PROCEEDINGS OF SCIENCE

CKM matrix and CP violation in charm and beauty

Marcella Bona[1], **Andrea Contu***[2], **Giacomo Fedi**[3,4], **Michael J. Morello**[4,5]
[1] *Queen Mary University of London*
[2] *CERN*
[3] *Università di Pisa*
[4] *Istituo Nazionale di Fisica Nucleare*
[5] *Scuola Normale Superiore*

E-mail: andrea.contu@cern.ch

This brief write-up covers the most recent LHC results on CKM matrix and *CP* violation measurements in the charm and beauty sectors. Future perspectives are also discussed.

VII Workshop italiano sulla fisica pp a LHC
16-18 Maggio 2016
Pisa, Italy

*Speaker.

PoS(PP@LHC2016)009

1. Introduction.

Precision measurements of known processes in heavy flavour physics allows searches of deviations from the Standard Model (SM) that are complementary to direct searches. Although theoretical predictions may be affected by large uncertainties hard to keep under control, the precise study of the dynamics of beauty and charm decays provides privileged probes to higher energy scales well beyond the reach of direct searches. Excellent progresses have been made in the past twenty years and nowadays the CKM structure is known at level of 20-30%[1]. However, there still exist a significant room for improvements which will be addressed at current and future facilities. While the violation of *CP* symmetry (CPV) is well established in beauty and strange systems and increasingly precise measurements are being performed, CPV in the charm sector is heavily suppressed due to the CKM structure and any observation above the per-mil level would be a sign that may be interpreted as New Physics. In the past years, LHC has proven itself to be a "gold mine" for heavy flavour physics, mainly due to the unprecedented statistics available [2, 3]. In this brief write-up, the current status and future plans for CKM related studies in the beauty and charm sectors at the LHC are presented.

2. LHC experiments and their upgrades.

LHCb, ATLAS and CMS have been performing measurements exploiting data collected during the LHC Run I and are now focused on analysing Run II data. In the near future, all experiments will be upgraded to cope with new beam conditions and collect more integrated luminosity. A summary of the collected and expected integrated luminosities is shown in Table1 for the different experiments. LHCb will be the first experiment to be upgraded with important changes to the tracking and acquisition systems and trigger strategy to be able to handle an instantaneous luminosity up to $2 \times 10^{33}\text{cm}^{-2}\text{s}^{-2}$, and thanks to these improvements it is conceivable to expect an increase in statistics by a factor much larger than that expected by the only increasing of the collected integrated luminosity, despite the harsher environment. CMS and ATLAS will upgrade their trackers in order to achieve a significantly better resolution on *b*-hadron decay vertex positions.

	LHC ERA			**HL-LHC ERA**	
years	(2010-2012)	(2015-2018)	(2020-2022)	(2025-2028)	(2030++)
	Run I	Run II	Run III	Run IV	Run V
ATLAS,CMS	25 fb^{-1}	100 fb^{-1}	300 fb^{-1}	$\rightarrow$	3000 fb^{-1}
LHCb	3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}

Table 1: Total integrated luminosity collected by ATLAS, CMS and LHCb at the end of each LHC run.

3. CKM measurements and CPV in the beauty system.

3.1 Measurement of ϕ_s in $B_s^0 \to J\psi\phi$ and $\phi_s^{\phi\phi}$ in $B_s^0 \to \phi\phi$.

The value of the mixing phase ϕ_s in $B_s^0 \to J\psi\phi$ is precisely predicted in the SM and represents an gold-plated probe to search for deviations from SM. The main diagrams contributing to the

PoS(PP@LHC2016)009

process are shown in Figure 1 and by neglecting contributions from penguin topologies the phase can be expressed as

$$\phi_s = \phi_M - 2\phi_D \stackrel{SM}{=} -2\arg\left(-\frac{V_{cb}V_{cs}^*}{V_{tb}V_{ts}^*}\right) \equiv -2\beta_s.$$

Current predictions from UTFit and CKM fitter are

$$\phi_s \stackrel{SM}{=} 0.0369 \pm 0.0013\,\text{rad}, \quad \phi_s \stackrel{SM}{=} -0.0376^{+0.0007}_{-0.0008}\,\text{rad},$$

respectively. Experimentally, ϕ_s is accessible via the time dependent asymmetry, as shown in the

