Introduction to flavour experiments

In memoriam of Sheldon Stone (Feb. 14, 1946 – Oct. 6, 2021)

https://cerncourier.com/a/sheldon-stone-1946-2021/

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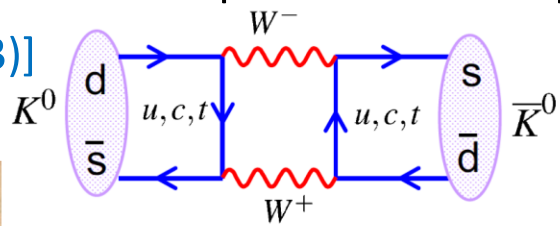
Outline

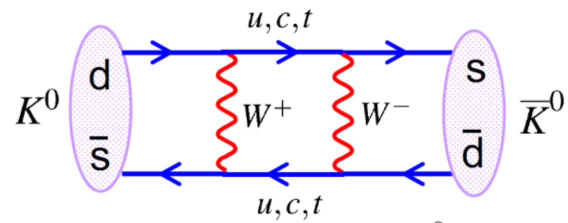
- Lesson 1: Introduction to flavour physics
- Lesson 2: The CKM matrix
- Lesson 3: Rare decays of heavy hadrons
- Lesson 4: Mixing and CP violation

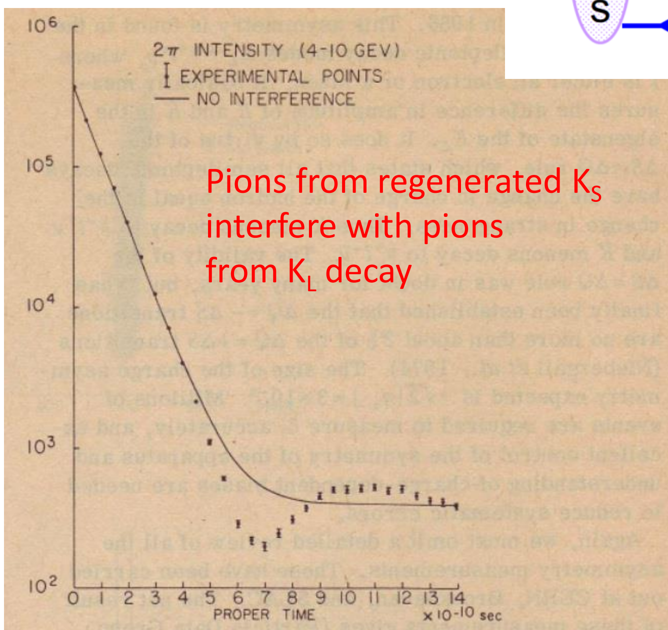
Mixing and CP violation

- Neutral mesons oscillates between particles and antiparticles (for K^0, D^0, B^0)

[PhysRev.132.2285 (1963)]





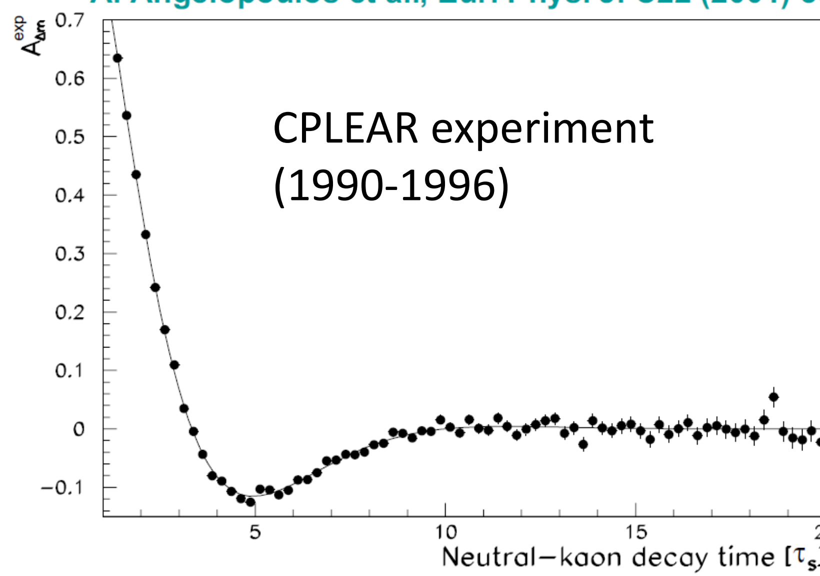


Pions from regenerated K_S interfere with pions from K_L decay

FIG. 2. Yield of $\pi^+\pi^-$ events as a function of proper time downstream from an 81 cm carbon regenerator placed in a K_L beam. Figure taken from thesis of T. Modis, Columbia University (1973); a published version of this work is given by Carithers *et al*. (1975).

James W. Cronin

A. Angelopoulos et al., Eur. Phys. J. C22 (2001) 55



CPLEAR experiment (1990-1996)

$$m(K_S) \approx m(K_L) \approx 498\,\mathrm{MeV}$$

$$\tau(K_S) = 0.9 \times 10^{-10}\,\mathrm{s}$$

$$\tau(K_L) = 0.5 \times 10^{-7}\,\mathrm{s}$$

$$|K_S\rangle \equiv \frac{1}{\sqrt{2}}(|K^0\rangle - |\overline{K}^0\rangle) \qquad K_S \to \pi\pi$$

$$|K_L\rangle \equiv \frac{1}{\sqrt{2}}(|K^0\rangle + |\overline{K}^0\rangle) \qquad K_L \to \pi\pi\pi$$

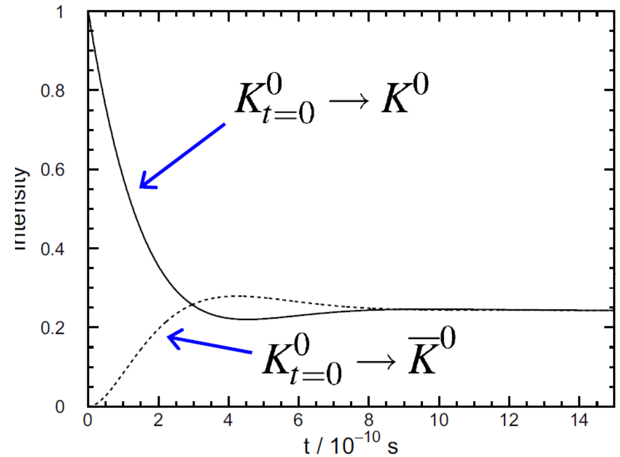
Mixing and CP violation

- The probability of oscillations is given by:

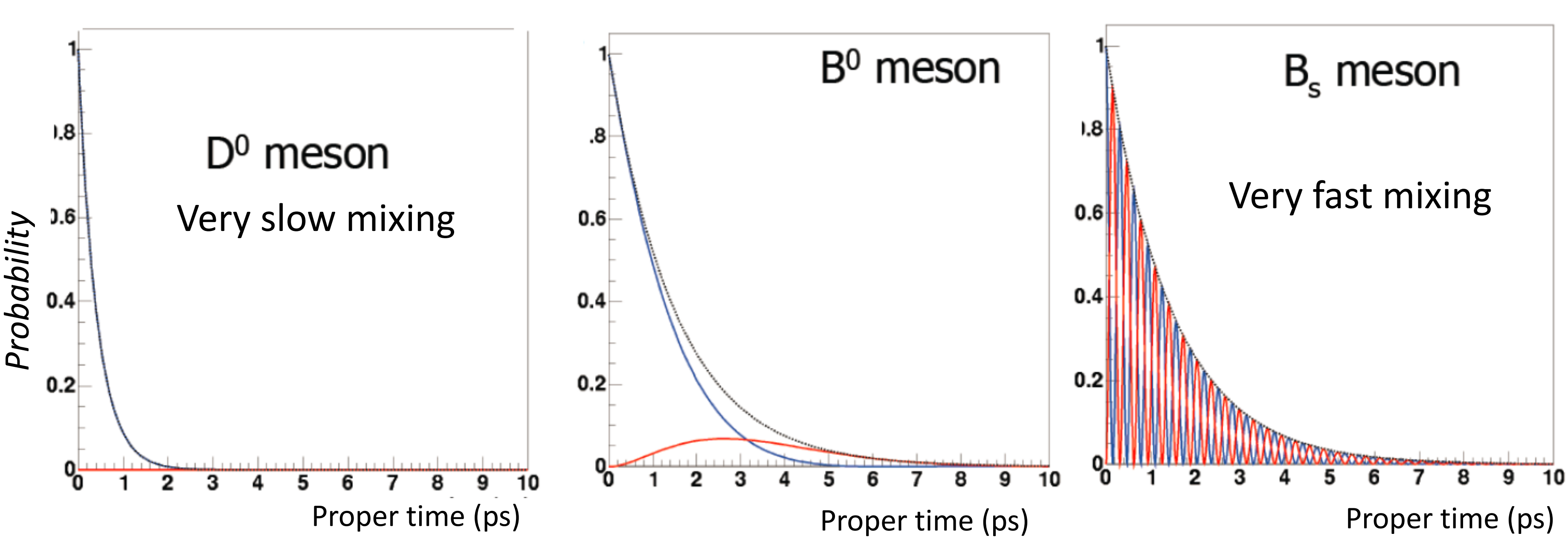
$$\Gamma(K^0_{t=0} \to K^0) = \frac{1}{4}\left[e^{-\Gamma_S t} + e^{-\Gamma_L t} + 2e^{-(\Gamma_S+\Gamma_L)t/2}\cos\Delta m t\right]$$

$$\Gamma(K^0_{t=0} \to \overline{K}^0) = \frac{1}{4}\left[e^{-\Gamma_S t} + e^{-\Gamma_L t} - 2e^{-(\Gamma_S+\Gamma_L)t/2}\cos\Delta m t\right]$$

$$\Delta m = m(K_L) - m(K_S) = (3.506 \pm 0.006) \times 10^{-15}\,\text{GeV}$$



- For charm and beauty systems:



B mixing and CP violation

Mixing of neutral B mesons governed by

$$i\frac{\partial}{\partial t}\begin{pmatrix}a\\b\end{pmatrix} = H\begin{pmatrix}a\\b\end{pmatrix} = \begin{pmatrix}M_{11}-\frac{i}{2}\Gamma_{11} & M_{12}-\frac{i}{2}\Gamma_{12}\\ M_{12}^*-\frac{i}{2}\Gamma_{12}^* & M_{22}-\frac{i}{2}\Gamma_{22}\end{pmatrix}\begin{pmatrix}a\\b\end{pmatrix}$$

Mass eigenstates:

$$|B_{L,H}\rangle = p|B^0\rangle \pm q|\overline{B^0}\rangle$$

p and q represent the amount of state mixing

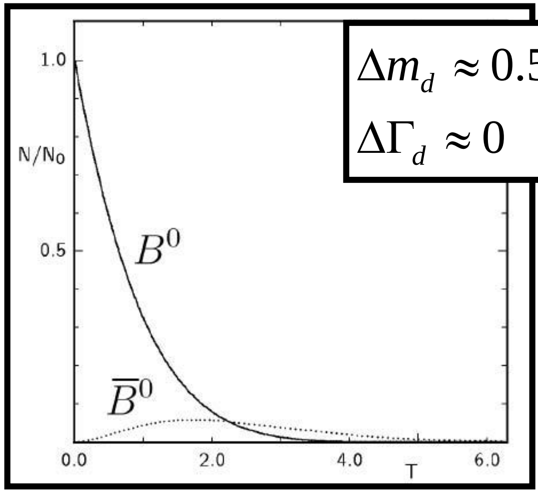
$$|p|^2 + |q|^2 = 1$$

$$|q/p| = 1$$

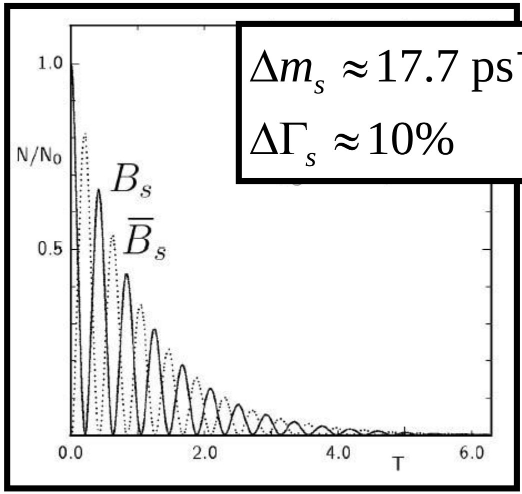
$$\frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}$$

$$\Delta m = m_H - m_L = 2|M_{12}|$$

$$\Delta\Gamma = \Gamma_L - \Gamma_H = 2|\Gamma_{12}|$$



$$\Delta m_d \approx 0.505\ \text{ps}^{-1}$$
$$\Delta\Gamma_d \approx 0$$

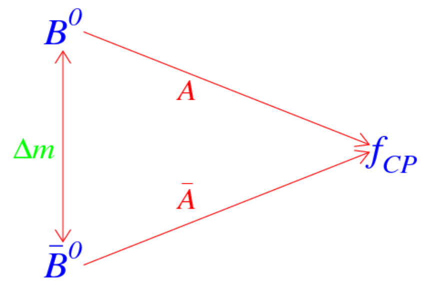


$$\Delta m_s \approx 17.7\ \text{ps}^{-1}$$
$$\Delta\Gamma_s \approx 10\%$$

B mixing and CP violation

Decay amplitudes of flavour states decaying to the same final state f

$$A_f = \langle f | H | B^0 \rangle \quad \overline{A_f} = \langle f | H | \overline{B^0} \rangle$$



