Search for CP violation in neutral B meson decays

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Contents

C and P Operators

- Charge conjugation (C) replaces a particle by its antiparticle:

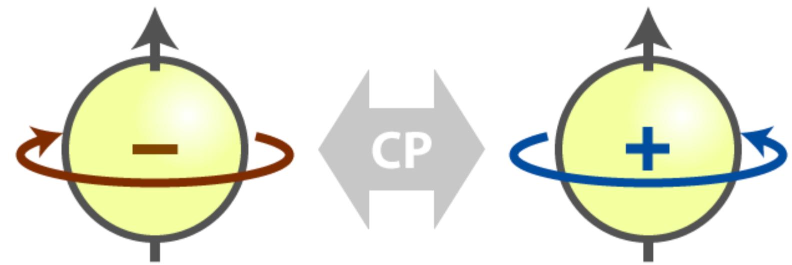
$$p \to \bar{p}$$

- Parity (P) reverses the spatial coordinates:

$$(t, \vec{x}) \to (t, -\vec{x})$$

CP Transformation

- CP transformation replaces a particle by its antiparticle and takes its mirror image



- Intuitively, we expect physics to remain the same under CP transformation

Symmetry Violation

- However, CP symmetry is violated in weak interactions.

“*If you don't like it, go somewhere else, to another universe!*” – Richard Feynman

CKM Matrix

- Quarks change flavour through charged weak interactions ($W^{\pm}$)
- The weak eigenstates are constructed by rotating the mass eigenstates with the Cabbibo-Kobayashi-Maskawa (CKM) matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \mathrm{V_{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} \mathrm{V_{ud}} & \mathrm{V_{us}} & \mathrm{V_{ub}} \\ \mathrm{V_{cd}} & \mathrm{V_{cs}} & \mathrm{V_{cb}} \\ \mathrm{V_{td}} & \mathrm{V_{ts}} & \mathrm{V_{tb}} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

CP Symmetry

- The charged current part of the SM Lagrangian is given by:

$$\mathcal{L}_{\mathrm{CC}} = -\frac{g}{2\sqrt{2}}\left[(\mathrm{V}_{\mathrm{CKM}})_{ij}\,\bar{u}_i W_\mu^+ \gamma^\mu (1-\gamma^5) d_j + (\mathrm{V}^*_{\mathrm{CKM}})_{ij}\,\bar{d}_j W_\mu^- \gamma^\mu (1-\gamma^5) u_i\right]$$

- Under CP transformation, the Lagrangian becomes:

$$\mathcal{L}^{\mathrm{CP}}_{\mathrm{CC}} = -\frac{g}{2\sqrt{2}}\left[(\mathrm{V}_{\mathrm{CKM}})_{ij}\,\bar{d}_j W_\mu^- \gamma^\mu (1-\gamma^5) u_i + (\mathrm{V}^*_{\mathrm{CKM}})_{ij}\,\bar{u}_i W_\mu^+ \gamma^\mu (1-\gamma^5) d_j\right]$$

- CP symmetry requires real matrix elements:

$$(\mathrm{V}^*_{\mathrm{CKM}})_{ij} = (\mathrm{V}_{\mathrm{CKM}})_{ij}$$

CP Violation

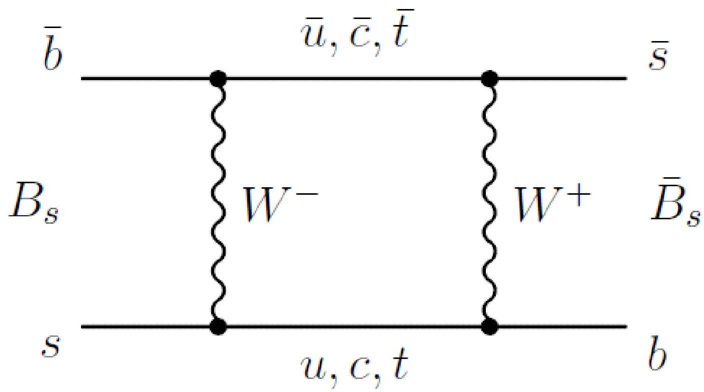
- The standard parametrisation of the CKM matrix is:

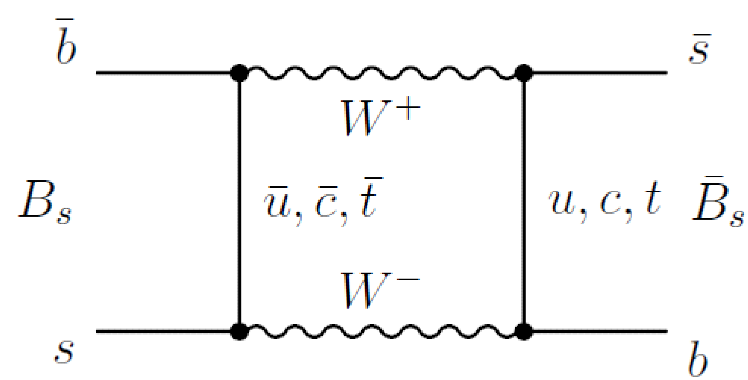
$$V_{\mathrm{CKM}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}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

- The phase factor δ leads to CP Violation.

Neutral B Meson Mixing

- B mesons oscillate between particle and antiparticle





- The Schrodinger equation governs the time evolution of the flavour eigenstates:

$$i\frac{\partial}{\partial t}\begin{pmatrix}|\mathrm{B}_\mathrm{q}^0\rangle \\ |\bar{\mathrm{B}}_\mathrm{q}^0\rangle\end{pmatrix} = \left(\mathrm{M} - \tfrac{i}{2}\Gamma\right)\begin{pmatrix}|\mathrm{B}_\mathrm{q}^0\rangle \\ |\bar{\mathrm{B}}_\mathrm{q}^0\rangle\end{pmatrix}$$

Neutral B Meson Mixing

- Diagonalising the Hamiltonian gives mass eigenstates in terms of flavour eigenstates:

$$\begin{aligned} |\mathrm{B_L}\rangle &= p|\mathrm{B_q^0}\rangle + q|\mathrm{\bar{B}_q^0}\rangle \\ |\mathrm{B_H}\rangle &= p|\mathrm{B_q^0}\rangle - q|\mathrm{\bar{B}_q^0}\rangle \end{aligned}$$

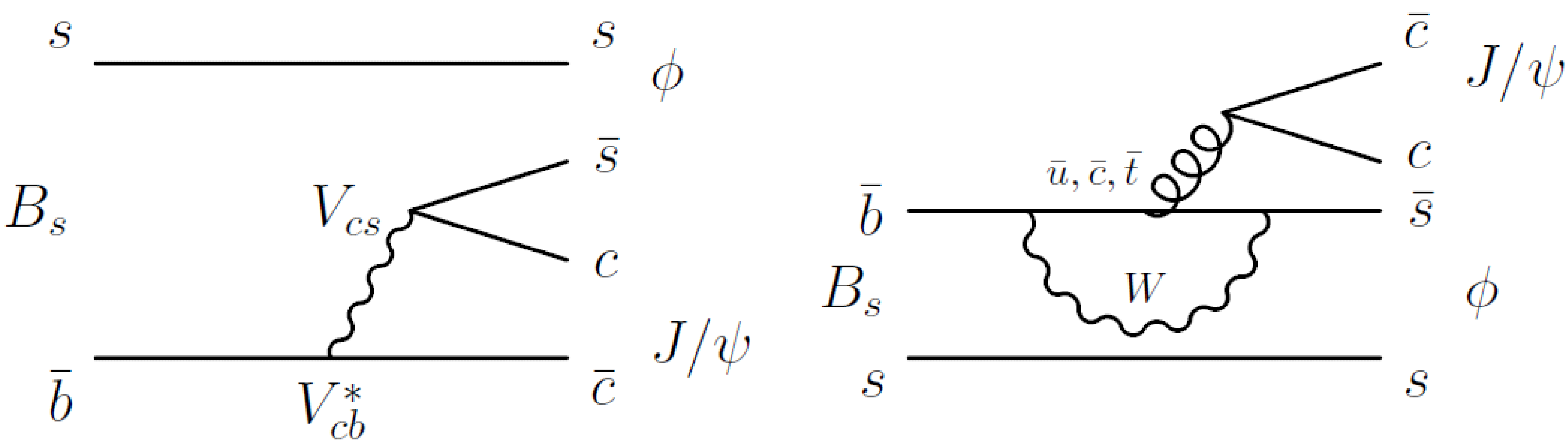
- These states evolve as:

$$\begin{aligned} |\mathrm{B_L}(t)\rangle &= e^{-i\mathrm{M_L t}} e^{-\frac{\Gamma_\mathrm{L}}{2}t} |\mathrm{B_L}\rangle \\ |\mathrm{B_H}(t)\rangle &= e^{-i\mathrm{M_H t}} e^{-\frac{\Gamma_\mathrm{H}}{2}t} |\mathrm{B_H}\rangle \end{aligned}$$

Neutral B meson decay

- Neutral B mesons have several decay modes.

- We study the decay channel $B_s^0 \to J/\psi\phi$:



(a) Tree contribution (b) Penguin contribution

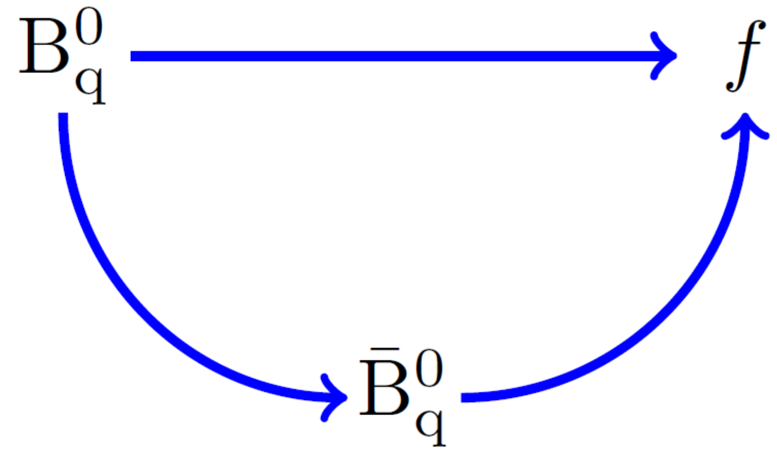
CP violation in direct decay

- Decay amplitudes depend on CKM matrix elements
- CP violation leads to different decay rates for the process $B_s^0 \rightarrow J/\psi\phi$ and its CP conjugate $\overline{B_s^0} \rightarrow \mathrm{J}/\psi\phi$.
- To characterise the degree of violation, we define the asymmetry parameter:

$$\mathcal{A}_{\mathrm{CP}} = \frac{\Gamma(\bar{\mathrm{B}}_{\mathrm{q}}^0 \to f) - \Gamma(\mathrm{B}_{\mathrm{q}}^0 \to \overline{f})}{\Gamma(\bar{\mathrm{B}}_{\mathrm{q}}^0 \to f) + \Gamma(\mathrm{B}_{\mathrm{q}}^0 \to \overline{f})}$$

Mixing Induced CP Violation

- Direct decay $B_s^0 \to J/\psi\phi$ interferes with oscillation $B_s^0 \leftrightarrow \overline{B_s^0}$ and subsequent decay $\overline{B_s^0} \to J/\psi\phi$.



- This gives rise to time-dependent CP asymmetry.

