BELLE2-NOTE-PH-2015-004
Version 5.0
July 20, 2015

Belle II - LHCb measurement extrapolation comparisons

Phillip Urquijo

School of Physics, The University of Melbourne, Victoria 3010

Abstract

This report presents a set of projected measurement uncertainties as a function of time for several key flavour physics measurements at Belle II and LHCb until 2025. The time basis is the expected integrated luminosity delivery date from the respective colliders.

Contents

I. INTRODUCTION

In this report we compare sets of projected measurement uncertainties as a function of time for several key flavour physics measurements at Belle II and LHCb until 2025. This report only covers modes that are considered precisely measurable by both the LHCb and Belle II experiments. Both experiments have extensive programs of measurements where they have unique capabilities, e.g. $B_s \to \mu\mu$ in LHCb and $B \to \mu\nu$ in Belle II, but they will not be covered here.

II. INTEGRATED LUMINOSITY PROFILES

The Belle II integrated luminosity profile is taken from the Belle II executive board in May 2015. The full detector will be available only from 2018 onwards. We base the flavour physics prospectives on the full detector configuration only. The SuperKEKB instantaneous luminosity ramp-up is subject to change, but provides us with a baseline. The LHC shutdown schedule and LHCb integrated luminosity projection are taken from the LHC roadmap, June 2015 `http://lhc-commissioning.web.cern.ch/lhc-commissioning/schedule/LHC%20schedule%20beyond%20LS1%20MTP%202015_Freddy_June2015.pdf` (Figure 1) and LHCb-PUB-2014-040 respectively. In the latter document LHCb states that they expect to take 2 fb^{-1} per year during Run-2 (2015-2018) (except for machine technical stops) at $\sqrt{s}$ =13 TeV for 3.5 years, and 5 fb^{-1} per year in Run-3 at $\sqrt{s}$ =14 TeV (2021-2023) for 3 years. The 2014 LHCb document has an outdated timeline, which we have updated according to the latest LHC roadmap above. The Belle II and LHCb integrated luminosities are shown in Figure 2. The comparison of Belle II to LHCb requires corrections due to cross section and efficiency differences in the varying conditions at the LHC, and the LHCb upgrade schedules. These parameters are taken from the LHCb upgrade document LHCb-PUB-2014-040. The following conditions are expected.

- Run-2 will operate at 13 TeV, and Run-3 at 14 TeV.
- The b and c quark production cross sections scale linearly with $\sqrt{s}$. We take a weighted average of the 7 and 8 TeV results in order to project to the 13 TeV and 14 TeV data taking runs.

