CP violation in beauty and charm

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UK input to the European Particle Physics Strategy Update IPPP Durham, 16–18 April 2018



Quark flavour mixing

$$V_{\mathsf{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet \end{pmatrix}$$

Sensitive to BSM physics without such hierarchy.

Irreducible phase is the sole source of CP violation in the SM*.

Highly predictive since V_{CKM} must be unitary, implying e.g.:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

*With $m_v = \theta_{QCD} = 0$ in the SM.

The Unitarity Triangle today





The CKM mechanism is the dominant source of CP violation in the SM.

We are nowhere near exhausting the potential of quarkmixing in the search for BSM effects.

Some of the LHCb highlights in these areas...



Amongst many notable results in rare B decays (Kostas' talk); and charm, kaons, electroweak, QCD/spectroscopy, heavy ions, etc...

Charm

Compared to the beauty sector, CPviolation and $(D-\overline{D})$ mixing is GIM and CKM suppressed, but QCD plays a more troublesome role.

With mixing now firmly established by LHCb, the emphasis is on indirect CP violation, which is cleanly predicted to be tiny in the SM.



LHC schedule to 2030



SuperKEKB and Belle II

BaBar and Belle were extremely successful experiments which confirmed the CKM mechanism as the leading source of CPV in the quark sector.

The e⁺e⁻ mode boasts several key advantages over hadron colliders, primarily because of the full event reconstruction and access to inclusive and missing-energy modes.





E.g. B→τν

SuperKEKB and Belle II



Target 50 ab⁻¹ by 2025 (compared to ~1 ab⁻¹ of Belle)

Exciting few years ahead.

However, no current plans for future e+e-B factory experiments after Belle II.

ATLAS and CMS phase II upgrades



New tracking detectors will lead to greatly enhance the b physics capabilities of ATLAS and CMS. Their L1 track trigger could allow CMS to accumulate large samples even in hadronic modes.

LHCb upgrade I

Upgrade scheduled in LS2, ready for data taking to start in Run-3.

- 1.Full software trigger to allow effective operation at higher luminosities with higher efficiency for hadronic decays.
- 2.Luminosity to be raised (x5) to $2x10^{33}$ cm⁻²s⁻¹.



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What will we know by 2030 then?

B2TiP report (in progress)

