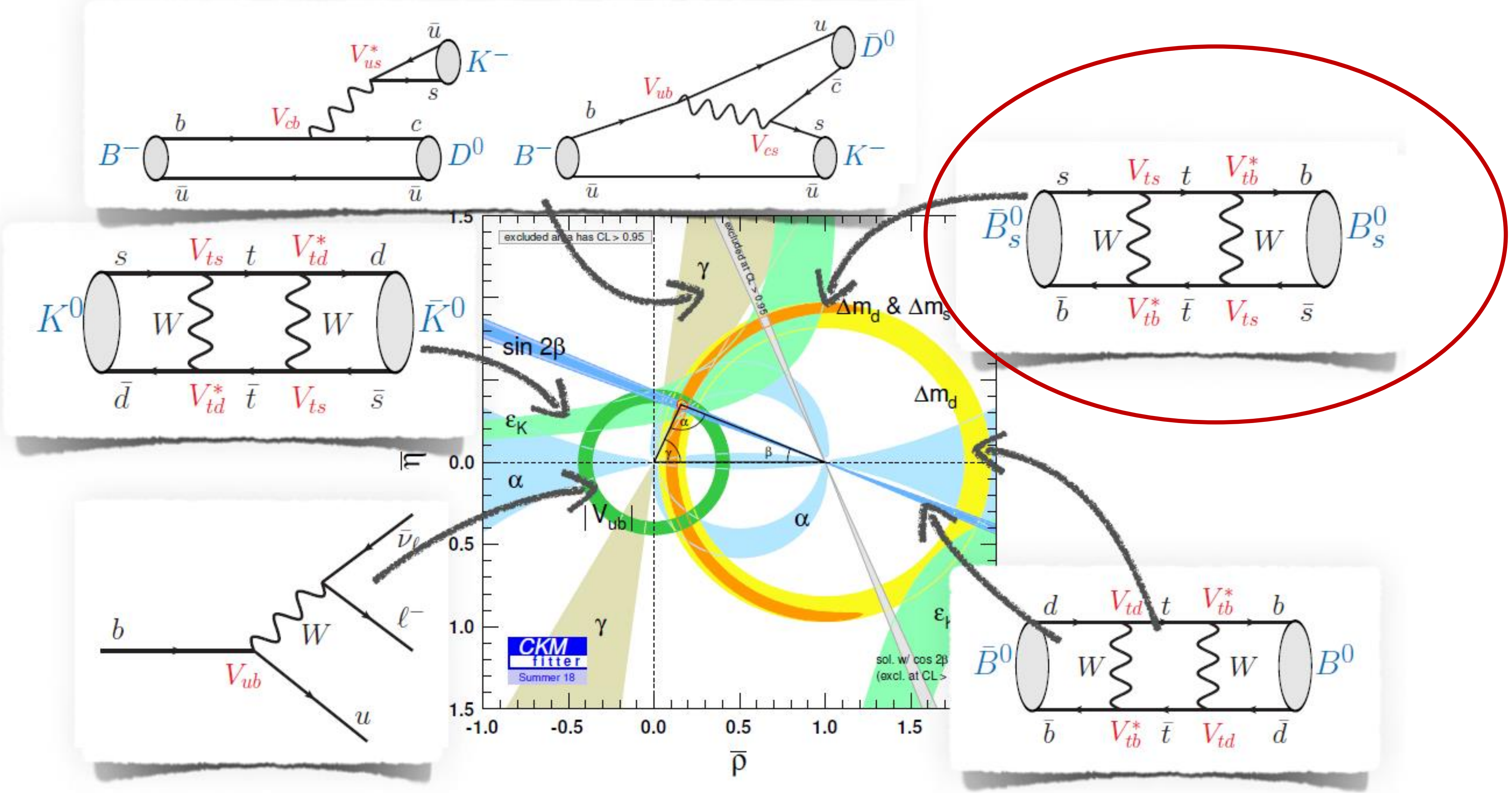

B^-
b
$\bar{u}$
V_{cb}
V_{us}^*
$\bar{u}$
s
K^-
c
$\bar{u}$
D^0
B^-
b
$\bar{u}$
V_{ub}
u
$\bar{D}^0$
$\bar{c}$
s
V_{cs}
K^-
$\bar{u}$
$\bar{B}_s^0$
s
V_{ts}
t
V_{tb}^*
b
W
W
B_s^0
$\bar{b}$
V_{tb}^*
$\bar{t}$
V_{ts}
$\bar{s}$
K^0
s
V_{ts}
t
V_{td}^*
d
W
W
$\bar{K}^0$
$\bar{d}$
V_{td}^*
$\bar{t}$
V_{ts}
$\bar{s}$
b
V_{ub}
W
$\bar{\nu}_\ell$
ℓ^-
u
$\bar{B}^0$
d
V_{td}
t
V_{tb}^*
b
W
W
B^0
$\bar{b}$
V_{tb}^*
$\bar{t}$
V_{td}
$\bar{d}$
excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
γ
α
$|V_{ub}|$
α
ε_K
γ
sol. w/ cos 2β
(excl. at CL >
CKM fitter
Summer 18
$\bar{\eta}$
$\bar{\rho}$
1.5
0.0
0.5
1.0
1.5
-1.0
-0.5
0.0
0.5
1.0
1.5

P, C, and CP Transformation

$$B_d^0 = (\bar{b}d) \qquad \bar{B}_d^0 = (b\bar{d})$$
$$B_s^0 = (\bar{b}s) \qquad \bar{B}_s^0 = (b\bar{s})$$

For pseudoscalar mesons P and $\bar{P}$, the parity transformation implies

$$\mathbf{P}\,|P(\vec{p})\rangle = -|P(-\vec{p})\rangle\,, \qquad \mathbf{P}\,|\bar{P}(\vec{p})\rangle = -|\bar{P}(-\vec{p})\rangle\,.$$

Charge conjugation is a transformation that relates particles and antiparticles, leaving all space-time coordinates unchanged, i.e.

$$\mathbf{C}\,|P(\vec{p})\rangle = |\bar{P}(\vec{p})\rangle\,, \qquad \mathbf{C}\,|\bar{P}(\vec{p})\rangle = |P(\vec{p})\rangle\,.$$

The combined transformation, $\boldsymbol{PC}$, acts on the pseudoscalar meson states as follows:

$$\mathbf{CP}\,|P(\vec{p})\rangle = -|\bar{P}(-\vec{p})\rangle\,, \qquad \mathbf{CP}\,|\bar{P}(\vec{p})\rangle = -|P(-\vec{p})\rangle\,.$$

For neutral mesons, P^0 and $\bar{P}^0$, one can construct the $\boldsymbol{CP}$ eigenstates

$$|P_1^0\rangle = \frac{1}{\sqrt{2}}\left(|P^0\rangle - |\bar{P}^0\rangle\right), \qquad |P_2^0\rangle = \frac{1}{\sqrt{2}}\left(|P^0\rangle + |\bar{P}^0\rangle\right),$$

which obey

$$\mathbf{CP}\,|P_1^0\rangle = |P_1^0\rangle\,, \qquad \mathbf{CP}\,|P_2^0\rangle = -|P_2^0\rangle\,.$$

Mixing

Effective Hamiltonian approximation:

"dispersive"

"absorptive"

$$i\frac{d}{dt}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = H\begin{pmatrix} a(t) \\ b(t) \end{pmatrix}; \quad P^0 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \overline{P}^0 = \begin{pmatrix} 0 \\ 1 \end{pmatrix}; \quad H_{ij} = \underset{\downarrow}{M_{ij}} - i\Gamma_{ij}/2$$

From flavor to mass eigenstates (P_L, P_H) ≈ CP eigenstates (P_1, P_2):

$$\left|P_L^0\right\rangle = p\left|P^0\right\rangle + q\left|\overline{P}^0\right\rangle = \frac{1}{\sqrt{1+|\tilde{\varepsilon}|^2}}\left(\tilde{\varepsilon}\left|P_1\right\rangle + \left|P_2\right\rangle\right) \qquad \tilde{\varepsilon} = \frac{p-q}{p+q}$$

$$\left|P_H^0\right\rangle = p\left|P^0\right\rangle - q\left|\overline{P}^0\right\rangle = \frac{1}{\sqrt{1+|\tilde{\varepsilon}|^2}}\left(\left|P_1\right\rangle + \tilde{\varepsilon}\left|P_2\right\rangle\right) \qquad |q|^2 + |p|^2 = 1$$

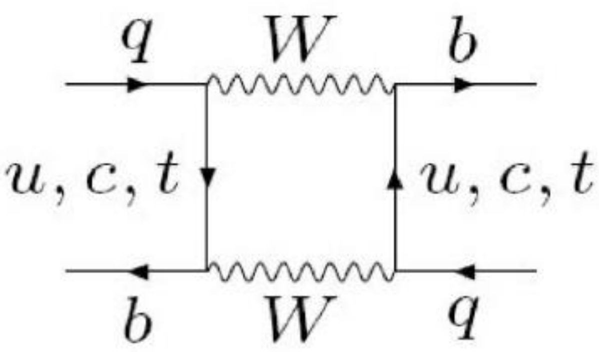
Solving the eigenvalue equations and defining: $\Delta m = m_H - m_L \quad \Delta\Gamma = \Gamma_H - \Gamma_L$

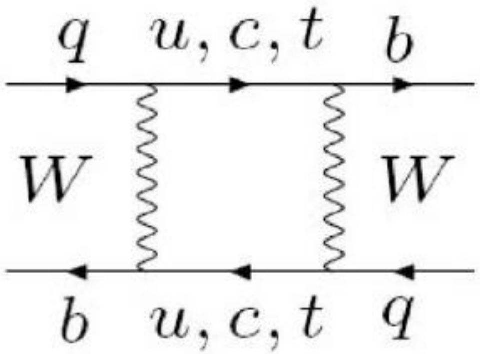
$$\Delta m^2 - 1/4\,\Delta\Gamma^2 = 4|M_{12}|^2 - |\Gamma_{12}|^2$$

$$\Delta m \Delta\Gamma = 4\Re\mathrm{e}\left(M_{12}\Gamma_{12}^*\right)$$

q, p, Δm and $\Delta\Gamma$ for B_d and B_s

$$B_d^0 = \left(\bar{b}\,d\right)$$
$$B_s^0 = \left(\bar{b}\,s\right)$$





$$\bar{B}_d^0 = \left(b\,\bar{d}\right)$$
$$\bar{B}_s^0 = \left(b\,\bar{s}\right)$$

$$B_d^0 = \left(\bar{b}\,d\right)$$

Now all three up quarks should be taken into account

$$B_s^0 = \left(\bar{b}\,s\right)$$

$$\frac{V_{ub}V_{ud}^*}{\hat{p}-m_u}+\frac{V_{cb}V_{cd}^*}{\hat{p}-m_c}+\frac{V_{tb}V_{td}^*}{\hat{p}-m_t}-\frac{\sum_i V_{ib}V_{id}^*}{\hat{p}}$$

$$\frac{V_{ub}V_{us}^*}{\hat{p}-m_u}+\frac{V_{cb}V_{cs}^*}{\hat{p}-m_c}+\frac{V_{tb}V_{ts}^*}{\hat{p}-m_t}-\frac{\sum_i V_{ib}V_{is}^*}{\hat{p}}$$

Three remaining diagram contributions in M_{12}:

cc: $(V_{cb}V_{cd}^*)^2 G_F^2 m_c^2 \approx A^2\lambda^6\, G_F^2 m_c^2$

$(V_{cb}V_{cs}^*)^2 G_F^2 m_c^2 \approx A^2\lambda^4\, G_F^2 m_c^2$

ct: $V_{cb}V_{cd}^* V_{tb}V_{td}^* G_F^2 m_c^2 \approx$
$-A^2\lambda^6(1-\rho+i\eta)G_F^2\, m_c^2 \ln(\frac{m_t}{m_c})^2$

$V_{cb}V_{cs}^* V_{tb}V_{ts}^* G_F^2 m_c^2 \approx$
$-A^2\lambda^4(1-i\lambda^2\eta)G_F^2 m_c^2 \ln(\frac{m_t}{m_c})^2$

tt: $(V_{tb}V_{td}^*)^2 G_F^2 m_t^2 \approx A^2\lambda^6\,(1-\rho+i\eta)^2 G_F^2 m_t^2$

$(V_{tb}V_{ts}^*)^2 G_F^2 m_t^2 \approx A^2\lambda^4\,(1-i\lambda^2\eta)^2 G_F^2 m_t^2$

q, p, Δm and $\Delta\Gamma$ for B_d and B_s

$$M_{12} = -\frac{G_F^2 B_{B_d} f_{B_d}^2}{12\pi^2} m_B m_t^2 \eta_B \boxed{V_{tb}^2 V_{td}^{*2}} I\left(\frac{m_t^2}{m_W^2}\right), \qquad I\left(\frac{m_t^2}{m_W^2}\right) = \left\{\begin{array}{ll} 1., & m_t = 0 \\ 0.5, & m_t = 175 GeV \\ 0.25, & m_t = \infty \end{array}\right\}$$

$$\Gamma_{12} = \frac{G_F^2 B_{B_d} f_{B_d}^2}{8\pi} m_B^3 \left[-V_{tb}V_{td}^* + O\left(\frac{m_c^2}{m_b^2}\right) V_{cb}V_{cd}^*\right]^2$$

Where η_B with the account of NLO corrections ($\eta_B^{NLO} = 0.55 \pm 0.01$) and $f_{B_d}\sqrt{B_{B_d}} = 216 \pm 15\text{MeV}$

In the SM
for B mesons:

M_{12} dominated by the top quark

Γ_{12} few common on-shell states

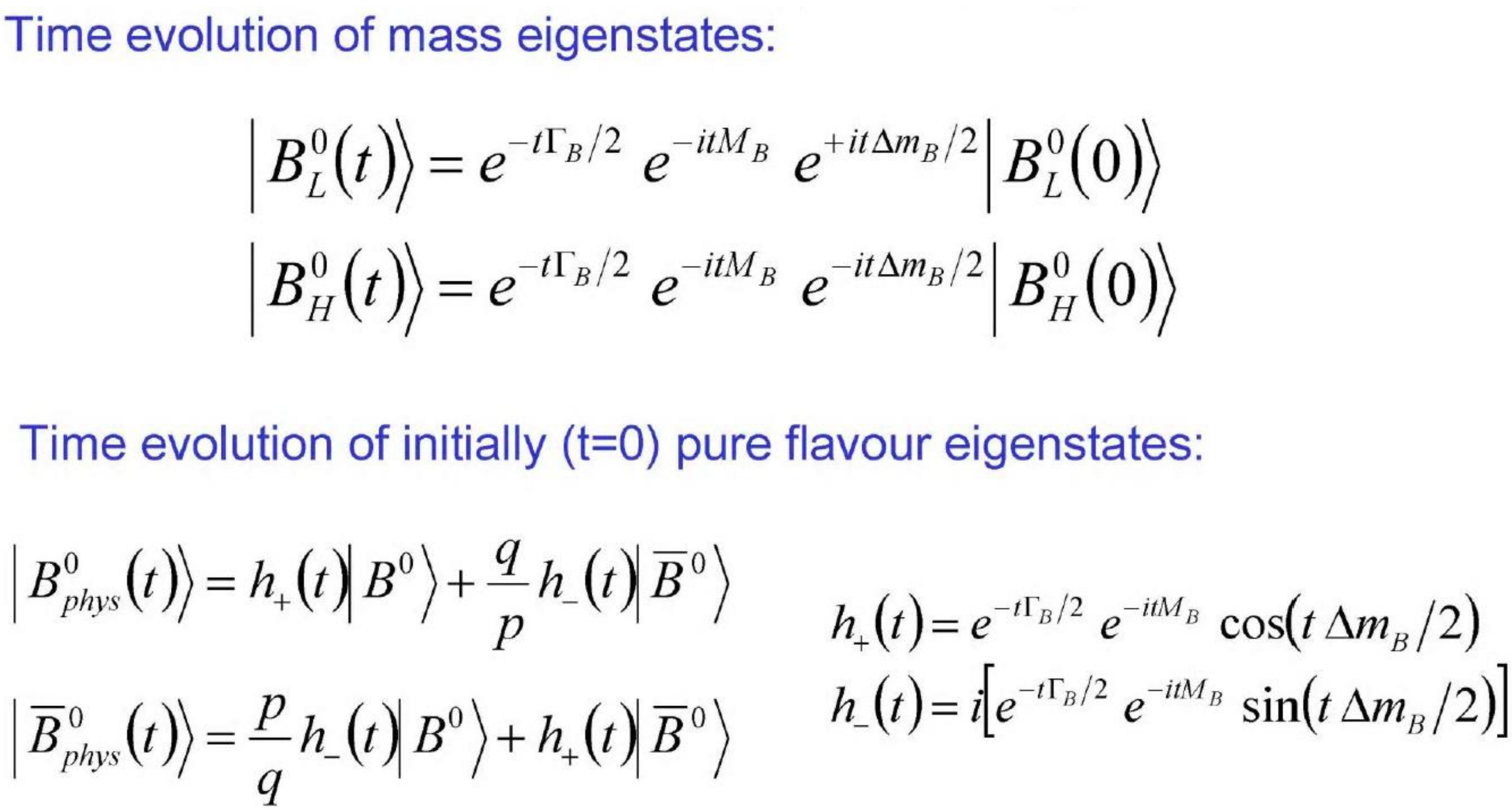
$$\Gamma_{12}/M_{12} << 1$$

$$\Rightarrow \Delta m \approx 2|M_{12}| \qquad \Delta\Gamma \approx \frac{2\Re e\left(M_{12}\Gamma_{12}^*\right)}{|M_{12}|} << \Delta m \qquad \frac{q}{p} = -\frac{\Delta m - i/2\Delta\Gamma}{2M_{12} - i\Gamma_{12}} \approx -\frac{|M_{12}|}{M_{12}}$$

CP-violating parameter: $\delta = |p|^2 - |q|^2 = \langle P_H | P_L \rangle = \dfrac{2\Im m\left(M_{12}^*\Gamma_{12}\right)}{(\Delta m)^2 + |\Gamma_{12}|^2} \approx 10^{-3}$

Time evolution of neutral *B* mesons

Assuming CPT conservation



Time evolution of mass eigenstates:

$$\left|B_L^0(t)\right\rangle = e^{-t\Gamma_B/2}\; e^{-itM_B}\; e^{+it\Delta m_B/2}\left|B_L^0(0)\right\rangle$$

$$\left|B_H^0(t)\right\rangle = e^{-t\Gamma_B/2}\; e^{-itM_B}\; e^{-it\Delta m_B/2}\left|B_H^0(0)\right\rangle$$

Time evolution of initially (t=0) pure flavour eigenstates:

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

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

$$h_+(t) = e^{-t\Gamma_B/2}\; e^{-itM_B}\; \cos(t\,\Delta m_B/2)$$

$$h_-(t) = i\left[e^{-t\Gamma_B/2}\; e^{-itM_B}\; \sin(t\,\Delta m_B/2)\right]$$

Time evolution of neutral *B* mesons

Flavour oscillations: for initially pure $B^0(t=0)$,
probability for finding $B^0\left(\overline{B}^0\right)$ at time t, assuming $|q/p|=1$

$$|h_\pm(t)|^2 = \frac{1}{2}e^{-t\Gamma_B}\left[1 \pm \cos(t\,\Delta m_B)\right] \quad \Rightarrow \quad a_{mix}(t) = \cos(t\,\Delta m) = \cos(x\Gamma t)$$