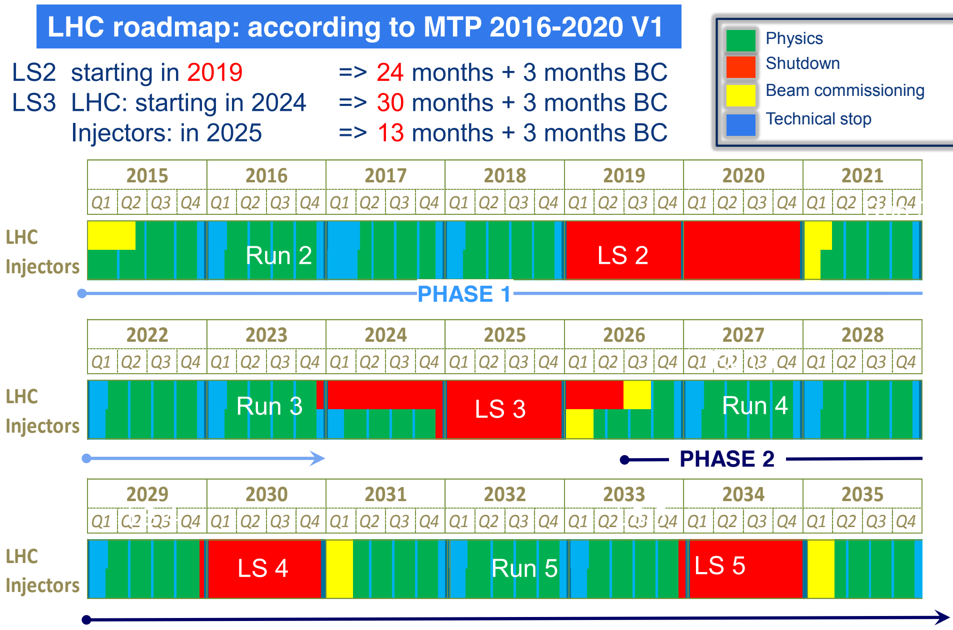

FIG. 1: LHC schedule.

- Run-2 will be 50% less efficient than Run-1 for modes found by hadronic triggers.
- During long-shutdown-2 LHCb will upgrade its trigger system, removing the hardware trigger. This will increase the hadronic trigger efficiency by a factor of two with respect to Run-1. Muon trigger efficiencies will remain at their current levels.
- The LHC will shut down again in 2023 for a period of 2.5 to 3 years.

The baseline statistical extrapolation for Belle II assumes that the same ratio of $\Upsilon(4S)$ data taking to the total data taken is used, which is close to 70%. We also consider three further scenarios for Belle II, beyond baseline statistical extrapolation:

- improved K_S acceptance and IP resolution,
- improved hadronic B-tagging,
- 100% data taking ratio at $\Upsilon(4S)$

Due to the larger SVD radius, lower material budget, and implementation of 2 PXD layers we expect K_S mesons to be reconstructed with approximately 30% greater efficiency than Belle. We also expect large improvements to hadronic B-tagging due to improved algorithms, implementation of many more modes, and overall detector enhancements. For this we nominate a factor 2 improvement based on estimates shown at the Feb 2015 B2GM. We compare the effective yield scaling, and reduction factor in statistical uncertainties with respect to measurements at Belle and LHCb as of early 2015. These are shown in Figure 3. Modes with K_S are expected to improve by a factor of 8, and B-tagged events may improve by as much as 10. Another scenario that may be considered in the future is for events with D^* slow pions. We will do these projections after the track algorithms for slow pions reach a stable efficiency projection.

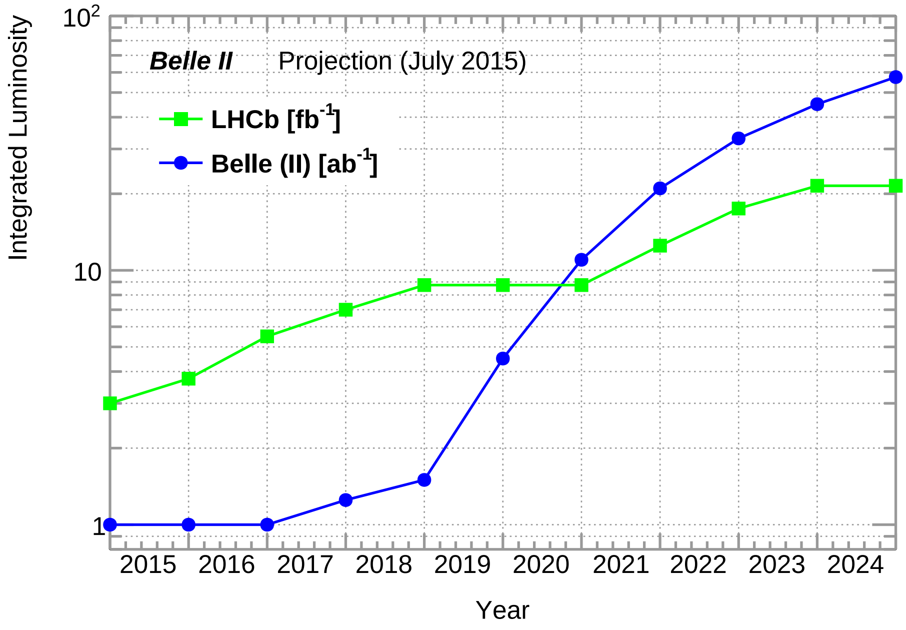

FIG. 2: SuperKEKB and LHCb integrated luminosity projections in fb^{-1} and ab^{-1} respectively.