	- 1								
Observables	Expected th. ac-	Expected exp. un-	Facility (2025)	Type	Observable	Current	LHCb	Upgrade	Theory
	curacy	certainty				precision	2018	$(50{\rm fb}^{-1})$	uncertainty
UT angles & sides				B^0_s mixing	$2\beta_s \ (B^0_s \to J/\psi \ \phi)$	0.10 [138]	0.025	0.008	~ 0.003
φ ₁ [°]	***	0.4	Belle II	0 0	$2\beta_s (B_c^0 \rightarrow J/\psi f_0(980))$	0.17 214	0.045	0.014	~ 0.01
φ ₂ [°]	**	1.0	Belle II		a_{s1}^{s}	6.4×10^{-3} [43]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
φ ₃ [°]	***	1.0	Belle II/LHCb	Gluonic	$\frac{2\beta^{\text{eff}}(B^0 \to \phi\phi)}{2\beta^{\text{eff}}(B^0 \to \phi\phi)}$		0.17	0.03	0.02
$S(B_s \rightarrow J/\psi \phi)$	***	0.01	LHCb	penguine	$2\beta_s (D_s \neq \psi \psi)$ $2\beta^{\text{eff}}(B^0 \rightarrow K^{*0} \overline{K}^{*0})$	_	0.13	0.00	< 0.02
V _{cb} incl.	***	1%	Belle II	penguins	$2\beta_s (D_s / K K)$ $2\beta_{\text{eff}} (D^0 \land \phi K^0)$	0.17 [42]	0.10	0.02	0.02
V _{cb} excl.	***	1.5%	Belle II	D: 1 / 1 1 1	$\frac{2\beta}{D} \xrightarrow{(D \to \psi \Lambda_S)} $	0.17 [43]	0.30	0.00	0.02
V _{ub} incl.	**	3%	Belle II	Right-handed	$2\beta_s^{\rm off}(B_s^\circ \to \phi\gamma)$	_	0.09	0.02	< 0.01
V _{ub} excl.	**	2%	Belle II/LHCb	currents	$\frac{\tau^{\rm en}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}}{\tau^{\rm en}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}}$	_	5%	1%	0.2%
CPV				Electroweak	$S_3(B^0 \to K^{*0} \mu^+ \mu^-; 1 < q^2 < 6 \text{GeV}^2/c^4)$	0.08[67]	0.025	0.008	0.02
$S(B \rightarrow \phi K^0)$	***	0.02	Belle II	penguins	$s_0 A_{\rm FB}(B^0 \to K^{*0} \mu^+ \mu^-)$	25% [67]	6%	2%	7%
$S(B \rightarrow \eta' K^0)$	***	0.01	Belle II		$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6{\rm GeV}^2/c^4)$	0.25 [76]	0.08	0.025	~ 0.02
$\beta_s^{\text{eff}}(B_s \rightarrow \phi \phi) \text{ [rad]}$	**	0.1	LHCb		$\mathcal{B}(B^+ \to \pi^+ \mu^+ \mu^-) / \mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)$	25% [85]	8%	2.5%	$\sim 10\%$
$\beta_s^{\text{eff}}(B_s \rightarrow K^{*0}\bar{K}^{*0})$ [rad]	**	0.1	LHCb	Higgs	$\mathcal{B}(B^0_s \to \mu^+ \mu^-)$	1.5×10^{-9} [13]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
$A(B \rightarrow K^0 \pi^0)[10^{-2}]$	***	4	Belle II	penguins	$\mathcal{B}(B^0 \to \mu^+ \mu^-) / \mathcal{B}(B^0_s \to \mu^+ \mu^-)$	_	$\sim 100\%$	$\sim 35\%$	$\sim 5\%$
$A(B \rightarrow K^{+}\pi^{-})$ [10 ⁻²]	***	0.20	LHCb/Belle II	Unitarity	$\gamma \ (B \to D^{(*)} K^{(*)})$	$\sim 10 - 12^{\circ} [244, 258]$	4°	0.9°	negligible
(Semi-)leptonic				triangle	$\gamma (B^0_s \to D_s K)$	_	11°	2.0°	negligible
$B(B \rightarrow \tau \nu)$ [10 ⁻⁶]	**	3%	Belle II	angles	$\beta (B^0 \rightarrow J/\psi K_c^0)$	0.8° [43]	0.6°	0.2°	negligible
$\mathcal{B}(B \rightarrow \mu\nu) [10^{-6}]$	**	7%	Belle II	Charm	Ap	2.3×10^{-3} [43]	0.40×10^{-3}	0.07×10^{-3}	
$R(B \rightarrow D\tau\nu)$	***	3%	Belle II	CP violation	Λ_{ACD}	2.1×10^{-3} [18]	0.65×10^{-3}	0.12×10^{-3}	_
$R(B \rightarrow D^* \tau \nu)$	***	2%	Belle II/LHCb			[10]	0.00 / 10		

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V _{cb} excl.	***	1.5%	Belle II	Dight handed	$\frac{2\beta (D \to \phi R_S)}{2\beta^{\text{eff}}(D^0 \to \phi s)}$	0.11 [40]	0.00	0.00	< 0.02
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$B(B \rightarrow \mu\nu) [10^{-6}]$	8.8	7%	Belle II	Charm	A_{Γ}	2.3×10^{-3} [43]	0.40×10^{-3}	0.07×10^{-3}	
$R(B \rightarrow D\tau\nu)$	888	3%	Belle II	CP violation	ΔA_{CP}	2.1×10^{-3} [18]	0.65×10^{-3}	0.12×10^{-3}	
$B(B \rightarrow D^* \tau \nu)$	市市市	2%	Belle II/LHCb			- [-~]			

In a nutshell:

- Belle-II / BaBar+Belle ~ 50
- LHCb Upgrade I / LHCb run 1 ~ 30-60
- I.e. roughly an order of magnitude in precision.

