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Heavy Flavour prospects at the HL-LHC

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Abstract. The development of flavour physics has been impetuous in recent years: there have been discoveries of CP violation in different B-meson systems, detailed studies of mixing effects in neutral B and D mesons, and observation of rare decays with unprecedented sensitivities. New discoveries can be expected for larger samples available in the near future. In these proceedings, future upgrades in the LHC detectors will be discussed.

INTRODUCTION

Searches of the physics beyond the Standard Model of elementary particles (SM), commonly known as New Physics (NP) searches, can be performed either directly or indirectly. The direct searches, a domain of the general purpose detectors, aim at discovering particles not included into the SM spectrum by its direct observation. The indirect searches instead look for virtual effects of unknown particles which might influence measurable quantities and alter their values with respect to SM predictions. Depending on the NP model under consideration, indirect searches can probe energy scales much larger than those accessible by direct searches [1].

The last fifteen years have been a golden age for flavour physics. Hundreds of experimental analyses and theoretical articles lead to a tremendous success of the CKM picture [2, 3]. This is clearly apparent in an overall agreement of all experimental constraints shown in Fig. 1, taken from Ref. [4] and updates online.

UPGRADE

In the next years, the LHC detectors will pass through some major upgrades that would allow new and more precise results to be obtained. The first upgrade will happen already after run 2 for LHCb, while ATLAS and CMS will make a large upgrade after run 3. The expected luminosity is shown in Table 1. An important fact for flavour physics is that the $b-\bar{b}$ cross-section is roughly doubled passing from the center-of-mass energy of 7 TeV to 14 TeV. The extrapolation of the detector performances is done using the results available from run 1. The full description of the impact of the ATLAS and CMS upgrades is described in Refs. [5] and [6], respectively.

TABLE 1. Cumulative integrated luminosity that will be collected by the ATLAS, CMS, and LHCb experiment by the ends of the runs given.

		LHC era			HL-LHC era	
Experiment	Run period Center-of-mass energy Years	Run 1 7,8 TeV 2010-2012	Run 2 13 TeV 2015-2018	Run 3 14 TeV 2020-2022	Run 4 14 TeV 2025-2028	Run 5 14 TeV 2030+
ATLAS, CMS		25 fb^{-1}	100fb^{-1}	300fb^{-1}		3000fb^{-1}
LHCb		3fb^{-1}	8fb^{-1}	23fb^{-1}	46fb^{-1}	100fb^{-1}

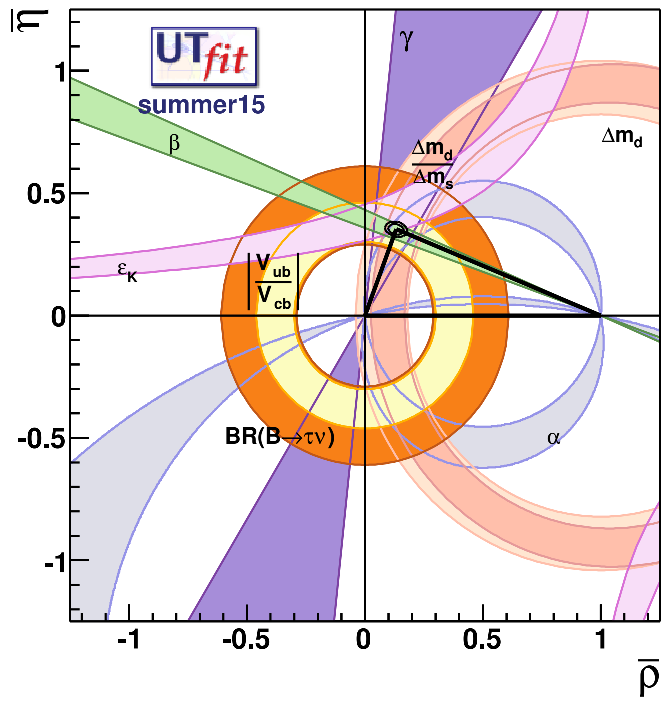

FIGURE 1. Determination of the Unitarity triangle apex within the SM. The two elliptical contours around the apex of the triangle correspond to 68% and 95% probability regions. The colored regions correspond to 95% probability for each single constraint. The analysis is performed using bayesian approach [4].

