CP Violation & BaBar, Continued
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Recap:

- Weak and flavour eigenstates of quarks are related by
  $$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$
  where $V_{CKM}$ is the 3x3 unitary CKM matrix.
  As unitary → Unitarity triangle
- Neutral mesons can "mix"
  $$\frac{N_{unmix} - N_{mix}}{N_{unmix} + N_{mix}} = \cos(\Delta m\, t)$$
  where $\Delta m$ is the mass difference between 2 mass eigenstates. $K_S$, $K_L$, $B_H$, $B_L$
- How to measure $\Delta m_B$
  - Measure $\Delta t$ between B decays
    Asymmetric beam energies, SVT
  - Identify whether $B^0$ or $\bar{B}^0$
    "Flavour tagging"
- 3 types of CPV in B decays
  - CPV in mixing
    $(P(B^0 \to \bar{B}^0) \neq P(\bar{B}^0 \to B^0)$
    $$\left|\frac{q}{p}\right| \neq 1$$
  - CPV in decay
    $P(B \to f) \neq P(\bar{B} \to \bar{f})$
    $$\left|\frac{\bar{A}}{A}\right| \neq 1$$
  - CPV in interference between decays with and without mixing
    $B^0 \to f_{cp}$
    $B^0 \to \bar{B}^0 \to f_{cp}$
    $\mathrm{Im}(\lambda) \neq 0$
    $$\lambda = \eta \left(\frac{q}{p}\right)\left(\frac{\bar{A}}{A}\right)$$

- Time dependent asymmetry

$$Asym(\Delta t) = \frac{\Gamma\left(B^0(\Delta t) \to f_{cp}\right) - \Gamma\left(\bar{B}^0(\Delta t) \to f_{cp}\right)}{\Gamma\left(B^0(\Delta t) \to f_{cp}\right) + \Gamma\left(\bar{B}^0(\Delta t) \to f_{cp}\right)}$$

$$= \frac{\left(1 - |\lambda|^2\right)\cos\left(\Delta m_B \Delta t\right) - 2\,\mathrm{Im}(\lambda)\sin\left(\Delta m_B \Delta t\right)}{1 + |\lambda|^2}$$

$$= -\mathrm{Im}(\lambda)\sin\left(\Delta m_B \Delta t\right) \; if \; |\lambda| = 1$$

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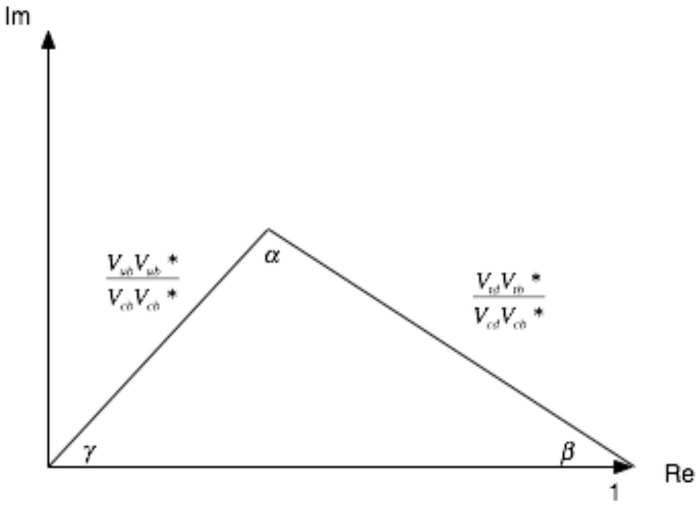
**Measuring** $\sin 2\beta$

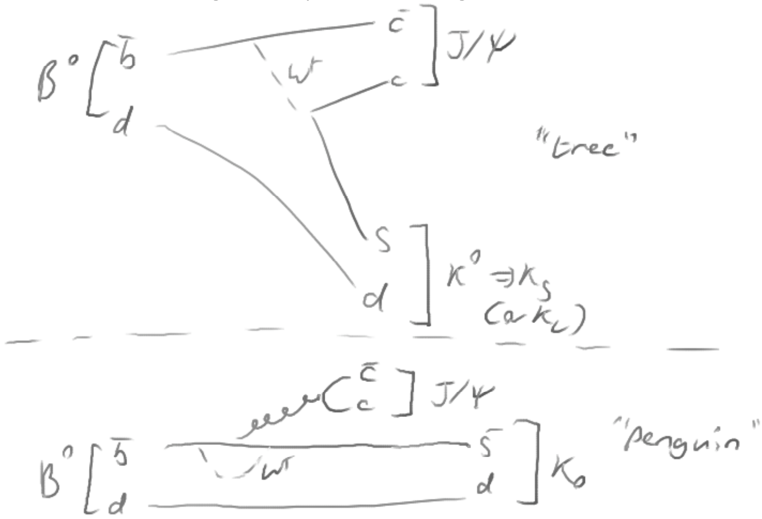
$\beta$ is the angle of the Unitarity Triangle.




