CP violation in the interference between mixing and decay, and an introduction to B-factories

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Reading material and references

Lecture material based on several textbooks and online lectures/notes.
Credits for material and figures include:

Literature

- Perkins, Donald H. (2000), *Introduction to High Energy Physics*.
- Griffiths, David J. (2nd edition), *Introduction to Elementary Particles*.
- Stone, Sheldon (2nd edition), B *decays*.

Online Resources

- Belle/BaBar Collaborations, *The Phyiscs of the* B*-Factories*.
  http://arxiv.org/abs/1406.6311
- Bona, Marcella (University of London), CP *Violation Lecture Notes*,
  http://pprc.qmul.ac.uk/ bona/ulpg/cpv/
- Richman, Jeremy D. (UCSB), *Heavy Quark Phyiscs and* CP *Violation*.
  https://courses.physics.ucsd.edu/2010/Winter/physics222/references/driver_houches12.pdf
- Thomson, Mark (Cambridge University), *Particle Physics Lecture Handouts*,
  http://www.hep.phy.cam.ac.uk/ thomson/partIIIparticles/welcome.html
- Grossman, Yuval (Cornell University), *Just a Taste. Lectures on Flavor Physics*,
  http://www.lepp.cornell.edu/ pt267/files/notes/FlavorNotes.pdf
- Kooijman, P. & Tuning, N., CP *Violation*,
  https://www.nikhef.nl/ h71/Lectures/2015/ppII-cpviolation-29012015.pdf

Recap & outline

So far, we:

- Developed the framework to describe particle anti-particle oscillations, both with and without CP violation. This was done for the neutral Kaon system, but is applicable to all neutral particle systems.
- Saw that CP-violation in mixing leads to $\Gamma(K^0_{t=0} \to \overline{K}^0) \neq \Gamma(\overline{K}^0_{t=0} \to K^0)$
- Studied direct CP violation in the B meson system, and looked at the example of $B \to K\pi$ decays which is currently an open question, referred to as the "$K\pi$ CP-puzzle."

Today, we'll:

- Study CPV in B^0-$\overline{B}^0$ oscillations.
- Finally, we'll introduce a third and the final type of CP violation, $\boldsymbol{CP}$ **violation in interference between mixing and decay** and study the "golden mode" $B^0 \to J/\psi K^0_S$.
- We'll also introduce B factories and experimental techniques along the way.

Recap: $K^0 - \overline{K}^0$ Oscillations with CP violation

Recall our derivation of mixing in the kaon system including CP violation (Lecture II, S29):

- Writing our $|K_S\rangle$ and $|K_L\rangle$ states (inc. CPV) in terms of the strong eigenstates $|K^0\rangle$ and $|\overline{K}^0\rangle$

$$|K_S\rangle = \frac{1}{\sqrt{1+|\varepsilon|^2}}\left[|K_1\rangle + \varepsilon|K_2\rangle\right] = \frac{1}{\sqrt{2}}\frac{1}{\sqrt{1+|\varepsilon|^2}}\left[(1+\varepsilon)|K^0\rangle - (1-\varepsilon)|\overline{K}^0\rangle\right]$$

$$|K_L\rangle = \frac{1}{\sqrt{1+|\varepsilon|^2}}\left[|K_2\rangle + \varepsilon|K_1\rangle\right] = \frac{1}{\sqrt{2}}\frac{1}{\sqrt{1+|\varepsilon|^2}}\left[(1+\varepsilon)|K^0\rangle + (1-\varepsilon)|\overline{K}^0\rangle\right]$$

- We know from before that the states $|\Psi(t)\rangle$ propagate as $|K_S\rangle$ and $|K_L\rangle$, i.e., independent particles with definite masses and lifetimes.
  Invert these expressions to switch to the $|K_S\rangle$ and $|K_L\rangle$ basis:

$$|K^0\rangle = \sqrt{\frac{1+|\varepsilon|^2}{2}}\frac{1}{1+\varepsilon}\left[|K_L\rangle + |K_S\rangle\right] \qquad |\overline{K}^0\rangle = \sqrt{\frac{1+|\varepsilon|^2}{2}}\frac{1}{1-\varepsilon}\left[|K_L\rangle - |K_S\rangle\right]$$

- If we add on the time dependence $\theta_S(t)$ and $\theta_L(t)$, we see that states which were initially produced as K^0, or $\overline{K}^0$, evolve with time as

$$|\Psi(t)\rangle_{K^0_{t=0}} = \sqrt{\frac{1+|\varepsilon|^2}{2}}\frac{1}{1+\varepsilon}\left[\theta_L(t)|K_L\rangle + \theta_S(t)|K_S\rangle\right] \quad \text{(K8)}$$

$$|\Psi(t)\rangle_{\overline{K}^0_{t=0}} = \sqrt{\frac{1+|\varepsilon|^2}{2}}\frac{1}{1-\varepsilon}\left[\theta_L(t)|K_L\rangle - \theta_S(t)|K_S\rangle\right] \quad \text{(K9)}$$

Recap: $K^0 - \overline{K}^0$ Oscillations with CP *violation*

If we want to study $\boldsymbol{K^0 - \overline{K}^0}$ oscillations, we need to switch to the $\boldsymbol{K^0\ \overline{K}^0}$ basis

- K8 and K9 become.

$$|\Psi(t)\rangle_{K^0_{t=0}} = \frac{1}{2}\left[(\theta_L(t)+\theta_S(t))\,|K^0\rangle + (\theta_L(t)-\theta_S(t))\left(\frac{1-\varepsilon}{1+\varepsilon}\right)|\overline{K}^0\rangle\right]$$

$$|\Psi(t)\rangle_{\overline{K}^0_{t=0}} = \frac{1}{2}\left(\frac{1+\varepsilon}{1-\varepsilon}\right)\left[(\theta_L(t)-\theta_S(t))\,|K^0\rangle + (\theta_L(t)+\theta_S(t))\,|\overline{K}^0\rangle\right]$$

Now lets change to the B-meson system. Recall we stated that the time-dependent formalism of mixing we derived for the Kaon system applies to all neutral particle systems undergoing oscillation.

- Replace K with B, and for simplicity, lets work in terms of $\frac{q}{p}$ (recall, $\frac{q}{p} = \frac{1-\varepsilon}{1+\varepsilon}$).
- Recall that in the Kaon system, the $|K_{\pm}\rangle$ eigenstates we obtained by solving the time-dependent shrodinger equation had significantly different lifetimes, which motivated us to name them "short" and "long" lifetime states $|K_S\rangle$ and $|K_L\rangle$.