One can define $\lambda_f = \dfrac{q}{p} \dfrac{\overline{A_f}}{A_f}$

$\tau \equiv 1/\Gamma$

$x \equiv \Delta m/\Gamma$

$y \equiv \Delta\Gamma/2\Gamma$

Time dependence of decay rate for initially pure flavour states:

$$\Gamma_f \equiv \left| \langle f | H | B^0(t) \rangle \right|^2 = \frac{1+|\lambda_f|^2}{2} |A_f|^2 e^{-t/\tau} \left[\cosh yt/\tau + A_{\Delta f} \sinh yt/\tau + C_f \cos xt/\tau - S_f \sin xt/\tau \right]$$

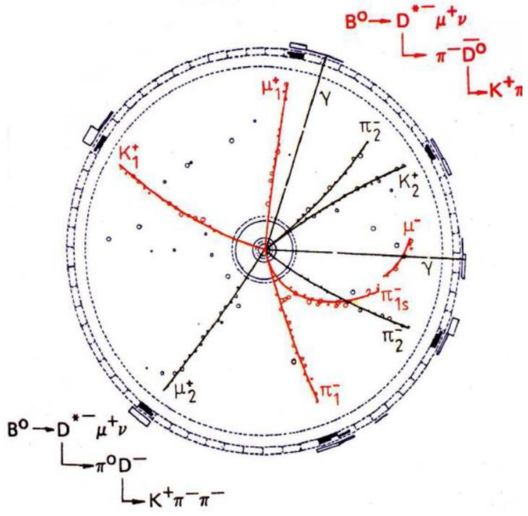
$$\overline{\Gamma}_f \equiv \left| \langle f | H | \overline{B}^0(t) \rangle \right|^2 = \frac{1+|\lambda_f|^2}{2} \left| \frac{p}{q} A_f \right|^2 e^{-t/\tau} \left[\cosh yt/\tau + A_{\Delta f} \sinh yt/\tau - C_f \cos xt/\tau + S_f \sin xt/\tau \right]$$

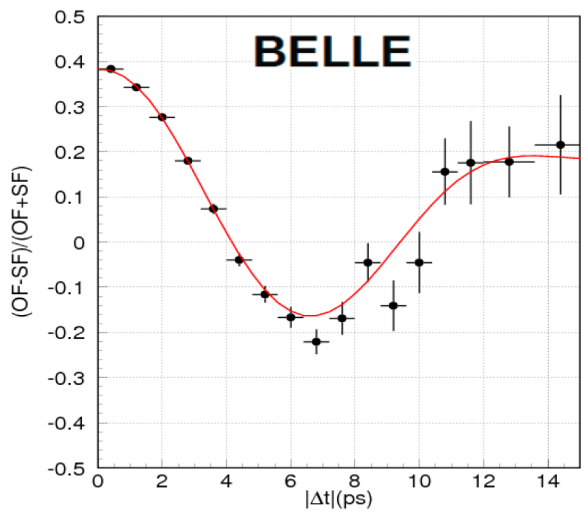
$$S_f \equiv \frac{2\,\mathrm{Im}\lambda_f}{1+|\lambda_f|^2} \qquad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \qquad A_{\Delta f}^2 + S_f^2 + C_f^2 = 1$$

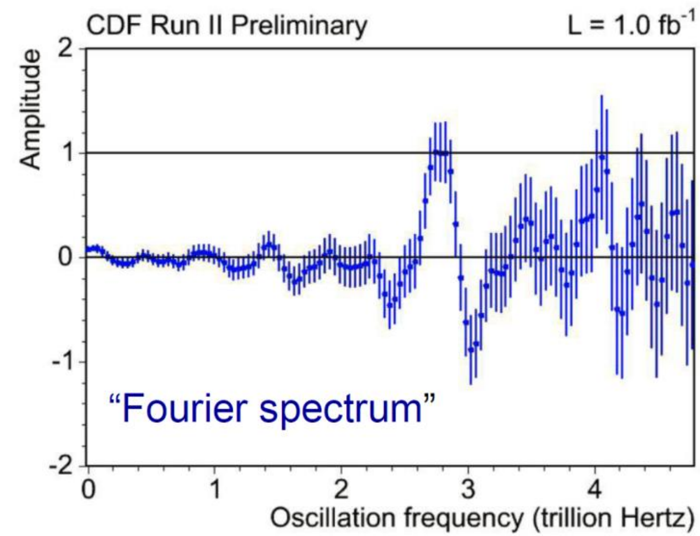
B mixing and CP violation

[Phys.Lett.B 192 (1987) 245-252]

[Phys.Rev.Lett.97 (2006) 062003]



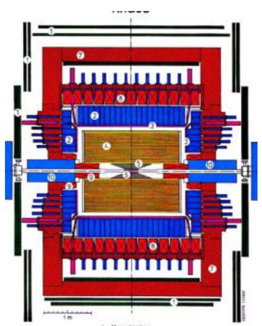


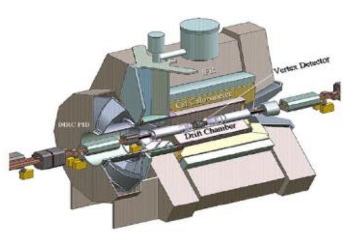


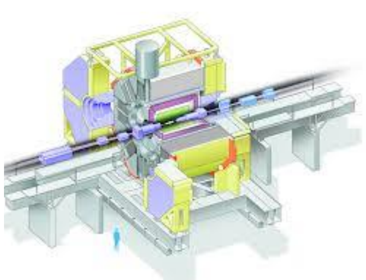
First observation
of B oscillations
at ARGUS (1987) (DESY)

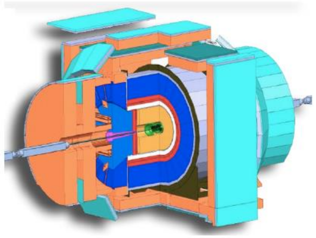
Precise measurements of
the B oscillation frequency
at B factories!

