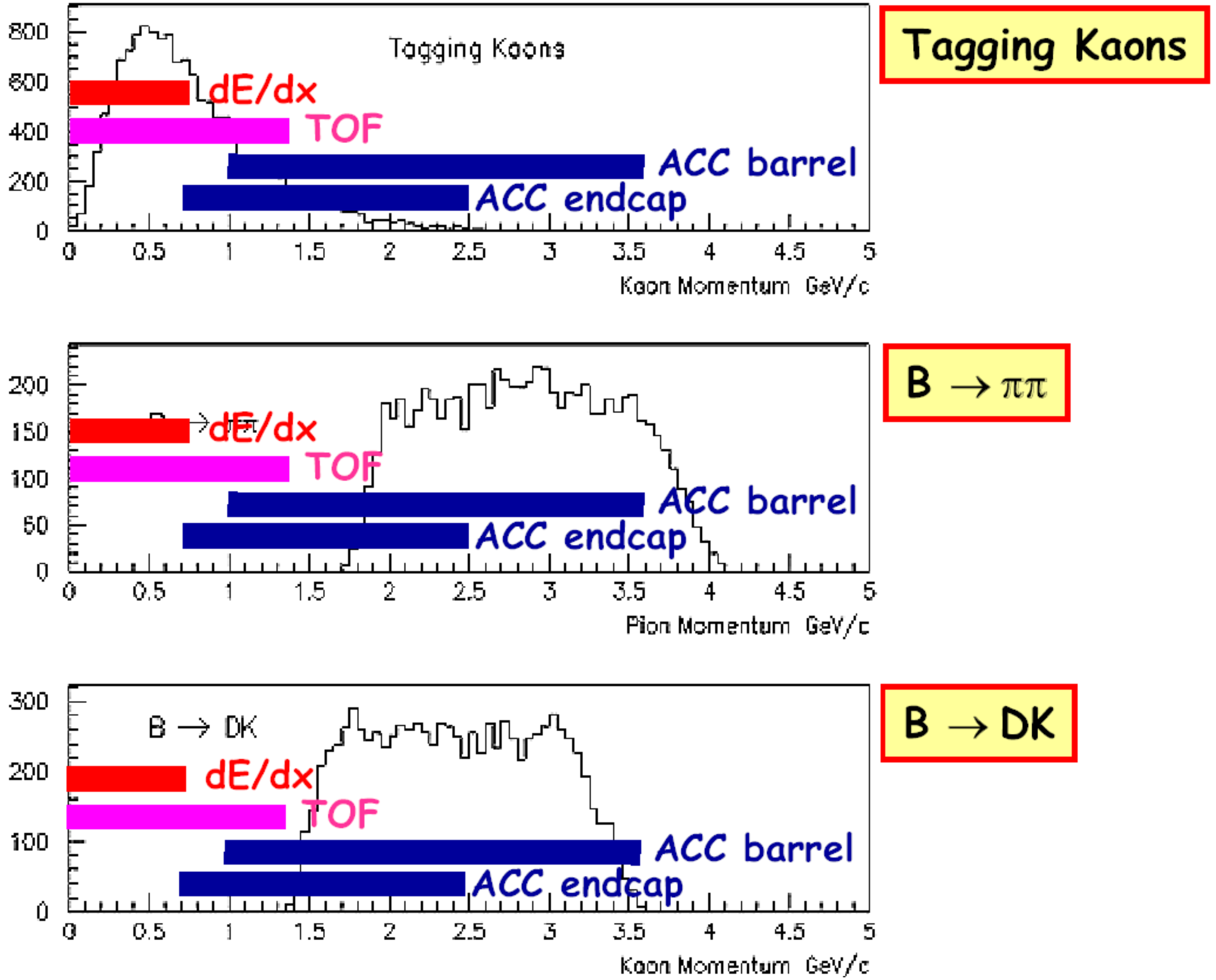
Electrons: electromagnetic calorimeter

Muon: instrumented magnet yoke

PID coverage of kaon/pion spectra



PID coverage of kaon/pion spectra



Cherenkov counters

Essential part of particle identification systems.

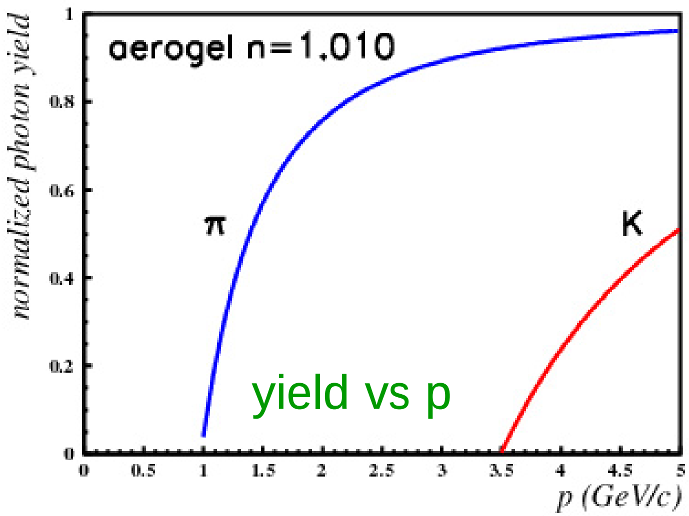
Cherenkov relation: $\cos\theta = c/nv = 1/\beta n$

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

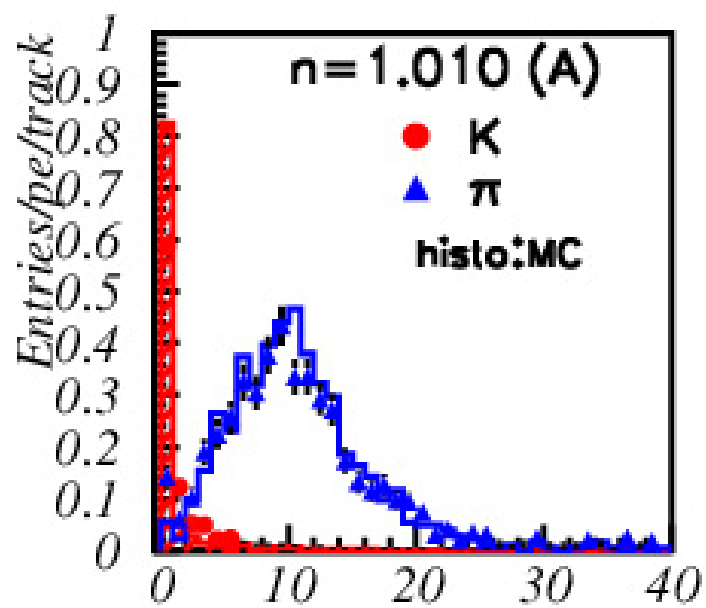
Ring Imaging (RICH) counter → measure Čerenkov angle and count photons

Belle ACC (aerogel Cherenkov counter): threshold Čerenkov counter

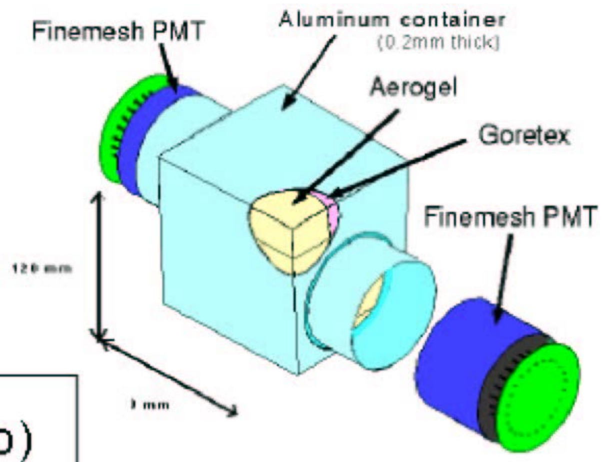
K (below thr.) vs. π (above thr.): adjust n



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

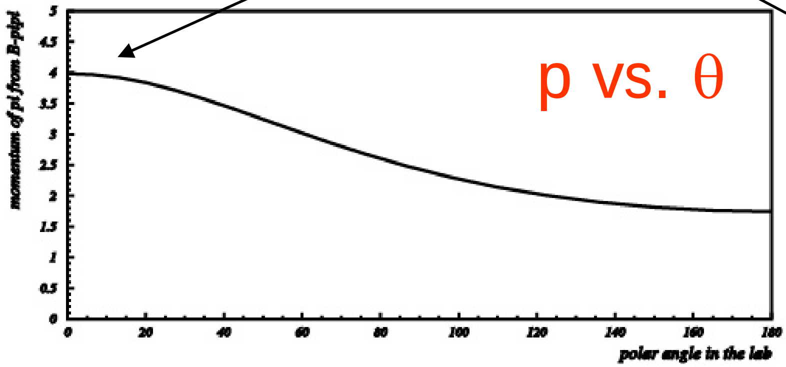


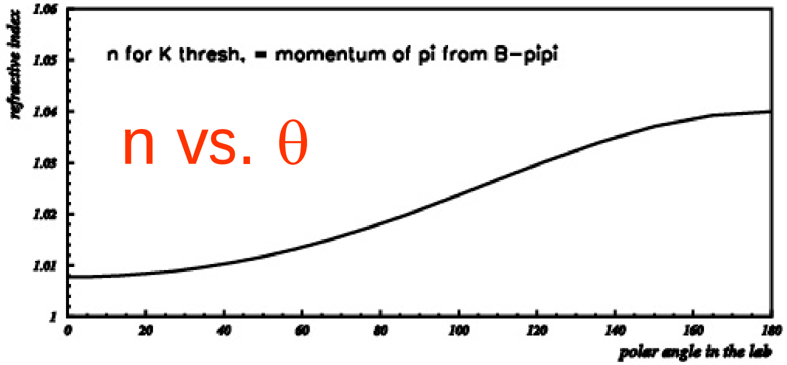
Detector unit: a block of aerogel and two fine-mesh PMTs

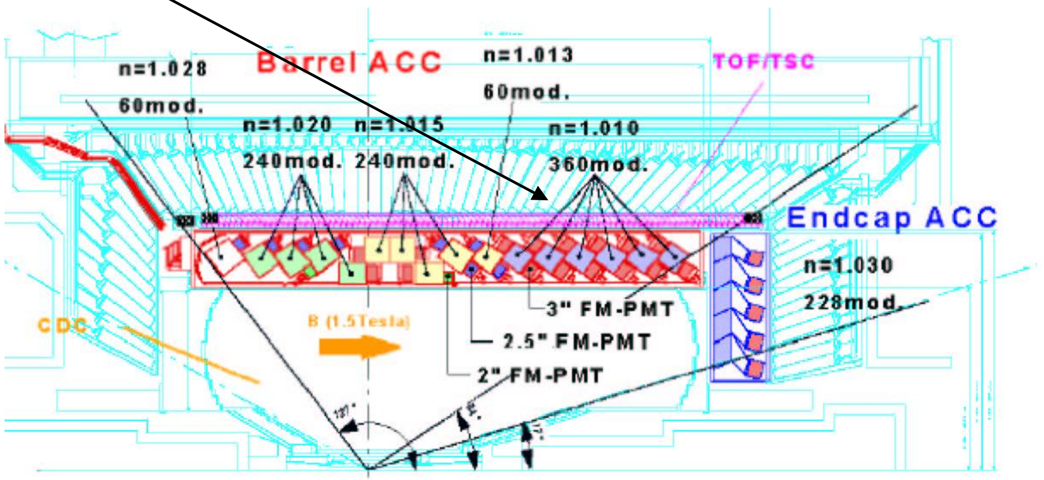


Belle ACC (aerogel Cherenkov counter): threshold Cherenkov counter

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

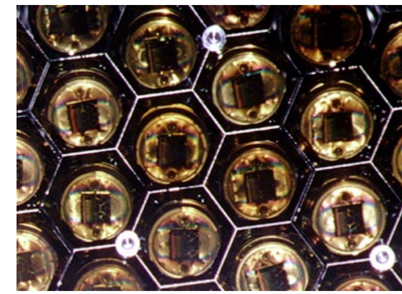




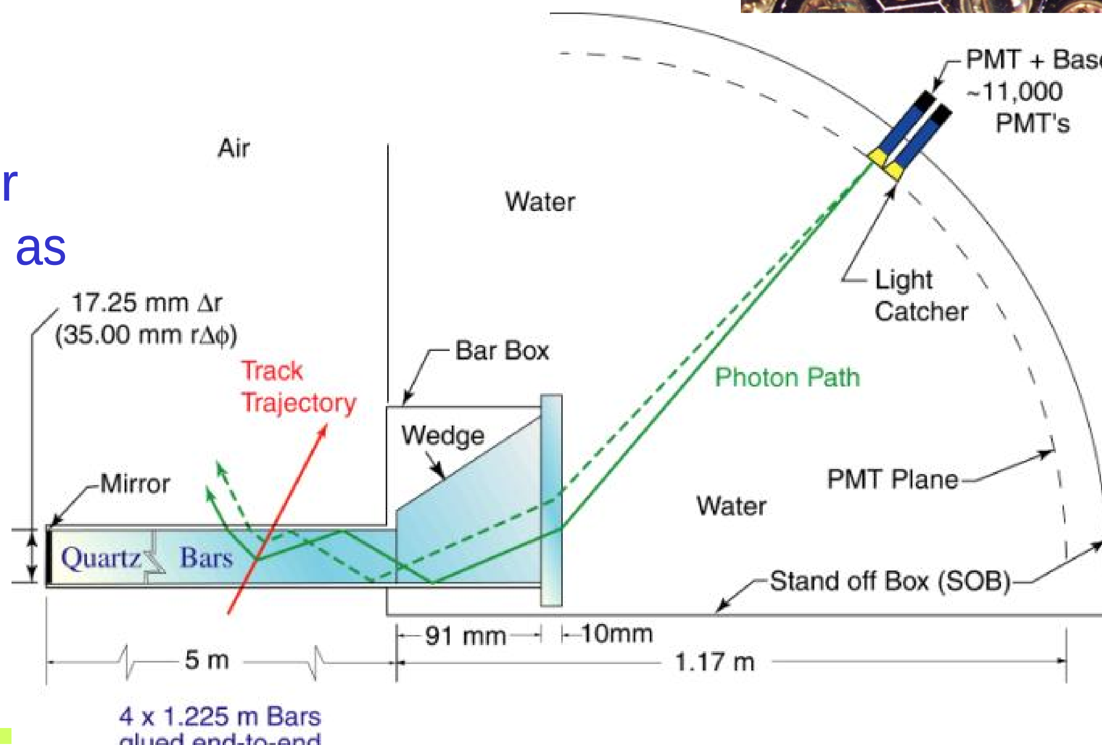


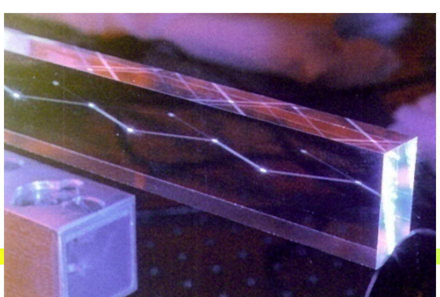
DIRC: Detector of Internally Reflected Cherekov photons

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



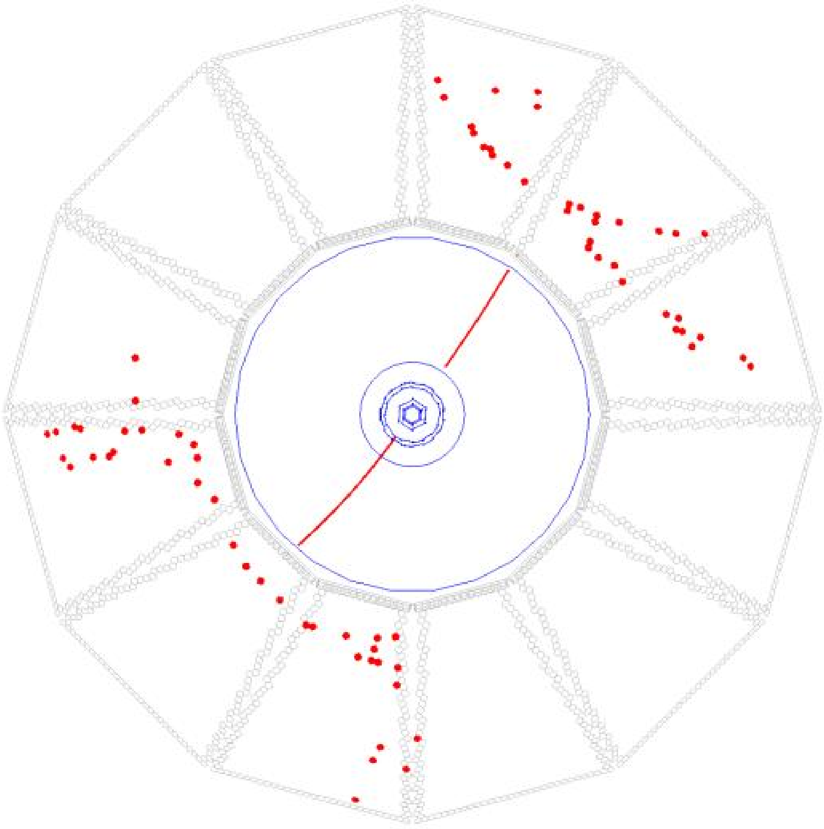
DIRC: a special kind of RICH (Ring Imaging Cherenkov counter) where Čerenkov photons trapped in a solid radiator (e.q. quartz) are propagated along the radiator bar to the side, and detected as they exit and traverse a gap.



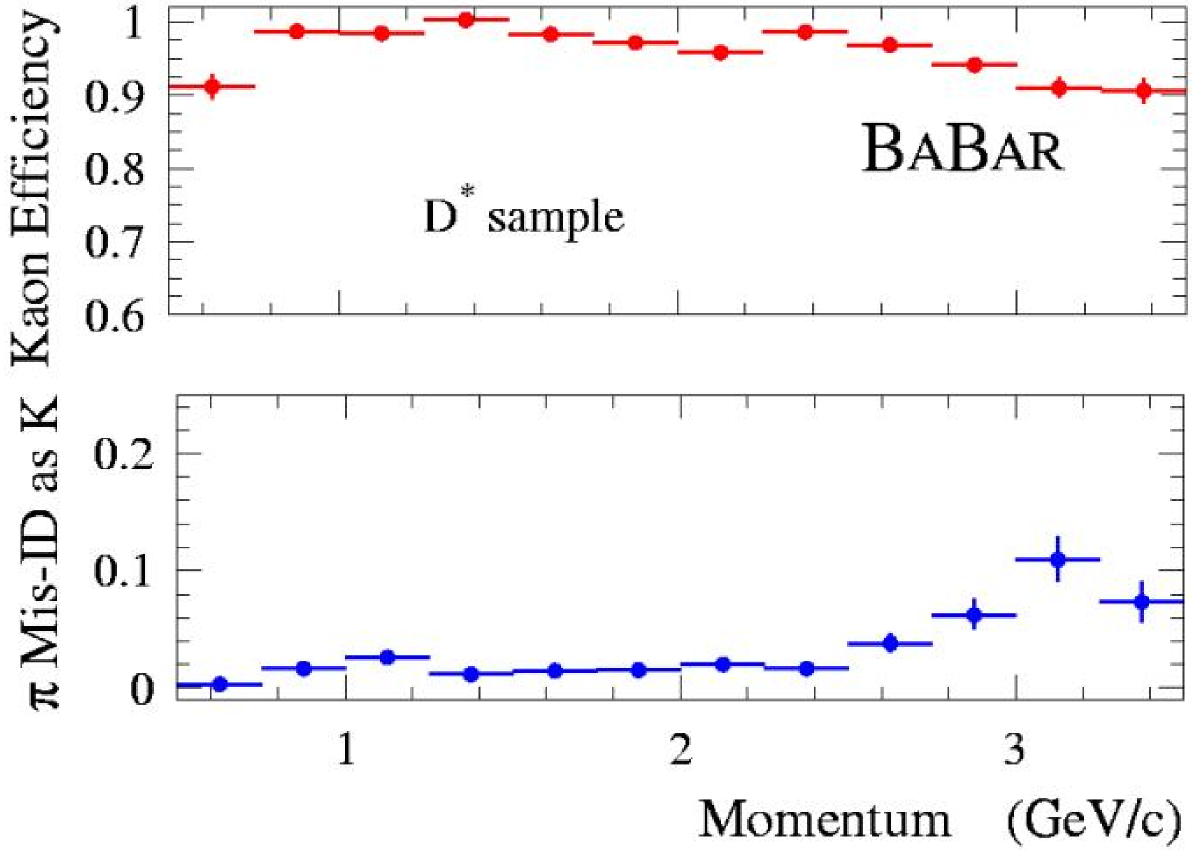


DIRC event

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



DIRC performance



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

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.

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

Bakelite RPCs at BABAR

(problems with aging)

Glass RPCs at Belle

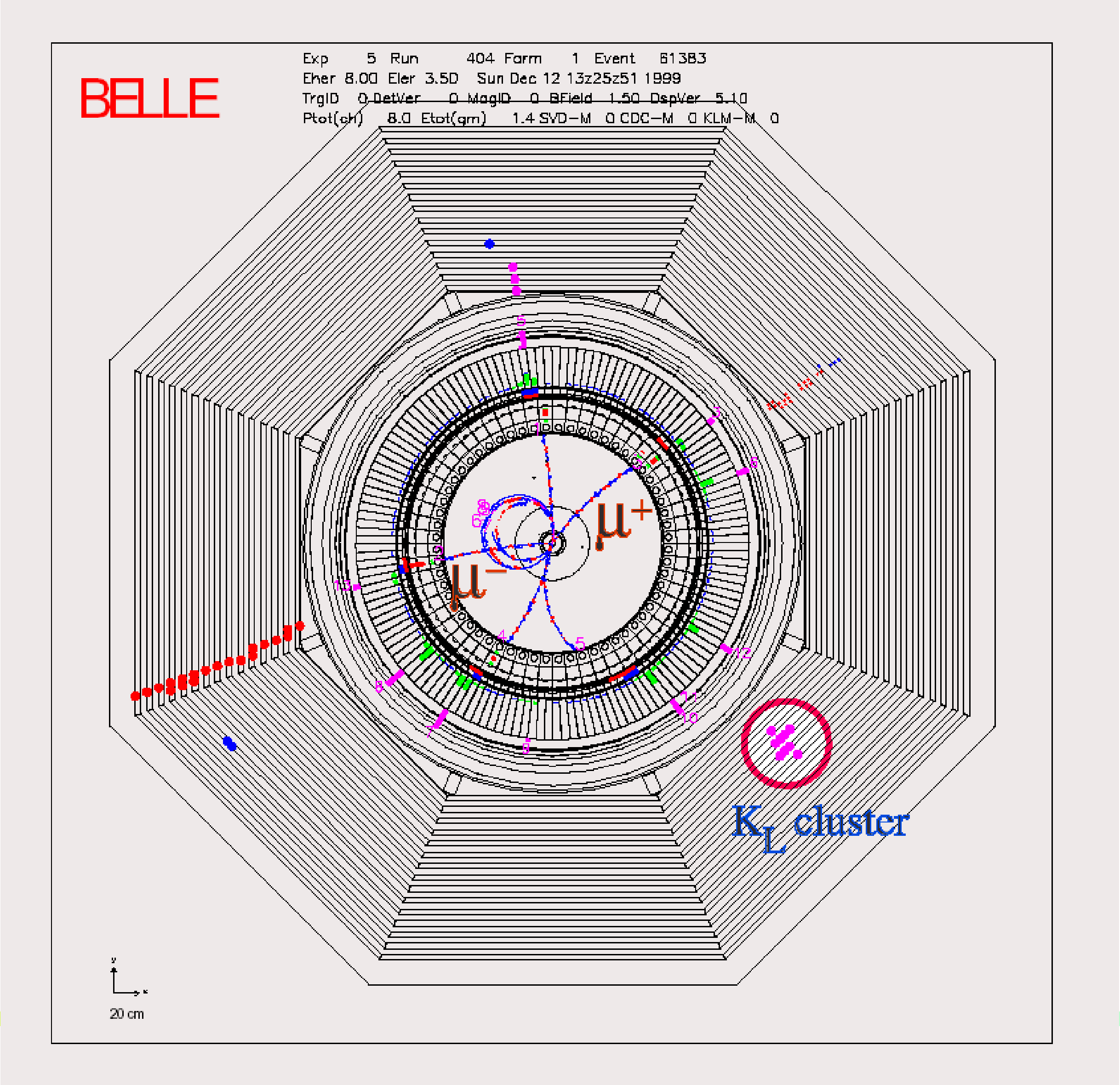
Muon and K_L detector

Example:

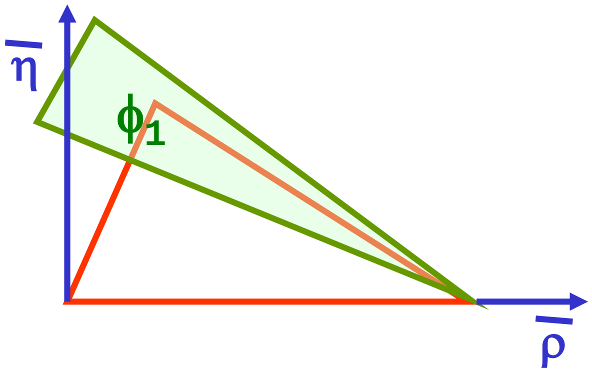
event with

- two muons and a
- K_L

and a pion that partly penetrated into the muon chamber system



How to measure sin2ϕ_1?



To measure sin2ϕ_1, we have to measure the time dependent CP asymmetry in $B^0 \to J/\Psi\ K_s$ decays

$$a_{f_{CP}} = -\mathrm{Im}(\lambda_{f_{CP}})\sin(\Delta m t) = \sin 2\phi_1 \sin(\Delta m t)$$

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

In addition to $B^0 \to J/\Psi\ K_s$ decays we can also use decays with any other charmonium state instead of J/Ψ. Instead of K_s we can use channels with K_L (opposite CP parity).

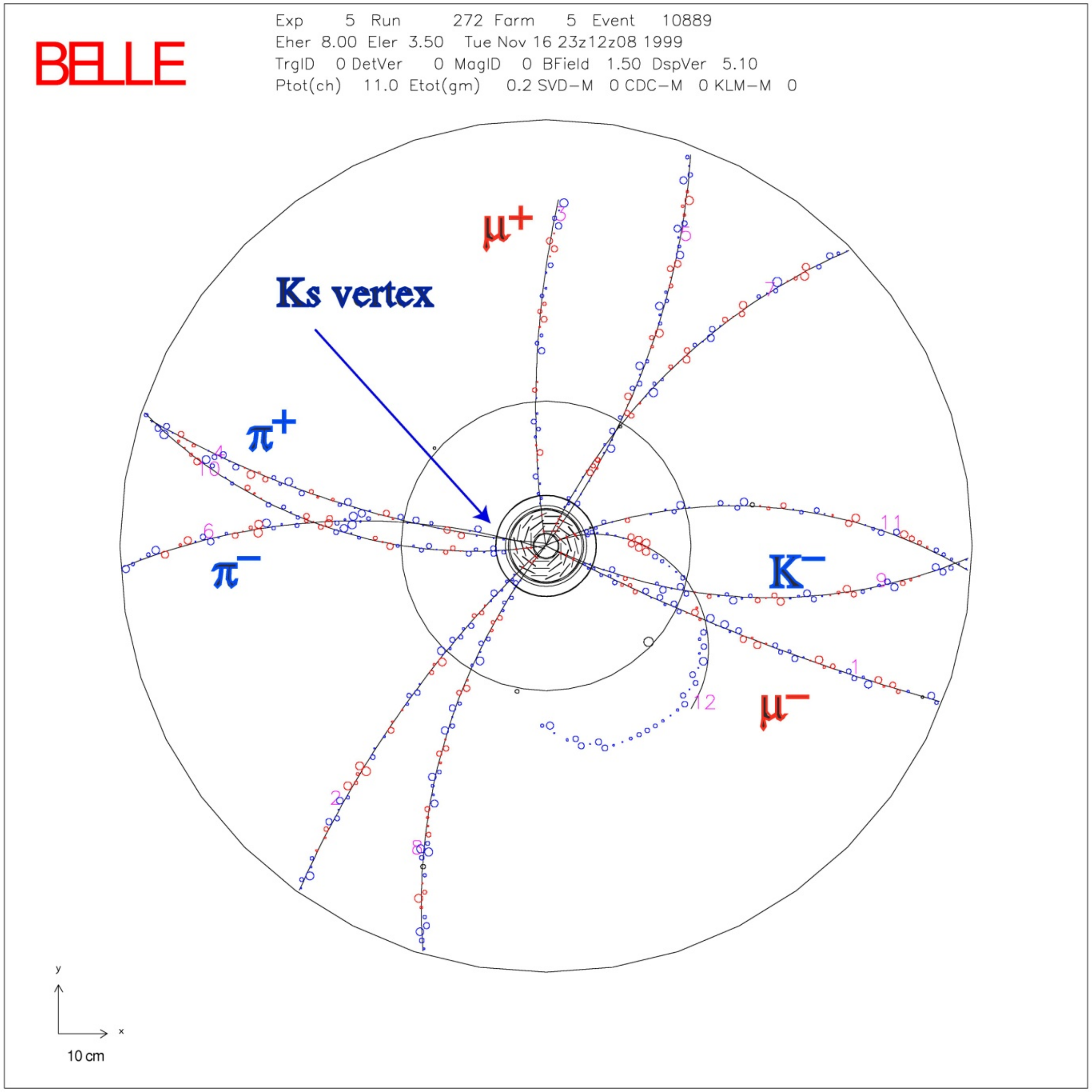
Reconstructing B $\rightarrow$J/Ψ K^0

Reconstructing a final state X which decayed to several particles (x,y,z):
From the measured tracks calculate the invariant mass of the system (i=x,y,z):

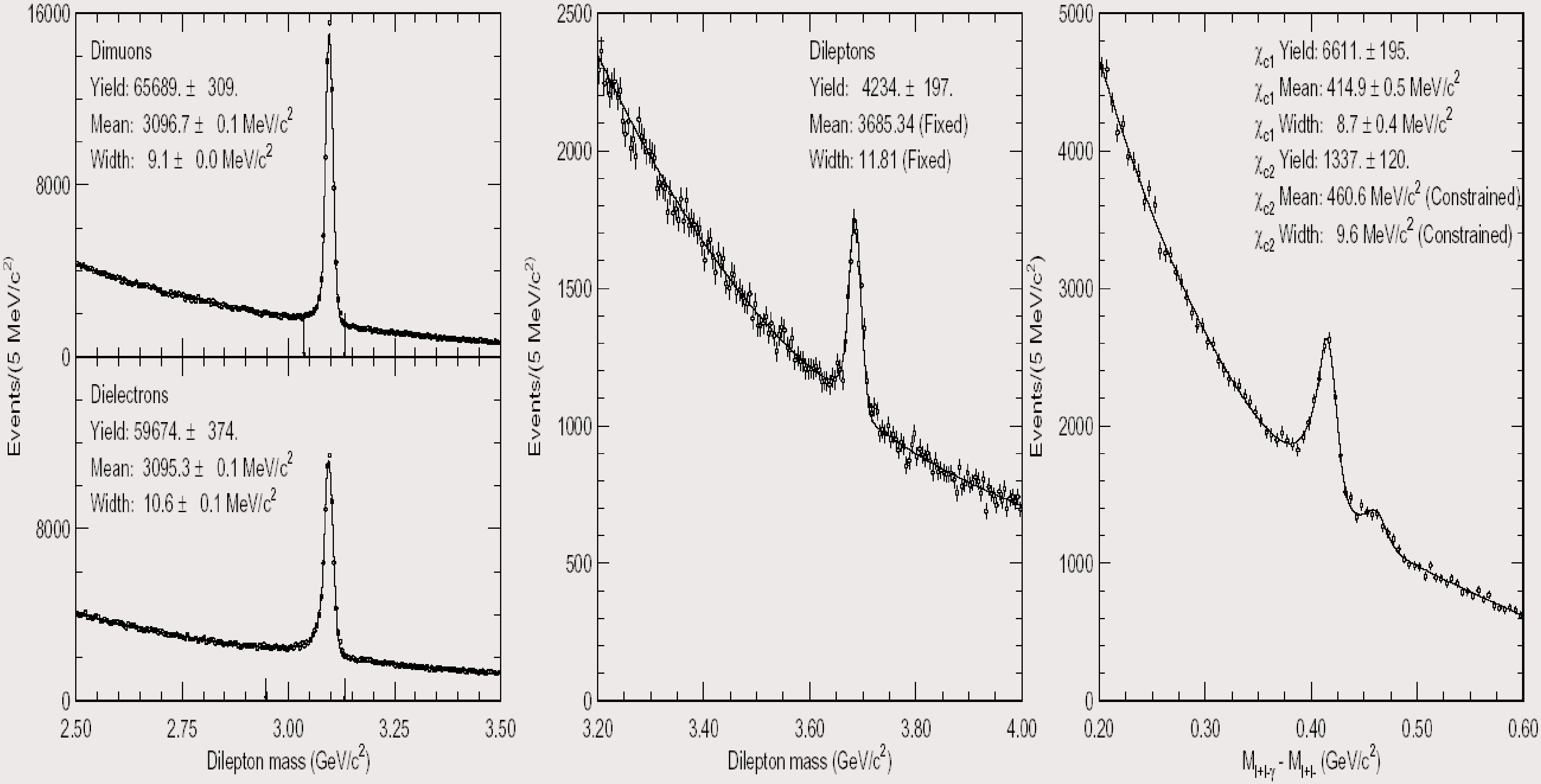
$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$

The candidates for the X->xyz decay show up as a peak in the distribution on (mostly combinatorial) background.
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 small peak width).