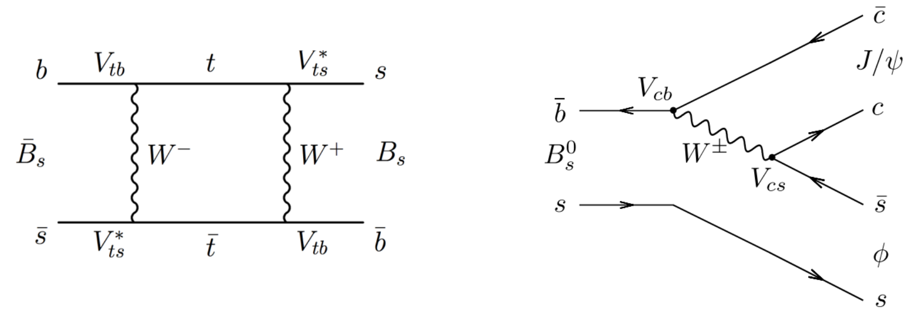


Figure 1: Diagrams contributing to (left) $B_s^0 - \bar{B}_s^0$ meson mixing and (right) decay.

expression below[1]:

$$A_{CP}(t) = \frac{\Gamma_{B_s^0} - \Gamma_{\bar{B}_s^0}}{\Gamma_{B_s^0} + \Gamma_{\bar{B}_s^0}} = \frac{S_f \sin(\Delta m t) - C_f \cos(\Delta m t)}{\cosh(\Delta\Gamma t/2) - A_{\Delta\Gamma}\sinh(\Delta\Gamma t/2)}.$$

ATLAS, CMS and LHCb collected samples of $B_s^0 \to J\psi\phi$ decays with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$. The signal yields range from 50K to 100K events and using a time-dependent and tagged analysis ϕ_s, along with other observables such as Δm_s, Γ_s, $\Delta\Gamma_s$, are determined. Since the process involves a pseudo-scalar meson decaying into two vector mesons, it is also important to distinguish among CP-even, CP-odd and KK S-wave components. These components are statistically disentangled by performing an angular analysis of the decay, with angles defined as in Figure 2. By

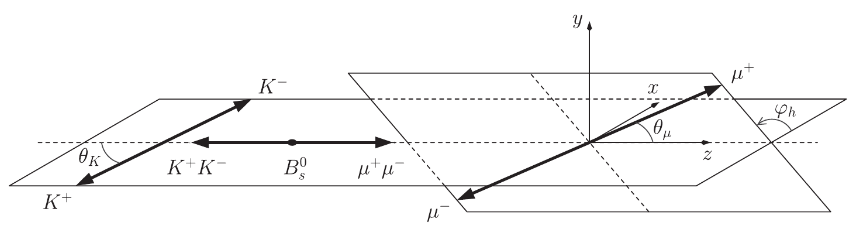


Figure 2: Definition of decay angles for $B_s^0 \to J\psi\phi$.

combining all the LHC measurements with previous ones performed at Tevatron, the values for ϕ_s and Γ_s are found to be $\phi_s = -0.034 \pm 0.033$, $\Gamma_s = +0.084 \pm 0.007$, which are compatible with the SM expectations. All the measurements, summarised in Figure 3, are statistically limited so that a

[1] $\lambda_f = \frac{qA_f}{p\bar{A}_f}$, $\phi_s = -\arg(\lambda_f)$, $C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$, $S_f = \frac{2\mathscr{I}(\lambda_f)}{1+|\lambda_f|^2}$, $A_{\Delta\Gamma} = -\frac{2\mathscr{R}(\lambda_f)}{1+|\lambda_f|^2}$

