# Physics at SuperKEKB

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- Highlights from Belle
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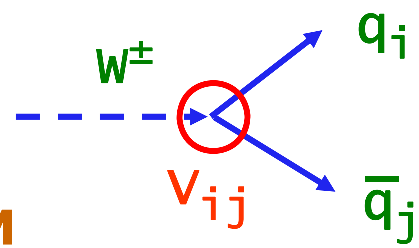
# B factory physics program

**B factory main task:** **measure CP violation in the system of B mesons**

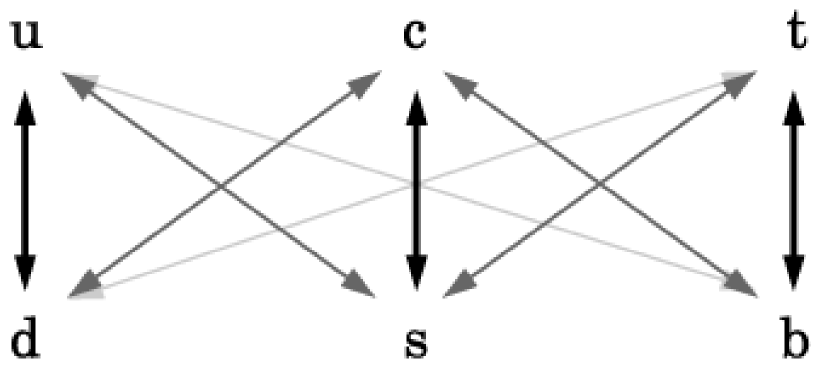
**specifically: various measurements of complex elements of Cabbibo-Kobayashi-Maskawa matrix**

**CKM matrix is unitary**




**deviations could signal processes not included in SM**

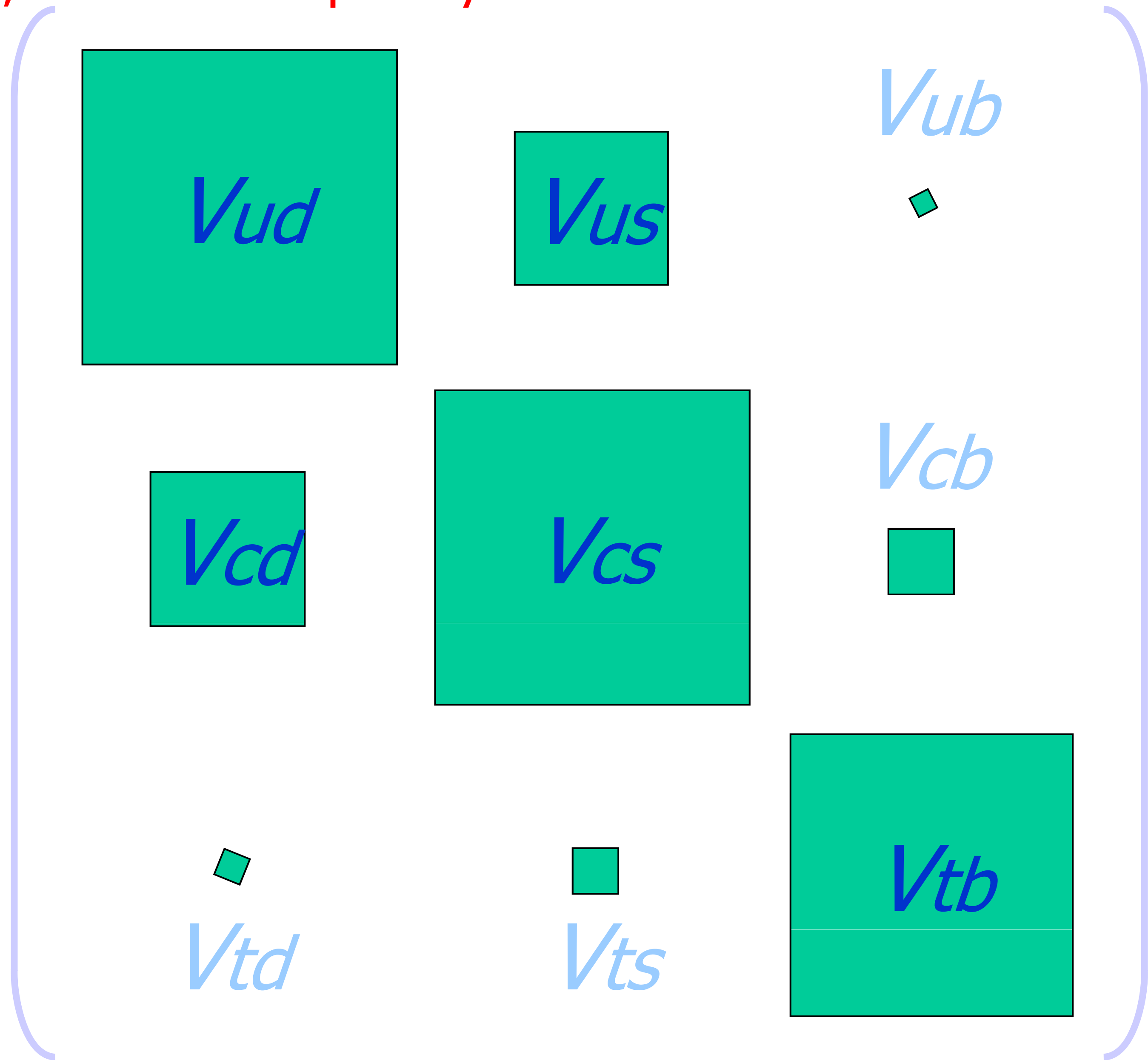
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$




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

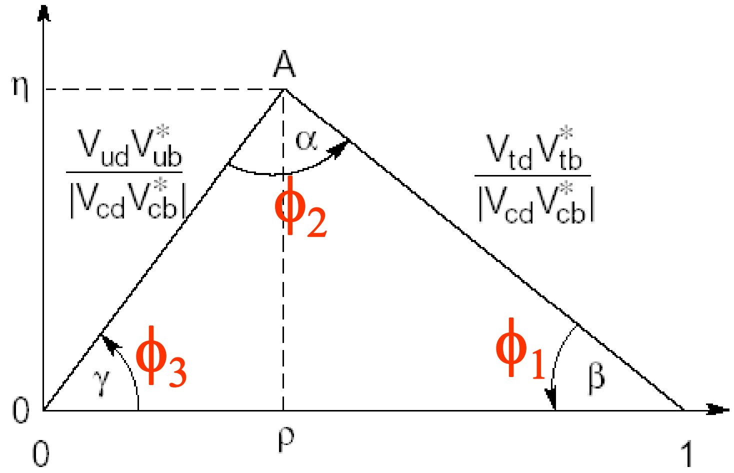
Wolfenstein parametrisation: expand in the parameter $\lambda$ (=$\sin\theta_c$=0.22)

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

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

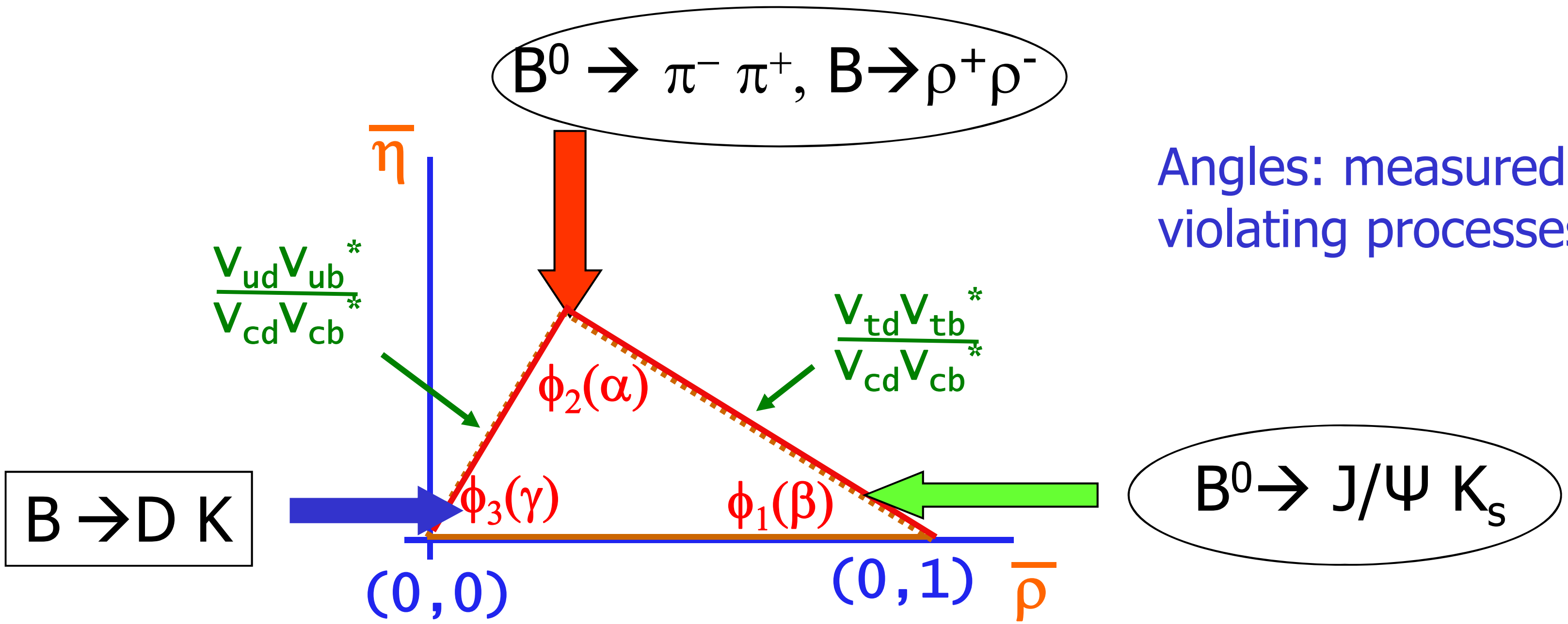
Unitarity condition:

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



Belle II

# Three Angles: $(\phi_1,\phi_2,\phi_3)$ or $(\beta, \alpha, \gamma)$




Angles: measured in CP violating processes

Big Questions: *Are determinations of angles consistent with determinations of the sides of the triangle? Are angle determinations from loop and tree decays consistent?*

# 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

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

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

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

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

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

# Time evolution of B's

Time evolution:

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

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

with

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

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

$M = (M_H + M_L)/2$

# 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: decay rate asymmetry vs. time

Decay rate asymmetry

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

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

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

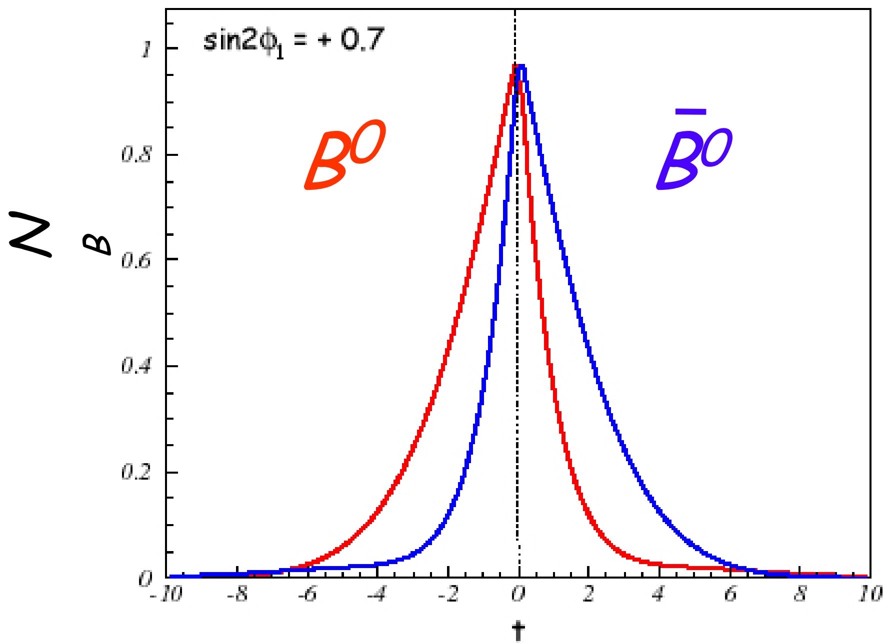
$$= C\cos(\Delta m t) + S\sin(\Delta m t)$$

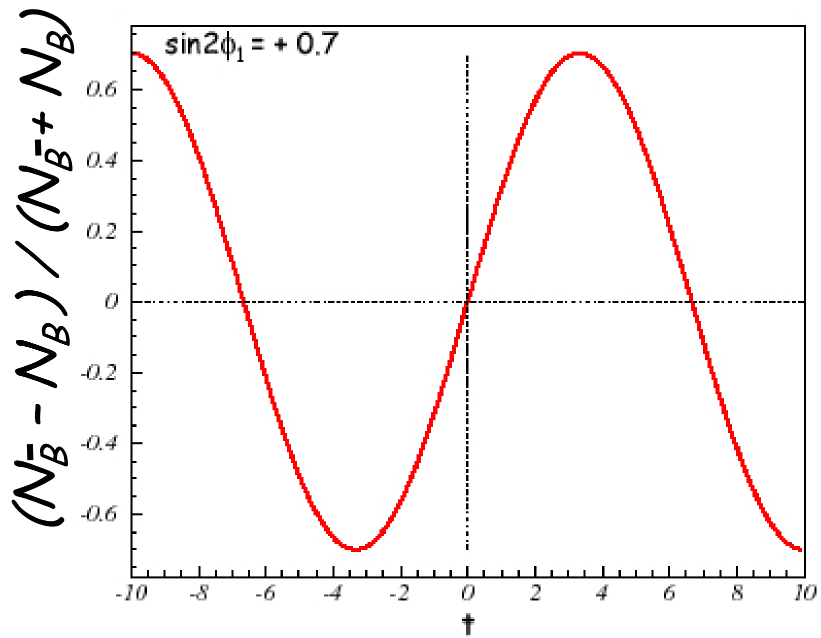
$$\lambda = \frac{q}{p}\frac{\overline{A}_f}{A_f}$$

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

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

# CP Violation in B decays to CP eigenstates $f_{CP}$



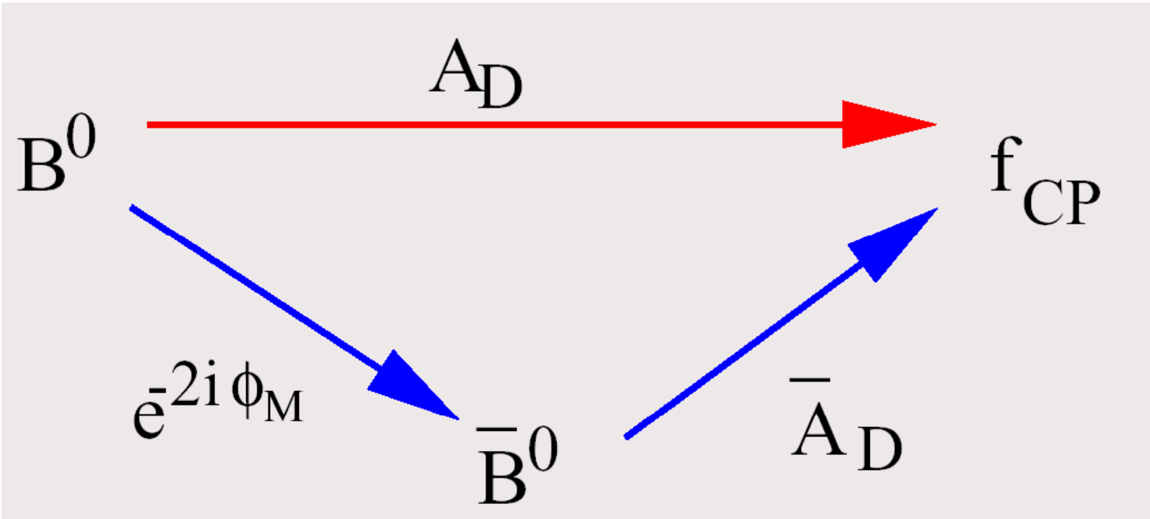

$$A_{CP}(t) = \frac{\Gamma(\overline{B}^0(t)\to f_{CP}) - \Gamma(B^0(t)\to f_{CP})}{\Gamma(\overline{B}^0(t)\to f_{CP}) + \Gamma(B^0(t)\to f_{CP})} = -\xi_f \sin 2\phi_1 \sin \Delta m_B t$$

$\xi_f = \pm 1$ *for* $CP = \pm 1$

# 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 $\pi^+ \pi^-$ or $J/\psi\, K_S$

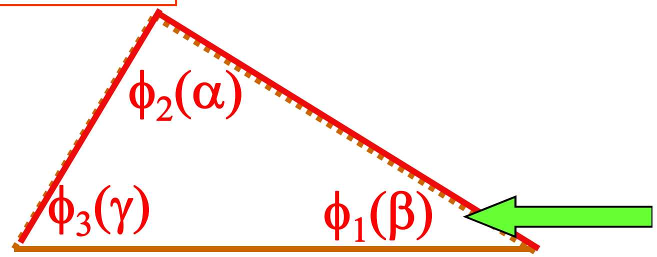



Decay rate asymmetry

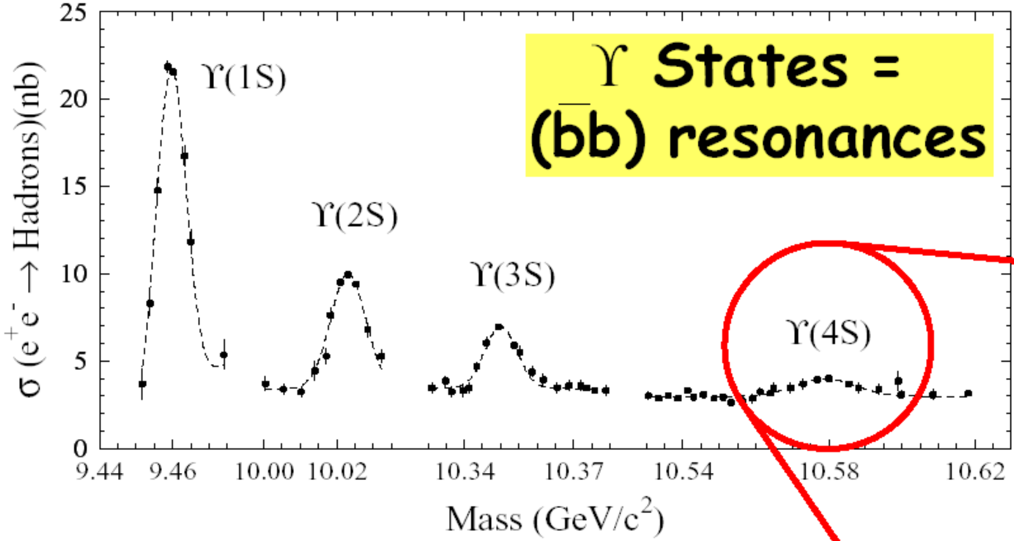
$$a_{f_{CP}} = -\mathrm{Im}(\lambda)\sin(\Delta m t)$$

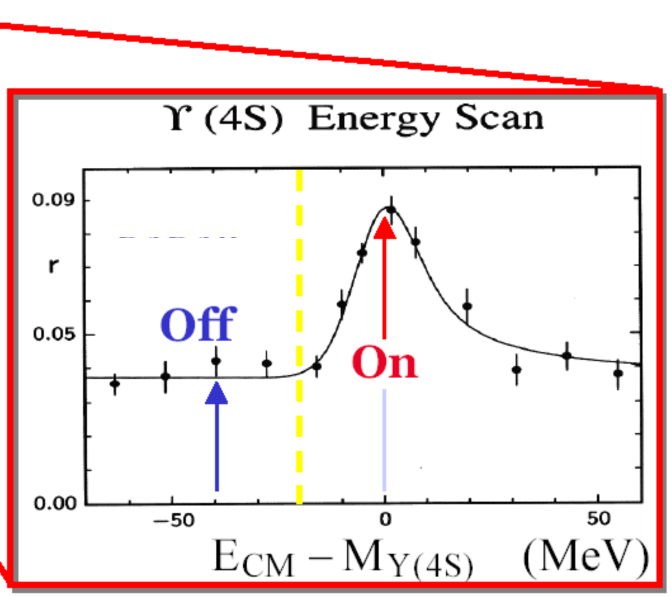
If $|\lambda| = 1$

For $J/\psi\, K_S$ ⇒ $\mathrm{Im}(\lambda) = \sin 2\phi_1$



# 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

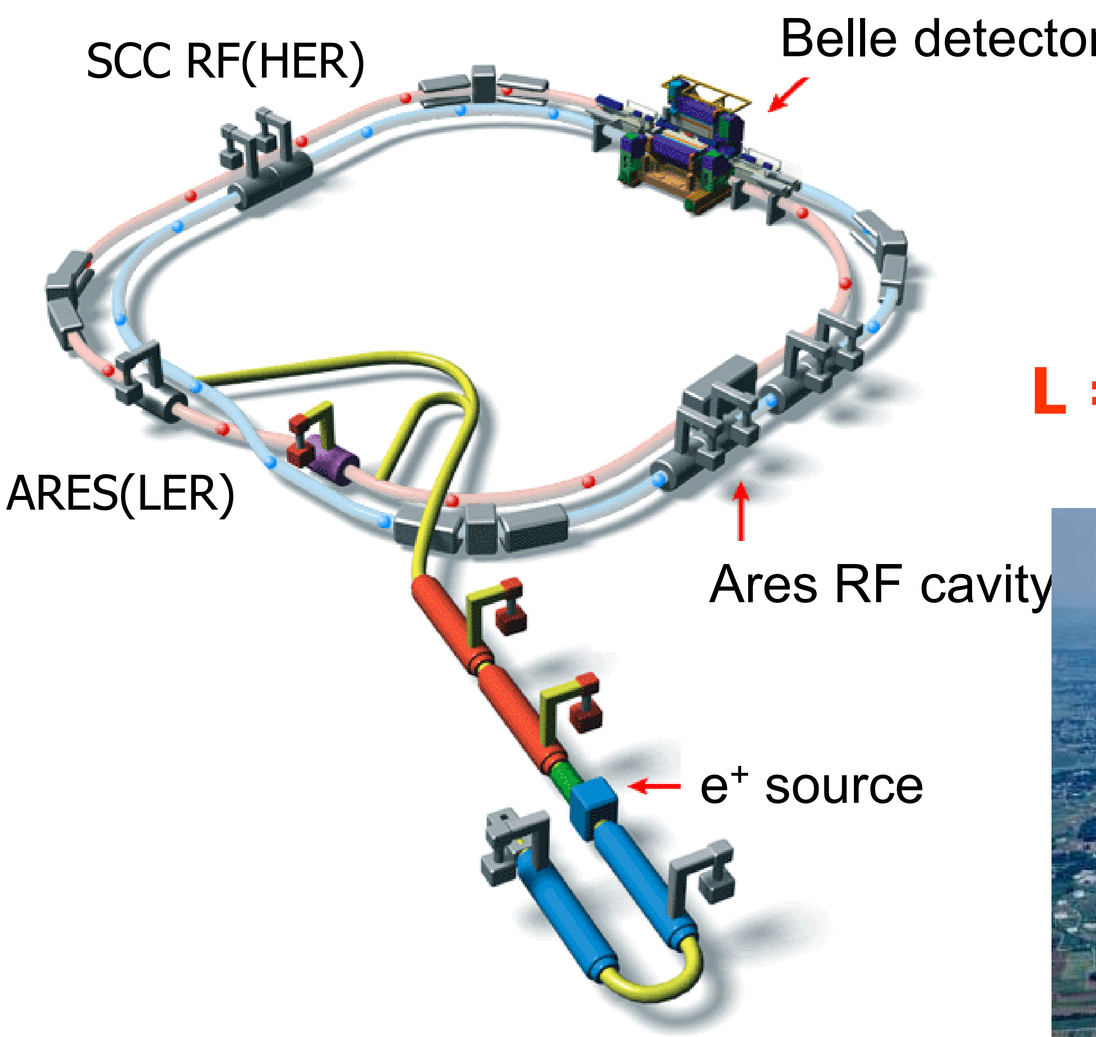
$u\bar{u} \sim 1.4$ nb

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

$L = 1$ state

Big advantage: low background

# The KEKB Collider



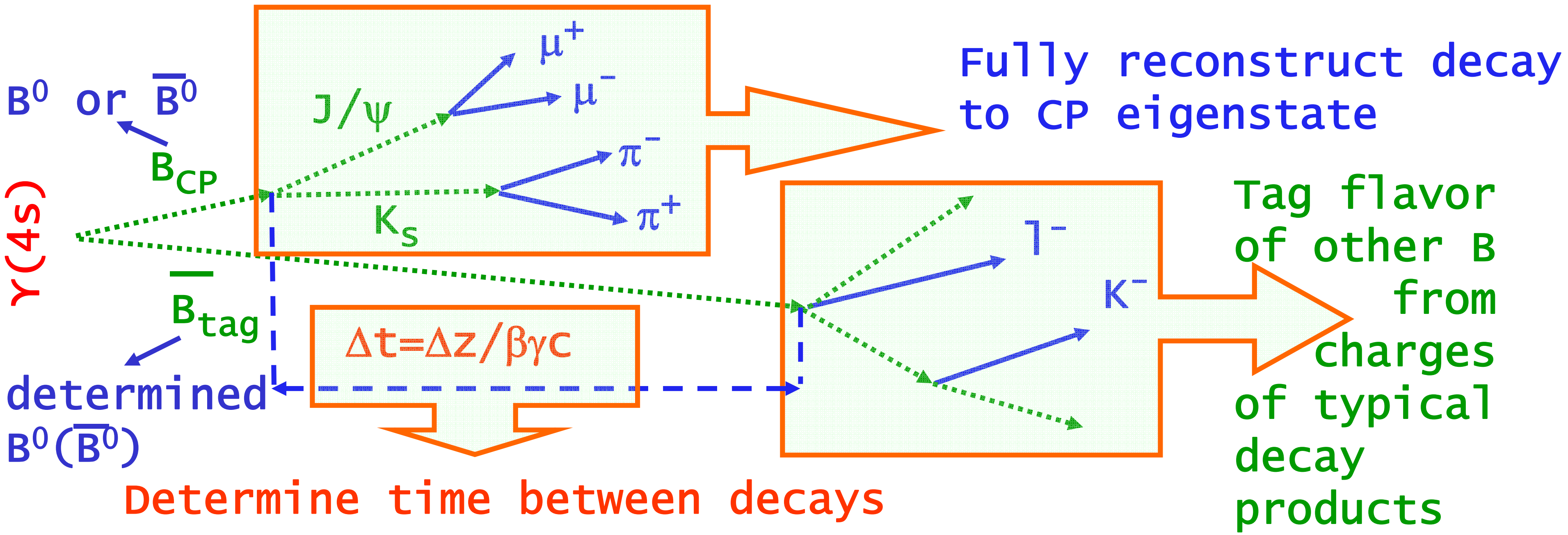

8 x 3.5 GeV
22mrad crossing angle

World record:

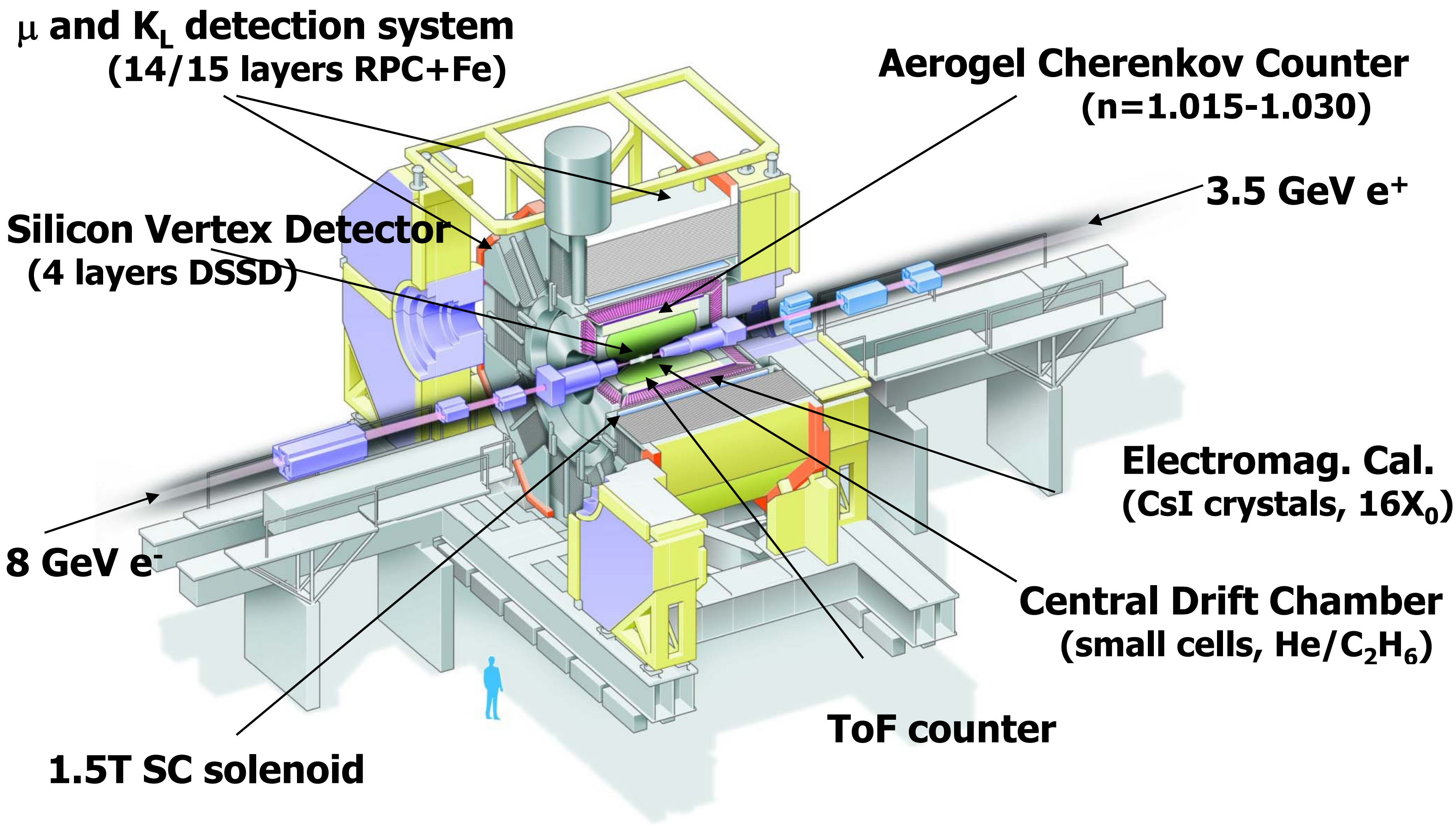
**$L = 2.1 \times 10^{34}/cm^2/sec$**

# Principle of measurement

$$A_{CP}(t)=\frac{\Gamma(\overline{B}^0(t)\to f_{CP})-\Gamma(B^0(t)\to f_{CP})}{\Gamma(\overline{B}^0(t)\to f_{CP})+\Gamma(B^0(t)\to f_{CP})}=-\xi_f\sin 2\phi_1\sin\Delta m_B t$$



# Belle spectrometer at KEK-B



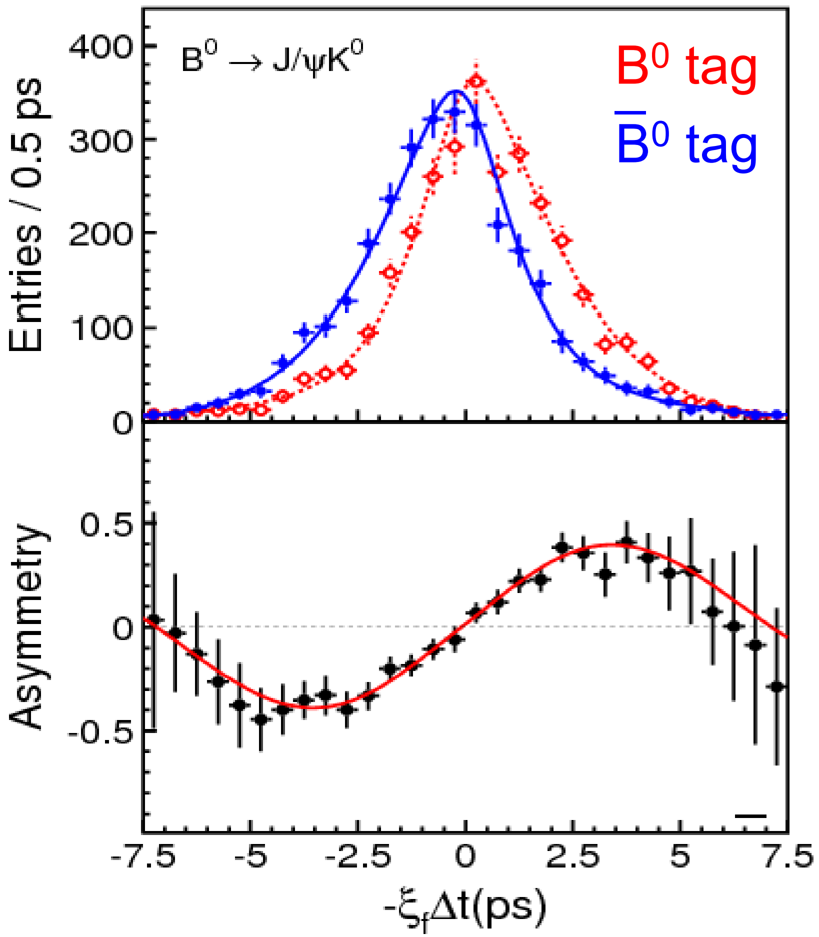

+ an extremely well operating KEK-B collider →

# CP violation in the B system

CP violation in B system: from the discovery (2001) to a precision measurement (2006)

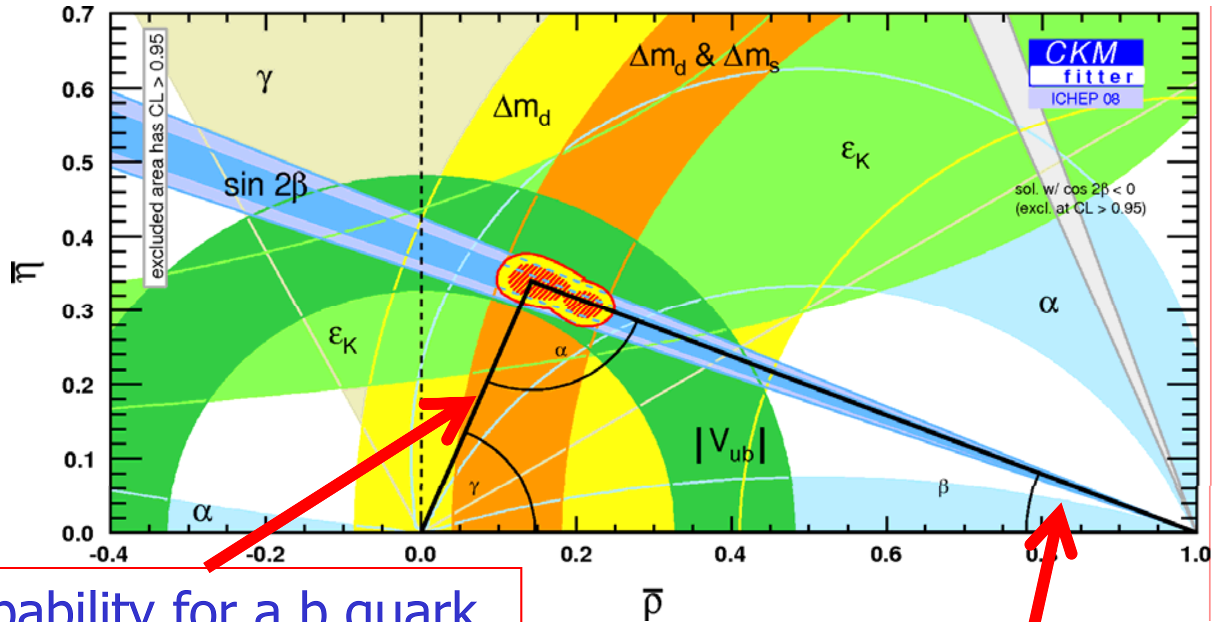
$\sin 2\phi_1/\sin 2\beta$ from $b \rightarrow ccs$

535 M $B\bar{B}$ pairs




**$\sin 2\phi_1$= 0.642 ±0.031 (stat) ±0.017 (syst)**

# All measurements combined...




Probability for a b quark to turn into a u quark → determines the length of the side **$V_{ub}$**

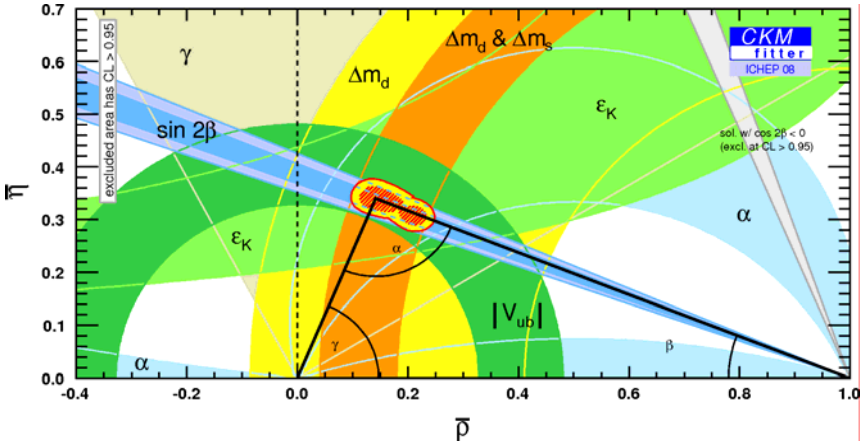
CP asymmetry oscillation amplitude → angle $\phi_1 = \beta$

Constraints from measurements of angles and sides of the unitarity triangle

→ Remarkable agreement

# Consistent picture

Relations between parameters as expected in the Standard model →





Nobel prize 2008!

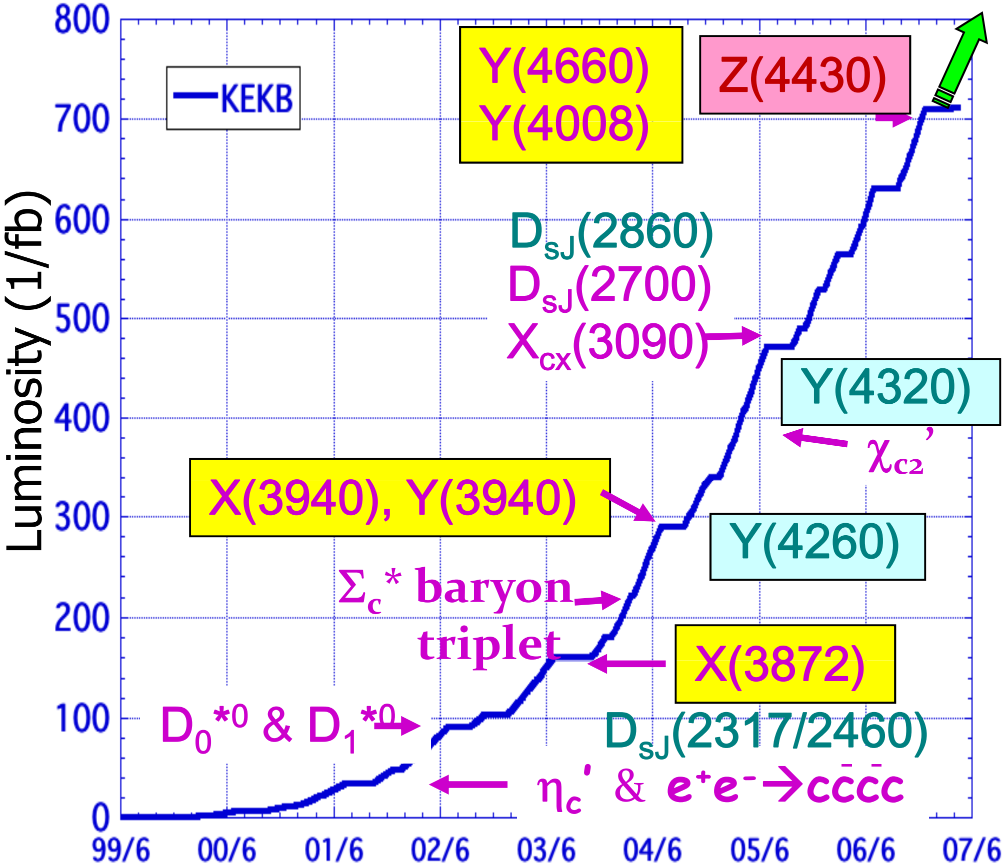
# Also for us a good reason to celebrate…

# B factories: a success story

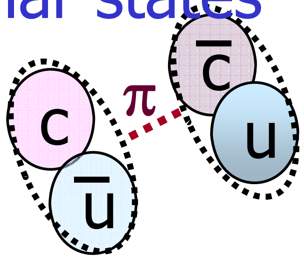
- Measurements of CKM matrix elements and angles of the unitarity triangle
- Observation of direct CP violation in B decays
- Measurements of rare decay modes (e.g., $B \to \tau\nu$, $D\tau\nu$)
- $b \to s$ transitions: probe for new sources of CPV and constraints from the $b \to s\gamma$ branching fraction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

# New hadrons at B-factories

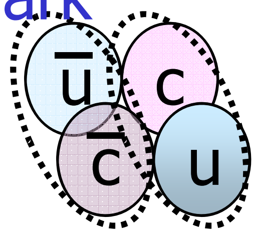
Discoveries of many new hadrons at B-factories have shed light on a new class of hadrons beyond the ordinary mesons.



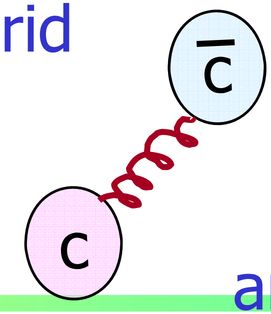

Molecular states




Tetra-quark

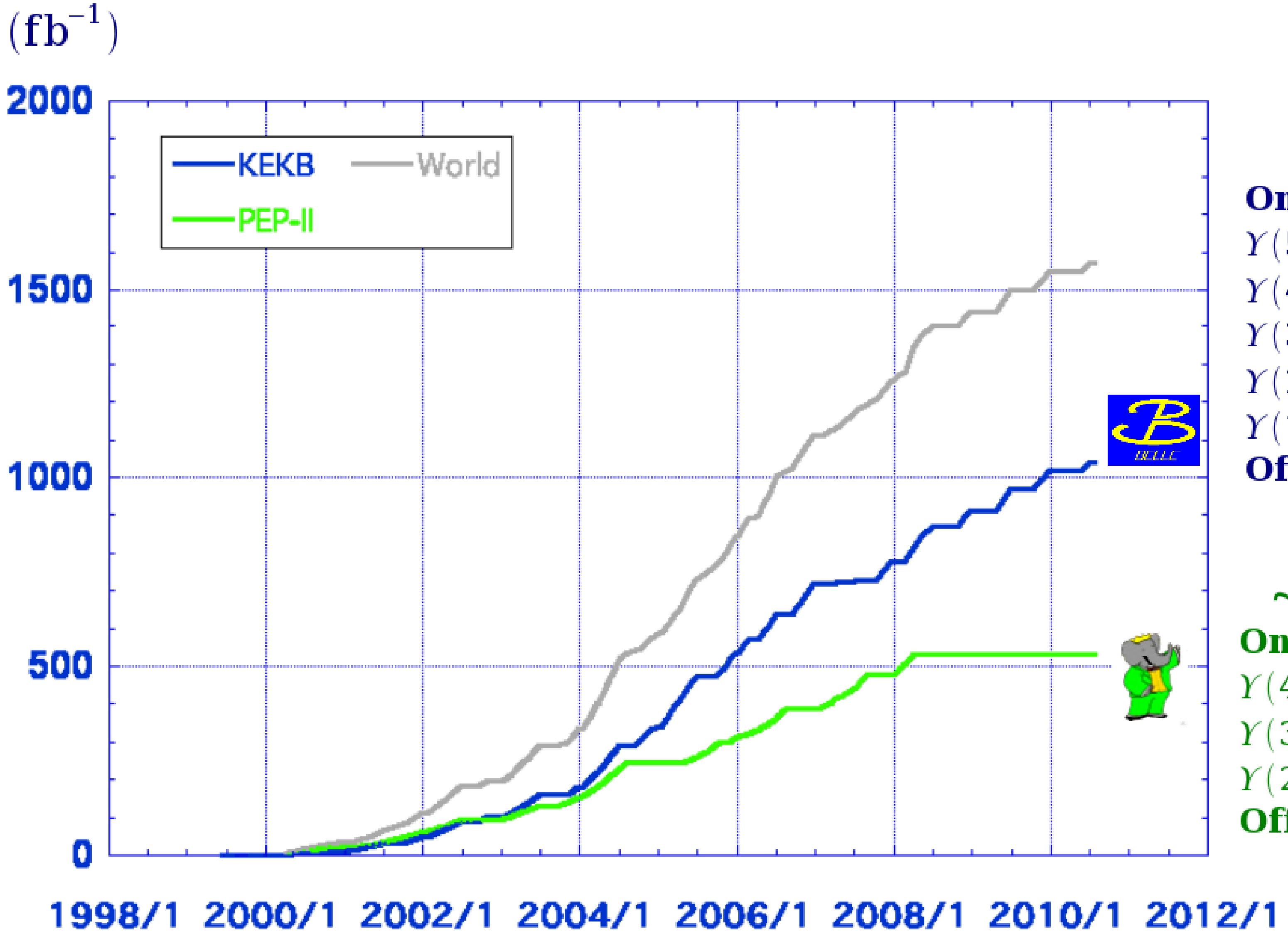



Hybrid




and more...

# Luminosity at B factories




**> 1 ab$^{-1}$**

**On resonance:**

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

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

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

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

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

**Off reson./scan:**

~ 100 fb$^{-1}$

**~ 550 fb$^{-1}$**

**On resonance:**

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

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

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

**Off resonance:**

~ 54 fb$^{-1}$

Fantastic performance much beyond design values!

# What next?

B factories → is SM with CKM right?

Next generation: Super B factories → in which way is the SM wrong?