A golden channel event



Reconstructing chamonium states



$J/\psi \to \mu^+\mu^-, e^+e^-$

$\sigma_M = 9.6(10.7)\mathrm{GeV}/c^2$

$\psi(2s) \to \mu^+\mu^-, e^+e^-$

$\sigma_M = 12.1\mathrm{GeV}/c^2$

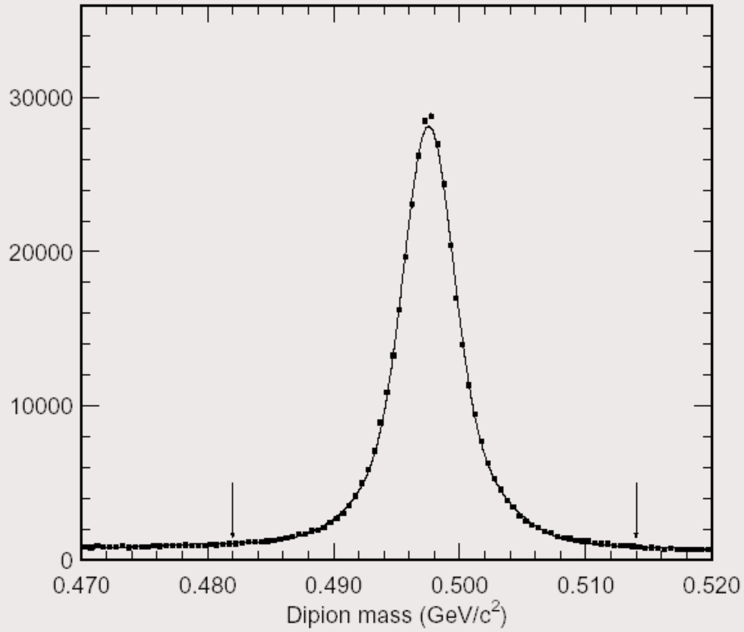
$\chi_{c1}, \chi_{c2} \to J/\psi\gamma$

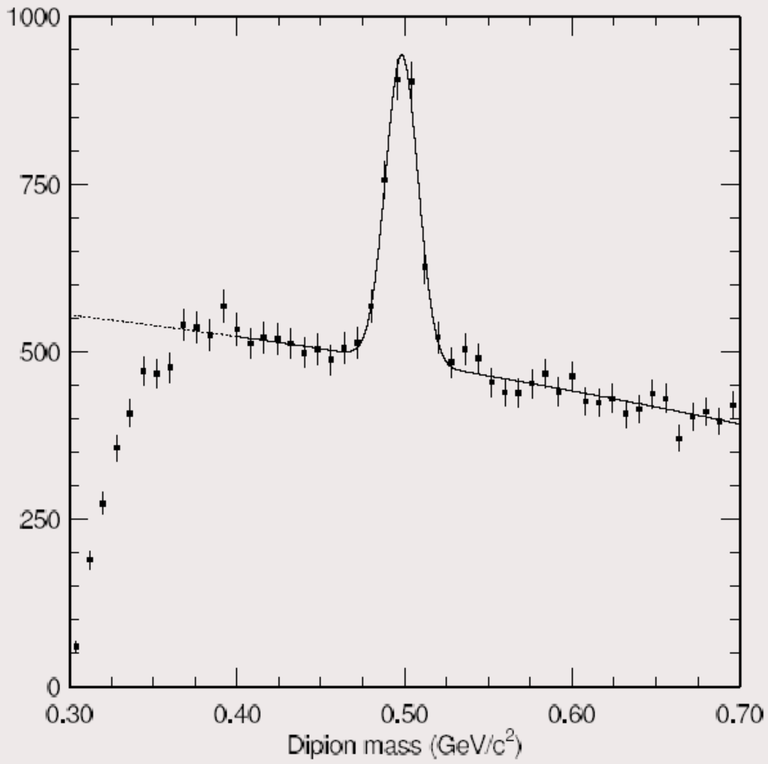
$\sigma_{\Delta M} = 7.0\mathrm{GeV}/c^2$

Reconstructing K^0_S

$K_S \to \pi^+\pi^-$

$\sigma_M = 4.1\mathrm{GeV}/c^2$

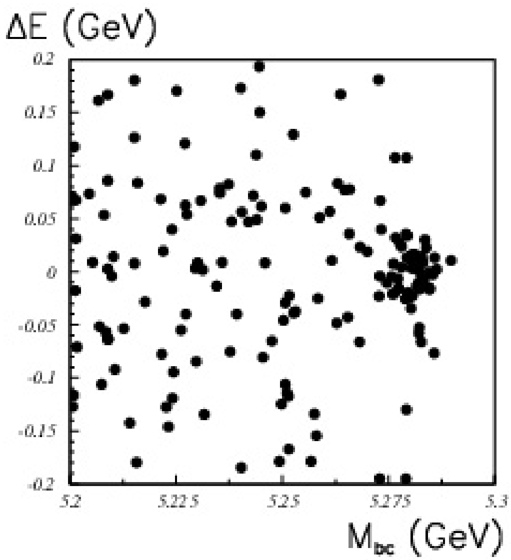


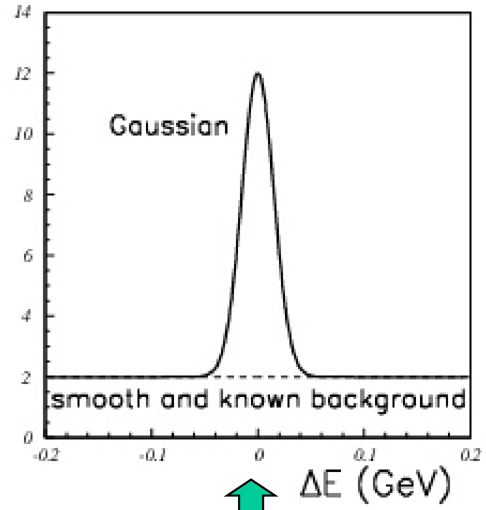


$K_S \to \pi^0\pi^0$

$\sigma_M = 9.3\mathrm{GeV}/c^2$

Reconstruction of rare B meson decays





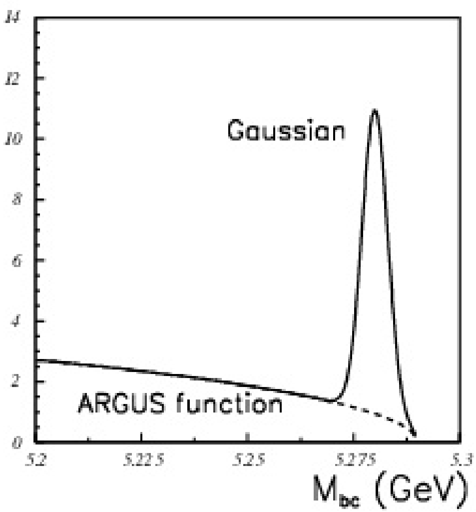
Reconstructing rare B meson decays at Y(4s): use two variables,

beam constrained mass M_{bc}

and

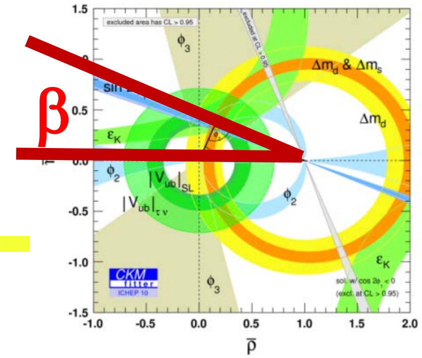
energy diference DE

$$\Delta E \equiv \sum E_i - E_{CM}/2$$



$$M_{bc} = \sqrt{(E_{CM}/2)^2 - (\sum \vec{p}_i)^2}$$

Final measurement of $\sin 2\phi_1$ ($=\sin 2\beta$)

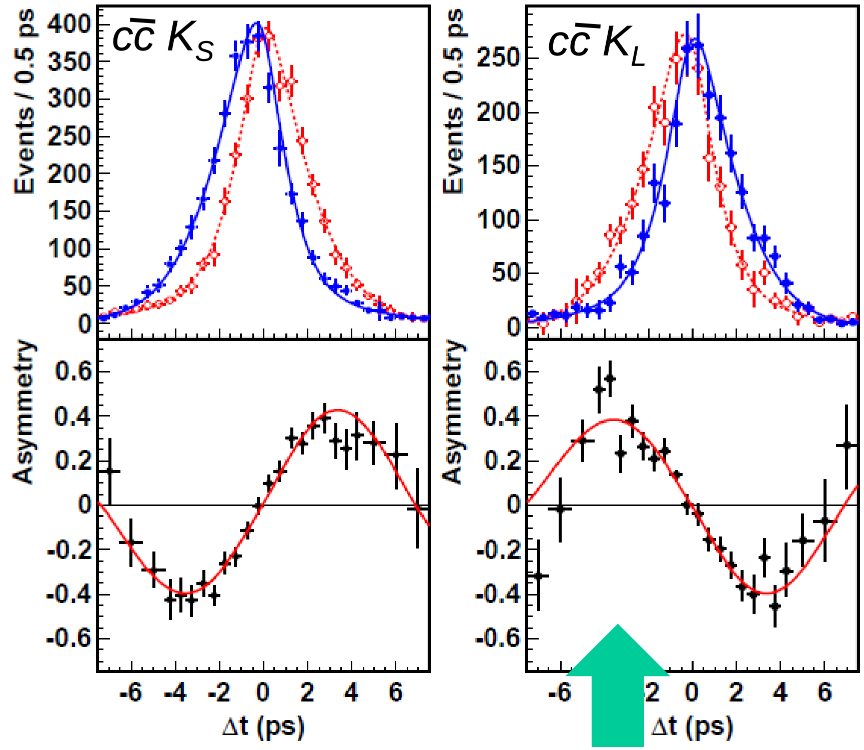


ϕ_1 from CP violation measurements in $B^0 \to c\bar{c}\, K^0$

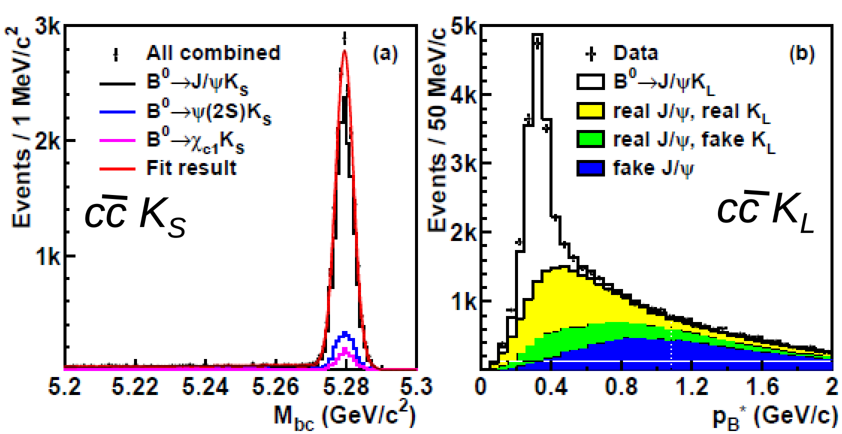
Final measurement: with improved tracking, more data, improved systematics (and more statistics

$cc = J/\psi,\ \psi(2S),\ \chi_{c1}$ → 25k events

Detector effects: wrong tagging, finite Δt resolution → determined using control data samples

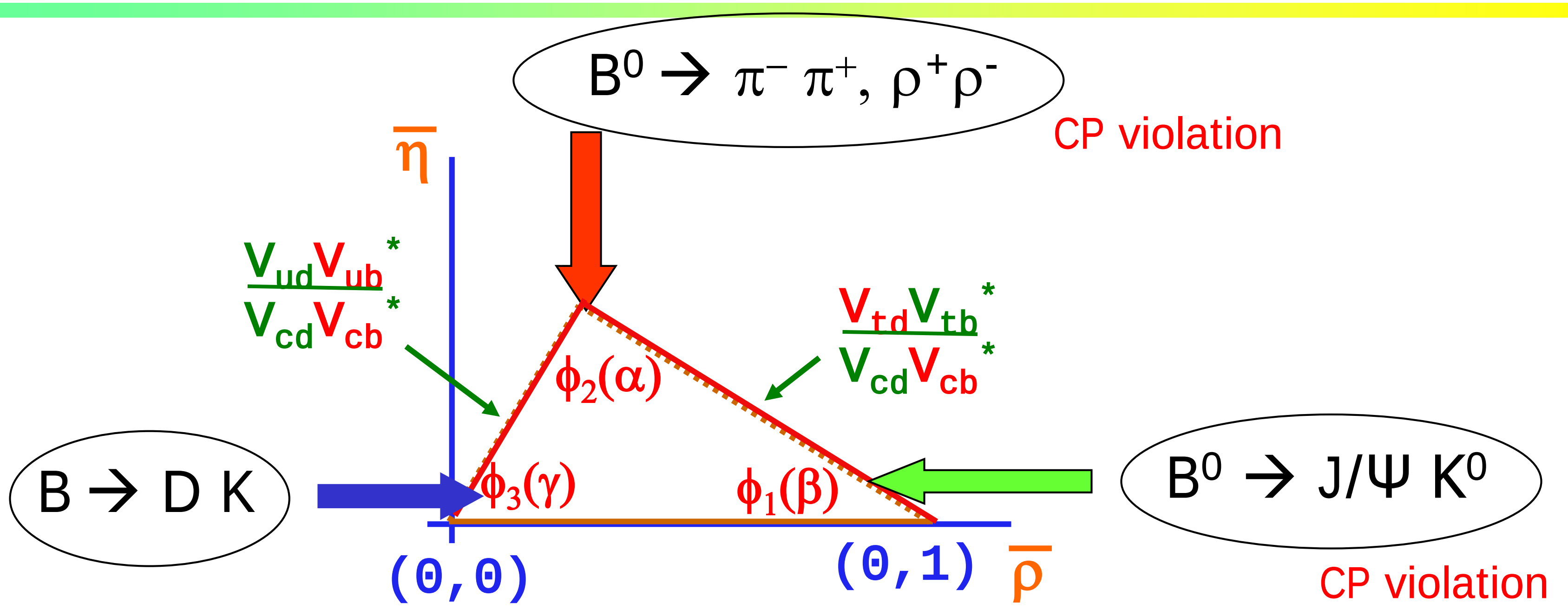


Opposite CP → sine wave with a flipped sign



Belle, final, 710 fb^{-1}, PRL 108, 171802 (2012)

Unitarity triangle: consistency checks



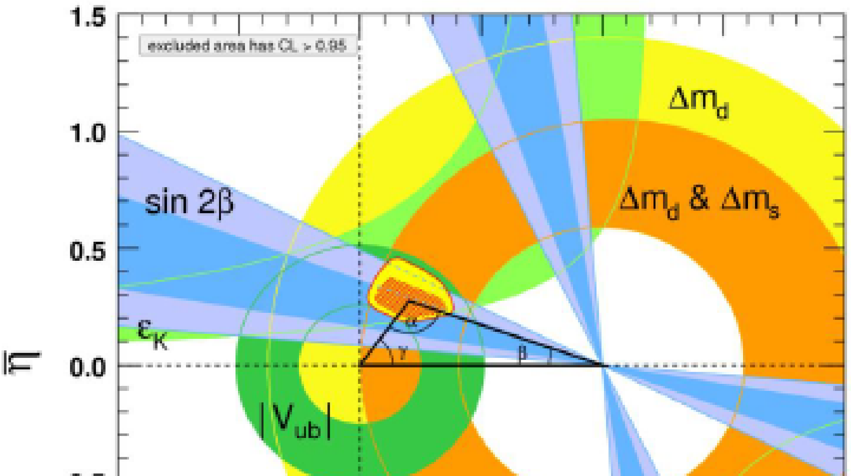
Consistency check of the unitarity triangle: precisely measure

- angles (through CP violation)
- sides ($b \to u$ and $b \to c$ rates) and B mixing

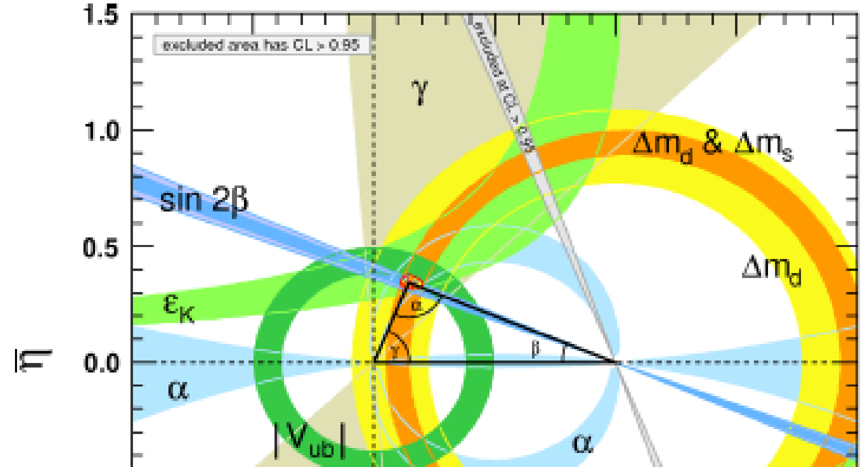
Summary: CP violation in the B system

B factories: CP violation in the B system: from the discovery (2001) to a precision measurement (2011) → remarkable agreement with KM

EPS 2001



EPS 2011

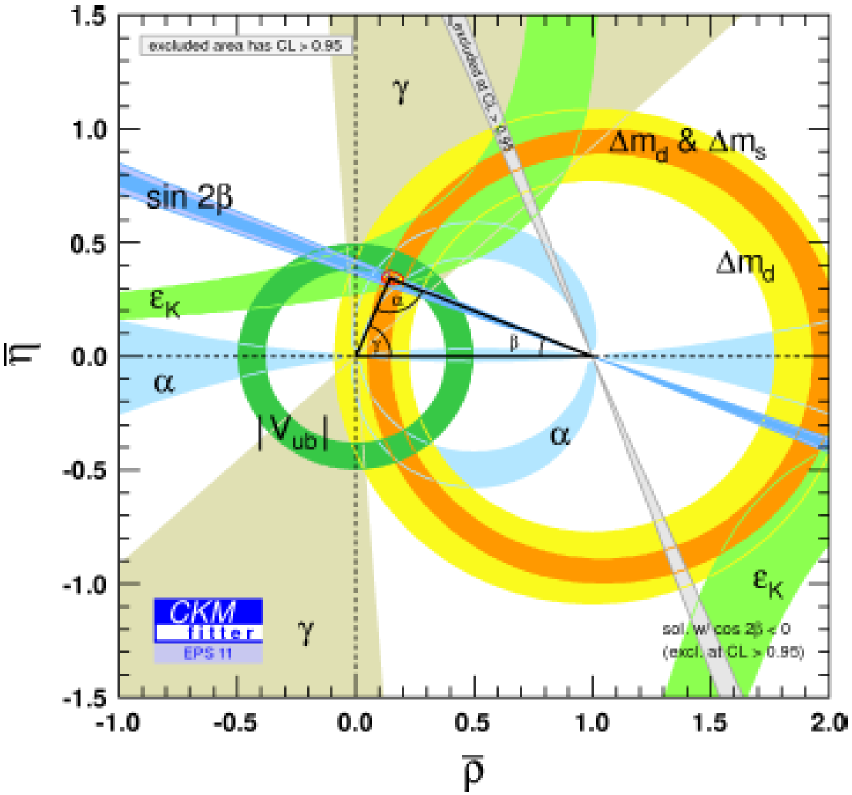


Contents, part 2

- Flavor physics: introduction, with a little bit of history
- Flavor physics at B factories: CP violation
- **Flavor physics at B factories: rare decays and searches for NP effects**
- **Super B factory**
- Flavor physics at hadron machines: history, LHCb and LHCb upgrade

The unitarity triangle – at present

Constraints from measurements of angles and sides of the unitarity triangle → remarkable agreement, but contributions of New Physics could be as high as 10-20%

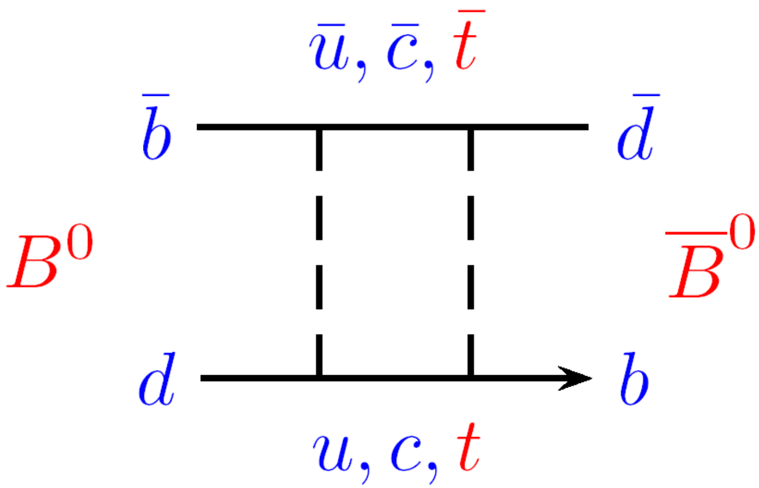


→investigate possible NP phenomena with precise measurements

→Intensity frontier

New particles in loops

<u>Mixing in the B⁰ system</u>: large mixing rate → high t quark mass; top quark has only been discovered



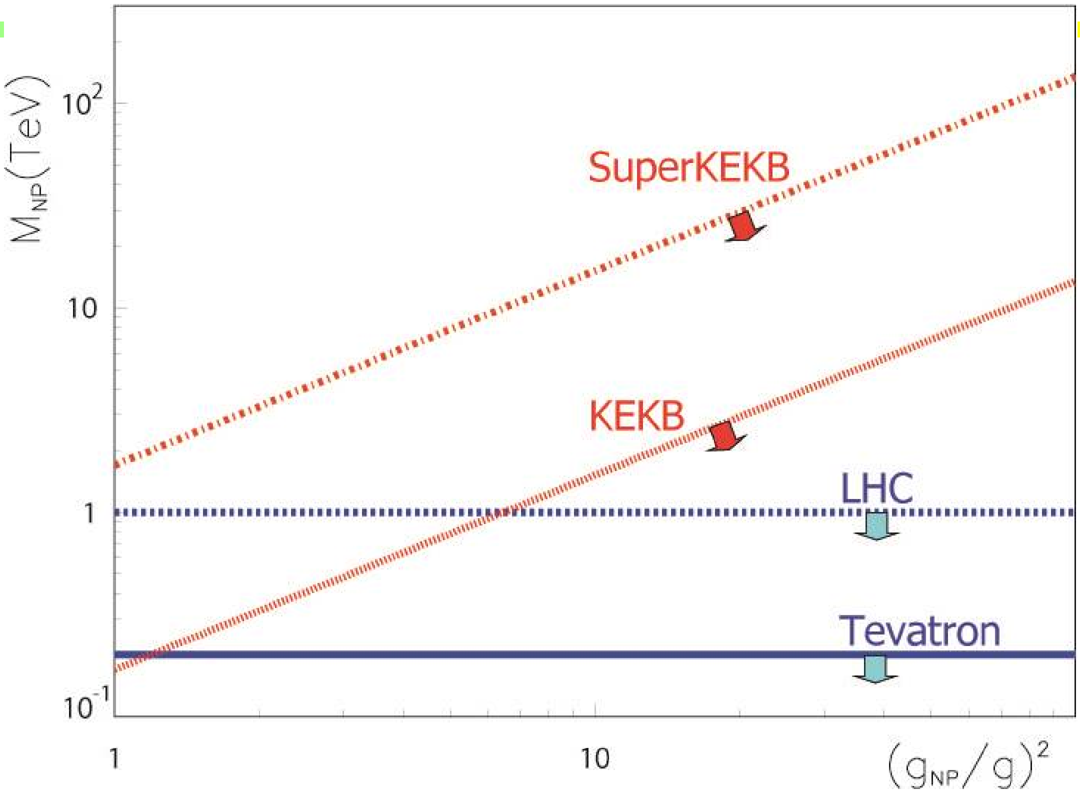
$$\Delta m \propto$$

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

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

Intensity Frontier vs Energy Frontier

Reach in mass of New Physics particles



New Physics coupling vs standard model

→ A very interesting complementarity of the two approaches

→see also lectures by Maxym Titov

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.

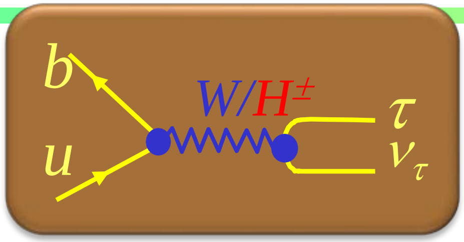
Energy frontier (LHC)

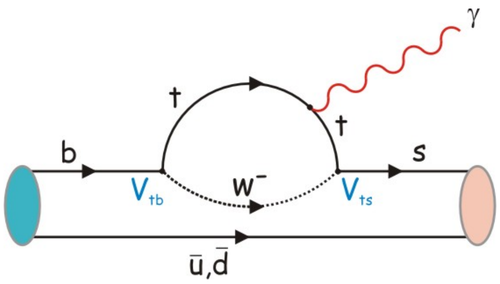
Luminosity frontier - (super) B factories

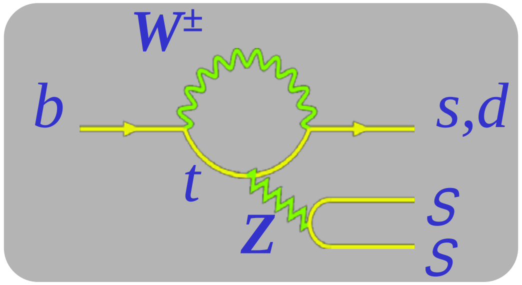
It worked already many times!

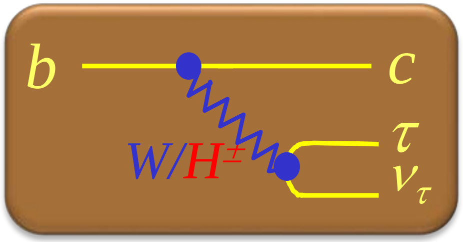
- The smallness of $K_L \to \mu^+\mu^-$ → GIM mechanism → need one more quark – c
- K^0 – anti-K^0 mixing frequency Δm_K → estimate the charm quark mass
- Mixing in the B^0 system: large mixing rate → high top mass; top quark has only been discovered seven years later!
- CP violation in K decays (1964) → KM mechanism (1973) → need three more quarks, discovered later in 1974, 1977, 1995

Rare B decays





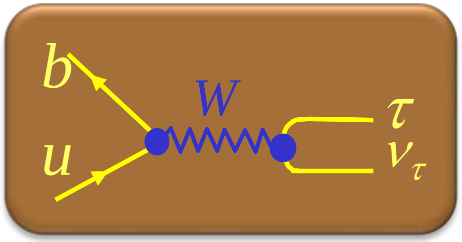




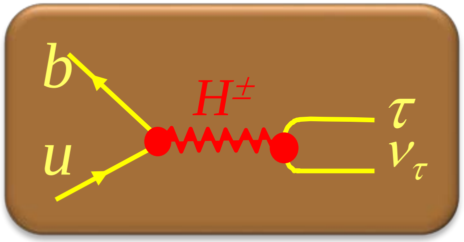
Search for effects of new particles and interactions

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

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



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



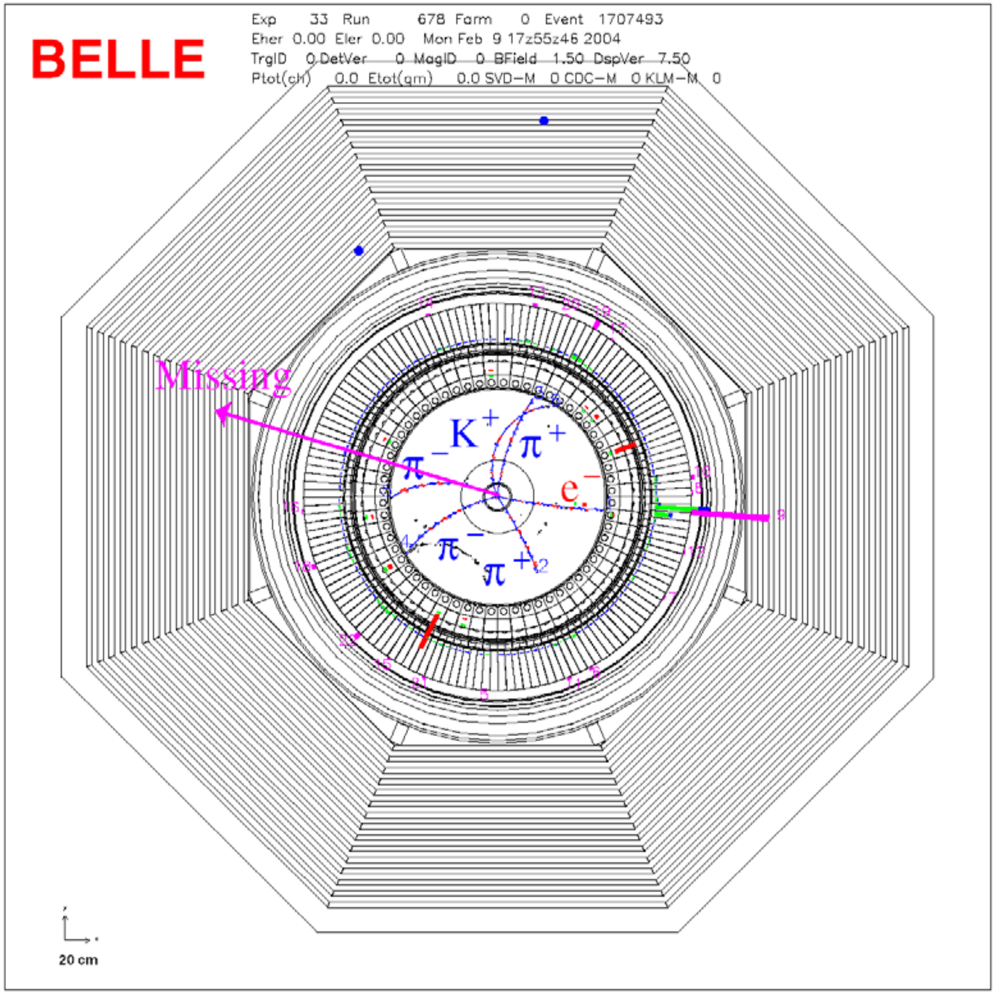
In some supersymmetric extension it can also proceed via a charged Higgs

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.

$B^- \rightarrow \tau^- \nu_\tau$

Example of a $B^- \rightarrow \tau^- \nu_\tau$ decay as measured at Belle

$$
\begin{aligned}
B^+ &\to D^0\pi^+ \\
&\qquad (\to K\pi^-\pi^+\pi^-) \\
B^- &\to \tau(\to e\nu\bar{\nu})\nu
\end{aligned}
$$

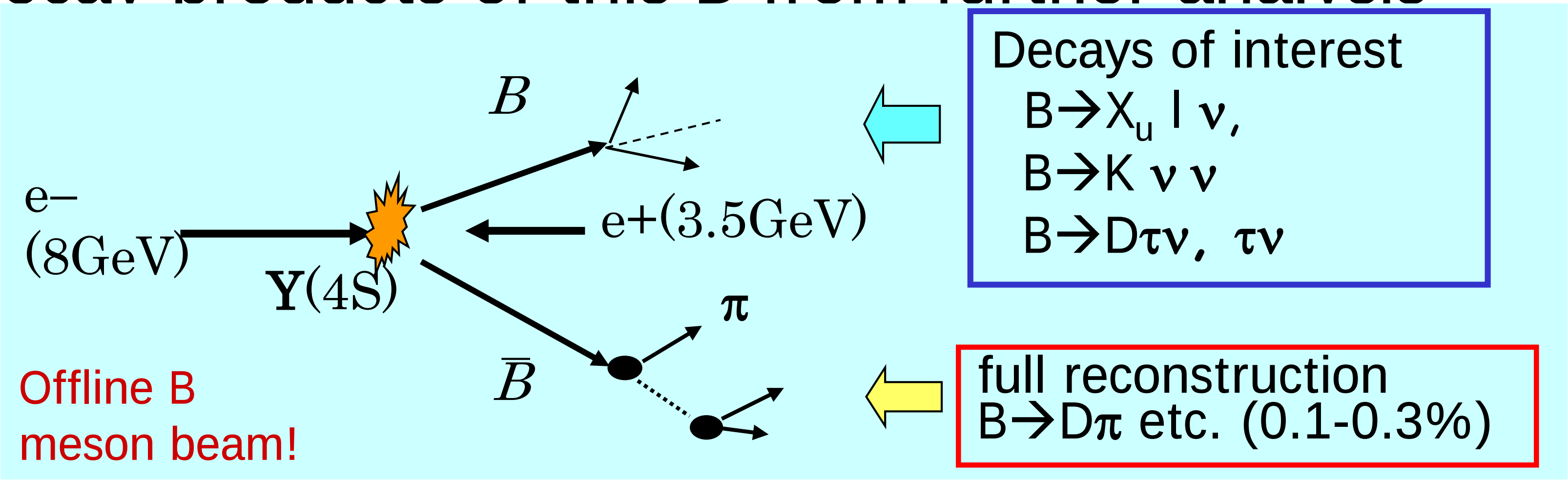


Tough to tackle experimentally: three neutrinos in the final state and only one charged particle from the B decay.

Can be carried out at B factories! →

Full reconstruction tagging

Idea: fully reconstruct one of the B's to tag B flavor/charge, determine its momentum, and exclude decay products of this B from further analysis



Powerful tool for B decays with neutrinos, used in several analyses in this talk

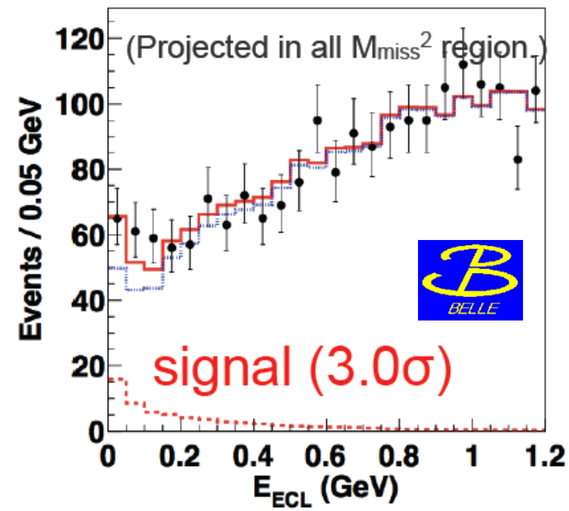
→unique feature at B factories

$B^- \to \tau^- \nu_\tau$

Method: tag one B with full reconstruction, look for the $B^- \to \tau^- \nu_\tau$ in the rest of the event.

Main discriminating variable on the signal side: remaining energy in the calorimeter, not associated with any charged track or photon

→ Signal at $E_{ECL} = 0$

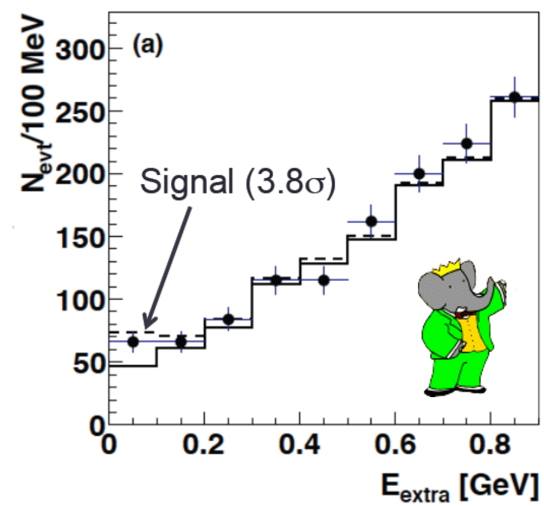


Belle $$Br(B \to \tau\nu) = [0.72\,^{+0.27}_{-0.25} \pm 0.11] \times 10^{-4}$$

PRL 110, 131801 (2013)

BaBar $$Br(B \to \tau\nu) = [1.83\,^{+0.53}_{-0.49} \pm 0.24] \times 10^{-4}$$

Phys. Rev. D 88, 031102(R) (2013)

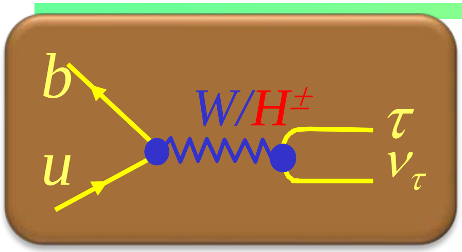


All measurements combined

$$BF(B \to \tau\nu) = (1.15 \pm 0.23) \cdot 10^{-4}$$

$$r_H = \frac{BF(B \to \tau\nu)_{meas}}{BF(B \to \tau\nu)_{SM}} = 1.14 \pm 0.40$$

Charged Higgs limits from B → $\tau^- \nu_\tau$



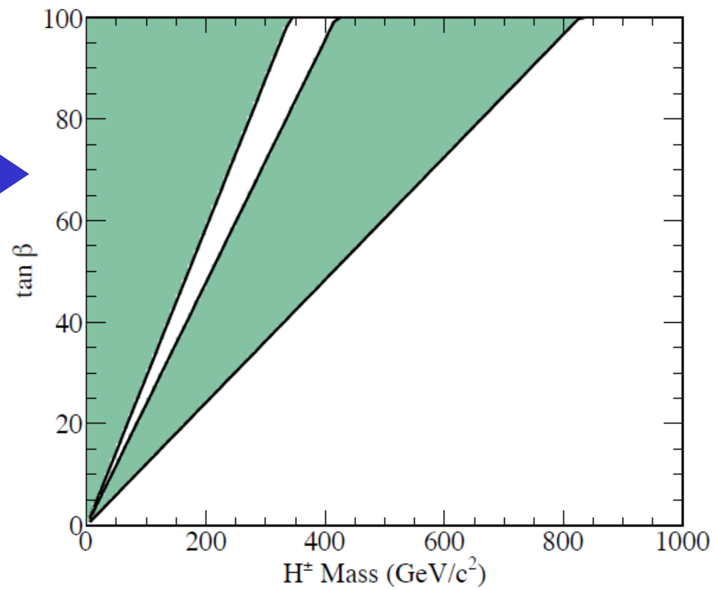
Measured value

$$r_H = \frac{BF(B\to\tau\nu)}{BF(B\to\tau\nu)_{SM}} = \left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2$$

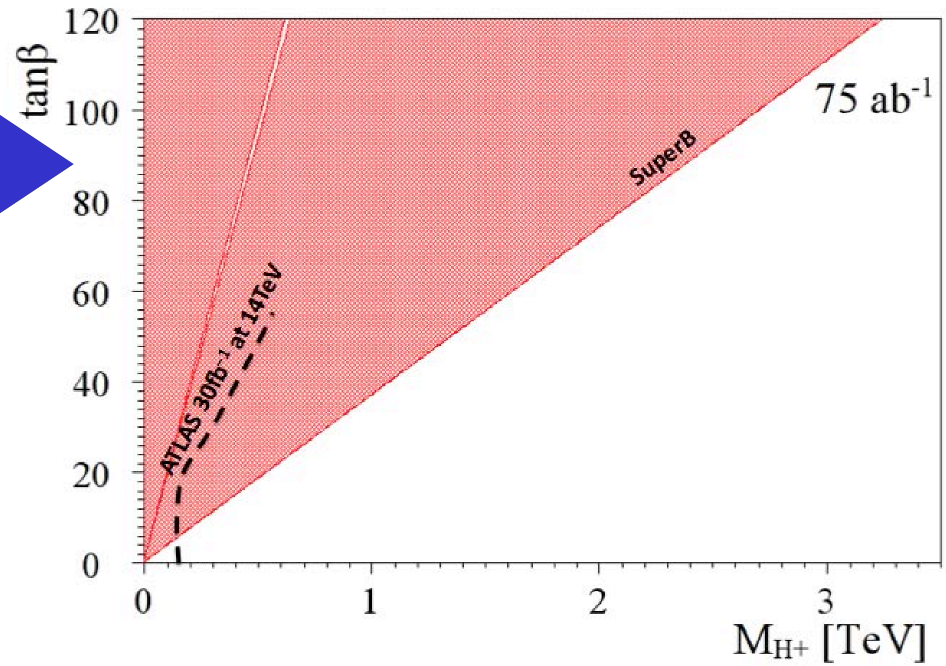
→ limit on charged Higgs mass vs. tanβ

(for type II 2HDM)

B factories: Exclusion plot

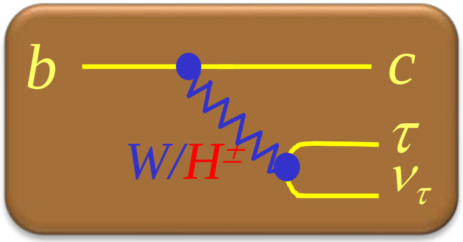


Super B factory: Discovery plot: very much competitive with LHC!



