5.4

CPLEAR asymmetry

$$\varepsilon = |\varepsilon| e^{i\phi(\varepsilon)}$$

Time evolution of transition amplitude

$$
\begin{aligned}
|\overline{K^0}(t)> &= \frac{1}{\sqrt{2}} | K_S^0(t) - K_L^0(t) > \\
A_{\pi^+\pi^-}^{\overline{K^0}(0)}(t) &= < \overline{K^0} \to \pi^+\pi^- | H_1 | K^0(t) > \\
&= < \frac{1}{\sqrt{2}} \left(< K_S^0(0) - K_L^0(0) | \to \pi^+\pi^- \right) | \frac{1}{\sqrt{2}} | K_S^0(t) - K_L^0(t) > \\
&= \frac{1}{\sqrt{2}} \frac{1}{\sqrt{1+|\varepsilon|^2}} < K_1(0) | \frac{1}{\sqrt{2}} \frac{1}{\sqrt{1+|\varepsilon|^2}} \left[\left(| K_1^0(0) > + \varepsilon | K_2^0(0) > \right) e^{-(im_s + \Gamma_s/2)t} - \left(\varepsilon | K_1^0(0) > + | K_2^0(0) > \right) e^{-(im_L + \Gamma_L/2)t} \right] \\
&= \frac{1}{2} \frac{1}{1+|\varepsilon|^2} \left(e^{-(im_S + \Gamma_S/2)t} - \varepsilon e^{-(im_L + \Gamma_L/2)t} \right) \\
&= \frac{1}{2} \left(e^{-(im_S + \Gamma_S/2)t} - \varepsilon e^{-(im_L + \Gamma_L/2)t} \right) \\
P_{\pi^+\pi^-}^{\overline{K^0}}(t) &= |A_{\pi^+\pi^-}(t)|^2 = A_{\pi^+\pi^-}^*(t) A_{\pi^+\pi^-}(t) \\
&= \frac{1}{2} \left(e^{(im_S + \Gamma_S/2)t} - \varepsilon^* e^{(im_L + \Gamma_L/2)t} \right) \frac{1}{2} \left(e^{-(im_S + \Gamma_S/2)t} - \varepsilon e^{-(im_L + \Gamma_L/2)t} \right) \\
&= \frac{1}{4} \left(e^{-\Gamma_S t} + |\varepsilon|^2 e^{-\Gamma_L t} - \varepsilon^* e^{(im_L + \Gamma_L/2)t} e^{-(im_S + \Gamma_S/2)t} - e^{(im_S + \Gamma_S/2)t} \varepsilon e^{-(im_L + \Gamma_L/2)t} \right) \\
&= \frac{1}{4} \left(e^{-\Gamma_S t} + |\varepsilon|^2 e^{-\Gamma_L t} - |\varepsilon| e^{(i(m_L - m_S) + (\Gamma_L - \Gamma_S)/2)t - \phi(\varepsilon)} - |\varepsilon| e^{-(i(m_L - m_S) + (\Gamma_L - \Gamma_S)/2)t - \phi(\varepsilon)} e^{(im_S + \Gamma_S/2)t} \right) \\
&= \frac{1}{4} \left(e^{-\Gamma_S t} + |\varepsilon|^2 e^{-\Gamma_L t} - 2|\varepsilon| e^{-(\Gamma_S + \Gamma_L)t/2} \cos((m_L - m_S)t + \phi(\varepsilon)) \right)
\end{aligned}
$$

