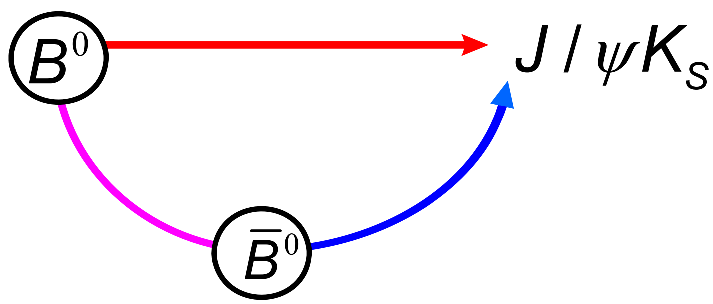
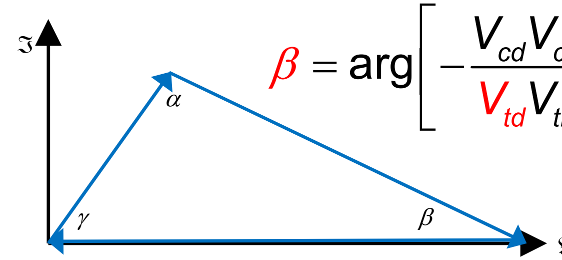
Measurement of the CKM phase β in $B^0 \to J/\psi K_s$

The decay $B^0 \to J/\psi K_s$ allows an interference between the decay with and without mixing:





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

With the master equation one obtains for small $\Delta\Gamma\approx 0$ and negligible (no) direct CPV (i.e. $|\bar{A}_f| = |A_f|$) and no CPV in mixing (q/p=1):

$$C_f = 0 \qquad S_f = \frac{2\Im\lambda_f}{1+|\lambda_f|^2}$$

$$A_{CP}(t) = \frac{\Gamma\left(B^0 \to J/\psi K_S\right)(t) - \Gamma\left(\bar{B}^0 \to J/\psi K_S\right)(t)}{\Gamma\left(B^0 \to J/\psi K_S\right)(t) + \Gamma\left(\bar{B}^0 \to J/\psi K_S\right)(t)} = -\Im\lambda_f \sin\left(\Delta m t\right)$$

For the final-state $f=f_{CP}= B^0 \to J/\psi K_s$ with CP $|f_{CP}\rangle = \eta_{CP}|f_{CP}\rangle$ and $\eta_{CP} = \pm 1$ one obtains for λ_f

$$\lambda_f \equiv \frac{q}{p}\cdot\frac{\bar{\mathcal{A}}_{f_{CP}}}{\mathcal{A}_{f_{CP}}} = \frac{q}{p}\cdot\eta_{CP}\frac{\bar{\mathcal{A}}_{\bar{f}_{CP}}}{\mathcal{A}_{f_{CP}}}$$

where we replaced $\bar{\mathcal{A}}_{f_{CP}}$ by $\eta_{CP}\bar{\mathcal{A}}_{\bar{f}_{CP}}$

$\mathcal{A}_{f_{CP}}$ and $\bar{\mathcal{A}}_{\bar{f}_{CP}}$ are related by CP-conjugation, i.e. they differ only in the

Sign of the weak phase: $\bar{\mathcal{A}}_{\bar{f}_{CP}}$ can be derived from $\mathcal{A}_{f_{CP}}$ by inverting the CKM (weak) phase.

For the final-state $J/\psi K_s$ one finds $\eta_{CP} = -1$.
Moreover for this final-state one needs to consider the following amplitudes:

$$\mathcal{A}\left(B^0 \to J/\psi K_S\right) = \mathcal{A}\left(B^0 \to J/\psi K^0\right) \cdot \mathcal{A}\left(K^0 \leftrightarrow K_S\right)$$

