CP violation in B mesons

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C and P symmetries

Strong and electromagnetic interactions are invariant under C and P

On the other hand, the weak interaction violate both C and P (reminder: lepton helicity).
CP is also not a perfect symmetry of the weak interaction (reminder: K^0 decays)

Kobayashi and Maskawa pointed out that the CP violation is possible with 3 generations of quarks (extension of Cabibbo theory)

The observation of the 3rd generation quarks opened the possibility to observe the CP violation in the B mesons

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Weak interaction with 3 quark generations

The weak interaction eigenstates do not coincide with the strong interaction ones (flavor). Cabibbo already explained this with 2 quark generations.

The down-type partners of the up-type quarks in the weak interaction result from the unitary complex Cabibbo-Kobayashi-Maskawa (CKM) matrix (this is a convention, we could rotate the up-type quarks instead):

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

containing a non-trivial complex phase, responsible of CP violation.

Some formalism

Consider the amplitudes for a B meson and its CP conjugate $\bar{B}$, to decay to the final state f and its CP conjugate $\bar{f}$ through a weak interaction hamiltonian H

$$A_f = \langle f|H|B\rangle \qquad A_{\bar{f}} = \langle \bar{f}|H|B\rangle \qquad \bar{A}_f = \langle f|H|\bar{B}\rangle \qquad \bar{A}_{\bar{f}} = \langle \bar{f}|H|\bar{B}\rangle$$

CP applied to initial and final states introduce a phase, so that $(CP)^2=1$

$$CP|B\rangle = e^{+i\xi_B}|\bar{B}\rangle \quad CP|\bar{B}\rangle = e^{-i\xi_B}|B\rangle \quad CP|f\rangle = e^{+i\xi_f}|\bar{f}\rangle \qquad CP|\bar{f}\rangle = e^{-i\xi_f}|f\rangle$$

If CP is conserved, $[CP,H]=0$ and A_f and $\bar{A}_{\bar{f}}$ have the same magnitude and differ for an unphysical arbitrary phase

$$\bar{A}_{\bar{f}} = e^{i(\xi_f - \xi_B)} A_f$$

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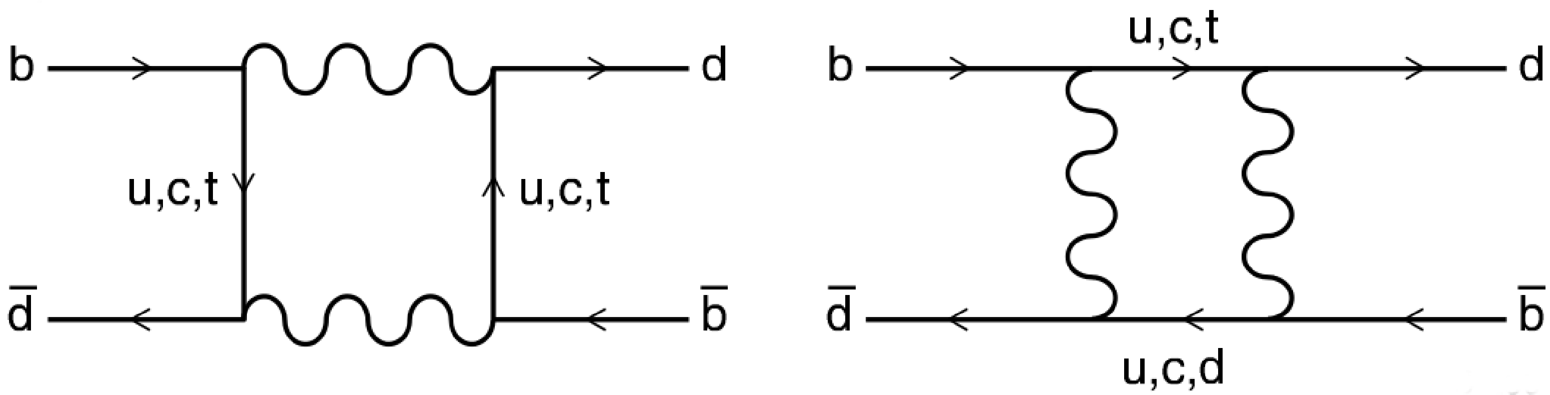
B^0-$\overline{B}^0$ mixing

As we already seen in the case of the K^0, the time evolution of $B^0/\overline{B}^0$ is governed by a complex matrix **H** that can be written in terms of hermitian matrices **M** and **Γ**

$$\boldsymbol{H} = \boldsymbol{M} - \frac{i}{2}\boldsymbol{\Gamma} = \begin{bmatrix} M_{11} & M_{12} \\ M_{12}^{*} & M_{22} \end{bmatrix} - \frac{i}{2}\begin{bmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^{*} & \Gamma_{22} \end{bmatrix}$$

diagonal elements conserve flavor while diagonal elements are related to $B^0 \leftrightarrow \overline{B}^0$ flavor violating transitions



B^0-$\overline{B}^0$ mixing

The light and heavy mesons are

$$|B_L\rangle = p|B^0\rangle + q|\overline{B}^0\rangle \qquad |B_H\rangle = p|B^0\rangle - q|\overline{B}^0\rangle$$

having mass $m_{H,L}$ and width $\Gamma_{H,L}$, and with p and q complex parameters normalized as $|p|^2+|q|^2=1$, whose ratio is linked to the H elements

$$\left(\frac{q}{p}\right)^2 = \frac{M_{12}^* - i/2\,\Gamma_{12}^*}{M_{12} - i/2\,\Gamma_{12}}$$

The time evolution of pure B^0 and $\overline{B}^0$ states at t=0 is:

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

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

$$g_\pm(t) = \frac{1}{2}\left(e^{-im_H t - \frac{1}{2}\Gamma_H t} \pm e^{-im_L t - \frac{1}{2}\Gamma_L t}\right)$$

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CP violating observables

1. CP violation in decay (or “direct” CP violation)

We have CP violation if $|\bar{A}_{\bar{f}}/A_f| \neq 1$
It results from CP violating interference between various terms contributing to the decay amplitude

This is the only possibility for CP violations in charged mesons

$$a_f = \frac{\Gamma(B^- \to f^-) - \Gamma(B^+ \to f^+)}{\Gamma(B^- \to f^-) + \Gamma(B^+ \to f^+)} = \frac{|\bar{A}_{f^-}/A_{f^+}|^2 - 1}{|\bar{A}_{f^-}/A_{f^+}|^2 + 1}$$

For neutral mesons the situation is complicated by the $B^0 \leftrightarrow \bar{B}^0$ oscillation

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CP violating observables

2. CP violation in mixing (or “indirect” CP violation)

If $|p/q| \neq 1$ CP violation results from the mass eigenstates being different from the CP eigenstates

