4 B - Mesons:

	$\tau = 1/\Gamma$	Δm	$x = \frac{\Delta m}{\Gamma}$	$y = \frac{\Delta\Gamma}{2\Gamma}$
K^0-System	$0.26 \cdot 10^{-9}\,s$	$5.29\ ns^{-1}$	0.477	-1
D^0-System	$0.4 \cdot 10^{-12}\,s$	$0.0024\ ps^{-1}$	0.0097	0.0078
B^0-System	$1.5 \cdot 10^{-12}\,s$	$0.507\ ps^{-1}$	0.78	0.0015
B_s System	$1.5 \cdot 10^{-12}\,s$	$17.7\ ps^{-1}$	26.8	0.07

Remember the Wolfenstein parametrization of V_{CKM}:

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \cdot e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| e^{-i\beta} & -|V_{ts}| \cdot e^{i\beta_s} & |V_{tb}| \end{pmatrix} + \mathcal{O}(\lambda^5)$$

$\Rightarrow$ usefull to evaluate the expected CP asym. in B-decays
It turns out that the phases β, β_s, γ as well as $V_{ub}, V_{cb}, V_{td}, V_{ts}$ can be measured in B-decays $\Rightarrow$ Test of UT

4.1 Measurement of CKM phase β in $B^0 \to J/\psi K^0_S$ decays

The channel $B^0 \to J/\psi K_S$ allows an interference of the decay w/ and w/o mixing:

$$\begin{array}{ccc} B^0 & \longrightarrow & J/\psi K_S \\ & \searrow \; \bar{B}^0 \; \nearrow & \end{array}$$

With the Master Eq. from Chap. 3.4E one obtains for small $\Delta\Gamma$ and for negligible (no) direct CPV (i.e. $|A_f| = |\bar{A}_f|$) no CPV in mixing:

$$A_{CP}(t) = \frac{\Gamma(B^0 \to f)(t) - \Gamma(\bar{B}^0 \to f)(t)}{\Gamma(\quad)(t) + \Gamma(\quad)(t)} = -\mathrm{Im}(\lambda_f)\sin(\Delta m t)$$

For the final-state $f = f_{CP}$ with $CP|f_{CP}\rangle = \eta_{CP}|f_{CP}\rangle$ and $\eta_{CP} = \pm 1$

one obtains for λ_{fcp}:

$$\lambda_{fcp} \equiv \frac{q}{p} \cdot \frac{\bar{A}_{fcp}}{A_{fcp}} = \frac{q}{p} \cdot \eta_{cp} \cdot \frac{\bar{A}_{\bar{f}cp}}{A_{fcp}}$$

where we have rewritten λ_{fcp} as a function of $\bar{A}_{\bar{f}cp}$.
$\bar{A}_{\bar{f}cp}$ and A_{fcp} are related be CP conjugation and differ only in the signs of the weak phases $\rightarrow$ $\bar{A}_{\bar{f}cp}$ can be calculated from A_{fcp} by inverting the phases!

For the finalstate $J/\psi K_S$: $\eta_{cp} = -1$
Moreover for this finalstate one has to consider the following amplitudes:

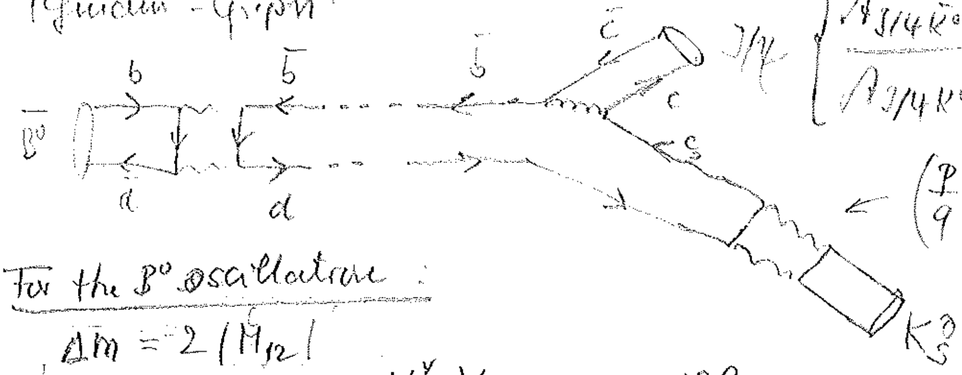
$$\mathcal{A}(B^0 \to J/\psi K_S) = \mathcal{A}(B^0 \to J/\psi K^0) \times \mathcal{A}(K^0 \leftrightarrow K_S)$$
$$\mathcal{A}(\bar{B}^0 \to J/\psi K_S) = \mathcal{A}(\bar{B}^0 \to J/\psi \bar{K}^0) \times \underbrace{\mathcal{A}(\bar{K}^0 \leftrightarrow K_S)}$$