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

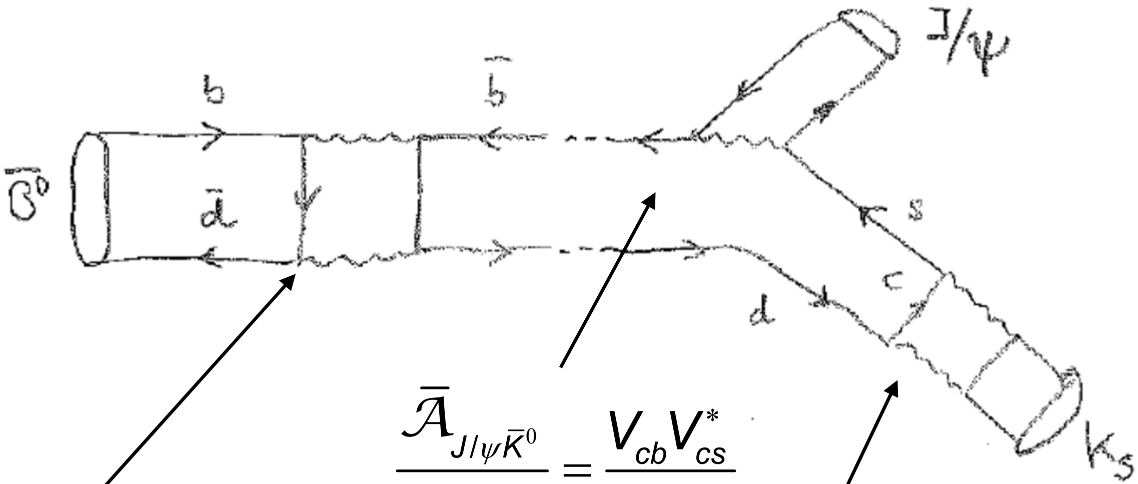
Reminder:

$$\left|K_S\right\rangle = p\left|K^0\right\rangle + q\left|\bar{K}^0\right\rangle$$

Considering the K^0 mixing one obtains:

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

The respective Feynman-diagram is:



$$\frac{\bar{\mathcal{A}}_{J/\psi \bar{K}^0}}{\mathcal{A}_{J/\psi K^0}} = \frac{V_{cb}V_{cs}^*}{V_{cs}^*V_{cs}}$$

B oscillation: $\Delta m \approx 2|M_{12}|$

$$\left(\frac{q}{p}\right)_{B^0} = \sqrt{\frac{M_{12}^*}{M_{12}}} = \frac{V_{td}V_{tb}^*}{V_{td}^*V_{tb}} = e^{-i2\beta}$$

Pure phase assuming |q/p|=1 (no CPV in mixing)

for B^0: $\Gamma_{12} \approx 0$

K^0 oscillation:

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

real in leading order

<u>Remark:</u>
Non trivial phase of λ_f is result of only B^0 mixing. Contribution from V_{td}

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

Putting everything together one obtains:

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

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

$$= +\sin(2\beta)$$

$$A_{CP}(t) = -\Im\left(\lambda_{J/\psi K_s}\right) = -\sin(2\beta)\sin(\Delta m t)$$

i.e. the observation of time-dependent A_{CP} → amplitude is a measure of CKM phase β (mixing phase)

The first measurements of the CKM angle β was performed by the BABAR and Belle collaborations in 2001 at the high-luminosity e^+e^- B—factories:

$e^+\underline{e}^-$ B—factories were operated at the center-of-mass energy of the Υ(4S) ($b\bar{b}$) resonance ($\sqrt{s}$=10.56 GeV) which decay nearly entirely to B^+B^- and B^0B^0:

$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B} \quad (\sqrt{s} = 10.58\,\text{GeV} \approx 2m_B)$$

The measurement of sin(2β) was the first observation of CP violation outside the Kaon system $\rightarrow$ predicted by the Standard Model