However, many key BSM-sensitive observables will still be far from the theory uncertainties.

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CERN-Council-S/106

High-priority large-scale scientific activities

After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

c) The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme. *Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*





Expression of interest for LHCb upgrade II submitted to the LHCC in February 2017.

Target at least 300 fb⁻¹ in Runs 5+6.

Luminosity increased to $1-2 \times 10^{34} \text{ cm}^{-2}$, which can be achieved with negligible cost to ATLAS and CMS.

Detector upgraded to maintain its high performance at these luminosities, and even improve in some areas (e.g. neutral and partially reconstructed modes).

Certain elements can already be installed in LS3, boosting the physics output in Run-4.









Challenging environment, but common themes of fast-timing, granularity++, rad-hardness. Clear synergies with ATLAS and CMS, and unique challenges.

The physics program

Physics case document, requested by the LHCC, in preparation

	5.4.2 Prospects with $R(J/\psi)$ and other ratios	8 Forward and high $p_{\rm T}$ physics
	5.5 Prospects with semileptonic D decays	8.1 Top physics in the forward region
3 Time-dependent CP-violation measurements		8.2 Gauge-boson production and implications for PDFs
3.1 Flavour tagging at high pileup	CP violation and mixing in charm	8.2.1 Future improvements of existing measurements
3.2 Measurements of β and ϕ_s	6.1 Neutral D-meson mixing and indirect CP violation	8.2.1.1 Boson production
3.2.1 $\sin 2\beta$ from $B^0 \to (c\bar{c})K^0_S$	6.1.1 Measurements with $D^0 \rightarrow K^{\mp} \pi^{\pm}$	8.2.1.2 Associated boson production
3.2.2 $\phi_s \text{ from } B^0_s \to J/\psi K^+ K^- \text{ and } B^0_s \to J/\psi \pi^+ \pi^-$	6.1.2 Measurements with $D^0 \rightarrow K^{\mp} \pi^{\pm} \pi^{+} \pi^{-}$	8.2.2 New measurements
3.2.3 Control of penguin pollution	6.1.3 Amplitude analysis of $D^0 \rightarrow K_s^0 h^+ h^-$	8.3 Measurement of the effective weak mixing angle
3.2.4 $\phi_d \text{ from } B^0 \to \overline{D}^0 \pi^+ \pi^-$	6.1.4 Measurement of A_{Γ}	8.3.1 Current precision
3.3 Prospects with charmless <i>B</i> decays	6.2 Direct CP violation	8.3.2 Future improvements
3.3.1 ϕ_s from $B^0_s \to \phi\phi$	6.2.1 Measurement of A_{CP} in $D^0 \to K^+ K^-$ and $D^0 \to \pi^+ \pi^-$	8.4 Prospects for W-mass measurement
3.3.2 $\phi_s \text{ from } B^0_s \to (K^+\pi^-)(K^-\pi^+)$	6.2.2 Measurements with $D^+ \rightarrow hhh$ and $D^+_s \rightarrow hhh$ decays	8.5 Measurement of Higgs decays to cc.
3.3.3 <i>CP</i> violation in $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$	6.2.3 Measurements with $D^0 \rightarrow h^+h^-h^+h^-$ decays	8.6 Searches for prompt and detached dark photons
3.3.4 α from $B^0 \to \pi^+\pi^-\pi^0$ and $B \to \rho\rho$	6.2.4 Prospects with neutral final states	8.7 Searches for semileptonic and hadronic decays of long-lived particles
3.3.5 <i>CP</i> violation in $B_s^0 \to K_s^0 h^+ h^-$ and $B_s^0 \to h^+ h^- \pi^0$	6.2.5 Prospects with charmed baryons	
3.4 Measurements of γ from $B_s^0 \to D_s^{\pm} K^{\mp}$ and $B^0 \to D^{\pm} \pi^{\mp}$		9 Exotic hadrons and spectroscopy with heavy flavours
	Rare and radiative decays	9.1 Measurements of tetraquark and pentaquark properties
