Detecting CP violation with B decays

Lecture 3: B decays

N. Tuning

Detecting CP violation with B decays

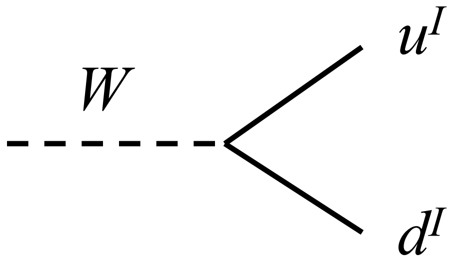
1) CP violation: CKM and the SM
2) Detecting: Detector requirements
3) B-decays: sin2β, ϕ_s, $B_s^0 \rightarrow D_s^+ K^-$

Recap

$$L_{SM} = L_{Kinetic} + L_{Higgs} + L_{Yukawa}$$

$$-L_{Yuk} = Y_{ij}^{d}\,(\overline{u_L^I}, \overline{d_L^I})_i \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} d_{Rj}^{I} + \ldots$$

$$L_{Kinetic} = \frac{g}{\sqrt{2}} \overline{u_{Li}^I} \gamma^\mu W_\mu^- d_{Li}^I + \frac{g}{\sqrt{2}} \overline{d_{Li}^I} \gamma^\mu W_\mu^+ u_{Li}^I + \ldots$$



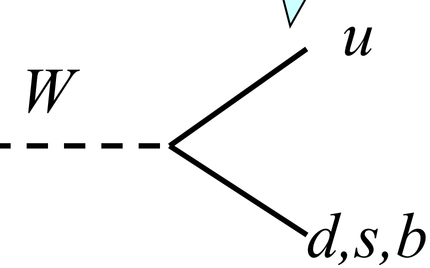
Diagonalize Yukawa matrix Y_{ij}

- Mass terms
- Quarks rotate
- Off diagonal terms in charged current couplings

$$\begin{pmatrix} d^I \\ s^I \\ b^I \end{pmatrix} \to V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$-L_{Mass} = (\bar{d}, \bar{s}, \bar{b})_L \cdot \begin{pmatrix} m_d & & \\ & m_s & \\ & & m_b \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}_R + (\bar{u}, \bar{c}, \bar{t})_L \cdot \begin{pmatrix} m_u & & \\ & m_c & \\ & & m_t \end{pmatrix} \cdot \begin{pmatrix} u \\ c \\ t \end{pmatrix}_R + \ldots$$

$$L_{CKM} = \frac{g}{\sqrt{2}} \overline{u_i} \gamma^\mu W_\mu^- V_{ij} \left(1-\gamma^5\right) d_j + \frac{g}{\sqrt{2}} \overline{d_j} \gamma^\mu W_\mu^+ V_{ij}^* \left(1-\gamma^5\right) u_i + \ldots$$



$$L_{SM} = L_{CKM} + L_{Higgs} + L_{Mass}$$

Charged Currents

The charged current term reads:

$$L_{CC} = \frac{g}{\sqrt{2}} \overline{u^I_{Li}} \gamma^\mu W^-_\mu d^I_{Li} \quad + \quad \frac{g}{\sqrt{2}} \overline{d^I_{Li}} \gamma^\mu W^+_\mu u^I_{Li} \quad = \quad J^{\mu-}_{CC} W^-_\mu + J^{\mu+}_{CC} W^+_\mu$$

$$= \frac{g}{\sqrt{2}} \overline{u_i} \left(\frac{1-\gamma^5}{2} \right) \gamma^\mu W^-_\mu V_{ij} \left(\frac{1-\gamma^5}{2} \right) d_j \quad + \quad \frac{g}{\sqrt{2}} \overline{d_j} \left(\frac{1-\gamma^5}{2} \right) \gamma^\mu W^+_\mu V^\dagger_{ji} \left(\frac{1-\gamma^5}{2} \right) u_i$$

$$= \frac{g}{\sqrt{2}} \overline{u_i} \gamma^\mu W^-_\mu V_{ij} \left(1-\gamma^5\right) d_j \quad + \quad \frac{g}{\sqrt{2}} \overline{d_j} \gamma^\mu W^+_\mu V^*_{ij} \left(1-\gamma^5\right) u_i$$

Under the CP operator this gives: (Together with (x,t) -> (-x,t))

$$L_{CC} \xrightarrow{CP} \frac{g}{\sqrt{2}} \overline{d_j} \gamma^\mu W^+_\mu V_{ij} \left(1-\gamma^5\right) u_i \quad + \quad \frac{g}{\sqrt{2}} \overline{u_i} \gamma^\mu W^i_\mu V^*_{ij} \left(1-\gamma^5\right) d_j$$

A comparison shows that CP is conserved only if $V_{ij} = V_{ij}^*$

In general the charged current term is CP violating

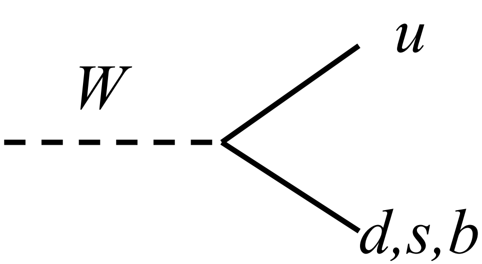
CKM-matrix: where are the phases?

- Possibility 1: simply 3 'rotations', and put phase on smallest:

$$V_{CKM} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} =$$

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}$$

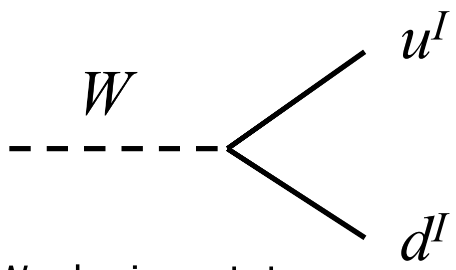
- Possibility 2: parameterize according to magnitude, in O(λ):



$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

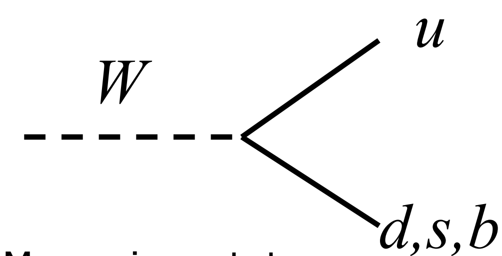
(CKM: a quick reminder)

- 1) Matrix to transform weak- and mass-eigenstates:



Weak eigenstates

$$\begin{bmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{bmatrix}.$$



Mass eigenstates

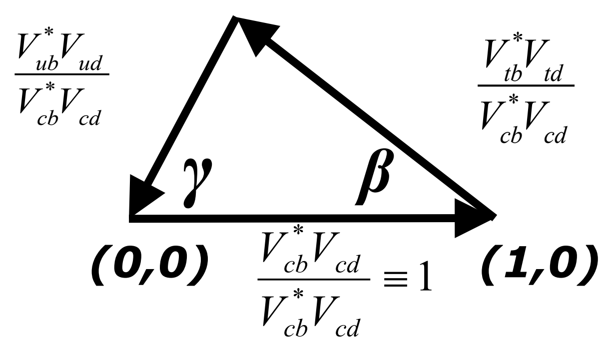
- 2) Matrix has imaginary numbers:

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

- 3) Matrix is unitary*:*

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

$$V^*_{ub}V_{ud} + V^*_{cb}V_{cd} + V^*_{tb}V_{td} = 0$$



Summary

- p, q: $|B_H\rangle = p|B^0\rangle + q|\overline{B}^0\rangle$

  $|B_L\rangle = p|B^0\rangle - q|\overline{B}^0\rangle$

- Δm, ΔΓ: $\Delta m = 2\Re\sqrt{\left(M_{12}-\frac{i}{2}\Gamma_{12}\right)\left(M_{12}^*-\frac{i}{2}\Gamma_{12}^*\right)}$

  $\Delta\Gamma = 4\Im\sqrt{\left(M_{12}-\frac{i}{2}\Gamma_{12}\right)\left(M_{12}^*-\frac{i}{2}\Gamma_{12}^*\right)}$

q,p,M_{ij},Γ_{ij} related through:

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

- x,y: mixing often quoted in *scaled* parameters: $x = \frac{\Delta m}{\Gamma}$ $y = \frac{\Delta\Gamma}{2\Gamma}$ $\cos(\Delta m t) = \cos\left(\frac{\Delta m}{\Gamma}\frac{t}{\tau}\right) = \cos\left(x\frac{t}{\tau}\right)$

Time dependence (if ΔΓ~0, like for B^0):

$$|B^0(t)\rangle = g_+(t)|B^0\rangle + \frac{q}{p}g_-(t)|\overline{B^0}\rangle$$

$$|\overline{B^0}(t)\rangle = g_+(t)|\overline{B^0}\rangle + \frac{p}{q}g_-(t)|B^0\rangle$$

with

$$g_+(t) = e^{-imt}e^{-\Gamma t/2}\cos\frac{\Delta m t}{2}$$

$$g_-(t) = e^{-imt}e^{-\Gamma t/2}\, i\sin\frac{\Delta m t}{2}$$

Meson Decays

- Formalism of meson *oscillations*:

$$\left|P^0(t)\right\rangle = \frac{1}{2}\left(e^{-im_H t-\frac{1}{2}\Gamma_H t} + e^{-im_L t-\frac{1}{2}\Gamma_L t}\right)|P^0\rangle + \frac{q}{2p}\left(e^{-im_H t-\frac{1}{2}\Gamma_H t} - e^{-im_L t-\frac{1}{2}\Gamma_L t}\right)|\bar{P}^0\rangle$$

$$|\langle \bar{P}^0(t)|P^0\rangle|^2 = |g_-(t)|^2 \left(\frac{p}{q}\right)^2$$

$$|g_\pm(t)|^2 = \frac{e^{-\Gamma t}}{2}\left(\cosh\frac{1}{2}\Delta\Gamma t \pm \cos\Delta m t\right)$$

- Subsequent: *decay*

$$P^0 \longrightarrow f$$

Notation: Define A_f and λ_f

$$P^0 \longrightarrow f$$

$$\begin{aligned} A(f) &= \langle f|T|P^0\rangle & \bar{A}(f) &= \langle f|T|\bar{P}^0\rangle \\ A(\bar{f}) &= \langle \bar{f}|T|P^0\rangle & \bar{A}(\bar{f}) &= \langle \bar{f}|T|\bar{P}^0\rangle \end{aligned}$$

and define the complex parameter λ_f (not be confused with the Wolfenstein parameter λ !):

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}, \qquad \bar{\lambda}_f = \frac{1}{\lambda_f}, \qquad \lambda_{\bar{f}} = \frac{q}{p}\frac{\bar{A}_{\bar{f}}}{A_{\bar{f}}}, \qquad \bar{\lambda}_{\bar{f}} = \frac{1}{\lambda_{\bar{f}}} \qquad (3.14)$$

The general expression for the time dependent decay rates, $\Gamma_{P^0\to f}(t) = |\langle f|T|P^0(t)\rangle|^2$,

Some algebra for the decay $P^0 \to f$

$$\left|P^0(t)\right\rangle = \frac{1}{2}\left(e^{-im_H t-\frac{1}{2}\Gamma_H t}+e^{-im_L t-\frac{1}{2}\Gamma_L t}\right)|P^0\rangle + \frac{q}{2p}\left(e^{-im_H t-\frac{1}{2}\Gamma_H t}-e^{-im_L t-\frac{1}{2}\Gamma_L t}\right)|\bar{P}^0\rangle$$

$$\Gamma_{P^0\to f}(t) = |A_f|^2 \left(|g_+(t)|^2 + |\lambda_f|^2|g_-(t)|^2 + 2\Re[\lambda_f g_+^*(t) g_-(t)]\right)$$

$$A(f) = \langle f|T|P^0\rangle$$

$$\bar{A}(f) = \langle f|T|\bar{P}^0\rangle$$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

Interference

$P^0 \to f$

$P^0 \to \bar{P}^0 \to f$

Some algebra for the decay P^0 → f

$$\begin{aligned}
\Gamma_{P^0\to f}(t) &= |A_f|^2 \left(|g_+(t)|^2 + |\lambda_f|^2|g_-(t)|^2 + 2\Re[\lambda_f g_+^*(t)g_-(t)]\right) \\
\Gamma_{P^0\to \bar{f}}(t) &= |\bar{A}_{\bar{f}}|^2 \left|\frac{q}{p}\right|^2 \left(|g_-(t)|^2 + |\bar{\lambda}_{\bar{f}}|^2|g_+(t)|^2 + 2\Re[\bar{\lambda}_{\bar{f}} g_+(t)g_-^*(t)]\right) \\
\Gamma_{\bar{P}^0\to f}(t) &= |A_f|^2 \left|\frac{p}{q}\right|^2 \left(|g_-(t)|^2 + |\lambda_f|^2|g_+(t)|^2 + 2\Re[\lambda_f g_+(t)g_-^*(t)]\right) \\
\Gamma_{\bar{P}^0\to \bar{f}}(t) &= |\bar{A}_{\bar{f}}|^2 \left(|g_+(t)|^2 + |\bar{\lambda}_{\bar{f}}|^2|g_-(t)|^2 + 2\Re[\bar{\lambda}_{\bar{f}} g_+^*(t)g_-(t)]\right) \qquad (3.15)
\end{aligned}$$

$$\begin{aligned}
|g_\pm(t)|^2 &= \frac{e^{-\Gamma t}}{2}\left(\cosh\frac{1}{2}\Delta\Gamma t \pm \cos\Delta m t\right) \\
g_+^*(t)g_-(t) &= \frac{e^{-\Gamma t}}{2}\left(\sinh\frac{1}{2}\Delta\Gamma t + i\sin\Delta m t\right) \\
g_+(t)g_-^*(t) &= \frac{e^{-\Gamma t}}{2}\left(\sinh\frac{1}{2}\Delta\Gamma t - i\sin\Delta m t\right) \qquad (3.16)
\end{aligned}$$

The 'master equations'

('direct') Decay — *Interference*

$$\Gamma_{P^0\to f}(t) = |A_f|^2 \frac{e^{-\Gamma t}}{2} \left((1+|\lambda_f|^2)\cosh\frac{1}{2}\Delta\Gamma t + 2\Re\lambda_f \sinh\frac{1}{2}\Delta\Gamma t + (1-|\lambda_f|^2)\cos\Delta m t - 2\Im\lambda_f \sin\Delta m t \right)$$

$$\Gamma_{\bar{P}^0\to f}(t) = |A_f|^2 \left|\frac{p}{q}\right|^2 \frac{e^{-\Gamma t}}{2} \left((1+|\lambda_f|^2)\cosh\frac{1}{2}\Delta\Gamma t + 2\Re\lambda_f \sinh\frac{1}{2}\Delta\Gamma t - (1-|\lambda_f|^2)\cos\Delta m t + 2\Im\lambda_f \sin\Delta m t \right) \quad (3.17)$$

The sinh- and sin-terms are associated to the interference between the decays with and without oscillation. Commonly, the master equations are expressed as:

The 'master equations'

('direct') Decay — *Interference*

$$\Gamma_{P^0\to f}(t) = |A_f|^2 \frac{e^{-\Gamma t}}{2} \left((1+|\lambda_f|^2)\cosh\frac{1}{2}\Delta\Gamma t + 2\Re\lambda_f \sinh\frac{1}{2}\Delta\Gamma t + (1-|\lambda_f|^2)\cos\Delta m t - 2\Im\lambda_f \sin\Delta m t \right)$$

$$\Gamma_{\bar{P}^0\to f}(t) = |A_f|^2 \left|\frac{p}{q}\right|^2 \frac{e^{-\Gamma t}}{2} \left((1+|\lambda_f|^2)\cosh\frac{1}{2}\Delta\Gamma t + 2\Re\lambda_f \sinh\frac{1}{2}\Delta\Gamma t - (1-|\lambda_f|^2)\cos\Delta m t + 2\Im\lambda_f \sin\Delta m t \right) \quad (3.17)$$

The sinh- and sin-terms are associated to the interference between the decays with and without oscillation. Commonly, the master equations are expressed as:

$$\Gamma_{P^0\to f}(t) = |A_f|^2 (1+|\lambda_f|^2)\frac{e^{-\Gamma t}}{2}\left(\cosh\frac{1}{2}\Delta\Gamma t + D_f \sinh\frac{1}{2}\Delta\Gamma t + C_f\cos\Delta m t - S_f \sin\Delta m t\right)$$

$$\Gamma_{\bar{P}^0\to f}(t) = |A_f|^2 \left|\frac{p}{q}\right|^2 (1+|\lambda_f|^2)\frac{e^{-\Gamma t}}{2}\left(\cosh\frac{1}{2}\Delta\Gamma t + D_f \sinh\frac{1}{2}\Delta\Gamma t - C_f\cos\Delta m t + S_f \sin\Delta m t\right) \quad (3.18)$$

with

$$D_f = \frac{2\Re\lambda_f}{1+|\lambda_f|^2} \qquad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \qquad S_f = \frac{2\Im\lambda_f}{1+|\lambda_f|^2}. \quad (3.19)$$

