CP violation in beauty and charm at Upgrade II

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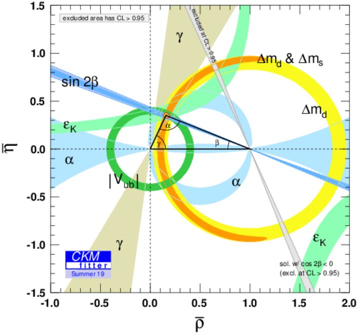
5th Workshop on LHCb Upgrade II - 30 March - 1 April 2020

Introduction

- SM picture accounts for wide range of measured CP observables
- But there is still room for NP!
- More and more precise measurements are needed to reveal possible inconsistencies
- Majority of measurements are still statistically limited after Run2
- We will take advantage of the HL-LHC era to produce a very precise picture of the physics of flavour



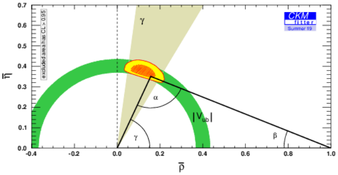
All the expected sensitivity for Phase 2 upgrade are taken from

arXiv.1808.08865

CKM angle γ

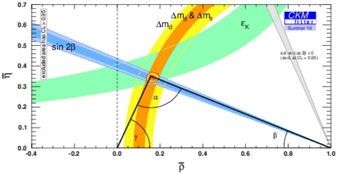
- Measurement of γ is crucial since it is still the least well-known UT angle
- Only CP-violating parameter that can be measured at the tree-level alone providing a good test for the SM (assuming no NP in tree-level decays [PRD92 (2015) 033002])
- Theoretically clean: $\delta_{\gamma}^{\text{th}}/\gamma < \mathcal{O}(10^{-7})$ [JHEP 1401 (2014) 051]
- Comparing tree-level with loop-level determination to get signs of NP

Tree-level



- Direct measurement $\gamma = (72.1^{+5.4}_{-5.7})^{\circ}$

Loop-level



- Indirect measurement (CKM fitter) $\gamma = (65.80^{+0.94}_{-1.29})^{\circ}$

Status of γ measurements at LHCb

$3\,\text{fb}^{-1}$ Run1 data
$+\ 2\,\text{fb}^{-1}$ Run2 data (2015-2016)
not yet included in LHCb combination [LHCb-CONF-2018-002]

		$B^+ \to DK^+$	$B^+ \to D\pi^+$	$B^0 \to DK^{*0}$	$B^+ \to DK^{*+}$	$B^+ \to DK^+\pi^-\pi^+$	$B^+ \to D^*K^+$
GLW	h^+h^-	PLB777 (18) 16		PRD93 (16) 112018 JHEP08(19)41	JHEP17(17)156	PRD92(15)112005	PLB777(18)16
	$\pi^+\pi^-\pi^+\pi^-$	PLB760 (16) 117		JHEP08(19)41	JHEP17(17)156		
	$h^+h^-\pi^0$	PRD91(25)112014					
ADS	$K^\pm\pi^\mp$	PLB760 (16) 117		JHEP08(19)41	JHEP17(17)156	PRD92(15)112005	
	$K^\pm\pi^\mp\pi^+\pi^-$	PLB760 (16) 117		JHEP08(19)41	JHEP17(17)156		
	$K^\pm\pi^\mp\pi^0$	PRD91(25)112014					
GGSZ	$K^0_s h^+h^-$	JHEP10(14)97 JHEP08(18)176		JHEP08(16)137 JHEP06(16)131			
GLS	$K^0_s K^+\pi^-$	PLB733(14)36					
Time dependent		$B^0_s \to D^\mp_s K^\pm$ [JHEP03(18)59] and $B^0 \to D^\mp\pi^\pm$ [JHEP06(18)84]					

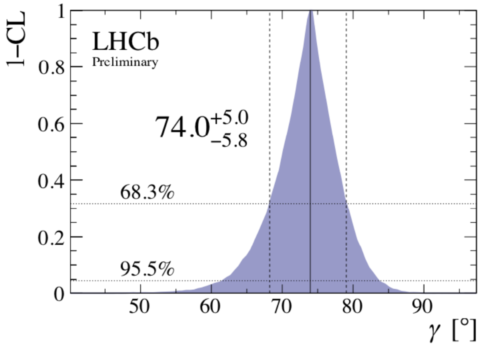
- Different modes as a consistency check
- Complementary measurements: different challenges and different source of systematic uncertainties