Time resolved asymmetry

$$
\begin{aligned}
A_{+-}(t) &= \frac{P_{\pi^+\pi^-}^{K^0}(t) - P_{\pi^+\pi^-}^{\overline{K^0}}(t)}{P_{\pi^+\pi^-}^{K^0}(t) + P_{\pi^+\pi^-}^{\overline{K^0}}(t)} \\
&= \frac{4|\varepsilon| e^{-(\Gamma_S + \Gamma_L)t/2} \cos((m_L - m_S)t + \phi(\varepsilon))}{2\left(e^{-\Gamma_S t} + |\varepsilon|^2 e^{-\Gamma_L t} \right)} \\
&= \frac{2|\varepsilon| e^{-(\Gamma_S + \Gamma_L)t/2} \cos((m_L - m_S)t + \phi(\varepsilon))}{e^{-\Gamma_S t} + |\varepsilon|^2 e^{-\Gamma_L t}} = \frac{e^{-\Gamma_S t} 2|\varepsilon| e^{-(\Gamma_L - \Gamma_S)t/2} \cos((m_L - m_S)t + \phi(\varepsilon))}{e^{-\Gamma_S t} \left(1 + |\varepsilon|^2 e^{(\Gamma_S - \Gamma_L)t} \right)} \\
&= \frac{2|\varepsilon| e^{(\Gamma_S - \Gamma_L)t/2} \cos((m_L - m_S)t + \phi(\varepsilon))}{1 + |\varepsilon|^2 e^{(\Gamma_S - \Gamma_L)t}}
\end{aligned}
$$

5.4

Direct CP – violation

CP violating Hamilton – operator H_1,
i.e. CP – violation happens at the instance of decay of CP – Eigenstates K_1 and K_2 .

$$
\begin{aligned}
& < \pi^+\pi^- | H_1 | K_2 > \neq 0 \\
& \frac{< \pi^+\pi^- | H_1 | K_L >}{< \pi^+\pi^- | H_1 | K_S >} = \frac{< \pi^+\pi^- | H_1 \left(\varepsilon | K_1^0 > + | K_2^0 > \right)}{< \pi^+\pi^- | H_1 \left(| K_1^0 > + \varepsilon | K_2^0 > \right)} \cong \varepsilon + \frac{< \pi^+\pi^- | H_1 | K_2 >}{< \pi^+\pi^- | H_1 | K_1 >} =: \varepsilon + \varepsilon' \\
& \frac{< \pi^0\pi^0 | H_1 | K_L >}{< \pi^0\pi^0 | H_1 | K_S >} = \frac{< \pi^0\pi^0 | H_1 \left(\varepsilon | K_1^0 > + | K_2^0 > \right)}{< \pi^0\pi^0 | H_1 \left(| K_1^0 > + \varepsilon | K_2^0 > \right)} \cong \varepsilon + \frac{< \pi^0\pi^0 | H_1 | K_2 >}{< \pi^0\pi^0 | H_1 | K_1 >} =: \varepsilon - 2\varepsilon'
\end{aligned}
$$

Definition von ε'

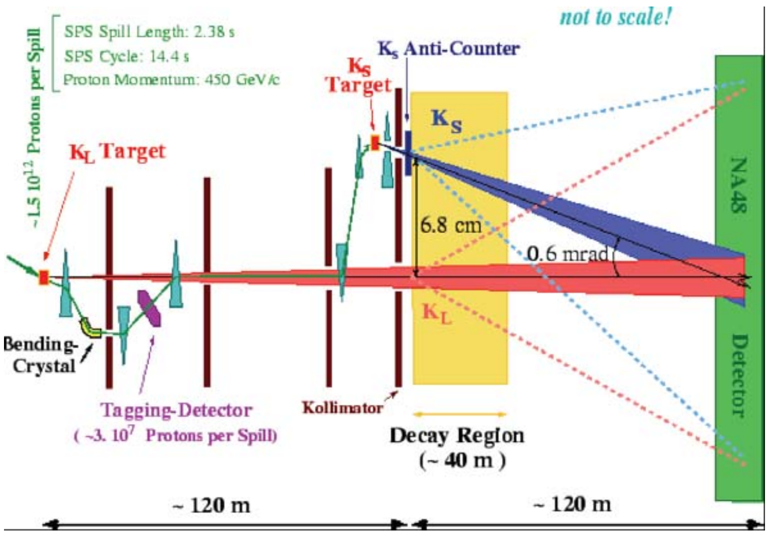
Clebsch-Gordan coefficients
In isospin space

Experimental signature?