  For the B meson system, the lifetimes are almost identical. Instead the eigenstates have significantly different masses, which motivates us to rename them as "heavy" and "light."

  $\rightarrow$ Denote the K_S eigenstate of the Kaon system as the "Heavy" eigenstate of the B system (B_H).

  $\rightarrow$ Denote the K_L eigenstate of the Kaon system as the "Light" eigenstate of the B system (B_L).
- Write the time-dependence explicitly, switching the subscripts $S \rightarrow H$ for the heavy eigenstate. Recall that for our derivation in the kaon system we had abbreviated this as follows:

$$\theta_S(t) = e^{-\left(im_S+\frac{\Gamma_S}{2}\right)t}, \quad \theta_L(t) = e^{-\left(im_L+\frac{\Gamma_L}{2}\right)t}$$

B meson system

The time dependence of state $|\Psi(t)\rangle$ which was a B^0 at $t = 0$ is given by:

$$|\Psi(t)\rangle_{B^0_{t=0}} = \boxed{|B^0(t)\rangle = e^{-iMt}e^{-\frac{\Gamma}{2}t}\left[\cos\left(\frac{\Delta M t}{2}\right)|B^0\rangle + i\sin\left(\frac{\Delta M t}{2}\right)\frac{q}{p}|\overline{B}^0\rangle\right]}$$

and for a state which was a $\overline{B}^0$ at $t = 0$ is given by:

$$|\Psi(t)\rangle_{\overline{B}^0_{t=0}} = \boxed{|\overline{B}^0(t)\rangle = e^{-iMt}e^{-\frac{\Gamma}{2}t}\left[\cos\left(\frac{\Delta M t}{2}\right)|\overline{B}^0\rangle + i\sin\left(\frac{\Delta M t}{2}\right)\frac{p}{q}|B^0\rangle\right]}$$

where we've abbreviated:

$$M = \frac{1}{2}(M_L + M_H), \quad \Delta M = M_H - M_L, \quad \Gamma = \Gamma_L = \Gamma_H$$

since the difference in lifetimes between the B_L and B_H is $\Delta\Gamma/\Gamma \ll 1$.

Note: Here we've introduced $|B^0(t)\rangle$ and $|\overline{B}^0(t)\rangle$ to denote the states $|\Psi(t)\rangle_{B^0_{t=0}}$ and $|\Psi(t)\rangle_{\overline{B}^0_{t=0}}$ for simplicity only.
Sometimes these are also called $|B^0_{\text{phys}}(t)\rangle$ and $|\overline{B}^0_{\text{phys}}(t)\rangle$ to remind readers what the initial state is at $t = 0$ (which is NOT what the state is at time t since it's a superposition of $|B^0\rangle$ & $|\overline{B}^0\rangle$!).

Time-evolution of B decays to a CP eigenstate

Now let these states decay into a common final state $|f_{CP}\rangle$ with eigenvalue $\eta_{CP}(f) = \pm 1$.

The amplitude for $B^0(t) \to f_{CP}$ is given by:

$$\langle f_{CP}|H|B^0(t)\rangle = e^{-iMt} e^{-\frac{\Gamma}{2}t} \left[\cos\left(\frac{\Delta M t}{2}\right) \langle f_{CP}|H|B^0\rangle + i \sin\left(\frac{\Delta M t}{2}\right) \frac{q}{p} \langle f_{CP}|H|\overline{B}^0\rangle \right]$$

while that for a $\overline{B}^0(t) \to f_{CP}$ is

$$\langle f_{CP}|H|\overline{B}^0(t)\rangle = e^{-iMt} e^{-\frac{\Gamma}{2}t} \left[\cos\left(\frac{\Delta M t}{2}\right) \langle f_{CP}|H|\overline{B}^0\rangle + i \sin\left(\frac{\Delta M t}{2}\right) \frac{p}{q} \langle f_{CP}|H|B^0\rangle \right]$$

Here we can explicitly see the 2 amplitudes whose interference can produce a CP asymmetry. Lets define a quantity λ_f to express the ratio of amplitudes

$$\lambda_f \equiv \frac{q}{p} \frac{\overline{A}_f}{A_f} = \frac{q}{p} \frac{\langle f_{CP}|H|\overline{B}^0\rangle}{\langle f_{CP}|H|B^0\rangle} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}} \frac{\langle f_{CP}|H|\overline{B}^0\rangle}{\langle f_{CP}|H|B^0\rangle}$$

(not to be confused with the Wolfenstein parameter λ).

Time-evolution of B decays to a CP eigenstate

To see how this λ_f comes into play, factor out $\langle f_{CP}|H|B^0\rangle$:

$$\langle f_{CP}|H|B^0(t)\rangle = e^{-iMt}e^{-\frac{\Gamma}{2}t}\langle f_{CP}|H|B^0\rangle\left[\cos\left(\frac{\Delta Mt}{2}\right) + i\sin\left(\frac{\Delta Mt}{2}\right)\frac{q}{p}\frac{\langle f_{CP}|H|\overline{B}^0\rangle}{\langle f_{CP}|H|B^0\rangle}\right]$$

$$\langle f_{CP}|H|\overline{B}^0(t)\rangle = e^{-iMt}e^{-\frac{\Gamma}{2}t}\langle f_{CP}|H|B^0\rangle\left[\cos\left(\frac{\Delta Mt}{2}\right)\frac{\langle f_{CP}|H|\overline{B}^0\rangle}{\langle f_{CP}|H|B^0\rangle} + i\sin\left(\frac{\Delta Mt}{2}\right)\frac{p}{q}\right]$$

If the initial state at $t = 0$ is a $|B^0\rangle$, the *probability* to produce $|f_{CP}\rangle$ at time t is thus

$$\left|\langle f_{CP}|H|B^0(t)\rangle\right|^2 = e^{-\Gamma t}\left|\langle f_{CP}|H|B^0\rangle\right|^2\cdot\left[\tfrac{1}{2}(1+|\lambda|^2) + \tfrac{1}{2}(1-|\lambda|^2)\cos(\Delta Mt) - \mathrm{Im}\lambda\cdot\sin(\Delta Mt)\right]$$

Likewise for an initial state of $|\overline{B}^0\rangle$ at $t = 0$, the *probability* to produce $|f_{CP}\rangle$ at time t is

$$\left|\langle f_{CP}|H|\overline{B}^0(t)\rangle\right|^2 = e^{-\Gamma t}\left|\langle f_{CP}|H|B^0\rangle\right|^2\left|\frac{p}{q}\right|^2\cdot\left[\tfrac{1}{2}(1+|\lambda|^2) + \tfrac{1}{2}(1-|\lambda|^2)\cos(\Delta Mt) + \mathrm{Im}\lambda\cdot\sin(\Delta Mt)\right]$$

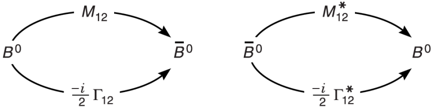
Notice how similar these expressions are. The only differences are the $\pm$ sign of the last term and the presence of $\left|\frac{p}{q}\right|^2$ in the second equation.