First evidence of B_s
oscillations at CDF
(Fermilab)









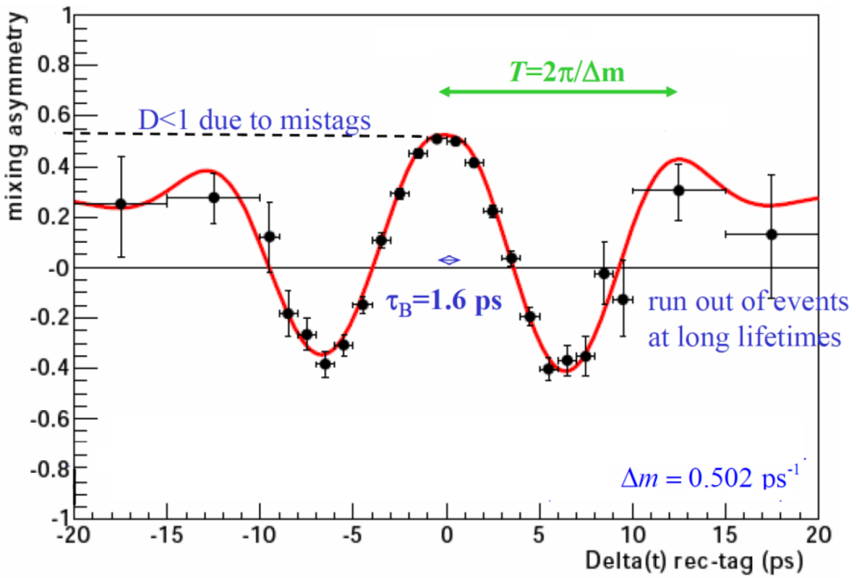
B mixing and CP violation

How to measure the B oscillation frequency?

$$\left(\frac{dN}{dt}\right)_{\text{nomix}} = \frac{1}{4\tau_B} \cdot e^{-\Gamma t} \cdot \left[1 + \cos(\Delta m_d \cdot t)\right]$$

$$\left(\frac{dN}{dt}\right)_{\text{mix}} = \frac{1}{4\tau_B} \cdot e^{-\Gamma t} \cdot \left[1 - \cos(\Delta m_d \cdot t)\right]$$

$$\Rightarrow A_{\text{mix}} = \frac{\left(\frac{dN}{dt}\right)_{\text{nomix}} - \left(\frac{dN}{dt}\right)_{\text{mix}}}{\left(\frac{dN}{dt}\right)_{\text{nomix}} + \left(\frac{dN}{dt}\right)_{\text{mix}}} = \cos(\Delta m \cdot t)$$



To measure the mixing asymmetry we need to know:

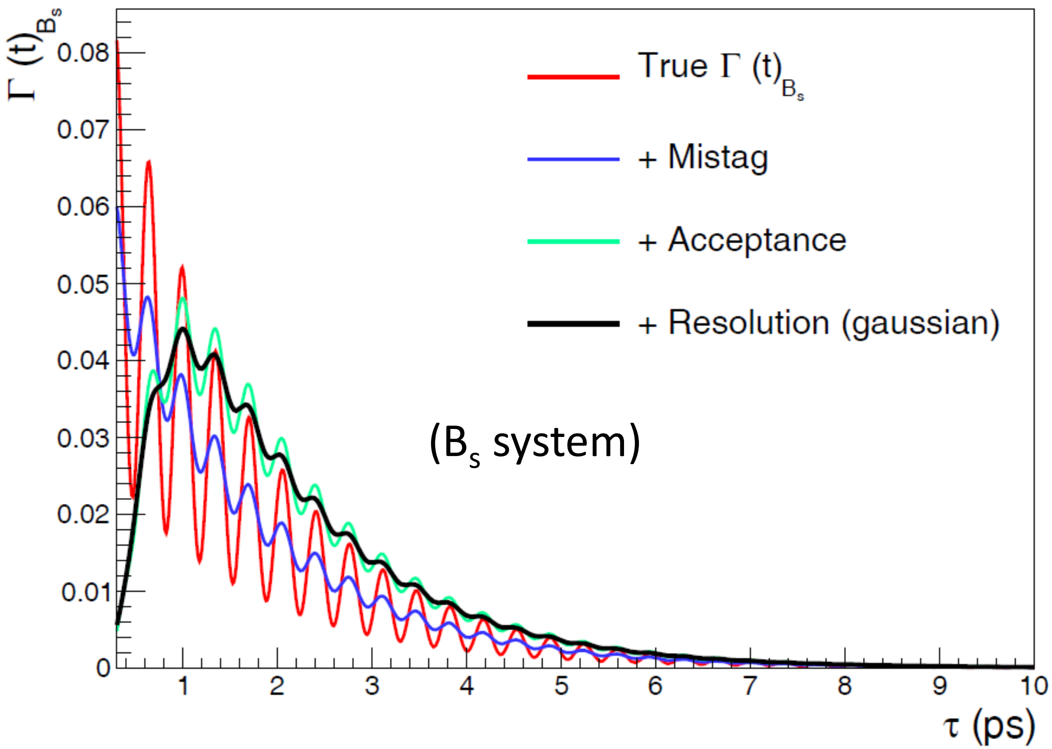
- When it was produced, was the meson a B^0 or anti-B^0?
- When it decayed, was the meson a B^0 or anti-B^0?
- What is the time difference between production and decay

Including experimental effects $A_{\text{mix}} \rightarrow \; = \{(1-2\omega) \times \cos \Delta m \Delta t\} \otimes R(\Delta t)$

B mixing and CP violation

- Experimental effects:

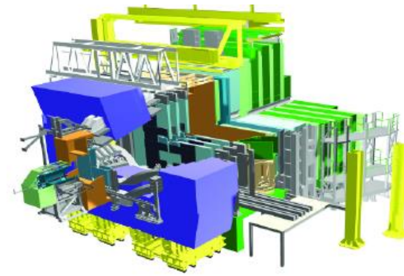
  Dilution of the oscillation (lost of sensitivity of the oscillation parameters) due to reconstruction effects