Time-integrated ratio and time-integrated oscillation probability:

$$r = \frac{N\left(\overline{B}^0\right)}{N\left(B^0\right)} = \frac{\int_0^\infty dt\,|h_-(t)|^2}{\int_0^\infty dt\,|h_+(t)|^2} = \frac{x^2}{2+x^2}, \qquad \chi = \frac{r}{1+r} = P\left(B^0 \to \overline{B}^0\right), \qquad x \equiv \frac{\Delta m}{\Gamma}$$

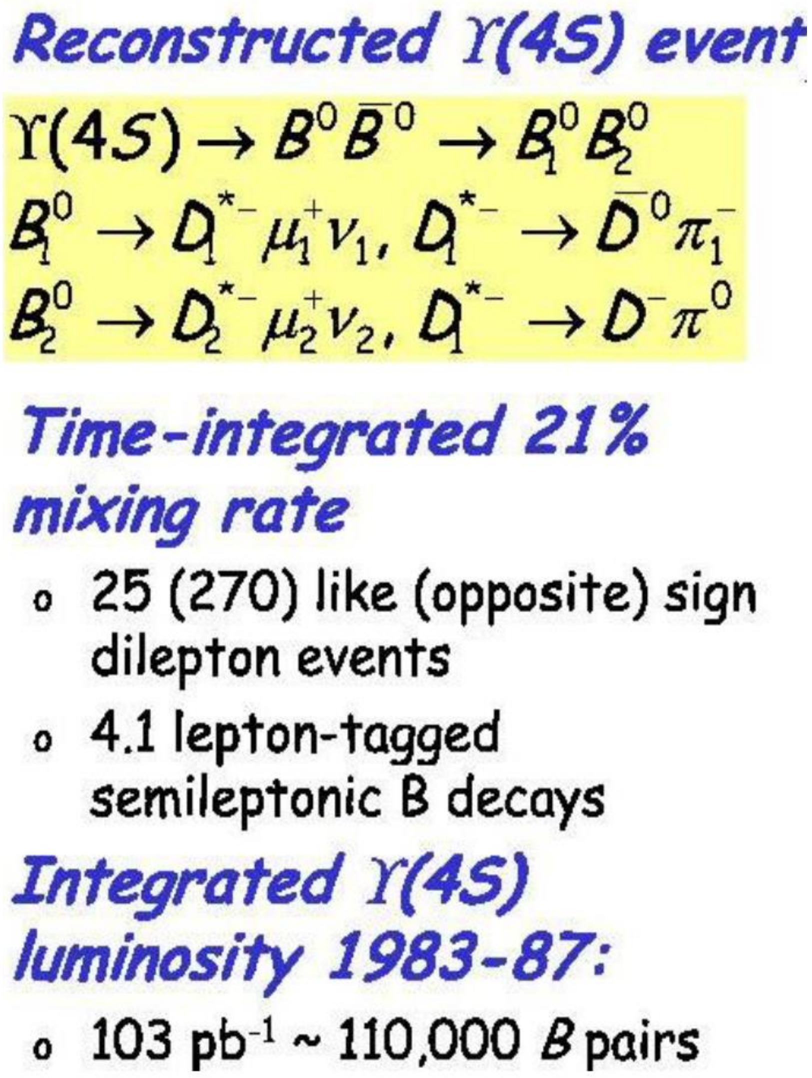
Observable by looking at self-flavour tagging semileptonic or hadronic decays! For example:

$$\begin{array}{ll} B^0 \to D^{*-} l^+ \nu & \overline{B}^0 \to D^{*+} l^- \overline{\nu} \\ B^0 \to D^- \pi^+ & \overline{B}^0 \to D^+ \pi^- \\ B_s^0 \to D_s^- l^+ \nu & \overline{B}_s^0 \to D_s^+ l^- \overline{\nu} \end{array}$$

Discovery $B\bar{B}$ oscillations

ARGUS Collaboration Observation of B – anti-B0 Mixing

PL B 192, 245
1987



Reconstructed $\Upsilon(4S)$ event

$\Upsilon(4S) \to B^0\bar{B}^0 \to B_1^0 B_2^0$

$B_1^0 \to D_1^{*-}\mu_1^+\nu_1,\ D_1^{*-} \to \bar{D}^0\pi_1^-$

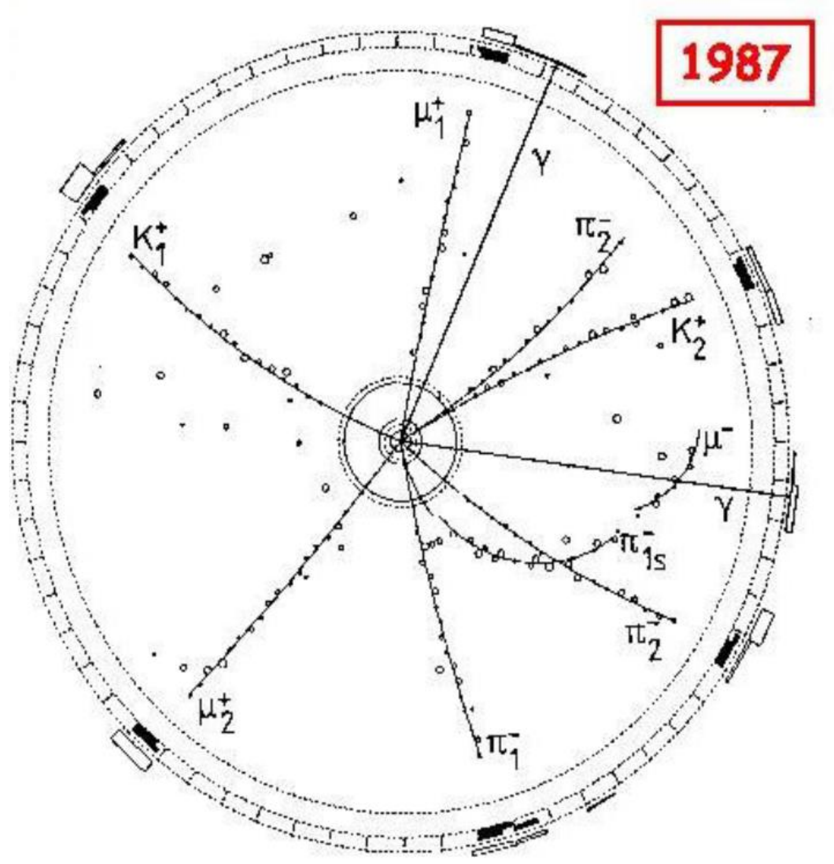
$B_2^0 \to D_2^{*-}\mu_2^+\nu_2,\ D_1^{*-} \to D^-\pi^0$

Time-integrated 21% mixing rate

- 25 (270) like (opposite) sign dilepton events
- 4.1 lepton-tagged semileptonic B decays

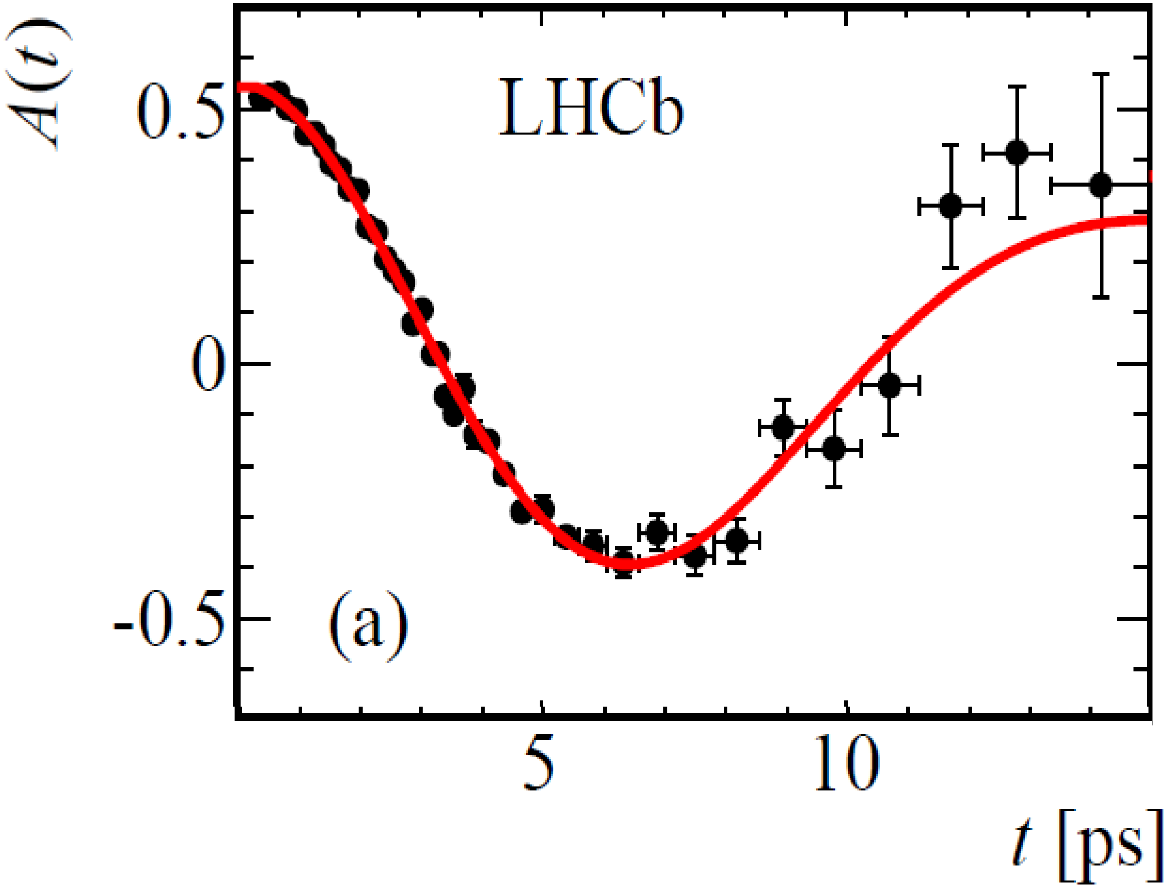
Integrated $\Upsilon(4S)$ luminosity 1983-87:

- 103 pb^{-1} ~ 110,000 *B* pairs



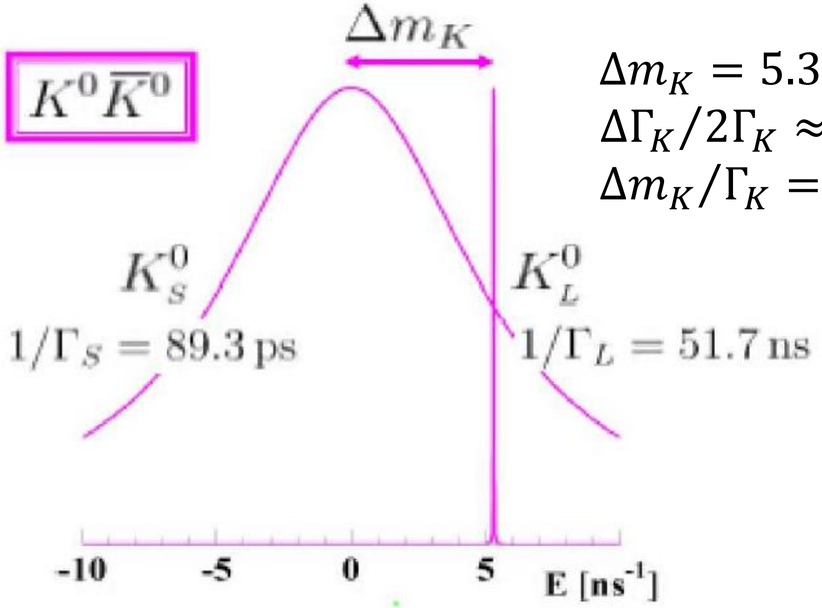
$B_d \bar{B}_d$ Mixing at LHCb

$$A(t) = \frac{N^{\text{unmix}}(t) - N^{\text{mix}}(t)}{N^{\text{unmix}}(t) + N^{\text{mix}}(t)} = \cos(\Delta m_d t)$$

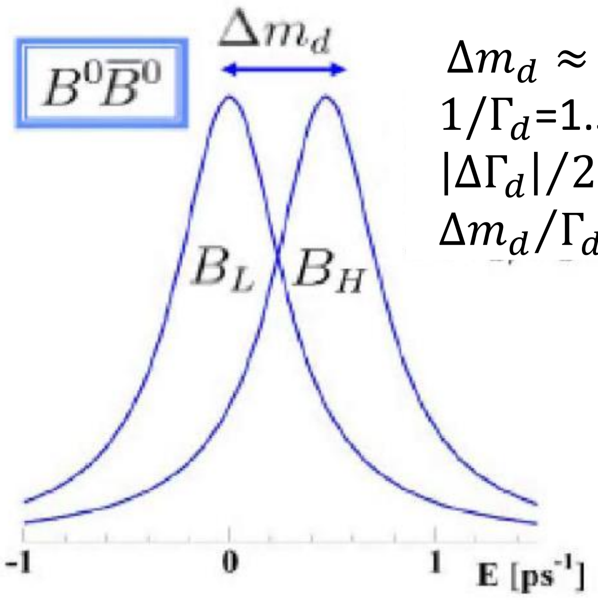


	Δm_d [ns^{-1}]
$B^0 \to D^- \mu^+ \nu_\mu X$	$505.5 \pm 2.7 \pm 1.1$
$B^0 \to D^{*-} \mu^+ \nu_\mu X$	$504.4 \pm 3.4 \pm 1.0$
combination	$505.0 \pm 2.1 \pm 1.0$

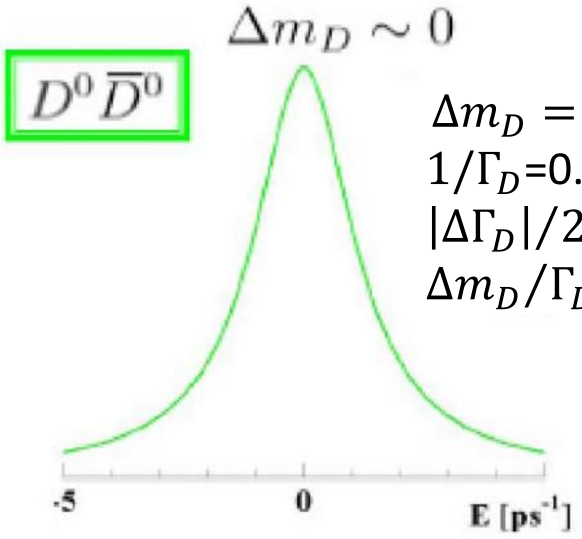
Mixing parameters



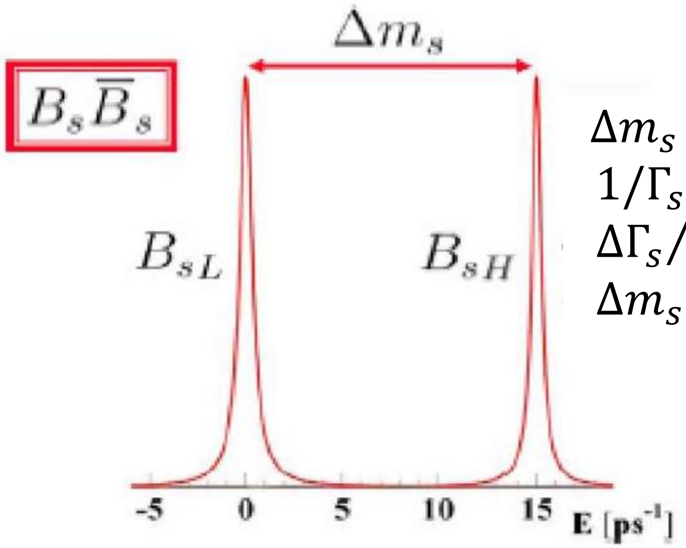
$\Delta m_K = 5.3 ns^{-1}$
$\Delta\Gamma_K/2\Gamma_K \approx -1$
$\Delta m_K/\Gamma_K = 0.945$



$\Delta m_d \approx 0.5 ps^{-1}$
$1/\Gamma_d$=1.56 ps
$|\Delta\Gamma_d|/2\Gamma_d \ll 0.01$
$\Delta m_d/\Gamma_d = 0.77$



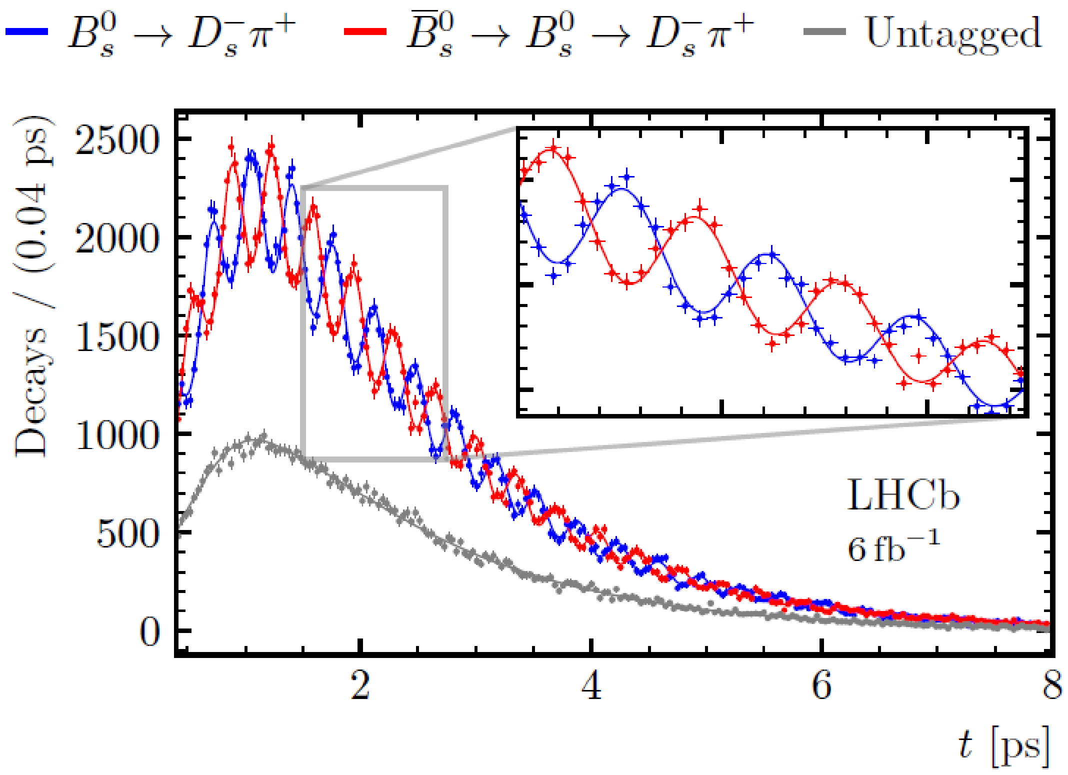
$\Delta m_D = 0.01 ps^{-1}$
$1/\Gamma_D$=0.415 ps
$|\Delta\Gamma_D|/2\Gamma_D = 0.007$
$\Delta m_D/\Gamma_D = 0.004$