Systematic uncertainties are taken into account in these projections. We base most projected systematic uncertainties on values presented in BELLE2-NOTE-21/BELLE2-NOTE-PH-2015-002, and LHCb EPJC 73, 2373. If projections are not provided in that report, the assumptions will be provided here.

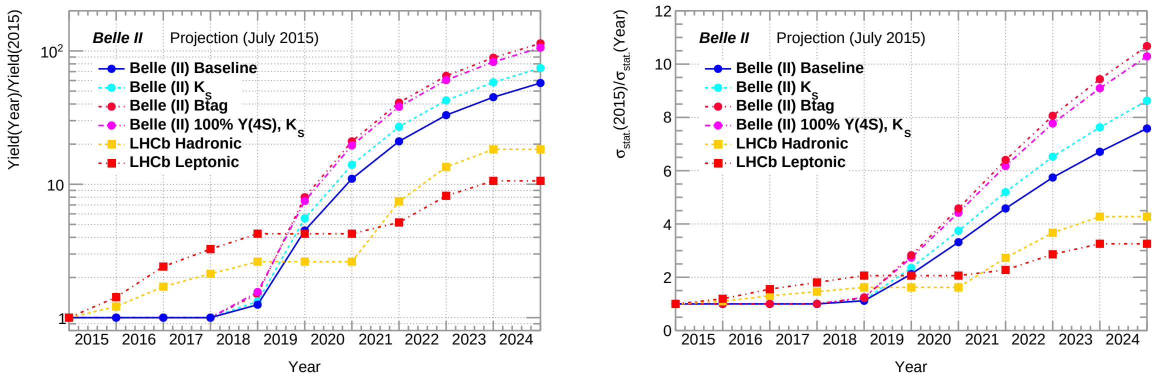

FIG. 3: Expected yield enhancement for selected analysis types in Belle II and LHCb (left), and expected statistical error reduction factors (right). It assumes that Belle II will spend 70% of the time at $\Upsilon(4S)$, which is a realistic, but conservative operating scenario.

III. TIME DEPENDENT CP VIOLATION

The Belle II extrapolation for the Belle golden mode $B \to J/\psi K_S$ is based on Belle2-Note-21 and is expected to be systematics limited although the systematic uncertainties are expected to improve. Two configurations are shown in Figure 4, baseline and improved K_S acceptance. To be conservative, we list only the baseline result in Table I. The LHCb run-1 sensitivities for $B \to \phi K_S$ are the LHCb best guess, since no time- dependent LHCb analyses exist for this mode (in earlier Belle II - LHCb comparisons the run-1 sensitivity estimate was 0.64). The Belle II extrapolations for the gluonic penguin modes are expected to be statistics limited for the lifetime of the experiment. Although the systematic uncertainties may be large, there will be close competition on the two-charged track TCPV measurements of $B \to \pi^+\pi^-$.

TABLE I: Projection summary and expected systematic uncertainties. The † symbol denotes an assumption about the level of irreducible systematic errors used in this document but not described elsewhere (typically a naive factor of 2 reduction), the symbol ‡ denotes a precision extrapolated from a partial data set, and the symbol # denotes a guess taken from the LHCb upgrade document.