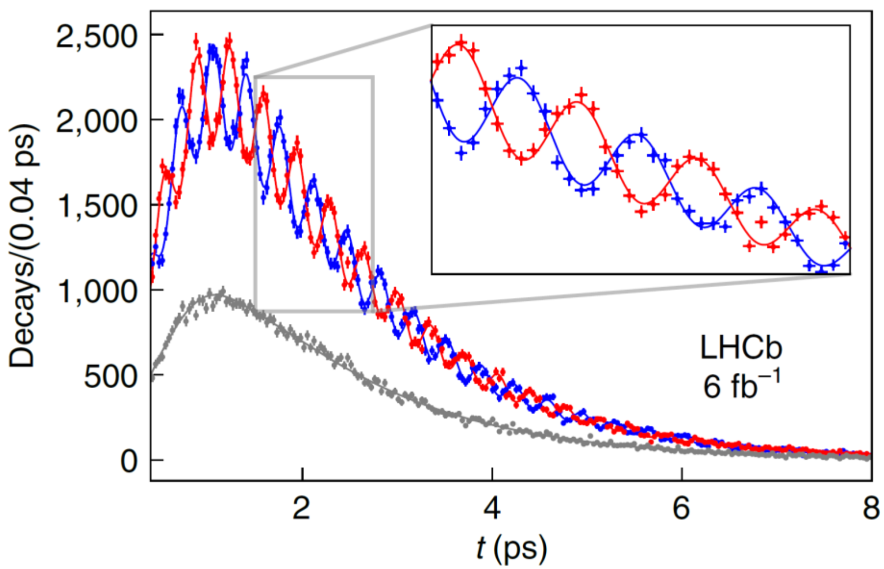
$$A_{mix}(t)\,\frac{N^{unmix}(t)-N^{mix}(t)}{N^{unmix}(t)+N^{mix}(t)} = \cos\Delta mt \quad \Rightarrow \quad = \{(1-2\omega)\times\cos\Delta m\Delta t\}\otimes R(\Delta t)$$

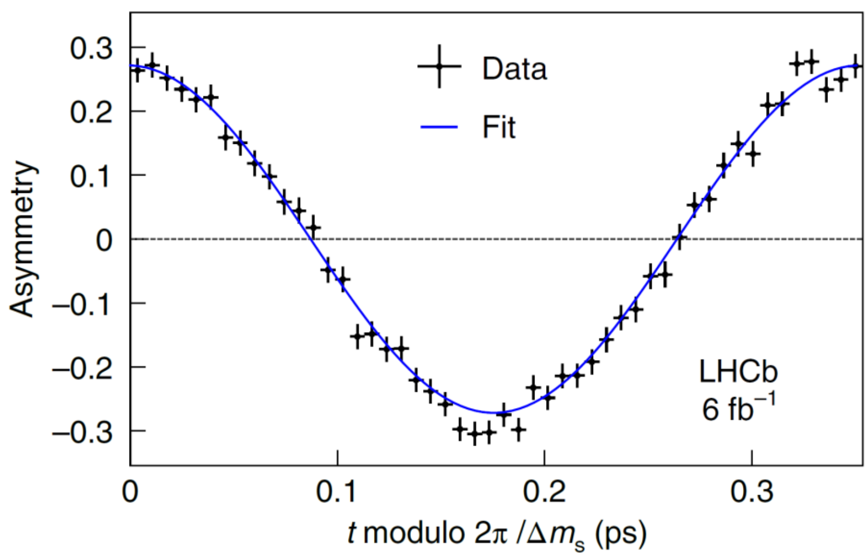
B mixing and CP violation

Precise measurement of Δm_s at LHCb:



$$A(t) = \frac{N(B_s^0 \to D_s^- \pi^+, t) - N(\overline{B}_s^0 \to D_s^- \pi^+, t)}{N(B_s^0 \to D_s^- \pi^+, t) + N(\overline{B}_s^0 \to D_s^- \pi^+, t)}$$



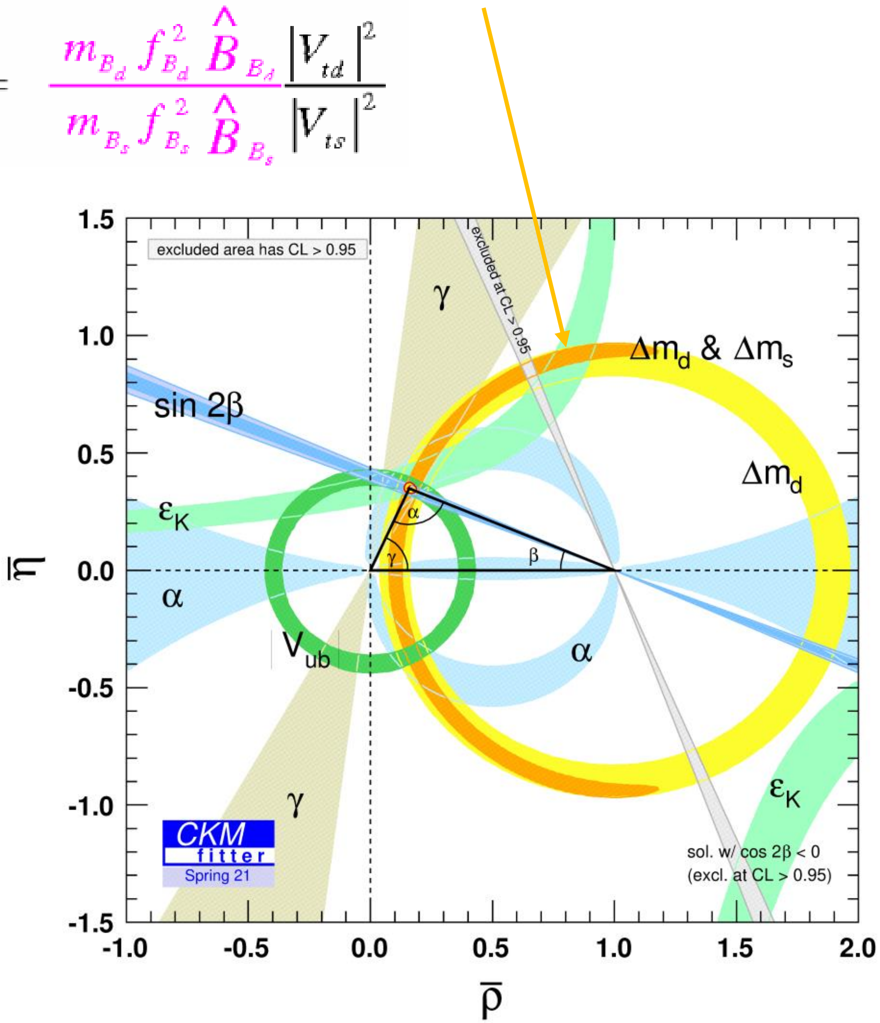


$$\Delta m_s = 17.768 \pm 0.023(stat) \pm 0.006(syst)\ ps^{-1}$$

B mixing and CP violation

Constraints on the CKM unitary triangle:

$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d} |V_{td}|^2}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s} |V_{ts}|^2}$$



Combining measurements of LEP, B factories, CDF, CMS, and LHCb

(HFLAV 2021)