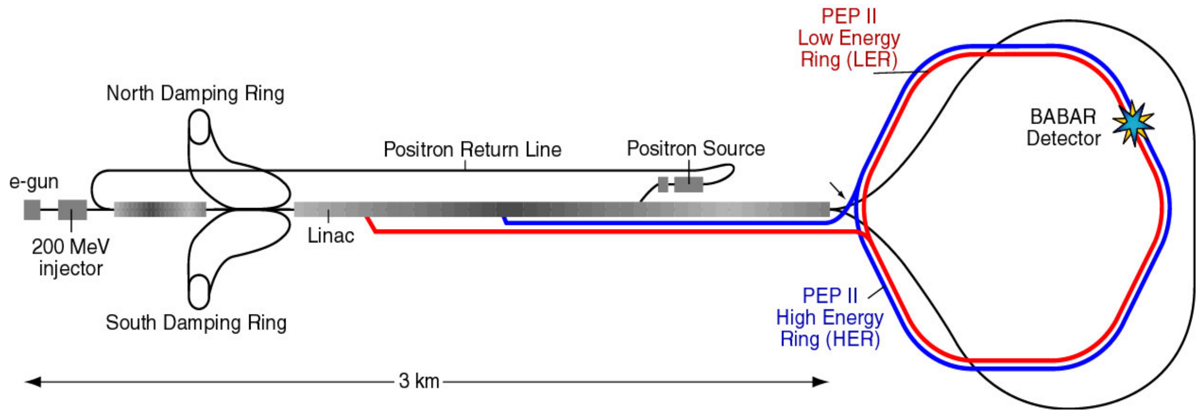
<u>Experimental problems:</u>

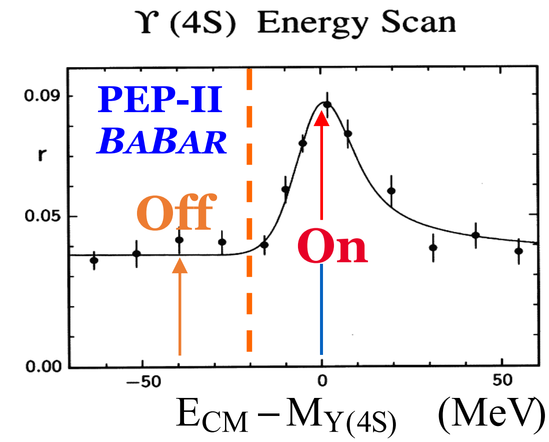
- In the Υ(4S) the BB-system has very small kinetic energy $\rightarrow$ γ-factor is very small $\rightarrow \gamma c\tau$ is very small: B's don't fly but decay at rest $\rightarrow$ can't perform t-dependent measurement (flight-length is usually used as measure of the decay-time).

$\rightarrow$ Idea: produce the Υ(4S) with a small boost by building an asymmetric storage ring

- Flavor-Tagging: Determine the flavor of signal-B at time of production.
  Idea: use the second B!

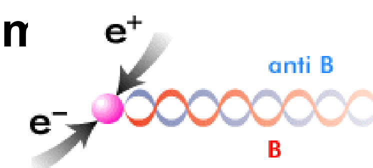
PEP-II B-factory and BABAR Experiment (Y(4S)→$B\bar{B}$)





	Design	Reached
E [GeV] e^- / e^+	9.0 / 3.1	✓
L [cm^{-2} s^{-1}]	3 x 10^{33}	6.58 x 10^{33}
L_{int} [pb^{-1}/day]	135	391