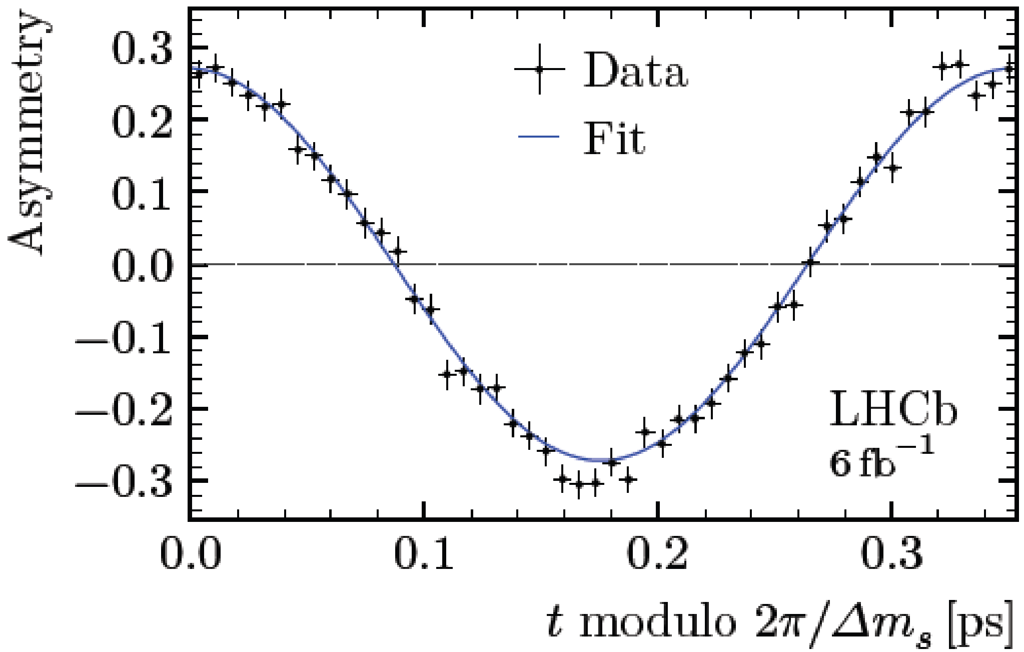
$\Delta m_s = 17.8 ps^{-1}$
$1/\Gamma_s$=1.47 ps
$\Delta\Gamma_s/2\Gamma_s \approx 0.13$
$\Delta m_s/\Gamma_s = 27$

$B_s\overline{B}_s$ Mixing at LHCb

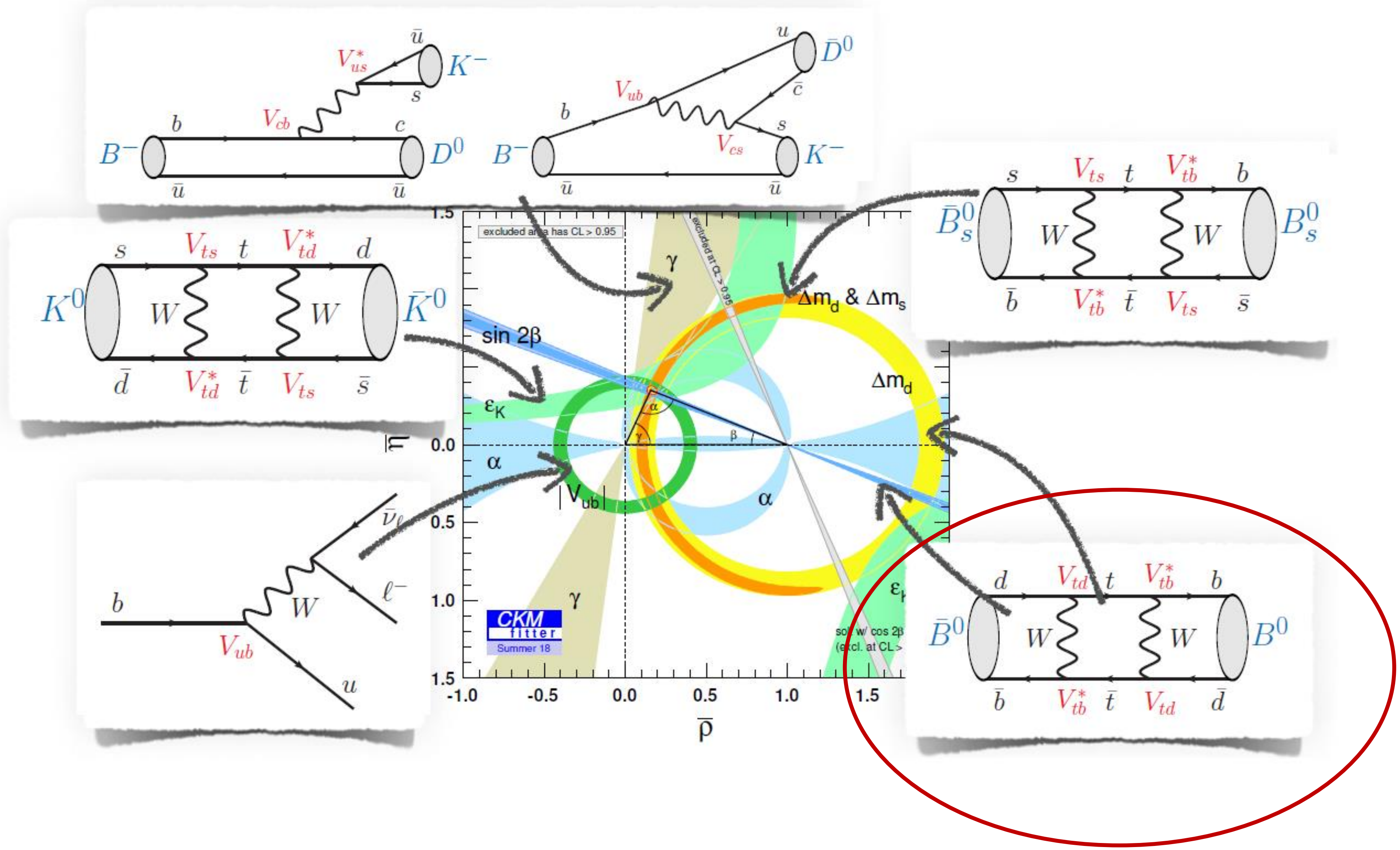
$$A(t) = \frac{N(B_s^0 \to D_s^- \pi^+, t) - N(\overline{B}_s^0 \to D_s^- \pi^+, t)}{N(B_s^0 \to D_s^- \pi^+, t) + N(\overline{B}_s^0 \to D_s^- \pi^+, t)},$$



$$\Delta m_s = 17.7683 \pm 0.0051\,(\text{stat}) \pm 0.0032\,(\text{syst})\,\text{ps}^{-1}$$



CP Violation in B Decays



Classification of CP-violating effects

CPV in decay:

$|\bar{A}_{\bar{f}}/A_f| \neq 1$

$$\mathrm{A}_{CP,f^\pm} \equiv \frac{\Gamma(P^- \to f^-) - \Gamma(P^+ \to f^+)}{\Gamma(P^- \to f^-) + \Gamma(P^+ \to f^+)} = \frac{\left|\bar{A}_{f^-}/A_{f^+}\right|^2 - 1}{\left|\bar{A}_{f^-}/A_{f^+}\right|^2 + 1}$$

CPV in mixing:

$|q/p| \neq 1$

$$\mathrm{A}_{SL}(t) \equiv \frac{d\Gamma/dt\left(\bar{P}^0_{phys} \to l^+ X\right) - d\Gamma/dt\left(P^0_{phys} \to l^- X\right)}{d\Gamma/dt\left(\bar{P}^0_{phys} \to l^+ X\right) + d\Gamma/dt\left(P^0_{phys} \to l^- X\right)} = $$

$$= \frac{1 - |q/p|^4}{1 + |q/p|^4}$$

CPV in the interference decay-mixing:

$\Im\mathrm{m}(\lambda_f) \neq 0$

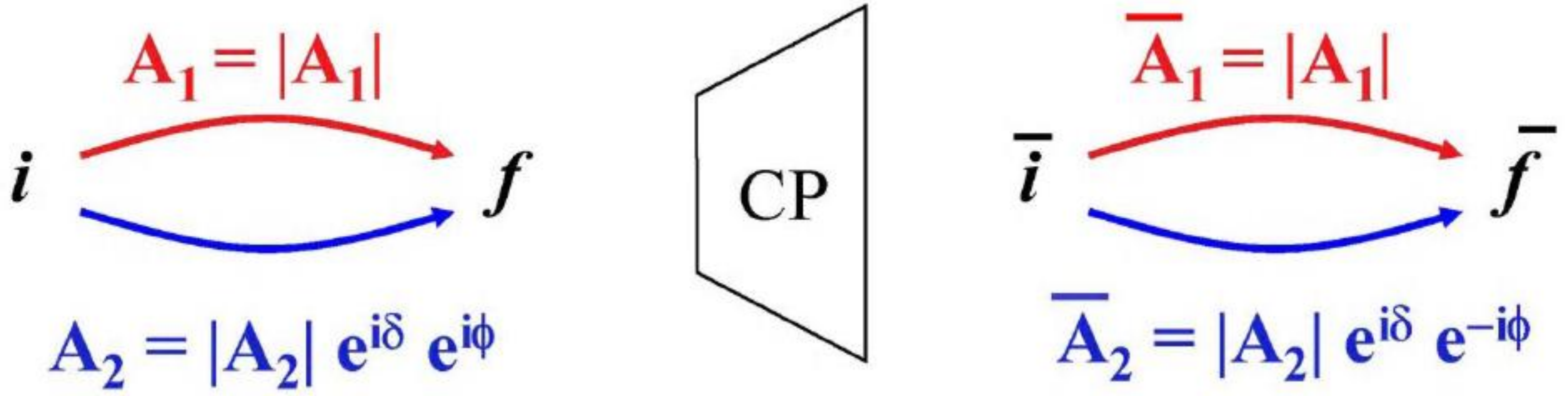
$\lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}$

For example: decays to CP eigenstates f_{CP}

$$\mathrm{A}_{f_{CP}}(t) \equiv \frac{d\Gamma/dt\left(\bar{P}^0_{phys} \to f_{CP}\right) - d\Gamma/dt\left(P^0_{phys} \to f_{CP}\right)}{d\Gamma/dt\left(\bar{P}^0_{phys} \to f_{CP}\right) + d\Gamma/dt\left(P^0_{phys} \to f_{CP}\right)}$$

Carter, Sanda
PRL 45, 952
1980

Observables: “direct” CP-violation



$$\mathbf{A_1 = |A_1|}$$

$$\mathbf{A_2 = |A_2|\, e^{i\delta}\, e^{i\phi}}$$

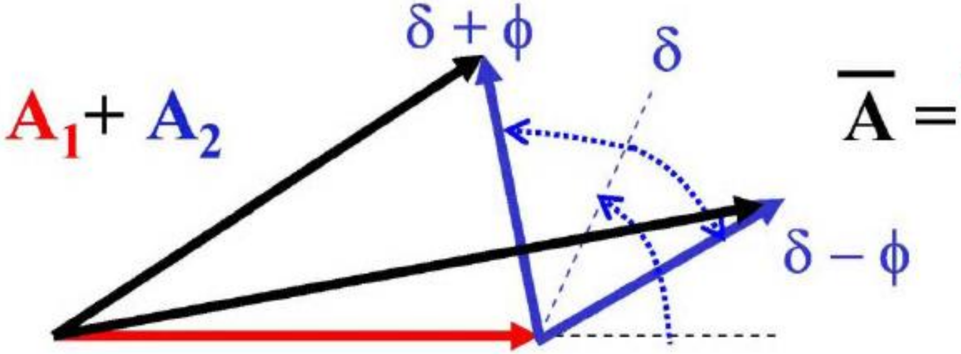
$$\mathbf{\bar{A}_1 = |A_1|}$$

$$\mathbf{\bar{A}_2 = |A_2|\, e^{i\delta}\, e^{-i\phi}}$$

$\delta \rightarrow \delta$ (CP-conserving)
$\phi \rightarrow -\phi$ (CP-violating)

Time-integrated “direct” CP asymmetry requires two amplitudes and $\delta \neq 0$:

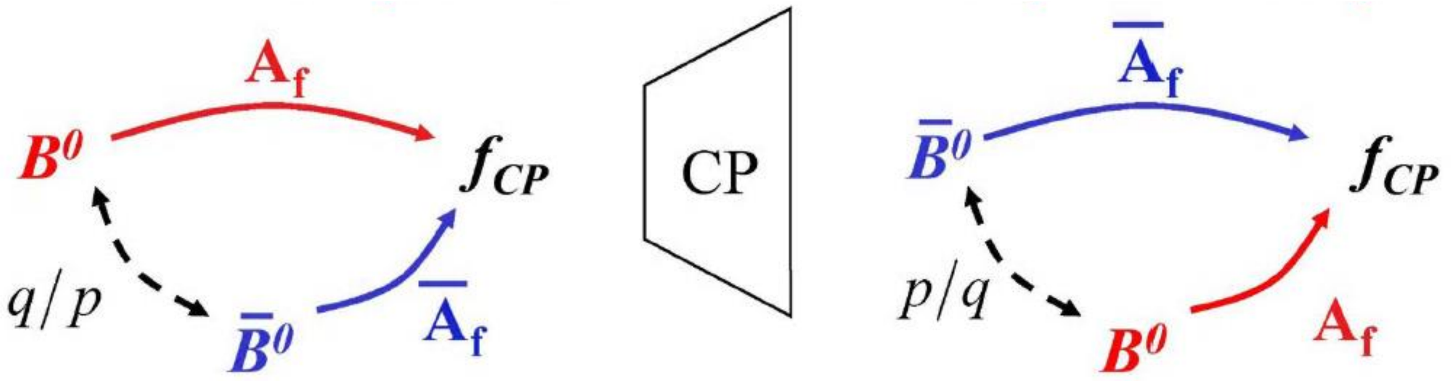
$$\mathbf{A = A_1 + A_2}$$



$$\mathbf{\bar{A} = \bar{A}_1 + \bar{A}_2 \neq A}$$

$$A_{CP} \equiv \frac{\Gamma(i \to f) - \Gamma(\bar{i} \to \bar{f})}{\Gamma(i \to f) + \Gamma(\bar{i} \to \bar{f})} = \frac{2|A_1||A_2| \sin\delta \sin\phi}{|A_1|^2 + |A_2|^2 + 2|A_1||A_2| \cos\delta \cos\phi}$$

CP-violation in the Time Evolution of B^0 mesons



Interference between mixing and decay to a CP eigenstate f_{CP}

$$\Rightarrow \quad \Gamma\left(B^0_{phys}(t) \to f_{CP}\right) \neq \Gamma\left(\bar{B}^0_{phys}(t) \to f_{CP}\right)$$

Flavor-tagged time-dependent decay rates are different!
they are governed by the “CP parameter”:

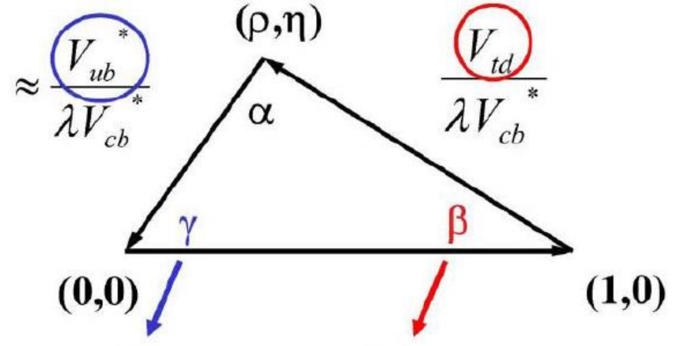
$$\lambda_{f_{CP}} = \eta_{f_{CP}} \frac{q}{p} \frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}$$

CP eigenvalue

$\approx e^{-i2\beta}$ from mixing

Amplitude ratio

$$\frac{q}{p} = -\frac{\Delta m - i/2\Delta\Gamma}{2M_{12} - i\Gamma_{12}} \approx -\frac{|M_{12}|}{M_{12}}$$



$\gamma \approx \arg V_{ub}^* \quad \beta \approx -\arg V_{td} \quad \alpha = \pi - \beta - \gamma$

CP-violation in the Time Evolution of B^0 mesons

Decay distributions $f_+(f_-)$ when tag = $B^0(\bar{B}^0)$, pair-produced at $\Upsilon(4S)$

$$f_{CP,\pm}(\Delta t) = \frac{\Gamma}{4} e^{-\Gamma \Delta t}[1 \pm S_{f_{CP}} \sin \Delta m_d \Delta t \mp C_{f_{CP}} \cos \Delta m_d \Delta t]$$

Asymmetry

$$A_{f_{CP}}(\Delta t) = C_{f_{CP}} \cos(\Delta m_d \Delta t) - S_{f_{CP}} \sin(\Delta m_d \Delta t)$$

CP parameter

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

$$\boxed{\begin{aligned} C_{f_{CP}} &= \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2} \\ S_{f_{CP}} &= \frac{-2 \operatorname{Im} \lambda_{f_{CP}}}{1 + |\lambda_{f_{CP}}|^2} \end{aligned}}$$

For single decay amplitude

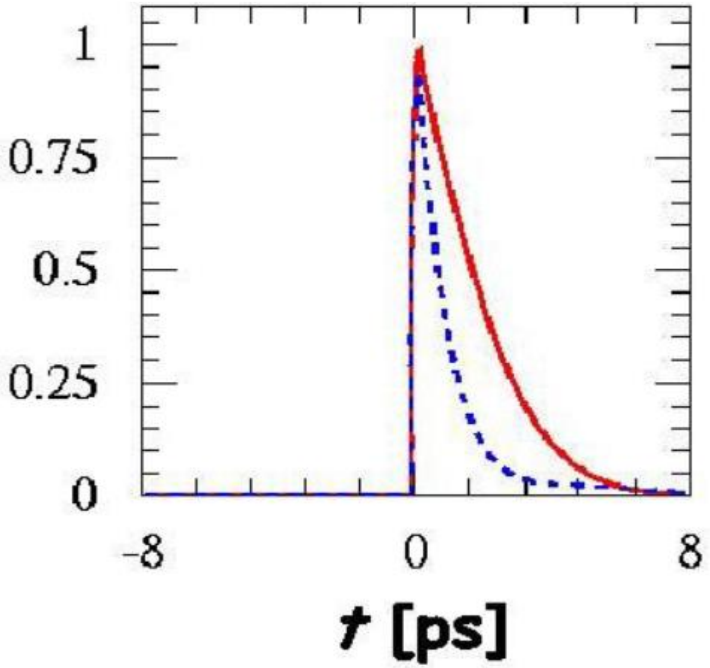
$$= 0$$

$$= -\operatorname{Im} \lambda_{f_{CP}}$$

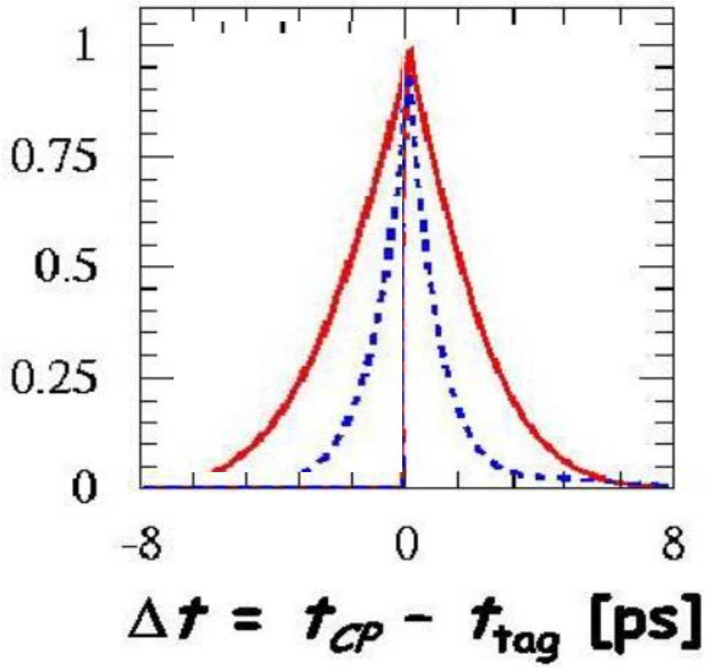
CP-violation in the Time Evolution of B^0 mesons

