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Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

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CMS prospects for heavy flavour physics

CMS Collaboration

Abstract

CMS statement of long term prospects for the Intensity Frontier Workshop (Nov 30 - Dec 2, 2011 - Rockville MD).

CMS prospects for heavy flavour physics

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1 Flavour physics landscape 2010-2017

CMS is a general-purpose experiment at the Large Hadron Collider (LHC) at CERN [1]. The experiment has been designed to cover new physics searches as well as Standard Model (SM) precision measurements. CMS has already proven its capability for B-physics measurements by producing a wealth of results on b production and $b\bar{b}$ correlations [2, 3], exclusive B production [4, 5, 6], quarkonia [7, 8, 9], and searches for rare decays [10].

LHC has performed very well so far. The integrated luminosity in 2011 exceeded 5 fb^{-1} and the peak instantaneous luminosity was 3.6×10^{33}cm^{-2}s^{-1}. A reasonable estimate for the integrated luminosity to be collected in 2012 is about 15 fb^{-1}. The first long shutdown (LS1) will take place in 2013-2014, and the next running period in 2015-2017 may produce an integrated luminosity of 75 fb^{-1} at 14 TeV (assuming 25 fb^{-1} per year). The second long shut-down (LS2) is scheduled around 2017-2018, followed by the third running period 2019-2021, producing possibly another 100 fb^{-1}. The following profile for the integrated luminosity build-up is assumed here for the CMS heavy flavour analyses: 20 fb^{-1} available at the end of 2012; 45 fb^{-1} by the end of 2015; 95 fb^{-1} by the end of 2017. The increase of the centre-of-mass energy from 7 to 14 TeV is neglected in this document. Proton-proton collisions at 14 TeV instead of 7 TeV would increase the absolute b-quark production cross section and the relative production cross section fraction, but on the other hand the CMS b-event rate is already heavily trigger-limited and b-triggers have a high purity.

LHCb is a dedicated heavy-flavour experiment at the LHC [11]. LHCb will collect about 5 fb^{-1} by the end of 2017, since the instantaneous luminosity has to be leveled to a constant rate due to limitations in the trigger and readout, and to collect data in relatively clean conditions (particle multiplicity affects the reconstruction efficiency). The integrated luminosity build-up for LHCb is assumed here to be: 2 fb^{-1} available by the end of 2012; 3 fb^{-1} by the end of 2015; 5 fb^{-1} by the end of 2017. LHCb will have a major upgrade concerning their trigger, readout, and several subdetectors to overcome some of the rate limitations [12]. The upgrade is scheduled to take place during LS2 (2017-2018). The goal is to be able to collect an integrated luminosity of about 5 fb^{-1} per year after the upgrade, reaching 50 fb^{-1} towards end of the 2020's [13].

The B factory at KEK, SuperKEKB [14], will be commissioned in 2015 according to the current planning schedule, and it is expected that the target integrated luminosity, 50 ab^{-1}, will be collected by 2021. The SuperB project [15], a B factory to be built in Rome, Italy, has also been approved for construction. The SuperB target integrated luminosity, 75 ab^{-1}, is expected to be collected by 2023.

Looking at the heavy flavour prospects at large, it seems that a general-purpose experiment at the LHC, CMS, has indeed a “window of opportunity” at least until LS2 in 2017-2018 for final states where CMS can take full advantage of the large collected integrated luminosity. This requires decay channels for which the trigger is efficient and the analysis is insensitive to pileup.

The main workhorse for CMS heavy flavour physics is dimuon triggers combined with precise tracking and vertexing capabilities. The flexibility of the CMS trigger system has made it possible to adapt the triggers to the increasing luminosity in a prompt and intelligent manner, by making use of selections on invariant mass, decay length, distance of closest approach, transverse momentum, and rapidity. At the same time, strict physics priorities at the trigger level have already been made, and with increasing instantaneous luminosities CMS will have to make even more difficult choices, targeting those decay channels with significant scientific interest and potential for competitive measurements. Upgrades in the trigger and data processing chain as early as during LS1 could possibly alleviate some of the bandwidth issues. Otherwise, from the B-physics point of view, the detector will remain the same until the pixel upgrade (end of 2016), apart from increasing the muon trigger efficiency in the forward region (LS1).

Heavy flavour physics during this decade will be focused in particular on searches for new physics through indirect measurements, and precision measurements of the CKM description of quark mixing. While the B factories have advanced our understanding on these fronts by investigating B^0 and B^+ decays, B^0_s and b-baryon final states will be the central objects for studies at the LHC experiments. Tevatron experiments have paved the way for heavy flavour analyses at hadron colliders with B^0_s, B_c and b-baryons with the observation of B^0_s-mixing, first measurements of the weak phase in B^0_s decays, and first observations of B_c and several b-baryons. A selection of key heavy flavour measurements at the LHC [16, 17] are shown in Table 1, together with the CMS goals.

