Summary

Within the domain of modern physics there exists a field that attempts to answer a fundamental question, that puzzled philosophers since the ancient times. Namely, identify and understand the fundamental-indivisible building blocks that constitute the natural world. Remarkably enough more that 2 millennia after Democritus, who introduced the idea of atoms or άτομα which in Greek means indivisible, contemporary scientists still have not found a definite answer. It seems that the observable universe consists of a handful of elementary particles and are classified in two distinct categories: Namely *gauge bosons*, responsible for mediating all the known particle interactions of nature (with the exception of gravity) and *fermions* which are the constituents of matter. The recently discovered Higgs particle [4, 5] is a special type of boson that plays a central role in explaining how particles acquire mass. Fermions can be divided further into *quarks*, which constitute particles like the proton and the neutron. In general *Leptons* do not build stable atoms. However, electrons constitute the nucleus of atoms and together with protons and neutrons do build atoms. Leptons, along with quarks, are present in crucial processes like the formation and evolution of stars (which has direct impact on the way life evolved on earth).

Particle Physics and The Standard Model

The state of the art mathematical framework necessary to describe interactions between the fermions is called *Standard Model* [6–8]. Describing a quantum mechanical process like particle interactions means being able to compute the probability for a certain outcome in that particular particle interaction and it involves non-trivial calculations. Thus the established predictive power of the Standard Model is an important achievement. Furthermore, the recently discovered Higgs boson [4, 5],

which plays a special role in the explanation of how particles acquire mass, makes Standard Model complete.

Despite its success, there are established phenomena and observations that the Standard Model does not account for. Perhaps the most striking one is the absence of any description of the most familiar, yet the weakest, interaction of nature, gravity. Or the observed amount of matter-antimatter imbalance in the universe [19–21] (Note that antimatter is a well understood state of matter that has its quantum numbers signs, such as electric charge, flipped with respect to matter.) The above phenomena are a few examples that reveal the incompleteness of the model. Thus the scientific method compels to continued testing Standard Model predictions and look for ways to improve it. Significant deviation from these predictions is a hint for the presence of *New Physics* beyond the established model.

CP violation and New Physics

According to the dominant theory, matter and antimatter were created in equal proportions during the initial phase of the big bang [19–21]. This idea invites the notion of a symmetry between matter and antimatter, known as Charge-Parity or *CP* symmetry. Perfect *CP* symmetry implies that nature interacts with matter in the same way as antimatter. However, at current time the observable universe appears to be almost entirely populated by matter. Thus the origin of *CP violation* follows as a natural question for which the Standard Model has to provide an explanation.

The established idea that nature indeed favors processes where the particles involved are matter and not antimatter particles is captured by the Standard Model. Despite this, it cannot account for the observed amount of matter-antimatter asymmetry [19–21]. Hence, other sources of *CP* violation beyond the Standard Model have to be active. A typical place to search for hints of non Standard Model *CP* violation is in parameters of the model where its predicted value of *CP* violation is very small. In that case any significant observation of *CP* violation is a direct hint for the presence of New Physics. Collecting many such hints helps particle physicists to identify the weaknesses in the Standard

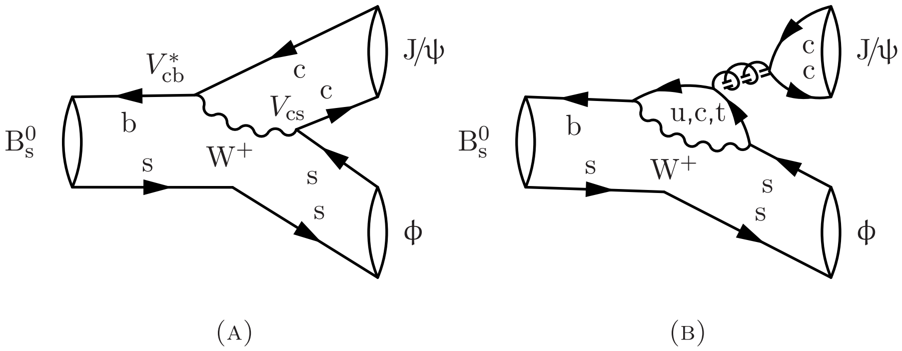

FIGURE S.2: Leading order *tree* (left) and sub-leading penguin (right) $B_s^0 \to J/\psi\,\phi$ decay topologies.

