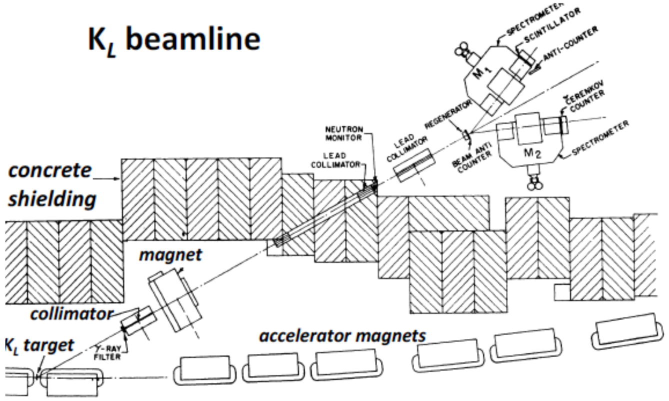
“Young scientists should know with what difficulty new knowledge was born.”

Misha Danilov

CPV discovery

Christenson, Cronin, Fitch and Turlay observed 45 events of the $K^0_L \to \pi^+\pi^-$ decay $(2\pm0.4)10^{-3}$

PRL 13, 138
1964



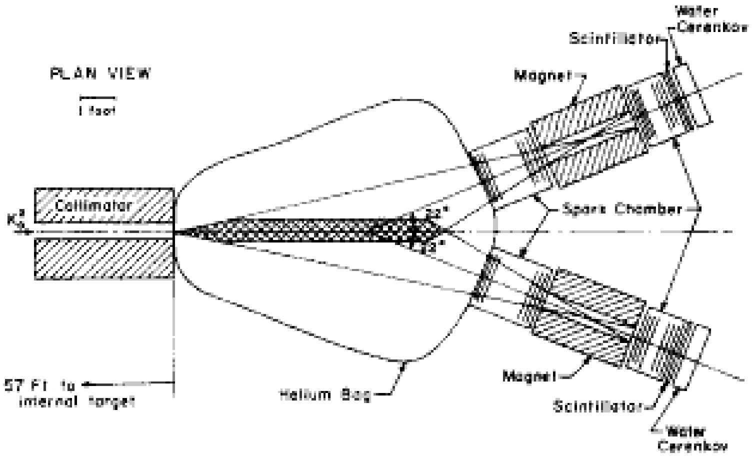
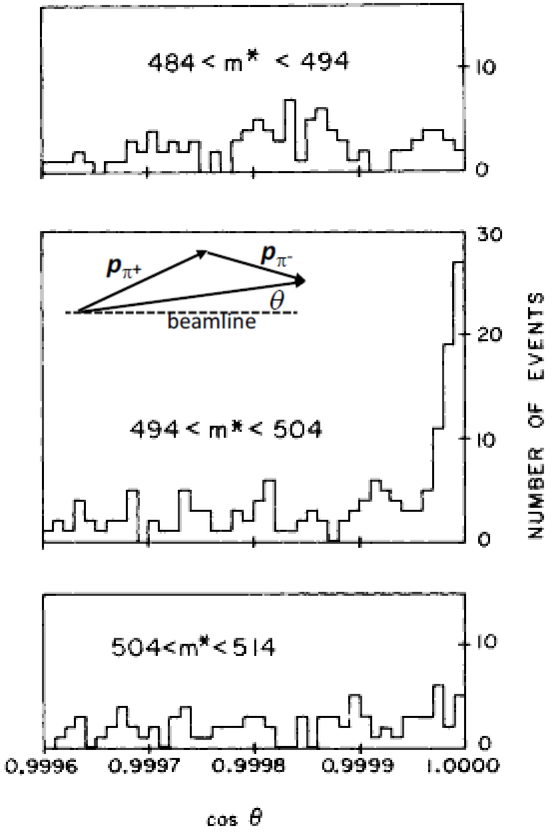


FIG. 1. Plan view of the detector arrangement.



This result was reported by Fitch at ICHEP1964 (Dubna) in August. At the same conference Okonov presented upper limit on the $K^0_L \to \pi^+\pi^-$ decay $<2.5\ 10^{-3}$ from Dubna experiment.

Why it's so important

Sakharov realized that CP violation is one of the necessary conditions of the excess of matter over antimatter in the Universe

JETP Lett. 6, 21 1967

The baryon asymmetry of the Universe is the measurement of

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$$

This means that 10^{-6} seconds after the Big Bang, when the temperature was T > 1 GeV, and quarks and antiquarks were in thermal equilibrium, there was a corresponding asymmetry between quarks and antiquarks.

Sakharov pointed out that for a theory to generate such an asymmetry in the course of its evolution from a hot Big Bang (assuming inflation washed out any possible prior asymmetry), it must contain:

(1) baryon number violating interactions;

(2) C and CP violation;

(3) deviation from thermal equilibrium.

Interestingly, the SM contains all three conditions, but CP violation is too small, and the deviation from thermal equilibrium is too small at the electroweak phase transition.

GIM mechanism

Glashou, Iliopoulos, Maiani Weak Interactions with Lepton-Hadron Symmetry

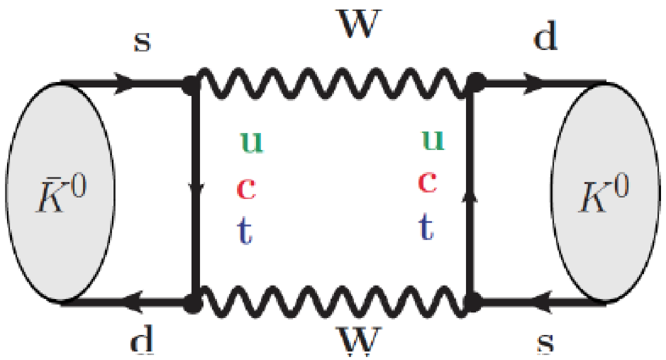
PRD v2, n7 1285
1970

Flavor change neutral current suppression due to unitarity in scheme with four quarks

$$\begin{pmatrix}u\\d\end{pmatrix} s \implies \begin{pmatrix}u\\d\end{pmatrix}\begin{pmatrix}c\\s\end{pmatrix}$$

$$\begin{pmatrix}d'\\s'\end{pmatrix} = \begin{pmatrix}\cos\theta_C & \sin\theta_C\\ -\sin\theta_C & \cos\theta_C\end{pmatrix}\begin{pmatrix}d\\s\end{pmatrix}$$

unitarity: $\sum_{i=u,c,t} V^*_{id}V_{is} = 0$

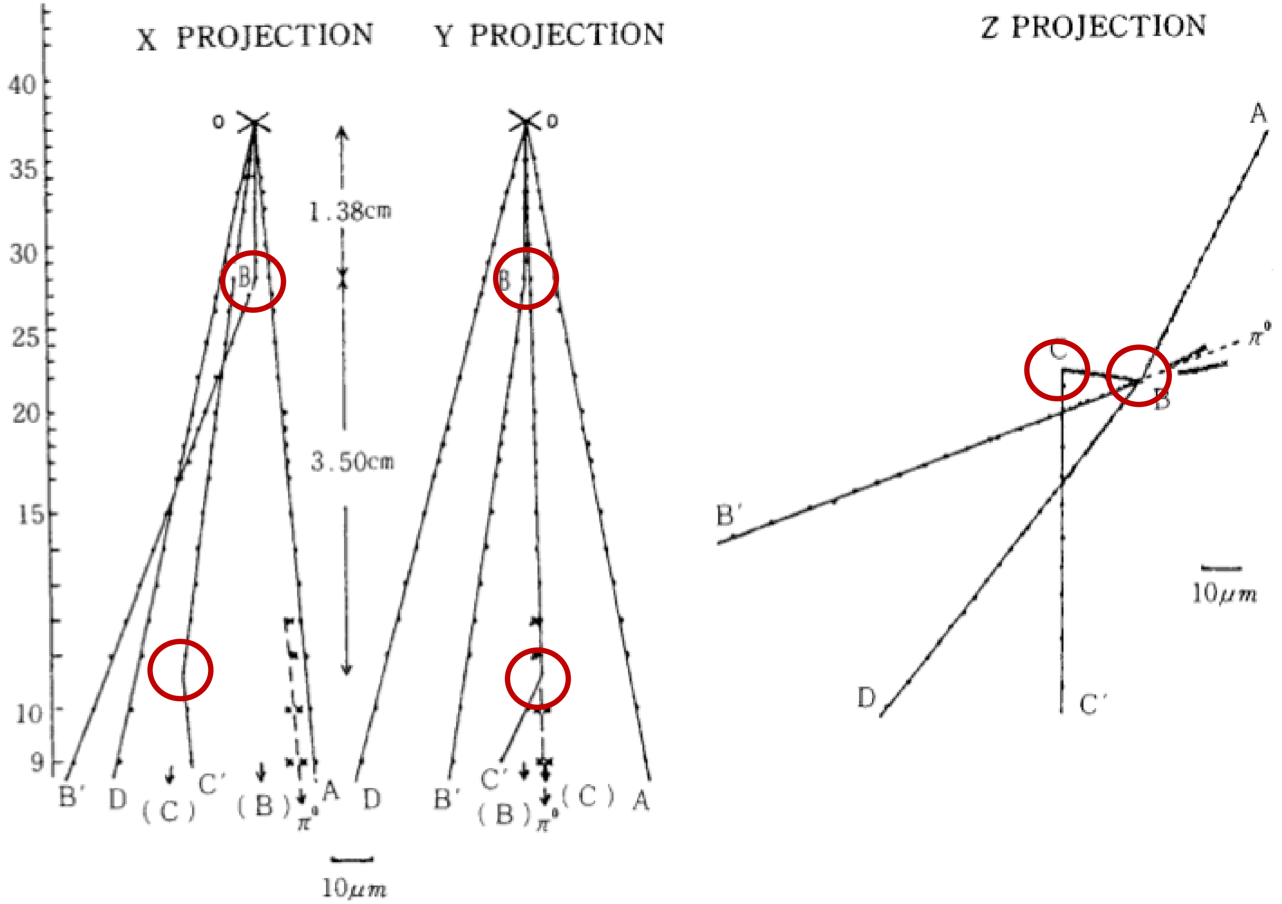


$$\mathcal{M} \propto \sum_{i,j=u,c,t} V^*_{id}V_{is}V^*_{jd}V_{js}F(x_i,x_j)$$

$F(x_i,x_j)$: loop function that depends on mass square ratios $x_i = m_i^2/M_W^2$

Kiyoshi Niu event

In 1970, a small team of experimenters in Japan led by Kiyoshi Niu, exposed a stack of photographic emulsions to cosmic rays in a high altitude commercial cargo airliner. They found a remarkable event, in which an ultra-high energy cosmic rays particle produced long lived particles with large masses.



Prog.Theor.Phys. 46, 1644, 1971

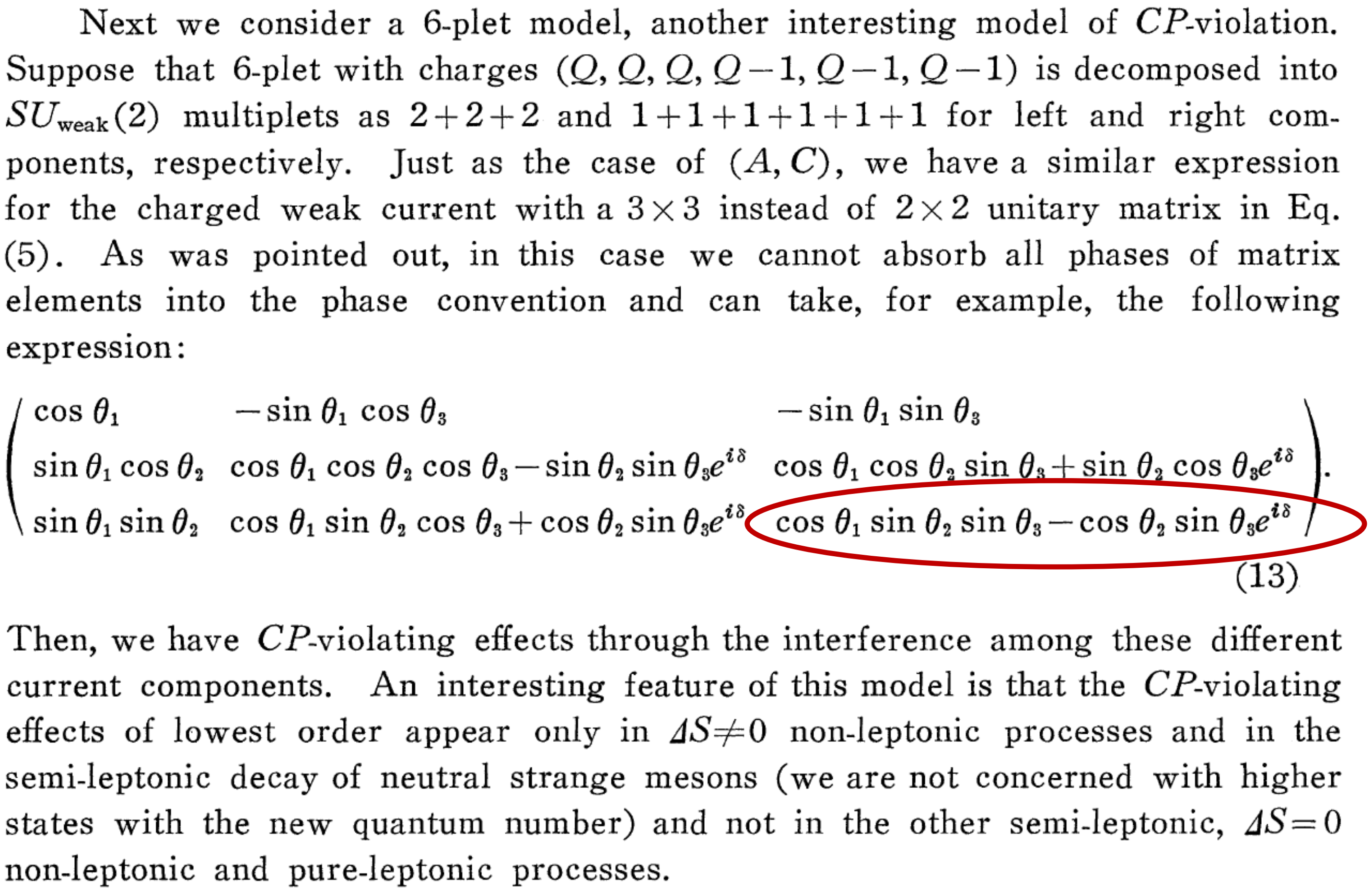
Assumed decay mode	Mass (GeV)	lifetime (sec)
$B \to \pi^+\pi^0$	1.78	2.2×10^{-14}
$C \to (\pi^0)p$	2.95	3.6×10^{-14},

Kobayashi Maskawa quark mixing

Kobayashi, Maskawa CP-Violation in the Renormalizable Theory of Weak Interaction

Prog.Theor.Phys.
49, 652,   1973

Eureka! With six-quarks there is room for a CP-violating phase!



Next we consider a 6-plet model, another interesting model of CP-violation. Suppose that 6-plet with charges $(Q, Q, Q, Q-1, Q-1, Q-1)$ is decomposed into $SU_{\text{weak}}(2)$ multiplets as $2+2+2$ and $1+1+1+1+1+1$ for left and right components, respectively. Just as the case of (A, C), we have a similar expression for the charged weak current with a 3×3 instead of 2×2 unitary matrix in Eq. (5). As was pointed out, in this case we cannot absorb all phases of matrix elements into the phase convention and can take, for example, the following expression:

$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\cos\theta_3 e^{i\delta} \end{pmatrix}. \tag{13}$$

Then, we have CP-violating effects through the interference among these different current components. An interesting feature of this model is that the CP-violating effects of lowest order appear only in $\Delta S\neq0$ non-leptonic processes and in the semi-leptonic decay of neutral strange mesons (we are not concerned with higher states with the new quantum number) and not in the other semi-leptonic, $\Delta S=0$ non-leptonic and pure-leptonic processes.

$$\theta_1, \theta_2, \theta_3, \delta \longrightarrow 0 \qquad \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

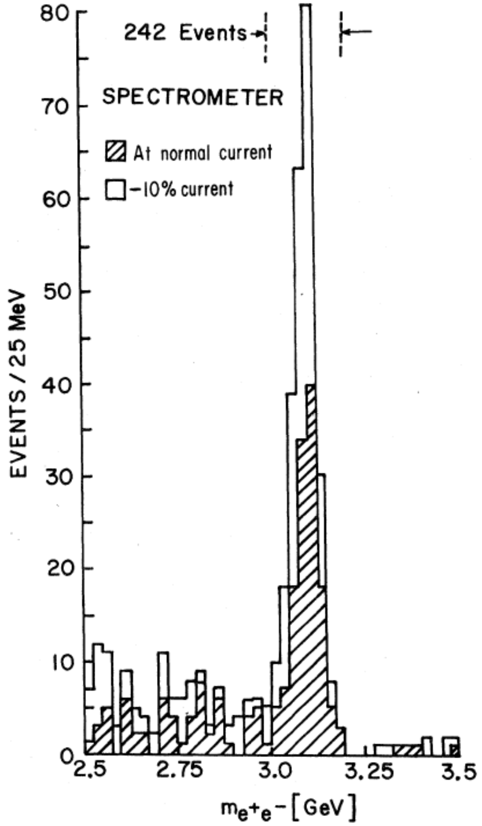
November 1974 Revolution

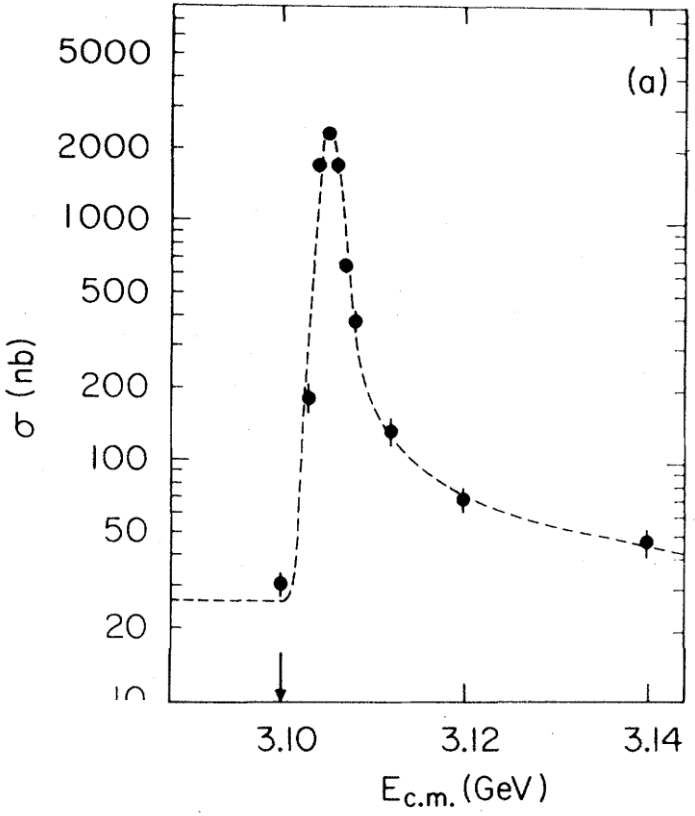
Aubert, … Ting, et al Experimental Observation of a Heavy Particle J

PRL 33, 1404
1974

Augustin, … Richter, et al Discovery of a Narrow Resonance in e^+e^- Annihilation

PRL 33, 1406
1974





Discovery of the third generation

Perl, et al Evidence for Anomalous Lepton Production in e^+e^- Annihilation

PRL 35, 1489
1975

Discovery of the $e^+e^- \rightarrow \tau^+\tau^- \rightarrow \mu^+\nu_\mu\bar{\nu}_\tau e^-\bar{\nu}_e\nu_\tau$

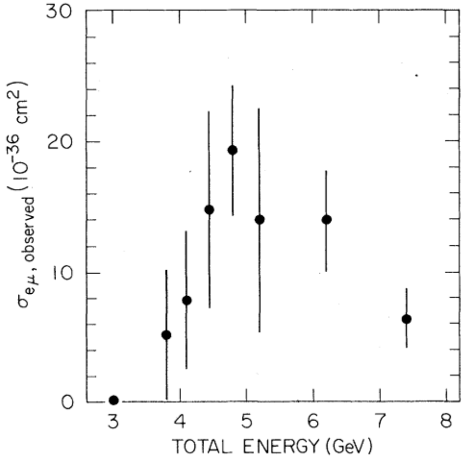
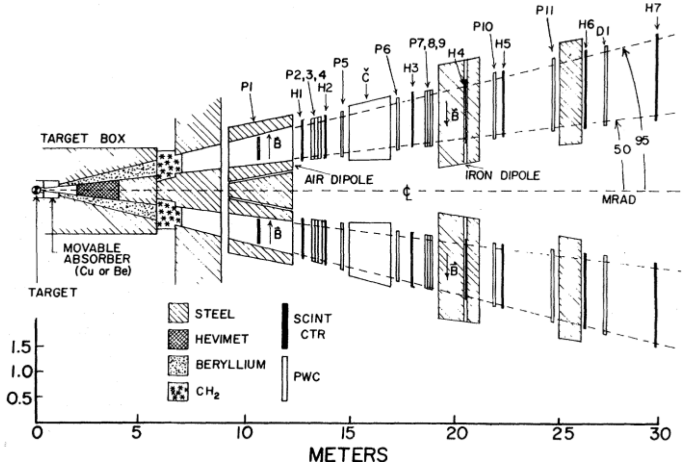


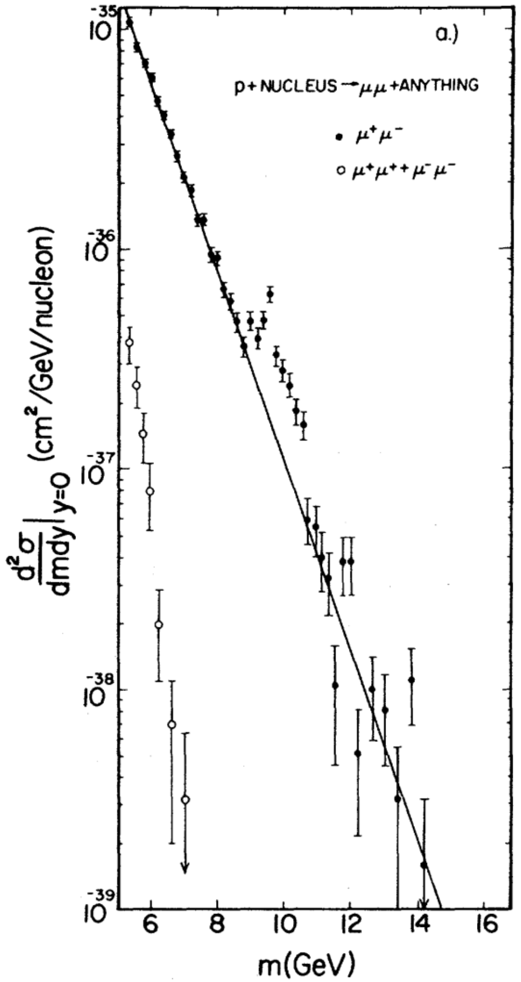
FIG. 2. The *observed* cross section for the signature e-μ events.