Coherent B^0 $\bar{B}^0$ system



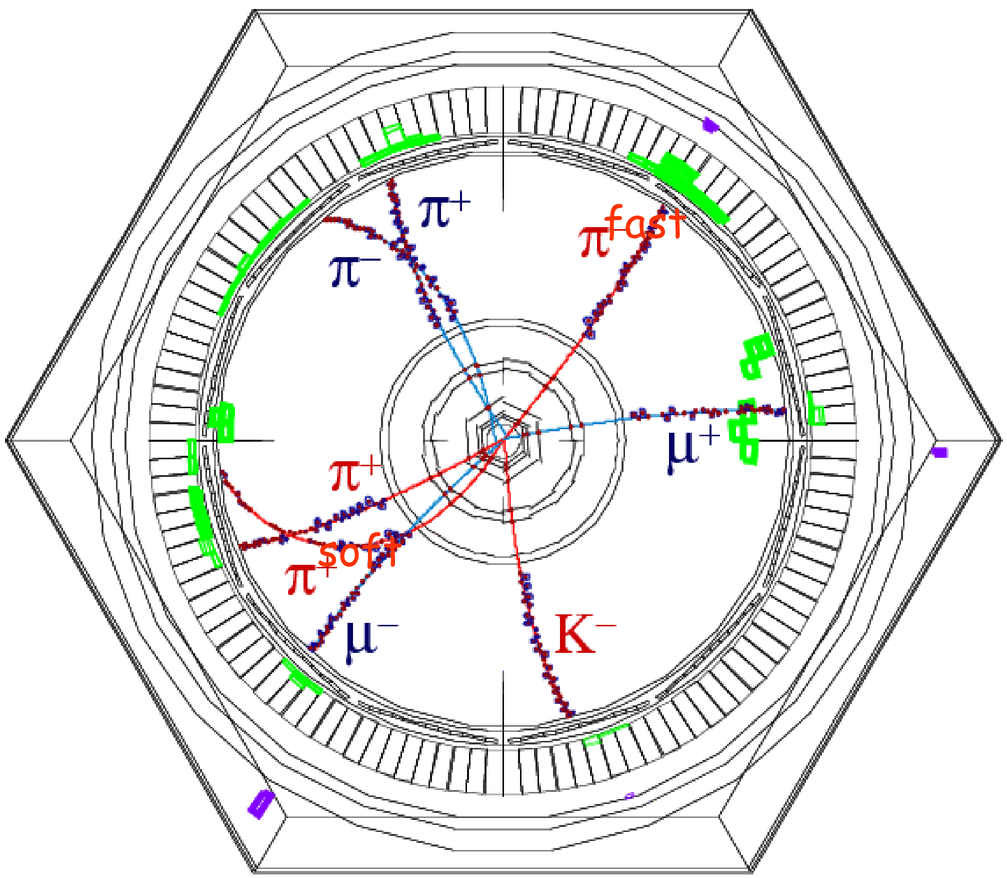
- 2 bosons ⇒ symmetric wavefunction

$$\Psi = \Psi_{Flavour} \cdot \Psi_{space}$$

- L=1: $\Psi_{space} \propto (-1)^L \rightarrow$ antisymmetric
- → $\Psi_{Flavour}$ antisymmetric

$$\Psi_{Flavour} = \frac{1}{\sqrt{2}}(B^0\overline{B^0} - \overline{B^0}B^0)$$

Example of a fully reconstructed $B^0 \to J/\psi K_s$ event



$\bar{B}^0 \to D^{*+}\ \pi^-_{fast}$

$\quad \hookrightarrow D^0 \pi^+_{soft}$

$\qquad \hookrightarrow K^-\pi^+$

EPR!