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon} \right) \cong \frac{\varepsilon'}{\varepsilon} = \frac{1}{6} \left(1 - \frac{\Gamma(K_L \to \pi^0\pi^0) \Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^0\pi^0) \Gamma(K_L \to \pi^+\pi^-)} \right)$$

5.4 Experimental setup for direct CPV measurement

NA48 /KTeV experiments at CERN/Fermilab



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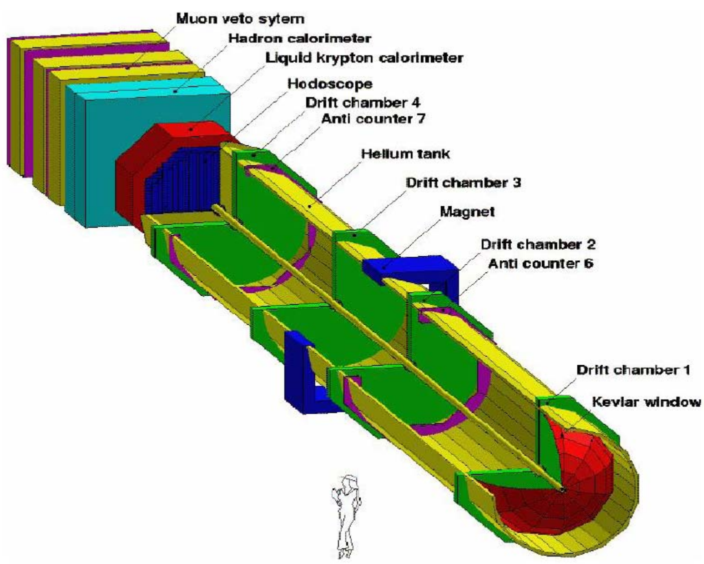
5.4 NA48 experiment



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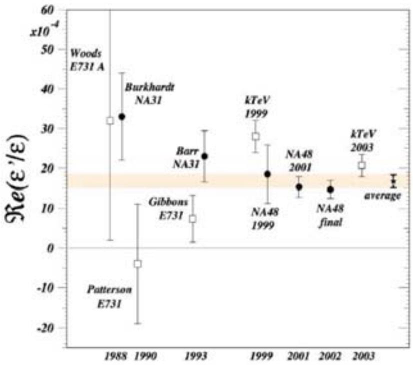
5.4

Status on direct CP - violation



$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) \cong \frac{\varepsilon'}{\varepsilon} = \frac{1}{6}\left(1 - \frac{\Gamma(K_L \to \pi^0\pi^0)\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^0\pi^0)\Gamma(K_L \to \pi^+\pi^-)}\right)$$

$$\frac{\varepsilon'}{\varepsilon} = (1.65 \pm 0.26)\cdot 10^{-3}$$

(PDG 2011)

5.4

Measuring CP violation with B - mesons

Searching strategy in kaon decays is mostly lifetime effect:

1) **Get 'pure' K_2 beam (long lifetime),**
2) **Look for K_2 decays that have the wrong CP.**

Method not applicable to B – meson system

The lifetimes of the neutral B weak eigenstates are equal so there is no way to separate the two components by allowing one of them to decay away.

$$\frac{\Gamma_S^K - \Gamma_L^K}{\Gamma_S^K + \Gamma_L^K} \approx 1 \qquad \frac{\Gamma_S^B - \Gamma_L^B}{\Gamma_S^B + \Gamma_L^B} \approx 0$$

Study the time evolution of $B^0\bar{B}^0$ pairs and look for a measurable quantity that depends on CP violation.