Model as well as choose between the various alternative models, such as *Supersymmetry e.g.* [41–43].

The Weak Phase ϕ_s

An interesting parameter where the Standard Model prediction is nearly zero is the weak phase ϕ_s. This parameter manifests itself in $b \to c\bar{c}s$ interactions, where a b quark decays into three other quarks. The most promising decay channel to measure ϕ_s is the $B_s^0 \to J/\psi\,\phi$ decay, see Figure S.2a. The Standard Model ϕ_s prediction as well as its most precise measurement by LHCb is:

$$\phi_s^{\text{LHCb}} = -0.010 \pm 0.039 \quad \text{rad}, \tag{S.6a}$$

$$\phi_s^{\text{SM,tree}} = -0.03761\ ^{+0.00073}_{-0.00082} \quad \text{rad}. \tag{S.6b}$$

Given the above measurement it follows that ϕ_s is compatible with the prediction and any New Physics effects that might appear in ϕ_s must be small. From an experimental point of view the situation is only now becoming interesting, where the statistical uncertainty of the experimental measurement is approaching the Standard Model prediction. Thus future ϕ_s measurements define a high precision era where the presence, or not, of New Physics will become apparent.

However, entering this promising era comes along with an important consideration that has to be taken into account in order to make a robust claim about New Physics hints in ϕ_s. In particular there are certain processes within the Standard Model that ϕ_s measurements did not take into account so far. The magnitude of these processes, which originate from *penguin topologies* and shown in Figure S.2, are known to be small. Despite that, the contribution of penguin topologies shift the Standard Model prediction, $\phi_s^{\mathrm{SM,tree}}$, by a small amount, $\Delta\phi_s^{\mathrm{peng}}$. Considering also that, as implied by Eq. S.6, potential New Physics in ϕ_s are also small; contributions to ϕ_s from Standard Model penguin topologies are crucial to disentangle from potential New Physics contributions, which also shift the Standard Model prediction by $\Delta\phi_s^{\mathrm{NP}}$. The situation is depicted in following equation:

$$\phi_s^{\mathrm{eff}} = \phi_s^{\mathrm{SM,tree}} + \Delta\phi_s^{\mathrm{peng}} + \Delta\phi_s^{\mathrm{NP}}, \tag{S.7}$$

where ϕ_s^{eff} represents the ϕ_s measurement. Thus, in order to overcome the above mentioned limitations it becomes mandatory to estimate contributions from penguin topology using different decay channels, also called control channels. These control channels, *e.g.* $B_s^0 \to J/\psi\, \bar{K}^{*0}$, have identical tree and penguin topologies with $B_s^0 \to J/\psi\, \phi$ and by exploiting certain quark symmetries it is possible to properly estimate the size of $\Delta\phi_s^{\mathrm{NP}}$ and thus assess the presence of potential New Physics effects.

Analyzing Particle Collisions

Having introduced the parameter $\Delta\phi_s^{\mathrm{peng}}$ and its role in the pursuit for New Physics it is interesting to point out some aspects relevant to the experimental measurement of the previous parameter. First and foremost by utilizing state of the art technologies scientists have built the most powerful accelerator, LHC, at CERN to improve and challenge the Standard Model. The machine is capable of accelerating two beams of protons up to almost the speed of light and collide them at a particular point in space called the interaction point, around which detectors are located. To put these very energetic collisions into perspective; the energy density of a single proton-proton collision at LHC is approximately as high as when the universe was about a billionth of second old. This effectively allows particle physicists to look back in time and probe information about the state of matter, and antimatter, in the early universe.

The LHCb experiment, located at CERN, is a dedicated experiment to the study of *CP* violation. The design of the detector, both at the hardware and software level, is optimized for detecting special interactions of *heavy* quarks, like the b and the c quarks. Emphasis is also given to the detection of muons, particularly to the ones that fly inside a small cone along the beam direction. Note that muons can be found among the decay products of many decay channels that LHCb is interested in.

After recording particle collisions that are interesting for physics measurements, like $\Delta\phi_{\mathrm{s}}^{\mathrm{peng}}$, the stored data are further processed such that the presence of noise is suppressed as much as possible. In addition biases and finite resolution effects introduced by detector imperfections are taken into account such that the physics model, which estimates the parameters of interest, is corrected for these effects and thus provides valid and robust estimates when fitting the data. The fitting process is based on the principle of *maximum likelihood*. The likelihood is a function of the parameters of interest given the observed data. At its maximum the likelihood function provides the *best fit* estimate for the parameters of interest given the data that were used to build the previous likelihood function.