PoS(PP@LHC2016)009

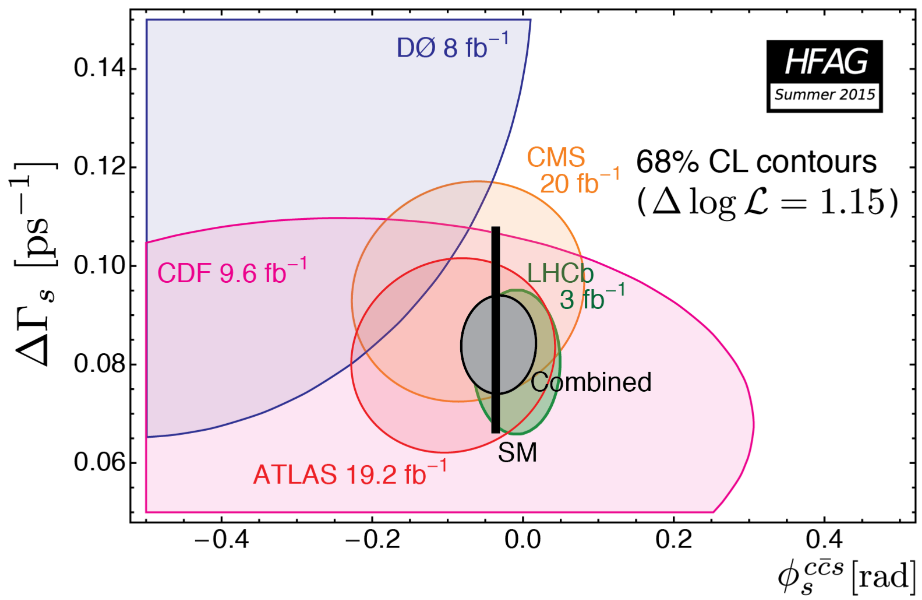


Figure 3: HFAG average of ϕ_s and Γ_s measurements.

significant improvement is still possible in the upgrade era. However, better estimation of penguin contributions are needed from the theory side as we enter the precision regime. The measurement of the $\phi_s^{\phi\phi}$ phase extracted from $B_s^0 \to \phi\phi$ decays is strictly related to this. In fact, such a decay is dominated by penguin diagrams and it is an ideal place for probing possibile virtual contributions from new particles in loops, by comparing with the ϕ_s measurement. LHCb performed the first measurement using the $B_s^0 \to \phi\phi$ decay, obtaining $\phi_s^{\phi\phi} = -170 \pm 150_{stat} \pm 30_{syst}$ [17] compatible with the predicted upper limit of $\phi_s^{\phi\phi,SM} < 0.02$.

Finally, Figure 4 contains extrapolations by LHCb and ATLAS. By 2030 the statistical uncertainty will be at the level of SM predictions.

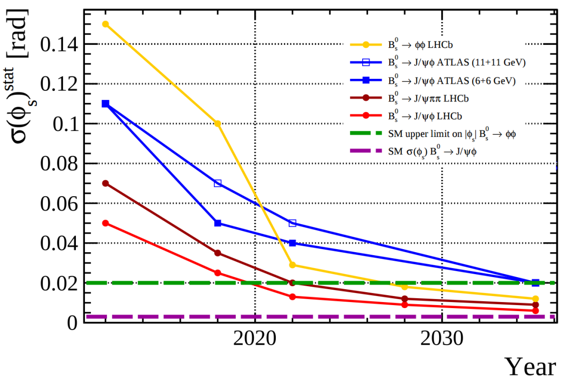


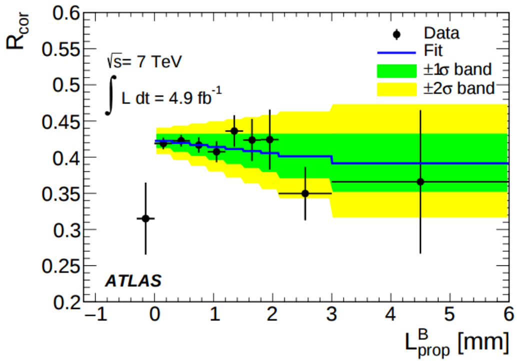
Figure 4: Extrapolation for the statistical uncertainty on the phase ϕ_s at LHCb and ATLAS.

3.2 Measurement of $\Delta\Gamma_d$ at ATLAS

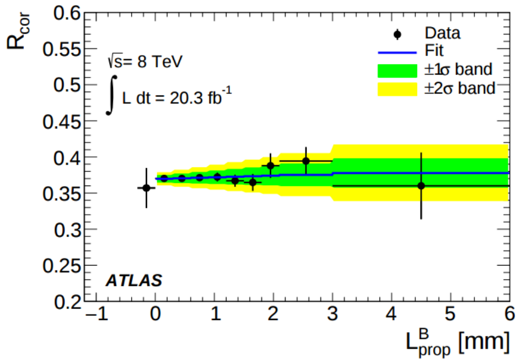
The ATLAS collaboration recently measured the relative width difference of the B^0-$\bar{B}^0$ sys-

PoS(PP@LHC2016)009

tem [4] using 25.2 fb^{-1} of Run I data. The SM prediction for the relative value is $\Delta\Gamma_d/\Gamma_d(SM) = (0.42 \pm 0.08) \times 10^{-2}$ [5] while the current world average is $\Delta\Gamma_d/\Gamma_d(SM) = (0.1 \pm 1.0) \times 10^{-2}$ [6]. The measurement is performed by comparing the decay-time distributions of $B^0 \to J/\psi K^0_S$ and $B^0 \to J/\psi K^{*0}(892)$, as shown in Figure 5. The final measurement is



(a)



(b)

Figure 5: Efficiency-corrected ratio of the observed decay length distributions for (a) $\sqrt{s} = 7$ TeV and (b) $\sqrt{s} = 8$ TeV.

$$\Delta\Gamma_d/\Gamma_d = (-0.1 \pm 1.1(stat) \pm 0.9(syst)) \times 10^{-2},$$

which is the single most precise measurement of this quantity and in agreement with SM predictions.