$$B = \arg\left( - \frac{V_{cd} V_{cb}\,*}{V_{td} V_{tb}\,*} \right)$$

- Measure using "golden channel"
  $B \to J/\psi\ K_s$
  $J/\psi$ is $c\bar{c}$ "charmonium". Decays to $\ell^+\ell^-$ 12% of the time.
- Why so good?
  - B.F. not so small $\left(\sim 10^{-3}\right)$
  - Clear experimental signature (low background)
  - Theoretically clean

- Can occur through 2 Feynmann diagrams.



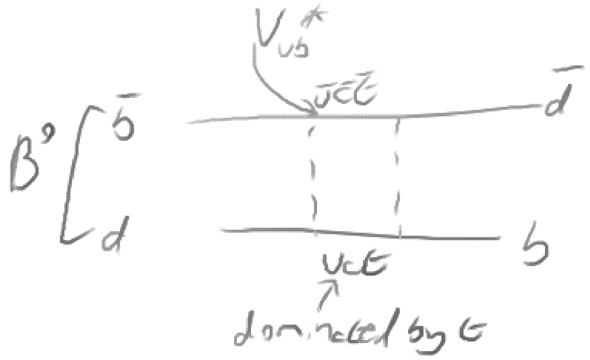

But both have the same phase → no interference.
Therefore no direct CPV. $|\lambda| = 1$.

$Asym(\Delta t) = -\mathrm{Im}(\lambda)\sin(\Delta m_B \Delta t)$

- What is $\lambda$?

$$\lambda = \underbrace{\eta_{J/\psi\ K_S}}_{\substack{=-1 \\ \left(\text{CP eigenstate of } J/\Psi\ K_S\right)}} \underbrace{\left(\frac{q}{p}\right)_B}_{B-mixing} \underbrace{\left(\frac{\bar{A}}{A}\right)}_{\substack{decay \\ amplitudes}} \underbrace{\left(\frac{q}{p}\right)_K}_{K-mixing}$$

B-mixing:




$$\left(\frac{q}{p}\right)_B = \frac{V_{tb}{}^* V_{td}}{V_{tb} V_{td}{}^*}$$

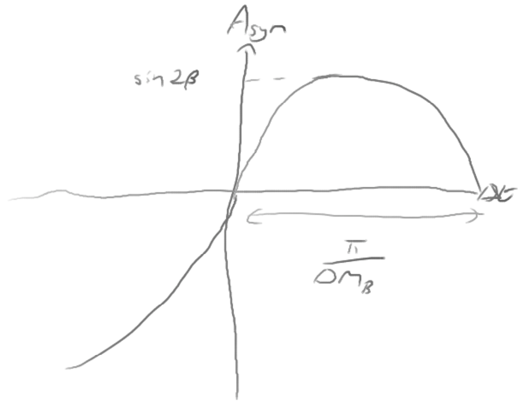
Decay amplitudes $= \dfrac{V_{cb}{}^* V_{cs}}{V_{cb} V_{cs}{}^*}$

K-mixing dominated by c quark. $= \dfrac{V_{cs}{}^* V_{cd}}{V_{cs} V_{cd}{}^*}$

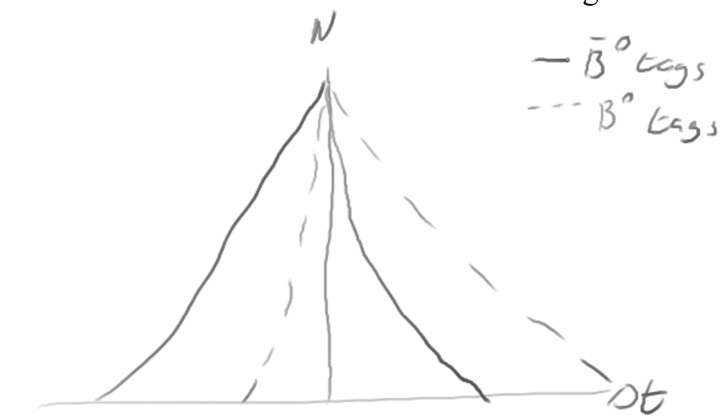
$$\lambda = -\frac{V_{tb}{}^* V_{td}}{V_{tb} V_{td}{}^*} \frac{V_{cb}{}^* V_{cd}}{V_{cb} V_{cd}{}^*} = e^{-2i\beta}$$