=> Look for rate differences to the same CP final state (f):

$$\mathbf{R(B^0 \to f) \neq R(\bar{B}^0 \to f)}$$

5.4

Mixing mechanisms

Mixing through decays → **y** $y = \frac{\Delta\Gamma}{2\Gamma}$
(indirect CPV)

Mixing through oscillations → **x** $x = \frac{\Delta m}{\Gamma}$
(direct CPV)

	$K^0/\overline{K}^0$	$D^0/\overline{D}^0$	$B^0/\overline{B}^0$
τ [ps]	89.4 ± 0.1; 51700 ± 400	$0.413 \pm .003$	1.548 ± 0.021
Γ [s^{-1}]	$5.61 \cdot 10^9$	$2.4 \cdot 10^{12}$	$(6.41 \pm 0.16) \cdot 10^{11}$
$y = \frac{\Delta\Gamma}{2\Gamma}$	-0.9966	$\lvert y\rvert < 0.06$	$\lvert y\rvert \lesssim 0.01^*$
Δm [s^{-1}]	$(5.300 \pm 0.012) \cdot 10^9$	$< 7 \cdot 10^{10}$	$(4.89 \pm 0.09) \cdot 10^{11}$
Δm [eV]	$(3.49 \pm 0.01) \cdot 10^{-6}$	$< 5 \cdot 10^{-6}$	$(3.2 \pm 0.1) \cdot 10^{-4}$
$x = \frac{\Delta m}{\Gamma}$	0.945 ± 0.002	< 0.03	0.76 ± 0.02

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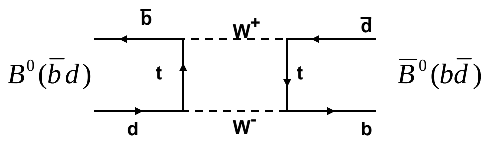
5.4

CPV in B – system

Mixing dominated by box diagram with t-quark



Relevant elements of the CKM – matrix:

$$\begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

$$V_{td} = |V_{td}| e^{-i\beta}$$

$$V_{ub} = |V_{ub}| e^{-i\gamma}$$

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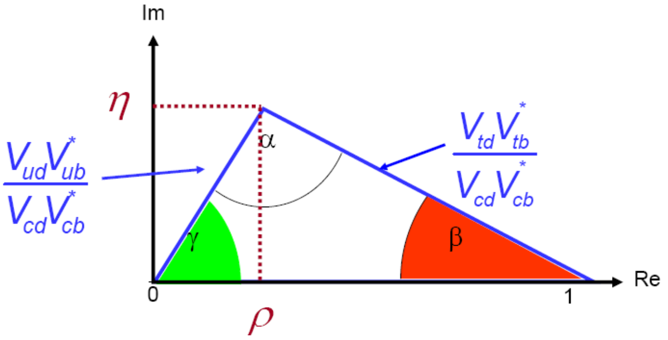
5.4

Rescaled unitarity triangle

Graphical representation:

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

Normalize by real number:



Wolfenstein parameters: ρ, η

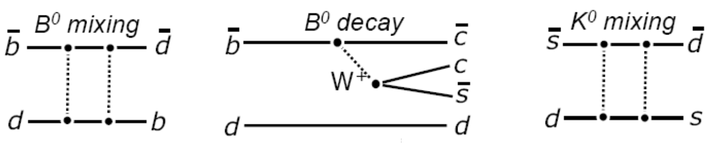
5.4

The golden decay: B0 -> J/ψ + K^0_S

$$B^0 \to J/\psi + K_S^0$$
$$J^P: \; 0^- \qquad 1^- \qquad 0^-$$

$$CP(J/\psi + K_S^0) = CP(J/\psi) \cdot CP(K_S^0) \cdot \underbrace{(-)^l}_{\text{orbital angular momentum}}$$
$$= (+1) \cdot (+1) \cdot (-1) = -1$$

Elements of transition amplitude



Dominating CKM – matrix elements:

$$A(B^0) \sim V_{td} V_{tb}^* \quad \cdot \quad V_{cs} V_{cb}^* \quad \cdot \quad V_{cd} V_{cs}^* \sim e^{-i\beta}$$

Asymmetry:

$$A_{CP}(t) = \frac{\Gamma(\overline{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\overline{B}^0(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})}$$
$$\overset{f_{CP} = J/\psi + K_S^0}{=} -\sin 2\beta \sin \Delta m t$$

5.4

Observation of CP violation with B - mesons

1) Produce B-mesons pairs using the reaction $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\bar{B}^0$
needs experiment at asymmetric collider: BABAR@SLAC, BELLE@KEK
to have distinct vertices

2) Reconstruct the decay of one of the B-mesons's into a CP eigenstate
e.g. $J/\psi + K_S$

3) Reconstruct the decay of the other B-meson to determine its flavor ("tag")
use high momentum leptons:

$$B^0 \rightarrow (e^+ \text{ or } \mu^+)X$$
$$\bar{B}^0 \rightarrow (e^- \text{ or } \mu^-)X$$

flavor of CP eigenstate is determined at time of the "tag" decay.

4) Measure the distance (L) between the two B meson decays and convert to proper time.
must reconstruct the position of both B decay vertices
$t = L/(\beta\gamma c)$

5) Build asymmetry (t) as decay rate difference (t) and fit to the functional form:

$$A(t) = \eta_{cp}(\sin 2\phi)\sin(\Delta m t)$$

$\eta_{cp} = \pm 1$
CP of final state
$= -1$ for $B^0 \rightarrow J/\psi K_S$

CP violating phase

$\phi = \beta$ for $B^0 \rightarrow J/\psi K_S$

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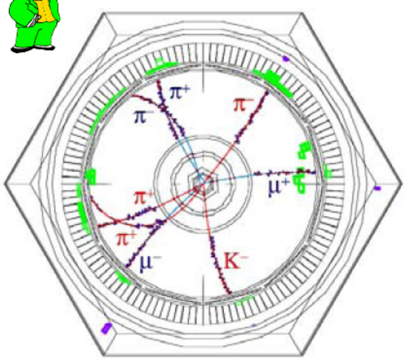
5.4

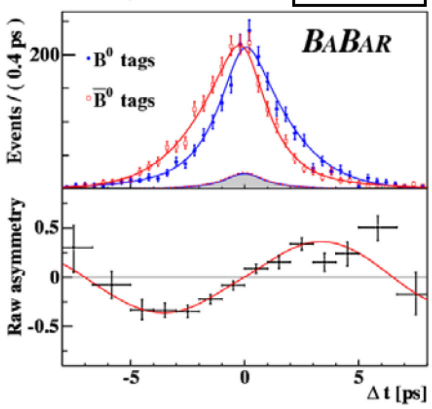
CP – violation in B - system

$B^0 \rightarrow \psi K_s$



PRL 94, 161803.

227 Mio $B\bar{B}$



$A_{CP}(t) = \sin 2\beta \sin(\Delta m t)$

$\sin 2\beta = 0.722 \pm 0.040 \pm 0.023$

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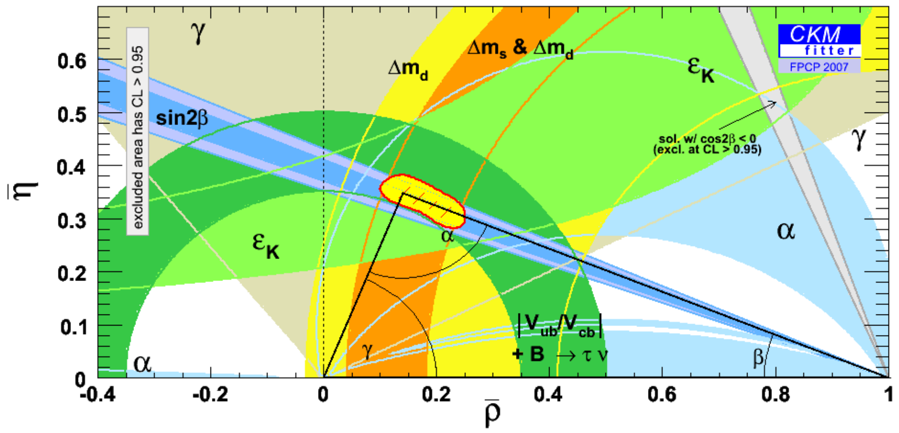
5.4

Status of unitarity triangle



5.4

LHCb detector