Observables	Belle	Belle II		LHCb	
	(2015)	50 ab^{-1} 70%@$\Upsilon(4S)$, improved K_S	50 ab^{-1}@$\Upsilon(4S)$	Run-1	22 fb^{-1}
	$(\sigma_{\rm stat}, \sigma_{\rm sys})$	$(\sigma_{\rm stat}, \sigma_{\rm sys})$	$(\sigma_{\rm stat}, \sigma_{\rm sys})$	$(\sigma_{\rm stat}, \sigma_{\rm sys})$	$(\sigma_{\rm stat}, \sigma_{\rm sys})$
$\sin(2\phi_1)$ in $B \to J/\psi K_S$	(0.023, 0.011)	(0.003, 0.007)	(0.007)	(0.035, 0.020)	(0.012, 0.007#)
$\sin(2\phi_1)$ in $B \to \phi K_S$	(0.14)	(0.018)	(0.015)	(0.30)#	(0.06)
$\sin(2\phi_1)$ in $B \to \eta' K_S$	(0.07, 0.03)	(0.008, 0.008)	(0.009)	–	–
$S_{CP}(B \to \pi^+\pi^-$	(0.08, 0.03)	(0.013, 0.015)	(0.018)	(0.13, 0.02)‡ 1 fb^{-1}	(0.018, 0.010)†
$C_{CP}(B \to \pi^+\pi^-$	(0.06, 0.03)	(0.010, 0.015)	(0.016)	(0.15, 0.02)‡ 1 fb^{-1}	(0.021, 0.010)†