For the ATLAS experiment, in addition to the much higher number of events which will be available, a particularly important consideration should be done for the extensive upgrade programme to the inner tracking detector, which will have a very significant impact on flavour physics measurements. During run 2 ATLAS operates IBL, the inner tracker contains a fourth layer added to the present Pixel Detector between a new beam pipe and the current inner pixel layer (B-layer). The Phase-II upgrade of the ATLAS detector will allow operation at five times the nominal LHC luminosity. It is expected that these upgrades will affect B meson proper time resolution. The results of the simulations can be seen in Fig. 2.

The CMS experiment is expected to be completely refurbished with enhancements to the muon system and a new inner tracker, with improved granularity, to cope with average occupancy resulting from 140 interactions expected per bunch crossing. In particular, the new inner tracker system is expected to have L1 tracking capabilities, in order to reconstruct efficiently all tracks above 2 GeV p_T. The muon system will also have improved coverage in the forward direction and extended trigger capabilities. With the changes envisioned it is possible to maintain the same efficiency in triggering and analysis as we have achieved up until now.

The new tracker detector will feature 4 pixel barrel layers and 5 disks on either endcaps. The outer tracker material budget will diminish by roughly a factor of 2 in the central region ($|\eta| < 1$) and about a factor of 3 in the intermediate region around $1.2 < |\eta| < 1.5$. This, combined with a smaller silicon sensors pitch will improve the momentum resolution by about a factor of 1.5 in the barrel region ($|\eta| < 1.4$) and 1.2 elsewhere.

LHCb will undergo one major upgrade [7] between now and after run 2 running up to 2028 to allow the operation of the detector at a luminosity of up to $2 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$. The detector upgrade consists of a complete redesign of the readout system and the trigger in order to read out the full detector at the bunch crossing rate, and perform a full software trigger to select efficiently the relevant heavy-flavour decay chains. All silicon detectors will be upgraded. In addition the aerogel will be removed from RICH1 since it gives too few photons to actually allow reconstructing the rings in the higher multiplicities of the upgrade.

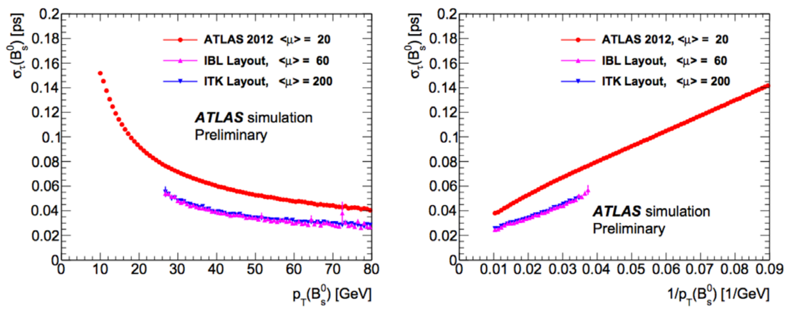

FIGURE 2. B_s^0 proper decay time resolution as a function of transverse momentum p_T of the B_s^0 meson, shown for three detector layouts: current ATLAS layout and pileup conditions of 2012 (red), IBL ATLAS layout with average number of pileup events, $<\mu>= 60$ (magenta) and ITK layout with, $<\mu>= 200$ (blue). The vertical axis gives an average value of per-candidate proper decay time errors for B_s^0 candidates within the p_T bin. Left and right plots are equivalent; the horizontal axis shows p_T in the left plot, and $1/p_T$ in the right plot.

BENCHMARK CHANNELS

In the following, I will briefly describe several important measurements that will be a benchmark of future upgrades: search for $B_{d,s} \to \mu\mu$, $B_d \to K^*\mu\mu$, mixing-induced CP violation in B_s, tree-level determination of the CKM angle γ.

The $B_{d,s} \to \mu\mu$ channel is one of the major players restricting the SUSY parameter space [8]. A joint observation of the $B_s \to \mu\mu$ decay has been published by LHCb and CMS [9] was published recently. The resulting branching fractions are:

$$\mathcal{B}(B_s \to \mu\mu) = \left(2.78\,^{+0.66}_{-0.60}(\text{stat})\,^{+0.27}_{-0.18}(\text{syst})\right) \times 10^{-9}, \tag{1}$$

$$\mathcal{B}(B_d \to \mu\mu) = \left(3.94\,^{+1.58}_{-1.41}(\text{stat})\,^{+0.31}_{-0.24}(\text{syst})\right) \times 10^{-10}, \tag{2}$$

with significances of 6.2 and 3.2 σ, respectively. An example of the expected sensitivities from CMS collaboration is shown in Table 2. The expected $B_{s,d} \to \mu\mu$ candidate invariant mass distribution can be seen in Fig. 3 corresponding to the end of run 3 and run 5.