In semileptonic B decays it can be observed as an asymmetry in the semi-leptonic decay

$$a_{SL} = \frac{\Gamma\left(\bar{B}^0_{phys}(t) \to l^+ X\right) - \Gamma\left(B^0_{phys}(t) \to l^- X\right)}{\Gamma\left(\bar{B}^0_{phys}(t) \to l^+ X\right) + \Gamma\left(B^0_{phys}(t) \to l^- X\right)} = \frac{1 - |q/p|^4}{1 + |q/p|^4}$$

CP violating observables

3. CP violation in the interference between decays with and without mixing

This is possible when bot B^0 and $\overline{B}^0$ can decay to the same final state which is a CP eigenstate f_{CP} and occurs when $Im(\lambda_{fCP}) \neq 0$

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

$$a_{fCP} = \frac{\Gamma(\bar{B}^0_{phys}(t) \to f_{CP}) - \Gamma(B^0_{phys}(t) \to f_{CP})}{\Gamma(\bar{B}^0_{phys}(t) \to f_{CP}) + \Gamma(B^0_{phys}(t) \to f_{CP})}$$

This asymmetry will always be present if any of the previous 2 type is present. If $|q/p|=1$ it can be simplified as:

$$a_{fCP} = S_f \sin(\Delta m_B t) - C_f \cos(\Delta m_B t) \qquad S_f = \frac{2\Im(\lambda_{fCP})}{1+|\lambda_{fCP}|^2} \qquad C_f = \frac{1-|\lambda_{fCP}|^2}{1+|\lambda_{fCP}|^2}$$

and also C_f vanishes if $|\bar{A}_f|=|A_f|$

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Aside: the strong CP problem

In the SM the only source of CP violation is in the weak interaction.

Nothing prevents, in principle, from CP to be violated in the strong interaction. The reason of CP conservation in the strong interaction is still not settled, this is called the “strong CP problem”

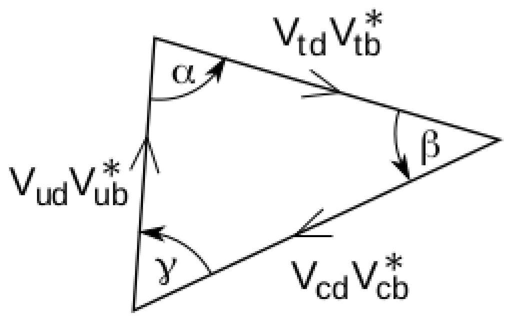
If CP is not conserved by the strong interaction the neutron could have an electric dipole moment (EDM).
The neutron is composed by quarks and has size of ~1 fm, that would make us guess an electric dipole of the order of $EDM_n \sim 10^{-13}$ e·cm

Experimental upper limit: $EDM_n < 10^{-26}$ e·cm

The CKM matrix

In the SM the CKM matrix is the only source of CP violation

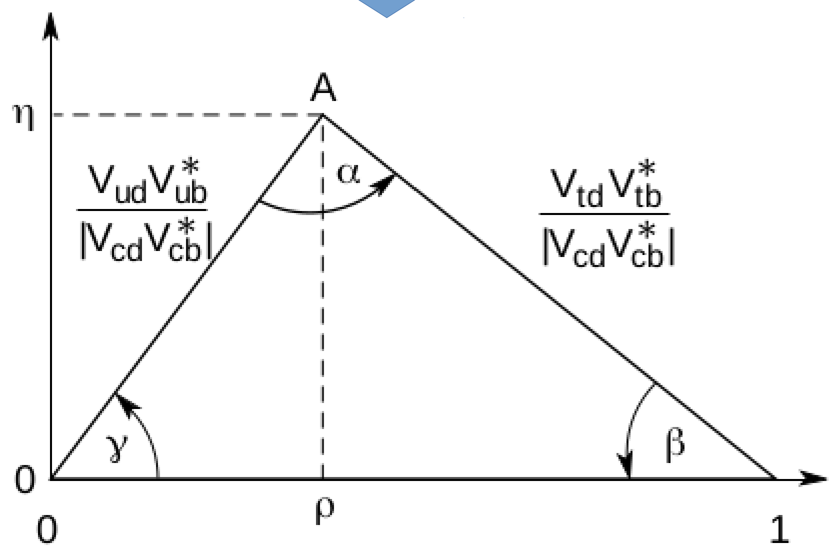
$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$



It can be expressed in terms of 4 real param. (3 angles and 1 complex phase)

The unitarity of V_{CKM} implies that the product of one of its columns with a different one (conjugate) is 0.

The important one for us is:
$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$
which can be drawn as a triangle in the complex plane, called the "unitarity triangle"



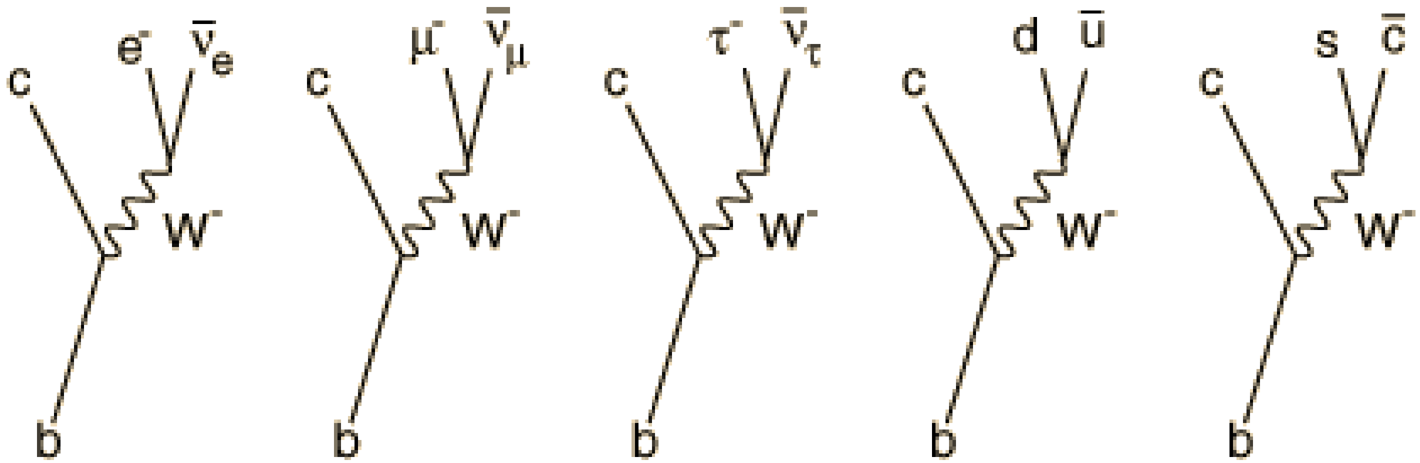
After normalization to $V_{cd}V_{cb}^*$

CP violation in the B meson

The exploration of the CP violation in the B meson is done by measurements of the sides and the angles of the unitary matrix.