What can we say about $\frac{q}{p}$ in the B meson system?

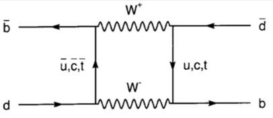
- Recall the definition from Lecture II:

$$\frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}$$

- The interference occurs between the set of amplitudes with short-distance, virtual (aka off-shell) intermediate states (M_{12}) and long-distance, on-shell intermediate states (Γ_{12}).



M_{12}: The off-shell intermediate states, e.g., $t\bar{t}$, arise from the box-diagrams



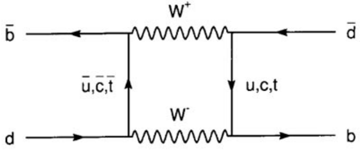
Γ_{12}: While a B can also evolve to a $\overline{B}^0$ through on-shell intermediate states such as K^+K^-, with mass $M_{K^+K^-} = M_{B^0}$

The B meson mixing phase $\phi_M(B^0)$

- Γ_{12} is very small for B^0-$\overline{B}^0$ mixing, so we can approximate

$$\frac{q}{p} \approx \sqrt{\frac{M_{12}^*}{M_{12}}}$$

- The short-distance, off-shell contribution from M_{12} depends on the size of the CKM-elements at the corners of the box-diagram, and on the mass of the particles in the box.



- In the SM, these amplitudes are completely dominated by the box diagrams with $t\bar{t}$, giving us:

$$M_{12} \propto (V_{tb}V_{td}^*)^2 e^{-2i\theta_{CP}(B)}$$
$$M_{12}^* \propto (V_{tb}^*V_{td})^2 e^{+2i\theta_{CP}(B)}$$

- Thus we have $\frac{q}{p} \approx \sqrt{\frac{M_{12}^*}{M_{12}}} = \frac{V_{tb}^*V_{td}}{V_{tb}V_{td}^*} e^{2i\theta_{CP}(B)} = e^{2i\phi_M(B^0)} e^{2i\theta_{CP}(B)}$

$\Rightarrow \left|\frac{q}{p}\right| = 1$ *Very important result!*

Time-dependent CP asymmetry

Using this result, we can write our time-dependent CP asymmetry using the rates we derived on S7, *which includes the effects of interference between mixing and decay*, as

$$\mathcal{A}_{\mathcal{CP}}(t) = \frac{\left|\langle f_{CP}|H|B^0(t)\rangle\right|^2 - \left|\langle f_{CP}|H|\bar{B}^0(t)\rangle\right|^2}{\left|\langle f_{CP}|H|B^0(t)\rangle\right|^2 + \left|\langle f_{CP}|H|\bar{B}^0(t)\rangle\right|^2}$$
$$= \frac{1-|\lambda|^2}{1+|\lambda|^2}\cos\left(\Delta M t\right) - \frac{2\mathrm{Im}\lambda}{1+|\lambda|^2}\sin\left(\Delta M t\right)$$
$$= A_f \cos\left(\Delta M t\right) - S_f \sin\left(\Delta M t\right)$$

$$A_f \equiv \frac{1-|\lambda|^2}{1+|\lambda|^2} \qquad S_f \equiv \frac{2\mathrm{Im}\lambda}{1+|\lambda|^2}$$

sometimes called A_{CP} and S_{CP}, or just A and S

How do we calculate λ_f?

For a given final state f, the magnitude and phase of λ_f fully describe the decay and oscillation of the B^0- and the $\overline{B}^0$-meson.

Our job is to search for decays which we can use to extract and *measure* a meaningful asymmetry.

On slide 10 we looked at $\frac{q}{p}$ and defined the B mixing angle ϕ_M.

Now lets study the decays of $B^0 \to f_{CP}$ and $\overline{B}^0 \to f_{CP}$.

Recall from our discussion of CPV in decay, that the total amplitude for the $B^0 \to f_{CP}$ decay is written as:

$$A \equiv A(B^0 \to f_{CP}) = \langle f_{CP}|H|B^0\rangle = \sum_j A_j = \sum_j a_j e^{i\phi_j} = \sum_j |a_j| \, e^{i\delta_j} e^{i\phi_j}$$

where ϕ_j is the weak phase which changes sign under CP, and δ_j is the CP-conserving strong phase.

How do we calculate λ_f?

Now lets look at a special case:

When the direct decay to f_{CP} is dominated by a single amplitude.

The $B^0 \to f_{CP}$ simplifies to one term:

$$\langle f_{CP}|H|B^0\rangle = |a|e^{i(\delta+\phi)}$$

For the $\overline{B}^0 \to f_{CP}$ decay, we have

$$\langle f_{CP}|H|\overline{B}^0\rangle = \eta_{CP}(f)e^{-2i\theta_{CP}(B)}|a|e^{i(\delta-\phi)}$$

What are these extra terms?

- $e^{-2i\theta_{CP}(B)}$ should ring a bell. It's the *intrinsic* CP phase factor associated with B. (Recall Lecture III S5 when we derived the condition for direct CPV).
- $\eta_{CP}(f)$ is the CP eigenvalue of the final state.

  Recall how we determined this in Lecture II S6-7, for Kaon decays to 2π,3π:

  the 2 pion system has eigenvalue $\eta_{CP}(f) = +1$ $[\mathcal{CP}|\pi^0\pi^0\rangle = +|\pi^0\pi^0\rangle]$,

  while the 3 pion system has $\eta_{CP}(f) = -1$ $[\mathcal{CP}|\pi^0\pi^0\pi^0\rangle = -|\pi^0\pi^0\pi^0\rangle]$

How do we calculate λ_f?