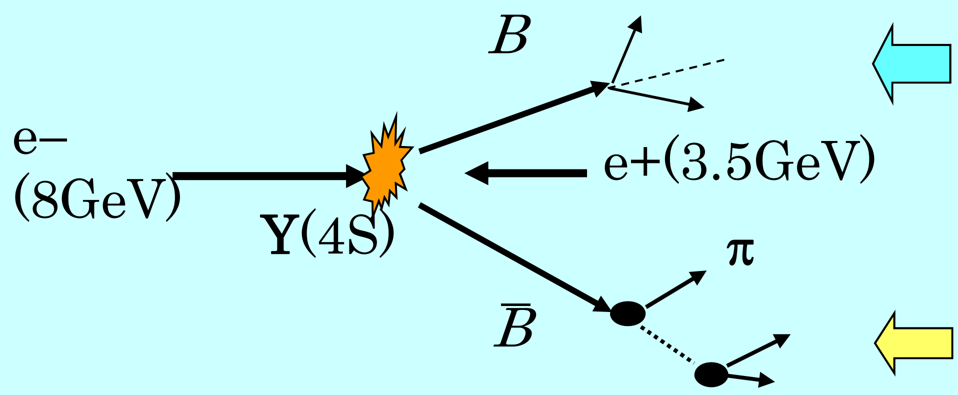
→ Need much more data (two orders!) because the SM worked so well until now → Super B factory

However: it will be a different world in four years, there will be serious competition from LHCb and BESIII

Still, $e^+e^-$ machines running at (or near) Υ(4s) will have considerable advantages in several classes of measurements, and will be complementary in many more

# 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
$B \rightarrow X_u\, l\, \nu$,
$B \rightarrow K\, \nu\, \nu$
$B \rightarrow D \tau \nu$, $\tau \nu$

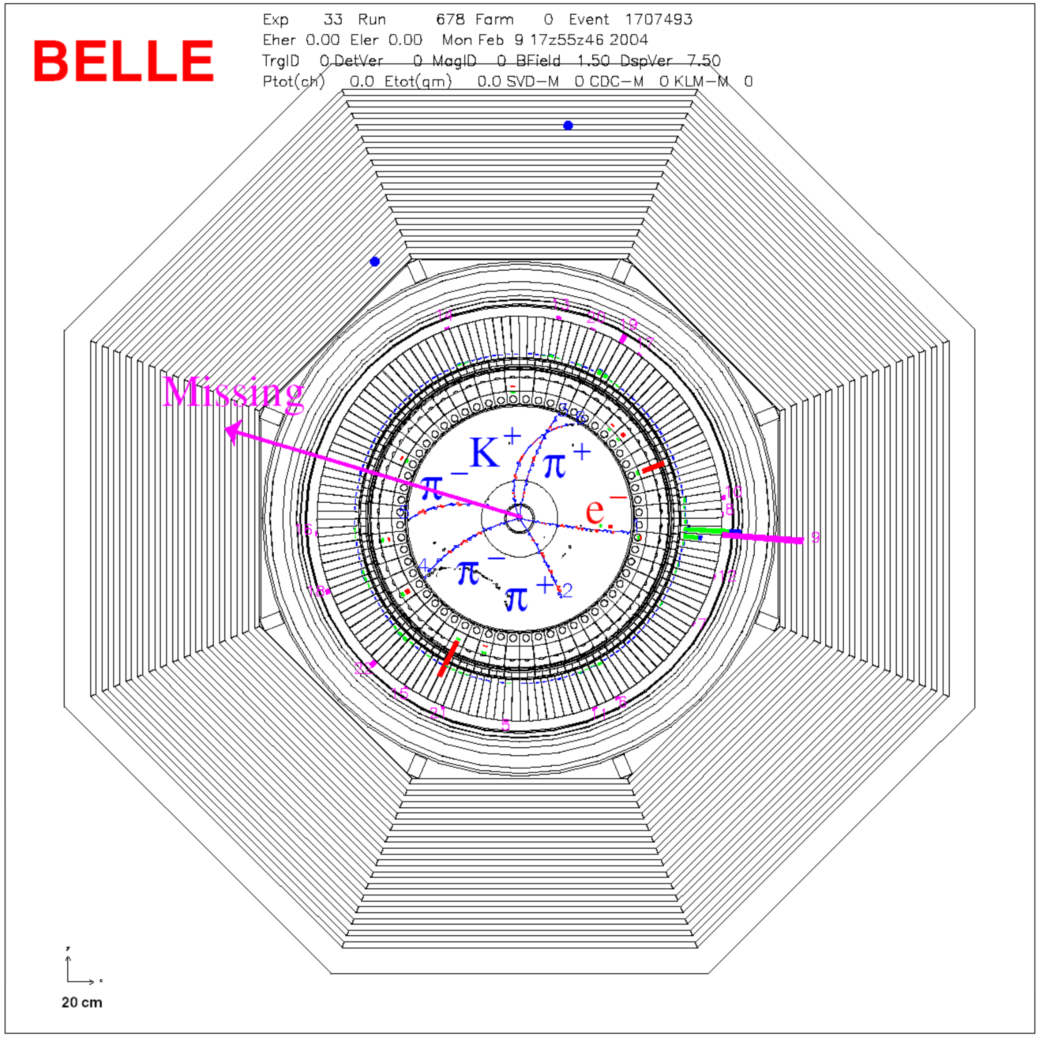
full reconstruction
$B \rightarrow D\pi$ etc. (0.1~0.3%)

→ Offline B meson beam!

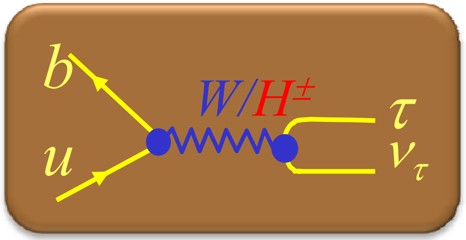
Powerful tool for B decays with neutrinos

# Event candidate $B^- \rightarrow \tau^- \nu_\tau$

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

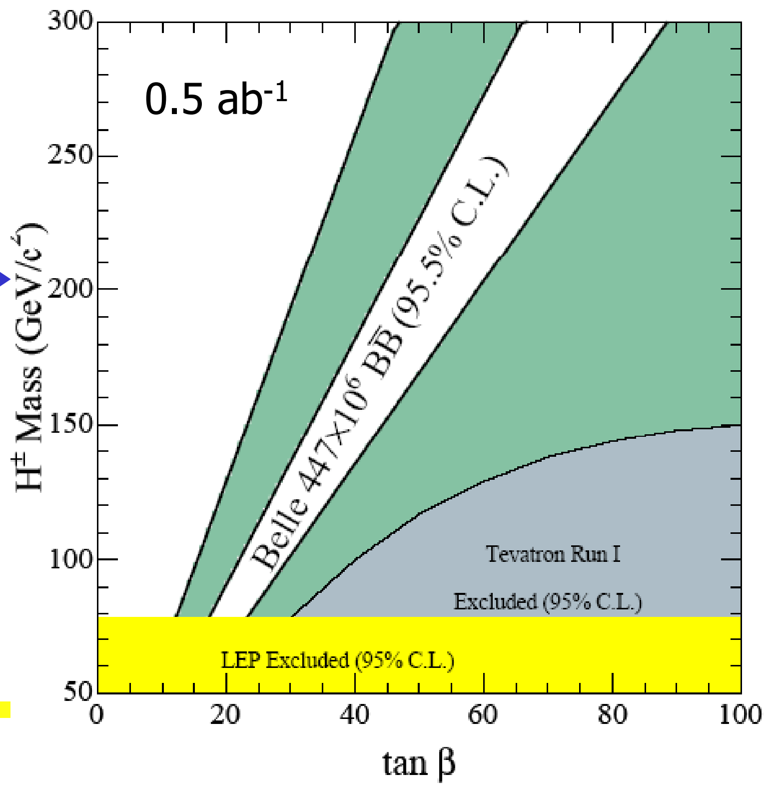


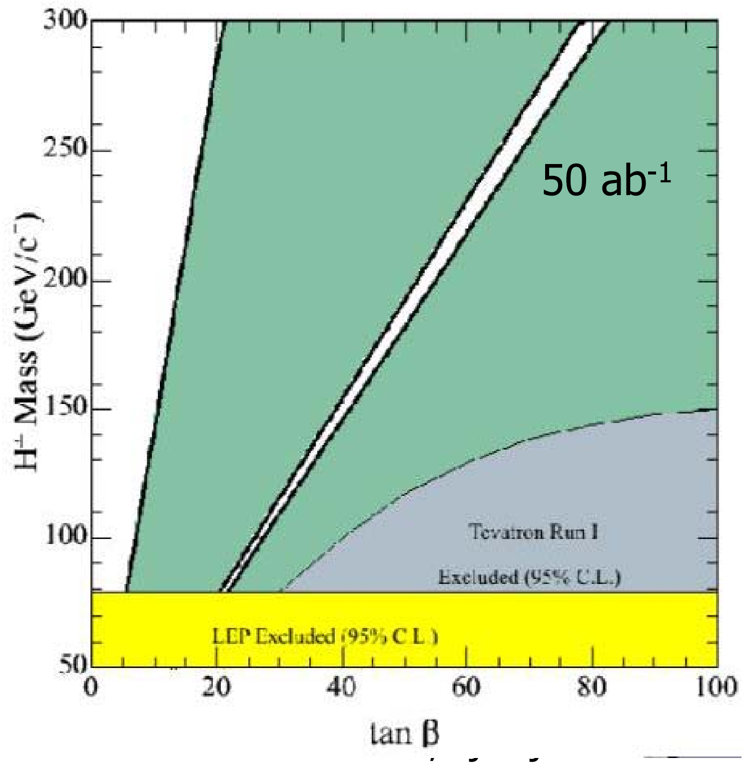
# Charged Higgs limits from $B^- \to \tau^- \nu_\tau$




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

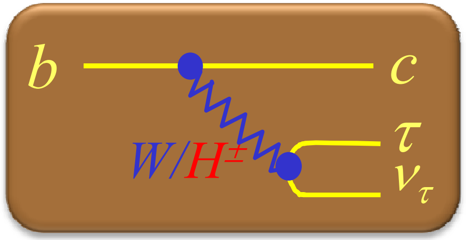
→ limit on charged Higgs mass vs. tanβ



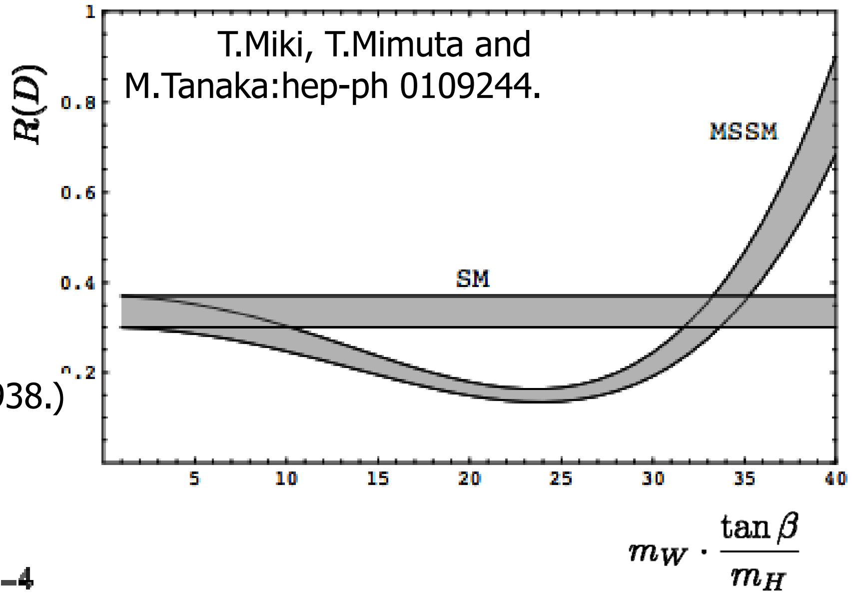
# $B \to D^{(*)}\tau\nu$

## Semileptonic decay sensitive to charged Higgs




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

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




Compared to $B \to \tau\nu$

1. Smaller theoretical uncertainty of R(D)

   ( For $B \to \tau\nu$,
   There is O(10%) $f_B$ uncertainty from lattice QCD )

2. Large expected Br (Ulrich Nierste arXiv:0801.4938.)

$$\mathcal{B}(B^- \to D^0\tau^-\bar{\nu}_\tau)^{SM} = (0.71 \pm 0.09)\%$$

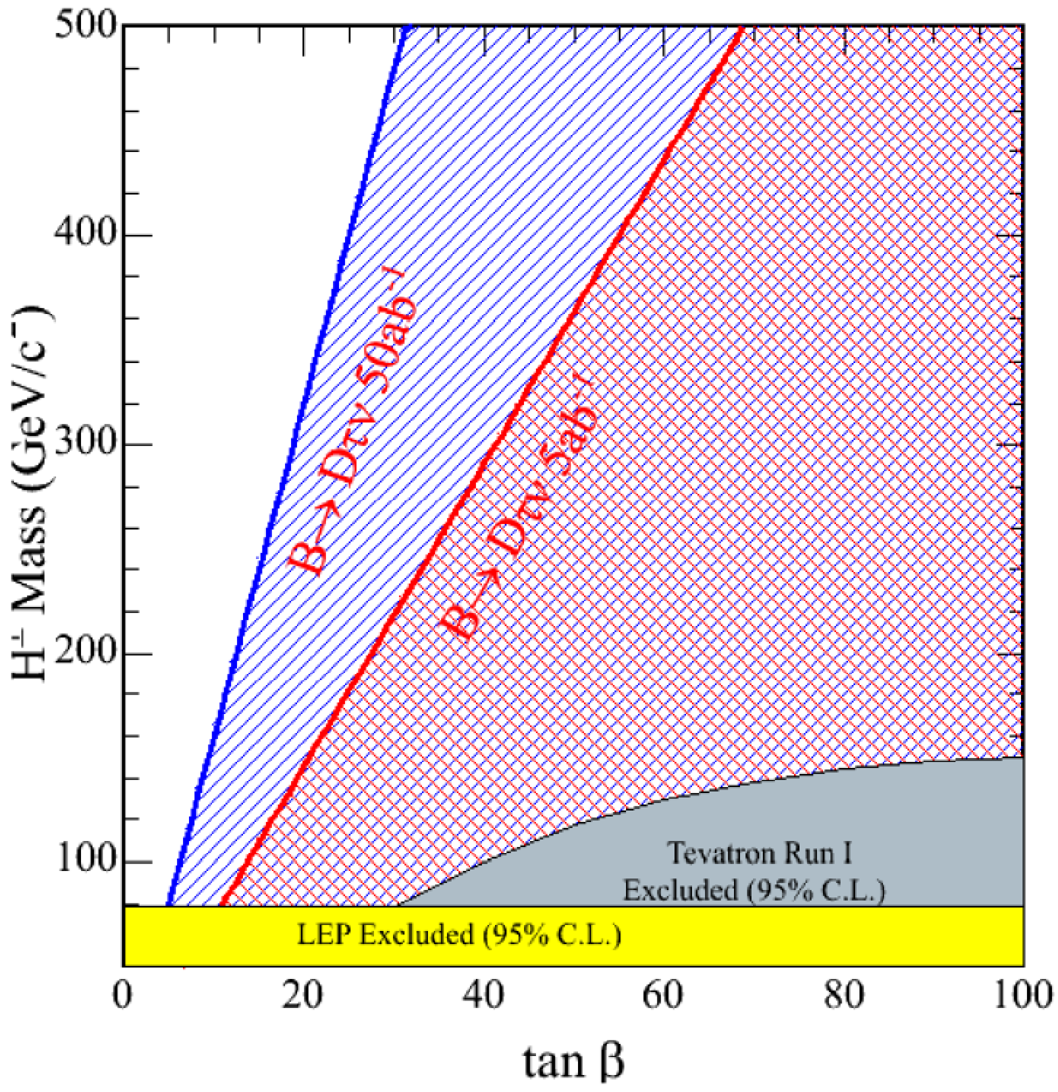
$$\mathcal{B}(\bar{B}^0 \to D^+\tau^-\bar{\nu}_\tau)^{SM} = (0.66 \pm 0.08)\%$$

$$\mathcal{B}(B \to \tau\nu) = [1.65^{+0.38}_{-0.37}(stat)^{+0.35}_{-0.37}(syst)] \times 10^{-4}$$

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)

# B→Dτν

Exclusion plots for
tanβ and $H^+$ mass
for 5ab$^{-1}$ and 50ab$^{-1}$



# $B \to D^* \tau \nu$ – similar constraints on $H^+$

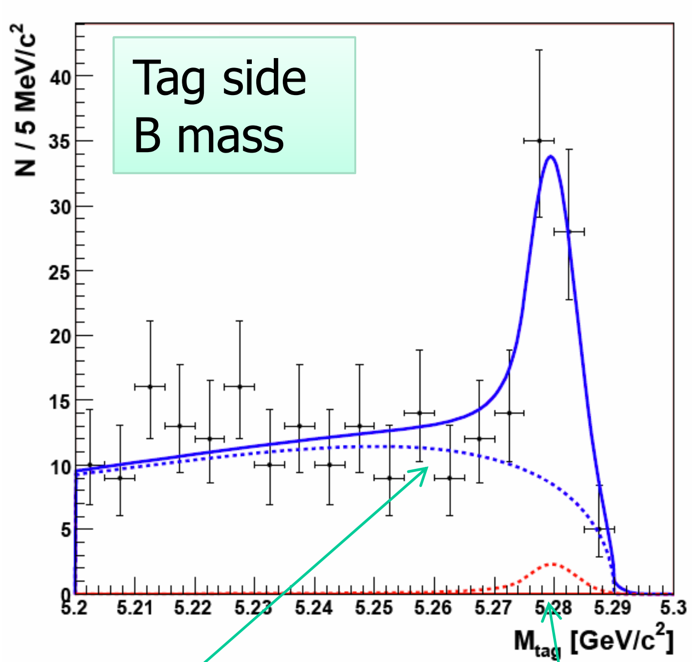
[PRL 99, 191807 (2007)]

535M $B\bar{B}$

**FIRST OBSERVATION - 2007**

$$BF(B^0 \to D^{*-}\tau^+\nu_\tau) = (2.02\,^{+0.40}_{-0.37}(stat) \pm 0.37(syst)) \times 10^{-2}$$

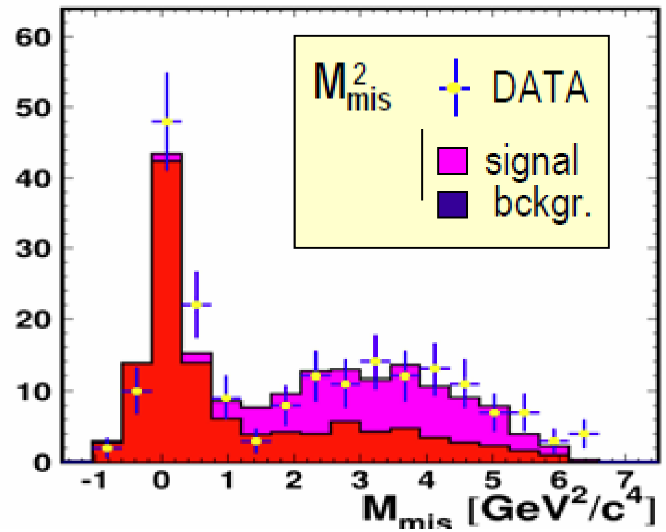
**SIGNAL YIELD** $N_s = 60\,^{+12}_{-11}$ **6.7σ (5.2σ with syst.)**




combinatorial background

peaking background ($D^{*}e\nu$)

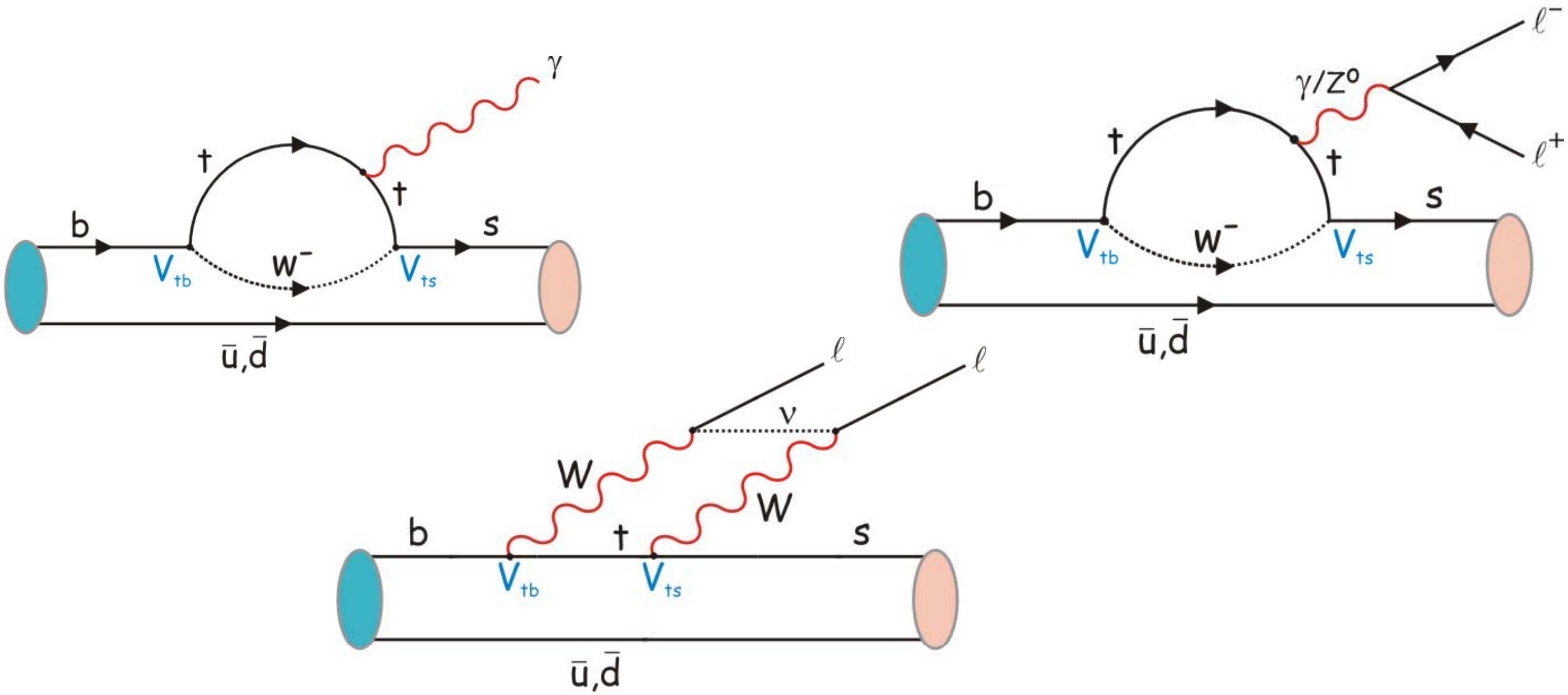
$$M^2_{mis} = (E_b - E_{D^{(*)}} - E_{l/h})^2 - (-\vec{p}_{tag} - \vec{p}_{D^{(*)}} - \vec{p}_{l/h})^2$$




Update soon!

# Search for new physics in FCNC decays

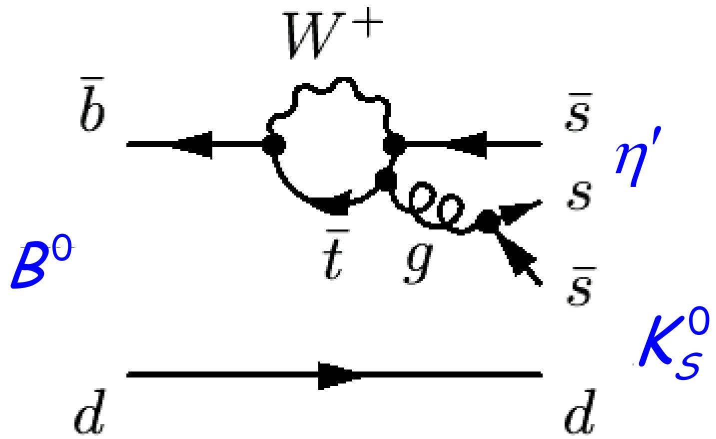
Flavour changing neutral current (FCNC) processes (like b→s, b→d) are fobidden at the tree level in the Standard Model. Proceed only at low rate via higher-order loop diagrams. Ideal place to search for new physics.