Time Evolution of the Tagged $B^0(\bar{B}^0) \rightarrow B_{CP}$

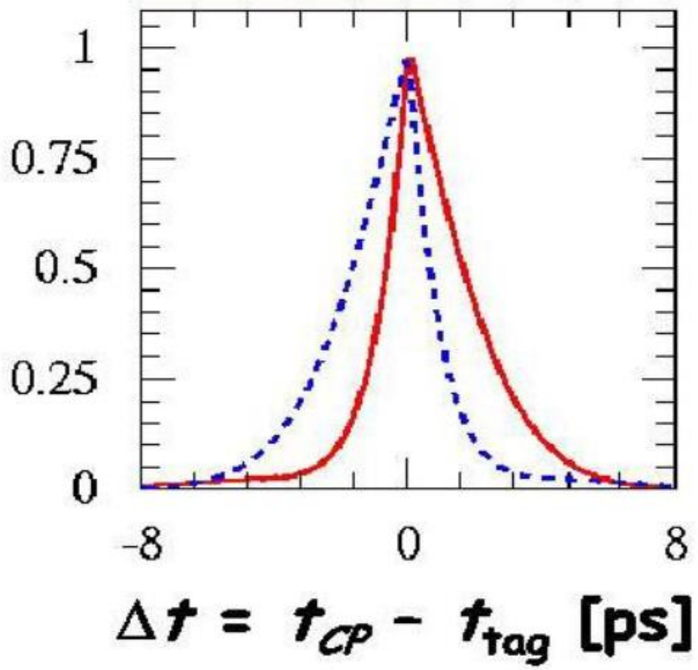
Incoherent $B_{J0}^{+} \rightarrow B^0\pi^+$



Coherent $e^+e^- \rightarrow B^0\bar{B}^{0*} \rightarrow B^0\bar{B}^0\gamma$

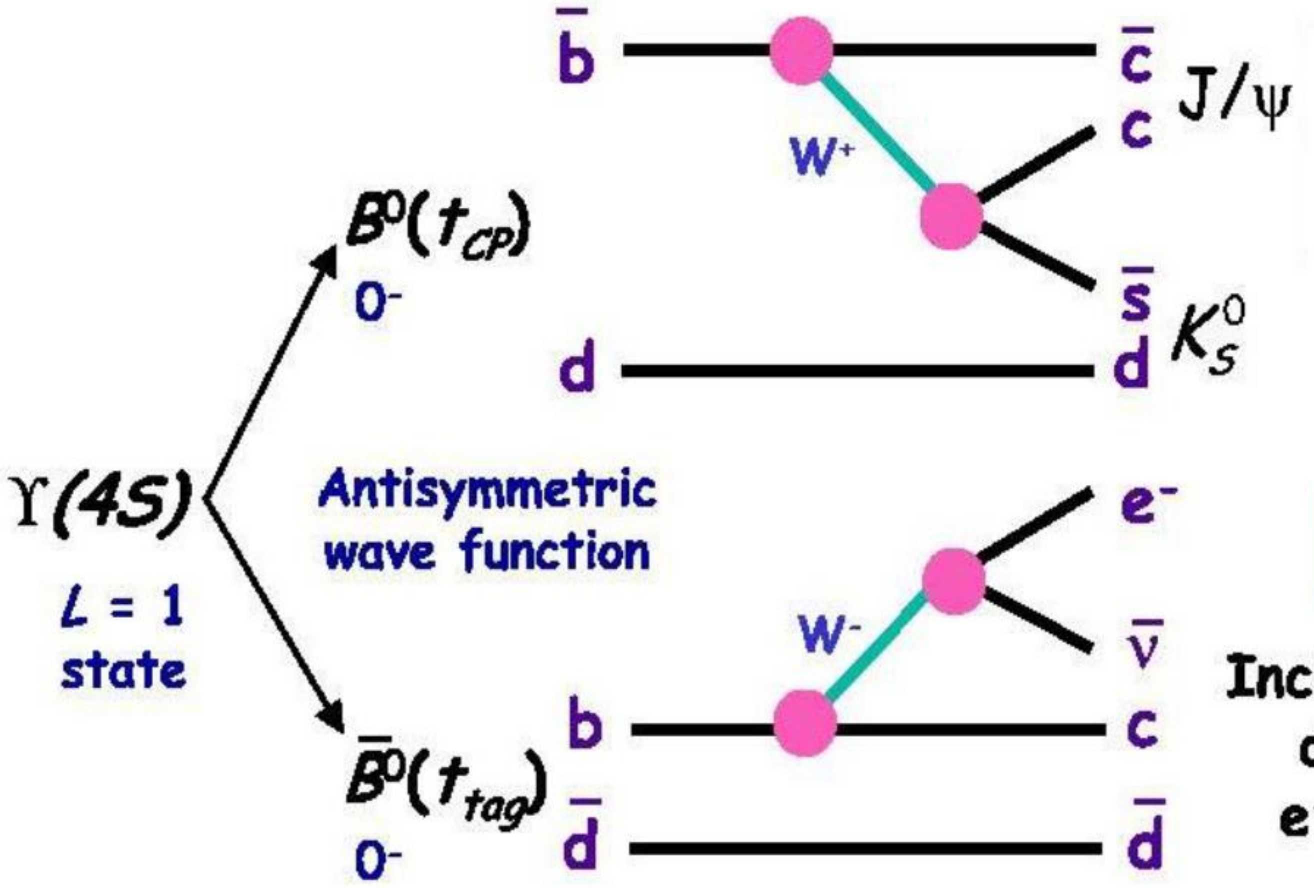


Coherent $e^+e^- \rightarrow B^0\bar{B}^0$



For antisymmetric source of $B^0\bar{B}^0$, integrated CP asymmetry is zero: must do a time-dependent measurements

Golden Channel



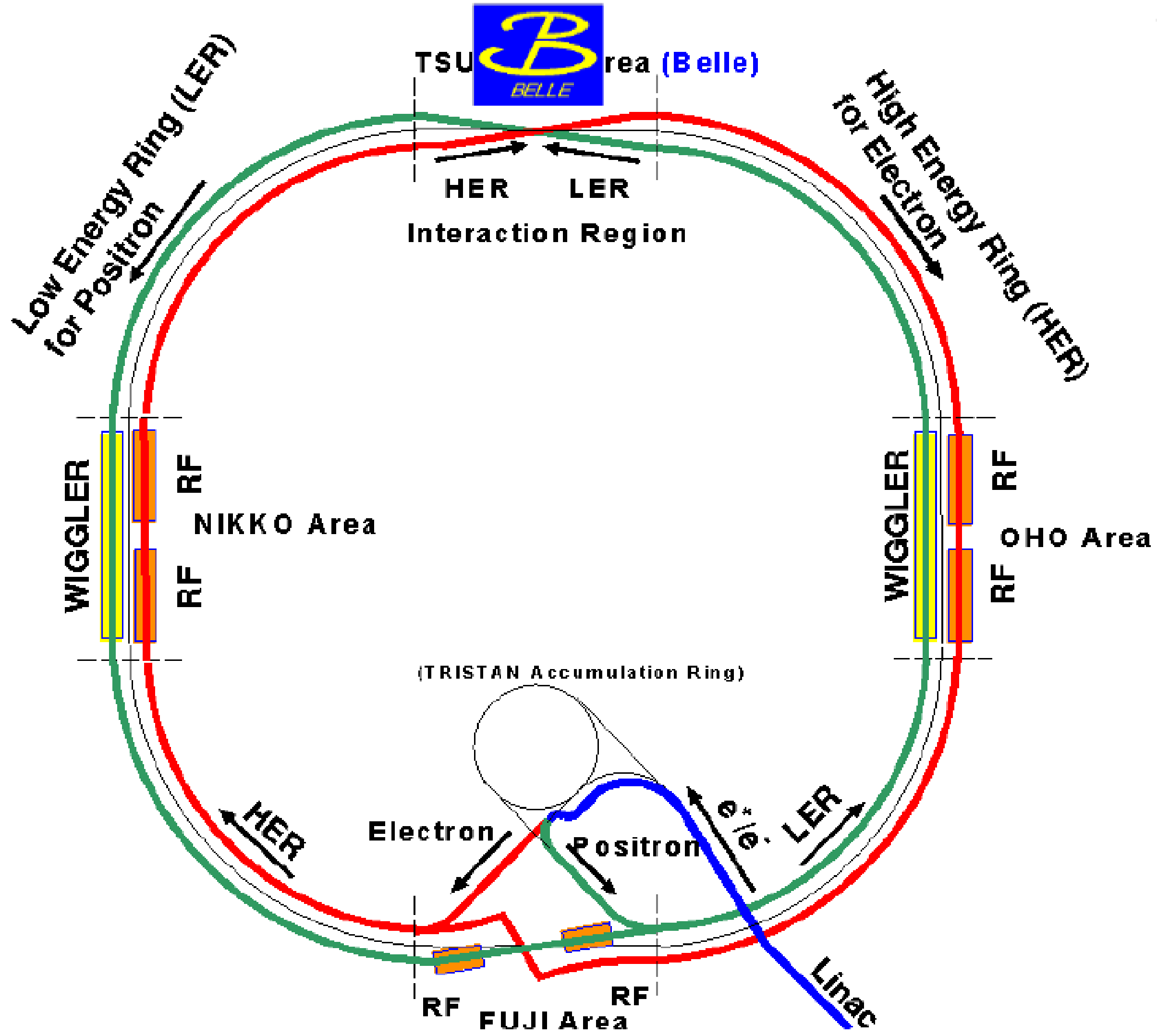
$$\Delta t = t_{CP} - t_{tag}$$

$$\boxed{B_{tag}(t_{tag}) = \bar{B}^0}$$

Inclusively tagged with decay product(s): e^-, μ^-, or K^- signal

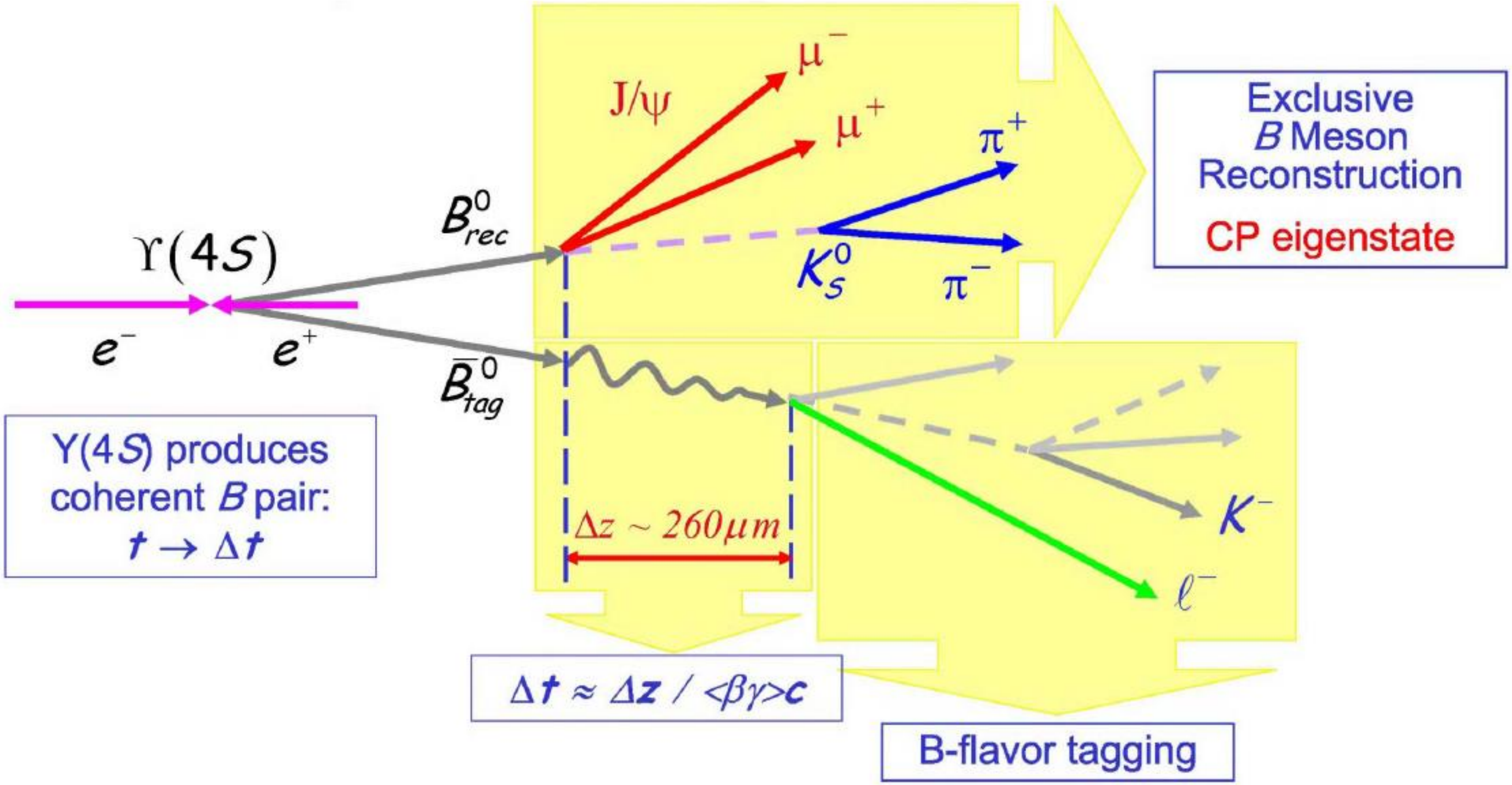
$$A_{f_{CP}}(\Delta t) = \frac{\Gamma(\bar{B}^0_{phys}(\Delta t) \to f_{CP}) - \Gamma(B^0_{phys}(\Delta t) \to f_{CP})}{\Gamma(\bar{B}^0_{phys}(\Delta t) \to f_{CP}) + \Gamma(B^0_{phys}(\Delta t) \to f_{CP})} = \sin 2\beta \sin \Delta m_d \Delta t$$

KEKB asymmetric e^+e^- collider



- Two separate rings
  - e^+ (LER) : 3.5 GeV
  - e^- (HER) : 8.0 GeV
  - $\beta\gamma = 0.425$
- E_{CM} : 10.58 GeV at Y(4S)
- Design:
  - Luminosity: 10^{34} $cm^{-2}s^{-1}$
  - Current: 2.6 / 1.1A (LER HER)
- Beam size: $\sigma_y \approx 3\ \mu m$
  - $\sigma_x \approx 100\ \mu m$
- ±11 mrad crossing angle

Time-Dependent CP Asymmetry Measurement



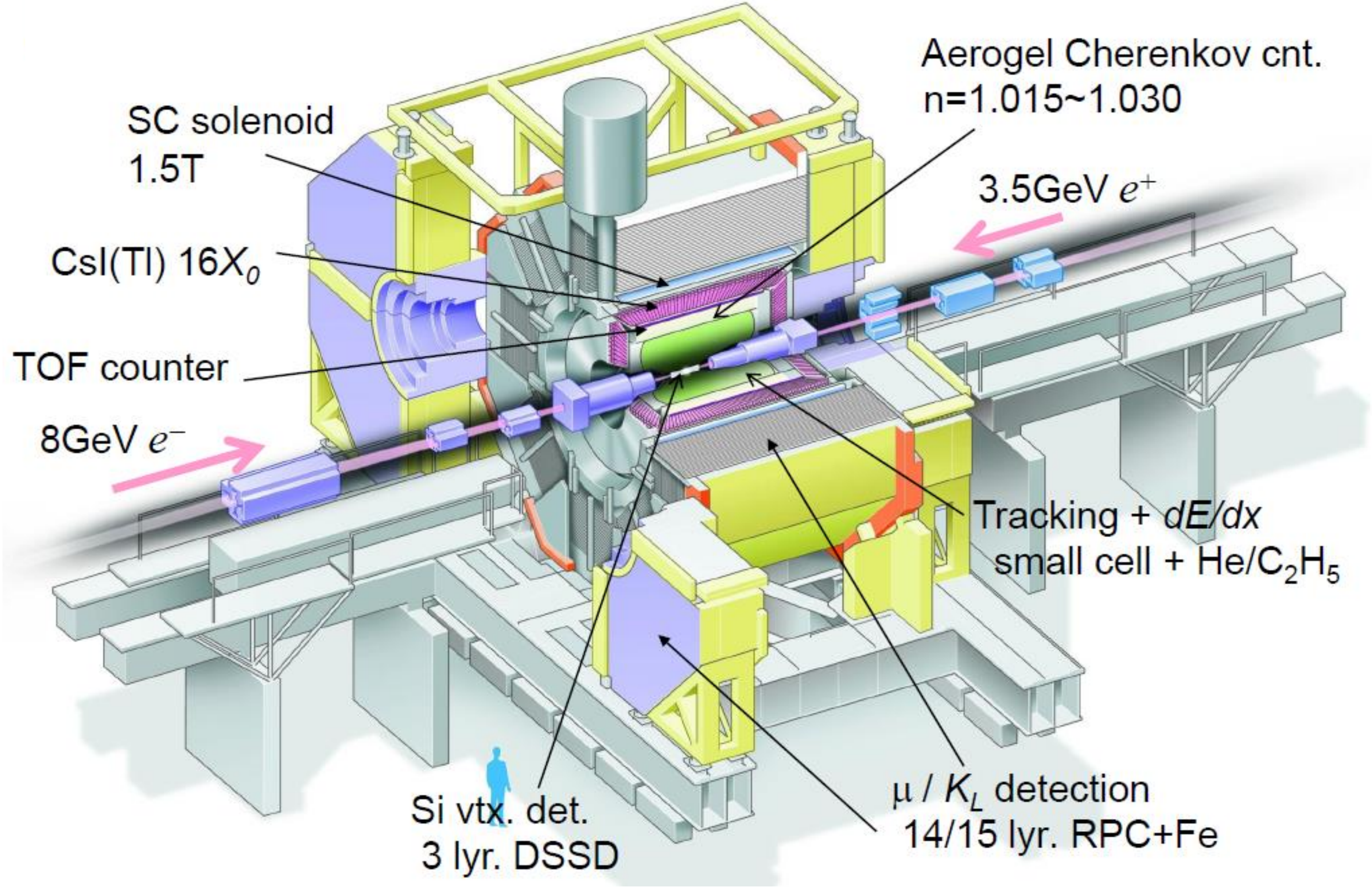
Υ(4*S*) produces coherent *B* pair:
$t \to \Delta t$