Classification of CP Violating effects

1. CP violation in decay

$$\Gamma(P^0 \to f) \neq \Gamma(\bar{P}^0 \to \bar{f})$$

This is obviously satisfied (see Eq. (3.15)) when

$$\left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1.$$

2. CP violation in mixing

$$\mathrm{Prob}(P^0 \to \bar{P}^0) \neq \mathrm{Prob}(\bar{P}^0 \to P^0)$$

$$\left|\frac{q}{p}\right| \neq 1.$$

3. CP violation in interference

$$\Gamma(P^0{}_{(\leadsto \bar{P}^0)} \to f)(t) \neq \Gamma(\bar{P}^0{}_{(\leadsto P^0)} \to f)(t)$$

$$\Im \lambda_f = \Im\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq 0$$

Meson Decays

- Formalism of meson *oscillations*:

$$\left|P^0(t)\right\rangle = \frac{1}{2}\left(e^{-im_H t-\frac{1}{2}\Gamma_H t} + e^{-im_L t-\frac{1}{2}\Gamma_L t}\right)|P^0\rangle + \frac{q}{2p}\left(e^{-im_H t-\frac{1}{2}\Gamma_H t} - e^{-im_L t-\frac{1}{2}\Gamma_L t}\right)|\bar{P}^0\rangle$$

- Subsequent: *decay*

$$\Gamma_{P^0\to f}(t) = |A_f|^2 \left(|g_+(t)|^2 + |\lambda_f|^2|g_-(t)|^2 + 2\Re[\lambda_f g_+^*(t)g_-(t)]\right)$$

$P^0 \to f$ | $P^0 \to \bar{P}^0 \to f$ | Interference

$$A(f) = \langle f|T|P^0\rangle$$

$$\bar{A}(f) = \langle f|T|\bar{P}^0\rangle$$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

Interference

$$\Gamma_{P^0\to f}(t) = |A_f|^2 \frac{e^{-\Gamma t}}{2} \left((1+|\lambda_f|^2)\cosh\frac{1}{2}\Delta\Gamma t + 2\Re\lambda_f \sinh\frac{1}{2}\Delta\Gamma t + (1-|\lambda_f|^2)\cos\Delta m t - 2\Im\lambda_f \sin\Delta m t\right)$$

('direct') Decay ***Interference***

CP violation: type 3

$$\Im\lambda_f = \Im\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq 0$$

$$\boxed{\Gamma(P^0{}_{(\leadsto\bar{P}^0)} \to f)(t) \neq \Gamma(\bar{P}^0{}_{(\leadsto P^0)} \to f)(t)}$$

$$A_{CP}(t) = \frac{\Gamma_{P^0(t)\to f} - \Gamma_{\bar{P}^0(t)\to f}}{\Gamma_{P^0(t)\to f} + \Gamma_{\bar{P}^0(t)\to f}}$$

$$\begin{aligned}
\Gamma_{P^0\to f}(t) &= |A_f|^2 \quad (1+|\lambda_f|^2)\frac{e^{-\Gamma t}}{2}\left(\cosh\frac{1}{2}\Delta\Gamma t + D_f \sinh\frac{1}{2}\Delta\Gamma t + C_f\cos\Delta m t - S_f \sin\Delta m t\right) \\
\Gamma_{\bar{P}^0\to f}(t) &= |A_f|^2\left|\frac{p}{q}\right|^2(1+|\lambda_f|^2)\frac{e^{-\Gamma t}}{2}\left(\cosh\frac{1}{2}\Delta\Gamma t + D_f \sinh\frac{1}{2}\Delta\Gamma t - C_f\cos\Delta m t + S_f \sin\Delta m t\right)
\end{aligned}$$

$$D_f = \frac{2\Re\lambda_f}{1+|\lambda_f|^2} \qquad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \qquad S_f = \frac{2\Im\lambda_f}{1+|\lambda_f|^2}.$$

$$\boxed{A_{CP}(t) = \frac{\Gamma_{P^0(t)\to f} - \Gamma_{\bar{P}^0(t)\to f}}{\Gamma_{P^0(t)\to f} + \Gamma_{\bar{P}^0(t)\to f}} = \frac{2C_f\cos\Delta m t - 2S_f\sin\Delta m t}{2\cosh\frac{1}{2}\Delta\Gamma t + 2D_f\sinh\frac{1}{2}\Delta\Gamma t}}$$

Classification of CP Violating effects - Nr. 3:

Consider $f=\bar{f}$:

$$A_{CP}(t) = \frac{\Gamma_{P^0(t)\to f} - \Gamma_{\bar{P}^0(t)\to f}}{\Gamma_{P^0(t)\to f} + \Gamma_{\bar{P}^0(t)\to f}} = \frac{2C_f \cos\Delta m t - 2S_f \sin\Delta m t}{2\cosh\frac{1}{2}\Delta\Gamma t + 2D_f \sinh\frac{1}{2}\Delta\Gamma t}$$

If one amplitude dominates the decay, then $A_f = \bar{A}_f$

$$A_{CP}(t) = \frac{-\Im\lambda_f \sin\Delta m t}{\cosh\frac{1}{2}\Delta\Gamma t + \Re\lambda_f \sinh\frac{1}{2}\Delta\Gamma t}$$

3. CP violation in interference

$$\Gamma(P^0{}_{(\rightsquigarrow\bar{P}^0)} \to f)(t) \neq \Gamma(\bar{P}^0{}_{(\rightsquigarrow P^0)} \to f)(t)$$

$$\Im\lambda_f = \Im\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq 0$$

Relax: $B^0 \rightarrow J/\Psi K_s$ simplifies…

$$D_f = \frac{2\Re\lambda_f}{1+|\lambda_f|^2} \qquad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \qquad S_f = \frac{2\Im\lambda_f}{1+|\lambda_f|^2}.$$

$$A_{CP}(t) = \frac{\Gamma_{P^0(t)\to f} - \Gamma_{\bar{P}^0(t)\to f}}{\Gamma_{P^0(t)\to f} + \Gamma_{\bar{P}^0(t)\to f}} = \frac{2C_f \cos\Delta m t - 2S_f \sin\Delta m t}{2\cosh\frac{1}{2}\Delta\Gamma t + 2D_f \sinh\frac{1}{2}\Delta\Gamma t}$$

$|\lambda_f|=1$

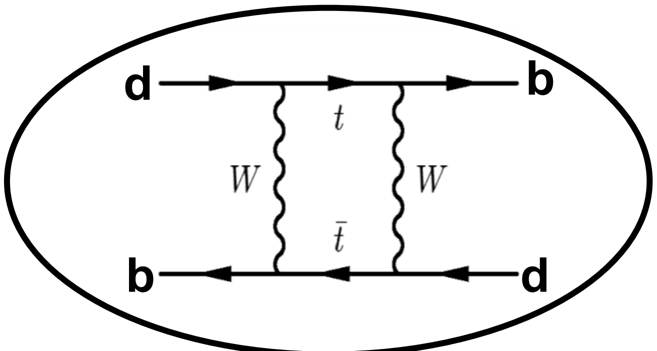
$\Delta\Gamma=0$

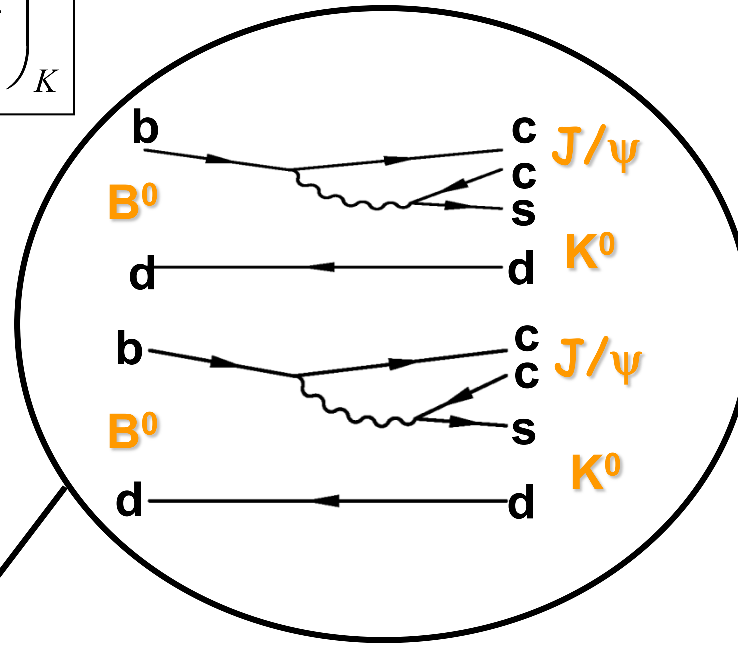
$$A_{CP}(t) = -\Im\lambda_f \sin(\Delta m t)$$

λ_f for $B^0 \rightarrow J/\psi K^0_S$

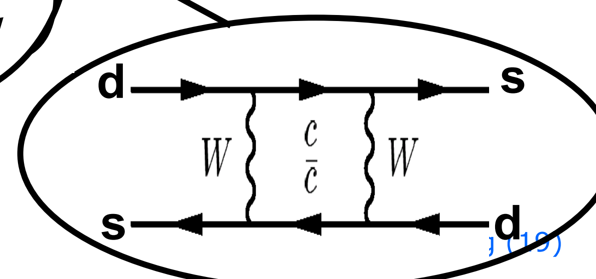
$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

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





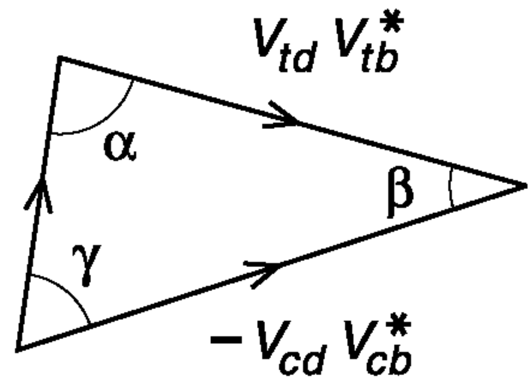
$$\lambda_{J/\psi K_s} = -\left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\right)\left(\frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}}\right)\left(\frac{V_{cs} V_{cd}^*}{V_{cs}^* V_{cd}}\right)$$



λ_f for $B^0 \to J/\psi K^0_S$

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

$$= -e^{-2i\beta}$$



Time-dependent *CP* asymmetry

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

- Theoretically clean way to measure β
- Clean experimental signature
- Branching fraction: $O(10^{-4})$
    - "Large" compared to other CP modes!

CP eigenvalue of final state $J/\psi K^0_S$

- CP $|J/\psi\rangle = +1\ |J/\psi\rangle$
- CP $|K^0_S\rangle = +1\ |K^0_S\rangle$
- CP $|J/\psi K^0_S\rangle = (-1)^l\ |J/\psi K^0_S\rangle$

(S(B)=0 → L(J/ψK^0_S)=1 !)

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

$$= -e^{-2i\beta}$$

Relative minus-sign between state and CP-conjugated state:

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

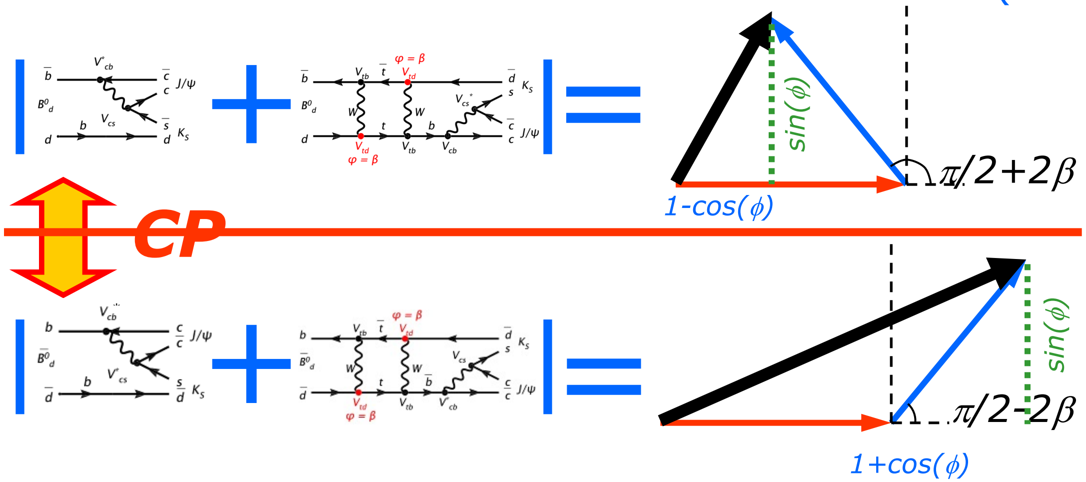
$$A_{CP}(t) = -\sin 2\beta\ \sin(\Delta m t)$$

Sum of 2 amplitudes: sensitivity to phase

- Now also look at CP-conjugate process
- Investigate situation at time t, such that $|A_1| = |A_2|$:

$\Gamma(B\to f)=$

$\Gamma(\overline{B}\to f)=$



$N(B^0 \to f) \propto |A|^2 \propto (1-\cos\phi)^2+\sin^2\phi$
$= 1 - 2\cos\phi + \cos^2\phi + \sin^2\phi$
$= 2-2\cos(\pi/2-2\beta)$
$\propto 1-\sin(2\beta)$

$$A_{CP} = \frac{N_{\overline{B^0}\to f} - N_{B^0\to f}}{N_{B^0\to f} + N_{\overline{B^0}\to f}} = \sin(2\beta)$$

$N(\overline{B^0} \to f) \propto (1+\cos\phi)^2+\sin^2\phi$
$= 2+2\cos(\pi/2-2\beta)$
$\propto 1+\sin(2\beta)$

- Directly observable result (essentially just from counting) measure CKM phase β directly!

$$A_{CP}(t=\pi/2\Delta m) = \frac{N_{\overline{B^0}\to f} - N_{B^0\to f}}{N_{B^0\to f} + N_{\overline{B^0}\to f}} = \sin(2\beta)$$

Remember!

Necessary ingredients for CP violation:

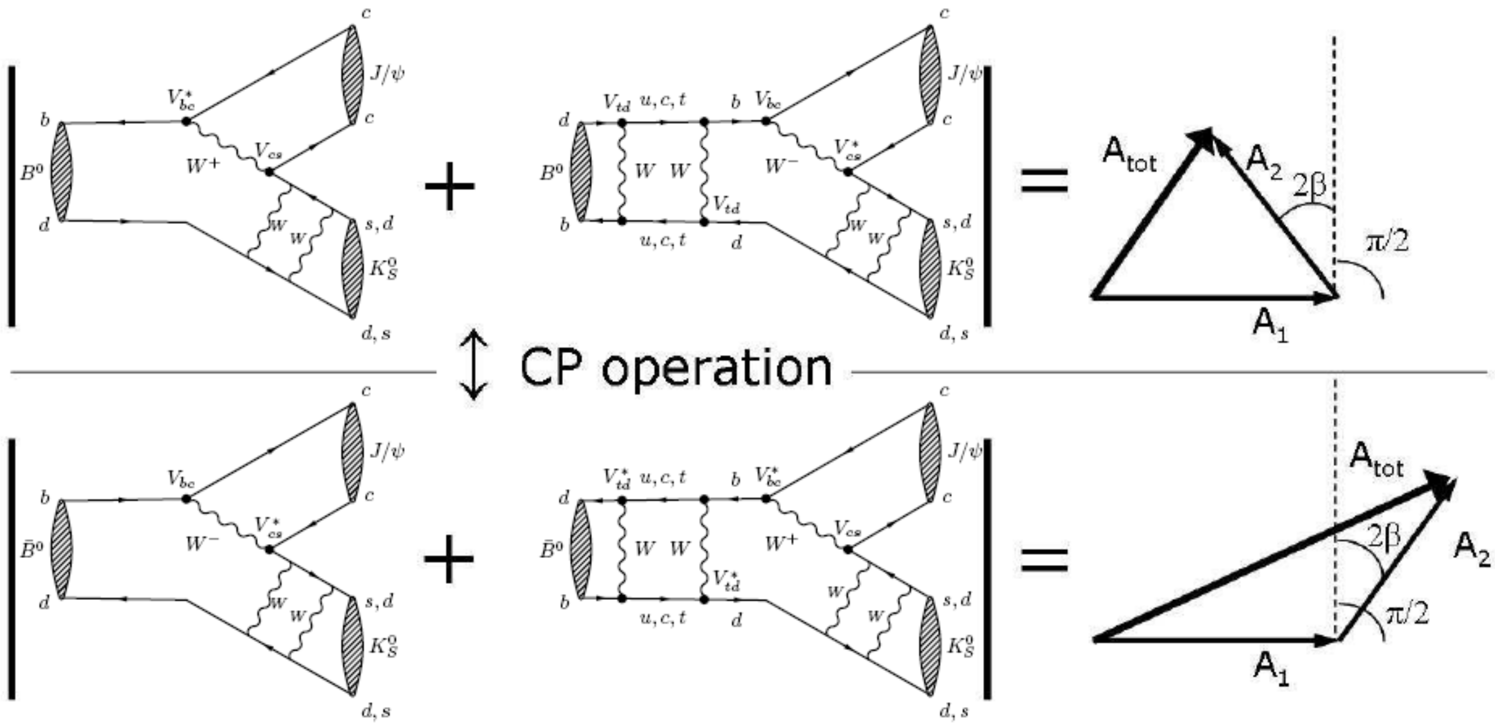
1) Two (interfering) amplitudes

2) Phase difference between amplitudes

- one CP conserving phase ('strong' phase)
- one CP violating phase ('weak' phase)