# How can New Physics contribute to b→s?

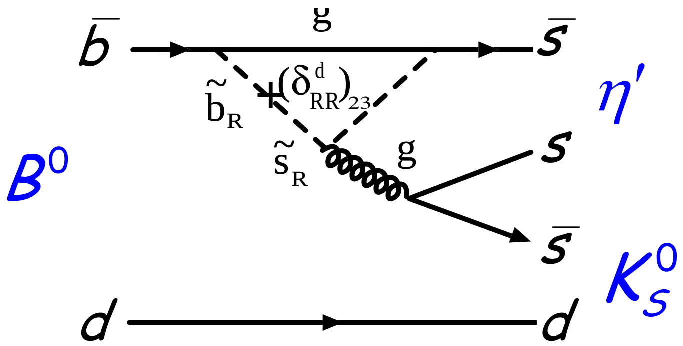
For example in the process:

$$B^0 \to \eta' K^0$$




Ordinary penguin diagram with a t quark in the loop

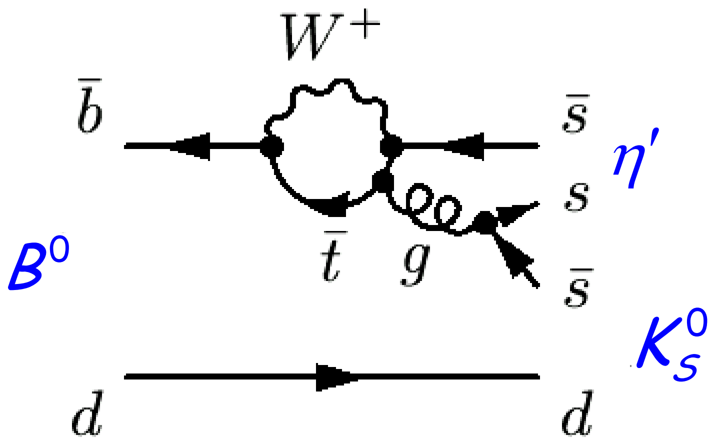
Diagram with supersymmetric particles



# Searching for new physics phases in CP violation measurements in b→s decays

Prediction in SM: CP violation parameter

$B^0 \to \eta' K^0$



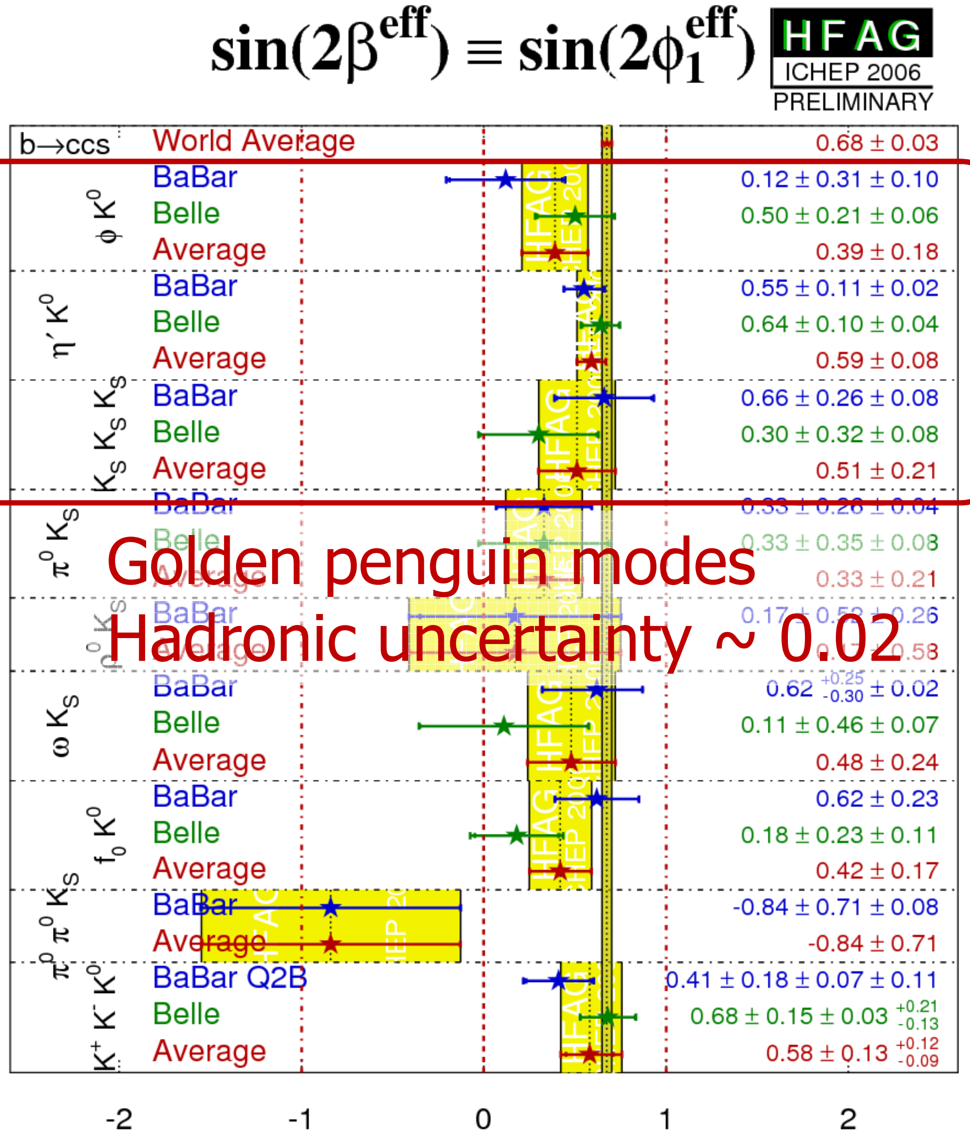

$$a_f = -\mathrm{Im}(\lambda_f)\sin(\Delta m t)$$

$$\mathrm{Im}(\lambda_f) = \xi_f \sin 2\phi_1$$

The same value as in the decay $B^0 \to J/\psi\, K_S$!

This is only true if there are no other particles in the loop! In general the parameter can assume a different value $\sin 2\phi_1^{\mathrm{eff}}$

# Search for NP: $b \to s\bar{q}$




Golden penguin modes

Hadronic uncertainty ~ 0.02

**ICHEP08**

BaBar
Belle
Naïve average

$0.26 \pm 0.25 \pm 0.04$
$0.67 \pm {}^{0.25}_{0.27} \pm 0.07$
$0.45 \pm 0.18$

$0.57 \pm 0.08 \pm 0.02$
$0.64 \pm 0.10 \pm 0.04$
$0.60 \pm 0.07$

$0.71 \pm 0.24 \pm 0.04$
$0.30 \pm 0.32 \pm 0.08$
$0.57 \pm 0.20$

Need much more data to clarify the issue

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

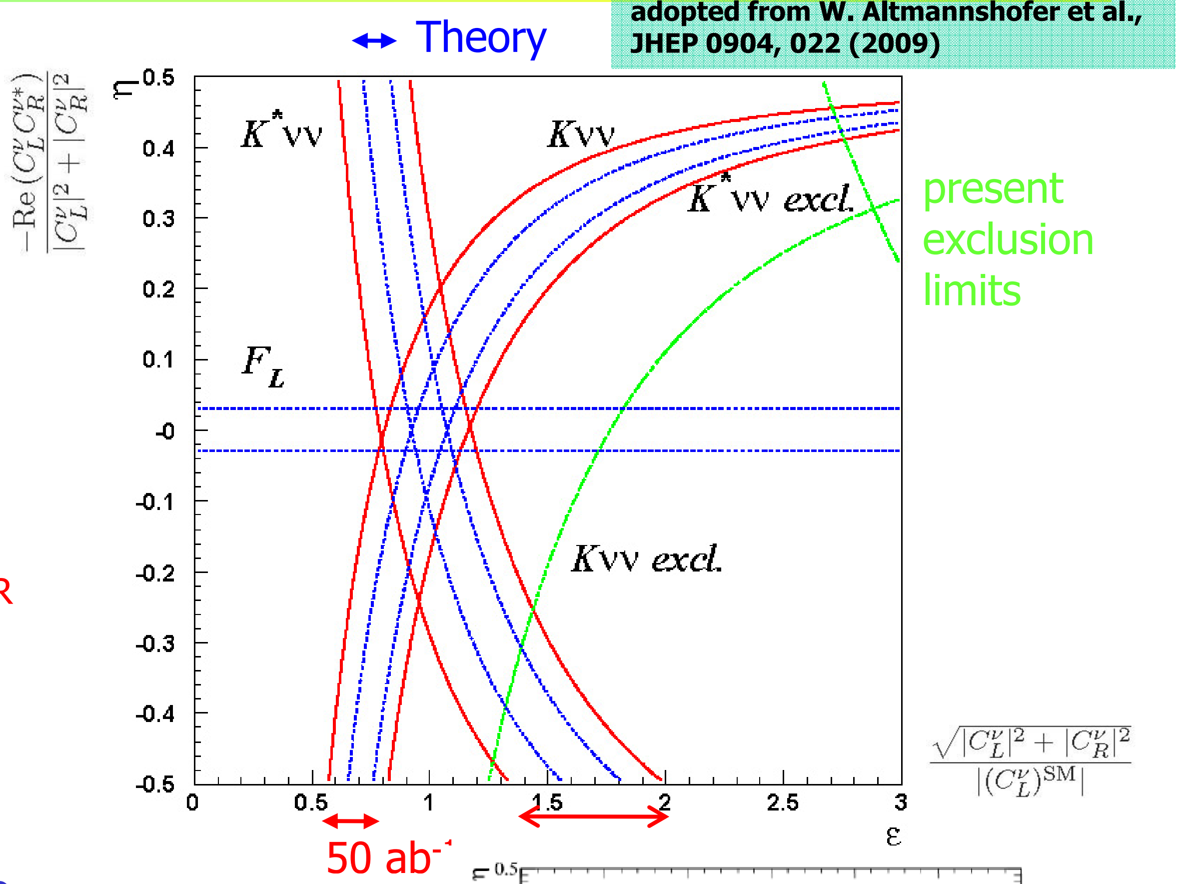
arXiv:1002.5012

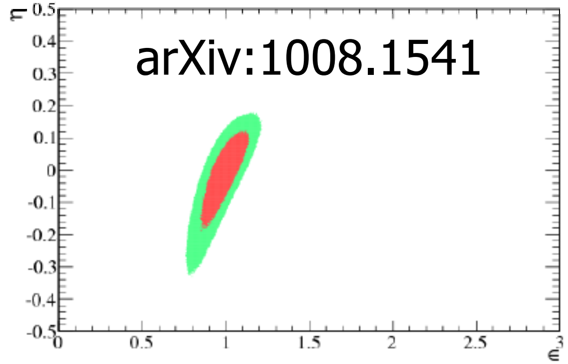
$B \to K\nu\nu$, $\mathcal{B} \sim 4 \cdot 10^{-6}$
$B \to K^*\nu\nu$, $\mathcal{B} \sim 6.8 \cdot 10^{-6}$

SM: penguin+box

Look for departure from the expected value → information on couplings $C^\nu_R$ and $C^\nu_L$ compared to $(C^\nu_L)^{SM}$

Again: fully reconstruct one of the B mesons, look for signal (+nothing else) in the rest of the event.



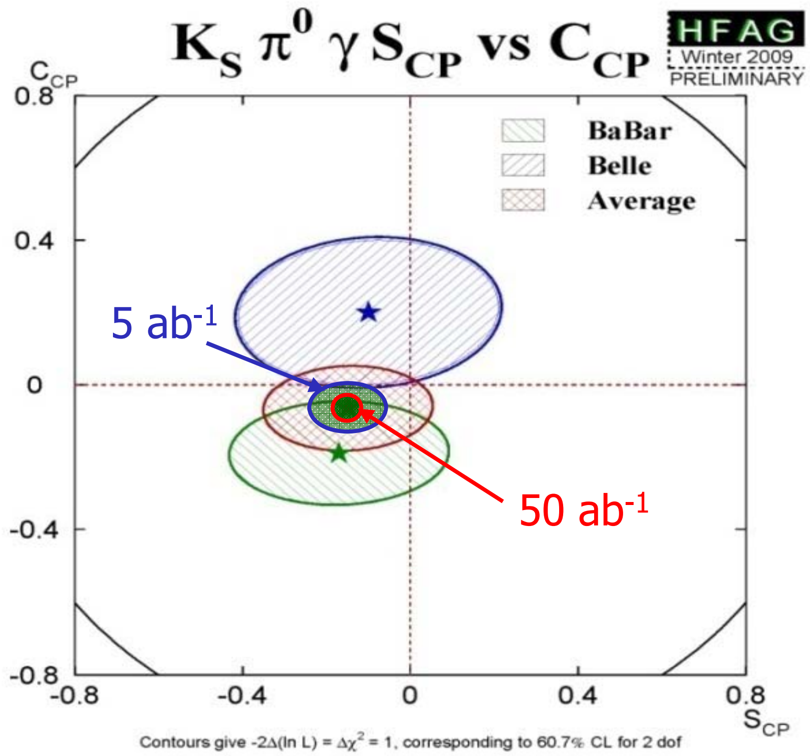

not possible @ LHCb

# CP violation in B→$K_S\pi^0\gamma$

CP violation in B→$K_S\pi^0\gamma$ decays:
Search for right-handed currents

$B \to K^*\gamma$, $\mathcal{B} \sim 4.0 \cdot 10^{-5}$

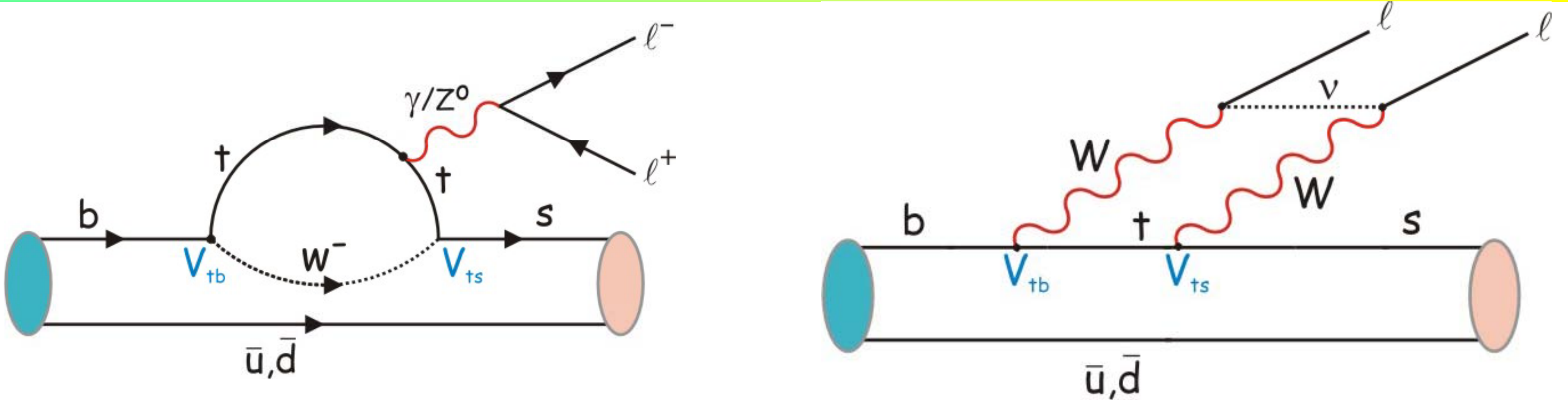
$\delta S \sim 0.2$ (present)
→ ~a few % at 50 $ab^{-1}$




adopted from HFAG

not possible @ LHCb

# Another FCNC decay: $B \rightarrow K^* l^+ l^-$




$b \rightarrow s\, l^+l^-$ was first measured in $B \rightarrow K\, l^+l^-$ by Belle (2001).

Important for further searches for the physics beyond SM

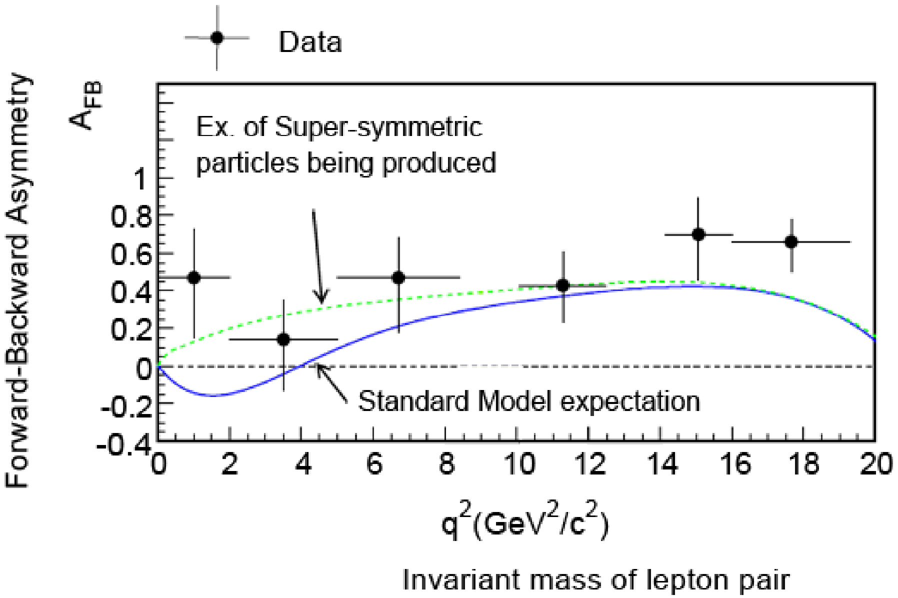
Particularly sensitive: backward-forward asymmetry in $K^* l^+l$

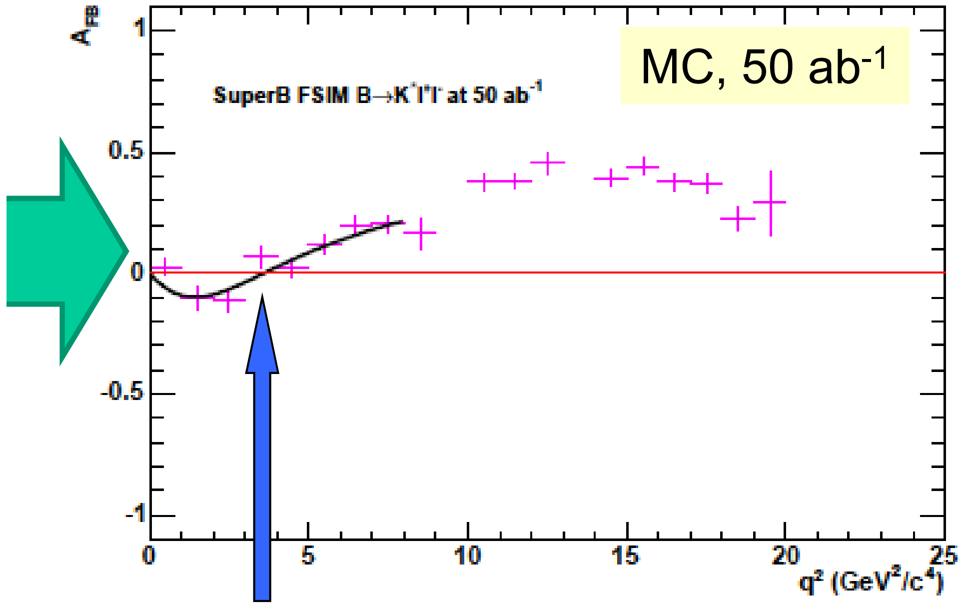
$$A_{FB} \propto \Re\left[ C_{10}^{*} \left( s C_9^{eff}(s) + r(s) C_7 \right) \right]$$

$C_i$ : Wilson coefficients, abs. value of $C_7$ from $b \rightarrow s\gamma$

s=lepton pair mass squared

# $A_{FB}(B \to K^* l^+ l^-)[q^2]$




Data: very interesting!

Zero-crossing $q^2$ for $A_{FB}$ will be determined with a 5% error with 50ab$^{-1}$.

Strong competition from LHCb and ATLAS/CMS

# A difference in the direct violation of CP symmetry in $B^+$ and $B^0$ decays


nature International weekly journal of science

nature Vol 452 | 20 March 2008 | doi:10.1038/nature06827

LETTERS

**Difference in direct charge-parity violation between charged and neutral *B* meson decays**

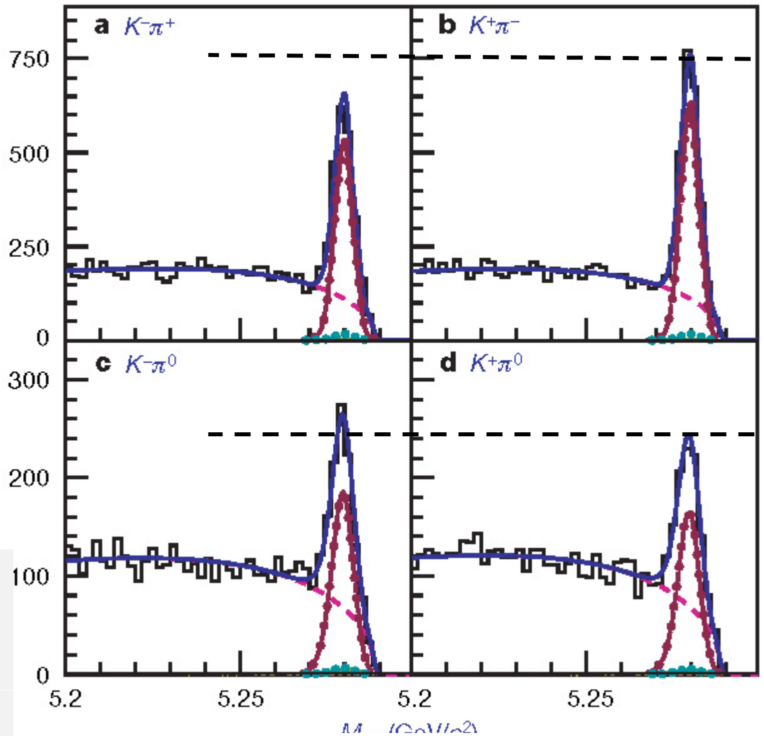
The Belle Collaboration*

## CP asymmetry

$$\mathcal{A}_f = \frac{N(\overline{B} \to \overline{f}) - N(B \to f)}{N(\overline{B} \to \overline{f}) + N(B \to f)}$$

## Difference between $B^+$ and $B^0$ decays

In SM expect $\mathcal{A}_{K^\pm\pi^\mp} \approx \mathcal{A}_{K^\pm\pi^0}$




Measure:

$$\mathcal{A}_{K^\pm\pi^\mp} = -0.094 \pm 0.018 \pm 0.008$$

$$\mathcal{A}_{K^\pm\pi^0} = +0.07 \pm 0.03 \pm 0.01$$

$$\Delta\mathcal{A} = +0.164 \pm 0.037$$

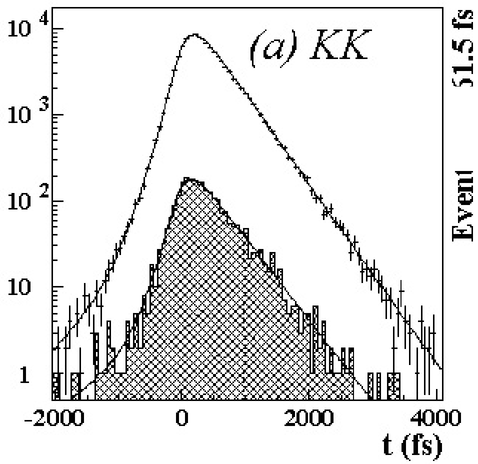
A problem for a SM explanation
(in particular when combined with other measurements)
A hint for new sources of CP violation?

~1 in $10^5$ B mesons decays in this decay mode

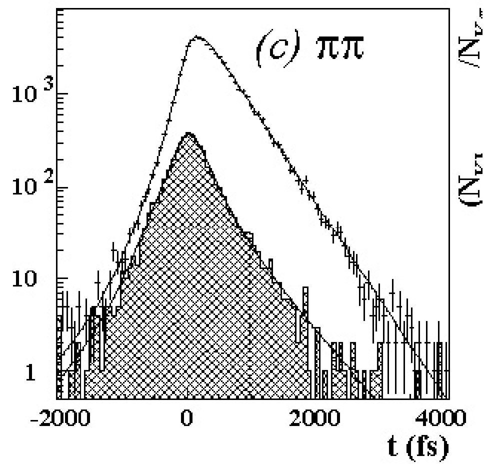
Belle, Nature 452, 332 (2008)

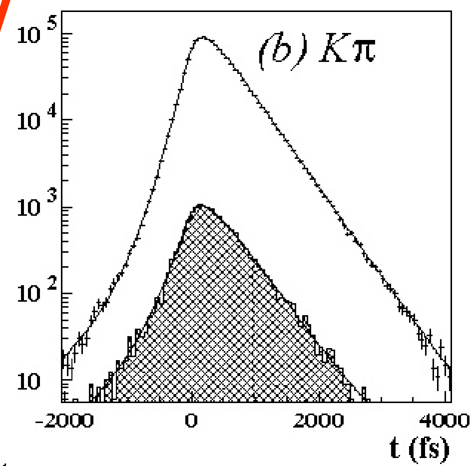
# $D^0$ mixing in $K^+K^-$, $\pi^+\pi^-$

Decay time distributions for KK, ππ, Kπ

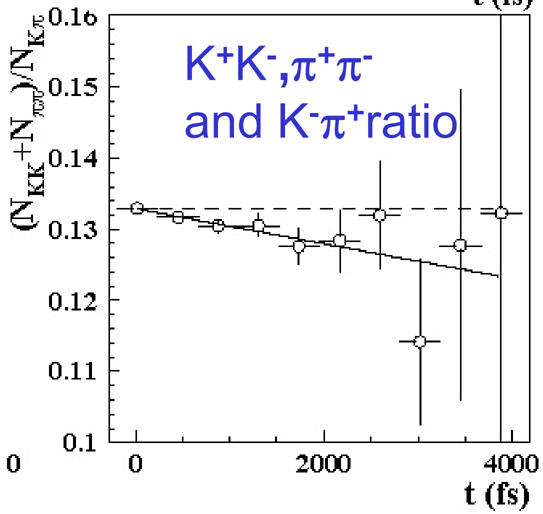



+




Difference of lifetimes visually observable in the ratio of the distributions →




Real fit:

$$y_{CP} = (1.31 \pm 0.32 \pm 0.25)\ \%$$

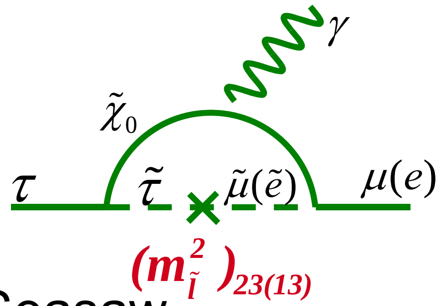
→ Observation of D mixing!