Exclusive
B Meson
Reconstruction
CP eigenstate

$\Delta t \approx \Delta z \,/\, \langle\beta\gamma\rangle c$

B-flavor tagging

Detector Belle



SC solenoid
1.5T

CsI(Tl) $16X_0$

TOF counter

8GeV e^-

Aerogel Cherenkov cnt.
n=1.015~1.030

3.5GeV e^+

Tracking + dE/dx
small cell + He/C_2H_5

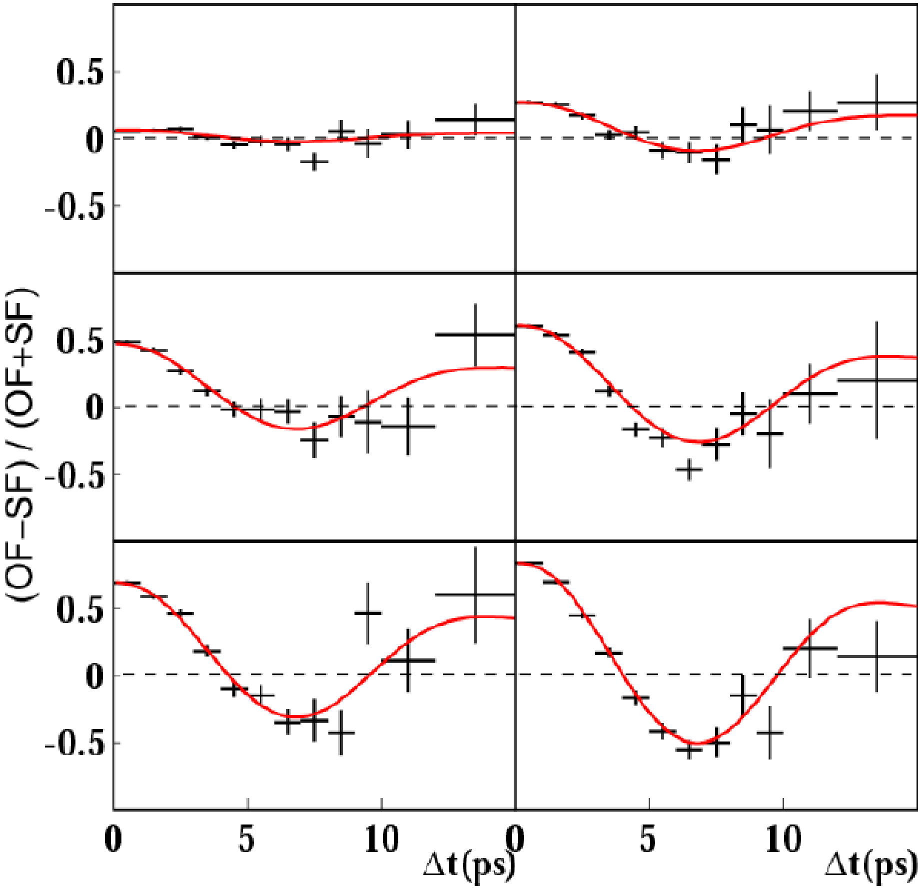
Si vtx. det.
3 lyr. DSSD

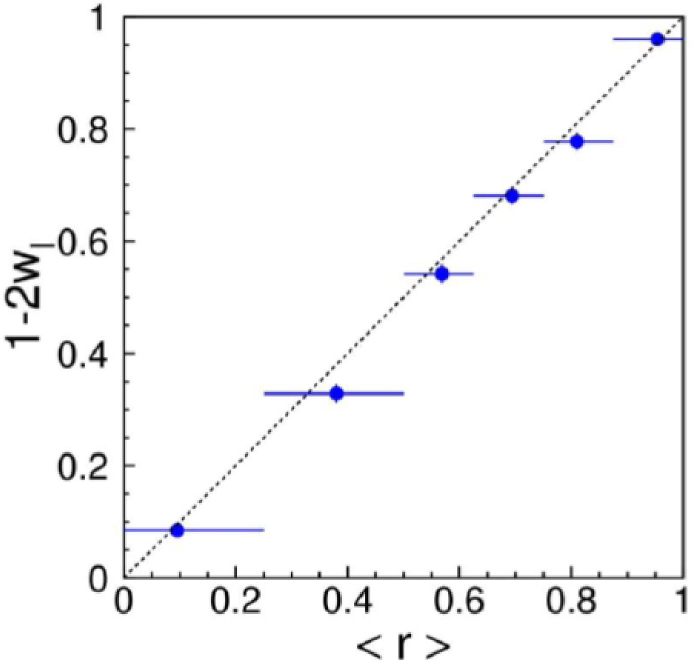
μ / K_L detection
14/15 lyr. RPC+Fe

Flavour tagging – dilution factor

$B^0 B^0 \rightarrow D^* l \nu$: reconstruction

↳ tag





Efficiency > 99.5%

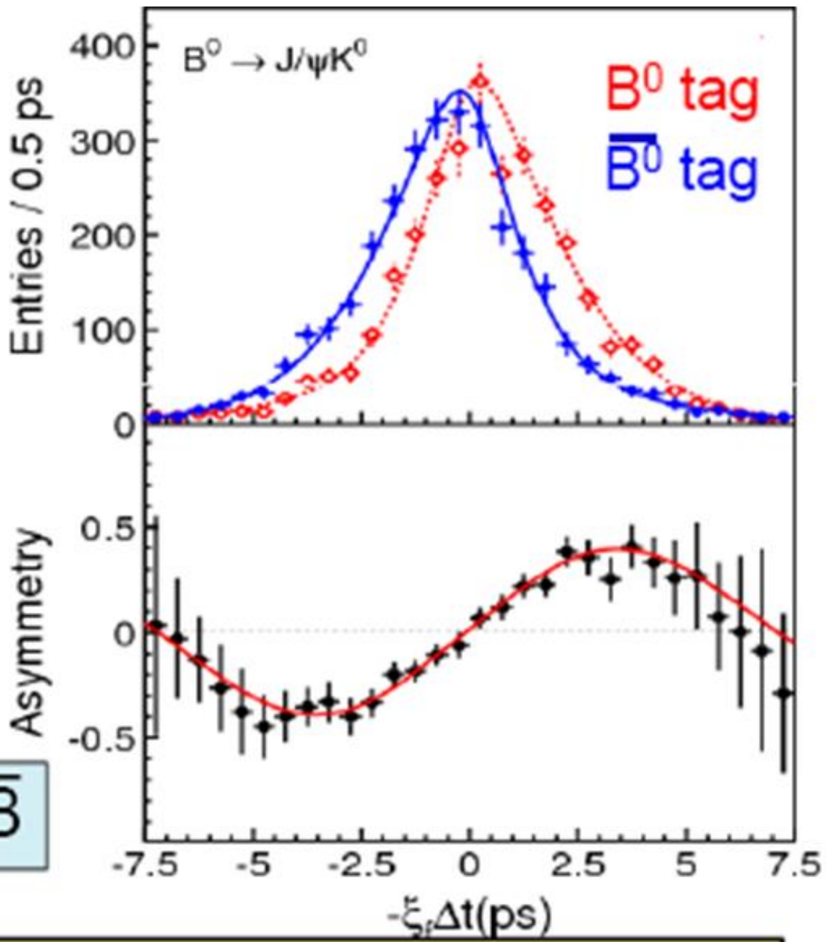
$\varepsilon_{\text{effective}} = 28.8 \pm 0.5\%$

CP asymmetry

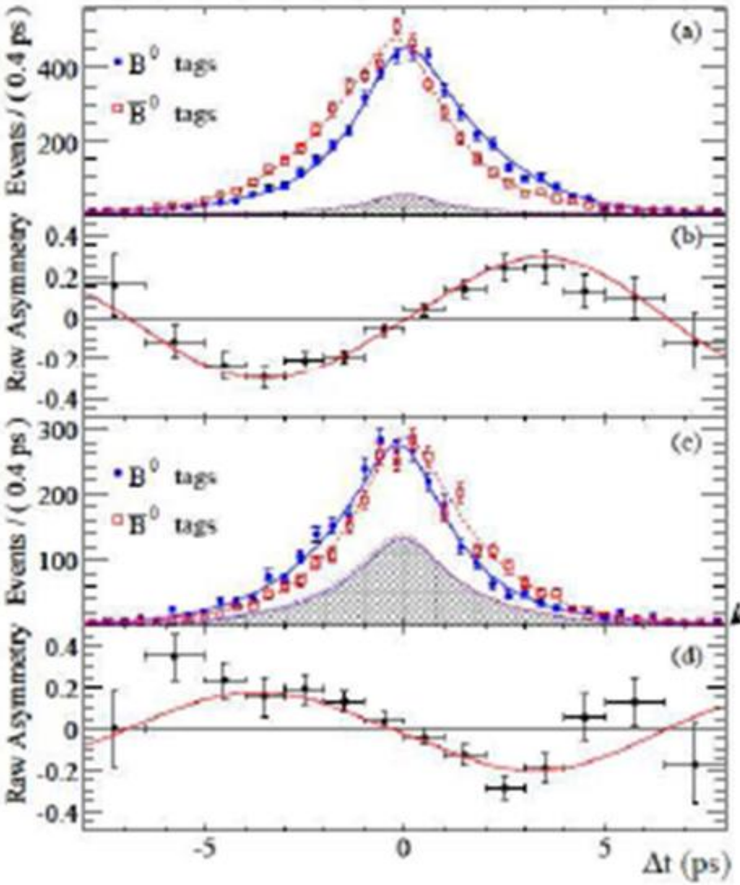
Sum of $J/\psi\ K_S$ and $J/\psi\ K_L$

[PRD98, 031802 (2007)]

535M $B\bar{B}$



$\sin 2\phi_1 = 0.642 \pm 0.031 \pm 0.017$



$J/\Psi\ K_S$
$\Psi(2S)\ K_S$
$\chi_{c1}\ K_S$
$\eta_c\ K_S$

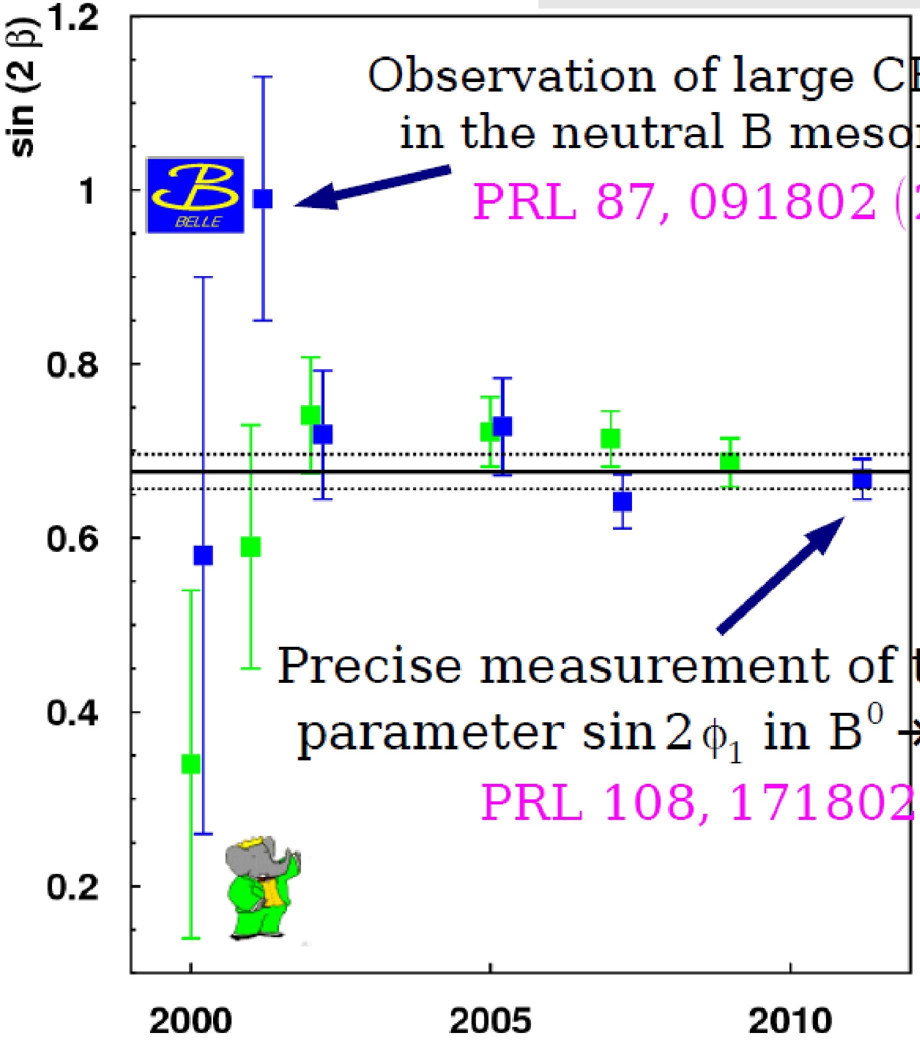
$J/\psi\ K_L$

[PRD79, 072009 (2009)]

465M $B\bar{B}$

$\sin 2\phi_1 = 0.687 \pm 0.028 \pm 0.012$

SIN(2β)



Observation of large CP violation in the neutral B meson system

PRL 87, 091802 (2001)

Precise measurement of the CP violation parameter $\sin 2\phi_1$ in $B^0 \to (c\bar{c})K^0$ decays

PRL 108, 171802 (2012)

2008 Nobel Prize in Physics

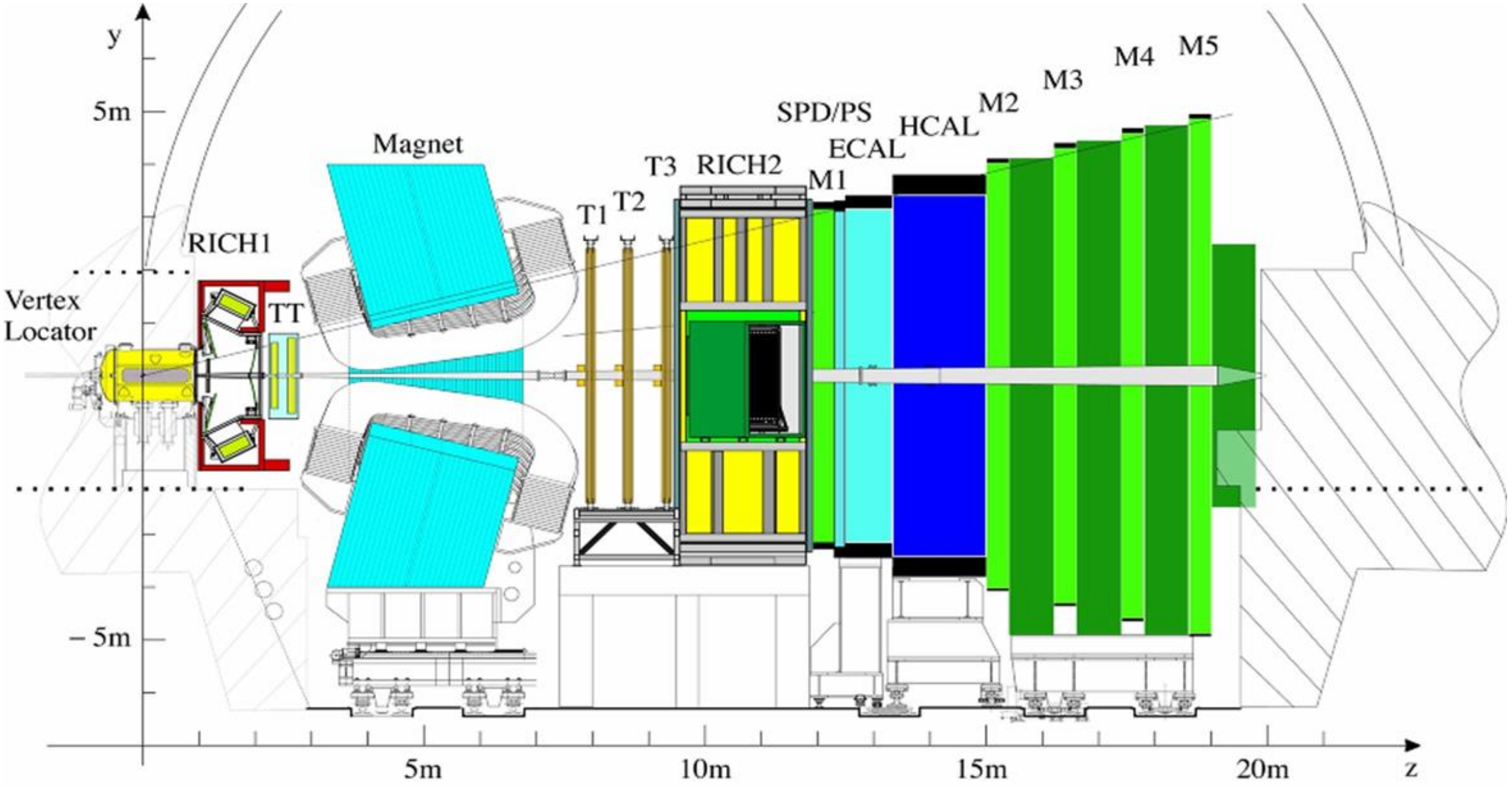
Makoto Kobayashi
Toshihide Maskawa

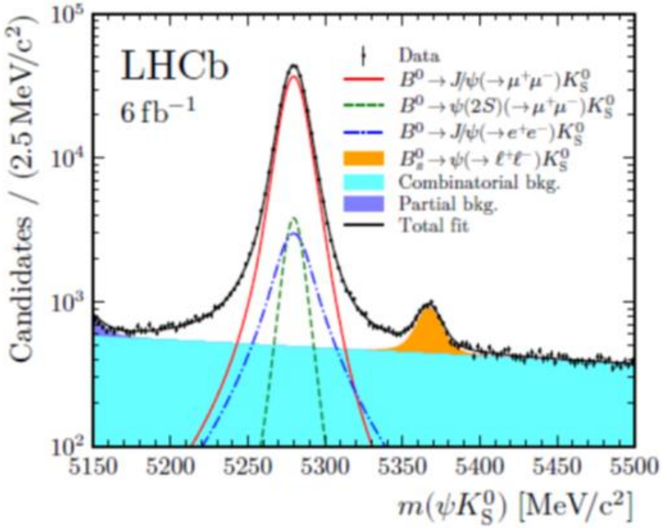
for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature

CP Violation

LHCb

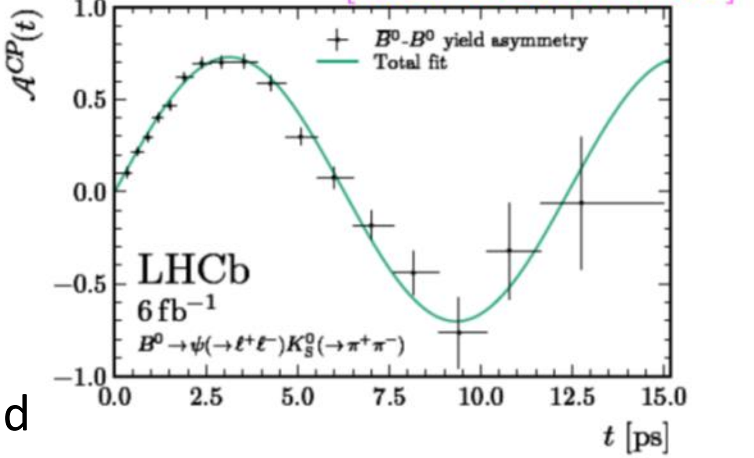
Search for New Physics by studying rare processes and precision CP violation measurements in B and D sectors





$$S(\psi K^0_S) = 0.717 \pm 0.013 \pm 0.008$$
$$C(\psi K^0_S) = 0.008 \pm 0.012 \pm 0.003$$

[arXiv:2309.09728]



- ✓ Good vertexing - Measure B_d /B_s oscillations, reject prompt background
- ✓ Particle identification - Flavour tagging, misID background
- ✓ Calorimetry - Reconstruction of neutral particles (γ, π^0)
- ✓ Efficient trigger, including hadronic modes

CP-violation in the Time Evolution of B^0 mesons

Time-dependent decay rate for $B^0_{phys} \to f$:

$$\frac{d\Gamma\left(B^0_{phys}(t)\to f\right)}{dt} = \left|\left\langle f\left|H\right|B^0_{phys}(t)\right\rangle\right|^2 =$$

$$= \frac{e^{-\Gamma t}}{2}\left[\begin{array}{l}\left(1+\cos(\Delta m\, t)\right)\left|A_f\right|^2 + \\ +\left(1-\cos(\Delta m\, t)\right)\left|\frac{q}{p}\right|^2\left|\overline{A}_f\right|^2 - \\ -2\Im\mathrm{m}\left(\frac{q}{p}A_f^*\overline{A}_f\right)\sin(\Delta m\, t)\end{array}\right] = \frac{e^{-\Gamma t}}{2}\left|A_f\right|^2\left[\begin{array}{l}\left(1+\cos(\Delta m\, t)\right)+ \\ +\left(1-\cos(\Delta m\, t)\right)\left|\lambda_f\right|^2 - \\ -2\Im\mathrm{m}(\lambda_f)\sin(\Delta m\, t)\end{array}\right]$$

"decay"

"oscillation, then decay"

"interference"

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

Historical Remarks

Carter, Sanda CP Nonconservation in Cascade Decays of B Mesons

PRL 45, 952
1980

$$e^+e^- \to \text{“}\Upsilon\text{”} \to B_d^0\bar{B}_d^0 + X_1 \to K^\pm K_S + X^\mp$$

$$(\Gamma - \bar{\Gamma})/(\Gamma + \bar{\Gamma}) \cong -x\alpha \sin 2\varphi/(1 + y\cos 2\varphi),$$

where $\varphi = \arg(U_{bt}U_{sc}U_{bc}{}^*)$.