3.3 Measurement of the semileptonic asymmetries a^d_{sl} and a^s_{sl}.

In 2014, the D0 collaboration reported deviations from the SM when looking at asymmetries in semileptonic decays of neutral B mesons [7]. The quantity measured is defined as

$$a^q = \frac{P(\bar{B}_q \to B_q \to f) - P(B_q \to \bar{B}_q) \to \bar{f}}{P(\bar{B}_q \to B_q \to f) + P(B_q \to \bar{B}_q \to \bar{f})} = 1 - \left|\frac{q}{p}\right|^2 \approx \frac{\Delta\Gamma_q}{\Delta m_q} \tan(\phi_q^{12})$$

and SM predictions exist both for B^0_d and B^0_s [10]:

$$a^d_{sl} = (-4.6 \pm 0.6) \times 10^{-4}, \quad a^s_{sl} = (2.22 \pm 0.27) \times 10^{-5}$$

While no distinction is made between B^0_d and B^0_s in the D0 measurement, LHCb measured the individual asymmetries [8, 9]. The quantities which are experimentally accessible are:

$$A^d_{raw}(t) = \frac{N(f,t) - N(\bar{f},t)}{N(f,t) + N(\bar{f},t)} \approx A_D + \frac{a^d_{sl}}{2} + \left(A_P - \frac{a^d_{sl}}{2}\right) \cos(\Delta m_d t)$$

$$A^s_{raw} = \frac{N(f) - N(\bar{f})}{N(f) + N(\bar{f})} \approx A_D + \frac{a^s_{sl}}{2} + \left(A_P - \frac{a^s_{sl}}{2}\right) \int \cos(\Delta m_s t) dt.$$

The LHCb measurements are in agreement with the SM predictions, as summarised in Figure 6 which includes also measurements from BaBar.

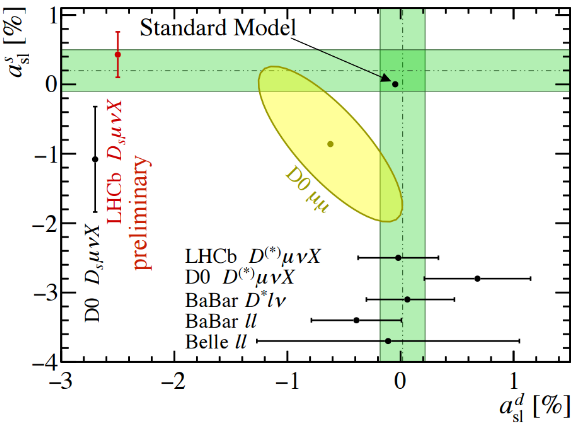
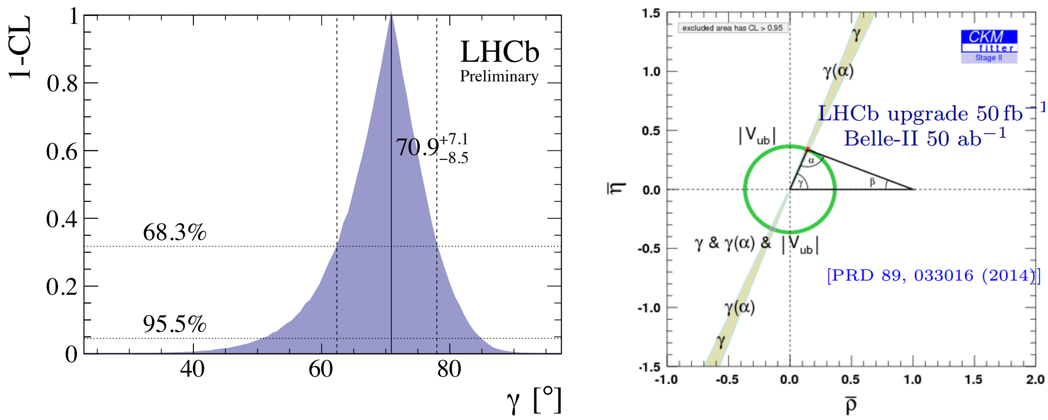


Figure 6: Summary of semileptonic asymmetries measurements.