→ on a high side of SM predictions

CP violation in the D system would be a clear sign of new physics

# LFV and New Physics

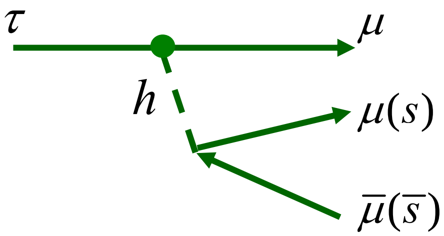
## $\tau \to l\gamma$




- SUSY + Seasaw
- Large LFV $Br(\tau \to \mu\gamma) = O(10^{-7\sim9})$

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

## $\tau \to 3l, l\eta$



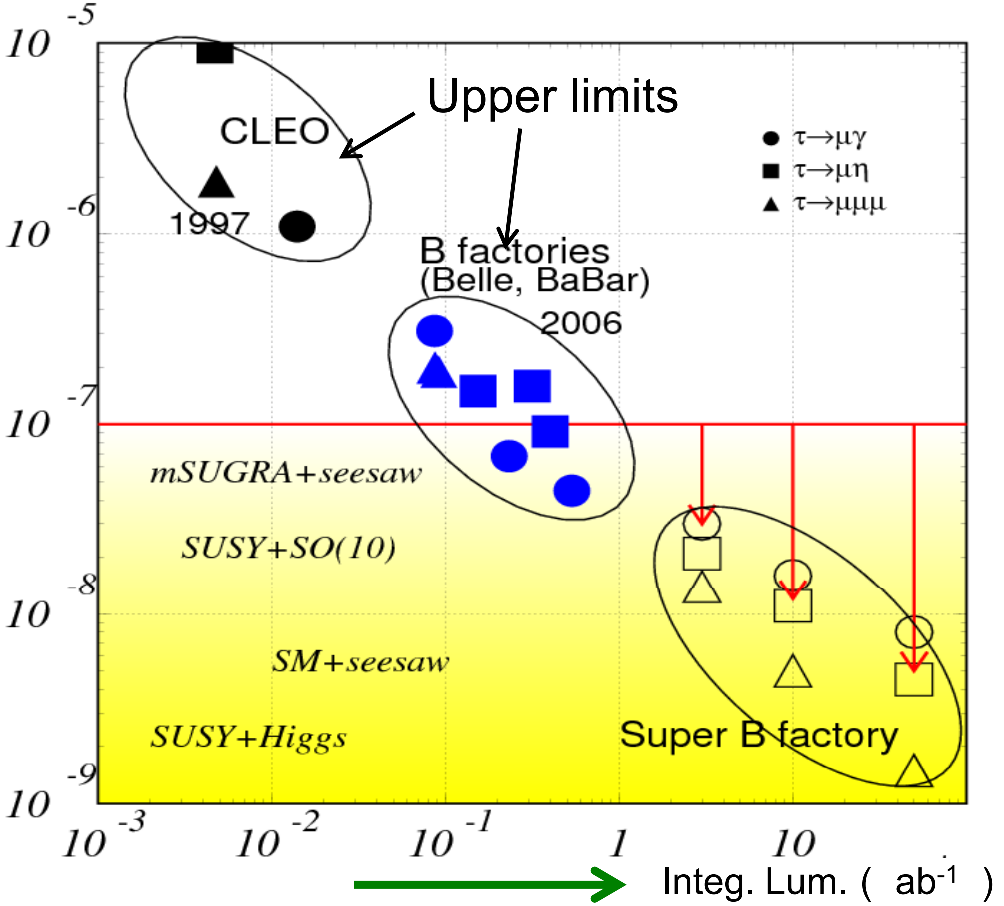

- Neutral Higgs mediated decay.
- Important when MSUSY >> EW scale.

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

| model | Br($\tau \to \mu\gamma$) | Br($\tau \to lll$ ) |
|---|---|---|
| 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 | $10^{-10}$ | $10^{-7}$ |

# Rare τ decays

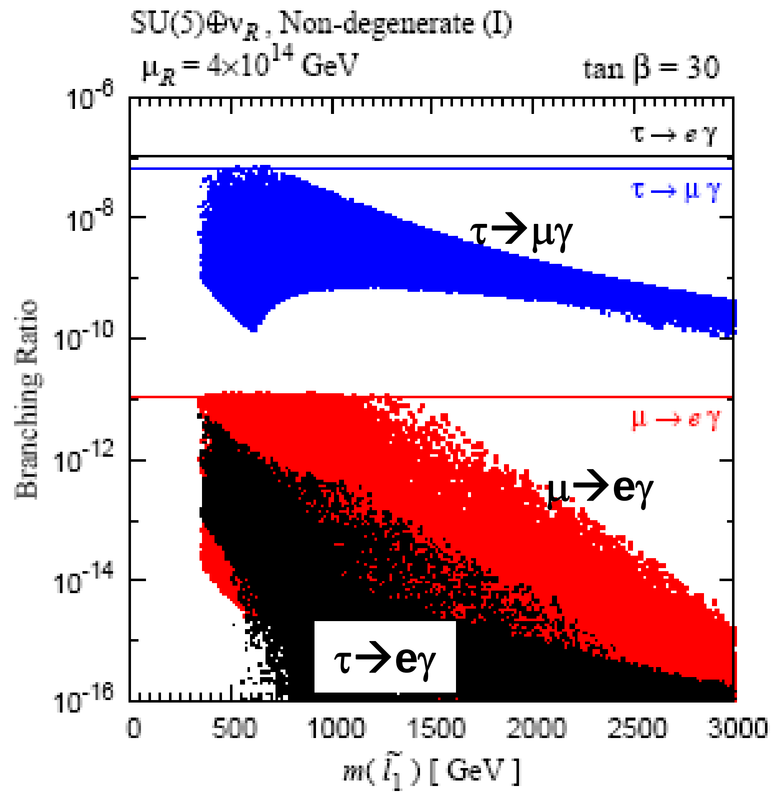
## LF violating τ decay?




**Reach of B factories**

**Super B factories**

Theoretical predictions compared to present experimental limits




T.Goto et al., 2007

## B Physics @ Y(4S)

| Observable | $B$ Factories ($2\ ab^{-1}$) | Super$B$ ($75\ ab^{-1}$) |
|---|---|---|
| $\sin(2\beta)$ ($J/\psi K^0$) | 0.018 | 0.005 (†) |
| $\cos(2\beta)$ ($J/\psi K^{*0}$) | 0.30 | 0.05 |
| $\sin(2\beta)$ ($Dh^0$) | 0.10 | 0.02 |
| $\cos(2\beta)$ ($Dh^0$) | 0.20 | 0.04 |
| $S(J/\psi \pi^0)$ | 0.10 | 0.02 |
| $S(D^+D^-)$ | 0.20 | 0.03 |
| $S(\phi K^0)$ | 0.13 | 0.02 (∗) |
| $S(\eta' K^0)$ | 0.05 | 0.01 (∗) |
| $S(K_S^0 K_S^0 K_S^0)$ | 0.15 | 0.02 (∗) |
| $S(K_S^0 \pi^0)$ | 0.15 | 0.02 (∗) |
| $S(\omega K_S^0)$ | 0.17 | 0.03 (∗) |
| $S(f_0 K_S^0)$ | 0.12 | 0.02 (∗) |
| $\gamma$ ($B \to DK$, $D \to CP$ eigenstates) | $\sim 15°$ | 2.5° |
| $\gamma$ ($B \to DK$, $D \to$ suppressed states) | $\sim 12°$ | 2.0° |
| $\gamma$ ($B \to DK$, $D \to$ multibody states) | $\sim 9°$ | 1.5° |
| $\gamma$ ($B \to DK$, combined) | $\sim 6°$ | 1–2° |
| $\alpha$ ($B \to \pi\pi$) | $\sim 16°$ | 3° |
| $\alpha$ ($B \to \rho\rho$) | $\sim 7°$ | 1–2° (∗) |
| $\alpha$ ($B \to \rho\pi$) | $\sim 12°$ | 2° |
| $\alpha$ (combined) | $\sim 6°$ | 1–2° (∗) |
| $2\beta+\gamma$ ($D^{(*)\pm}\pi^\mp$, $D^\pm K_S^0 \pi^\mp$) | 20° | 5° |

| Observable | $B$ Factories ($2\ ab^{-1}$) | Super$B$ ($75\ ab^{-1}$) |
|---|---|---|
| $\vert V_{cb}\vert$ (exclusive) | 4% (∗) | 1.0% (∗) |
| $\vert V_{cb}\vert$ (inclusive) | 1% (∗) | 0.5% (∗) |
| $\vert V_{ub}\vert$ (exclusive) | 8% (∗) | 3.0% (∗) |
| $\vert V_{ub}\vert$ (inclusive) | 8% (∗) | 2.0% (∗) |
| $\mathcal{B}(B \to \tau\nu)$ | 20% | 4% (†) |
| $\mathcal{B}(B \to \mu\nu)$ | visible | 5% |
| $\mathcal{B}(B \to D\tau\nu)$ | 10% | 2% |
| $\mathcal{B}(B \to \rho\gamma)$ | 15% | 3% (†) |
| $\mathcal{B}(B \to \omega\gamma)$ | 30% | 5% |
| $A_{CP}(B \to K^*\gamma)$ | 0.007 (†) | 0.004 († ∗) |
| $A_{CP}(B \to \rho\gamma)$ | $\sim 0.20$ | 0.05 |
| $A_{CP}(b \to s\gamma)$ | 0.012 (†) | 0.004 (†) |
| $A_{CP}(b \to (s+d)\gamma)$ | 0.03 | 0.006 (†) |
| $S(K_S^0 \pi^0 \gamma)$ | 0.15 | 0.02 (∗) |
| $S(\rho^0 \gamma)$ | possible | 0.10 |
| $A_{CP}(B \to K^*\ell\ell)$ | 7% | 1% |
| $A^{FB}(B \to K^*\ell\ell)s_0$ | 25% | 9% |
| $A^{FB}(B \to X_s\ell\ell)s_0$ | 35% | 5% |
| $\mathcal{B}(B \to K\nu\bar{\nu})$ | visible | 20% |
| $\mathcal{B}(B \to \pi\nu\bar{\nu})$ | – | possible |

## Charm mixing and CP

| Mode | Observable | $\Upsilon(4S)$ ($75\ ab^{-1}$) | $\psi(3770)$ ($300\ fb^{-1}$) |
|---|---|---|---|
| $D^0 \to K^+\pi^-$ | $x'^2$ | $3 \times 10^{-5}$ | |
| | $y'$ | $7 \times 10^{-4}$ | |
| $D^0 \to K^+K^-$ | $y_{CP}$ | $5 \times 10^{-4}$ | |
| $D^0 \to K_S^0\pi^+\pi^-$ | $x$ | $4.9 \times 10^{-4}$ | |
| | $y$ | $3.5 \times 10^{-4}$ | |
| | $\vert q/p\vert$ | $3 \times 10^{-2}$ | |
| | $\phi$ | $2°$ | |
| $\psi(3770) \to D^0\overline{D}^0$ | $x^2$ | | $(1-2) \times 10^{-5}$ |
| | $y$ | | $(1-2) \times 10^{-3}$ |
| | $\cos\delta$ | | $(0.01-0.02)$ |

## Charm FCNC

| | Sensitivity |
|---|---|
| $D^0 \to e^+e^-$, $D^0 \to \mu^+\mu^-$ | $1 \times 10^{-8}$ |
| $D^0 \to \pi^0 e^+e^-$, $D^0 \to \pi^0\mu^+\mu^-$ | $2 \times 10^{-8}$ |
| $D^0 \to \eta e^+e^-$, $D^0 \to \eta\mu^+\mu^-$ | $3 \times 10^{-8}$ |
| $D^0 \to K_S^0 e^+e^-$, $D^0 \to K_S^0\mu^+\mu^-$ | $3 \times 10^{-8}$ |
| $D^+ \to \pi^+e^+e^-$, $D^+ \to \pi^+\mu^+\mu^-$ | $1 \times 10^{-8}$ |
| $D^0 \to e^\pm\mu^\mp$ | $1 \times 10^{-8}$ |
| $D^+ \to \pi^+e^\pm\mu^\mp$ | $1 \times 10^{-8}$ |
| $D^0 \to \pi^0 e^\pm\mu^\mp$ | $2 \times 10^{-8}$ |
| $D^0 \to \eta e^\pm\mu^\mp$ | $3 \times 10^{-8}$ |
| $D^0 \to K_S^0 e^\pm\mu^\mp$ | $3 \times 10^{-8}$ |
| $D^+ \to \pi^-e^+e^+$, $D^+ \to K^-e^+e^+$ | $1 \times 10^{-8}$ |
| $D^+ \to \pi^-\mu^+\mu^+$, $D^+ \to K^-\mu^+\mu^+$ | $1 \times 10^{-8}$ |
| $D^+ \to \pi^-e^\pm\mu^\mp$, $D^+ \to K^-e^\pm\mu^\mp$ | $1 \times 10^{-8}$ |

## τ Physics

| | Sensitivity |
|---|---|
| $\mathcal{B}(\tau \to \mu\gamma)$ | $2 \times 10^{-9}$ |
| $\mathcal{B}(\tau \to e\gamma)$ | $2 \times 10^{-9}$ |
| $\mathcal{B}(\tau \to \mu\mu\mu)$ | $2 \times 10^{-10}$ |
| $\mathcal{B}(\tau \to eee)$ | $2 \times 10^{-10}$ |
| $\mathcal{B}(\tau \to \mu\eta)$ | $4 \times 10^{-10}$ |
| $\mathcal{B}(\tau \to e\eta)$ | $6 \times 10^{-10}$ |
| $\mathcal{B}(\tau \to \ell K_S^0)$ | $2 \times 10^{-10}$ |

## $B_s$ Physics @ Y(5S)

| Observable | Error with $1\ ab^{-1}$ | Error with $30\ ab^{-1}$ |
|---|---|---|
| $\Delta\Gamma$ | $0.16\ ps^{-1}$ | $0.03\ ps^{-1}$ |
| $\Gamma$ | $0.07\ ps^{-1}$ | $0.01\ ps^{-1}$ |
| $\beta_s$ from angular analysis | 20° | 8° |
| $A_{SL}^s$ | 0.006 | 0.004 |
| $A_{CH}$ | 0.004 | 0.004 |
| $\mathcal{B}(B_s \to \mu^+\mu^-)$ | - | $< 8 \times 10^{-9}$ |
| $\vert V_{td}/V_{ts}\vert$ | 0.08 | 0.017 |
| $\mathcal{B}(B_s \to \gamma\gamma)$ | 38% | 7% |
| $\beta_s$ from $J/\psi\phi$ | 10° | 3° |
| $\beta_s$ from $B_s \to K^0\bar{K}^0$ | 24° | 11° |

M. Giorgi, ICHEP2010

# Physics at a Super B Factory

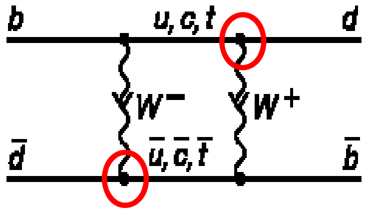
- There is a good chance to see new phenomena;
  - **CPV in B decays from the new physics (non KM).**
  - **Lepton flavor violations in $\tau$ decays.**
- They will help to diagnose (if found) or constrain (if not found) new physics models.
- $B \rightarrow \tau\nu$, $D\tau\nu$ can probe the charged 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).

There are many more topics: CPV in charm, new hadrons, …

# 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



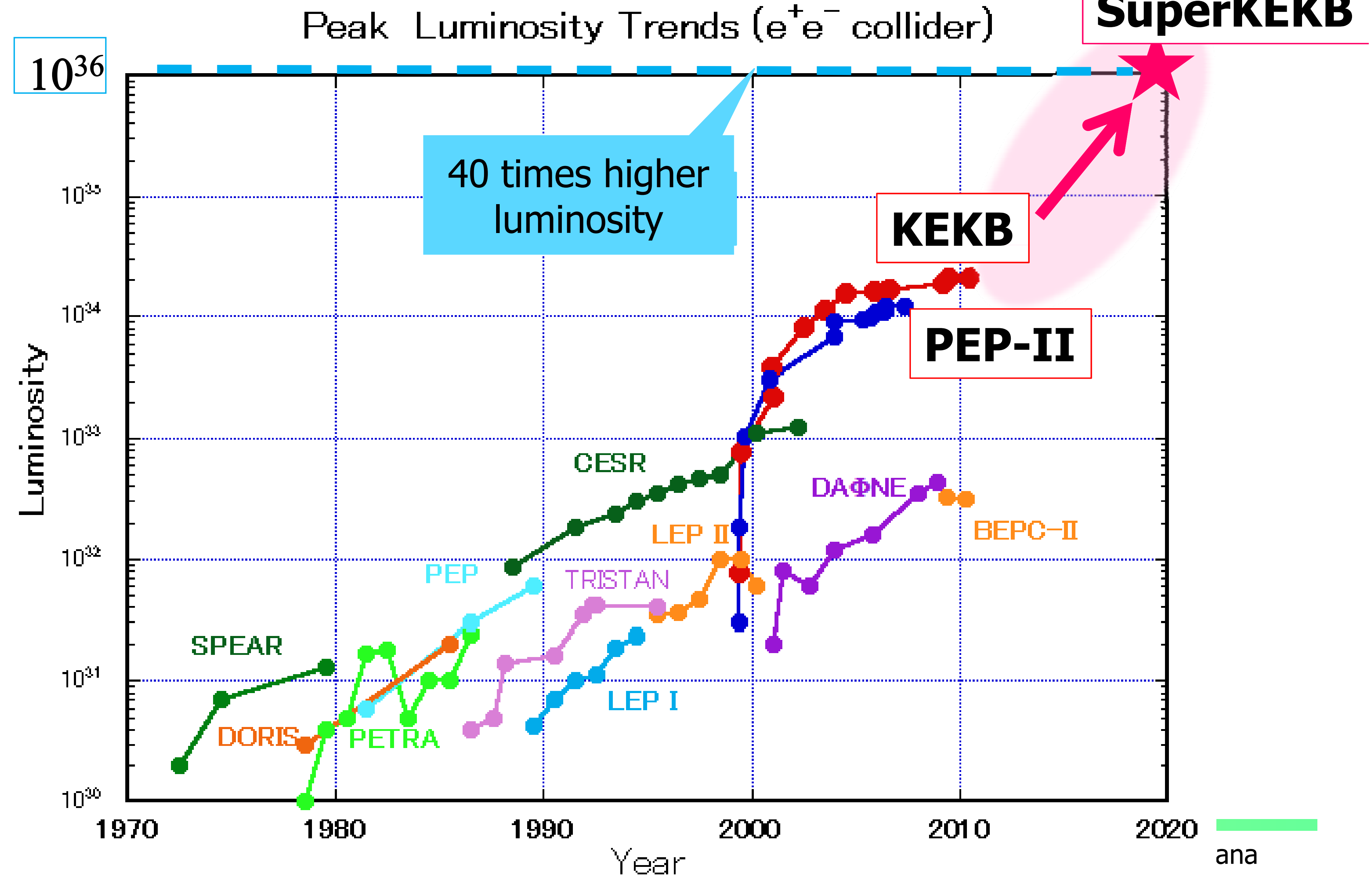

$$V_{CKM}=\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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

Recent update of the physics reach with 50 $ab^{-1}$:
Physics at Super B Factory (Belle II authors + guests)
hep-ex > arXiv:1002.5012

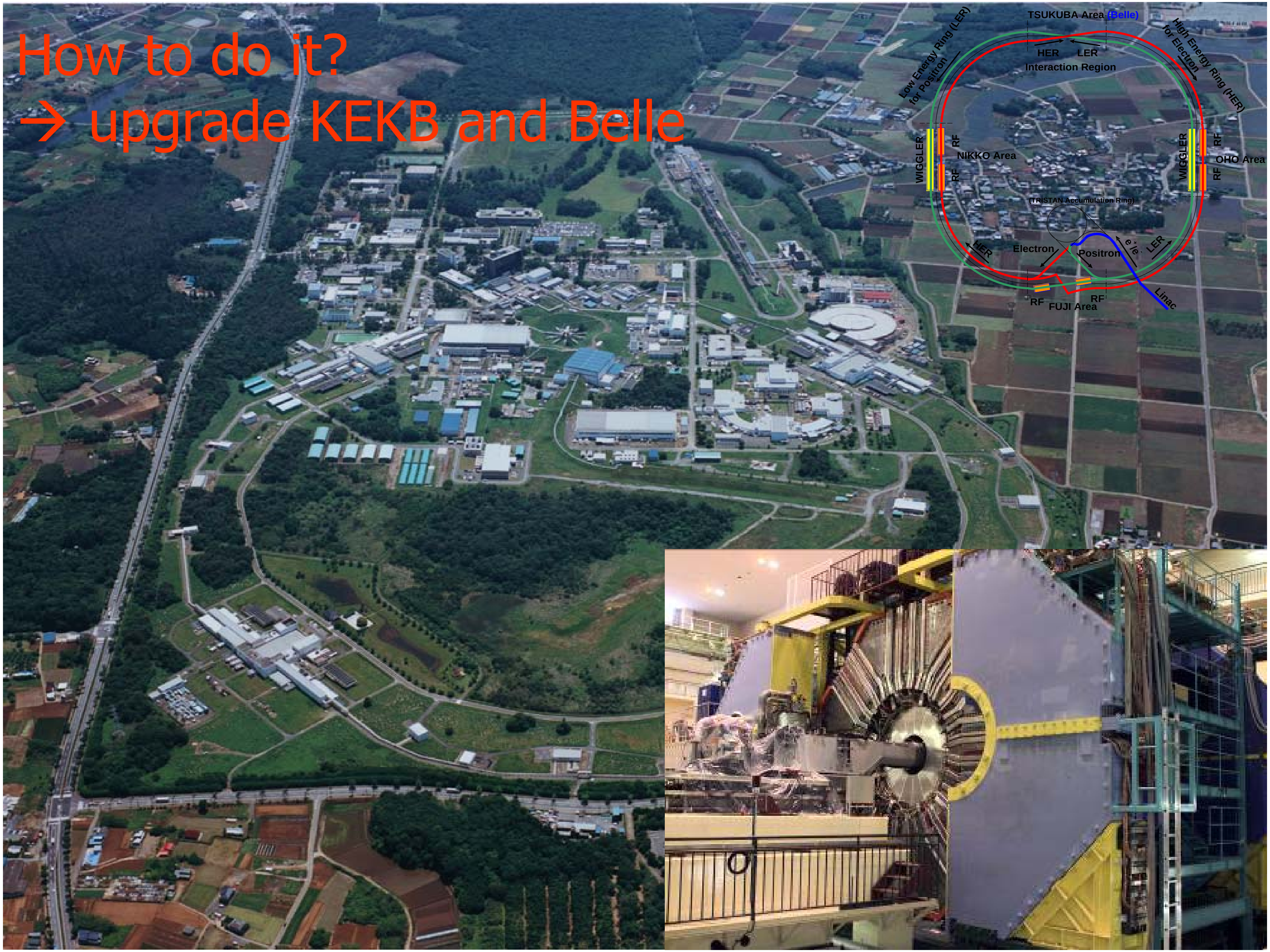
# Accelerator

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

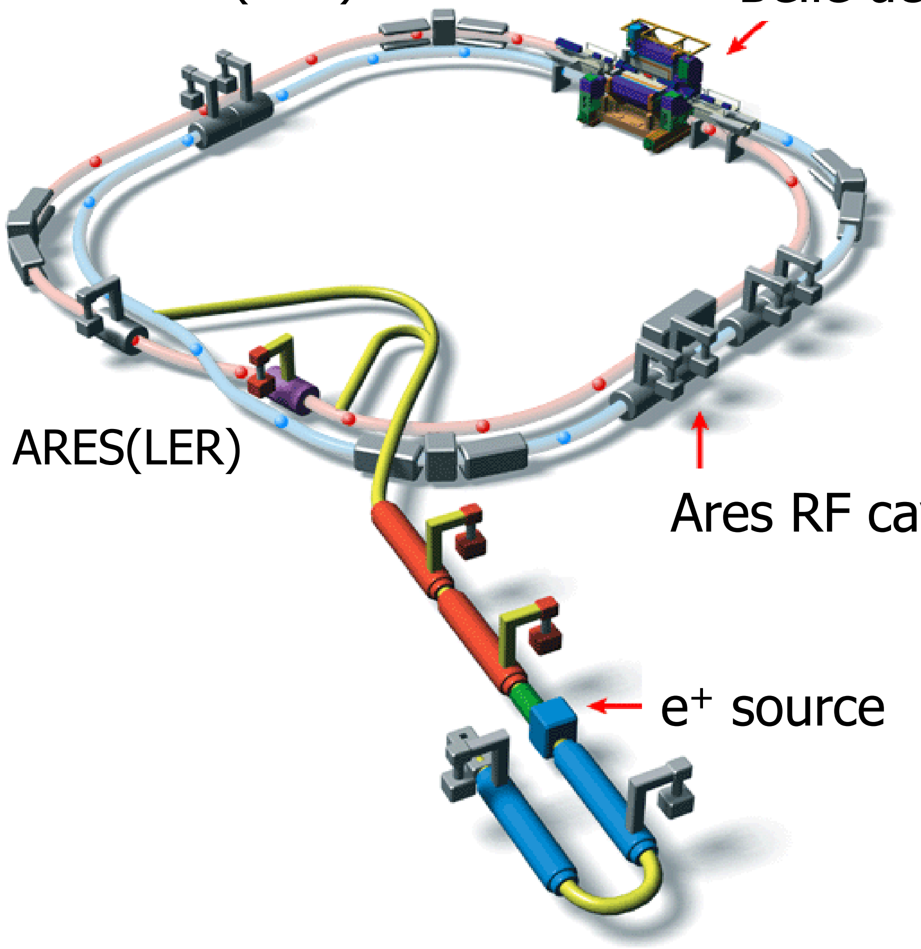



ana

# How to do it?
# → upgrade KEKB and Belle



# The KEKB Collider & Belle Detector




- $e^-$ (8 GeV) on $e^+$(3.5 GeV)
  - $\sqrt{s} \approx m_{\Upsilon(4S)}$
  - Lorentz boost: $\beta\gamma$=0.425
- 22 mrad crossing angle
- Operating since 1999