Herb,…Lederman et al Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleus

PRL 39, 252
1977



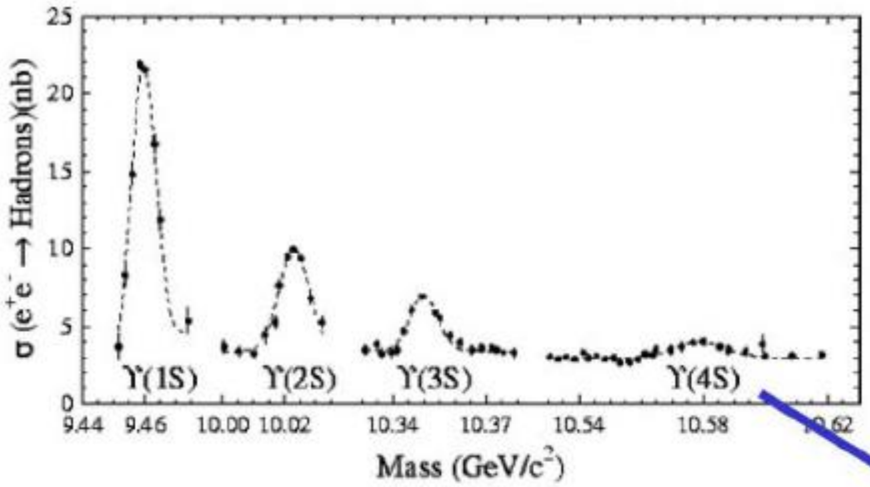
Discovery of the $\Upsilon(9.46) \rightarrow \mu^+\mu^-$ interpreted as $^3S_1\ b\bar{b}$



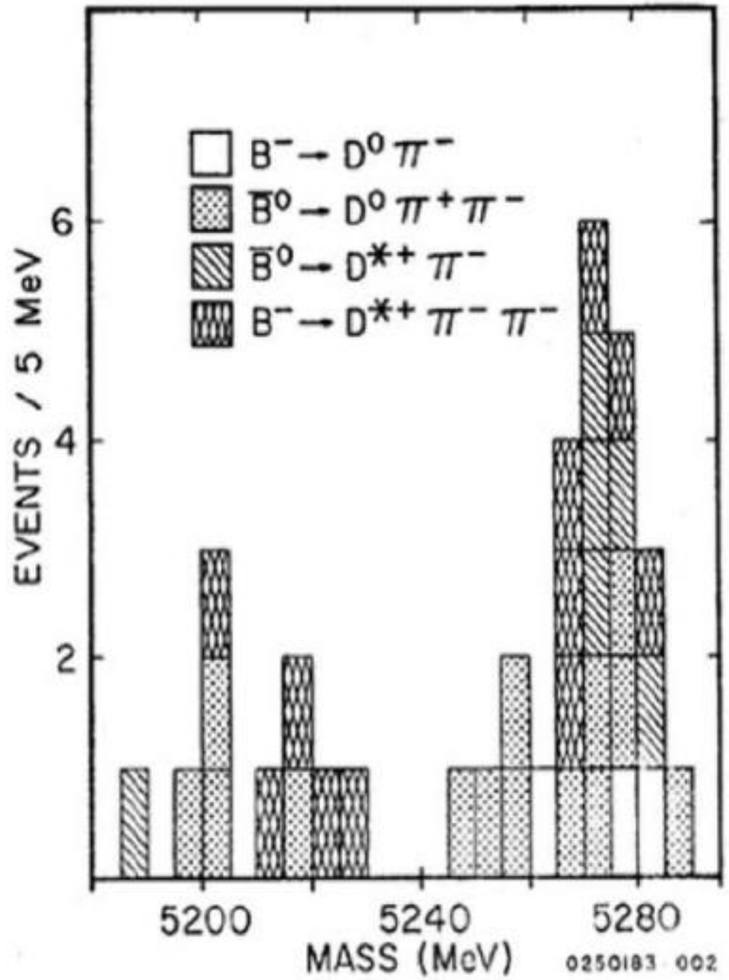
B mesons production at e^+e^- colliders

CLEO Collaboration Observation of Exclusive Decay Modes of b-Flavored Mesons

PRL 50, 881
1983



CESR at Cornell:
“naked beauty”

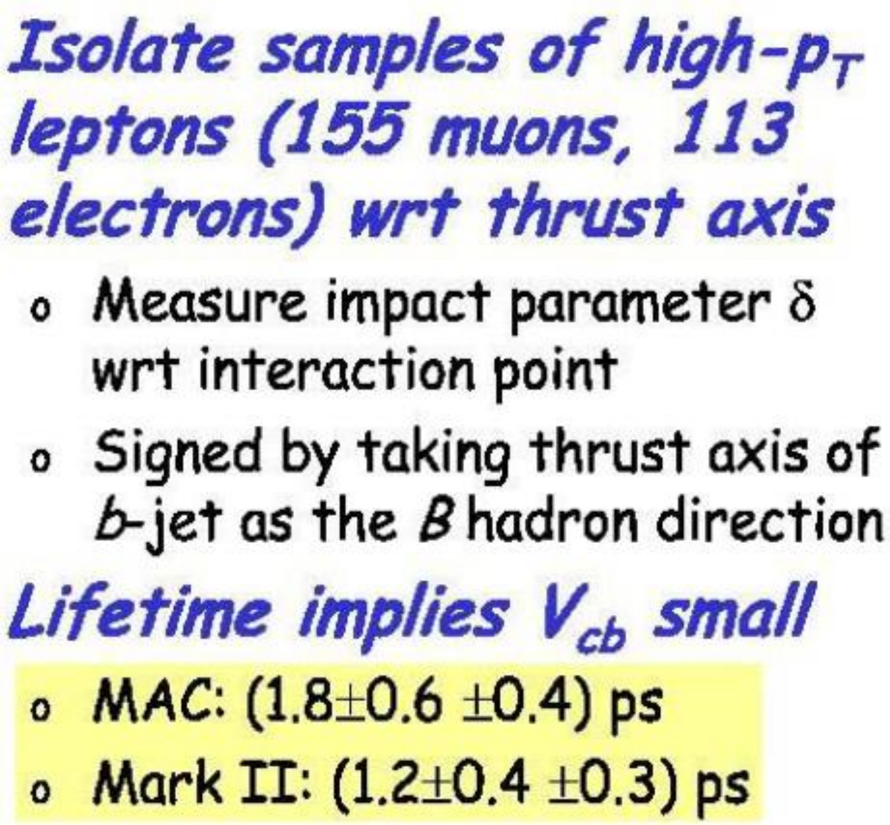


b lifetime

MAC Collaboration

MARK II Collaboration

PRL 51, 1022
1983
PRL 51, 1316
1983

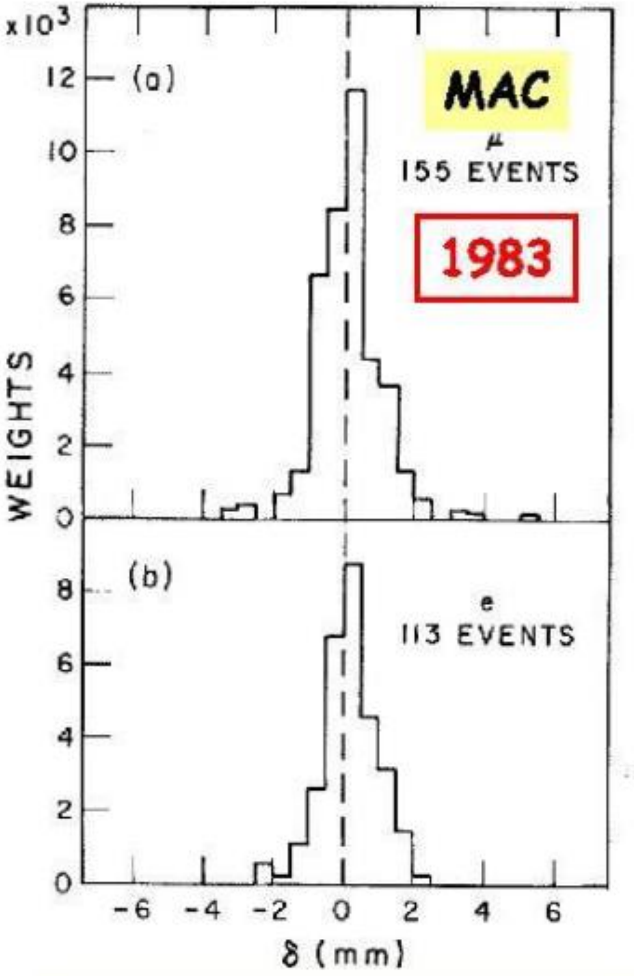


Isolate samples of high-p_T leptons (155 muons, 113 electrons) wrt thrust axis

- Measure impact parameter δ wrt interaction point
- Signed by taking thrust axis of *b*-jet as the *B* hadron direction

Lifetime implies V_{cb} small

- MAC: (1.8±0.6 ±0.4) ps
- Mark II: (1.2±0.4 ±0.3) ps



CKM matrix Wolfenstein parameterization

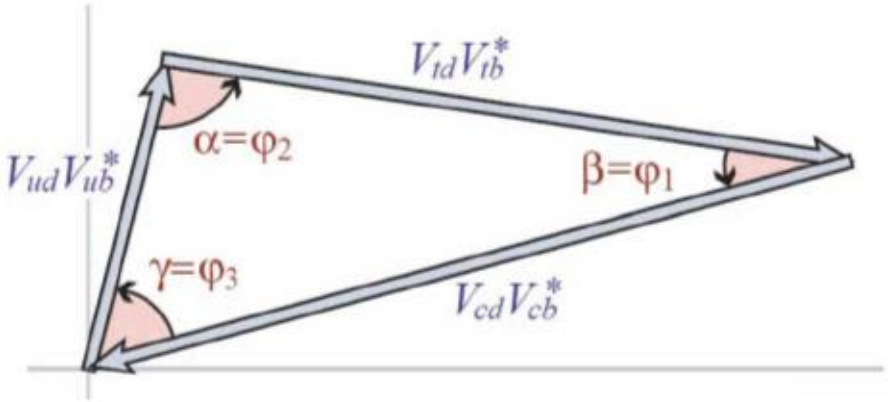
$$\begin{array}{cc}
\begin{pmatrix}
1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\
-\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\
A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4
\end{pmatrix} & \begin{array}{c} u \\ c \\ t \end{array} \\
\begin{array}{ccc} d & \qquad\qquad s & \qquad\qquad b \end{array} &
\end{array}$$

$$\alpha \equiv \varphi_2 \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right),$$

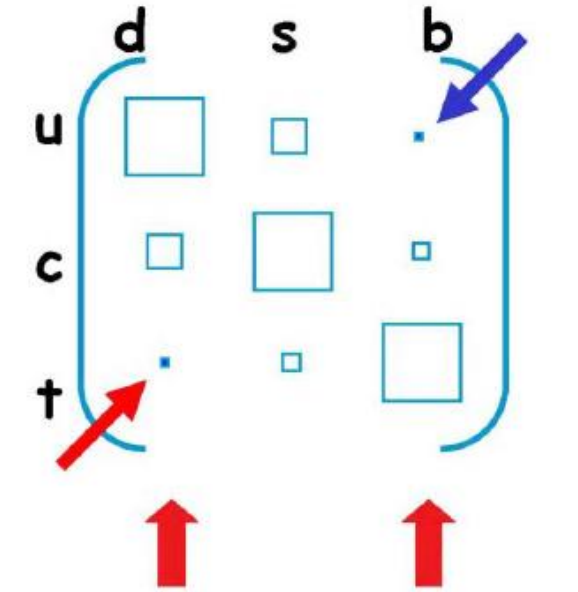
$$\beta \equiv \varphi_1 \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right),$$

$$\gamma \equiv \varphi_3 \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right),$$

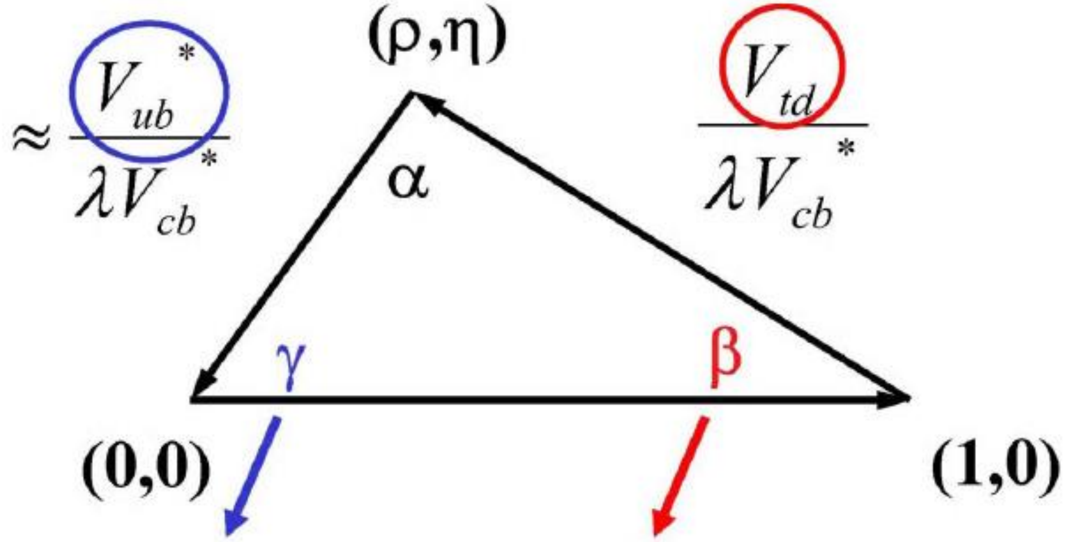
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0\,.$$



Unitarity Triangle



apply unitarity constraint to these two columns



$$\approx \frac{V_{ub}^*}{\lambda V_{cb}^*} \qquad \frac{V_{td}}{\lambda V_{cb}^*}$$

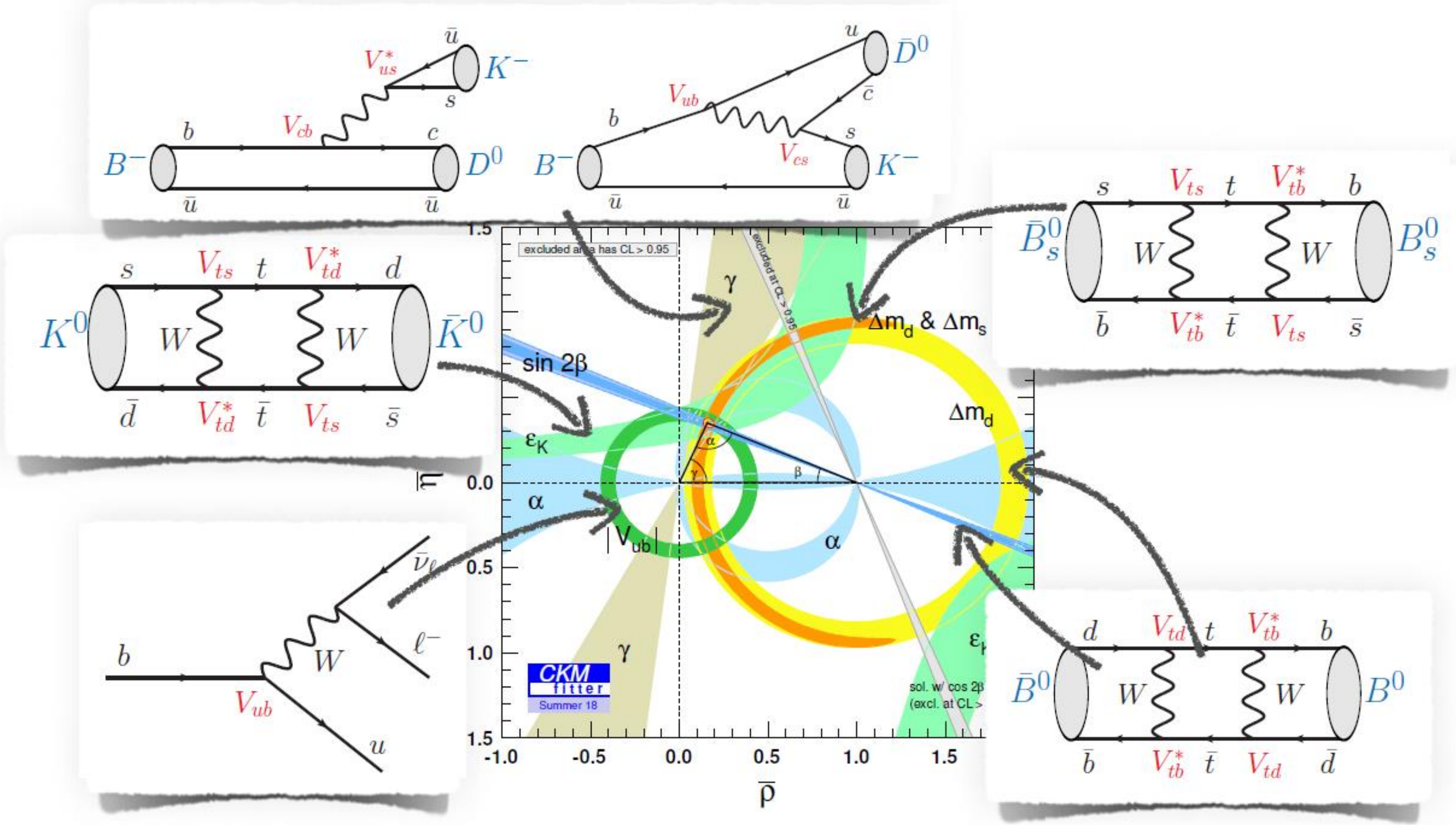
$$\gamma \approx \arg V_{ub}^* \qquad \beta \approx -\arg V_{td} \qquad \alpha = \pi - \beta - \gamma$$

Orders of magnitude for Wolfenstein parameters:

$$\lambda \approx 0.22\,, \quad A \approx 0.8\,, \quad \sqrt{\rho^2 + \eta^2} \approx 0.4$$

$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$$

$$V_{cd} = \lambda\,, \quad V_{ud} \approx V_{tb} \approx 1$$


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

B Mesons Mixing

Mixing

Effective Hamiltonian approximation:

“dispersive”

“absorptive”

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

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: $\Delta m=m_H-m_L\quad \Delta\Gamma=\Gamma_H-\Gamma_L$