The same quantity can be accessed through different processes, over-constraining the unitary triangle, with the possibility to extract hints of new physics

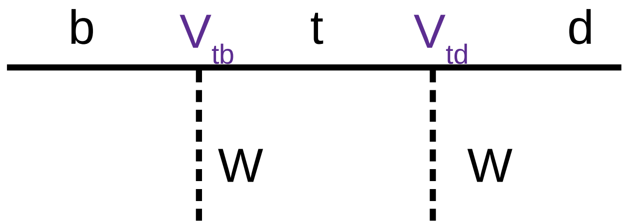
Interesting processes are of the type: $b \rightarrow q_1 \bar{q}_2 q_3$ or $q\, l\, \nu$



Example: β measurement with $B^0 \rightarrow J/\psi\, K_S$

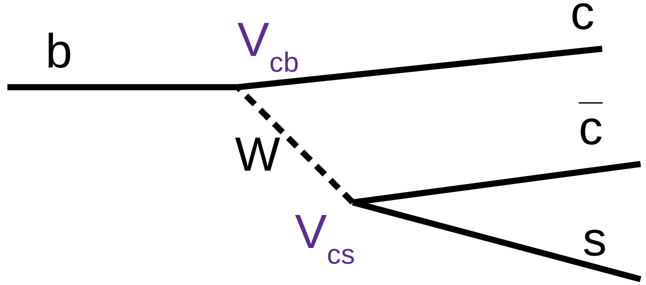
Three contributing processes: B mixing, B decay, K mixing

B mixing $\left[\frac{q}{p}\right]_B \propto \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}$



K mixing $\left[\frac{q}{p}\right]_K \propto \frac{V_{cs} V_{cd}^*}{V_{cs}^* V_{cd}}$

B decay $\frac{\bar{A}_{\psi K_S}}{A_{\psi K_S}} \propto \frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}}$



The angle β of the unitary triangle is given by: $\beta = arg\left[-\frac{V_{cd} V_{cb}^*}{V_{td} V_{tb}^*}\right]$

With some math: $\Im \lambda_{\psi K_S} = \sin 2\beta$

Putting pieces together, β is measured from time-dependent asymmetry:

$$a_{fCP} \propto \sin 2\beta \;\cdot\; \sin \Delta m\, t$$

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B-factories

Dedicated experiments (collider + detector) designed for the precision measurement of CP violation in the B meson

1) CP violation effects in the B meson are small → to reach the necessary statistical significance a large number of B mesons is needed → high luminosity colliders

2) The flavor of one B meson (B or $\overline{B}$) at the decay to be related to the flavor of the other → e^+e^- collider with center of mass energy on the peak of the Y(4S) to obtain coherent production of $B\overline{B}$ pairs

3) Measure the time at the decay to measure time dependent CP violation → produce the Y(4s) with a boost in the laboratory → asymmetric collider

4) Fully reconstruct several final states → general purpose detectors with good PID

Pier Oddone
Panofsky prize 2005

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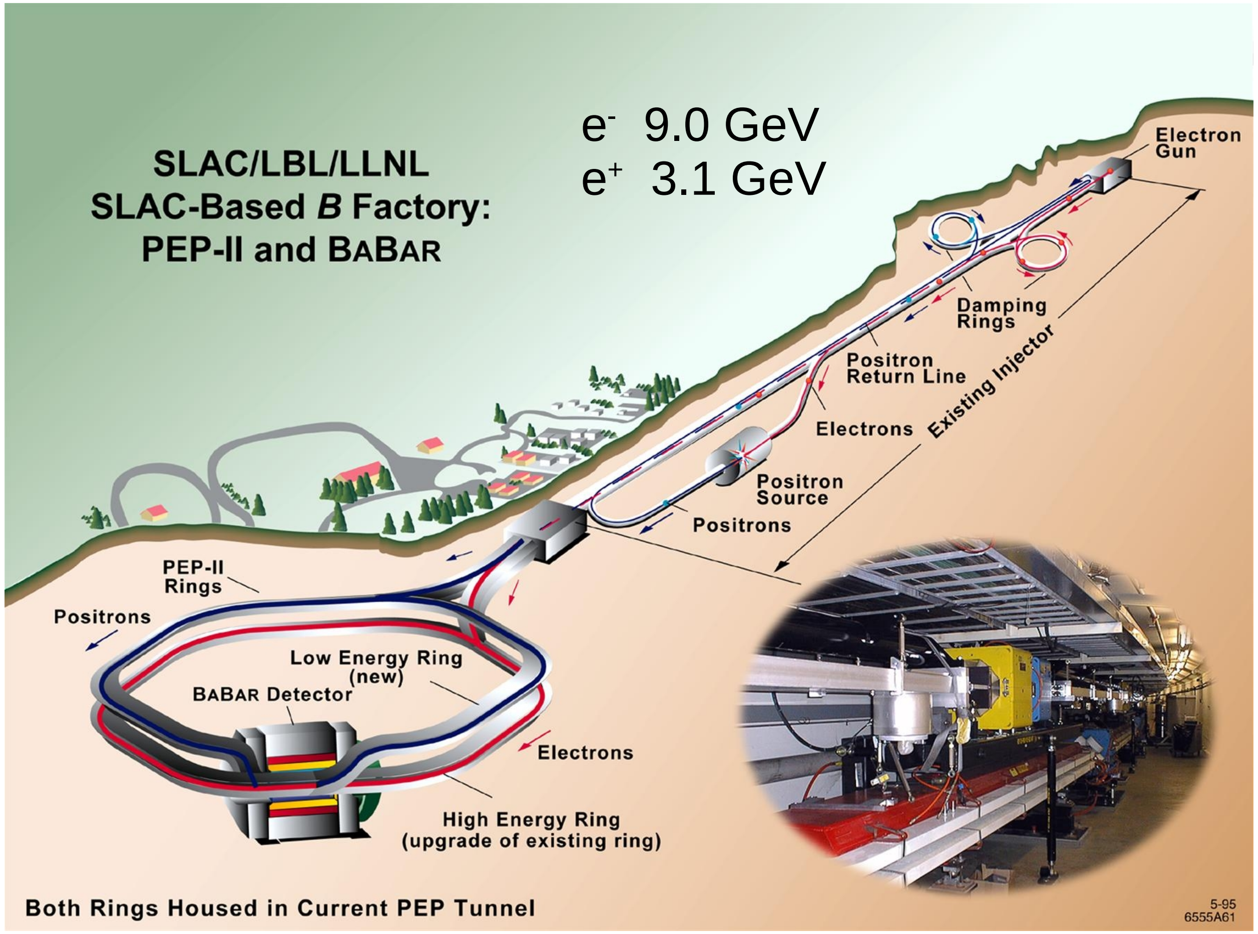
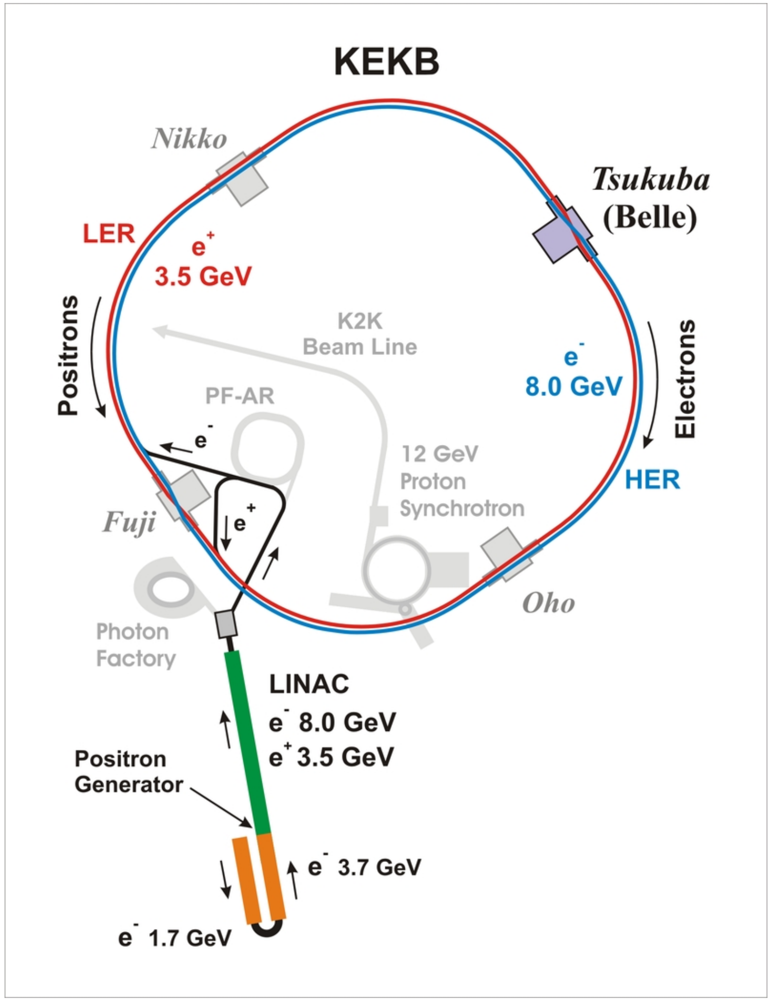
Two colliders: PEP-II and KEKB

