$\sin(2\beta)$ with $B^0 \to J/\psi K^0_S$ at the LHCb experiment

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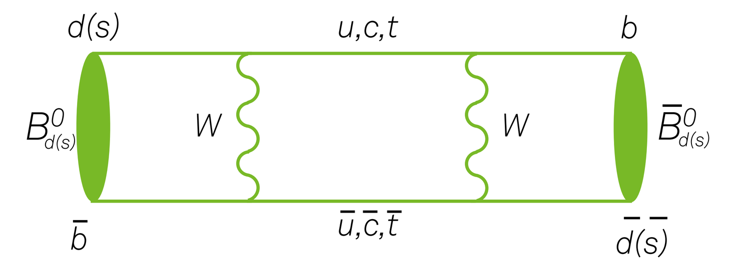
CP Violation in Neutral Meson Systems

Neutral B Meson Mixing

Neutral B mesons oscillate between their matter and antimatter state. The oscillation frequency is proportional to Δm, which is the mass difference between the heavy and the light mass eigenstate of the B meson.

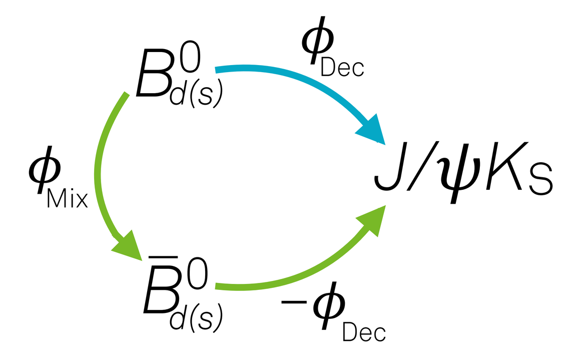


Interference CP Violation

In a final state common to both the B and $\bar{B}$, the interference of the direct decay and the decay after oscillation leads to a decay rate asymmetry that depends on the decay time t

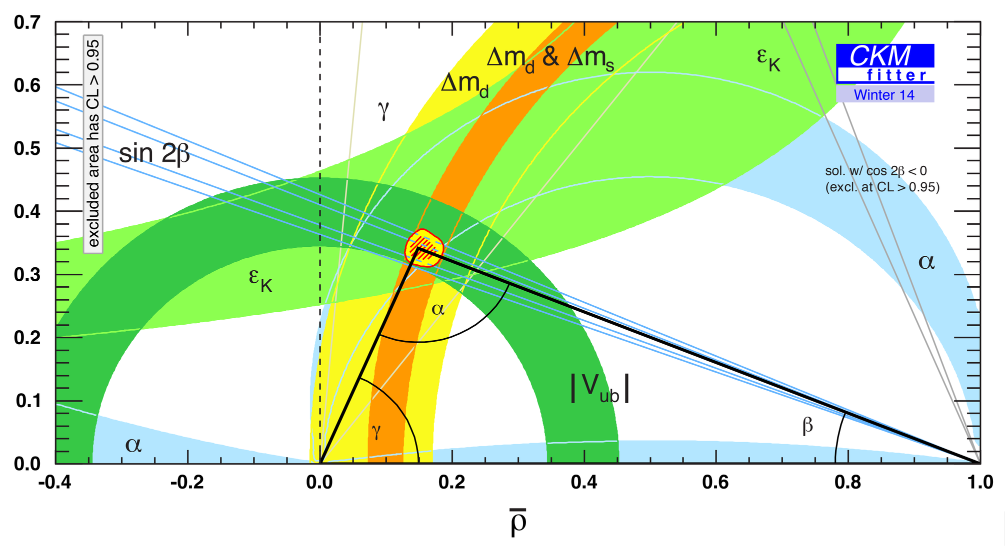
$$\mathcal{A}_{CP}(t) \equiv \frac{\Gamma(\bar{B}(t)\to f) - \Gamma(B(t)\to f)}{\Gamma(\bar{B}(t)\to f) + \Gamma(B(t)\to f)} = \frac{S\sin(\Delta m\, t) - C\cos(\Delta m\, t)}{\cosh(\Delta\Gamma\, t/2) + \mathcal{A}_{\Delta\Gamma}\sinh(\Delta\Gamma\, t/2)},$$

with $\Delta\Gamma$ being the decay width difference between the heavy and the light mass eigenstate of the B meson. The CP amplitudes S, C, and $\mathcal{A}_{\Delta\Gamma}$ provide sensitivity to the phase difference, $\phi_q = \phi_{\text{Mix}} - 2\phi_{\text{Dec}}$, between direct decay and decay after oscillation.