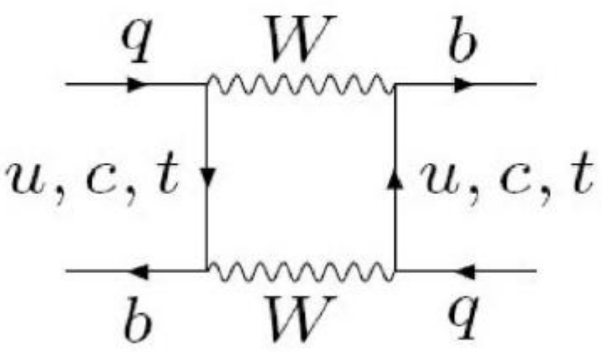
$$\Delta m^2-1/4\,\Delta\Gamma^2=4|M_{12}|^2-|\Gamma_{12}|^2$$

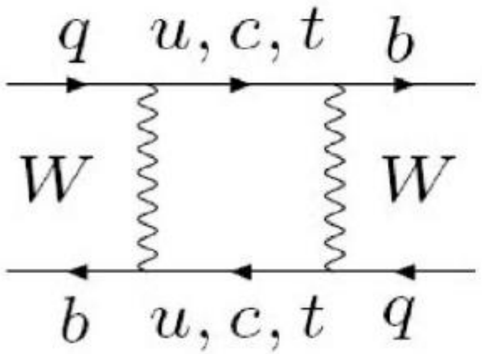
$$\Delta m\Delta\Gamma=4\Re\mathrm{e}\left(M_{12}\Gamma_{12}^*\right)$$

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

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

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





$\bar{B}_d^0 = (b\bar{d})$

$\bar{B}_s^0 = (b\bar{s})$

$B_d^0 = (\bar{b}d)$ Now all three up quarks should be taken into account $B_s^0 = (\bar{b}s)$

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

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

Three remaining diagram contributions in M_{12}:

cc: $(V_{cb}V_{cd}^*)^2 G_F^2 m_c^2 \approx A^2\lambda^6\, G_F^2 m_c^2$ $\quad(V_{cb}V_{cs}^*)^2 G_F^2 m_c^2 \approx A^2\lambda^4\, G_F^2 m_c^2$

ct: $V_{cb}V_{cd}^* V_{tb}V_{td}^* G_F^2 m_c^2 \approx -A^2\lambda^6(1-\rho+i\eta)G_F^2\, m_c^2 \ln(\frac{m_t}{m_c})^2$ $\quad V_{cb}V_{cs}^* V_{tb}V_{ts}^* G_F^2 m_c^2 \approx -A^2\lambda^4(1-i\lambda^2\eta)G_F^2 m_c^2 \ln(\frac{m_t}{m_c})^2$

tt: $(V_{tb}V_{td}^*)^2 G_F^2 m_t^2 \approx A^2\lambda^6\,(1-\rho+i\eta)^2 G_F^2 m_t^2$ $\quad(V_{tb}V_{ts}^*)^2 G_F^2 m_t^2 \approx A^2\lambda^4\,(1-i\lambda^2\eta)^2 G_F^2 m_t^2$

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

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

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

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

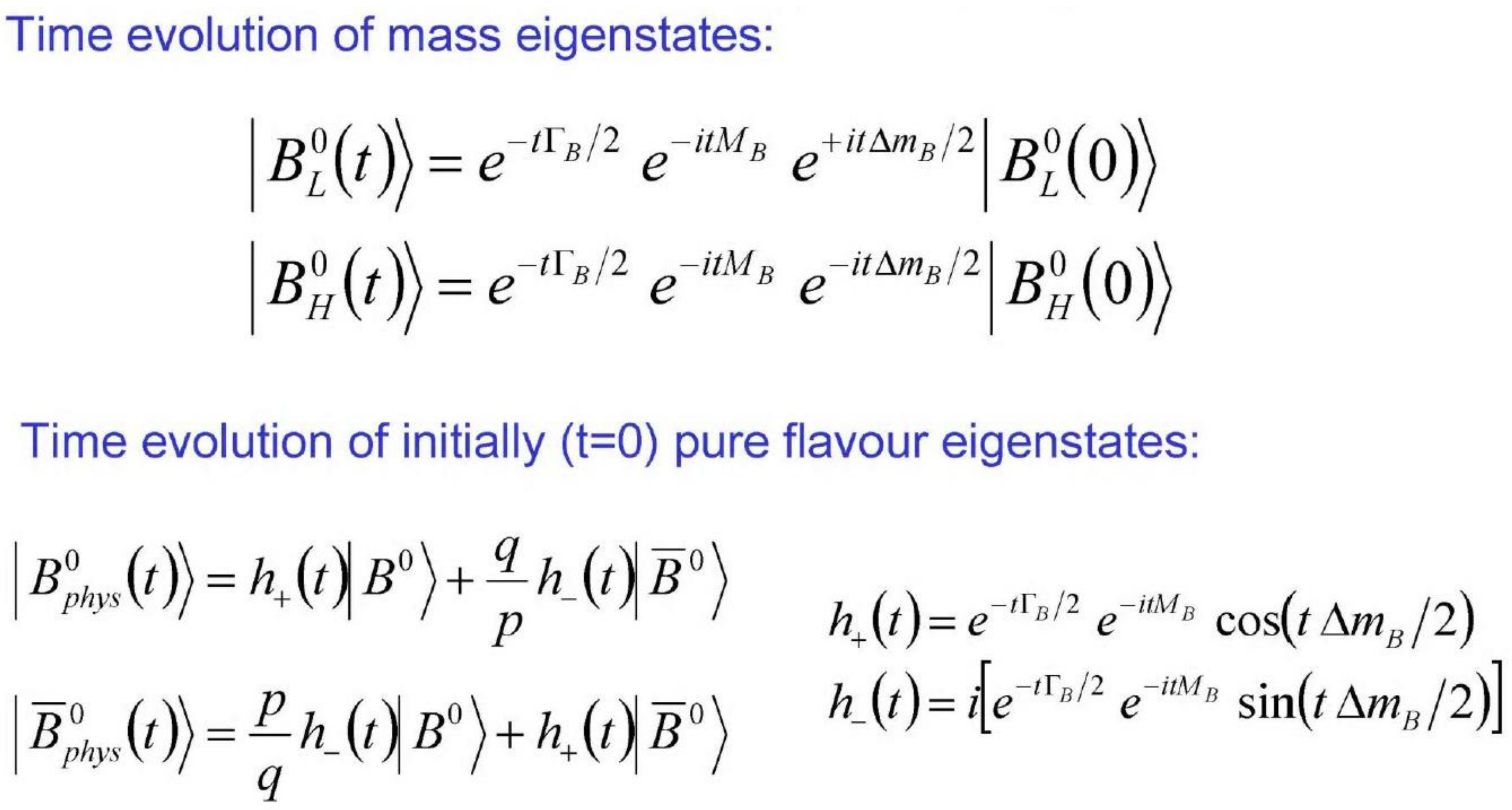
$$\Gamma_{12}/M_{12} << 1$$

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

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

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:

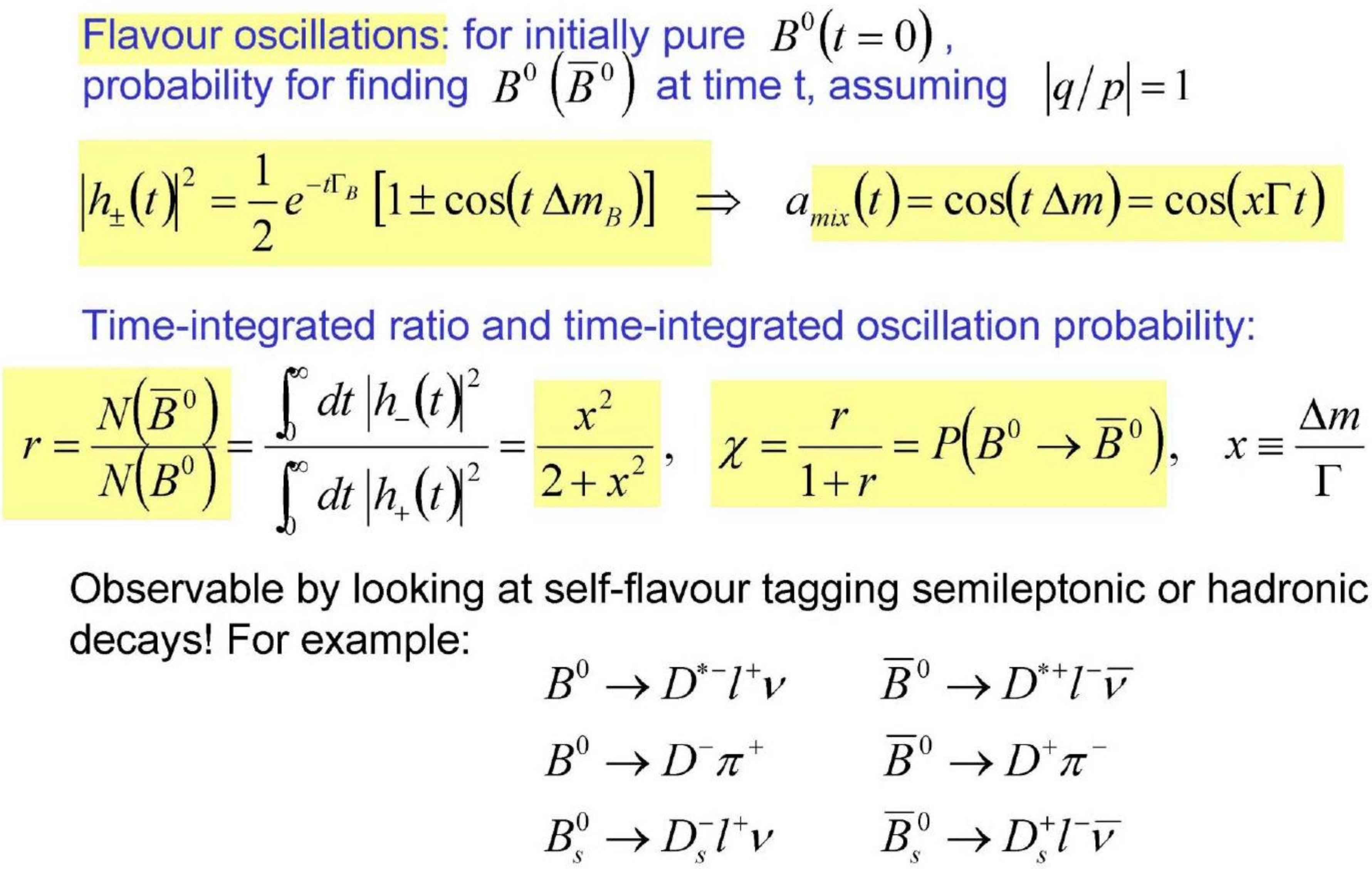
$$\left|B_{phys}^0(t)\right\rangle = h_+(t)\left|B^0\right\rangle + \frac{q}{p}h_-(t)\left|\overline{B}^0\right\rangle$$

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

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

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

Time evolution of neutral *B* mesons



Flavour oscillations: for initially pure $B^0(t=0)$, probability for finding $B^0\ (\overline{B}^0)$ 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:

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

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

$$B^0\to D^{*-}l^+\nu \qquad \overline{B}^0\to D^{*+}l^-\overline{\nu}$$

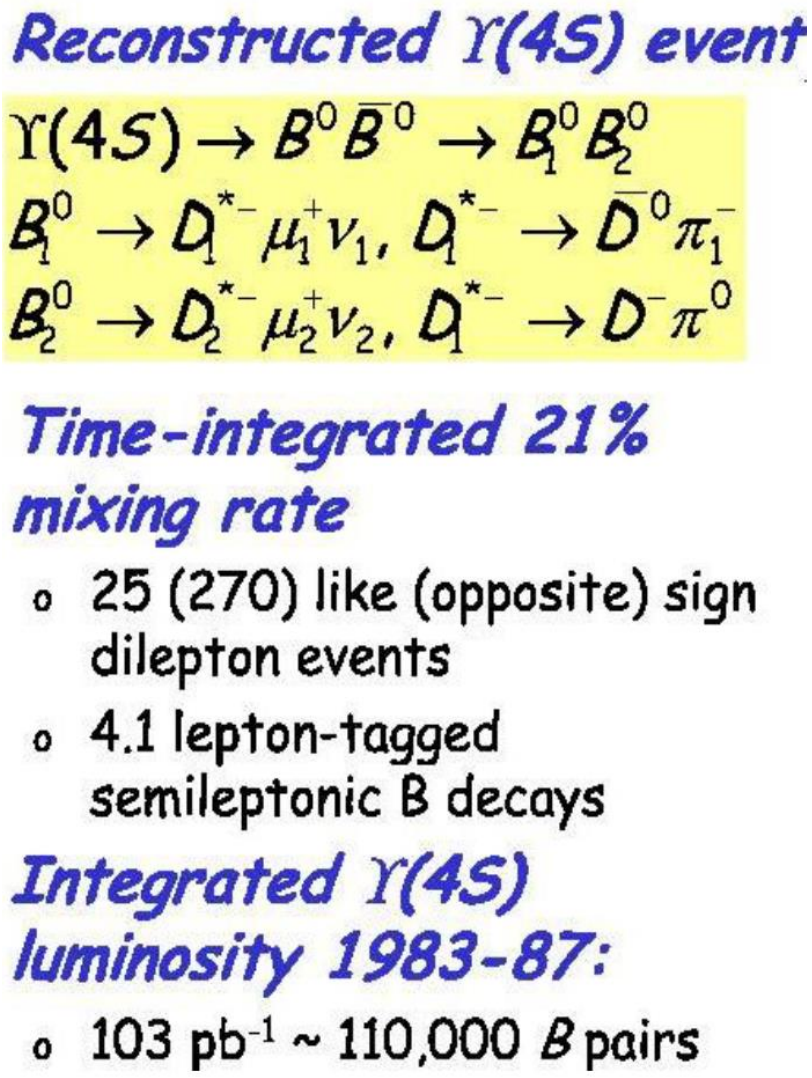
$$B^0\to D^-\pi^+ \qquad \overline{B}^0\to D^+\pi^-$$

$$B_s^0\to D_s^-l^+\nu \qquad \overline{B}_s^0\to D_s^+l^-\overline{\nu}$$

Discovery $B\bar{B}$ oscillations

ARGUS Collaboration Observation of B – anti-B0 Mixing

PL B 192, 245
1987



Reconstructed $\Upsilon(4S)$ event

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

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

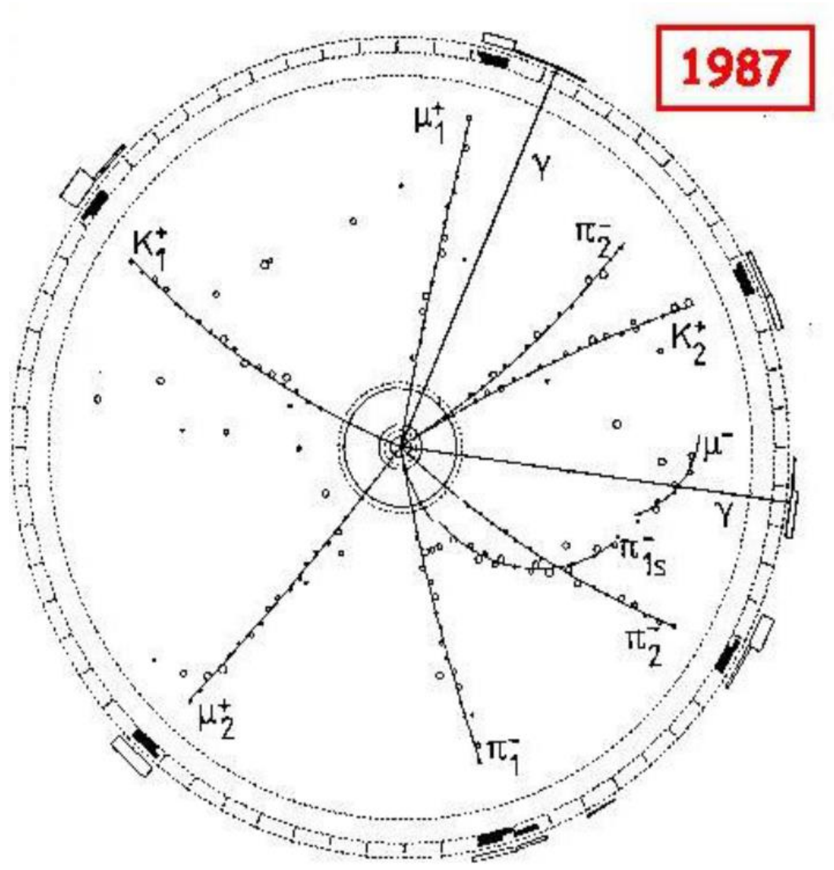
$B_2^0 \to D_2^{*-}\mu_2^+\nu_2,\ D_1^{*-} \to D^-\pi^0$

Time-integrated 21% mixing rate

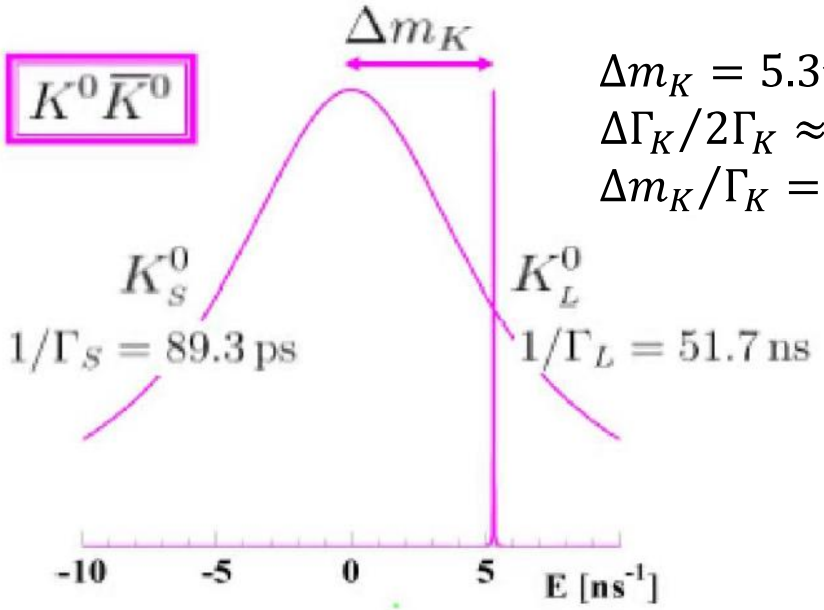
- 25 (270) like (opposite) sign dilepton events
- 4.1 lepton-tagged semileptonic B decays

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

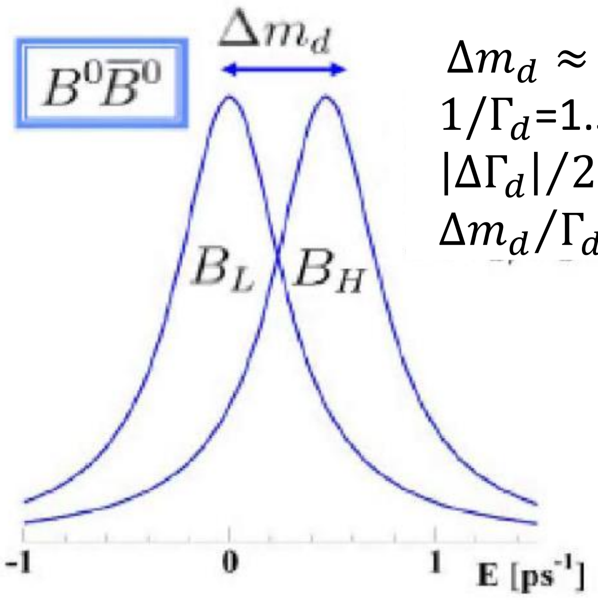
- 103 pb^{-1} ~ 110,000 *B* pairs



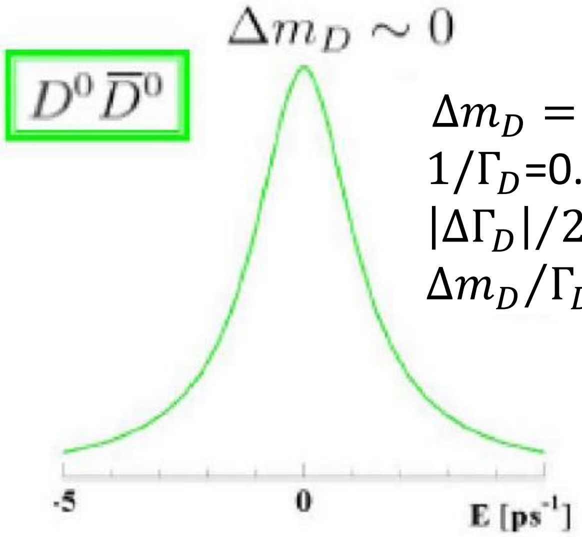
Mixing parameters



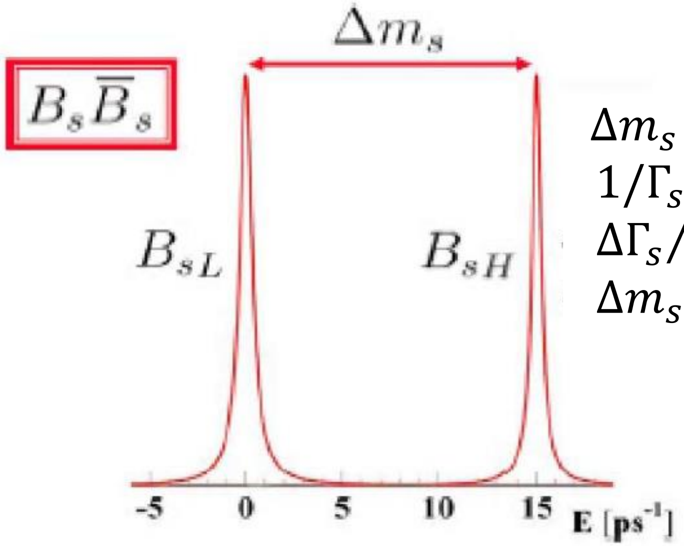
$\Delta m_K = 5.3 ns^{-1}$
$\Delta\Gamma_K/2\Gamma_K \approx -1$
$\Delta m_K/\Gamma_K = 0.945$