3.4 Measurement of the CKM angle γ with tree level processes.

A precise measurement of the CKM angle γ, the least known angle of the Unitarity Triangle, is an important probe for processes beyond the Standard Model. This is pursued by comparing the value of γ measured using theoretically clean decays, where it appears at tree-level (most notably the family of $B \to DK$ decay modes), and decays where the presence of significant loop contribution may exhibit unexpected new CP-violating effects. The current experimental sensitivity is achieved by exploiting the following processes: $B^+ \to Dh^+$, $D \to hh$ (GLW/ADS), $B^+ \to Dh^+$, $D \to K\pi\pi\pi$ (ADS) $B^+ \to DK^+$, $D \to K_S^0 hh$ (GGSZ), $B^+ \to DK^+$, $D \to K_S^0 K\pi$ (GLS), $B^0 \to DK^{0*}$, $D \to hh$ (GLW/ADS), and time dependent $B_s^0 \to D_s K$. The world average is currently dominated by the combination of LHCb measurements [11] $\gamma = (70.9^{+7.1}_{-8.5})^\circ$ where the quoted uncertainty is the statistical and systematic combined (see Figure 7). Belle II is expected to achieve a similar pre-



(a) (b)

Figure 7: Right: $1-$CL curve for the LHCb combination of angle γ measurement, with central values (solid vertical lines) and 1σ uncertainties (dashed vertical lines) labelled. The 1σ and 2σ levels are indicated by the horizontal dotted lines. Left: sensitivity projections of Unitarity Triangle angles.

cision once data taking will start. Both experiments should achieve sub-degree precision by 2030 (end of Run3 for LHCb) [12] as shown in the Unitarity Triangle projections shown in Figure 7.

3.5 Measurement of $|V_{ub}|$ with baryonic decays.

The interest in the measurement of $|V_{ub}|$ is not only due to it being an important parameter in the CKM matrix, but also to the outstanding discrepancies between inclusive and exclusive estimates. Despite the non-optimal hadronic environment, in 2015 the LHCb collaboration published an exclusive measurement of $|V_{ub}|$ using Λ_b^0 decays [13]. The measured quantity is the ratio of branching fractions

$$\mathscr{B}\left(\Lambda_b^0 \to p\mu\nu\right)/\mathscr{B}\left(\Lambda_b^0 \to \Lambda_c(\to pK\pi)\mu\nu\right)$$

which is proportional to $|V_{ub}|/|V_{cb}|$. The measurement is performed at high q^2 for the $\mu\nu$ system to minimise uncertainties on the form factors [14]. After tight signal isolation requirements, the yields of for the two semileptonic decays are derived from a fit to the corrected mass shown in Figure 8.

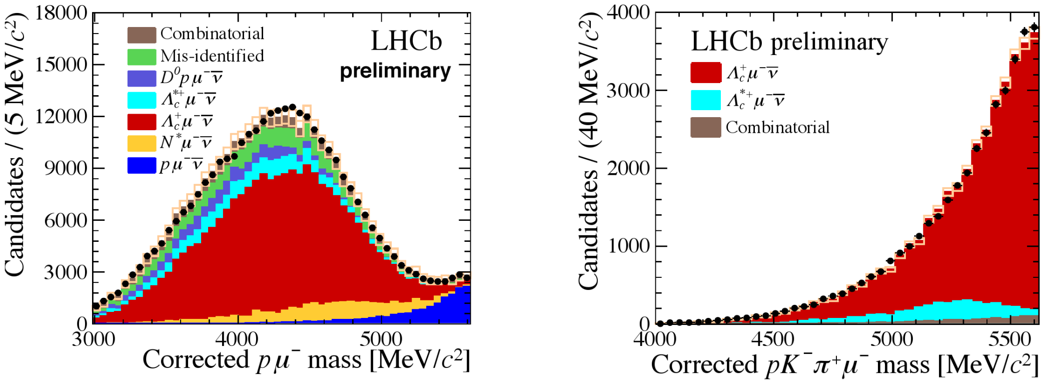


Figure 8: Corrected mass for (a) $\left(\Lambda_b^0 \to p\mu\nu\right)$ and (b) $\left(\Lambda_b^0 \to \Lambda_c(\to pK\pi)\mu\nu\right)$.