4 Time-integrated <i>CP</i> -violation measurements	7.1 Leptonic B decays	9.2 Further pentaquark searches
4.1 Determination of the γ angle from tree-level decays	7.1.1 Measurements with $B \rightarrow \mu\mu$ decays	9.2.1 Beautiful Pentaquarks
4.1.1 $B \rightarrow DK$ GLW/ADS	7.1.1.1 Branching fractions	9.2.2 Radiative decays and baryon magnetic moments
$4.1.2 B \to DK \ \text{GGSZ} \qquad \dots \qquad $	7.1.1.2 Effective lifetime and CP violation	9.3 Exotic spectroscopy with B_c^+ decays to triple-charm final states
4.1.3 Prospects with neutral modes	7.1.2 Search for $B_{(r)}^0 \rightarrow \mu^+ \mu^- \gamma$ decays	9.4 Study of double-heavy baryons in charm and beauty
4.1.4 Prospects with nigh-multiplicity modes	7.1.3 Search for $B \to \tau \tau$ decays	9.4.1 Double-charm baryons
4.2 Utimate γ sensitivity and considerations on external inputs to the analy	7.1.4 Search for $B \rightarrow ee$ decays	9.4.2 Baryons with beauty and charm: Ξ_{bc} and Ω_{bc}
4.3 Amplitude analysis of $B^+ \rightarrow h^+h^-h^-$ decays	7.2 Lepton-flavour, lepton-number and baryon-number violating decays	9.5 Precision measurements of conventional quarkonium states
4.4 CF violation in two-body and multibody o-baryon decays	7.2.1 Search for $B \rightarrow e\mu$ decays	9.5.1 Precise measurement of double quarkonia production
5 Measurements of unitarity triangle sides and semileptonic decays	7.2.2 Search for $B \to \tau \mu$ decays	
5.1 Determination of V.1 and V.1	7.2.3 Search for $B \to Ke\mu$ and $B \to K\tau\mu$ decays	10 Further opportunities 1
5.2 Considerations about Δm_{J} and Δm_{z} and role of Lattice OCD	7.2.4 Search for $\tau \rightarrow \mu\mu\mu$ decays	10.1 Prospects with heavy-ion and fixed-target physics
5.3 Semileptonic asymmetries a_1^d and a_2^s	7.2.5 Search for lepton-number and baryon-number violating decays	10.1.1 Physics with pA and AA collisions
5.4 Lepton-flavour universality tests with $b \rightarrow cl\nu$ transitions	7.3 Flavour-changing $b \to sl^+l^-$ and $b \to dl^+l^-$ transitions	10.1.1.1 Quarkonium and open heavy-flavour
5.4.1 $R(D)$ and $R(D^*)$ with muonic and hadronic τ decays		10.1.1.2 Low-mass dileptons
	7.3.1 Branching fractions and angular observables in $b \rightarrow sl^+l^-$ transitions.	
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5.4.2 Prospects with $R(J/\psi)$ and other ratios	7.3.1 Branching fractions and angular observables in $b \to sl^+l^-$ transitions 7.3.2 Branching fractions and angular observables in $b \to dl^+l^-$ transitions 7.3.3 Lepton-flavour universality tests	10.1.1.2 Dow-mass dispersion 10.1.1.3 Drell-Yan, photons, cc̄ and bb in pA collisions in view of nuclear PDfs and saturation
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5.4.2 Prospects with $R(J/\psi)$ and other ratios	7.3.1 Branching fractions and angular observables in $b \to sl^+l^-$ transitions 7.3.2 Branching fractions and angular observables in $b \to dl^+l^-$ transitions 7.3.3 Lepton-flavour universality tests 7.3.4 Time-dependent analysis of $B^0_s \to \phi\mu\mu$ and $B^0 \to \rho^0\mu\mu$ 7.4 Radiative beauty and charm decays 7.4.1 Radiative B decays 7.4.2 Angular analysis with $B^0 \to K^{*0}e^+e^-$ decays in the low- a^2 region	10.11.12 Dow mass dispects 10.1.1.3 Drell-Yan, photons, oč and bb in pA collisions in view of nuclear PDfs and saturation
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The physics program