$B \to D^{(*)}\tau\nu$ decays

Semileptonic decay sensitive to charged Higgs



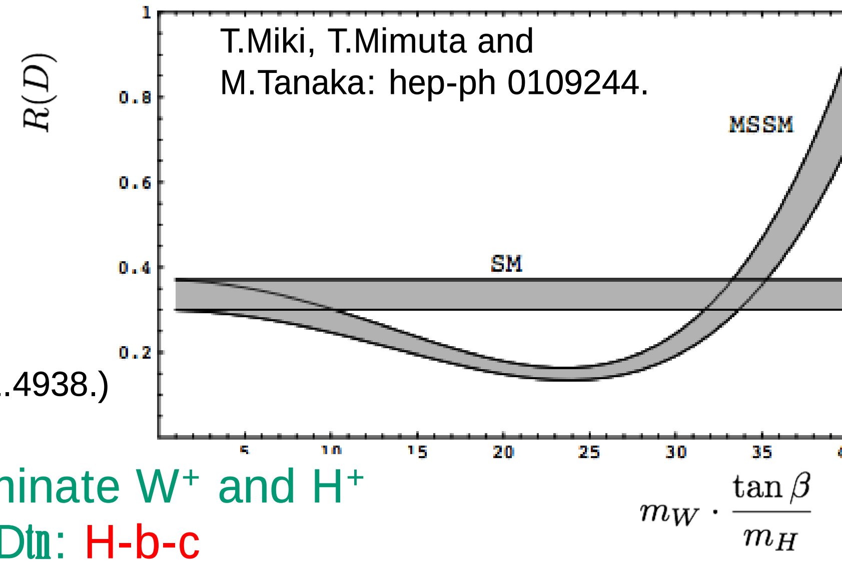
Ratio of τ to μ,e could be reduced/enhanced significantly

Kamenik, Mescia arXiv:0802.3790

$$R(D) \equiv \frac{\mathcal{B}(B \to D\tau\nu)}{\mathcal{B}(B \to D\ell\nu)}$$

Complementary and competitive with $B \to \tau\nu$

1. Smaller theoretical uncertainty of R(D)
   (For $B \to \tau\nu$,
   There is O(10%) f_B uncertainty from lattice QCD)
2. Large Brs (~1%) in SM (Ulrich Nierste arXiv:0801.4938.)

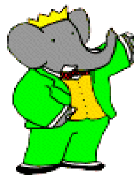


3. Differential distributions can be used to discriminate W^+ and H^+
4. Sensitive to different vertex $B \to \tau\nu$: H-b-u, $B \to D\tau\nu$: H-b-c
   (LHC experiments sensitive to H-b-t)

First observation of $B \to D^{*-}\tau\nu$ by Belle (2007) → PRL 99, 191807 (2007)

$B \to D^{(*)} \tau \nu$ decays

Exclusive hadron tag data



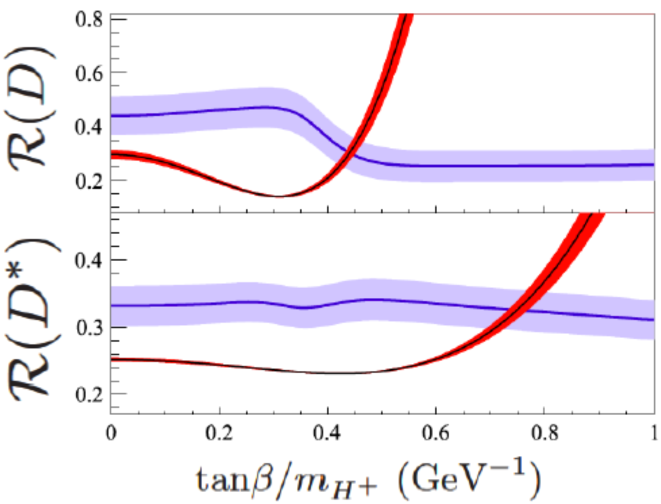
$$\mathcal{R}(D)_{\rm exp} = 0.440 \pm 0.072 \quad \mathcal{R}(D^*)_{\rm exp} = 0.332 \pm 0.030$$

2.0σ   2.7σ

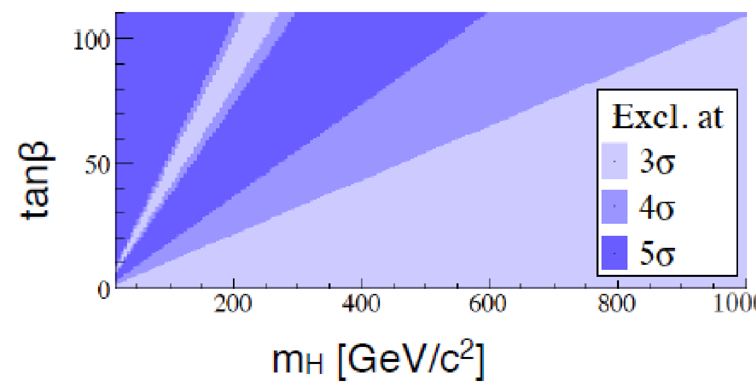
$$\mathcal{R}(D)_{\rm SM} = 0.297 \pm 0.017 \quad \mathcal{R}(D^*)_{\rm SM} = 0.252 \pm 0.003$$

SM expectations in S. Fajfer, J. Kamenik, I. Nisandzic, PRD 85, 094025 (2012).

→ Combined result: 3σ away from SM.



Blue: this result, red: Type-II 2HDM.

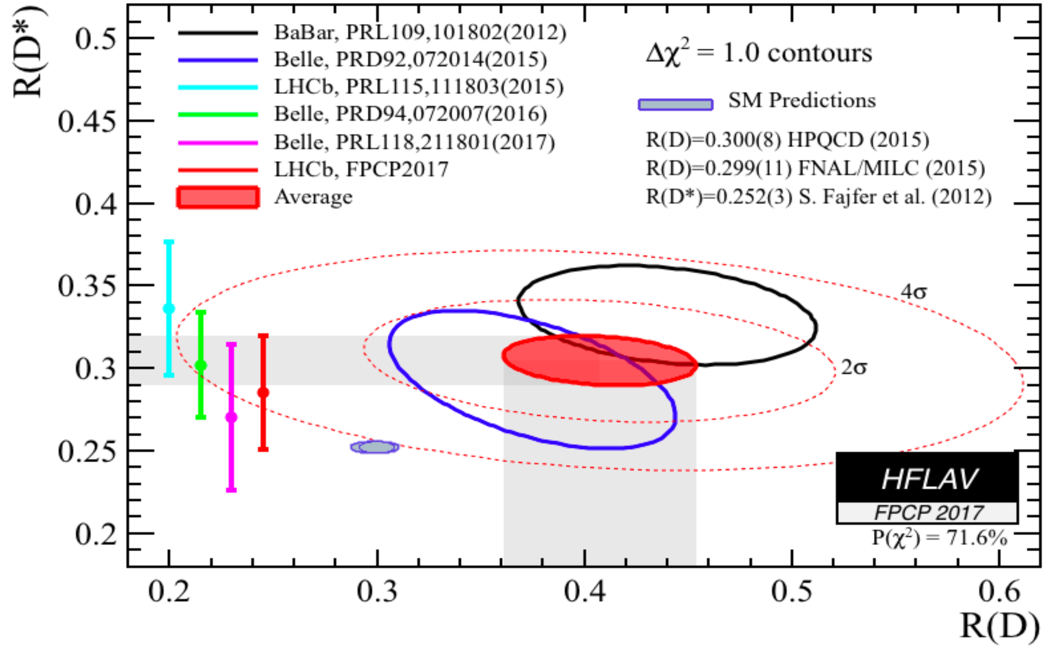


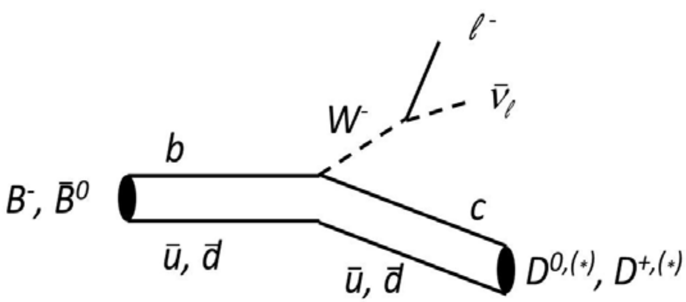
→ Combined result: Type II 2HDM excluded at 99.8% C.L. for any values of tanβ and charged Higgs mass

More discussion of the implications: BaBar, Phys. Rev. Lett. 109, 101802 (2012)

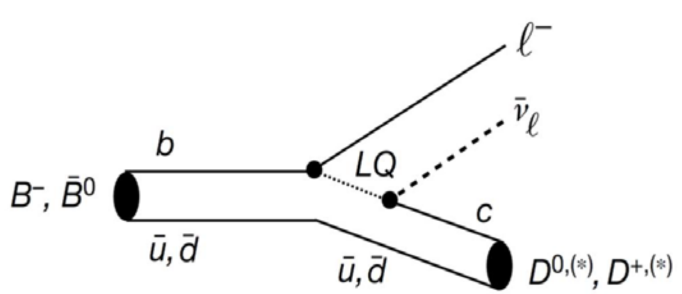
$B \to D^{(*)} \tau\nu$ decays

Average of measurements of R(D) and R(D*) compared to the SM predictions





Diagrams for the $B \to D(^*)\tau\nu$ transition, mediated by the charged SM weak interaction



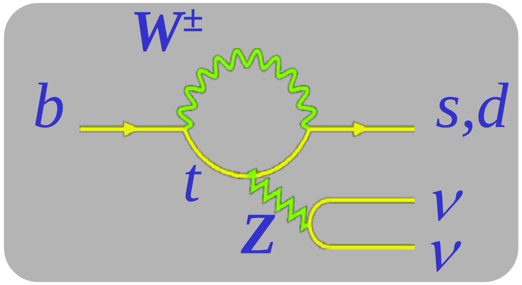
A possible non-SM decay process.

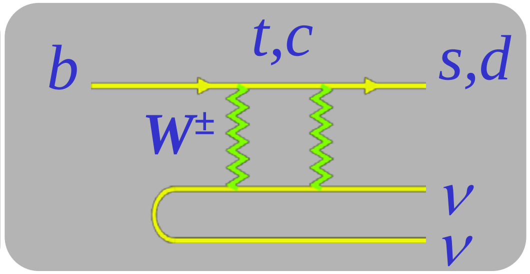
$B \to K^{(*)}\nu\bar{\nu}$

arXiv:1002.5012

adopted from W. Altmannshofer et al., JHEP 0904, 022 (2009)

SM: penguin + box diagrams

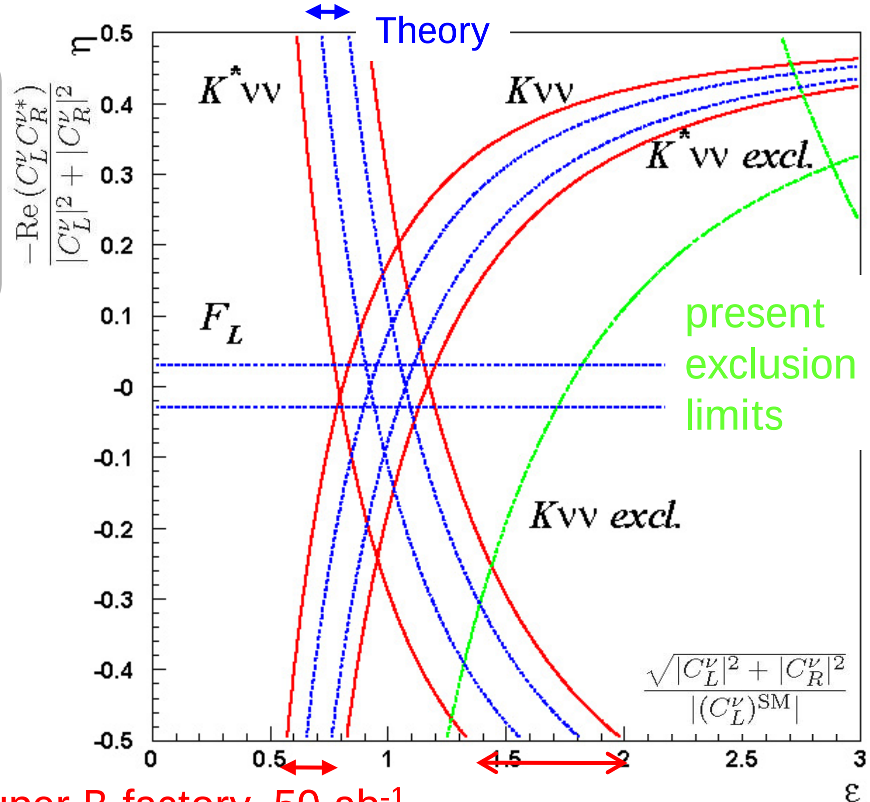




$B \to K\nu\nu,\ \mathcal{B} \sim 4{\cdot}10^{-6}$

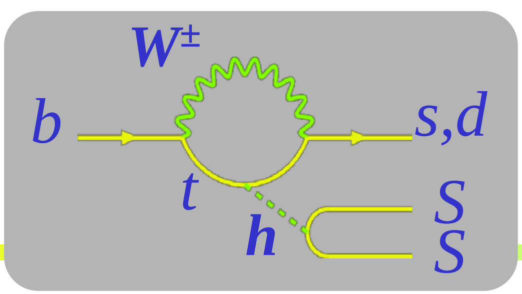
$B \to K^*\nu\nu,\ \mathcal{B} \sim 6.8{\cdot}10^{-6}$

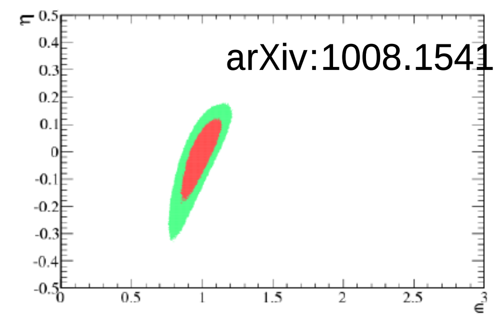
Look for deviations from the expected values → information on anomalous couplings C^{ν}_{R} and C^{ν}_{L} compared to $(C^{\nu}_{L})^{SM}$



super B factory, 50 ab^{-1}

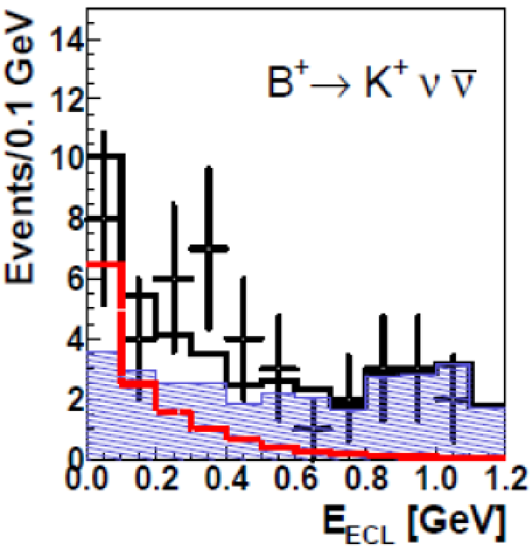
from, e.g.,





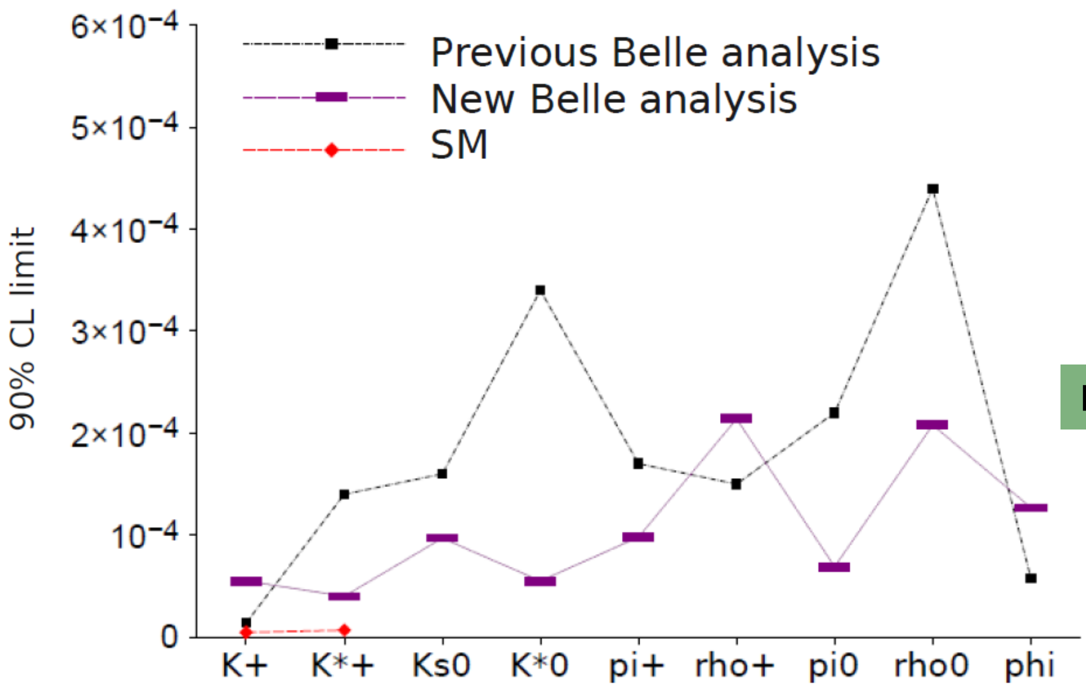
$B \to h\nu\bar{\nu}$ decays

Method: again tag one B with full reconstruction, search for signal in the remaining energy in the calorimeter, at $E_{ECL} = 0$



$$N_{Sig} =$$
$$13.3^{+7.4}_{-6.6}(stat) \pm 2.3(syst)$$
$$S_{stat+syst} = 2.0\sigma$$

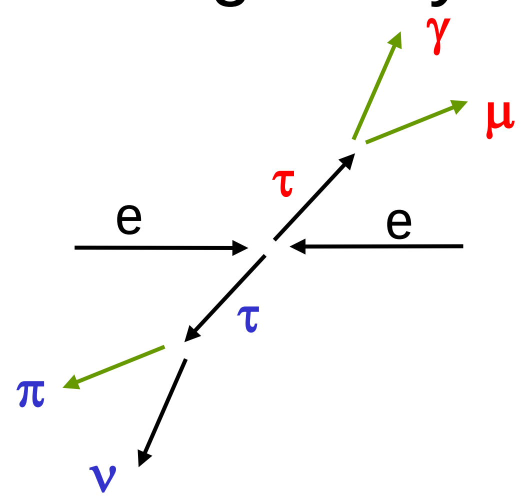
Present status: recent update from Belle



Belle, Phys. Rev. D 87, 111103(R) (2013)

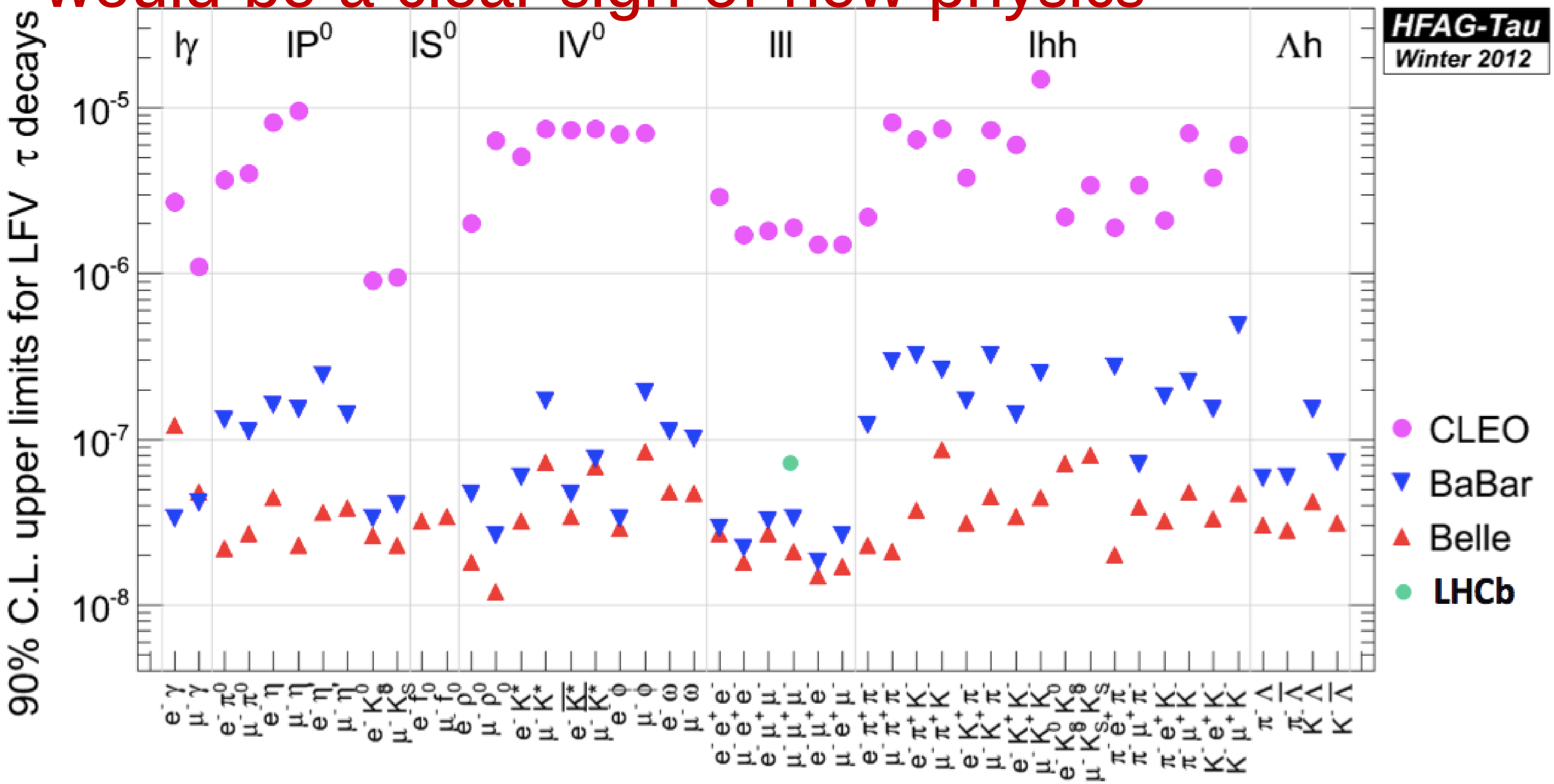
Rare τ decays

Example: lepton flavour violating decay $\tau \to \mu \gamma$



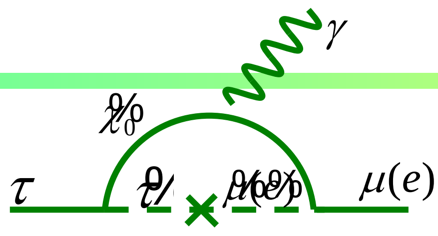
LFV in tau decays: present status

Lepton flavour violation (LFV) in tau decays: would be a clear sign of new physics

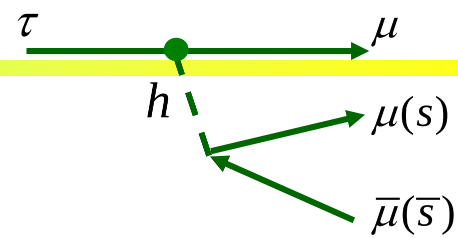


LFV and New Physics

$\tau \rightarrow l\gamma$



$\tau \rightarrow 3l, l\eta$

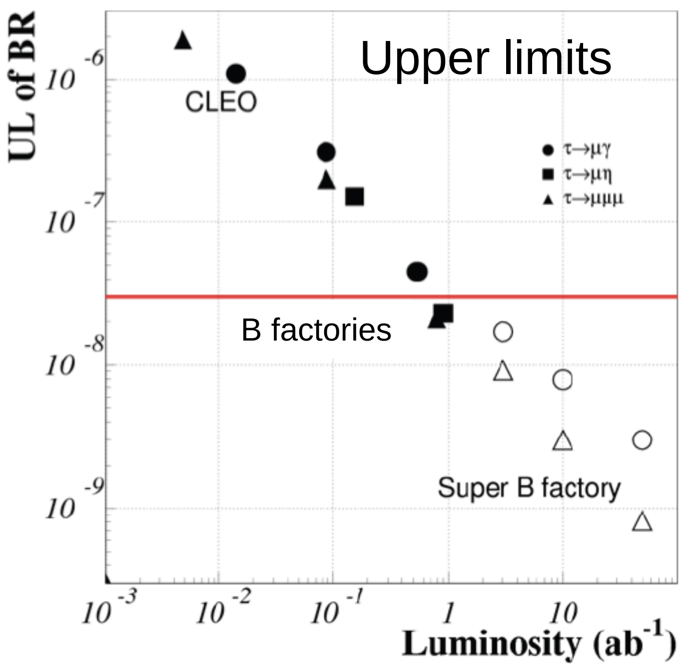


- SUSY + Seasaw $(m^2_{\tilde{L}})_{23(13)}$
- Large LFV $Br(\tau \rightarrow \mu\gamma) = O(10^{-7\sim 9})$

$$Br(\tau \rightarrow \mu\gamma) \doteq 10^{-6} \times \left(\frac{(m^2_{\tilde{L}})_{32}}{\bar{m}^2_{\tilde{L}}} \right) \left(\frac{1\,TeV}{m_{SUSY}} \right)^4 \tan^2\beta$$

- Neutral Higgs mediated decay.
- Important when M_{SUSY} >> EW scale.

$$Br(\tau \rightarrow 3\mu) = 4 \times 10^{-7} \times \left(\frac{(m^2_{\tilde{L}})_{32}}{\bar{m}^2_{\tilde{L}}} \right) \left(\frac{\tan\beta}{60} \right)^6 \left(\frac{100 GeV}{m_A} \right)^4$$



model	Br(τ→μγ)	Br(τ→lll)
mSUGRA+seesaw	10^{-7}	10^{-9}
SUSY+SO(10)	10^{-8}	10^{-10}
SM+seesaw	10^{-9}	10^{-10}
Non-Universal Z’	10^{-9}	10^{-8}
SUSY+Higgs	10^{-10}	10^{-7}

Integ. Lum.(ab^{-1})

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., $B \to \tau\nu$, $D\tau\nu$)
- $b \to s$ transitions: probe for new sources of CPV and constraints from the $b \to s\gamma$ branching fraction
- Forward-backward asymmetry (A_{FB}) in $b \to s l^+ l^-$
- Observation of D mixing
- Searches for rare τ decays
- Discovery of exotic hadrons including charged charmonium- and bottomonium-like states

What next?

Next generation: Super B factory → Looking for New Physics

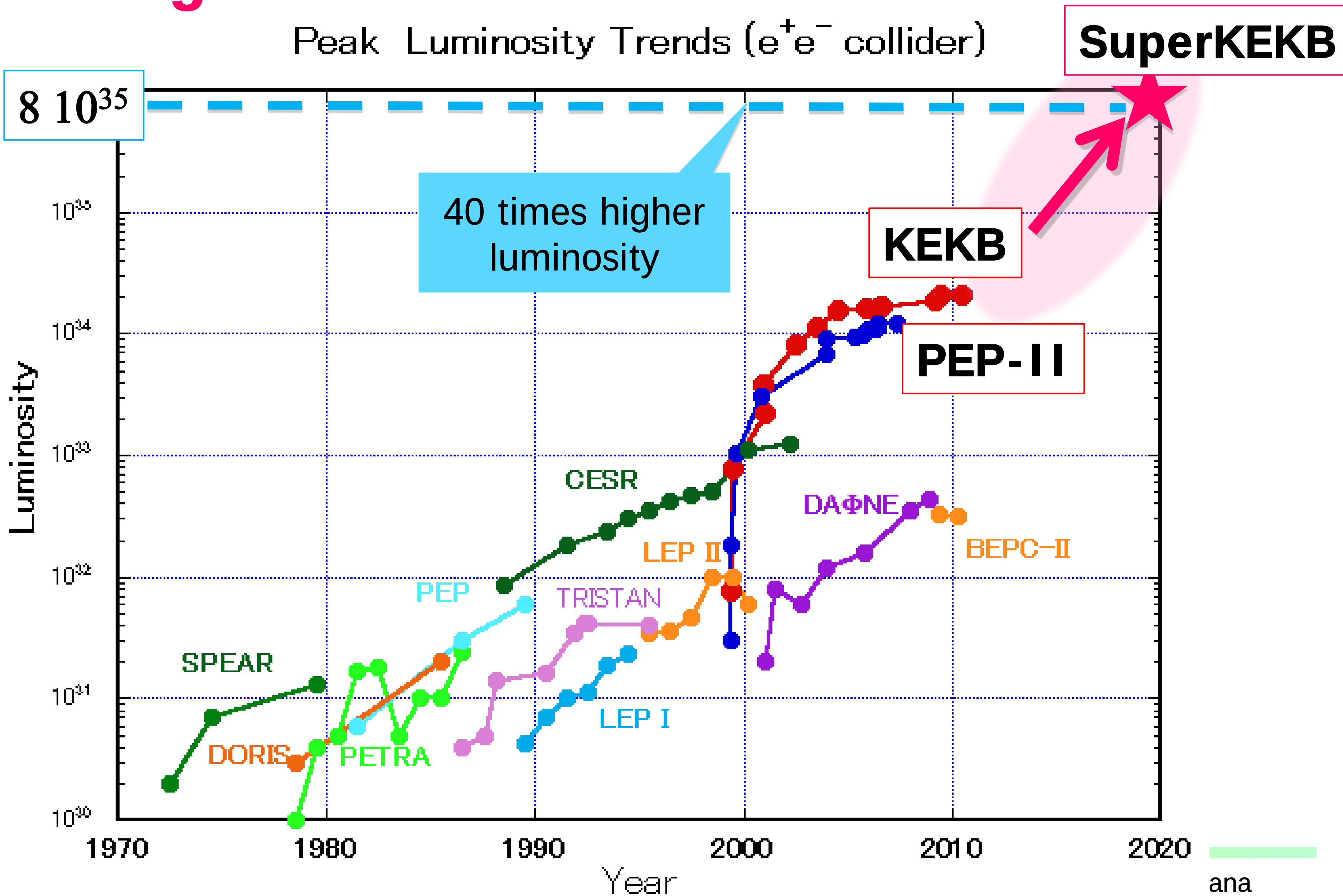
→ Need much more data (almost two orders!)

However: a different world in two years, there is a hard competition from LHCb (and BESIII)

Still, a e^+e^- machine running at (or near) $\Upsilon(4s)$ has considerable advantages in several classes of measurements, and is complementary in many more

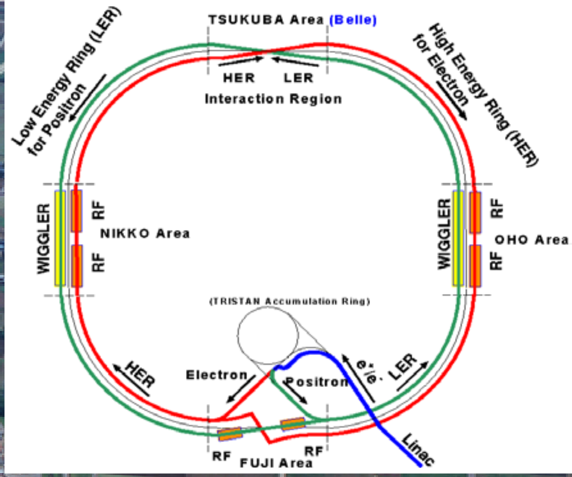
→ Physics at Super B Factory, arXiv:1002.5012 (Belle II)
→ SuperB Progress Reports: Physics, arXiv:1008.1541 (SuperB)

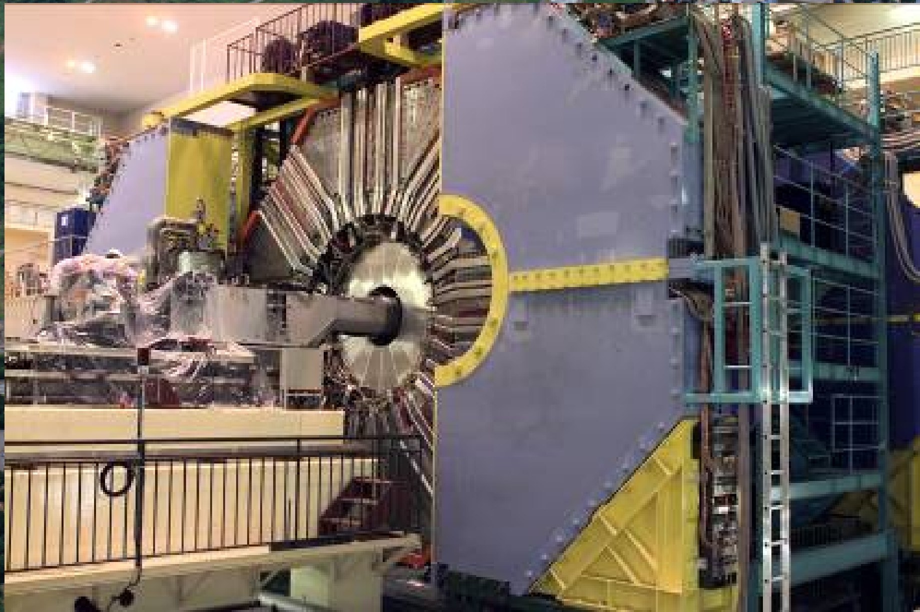
Need O(100x) more data →Next generation B-factories



ana

How to do it?
→ upgrade the existing KEKB and Belle facility





How to increase the luminosity?

$$L = \frac{\gamma_{e\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

Lorentz factor

Beam current

Beam-beam parameter

Classical electron radius

Beam size ratio@IP
1 - 2 % (flat beam)

Vertical beta function@IP

Lumi. reduction factor (crossing angle)&
Tune shift reduction factor (hour glass effect)
0.8 - 1
(short bunch)

(1) Smaller β_y^*

(2) Increase beam currents

(3) Increase ξ_y

"Nano-Beam" scheme

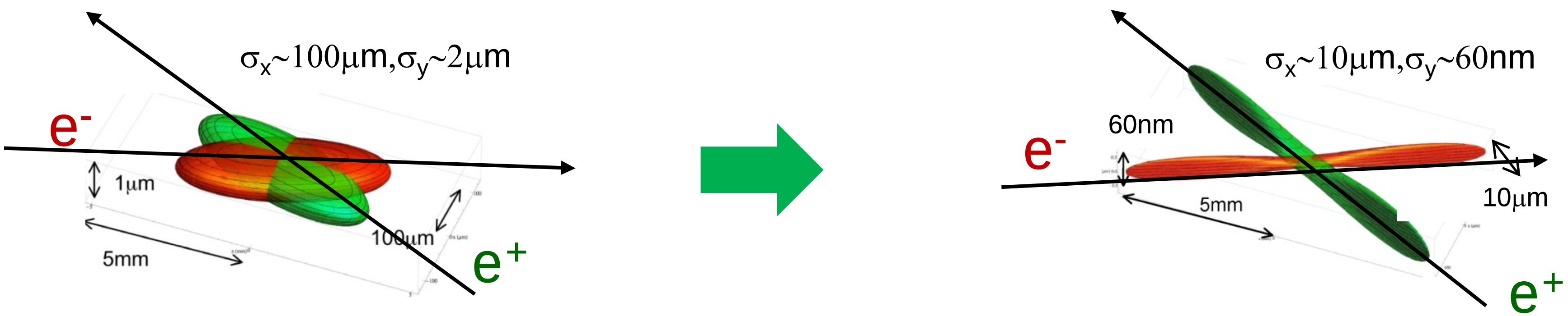
Collision with very small spot-size beams

Invented by Pantaleo Raimondi for SuperB

How big is a nano-beam ?