The scope of the CMS heavy flavour programme is limited to final states with di- or multimuons, and b-jets. The strength of CMS is that CMS will collect much more integrated luminosity than LHCb, because the LHCb luminosity is leveled to a constant rate. The rate advantage of CMS depends naturally also on the allocated trigger bandwidth and the trigger efficiency. The mass and decay time resolutions of CMS are somewhat worse than at LHCb, which puts constraints to some physics channels (*eg.* B^0_s mixing), while “counting” analyses such as $B^0_s \to \mu^+\mu^-$are much less sensitive. CMS can also choose to use only the central region where the mass resolution is better for channels where statistics are less critical (for example quarkonia analyses). In some cases CMS can take

Table 1: A selection of key heavy flavour analyses at the LHC. Column "CMS physics target" gives an indication of the physics goals of CMS up to LS2.

Channel	CMS physics target
$B_s^0 \to \mu^+\mu^-$	Measure the branching fraction
$B^0 \to \mu^+\mu^-$	Upper limit for the branching fraction
$B^0 \to \mu^+\mu^- K^{*0}$	Consistency with the SM
$B_s^0 \to J/\psi\phi$ ($B_s^0 \to J/\psi f_0$)	Measure ϕ_s
$\tau^- \to \mu^-\mu^+\mu^-$	Improved upper limit for the branching fraction
$D^0 \to \mu^+\mu^-$	Improved upper limit for the branching fraction
Exotic quarkonium states	Discovery of new states

special advantage of the large tracker volume through using conversions, such as in the case of χ_{c0}, χ_{c1} and χ_{c2} observations [18], with a mass resolution of (9.6 ± 0.2) MeV/c^2. The CMS heavy flavour analyses have been shown to be relatively insensitive to pileup, in particular thanks to the pixel detector with a good resolution in the z-coordinate. Concerning generic measurements of heavy flavour production CMS and LHCb are complementary in their angular coverage, which is an important asset for obtaining a complete picture of heavy flavour physics at the LHC. Furthermore, a central pseudorapidity coverage can have advantages for angular analyses.

2 CMS key heavy-flavour measurements

2.1 Rare decays $B_s^0 \to \mu^+\mu^-$, $B^0 \to \mu^+\mu^-$, $B \to \mu^+\mu^- X_s$

The rare decay $B_s^0 \to \mu^+\mu^-$ is extremely interesting for new physics searches. The decay is a flavour-changing neutral current (FCNC) process which is forbidden in the SM at a tree level, occurring only via higher order diagrams. Therefore any new particles contributing in the loops typically increase the branching ratio. Experimentally the channel is simple to trigger and reconstruct. The branching ratio predicted by the SM is $(3.2 \pm 0.2) \cdot 10^{-9}$ [22].

Recent measurements from CMS [10] and LHCb [23] are:

- CMS measurement with 1.14 fb^{-1}: $\mathrm{Br}(B_s^0 \to \mu^+\mu^-) < 1.9 \cdot 10^{-8}$ at 95% CL (median expected upper limit for background and SM signal prediction $1.8 \cdot 10^{-8}$ at 95% CL),
- LHCb measurement with 300 pb^{-1}: $\mathrm{Br}(B_s^0 \to \mu^+\mu^-) < 1.5 \cdot 10^{-8}$ at 95% CL ($\mathrm{Br}(B_s^0 \to \mu^+\mu^-) < 1.6 \cdot 10^{-8}$ at 95% CL by using the 2011 data only, with expected upper limit for background and SM signal prediction $1.5 \cdot 10^{-8}$ at 95% CL).

The combined result for CMS and LHCb is $\mathrm{Br}(\mathrm{B_s^0} \to \mu^+\mu^-) < 1.1 \cdot 10^{-8}$ at 95% CL [24]. This result already gives the strongest constraint on supersymmetric Higgs bosons with a large value of $\tan\beta$, so it is clear that this measurement will receive intense attention also in the coming years.

The current CMS limit stems from 2011 data, with an average of 5.5 primary vertices reconstructed per event. The analysis was shown to be insensitive to pileup in this dataset. Furthermore, the result was obtained with a simple cut-and-count analysis, so there is still room for improvement of the analysis efficiency with multivariate methods. Extrapolating the expected CMS and LHCb limits with a simple luminosity scaling, the upper limits at the end of 2012 would be $\mathrm{Br}(\mathrm{B_s^0} \to \mu^+\mu^-) < 4.3 \cdot 10^{-9}$ at 95% CL for CMS (20 fb^{-1}), and $\mathrm{Br}(\mathrm{B_s^0} \to \mu^+\mu^-) < 6.2 \cdot 10^{-9}$ at 95% CL for LHCb (2 fb^{-1}).