Physics case document, requested by the LHCC, in preparation

	5.4.2 Prospects with $R(J/\psi)$ and other ratios	8 Forward and high p _T physics
	5.5 Prospects with semileptonic D decays	8.1 Top physics in the forward region
3 Time-dependent CP-violation measurements		8.2 Gauge-boson production and implications for PDFs
3.1 Flavour tagging at high pileup	6 CP violation and mixing in charm	8.2.1 Future improvements of existing measurements
3.2 Measurements of β and ϕ_s	6.1 Neutral D-meson mixing and indirect CP violation	8.2.1.1 Boson production
3.2.1 $\sin 2\beta$ from $B^0 \to (c\bar{c})K^0_S$	6.1.1 Measurements with $D^0 \to K^{\mp} \pi^{\pm}$	8.2.1.2 Associated boson production
3.2.2 ϕ_s from $B_s^0 \to J/\psi K^+ K^-$ and $B_s^0 \to J/\psi \pi^+ \pi^-$	6.1.2 Measurements with $D^0 \rightarrow K^{\mp} \pi^{\pm} \pi^{+} \pi^{-}$	8.2.2 New measurements
3.2.3 Control of penguin pollution	6.1.3 Amplitude analysis of $D^0 \to K_s^0 h^+ h^-$	8.3 Measurement of the effective weak mixing angle
3.2.4 $\phi_d \text{ from } B^0 \to \overline{D}^0 \pi^+ \pi^-$	6.1.4 Measurement of A_{Γ}	8.3.1 Current precision
3.3 Prospects with charmless B decays	6.2 Direct CP violation	8.3.2 Future improvements
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3.3.2 ϕ_s from $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$	6.2.2 Measurements with $D^+ \rightarrow hhh$ and $D^+_+ \rightarrow hhh$ decays	8.5 Measurement of Higgs decays to $c\bar{c}$
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3.3.4 α from $B^0 \to \pi^+ \pi^- \pi^0$ and $B \to \rho \rho$	6.2.4 Prospects with neutral final states	8.7 Searches for semileptonic and hadronic decays of long-lived particles
3.3.5 <i>CP</i> violation in $B_s^0 \to K_S^0 h^+ h^-$ and $B_s^0 \to h^+ h^- \pi^0$	6.2.5 Prospects with charmed baryons	
3.4 Measurements of γ from $B_s^0 \to D_s^{\pm} K^{\mp}$ and $B^0 \to D^{\pm} \pi^{\mp}$		9 Exotic hadrons and spectroscopy with heavy flavours
	7 Rare and radiative decays	9.1 Measurements of tetraquark and pentaquark properties
4 Time-integrated <i>CP</i> -violation measurements	7.1 Leptonic B decays	9.2 Further pentaquark searches
4.1 Determination of the γ angle from tree-level decays	7.1.1 Measurements with $B \rightarrow \mu\mu$ decays	9.2.1 Beautiful Pentaguarks
4.1.1 $B \rightarrow DK$ GLW/ADS	7.1.1.1 Branching fractions	9.2.2 Radiative decays and baryon magnetic moments
$4.1.2 B \to DK \text{ GGSZ} \dots \dots \dots \dots \dots \dots \dots \dots \dots $	7.1.1.2 Effective lifetime and <i>CP</i> violation	9.3 Exotic spectroscopy with B_c^+ decays to triple-charm final states
4.1.3 Prospects with neutral modes	7.1.2 Search for $B_{\ell_{\lambda}}^{0} \rightarrow \mu^{+}\mu^{-}\gamma$ decays	9.4 Study of double-heavy baryons in charm and beauty
4.1.4 Prospects with high-multiplicity modes	7.1.3 Search for $B \to \tau \tau$ decays	9.4.1 Double-charm baryons
4.2 Ultimate γ sensitivity and considerations on external inputs to the analy	7.1.4 Search for $B \rightarrow ee$ decays	9.4.2 Baryons with beauty and charm: Ξ_{br} and Ω_{br}