$\Delta m_d = (0.5065 \pm 0.0019)\ ps^{-1}$

$\Delta m_s = (17.741 \pm 0.020)\ ps^{-1}$

B mixing and CP violation

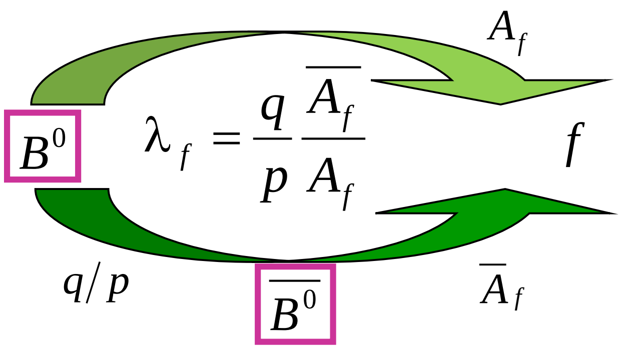
CP Violation $\rightarrow \Gamma_f \neq \overline{\Gamma}_f$

Three types:

- **CPV in Decay:** $B^0 \rightarrow f \quad \neq \quad \overline{B^0} \rightarrow \overline{f}$ $\qquad \left| \frac{\overline{A}_{\overline{f}}}{A_f} \right| \neq 1$
- **CPV in Mixing:** $B^0 \rightarrow \overline{B^0} \quad \neq \quad \overline{B^0} \rightarrow B^0$ $\qquad \left| \frac{q}{p} \right| \neq 1$ $\qquad \mathrm{Im}\left\{\Gamma_{12}^* M_{12}\right\} \neq 0$
- **CPV in Interference between mixing and decay:**

$$\left|\lambda_f\right| = 1, \quad \mathrm{Im}\left\{\lambda_f\right\} \neq 0$$

$$A_f^{CP}(t) = \frac{\Gamma_f(t) - \overline{\Gamma}_f(t)}{\Gamma_f(t) + \overline{\Gamma}_f(t)} = \frac{-C_f \cos(\Delta m t) + S_f \sin(\Delta m t)}{\cosh(\Delta\Gamma t/2) + A_{\Delta f} \sinh(\Delta\Gamma t/2)}$$



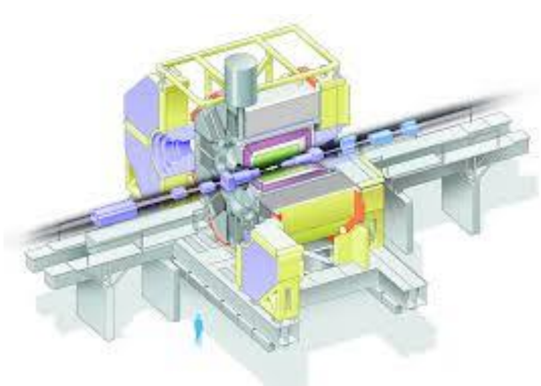
B mixing and CP violation

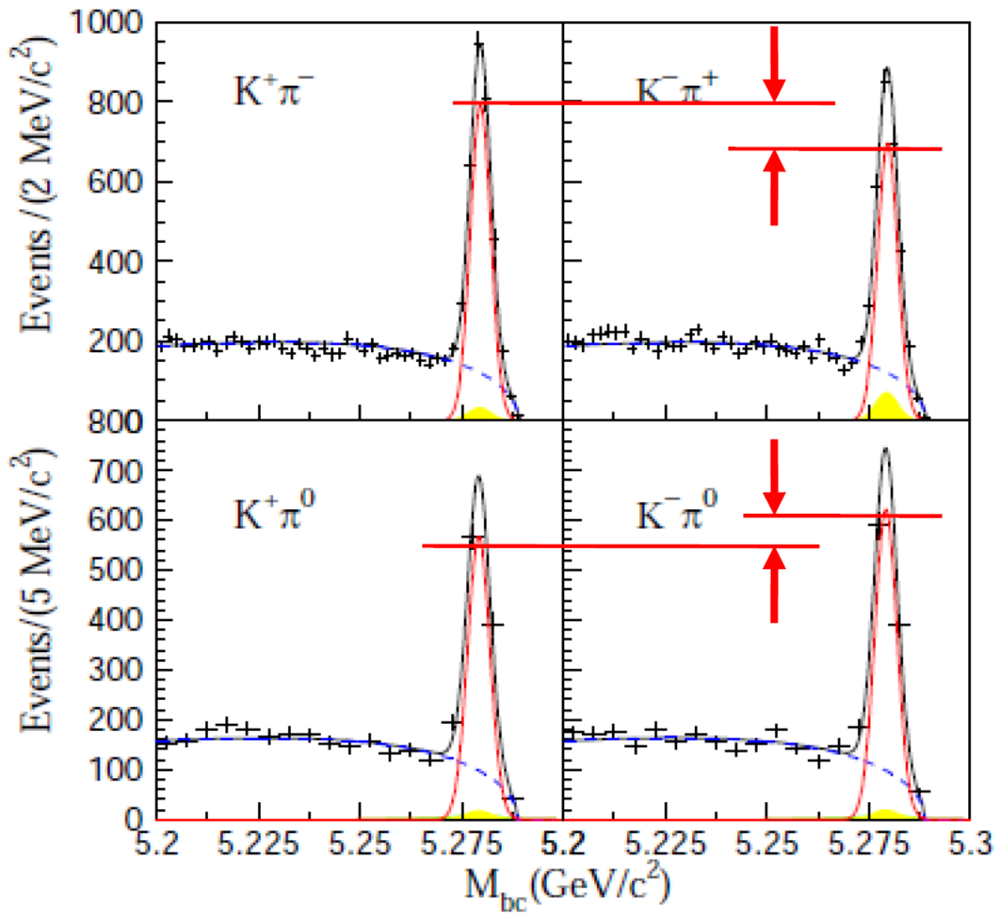
Direct CP violation in the B $\rightarrow$ Kπ system

$$A_{CP}(B^0 \to K\pi) = \frac{\Gamma(\overline{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(\overline{B}^0 \to K^-\pi^+) + \Gamma(B^0 \to K^+\pi^-)}$$

At Belle, 772 M B$\overline{\text{B}}$ events:

[Belle, PRD 87, 031103 (2013)]





B mixing and CP violation

How to measure the time dependent CP asymmetry?