Assuming that the present trigger and analysis efficiencies will be retained, the CMS expected upper limit will reach the SM prediction $3.2 \cdot 10^{-9}$ with about 36 fb^{-1}, *i.e.* mid-2015. Here the increase of the centre-of-mass energy in 2015, which will increase the b-production cross section, has been neglected. The LHCb expected upper limit at that time would be $5.4 \cdot 10^{-9}$ at 95% CL with the same assumptions. CMS has thus great chances for the first observation and measurement of the $\mathrm{B_s^0} \to \mu^+\mu^-$ rare decay.

The predicted SM branching ratio for the decay $\mathrm{B^0} \to \mu^+\mu^-$ is $(1.0 \pm 0.1) \cdot 10^{-10}$ [22], a factor of about 30 below the predicted SM branching ratio for $\mathrm{B_s^0}$. The production of $\mathrm{B^0}$ in b-quark hadronization is enhanced by a factor of about four compared to the production of $\mathrm{B_s^0}$, but the experimental situation is more difficult for $\mathrm{B^0}$ because of larger peaking background. Considering these facts, it is unlikely that the decay $\mathrm{B^0} \to \mu^+\mu^-$ would be observed at the LHC before the LS2 without enhancements to the SM rate from new physics.

Rare decays $\mathrm{B} \to \mu^+\mu^-\mathrm{X_s}$, where a B hadron decays to a muon pair and $\mathrm{X_s}$, which is a fully reconstructed hadronic final state, are also sensitive to physics beyond the SM through a wealth of kinematic observables. Examples of these decay modes are $\mathrm{B^0} \to \mu^+\mu^-\mathrm{K^{*0}}$, $\mathrm{B^+} \to \mu^+\mu^-\mathrm{K^+}$, $\mathrm{B_s^0} \to \mu^+\mu^-\phi$ and $\Lambda_\mathrm{b} \to \mu^+\mu^-\Lambda$. The branching ratios are larger than for the purely dimuon decay modes, $\mathcal{O}(10^{-6} - 10^{-7})$, so large samples will be available at the LHC, and many of the observables provide complementary constraints for various new physics models or parameters. LHCb has performed their first measurements of $\mathrm{B^0} \to \mu^+\mu^-\mathrm{K^{*0}}$ decays, with greater accuracy than CDF, BaBar and Belle, with an integrated luminosity of 309 pb^{-1} (323 signal candidates) [25]. The studied observables were consistent with the SM predictions, although the errors are still larger than the theory uncertainty. CMS should have good potential for measurements with these channels, the main challenge coming from trigger rate due to the large dimuon mass range required.

2.2 Measurement of the CP-violation phase ϕ_s in $\mathrm{B_s^0} \to \mathrm{J}/\psi\phi$ decays

The decay $\mathrm{B_s^0} \to \mathrm{J}/\psi\phi$ is a golden mode to measure the CP-violation phase ϕ_s ($\phi_s = -2\beta_s$, where $\beta_s = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$). The decay is theoretically clean, since it is dominated by a single CKM phase $b \to c\bar{c}s$. In the SM, the angle β_s is expected to be very small ($\sin(-2\beta_s) = -0.036 \pm 0.02$) [19], but new physics effects might increase the angle by introducing a new phase.

CMS has measured the production cross section of $B_s^0 \to J/\psi\phi$ [6] with a sample of about 560 signal events from an integrated luminosity of 40 pb^{-1} collected during 2010. During the first year of LHC running at 7 TeV, the instantaneous luminosity was low, and consequently a generic dimuon trigger could be used to trigger these final states. For the data taken in 2011, the signal yield per unit luminosity was lower than in 2010 due to tighter trigger requirements (muon p_T and dimuon lifetime cuts at the trigger level). Nevertheless, the 2011 data sample should exceed 10 000 events, with a lower background than in 2010.

This channel was studied extensively for the CMS Physics TDR [20]. It was concluded that a relative statistical precision of about 8.4% for the relative width difference, $\Delta\Gamma_s/\Gamma_s$ could be obtained with about 74 000 reconstructed and selected signal events, and the statistical error on ϕ_s was 0.076 rad (untagged analysis). Comparing this with the current data, similar statistics could be obtained with about 35 fb^{-1}. Detector resolutions have been found to be similar to those assumed in the TDR simulations, and the background under the signal is actually lower in data compared to the TDR results. Therefore, CMS should be able to provide measurements with these accuracies in 2015.

