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B Physics at the LHC

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Abstract

The LHC is scheduled to start its first physics data taking period later in 2009. Primarily LHCb but also ATLAS and CMS will start a rich B physics programme with the potential of revealing New Physics in the heavy flavour sector. This contribution will cover the prospects for B physics at the LHC with particular emphasis to early measurements. This includes CP violation measurements in B_d^0 and B_s^0 decays, searches for rare decays such as $B_s^0 \to \mu\mu$, as well as semileptonic and radiative channels.

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1 Introduction

Flavour physics has celebrated many successes over the past decades. Recently, the B factory experiments BaBar and Belle, as well as CDF and D0 at the Tevatron, have produced a wealth of high precision B physics measurements. These range from the determination of the CKM unitarity triangle angle β over the discovery of CP violation in the B system to the first measurements of B_s^0 oscillations and the weak mixing phase in the B_s^0 system ϕ_s.

The experiments at the LHC will open the door to areas of flavour physics that were thus far unreachable. With the full spectrum of flavour production at hadron colliders, B physics at the LHC will have unique access to the B_s^0 system as well as others that are beyond the reach of B factories running at the $\Upsilon(4S)$ resonance. Furthermore, the increase of the $b\bar{b}$ production cross-section with collision energy together with the increased luminosity compared to the Tevatron will allow precision measurements of rare decays.

2 B Physics Experiments at the LHC

The LHC will have a dedicated B physics experiment, LHCb. In addition, the two main experiments, ATLAS and CMS, also have a B physics programme. All experiments have been presented in detail [1].

At the LHC design centre of mass energy of 14 TeV the $b\bar{b}$ production cross-section is estimated to be 0.5 mb which represents about 1% of all visible interactions. As the $b\bar{b}$ pairs are predominantly produced co-linear with either beam direction, the cross-section for interactions visible inside the detector acceptance is more than a factor two lower for ATLAS and CMS comared to LHCb, which benefits from its forward geometry and lower thresholds in transverse momentum (p_T). The b quarks will hadronise to B_d^0 and $B_u^\pm$ in 40% of the cases each, to B_s^0 and Λ_b^0 in about 10% each, and in about 0.1% to $B_c^\pm$. The challenge for the LHC experiments is to select the interesting decays, which have usual branching ratios in the range of 10^{-5} to 10^{-9}, among the background of other heavy flavour events and general backgrounds. In addition to a highly selective trigger, high precision vertexing is needed to separate the secondary vertices from B decays from the primary interactions. Finally, particle identification is required for leptons and hadrons, particularly for the separation of pions and kaons.

In their initial years of running, ATLAS and CMS aim at operating at a luminosity of 10^{33} cm^{-2}s^{-1}, which is a factor 10 below their design luminosity. This will greatly benefit their B physics programme as the number of interactions per bunch crossing is about 4, which simplifies the detection of displaced vertices. The annual integrated luminosity in this period would be 10 fb^{-1}. Both experiments have a hardware trigger stage based on the transverse momentum of a single particle that reduces the event rate from 40 MHz to below 100 kHz, exploiting mainly their excellent muon detectors. Software triggers reduce the rate to an output rate of roughly 200 Hz, of which about 10 Hz are foreseen for B physics events.

LHCb is designed to run at a luminosity of 2×10^{32} cm^{-2}s^{-1}, which results in less than one interaction per bunch crossing on average. The annual integrated luminosity is 2 fb^{-1}. Starting from the same input trigger rate as ATLAS and CMS, the LHCb event rate is only reduced to 1 MHz by a hardware trigger by applying much smaller p_T thresholds. The remaining reduction is performed by software trigger stages that exploit the full detector readout and lead to an output rate of 2 kHz of heavy flavour events. With the high precision of the LHCb vertex locator it is possible to trigger on displaced vertices in the software trigger. Furthermore, it allows to resolve the fast B_s oscillation with high accuracy. Two ring imaging Cherenkov detectors allow pion-kaon separation over a momentum range of $2 - 100$ GeV/c, which is essential for the reconstruction of hadronic decays and flavour tagging with kaons.