2 amplitudes
2 phases

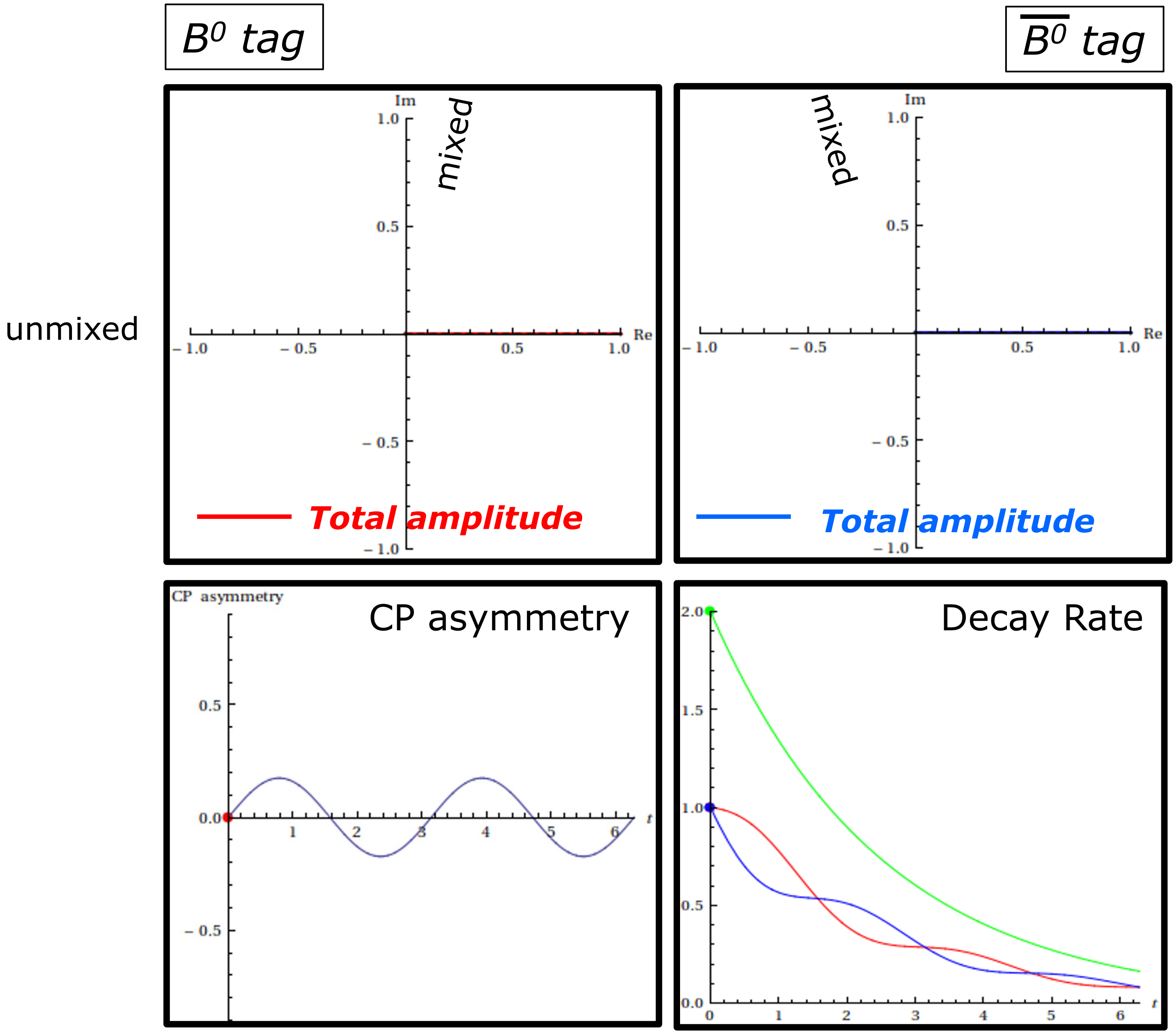
Remember!



2 amplitudes

2 phases

Time dependent CP violation

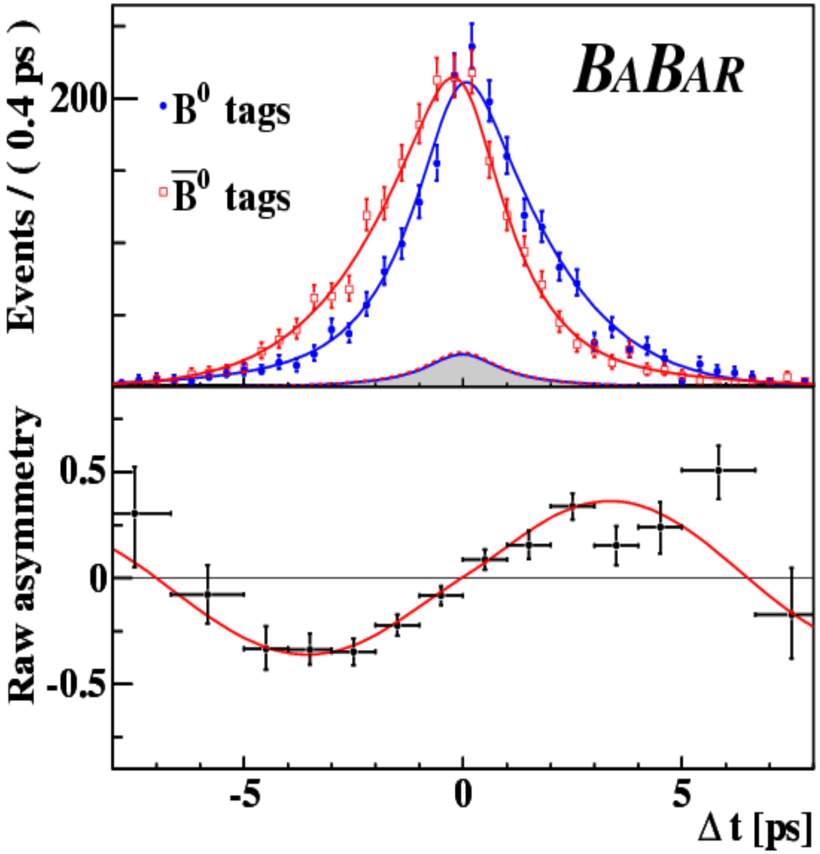


ϕ = 10 deg
$\Gamma/\Delta m$ = 1.3

B-system - Time-dependent CP asymmetry

$$B^0 \to J/\psi K_s$$

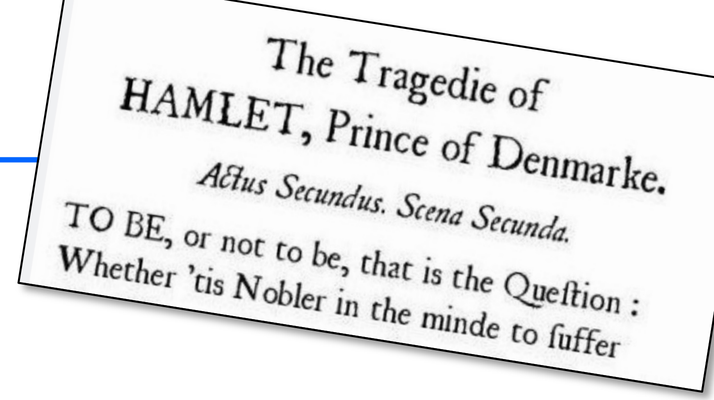
$$A_{CP}(t) = \frac{N_{\overline{B^0}\to f} - N_{B^0\to f}}{N_{B^0\to f} + N_{\overline{B^0}\to f}} = \sin(2\beta)\sin(\Delta m t)$$



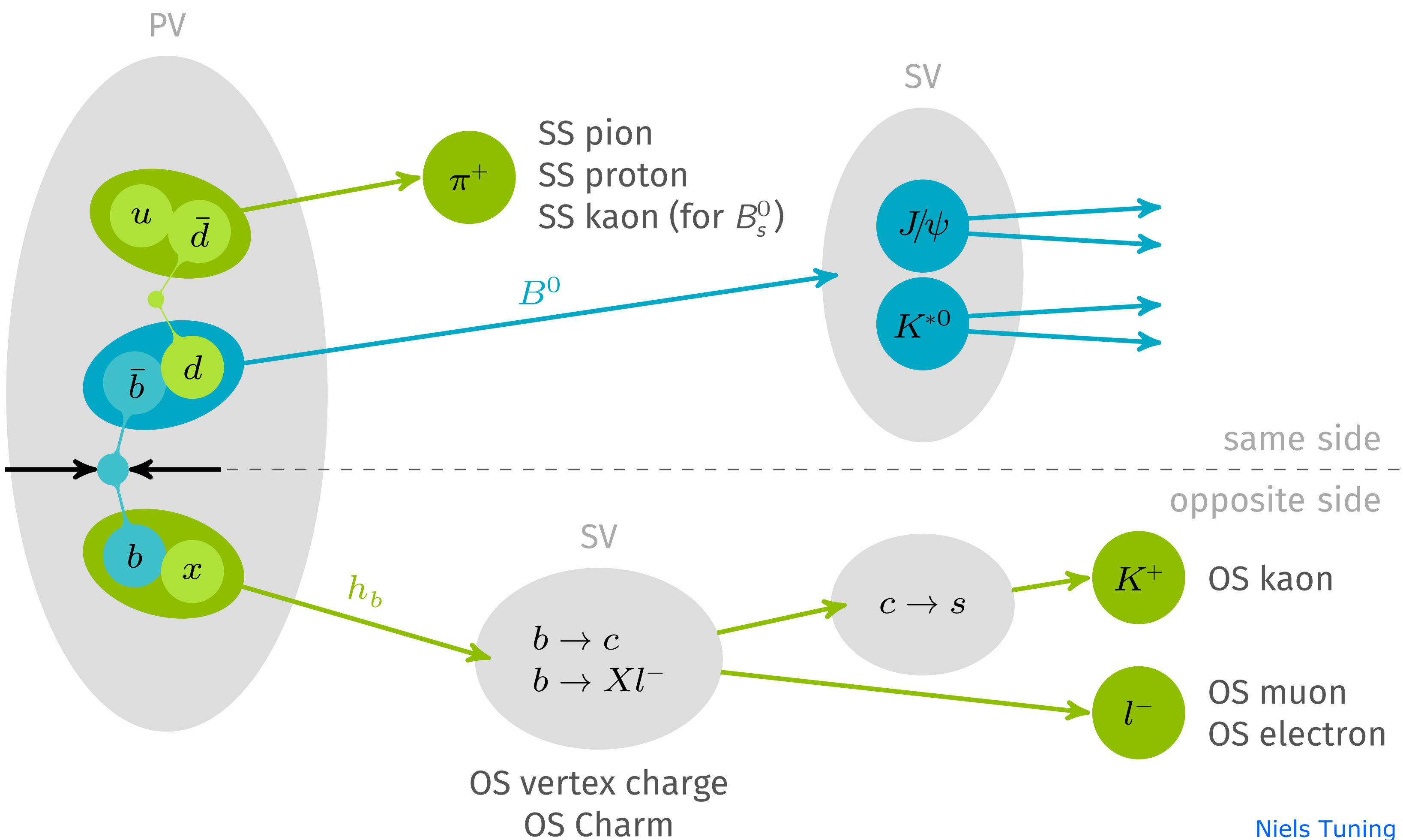
BaBar (2002)

sin2β in LHCb

- Flavour tagging: *to "B^0" or not to "B^0"* ?



The Tragedie of
HAMLET, Prince of Denmarke.
Actus Secundus. Scena Secunda.
TO BE, or not to be, that is the Queſtion :
Whether 'tis Nobler in the minde to ſuffer



sin2β in LHCb

- Flavour tagging: *to "B^0" or not to "B^0"* ?
- Various algorithms
  - Not perfect event-by-event, but statistically useful!
    - **Key parameters: efficiency and wrong-tag fraction → $\varepsilon(1-2\omega)^2$**
  - Measure perfromance with $B^0 \rightarrow J/\psi K^{*0}$, $B^+ \rightarrow J/\psi K^+$, $B_s^0 \rightarrow D_s^+ \pi^-$

Tagger	ε [%]	ω [%]	$\varepsilon\langle D^2\rangle = \varepsilon(1-2\omega)^2$ [%]
OSμ	0.915 ± 0.053	30.713 ± 0.434	1.361 ± 0.062

sin2β in LHCb

- Flavour tagging: *to "B^0" or not to "B^0"* ?
- Various algorithms
  - Not perfect event-by-event, but statistically useful!
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Tagger	ε [%]	ω [%]	$\varepsilon\langle D^2\rangle = \varepsilon(1-2\omega)^2$ [%]
OSμ	0.915 ± 0.053	30.713 ± 0.434	1.361 ± 0.062
OSe	4.451 ± 0.038	34.038 ± 0.604	0.454 ± 0.035
OSK	19.600 ± 0.073	37.557 ± 0.315	1.214 ± 0.061
OSVtx	20.834 ± 0.075	36.994 ± 0.308	1.410 ± 0.067
OSc	5.025 ± 0.040	34.062 ± 0.620	0.511 ± 0.040
OScomb	40.154 ± 0.090	35.123 ± 0.211	3.555 ± 0.101
SSK	68.190 ± 0.177	39.667 ± 0.507	2.912 ± 0.286
SSπ	83.486 ± 0.068	42.561 ± 0.145	1.848 ± 0.072
SSp	37.767 ± 0.089	43.645 ± 0.221	0.610 ± 0.042
SScomb	87.590 ± 0.061	41.787 ± 0.142	2.364 ± 0.081

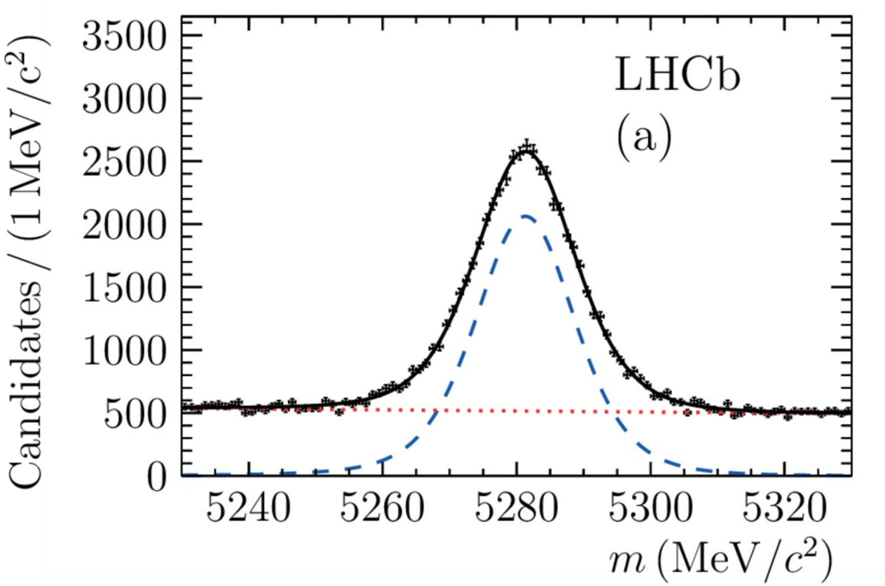
From D.Fazzini, LHCP20218

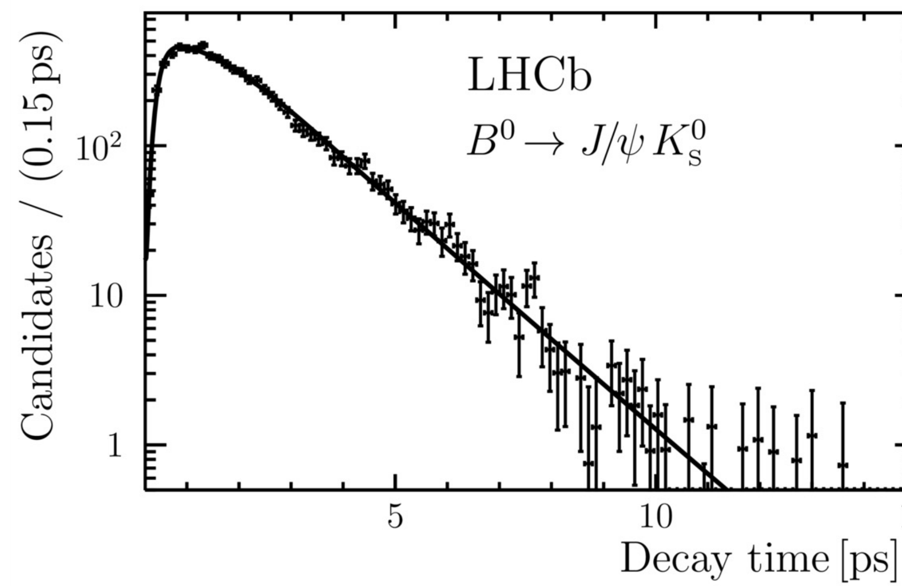
sin2β

$$\mathcal{A}_{[c\bar{c}]K^0_S}(t) \equiv \frac{\Gamma(\overline{B}^0(t) \to [c\bar{c}]K^0_S) - \Gamma(B^0(t) \to [c\bar{c}]K^0_S)}{\Gamma(\overline{B}^0(t) \to [c\bar{c}]K^0_S) + \Gamma(B^0(t) \to [c\bar{c}]K^0_S)}$$

$$= \frac{S\sin(\Delta m\, t) - C\cos(\Delta m\, t)}{\cosh(\Delta\Gamma\, t/2) + A_{\Delta\Gamma}\sinh(\Delta\Gamma\, t/2)} \approx S\sin(\Delta m\, t)$$

- Flavour tagging essential
  - Which B^0 was a $\overline{B^0}$?