Visualizing the result of the fit to the $\mathrm{B_s^0} \to \mathrm{J/\psi}\,\bar{\mathrm{K}}^{*0}$ control channel involves plotting the fitted model on top of the data, see Figure S.3. The data consist of three variables, $(\cos\theta_{\mathrm{K}}, \cos\theta_{\mu}, \varphi_{\mathrm{h}})$, which are related to the direction of the $\mathrm{B_s^0} \to \mathrm{J/\psi}\,\bar{\mathrm{K}}^{*0}$ decay particles.

Having performed the likelihood fit to the data and following the strategy indicated by [37, 48, 51, 93] the final result regarding penguin topology contributions to ϕ_{s} is:

$$\Delta\phi_{\mathrm{s},0}^{\mathrm{peng}} = 0.000\,^{+0.010}_{-0.014}, \quad \Delta\phi_{\mathrm{s},\parallel}^{\mathrm{peng}} = 0.001\,^{+0.012}_{-0.016}, \\ \Delta\phi_{\mathrm{s},\perp}^{\mathrm{peng}} = 0.003\,^{+0.012}_{-0.016}. \tag{S.8}$$

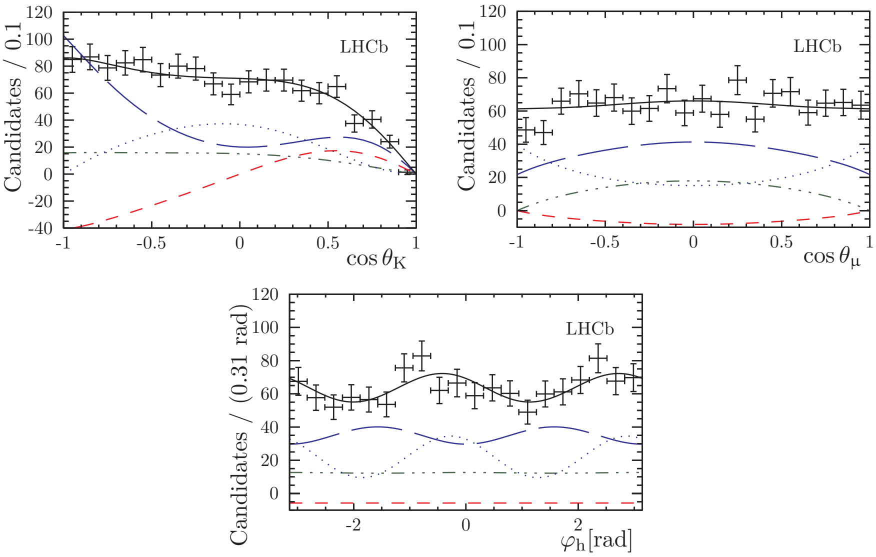

FIGURE S.3: Fitted model (black line) plotted on top of $B_s^0 \to J/\psi \bar{K}^{*0}$ data (black crosses). Various components of the model relevant to its *CP* structure are shown with colored lines.

where quantities are expressed in rad (ϕ_s is the argument of a complex number). Note that the parameter $\Delta\phi_s^{peng}$ is split in its *polarization* components. Essentially the $B_s^0 \to J/\psi\,\phi$ decay probability, as well as the ϕ_s value are in principle different depending on the configuration of the particle spin quantum numbers in the $B_s^0 \to J/\psi\,\phi$ decay resulting in three polarization components $\|, \perp$ and 0 respectively for parallel, perpendicular and longitudinal. Thus, the penguin parameter $\Delta\phi_s^{peng}$ is expressed in a similar footing.

Impact and Conclusions

The shifts $\Delta\phi_s^{peng}$ quoted in Eq. S.8 suggest that contributions of penguin topologies to the $B_s^0 \to J/\psi\,\phi$ decay amplitude are indeed small, < 0.017 rad or $< 1°$. Given the also small ϕ_s measured value, shown in Eq. S.6a, it becomes mandatory to control penguin contributions in future ϕ_s measurements. Increasing the amount of data in the LHC Run 2 might not be enough to yield a significant claim on the presence of physics beyond the Standard Model and hence the upgraded LHCb detector becomes important in the pursuit for New Physics with ϕ_s in the future.