CP Parameter sin2β

The decay time-dependent CP asymmetry in the decay $B^0 \to J/\psi K^0_S$ provides access to $\beta = \arg[-(V_{cd}V^*_{cb})/(V_{td}V^*_{tb})]$, one of the angles of the CKM unitary triangle.



[1]

The $B^0 \to J/\psi K^0_S$ decay is dominated by a $b \to c\bar{c}s$ transition, where CP violation in decay is negligible ($C \approx 0$) and the decay width difference $\Delta\Gamma$ is compatible with zero.

$$\mathcal{A}_{CP}(t) = S\sin(\Delta m_d t) - C\cos(\Delta m_d t)$$
$$S = \sqrt{1-C^2}\cdot\sin(2\beta) \approx \sin(2\beta).$$

The measured averages of S and C by BaBar and Belle are [2][3]:

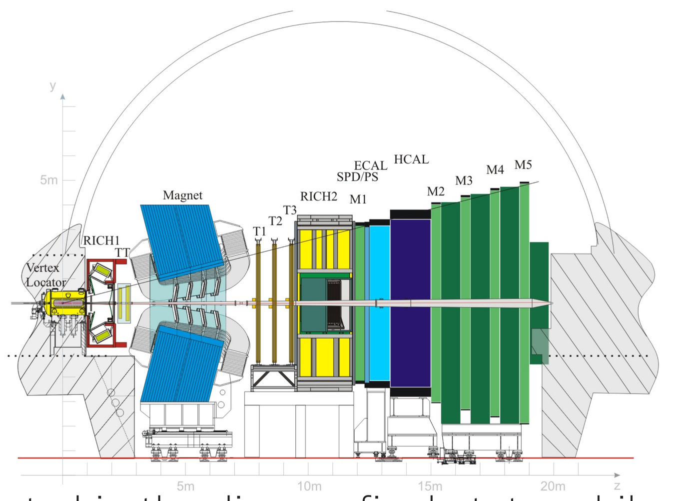
$$S(B^0 \to J/\psi K^0_S) = 0.665 \pm 0.024,$$
$$C(B^0 \to J/\psi K^0_S) = 0.024 \pm 0.026.$$

Dataset

The analysis is performed using a dataset taken with LHCb, corresponding to integrated luminosities of

- $1\,\text{fb}^{-1}$ at 7 TeV
- $2\,\text{fb}^{-1}$ at 8 TeV.

The B meson decays into a J/ψ and a K^0_S meson.