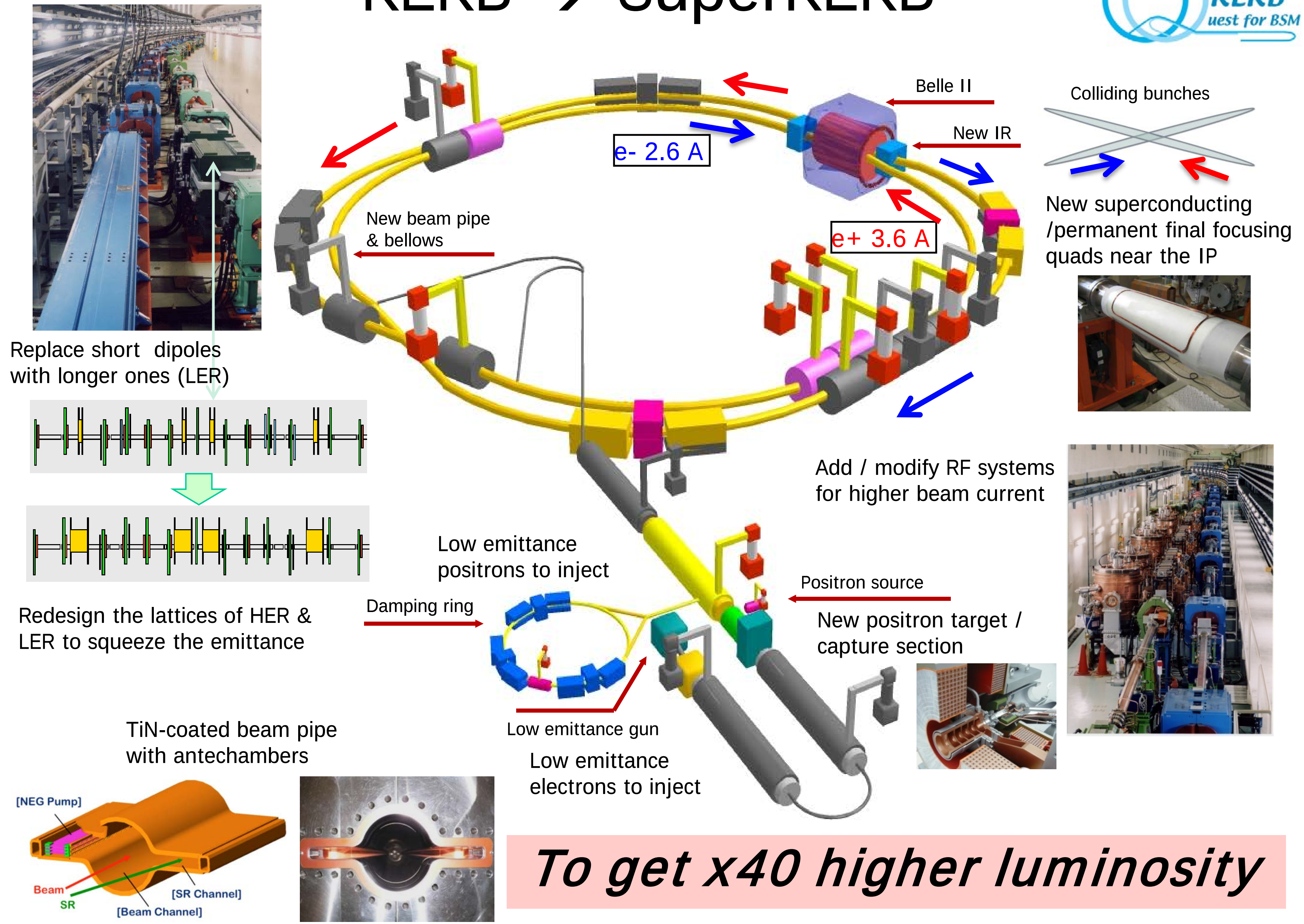
How to go from an excellent accelerator with world record performance – KEKB – to a 40x times better, more intense facility?

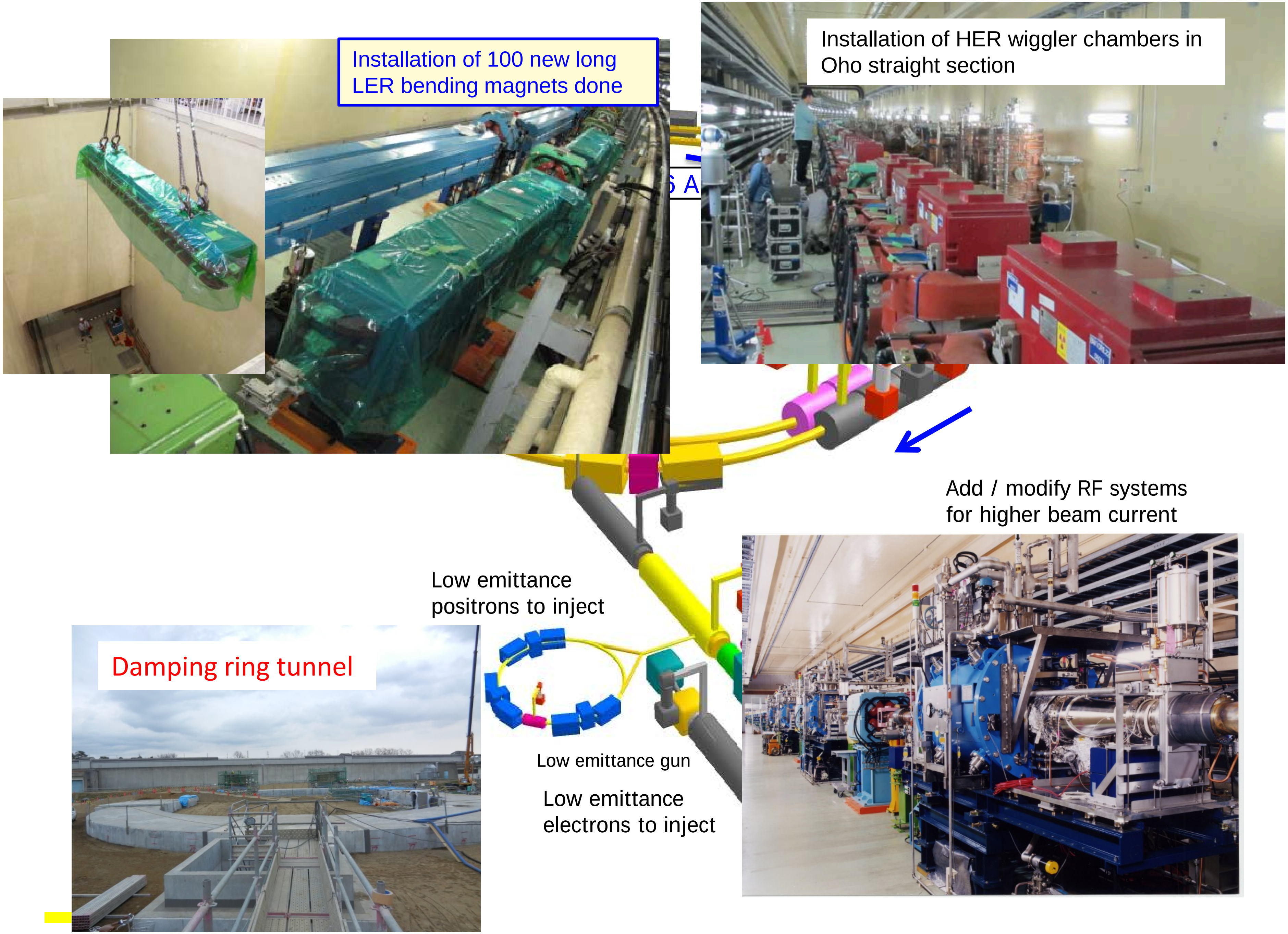
In KEKB, colliding electron and positron beams were already much thinner than a human hair...



... For a 40x increase in intensity you have to make the beam as thin as a few x100 atomic layers!

KEKB → SuperKEKB

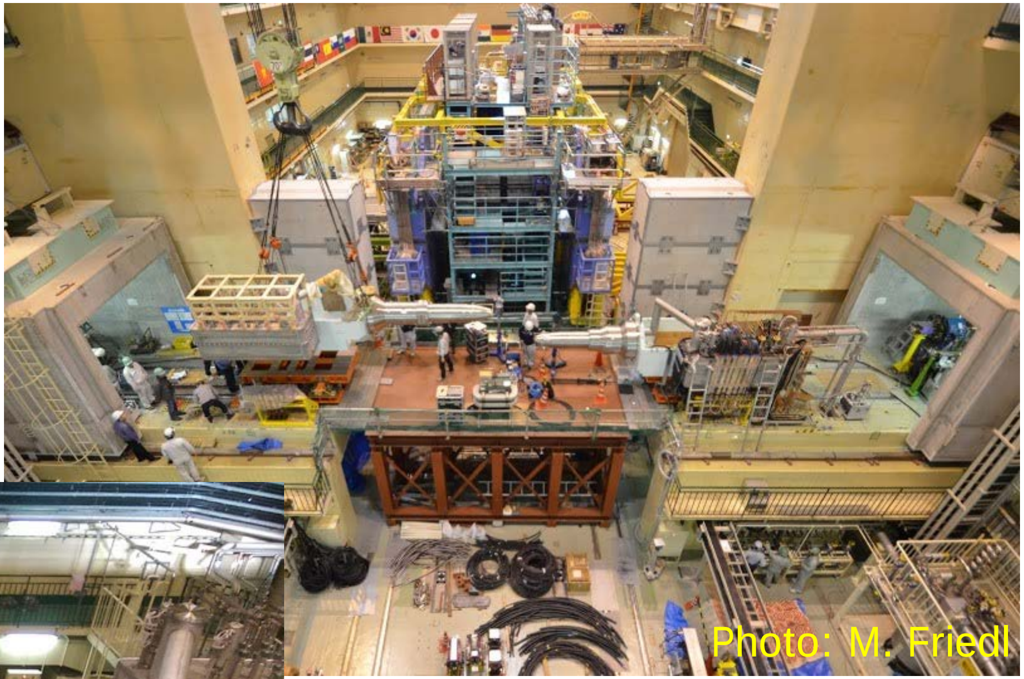



Installation of 100 new long LER bending magnets done
Installation of HER wiggler chambers in Oho straight section
Add / modify RF systems for higher beam current
Low emittance positrons to inject
Damping ring tunnel
Low emittance gun
Low emittance electrons to inject

Final focus magnets

Superconducting quadrupole magnets with 30+25 coils

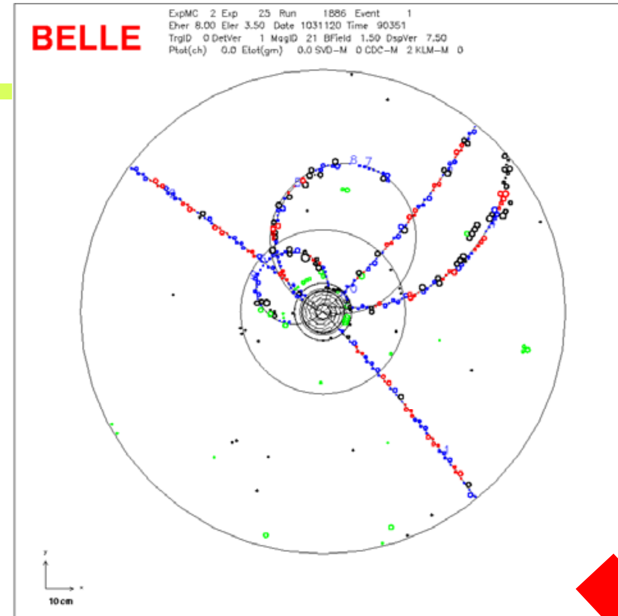
The final one delivered on Feb 13.

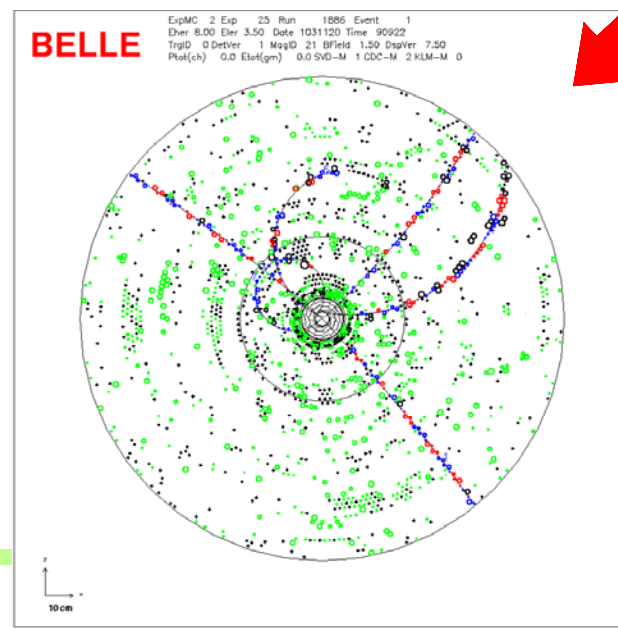


Requirements for the Belle II detector

Critical issues at L= 8 x 10^{35}/cm^2/sec

- **Higher background (×10-20)**
  - radiation damage and occupancy
  - fake hits and pile-up noise in the EM
- **Higher event rate (×10)**
  - higher rate trigger, DAQ and computing
- **Require special features**
  - low p μ identification ← $s\mu\mu$ recon. eff.
  - hermeticity ← ν "reconstruction"



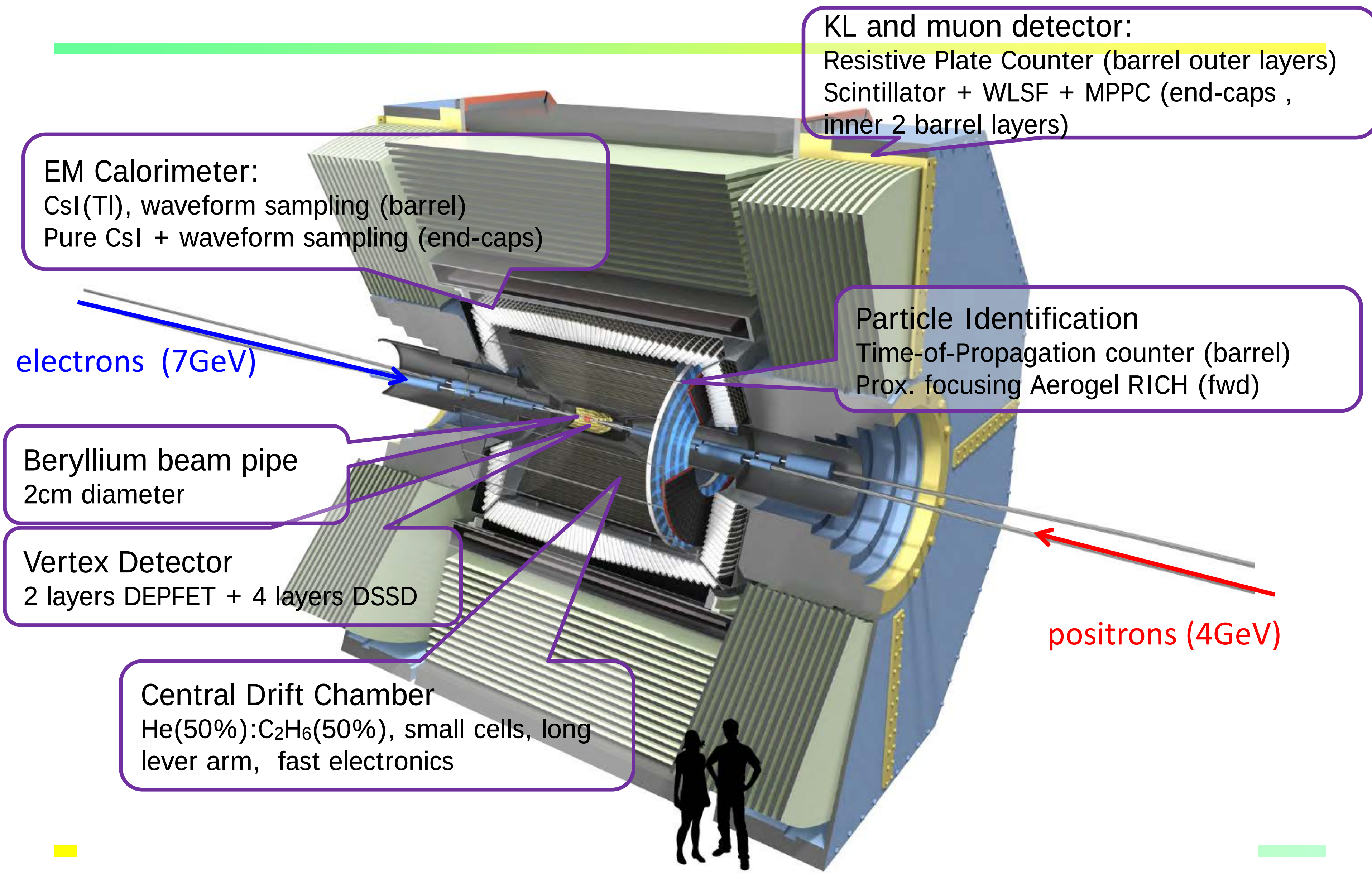


Solutions:

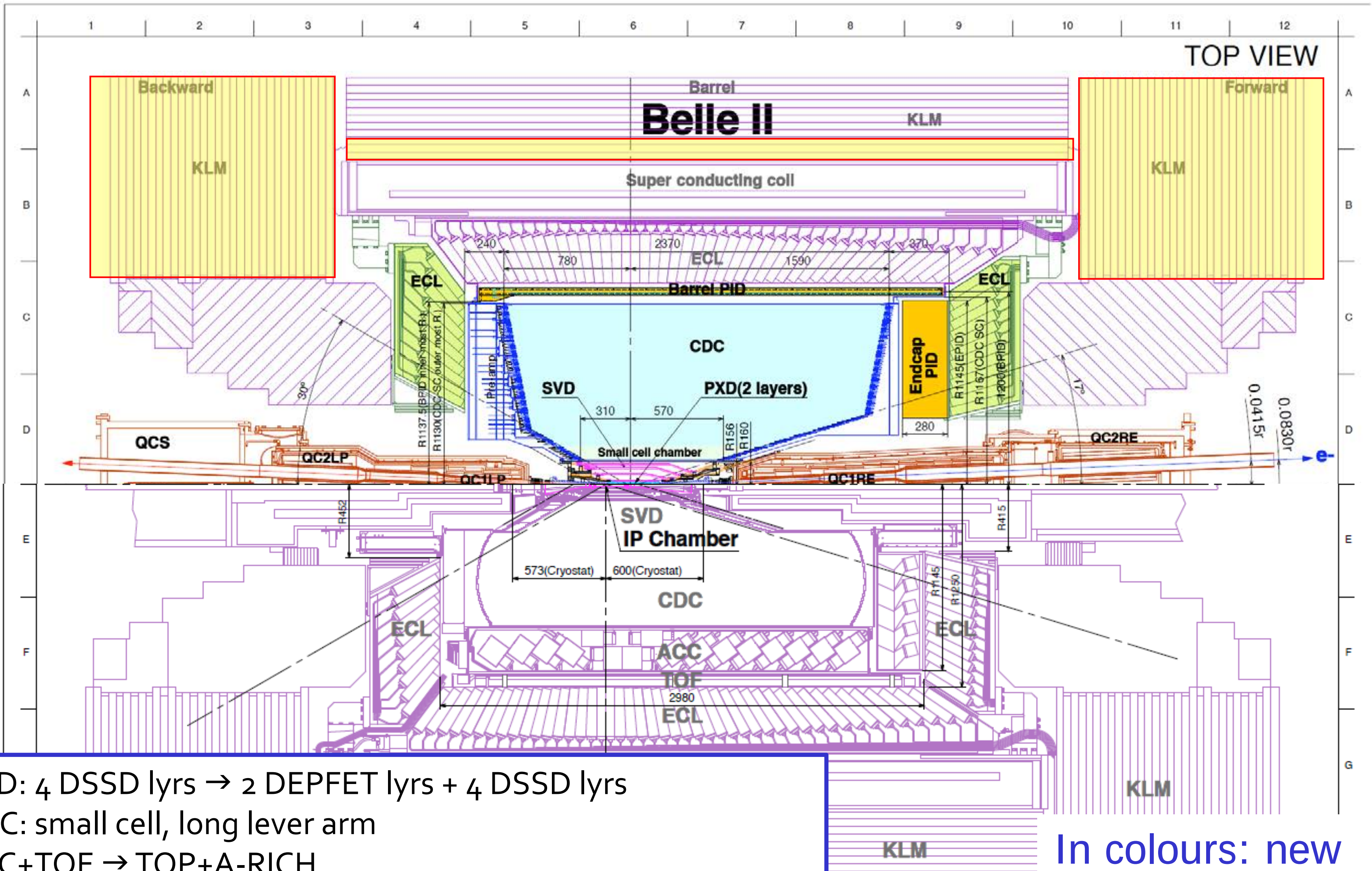
- Replace inner layers of the vertex detector with a pixel detector.
- Replace inner part of the central tracker with a silicon strip detector.
- Better particle identification device
- Replace endcap calorimeter crystals
- Faster readout electronics and computing system.

Belle II TDR, arxiv:1011.0352v1[physics.ins-det]

Belle II Detector



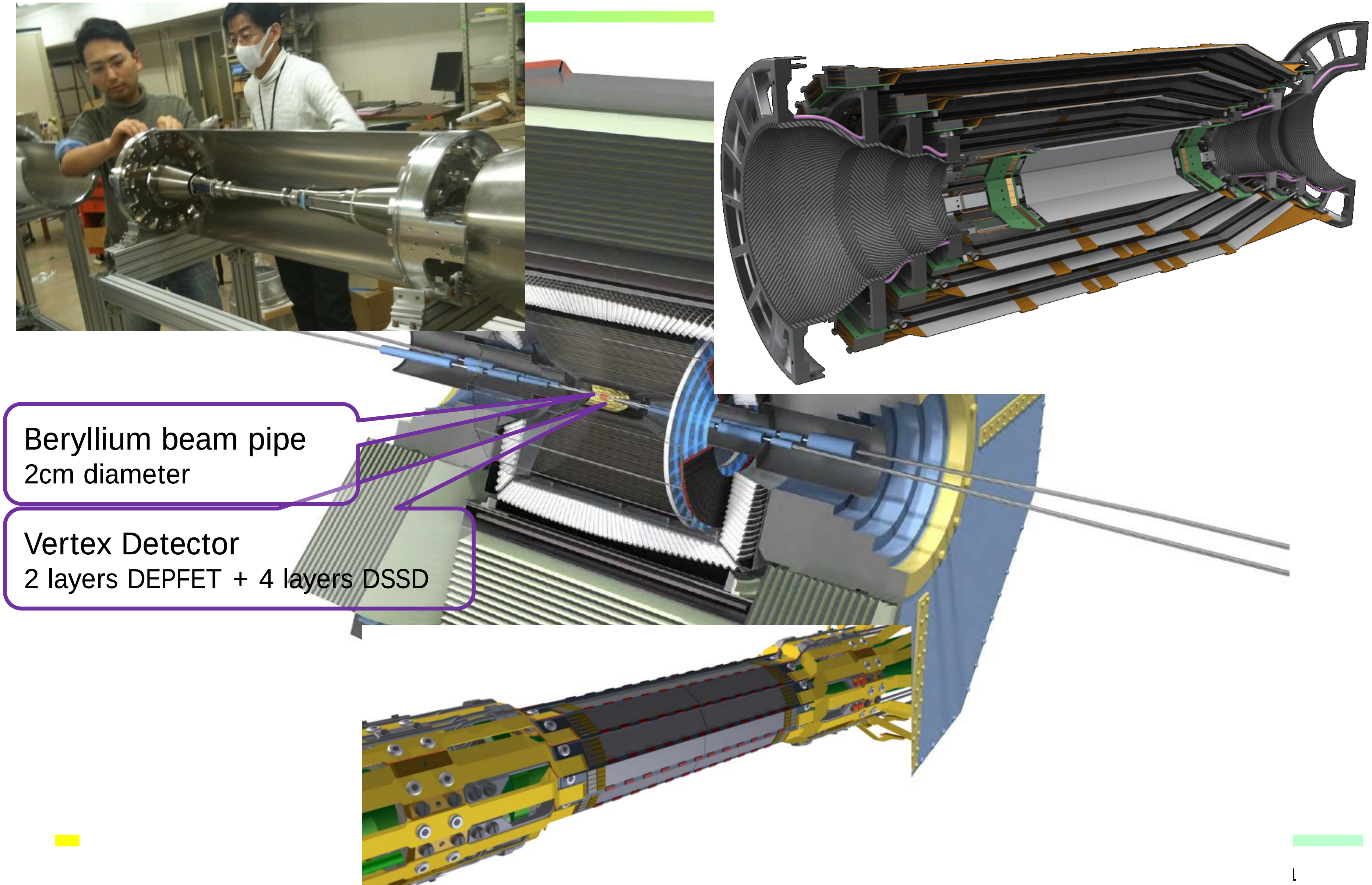
Belle II Detector (in comparison with Belle)



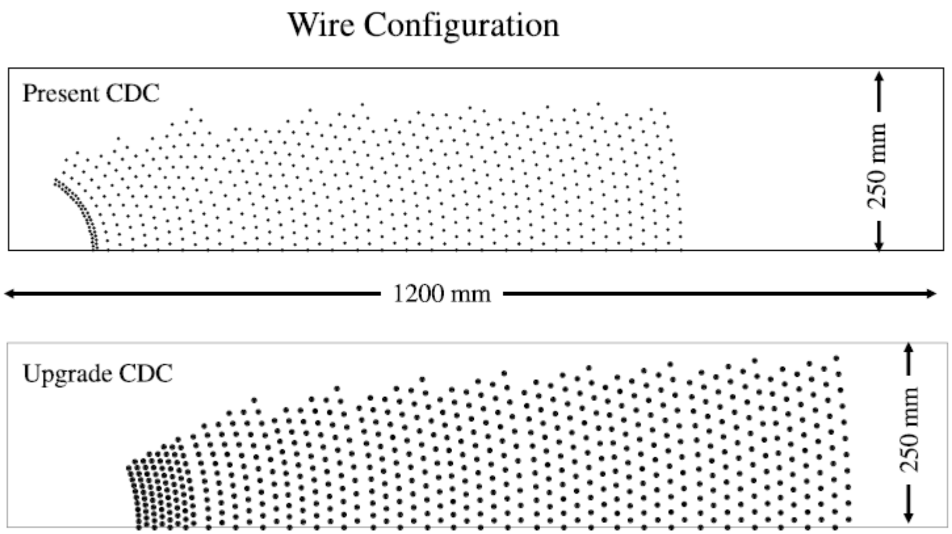
SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling (+pure CsI for endcaps)
KLM: RPC → Scintillator +MPPC (endcaps, barrel inner 2 lyrs)

In colours: new components

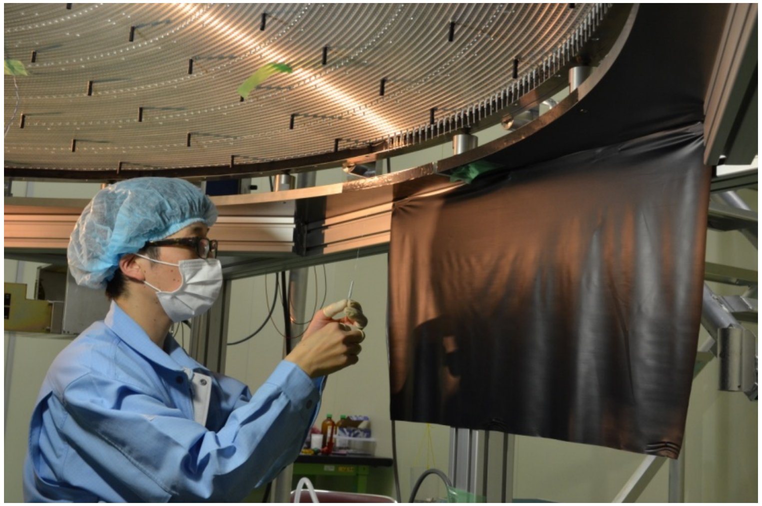
Belle II Detector – vertex region



Belle II CDC



Much bigger than in Belle!

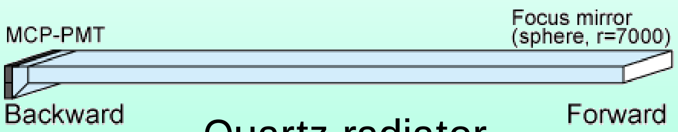


Wire stringing in a clean room

- thousands of wires,
- 1 year of work…

Particle Identification Devices

Barrel PID: Time of Propagation Counter (TOP)



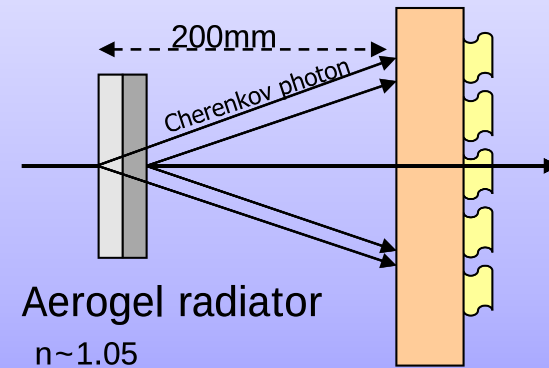
Quartz radiator

Focusing mirror

Small expansion block

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

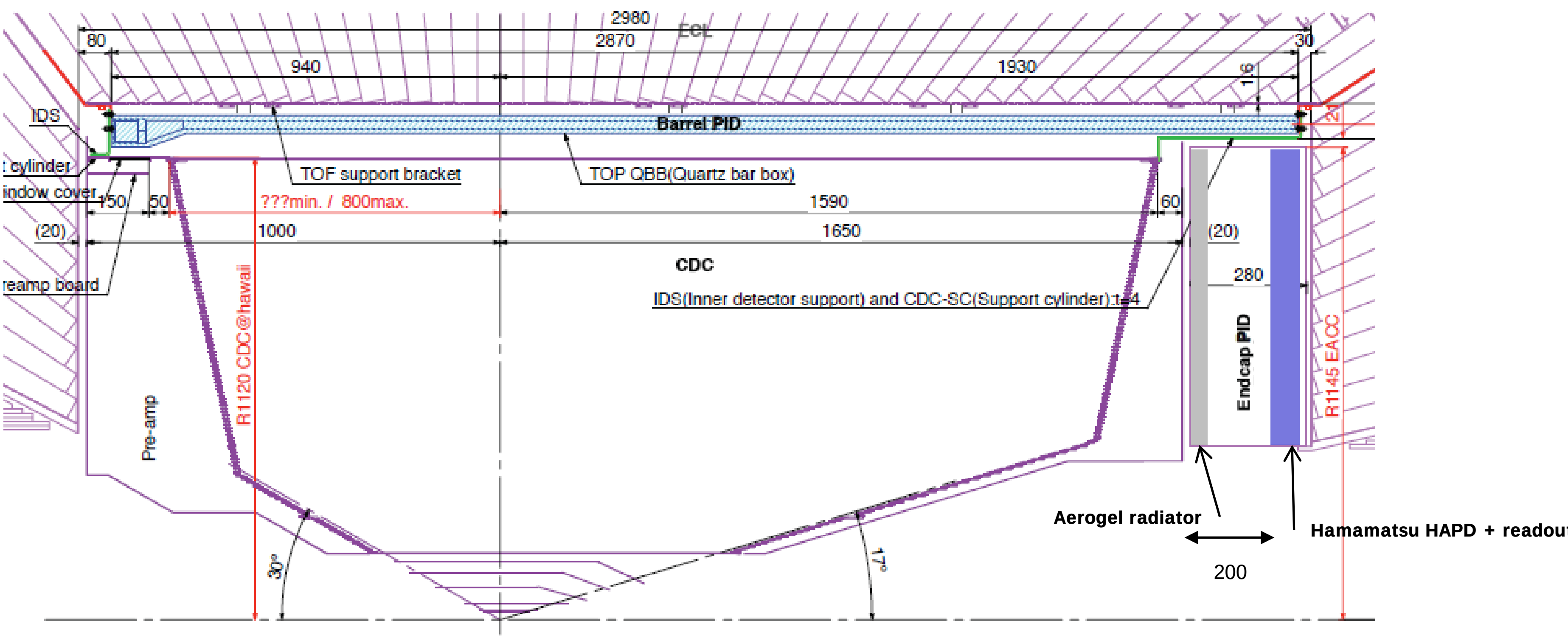
Endcap PID: Aerogel RICH (ARICH)



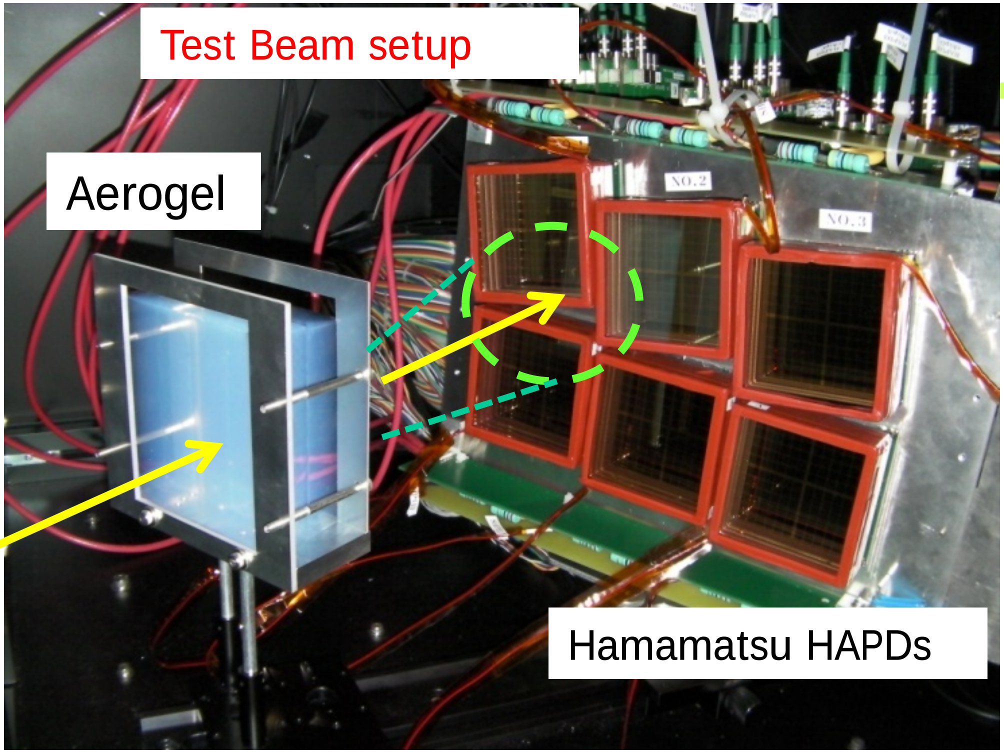
Aerogel radiator

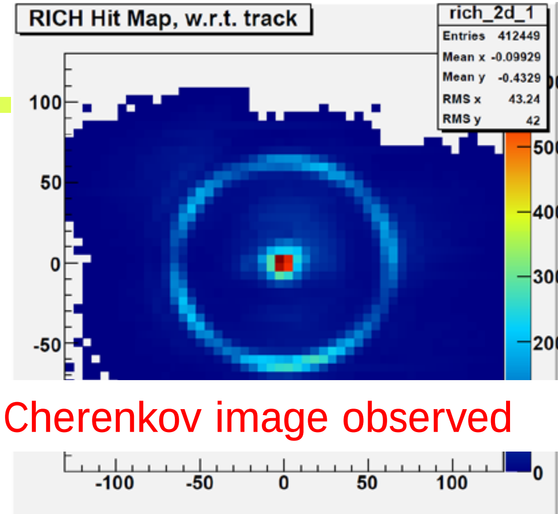
n~1.05

Hamamatsu HAPD



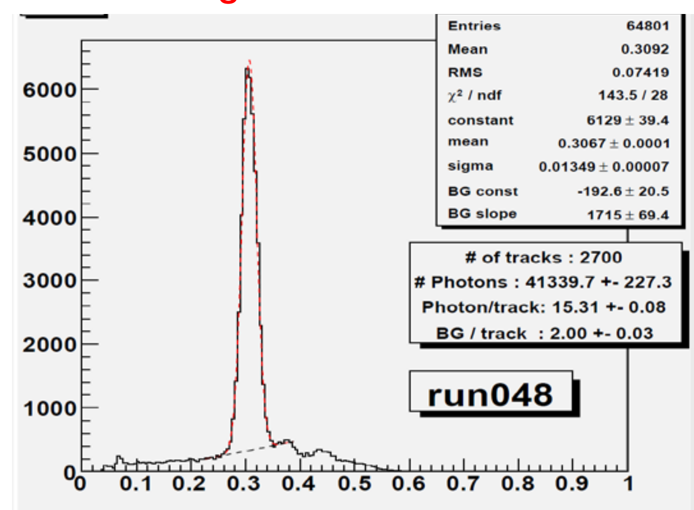
Aerogel RICH (endcap PID)





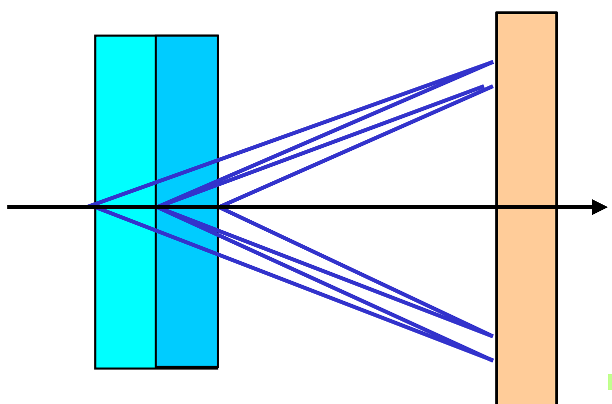
Clear Cherenkov image observed

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.