**Peak luminosity (WR!) :**

**$2.1 \times 10^{34}$ cm$^{-2}$s$^{-1}$**

=2x design value

First physics run on June 2, 1999
Last physics run on June 30, 2010
$L_{peak} = 2.1 \times 10^{34}/cm^2/s$
$L > 1 ab^{-1}$

# The last beam abort of KEKB on June 30, 2010


**→ Can start construction of SuperKEKB and Belle II**

# Strategies for increasing luminosity

Beam-beam parameter

Lorentz factor

Beam current

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

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

Classical electron radius

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

Vertical beta function@IP

**(1) Smaller $\beta_y^*$**

**(2) Increase beam currents**

(3) Increase $\xi_y$

**"Nano-Beam" scheme**

***Collision with very small spot-size beams***

Invented by Pantaleo Raimondi for SuperB

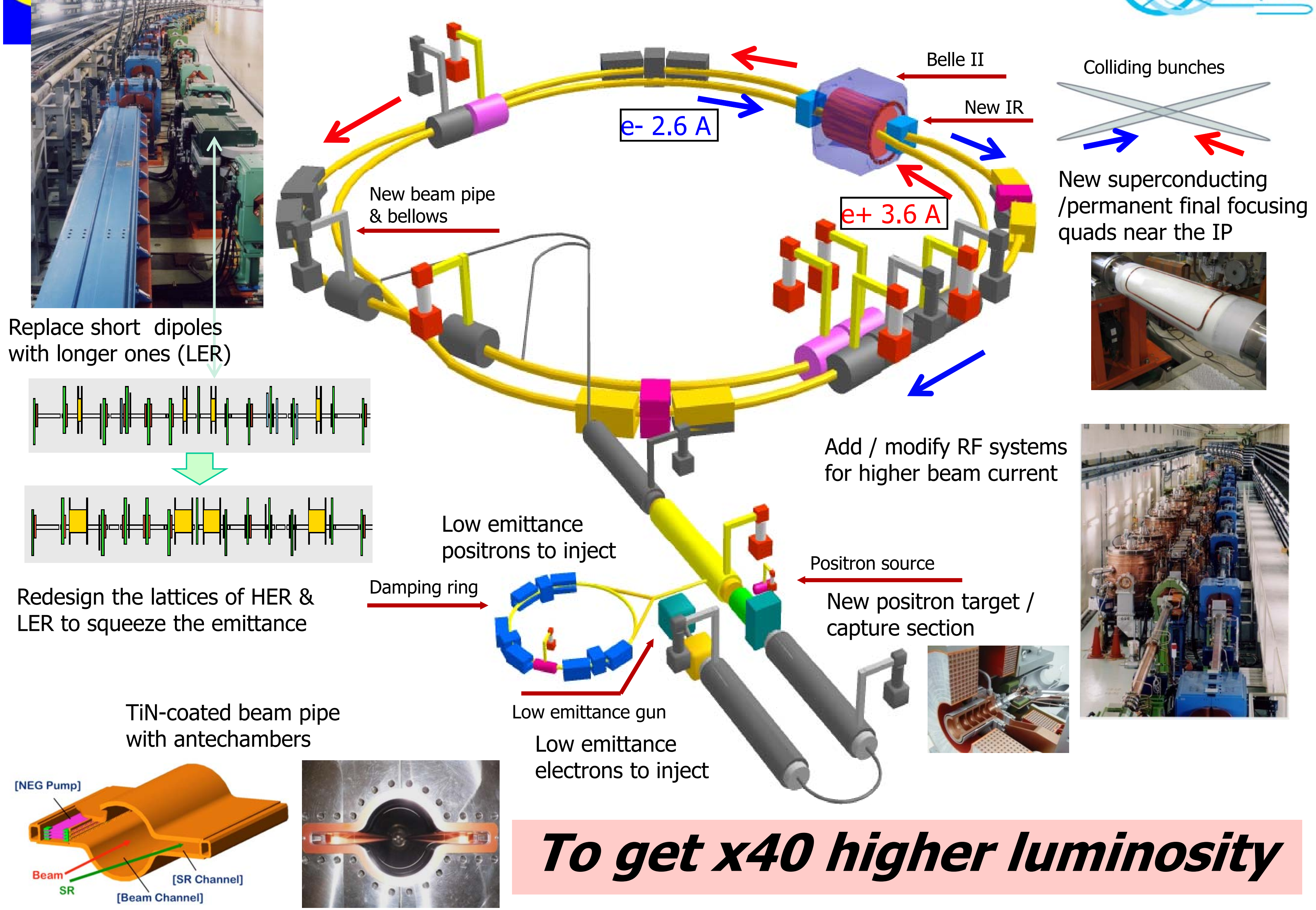
# Machine design parameters

| parameters | | KEKB | | **SuperKEKB** | | units |
|---|---|---|---|---|---|---|
| | | LER | HER | LER | HER | |
| Beam energy | $E_b$ | 3.5 | 8 | 4 | 7 | GeV |
| Half crossing angle | $\varphi$ | 11 | | 41.5 | | mrad |
| Horizontal emittance | $\varepsilon_x$ | 18 | 24 | 3.2 | 5.0 | nm |
| Emittance ratio | $\kappa$ | 0.88 | 0.66 | 0.27 | 0.25 | % |
| Beta functions at IP | $\beta_x^*/\beta_y^*$ | 1200/5.9 | | 32/0.27 | 25/0.31 | mm |
| Beam currents | $I_b$ | 1.64 | 1.19 | 3.60 | 2.60 | A |
| beam-beam parameter | $\xi_y$ | 0.129 | 0.090 | 0.0886 | 0.0830 | |
| **Luminosity** | **L** | **$2.1 \times 10^{34}$** | | **$8 \times 10^{35}$** | | **$cm^{-2}s^{-1}$** |

- **Small beam size & high current** to increase luminosity
- **Large crossing angle**
- **Change beam energies** to solve the problem of LER short lifetime

M. Iwasaki, ICHEP2010

# KEKB to SuperKEKB



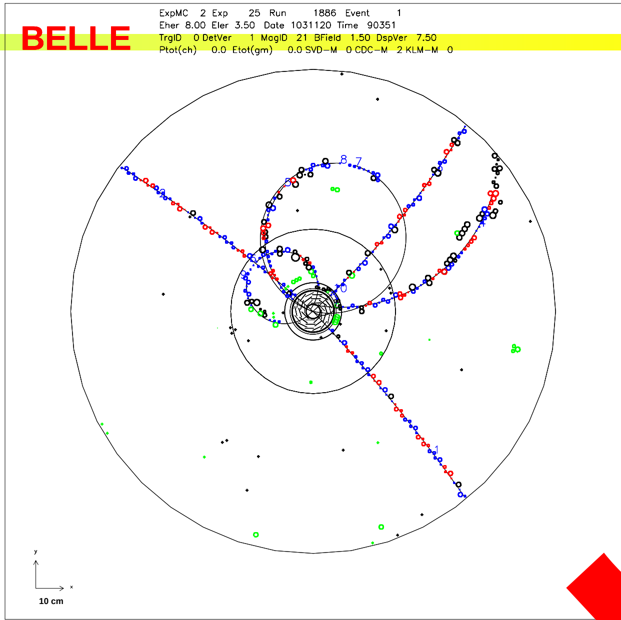

***To get x40 higher luminosity***

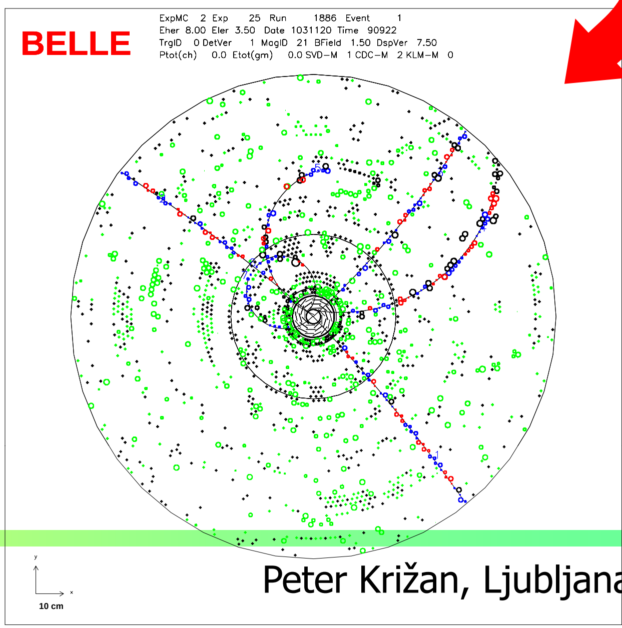
# Detector

# 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 ← sμμ recon. eff.
  - hermeticity ← ν "reconstruction"

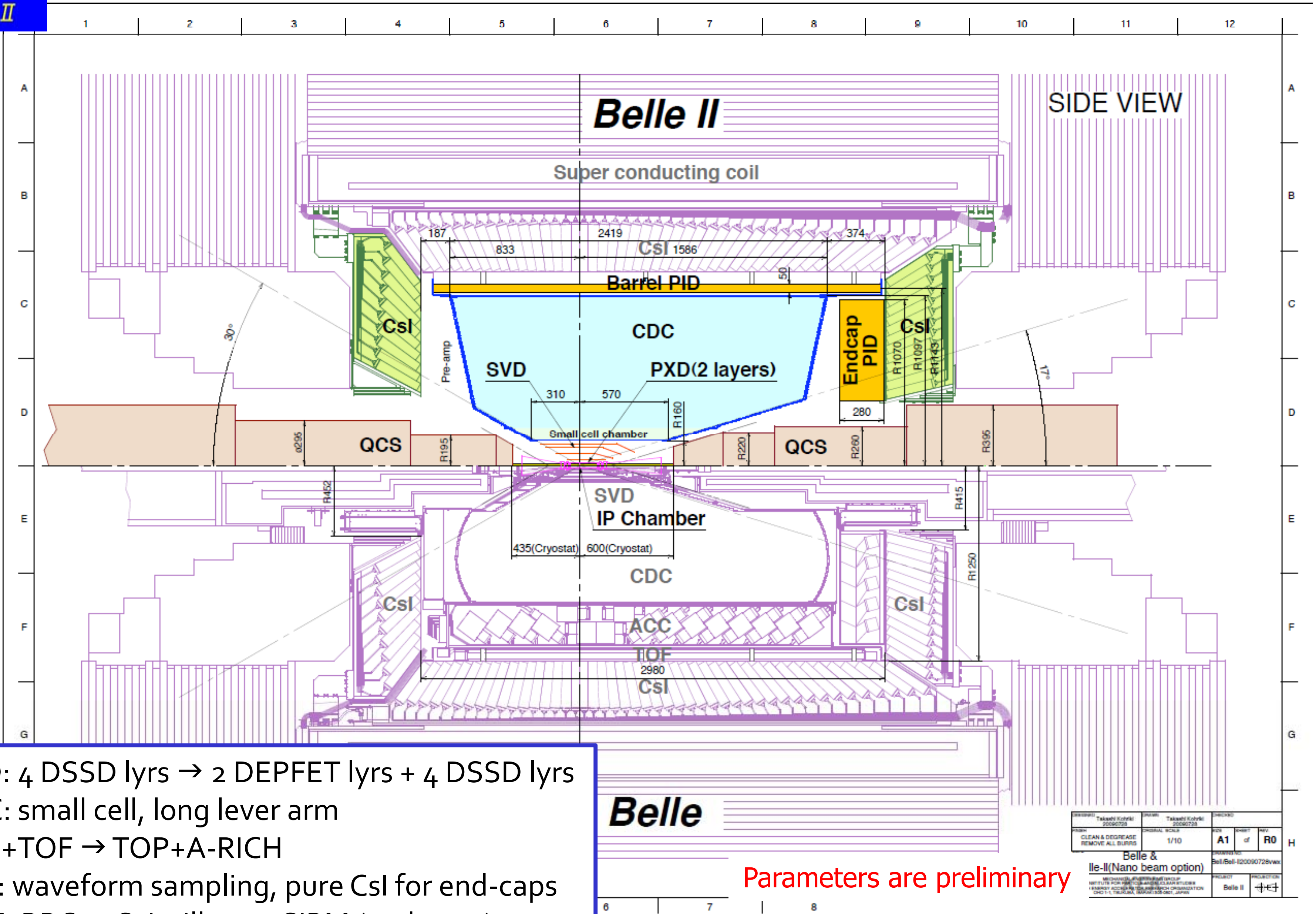



Solutions:

- 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 in comparison with Belle



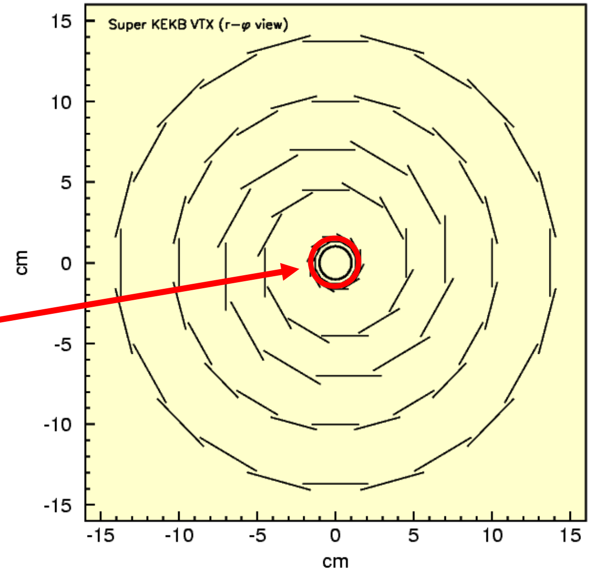

SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling, pure CsI for end-caps
KLM: RPC → Scintillator +SiPM (end-caps)

Parameters are preliminary

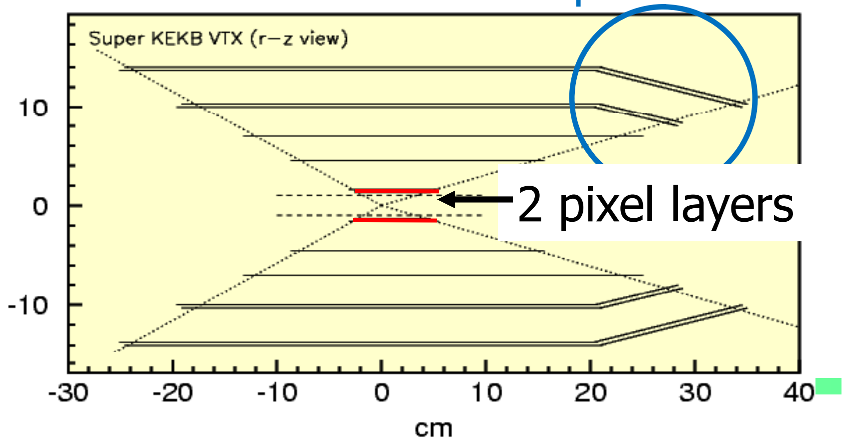
Y. Ushiroda, ICHEP2010

# Vertex detector upgrade: PXD+SVD

- Configuration: 4 layers → 6 layers (outer radius = 8cm→14cm)
  - More robust tracking
  - Higher Ks vertex reconstr. efficiency
- Inner radius: 1.5cm → 1.3cm
  - Better vertex resolution
- Sensors of the two innermost layers L1+L2: DEPFET Pixel sensors →PXD
- Layers 3-6: normal double sided Si detector (DSSD) →SVD
- Strip readout chip: VA1TA → APV25
  - Reduction of occupancy coming from beam background.
  - Pipeline readout to reduce dead time.

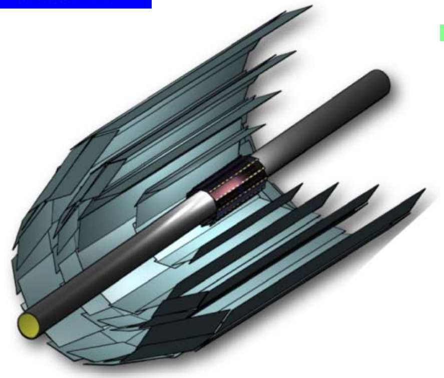



Slanted layers to keep the acceptance



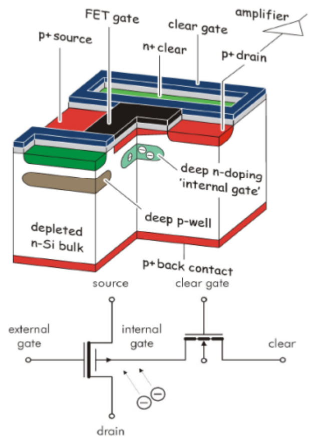
# Vertex Detector

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

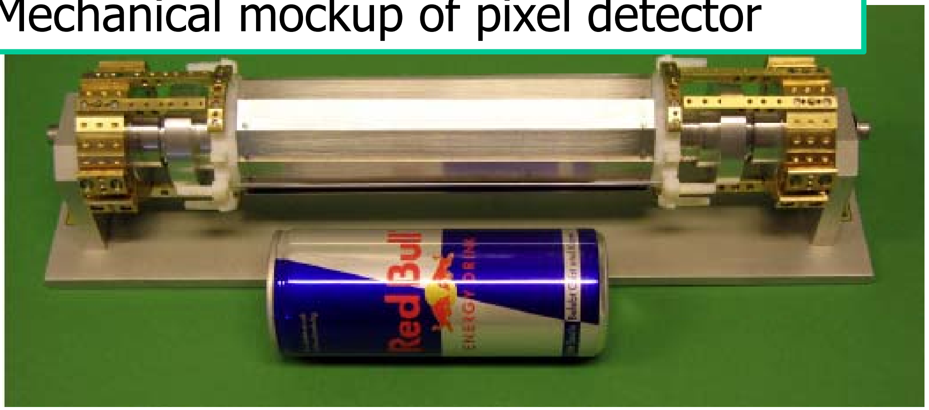


| | | |
|---|---|---|
| **Beam Pipe** | | **r = 10mm** |
| **DEPFET** | | |
| | **Layer 1** | **r = 14mm** |
| | **Layer 2** | **r = 22mm** |
| **DSSD** | | |
| | **Layer 3** | **r = 38mm** |
| | **Layer 4** | **r = 80mm** |
| | **Layer 5** | **r = 115mm** |
| | **Layer 6** | **r = 140mm** |

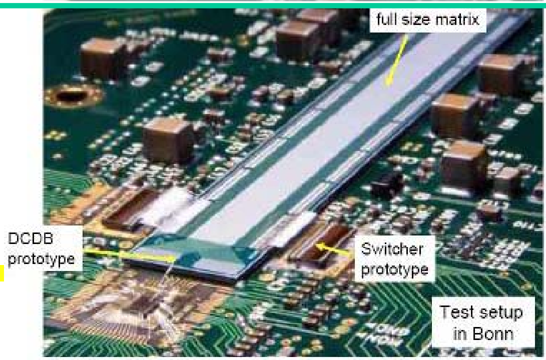
DEpleted P-channel FET

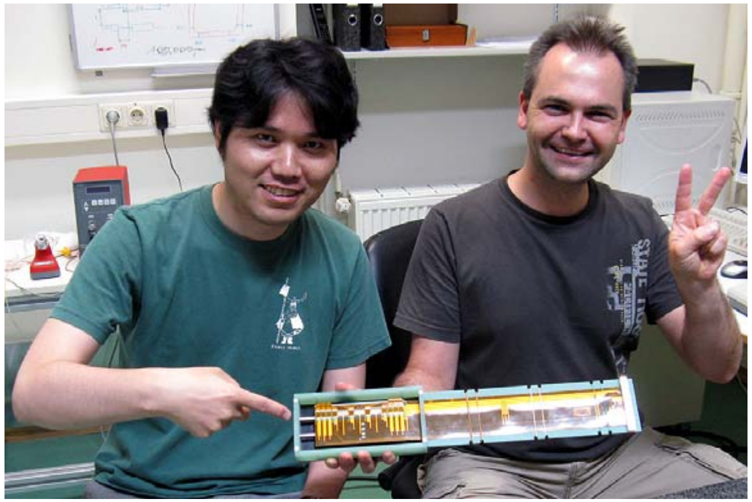



Mechanical mockup of pixel detector




Prototype DEPFET pixel sensor and readout



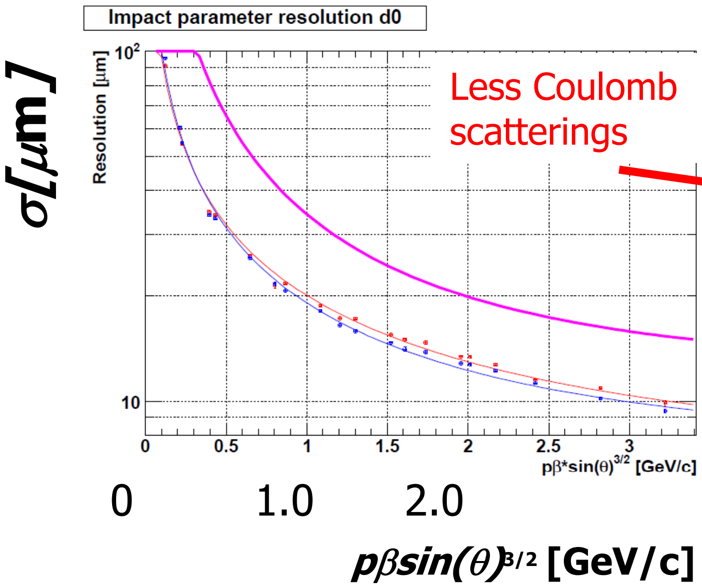



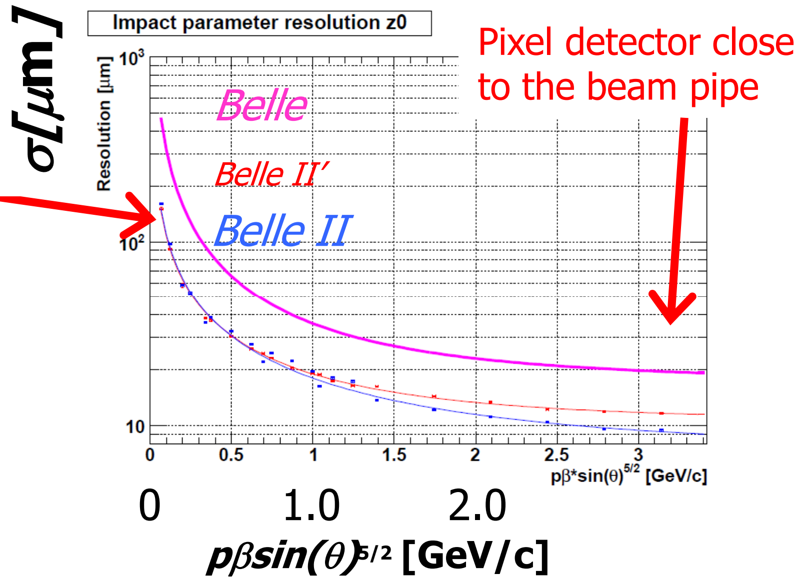
A prototype ladder using the first 6 inch DSSD from Hamamatsu has been assembled and tested.