Determine the initial state (tag from the other B) [flavor tagging]

$$A_{CP}(\Delta t) \equiv \frac{\Gamma\left(\overline{B}^0(\Delta t) \to f_{CP}\right) - \Gamma\left(B^0(\Delta t) \to f_{CP}\right)}{\Gamma\left(\overline{B}^0(\Delta t) \to f_{CP}\right) + \Gamma\left(B^0(\Delta t) \to f_{CP}\right)}$$

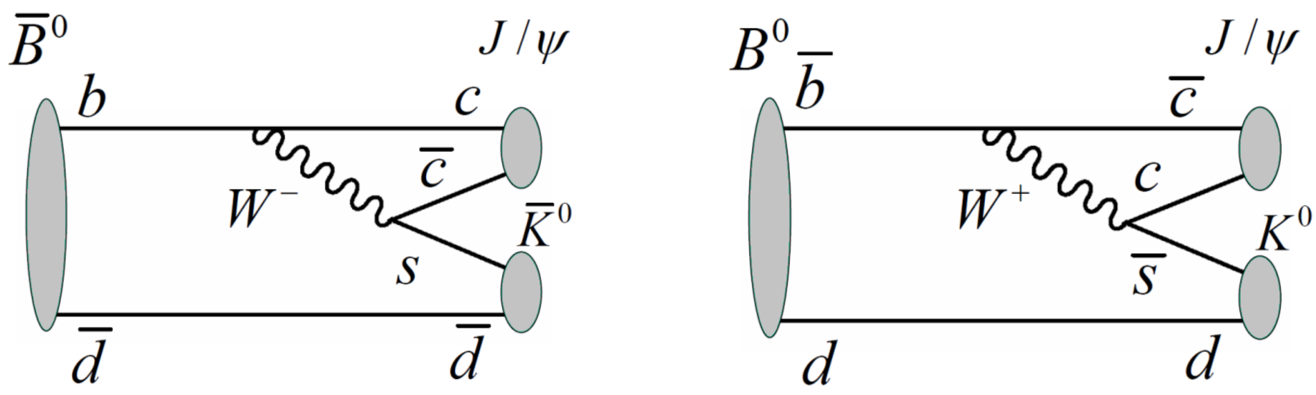
Reconstruct the final state system

[PID]

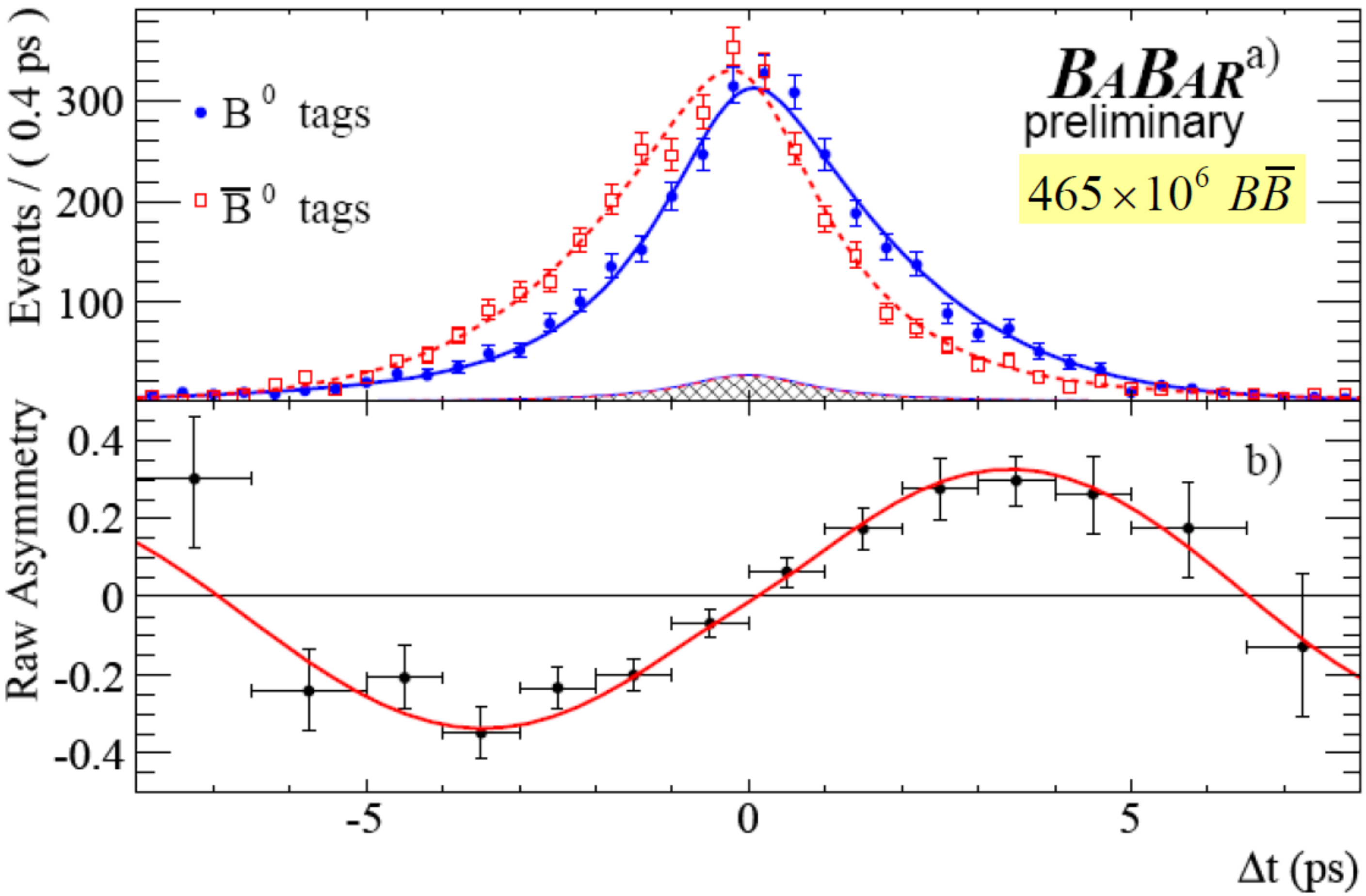
Measure the time dependence

[time resolution]