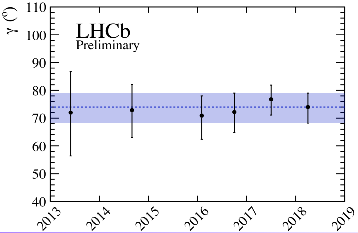
The LHCb combination [LHCb-CONF-2018-002]

- Combination using $B^+ \to D^{(*)}K^{(*)+}$, $B^0 \to DK^{*0}$, $B^0 \to D^{\mp}\pi^{\pm}$ and $B_s^0 \to D_s^{\mp}K^{\pm}$ decays in a maximum likelihood fit
- Most precise determination of γ by single experiment

$$\gamma = (74.0^{+5.0}_{-5.8})^{\circ}$$

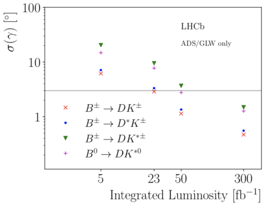
- In agreement with world averages
- Target precision with Run2 data: $\sigma(\gamma) = 4^{\circ}$



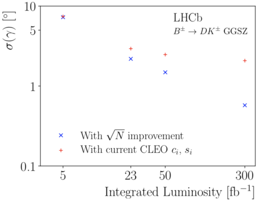


Upgrade2 γ prospects

ADS/GLW



GGSZ



- Statistically limited
- Dominant systematic uncertainties expected to scale with statistics
  - Instrumentation asymmetries (calibration samples)
  - Background contributions (studies with larger sample)

- Statistically limited
- Precision of external charm inputs
  - Current syst. due to CLEO inputs $\sim 2^{\circ}$
  - Future datasets at BESIII crucial
- Dalitz efficiency (data/simulation agreement, fast simulation techniques)

TD

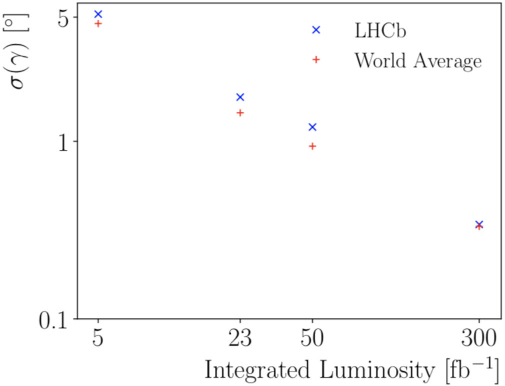
- Syst. Unc. from decay time acceptance and resolution and from calibration of flavour tagging
- Expected to scale with statistics due to the data-driven methods

Upgrade2 γ prospects

- Improvements in the detector will make new modes entering the game
  - Improvements in the electromagnetic calorimeter ECAL (granularity and energy resolution)
    - ADS/GLW and GGSZ with modes with an additional π^0 in the final state ($hh\pi^0$, $K_s^0\pi\pi\pi^0$) or D^{*0}
  - Improvements in low-momentum tracking with addition of magnet-side stations (soft track reconstruction, removal of ghosts)
  - Reduction in the VELO material: improve vertex resolution
    - Multi body decays ($D \to 4h$)

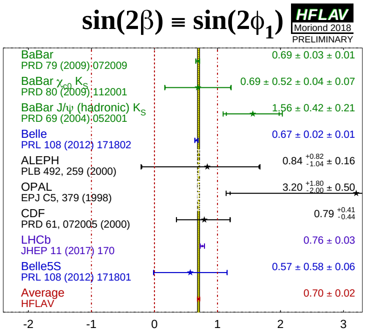
Upgrade2 γ prospects

- Sub-degree precision level on γ: $\sigma(\gamma) \sim 0.35^\circ$ with $300\,\text{fb}^{-1}$
- Belle II precision of 1.5° with $50\,\text{ab}^{-1}$