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

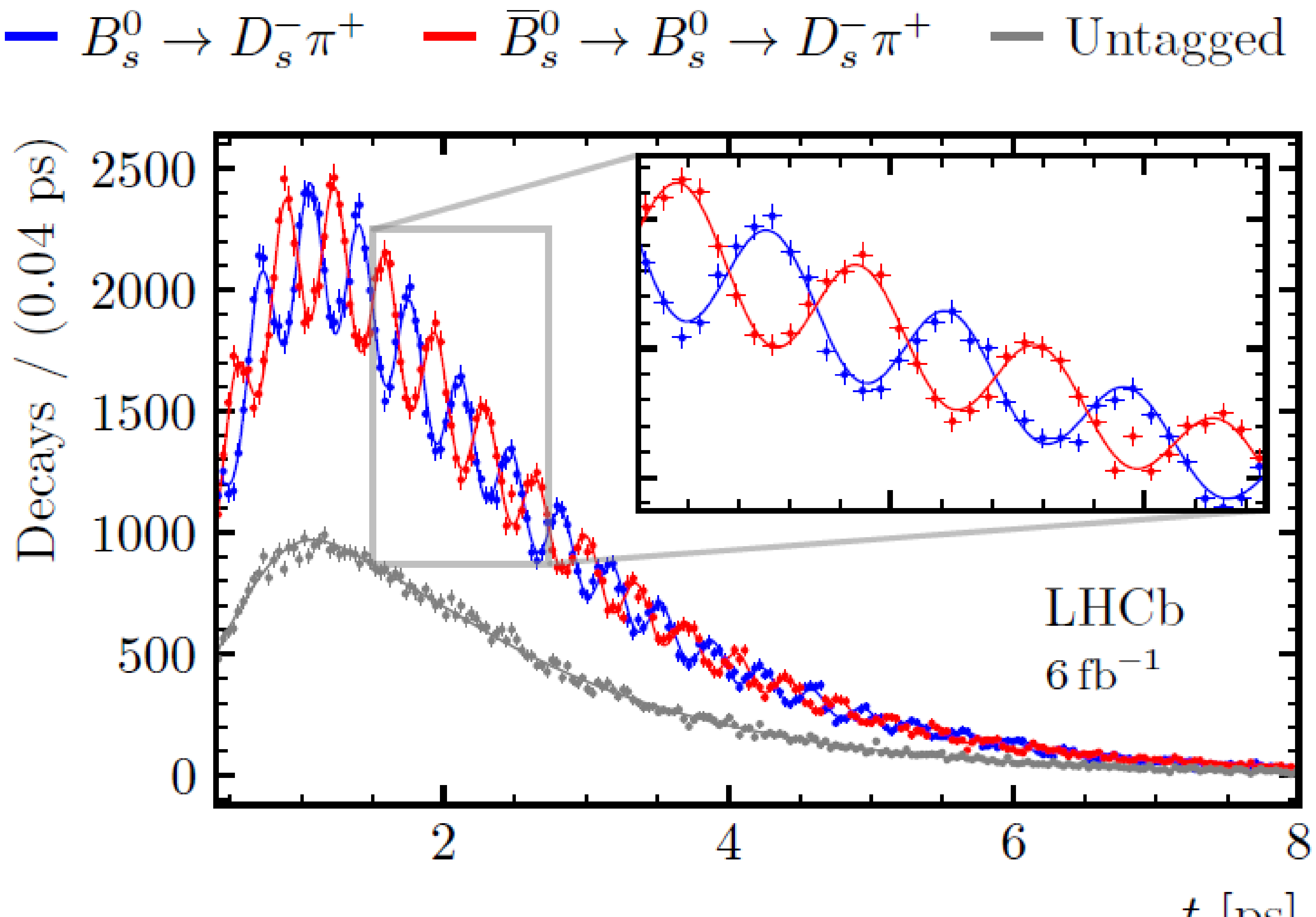


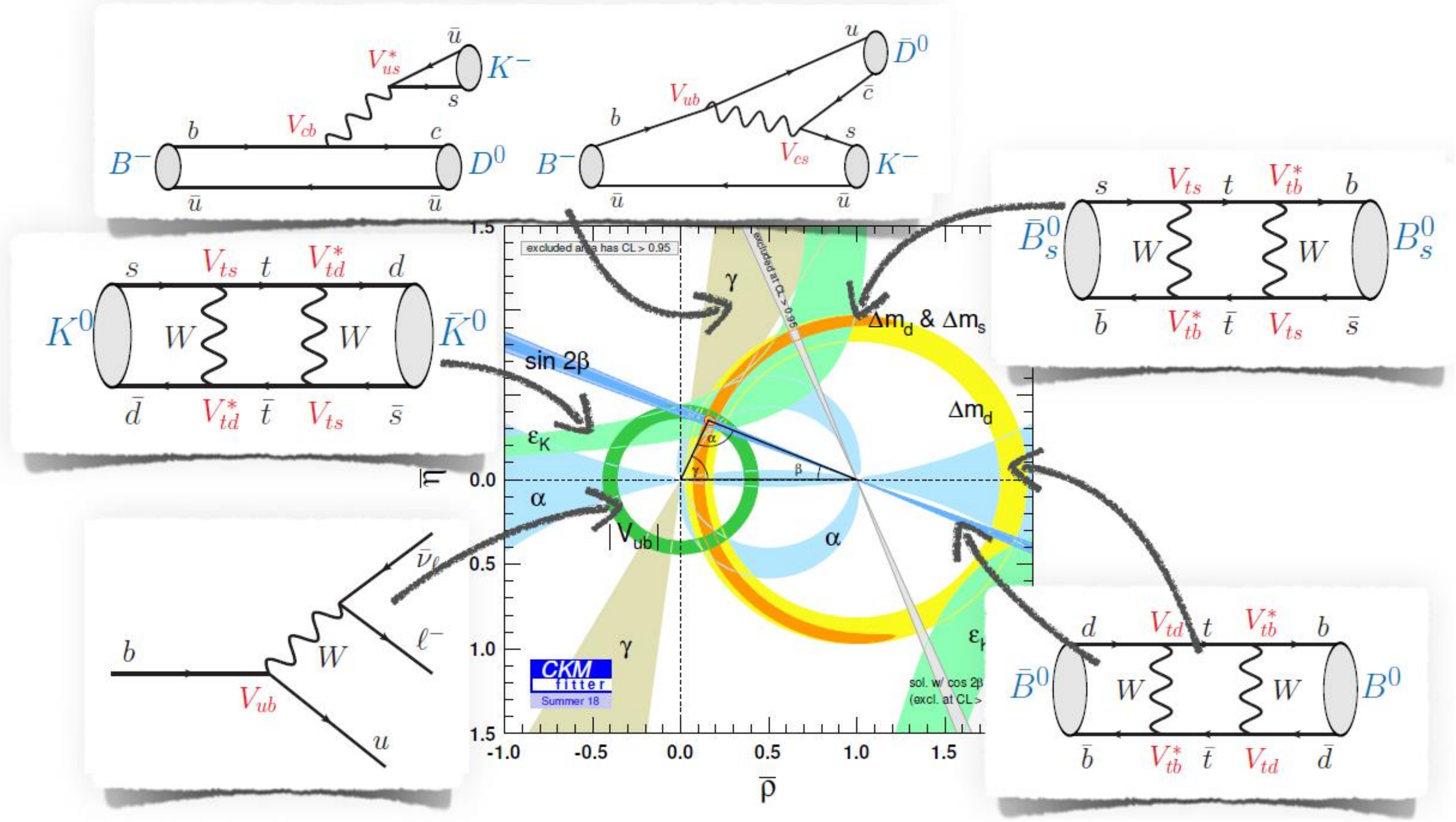
$\Delta m_D = 0.01 ps^{-1}$
$1/\Gamma_D$=0.415 ps
$|\Delta\Gamma_D|/2\Gamma_D = 0.007$
$\Delta m_D/\Gamma_D = 0.004$



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

$B_s\overline{B}_s$Mixing




B^-
b
V_{cb}
V^*_{us}
$\bar{u}$
s
K^-
c
D^0
$\bar{u}$
$\bar{u}$
B^-
b
V_{ub}
u
$\bar{D}^0$
$\bar{c}$
s
V_{cs}
K^-
$\bar{u}$
$\bar{u}$
K^0
s
V_{ts}
t
V^*_{td}
d
W
W
$\bar{K}^0$
$\bar{d}$
V^*_{td}
$\bar{t}$
V_{ts}
$\bar{s}$
$\bar{B}^0_s$
s
V_{ts}
t
V^*_{tb}
b
W
W
B^0_s
$\bar{b}$
V^*_{tb}
$\bar{t}$
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
sin 2β
Δm_d & Δm_s
Δm_d
ε_K
α
β
γ
α
$|V_{ub}|$
α
γ
ε_K
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

CP Violation in B Decays

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

$$\begin{tikzcd} \mathrm{B}_\mathrm{d}^0 \arrow[dr] & \\ & \psi \mathrm{K}_\mathrm{S} \\ \bar{\mathrm{B}}_\mathrm{d}^0 \arrow[ur] & \end{tikzcd}$$

Great idea! But is it practical?

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

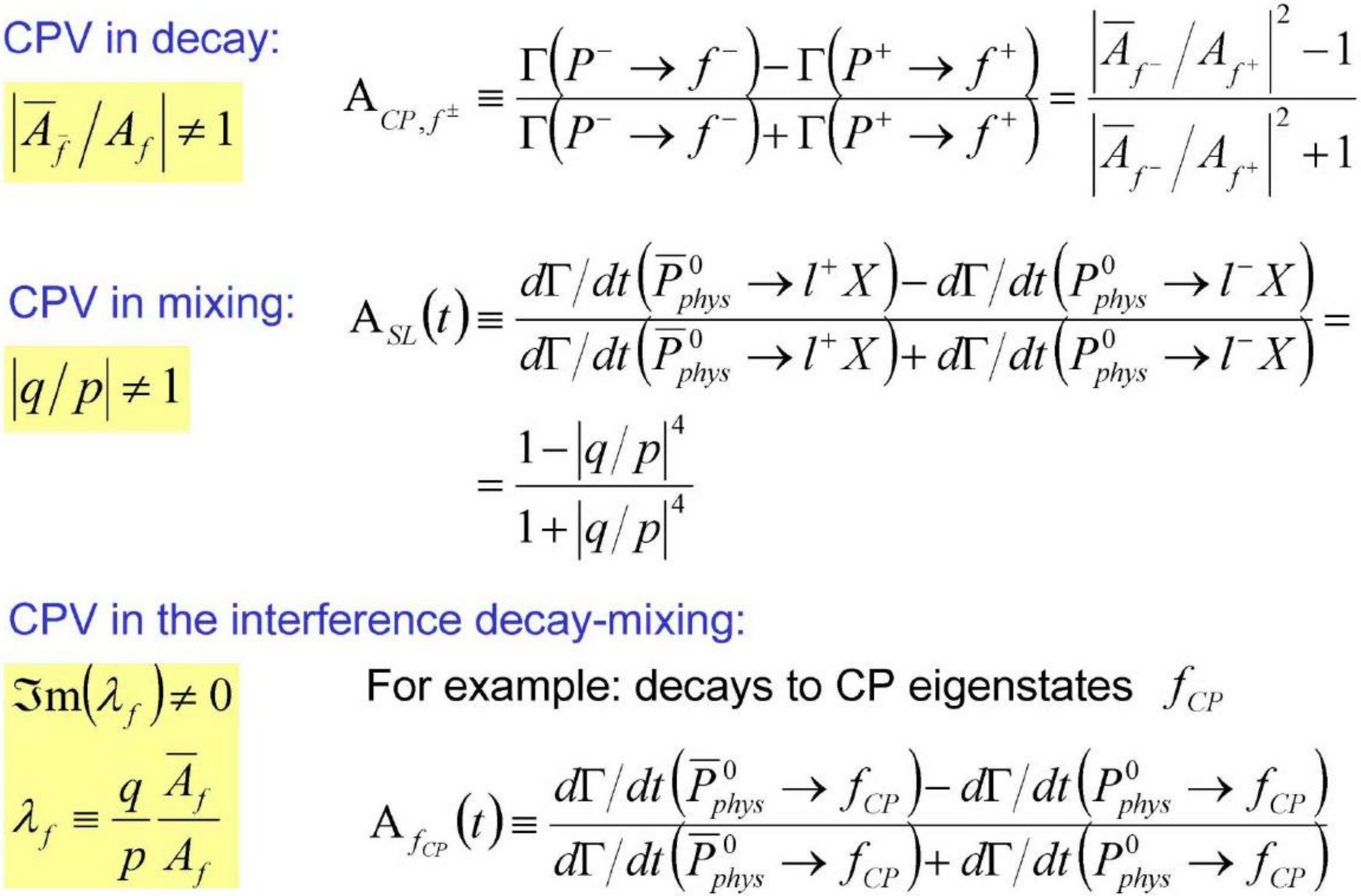
How large fraction of B^0 oscillate into a $\bar{B}^0$ before they decay?

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

Classification of CP-violating effects



CPV in decay:

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

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

CPV in mixing:

$|q/p| \neq 1$

$$A_{SL}(t) \equiv \frac{d\Gamma/dt\left(\overline{P}^0_{phys} \to l^+ X\right) - d\Gamma/dt\left(P^0_{phys} \to l^- X\right)}{d\Gamma/dt\left(\overline{P}^0_{phys} \to l^+ X\right) + d\Gamma/dt\left(P^0_{phys} \to l^- X\right)} = \\ = \frac{1 - |q/p|^4}{1 + |q/p|^4}$$

CPV in the interference decay-mixing:

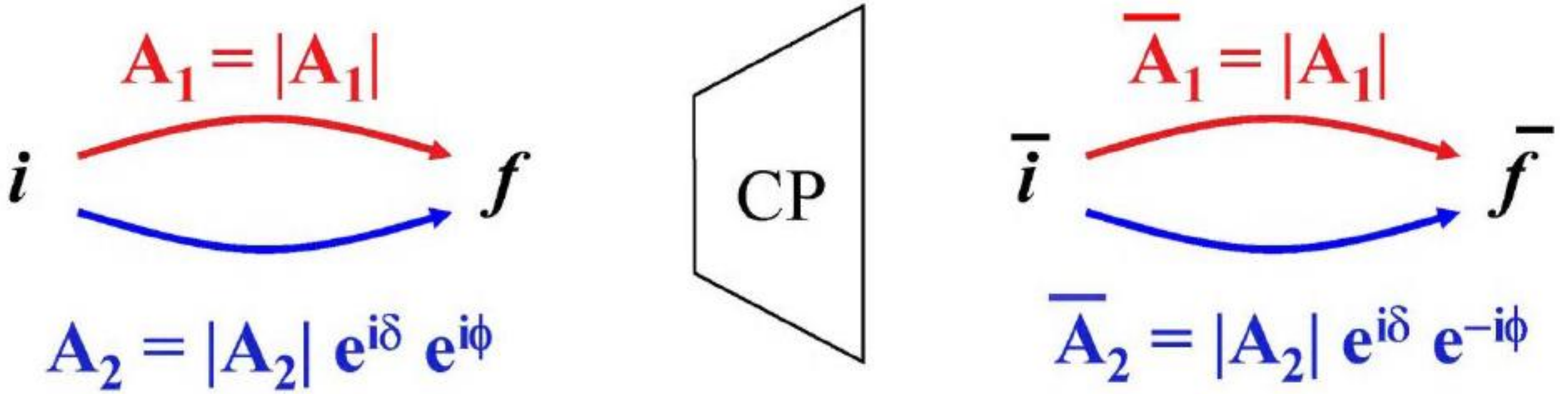
$\Im\mathrm{m}\left(\lambda_f\right) \neq 0$

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

For example: decays to CP eigenstates f_{CP}

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

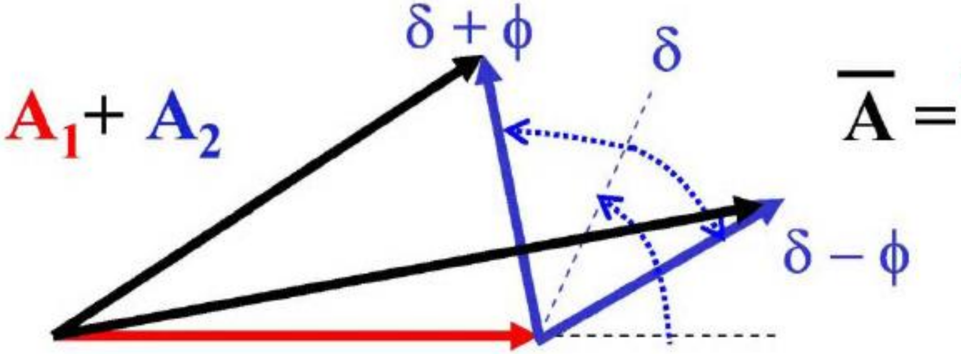
Observables: "direct" CP-violation



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

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

$A = A_1 + A_2$



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

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* $\delta \neq 0$

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

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

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

"decay"

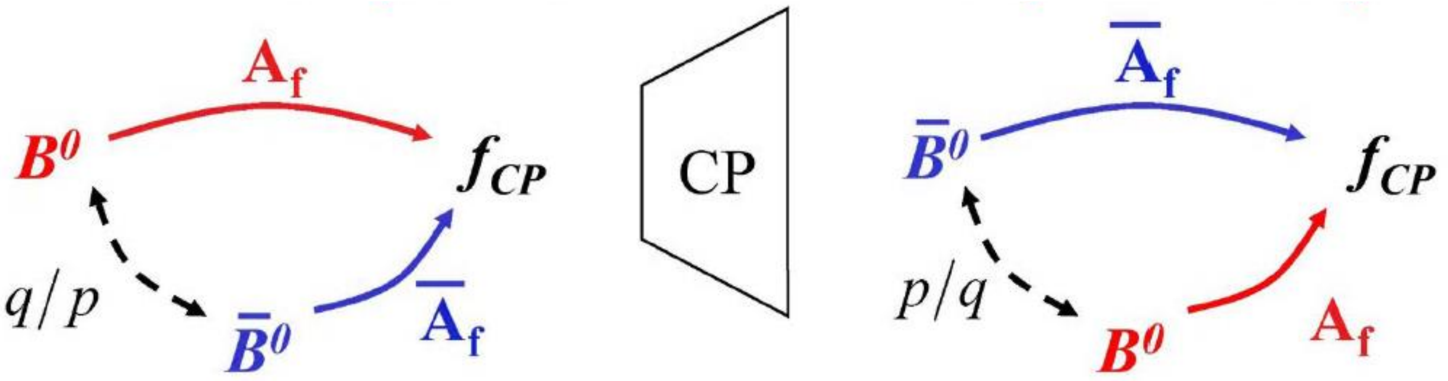
"oscillation, then decay"

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

"interference"

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

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

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

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

$$C_{f_{CP}} = \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2}$$

$$S_{f_{CP}} = \frac{-2 \mathrm{Im}\, \lambda_{f_{CP}}}{1 + |\lambda_{f_{CP}}|^2}$$