To improve the precision and to reduce the ambiguities of the ϕ_s measurement flavour tagging will be needed. CMS can perform flavour tagging with opposite side leptons and with jet- or vertex-charge methods. Both muons and electrons can be used for lepton tagging, since the signal itself provides the dimuon trigger. The powerful particle flow jet reconstruction algorithm, combined with b-tagging, is a good basis for flavour tagging of jets. Compared to dedicated B experiments, only the possibility for kaon tagging is missing. The tagging power (tagging efficiency times the dilution factor squared) of CDF and LHCb is typically from 1 to 4%; without kaon tagging one can expect CMS to reach a tagging power of at least 1%. New results from LHCb [21] indicate that the weak phase ϕ_s is not significantly larger than the SM value: $\phi_s = (0.03 \pm 0.16 \pm 0.07)$ rad, but the errors are still too large to draw any conclusions. CMS should possess all the means to measure ϕ_s with a statistical precision approaching the SM predicted value with a few tens of fb^{-1}, collected already by end of 2015, if the trigger and reconstruction performance can be kept at the same level as in 2011. The ϕ_s measurement can also be complemented by using the $B_s^0 \to J/\psi f_0(980)$ decay mode, which does not require an angular analysis to perform the measurement.

2.3 Other rare or exotic decays

Lepton flavour violation (LFV) is forbidden in the SM, but many new physics models predict the existence of lepton flavour violation in charged lepton decays. Experimentally, the decay mode $\tau^- \to \mu^-\mu^+\mu^-$ is the most promising candidate to search for LFV at the LHC. The current best limit comes from the Belle experiment, $\mathrm{Br}(\tau^- \to \mu^-\mu^+\mu^-) < 2.1 \cdot 10^{-8}$ [26] at 90% CL, obtained with 719 million produced τ-pairs. At the LHC, the most abundant source of τ's is $\mathrm{D_s} \to \tau^+\nu_\tau$ decays. Very preliminary estimates indicate that CMS might be able to produce a competitive upper limit for the $\tau^- \to \mu^-\mu^+\mu^-$ branching fraction with about 10 fb^{-1} of data, triggering on trimuons, if the efficiency will be at least 10% for τ's within the detector acceptance and with $p_\mathrm{T} > 12$ GeV/c. The LHCb collaboration states that according to their current studies, LHCb will be able to match the Belle sensitivity with a few fb^{-1} [12] .

In the SM, the FCNC decay $\mathrm{D}^0 \to \mu^+\mu^-$ is highly suppressed. Theoretical estimates of the branching ratio are of the order of 10^{-13}, and the present experimental upper limit is $1.4 \cdot 10^{-7}$ at the 90% [27]. Again, the branching ratio could be enhanced by contributions from new physics.

Around 15 new exotic charmonium states, not predicted by the SM, have been discovered in the last decade. The speculative explanations include quark-gluon hybrids, mesonic molecules and tetraquarks. Several of the found states lack confirmation from a second experiment and have unknown quantum numbers. Corresponding states in the bottomonium sector should be discovered at the LHC, given that the collision energies are much higher than what was available at Belle and BaBar. CMS is extremely well suited to perform detailed studies of such exotic quarkonium states, given the dimuon signature and good mass resolution. The analysis of 2010 data showed roughly the same X(3872) yield for CMS and LHCb, for the same integrated luminosity, showing that CMS can be very competitive in these physics channels. Given that these states are low p_T signals, collected with constant-rate trigger paths, the yearly event samples will remain constant after 2011.

3 Summary

After the first two years of LHC running, CMS has shown its strength in heavy flavour physics through measurements of b and $\mathrm{b\bar{b}}$ production, investigations of several exclusive B and quarkonia final states, and searches for rare decays. Flexible trigger, efficient muon reconstruction, good mass resolution and accurate vertexing have been the the main factors facilitating the successful CMS heavy flavour programme.

In the coming years, the increasing instantaneous luminosity will impose constraints on this programme through trigger limitations. CMS should target in particular those decay channels which are of significant scientific interest and for which CMS has potential for competitive measurements, such as $\mathrm{B_s^0} \to \mu^+\mu^-$ and other channels considered in this document. If CMS can take full advantage of the much higher integrated luminosity than LHCb, CMS has a fantastic "window of opportunity" at least until 2017-2018, *i.e.* before the LHCb upgrade and before the upcoming B factories have collected substantial amounts of data. This requires, however, further work to adapt the triggers and keep the analyses insensitive to pileup.

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