World average includes Belle II projections

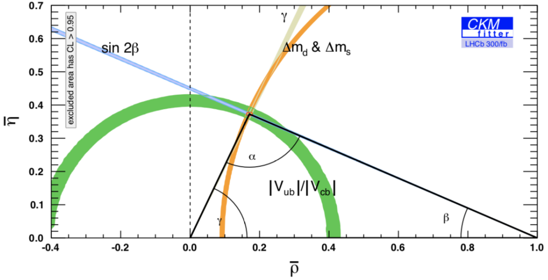
Status of $\sin 2\beta$



- Accessed via interference in B^0 mixing and decay
- Golden channel: $B^0 \to J/\psi K_s^0$
- LHCb measurements
  - $B^0 \to J/\psi K_s^0$ (Run1)
    [PRL115(2015)031601]
  - $B^0 \to D^+ D^-$ (Run1)
    [PRL117(2016)261801]
  - $B^0 \to \psi(2S) K_s^0$,
    $B^0 \to J/\psi(e^+e^-) K_s^0$ (Run1)
    [JHEP11(2017)170]
  - $B^0 \to D^{*\pm} D^{\mp}$ (Run1+Run2)
    arXiv:1912.03727

Prospects for $\sin 2\beta$

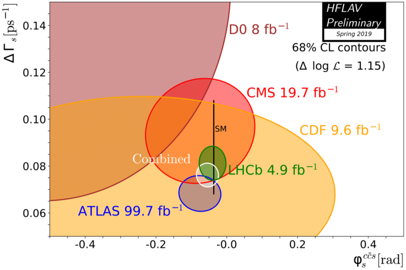
- Systematic uncertainties: tag asymmetries in bkg, flavour tagging calibration, decay-time efficiency
- Not expected to be limiting since control samples will scale with increased data
- Need clearly a good flavour tagging performance
- Good control of K^0-$\bar{K}^0$ CP violation and nuclear cross-section asymmetry
- Control of penguin pollution



- $\sigma_{stat} = 0.003$ at $300\,\mathrm{fb}^{-1}$
- Belle II at $50\,\mathrm{ab}^{-1}$: $\sigma_{stat} = 0.005$

CP violation in $B_{(s)}$ mixing and decay:

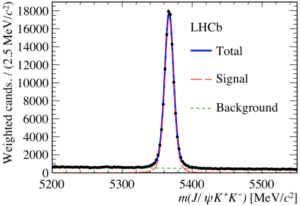
- CP-violating phase arising from interference between mixing and decay
- Precisely predicted by the SM
- Golden channel: $B_s^0 \to J/\psi\phi$
- Exploited not only by LHCb but also by ATLAS and CMS
- Measurement in other channels by LHCb to improve precision and as consistency check
  - $B_s^0 \to J/\psi\phi$ [EPJC79(2019)706] (2015+2016)
  - $B_s^0 \to J/\psi\pi^+\pi^-$ [PLB797(2019)134789] (2015+2016)
  - $B_s^0 \to D_s D_s$ [PRL113(2014)211801]
  - $B_s^0 \to \psi(2S)\phi$ [PLB762(2016)253]
  - $B_s^0 \to J/\psi KK$ high mass [JHEP08(2017)037]



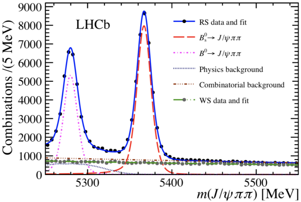
- Indirect measurement: $\phi_s = -36.4 \pm 1.2$
- Experimental uncertainty $\gg$ uncertainty on indirect determination

Run2 data results [EPJC79(2019)706, PLB797(2019)134789]

- Flavour-tagged decay-time dependent angular analysis
- Flavour tagging and excellent time resolution are a key ingredients
- Simultaneous fit to the decay time and three helicity angles in 6 $m(K^+K^-)$ bins and in $m(\pi^+\pi^-)$
- Per-candidate decay time error calibrated using prompt J/ψcontrol sample
- Studies of variation of efficiency with angular variables and decay-time acceptance are fundamental (data-driven approach)
- Resonance modelling of the $\pi^+\pi^-$ spectrum is giving one of the largest systematics



$$N(B_s^0 \to J/\psi K^+K^-) \sim 117K$$

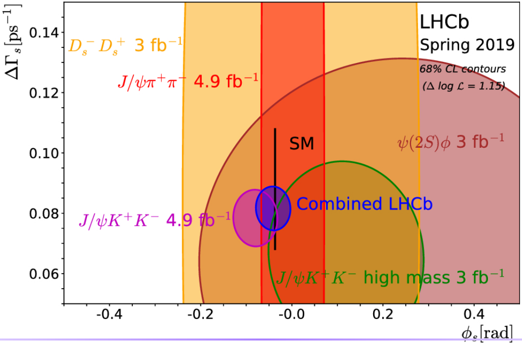


$$N(B_s^0 \to J/\psi\pi^+\pi^-) \sim 33.5K$$

Combination of LHCb results

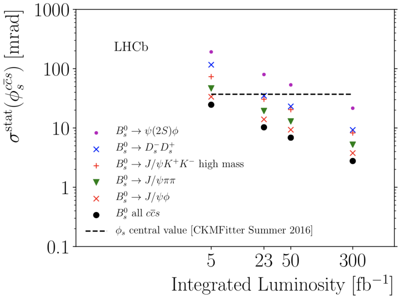
$$\phi_s = -0.042 \pm 0.025\,\text{rad}$$
$$|\lambda| = 0.993 \pm 0.010$$
$$\Gamma_s = 0.6563 \pm 0.0021\,\text{ps}^{-1}$$
$$\Delta\Gamma_s = 0.0813 \pm 0.0048\,\text{ps}^{-1}$$

- ϕ_s consistent with SM
- λ consistent with no direct CPV



Prospects for U2

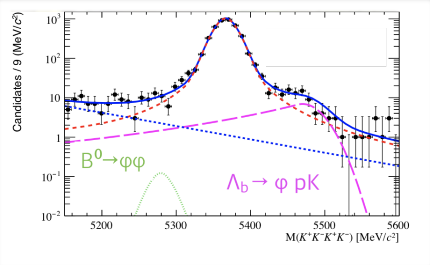
- Fundamental to maintain (or improve) current detector performance: vertex position resolution and decay time resolution for high pile-up conditions
- Improve flavour-tagging (sensitive to event multiplicity)
- Include new modes (as it has been already done for $B_s^0 \to D_s^+ D_s^-$ and $B^0 \to D^+ D^-$ (which will benefit from the enhanced trigger efficiency for hadrons) but also $B_s^0 \to J/\psi(ee)\phi$ and $B_s^0 \to J/\psi\eta^{(\prime)}$ involving neutrals with improved calorimeter performance
- Control of penguin pollution using SU(3) flavour (expected to be $\lesssim 1.5\,\mathrm{mrad}$) using $B^0 \to J/\psi\pi^0$ and $B_s^0 \to J/\psi K_s^0$ (already studied) from Belle II and improving ECAL capabilities



$\sigma(\phi_s) \sim 4\,\mathrm{mrad}$ from $B_s^0 \to J/\psi\phi$
$\sigma(\phi_s) \sim 3\,\mathrm{mrad}$ from combined modes

$\phi_s^{s\bar{s}\bar{s}}$ and $\phi_s^{d\bar{d}s}$ from charmless

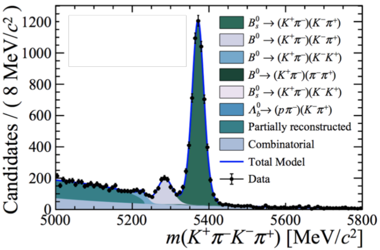
- $B_s^0 \to \phi\phi$: $\bar{b} \to s\bar{s}s$ gluonic penguin: excellent probe of physics BSM
- Measurement using $5\,\mathrm{fb}^{-1}$ (Run1 + 2015 + 2016)
- Statistically limited
- Main syst. unc.: angular acceptance determined from simulations



JHEP 12 (2019) 155

$\phi = -0.073 \pm 0.115 \pm 0.027\,\mathrm{rad}$

- $B_s^0 \to (K^+\pi^-)(K^+\pi^-)$: $\bar{b} \to d\bar{d}s$
- Measurement using Run1 data
- Comparable statistical and syst. unc.
- Main systematic uncertainties:
  - Acceptance determination from simulations
  - Modelling of the $K\pi$ spectrum

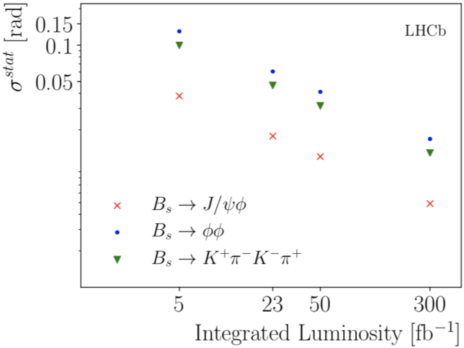


JHEP 03 (2018) 140

$\phi = -0.10 \pm 0.13 \pm 0.14\,\mathrm{rad}$

Prospects for $\phi_s^{ss\bar{s}}$ and $\phi_s^{d\bar{d}s}$

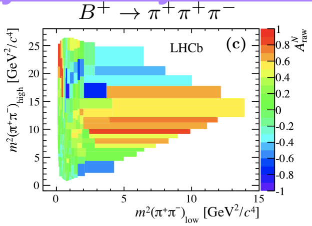
- $\phi_s^{ss\bar{s}}$ statistically limites with full U2 data sample
- Syst. Unc. expected to scale with statistics
- Treatment of acceptance: rapid simulation due to large samples needed
- For $\phi_s^{d\bar{d}s}$, modelling of the $K\pi$ spectrum irriducible ($\sigma_{syst} \sim 0.03\,\mathrm{rad}$)

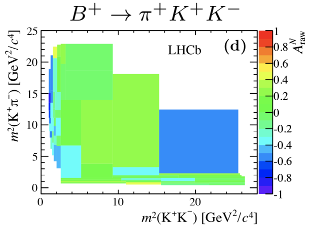


Decay mode	σ(stat.) [rad]			
	3 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$B_s^0 \to \phi\phi$	0.154	0.039	0.026	0.011
$B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ (inclusive)	0.129	0.033	0.022	0.009
$B_s^0 \to K^*(892)^0\overline{K}^*(892)^0$	–	0.127	0.086	0.035

CP violation in three-body B decays

- Interest due to the observation of large CPV in localised regions of the phase space [PRD90 (2014) 112004] not only associated with a resonance
- Rescattering process can generate additional strong phase difference
- Several quasi-two-body amplitudes interfering in multi-body final state decays with access to strong and weak phases
- Extraction of CKM parameters by combining amplitude measurements using isospin partner decays
- Amplitude analysis of $B^+ \to \pi^+ K^+ K^-$ [PRL123(2019)231802] and $B^+ \to \pi^+ \pi^+ \pi^-$ [PRD101(2020)012006]





- Observed CPV in rescattering in $B^+ \to \pi^+ K^+ K^-$
- For $B^+ \to \pi^+ K^+ K^-$
  - Significant CP at low $m(\pi^+\pi^-)$
  - Large CPV in the $f_s(1270)$ region (tensor resonance)
  - Observed CPV in the interference between S and P interference

Status and prospects

- Measurement of A_{CP} are currently statistically limited
- Current dominant systematic uncertainties
  - Parametrisation of signal and backgrounds
  - Modelling of efficiency on the Dalitz phase space
  - Amplitude model (Resonance fixed parameters and alternative models)
- $B \to hhh$ measurement will become systematically limited
  - Parametrisation of signal and backgrounds will scale with integrated luminosity
  - Modelling of efficiency on the Dalitz phase space: larger simulation samples, more uniform efficiencies
  - Amplitude model will not scale with data

CP violation in charmless

- CP violation studies in $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$: constraints on γ and $-2\beta_s$ [JHEP10(2013)183, PRD98(2018) 032004]
- Determination of the angle α using $B \to \pi\pi$, $B \to \rho\rho$, $B \to \pi^+\pi^-\pi^0$
  - CP measurements in $B^0 \to \pi^+\pi^-$ will be dominated by LHCb
  - Possibility to study $B^+ \to \pi^+\pi^0$ (as done for the $B^+ \to K^+\pi^0$) with the improvements in the calorimeter system
  - $B^0 \to \rho^0\rho^0$ study of CP violating parameters will be performed at LHCb (Time integrated angular analysis performed with Run1 data [PLB747 (2015) 468])
  - $B \to \pi^+\pi^-\pi^0$ with the improvements in the calorimeter system but need tagged time-dependent analysis and knowledge of the resonant substructures
  - Other golden modes more criticals ($B^0 \to \pi^0\pi^0$, $B^0 \to rho^+\rho^-$)
- Belle II will dominate α measurement
- Loop-dominated modes will become interesting due to the more efficient hadron trigger and improved ECAL
  - Decay-time-dependent flavour-tagged Dalitz analysis of $B_s^0 \to K_s^0 hh$ decays will be possible in the U2 thanks to the large yields available (Time integrated analysis with Run1 data [PRL120(2018) 261801])

CP violation in b baryon decays

- LHCb is the only experiment to have access to b-baryon decays
- Measurement program of CPV is on-going
  - $\Lambda_b^0 \rightarrow K_s^0 p\pi$ [JHEP04(2014)087]
  - $\Lambda_b^0 \rightarrow \Lambda hh$ [JHEP05(2016)081]
  - $\Lambda_b^0 \rightarrow ph$ [PLB787(2018)182]
  - $\Lambda_b^0 \rightarrow D^0 pK$ [PRD89(2014)032001]
  - $\Lambda_b^0 \rightarrow phhh$ [EPJC79(2019)745, Nature Phys12(2017)341, JHEP08(2018)039, 1912.10741] with the first observation of P violation at 5.5σ integrated over phase space and CP violation at 2.9σ in regions of phase space
- Very large yields open to new b-baryons and new decay modes
- Not only b-baryons but also charm baryons (Ξ_c^+)
- Main experimental issues
  - Particle-antiparticle production asymmetries
  - Detector reconstruction asymmetries: difficult to calibrate different interactions baryons/antibaryons with material
- Use quantities not affected by experimental effects (ΔA_{C}, TPA, ET, ...)

Charm physics

- Motivations: unique access to mixing and CPV in the up-type quark sector
- Taking advantage of the enourmous ($\sim 10\,\mathrm{MHz}$) production rate of charm mesons and baryons expected in the U2
- Fully software trigger and use of real-time analysis is fundamental
- First observation of CPV in charm (5.3σ) using Run1+Run2 data! [PRL122 (2019) 211803]
  - $\Delta A_{\mathrm{CP}} = A_{CP}(K^+K^-) - A_{\mathrm{CP}}(\pi^+\pi^-) = (-1.54 \pm 0.29) \times 10^{-3}$
  - Cancellation of both production and detection asymmetries!
- Extended program to measure CP asymmetries in many different channels
- Exploit both direct CP and mixing and time-dependent measurements

Direct CP

Direct CPV in $D \to K^- K^+$ and $D \to \pi^- \pi^+$

- Enhanced sensitivity to direct CPV through a measurement of $\Delta A_{\rm CP}$
- Disentangle the two contributions measuring the two individual asymmetries $A_{CP}(K^- K^+)$ and $A_{CP}(\pi^- \pi^+)$
  - Measurement of $A_{CP}(K^- K^+)$ with Run1 data [PLB767(2017)177]
  - Asymmetries subtracted using control samples
  - Statistical precision reduced to the kinematic weighting due to the different topologies of the decays
  - No systematic uncertainties expected to have irriducible contributions but need a precise control of the detection asymmetries (K^0 asymmetry due to the knowledge of the material budget)

Sample ($\mathcal{L}$)	Tag	Yield $D^0 \to K^- K^+$	Yield $D^0 \to \pi^- \pi^+$	$\sigma(\Delta A_{CP})$ [%]	$\sigma(A_{CP}(hh))$ [%]
Run 1–2 (9 fb^{-1})	Prompt	52M	17M	0.03	0.07
Run 1–3 (23 fb^{-1})	Prompt	280M	94M	0.013	0.03
Run 1–4 (50 fb^{-1})	Prompt	1G	305M	0.007	0.015
Run 1–5 (300 fb^{-1})	Prompt	4.9G	1.6G	0.003	0.007

Direct CPV

- Other channels which can gain from the improved downstream tracking, calorimetry and trigger in Upgrade2
  - CPV enhanced to the percent level such as in $D^0 \to K^0_s K^0_s$ [JHEP 1811 (2018) 048] and $D^0 \to K^0_s K^{*0}$ [PRD93(2016)052018]
  - $D_s^+ \to K^0_s \pi^+$, $D^+ \to K^0_s K^+$, $D^+ \to \phi\pi^+$ [PRL122(2019)191803]
  - Decays with neutrals: $D^+ \to \eta^{'}\pi^+$, $D_s^+ \to \eta^{'}\pi^+$ [PLB771(2017)21] or radiative decays $D^0 \to \phi\gamma$ and $D^0 \to \rho\gamma$
  - Quasi-two body modes such as $D^0 \to K^* K$, $D_s \to \rho K$: overlapping amplitudes in $D \to hhh$ decays with varyong strong phase
  - $D^0 \to h^+h^-h^+h^-$ using both T-odd asymmetries [JHEP10(2014)005], energy test [PLB769(2017)345] or model-dependent analysis
  - Charmed baryons

	Current Best		LHCb U2 $(300\,\mathrm{fb}^{-1})$
$A_{\mathrm{CP}}(D^0 \to K^0_s K^0_s)$	Belle	15	2.8
$A_{\mathrm{CP}}(D^0 \to K^0_s K^{*0})$	LHCb $(9\,\mathrm{fb}^{-1})$	4.0	1.5
$A_{\mathrm{CP}}(D^+ \to \pi^+\pi^0)$	Belle	12.6	1.7
$A_{\mathrm{CP}}(D^+ \to \phi\pi^+)$	LHCb $(4.8\,\mathrm{fb}^{-1})$	0.49	0.06
$A_{\mathrm{CP}}(D^+ \to K^0_s K^+)$	LHCb $(6.8\,\mathrm{fb}^{-1})$	0.76	0.12
$A_{\mathrm{CP}}(D^+ \to K^0_s \pi^+)$	LHCb $(6.8\,\mathrm{fb}^{-1})$	1.8	0.32
$A_{\mathrm{CP}}(D^+ \to \eta^{'}\pi^+)$	LHCb $(3\,\mathrm{fb}^{-1})$	8.9	0.35

Mixing and time-dependent CPV

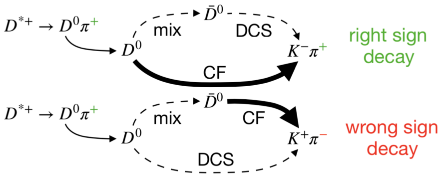
A_Γ

- Time-dependent CP of D^0 mesons into CP eigenstates ($D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$)
- $A_{\rm CP} \simeq A_{CP}^{\rm dir} - \frac{t}{\tau_D} A_\Gamma$
- Experimentally robust
  - Self-conjugate final state: detection asymmetry only from tagging π^+ or μ^+
  - Sensitive to detector asymmetries through correlations between momentum and proper decay time
  - Large CF $D^0 \to K^-\pi^+$ control sample
- Measurement using $5.4\,\mathrm{fb}^{-1}$ [PRD101 (2020) 012005]

Sample ($\mathcal{L}$)	Tag	Yield K^+K^-	$\sigma(A_\Gamma)$	Yield $\pi^+\pi^-$	$\sigma(A_\Gamma)$
Run 1–2 (9 fb^{-1})	Prompt	60M	0.013%	18M	0.024%
Run 1–3 (23 fb^{-1})	Prompt	310M	0.0056%	92M	0.0104 %
Run 1–4 (50 fb^{-1})	Prompt	793M	0.0035%	236M	0.0065 %
Run 1–5 (300 fb^{-1})	Prompt	5.3G	0.0014%	1.6G	0.0025 %

- SM predictions $A_\Gamma^{\rm SM} \approx 0.3 \times 10^{-4}$
- Need to save 50 billion CF $D^0 \to K^-\pi^+$ control decays

WS/RS ratio



- Comparison of decay-time-dependent ratios of favoured (RS) wrt suppressed (WS) $R^{\pm}(t) = \Gamma_{WS}(t)/\Gamma_{RS}(t)$ for D^0 and $\bar{D}^0$
- Related to the mixing parameters x and y and the CP-violation parameters $|q/p|$ and ϕ

- LHCb measurement for $D^0 \to K^-\pi^+$ (Run1 + 2015 + 2016) [PRD 97 (2018) 031101]
- Similar analysis for $D^0 \to K^+\pi^-\pi^+\pi^-$
- Phase-space integrated measurement [PRL 116 (2016) 241801]
- Enhanced sensitivity thanks to the variation of strong phases in the phase space (but strong phases have to be determined)
- Magnet-side stations will increase flavour-tagged charm sample (from the charge of the low-momentum pion)
- Syst. Unc. estimated using control samples, no irreducible contributions

Conclusions

- For the beauty sector: great progress in probing SM, but considerable space for NP remains
- LHCb will drive tree-level CPV γ precision through Phase 2 to sub-degree precision
- ϕ_s will be measured with a precision of $3\,\mathrm{mrad}$: good control of penguin pollution
- Test of CPV in charm has just started: expected 10^{-5} precision
- Improve/maintain detector performance (vertex/time resolution, flavour tagging/PID/...)
- Use high-yield control channels to control efficiencies

Spare Slides