For single decay amplitude

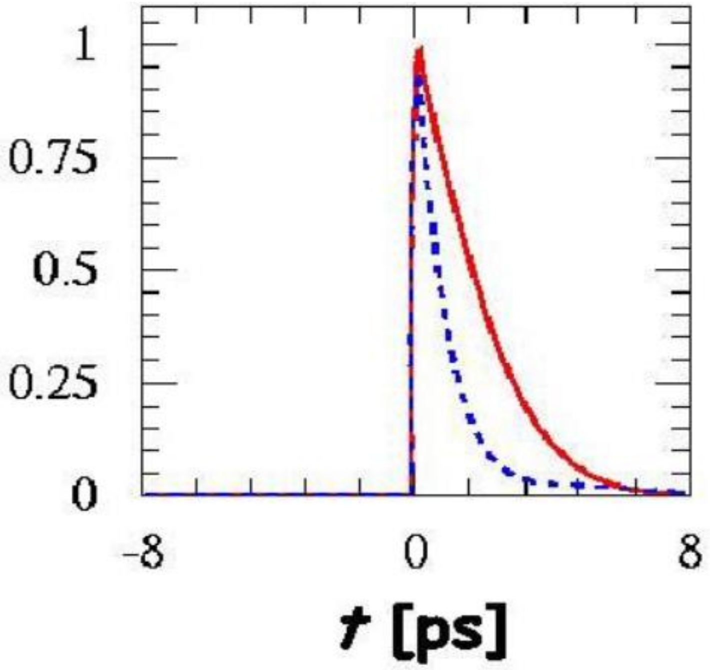
$= 0$

$= -\mathrm{Im}\, \lambda_{f_{CP}}$

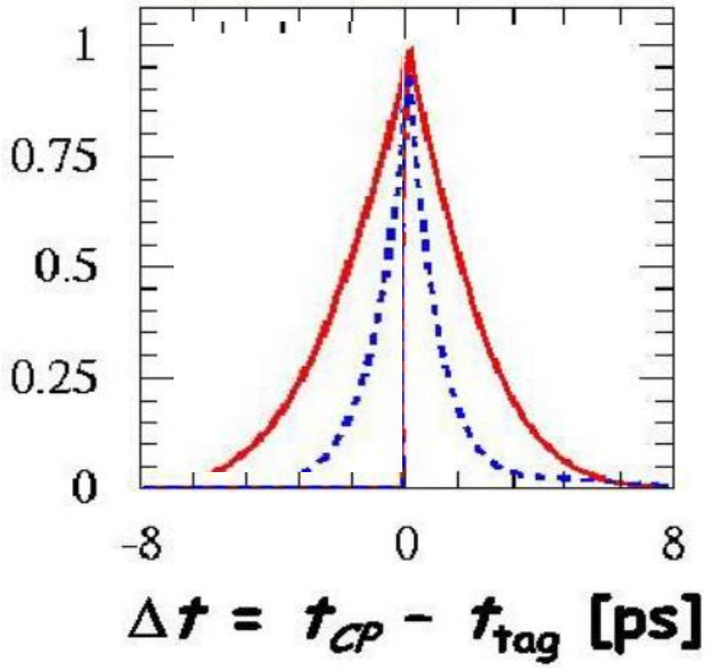
CP-violation in the Time Evolution of B^0 mesons

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

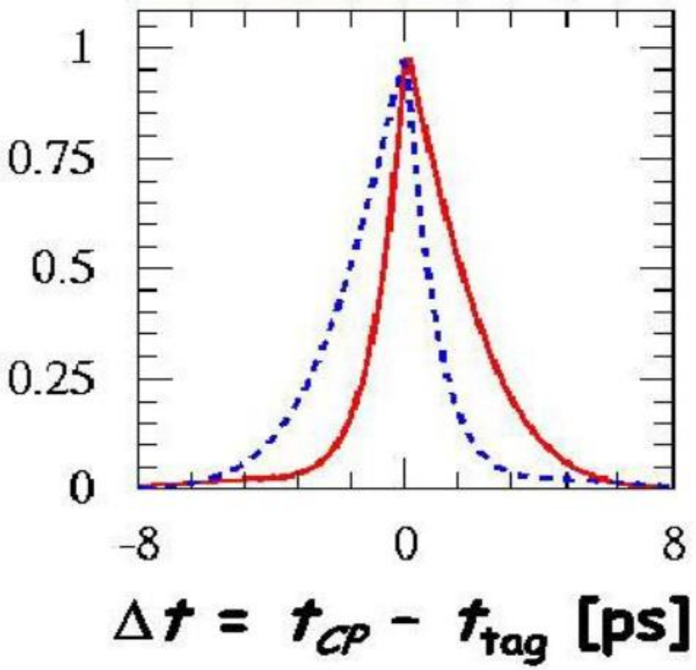
Incoherent $B_{J0}^+ \to B^0\pi^+$



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

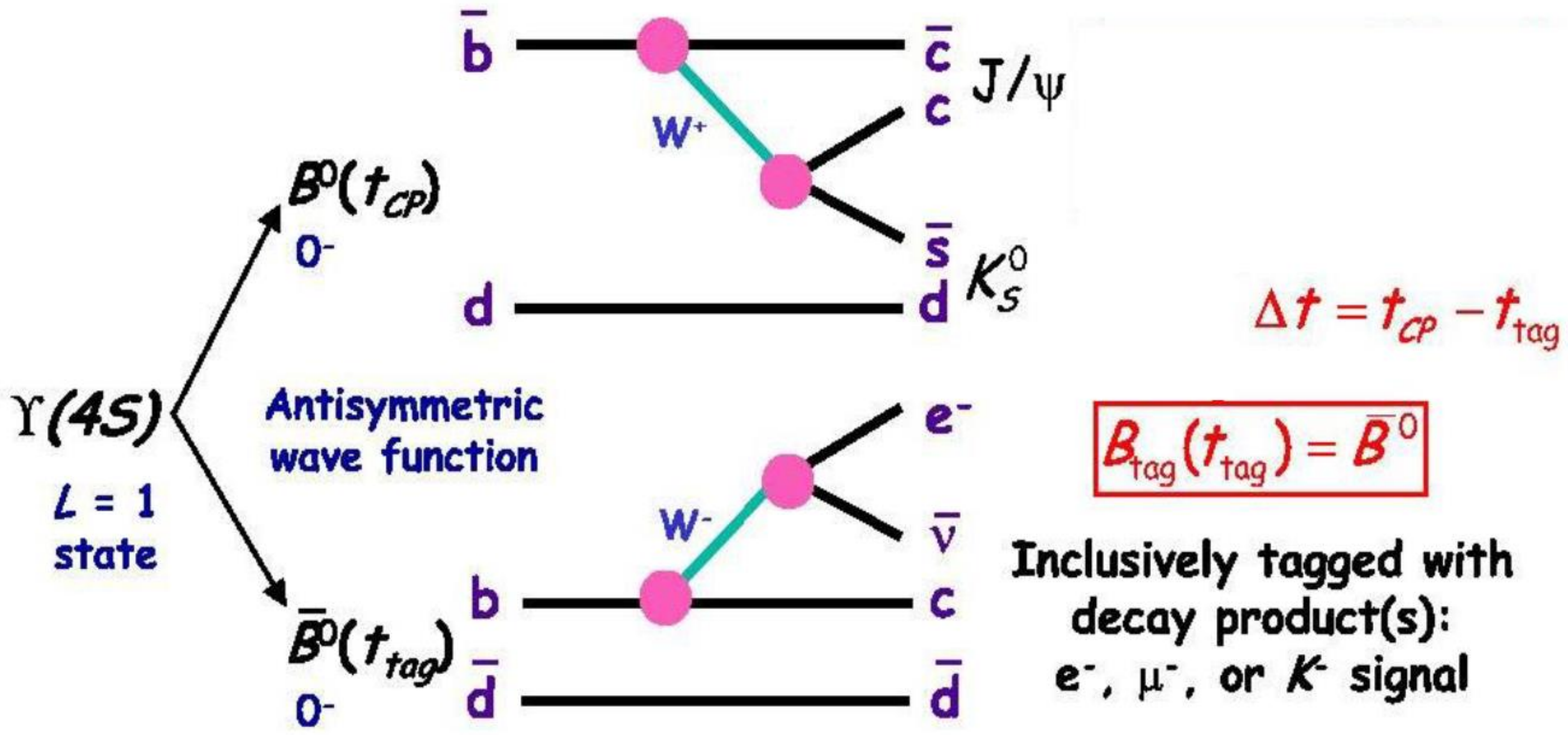


Coherent $e^+e^- \to B^0\bar{B}^0$



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

Golden Channel



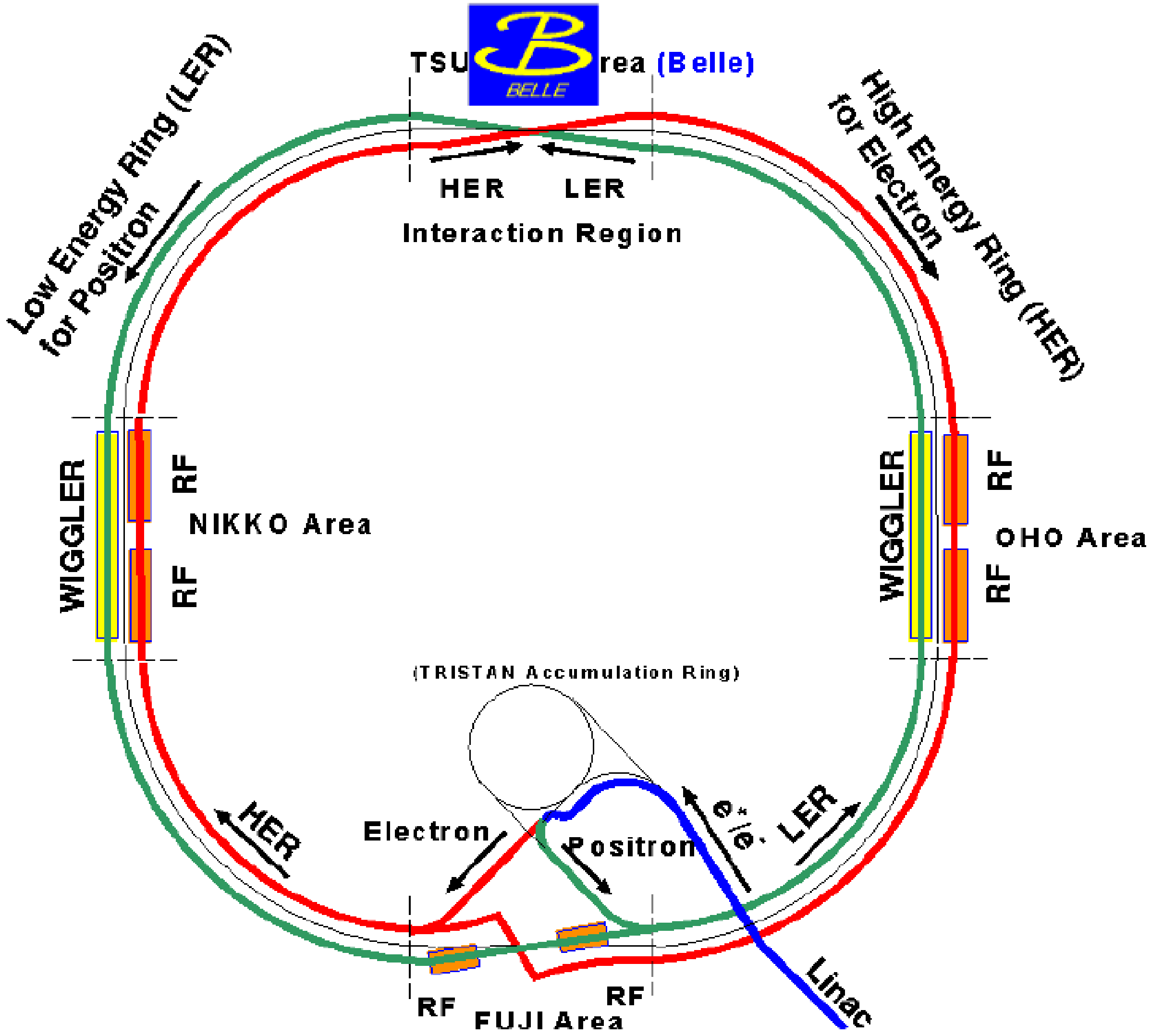
$\Delta t = t_{CP} - t_{tag}$

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

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

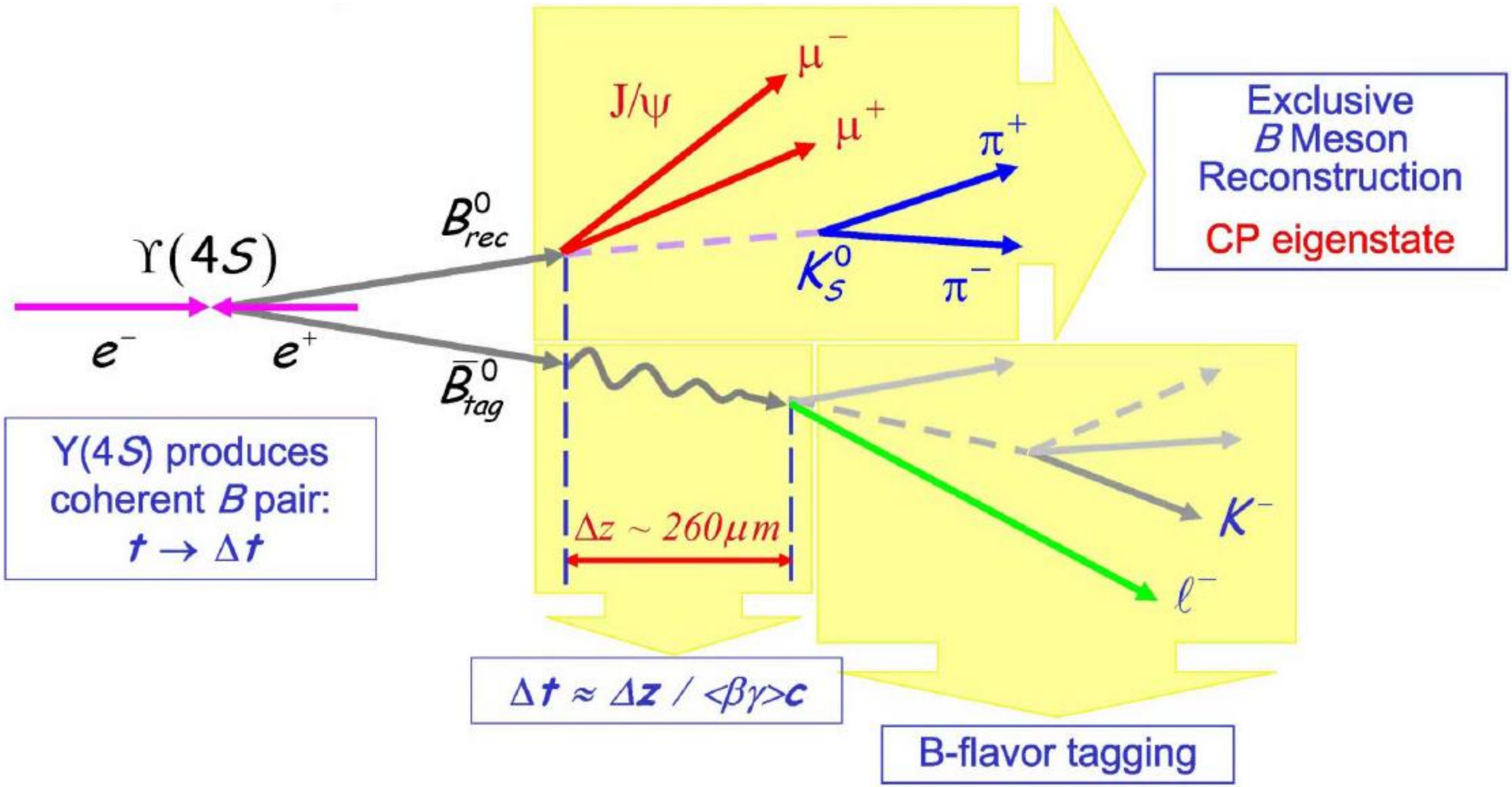
$$A_{f_{CP}}(\Delta t) = \frac{\Gamma(\bar{B}^0_{phys}(\Delta t) \to f_{CP}) - \Gamma(B^0_{phys}(\Delta t) \to f_{CP})}{\Gamma(\bar{B}^0_{phys}(\Delta t) \to f_{CP}) + \Gamma(B^0_{phys}(\Delta t) \to f_{CP})} = \sin 2\beta \sin \Delta m_d \Delta t$$

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 Υ(4S)
- Design:
  - Luminosity: 10^{34} $cm^{-2}s^{-1}$
  - Current: 2.6 / 1.1A (LER HER)
- Beam size: $\sigma_y \approx 3$ μm
  - $\sigma_x \approx 100$ μm
- ±11 mrad crossing angle

Time-Dependent CP Asymmetry Measurement



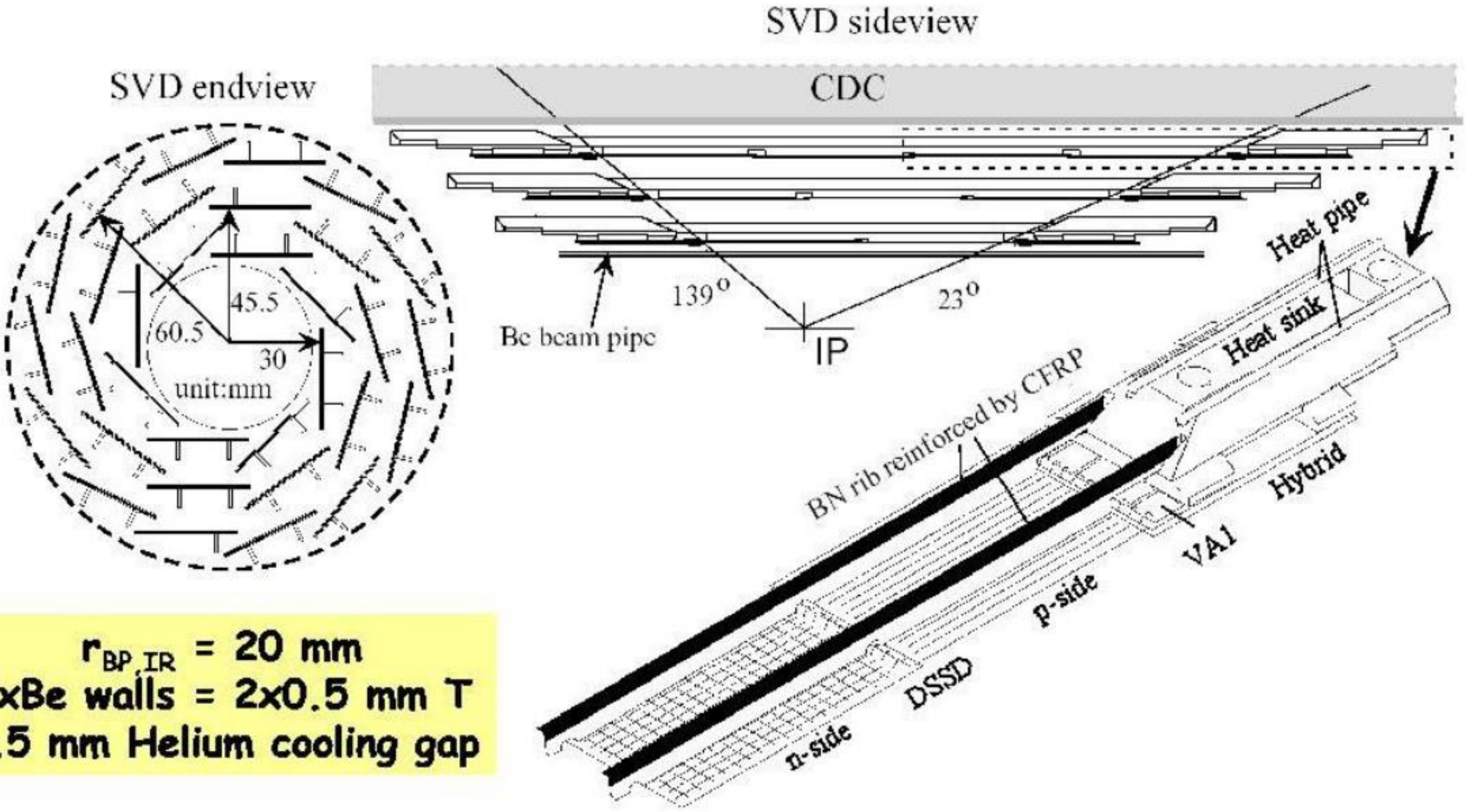
Y(4*S*) produces
coherent *B* pair:
$t \to \Delta t$