Lets put the pieces together

Start with our definition:

$$\lambda_f \equiv \frac{q}{p}\frac{\langle f_{CP}|H|\overline{B}^0\rangle}{\langle f_{CP}|H|B^0\rangle} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}\frac{\langle f_{CP}|H|\overline{B}^0\rangle}{\langle f_{CP}|H|B^0\rangle}$$

Substitute in our result from B^0-$\overline{B}^0$ oscillation

$$\lambda_f = \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} e^{2i\theta_{CP}(B^0)} \frac{\langle f_{CP}|H|\overline{B}^0\rangle}{\langle f_{CP}|H|B^0\rangle}$$

recalling how we defined the mixing phase $\phi_M(B^0)$

$$\lambda_f = e^{2i\phi_M(B^0)} e^{2i\theta_{CP}(B^0)} \frac{\langle f_{CP}|H|\overline{B}^0\rangle}{\langle f_{CP}|H|B^0\rangle}$$

and including our result from the direct decays $B^0 \to f_{CP}$ & $\overline{B}^0 \to f_{CP}$

$$\lambda_f = e^{2i\phi_M(B^0)} e^{2i\theta_{CP}(B^0)} \frac{\eta_{CP}(f) e^{-2i\theta_{CP}(B)} |a| e^{i(\delta-\phi)}}{|a| e^{i(\delta+\phi)}}$$

We arrive at the final expression:

$$\boldsymbol{\lambda_f = \eta_{CP}(f) e^{2i(\phi_M(B^0)-\phi)}}$$

$\mathcal{A}_{\mathcal{CP}}(t)$ for a single weak phase in the decay amplitude

What can we obtain from this result?

$$\boldsymbol{\lambda_f = \eta_{CP}(f) e^{2i(\phi_M(B^0)-\phi)}}$$

Immediately we see that $|\lambda_f| = 1$

How can we take advantage of this?

It simplifies our $\mathcal{A}_{\mathcal{CP}}(t)$ considerably

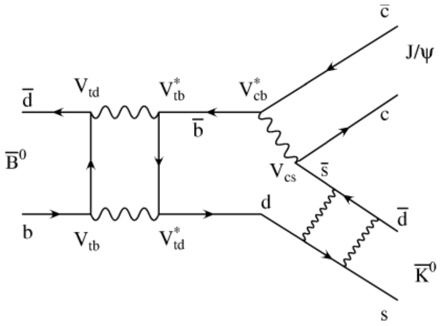
$$\mathcal{A}_{\mathcal{CP}}(t) = \frac{\left|\langle f_{CP}|H|B^0(t)\rangle\right|^2 - \left|\langle f_{CP}|H|\bar{B}^0(t)\rangle\right|^2}{\left|\langle f_{CP}|H|B^0(t)\rangle\right|^2 + \left|\langle f_{CP}|H|\bar{B}^0(t)\rangle\right|^2}$$

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

$$\boldsymbol{= -\mathrm{Im}\lambda\ \sin(\Delta M t)}$$

$\Rightarrow$ ***Now our task is to find a decay where we can exploit this nice result***

The golden mode: $B^0 \to J/\psi K_S^0$

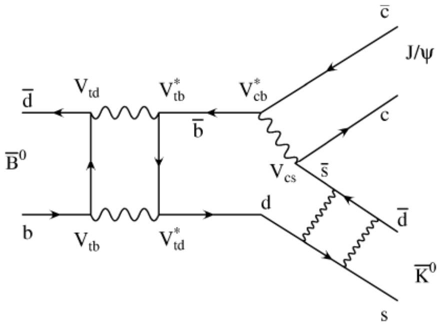


Two important criteria:

- The $J\psi K_S^0$ is a CP eigenstate accessible to **both** B^0 and $\overline{B}^0$.
- This is the only major diagram contributing to this decay, so there is only one weak phase ϕ.

$\Rightarrow$ *now lets study this diagram in detail*

The golden mode: $B^0 \to J/\psi K^0_S$



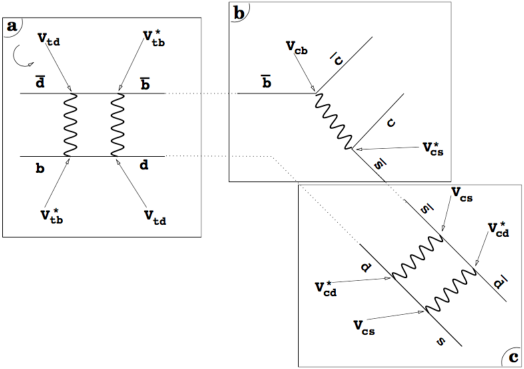
$$\lambda_{J/\psi K^0_S} = \left(\frac{q}{p}\right)_{B^0} \left(\eta_{J/\psi K^0_S} \frac{\overline{A}_{J/\psi K^0_S}}{A_{J/\psi K^0_S}}\right) = -\left(\frac{q}{p}\right)_{B^0} \left(\frac{\overline{A}_{J/\psi \bar{K}^0}}{A_{J/\psi K^0}}\right) \left(\frac{p}{q}\right)_K$$

Do you see why we need the K^0-$\overline{K}^0$ mixing?

$B^0 \to J/\psi K^0$ but $\overline{B}^0 \to J/\psi \overline{K}^0$, so the K^0's must mix in order to reach the same final state f for the B^0 and $\overline{B}^0$ decay (recall $|K_S\rangle = p|K^0\rangle + q|\overline{K}^0\rangle$) .

Do you see why the CP eigenvalue of $J/\psi K^0_S$ is -1?