Bigi, Sanda Notes on the Observability of CP Violations in B Decays

Nucl. Phys. B193, 85
1981

$$\begin{tikzcd}
\mathbf{B}_d^0 \arrow[dr] & \\
& \psi \mathbf{K}_S \\
\bar{\mathbf{B}}_d^0 \arrow[ur] &
\end{tikzcd}$$

Great idea! But is it practical?

$$\underbrace{\mathcal{B}(B^0 \to K_S J/\psi)}_{\sim 10^{-3}} \underbrace{\mathcal{B}(K_S \to \pi^+\pi^-)\mathcal{B}(J/\psi \to \ell\ell)}_{\sim 10^{-1}} \underbrace{(\epsilon_{\text{trk}})^4 \epsilon_{\text{eff}}^{\text{tag}}}_{\sim 10^{-1}} \approx 10^{-5}$$

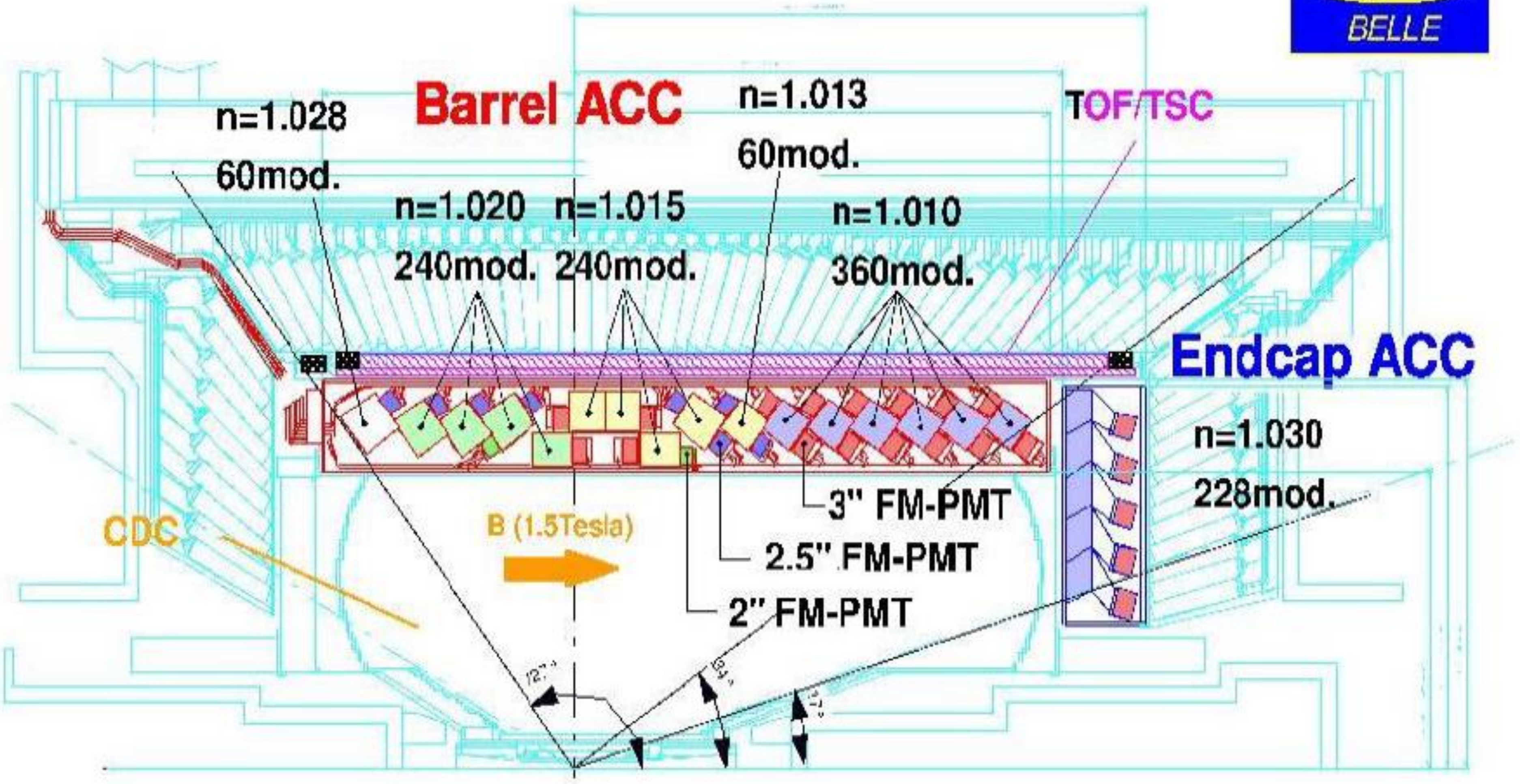
How large fraction of B^0 oscillate into a $\bar{B}^0$ before they decay?

How measure Δt at $\Upsilon(4S)$?

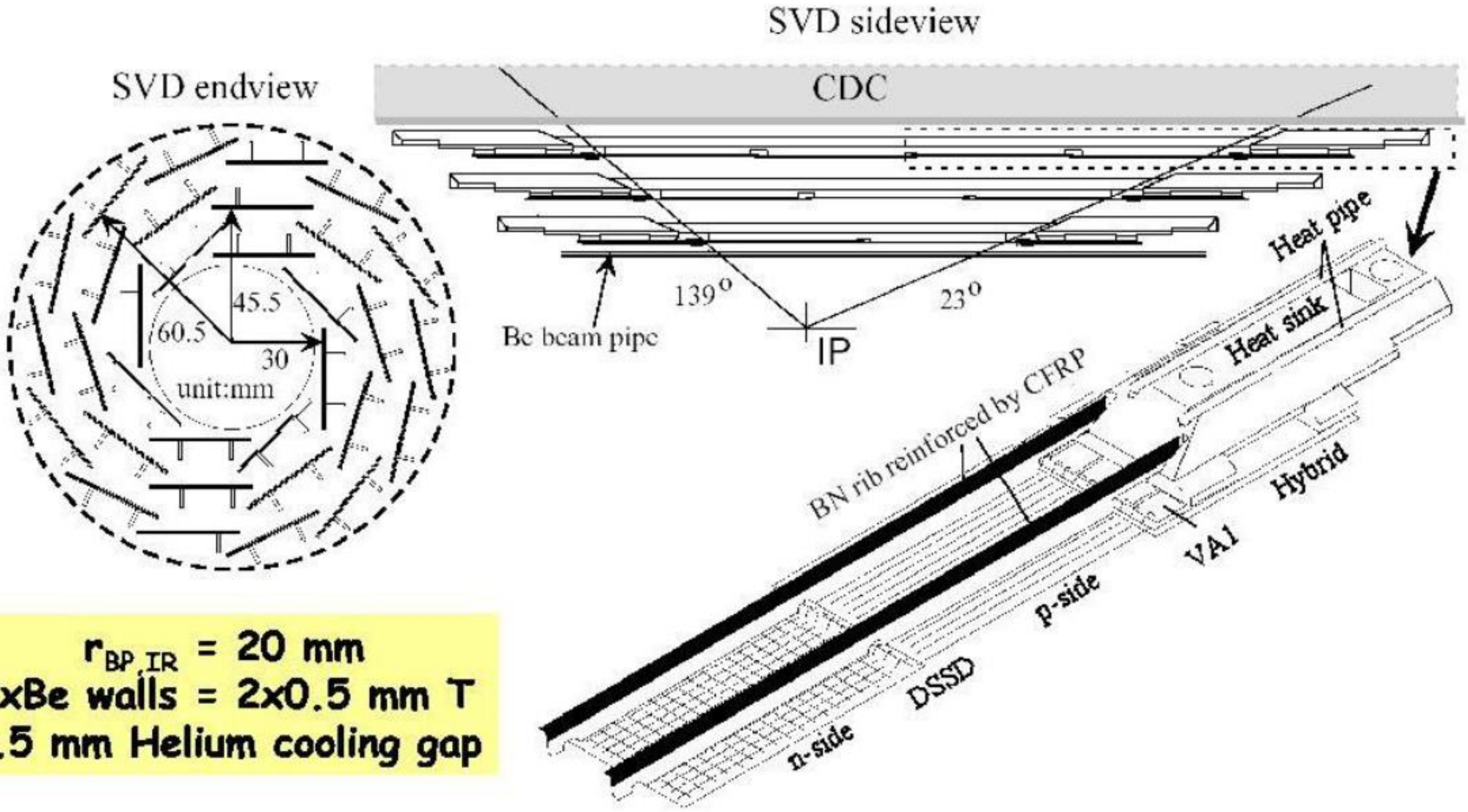
Odonne Concept of Asymmetric e+e- B Factory

Proceedings, Conference on Linear Collider, Los Angeles, 26-30 Jan. 1987

Particle Identification System at Belle



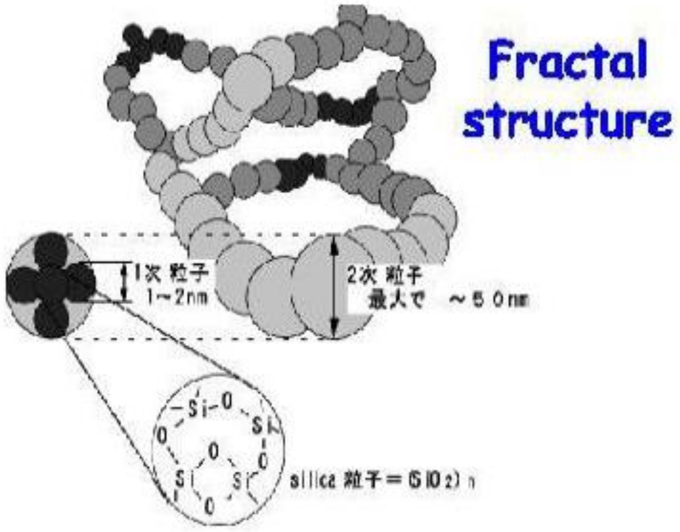
Silicon Vertex Detector at Belle



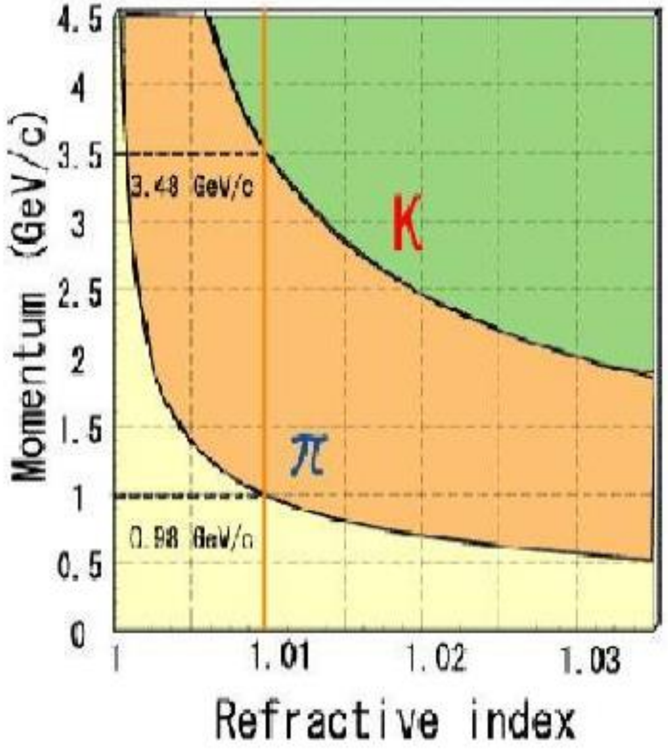
$r_{BP,IR}$ = 20 mm
2xBe walls = 2x0.5 mm T
2.5 mm Helium cooling gap

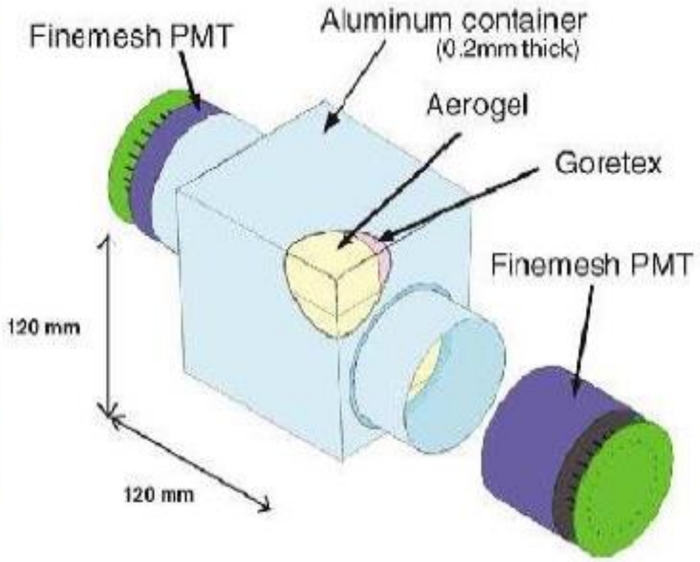
Aerogel Cherenkov Counters

- Hydrophobic silica-aerogels
- n = 1.01~1.028 (barrel), 1.03 (endcap)
- 960 modules (barrel) ->1560 PMT's
- 228 modules (endcap) -> 228 PMT's