TABLE 2. Number of expected events for $B_s \to \mu\mu$ and $B_d \to \mu\mu$ decays at CMS corresponding to different values of integrated luminosities. We also report the expected uncertainty in the branching fraction measurement for the $B_s \to \mu\mu$ and $B_d \to \mu\mu$, the range of significance of $B_d \to \mu\mu$ (the range indicates the $\pm1\sigma$ of the distribution of significance), and the relative uncertainty on the B_d to B_s branching fractions.

$\mathcal{L}$, fb^1	No. of B_s	No. of B_d	$\delta\mathcal{B}/\mathcal{B}(B_s \to \mu\mu)$	$\delta\mathcal{B}/\mathcal{B}(B_d \to \mu\mu)$	B_d sign.	$\delta\,(\mathcal{B}(B_d \to \mu\mu)/\mathcal{B}(B_s \to \mu\mu))$
20	16.5	2.0	35%	> 100%	0.01.5 σ	> 100%
100	144	18	15%	66%	0.52.4 σ	71%
300	433	54	12%	45%	1.33.3 σ	47%
3000	2096	256	12%	18%	5.47.6 σ	21%

An important decay that is expected to be sensitive to NP contributions is the decay $B_s \to J\psi\phi$. CP violation in the $B_s \to J\psi\varphi$ decay occurs due to interference between direct decays and decays proceeding through B_s-$\bar{B}_s$ mixing. The oscillation frequency of B_s meson mixing is characterized by the mass difference ΔM_s of the heavy and light mass eigenstates. The CP-violating phase ϕ_s is defined as the weak phase difference between the B_s-$\bar{B}_s$ mixing amplitude and the $b \to c\bar{c}s$ decay amplitude. In the SM the phase ϕ_s is small and can be related to CKM quark mixing matrix elements V_{ij} via the relation $\phi_s \approx 2\beta_s$, where $\beta_s = \arg\left(-(\mathrm{V_{ts}V^*_{tb}})/(\mathrm{V_{cs}V^*_{cb}})\right)$.

This analysis is very demanding to the detector and reconstruction performance as it requires not only good determination of the signal decay chain but also the high performance of the flavour tagging algorithm (i.e. the determination of initial b-flavour of the B_s meson). This is particular hard due to the high center-of-mass energy and pile up in the future runs.

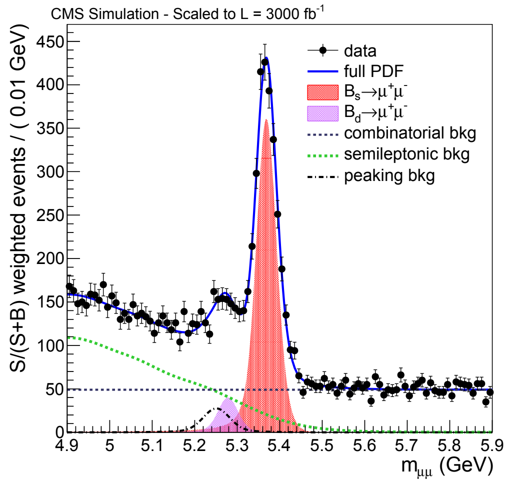

FIGURE 3. Fit results of the invariant mass distribution for 300 $^{-1}$ and 3000 fb^{-1} of the CMS simulated sample. The improvement in the mass resolution for the 3000 $^{-1}$ projection is expected from an improved inner tracker system and removing endcap candidates

ATLAS [10], CMS [11], and LHCb [12] carried out the analysis on the full data sets available for run 1. The realtive sensitivities of the various experiments can be seen in the HFAG compilation [13] shown in Fig. 4. The current experimental average is $\phi_s = -34 \pm 33$ mrad, compatible to the global fits prediction, $2\beta_s = 36.3^{+1.2}_{-1.4}$ mrad [14].

A dedicated study was performed by ATLAS to estimate sensitivity on the ϕ_s by the end of future runs. The study included the variation of the detector performance with the upgrade and the harsher conditions of the various runs. The results are reported in Table 3

TABLE 3. Estimated ATLAS statistical precision on ϕ_s for the considered LHC periods.