# Expected performance

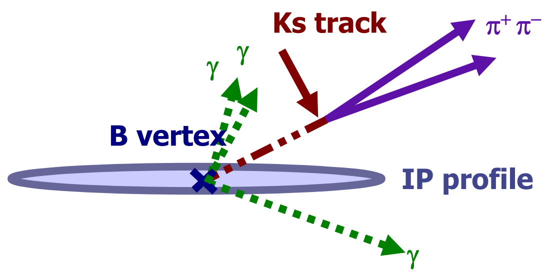
$$\sigma = a + \frac{b}{p\beta \sin^{\nu}\theta}$$

**Significant improvement in IP resolution!**

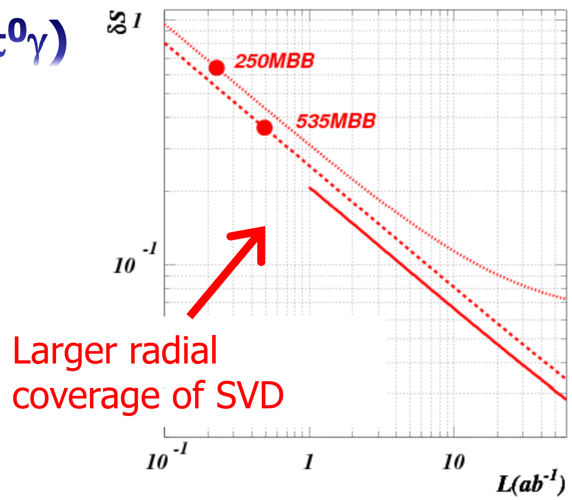



**Significant improvement in $\delta S(K_S\pi^0\gamma)$**

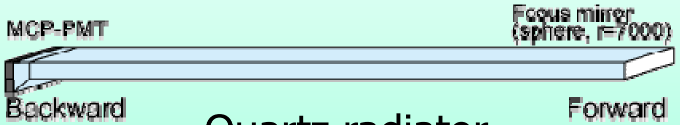



B decay point reconstruction with $K_S$ trajectory



# Particle Identification Devices

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



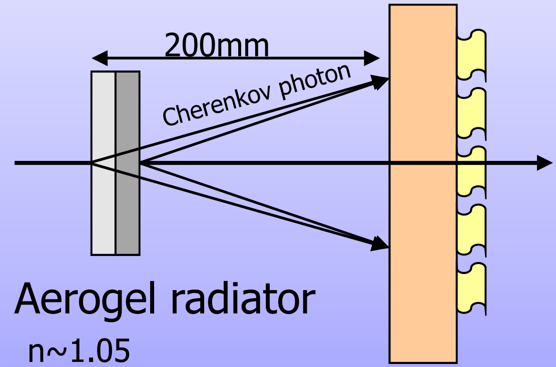

Quartz radiator

Focusing mirror

Small expansion block

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

## Endcap PID: Aerogel RICH (ARICH)

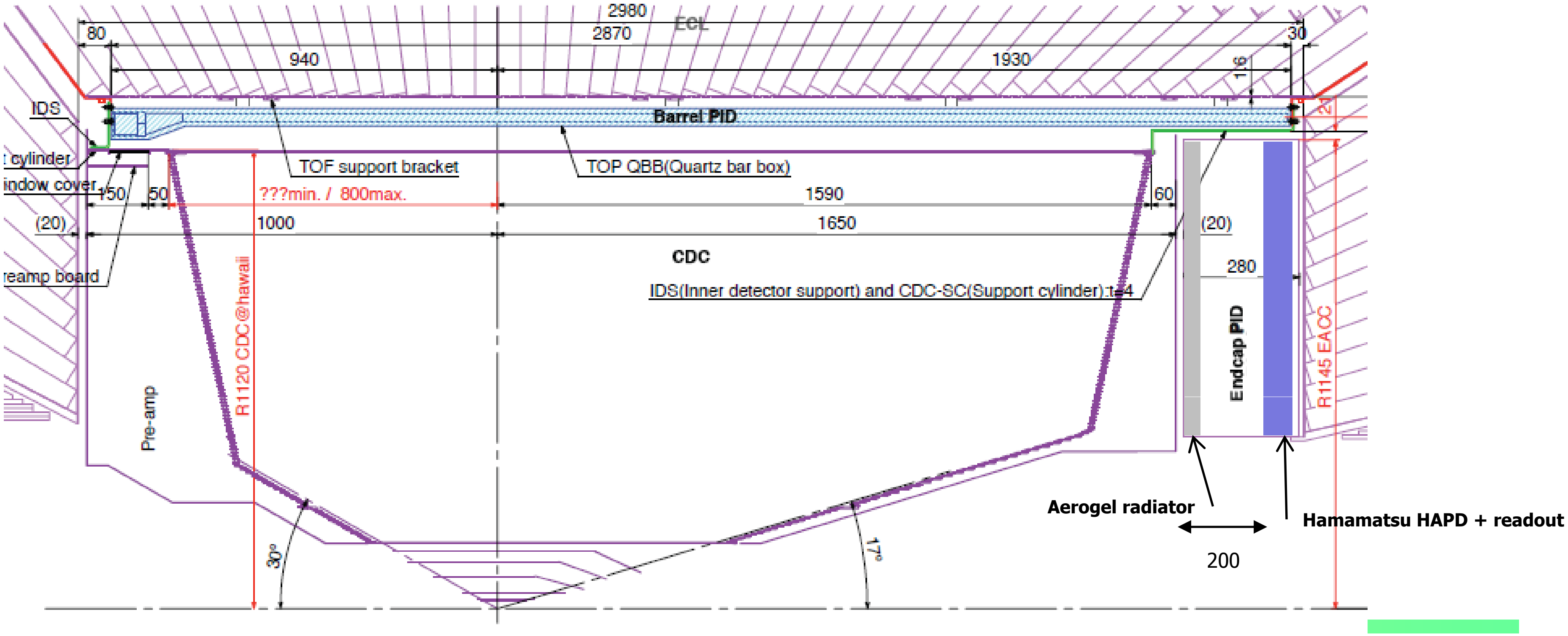



Aerogel radiator

n~1.05

Hamamatsu HAPD

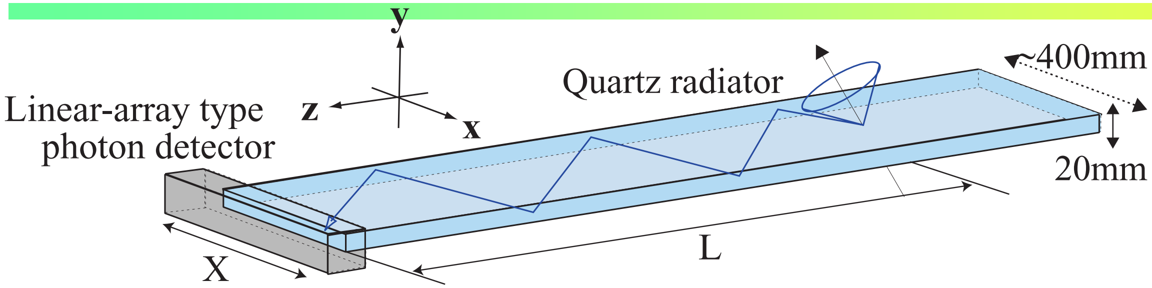
+ new ASIC

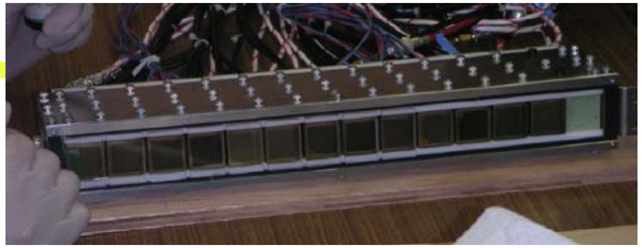




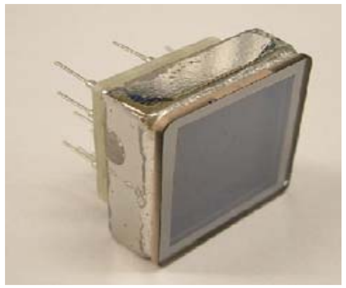
Peter Križan, Ljubljana

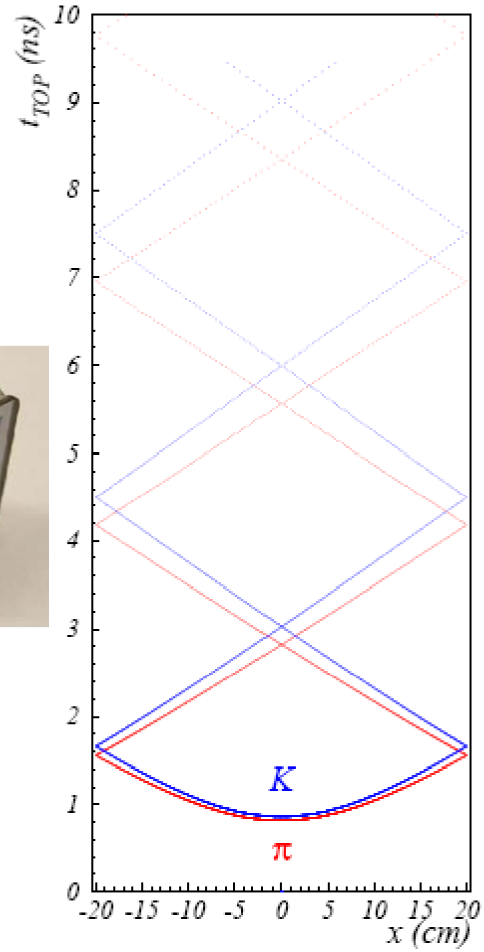
# Barrel PID: Time of propagation (TOP) counter

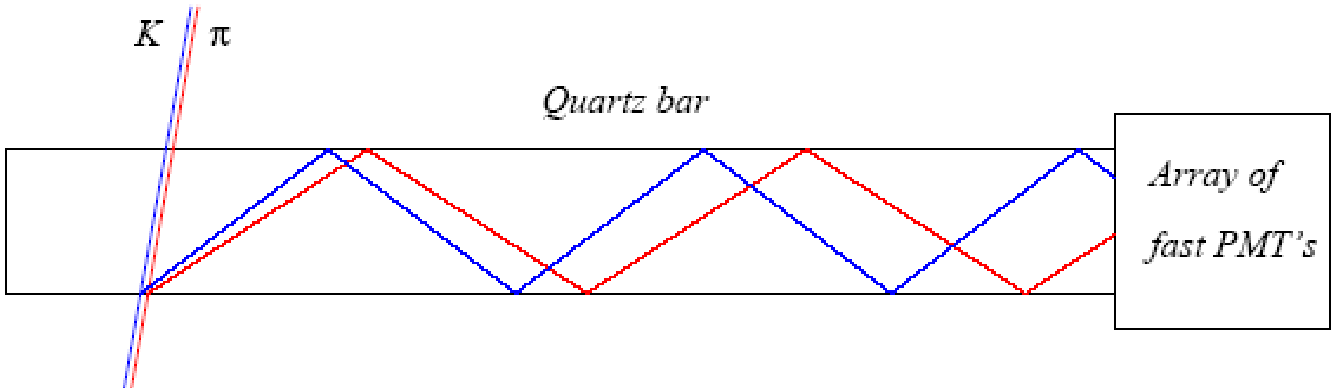


- Cherenkov ring imaging with precise time measurement.
- Reconstruct angle from two coordinates and the time of propagation of the photon
  - Quartz radiator (2cm)
  - Photon detector (MCP-PMT)
    - Good time resolution ~ 40 ps
    - Single photon sensitivity in 1.5



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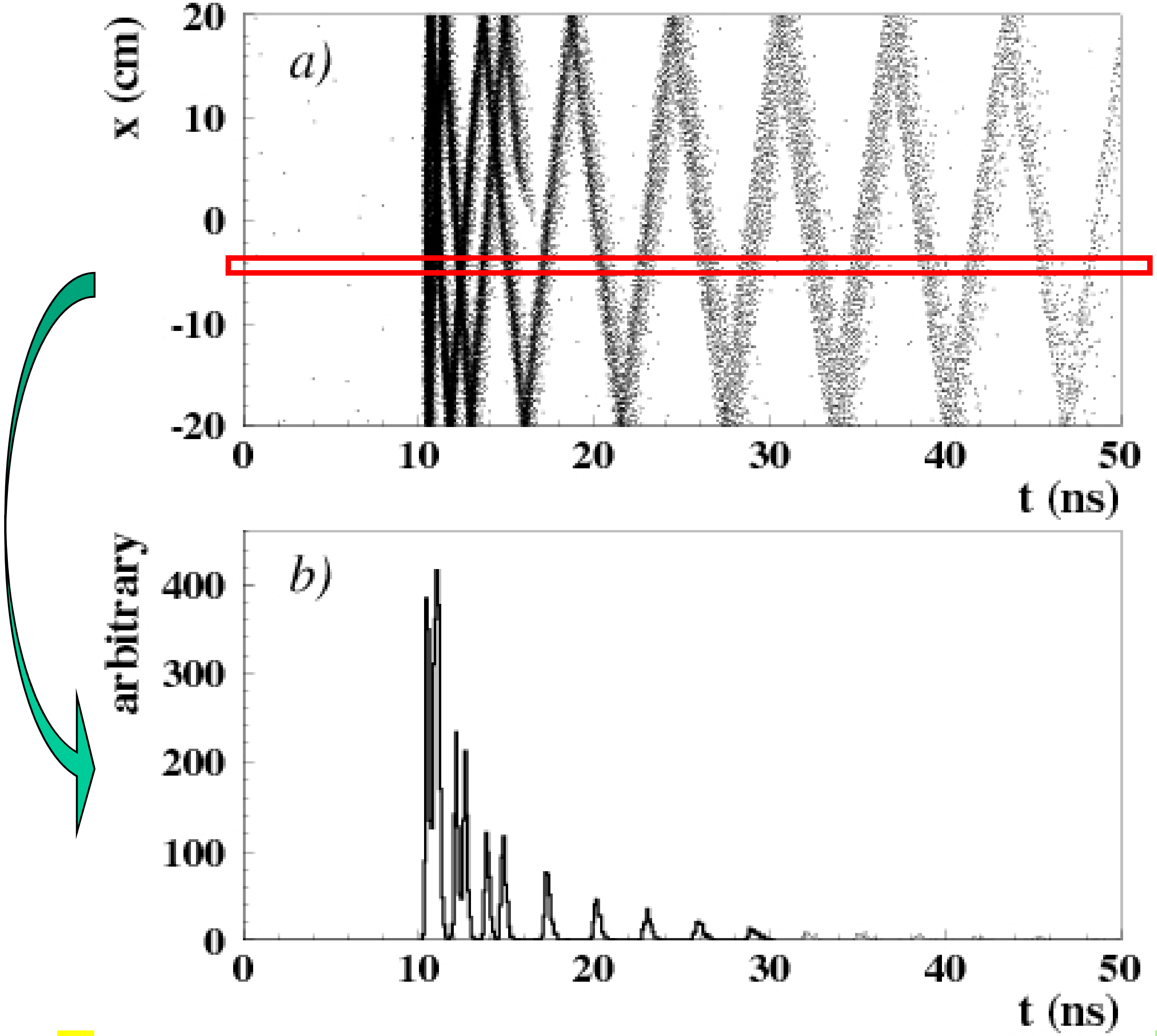
# TOP image

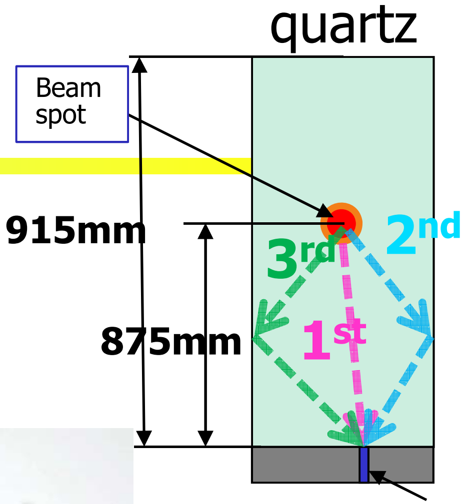


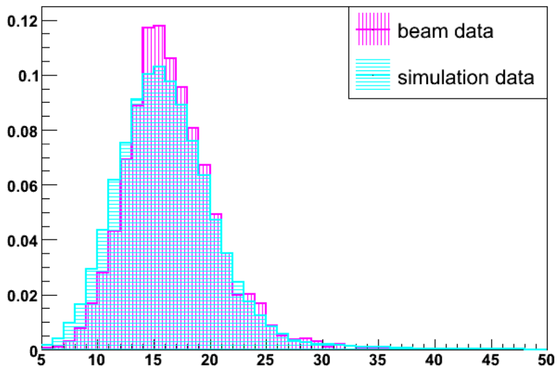

Pattern in the coordinate-time space ('ring') of a pion hitting a quartz bar with ~80 MCP-PMT channels

Time distribution of signals recorded by one of the PMT channels: different for $\pi$ and K

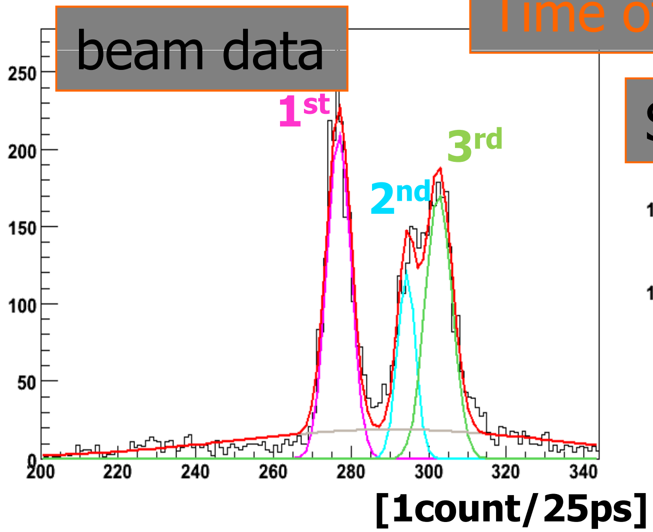
# TOP (Barrel PID)

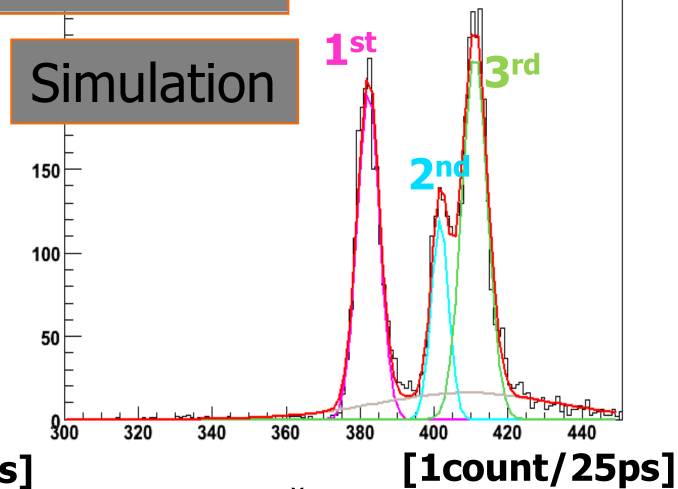
- Quartz radiator
  - 2.6m$^L$ x 45cm$^W$ x 2cm$^T$
  - Excellent surface accuracy
- MCP-PMT
  - Hamamatsu 16ch MCP-PMT
    - Good TTS (<35ps) & enough lifetime
    - Multialkali photo-cathode → SBA
- Beam test in 2009
  - # of photons consistent
  - Time resolution OK




Time of arrival

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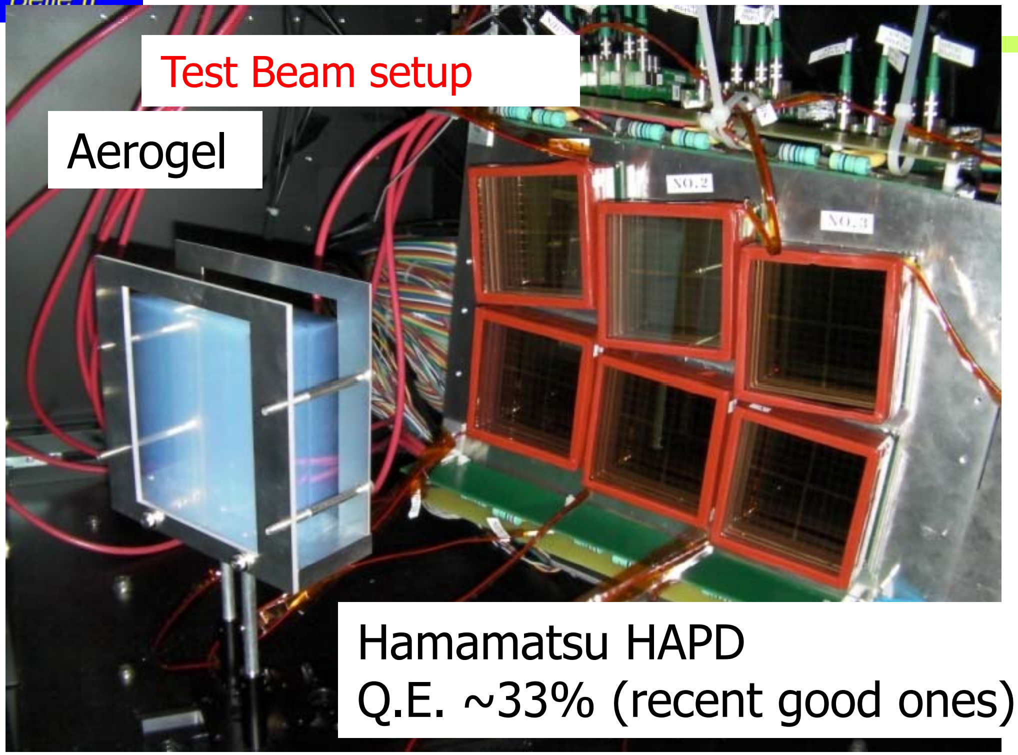
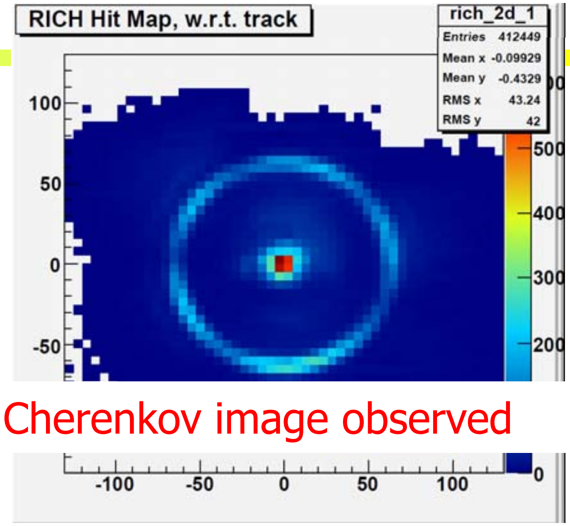
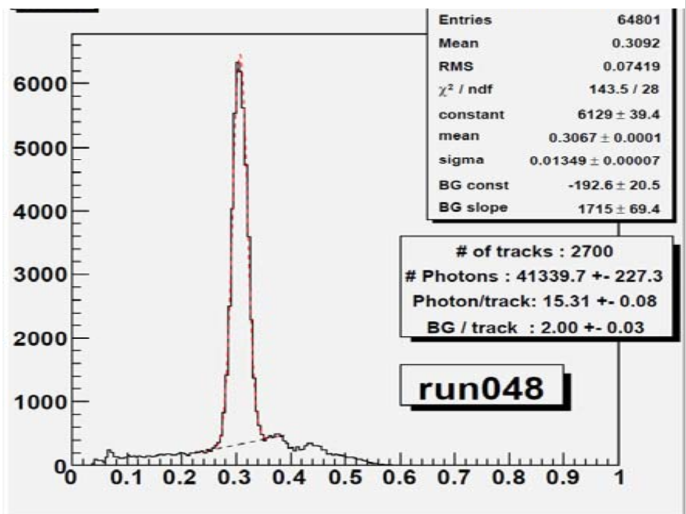
# Aerogel RICH (endcap PID)