The golden mode: $B^0 \to J/\psi K_S^0$



In terms of the CKM matrix elements

(a) B^0-$\overline{B}^0$ mixing:
$$\left(\frac{q}{p}\right)_{B^0} = \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}$$

(b) $b \to c$ decay
$$\left(\frac{\overline{A}}{A}\right) = \frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}}$$

(c) K^0-$\overline{K}^0$ mixing:
$$\left(\frac{p}{q}\right)_K = \frac{V_{cs} V_{cd}^*}{V_{cs}^* V_{cd}}$$

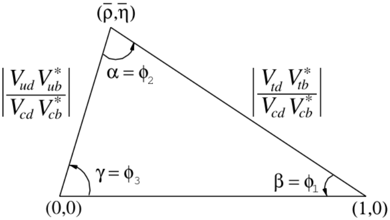
The golden mode: $B^0 \to J/\psi K_S^0$

Lets put the pieces together

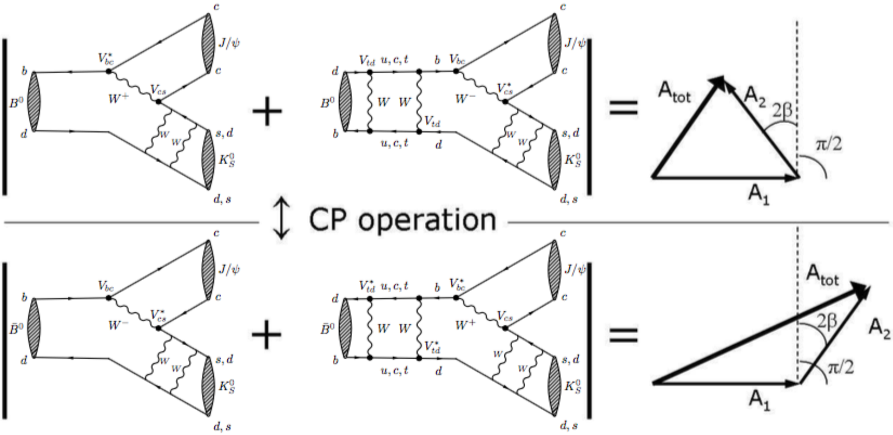
$$\lambda_{J/\psi K_S^0} = (-1)\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \cdot \frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}} \cdot \frac{V_{cs} V_{cd}^*}{V_{cs}^* V_{cd}} = (-1)\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \cdot \frac{V_{cb} V_{cd}^*}{V_{cb}^* V_{cd}}$$

$$\mathrm{Im}\lambda_{J/\psi K_S^0} = -\sin\left\{\arg\left(\frac{V_{tb}^* V_{td} V_{cb} V_{cd}^*}{V_{tb} V_{td}^* V_{cb}^* V_{cd}}\right)\right\} = -\sin\left\{2\arg\left(\frac{V_{cb} V_{cd}^*}{V_{tb} V_{td}^*}\right)\right\} \equiv \sin(2\beta)$$

$$\mathcal{A}_{\mathcal{CP}}(t) = -\sin(2\beta)\sin(\Delta M t)$$

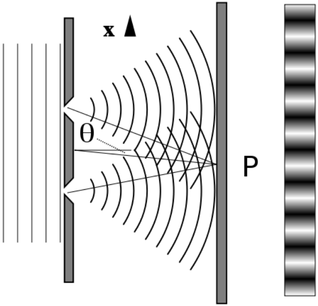


Adding two amplitudes results in a A_{tot} with a different magnitude under CP.



Recall your QM basics

The difference in decay rates arises from a different interference term for the matter vs. antimatter process. Analogy to double-slit experiment:



Classical double-slit experiment

Relative phase variation due to different path lengths leads to interference pattern in space.

B meson system $\Rightarrow$ ***Experiment***

Observing CP violation with B-mesons is much more difficult than with Kaons

- B_L and B_H have essentially the same lifetimes. No way to get a beam of B_L and look for "forbidden" decay modes.
- It is much harder to produce large quantities of B-mesons than Kaons.

$\Rightarrow$ *Kobayashi-Maskawa mechanism quantitatively predicts large CP violating asymmetries in the decays of the B meson system. Worthwhile to try to measure!*

Time evolution of $B^0\overline{B}^0$ pairs at B-factories

Production mechanism:

$$e^+e^- \to \Upsilon(4S) \to B^0\,\overline{B}^0$$

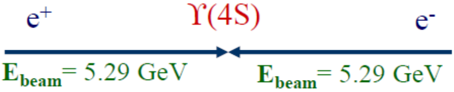
The wave function of the B meson pair in a coherent $P - wave$ state:

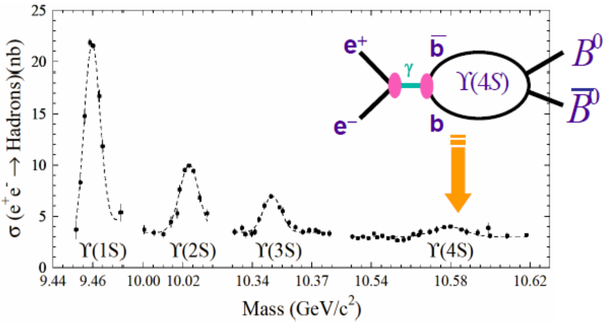
$$\Psi = \frac{1}{\sqrt{2}}\left[|B^0\rangle|\overline{B}^0\rangle - |\overline{B}^0\rangle|B^0\rangle\right]$$

- At all times one B^0 and one $\overline{B}^0$ meson, until one of them decays.
- The remaining un-decayed B meson will continue to propagate through space-time and mix until it decays.

B mesons produced in $\Upsilon(4S)$ decays

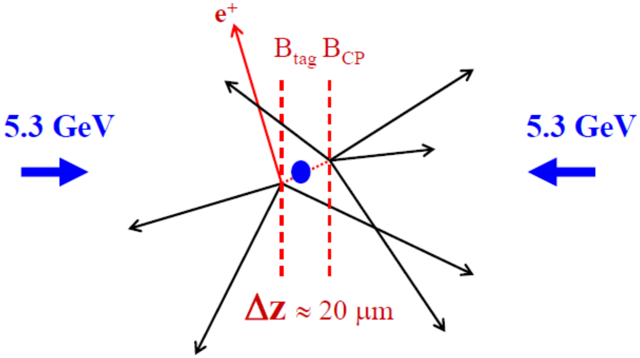
What can we say about the B-mesons produced from beams where $E(e^+) = E(e^-)$?