One example: $B^0 \to J/\psi\, K^0$



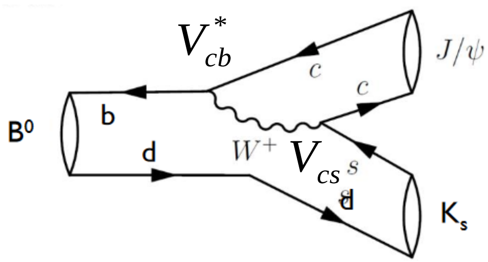
B mixing and CP violation

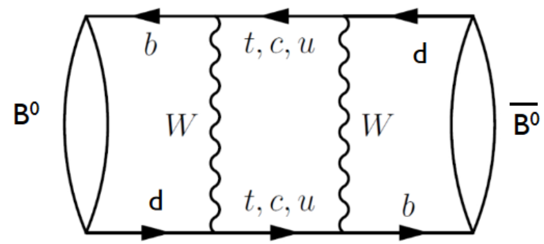


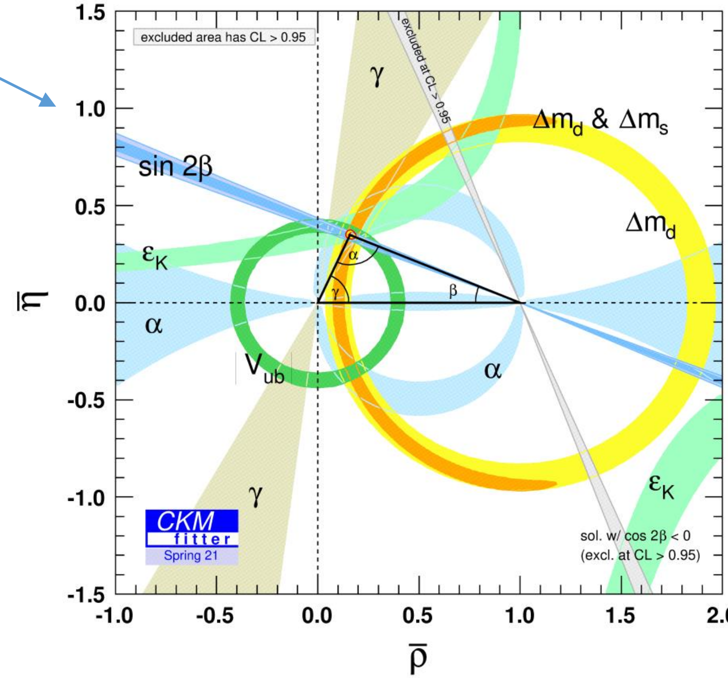
B mixing and CP violation

Measuring the β angle of the CKM triangle

Golden channel: $B^0 \to J/\psi\, K^0$







$$A_f^{CP}(t) = \frac{\Gamma_f(t) - \bar{\Gamma}_f(t)}{\Gamma_f(t) + \bar{\Gamma}_f(t)} = \frac{-C_f \cos(\Delta m t) + S_f \sin(\Delta m t)}{\cosh(\Delta\Gamma t/2) + A_{\Delta f} \sinh(\Delta\Gamma t/2)}$$

$$\sim -C_f \cos(\Delta m t) + S_f \sin(\Delta m t)$$

$$S_f \equiv \frac{2\,\mathrm{Im}\lambda_f}{1 + |\lambda_f|^2}$$

$$\mathrm{Im}\{\lambda_f\} = \mathrm{Im}\{-e^{-2i\beta}\} = \sin 2\beta$$

C_f ~0 in the SM

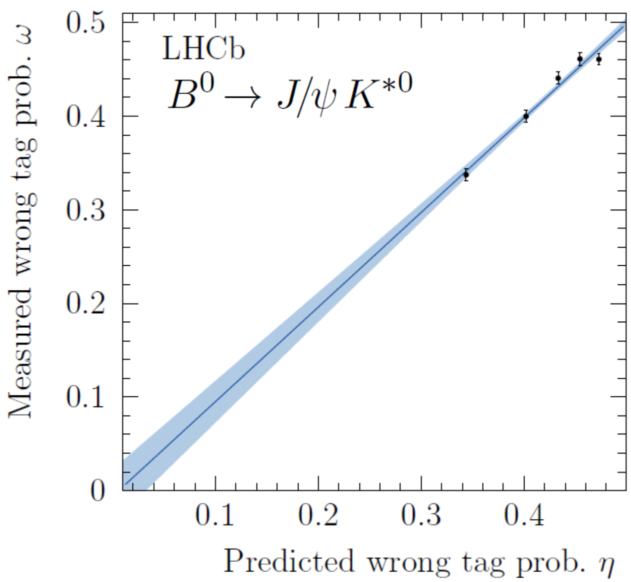
$$A_f^{CP}(t) \sim \sin 2\beta \sin(\Delta m t)$$

B mixing and CP violation

Count number of tagged signal events reconstructed as function of time

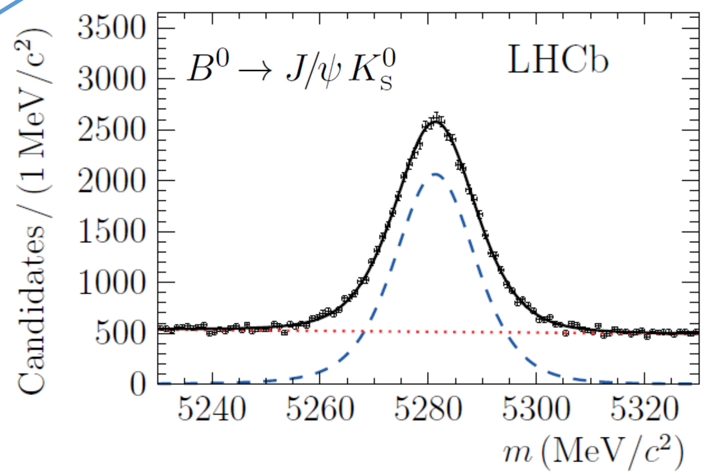
$$A_{CP}(t) = \frac{N\left(B_{tag} = B^0\right) - N\left(B_{tag} = \overline{B}^0\right)}{N\left(B_{tag} = B^0\right) + N\left(B_{tag} = \overline{B}^0\right)} \approx \pm\left\{(1-2\omega) \times \sin 2\beta \times \sin(\Delta m \Delta t)\right\} \otimes \mathrm{R}(\Delta t)$$

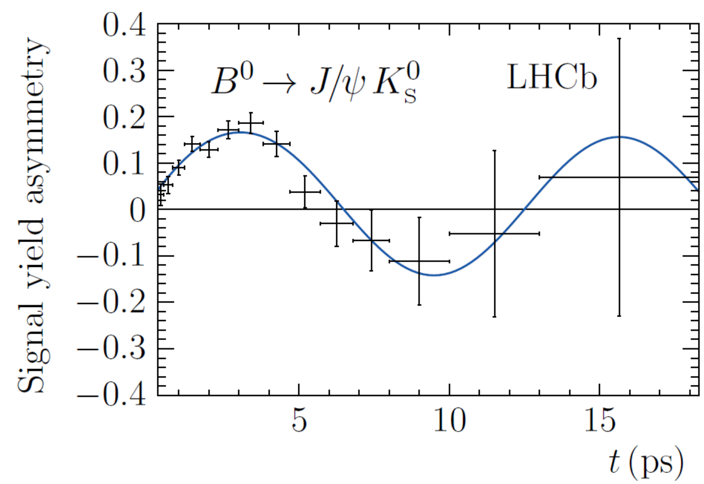
Flavour mistag calibrated using a control sample flavour specific ($K^{*0} \to K^- \pi^+$)



$\omega = (35.62 \pm 0.12)\,\%$

$\varepsilon_{\rm tag} = (36.54 \pm 0.14)\,\%$





B mixing and CP violation

CKM fitter:
http://ckmfitter.in2p3.fr/