Remember: $|K_S\rangle = p|K^0\rangle + q|\bar{K}^0\rangle$

Considering the K^0 mixing one obtains:

$$\lambda_{J/\psi K_S} = \left(\frac{q}{p}\right)_{B^0} \cdot \eta_{cp} \frac{\bar{A}_{J/\psi K_S}}{A_{J/\psi K_S}} = \left(\frac{q}{p}\right)_{B^0} \eta_{cp} \frac{\bar{A}_{J/\psi \bar{K}^0}}{A_{J/\psi K^0}} \cdot \left(\frac{p}{q}\right)_{K^0}$$

Feynman-Graph



$$\left\{ \frac{\bar{A}_{J/\psi \bar{K}^0}}{A_{J/\psi K^0}} = \frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}} \right.$$

$$\left(\frac{p}{q}\right)_{K^0} = \sqrt{\frac{M_{12}^*}{M_{12}}}\Bigg|_{K} = \frac{V_{cs} V_{cd}^*}{V_{cs}^* V_{cd}}$$

<u>For the B^0 oscillation:</u>

$\Delta m = 2|M_{12}|$

$$\underbrace{q/p}_{\text{a pure phase, } |q/p| \approx 1} = \sqrt{\frac{M_{12}^*}{M_{12}}} = \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} = e^{-i2\beta}$$

Putting everything together one obtains for $\lambda_{J/\psi K_S}$:

$$\lambda_{J/\psi K_S} = -\left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\right)\cdot\left(\frac{V_{cb} \cdot V_{cs}^*}{V_{cb}^* V_{cs}}\right)\left(\frac{V_{cs} V_{cd}^*}{V_{cs}^* V_{cd}}\right)$$

$$= -\left(\frac{V_{tb}^* V_{td} \; V_{cb} V_{cd}^*}{V_{tb} V_{td}^* \; V_{cb}^* V_{cd}}\right)$$

$$\mathrm{Im}\left(\lambda_{J/\psi K_S}\right) = -\sin\left(\arg\left(\dots \right)\right) = -\sin\left(2\arg\left(\frac{V_{cb} V_{cd}^*}{V_{tb} V_{td}^*}\right)\right)$$

$$= -\sin 2\beta$$

$$\rightarrow \quad A_{CP}(t) = \underbrace{-\sin(2\beta)}_{2\times \text{ phase of } V_{td}} \sin(\Delta m t)$$

One often short cuts the argumentation by saying that the $B^0 \to \bar{B}^0$ mixing leads to the factor $(q/p)_{B^0} = e^{-2i\beta}$ and all other amplitudes are essentially real!

For different final states e.g. $B^0 \to J/\psi K_L$ one has to consider the different CP eigenvalues. In general one therefore often writes:

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

The measurement of 2β was performed by BABAR and Belle, both experiments at a high-luminosity e^+e^- B-factory: e^+e^- B-factories operate at the center-of-mass energy of the $\Upsilon(4S)$ resonance which decays nearly entirely to $B^0\bar{B}^0$ or B^+B^-: $e^+e^- \to \Upsilon(4S) \to B^0\bar{B}^0, B^+B^-$ ($E_S = 10.58$ GeV)

Measurement of $\sin(2\beta)$ was the first observation of CPV outside K^0-system $\rightarrow$ correctly predicted by SM.

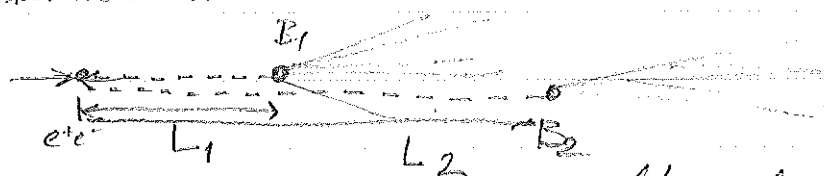
<u>Experimental problems of the measurement:</u>