- Enough energy to barely produce 2 B mesons, nothing else!
- B-mesons produced with ~ 300 MeV momentum

B mesons produced in $\Upsilon(4S)$ decays



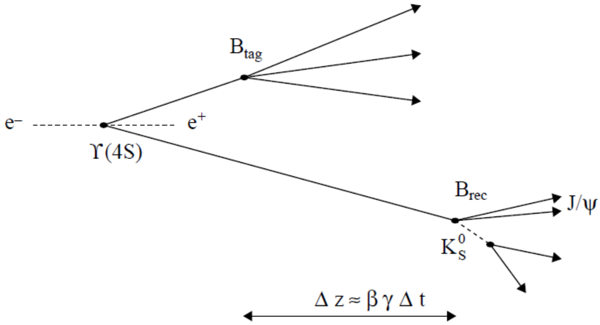
- Experimentally the decay time is measured by measuring the decay length
- Distances of a few 10 μm are too small to measure

Asymmetric energy B-factories

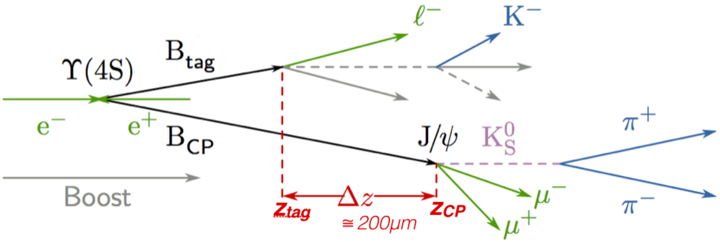
Solution:

- Boost $\Upsilon(4S)$ in laboratory frame by colliding beams of unequal energy but same CM energy

$$E_{CM}^2 = 4E_{LER}E_{HER} = m_{\Upsilon(4S)}^2$$



Asymmetric energy B-factories



- Decay of first B (as B^0) at $t_{\rm tag}$ ensures the other B is $\overline{B}^0$.

  $\Rightarrow$ *End of quantum entanglement!*
  Defines a reference time

- At $t > t_{\rm tag}$, B^0 can mix to $\overline{B}^0$ before it decays.

- Possible outcomes:

$$B^0 B^0,\ B^0\overline{B}^0, \overline{B}^0\overline{B}^0$$

Asymmetry as a function of Δt

In our derivation earlier, we simply used time t, but now it's clear we need to consider Δt, defined as $t_{CP} - t_{tag}$

Our general time-dependent asymmetry as a function of $\Delta t = t_{CP} - t_{tag}$ is:

$$\mathcal{A}_{\mathcal{CP}}(\Delta t) = \frac{f_{B_{\mathrm{tag}=\mathrm{B}^0}}(\Delta t) - f_{B_{\mathrm{tag}=\bar{\mathrm{B}}^0}}(\Delta t)}{f_{B_{\mathrm{tag}=\mathrm{B}^0}}(\Delta t) + f_{B_{\mathrm{tag}=\bar{\mathrm{B}}^0}}(\Delta t)} = \frac{1-|\lambda|^2}{1+|\lambda|^2} \cos\left(\Delta M \Delta t\right) - \frac{2Im[\lambda]}{1+|\lambda|^2} \sin\left(\Delta M \Delta t\right)$$

$\Rightarrow$ *Need to know the flavor of the* B_{tag}

Flavor tagging

B^0 or $\overline{B}^0$ flavor identified from the decay products.

Several different categories of tagging, e.g.,

1. Lepton tag
2. Kaon tag
3. Pion tag
4. Lambda tag

   ...

Lepton tag

Primary leptons originate directly from B mesons in semileptonic decays. These modes are due to leading order weak interaction mediated by a charged $W^{\pm}$ boson. The charge of

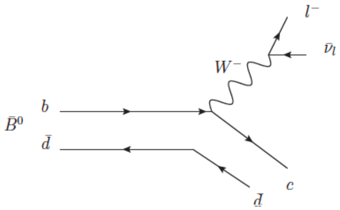


FIG. 3: Production process for direct leptons.

direct leptons is associated with the flavor of its mother particle (Fig. 3). In a $b \to cl^-\bar{\nu}_l$ semileptonic decay a positively (negatively) charged lepton indicates a B^0 ($\bar{B}^0$) decay

$$\bar{B}^0 \to Xl^-\bar{\nu}_l, \tag{3}$$

where X indicates another hadronic particle.

Secondary leptons descend from semileptonic decaying D mesons via $b \to c \to s$ transitions. In this cascade decay the charge of the lepton corresponding to the B meson is reversed: a negatively (positively) charged lepton indicates a B^0 ($\bar{B}^0$)

$$\bar{B}^0 \to DX \to X'l^+\nu_l. \tag{4}$$

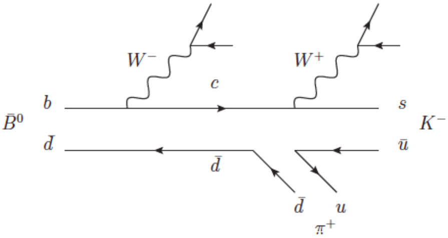
Kaon tag

3. Kaons

Kaons give the most powerful flavor identification and also have a high occurrence in B^0 decays. They mainly originate from $b \to c \to s$ cascade decays

$$\begin{aligned} \bar{B}^0 \to & DX \\ & \to K^- X'. \end{aligned} \tag{7}$$

A positively (negatively) charged kaon indicates a B^0 ($\bar{B}^0$), as illustrated in Fig. 7. Since the mother of the kaon is unclear, it can also originate from charm decay or $s\bar{s}$ quark pair popping out of the vacuum, therefore combining the total charge is important. Emerging K_S^0 can indicate a kaon from $s\bar{s}$ quark pair popping. In addition to kinematic variables like p_{cms} and θ_{lab}, the charge and PID can help to identify candidates.



Pion tag

Pions are the most common final state particles. Slow pions originate from a $D^{*\pm}$ decay, where a negatively (positively) charged pion indicates a B^0 ($\bar{B}^0$)

$$\begin{aligned} \bar{B}^0 \to & D^{*+} X \\ & \to D^0 \pi^+. \end{aligned} \tag{5}$$

Because of the low mass difference between the D^{*+} and the D^0, slow pions are produced nearly at rest in the D^{*+} frame. The pion moves nearly in the same direction as the D^0 in the B_{tag} frame. On the contrary, pions coming from the hadronization of a W boson have

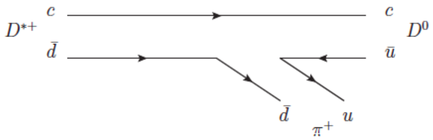


FIG. 5: Production process for slow pions.

a higher momentum, e.g., in the decay

$$\bar{B}^0 \to D^{*+} \pi^- X. \tag{6}$$

Lambda tag

4. Lambdas

Lambdas are not directly measured as final state particles but have to be reconstructed from protons and pions. They can arise through a $b \to c \to s$ cascade decay, such as

$$\begin{aligned} \bar{B}^0 \to & \bar{\Lambda}_c^+ X \\ & \to \bar{\Lambda}_0 X'. \end{aligned} \tag{8}$$

Despite their very low occurrence in B meson events, they are valuable for flavor determination. A lambda (anti-lambda) indicates a B^0 (B^0). The quality of a lambda candidate depends on a correct reconstruction, therefore the quality of the lambda vertex is of interest. The angle between the lambda momentum, its vertex and the interaction point θ_Λ can also give information about a good candidate, as well as its mass M_Λ.