Exclusive
B Meson
Reconstruction
CP eigenstate

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

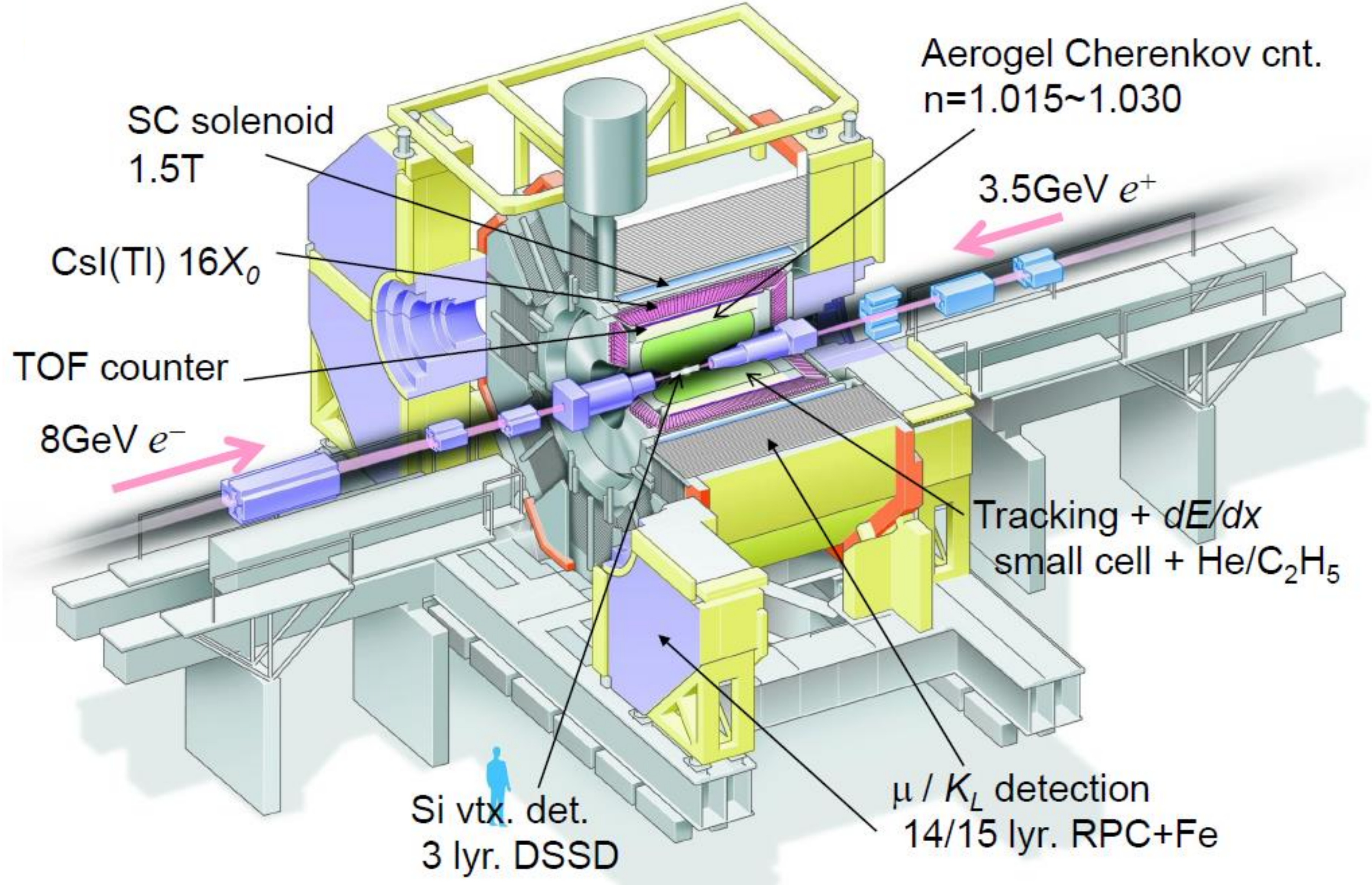
B-flavor tagging

Silicon Vertex Detector at Belle

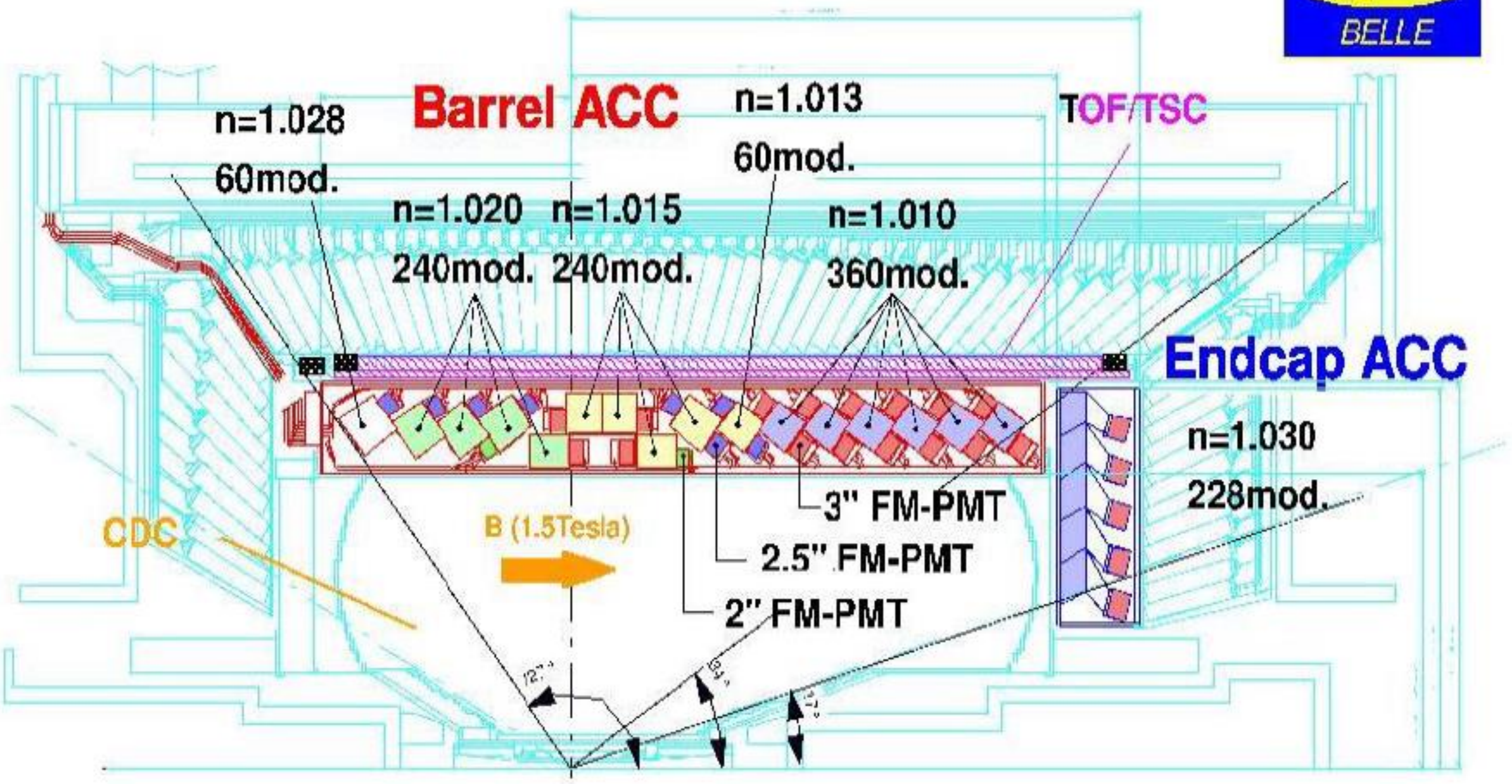


$r_{BP,IR}$ = 20 mm
2xBe walls = 2x0.5 mm T
2.5 mm Helium cooling gap

Detector Belle

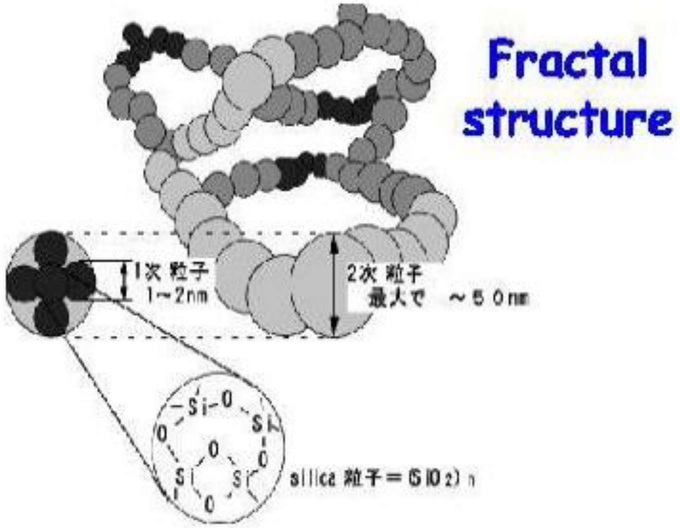


Particle Identification System at Belle

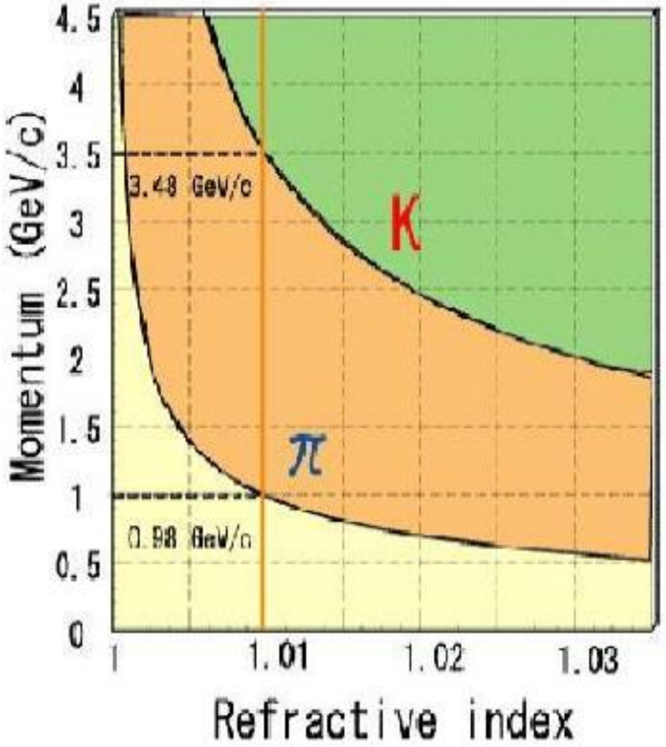


Aerogel Cherenkov Counters

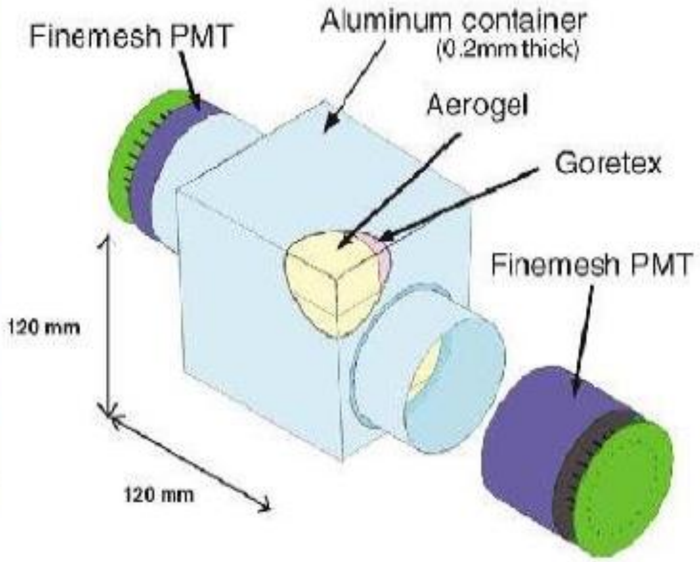
- Hydrophobic silica-aerogels
- n = 1.01~1.028 (barrel), 1.03 (endcap)
- 960 modules (barrel) ->1560 PMT's
- 228 modules (endcap) -> 228 PMT's


Fractal structure

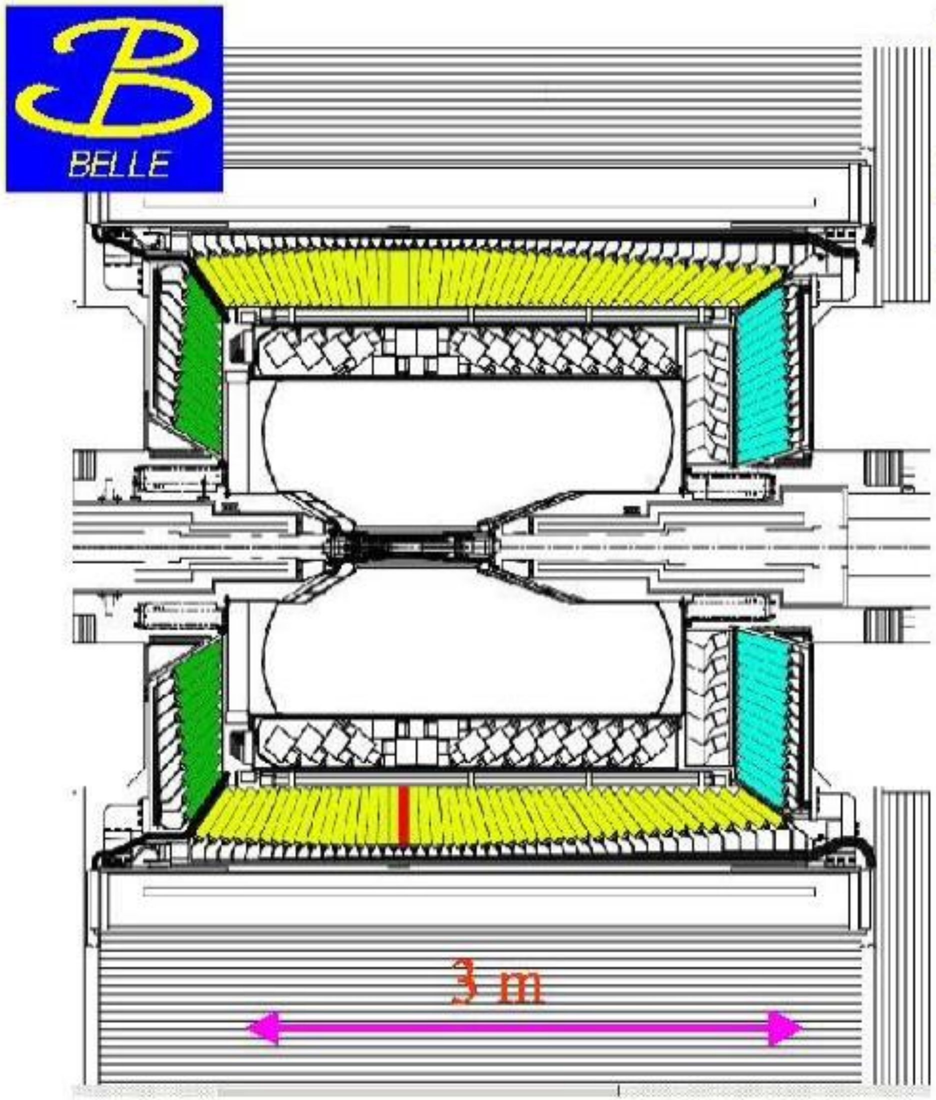
Cherenkov light thresholds



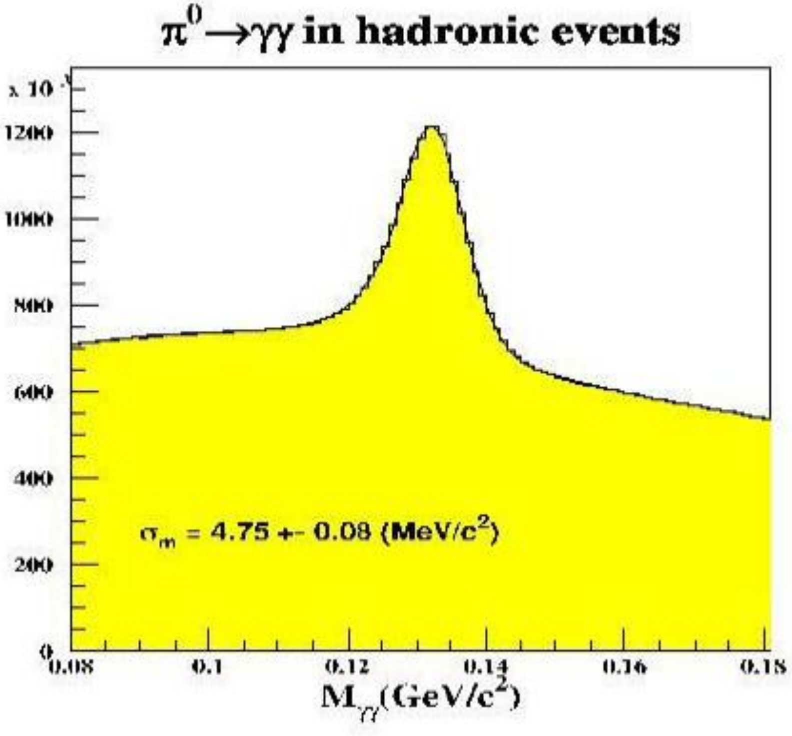
BELLE



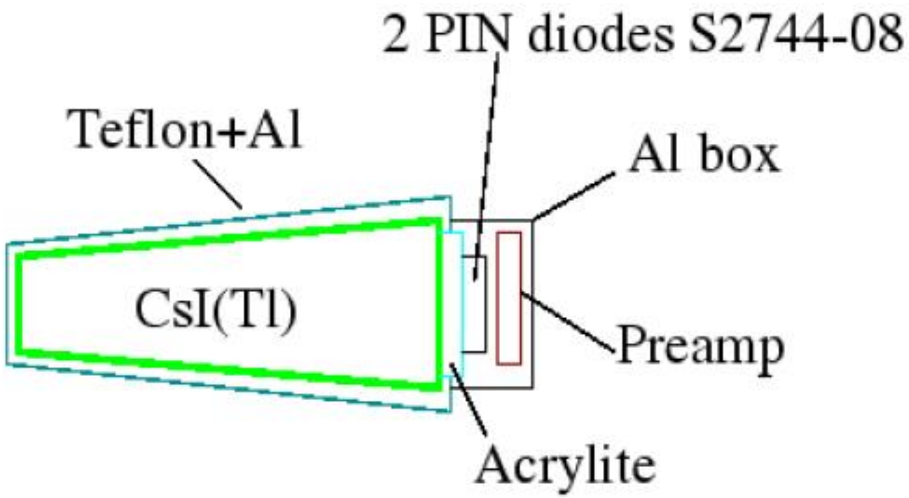
Electromagnetic Calorimeter



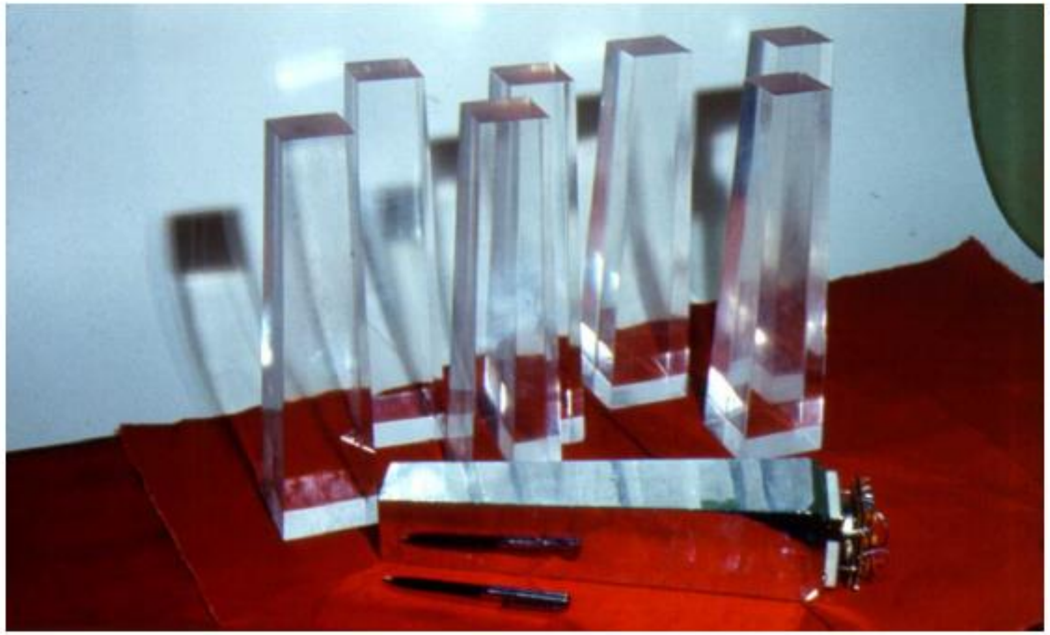
- *8736 CsI(Tl) crystals with photodiode readout*
- *About 16.2 X0, inside solenoid*
- *Coverage from 12 to 155°*