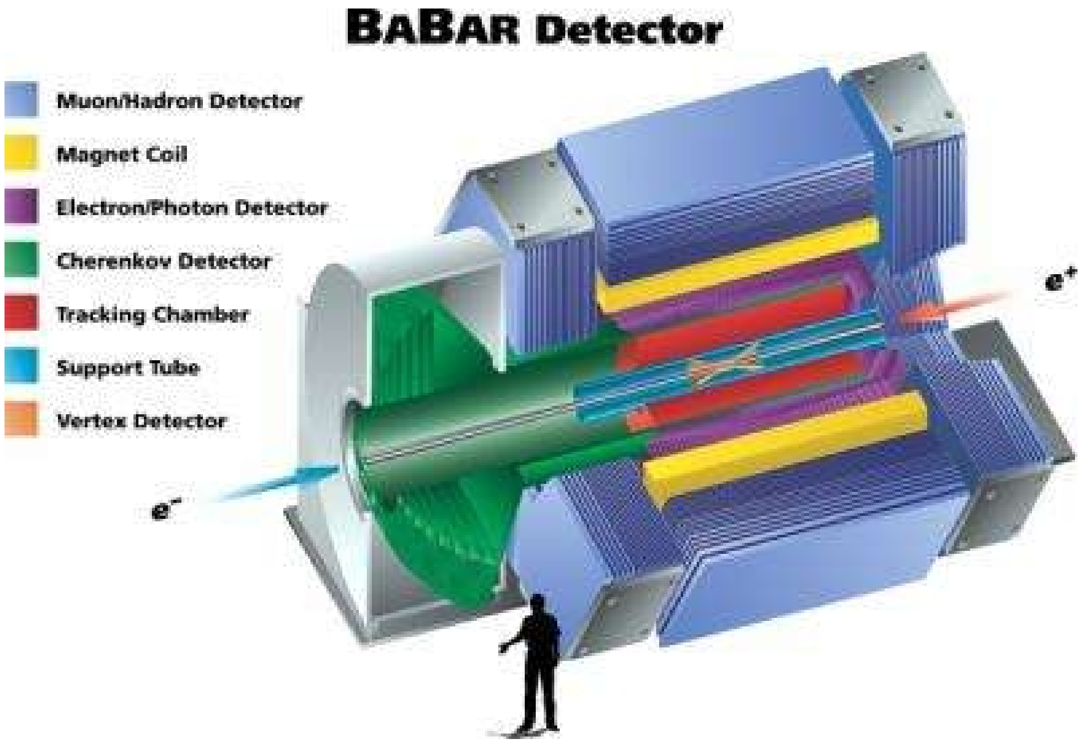


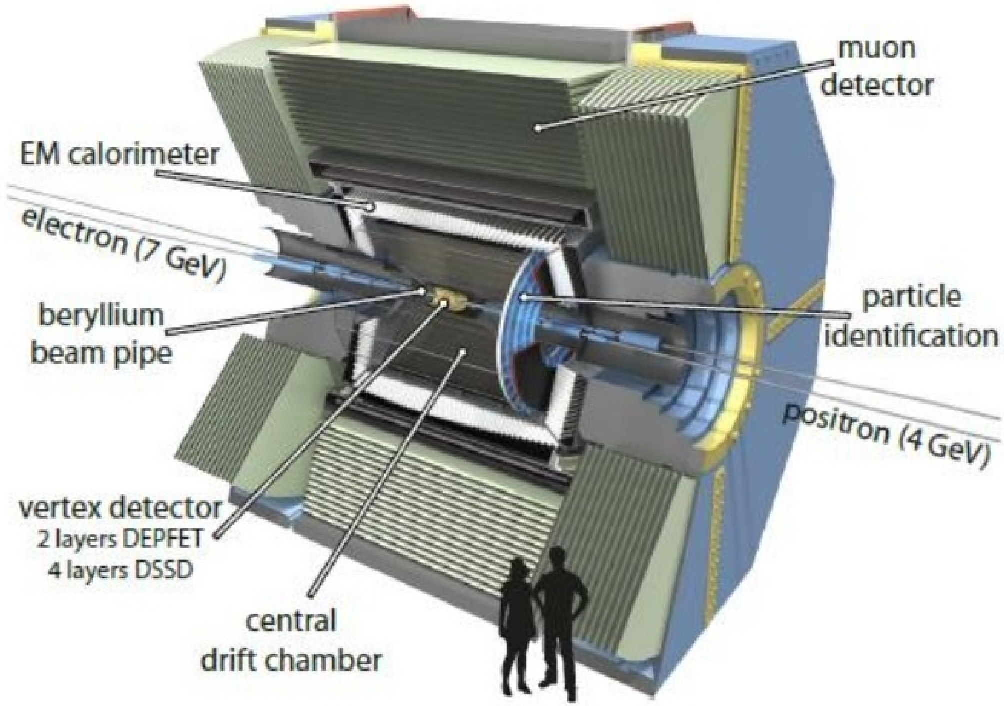


$\beta\gamma$=0.56

$\beta\gamma$=0.42

Two experiments: BaBar and Belle





Typical B path length in BaBar: 250 μm (τ=1.5 ps, $\Delta z=\beta\gamma c\tau=0.56\cdot 3\cdot 10^{8}\cdot 1.5\cdot 10^{-12}$ m)