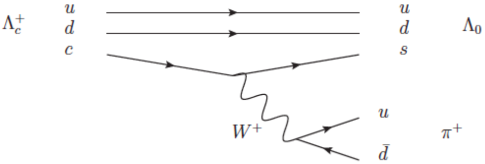
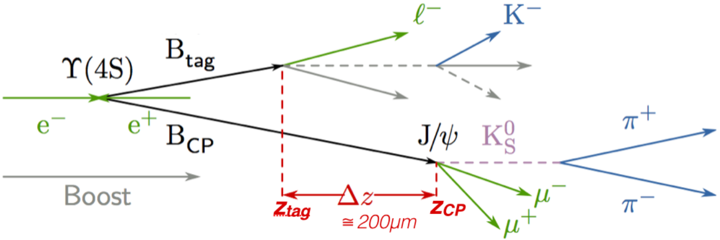


FIG. 8: Production process for lambdas.

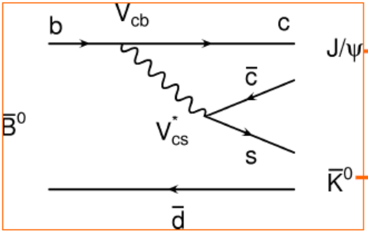
B-meson reconstruction

How do we build our B-mesons?



⇒ *Work backwards from the final-state particles, which we can identify in our detector*

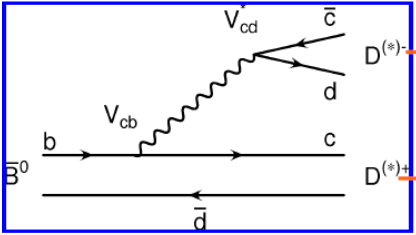
Start with the final-state particles (e, μ, π, K, γ)



$\mu^+\mu^-$ or e^+e^-

$\pi^+\pi^-$ displaced vertex (cτ=2.7cm)

⇒ Work Backwards



$D^{*+} \to D^0\pi^+$

↘ $K^-\pi^+$

$D^{*-} \to D^-\pi^0$

↘ ↘ $\gamma\gamma$

$K^+\pi^-\pi^-$

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Use energy-momentum to build the intermediate states

- Reconstruct J/ψ (first measurement @Belle with $5.5\mathrm{fb}^{-1}$)

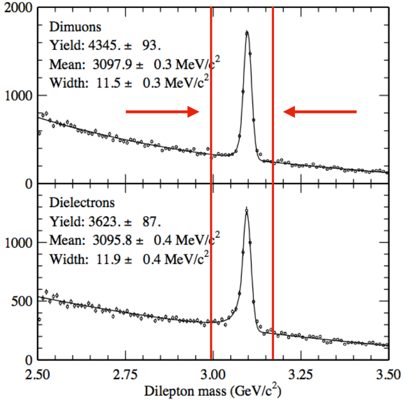


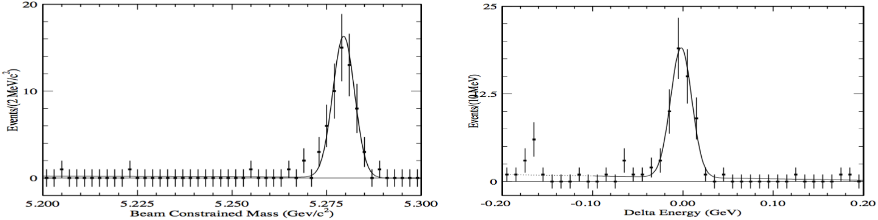
Figure 2: The J/ψ invariant mass distributions for the 5.5 fb^{-1} inclusive J/ψ data.

Make "cuts" (vertical lines) to remove obvious background-dominated regions

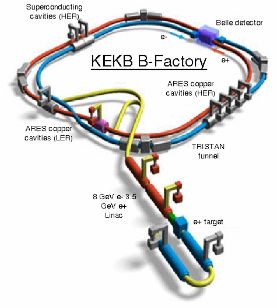
Finally arrive at your B mesons

Main variables:

- Energy difference: $\Delta E = E^*_B - E^*_{\text{beam}}$
- Beam constrained mass: $M_{bc} = \sqrt{(E^*_{\text{beam}})^2 + (p^*_B)^2}$

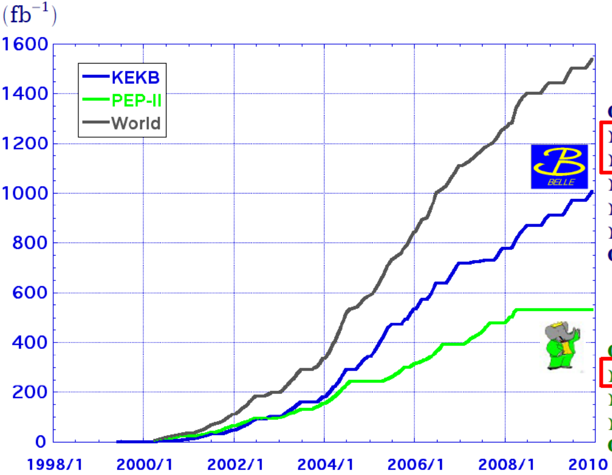


Belle Experiment @ KEKB accelerator



- Asymmetric energy collider: $e^{+}(3.5\text{GeV}) \rightarrow\leftarrow e^{-}(8\text{GeV})$
- Energy released in collisions: $\sqrt{s} = 10.58$ GeV $\approx M_{\Upsilon(4S)}$

Total datasets from Belle and BaBar (B-factory at SLAC)



> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 24 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