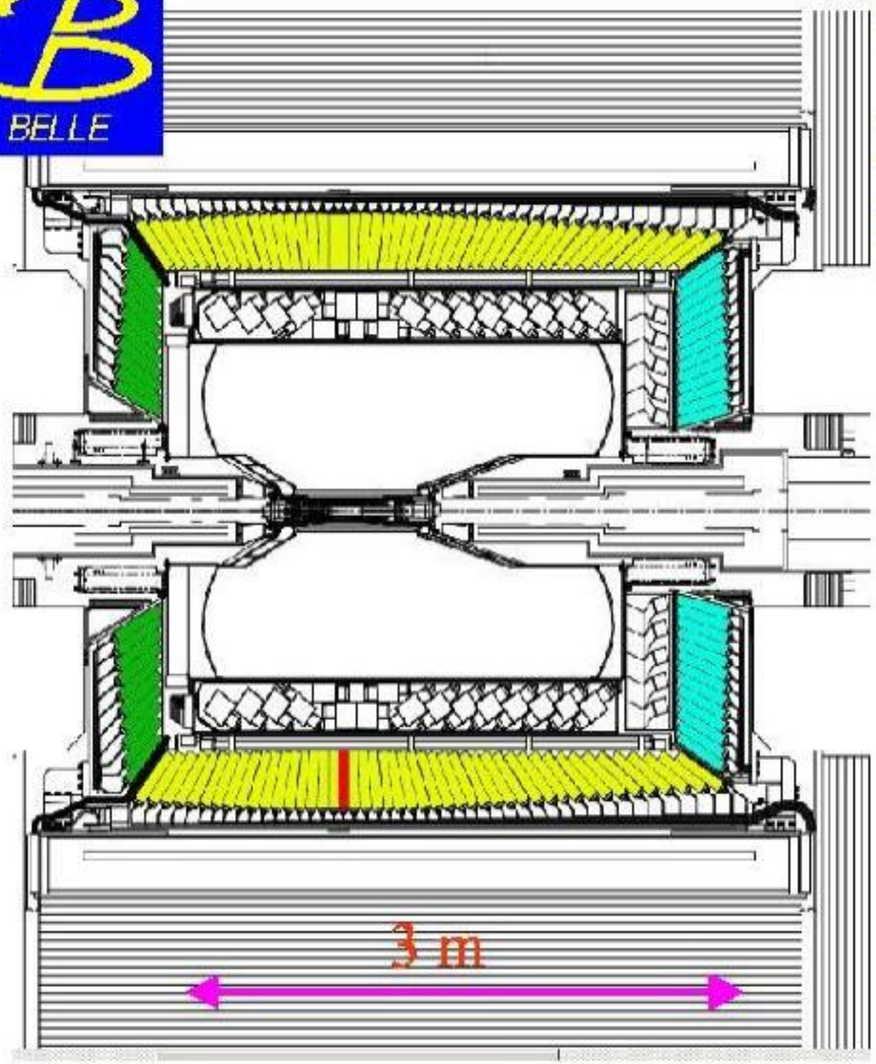
Cherenkov light thresholds



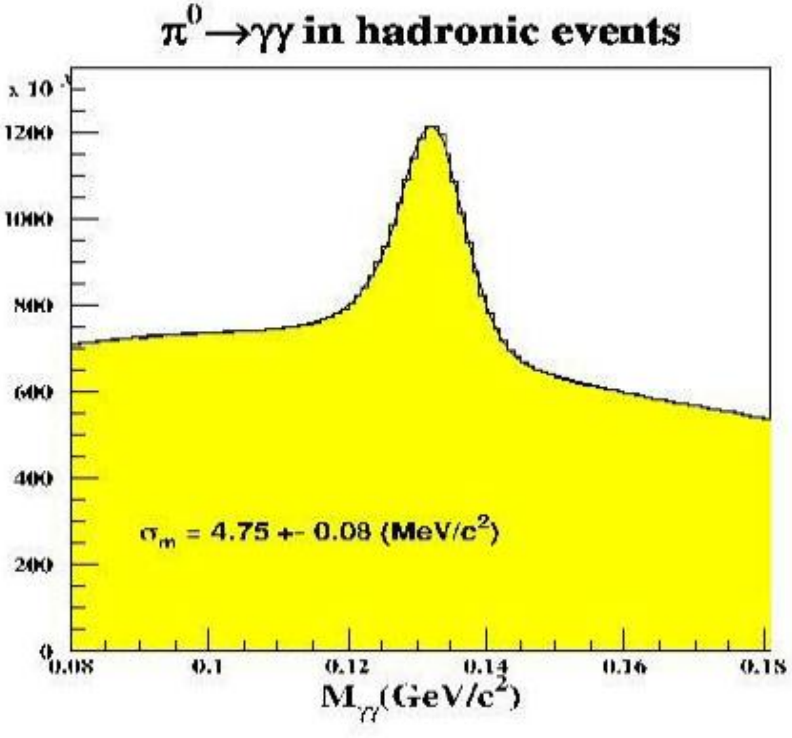


Electromagnetic Calorimeter

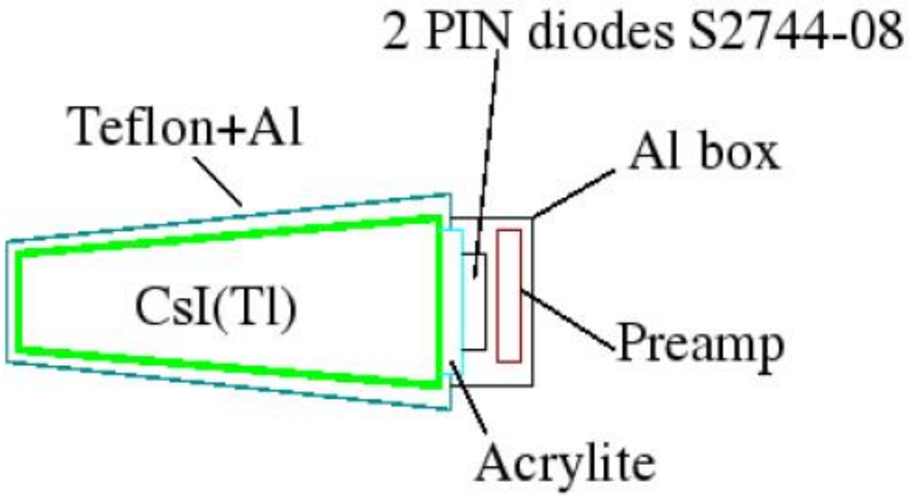
BELLE



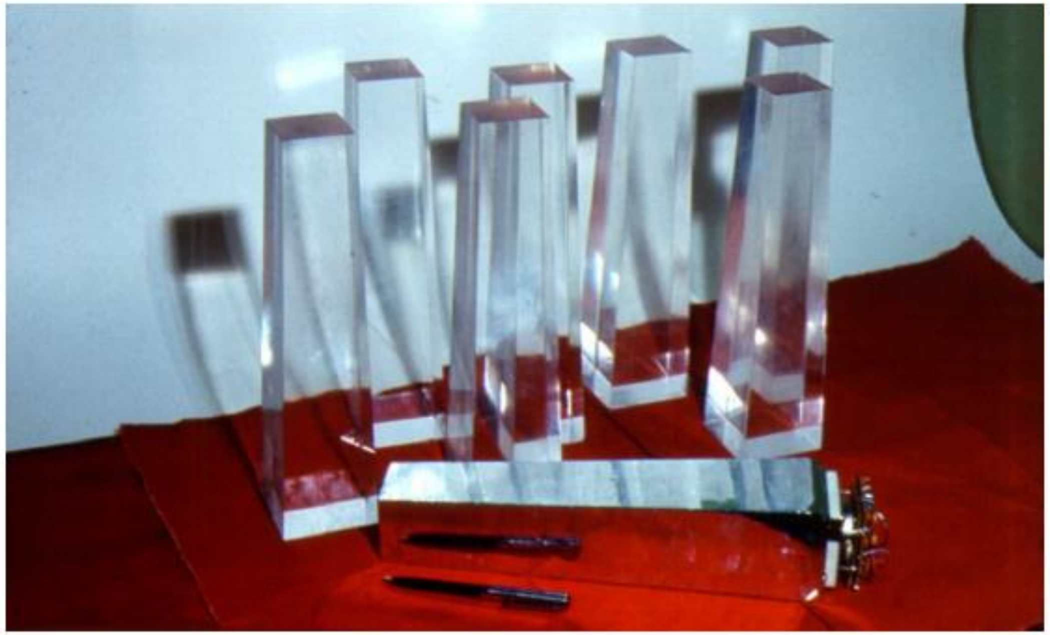
- 8736 CsI(Tl) crystals with photodiode readout
- About 16.2 X0, inside solenoid
- Coverage from 12 to 155°


$\pi^0 \to \gamma\gamma$ in hadronic events

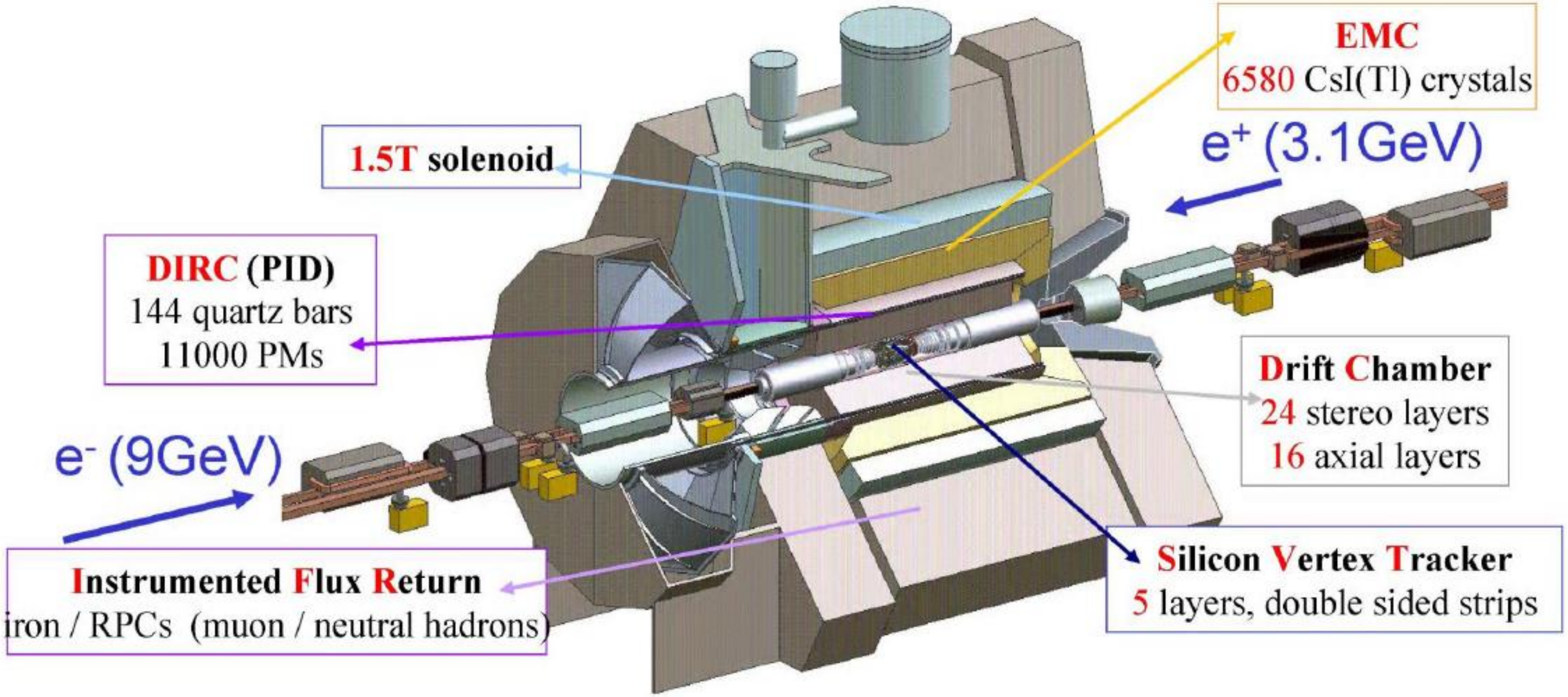
CsI(Tl) Crystals



Light output – 5000 ph.el./MeV
Electronics noise σ~200 KeV



Detector Babar



EMC
6580 CsI(Tl) crystals

e^+ (3.1GeV)

1.5T solenoid

DIRC (PID)
144 quartz bars
11000 PMs

Drift Chamber
24 stereo layers
16 axial layers

e^- (9GeV)

Silicon Vertex Tracker
5 layers, double sided strips

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

SVT: vertexing and tracking: crucial for Δt and low p_T tracks

DCH: main tracking device, also dE/dx for particle ID

DIRC: K-π separation > 3.4σ for $P < 3.5$GeV/c

EMC: very good energy resolution; electron ID, π^0 and γ reco.

IFR: Muon and neutral hadrons (K^0_L) ID

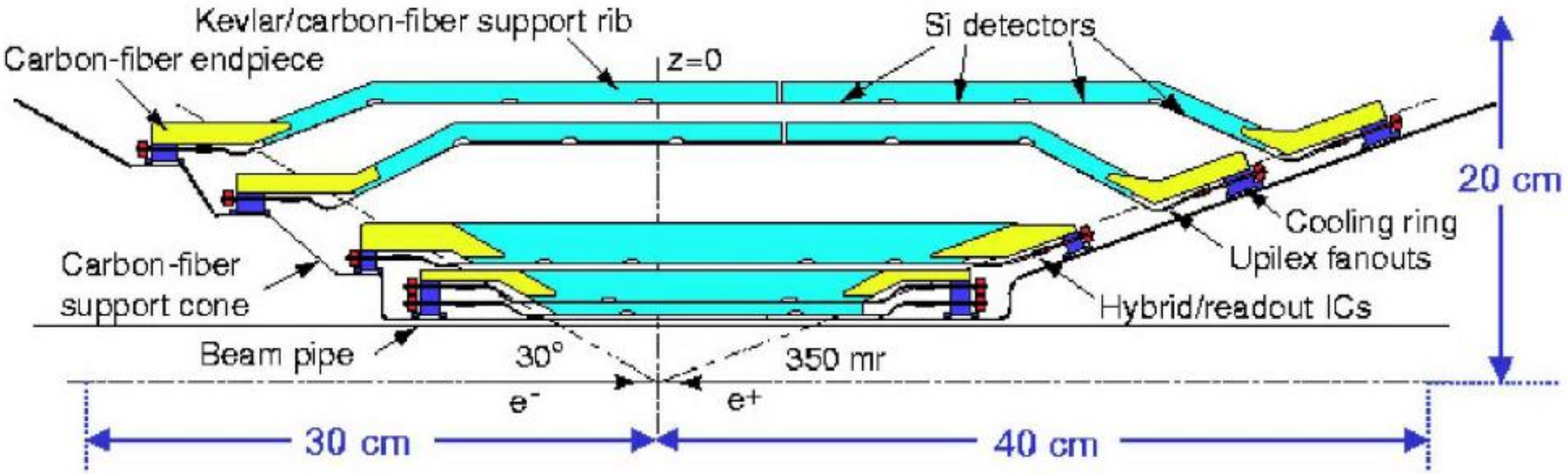
Silicon Vertex Tracker

double-sided Si microstrip detectors

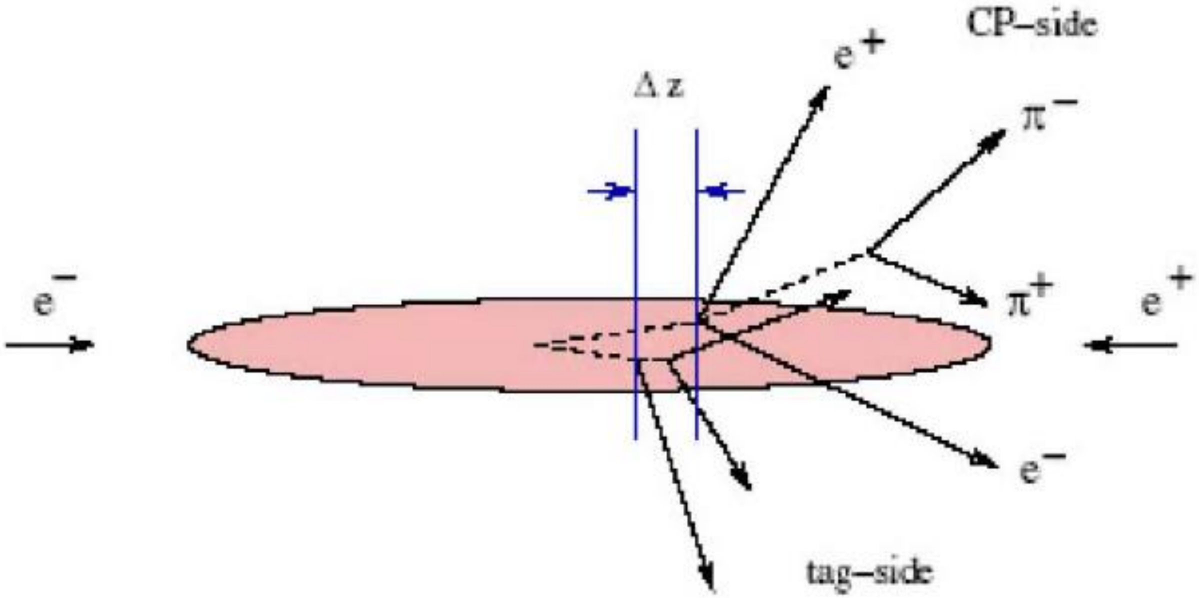
5 layers: 340 wafers, 150000 readout channels

$20^o < \theta < 150^o$

$\sigma_{point} \approx$ 10-15 μm for the inner layers



Silicon Vertex Tracker (Babar vs Belle)



- $\Delta z = z_{cp} - z_{tag}$

  $\Delta t \simeq \Delta z/(\gamma\beta c)$
- Interaction Point $\gg \Delta z$

  B flight-length in x-y: only $\sim 30\mu$
- C conservation in $\Upsilon(4S) \to B\bar{B}$

  $\psi(t) = |B_1^0 > |\bar{B}_2^0 > - |\bar{B}_1^0 > |B_2^0 >$

  (one is B^0 and other is $\bar{B}^0$ at any time)

The other B provides time reference and flavor tagging at $\Delta t = 0$

Parameters	BaBar	Belle
e^+e^- energy	$3.1 \times 9\,\mathrm{GeV}$	$3.5 \times 8.5\,\mathrm{GeV}$
$\gamma\beta$	0.56	0.425
Interaction point ($h \times v \times l$)	$120\,\mu\mathrm{m} \times 5\,\mu\mathrm{m} \times 8.5\,\mathrm{mm}$	$80\,\mu\mathrm{m} \times 2\,\mu\mathrm{m} \times 3.4\,\mathrm{mm}$
Typical Δz	$260\mu\mathrm{m}$	$200\mu\mathrm{m}$
σ_z (CP-side)	$50\,\mu\mathrm{m}$	$75\,\mu\mathrm{m}$
σ_z (tag-side)	$100 \sim 150\,\mu\mathrm{m}$	$140\,\mu\mathrm{m}$

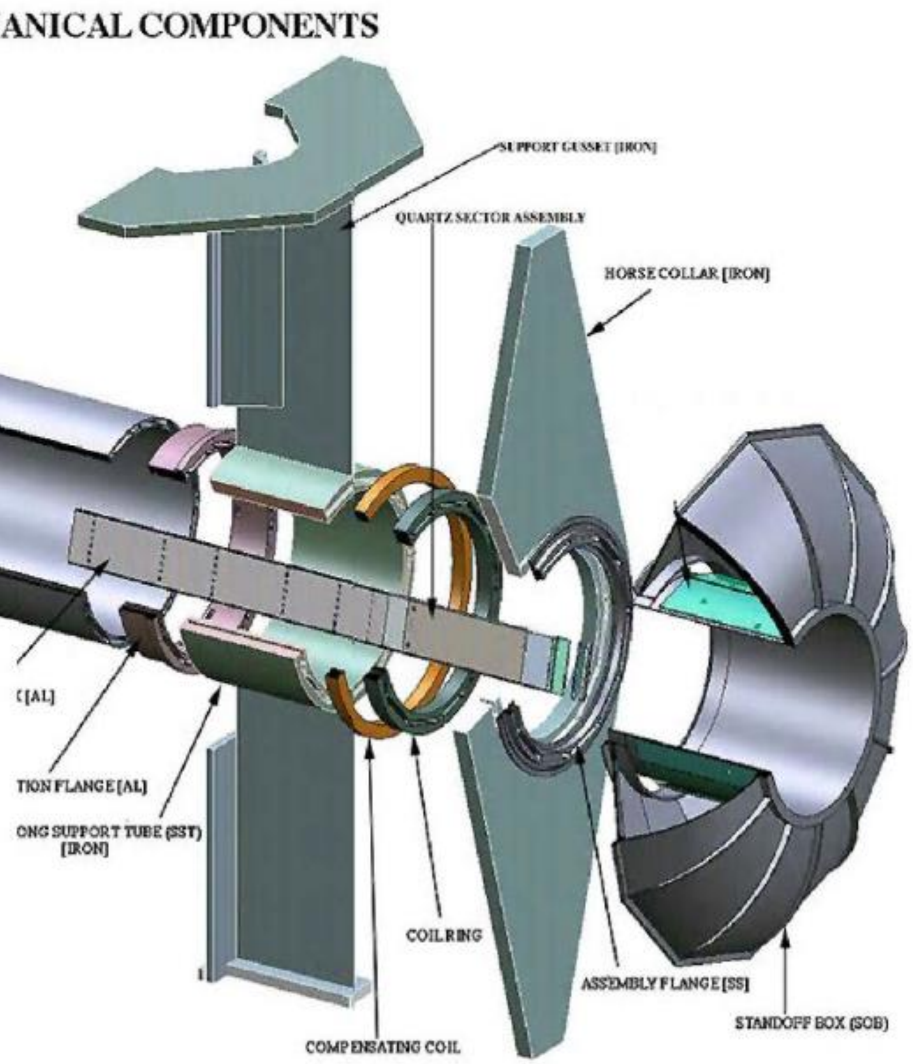
DIRC

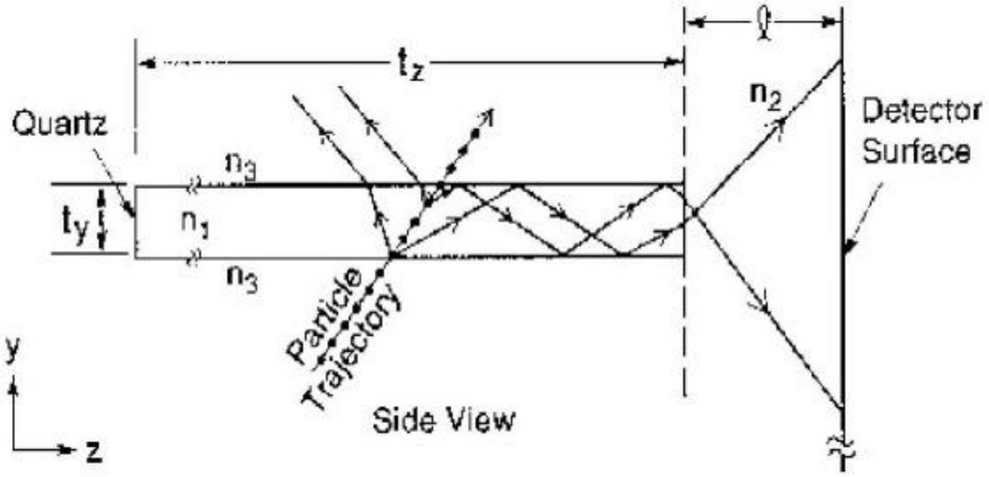
- Detector of Internally Reflected Cherenkov light