LHCb, PRL 115 (2015) 031601

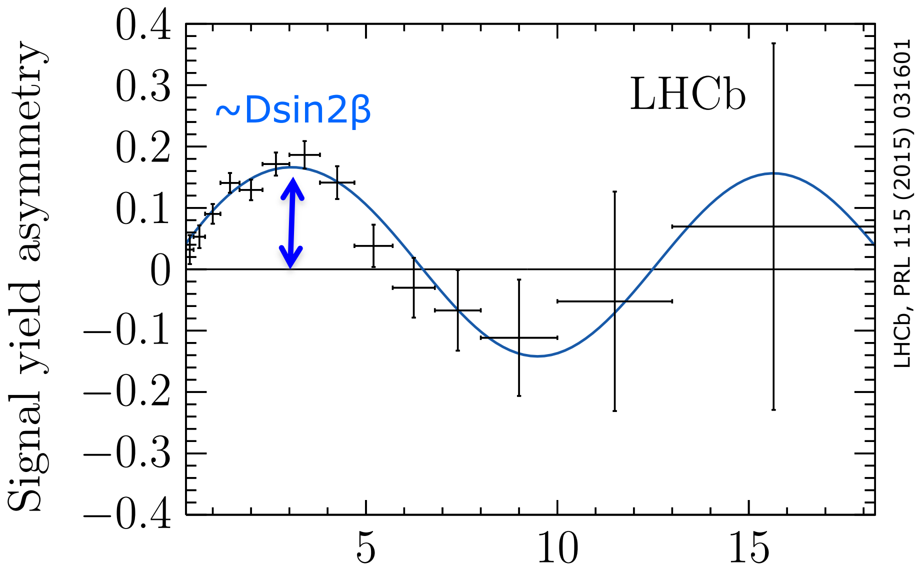
sin2β

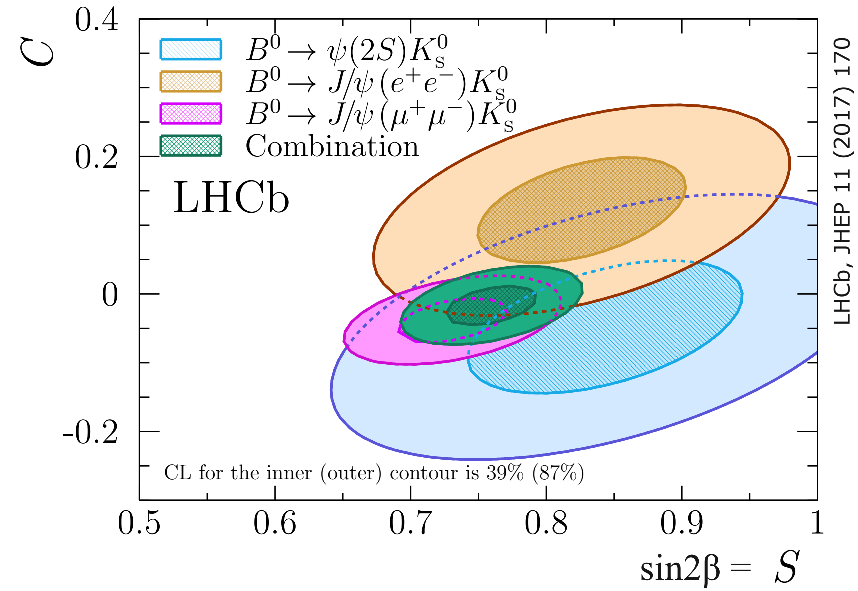
$$\mathcal{A}_{[c\bar{c}]K^0_S}(t) \equiv \frac{\Gamma(\overline{B}^0(t) \to [c\bar{c}]K^0_S) - \Gamma(B^0(t) \to [c\bar{c}]K^0_S)}{\Gamma(\overline{B}^0(t) \to [c\bar{c}]K^0_S) + \Gamma(B^0(t) \to [c\bar{c}]K^0_S)}$$

$$= \frac{S\sin(\Delta m\,t) - C\cos(\Delta m\,t)}{\cosh(\Delta\Gamma\,t/2) + A_{\Delta\Gamma}\sinh(\Delta\Gamma\,t/2)} \approx S\sin(\Delta m\,t)$$

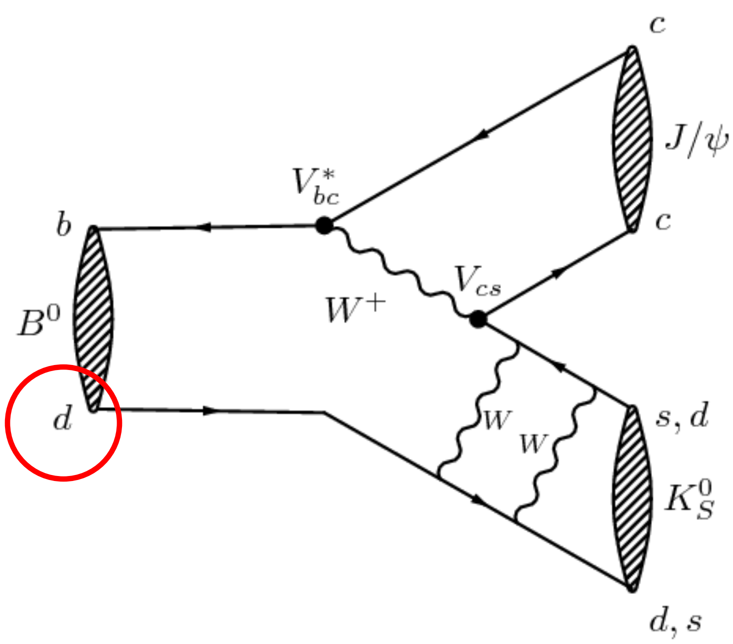
- Flavour tagging essential
  - Wrong tag fraction w~35%
  - D=(1-2w)~0.3

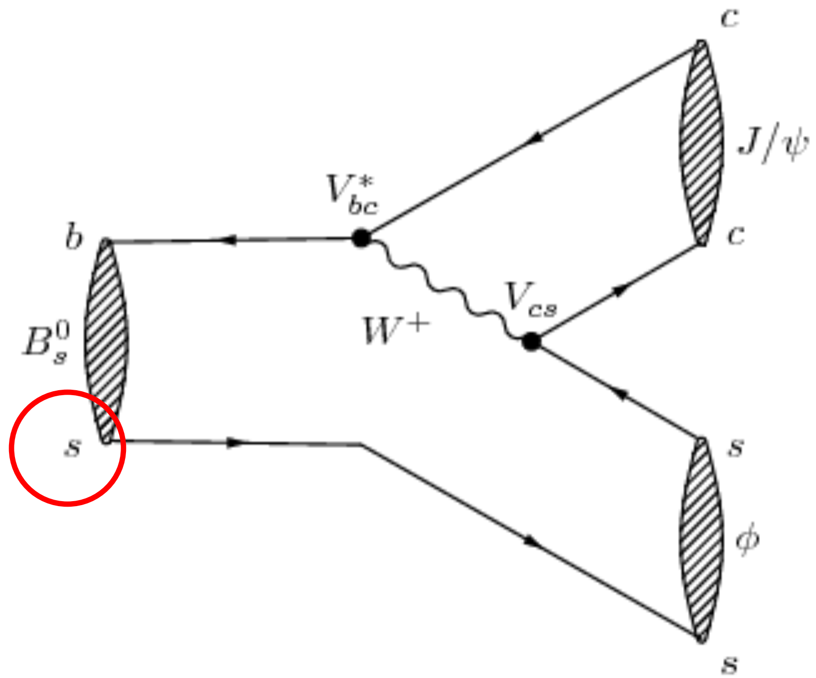
$$\boldsymbol{A_{CP}(t) = D\sin(2\beta)\sin(\Delta m t)}$$





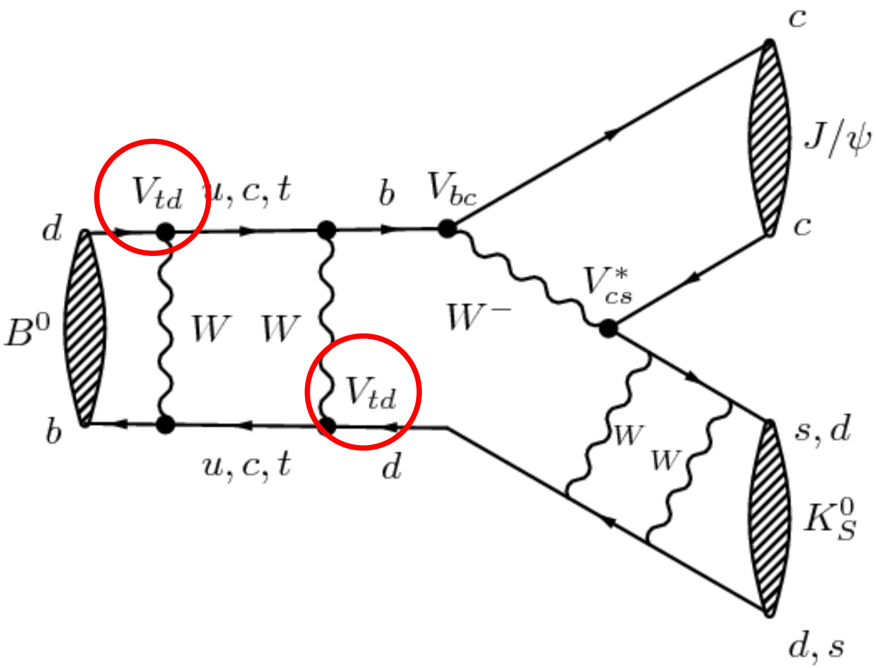
β_s: $B_s^0 \to J/\psi\phi$: B_s^0 analogue of $B^0 \to J/\psi K^0_S$



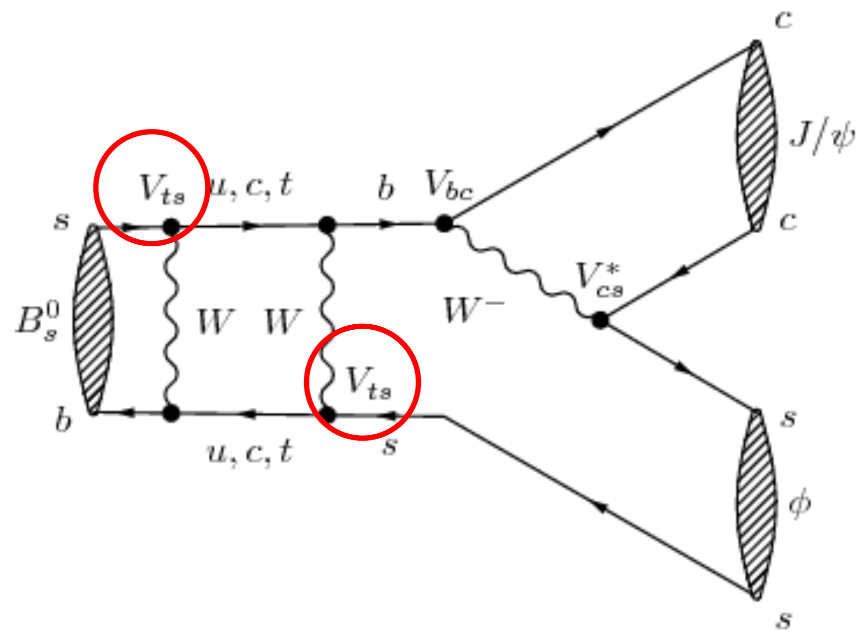


- Replace spectator quark d → s

β_s: $B_s^0 \to J/\psi\phi$: B_s^0 analogue of $B^0 \to J/\psi K^0_S$



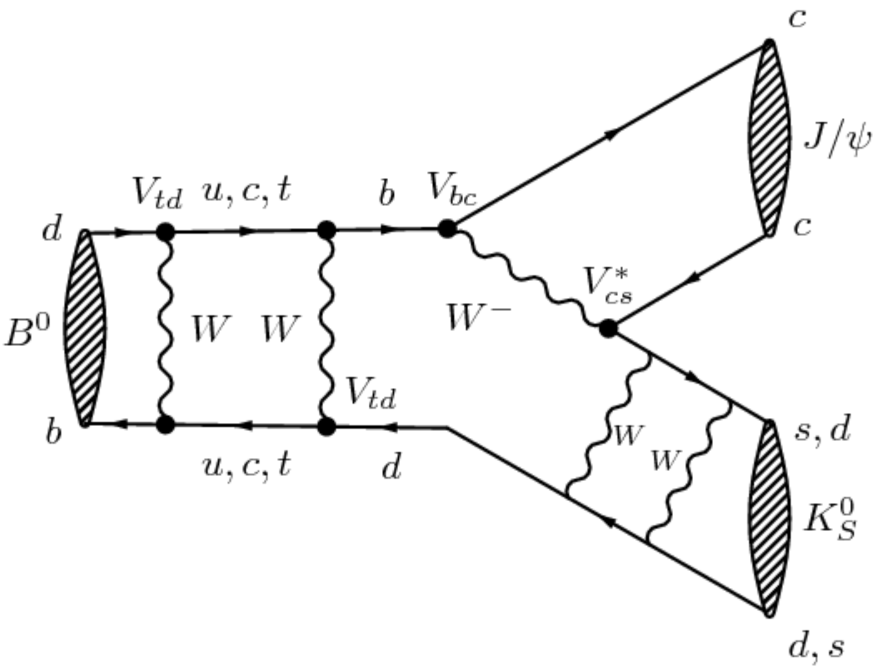
$$\beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

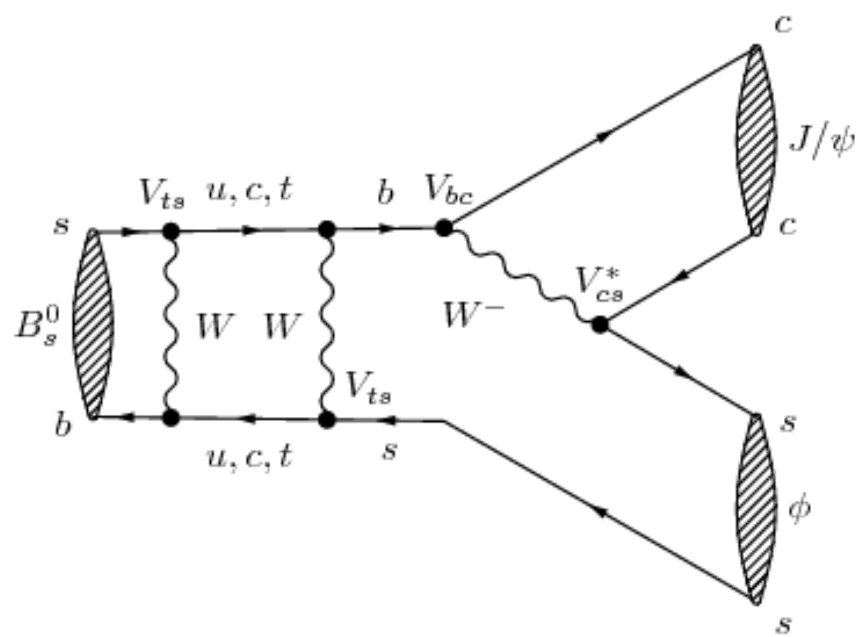


$$\beta_s \equiv \arg\left[-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right]$$

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

β_s: $B_s^0 \to J/\psi\varphi$: B_s^0 analogue of $B^0 \to J/\psi K^0_S$





Differences:

	B^0	B^0_s
CKM	V_{td}	V_{ts}
$\Delta\Gamma$	~0	~0.1
Final state (spin)	K^0 : s=0	φ: s=1
Final state (K)	K^0 mixing	-

β_s: $B_s^0 \rightarrow J/\psi\phi$

$$A_{CP}(t) = \frac{\Gamma_{B_s^0(t)\rightarrow J/\psi\phi} - \Gamma_{\bar{B}_s^0(t)\rightarrow J/\psi\phi}}{\Gamma_{B_s^0(t)\rightarrow J/\psi\phi} + \Gamma_{\bar{B}_s^0(t)\rightarrow J/\psi\phi}} = \frac{-\Im\lambda_{J/\psi\phi}\sin\Delta m t}{\cosh\frac{1}{2}\Delta\Gamma t + \Re\lambda_{J/\psi\phi}\sinh\frac{1}{2}\Delta\Gamma t}$$