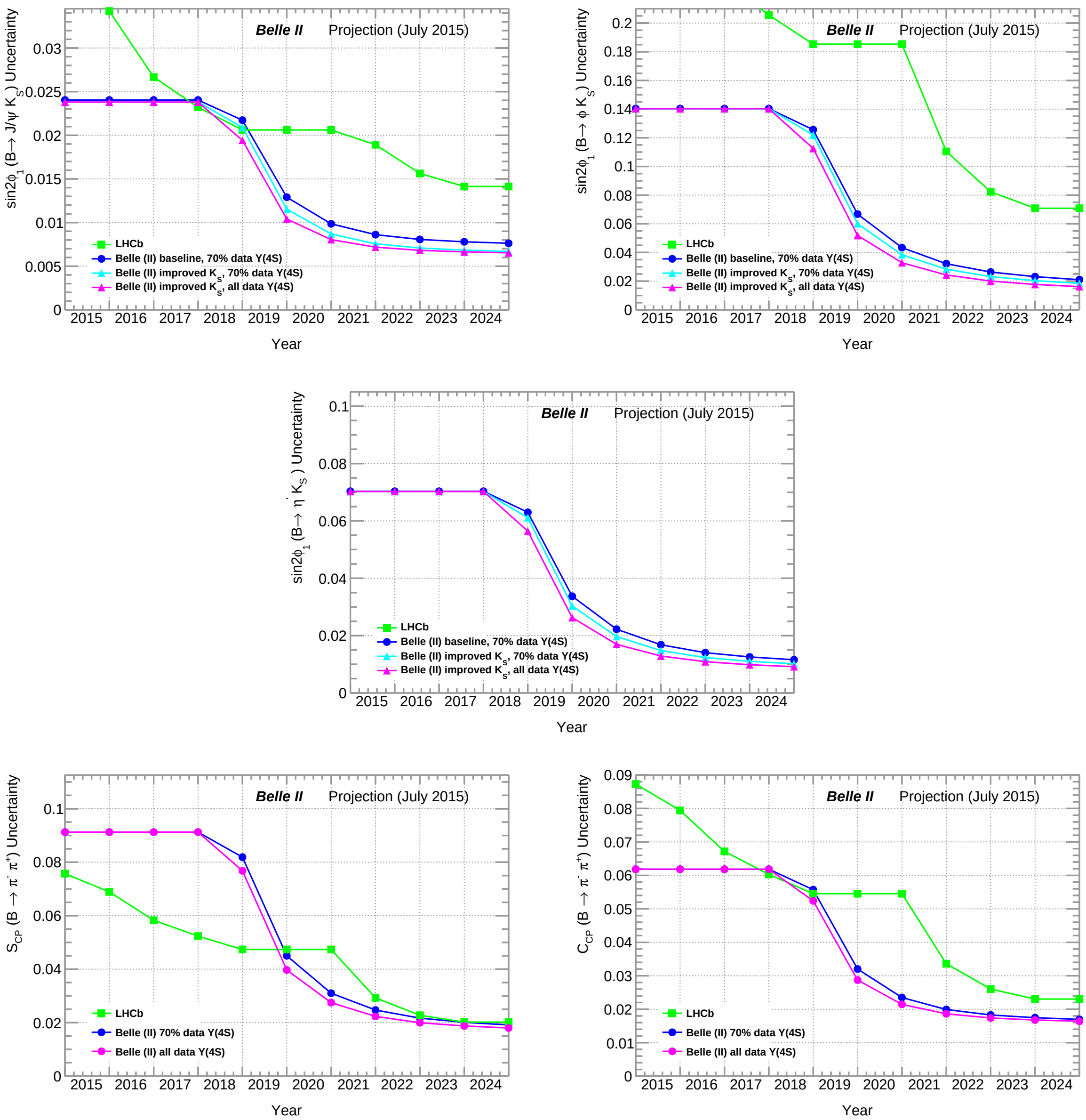

FIG. 4: Projected precision for various measurements of time dependent CP violation.

IV. DIRECT CP VIOLATION

The measurement of ϕ_3 is considered to be very clean: both the experimental systematic and theoretical uncertainties are expected to be negligible for the lifetime of the experiment. For Belle II, we base the projections on a combination of $B \to DK$ measurements (already performed at Belle), where the D meson decays to

- $D \to KK$, $D \to \pi\pi$, $D \to K\pi$
- $D \to K\pi\pi\pi$
- $D \to K_S\pi\pi$

where the combined precision on ϕ_3 for Belle is taken from CKMFitter.

The LHCb value is based on an extrapolation of the 2015 Run-1 results in LHCb-PAPER-2014-041 and also analysed by CKMFitter. The results are based on a combination of measurements from $B^+ \to Dh^+$ and $B^0 \to DK^{*0}$ decays, where h^+ corresponds to either K^+ or π^+ and the D meson decays into

- $D \to KK$, $D \to \pi\pi$, $D \to K\pi$
- $D \to K\pi\pi\pi$
- $D \to K_S\pi\pi$

Clearly LHCb has included more modes and intends to include even more in the future, however we base the extrapolation on these available combinations.

Direct CP Violation measurements in $B \to K\pi$ modes currently have large systematic uncertainties, which should be improved in Belle II due to better particle identification and K_S reconstruction. Using a naive scaling for the systematic errors, we expect reasonably close competition in both modes.

The direct CP violation projections are shown in Table II and Figure 5.

TABLE II: Extrapolations for selected direct CP violation measurements. See Table I for a description of the symbols.

Observables	Belle	Belle II		LHCb	
	(2015)	50 ab^{-1} 70%@$\Upsilon(4S)$ (improved K_S)	50 ab^{-1} @$\Upsilon(4S)$	Run-1	22 fb^{-1}
	$(\sigma_{\text{stat}}, \sigma_{\text{sys}})$	$(\sigma_{\text{stat}}, \sigma_{\text{sys}})$	$(\sigma_{\text{stat}}, \sigma_{\text{sys}})$	$(\sigma_{\text{stat}}, \sigma_{\text{sys}})$	$(\sigma_{\text{stat}}, \sigma_{\text{sys}})$
$\phi_3(B \to D^{(*)}K^{(*)})$ Combined [deg]	(14)	(1.9)	(1.5)	(8.8)	(2.0)
$A_{CP}(B \to K^0\pi^-)$ [10^{-3}]	(2.1, 0.6)	(0.3, 0.3)	(0.35)	(2.5, 1.0)	(0.6, 0.5)
$A_{CP}(B \to K^+\pi^-)$ [10^{-3}]	(1.4, 0.7)	(0.2, 0.3)	(0.34)	(0.7, 0.3)	(0.16, 0.15)

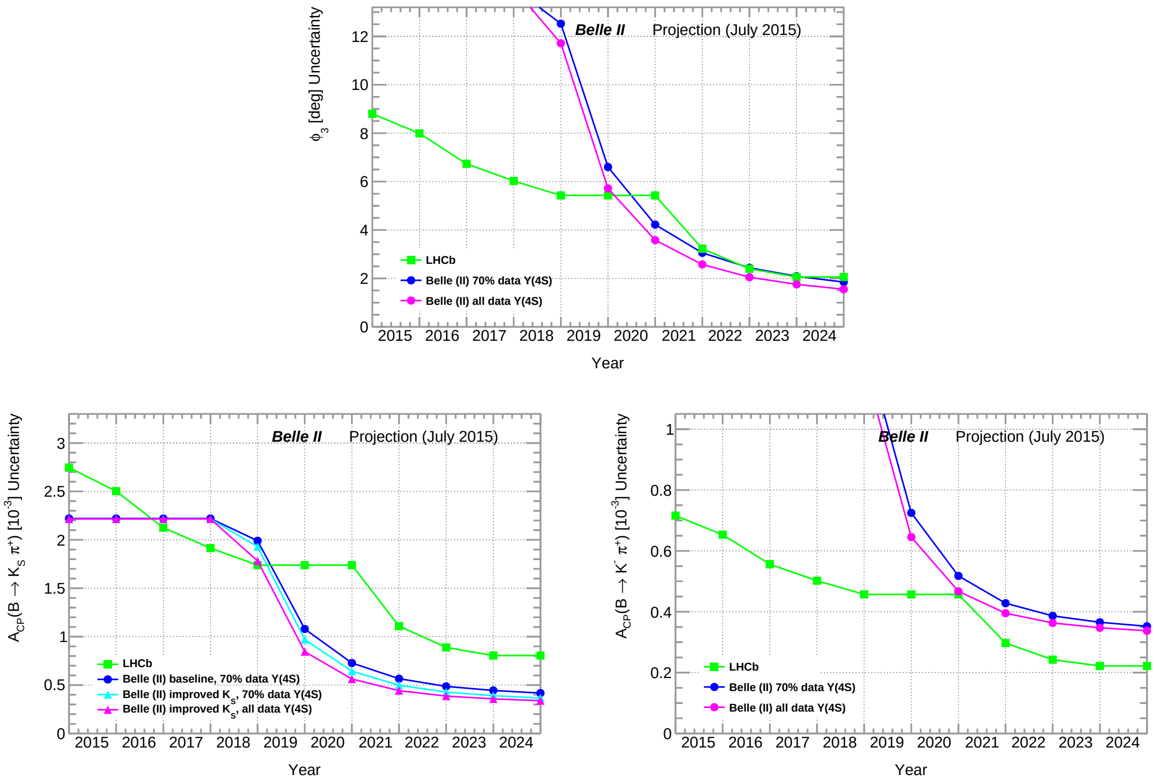

FIG. 5: Projected precision for various measurements of direct CP violation.

V. SEMILEPTONIC B DECAYS

The Belle $|V_{ub}|$ exclusive precision value is taken from a naive average of the hadron tagged and untagged partial branching fraction measurements in the LQCD safe region at high q^2. The LHCb result, based on a measurement of $\Lambda_b \to p\mu\nu$ was shown at Moriond Electroweak 2015. The measurement is dominated by systematic uncertainties. Exclusive $|V_{ub}|$ will continue to be theory and systematics limited, so it is difficult to give a reliable projection. The projections are shown in Table III and Figure 6. LHCb and Belle are expected to release new measurements of $R(B \to D^*\tau\nu)$. We therefore await those results before providing comparisons here.

TABLE III: Extrapolations for selected semileptonic B decay measurements. See Table I for a description of the symbols.