1) $M_{\Upsilon(4S)} = 10.56\ \mathrm{GeV}/c^2 \approx 2\, m_B$

→ If the $\Upsilon(4S)$ is produced at rest the 2 B's have very little momentum. A lifetime measurement which is based on the measurement of the flight-length is not possible (B's don't fly!).
To overcome this problems the $\Upsilon(4S)$ is instead produced with a boost:

$$\underset{3.1\ \mathrm{GeV}}{\longrightarrow} e^+ + e^- \underset{9\ \mathrm{GeV}}{\longleftarrow} \Rightarrow \beta\gamma = 0.56$$

Decay kinematics:

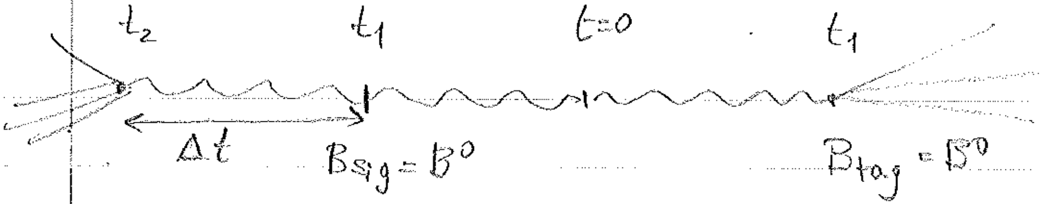


{ typical $\beta\gamma c\tau \approx 250\,\mu m$
{ w/ $\tau \approx 1.5\,ps$

2) Flavor-tagging:
To measure $A_{CP}(t)$ one has to know whether a $B^0 \to J/\psi K_S$ was produced originally as B^0 or as $\overline{B^0}$.
In general one uses the „2nd B" in the event which always contains two B's w/ opposite flavor:

$$B_{tag} = B|_b \text{ or } B|_{\bar b} \Longrightarrow B_{signal} = B^0|_{\bar b} \text{ or } \overline{B^0}|_b$$

However for $B_{tag} = B^0$ one has the problem of oscillation, i.e. when decaying the B_{tag} might have changed its flavor!
→ wrong tag!!
At $\Upsilon(4S)$ the problem can be solved:
Both B-mesons are produced coherently and are entangled.
One does not know which one is $B^0/\overline{B^0}$.



If one of the two decays in a given state it defines at that time also the flavor of the other one!
(opposite)

↳ After the decay of the tagging B (e.g. $B_{tag} = B^0$) the clock of the signal B ($B_{sig} = \bar{B}^0$ at t_1) starts to tick ($\Delta t = t - t_1$).

Instead of measuring A_{CP} as function of the absolute time t, it is measured as function of Δt (time after the tagging B has decayed!):

$$A_{CP}(\Delta t) = \frac{\Gamma(B^0(\Delta t) \to f) - \Gamma(\bar{B}^0(\Delta t) \to f)}{\Gamma \qquad + \Gamma}$$

$$= \frac{\Gamma(B_{tag} = \bar{B}^0, B \to f) - \Gamma(B_{tag} = B^0, B \to f)}{\cdots}(\Delta t)$$

$$= -\sin(2\beta)\sin(\Delta m t)$$

Of course the signal B can also decay before the tagging B. In this case $\Delta t < 0$.

BABAR plots for $\sin(2\beta)$ in $J/\psi K_S$ and $J/\psi K_L$!

2. Measurement of β_s in $B_s \to J/\psi\,\phi$

Changing spectator quark $d \to s$ one obtains the B_s counter-part:

$$\begin{array}{ccc} B_s^0 & \longrightarrow & J/\psi\,\phi \\ & \searrow_{(q/p)_{B_s^0}} \quad \bar{B}_s^0 \nearrow & \end{array} \qquad \phi = |s\bar{s}\rangle$$

Differences w/r to $J/\psi K_s$

1) $$\left(q/p\right)_{B_s^0} = \left(\frac{V_{ts} V_{tb}^*}{V_{ts}^* V_{tb}}\right) \approx e^{i2\beta_s}$$

$$\text{w/ } \beta_s = \arg\left(-\frac{V_{ts} V_{tb}^*}{V_{cs} V_{cb}^*}\right) \approx \arg(-V_{ts})$$

$$\longrightarrow \quad Im(\lambda_{J/\psi\phi}) = \sin(-2\beta_s)$$

$2\beta_s$ ist very small $\sim \eta\lambda^2$ $\to$ very small CPV

2) ϕ is not oscillating

3) $\Delta\Gamma \neq 0$: $$A_{CP}(t) = \frac{\Gamma(B_s \to J/\psi\,\phi)(t) - \Gamma(\bar{B}_s \to J/\psi\,\phi)}{\Gamma(\quad) + \Gamma(\quad)}$$

$$= \frac{-Im(\lambda_{J/\psi\phi}) \sin(\Delta m_s t)}{\cosh\left(\frac{\Delta\Gamma}{2} t\right) + Re(\lambda_{J/\psi\phi}) \sinh\left(\frac{\Delta\Gamma}{2} t\right)}$$

4) Additional problem:
$J/\psi\,\phi$ is not a pure CP eigenstate but a mixture of $\eta_{CP} = \pm 1$ states.
Reason: J/ψ and ϕ are both vector (Spin-1) particles

$$\begin{array}{cccc} & B_s \longrightarrow & J/\psi & + \;\phi \\ J^{PC}: & 0^{-+} & 1^{--} & 1^{--} \end{array}$$

implies relative angular momenta $\ell = 0, 1, 2$ possible

$$\Rightarrow \quad \eta_{CP}(J/\psi\,\phi) = \underset{(+1)}{\eta_{CP}(J/\psi)} \cdot \underset{(+1)}{\eta_{CP}(\phi)} \, \underset{(-1)^\ell}{(-1)^\ell}$$

$\ell = 1 \to$ CP-odd
$\ell = 0, 2 \to$ CP-even

If one does not separate the $\ell = 0, 1, 2$ states from each other one might not observe any CPV even if there are large effects.

→ Solved by performing an angular analysis of the final states which allow to separate the $CP = +1/-1$ states

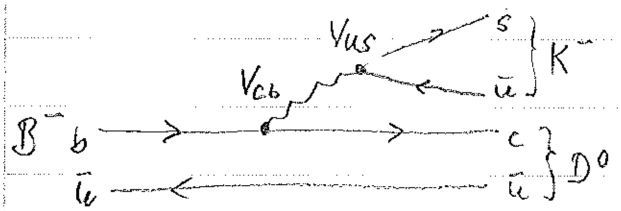
Measurement: LHCb 2013 $\phi_M = -2\beta_s = 0.01 \pm 0.07$

SM $\phi_s^{SM} = -2\beta_s = -0.036 \pm 0.002$

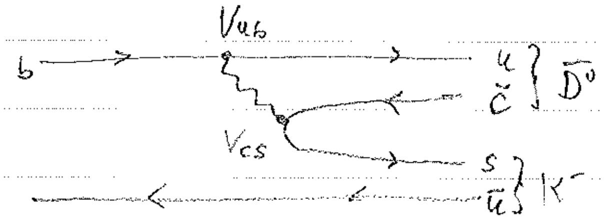
4.3 Measurement of the CKM phase γ using $B^\pm \to \overset{(-)}{D^0} K^\pm$

To measure γ one exploits „direct CPV", i.e. CPV in the decay. However to get the interference is a bit more tricky.

Cabibbo favored $B^- \to D^0 K^-$



Cabibbo suppressed $B^- \to \bar{D}^0 K^-$



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

In general the 2 amplitude lead to a different final states and thus cannot interfere, However if D^0 and $\bar{D}^0$ decay to the same final state:

e.g. $D^0/\bar{D}^0 \to KK, \pi\pi$ (there are others)

the interference of the 2 amplitude can result in CPV and allows to measure the weak phase $\gamma = -\arg(V_{ub})$

The extraction of the weak phase γ from the CPV in $B^\pm \to \overset{(-)}{D^0} K^\pm$ decays is rather complicated.

The most precise determination of γ is from LHCb.

$$\text{LHCb 2013:} \quad \gamma = (67 \pm 12)^\circ$$

4.4 The unitarity triangle:

CKM phase β: $B^0 \to J/\psi K_s$
CKM phase γ: $B^\pm \to \overset{(-)}{D^0} K^\pm$
CKM phase β_s: $B_s^0 \to J/\psi \phi$
(CKM phase α: $B^0 \to \pi^+\pi^-$: Measures $\pi - \beta - \gamma = \alpha$)
not discussed

The sides:

$V_{cb}, V_{ub} \to$ measured from semilept. BR
$b \to c l \nu \quad b \to u l \nu$

$V_{ts}/V_{td} \to$ measured from oscillation