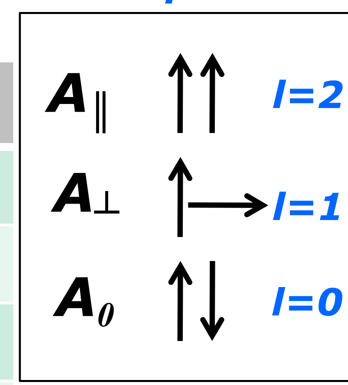
$$\lambda_{J/\psi\phi} = \left(\frac{q}{p}\right)_{B_s^0}\left(\eta_{J/\psi\phi}\frac{\bar{A}_{J/\psi\phi}}{A_{J/\psi\phi}}\right) = (-1)^l\left(\frac{V_{tb}^*V_{ts}}{V_{tb}V_{ts}^*}\right)\left(\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}\right)$$

$$\Im\lambda_{J/\psi\phi} = (-1)^l\sin(-2\beta_s)$$

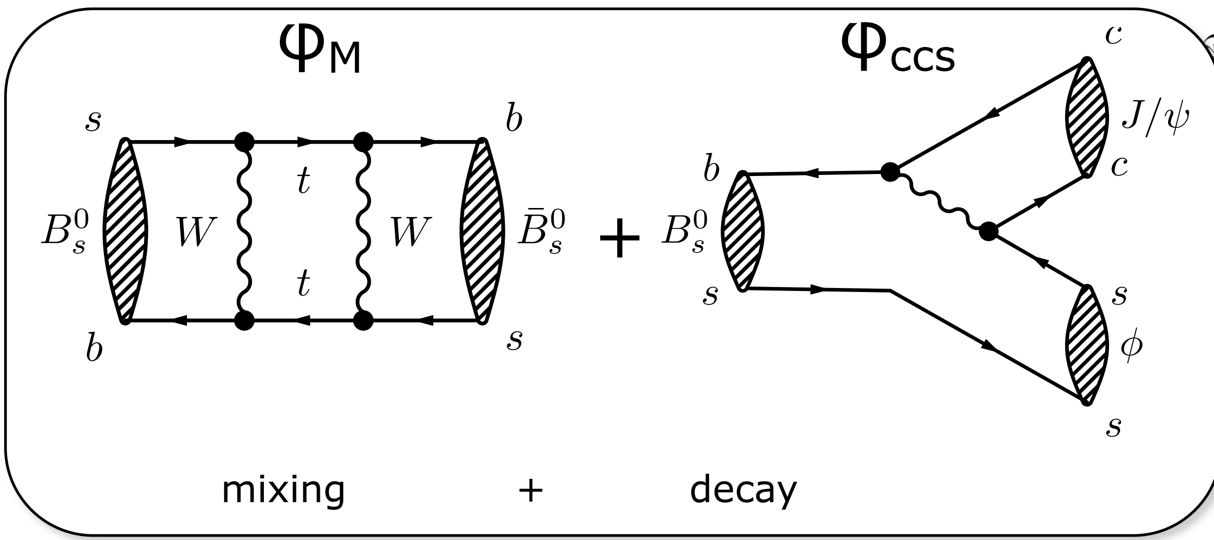
$$\mathrm{CP}|J/\psi\phi\rangle_l = (-1)^l|J/\psi\phi\rangle_l$$

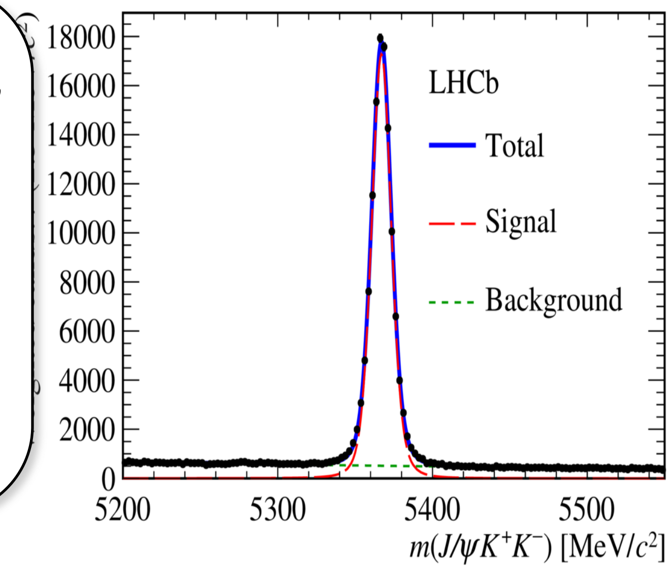
V_{ts} large, oscillations fast,
need good vertex detector
3 amplitudes

	B^0	B^0_s
CKM	V_{td}	V_{ts}
$\Delta\Gamma$	~0	~0.1
Final state (spin)	K^0 : s=0	ϕ: s=1
Final state (K)	K^0 mixing	-



ϕ_s with $B_s^0 \to J/\psi\phi$ ("the sin2β of the B_s^0 system")





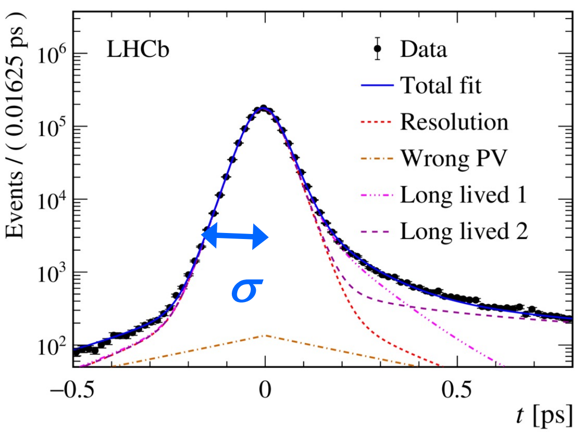
ϕ_s

LHCb, arXiv:1906.08356
EPJC 79 (2019) 8, 706,
EPJC 80 (2020) 7, 601 (erratum)

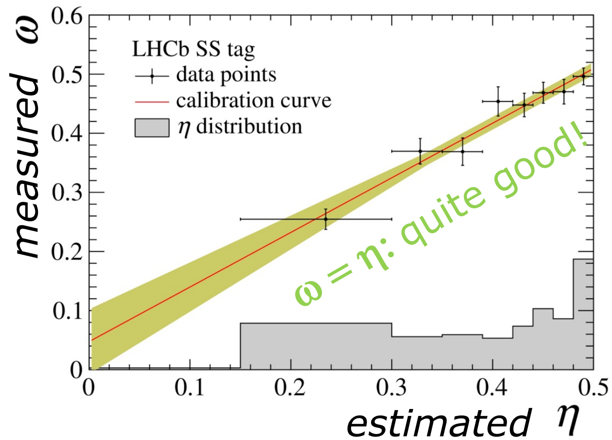
φ_s with $B_s^0 \rightarrow J/\psi\varphi$

- Some challenges:
  1) Rapid B_s^0 oscillations: decay time resolution
  2) "Same side" kaon-tagging: calibration with hadronic final state
  3) Mix of CP eigenstates: angular analysis

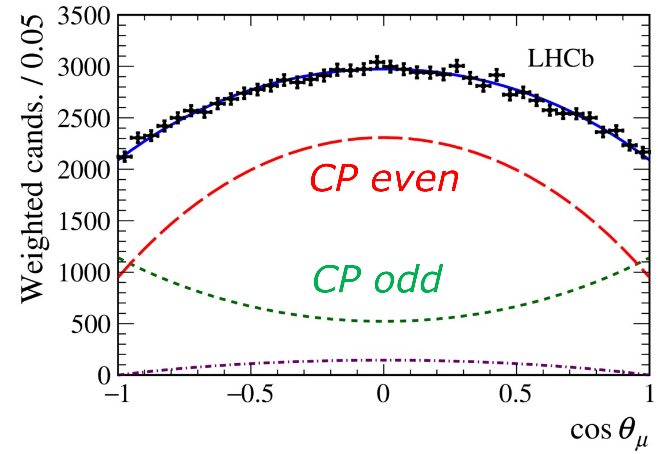
1) Decay time resolution from prompt J/ψ :



2) Tagging calibration from $B_s^0 \rightarrow D_s\pi$



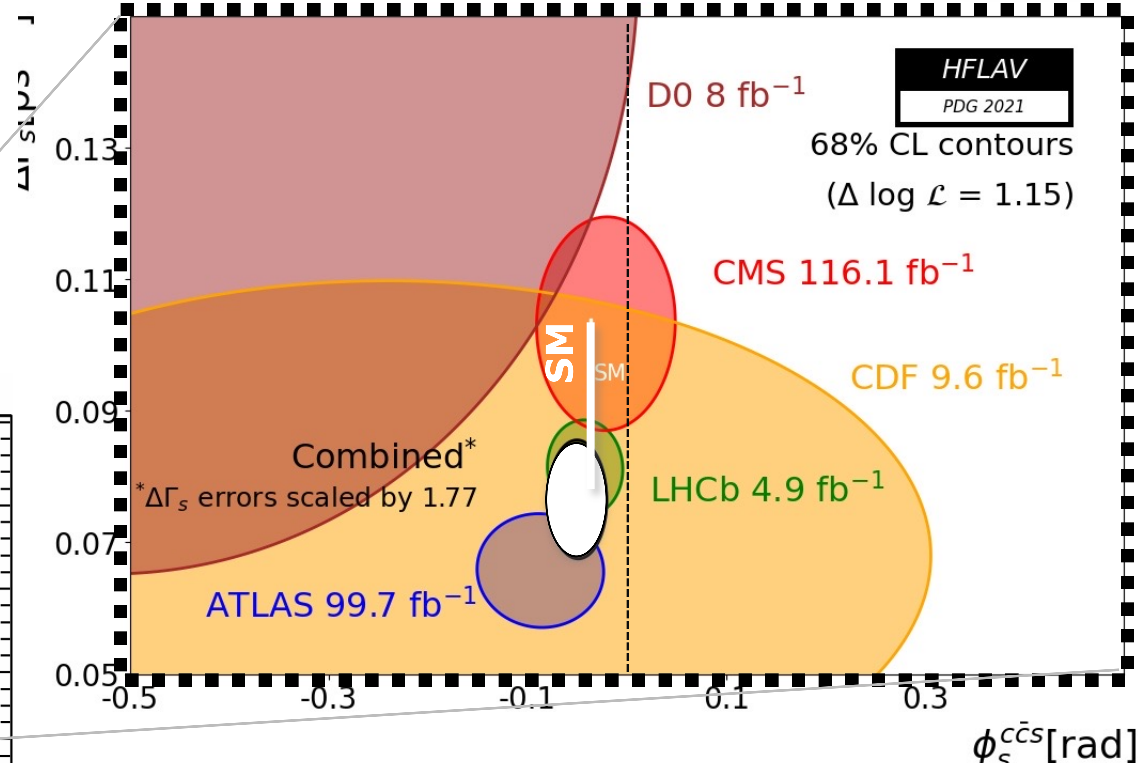
3) Angular analysis to disentable CP + and CP -



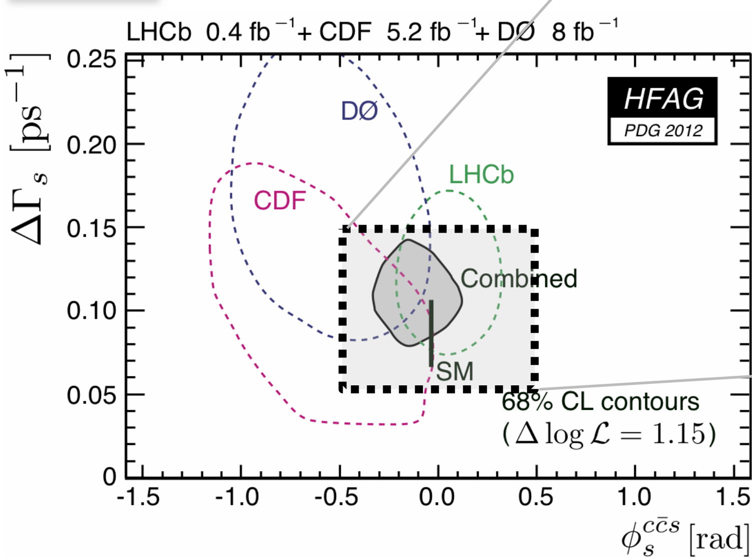
φ_s

2021

- LHCb 2011-2016



2012



$\phi_s = -50 \pm 19$ mrad (HFLAV)

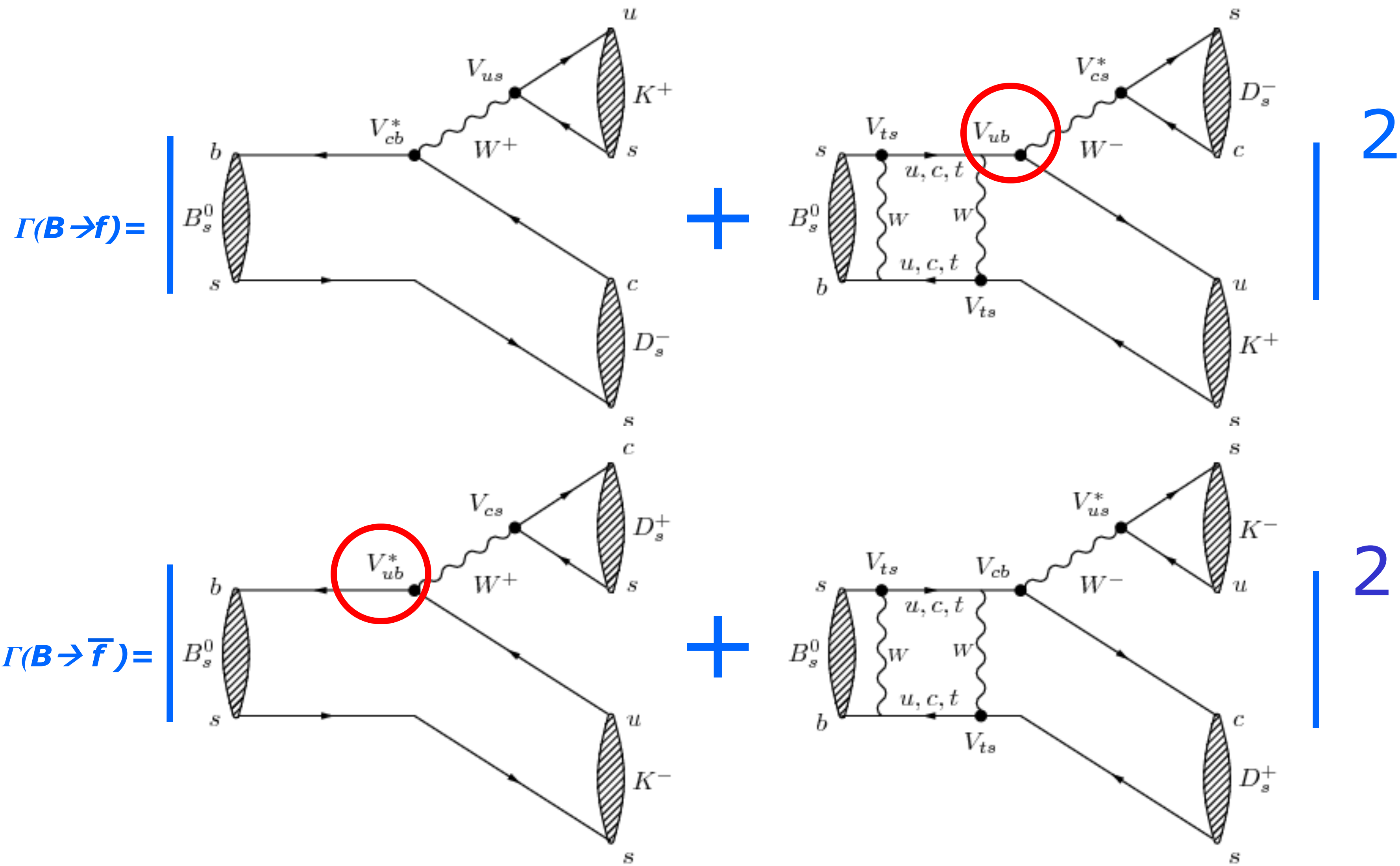
$\phi_s = -42 \pm 25$ mrad (LHCb)

$\phi_s = -37 \pm 1$ mrad (SM)

CKMfitter,
Phys. Rev. D84, 033005 (2011),
updated with Summer 2019 results

https://hflav-eos.web.cern.ch/hflav-eos/osc/PDG_2021/HFLAV_phis_inputs.pdf

Measure γ: $B^0_s \to D_s^{\pm}K^{-/+}$: both λ_f and $\lambda_{\bar{f}}$



NB: In addition $\bar{B}_s \to D_s^{\pm}K^{-/+}$: both $\bar{\lambda}_f$ and $\bar{\lambda}_{\bar{f}}$

Formalism: $B_s^0 \to D_s^+ K^-$

- Time-dependent decay rates:

$$\frac{\mathrm{d}\Gamma_{B_s^0\to f}(t)}{\mathrm{d}t} = \frac{1}{2}|A_f|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right.$$
$$\left. + C_f\cos(\Delta m_s t) - S_f\sin(\Delta m_s t)\right],$$

$$\frac{\mathrm{d}\Gamma_{\overline{B}_s^0\to f}(t)}{\mathrm{d}t} = \frac{1}{2}|A_f|^2\left|\frac{p}{q}\right|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right.$$
$$\left. - C_f\cos(\Delta m_s t) + S_f\sin(\Delta m_s t)\right],$$

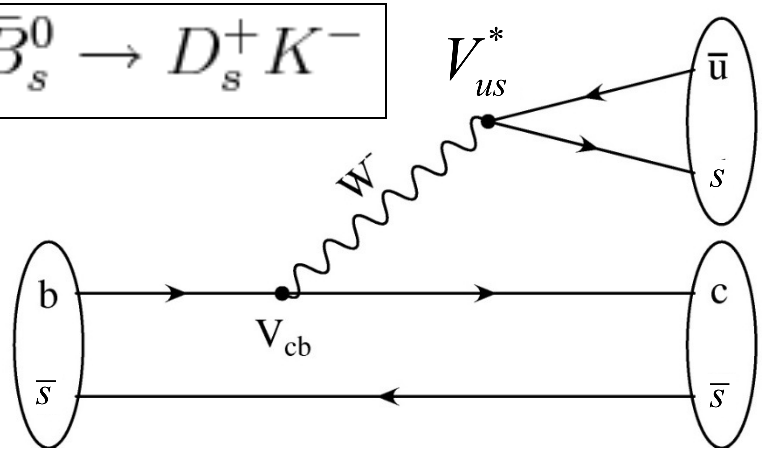
$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} = -C_{\overline{f}} = -\frac{1-|\lambda_{\overline{f}}|^2}{1+|\lambda_{\overline{f}}|^2}$$

$$S_f = \frac{2\mathcal{I}m(\lambda_f)}{1+|\lambda_f|^2}, \quad A_f^{\Delta\Gamma} = \frac{-2\mathcal{R}e(\lambda_f)}{1+|\lambda_f|^2}$$

$$S_{\overline{f}} = \frac{2\mathcal{I}m(\lambda_{\overline{f}})}{1+|\lambda_{\overline{f}}|^2}, \quad A_{\overline{f}}^{\Delta\Gamma} = \frac{-2\mathcal{R}e(\lambda_{\overline{f}})}{1+|\lambda_{\overline{f}}|^2}$$