The ratio of branching fraction is measured to be

$$\frac{\mathscr{B}\left(\Lambda_b^0 \to p\mu\nu\right)_{q^2>15\,\mathrm{GeV}^2}}{\mathscr{B}\left(\Lambda_b^0 \to \Lambda_c\mu\nu\right)_{q^2>7\,\mathrm{GeV}^2}} = (1.00 \pm 0.04 \pm 0.08) \times 10^{-2}.$$

Using exclusive measurements of $|V_{cb}|$, $|V_{ub}|$ is measured to be

$$|V_{ub}| = (3.27 \pm 0.15(exp) \pm 0.17(theory) \pm 0.06(|V_{cb}|)) \times 10^{-3},$$

which confirms the discrepancy with respect to inclusive measurement at 3.5σ level, as summarised in Figure 9. The measurement is currently limited by lattice QCD estimates of the form factors and by the knowledge of $\mathscr{B}(\Lambda_c \to pK\pi)$. Improvements on both these fronts are foreseeable in the future and a measurement using $B_s^0 \to K\mu\nu$ may help in further reducing the statistical uncertainty. In addition, Belle II will soon join with an expected precision of 2-3%.

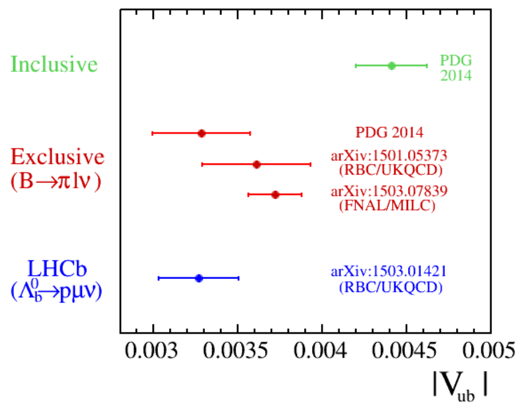


Figure 9: Summary of the various $|V_{ub}|$ determinations.

4. Charm physics at the LHCb experiment: the beginning of a new era.

The main advantage of investigating charm physics in hadronic environment, like the LHC, is the copious production cross section of charm hadrons. An unprecedented huge amount of decays of all charm species was produced in Run1 from pp collisions at the LHC, with $\approx 5 \times 10^{12}$ D^0 decays within the LHCb acceptance corresponding to a cross section of $\approx 1600\mu$b. However the large c-cross-section has to be compared with the total inelastic pp cross-section which is about 1000 times larger. This means that charm events are overwhelmed by an amount of uninteresting background events larger by at least three orders of magnitude when considering the branching fraction of the process of interest. The task of improving such an unfavorable ratio between c events and background is performed by the LHCb data acquisition and trigger systems that allow collecting high-purity and abundant samples of charm decays. In Run1 the LHCb experiment collected 3fb^{-1} of integrated luminosity at an instantaneous luminosity of 4×10^{32} cm^{-2}s^{-1}, 1 fb^{-1} (2 fb^{-1}) at 7 TeV (8 TeV) centre-of-mass energy. This yields very pure reconstructed samples of charm mesons decays, about 0.7×10^9 Cabibbo-favored untagged $D^0 \to K\pi$ decays, that become about 0.1×10^9 decays when the flavour of the D^0 meson is inferred by the charge of the soft pion from the strong $D^{*+} \to D^0\pi^+$ decays, corresponding approximately to an improvement by a factor of 30 over the full data sample collected by the previous CDF II experiment in its full data sample. Considering that in Run1 the total efficiency of LHCb detector in collecting charm decays is below 1% level, a large room of improvement in collecting even larger sample of charm decays, well beyond the gain in statistics, is conceivable. In this landscape current LHCb measurements represent the beginning of new era aiming at an extreme precise experimental exploration of the charm sector, trough the full exploitation of the LHC.

4.1 Measurement of A_Γ in $D^0 \to hh$ decays

One of the main areas to search for indirect CPV in charm is the measurement of A_Γ observable, defined as

$$A_\Gamma = \frac{\tau^{eff}_{\bar{D}^0} - \tau^{eff}_{D^0}}{\tau^{eff}_{\bar{D}^0} + \tau^{eff}_{D^0}} \approx \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y\cos\phi - \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x\sin\phi,$$

where τ_{eff} are the effective lifetimes. It can be seen that this quantity is mostly sensitive to indirect CPV through the mixing parameters x and y. The knowledge of the D^0 flavour at production is necessary and it is achieved through either $B \to D\mu\nu$ or $D^{*+} \to D^0\pi^+$ decays. The latest measurement from LHCb [15] falls in the former category. $A_\Gamma^{KK(\pi\pi)}$ is determined through a fit of the yield ratio of D^0 and $\bar{D}^0$ in bins of lifetime, shown in Figure 10. The measurement is