Single vertex resolution < 80 μm

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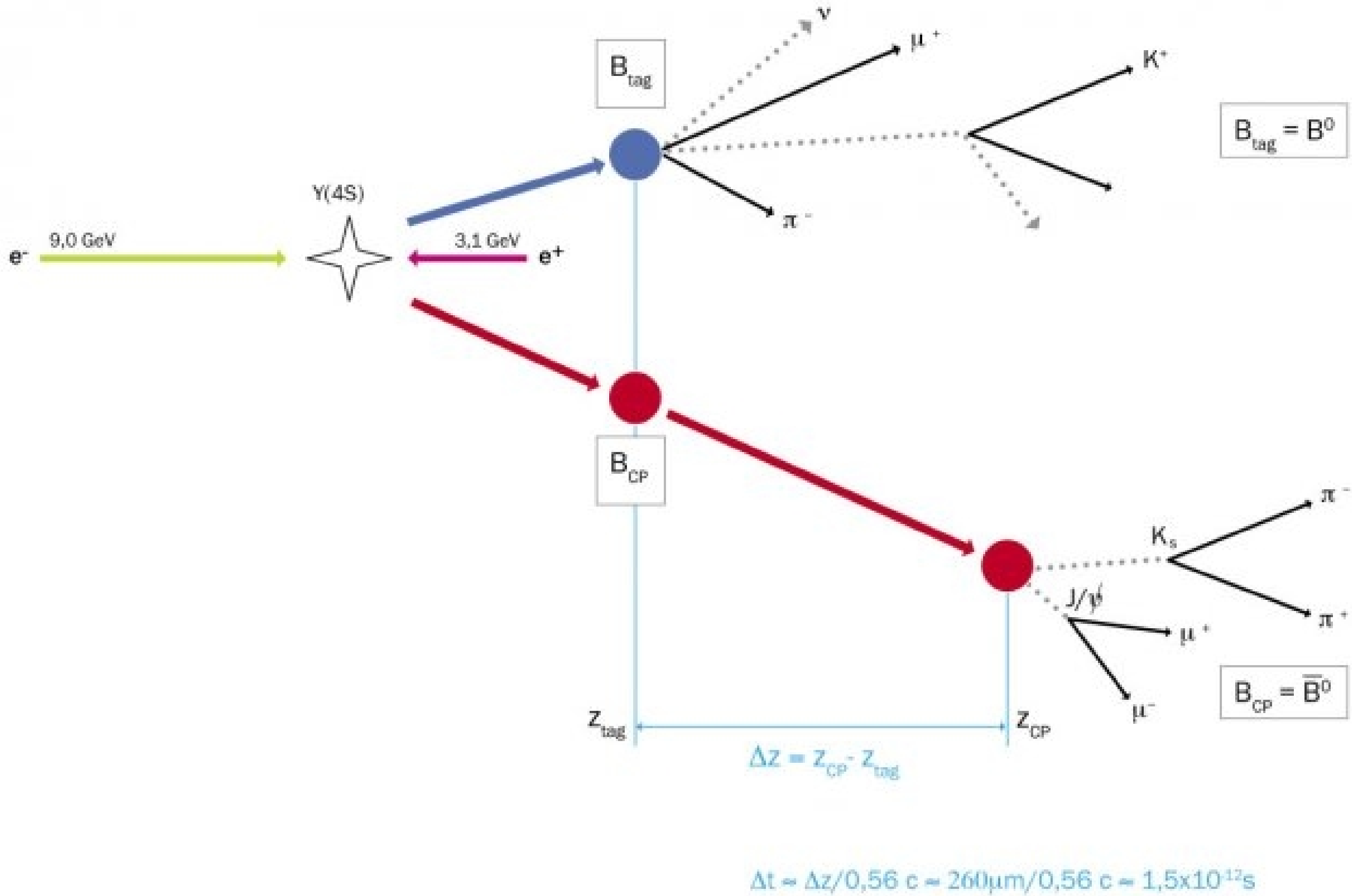
Overview of experimental technique



sin 2β measurement

Looking for neutral B mesons decaying to CP eigenstates
$J/\psi\ K_S$, $\psi(2S)\ K_S$, $J/\psi\ K_L$, …

The flavor of the other B meson can be tagged from the charge of the D meson in B decays (example: $B \to D\pi$)

Distribution f_+ (f_-) of the decay rate when the tagging meson is a B^0 ($\bar{B}^0$)

$$f_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{2\tau_{B^0}(1 + |\lambda|^2)} \times \left[\frac{1 + |\lambda|^2}{2} \pm \mathrm{Im}\lambda \sin(\Delta m_{B^0} \Delta t) \mp \frac{1 - |\lambda|^2}{2} \cos(\Delta m_{B^0} \Delta t)\right]$$

The time-dependent asymmetry is (η_f=-1 for $J/\psi K_S$, η_f=+1 for $J/\psi K_L$)

$$a_{fCP} = \frac{f_+(\Delta t) - f_-(\Delta t)}{f_+(\Delta t) + f_-(\Delta t)} = -\eta_f \sin 2\beta \cdot \sin(\Delta m_B \Delta t)$$

(In the following showing BaBar results, analogous from Belle exist!)

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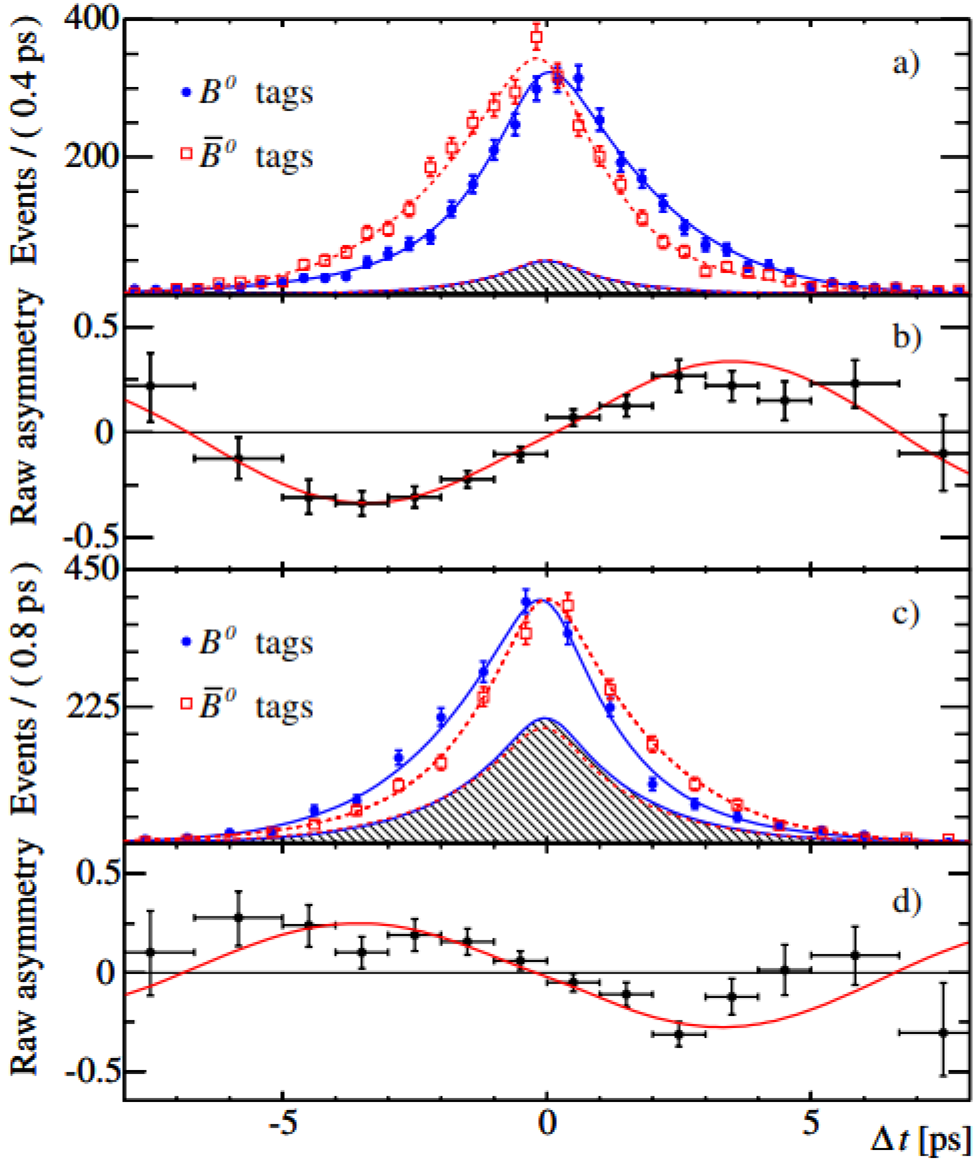
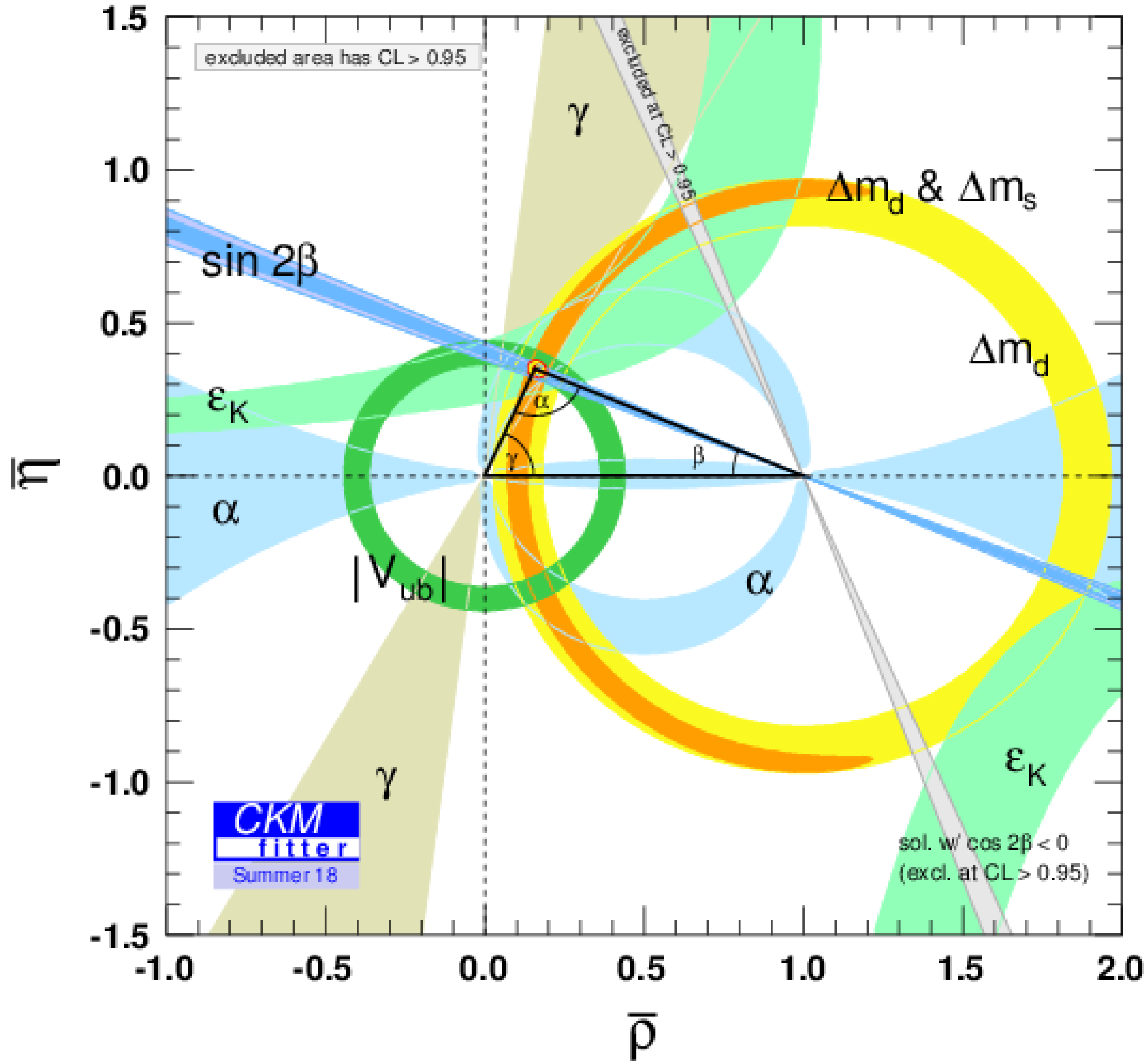
sin 2β measurement



Current value from global fit:

sin 2β = 0.71 ± 0.01

Global fit of unitarity triangle



Sides / angles of the unitarity triangle measured in different processes

All measurements consistent with SM picture of CP violation

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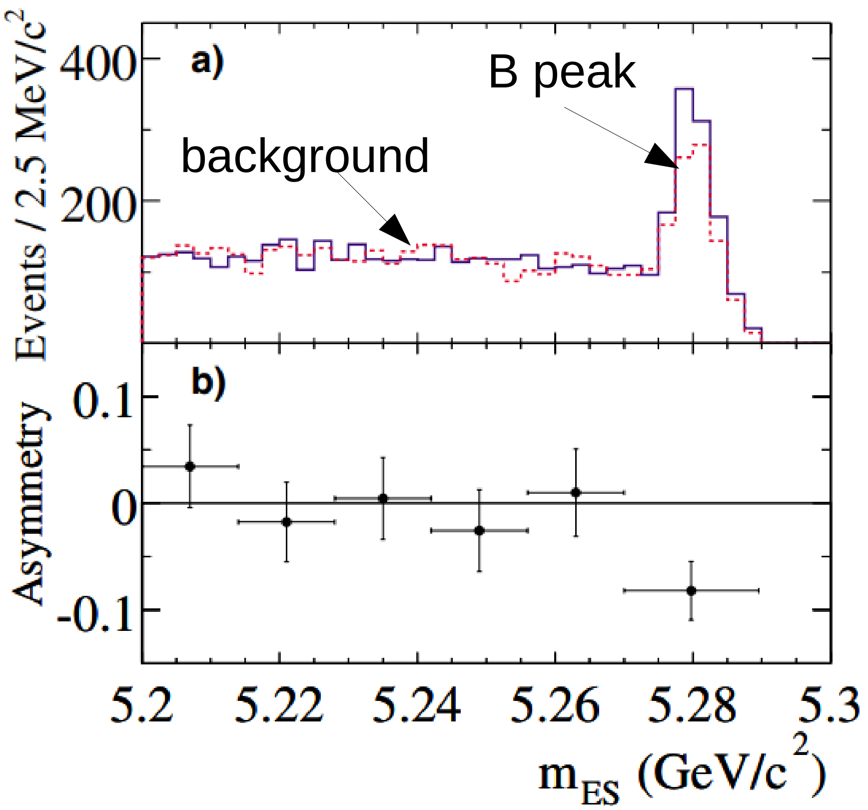
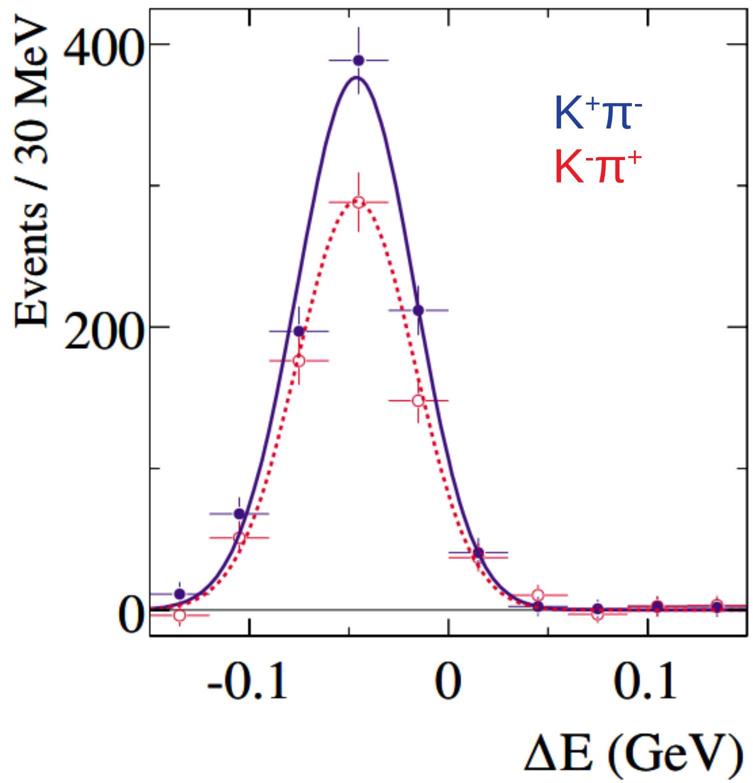
Direct CP violation in B decay

Direct CP violation does not involve oscillations and is expected to be small in the SM
Can be observed as an asymmetry in the yields of a decay process, such as $B^0 \rightarrow K^+\pi^-$, and its charge conjugate