3 Physics Goals

The B physics goals at the LHC span a wide range. The major analyses will be discussed in some detail while others cannot be covered in the scope of this contribution. The focus will be fully on analyses of B decays. Studies of B production, which are also actively pursued by all three experiments, are not reported on.

One of the measurements which recently received significant attention is that of the measurement of the weak mixing phase in the B_s system. Measurements of the mixing phase using the decay $B_s^0 \to J/\psi\phi$ by CDF and D0 disagree with the Standard Model (SM) prediction by more than 2σ [2, 3]. All LHC experiments have access to this decay as they can trigger on the J/ψ decaying into a lepton pair. The studies presented here are based on the reconstruction of the final state from the decays $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$.

Being a decay into two vector particles, this analysis requires to distinguish several states of the orbital angular momentum, L, since they lead to different CP eigenvalues of the final state. Determination of the CP violation parameter as well as the contributions from the different angular momentum states is achieved by a time-dependent, flavour-tagged, angular analysis of the decay rates. The angles are those between the two positive final state particles and their respective mother particles in the centre of mass frame of the B_s^0 meson, as well as the angle between the two planes defined by the decays of the two B daughters.

For one nominal year of data taking all experiments expect to acquire roughly 110k signal events[1)] [4, 5, 6]. ATLAS have not yet published a sensitivity for the mixing phase measurement. For CMS, a flavour-untagged analysis has led to a statistical error on $\phi_s^{J/\psi\phi}$ of 0.06. LHCb estimates a sensitivity of 0.03 including systematic uncertainties. With a data set equivalent to only one tenth of a nominal year, LHCb expects to already achieve better sensitivity than that expected for the Tevatron experiments with an integrated luminosity of 9 fb^{-1} each.

A measurement with great exclusion power in the parameter space of Super Symmetry is that of the branching ratio of the decay $B_s^0 \to \mu^+\mu^-$ [8].The SM decay mainly goes via a penguin annihilation diagram which results in a branching ratio prediction of $(3.35 \pm 0.32) \times 10^{-9}$. An example of New Physics contributions could be a "Higgs penguin" diagram, where the incoming anti-s quark converts to an anti-b quark via a loop with SUSY particles and then annihilates with the b-quark to produce a virtual Higgs which decays into a pair of muons. The contribution from this diagram is proportional to $\tan^6\beta$. Hence, in a large $\tan\beta$ scenario, the branching ratio of the decay $B_s^0 \to \mu^+\mu^-$ could be significantly enhanced.

One of the main challenges for this measurement is the normalisation. LHCb plans to do this without relying too much on the simulation, by comparing it to well measured branching fractions where the final states have a similar topology to that of $B_s^0 \to \mu^+\mu^-$. Using a precisely measured decay of a B_d^0 or B_u^+ is not desirable as the relative production fractions of the various B mesons are only known to rather poor precision. On the other hand, there is no precise measurement of a B_s^0 decay branching ratio. The hope is to use a measurement of the branching ratio of $B_s^0 \to K^+K^-$ currently being studied by Belle, which is expected to have a precision of 10%.

Within a nominal year of data taking and assuming the SM branching ratio, ATLAS expect to have 5.7 (14) signal (background) candidates, CMS expects 6.1 (14), and LHCb 7.6 (22) [4, 5, 9]. With this dataset, branching ratios down to the SM level can be excluded at 90% C.L. Already with about one tenth of this data set, it will be possible to improve on the limits set by CDF and D0 [10, 11].

The decay $B_d^0 \to K^*\mu^+\mu^-$ is a flavour-changing neutral current process that can occur

[1)] The numbers for ATLAS and CMS have been extrapolated from 1.5 fb^{-1} and 6.8 fb^{-1} to 10 fb^{-1}, respectively.

through various penguin diagrams in the SM. However, NP particles may enter through additional penguin diagrams. This channels leads to sensitivity to the Wilson coefficients C_7, C_9, and C_{10} through various angular analyses. One observable, which has been studied by BaBar and Belle [12, 13], is the forward-backward asymmetry (FBA) of the angle between the μ^+ and the direction of flight of the di-muon system in the centre of mass system of the B_d^0 as a function of the $\mu^+\mu^-$ invariant mass squared.