Year	2011	2012	2015-17		2019-21	2023-30+
Detector	current	current	IBL		IBL	ITK
Average interactions per BX $<\mu>$	6-12	21	60		60	200
Luminosity, fb^{-1}	4.9	20	100		250	3000
Signal events per fb^{-1}	4400	4320	3280	460	460	330
Signal events	22000	86400	327900	45500	114000	810 000
Total events in analysis	130000	550000	1874000	284000	758000	6461000
MC $\sigma(\phi_s)$ (stat.), rad	0.25	0.12	0.054	0.10	0.064	0.022

While channels with muons are generally considered as a mixed domain of ATLAS/CMS and LHCb, the fully hadronic channels are instead a prerogative of LHCb. Here the possibility to trigger on hadronic particles is particularly important. This is one of the main reasons for the forthcoming LHCb trigger upgrade [15].

Amongst other interesting measurement, the measurement of the CKM angle γ is attracting a lot of attention from the experimental community. This angle is one of the least known parameters of the unitarity triangle. The various measurements use B meson decays into $D^{(*)}_{(s)}K^{(*)}$ and $D^{(*)}\pi$ final states which have no penguin contribution. There is an important difference from most of other measurements of the unitarity triangle angles. These processes are theoretically clean provided that hadronic unknowns are determined from experiment. The LHCb experiment has already provided a number of analyses, which, combined with results from the B factories results, give the unprecedented precision of 7° [4], to be compared to the SM prediction of $(69 \pm 3)°$. The LHCb combination [16] gives $\gamma = (73^{+9}_{10})°$ and this will greatly improve owing to the next runs.

The LHCb experiment is expected to play a crucial role in the flavour physics programme of LHC. Expected sensitivities on several key flavour observables are reported in Table 4.

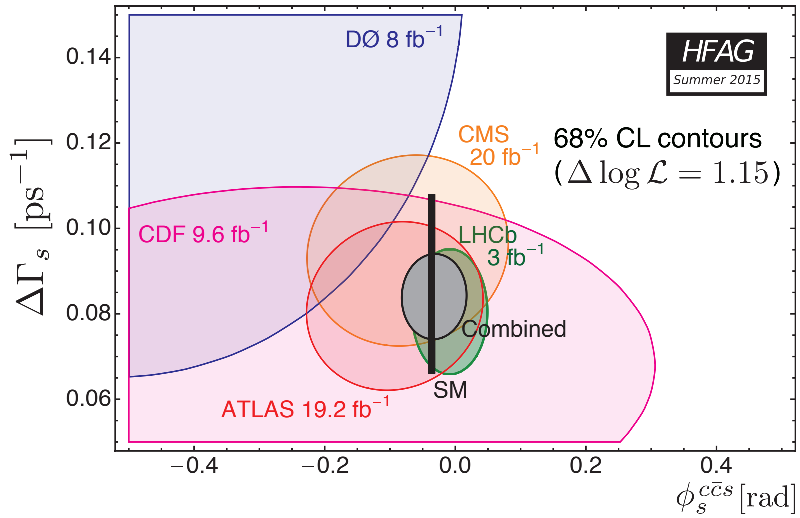

FIGURE 4. Individual contours of ATLAS, CMS, CDF, D0 and LHCb measurements, their combined contour (grey area) and the SM predictions (thin black rectangle). The prediction for ϕ_s is taken as the indirect determination of $2\beta_s$ via a global fit to experimental data within the SM.

TABLE 4. Statistical sensitivities of the LHCb upgrade to key observables. For each observable the current sensitivity is compared to that which will be achieved by LHCb before the upgrade, and that which will be achieved with 50fb[1] by the upgraded experiment. Systematic uncertainties are expected to be non-negligible for the most precisely measured quantities.

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.050	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.023**	0.02
penguin	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
currents	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	0.2 %
Electroweak	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
penguin	$q_0^2\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
penguin	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**1.1°**	negligible
triangle	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.4°**	negligible
angles	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.5**	–
CP violation	ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–

CONCLUSIONS

The hunt for NP at the LHC is entering a new era with the great experience gained by the community from run 1. The CMS, ATLAS, and LHCb detectors have already given a lot of important results in the flavour physics sector. The present performances of the detectors and their planned upgrades lead to very promising estimations of the sensitivities for the HL-LHC phase.

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