4.3 Amplitude analysis of $B^+ \to h^+ h^- h^-$ decays	7.2 Lepton-flavour, lepton-number and baryon-number violating decays.	9.5 Precision measurements of conventional guarkonium states
4.4 CP violation in two-body and multibody b-baryon decays	7.2.1 Search for $B \rightarrow e\mu$ decays	9.5.1 Precise measurement of double guarkonia production
* Managements of an iterationals sides and anniholderic descent	7.2.2 Search for $B \rightarrow \tau \mu$ decays	
5 Measurements of unitarity triangle sides and semileptonic decays	7.2.3 Search for $B \rightarrow Ke\mu$ and $B \rightarrow K\tau\mu$ decays	10 Further opportunities 1
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5.2 Considerations about Δm_d and Δm_s and role of Lattice QCD 5.3 Somileptonic asymptotes a^d and a^s	7.2.5 Search for lepton number and baryon number violating decays	10.1.1 Physics with pA and AA collisions
5.5 Semineptonic asymmetries u_{sl} and u_{sl}	7.2. Flavour changing $b \rightarrow d^{\pm}l^{-}$ and $b \rightarrow d^{\pm}l^{-}$ transitiong	10.1.1.1 Quarkonium and open heavy-flavour
5.4 Lepton-navour universanty tests with $0 \rightarrow etc$ transitions	7.3 Flavour-changing $0 \rightarrow st \ t$ and $0 \rightarrow at \ t$ distributes $\dots \dots \dots \dots$	10.1.1.2 Low-mass dileptons
$(5.4.1 R(D) \text{ and } R(D^{*}) \text{ with indonic and hadronic 7 decays} \dots \dots$	7.3.1 Dranching fractions and angular observables in $b \to st^{-1}$ transitions.	10.1.1.3 Drell-Yan, photons, $c\bar{c}$ and $b\bar{b}$ in pA collisions in view of nuclear
5.4.2 Prospects with $R(J/\psi)$ and other ratios	1.5.2 Branching fractions and angular observables in $\theta \rightarrow dt^{-1}t^{-1}$ transitions .	PDfs and saturation
5.5 Prospects with semileptonic D decays	7.2.4 Time dependent analysis of PU betweend PU believe	10.1.1.4 Other opportunities
	1.3.4 Time-dependent analysis of $B_{\delta}^{*} \to \phi \mu \mu$ and $B^{*} \to \rho^{*} \mu \mu$	10.1.2 Prospects with fixed-target physics
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6.1.3 Amplitude analysis of $D^0 \to K_s^0 h^+ h^-$	7.4.4 Radiative D decays	
6.1.4 Measurement of A_{Γ}	7.5 Rare charm decays	
6.2 Direct <i>CP</i> violation	7.5.1 Search for $D \to \mu\mu$ decays	
6.2.1 Measurement of A_{CP} in $D^0 \to K^+ K^-$ and $D^0 \to \pi^+ \pi^-$	7.5.2 Search for $D \to h\mu\mu$ and $\Lambda_c \to p\mu\mu$ decays	
6.2.2 Measurements with $D^+ \to hhh$ and $D^+_s \to hhh$ decays	7.5.3 Measurements with $D \rightarrow hhll$ decays	
6.2.3 Measurements with $D^0 \rightarrow h^+h^-h^+h^-$ decays	7.6 Rare strange decays	* *
6.2.4 Prospects with neutral final states	7.6.1 Rare kaon decays	
6.2.5 Prospects with charmed baryons	7.6.2 Rare hyperon decays	
	7.6.2.1 Rare decays of Σ hyperons	* *
	7.6.2.2 Rare decays of A hyperons	and the second

It was encouraging to see 100+ LHCb authors keenly contributing to this document.