After one nominal year of data taking, LHCb expect a sample of 7200 signal decays [14]. This will allow a measurement of the zero crossing point in the distribution of the FBA with a precision of $0.4 - 0.5$ GeV^2/c^4. With 10 fb^{-1}, i.e. after five nominal years of data taking, LHCb will also be able to exploit additional distributions that give access to a parameter space which the FBA is insensitive to.

The CKM angle γ is the least well constrained of the angles of the unitarity triangle. LHCb will greatly improve the precision on γ. As the decays used to measure γ have fully hadronic final states, ATLAS and CMS will not be able to contribute to these measurements.

The bulk of the analyses to extract γ are performed with decay final states where the two tree diagrams, $b \to u + W(s + \overline{c})$ and $b \to c + W(s + \overline{u})$ contributes, followed by the D meson decays [15]. In this case NP influence is completely negligible. Among the time-integrated measurements, LHCb plans to combine the ADS [16] and GLW [17] measurements in order to control the strong phases involved. These will be made using the self-tagging decays $B^{\pm} \to DK^{\pm}$ and $B^0 \to DK^{*0}$, where the D decays into $K^{\pm}\pi^{\mp}$ (ADS) and K^+K^- (GLW). The time-integrated measurements are completed by Dalitz plot analyses [18, 19], e.g. in $B^{\pm} \to D(K_S\pi\pi)K^{\pm}$. Two methods have been exploited for this measurement: a model-dependent un-binned fit, and a model-independent binned fit. While the model-dependent fit suffers from large model errors $(6^{\circ} - 14^{\circ})$, the binned fit requires external input on strong phases, which bring an uncertainty of 2°, and it has potentially worse statistical power.

A measurement that is likely to be exclusive to LHCb is the time-dependent analysis of the decay $B_s^0 \to D_s^{\pm}K^{\mp}$ [20]. It allows the extraction of γ from the measurement of the time-dependent CP asymmetries. This measurement can be combined with the one from the decay $B_d^0 \to D^{(*)\pm}\pi^{\mp}$ assuming U-spin symmetry. The combined sensitivity after one nominal year of data taking for these modes is $\sigma(\gamma) = 4^{\circ} - 5^{\circ}$, depending on the exact values of the parameters involved.

Another measurement based on U-spin is the extraction of γ from decays where both the $b \to u$ tree and, $b \to d$ for B_d and $b \to s$ for B_s penguin decay amplitudes, contribute equally. The U-spin symmetry is used to connect the contribution of the penguin diagrams between the two decay modes. The combination of the time-dependent CP asymmetries of the decays $B_d^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ allows the measurement of γ [21, 22]. If NP particles enter the loops in these decays, the value extracted for γ can differ from that extracted from tree-level only decays. This measurement requires a simultaneous 68 parameter fit. The fit comprises models for eight $H_b^0 \to h^+h'^-$ modes, where H_b^0 stands for B_d^0, B_s^0, and Λ_b^0, while h stands for a pion or a kaon, or a proton as one daughter of the Λ_b^0 decays. The fit parameters are event yields, charge asymmetries, time-dependent asymmetries, mixing parameters, mass model parameters and lifetimes, and flavour tagging parameters. It yields a sensitivity to γ of about 7° for one nominal year of data taking.

Finally, LHCb will be able to study exclusive decays involving $b \to s\gamma$ transitions [23]. CP asymmetries as well as photon polarisations will be measured in the decays $B_d^0 \to K^*\gamma$, $B_s^0 \to \phi\gamma$, and $B^{\pm} \to \phi K^{\pm}\gamma$. For a nominal year of data taking the event yields are $70k$, $11k$, and $7k$, respectively. This allows to make some of these measurements even with very early data.

4 Conclusion

The LHC experiments involved in B physics measurements have been presented. An overview was given on the broad B physics programme of LHCb, as well as on the B physics activities of ATLAS and CMS. The various SM tests and opportunities for NP discoveries were discussed. However, many more B physics analyses will be performed which could not be covered within the scope of this presentation. In addition, there are flavour physics programmes beyond the main B physics initiative, which involve charm and tau physics.

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