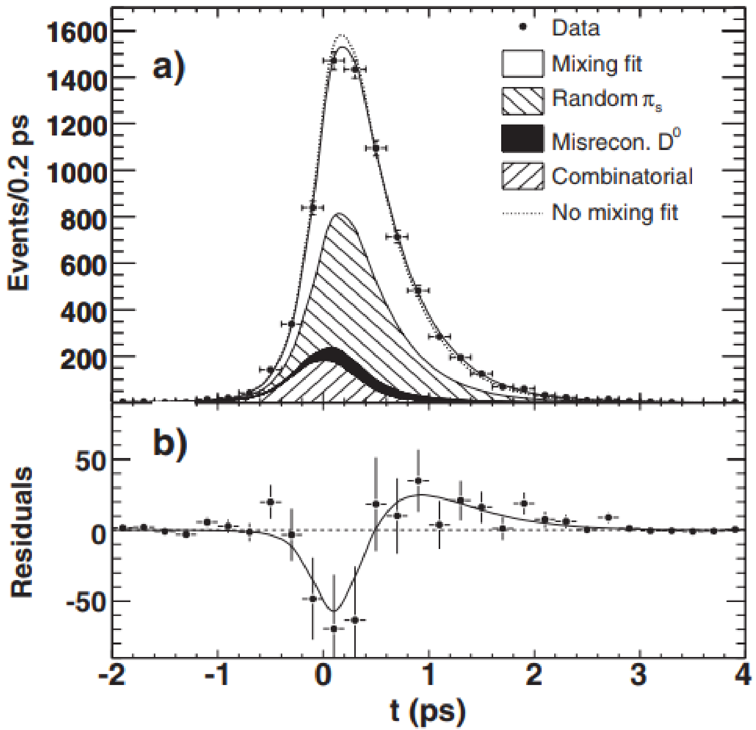


m_{ES} = beam-energy substituted mass

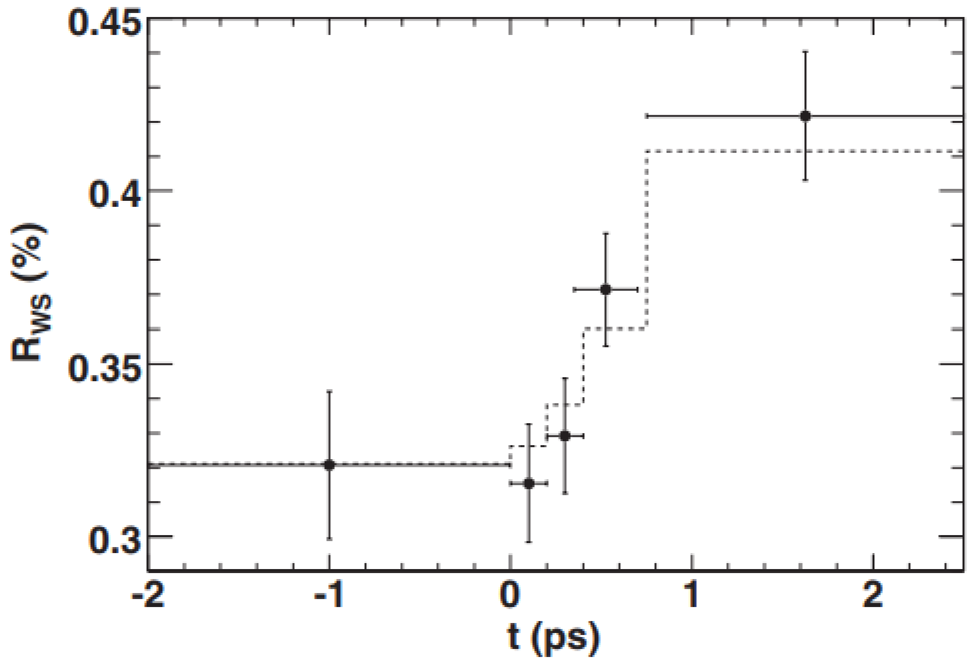
D^0-$\overline{D}^0$ mixing

D^0-$\overline{D}^0$ mixing observed at the b-factories (but no evidence of CP violation)

Time-dependent comparison of “right” sign (Cabibbo favored) $D^0 \to K^-\pi^+$ with “wrong” sign (Cabibbo suppressed) $D^0 \to K^+\pi^-$



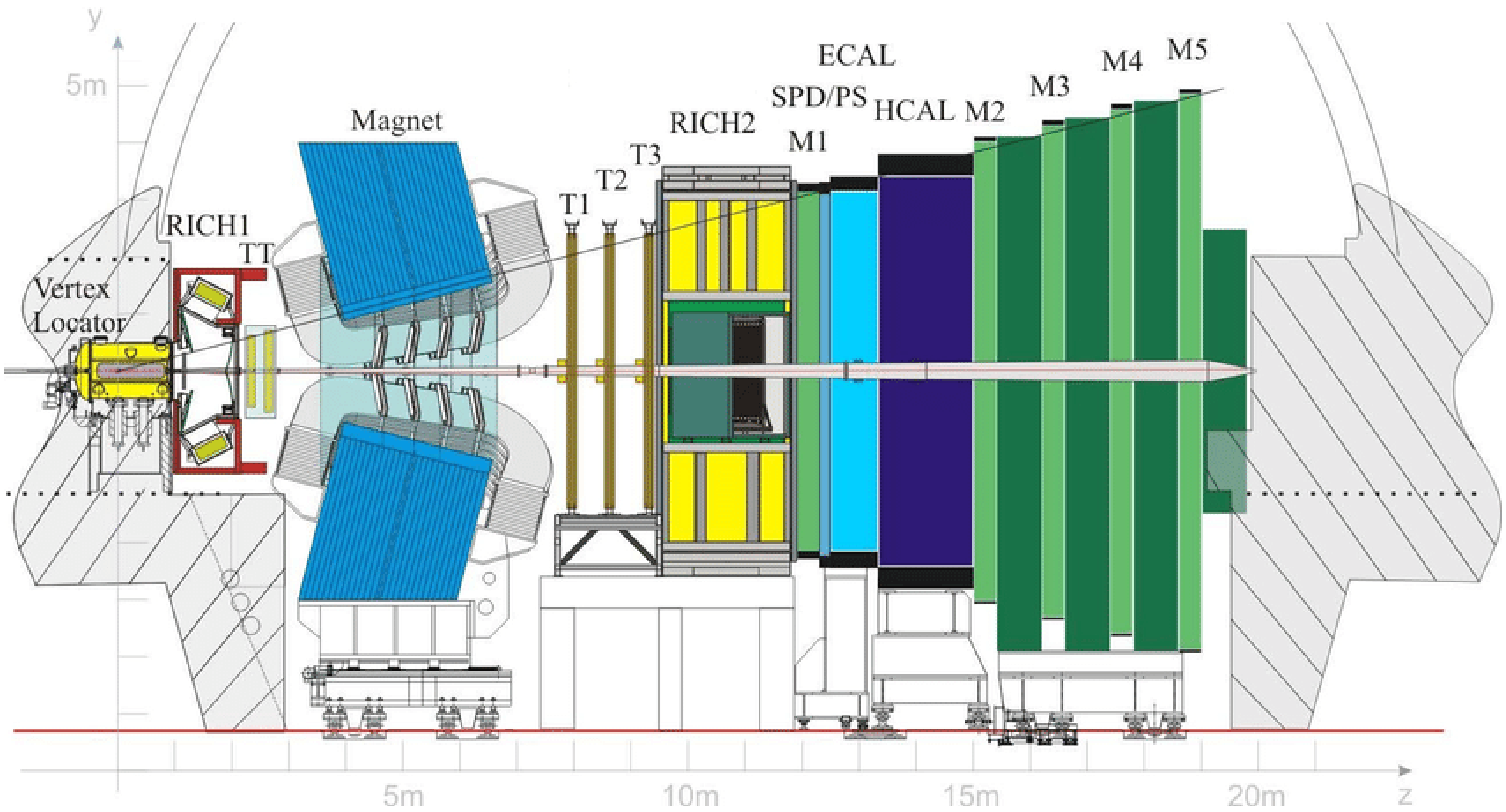
Proper time distribution of wrong sign D^0 and $\overline{D}^0$ candidates
Fit with and without mixing hypothesis (residuals shown below)



Wrong sign branching fraction as a function of proper time and fit including mixing hypothesis
No mixing would be a constant fraction

Today: LHCb

Dedicated experiment for flavor physics at the LHC



Direct CP violation in the D meson

First observation of CP violation in the D^0 by LHCb (March 2019)

Look for $D^0 \rightarrow K^+K^-$, $\pi^+\pi^-$
D flavor: tagged from the π charge in reconstructed $D^* \rightarrow D\pi$ decays

The asymmetry is given by:

$$a_f = \frac{N(D^0 \rightarrow f) - N(\bar{D}^0 \rightarrow f)}{N(D^0 \rightarrow f) + N(\bar{D}^0 \rightarrow f)}$$

In order to cancel the effect of the asymmetries in D production, the asymmetry difference between the K and π channel is extracted

$$\Delta a_{CP} = a_{K^+K^-} - a_{\pi^+\pi^-}$$

Direct CP violation in the D meson

KK ππ

$$\Delta a_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

π-tag

μ-tag