Mixing Induced CP Violation

- The time-dependent asymmetry parameter is given by:

$$\mathcal{A}_{\mathrm{CP}}(t) = \frac{-\eta_{\mathrm{J}/\psi\phi}\sin(\phi_s)\sin(\Delta m_{\mathrm{s}}t)}{\cosh\left(\frac{\Delta\Gamma_{\mathrm{s}}}{2}t\right) - \eta_{\mathrm{J}/\psi\phi}\cos(\phi_s)\sinh\left(\frac{\Delta\Gamma_{\mathrm{s}}}{2}t\right)}$$

$$\Delta m = \mathrm{M_H} - \mathrm{M_L}$$

$$\Delta\Gamma = \Gamma_{\mathrm{L}} - \Gamma_{\mathrm{H}}.$$

ϕ_s arises from the interference between direct and indirect decay

LHC Measurements

- Data collected by the ATLAS detector from LHC pp collisions has been used to determine
  - asymmetry phase ϕ_s
  - rate difference $\Delta\Gamma_s = \Gamma_L - \Gamma_H$
  - mean rate $\Gamma = \frac{\Gamma_L + \Gamma_H}{2}$
- Experiments performed with collision parameters:

$$\sqrt{s} = 7 \text{ TeV}$$

Integrated luminosity 4.9 fb^{-1}

Results

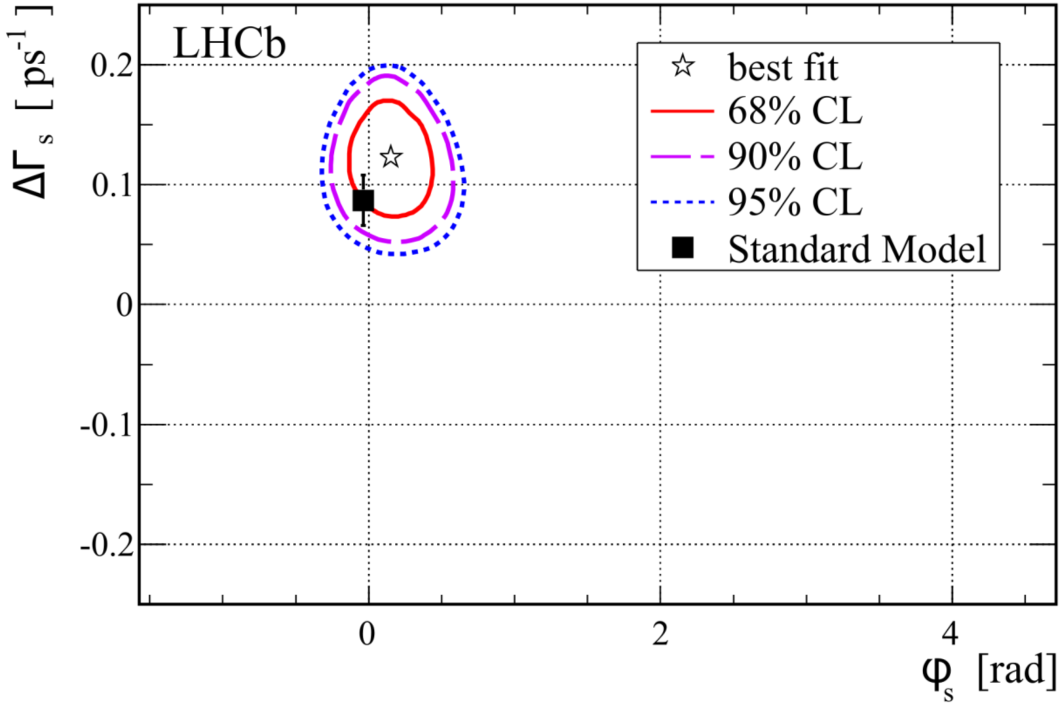
$$\phi_s = 0.22 \pm 0.41 \text{ (stat.)} \pm 0.10 \text{ (syst.) rad}$$

$$\Delta\Gamma_s = 0.053 \pm 0.021 \text{ (stat.)} \pm 0.010 \text{ (syst.) ps}^{-1}$$

$$\Gamma_s = 0.677 \pm 0.007 \text{ (stat.)} \pm 0.004 \text{ (syst.) ps}^{-1}$$

Results

- Measurements consistent with standard model predictions



Danke!