Observables	Belle	Belle II	LHCb	
	(2015)	50 ab^{-1} 70%@$\Upsilon(4S)$	Run-1	22 fb^{-1}
	$(\sigma_{\rm stat}, \sigma_{\rm sys}, \sigma_{\rm th})$	$(\sigma_{\rm stat}, \sigma_{\rm sys}, \sigma_{\rm th})$	$(\sigma_{\rm stat}, \sigma_{\rm sys}, \sigma_{\rm th})$	$(\sigma_{\rm stat}, \sigma_{\rm sys}, \sigma_{\rm th})$
$\lvert V_{ub}\rvert$ Exclusive	(3.0, 2.2, 4.0)	(0.2, 0.8, 2.0)	$(4.6_{\rm exp}$,5.0)	(2.0‡,3.0)
$R(B \to D^*\tau\nu)$				

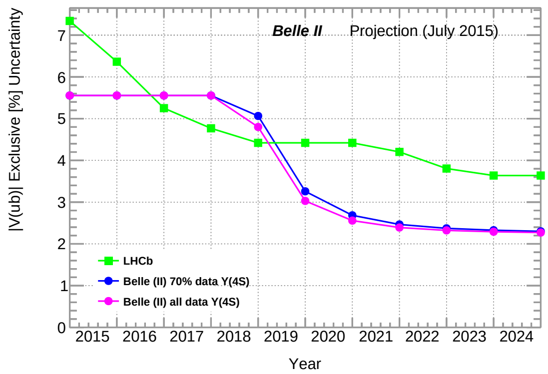

FIG. 6: Projected precision for various measurements of semileptonic B decays.

VI. CHARM

In charm, the measurements of ΔA_{CP} and A_Γ in hadronic decays ($D \to K^+K^-$, $D \to \pi^+\pi^-$) are the known strength of LHCb, with precision $2\times$ to $3\times$ better than Belle. Both experiments were highly statistics limited, and therefore the upgrades will see big improvements. The large charm cross section and canceled errors in ΔA_{CP} makes it a powerful test at LHCb. This mode will be competitive, although it depends on the systematic limitations of LHCb. Recently LHCb also showed very precise methods for A_{CP}, which are highly competitive with Belle and worth watching for Belle II. These projections are shown in Table IV and Figure 7.