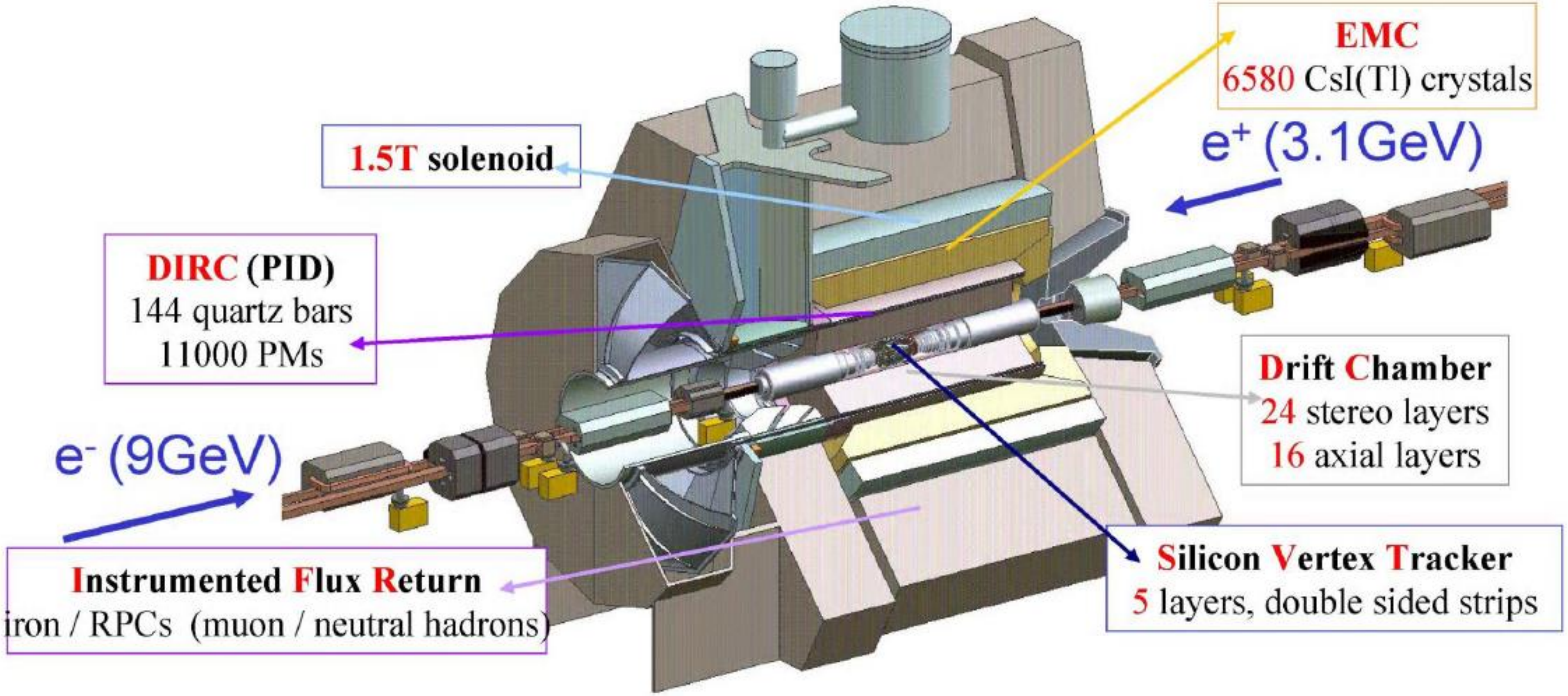
CsI(Tl) Crystals



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



Detector Babar



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 < 3.5GeV/c

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

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

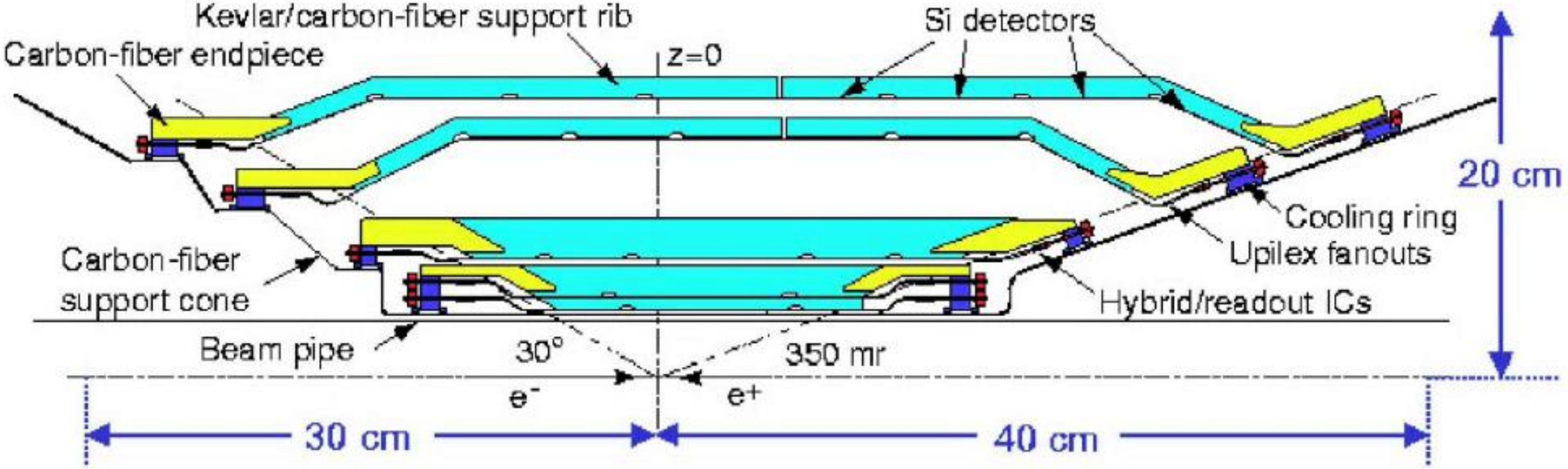
Silicon Vertex Tracker

double-sided Si microstrip detectors

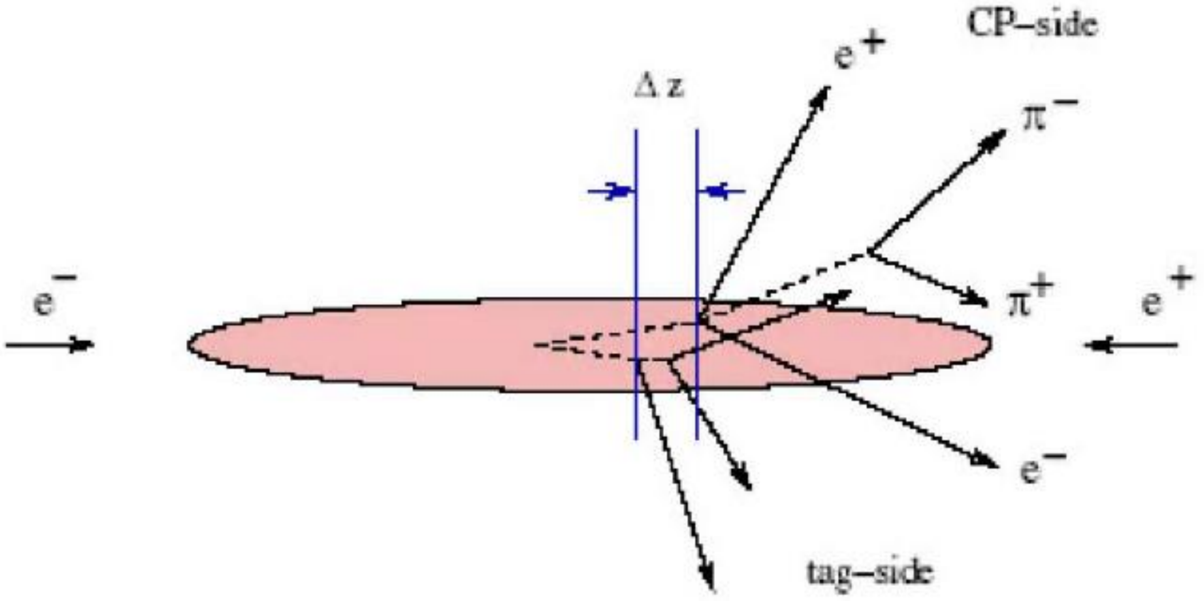
5 layers: 340 wafers, 150000 readout channels

20° < θ < 150°

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



Silicon Vertex Tracker (Babar vs Belle)



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

  $\Delta t \simeq \Delta z/(\gamma\beta c)$
- 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	$3.1 \times 9\,\text{GeV}$	$3.5 \times 8.5\,\text{GeV}$
$\gamma\beta$	0.56	0.425
Interaction point ($h \times v \times l$)	$120\,\mu\text{m} \times 5\,\mu\text{m} \times 8.5\,\text{mm}$	$80\,\mu\text{m} \times 2\,\mu\text{m} \times 3.4\,\text{mm}$
Typical Δz	$260\mu\text{m}$	$200\mu\text{m}$
σ_z (CP-side)	$50\,\mu\text{m}$	$75\,\mu\text{m}$
σ_z (tag-side)	$100 \sim 150\,\mu\text{m}$	$140\,\mu\text{m}$

DIRC

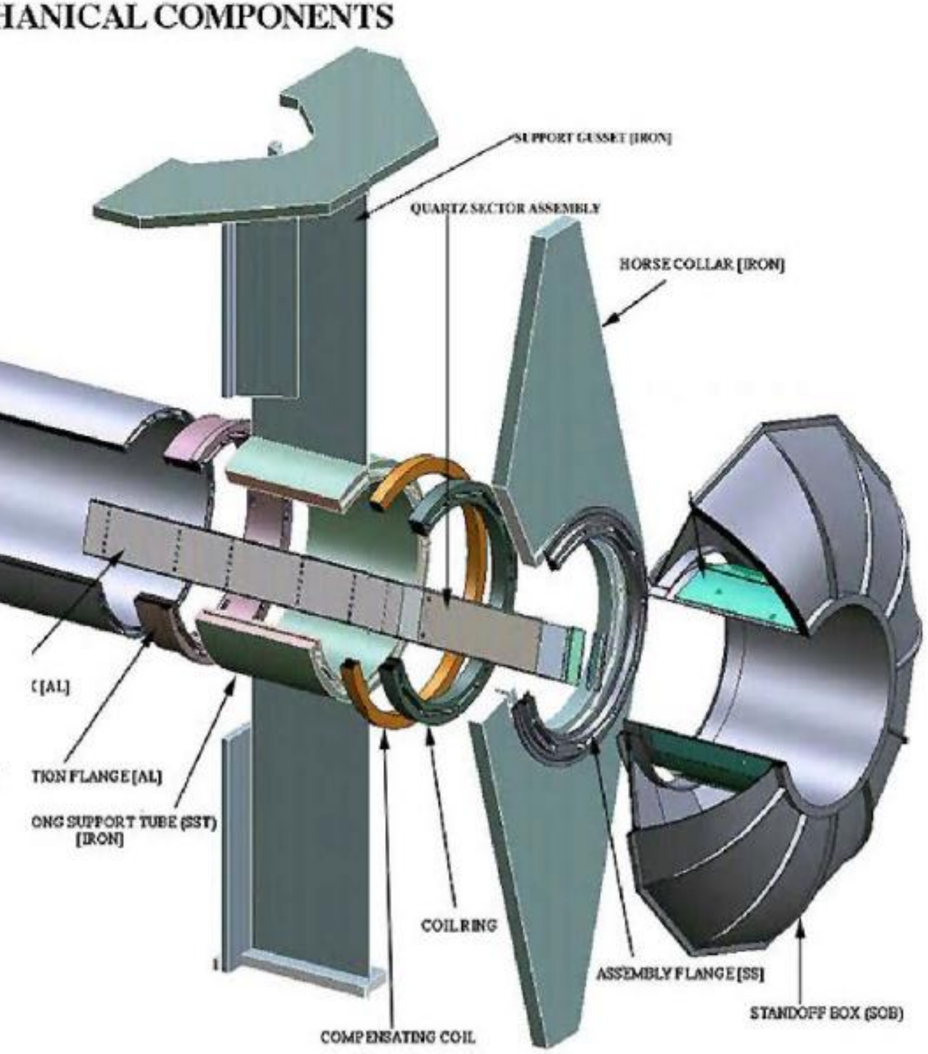
- Detector of Internally Reflected Cherenkov light

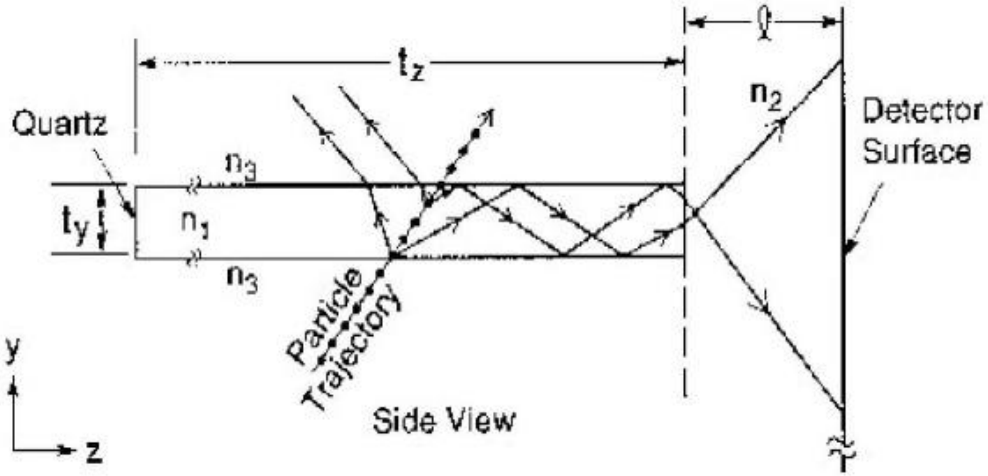
144 quartz bars (1.5 cm thick)

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

9mrad single photon resolution

DIRC MECHANICAL COMPONENTS





Identification Performance

Charged K identified by

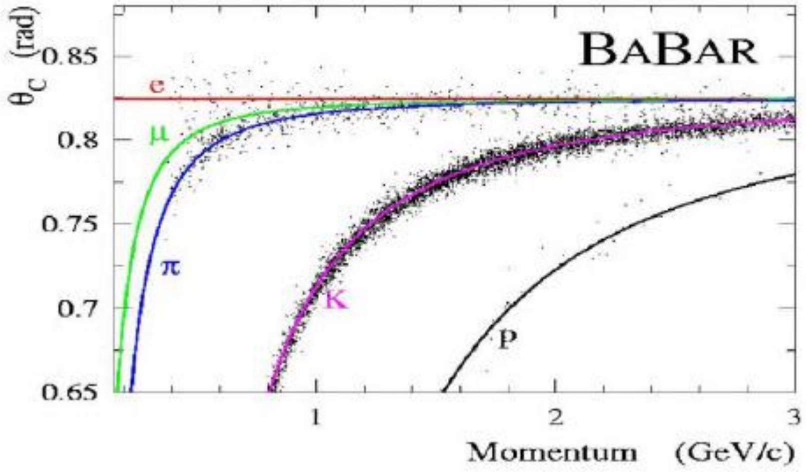
DIRC: Cerenkov angle

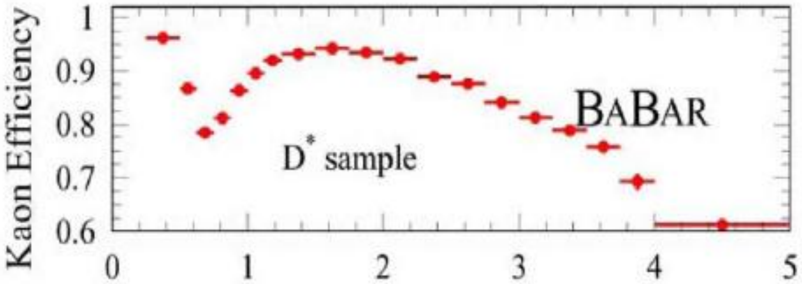
DCH: dE/dx ($p < 0.7$ GeV/c)

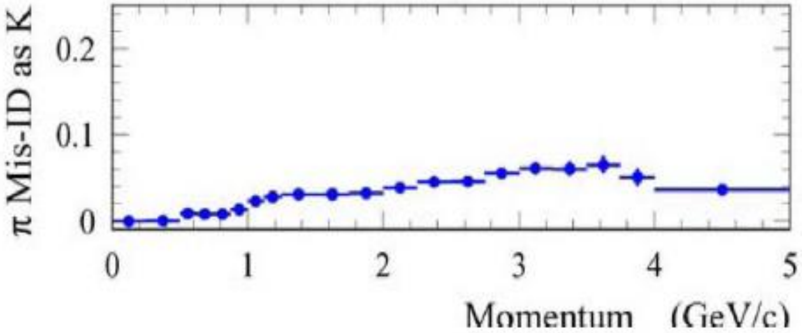
Efficiency and purity measured on control samples (soft pion tag)

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

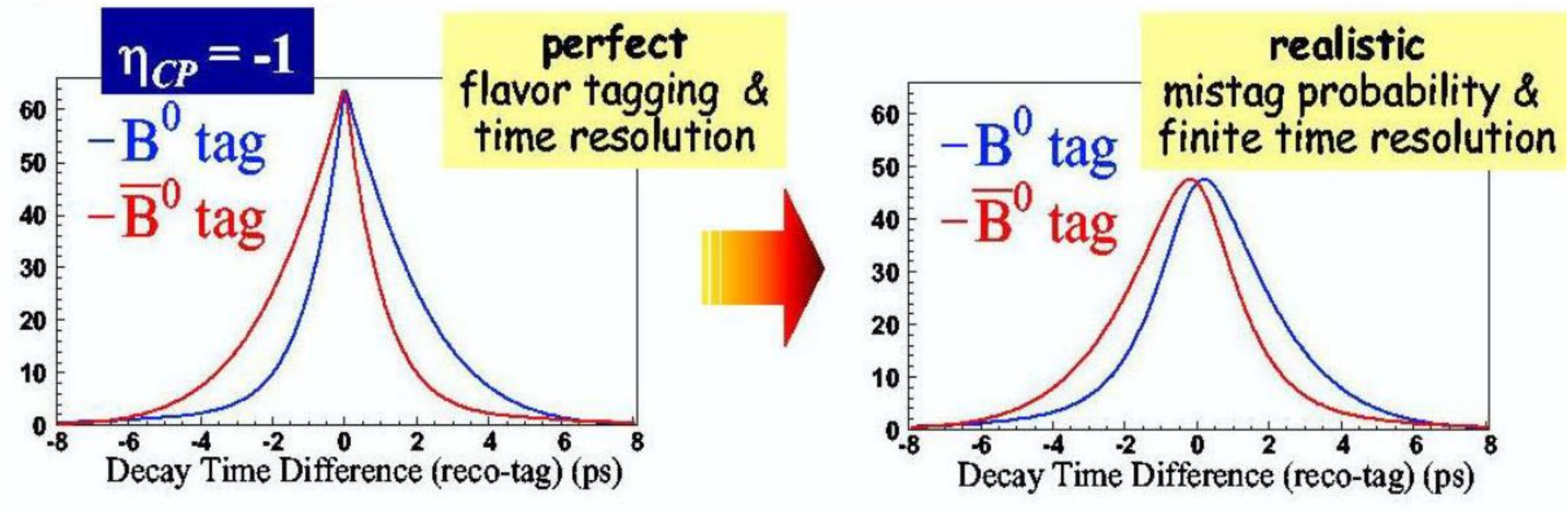
$> 3.4\sigma$ π/K separation up to ≈ 3.5 GeV/c