Now for some prospects in the areas of beauty and charm CP violation...

The tree-level UT apex



The phase γ is determined via the family of tree-level B→DK decays. Extremely clean theoretically and experimentally, but statistically challenging. LHCb Upgrade II can reach sub-degree precision in multiple modes.

The corresponding length depends on $|V_{ub}|/|V_{cb}|$. Belle-II + lattice improvements will greatly improve our knowledge, but LHCb will have access to decays with all b hadron species, including decays which are currently beyond statistical reach.

Tree-level LFU tests



LHCb Run-II and Belle-II could already confirm this anomaly so why would we need more luminosity?

Distinguishing between BSM solutions would require far greater precision and more observables.

LHCb Upgrade II will allow differential measurements^{*}, in addition to percent level ratios with a range of b meson and baryon species.

^{*}In order to fully distinguish different operators we need measurements of the tau polarisation (1st measurement by Belle https://arxiv.org/abs/1612.00529) and other kinematic and angular properties of the decays. These are statistically far more challenging than the simple ratios in the plot above.

CPV in $B-\overline{B}$ mixing and decays



The measurement of Φ_s requires that we can maintain our performant flavour tagging in high pileup conditions^{*}. This is a good example of why the detector upgrades must include fast timing, to unambiguously associate signals to primary vertices.

^{*}Early studies on deep neural network inclusive flavour tagging look promising. See G. Cowan talk at the concurrent flavour workshop in Warwick https://indico.cern.ch/ event/694666/contributions/2916469/.

CP violation in charm



Charm mixing is already well established but the theoretically clean, and BSM sensitive, indirect CP violation parameters Φ and |q/p| are poorly known. LHCb Upgrade II will reach incredible precision.

It will also be capable of characterising patterns of direct CP violation down to the 10⁻⁵ level across a range of D decay modes.

Conclusions

LHCb Upgrade-I and Belle II will greatly extend our knowledge of quark flavour physics by 2030.

Yet we will still be far from realising the full potential in BSM sensitivity.

LHCb Upgrade-II is the experiment to push the frontier of quark flavour physics through the 2030s.

Backup slides start here...

Machine considerations

β^*	Maximum \mathcal{L}		Target levelling \mathcal{L}	Fill length		Levelling time		$\int \mathcal{L} dt$	
[m]	$[\times 10^{34} {\rm cm}^{-2} {\rm s}^{-1}]$		$[\times 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}]$	[h]		[h]		$[\mathrm{fb}^{-1}/\mathrm{yr}]$	
	_	+		_	+	_	+	—	+
3	1.04	0.78	0.20	8.1	8.1	8.1	8.1	10	10
2	1.53	1.04	1.00	7.7	7.8	2.8	0.4	39	31
2	1.53	1.04	/	7.6	7.8	/	/	43	31
1	2.90	1.66	1.00	7.5	7.6	6.0	3.5	48	42
1	2.90	1.66	2.00	7.3	7.5	2.3	0	73	48
1	2.90	1.66	/	7.2	7.5	/	/	80	48



Figure 4.4: Fraction of *b*-hadron decays mismatched to the wrong PV as a function of the time resolution per hit at a luminosity of $2 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$. The horizontal dashed line shows the approximate performance of the Phase-I Upgrade VELO at $2 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$. The hit information used as input to the study is obtained from a sample of simulated events assuming the layout of the Phase-I Upgrade VELO.

1995



2009



2016



The BaBar and Belle legacy



LHCb approaching Run-II culmination



A further 2 fb⁻¹ is anticipated in 2018.

Given the higher b, c cross sections at $\sqrt{s} = 13$ TeV, and trigger improvements, the Run-II dataset will correspond to a typical 4-5x increase over Run-I.