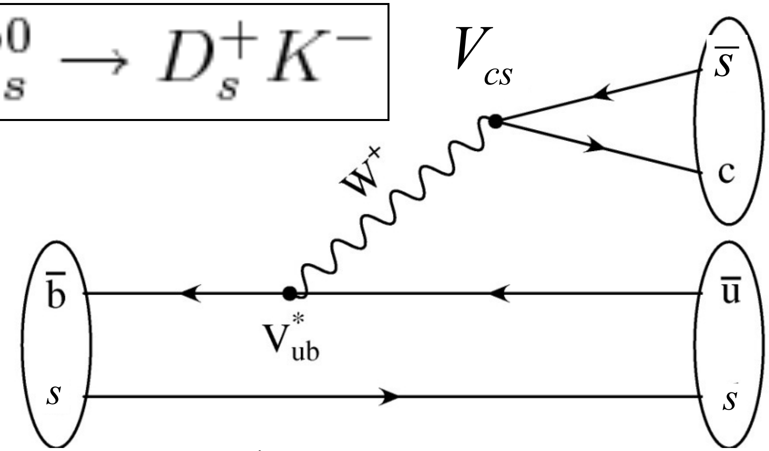
Measure γ: $B_s \rightarrow D_s^{\pm}K^{-/+}$ --- first one f: $D_s^+K^-$

$\bar{B}_s^0 \rightarrow D_s^+ K^-$



$$V_{cb}V_{us}^* \propto \lambda^3$$

$B_s^0 \rightarrow D_s^+ K^-$



$$V_{ub}^*V_{cs} \propto \lambda^3 e^{i\gamma}$$

- This time $|A_f| \neq |\bar{A}_f|$, so $|\lambda| \neq 1$!

$$\left(\frac{\bar{A}_{D_s^-K^+}}{A_{D_s^-K^+}}\right) = \left(\frac{V_{ub}V_{cs}^*}{V_{cb}^*V_{us}}\right)\left(\frac{A_2}{A_1}\right)$$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

- In fact, not only magnitude, but also phase difference:

$$\frac{A_{D_s^-K^+}}{\bar{A}_{D_s^-K^+}} = \frac{|A_{D_s^-K^+}|}{|\bar{A}_{D_s^-K^+}|}e^{i(\delta_s-\gamma)}$$

Measure γ: $B_s \rightarrow D_s^{\pm}K^{-/+}$

- $B^0_s \rightarrow D_s^- K^+$ has phase difference $(\delta - \gamma)$:

$$\frac{A_{D_s^- K^+}}{\bar{A}_{D_s^- K^+}} = \frac{|A_{D_s^- K^+}|}{|\bar{A}_{D_s^- K^+}|} e^{i(\delta_s - \gamma)}$$

- Need $B^0_s \rightarrow D_s^+ K^-$ to disentangle δ and γ:

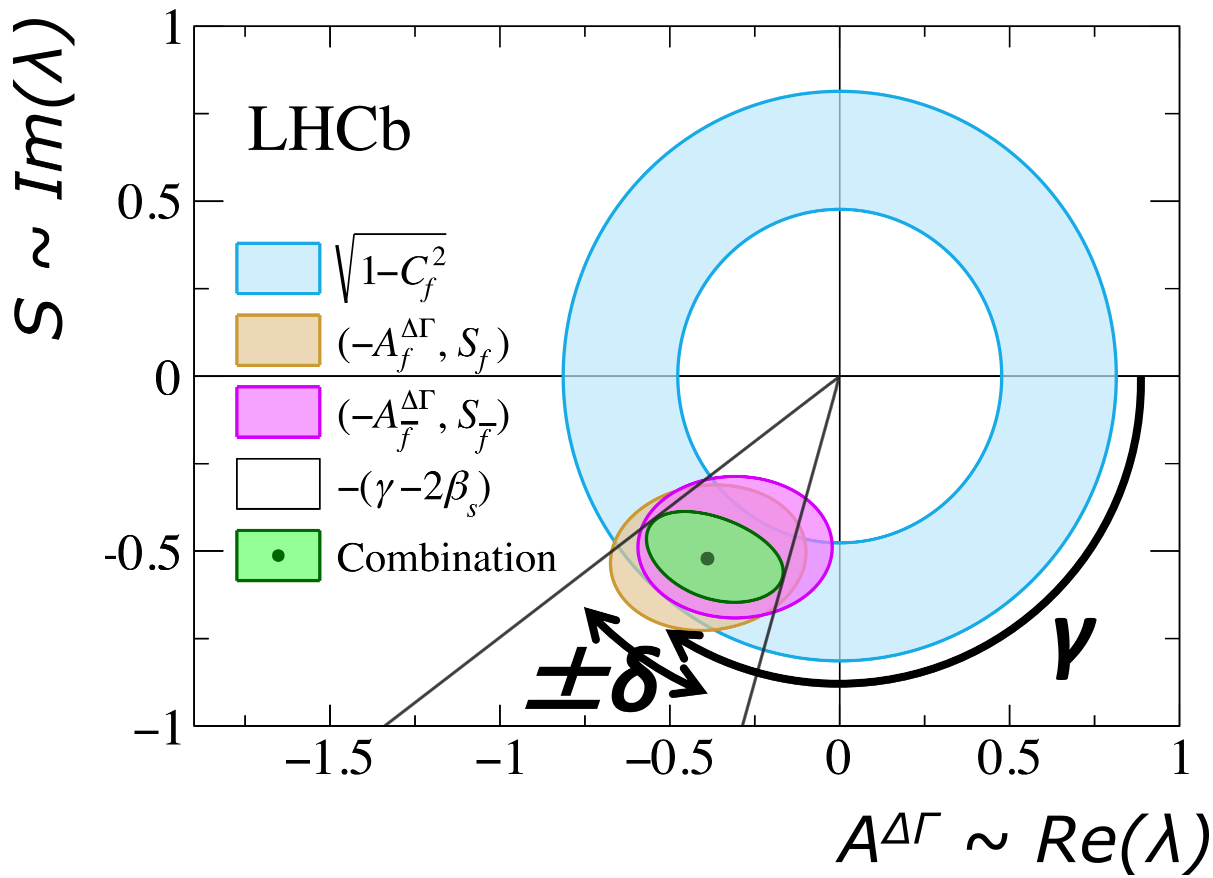
$$\lambda_{D_s^- K^+} = \left(\frac{q}{p}\right)_{B_s^0} \left(\frac{\bar{A}_{D_s^- K^+}}{A_{D_s^- K^+}}\right) = \left|\frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*}\right| \left|\frac{V_{ub} V_{cs}^*}{V_{cb}^* V_{us}}\right| \left|\frac{A_2}{A_1}\right| e^{i(-2\beta_s - \gamma + \delta_s))}$$

$$\lambda_{D_s^+ K^-} = \left(\frac{q}{p}\right)_{B_s^0} \left(\frac{\bar{A}_{D_s^+ K^-}}{A_{D_s^+ K^-}}\right) = \left|\frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*}\right| \left|\frac{V_{us}^* V_{cb}}{V_{cs} V_{ub}^*}\right| \left|\frac{A_1}{A_2}\right| e^{i(-2\beta_s - \gamma - \delta_s))}$$

Formalism

- Polar: $|\lambda|$ and γ
- Cartesian: $A^{\Delta\Gamma}$ and S

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$



<u>*A note on conventions:*</u>

1)We use: $\Delta\Gamma_s = \Gamma_L - \Gamma_H > 0$

2)Opposite convention is equivalent if at the same time $A^{\Delta\Gamma} \rightarrow -A^{\Delta\Gamma}$

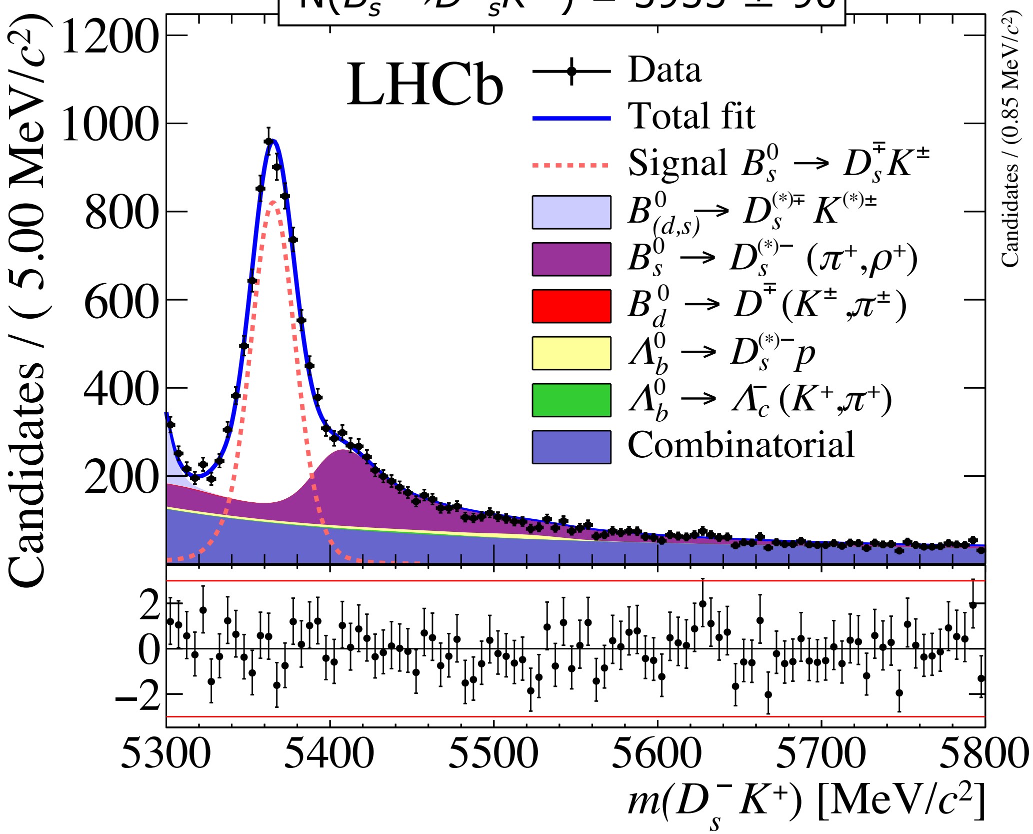
$B_s^0 \to D_s^{\pm} K^{\mp}$ Analysis

- Obtain B_s^0 signal sample: 3D fit to (m_B, m_{Ds}, PID)
- B_s^0 or $\overline{B}_s^0$: Flavour Tagging
- Decay time: Resolution & acceptance
- Result: Decay time fit

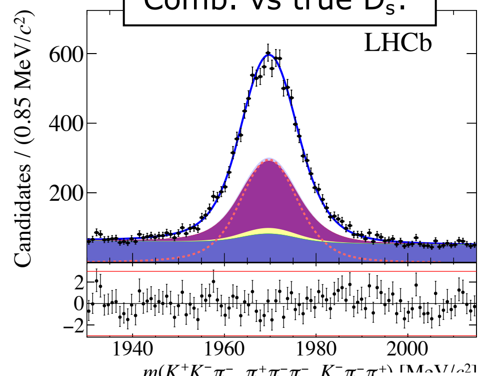
$B_s^0 \to D^{\pm}_s K^{\mp}$ Analysis: mass fit

- Need to (statistically) separate signal from background
- Backgrounds:
  - Combinatorial
  - Partially reconstructed background ($B_s^0 \to D^{*}_s K^{\mp}$, etc)
  - Misidentified background ($B_s^0 \to D^{\pm}_s \pi^{\mp}$)

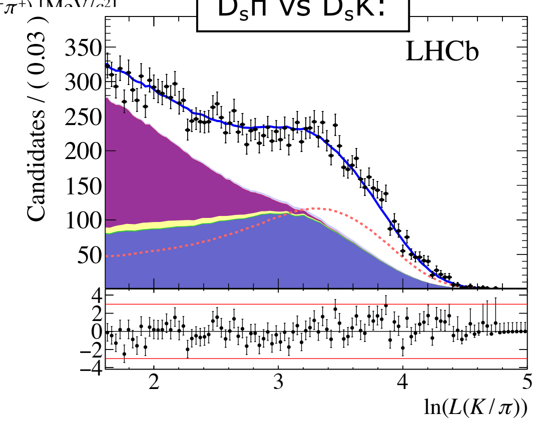
N($B_s^0 \to D^{\pm}_s K^{\mp}$) = 5955 ± 90



Comb. vs true D_s:

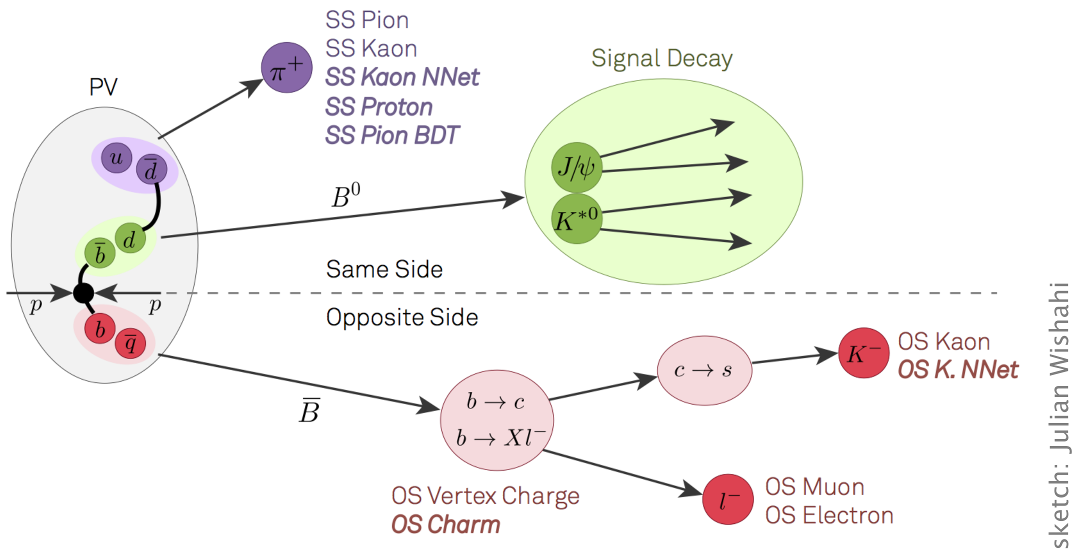


$D_s\pi$ vs D_sK:



$B_s^0 \rightarrow D^{\pm}_s K^{\mp}$ Analysis: Flavour Tagging

- *To B_s^0 or not to B_s^0 :*



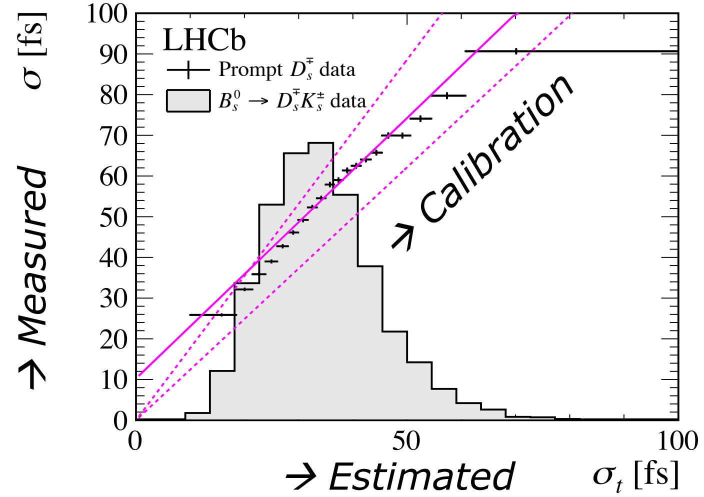
- Use $B_s^0 \rightarrow D^+_s \pi^-$ to calibrate!

$B^0_s \rightarrow D^-_s \pi^+$	ε_{tag} [%]	ε_{eff} [%]
OS only	12.94 ± 0.11	1.41 ± 0.11
SS only	39.70 ± 0.16	1.29 ± 0.13
Both OS and SS	24.21 ± 0.14	3.10 ± 0.18
Total	76.85 ± 0.24	5.80 ± 0.25

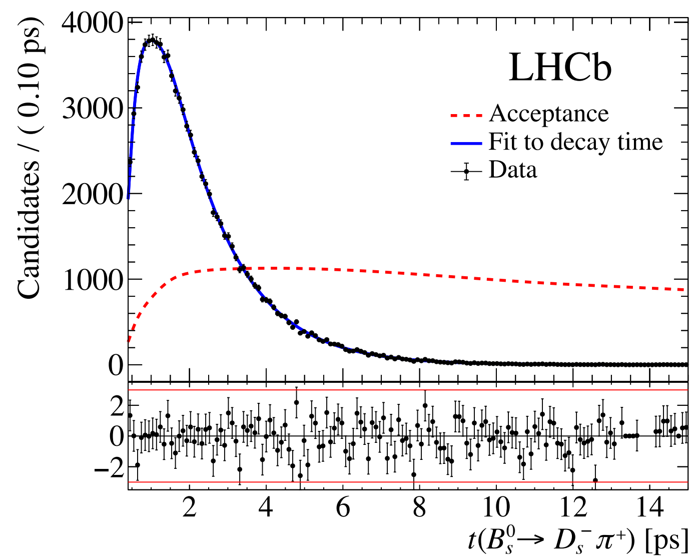
$B_s^0 \to D^{\pm}_s K^{\mp}$ Analysis: Decay time

Use $B_s^0 \to D^+_s \pi^-$ to calibrate!