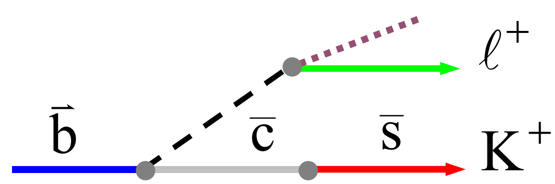
$B^0(\Delta t)$

$\hookrightarrow J/\psi \quad K_s$

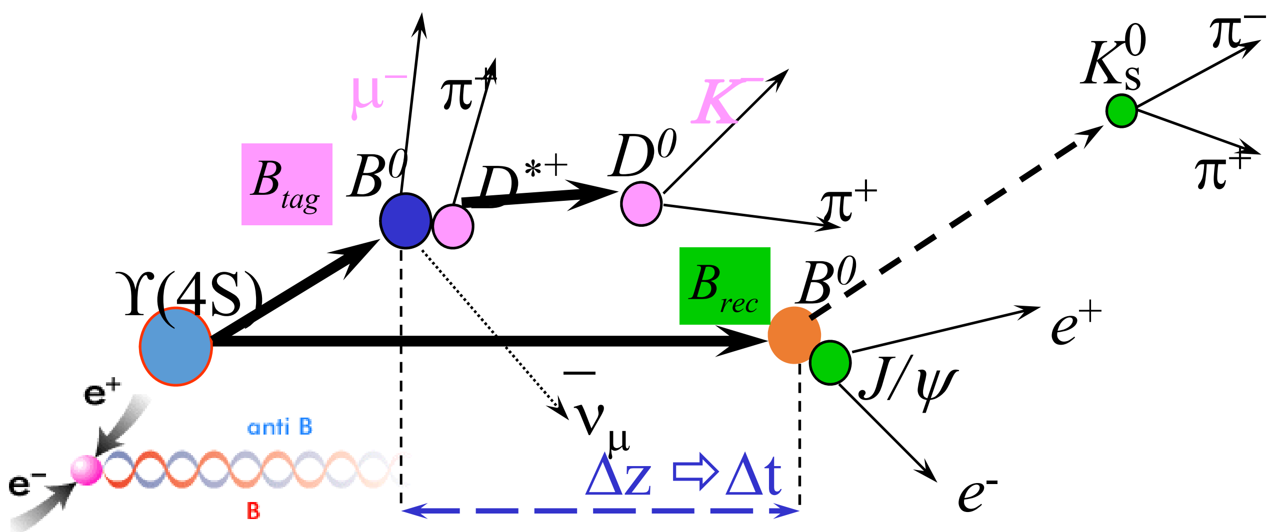
$\quad \hookrightarrow \mu^+\mu^- \hookrightarrow \pi^+\pi^-$

In general, use charges of identified
- leptons,
- kaons,
- soft pions

from the "the rest of the event" to tag B flavour

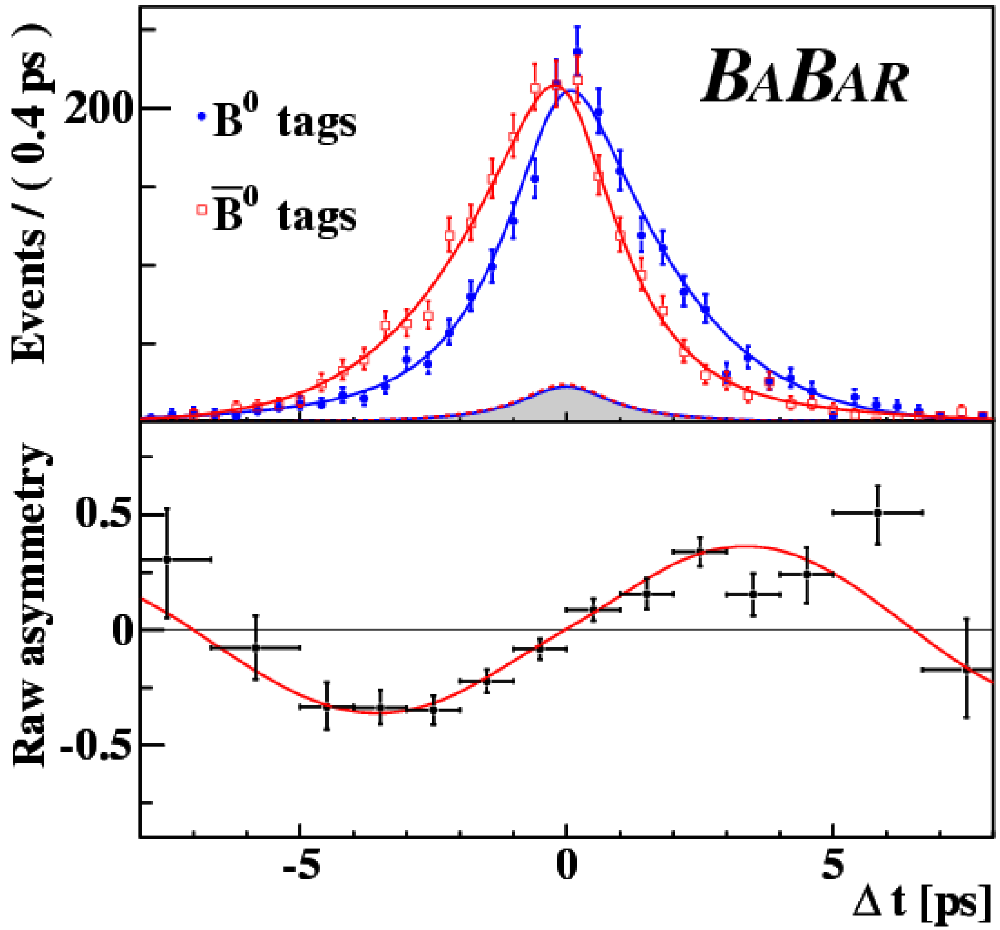


Event configuration:



The variable Δt for the coherent state allows for negative values (tagging B decays after the signal B)

$(c\bar{c})\ K_S$ (CP odd) modes



BABAR:

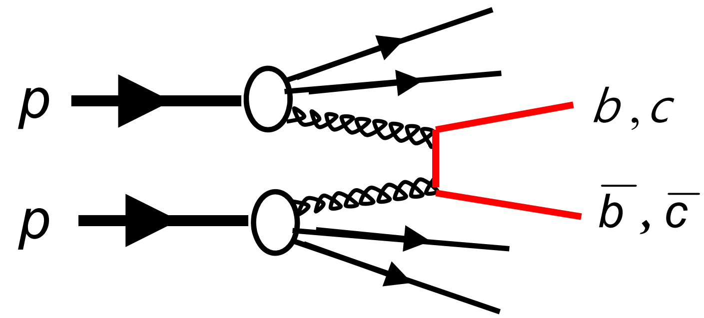
$\sin(2\beta) = 0.687 \pm 0.028 \pm 0.012$

Measurement at LHCb

Flavor-tagging w/ 2nd b-hadron in the event:

- b and anti-b-quarks are always produced in pairs. Use flavor specific decays

$$b \rightarrow c + \ell^-$$
$$\bar{b} \rightarrow \bar{c} + \ell^+$$
$$B_{tag} \rightarrow D + \ell\,\nu$$

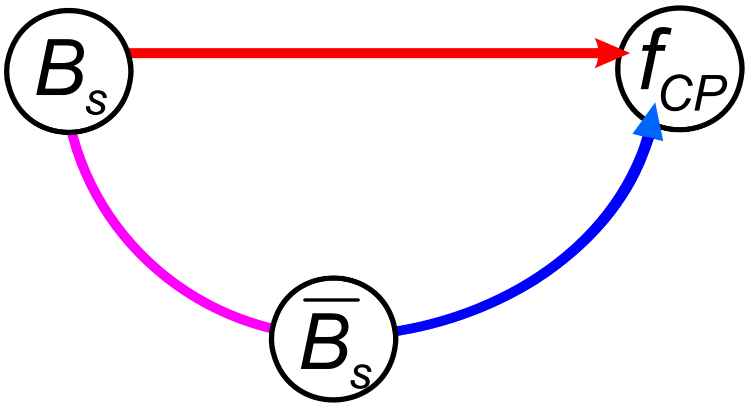


- Hadronization allows the production of two different b-hadrons. No coherence! (large mistag fraction)

sin (2β) = 0.76 ± 0.034

Measurement of the CKM phase β_s

Reminder: β_s is the phase of V_{ts} (very small)



$$f_{CP} = J/\psi\ \phi$$

$$\phi = |s\bar{s}\rangle$$

Probes again the "mixing phase". Here:

$\arg(V_{ts})$

(in SM only at $O(\lambda^5) \neq 0$)

Differences w/r to $B^0 \to J/\psi\ K_S$

1.) $$\left(\frac{q}{p}\right)_{B_s^0} = \frac{V_{ts}V_{tb}^*}{V_{ts}^*V_{tb}} \approx e^{-i2\beta_s} \quad \Longrightarrow \quad \Im\left(\lambda_{J/\psi\phi}\right) = +\sin\left(-2\beta_s\right)$$

($2\beta_s$ is very small (0.04) $\to$ very small CPV)