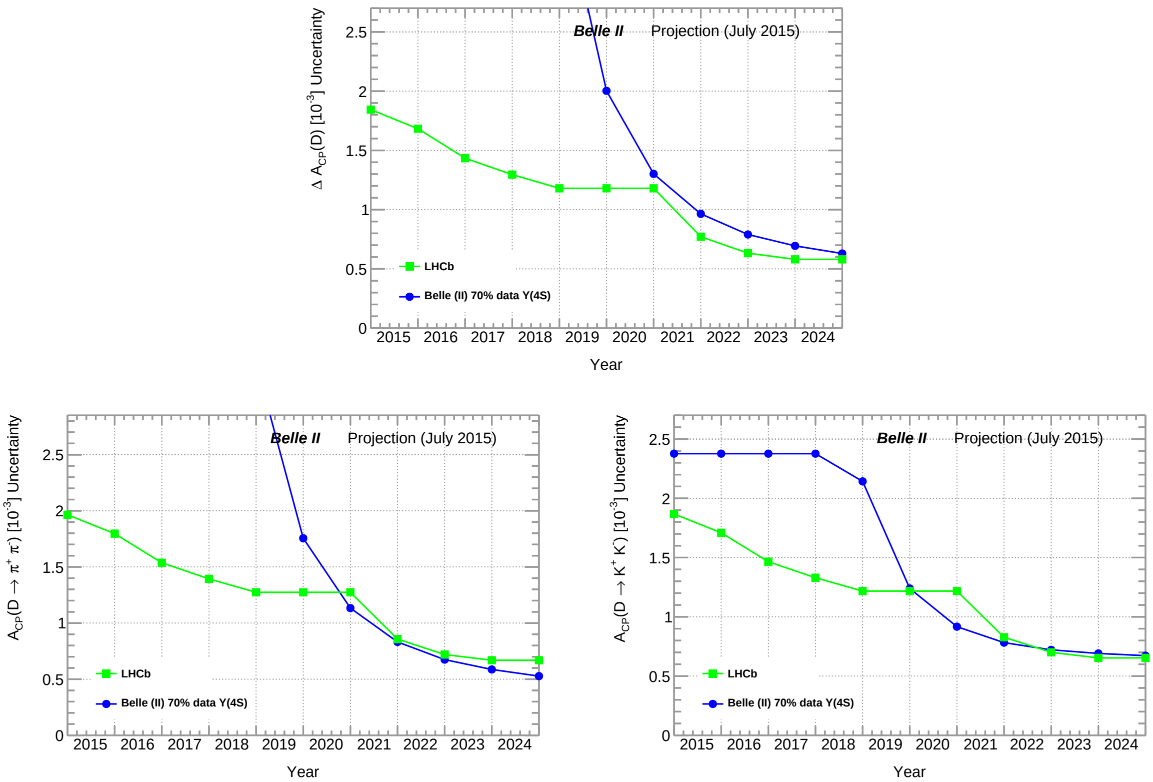

FIG. 7: Precision projection for direct CP violation in 2-body all charged final state D decays.

Although the indirect CP violation parameter A_Γ will be determined better in the LHCb upgrade, we may do better on y_{CP}. On y_{CP} LHCb appears to be systematics limited (although they have only an old result). The former is shown in Figure 8.

Just like in B decays, the full isospin information is important for resolving issues in strong phase contributions for theoretical interpretation and LHCb will struggle with K_S and π^0. For more information on these modes see Belle II Note 21 (this note focuses only on direct competition modes). Therefore we can extend beyond K^+K^-, and $\pi^+\pi^-$ to eigenstates with neutrals. We will do well on charm mixing parameters, extracted from Dalitz decays $D \to K_S\pi\pi$. We don?t have reliable projections from LHCb on those. Then there are modes that are our obvious strengths on $D_{(s)} \to \tau\nu$, $\mu\nu$, $e\nu$, $\gamma\gamma$, $\nu\bar{\nu}$. Semileptonic modes should be considered too, but the competition is BESIII.

TABLE IV: Extrapolations for selected charm decay measurements. See Table I for a description of the symbols.

Observables	Belle (2015) $(\sigma_{\rm stat}, \sigma_{\rm sys})$	Belle II 50 ab^{-1} $(\sigma_{\rm stat}, \sigma_{\rm sys})$	LHCb Run-1 $(\sigma_{\rm stat}, \sigma_{\rm sys})$	22 fb^{-1} $(\sigma_{\rm stat}, \sigma_{\rm sys})$
$A_{CP}(D \to K^+K^-)$ $[10^{-3}]$	(2.1, 0.8)	(0.3, 0.6)	(1.5, 1.0)	(0.4, 0.5†)
$A_{CP}(D \to \pi^+\pi^-)$ $[10^{-3}]$	(3.8, 1.0)	(0.5, 0.2)	(1.9, 1.0)	(0.4, 0.5†)
ΔA_{CP} $[10^{-3}]$	(4.1, 0.6)	(0.6, 0.3†)	(1.6, 0.8)	(0.4, 0.4†) $(B \to D^0 \mu X)$
A_Γ $[10^{-4}]$	(20, 8)	(3, 2)	(6.2, 1.2)	(1.3, 0.6‡) $(D \to KK)$
y_{CP} $[10^{-3}]$	(2.2, 1.0)	(0.3, 0.4)	*To be included*	

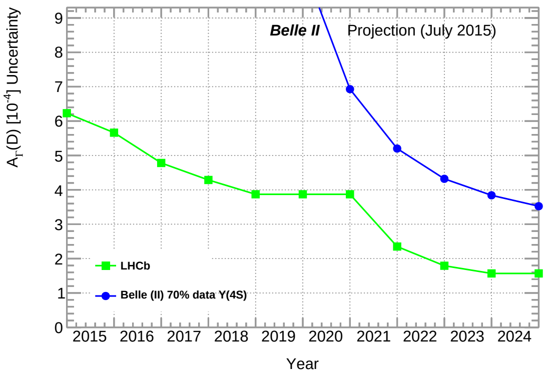

FIG. 8: Precision projection for indirect CP violation in 2-body all charged final state D decays.