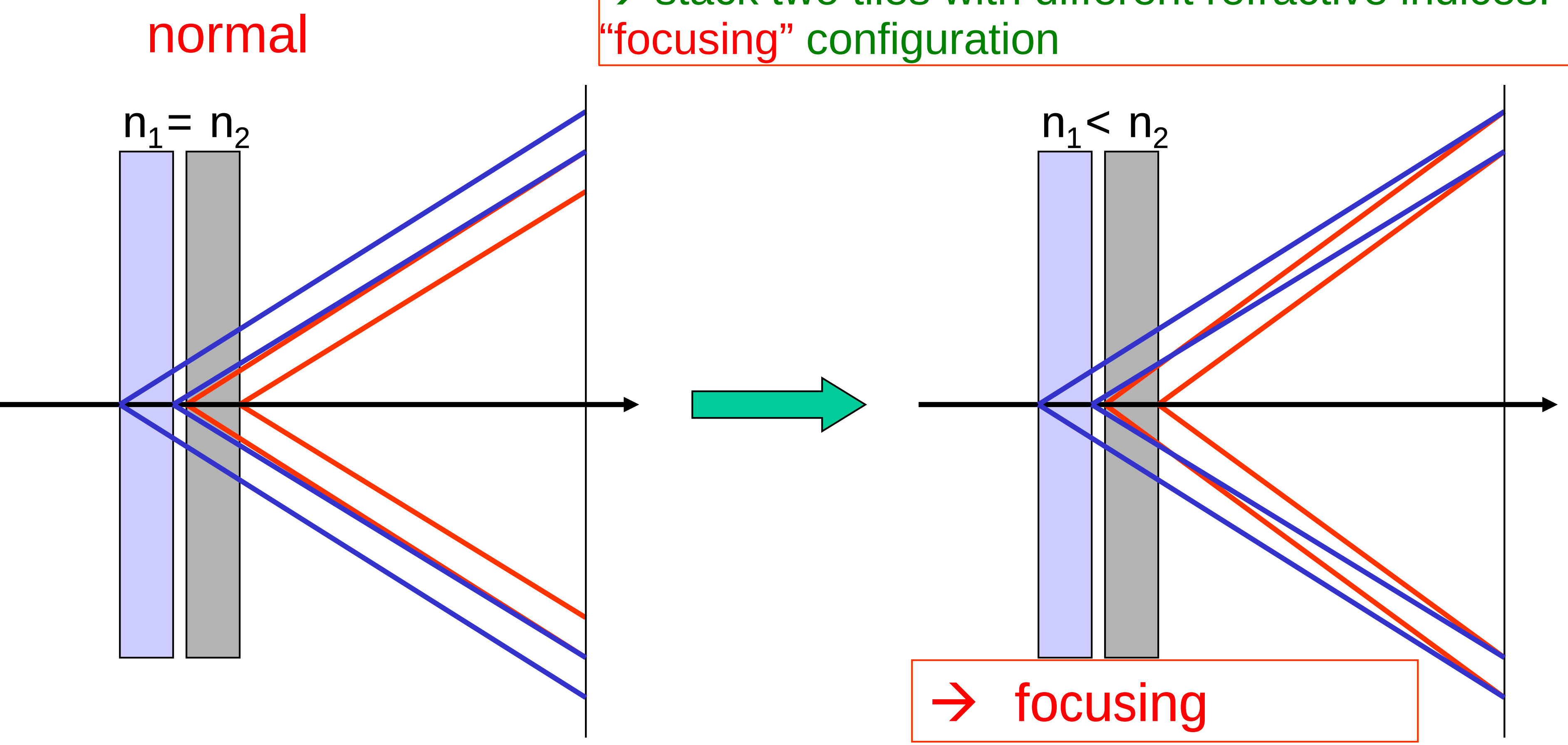
6.6 σ π/K at 4GeV/c !

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

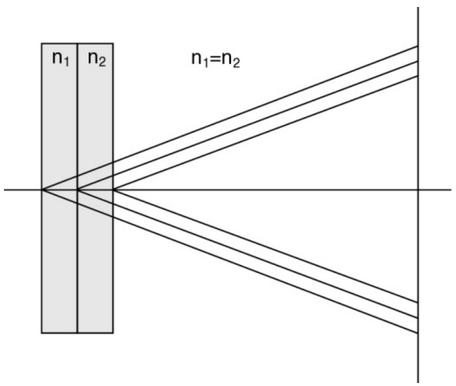


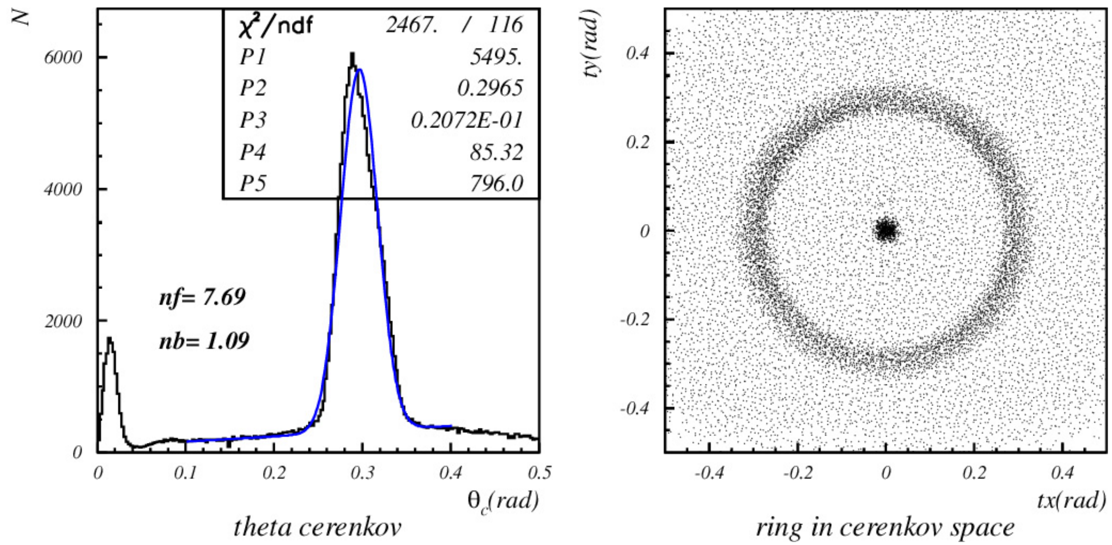
Such a configuration is only possible with aerogel (a form of Si_xO_y) – material with a tunable refractive index between 1.01 and 1.13.

Focusing configuration – data

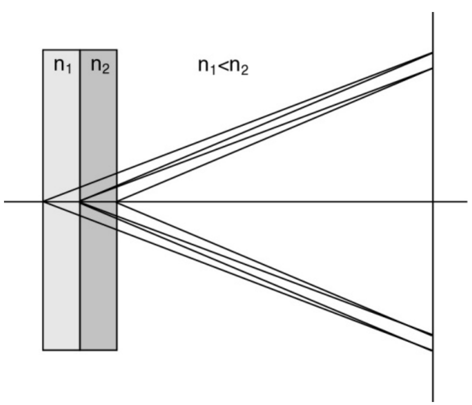
Increases the number of photons without degrading the resolution

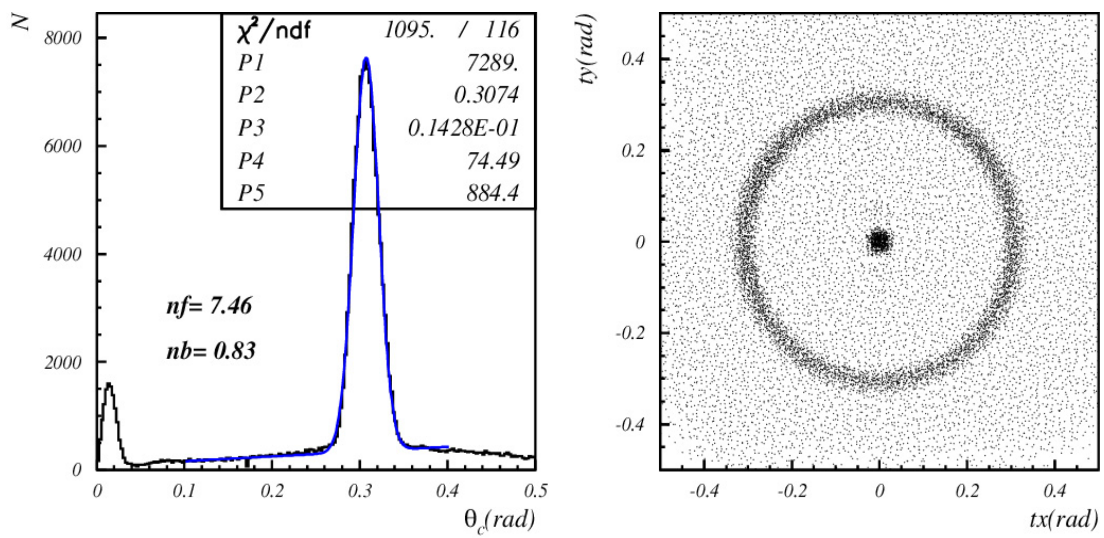
4cm aerogel single index





2+2cm aerogel

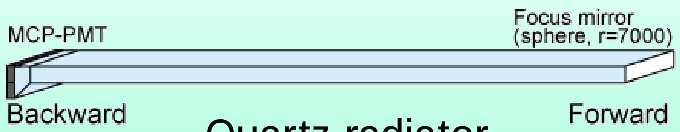




→NIM A548 (2005) 383

Cherenkov detectors

Barrel PID: Time of Propagation Counter (TOP)



Quartz radiator

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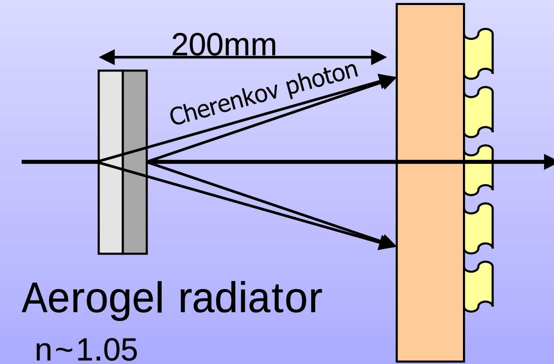
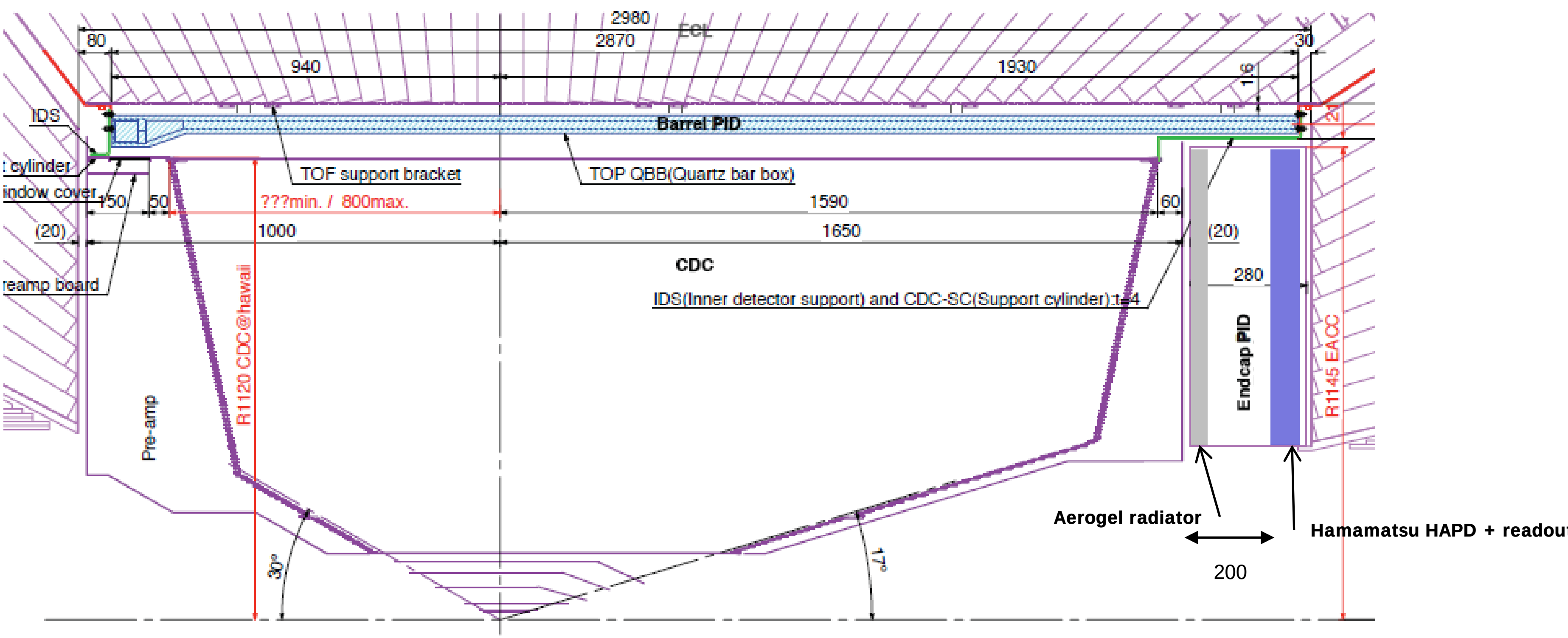


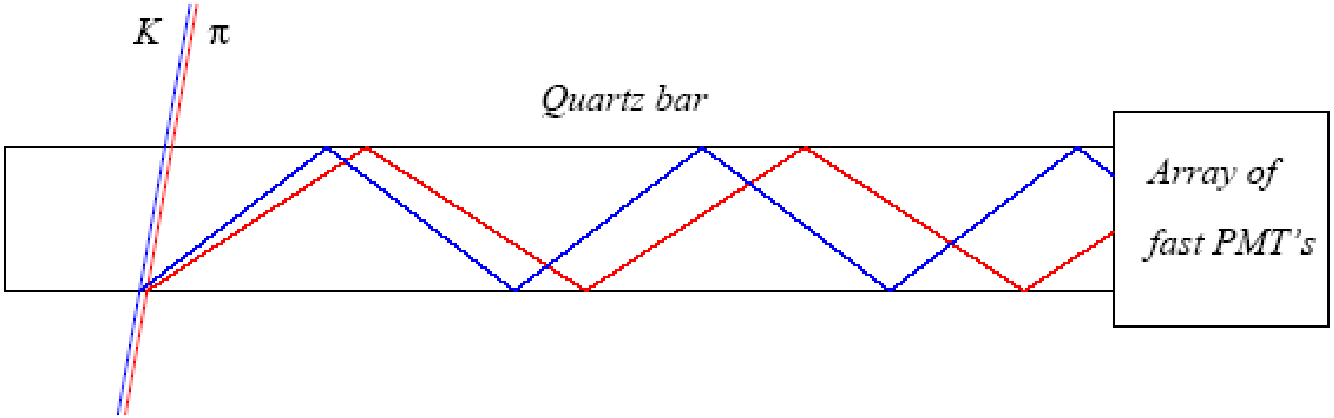
Aerogel radiator

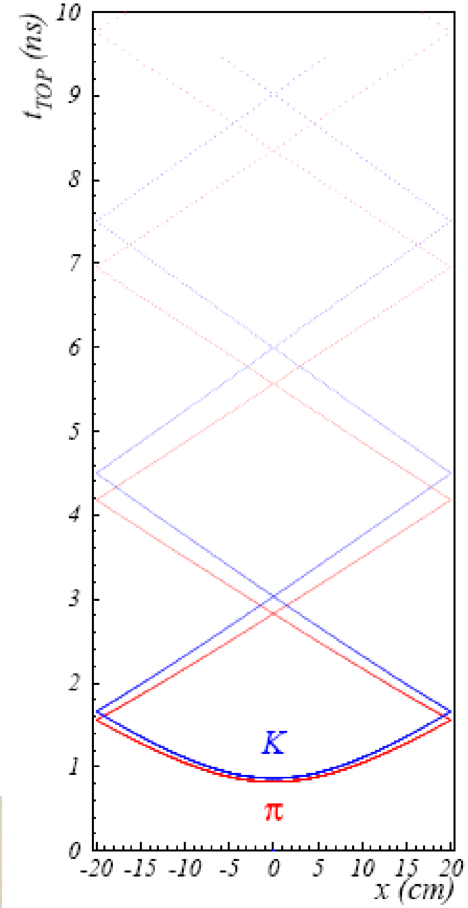
n~1.05

Hamamatsu HAPD
+ new ASIC



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

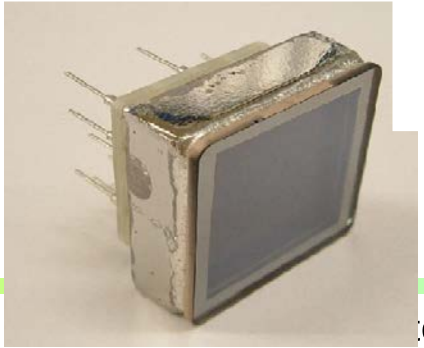




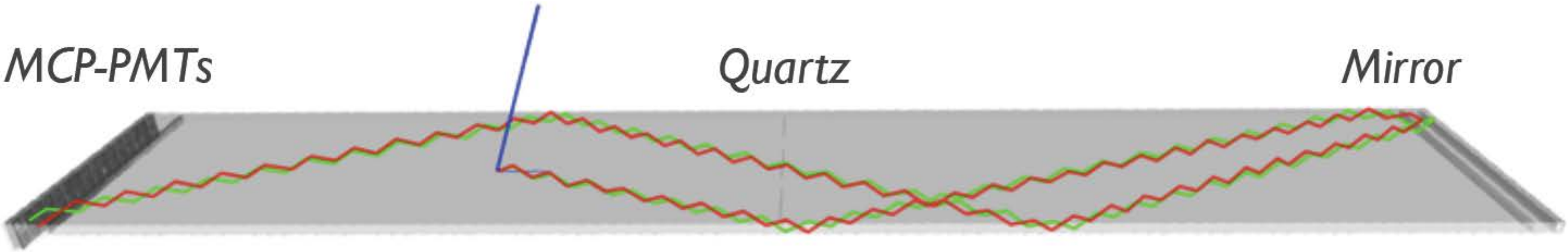
- Cherenkov ring imaging with precise time measurement.
- Uses internal reflection of Cherenkov ring images from quartz like the BaBar DIRC.
- Reconstruct Cherenkov angle from two hit coordinates and

the time of propagation of the photon

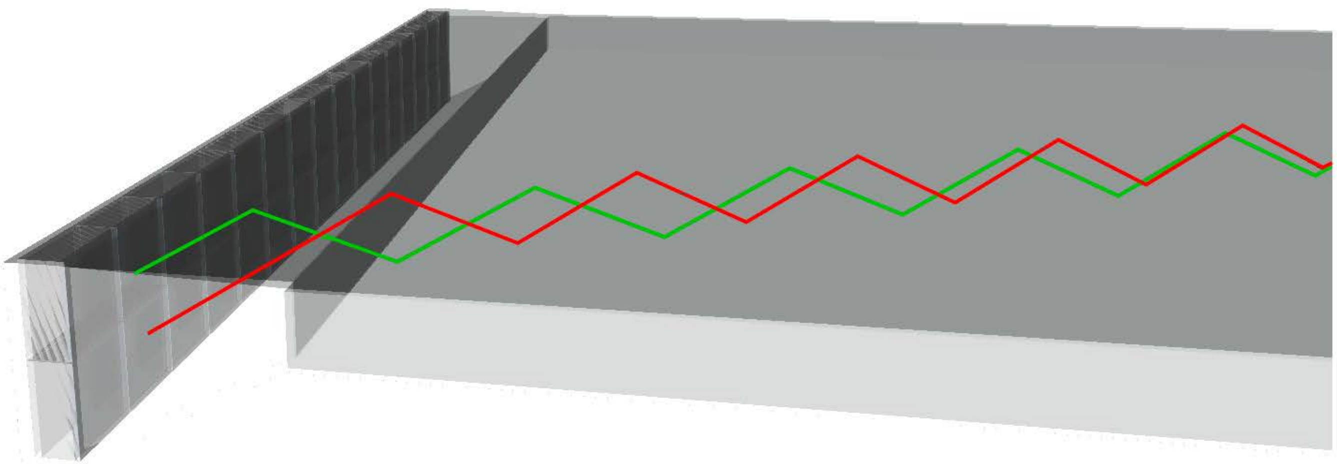
- Quartz radiator (2cm thick)
- Photon detector (MCP-PMT)
  - Excellent time resolution ~ 40 ps
  - Single photon sensitivity in 1.5



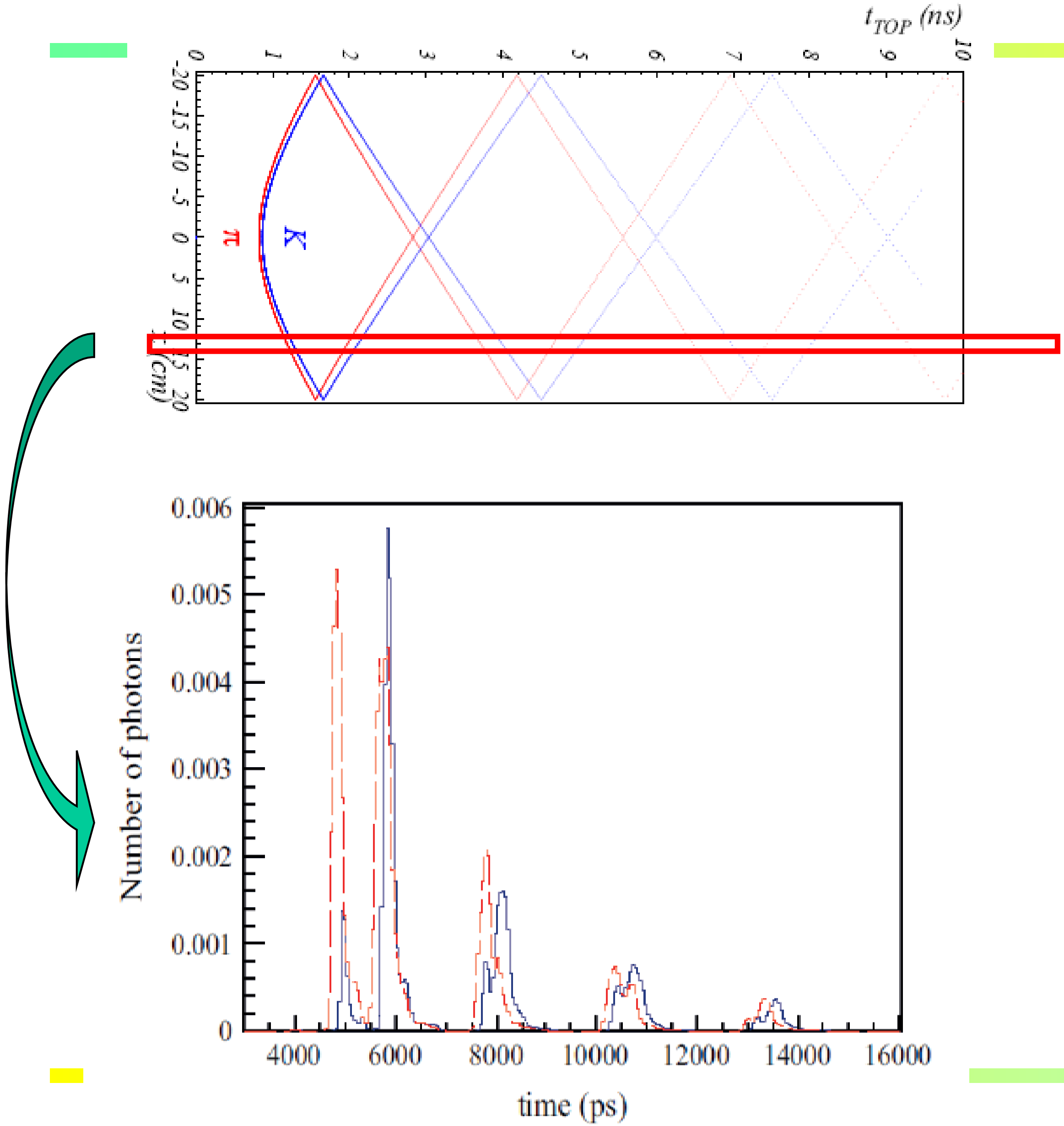
Barrel PID: Time of propagation (TOP) counter



Example of Cherenkov-photon paths for 2 GeV/c $\pi^{\pm}$ and $K^{\pm}$.



TOP image

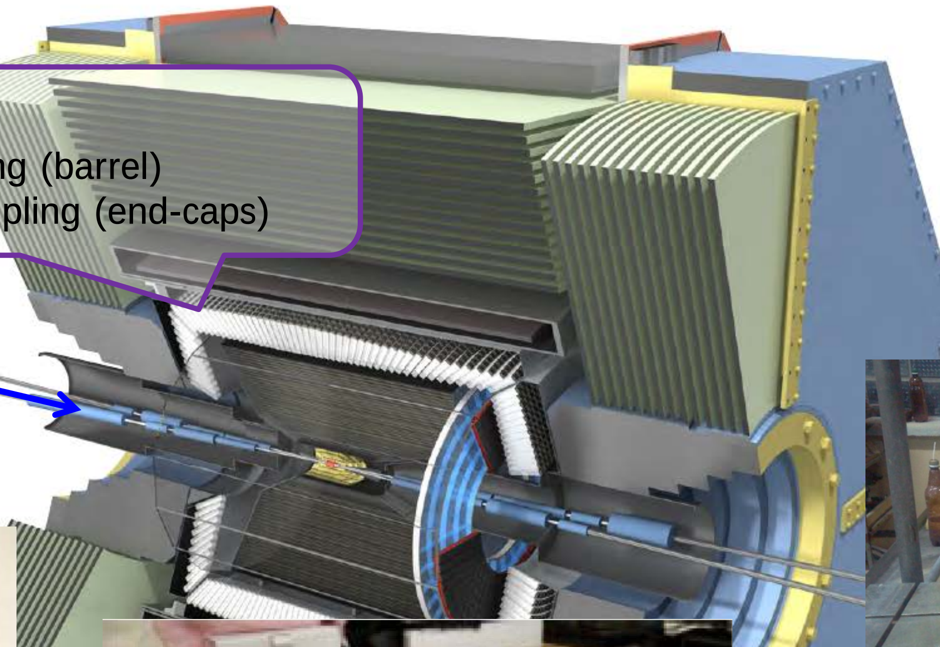


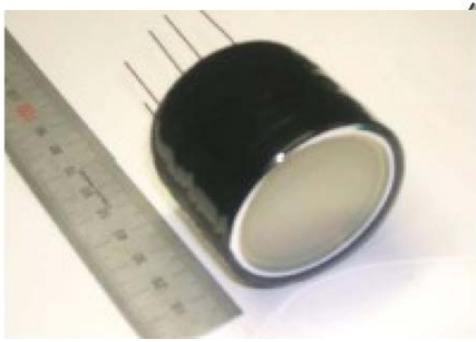
Pattern in the coordinate-time space ('ring') of a pion hitting a quartz bar with ~80 MAPMT channels

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

EM calorimeter: upgrade needede 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)

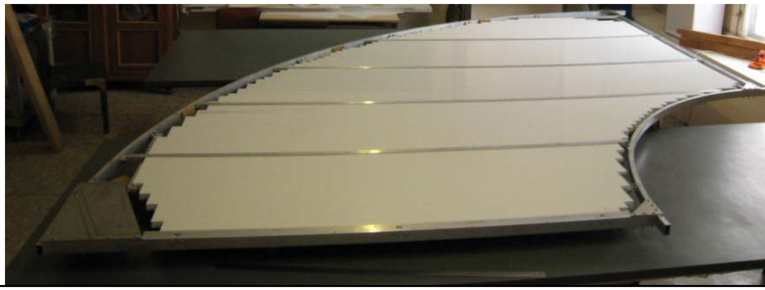


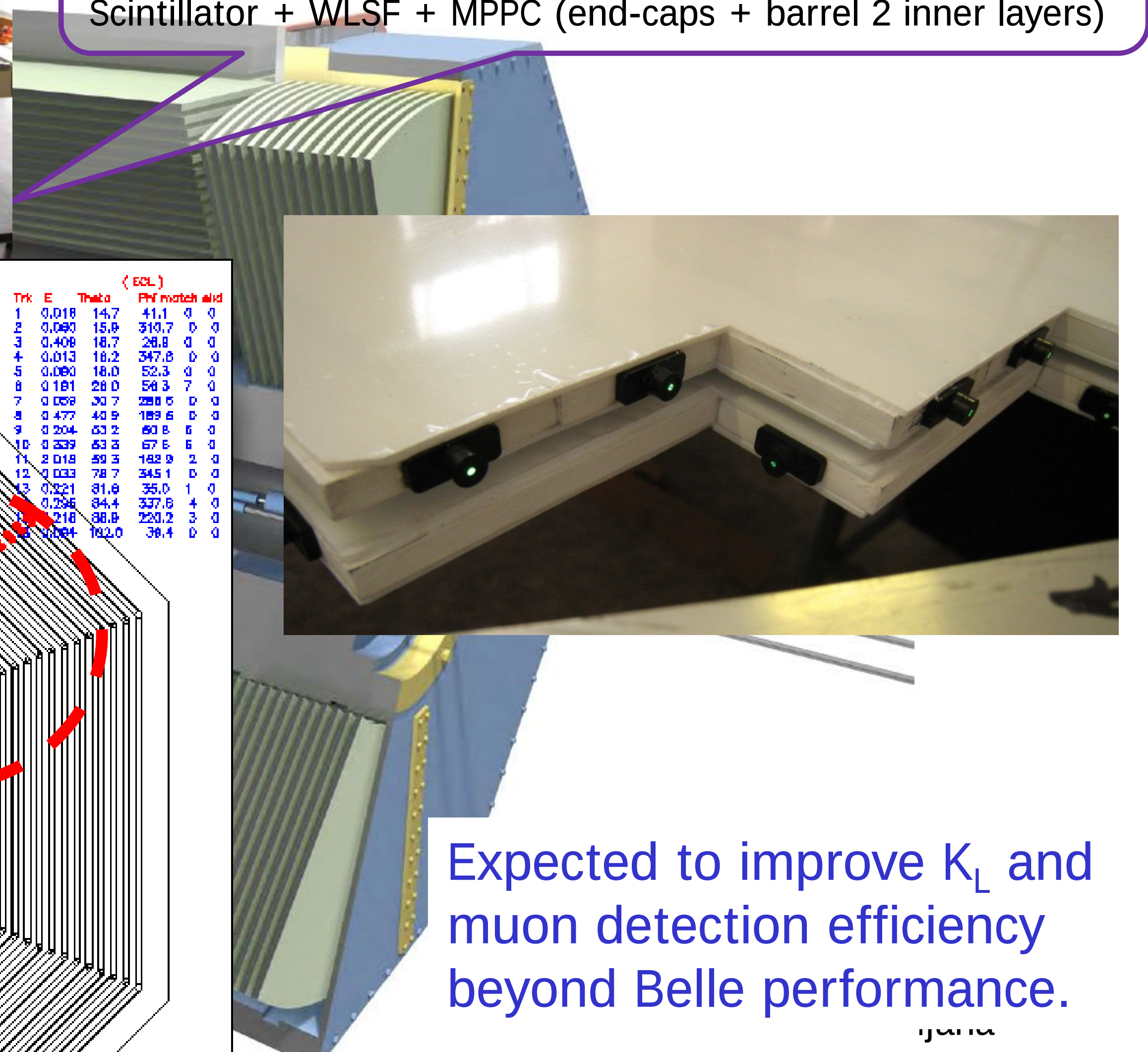


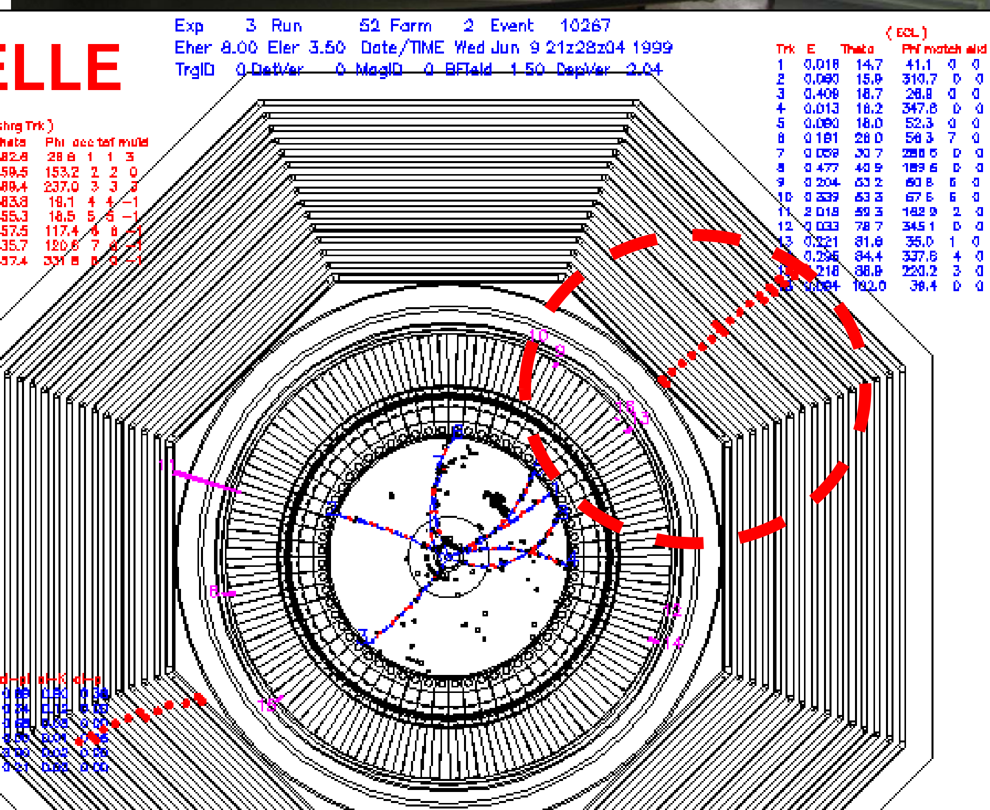
Upgrade to pure CsI: a major collaborative effort of Russia, Japan, Canada, Italy, Ukraine

Detection of muons and K_Ls: a sizable part 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)



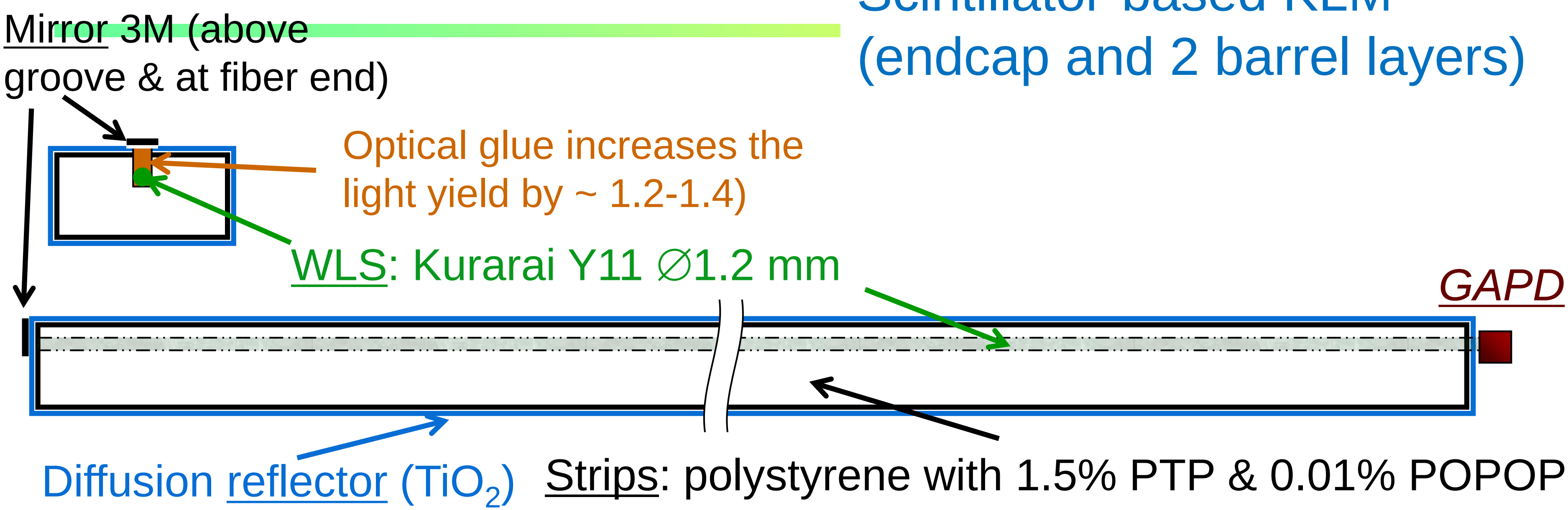




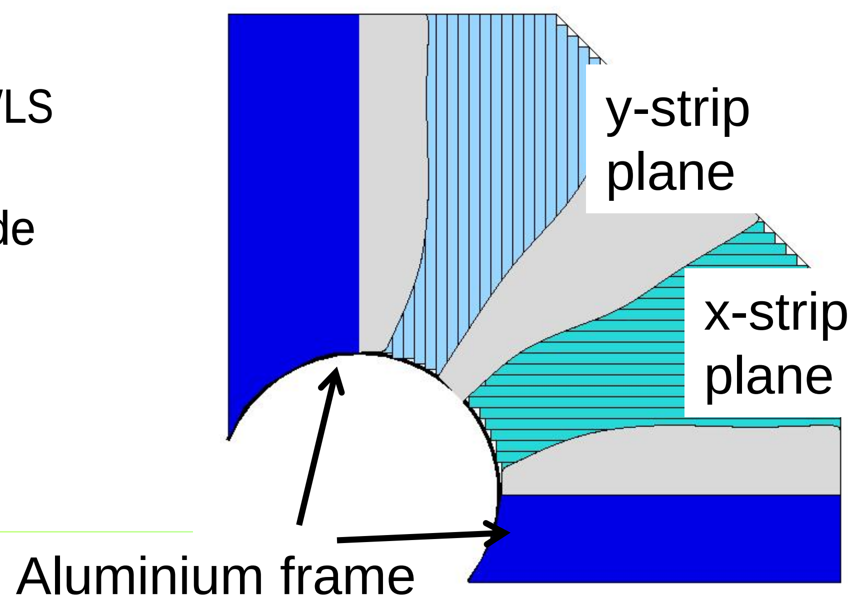
Expected to improve K_L and muon detection efficiency beyond Belle performance.

Muon detection system upgrade

Scintillator-based KLM (endcap and 2 barrel layers)



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



The Belle II Collaboration

A very strong group of >700 highly motivated scientists!

SuperKEKB/Belle II Status

SuperKEKB and Belle II construction proceeding, nearly on schedule.

Commissioning started

First data taking (no vertex detector): sping 2018

First data taking (with vertex detector): in autumn 2018

Contents, part 3

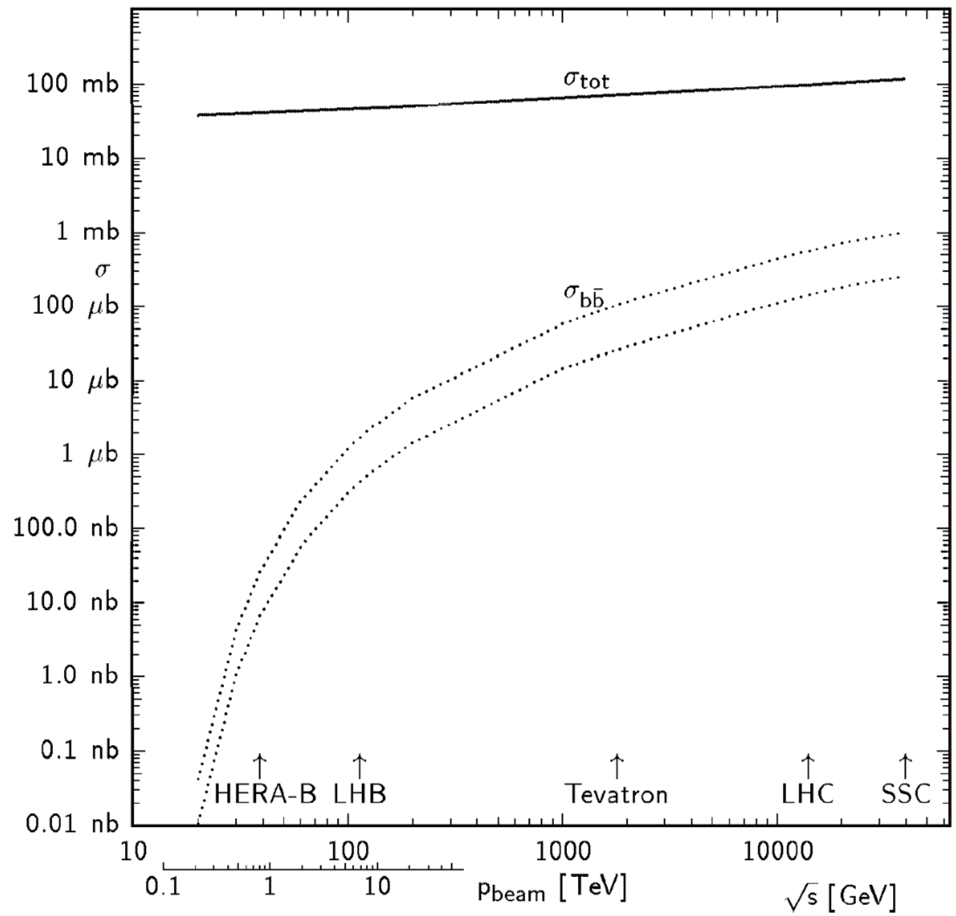
- Flavor physics: introduction, with a little bit of history
- Flavor physics at B factories: CP violation
- Flavor physics at B factories: rare decays and searches for NP effects
- Super B factory
- **Flavor physics at hadron machines: history, LHCb and LHCb upgrade**

Why hadron machines?

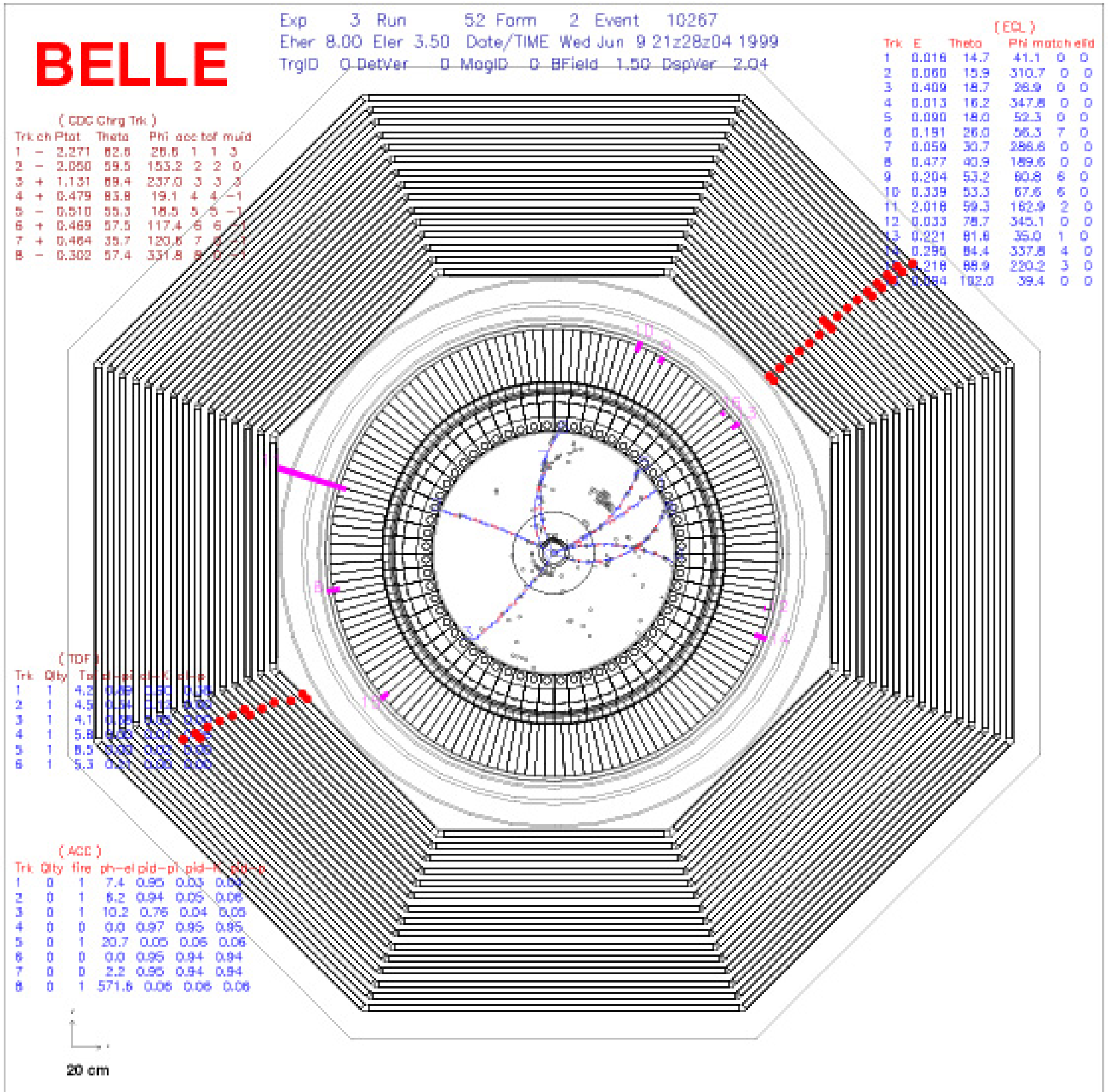
- large bb production rates - compare to 1.1nb at Y(4s)
- large boosts → $\langle L \rangle = \langle \beta\gamma \rangle$ 480 μm
- in addition to B^0/B^{+-} also B_s, B_c, Λ_b,..

LHC →

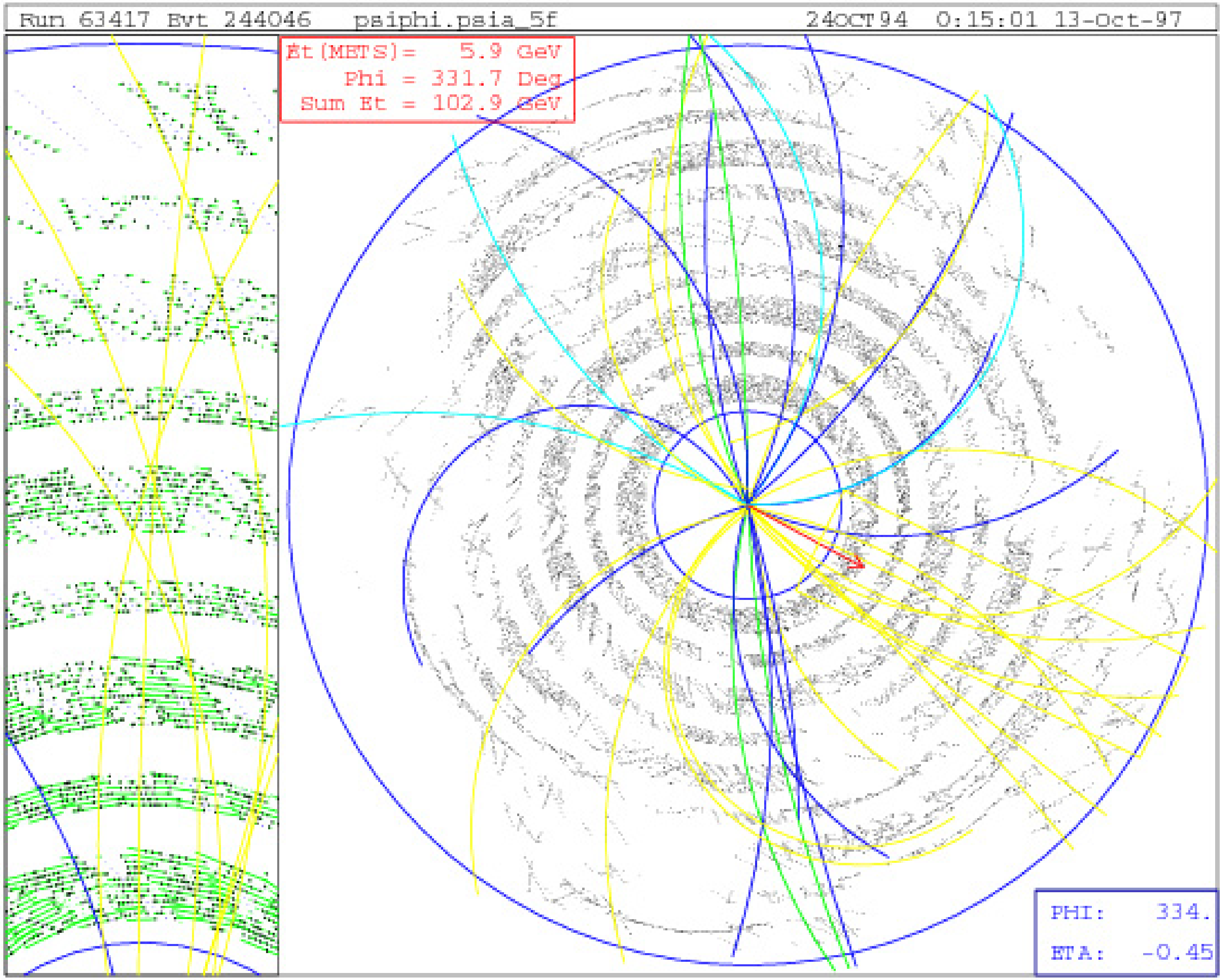
Y(4s) →



bb events at e^+e^- machines: BELLE



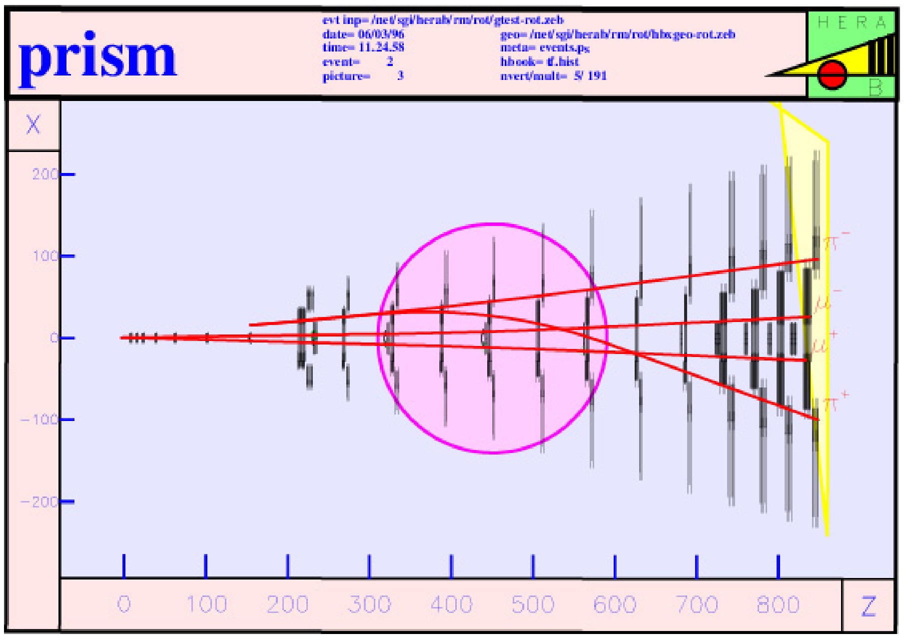
bb event at CDF

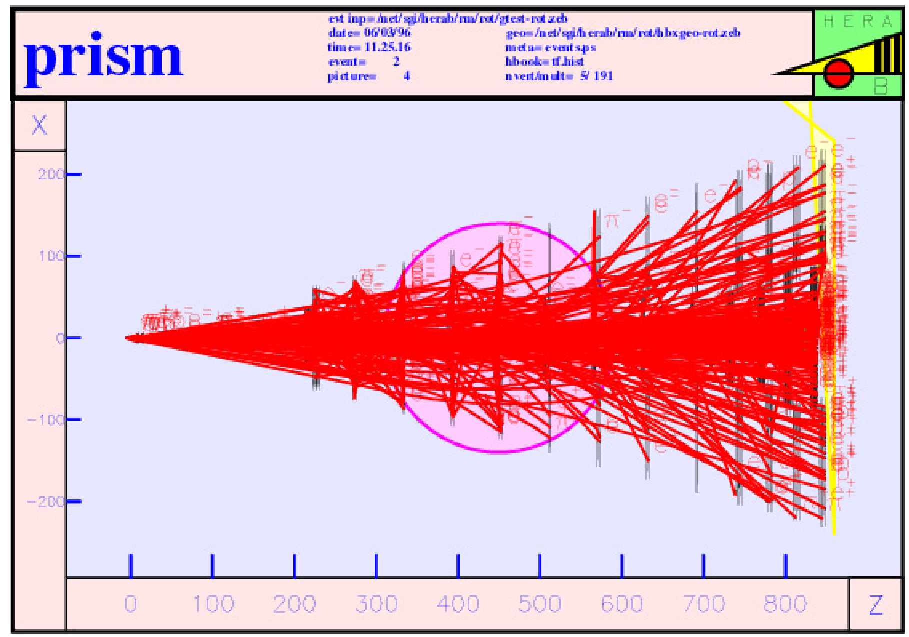


bb event at HERA-B:

Needle

in haystack…

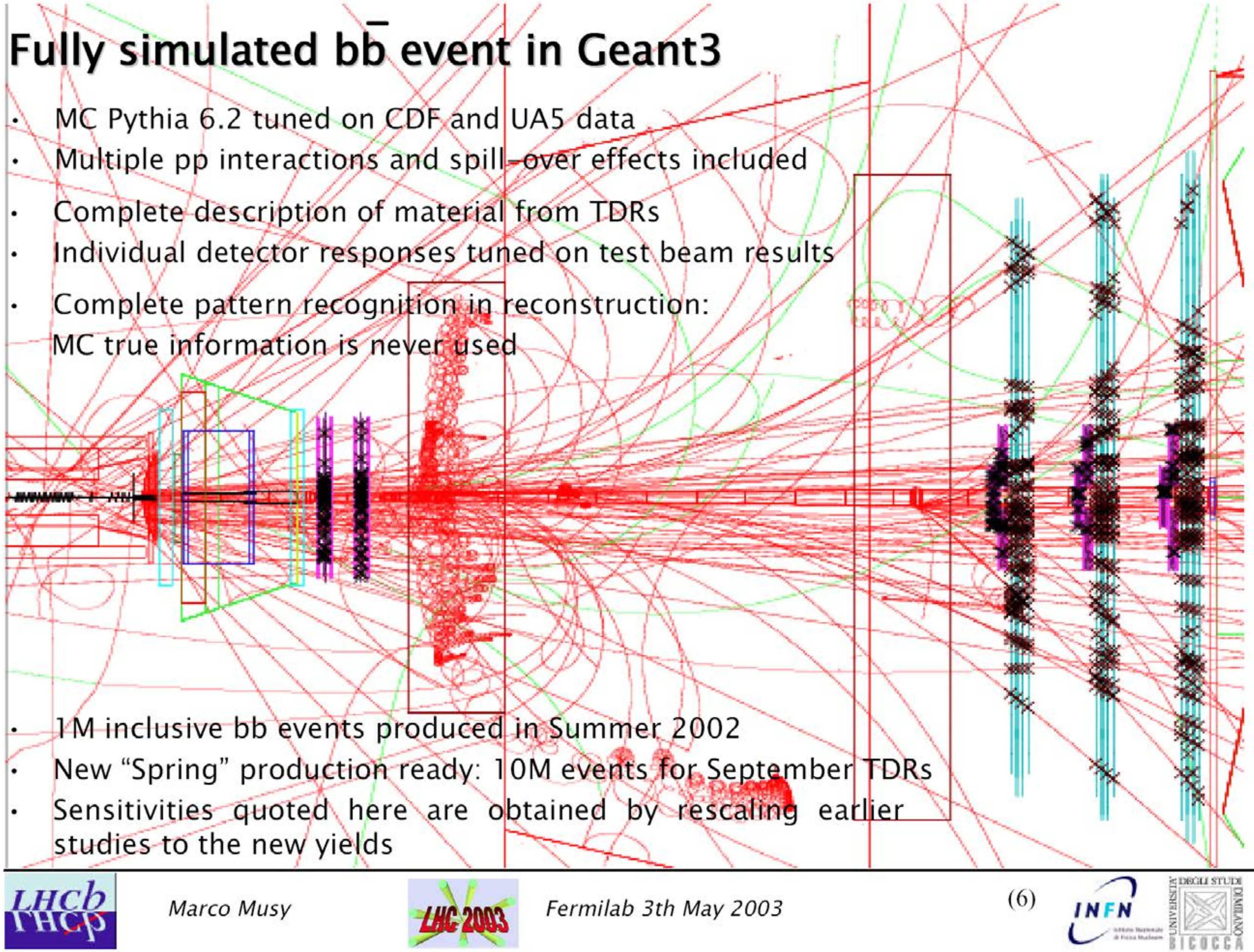




B → J/ψ Ks

and the rest

bb event at LHCb:



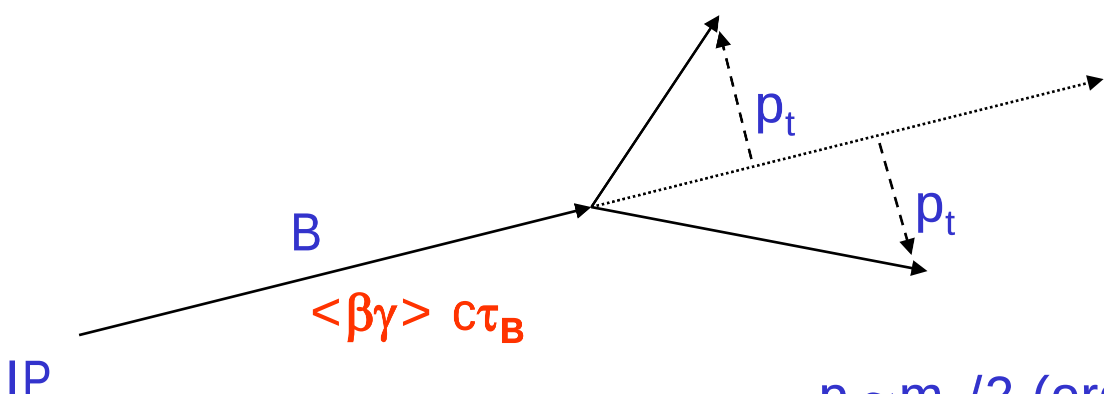
B detection in hadron collisions

What do we have to consider when designing a detector for b mesons and baryons at a hadron machine?

High particle fluxes → radiation hard detectors

Early selection of interesting events → selective triggers

Use the characteristic features of a B decay



$p_t \sim m_B/2$ (order of magnitude)

B detection in hadron collisions

Early selection of interesting events → selective triggers:

• high p_t decay products: B → $\mu\nu$X, B → J/ψ Ks → $\mu^+\mu^-$ $\pi^+\pi^-$, B → $\pi^+\pi^-$
→helps because decay products carry a lot of momentum - typically ~1-2 GeV/c - perpendicularly to the flight direction (p_t), while backgrounds have low p_t

• displaced vertex: $\langle L \rangle = \langle \beta\gamma \rangle c\tau_B = \langle \beta\gamma \rangle$ 480 μm → helps because other decay products are promt = originate directly in the interaction point

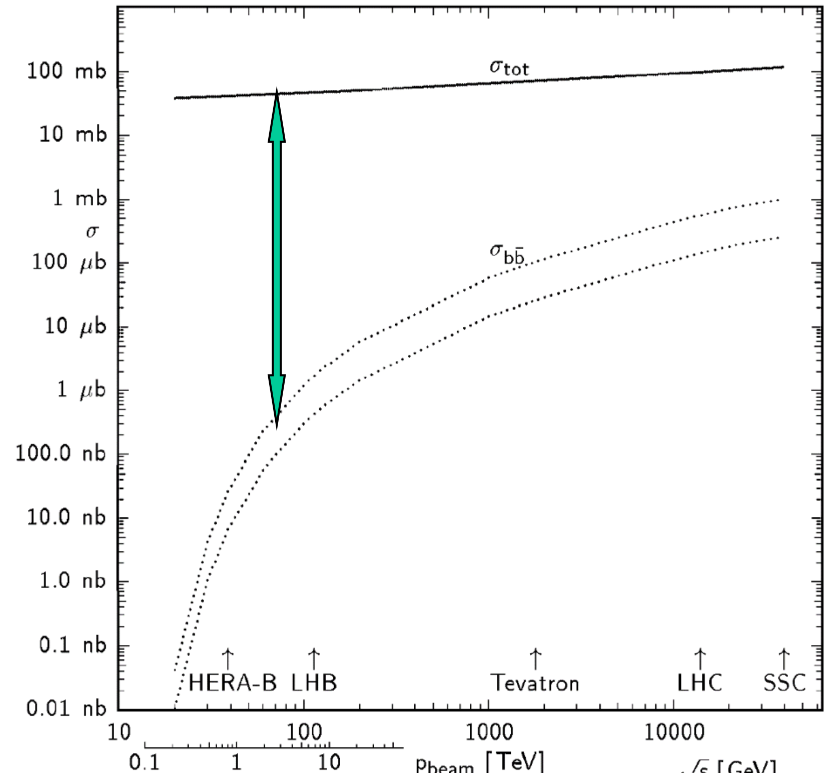
Proof of principle: CDF, D0 at the Tevatron collider. Most importnat measurement: Observation of B_s mixing.

HERA-B

First attempt to make a precision flavour physics measurement at a hardon machine.

Fixed target B - Factory at HERA (DESY): parasitic use of the proton beam with an adaptable target in the beam halo

Originally designed for measurement of CP violation in $B \rightarrow J/\psi K_S^0$



920 GeV prootons, sqrt(s)=42 GeV

σ(b bar-b) ~ 12 nb -> σ(b bar-b)/ σ(inel) ~10^{-6}

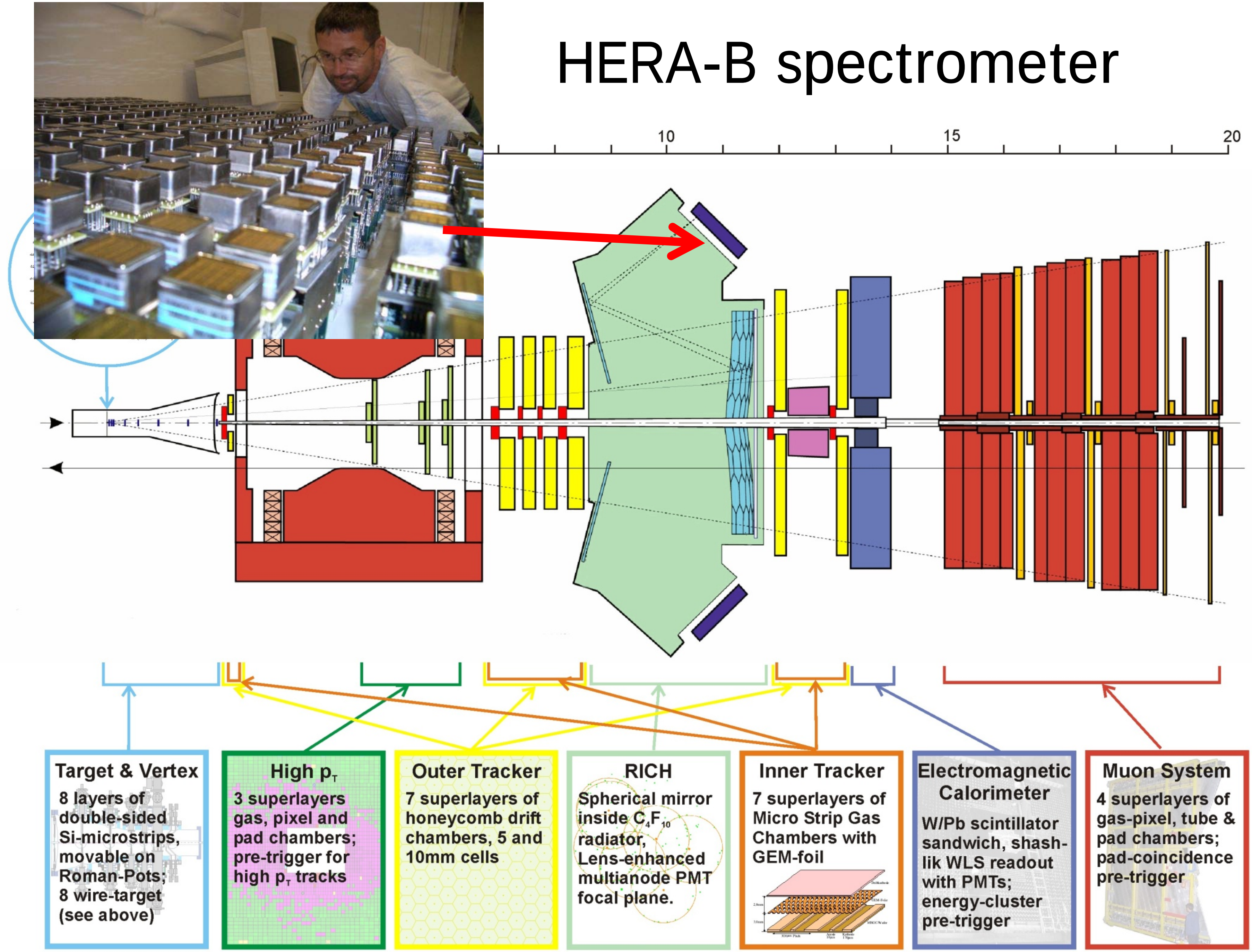
BR for interesting decays of ~ 10^{-5}-10^{-4}

→ 11 orders of magnitude

→ Need multiple events for 40 MHz interaction rate (=0.4 10^8 s^{-1})

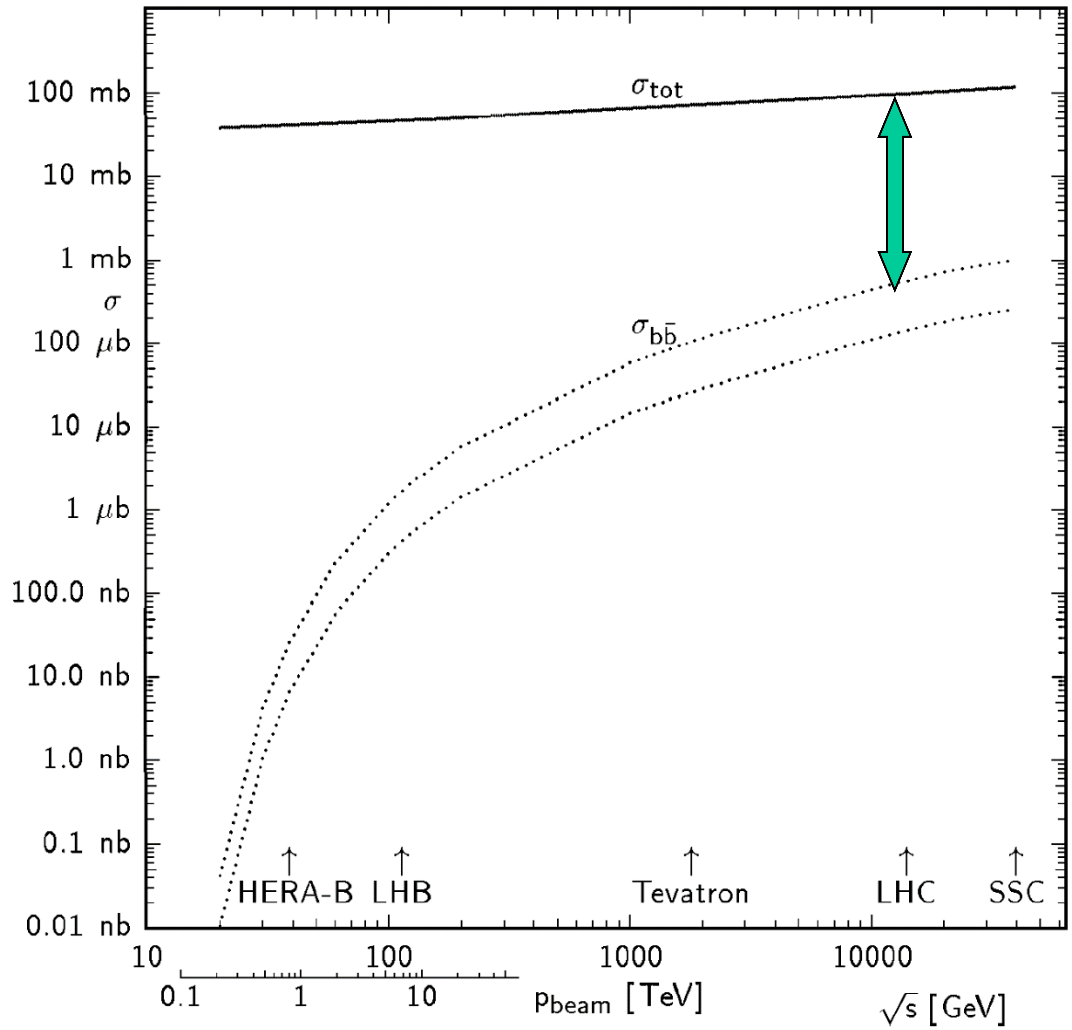
→LHC like experiment 10 years before LHC

HERA-B spectrometer



b-production in pp collisions at LHC

Cross section for bb pair production much higher at LHC



b-production in pp collisions

- Pairs of $b\bar{b}$ quarks are mostly produced in the forward/backward direction:

$$\sigma_{b\bar{b}} = 500\mu b$$

$10^{12}\, b\bar{b}$ produced per year

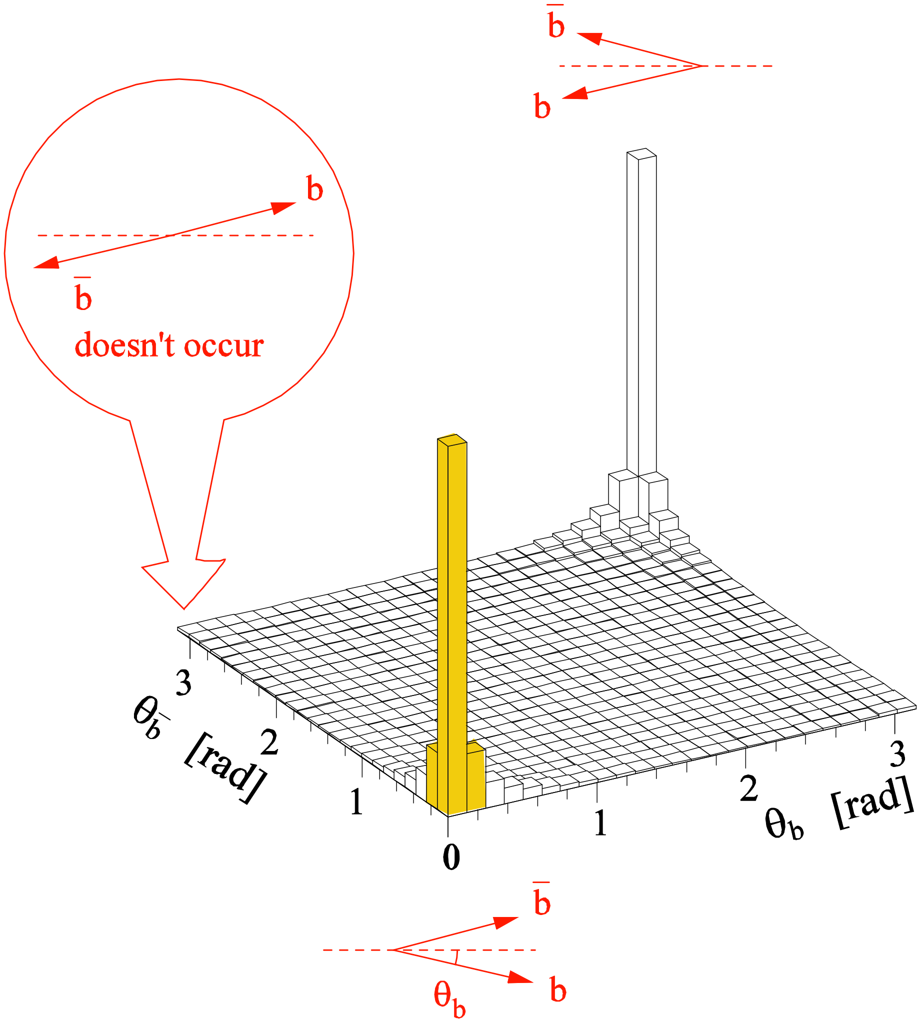
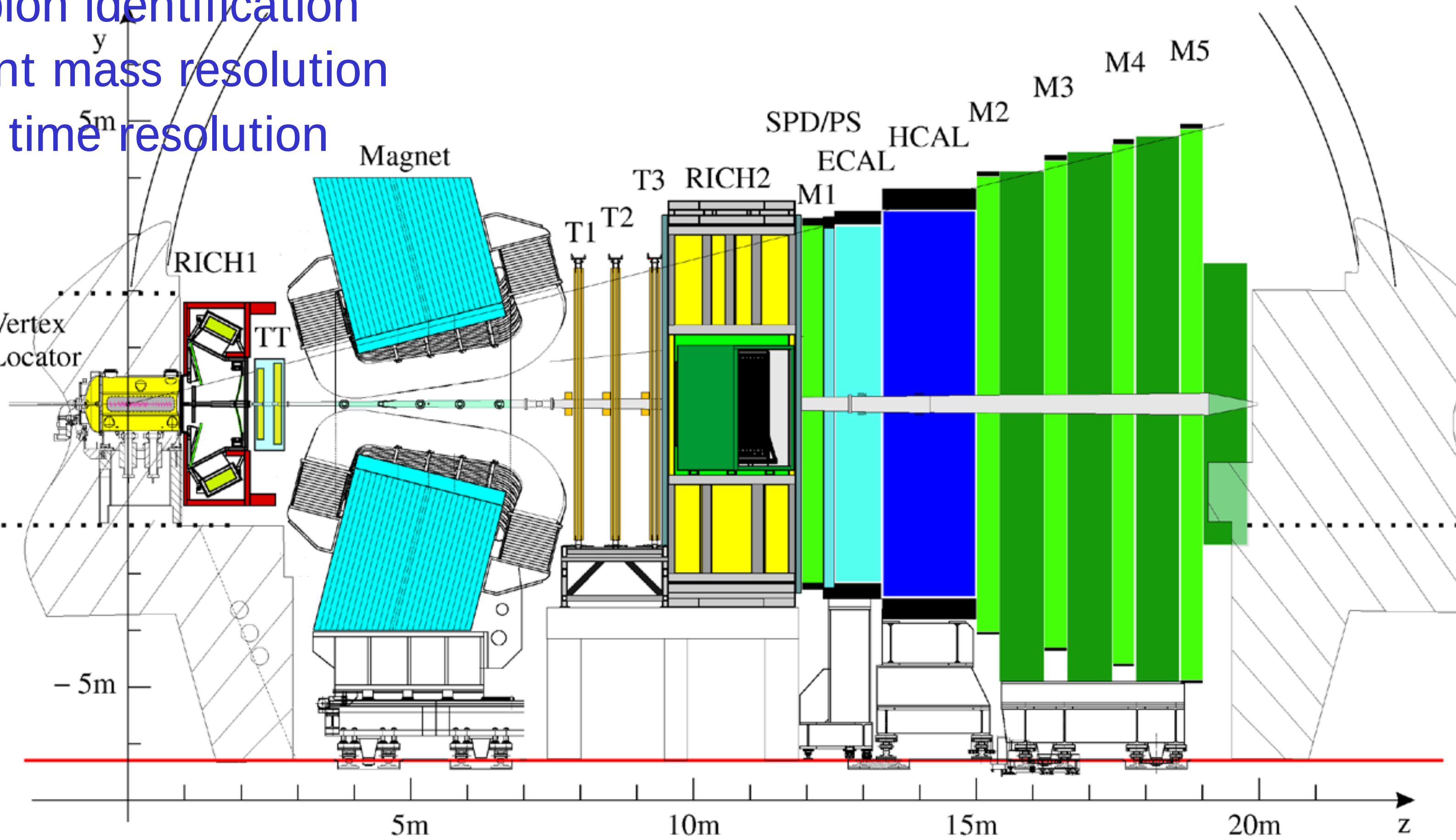


Figure 2.1: Polar angles of the b- and $\bar{b}$-hadrons calculated by the PYTHIA event generator.

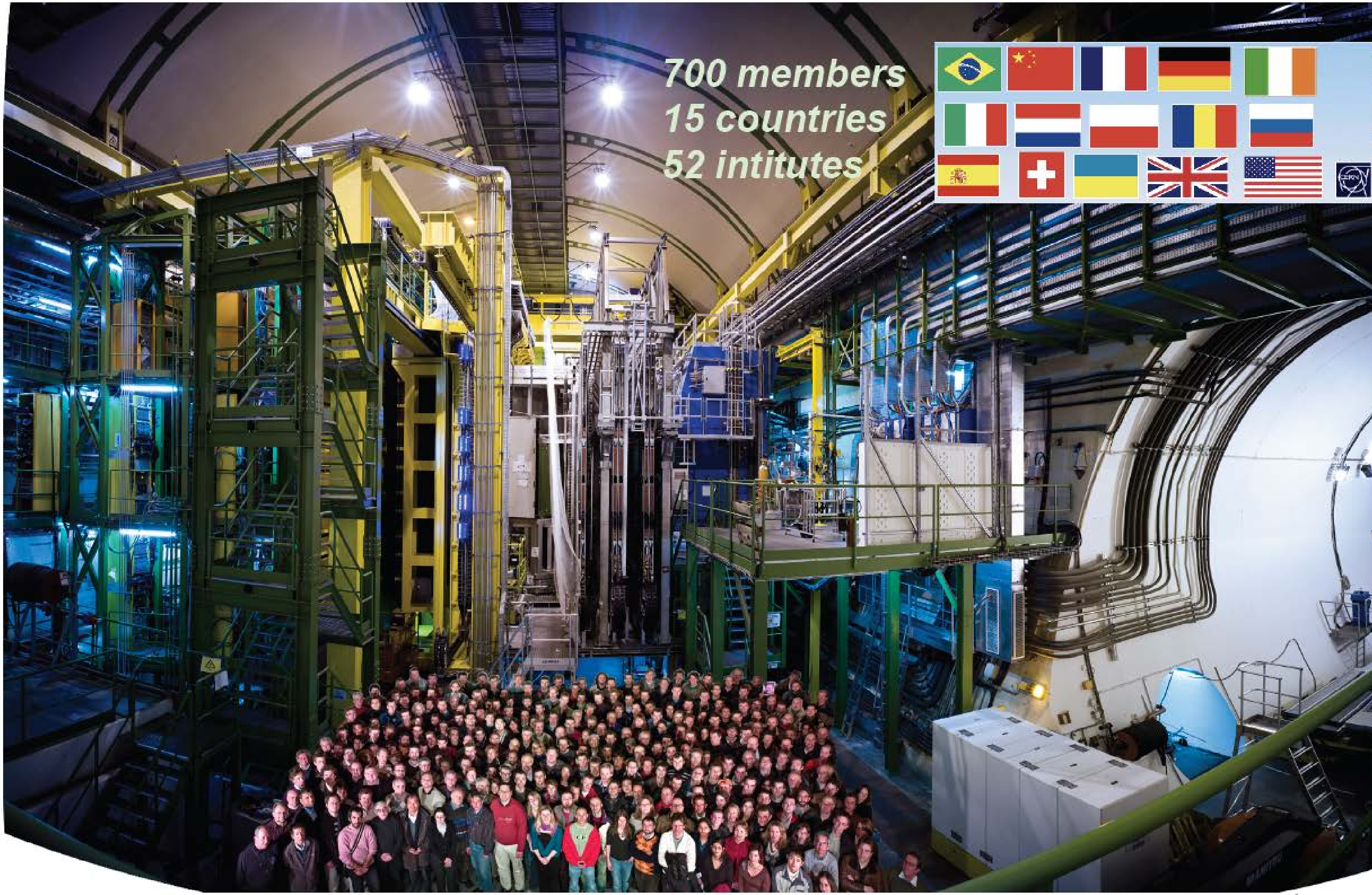
LHCb

LHCb is a forward spectrometer:

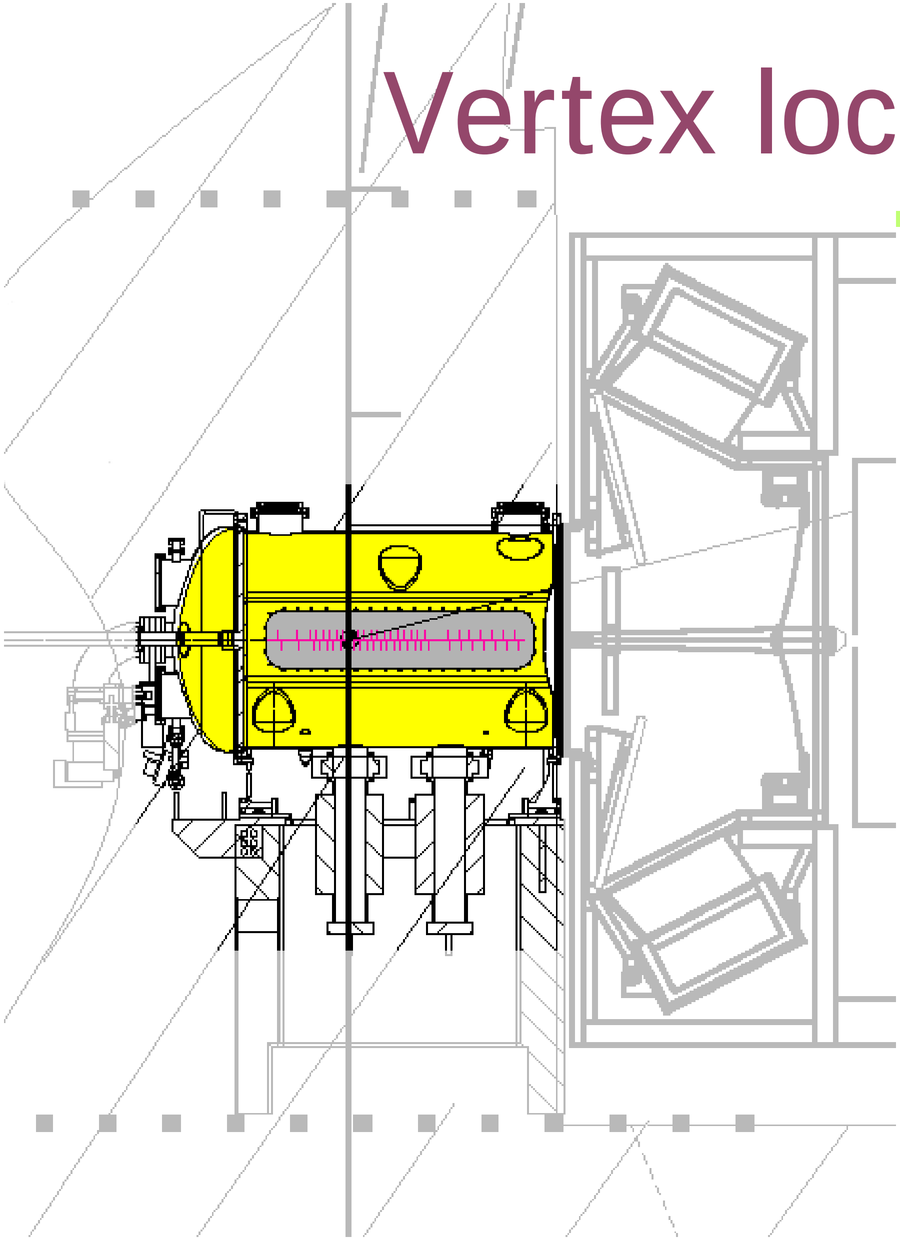
- Acceptance 10-300 mrad
- Efficient B-mesons trigger
- Good Kaon/pion identification
- Good invariant mass resolution
- Good proper time resolution



LHCb Collaboration



Vertex locator - VELO



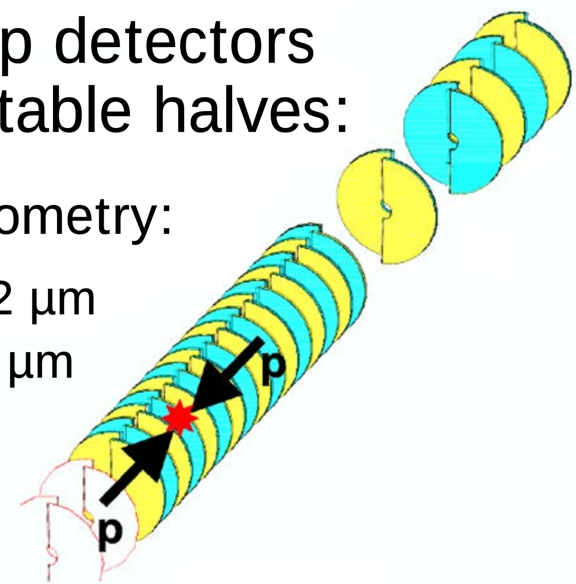
Vertex detector

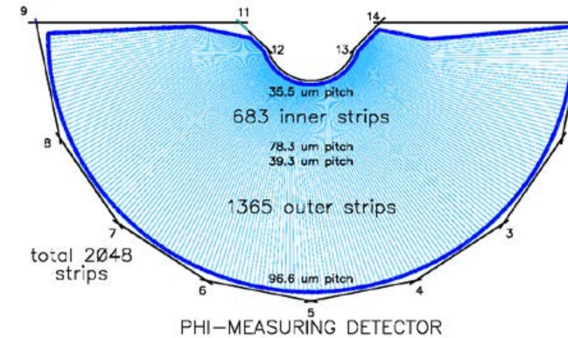
Key element surrounding the IP:

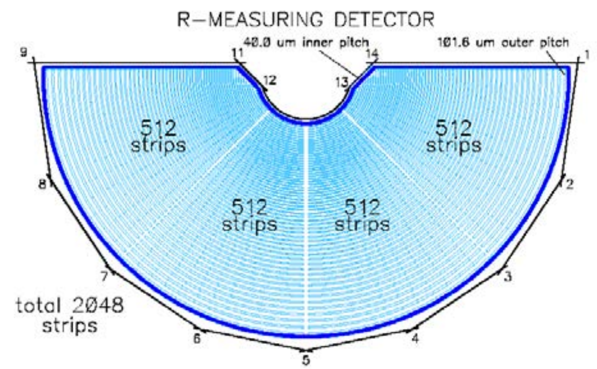
- Measure the position of the primary and the $B_{d,s}$ vertices
- Used in L1 trigger.

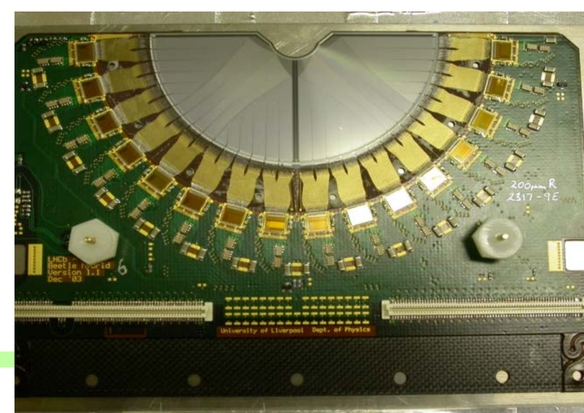
Vertex locator

- 21 pairs of silicon strip detectors arrange in two retractable halves:
  - Strips with an R-φ geometry:
    - R strip pitch: 40-102 μm
    - φ strip pitch: 36-97 μm
  - 172k channels.



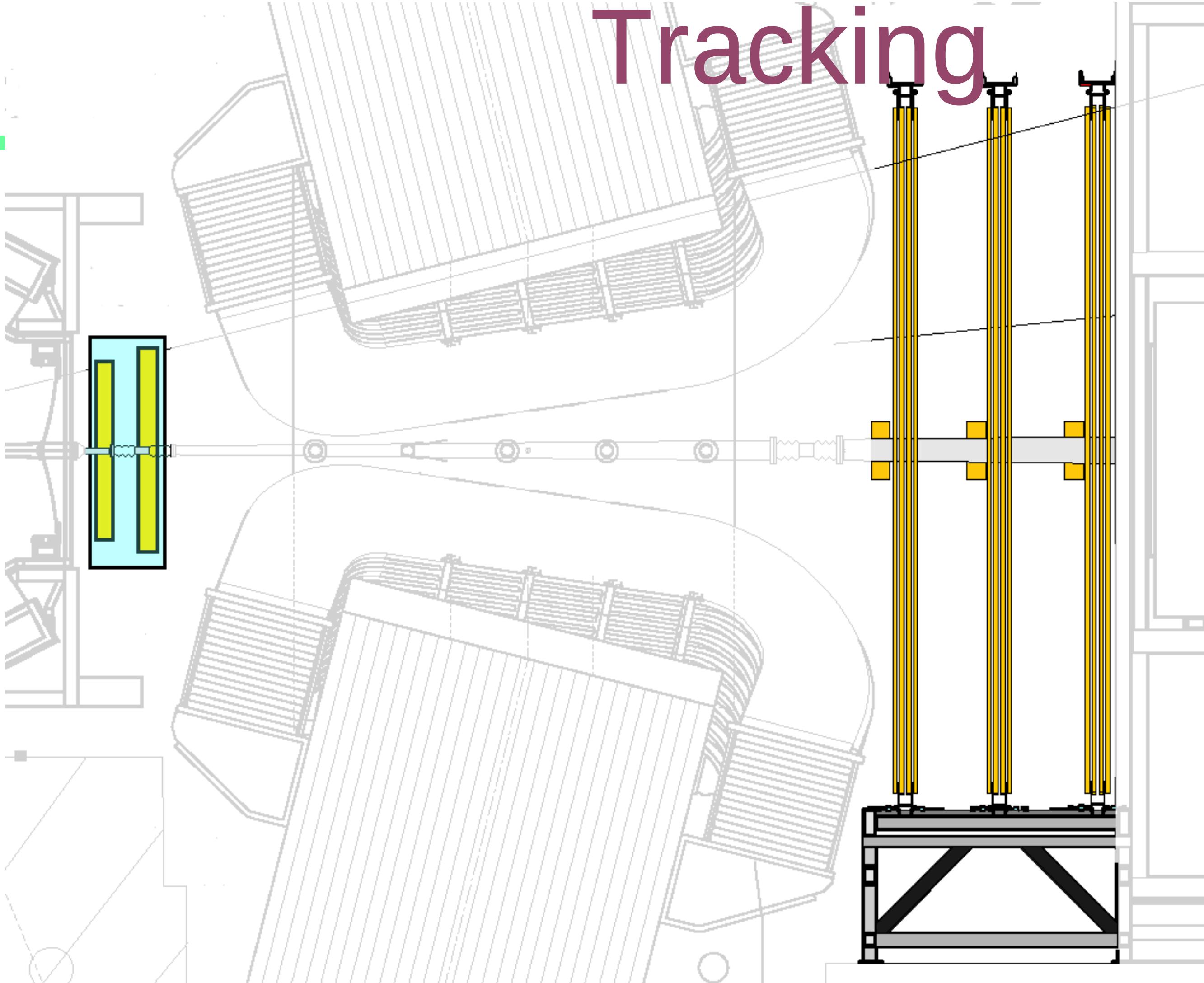






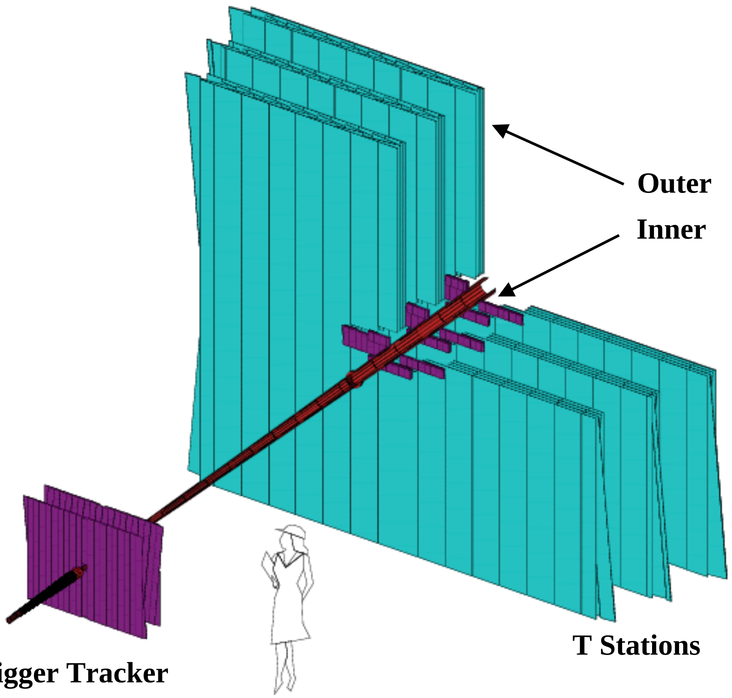
- Operated:
  - In vacuum, separated from beam vacuum by an Al foil
  - Close to the beam line (7 mm)
  - Radiation ≤ 1.5×10^{14} n_{eq}/cm^2 per year
  - Cooled at -5 °C

Tracking



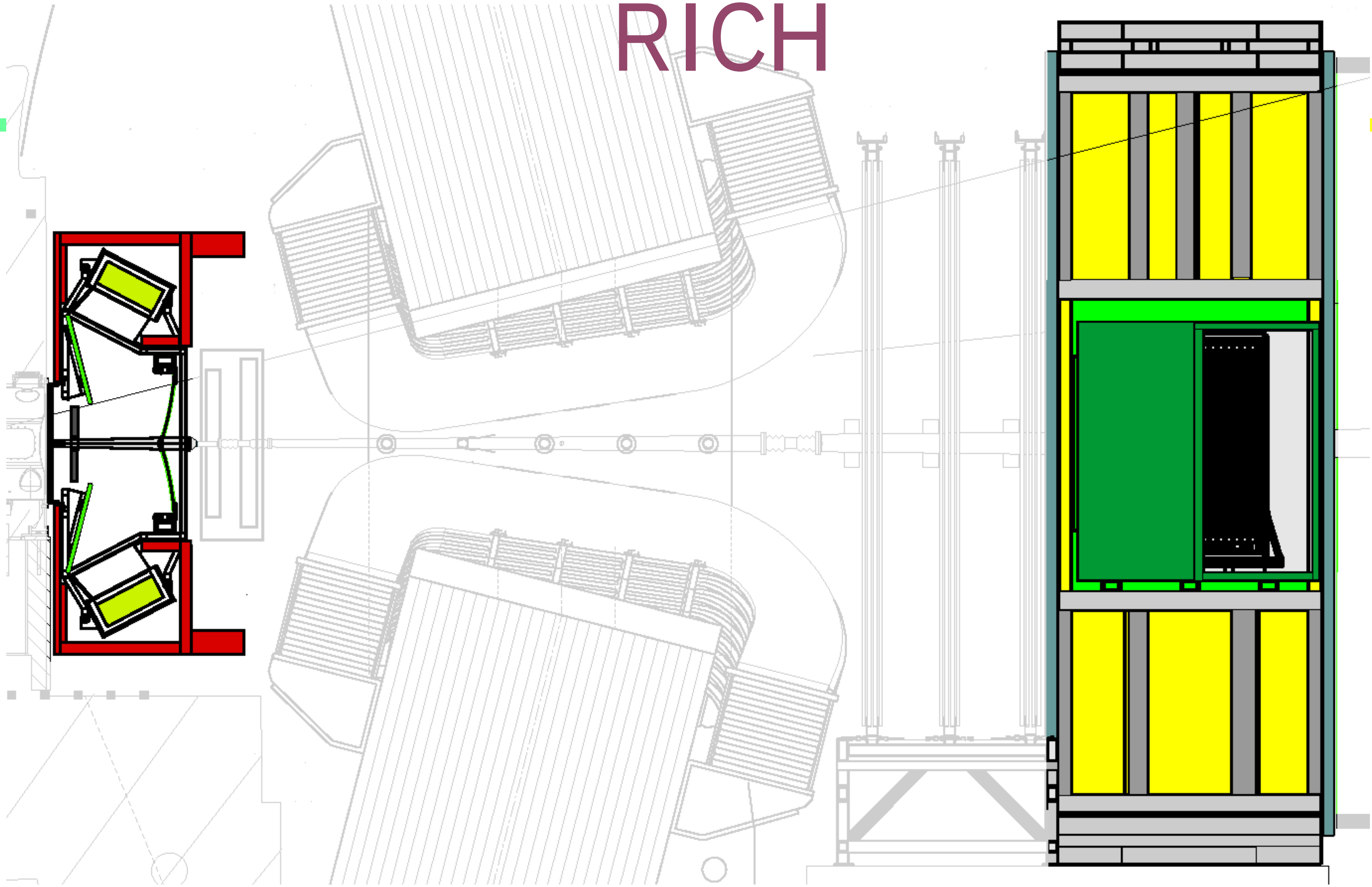
Key elements to find tracks and to measure their momentum.

Tracking system



- Trigger Tracker:
  - Microstrip silicon detector
  - 144k channels
- Three T stations:
  - Inner tracker:
    - Microstrip Silicon detector
    - 130k channels
  - Outer tracker:
    - Straw tubes (5 mm)
    - 56k channels

RICH



Key elements to identify pions and kaons in the momentum range $p \in [2, 100]\,\mathrm{GeV}/c$

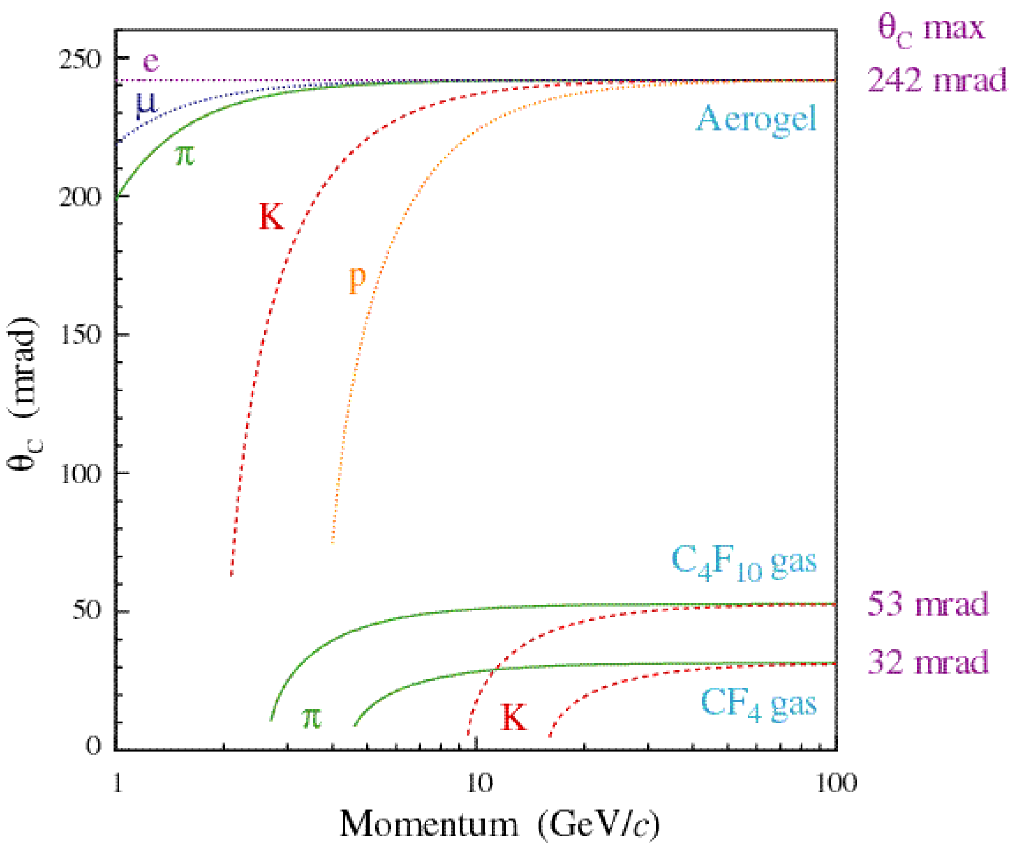
LHCb RICHes

RICH system divided in two detectors equipped with 3 radiators to cover the full acceptance and momentum range:

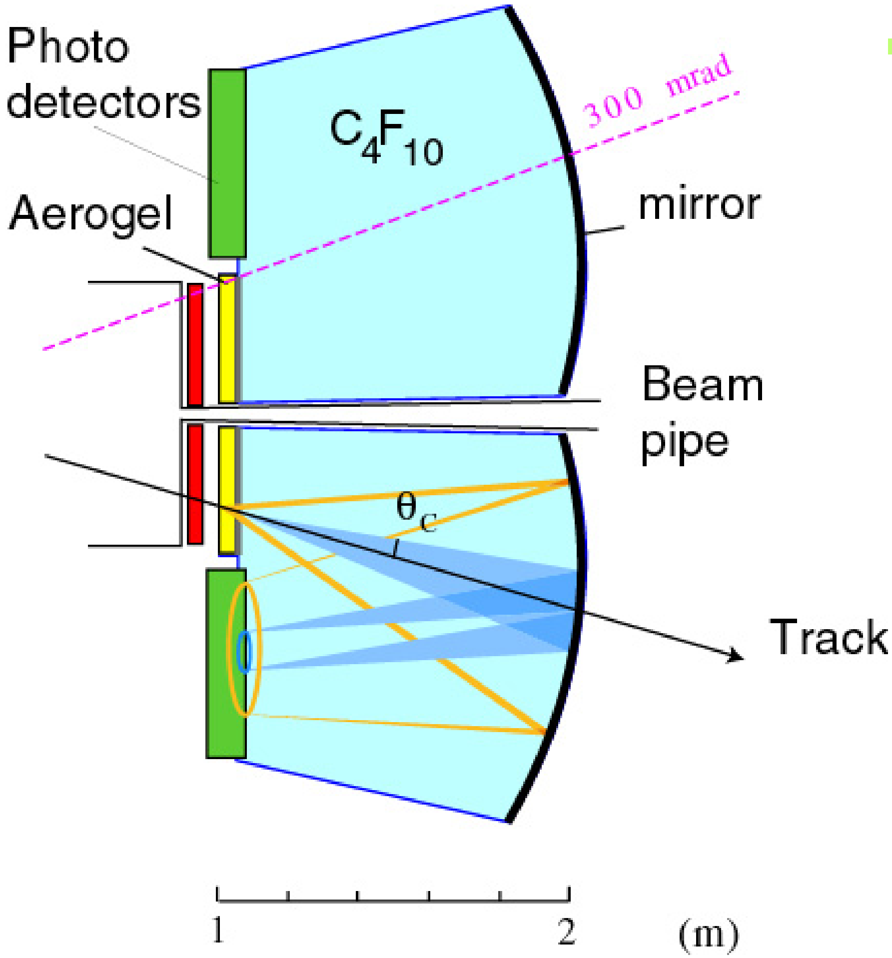
- from a few GeV (tagging kaons)
- up to 100 GeV: two body B decays

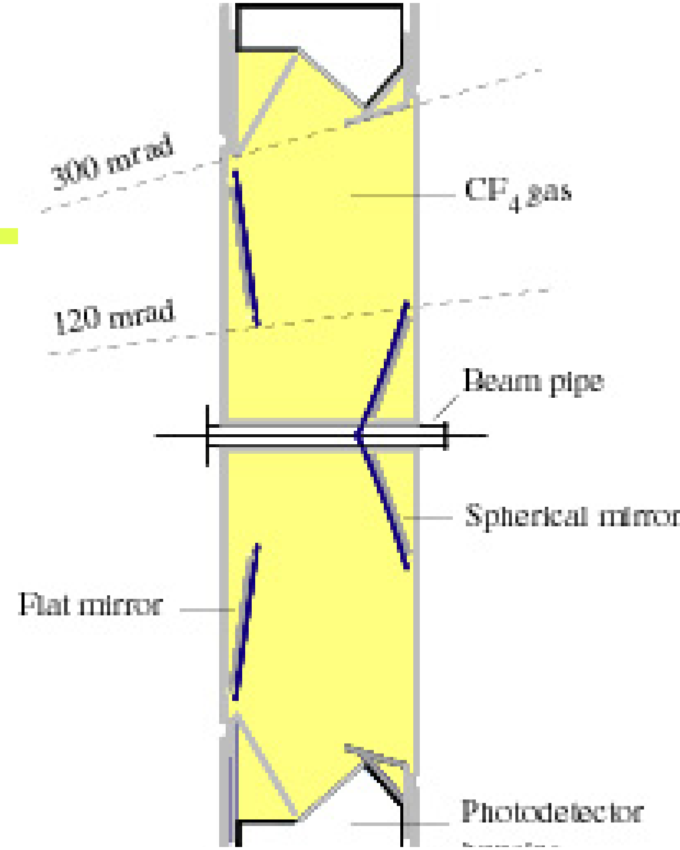
General rule: for 3σ separation, a RICH with a single radiator can cover a factor of 4-7 in momentum from threshold to the max. p.

Larger region → more radiators!



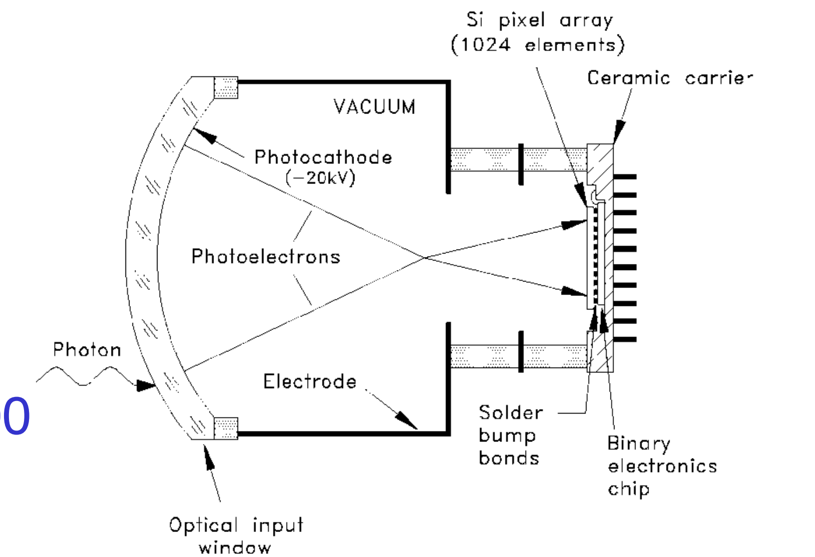
RICH with three radiators



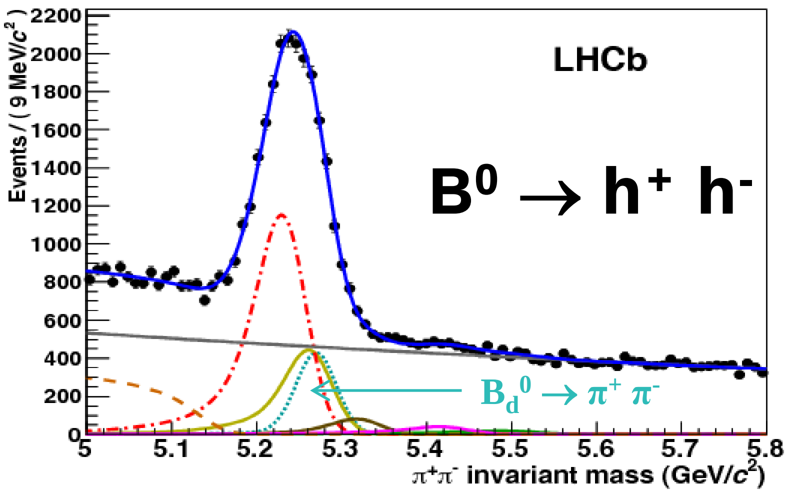


Hybrid photodetector:

32×32 pixel sensor array (500×500 μm²), 20 kV operation voltage, demagnification factor ~5



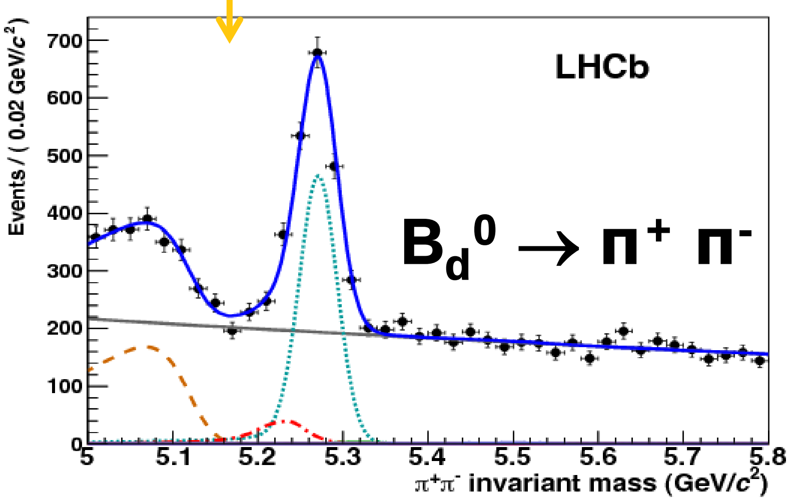
Particle ID with RICH



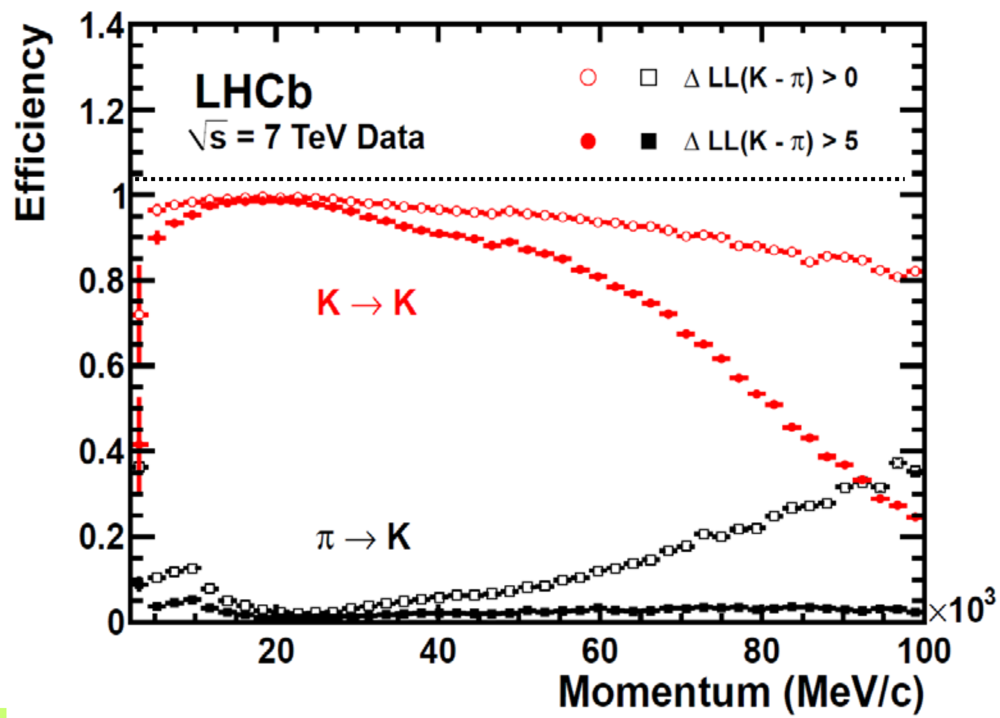
Efficient particle ID of π, K, p essential for selecting rare beauty and charm decays

K-identification and π-misidentification efficiencies vs. particle momentum

particle identification of 2 pions



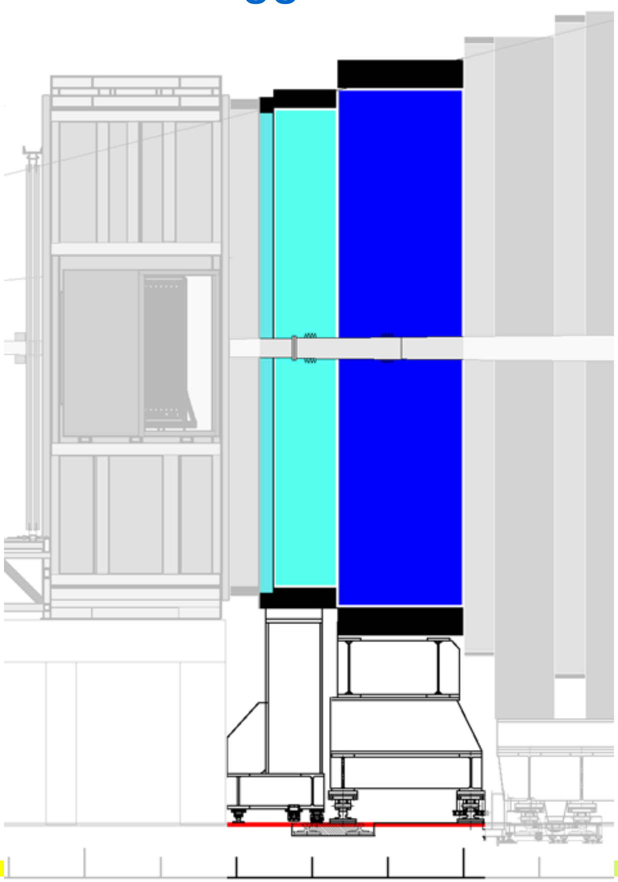
Eur. Phys. J. C (2013) 73:2431

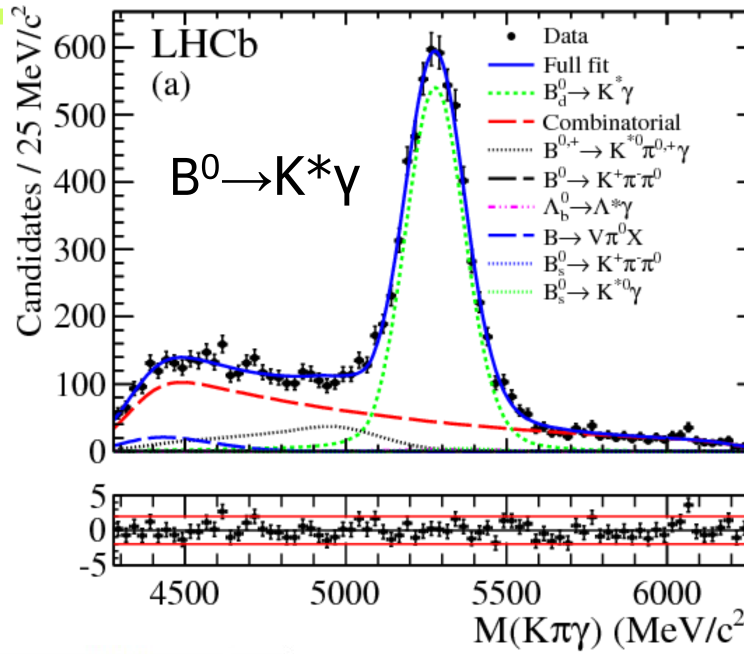


Calorimeters

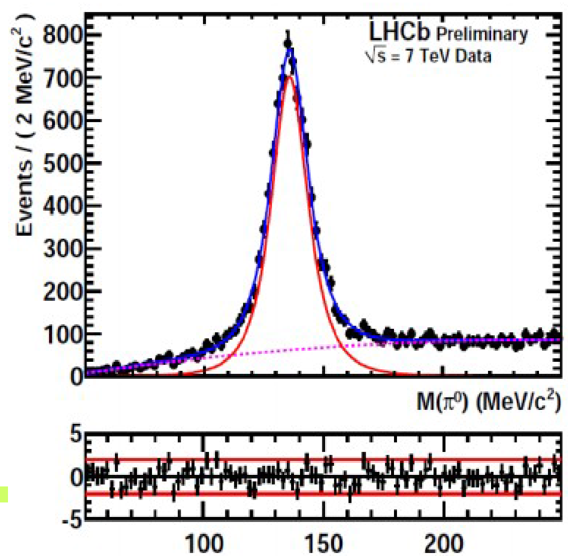
Key element to identify γ, π^0 and to measure their energy.

Used in L0 trigger.



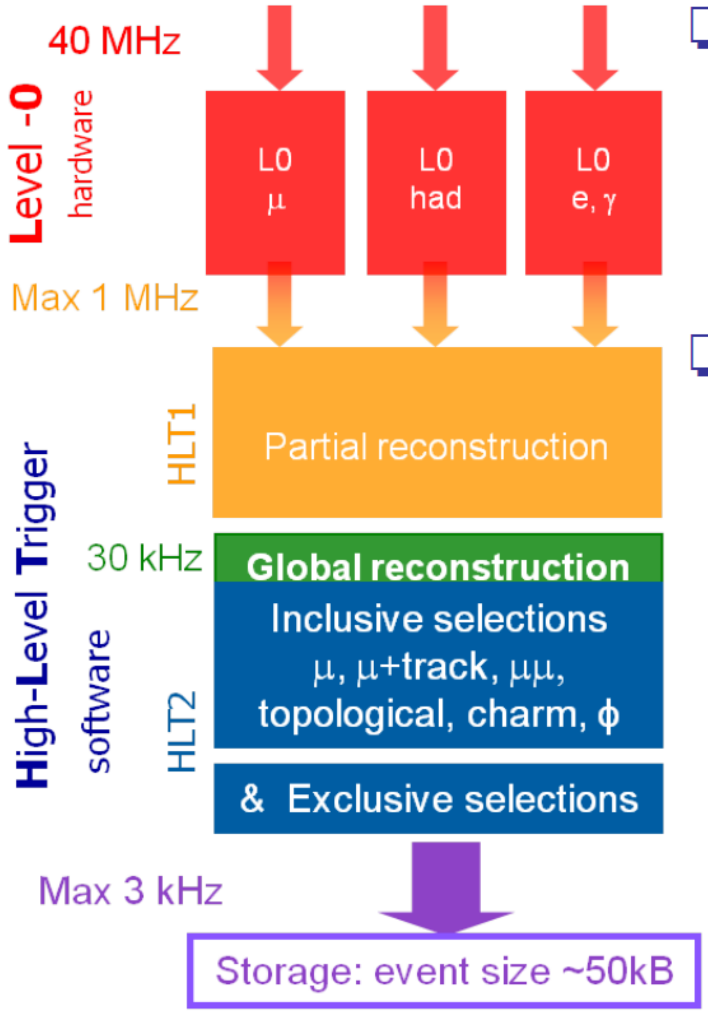


Nuclear Physics, Section B 867 (2013) 1



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

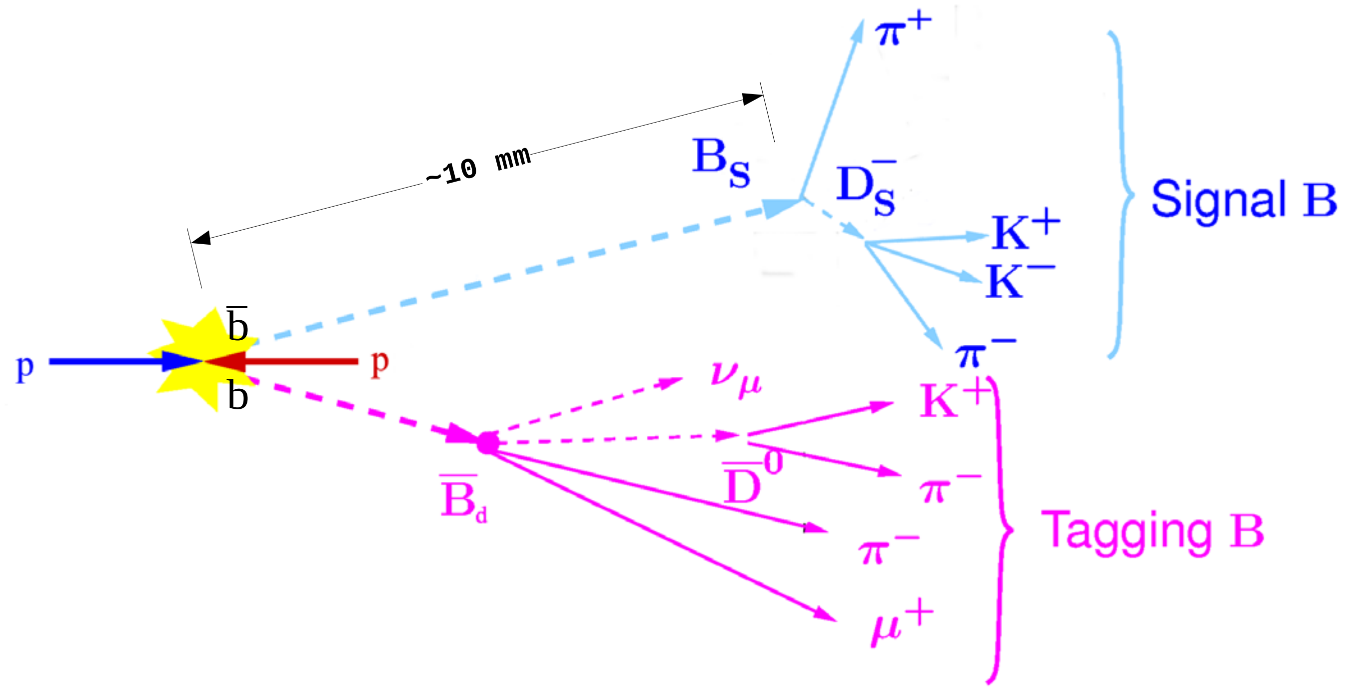
Triggers



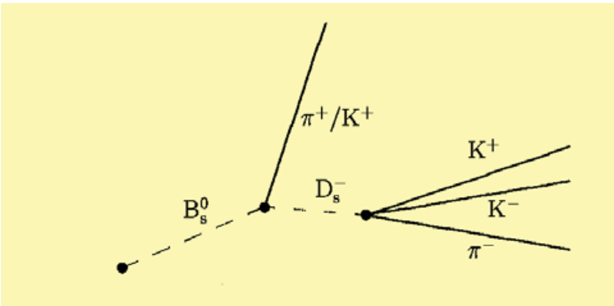
- **Level-0:**
  - — fully synchronous custom electronics at 40 MHz
    - 11 MHz of visible interactions reduced to max. 1 MHz
    - select single objects with large p_T (E_T), typically $p_T(\mu) > 1$ GeV/c and $E_T(h,e,\gamma,\pi^0) > 3–4$ GeV
- **High-level trigger**
  - — Farm of 1500 multi-processor boxes
  - — Stage 1: add tracking info, impact parameter cuts
  - — Stage 2: full reconstruction + selections
  - — Output:
    - ~1 kHz charm, ~ 1 kHz B, ~1 kHz others

	Typical efficiencies
B decays with μμ	70–90%
Fully hadronic B decays	20–45%
Fully hadronic charm decays	10–20%

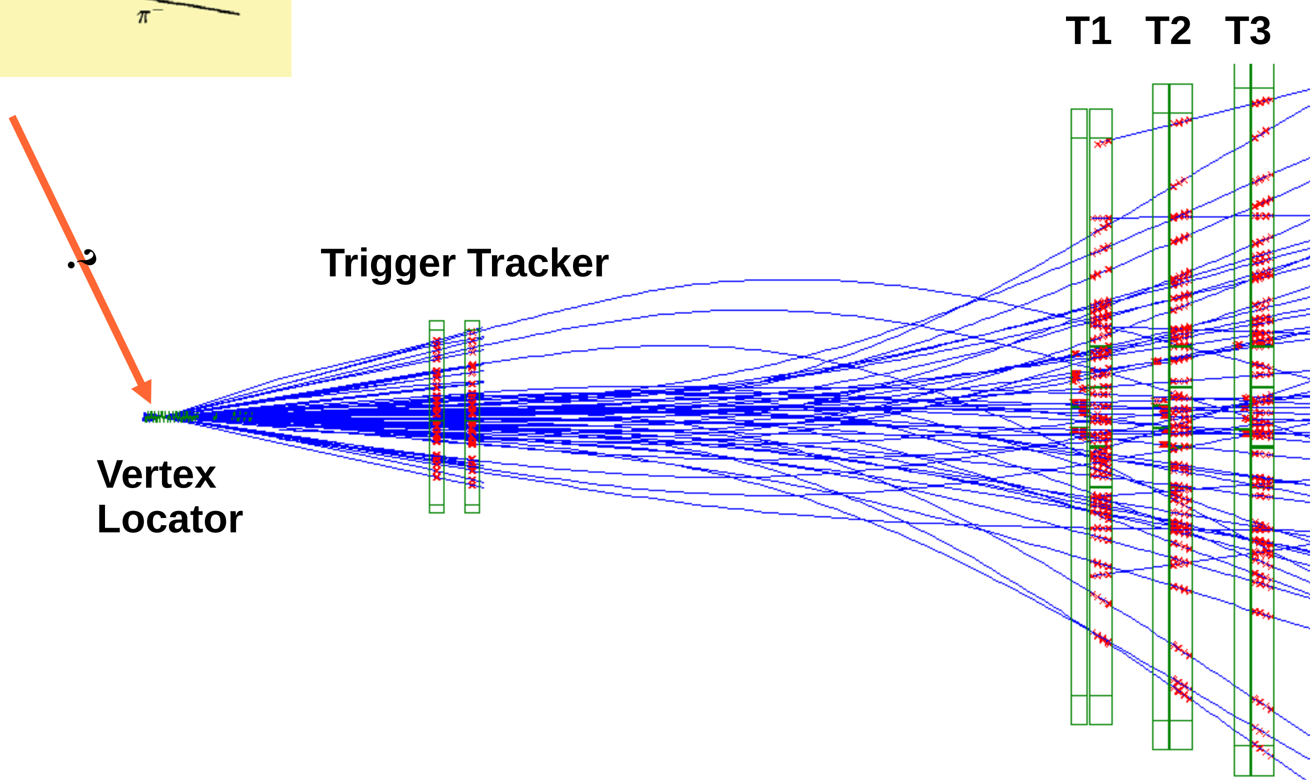
Time dependent measurements at LHCb



- The proper time of the signal B decay is measured via:
  - the position of the primary and secondary vertexes;
  - the momentum of the signal B state from its decay products.



$$B_s \rightarrow D_s^{\pm} K^{m} \rightarrow \left(K^+ K^- \pi^{\pm}\right) K^{m}$$



Reconstructed event: ~72 tracks

Measurement of Δm_s

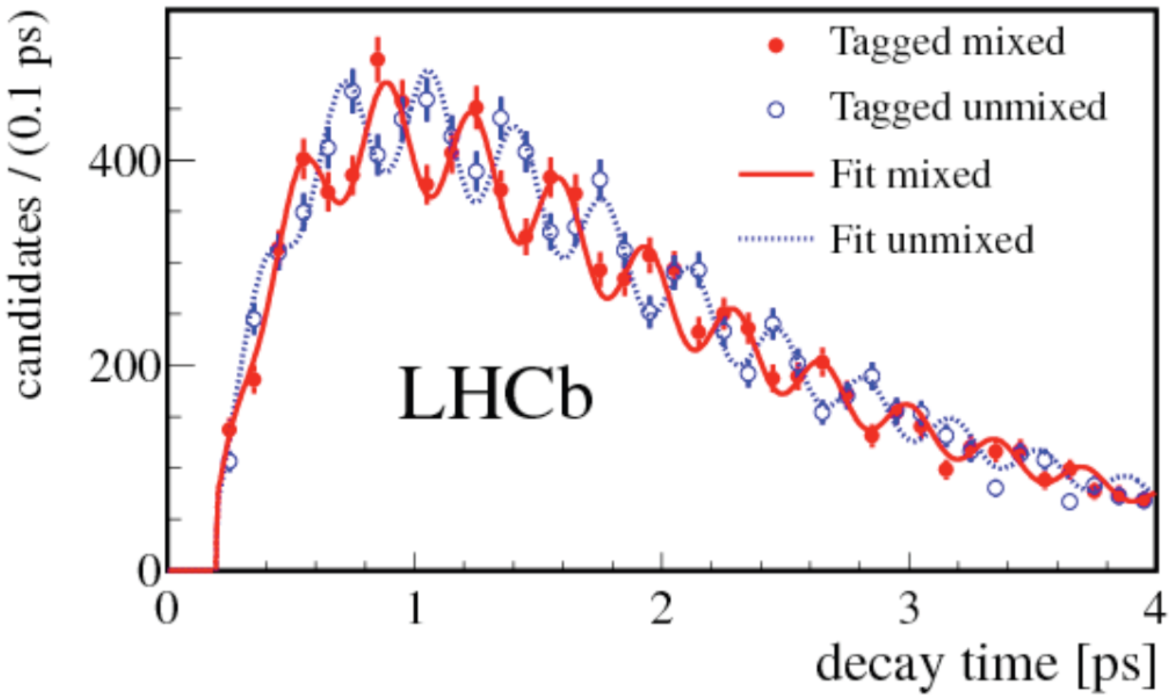
B_s mix much faster the B_d mesons!

First observed at CDF in 2005: $\Delta m_s = 17.33^{+0.42}_{-0.21}$ (stat) +- 0.07 (syst) ps^{-1}

LHCb: Precision measurement

New J.Phys. 15 (2013) 053201

Uses 34,000 $B_s \rightarrow D_s\pi$ decays from 1/fb of 2011 data

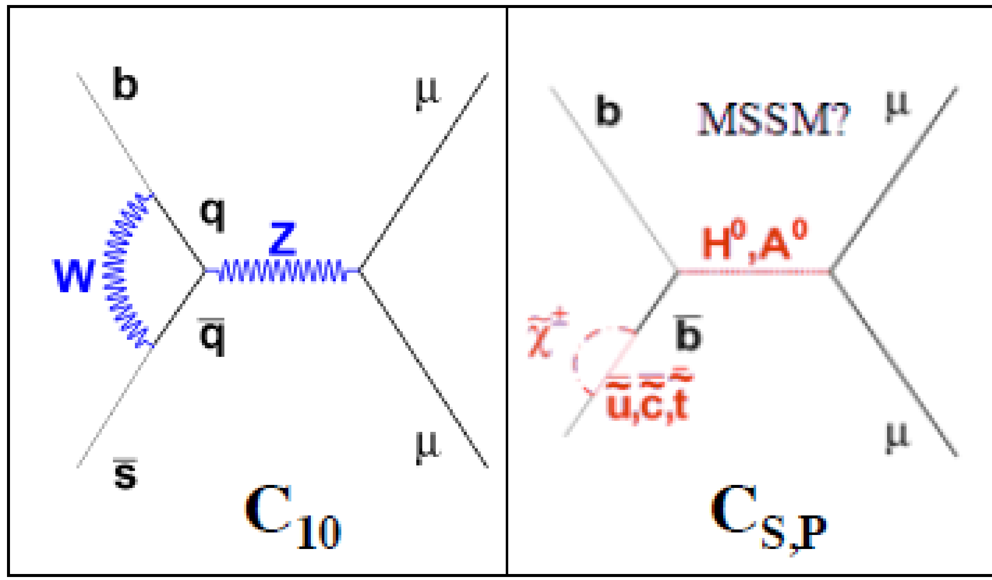


Timing resolution makes fast oscillations visible

Δm_s = 17.768 +- 0.023 (stat) +- 0.006 (syst) ps^{-1}

New physics search in the decay $B_s \to \mu^+ \mu^-$

Decay, very sensitive to the presence of New Physics (remember the role of $K_L \to \mu\mu$ in getting an indication of the charm quark)



Standard Model prediction

$$BR_{SM} = (3.2 \pm 0.2) \times 10^{-9}$$

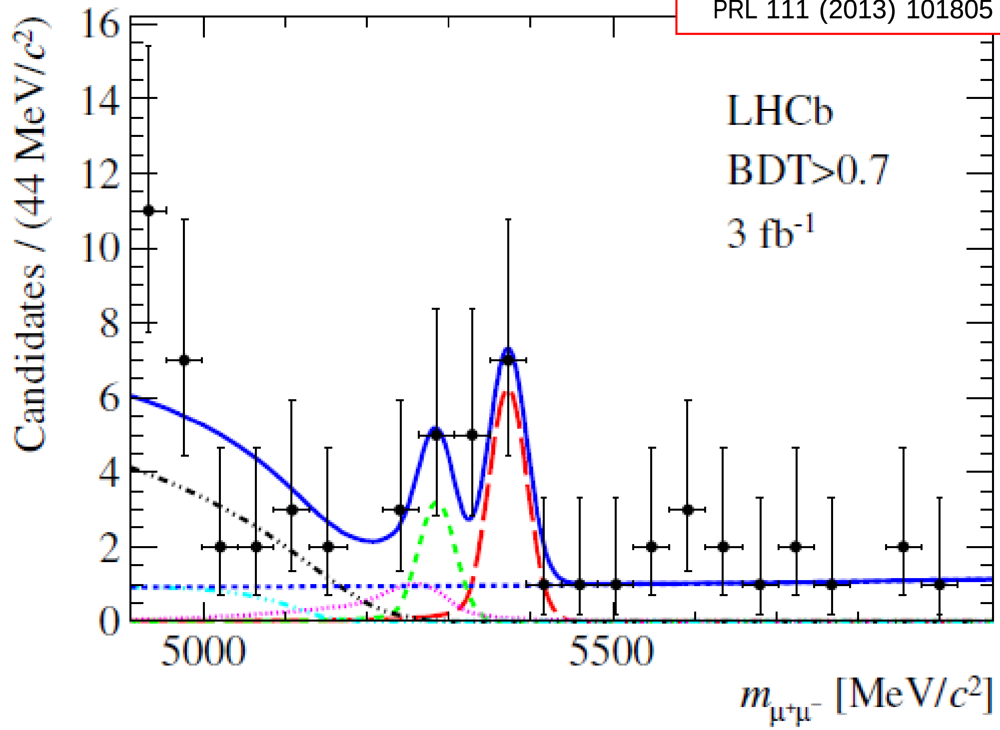
Buras et al., JHEP 10 (2010) 009

New physics search in the decay $B_s \to \mu^+\mu^-$

Challenge: very very rare in SM

Advantage: extremly clear signature, two high transverse momentum muons

PRL 111 (2013) 101805



Result

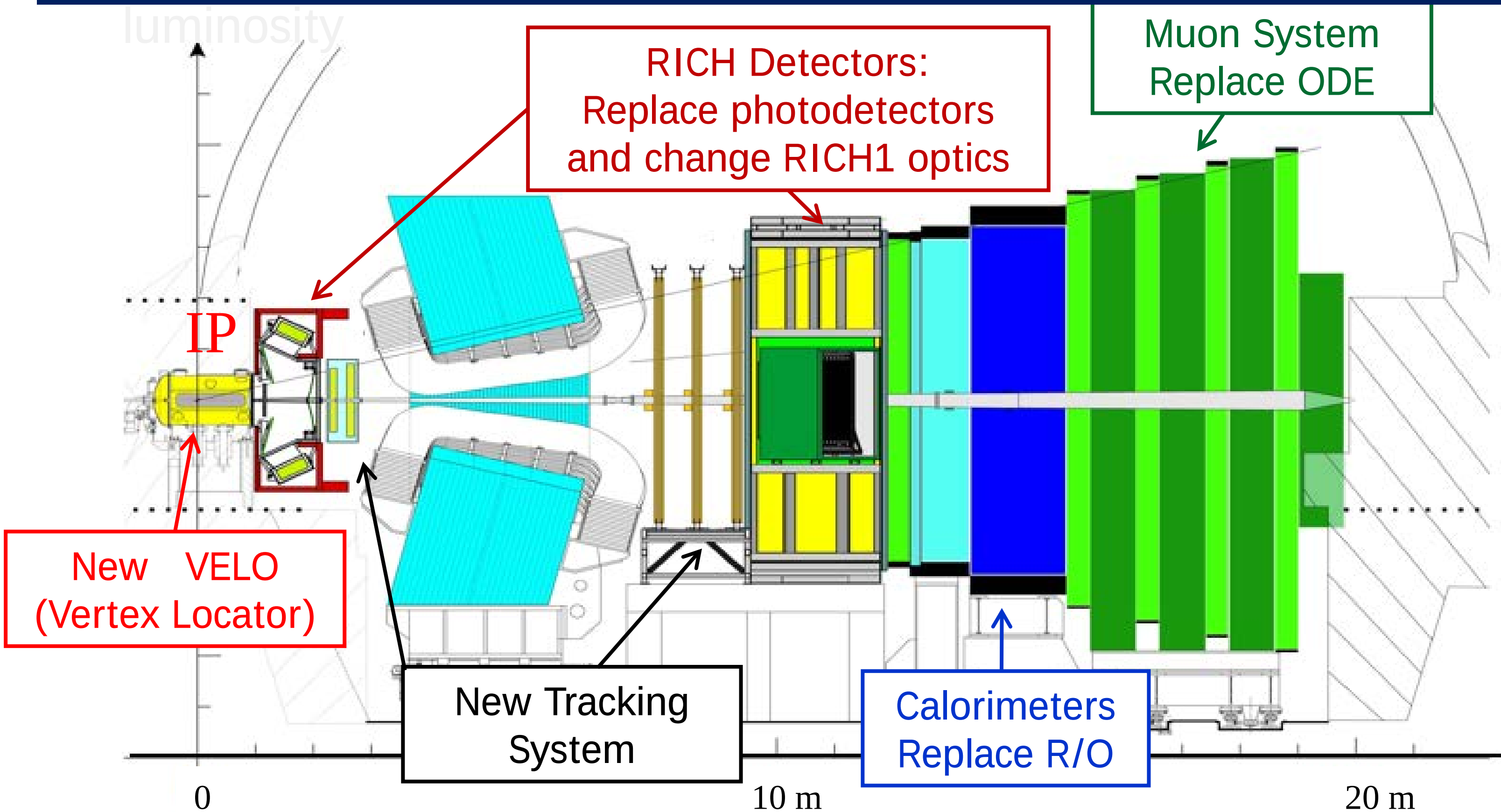
$$BR(B_S^0 \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}(stat)^{+0.3}_{-0.1}(syst)) \times 10^{-9}$$

In excellent agreement with SM prediction $BR_{SM} = (3.2 \pm 0.2) \times 10^{-9}$

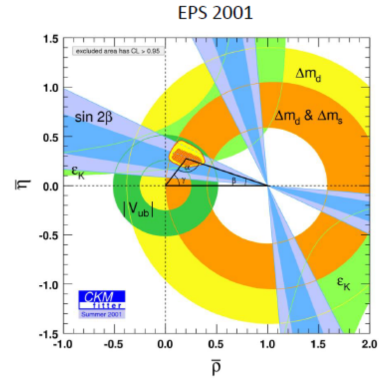
Buras et al., JHEP 10 (2010) 009

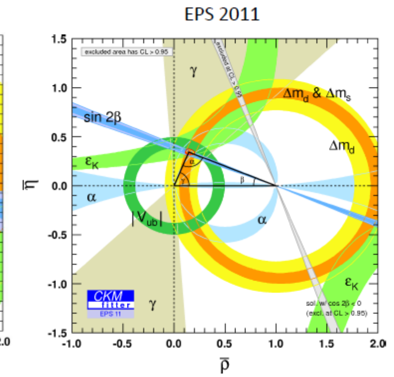
Detector upgrade to 40 MHz R/O

- upgrade ALL sub-systems to 40 MHz Front-End (FE) electronics
- replace complete sub-systems with embedded FE electronics
- adapt sub-systems to increased occupancies due to higher luminosity
- keep excellent performance of sub-systems with 5 times higher luminosity



Summary





- B factories have proven to be an excellent tool for flavour physics, with reliable long term operation, constant improvement of the performance, achieving and surpassing design perfomance
- Next generation: intensity frontier experiment, look for New Physics effects
  - In the last few years, LHCb has dominated the progress in flavour physics, with a number of very important results
  - Preparations for the upgrade of LHCb well underway
- Super B factory at KEK under construction 2010-18 → SuperKEKB+Belle II, L x40, final construction at full speed
- Expect a new, exciting era of discoveries from complementary experiments