CPV Analysis: Time Distribution



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

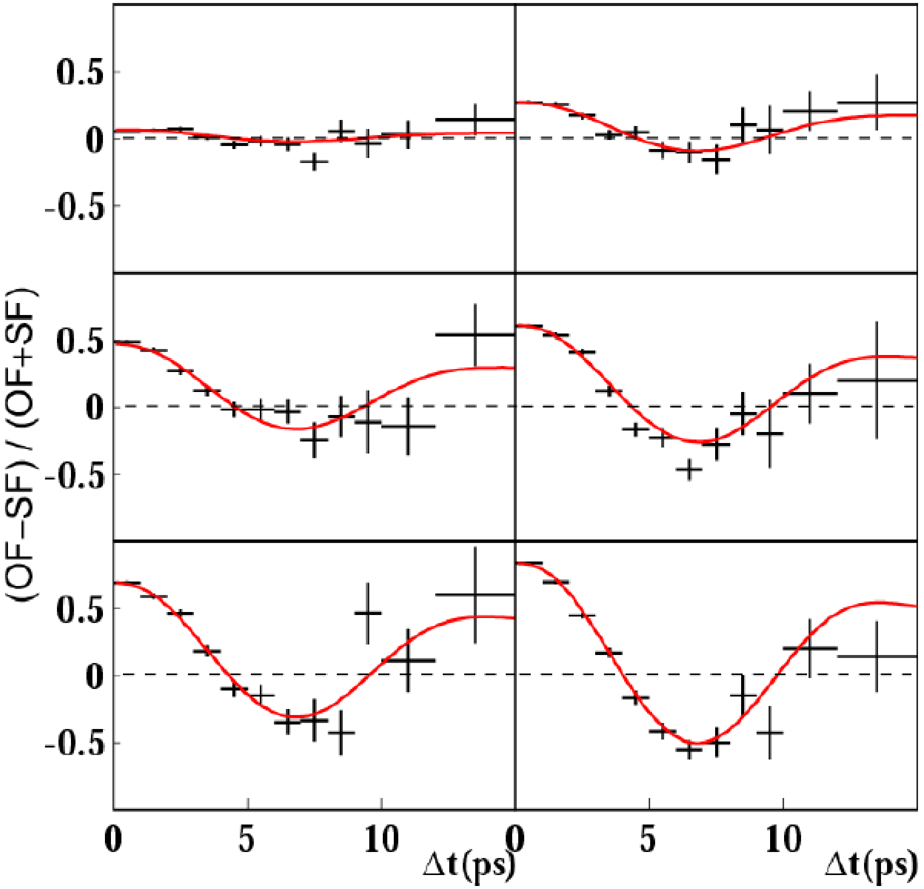
ω – mistag probability

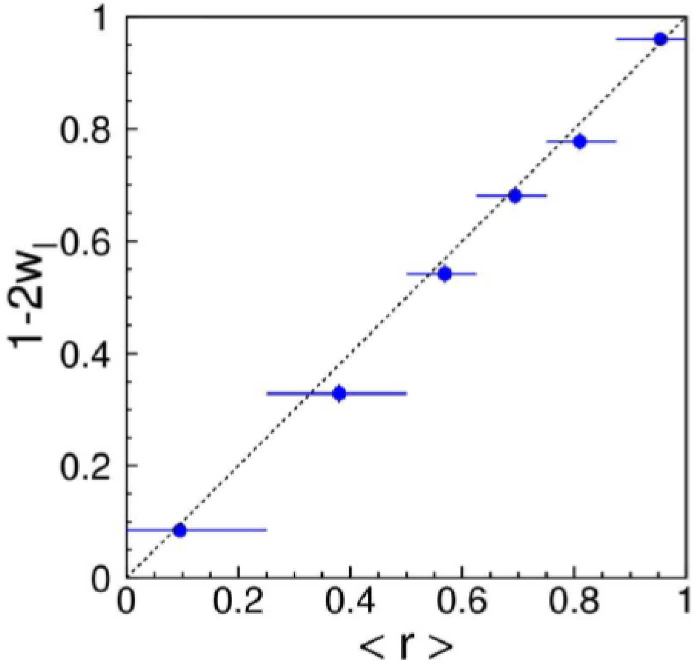
$R(\Delta t)$- time-resolution function

Flavour tagging – dilution factor

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

↳ tag

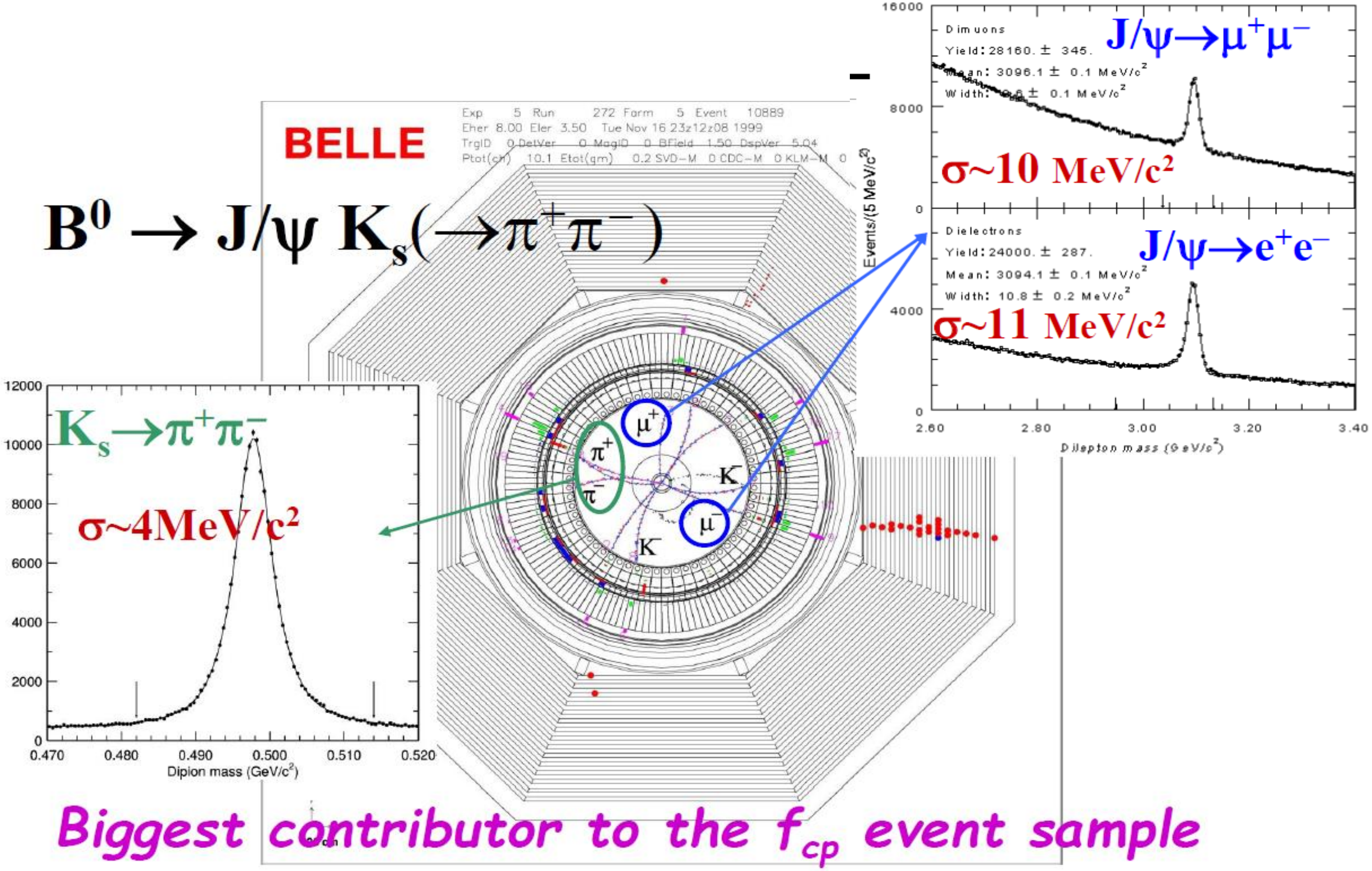




Efficiency > 99.5%

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

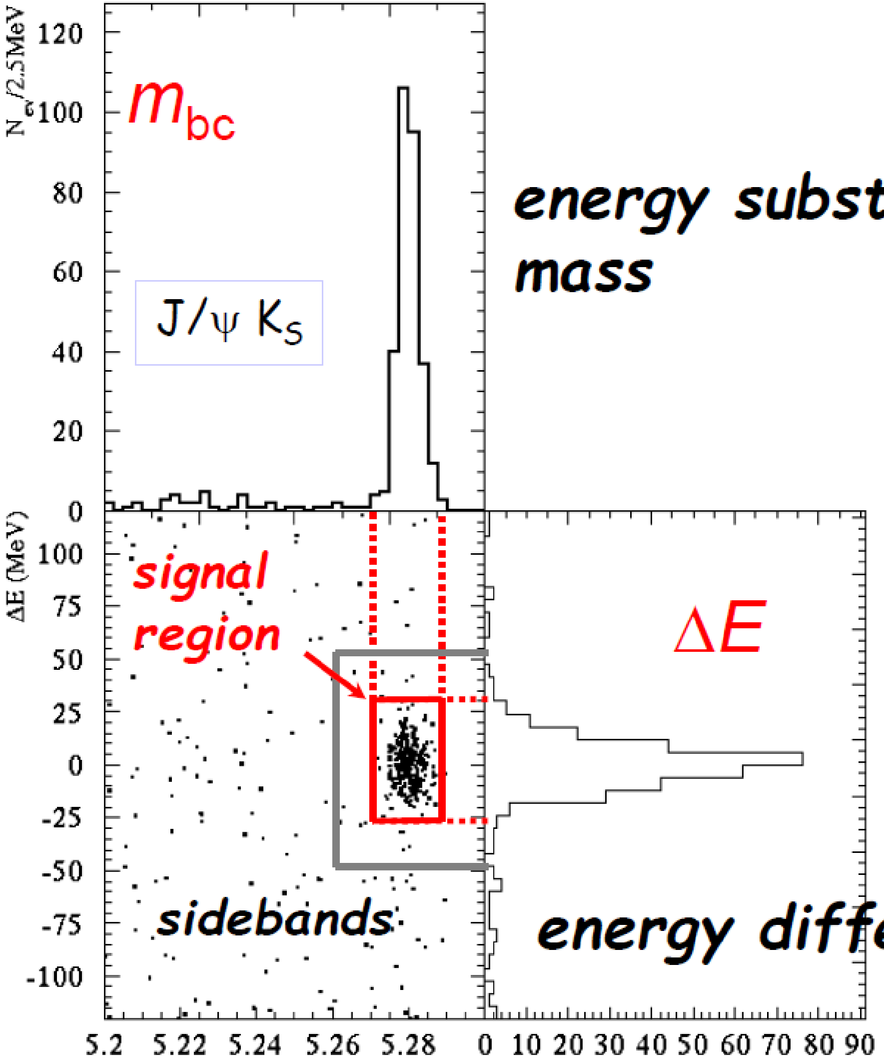
“Golden Mode” Event



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

Biggest contributor to the f_{cp} event sample

Reconstruction of B mesons



energy substituted mass

energy difference

Initial state kinematic constraint

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

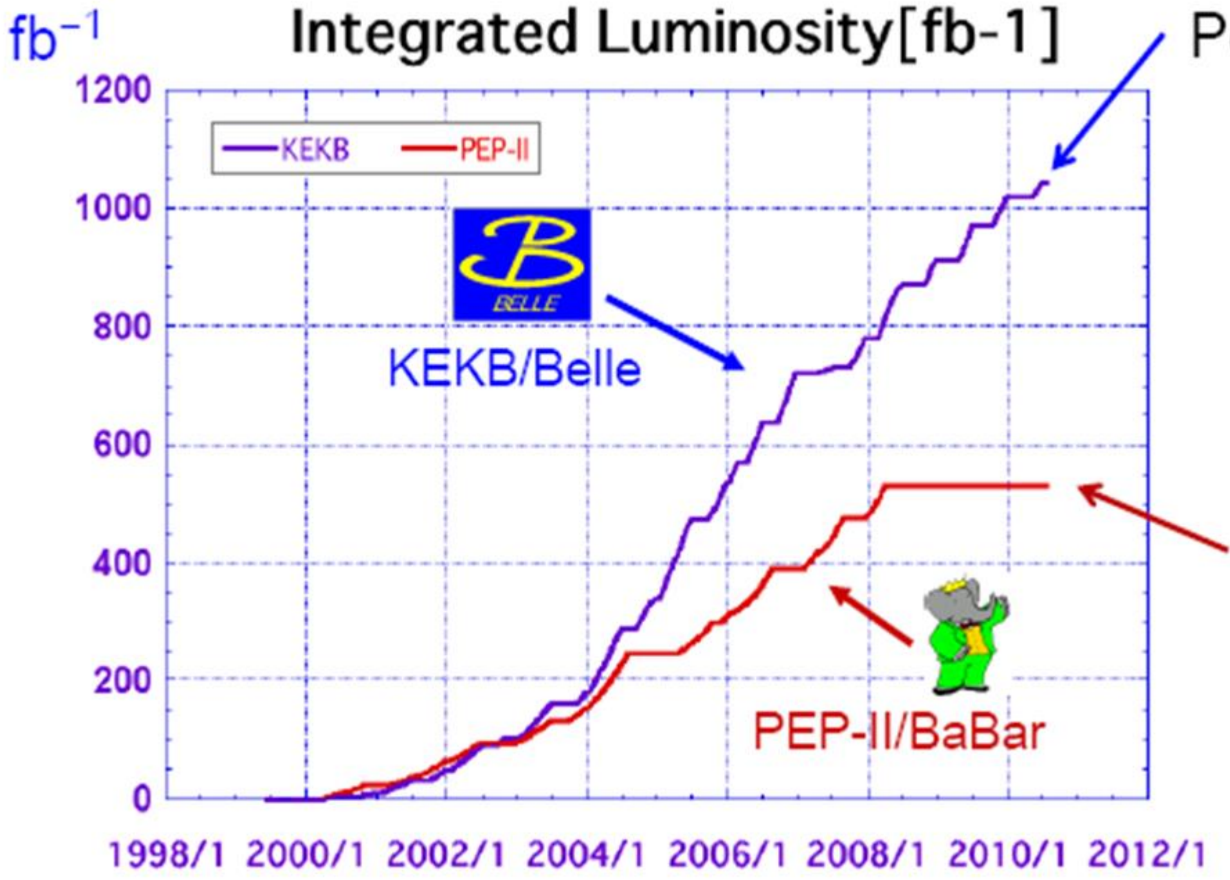
$$m_{\mathrm{bc}} = \sqrt{E_{\mathrm{beam}}^{*2} - p_B^{*2}}$$

$$\Delta E = E_B^* - E_{\mathrm{beam}}^*$$

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 $2.11 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

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 $1.21 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

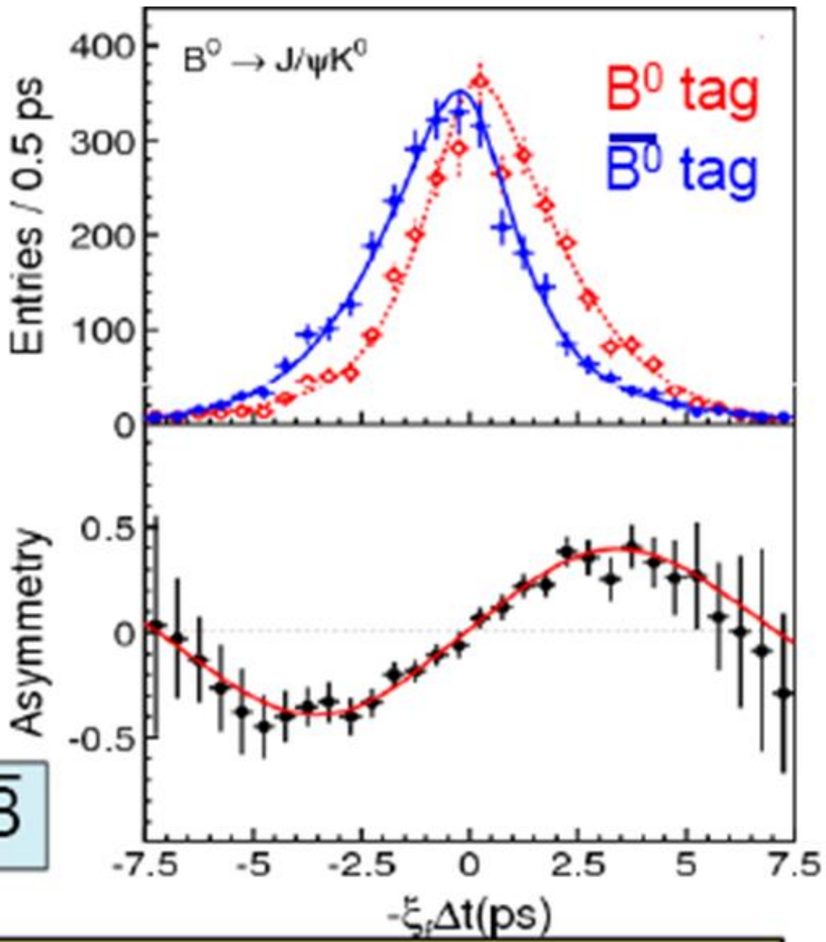
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

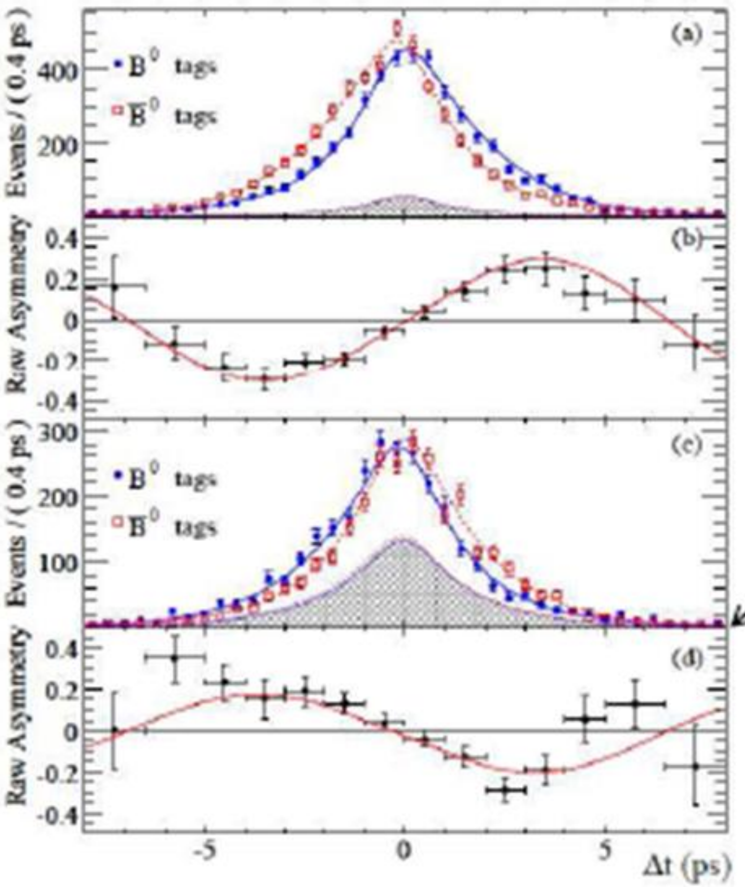
CP asymmetry

Sum of
J/ψ K_S
and
J/ψ K_L

[PRD98,
031802
(2007)]

535M $B\bar{B}$





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

J/ψ K_L

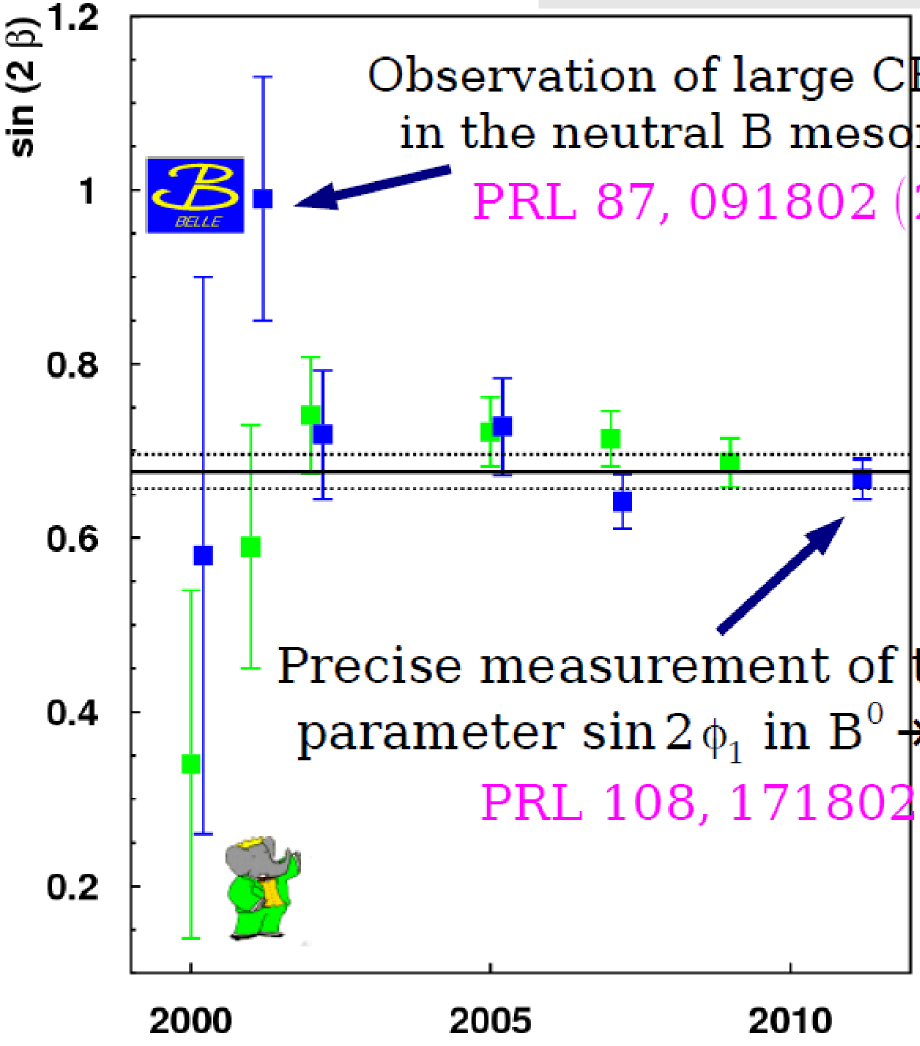
[PRD79,
072009
(2009)]

465M $B\bar{B}$

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

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

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 $B^0 \rightarrow (c\bar{c})K^0$ 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