144 quartz bars (1.5 cm thick)

11000 PMTs, 25-50 p.e./particle,

9mrad single photon resolution





Identification Performance

Charged K identified by

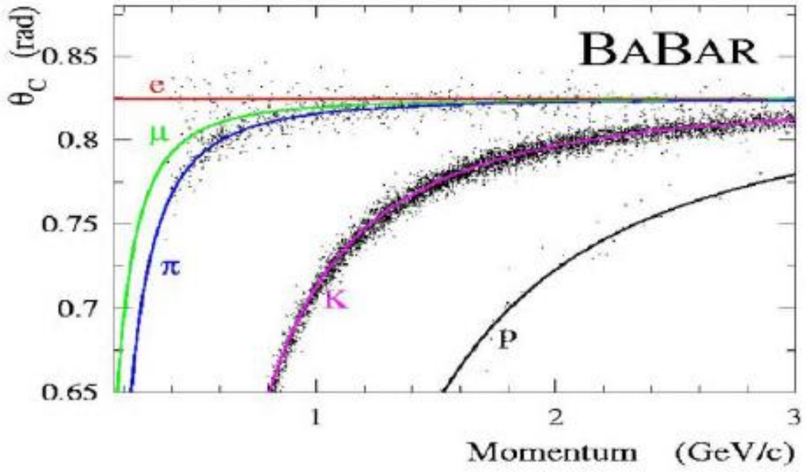
DIRC: Cerenkov angle

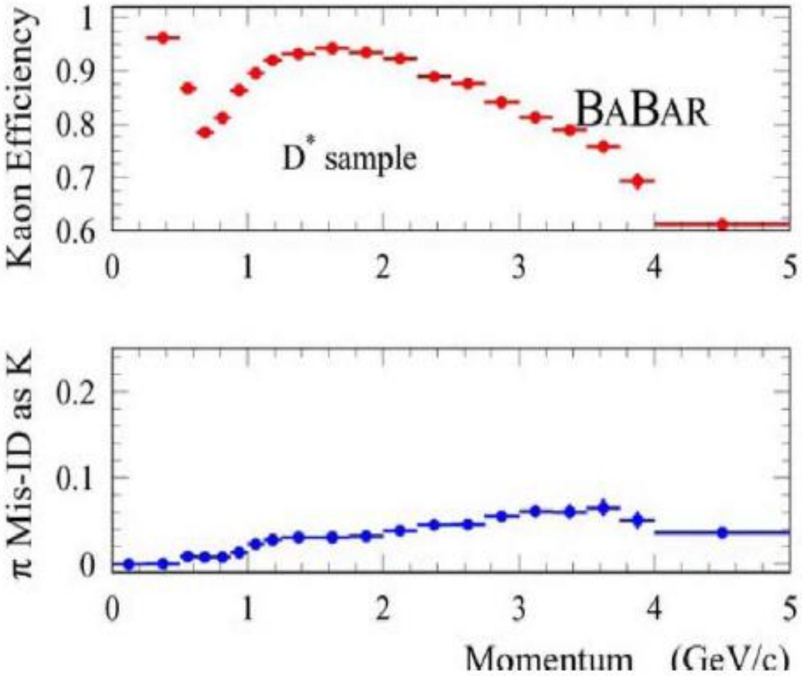
DCH: dE/dx ($p < 0.7$ GeV/c)

Efficiency and purity measured on control samples (soft pion tag)

$D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K^-\pi^+$

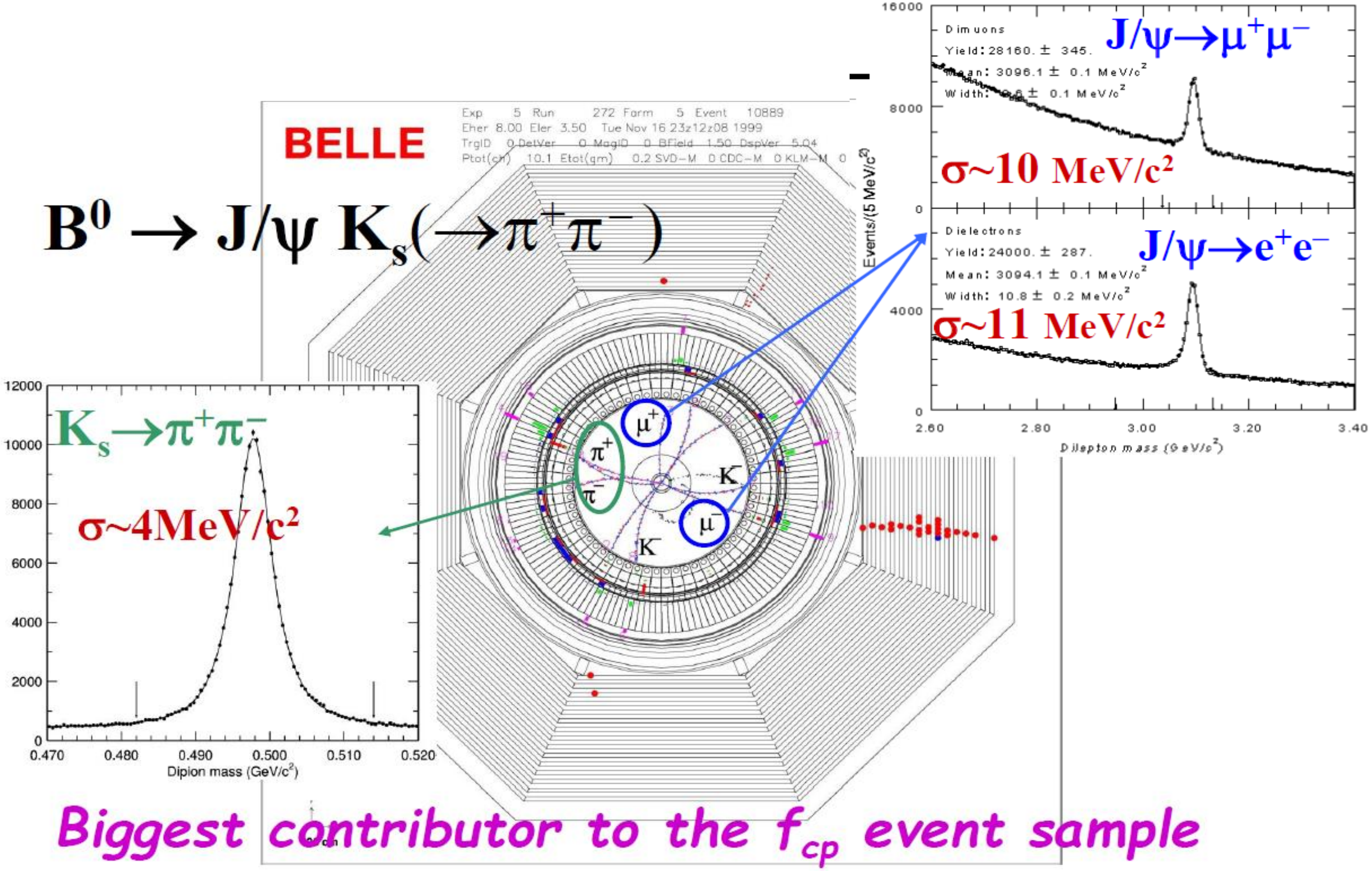
$> 3.4\sigma$ π/K separation up to ≈ 3.5 GeV/c





“Golden Mode” Event

$B^0 \rightarrow J/\psi\ K_s(\rightarrow \pi^+\pi^-)$

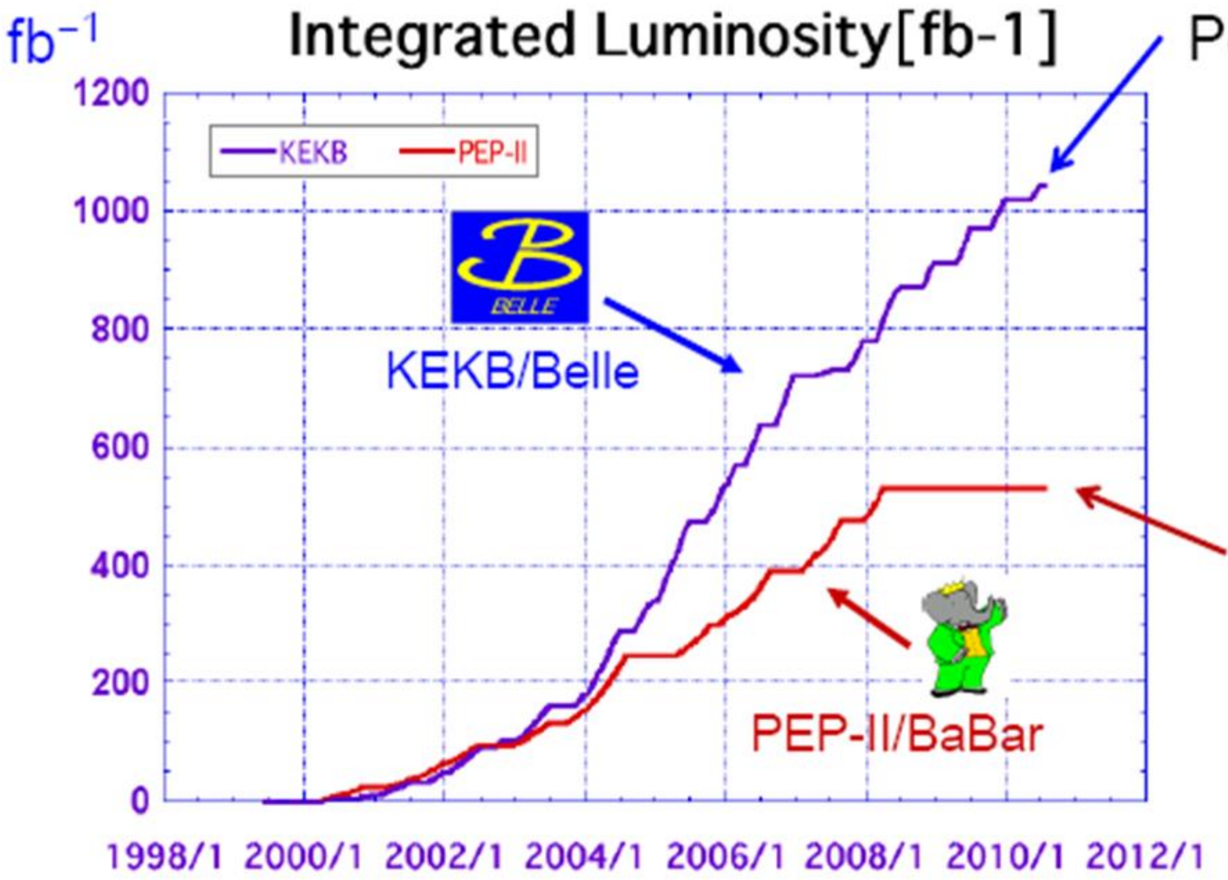


Biggest contributor to the f_{cp} event sample

Luminosity

$e^+e^- \to \Upsilon(4S) \to B\bar{B}$ (1.1nb)

$1\ \mathrm{fb}^{-1} \sim 10^6\ B\bar{B}$ @ $\Upsilon(4S)$



Total ~1020 fb^{-1}

Peak 2.11×10^{34} cm^{-2} s^{-1}

On resonance:
$\Upsilon(5S)$: 121 fb^{-1} ← B_s
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 24 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off resonance, scan:
~ 100 fb^{-1}

Total 550 fb^{-1}

Peak 1.21×10^{34} cm^{-2} s^{-1}

On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

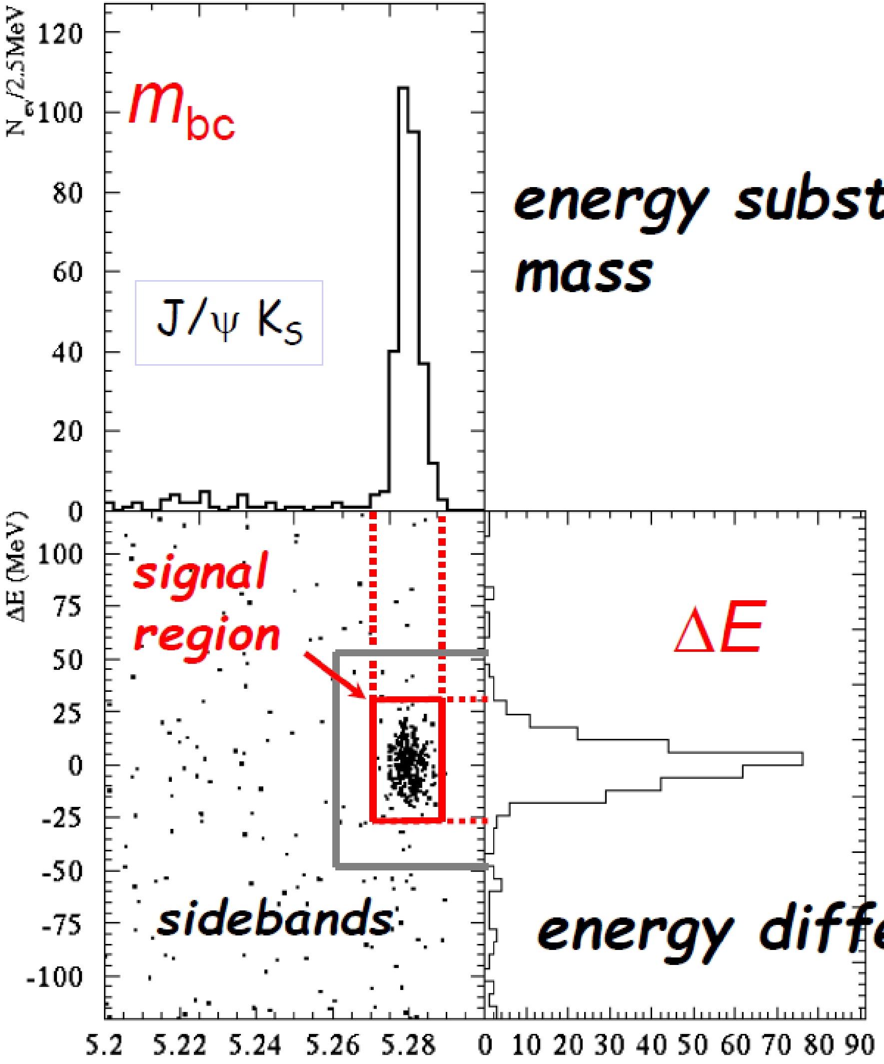
Observables: “direct” CP-violation

Time-integrated “direct” CP asymmetry (“CP violation in decay”):

$$A_{CP} \equiv \frac{\Gamma(i \to f) - \Gamma(\bar{i} \to \bar{f})}{\Gamma(i \to f) + \Gamma(\bar{i} \to \bar{f})} = \frac{2|A_1||A_2|\sin\delta\sin\phi}{|A_1|^2 + |A_2|^2 + 2|A_1||A_2|\cos\delta\cos\phi}$$

- the only possibile CPV effect for *charged* mesons decays !
- requires at least two amplitudes *and* $\delta \neq 0$

Reconstruction of B mesons



energy substituted mass

energy difference

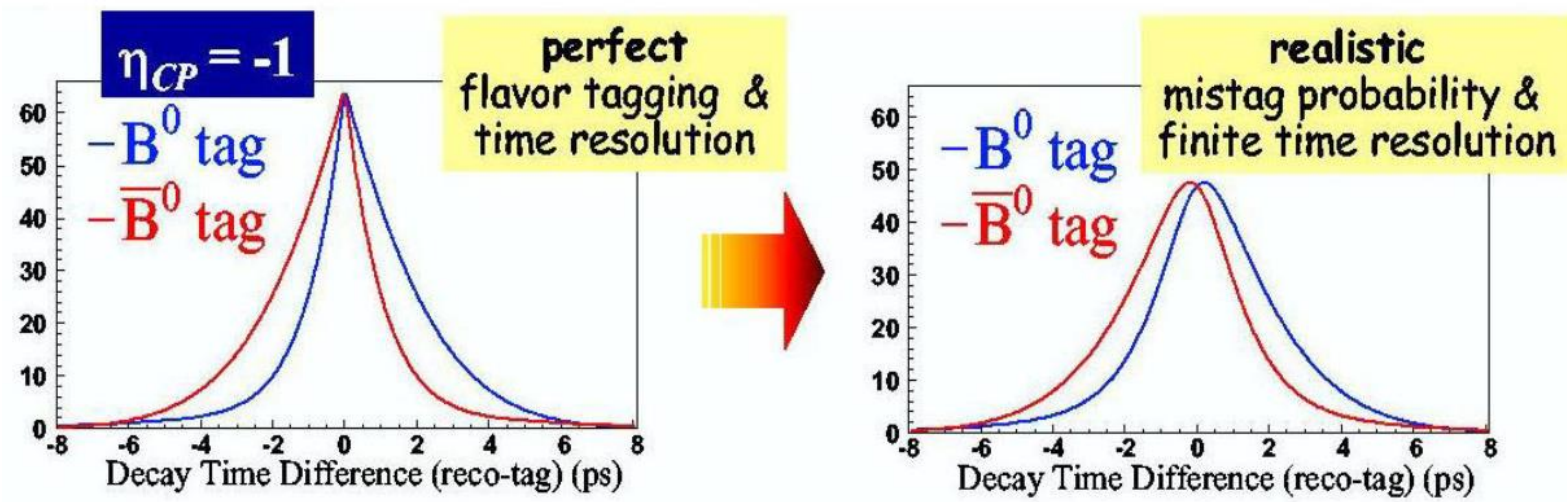
Initial state kinematic constraint

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

$$m_{\mathrm{bc}} = \sqrt{E^{*2}_{\mathrm{beam}} - p^{*2}_{B}}$$

$$\Delta E = E^*_B - E^*_{\mathrm{beam}}$$

CPV Analysis: Time Distribution



$$f_{CP\pm}(\Delta t) = \left\{ \frac{\Gamma}{4} e^{-\Gamma|\Delta t|} (1 \mp \eta_f (1 - 2\omega) sin(2\beta) sin(\Delta m_d \Delta t) \right\} \otimes R(\Delta t)$$

ω – mistag probability

$R(\Delta t)$- time-resolution function