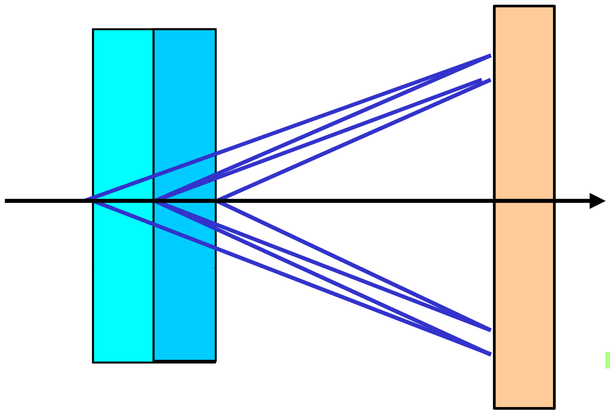

Clear Cherenkov image observed

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 !**

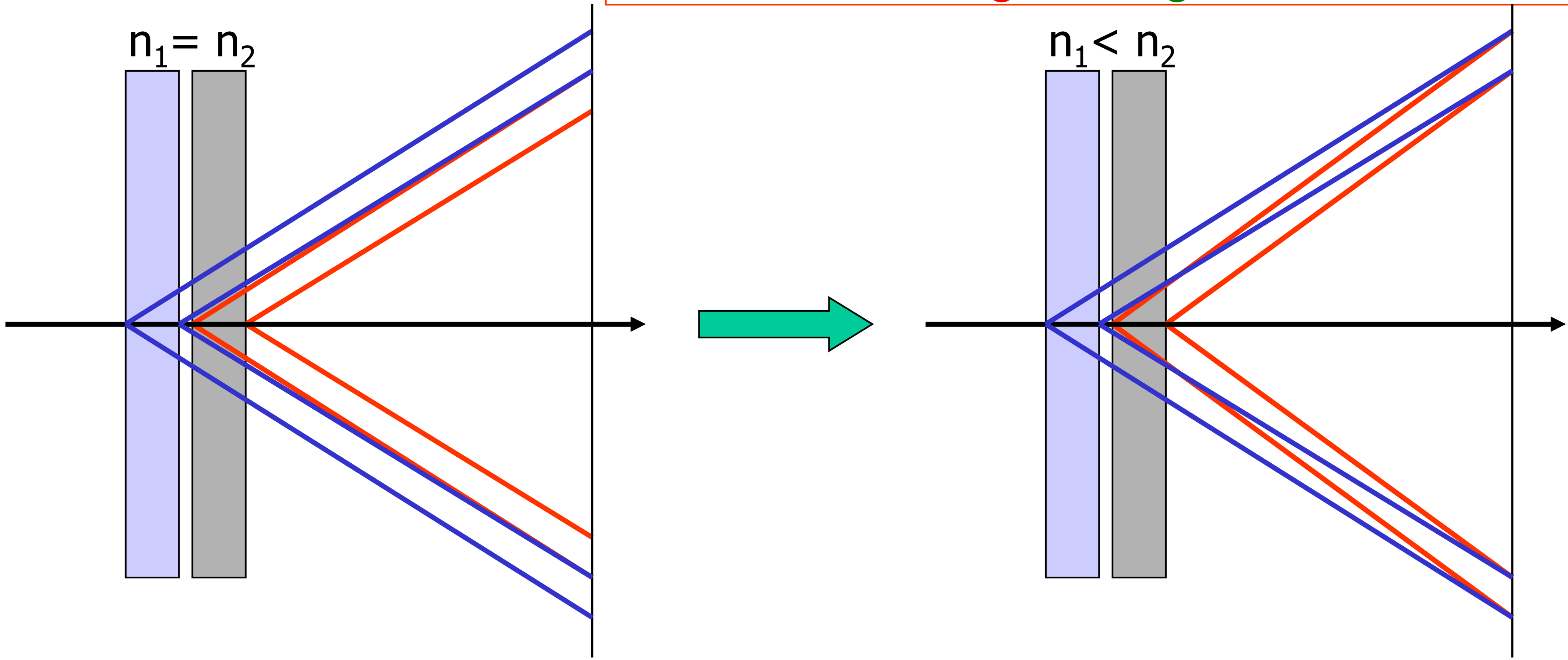
Peter Križan, Ljubljana

# Radiator with multiple refractive indices

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

normal

→ stack two tiles with different refractive indices: “focusing” configuration

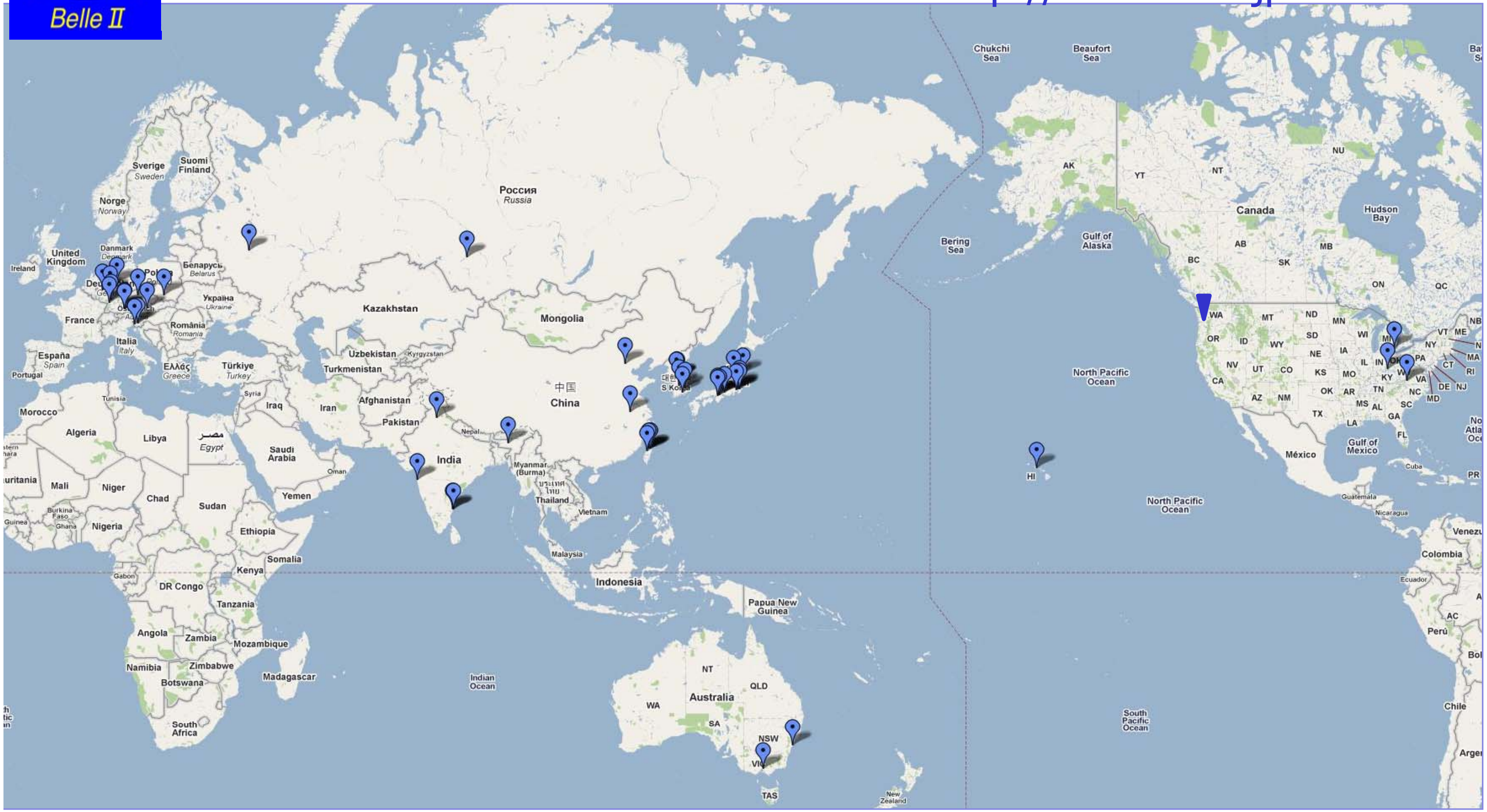



→ focusing radiator

# Status of the project

# Belle II Collaboration

http://belle2.kek.jp




13 countries/regions, 54 institutes

>300 collaborators

# Tokyo Metropolitan in Belle and Belle-II

TMU@Belle:

- Sumiyoshi-san at the heart of the experiment!
- Important analyses (full reconstruction sample)

The TMU group has been contributing significantly to the Belle-II project:

- PID systems, in particular the research and development of the aerogel RICH photo-sensor, the HAPD (in collaboration with Hamamatsu), and its read-out

Belle II is looking forward to a continuation of the excellent collaboration with TMU

# SuperKEKB/Belle II funding Status

**KEKB upgrade has been approved**

- 5.8 oku yen (~MUSD) for Damping Ring (FY2010)
- **100 oku yen** for machine -- Very Advanced Research Support Program (FY2010-2012)

Continue efforts to obtain additional funds to complete construction as scheduled.

Several non-Japanese funding agencies have already allocated sizable funds for the upgrade.

→construction started!

Press Release

>Top >PressRelease >this page — last update: 10/06/23

**KEKB upgrade plan has been approved**

June 23, 2010
High Energy Accelerator Research Organization (KEK)

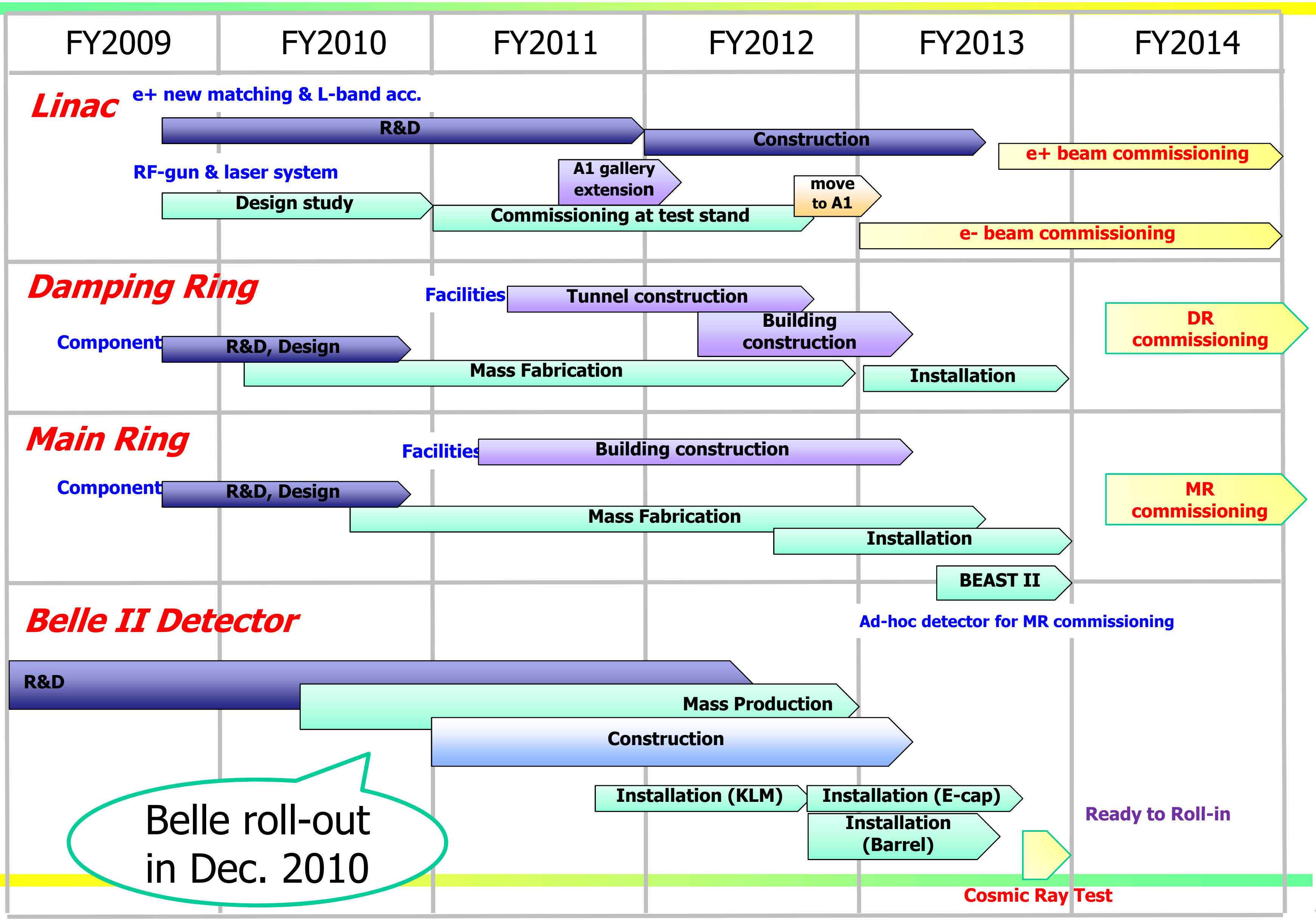
The MEXT, the Japanese Ministry that supervises KEK, has announced that it will appropriate a budget of 100 oku-yen (approx $110M) over the next three years starting this Japanese fiscal year (JFY2010) for the high performance upgrade program of KEKB. This is part of the measures taken under the new "Very Advanced Research Support Program" of the Japanese government.

"We are delighted to hear this news," says Masanori Yamauchi, former spokesperson for the Belle experiment and currently a deputy director of the Institute of Particle and Nuclear Studies of KEK. "This three- year upgrade plan allows the Belle experiment to study the physics from decays of heavy flavor particles with an unprecedented precision. It means that KEK in Japan is launching a renewed research program in search for new physics by using a technique which is complementary to what is employed at LHC at CERN."

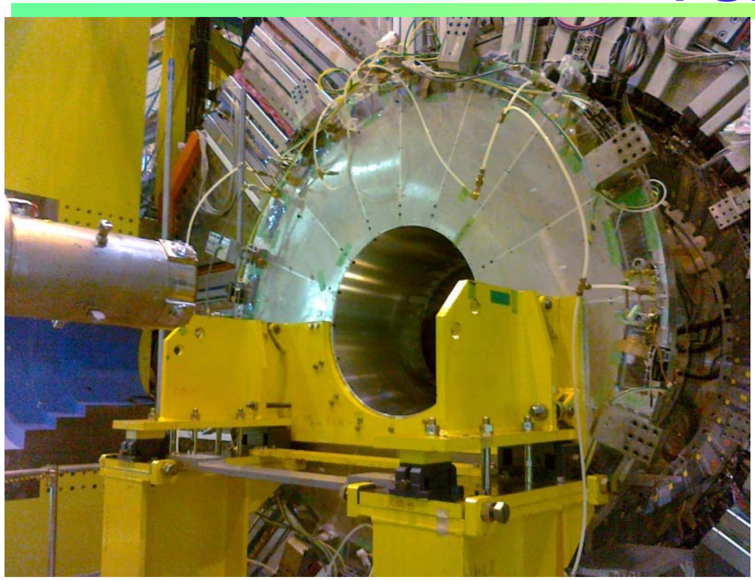
**[ Media Contact ]** Youhei Morita,
Head of Public Relations Office, KEK
tel. +81-29-879-6047

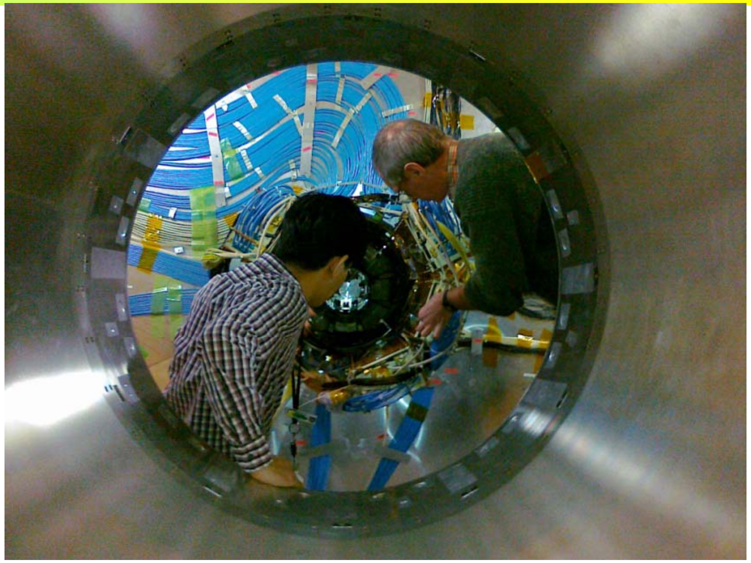
# Construction Schedule of SuperKEKB/Belle II

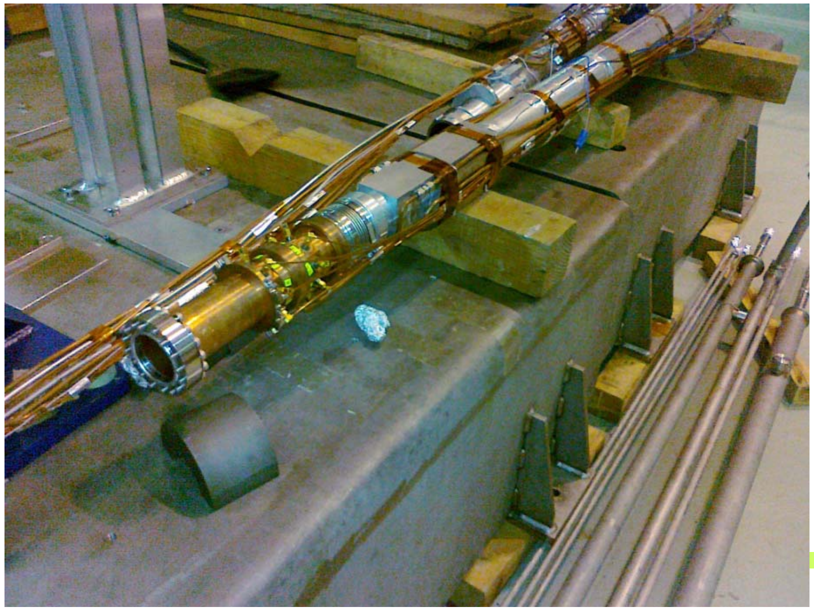
Jun. 24, 2010

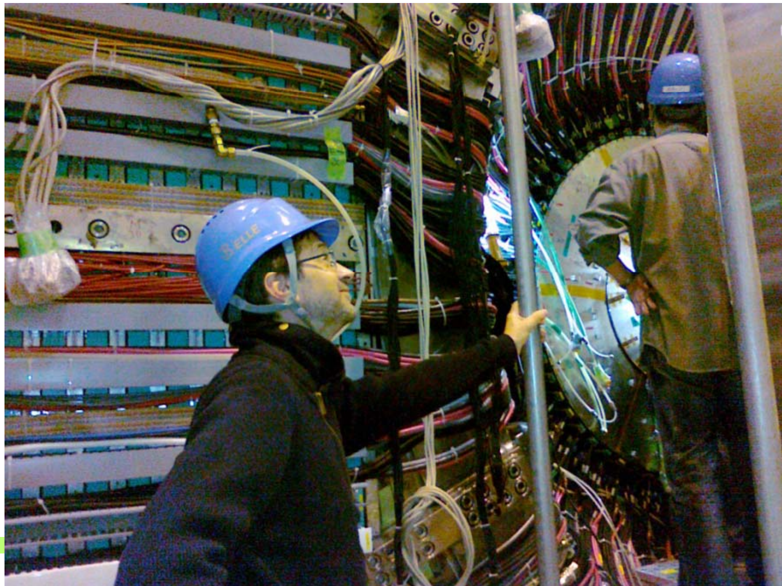


# This week: taking out the SVD2 – vertex detector

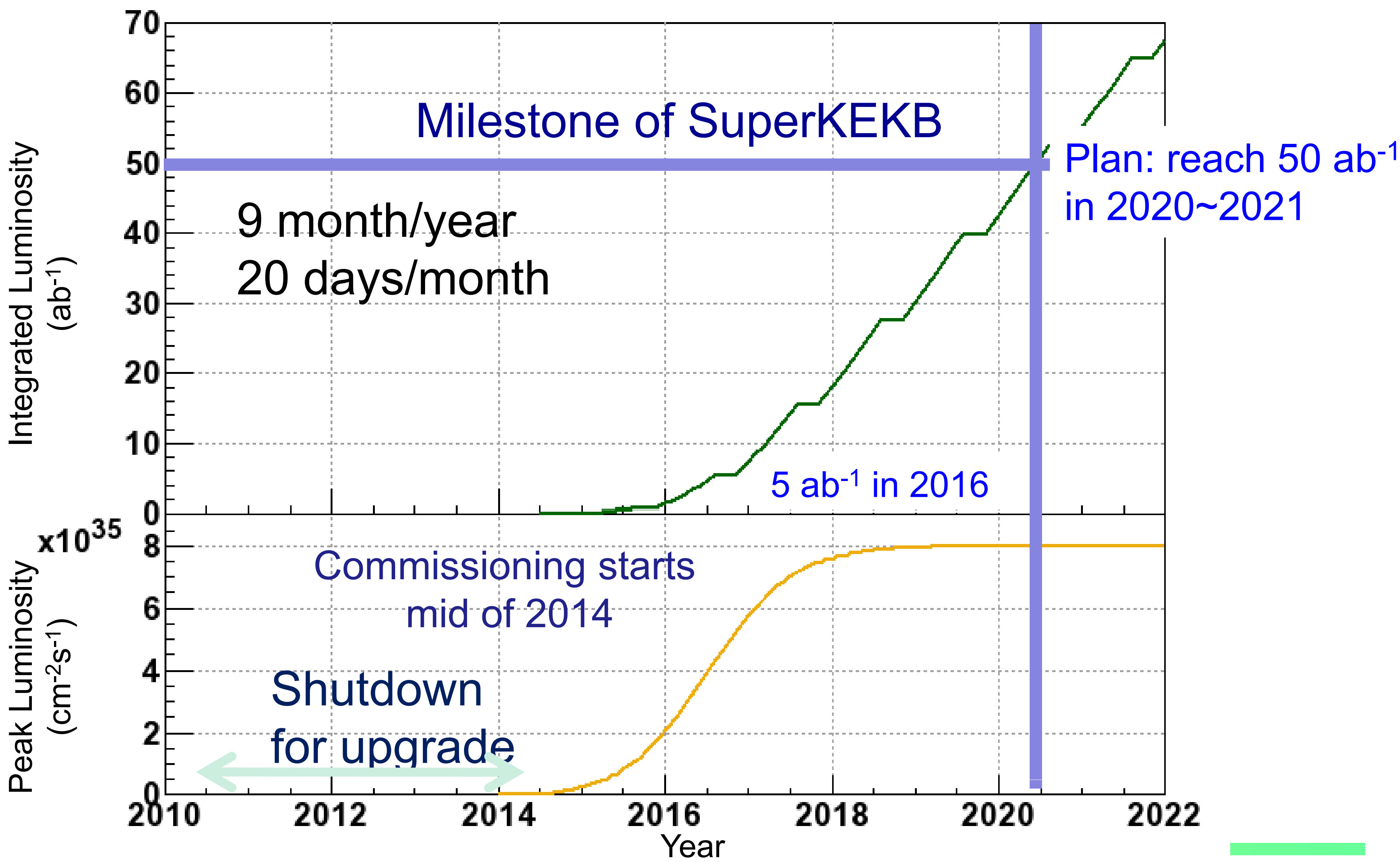








# Luminosity upgrade projection



# 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 surpasing design perfomance
- Major upgrade at KEK in 2010-14 → SuperKEKB+Belle II, L x40, construction started
- Physics reach updates available
- Expect a new, exciting era of discoveries, complementary to the LHC
- Belle II is looking forward to a continuation of an excellent collaboration with Tokyo Metropolitan U.