- Resolution



- Acceptance



$B_s^0 \to D_s^{\pm} K^{\mp}$ Analysis: Result from fit

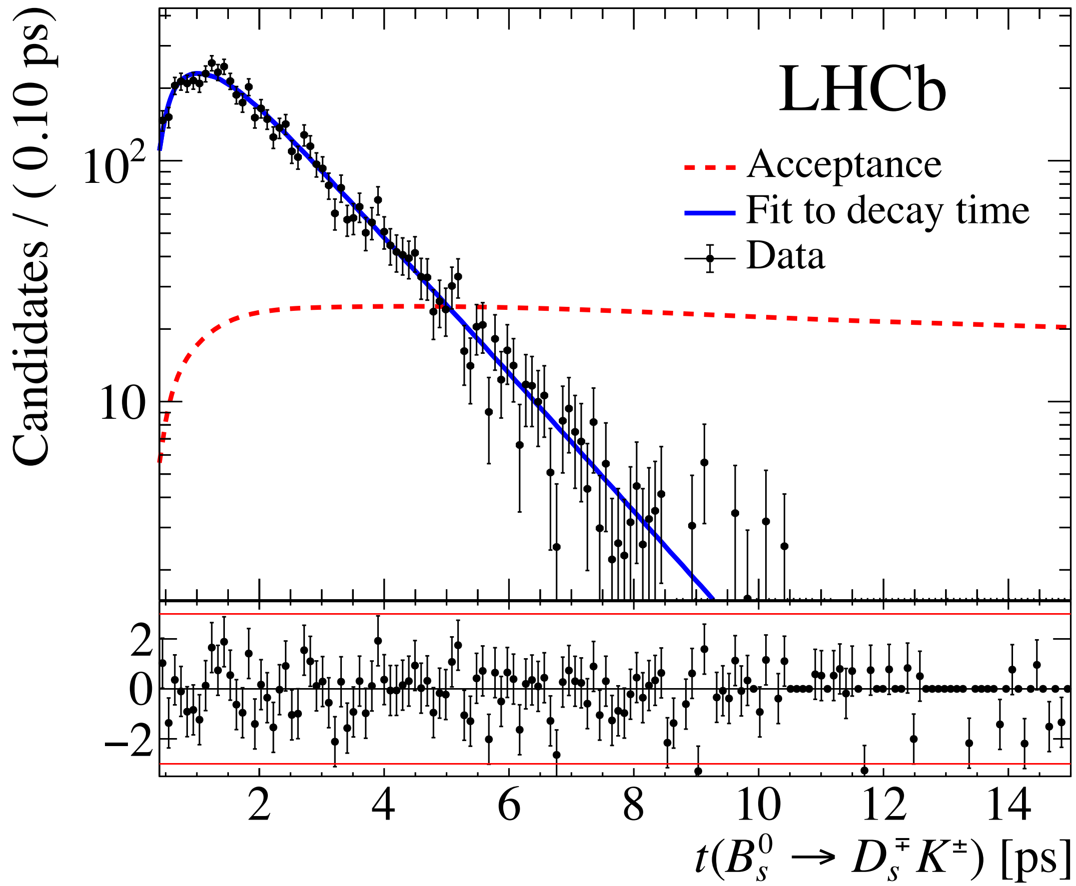
- Decay time fit:
  - Fix some parameters

$$\left\{\begin{aligned} \Delta m_s &= (17.757 \pm 0.021)\ \mathrm{ps}^{-1}\,, \\ \Gamma_s &= (0.6643 \pm 0.0020)\ \mathrm{ps}^{-1}\,, \\ \Delta\Gamma_s &= (0.083 \pm 0.006)\ \mathrm{ps}^{-1}\,, \\ \rho(\Gamma_s, \Delta\Gamma_s) &= -0.239\,, \\ A_{\mathrm{prod}} &= (1.1 \pm 2.7)\%, \\ A_{\mathrm{det}} &= (1 \pm 1)\% \end{aligned}\right.$$

$$\frac{\mathrm{d}\Gamma_{B_s^0\to f}(t)}{\mathrm{d}t} = \frac{1}{2}|A_f|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_f\cos(\Delta m_s t) - S_f \sin(\Delta m_s t)\right],$$

$$\frac{\mathrm{d}\Gamma_{\bar{B}_s^0\to f}(t)}{\mathrm{d}t} = \frac{1}{2}|A_f|^2\left|\frac{p}{q}\right|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C_f\cos(\Delta m_s t) + S_f \sin(\Delta m_s t)\right],$$

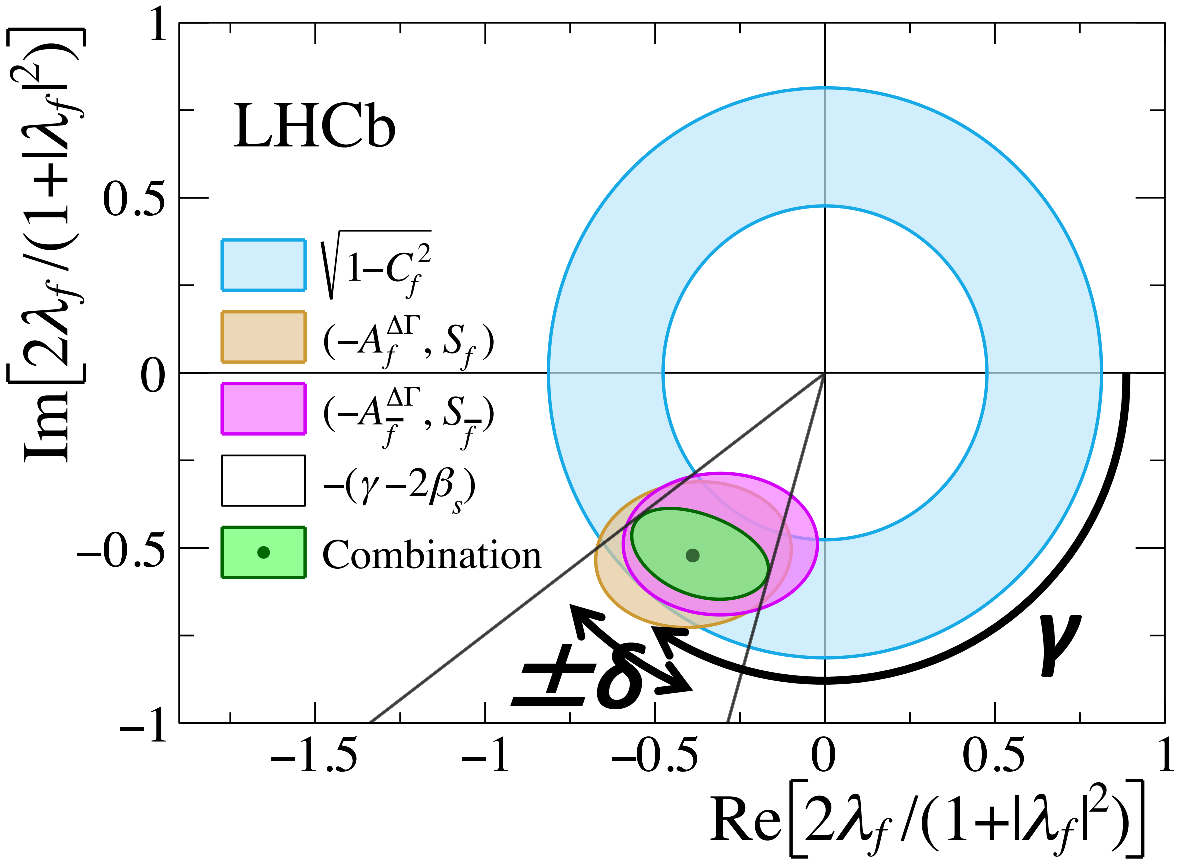
Parameter	Value
C_f	$0.730 \pm 0.142 \pm 0.045$
$A_f^{\Delta\Gamma}$	$0.387 \pm 0.277 \pm 0.153$
$A_{\overline{f}}^{\Delta\Gamma}$	$0.308 \pm 0.275 \pm 0.152$
S_f	$-0.519 \pm 0.202 \pm 0.070$
$S_{\overline{f}}$	$-0.489 \pm 0.196 \pm 0.068$



$B_s^0 \to D_s^{\pm} K^{\mp}$ Analysis: Result

- From *A*, *S*, *C* to γ, δ, r

$$\gamma = (128\,^{+17}_{-22})^\circ\,,$$
$$\delta = (358\,^{+13}_{-14})^\circ\,,$$
$$r_{D_sK} = 0.37\,^{+0.10}_{-0.09}\,,$$



$B_s^0 \to D_s^{\pm} K^{\mp} \pi^+ \pi^-$ Analysis:

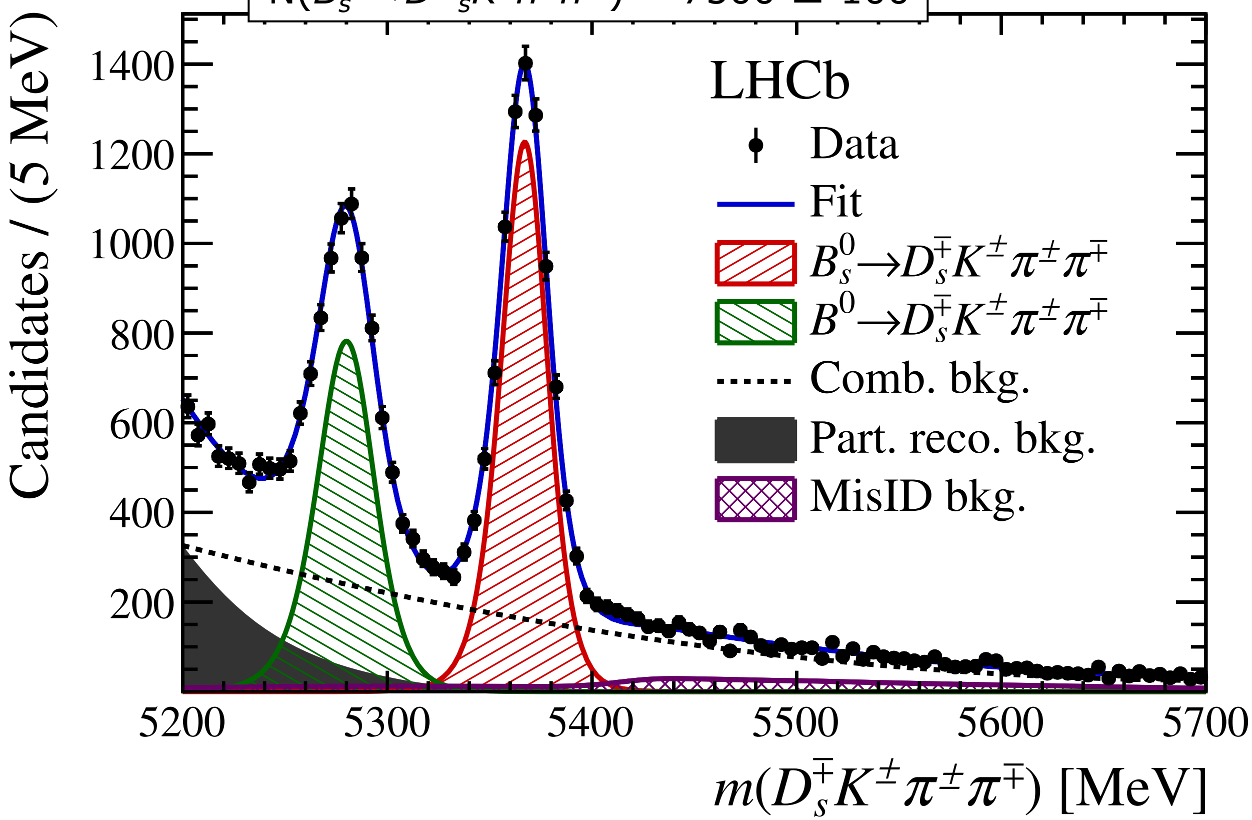
- Obtain B_s^0 signal sample: Fit to m_B
- B_s^0 *or* B_s^0 *:* Flavour Tagging
- Decay time: Resolution & acceptance
- Result: Decay time fit

- + Amplitude analysis

$B_s^0 \to D^\pm_s K^\mp \pi^+ \pi^-$ Analysis: mass fit

- Need to (statistically) separate signal from background
- Backgrounds:
  - Combinatorial
  - Partially reconstructed background ($B_s^0 \to D^*_s K^\mp$, etc)
  - Misidentified background ($B_s^0 \to D^\pm_s \pi^\mp$)

N($B_s^0 \to D^\pm_s K^\mp \pi^+ \pi^-$) = 7500 ± 100



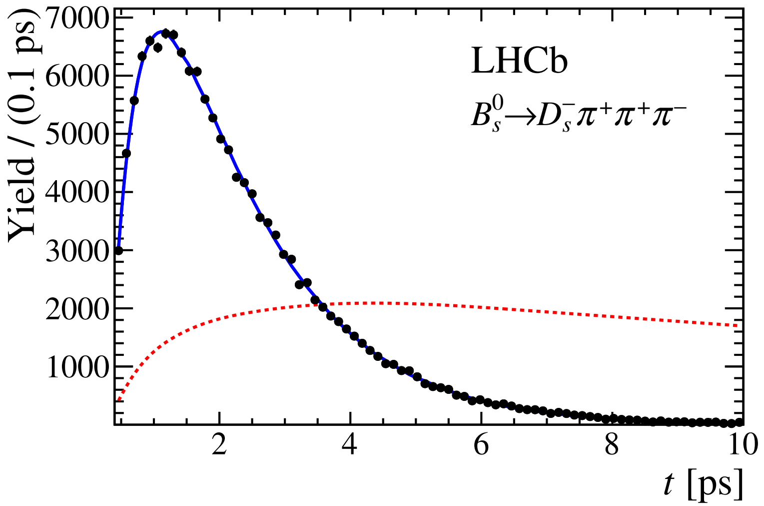
$B_s^0 \to D^{\pm}_s K^{\mp} \pi^+ \pi^-$ Analysis:

- Flavour Tagging

(b) Run 2 data.