Therefore $\mathrm{Im}(\lambda) = -i\sin 2\beta$

Therefore $Asym(\Delta t) = \sin(2\beta)\sin(\Delta m_B \Delta t)$



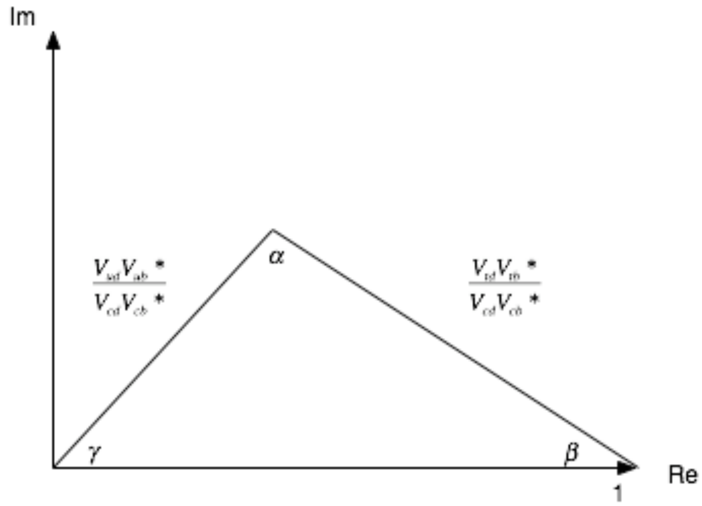

- How do we measure it?
  - Reconstruct $B \to (J/\Psi)\,K_S$ decay
  - Measure $\Delta t$ between B-decays
  - Flavour tag other $B$ in the event.
- Reconstructing $(J/\psi)K_s$
  - $(J/\psi) \to e^+e^-$ or $\mu^+\mu^-$ 12% of the time.
    - Charged leptons will leave tracks in the tracking system (SVT and DCH).
    - Locate $(J/\psi)$ (therefore $B$) decay vertex in SVT
    - Measure momentum using DCH
      Combine 4-momenta, to get $J/\psi$ "candidate".
  - $K_S \to \pi^+\pi^-$ 68% of the time (the rest of the time, it goes to $\pi^0\bar{\pi}^0$)
    - Pions leave tracks in SVT and DCH.
    - $K_S$ has $c\tau \sim 2.7cm$ so decay vertex will be displaced from the interaction region – this helps reduce background.
    - Measure momentum, combine to get $K_S$ candidate.
  - Add 4-momenta of $(J/\psi)$ and $K_S$ candidates to get $B$-candidate.
- Put it all together.
  - Plot $\Delta t$ distributions for events with $B^0$ tag and events with $\bar{B}^0$ tag.




- Experimental complications
  - Imperfect $\Delta t$ resolution function $R(\Delta t)$
  - Non-zero mistag fraction $w$
  - Backgrounds

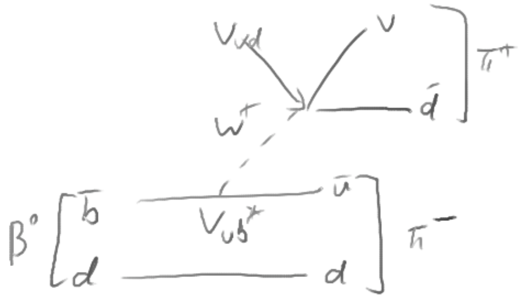
- Can also use other "charmonium" decay modes
  e.g. $\psi(2s)K_S$, $(J/\psi)K_L$, $\eta_c K_S$
- In 2001, both BABAR and Belle measured $\sin 2\beta$ to be $> 3\sigma$ from 0.
    - First observation of CP violation outside Kaon system.
- Measurement now quite precise.
  Current world average: $\sin 2\beta = 0.687 \pm 0.032$
- Excellent agreement with standard model expectation.

**Measuring $\alpha$**




$$\alpha = \arg\left[-\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right]$$

Use decays with $b \to u\bar{u}d$ transition, e.g. $B \to \pi^+\pi^-$ or $B \to \rho^+\rho^-$
If only "tree" diagrams contribute




$$\lambda\left(B \to \pi^+\pi^-\right) = -\left(\frac{V_{tb}^* V_{td}}{V_{tb}V_{td}^*}\right)\left(\frac{V_{ud}^* V_{ub}}{V_{ud}V_{ub}^*}\right)$$
$$= e^{-2i(\alpha-\pi)}$$

But, "penguin" diagram also expected.

Therefore expect interference → direct CPV. $|\lambda| \neq 1$.

- Terms in both $\cos(\Delta m_B \Delta t)$ as well as $\sin(\Delta m_B \Delta t)$.
- Both must be fitted.

Also:

- BF (Branching Fraction) $B \to \pi^+\pi^-$ is very small $\left(\sim 5\times 10^{-6}\right)$
- Much harder to remove background events.

Best BABAR value $\left(B \to \rho^+\rho^-\right)$:

$\alpha = (103 \pm 10)°$

**Measuring $\gamma$**

Very difficult at B-factories.

$$\gamma = \arg\left[-\frac{V_{ud}V_{ub}*}{V_{cd}V_{cb}*}\right]$$

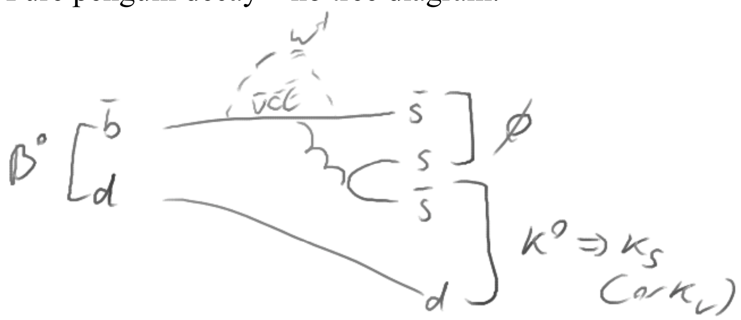
Use $B^\pm \to DK^\pm$ decays where $D$ decays to final state accessible to both $D^0$ and $\bar{D}^0$.
Complicated analysis.
Current value from BABAR:

$$\gamma = \left(67 \pm \underbrace{28}_{statistical} \pm \underbrace{13}_{systematic} \pm \underbrace{11}_{theory}\right)°$$

**Measuring $\sin 2\beta$ in other decay channels**

Can also use $b \to s\bar{s}u$ or $b \to s\bar{u}u$ transitions.
e.g. $B \to \phi K_S$

$\phi$ is $s\bar{s}$, and decays to $K^+K^-$ 50% of the time.
Pure penguin decay – no tree diagram.




Therefore no direct CPV, $|\lambda| = 1$.

Any discrepancy between $\sin 2\beta$ in these modes and $\sin 2\beta$ in charmonium would be a sign of New Physics.
At the moment, naïve average gives $2.7\sigma$ discrepancy.
However, not all these modes are pure penguin, there may be some direct CPV.
Still, one of most exciting areas in B-factories.

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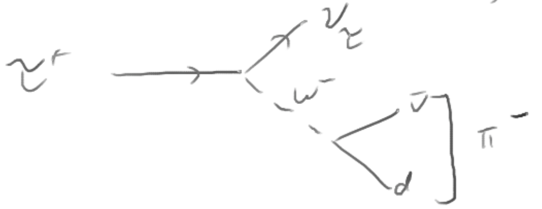
**Tau Physics at BABAR**

BABAR / PEPII is also a $\tau$-factory.

Cross-section for $\tau$ pair production at CM energy $10.58 GeV$ is $0.89 nb$.
Therefore ~270 million $\tau^+\tau^-$ events in BABAR dataset.
$\tau$ is the heaviest lepton $\left(m_\tau = 1.777 GeVc^{-2}\right)$. It is the only lepton that can decay to hadrons as well as leptons.



85% of $\tau$ decays are to 1 charged track, and zero or more neutral particles.
- Look for events with one isolated charged track in hemisphere
Almost all other 15% decays are to 3 charged tracks plus zero or more neutrals.

**Examples of $\tau$ analyses**

- Charged current universality
  - Does the W couple equally to all leptons?
  - Need to measure $BF\left(\tau \to e\nu\bar{\nu}\right)$, $BF\left(\tau \to \mu\nu\bar{\nu}\right)$, and measure $\tau$ lifetime.
- Studies of light hadrons
  - Clean environment to study properties of e.g. $\rho$, $K*$ resonances
- Mass of $\tau$ neutrino
  - Neutrino oscillation measurements give mass differences, not absolute masses.
  - BABAR and Belle should be able to reduce upper limit on $m_{\nu_\tau}$.
- Lepton flavour violation
  - Neutrinoless Decays such as $\tau \to e\gamma$ or $\tau \to \mu\gamma$ are forbidden in standard model.
  - Observing these decays would be unambiguous sign of New Physics.
  - Look for events with 1 isolated track in one hemisphere, lepton and neutral EMC cluster in other hemisphere.
  - Combine 4-momenta of lepton and gamma, see if result is consistent with $\tau$ mass.
  - Need to rule out possibility of very low momentum neutrinos – need to know energy resolution, background distributions very well.

- Latest results:
  $B.F.\left(\tau^{\pm} \to \mu^{\pm}\gamma\right) < 6.8 \times 10^{-8}$
  $B.F.\left(\tau^{\pm} \to e^{\pm}\gamma\right) < 1.1 \times 10^{-7}$
  Both at 90% confidence level.
  Already starting to become useful in constraining or even ruling out New Physics models.