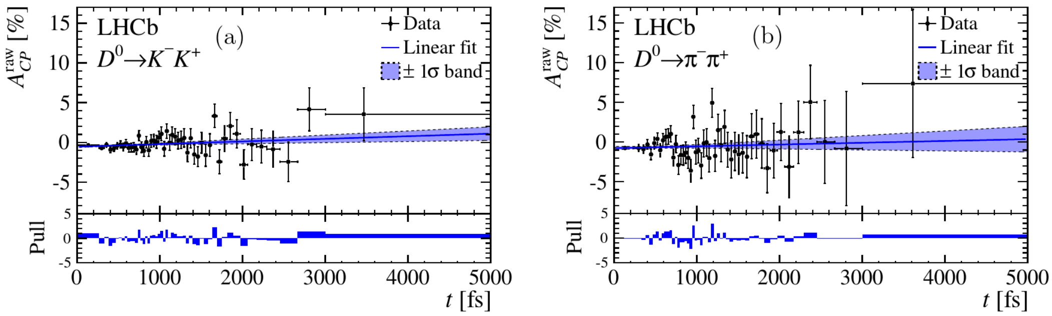


Figure 10: Fits for A_Γ for $D^0 \to KK$ and $D^0 \to \pi\pi$. A_Γ is approximately the slope of the fitted line since $A_{CP}(t) \approx A_0 - A_\Gamma \frac{t}{\tau}$.

$$A_\Gamma(KK) = (-0.134 \pm 0.077_{stat}{}^{+0.026}_{-0.034})\% \quad A_\Gamma(\pi\pi) = (-0.092 \pm 0.145_{stat}{}^{+0.025}_{-0.033})\%.$$

Figure 11 shows a summary of current experimental knowledge of A_Γ, and all measurements are

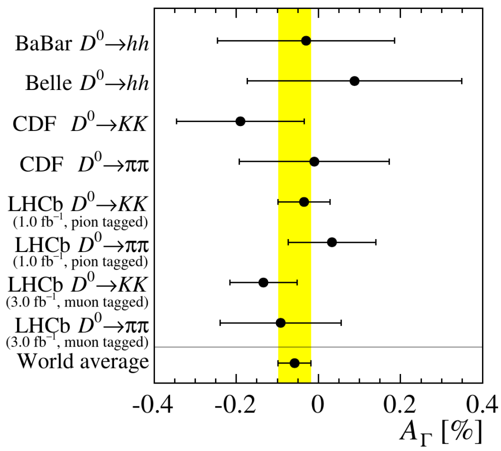


Figure 11: Summary of all A_Γ measurements. The world average assumes that the indirect CPV is universal, e.g. it does not depend on the final state.

compatible with zero, which implies no hints of CPV. The word average is dominated by LHCb, which is still statistically limited.

4.2 Measurement of ΔA_{CP} in $D^0 \to hh$ decays.

The time integrated CP asymmetry $\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$, sensitive to direct CP violation raised some attention in the recent past due to $\sim 2\sigma$ deviation from zero reported both by CDF and LHCb. Although this deviation went away with further measurements, this is a relatively clean measurement still dominated by the statistical uncertainty. The current most precise measurement, which dominates the world average, comes from the LHCb collaboration. Using Run I data [16], LHCb reported the following result:

$$\Delta A_{CP} = (-0.10 \pm 0.08 \pm 0.03)\%.$$

4.3 Study of $D^0 \to K^0_S hh$ decays.

Studies of $D^0 \to K^0_S hh$ decays deserve a special mention since they give direct access to several observables such as x, y, q/p and ϕ through Dalitz time-dependent analysis. Two approaches are possible: a “model dependent” one with an amplitude analysis and a “model independent” in bin of the Dalitz plane with external inputs (such as the strong phases from CLEO). LHCb recently published results for the mixing parameters using 2011 data and the model independent approach:

$$x = (-0.86 \pm 0.53 \pm 0.17) \times 10^{-2},$$

$$y = (+0.03 \pm 0.46 \pm 0.13) \times 10^{-2}.$$

Again, the statistical uncertainty is the dominant one. Figure 12 shows the prospects for indirect CPV searches at LHCb.