	$\epsilon_{tag}[\%]$	$\langle\omega\rangle[\%]$	$\epsilon_{eff}[\%]$
Only OS	11.91 ± 0.04	37.33 ± 0.41	1.11 ± 0.05
Only SS	40.95 ± 0.08	42.41 ± 0.29	1.81 ± 0.10
Both OS-SS	28.96 ± 0.12	35.51 ± 0.32	3.61 ± 0.13
Combined	81.82 ± 0.15	39.23 ± 0.32	6.52 ± 0.17

- Decay time acceptance

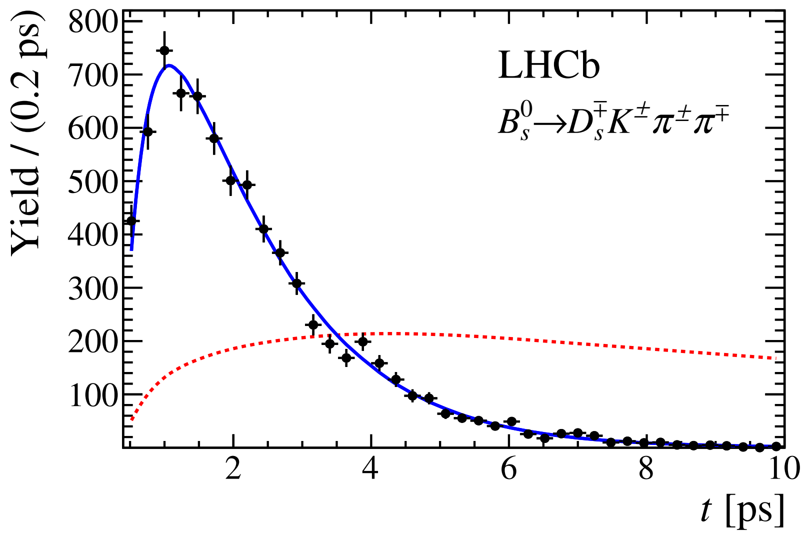


$B_s^0 \to D^{\pm}_s K^{\mp} \pi^+ \pi^-$ Analysis: Result

- Time fit:

Fit parameter	Value
C_f	$0.631 \pm 0.096 \pm 0.032$
$A_f^{\Delta\Gamma}$	$-0.334 \pm 0.232 \pm 0.097$
$A_{\bar{f}}^{\Delta\Gamma}$	$-0.695 \pm 0.215 \pm 0.081$
S_f	$-0.424 \pm 0.135 \pm 0.033$
$S_{\bar{f}}$	$-0.463 \pm 0.134 \pm 0.031$

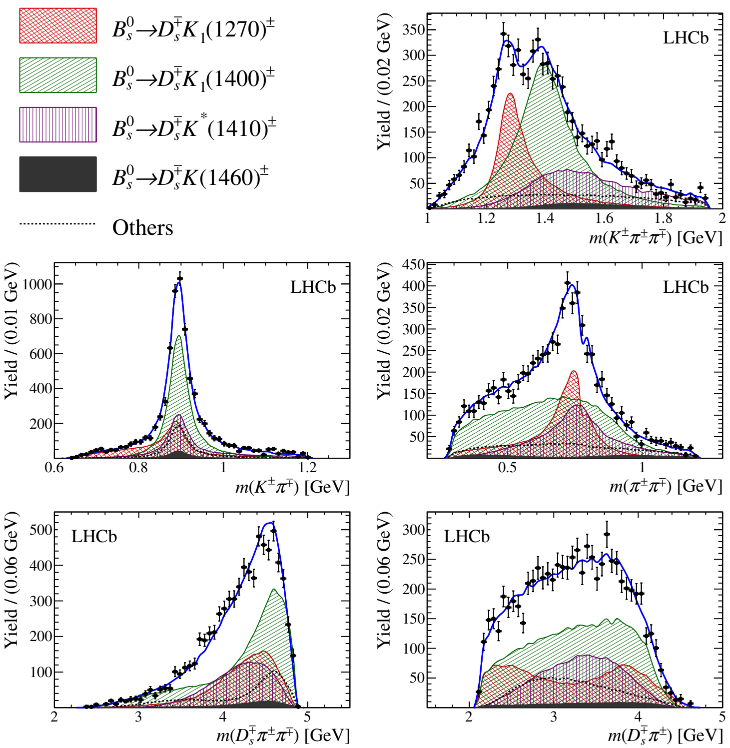
Parameter	Model-independent
r	$0.47\,^{+0.08}_{-0.08}\,^{+0.02}_{-0.03}$
κ	$0.88\,^{+0.12}_{-0.19}\,^{+0.04}_{-0.07}$
δ [°]	$-6\,^{+10}_{-12}\,^{+2}_{-4}$
$\gamma - 2\beta_s$ [°]	$42\,^{+19}_{-13}\,^{+6}_{-2}$



$B_s^0 \to D_s^{\pm} K^{\mp} \pi^+ \pi^-$ Analysis: Amplitude analysis

- Let's take it one step further:
- Time-dependent amplitude fit

Decay channel	$F_i^c[\%]$	$F_i^u[\%]$
$B_s^0 \to D_s^{\mp}\,(K_1(1270)^{\pm} \to K^*(892)^0\,\pi^{\pm})$	$13.0 \pm 2.4 \pm 2.7 \pm 3.4$	$4.1 \pm 2.2 \pm 2.9 \pm 2.6$
$B_s^0 \to D_s^{\mp}\,(K_1(1270)^{\pm} \to K^{\pm}\,\rho(770)^0)$	$16.0 \pm 1.4 \pm 1.8 \pm 2.1$	$5.1 \pm 2.2 \pm 3.5 \pm 2.0$
$B_s^0 \to D_s^{\mp}\,(K_1(1270)^{\pm} \to K_0^*(1430)^0\,\pi^{\pm})$	$3.4 \pm 0.5 \pm 1.0 \pm 0.4$	$1.1 \pm 0.5 \pm 0.6 \pm 0.5$
$B_s^0 \to D_s^{\mp}\,(K_1(1400)^{\pm} \to K^*(892)^0\,\pi^{\pm})$	$63.9 \pm 5.1 \pm 7.4 \pm 13.5$	$19.3 \pm 5.2 \pm 8.3 \pm 7.8$
$B_s^0 \to D_s^{\mp}\,(K^*(1410)^{\pm} \to K^*(892)^0\,\pi^{\pm})$	$12.8 \pm 0.8 \pm 1.5 \pm 3.2$	$12.6 \pm 2.0 \pm 2.6 \pm 4.1$
$B_s^0 \to D_s^{\mp}\,(K^*(1410)^{\pm} \to K^{\pm}\,\rho(770)^0)$	$5.6 \pm 0.4 \pm 0.6 \pm 0.7$	$5.6 \pm 1.0 \pm 1.2 \pm 1.8$
$B_s^0 \to D_s^{\mp}\,(K(1460)^{\pm} \to K^*(892)^0\,\pi^{\pm})$		$11.9 \pm 2.5 \pm 2.9 \pm 3.1$
$B_s^0 \to (D_s^{\mp}\,\pi^{\pm})_P\;K^*(892)^0$	$10.2 \pm 1.6 \pm 1.8 \pm 4.5$	$28.4 \pm 5.6 \pm 6.4 \pm 15.3$
$B_s^0 \to (D_s^{\mp}\,K^{\pm})_P\;\rho(770)^0$	$0.9 \pm 0.4 \pm 0.5 \pm 1.0$	
Sum	$125.7 \pm 6.4 \pm 6.9 \pm 19.9$	$88.1 \pm 7.0 \pm 10.0 \pm 20.9$

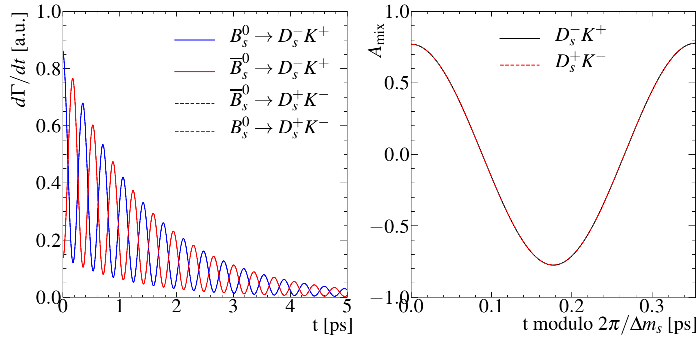


Parameter	Model-independent	Model-dependent
r	$0.47\,^{+0.08}_{-0.08}\,^{+0.02}_{-0.03}$	$0.56 \pm 0.05 \pm 0.04 \pm 0.07$
κ	$0.88\,^{+0.12}_{-0.19}\,^{+0.04}_{-0.07}$	$0.72 \pm 0.04 \pm 0.06 \pm 0.04$
$\delta\ [^\circ]$	$-6\,^{+10}_{-12}\,^{+2}_{-4}$	$-14 \pm 10 \pm 4 \pm 5$
$\gamma - 2\beta_s\ [^\circ]$	$42\,^{+19}_{-13}\,^{+6}_{-2}$	$42 \pm 10 \pm 4 \pm 5$

Gain in precision

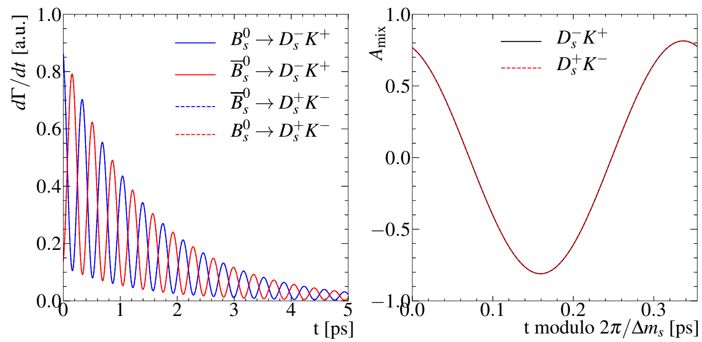
Comparison: $B_s^0 \rightarrow D^{\pm}_s K^{\mp} \pi^+ \pi^-$ vs $B_s^0 \rightarrow D^{\pm}_s K^{\mp}$

- Illustration of weak and strong phase:



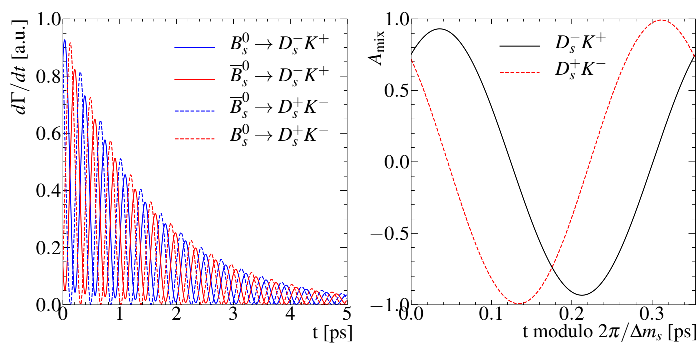
(a) Effect of interference for $r = 0.4$, $\delta = 0$, $\gamma = 0$.

δ=0, γ=0



(b) Effect of the strong phase difference $r = 0.4$, $\delta = 20°$, $\gamma = 0$.

δ=20, γ=0



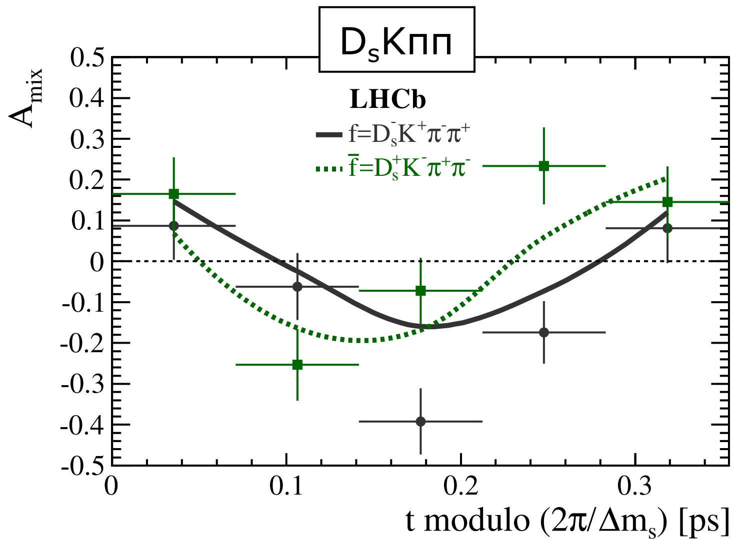
(c) Effect of the weak phase difference $r = 0.4$, $\delta = 20°$, $\gamma = 70°$.

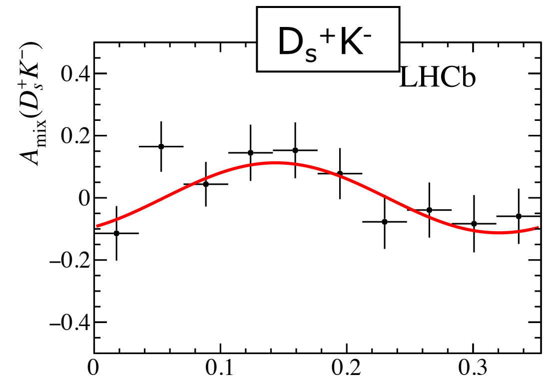
δ=20, γ=70

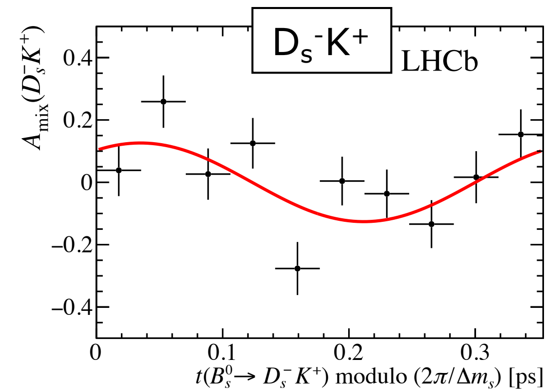
Quantum oscillations of neutral particles with the beauty quark / Veronesi, Michele CERN-THESIS-2021-193

Comparison: $B_s^0 \to D_s^{\pm} K^{\mp} \pi^+ \pi^-$ vs $B_s^0 \to D_s^{\pm} K^{\mp}$

- Confirmed results with identical code...







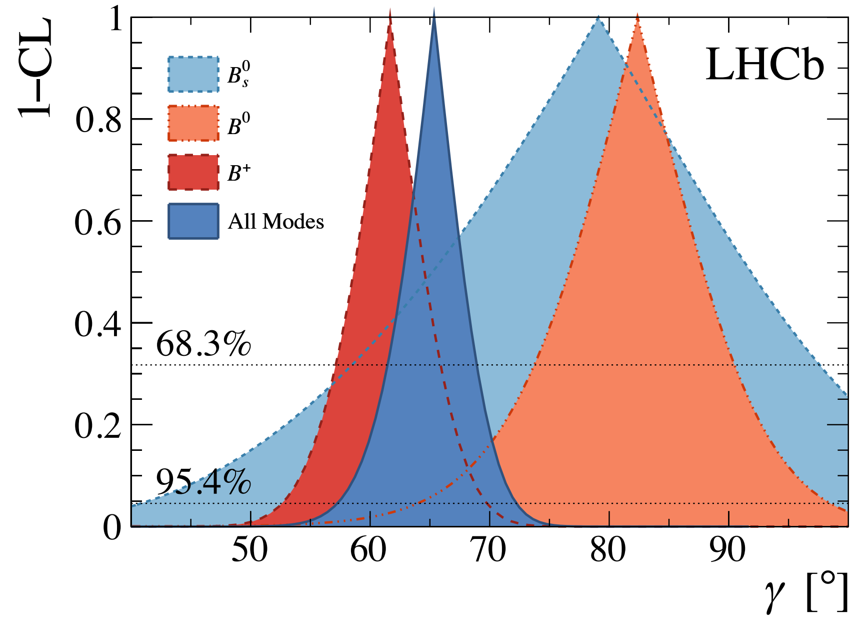
Parameter	Model-independent
r	$0.47\,^{+0.08}_{-0.08}\,^{+0.02}_{-0.03}$
κ	$0.88\,^{+0.12}_{-0.19}\,^{+0.04}_{-0.07}$
δ [°]	$-6\,^{+10}_{-12}\,^{+2}_{-4}$
$\gamma - 2\beta_s$ [°]	$42\,^{+19}_{-13}\,^{+6}_{-2}$

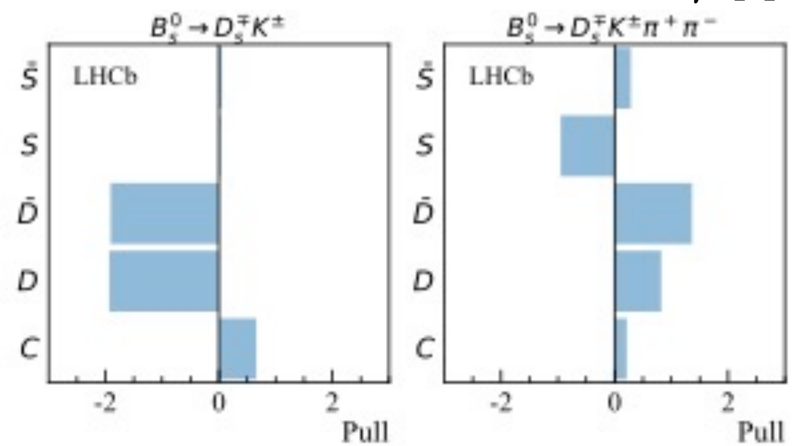
$$\gamma = (128\,^{+17}_{-22})^\circ\,,$$
$$\delta = (358\,^{+13}_{-14})^\circ\,,$$
$$r_{D_sK} = 0.37\,^{+0.10}_{-0.09}\,,$$

γ from $B_s^0 \to D_s^{\pm} K^{\mp}\pi^+\pi^-$ and $B_s^0 \to D_s^{\pm} K^{\mp}$

- Contribution to γ average

	Measurement	χ^2	No. of obs.
Beauty sector	$B^{\pm} \to Dh^{\pm}, D \to h^{\pm}h'^{\mp}$	2.71	8
	$B^{\pm} \to Dh^{\pm}, D \to h^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$	7.36	8
	$B^{\pm} \to Dh^{\pm}, D \to h^{\pm}h'^{\mp}\pi^{0}$	7.14	11
	$B^{\pm} \to Dh^{\pm}, D \to K_S^0 h^{+}h^{-}$	4.67	6
	$B^{\pm} \to Dh^{\pm}, D \to K_S^0 K^{\pm}\pi^{\mp}$	7.57	7
	$B^{\pm} \to D^{*}h^{\pm}, D \to h^{\pm}h'^{\mp}$	7.31	16
	$B^{\pm} \to DK^{*\pm}, D \to h^{\pm}h'^{\mp}(\pi^{+}\pi^{-})$	3.71	12
	$B^{0} \to DK^{*0}, D \to h^{\pm}h'^{\mp}(\pi^{+}\pi^{-})$	9.45	12
	$B^{0} \to DK^{*0}, D \to K_S^0 h^{+}h^{-}$	3.26	4
	$B^{\pm} \to Dh^{\pm}\pi^{+}\pi^{-}, D \to h^{\pm}h'^{\mp}$	1.34	11
	$B_s^0 \to D_s^{\mp}K^{\pm}$	5.71	5
	$B_s^0 \to D_s^{\mp}K^{\pm}\pi^{+}\pi^{-}$	2.88	5
	$B^{0} \to D^{\mp}\pi^{\pm}$	0.00	2





LHCb Coll., arXiv:2110.02350
"Simultaneous determination of CKM angle γ and charm mixing parameters"
JHEP 12 (2021) 141

Detecting CP violation with B decays

1) CP violation: CKM and the SM
2) Detecting: Detector requirements
3) B-decays: sin2β, ϕ_s, $B_s^0 \rightarrow D_s^+ K^-$