$\sim$ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

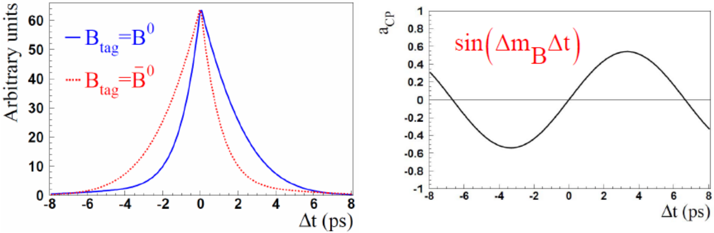
Off resonance:

$\sim$ 54 fb^{-1}

$\sim$770 M$B\overline{B}$ for Belle, $\sim$ 470 M$B\overline{B}$ for BaBar

$\sim$14M B_s also! ($\Upsilon(5S)$ runs)

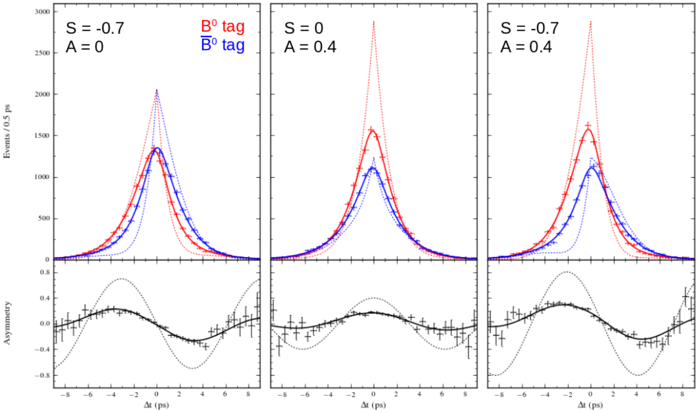
For the case of $B^0 \to J/\psi\, K_S^0$, where $A_f = 0$



$$\mathcal{A}_{\mathcal{CP}}(\Delta t) = \frac{2\mathrm{Im}\lambda}{1+|\lambda|^2}\sin\left(\Delta M \Delta t\right)$$

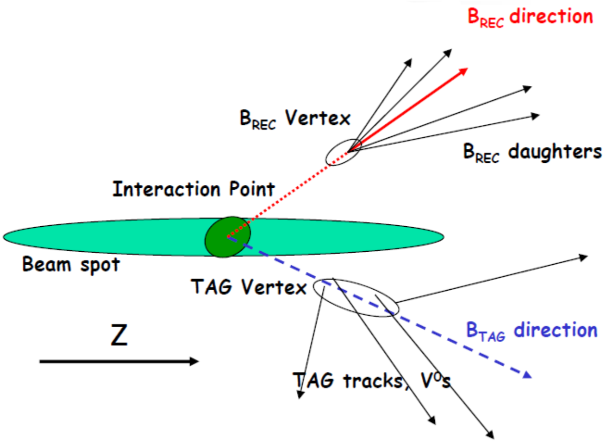
Perfect detector vs. reality

See the effect of different values of A_f and S_f:

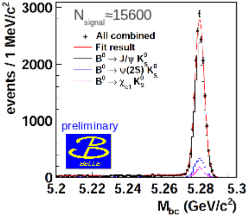


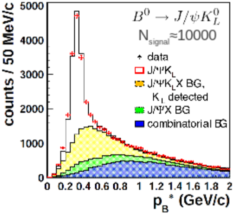
⇒ Need to take into account mis-tagging and Δt resolution, which smear the Δt distribution

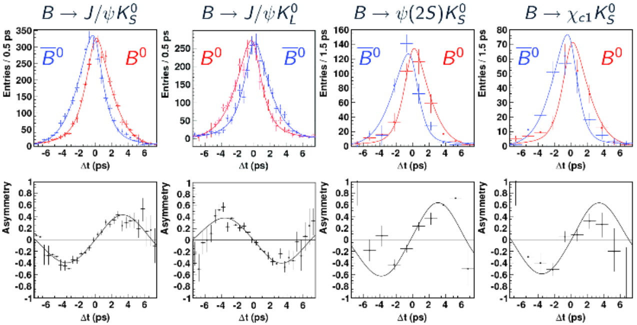
Vertex and Δt reconstruction



CP violation in $B^0 \to J/\psi K^0_S, J/\psi K^0_L, \psi(2S)K^0_S, \chi K^0_S$







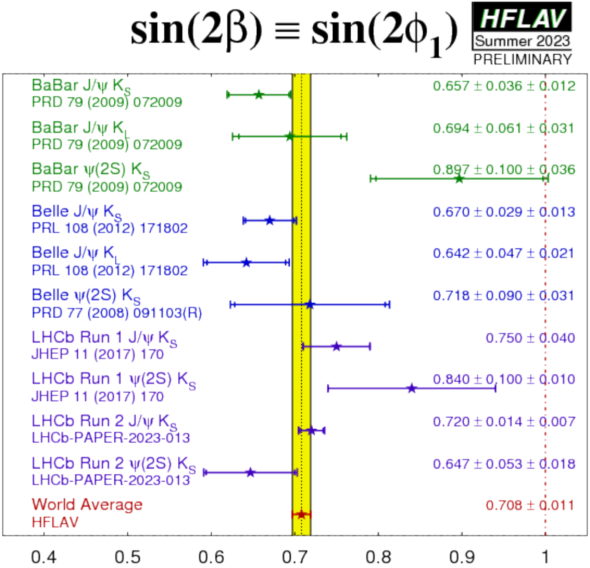
Belle with 772×10⁶ BB:

$$\mathcal{A} = 0.007 \pm 0.016\,(\text{stat}) \pm 0.013\,(\text{syst})$$

$$\sin(2\phi_1) = 0.668 \pm 0.023 \qquad \pm 0.013$$

preliminary

Combination of results



To summarize:

To measure CP violation at the $\Upsilon(4\mathrm{S})$ using the interference between mixing and decay, one must:

1. Determine the flavor of one of the neutral B mesons directly from its decay products (e.g., from semileptonic decays).
2. Reconstruct the other B meson in a state that both B^0 and $\overline{B}^0$ can decay into.
3. Measure the time difference, $\Delta t = t_1 - t_2$, between the decays. Requires precise vertexing information to measure Δz.

Extra reading

- Richman, Jeremy D. (UCSB), *Heavy Quark Phyiscs and CP Violation*.
  http://physics.ucsd.edu/students/courses/winter2010/physics222/references/driver_houches12.pdf
  Pages 199-220.

- Kooijman, P. & Tuning, N., *CP Violation*,
  http://master.particles.nl/LectureNotes/2011-CP.pdf
  Pages 38-46.