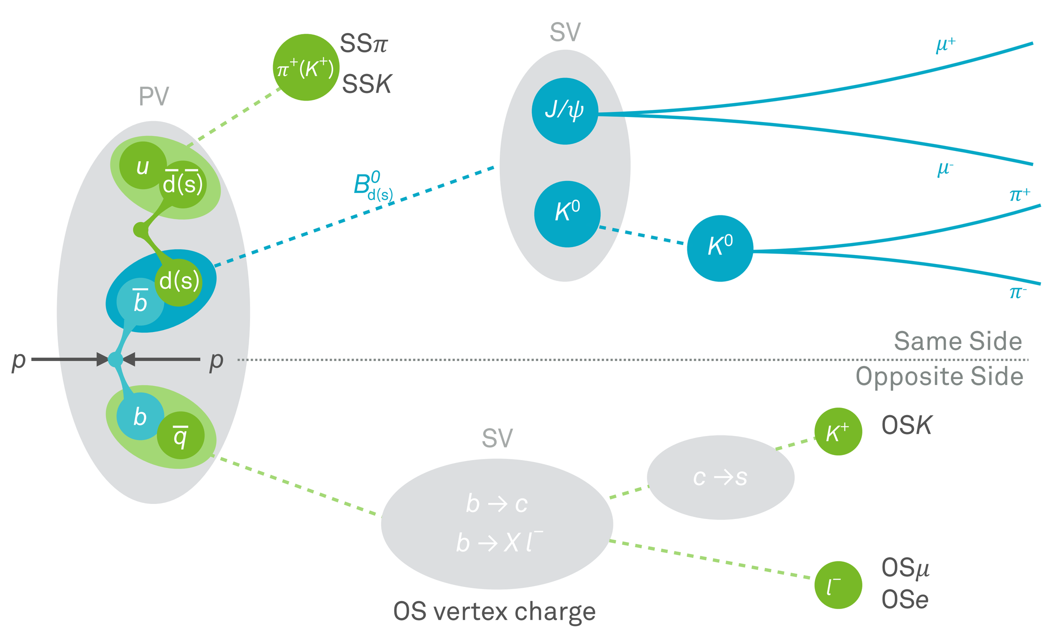


The J/ψ meson is reconstructed in the dimuon final state, while two oppositely charged pions are combined to form a K^0_S candidate.

Flavour Tagging

It is essential to determine the initial flavour of the neutral B meson. The flavour tagging algorithms provide:

- decision d on the flavour of the B candidate (tag)
- calibrated mistag probability ω of B candidates



The B^0 analysis uses a combination of the OSK, μ, e, vertex charge as well as the SSπ tagger. The effective tagging efficiency $\varepsilon_{\text{tag}}(1-2\omega)^2$ is the ratio between a hypothetically perfectly tagged number of signal candidates, leading to the same statistical precision, and the actually observed number with imperfect tagging. In the B^0 analysis an effective tagging efficiency of $\epsilon_{\text{eff}} = (3.02 \pm 0.05)\,\%$ is observed.

Measurement of CP Violation in $B^0 \to J/\psi K_S$

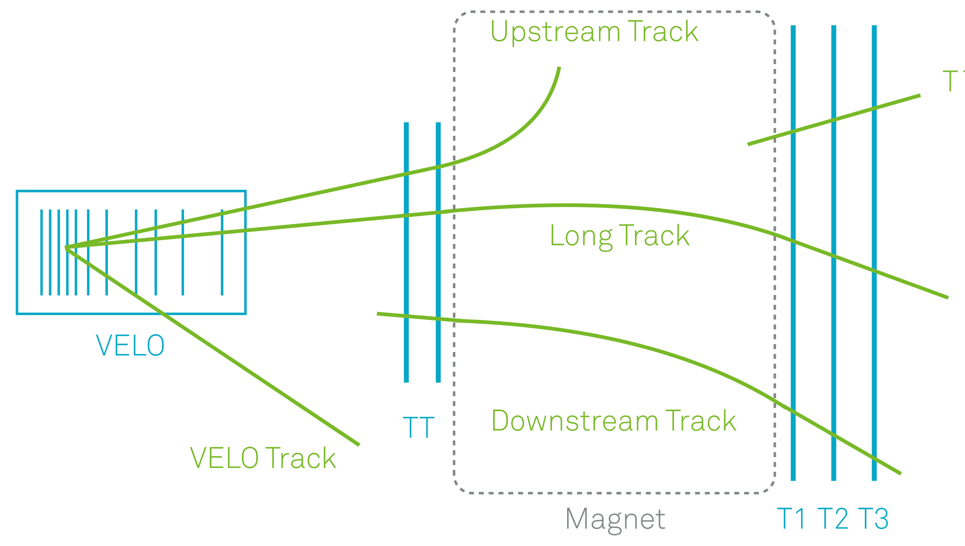
The data sample used in the analysis consists of 41 500 flavour tagged $B^0 \to J/\psi K^0_S$ decays.

Selection

Due to the long lifetime of the K^0_S meson, its daughter pions may not leave hits in different detector components. The analysis uses

- reconstructed long track
- reconstructed downstream track

pions. Different requirements are applied for the two types of K^0_S candidates.



After selection the data sample contains

- 29 % long track and
- 71 % downstream

reconstructed signal candidates.

Requirements comprise:

- kinematic variables and daughter masses
- quality of the reconstructed decay topology

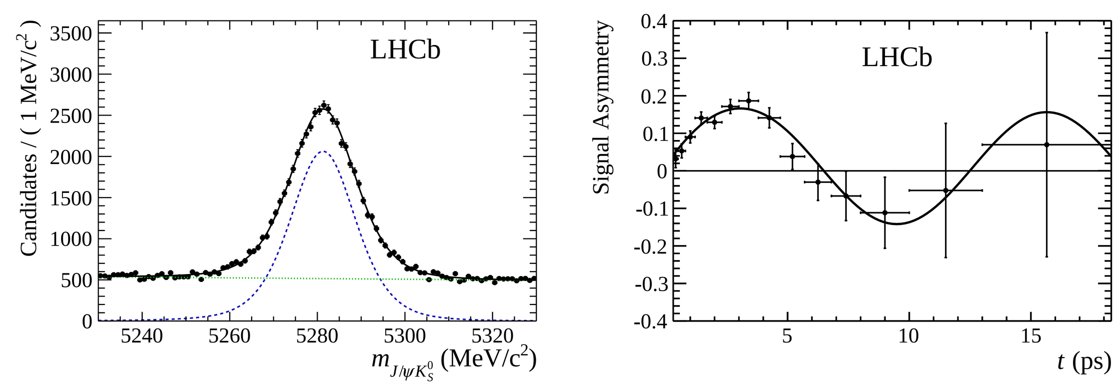
Fit Model

Multidimensional unbinned maximum likelihood fit in:

- reconstructed mass and decay time
- per-event decay time error estimate
- mistag probability estimates
- flavour tagging decisions

Fit model considers:

- production asymmetry
- tagging asymmetry



Systematic Uncertainties

Largest systematic uncertainties on S originate from

- ignoring tagging asymmetries in the background model
- uncertainties of the flavour tagging calibration
- assuming a vanishing decay width difference $\Delta\Gamma_d$.

Largest systematic uncertainties on C originate from

- systematic uncertainties on Δm_d
- uncertainties of the flavour tagging calibration.

Results

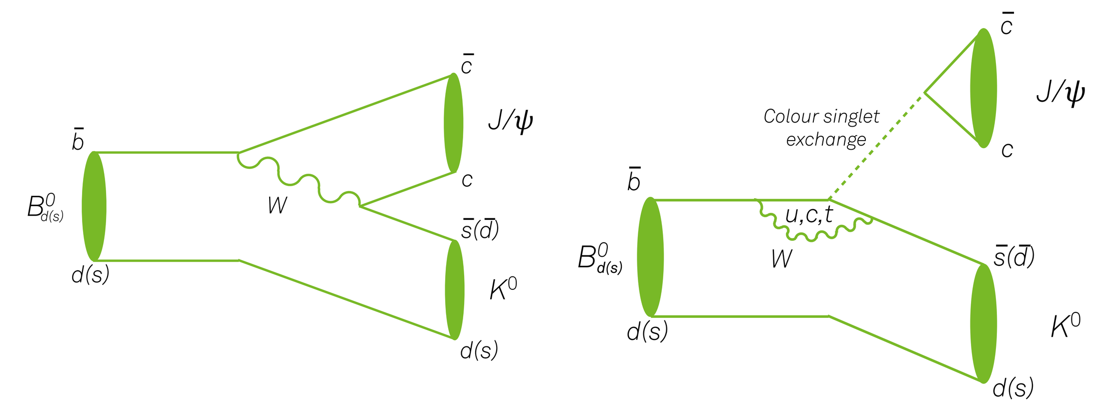
The measurement of the time-dependent asymmetry yields [4]

$$S(B^0 \to J/\psi K^0_S) = 0.731 \pm 0.035\,(\text{stat}) \pm 0.020\,(\text{syst}),$$
$$C(B^0 \to J/\psi K^0_S) = -0.038 \pm 0.032\,(\text{stat}) \pm 0.005\,(\text{syst}).$$

This is the most precise measurement of CP violation in $B^0 \to J/\psi K^0_S$ at a hadron collider, and in good agreement with the results of the B factories [2][3].

Controlling Theory Uncertainties on sin2β

Imposing $d \leftrightarrow s$ symmetry principles, $B^0_s \to J/\psi K^0_S$ decays can be used to determine the penguin pollution in $B^0 \to J/\psi K^0_S$ by measuring the decay time-dependent CP asymmetry.



In the B^0_s mode both, penguin and tree diagram, carry similar suppression factors. Major challenges of this analysis are:

- B^0_s 100 times less frequent than B^0 decays
- B^0_s oscillation frequency 35 higher than B^0 systems

Selection

Differences to the B^0 analysis:

- employment of two neural nets to eliminate
  - misreconstructed $B \to J/\psi K^*$ background decays
  - combinatorial background
- requirements to omit wrongly associated primary vertices

Tagging

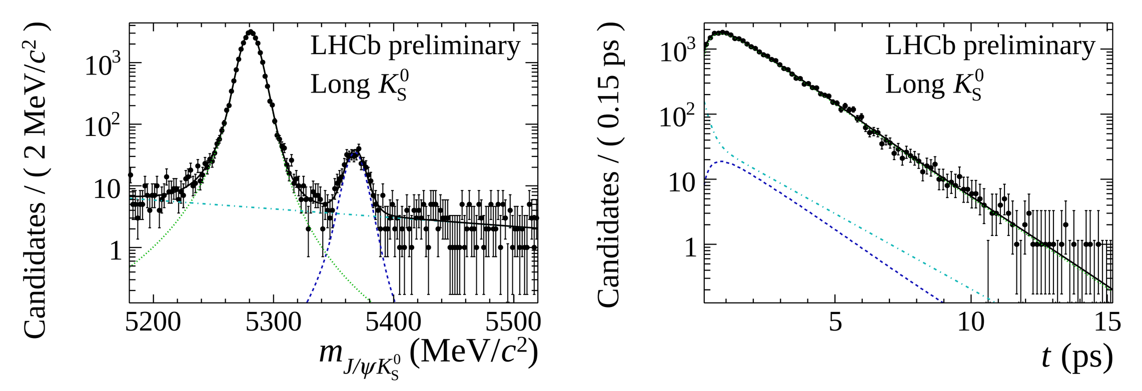
Compared to the B^0 analysis, the B^0_s analysis includes the SSK tagger. Additionally, the challenge is to deal with a response of this tagger for the B^0 candidates.

The total effective tagging efficiency is around

- 4 % for B^0_s signal candidates
- 2.6 % for B^0 signal candidates.

Fit Model

The multidimensional fit is similar to the $B^0 \to J/\psi K^0_S$ analysis. Though, besides the B^0_s signal candidates and the combinatorial background, it is necessary to describe the B^0 component as well.



The sample contains around 80000 B^0 and 900 B^0_s signal candidates.

Results

The measured CP parameters [5] are

$$\mathcal{A}_{\Delta\Gamma}(B^0_s \to J/\psi K^0_S) = 0.49 \pm^{0.77}_{0.65}\,(\text{stat}) \pm 0.06\,(\text{syst}),$$
$$C(B^0_s \to J/\psi K^0_S) = -0.28 \pm 0.41\,(\text{stat}) \pm 0.08\,(\text{syst}),$$
$$S(B^0_s \to J/\psi K^0_S) = -0.08 \pm 0.40\,(\text{stat}) \pm 0.08\,(\text{syst}).$$

Additionally, a measurement of the branching ratio has been updated [5] to

$$\frac{\mathcal{B}(B^0_s \to J/\psi K^0_S)}{\mathcal{B}(B^0 \to J/\psi K^0_S)} = 0.0427 \pm 0.0017\,(\text{stat}) \pm 0.0012\,(\text{syst}) \pm 0.0025\,(f_s/f_d),$$

where the dominant part of the systematic uncertainty comes from the mass modelling and mass resolution.

References

[1] CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005) [hep-ph/0406184], updated results and plots available at: http://ckmfitter.in2p3.fr

[2] BaBar collaboration, B. Aubert et al., *Measurement of time-dependent CP Asymmetry in $B^0 \to c\bar{c}K^{(*)0}$ Decays*, *Phys. Rev.* D79 (2009) [arXiv:0902.1708]

[3] Belle collaboration,I. Adachi et al., *Precise measurement of the CP violation parameter $\sin 2\phi_1$ in $B^0 \to (c\bar{c})K^0$ decays*, *Phys. Rev. Lett.* 108 (2012) [arXiv:1201.4643]

[4] LHCb Collaboration, R. Aaij et. al., *Measurement of CP violation in $B^0 \to J/\psi K^0_S$, LHCb-PAPER-2015-004* (2015)

[5] LHCb Collaboration, R. Aaij et. al., *Search for CP violation in the decay $B^0_s \to J/\psi K^0_S$, LHCb-PAPER-2015-005* (2015)