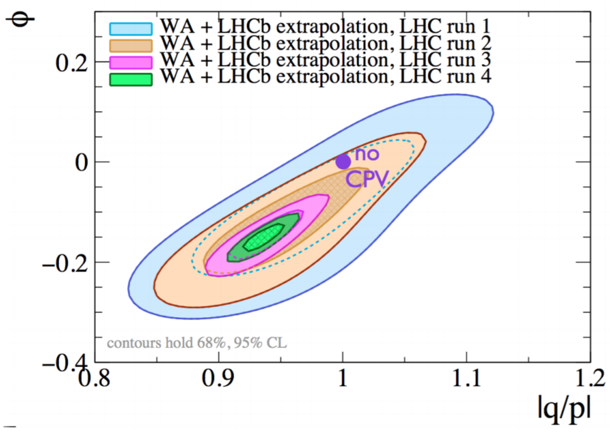


Figure 12: Prospects for indirect CPV at LHCb.

5. Conclusions.

LHC is the most copious ever source of charm and beauty decays and experiments (ATLAS, CMS and LHCb) have been doing an excellent job at collecting the largest ever data samples of b- and c-hadrons decays. In Run1 statistical precisions at an unprecedented level have already been achieved with systematic uncertainties still much lower, providing the possibility to approach in many case for the first time the upper bounds of SM expectations (for instance in charm sector).

LHC experiments are currently taking data and it is conceivable that the size of data samples will increase much more than proportionally to the integrated luminosity, both in Run2 and in the Upgrades, opening a privileged door for studying at very high precision the structure of flavour dynamics, and consequently effects of New Physics.

References

[1] R. Barbieri, D. Buttazzo, F. Sala and D. M. Straub, JHEP **1405** (2014) 105 doi:10.1007/JHEP05(2014)105 [arXiv:1402.6677 [hep-ph]].

[2] R. Aaij *et al.* [LHCb Collaboration], JHEP **1308** (2013) 117 doi:10.1007/JHEP08(2013)117 [arXiv:1306.3663, arXiv:1306.3663 [hep-ex]].

[3] R. Aaij *et al.* [LHCb Collaboration], JHEP **1603** (2016) 159 doi:10.1007/JHEP03(2016)159 [arXiv:1510.01707 [hep-ex]].

[4] M. Aaboud *et al.* [ATLAS Collaboration], arXiv:1605.07485 [hep-ex].

[5] A. Lenz and U. Nierste, arXiv:1102.4274 [hep-ph].

[6] K. A. Olive *et al.* [Particle Data Group Collaboration], Chin. Phys. C **38** (2014) 090001. doi:10.1088/1674-1137/38/9/090001

[7] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. D **89** (2014) no.1, 012002 doi:10.1103/PhysRevD.89.012002 [arXiv:1310.0447 [hep-ex]].

[8] R. Aaij *et al.* [LHCb Collaboration], Phys. Lett. B **739**, 218 (2014) doi:10.1016/j.physletb.2014.10.005 [arXiv:1408.0275 [hep-ex]].

[9] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **114** (2015) 041601 doi:10.1103/PhysRevLett.114.041601 [arXiv:1409.8586 [hep-ex]].

[10] M. Artuso, G. Borissov and A. Lenz, arXiv:1511.09466 [hep-ph].

[11] The LHCb Collaboration [LHCb Collaboration], LHCb-CONF-2016-001, CERN-LHCb-CONF-2016-001.

[12] J. Charles, S. Descotes-Genon, Z. Ligeti, S. Monteil, M. Papucci and K. Trabelsi, Phys. Rev. D **89** (2014) no.3, 033016 doi:10.1103/PhysRevD.89.033016 [arXiv:1309.2293 [hep-ph]].

[13] R. Aaij *et al.* [LHCb Collaboration], Nature Phys. **11** (2015) 743 doi:10.1038/nphys3415 [arXiv:1504.01568 [hep-ex]].

[14] W. Detmold, C. Lehner and S. Meinel, Phys. Rev. D **92** (2015) no.3, 034503 doi:10.1103/PhysRevD.92.034503 [arXiv:1503.01421 [hep-lat]].

[15] R. Aaij *et al.* [LHCb Collaboration], JHEP **1504** (2015) 043 doi:10.1007/JHEP04(2015)043 [arXiv:1501.06777 [hep-ex]].

[16] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **116** (2016) no.19, 191601 doi:10.1103/PhysRevLett.116.191601 [arXiv:1602.03160 [hep-ex]].

[17] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **110** (2013) no.24, 241802 doi:10.1103/PhysRevLett.110.241802 [arXiv:1303.7125 [hep-ex]].

PoS(PP@LHC2016)009