2.) ϕ is not oscillating like the K^0

3.) $\Delta\Gamma \neq 0$: A_{CP} (t) is described by the more complicated Master formula

$$A_{CP}(t) = \frac{-\Im\left(\lambda_{J/\psi\phi}\right)\sin\left(\Delta m_s t\right)}{\cosh\left(\frac{1}{2}\Delta\Gamma_s t\right) + \Re\left(\lambda_{J/\psi\phi}\right)\sinh\left(\frac{1}{2}\Delta\Gamma_s t\right)}$$

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 mesons (Spin = 1)

$$\begin{array}{ccccc} B_s & \rightarrow & J/\psi & + & \phi \\ J^{PC} = 0^{--} & & J^{PC} = 1^{--} & & J^{PC} = 1^{--} \end{array}$$

Relative angular momentum L=0,1,2,

$$\eta_{CP} = \underset{+1}{\eta_{CP}(J/\psi)} \cdot \underset{+1}{\eta_{CP}(\phi)} \cdot (-1)^L$$

L=1: CP-odd
L=0.2: CP-even

Requires an angular analysis to separate the CP even from the CP odd states.

Simultaneous measurement of $\Delta\Gamma$ and $\phi_s = -2\beta_s$

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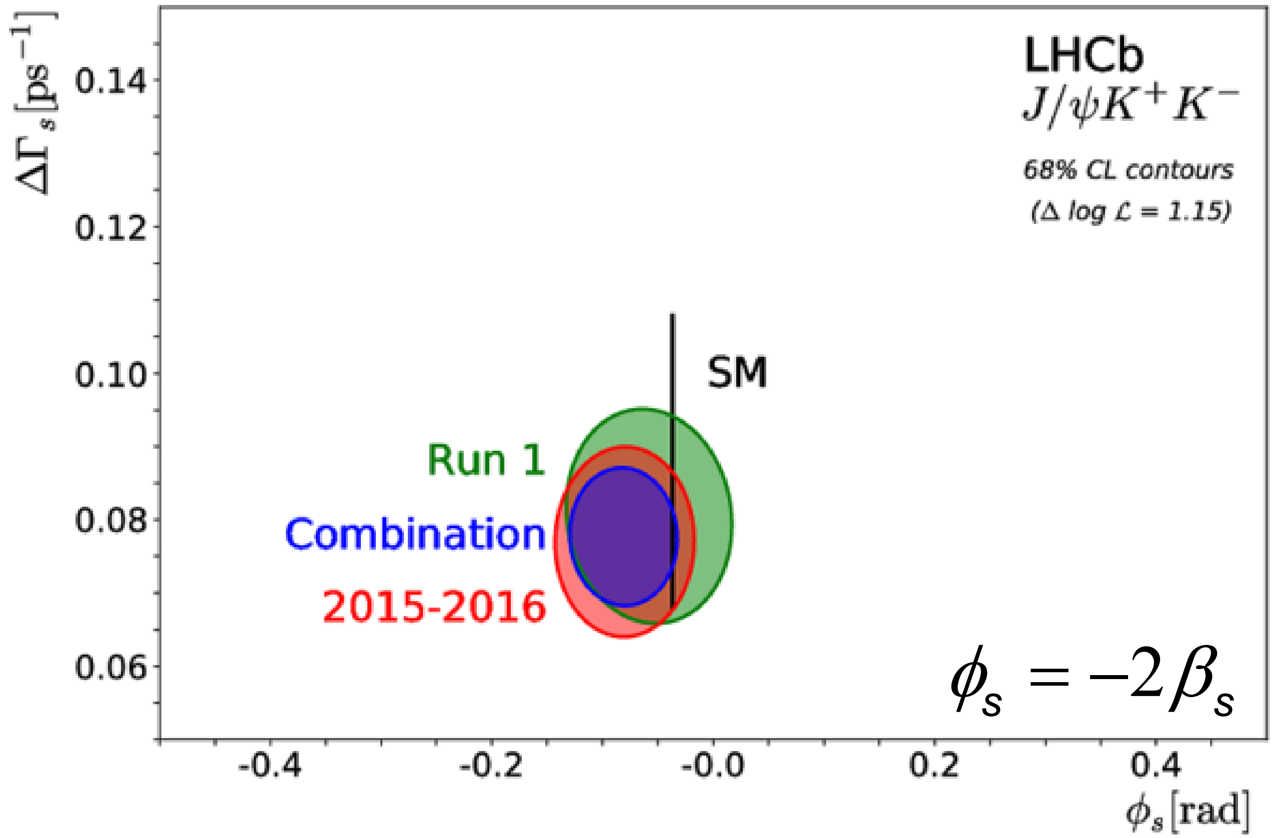
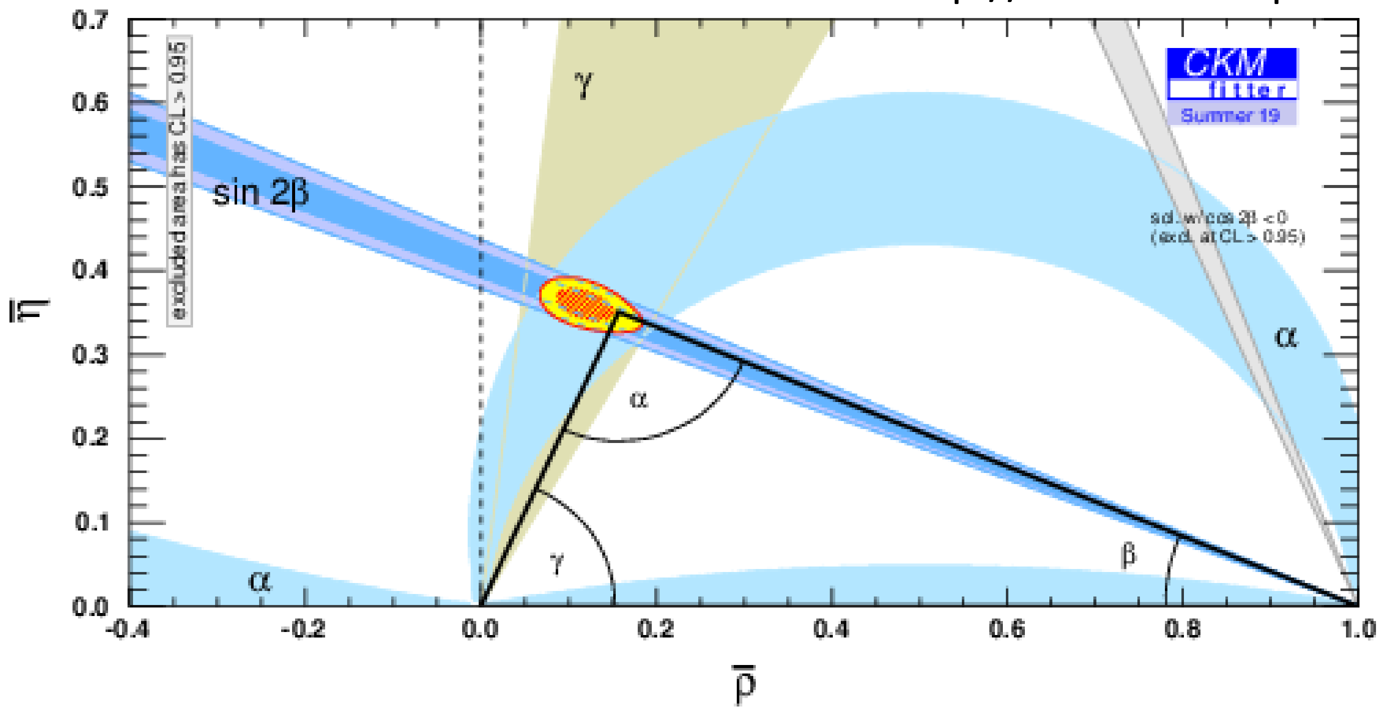


Similarly to the β determination in $B^0 \rightarrow J/\psi K_s$ the determination of the weak phase has very little uncertainty: Using the β-measurement $\rightarrow$ predict $\phi_s = -2\beta_s$ with an excellent precision.

Status of CKM angles

Unitarity triangle can be checked with only measurements of angles (CPV):

http://ckmfitter.in2p3.fr



and compared to the determination of unitarity triangle using all information: