Prospects for CP violation in Beauty and Charm at LHCb

Beyond the LHCb Phase-1 Upgrade

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on behalf of the LHCb collaboration

29th May 2017

Introduction

$3\ fb^{-1}$	$+5\ fb^{-1}$	$+50\ fb^{-1}$		$+300\ fb^{-1}$
Run 1	Run 2	Run 3	Run 4	Run 5...
2010	2015	2021	2027	2031

Today

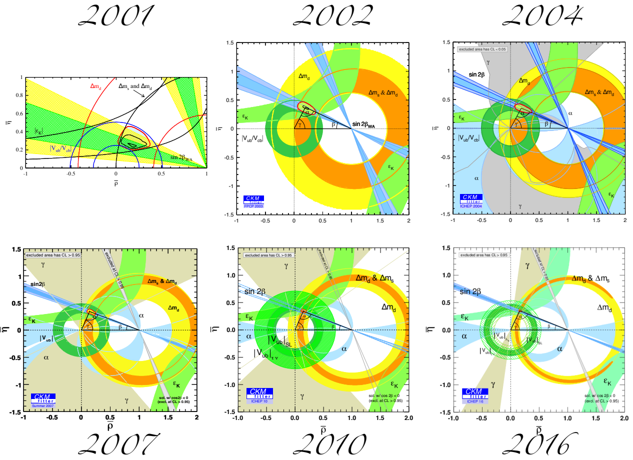
Snapshot of LHCb CP violation studies & estimates for Phase-2 sensitivity

I will:

- refer to the milestones indicated above
- emphasise **theoretically clean UT angle** measurement & **charm CPV**
- highlight **systematic & detector challenges** in parallel
- return to the issue of **external inputs from CLEO and BES-III** at the end

Introduction

Baryogenesis tells us that there **must** be New Physics in CP violation.
Can we find it in flavour-changing processes in the quark sector? Great progress:



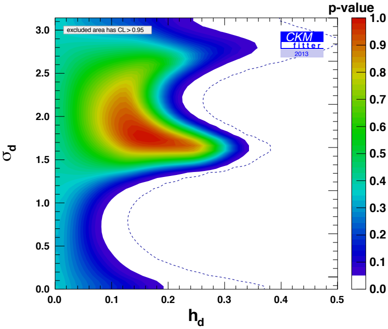
SM picture accounts for **wide** range of measured CP observables

Introduction

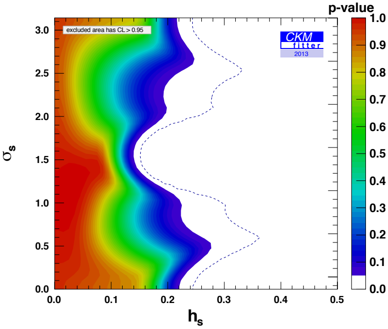
But there is **room for more:**

- Assume no NP at tree-level
- Allow common (loop-level) NP effect in B^0 and B_s^0 mixing
- $M_{12} \to M_{12}^{SM}(\rho, \eta)(1 + h_d \exp(2i\sigma_d))$

B^0 mixing



B_s^0 mixing



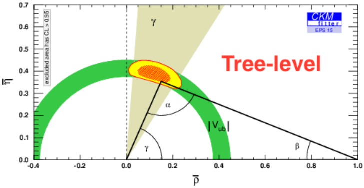
Only limit amplitude of NP effects in $B_{d,s}$ mixing to $< 30\%$! (PRD89 033016 (2014))

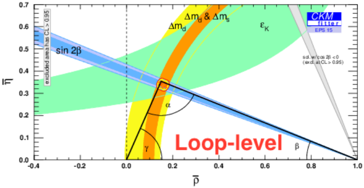
Theoretically clean UT measurement

$$\gamma$$

The UT angle γ

- Least well-known UT angle
- Only one that can be measured at tree-level alone ($\frac{\sigma_{\mathrm{th}}^{\mathrm{tree}}}{\gamma} < \mathcal{O}(10^{-7})$) (JHEP 01 051 (2013))
- Sensitive NP probe: compare direct and indirect determination:





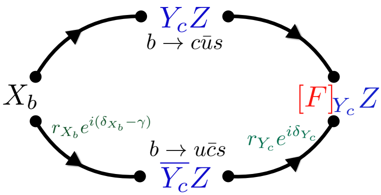
- Direct measurements: $\gamma = 73.2^{+6.3\circ}_{-7.0}$ Indirectly: $\gamma = 66.9^{+0.94\circ}_{-3.44}$
  - NB: NP could manifest at tree-level - still room for 10% modifications to $\mathcal{C}_1$ and $\mathcal{C}_2$ (PRD 92 033002 (2015))

The UT angle γ

Exploit interference between decays via charm to a common final state

$$X_b \to [F]_{Y_c} Z \qquad \text{(e.g. } B^\pm \to [K^\mp\pi^\pm]_D K^\pm\text{)}$$

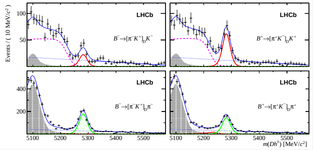
- F accessible to Y_c and $\overline{Y_c}$:
- $Z \in \{K, \pi, K^*, K\pi\pi ...\}$



γ is the weak phase difference between decay amplitudes with $b \to c\bar{u}s$ and $b \to u\bar{c}s$ transitions

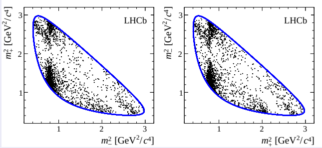
The UT angle γ

2-body 'ADS' : $B^{\pm} \to [\pi^{\pm} K^{\mp}] h^{\pm}$



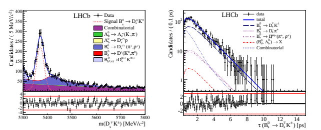
- Suppressed: 550 candidates in Run 1
- Large interference; 8σ CPV (PLB 760 117)

'GGSZ' : $B^{\pm} \to [K^0_S h^+ h^-] h^{\pm}$



- Mod. indep.; 2,600 candidates in Run 1
- Reduced γ ambiguity (JHEP 1410 097)

TD : $B^0_s \to D^{\pm}_s K^{\mp}$



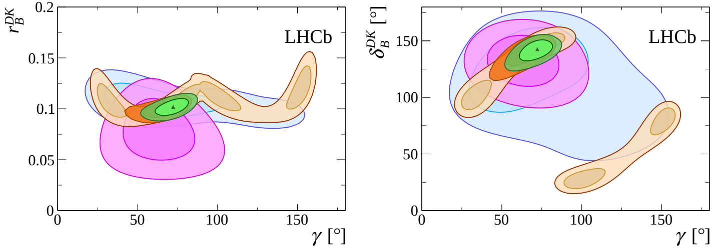
- 1,800 candidates in $1\,\text{fb}^{-1}$ (JHEP 1411 060)
- Measures $\gamma - 2\beta_s$; $B^0_s \to J/\psi\, hh$ input

Many more

- ADS/(pseudo-)GLW 2/4 body (PLB 760 117)
- GLS $B \to (K^0_S K^{\mp} \pi^{\pm}) K$ (PLB 733 36)
- ADS $B^0 \to DK^{*0}$ (PRD 90 112002)
- Dalitz $B^0 \to [hh]_D K\pi$ (PRD 93 112018)
- ADS $B^0 \to [hh\pi^0]_D K$ (PRD 91 112014)
- GGSZ $B^0 \to DK^{*0}$ (JHEP 06 131)
- ADS/GLW $B^{\pm} \to DK^{*\pm}$ (LHCb-CONF 2016 014)

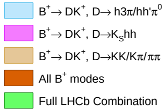
The UT angle γ

B^+ combination

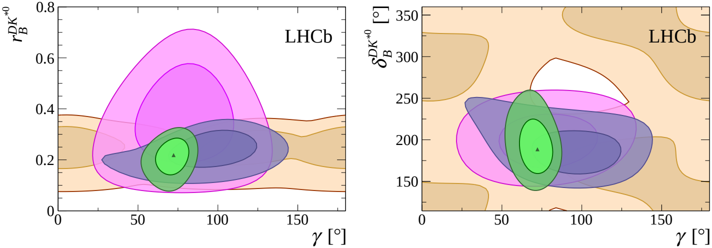


$r_B^{DK} = 0.1019 \pm 0.0056$

$\delta_B^{DK} = (142.6^{+5.7}_{-6.6})^\circ$

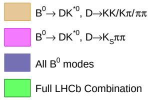


B^0 combination

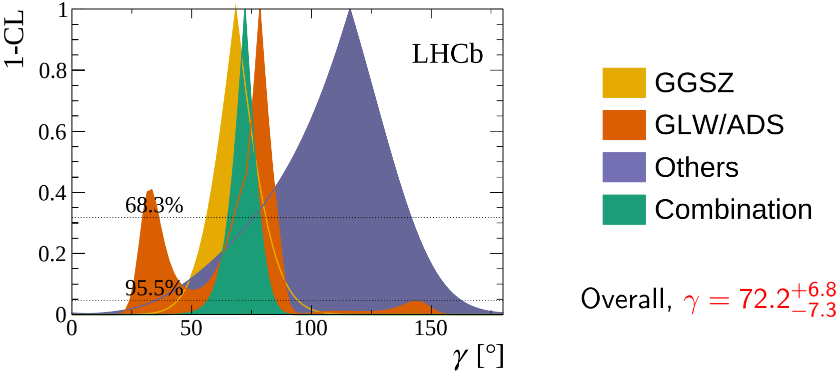


$r_B^{DK^{*0}} = 0.218^{+0.045}_{-0.047}$

$\delta_B^{DK^{*0}} = (189^{+23}_{-20})^\circ$



Result for γ (JHEP 12 087)



Overall, $\gamma = 72.2^{+6.8}_{-7.3}$

- Improves the previous LHCb-only determination by 2°
- Reaches Run 1 target sensitivity; LHCb dominates world average
- Good agreement with the B-factory results:
  - BaBar: $\gamma = (70 \pm 18)^\circ$
  - Belle: $\gamma = (73^{+13}_{-15})^\circ$

The UT angle γ

Need $\sigma^{\text{direct}}(\gamma) < 1^\circ$ to match indir. determination (σ_{LQCD} will fall more)

Statistical uncertainties:

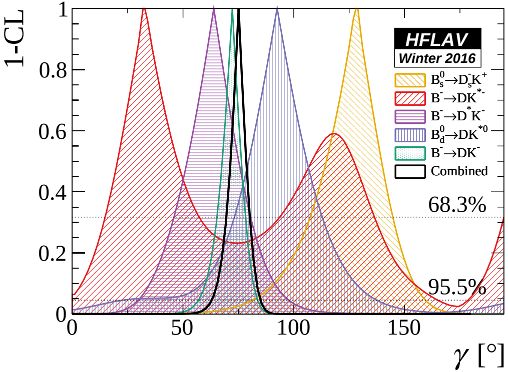
Sample	$\mathcal{L}$ (fb^{-1})	Units of Run-1	
Run 1	3	1	
Run 2	5	3	$\sigma(b\bar{b}) \to 2\sigma(b\bar{b})$; $\uparrow \epsilon(\text{trig/offline})$
Upgrade	~50	~60	$\epsilon_{trig}^{hadrons} \to 2\epsilon_{trig}^{hadrons}$
Phase-2 Upgrade	~300	~360	

The UT angle γ

Need $\sigma^{\text{direct}}(\gamma) < 1^\circ$ to match indir. determination (σ_{LQCD} will fall more)

- Some channels' $\sigma(\gamma) \sim 1^\circ$; compare species/modes (tree-level NP)
- LHCb and Belle II precision similar in the Upgrade period

Sample	$\sigma_{\text{stat}}(\gamma)^\circ$
Run 1	8
Run 2	4
Upgrade	~ 1
Phase-2 upgrade	<0.5



(arXiv:1612.07233)

The UT angle γ

Prospects for existing systematic uncertainties:

- Diverse systematic uncertainty exposure
  - GGSZ: Dalitz efficiency. Insensitive to B prod or K det. asymmetry
  - ADS/GLW: inst. charge asymmetries/PID
  - TD: decay time resolution/acceptance
  - Differences between methods (systematic?) or modes (NP?)
- One's signal is another's background: constrain CPV in part. reco. modes
- Improved precision on charm inputs (more later)

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- Mixing and CPV in the kaon system (as we do for charm) and regeneration effects
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Increased statistics and detector capability: power in combination

- Improved calorimetry for exploitation of π^0 D final states or D^{*0}, $D_s^{*\pm}$
- Extended soft track reconstruction for higher multiplicity B and D final states
- Widen pool of modes: $D \to KK\pi\pi$, $D \to K_S^0\pi\pi\pi^0$, $B \to D^{*0}K$, $B_s^0 \to D_s^{*\pm}K$

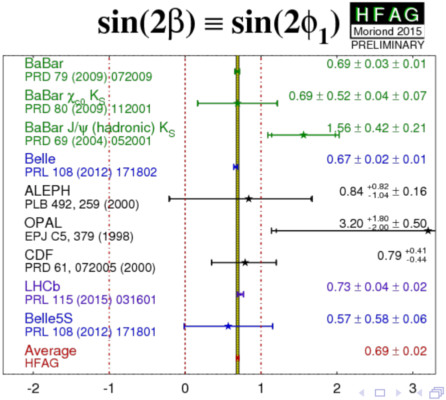
Theoretically clean UT measurement

$$\beta,\ \beta_s$$

The UT angle β

- Accessed via interference in B^0 mixing and decay
- Theory uncertainty due to mode-dependent role of penguin amplitudes
- Data-driven methods to control penguin pollution

Indirect determination (CKMfitter): $sin(2\beta) = 0.7094^{+0.0098}_{-0.0094}$

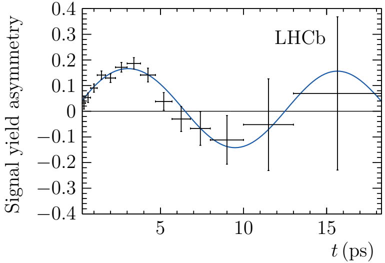


The UT angle β

- CKM hierarchy in $b \to c\bar{c}s$ transitions
  $\Rightarrow$ negligible theory uncertainty
  $\Rightarrow$ 'gold-plated' mode $B^0 \to J/\psi\, K^0_S$
- TD flavour tagged ($\epsilon_{\rm eff} = 3\%$) Run 1 study of 42,000 B^0,$\bar{B}^0$ decays (PRL 115 031601)

Systematic uncertainties

- Main $\sigma_{\rm syst}(S_{J/\psi\, K^0_S})$: possible bg tagging asymmetry ((2.5%)). Others $< 1\%$
- Main $\sigma_{\rm syst}(C_{J/\psi\, K^0_S})$: Δm input ((10%)). FT calib & z-scale ((7%))



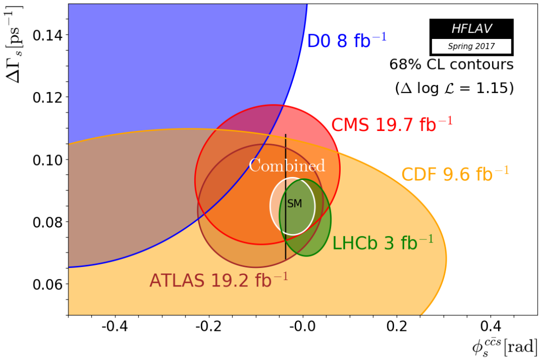
Approaching **B-factory precision**:
$S = 0.731 \pm 0.035 \pm 0.020$; $C = -0.038 \pm 0.032 \pm 0.005 \Rightarrow sin(2\beta) = 0.746 \pm 0.030$

Contribution of sub-dominant amplitudes well below experimental uncertainties ($\mathcal{O}(\%)$)

The UT$_s$ angle β_s

- CPV phase in int. between B_s^0 mixing and decay (assume $|q/p| = 1$ for now)
- Unlike B^0, $\Delta\Gamma/\Gamma$ not small; access β_s in TD & untagged effective-lifetime studies
- Data-driven methods to control penguin pollution; $\phi_s \approx -2\beta_s$

Indirect determination (CKMfitter): $\beta_s = 0.01852 \pm 0.00032$

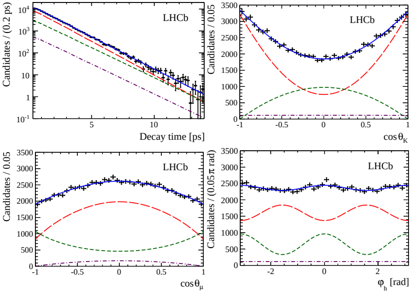


The UT$_s$ angle β_s

- Again, smallest theory uncertainty in $b \to c\bar{c}s$ transitions
- $B_s^0 \to J/\psi\,\phi$: Run 1 TD, tagged ang. analysis 96k $B_s^0 \to J/\psi\, K^+K^-$ ($\epsilon_{\rm eff} = 3.9\%$)
  - $B \to VV$: ang. analysis disentangles CP odd/even components (PRL 114 041801)
- $B_s^0 \to J/\psi\,\pi^+\pi^-$: Run 1 TD analysis 22k signal candidates ($\epsilon_{\rm eff} = 3.9\%$)
  - Final state found to be dominantly CP-even (PLB 736 186)

Systematic uncertainties

- Largest $\sigma_{\rm syst}(\phi_s^{J/\psi\,K^+K^-})$: MC sample for angular efficiency ($< 0.1\sigma_{\rm stat}$)
- Largest $\sigma_{\rm syst}(\phi_s^{J/\psi\,\pi^+\pi^-})$: Production asymmetry & amp. model ($< 0.1\sigma_{\rm stat}$)



$$\phi_s^{c\bar{c}s} = -0.010 \pm 0.039\,\mathrm{rad}$$

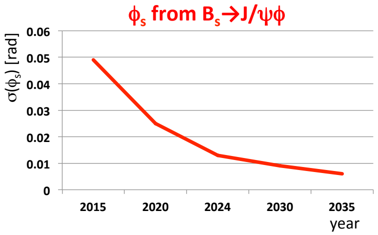
Contribution of sub-dominant amplitudes well below experimental uncertainties ($\mathcal{O}(\%)$)

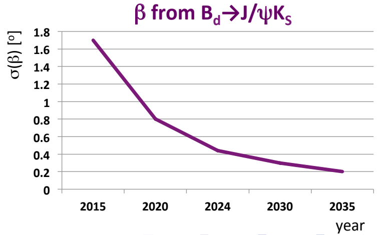
The UT angles β, ϕ_s

Phase 2 penguin pollution:

No immediate show-stoppers

- ϕ_s DCS penguin will be important
  - Assuming SU(3); pollution studied in $B^0 \to J/\psi\,\rho^0$ and $B^0_s \to J/\psi\,\bar{K}^{*0}$ (PLB 742 38)(JHEP 11 082)
    - ★ $\Delta\phi_s = 1.4^{+9.8}_{-12.6}{}^{+2.6}_{-2.3}\mathrm{mrad}$
  - Expect control Phase 2 pollution: $\sigma(\phi_s) = 0.9\,(\mathrm{stat}), 1.2\,(\mathrm{syst})\,\mathrm{mrad}$
- Control β penguin pollution using SU(3) and $B^0_s \to J/\psi\,\rho^0$; will be a challenge in Phase 2





The UT angles β, ϕ_s

Systematic uncertainties:

Well controlled. No problems anticipated, even at Phase 2:

- Apply full angular analysis to $B_s^0 \to J/\psi\,\pi^+\pi^-$ as for $B_s^0 \to J/\psi\,\phi$
- Model-independent S-wave description in $J/\psi\,\pi^+\pi^-$
- High pile-up $\Rightarrow$ maintain PV association & decay time resolution
- Lower momentum reconstruction $\Rightarrow$ improved flavour-tagging

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Exploiting new modes in the high statistics era

- Already widening the net:
  - $B_s^0 \to D_s^+ D_s^-$: $\phi_s^{c\bar{c}s} = 0.02 \pm 0.17 \pm 0.02\,\mathrm{rad}$ (PRL 113 211801)
  - $B^0 \to D^+ D^-$: $S = -0.54^{+0.17}_{-0.16} \pm 0.05$, $C = 0.26^{+0.18}_{-0.17} \pm 0.02$ (PRL 117 261801)
    - ★ $\epsilon_{\mathrm{eff}} = 8.1\%$!
    - ★ Benefit from upgrade $\epsilon^{\mathrm{trigger}}_{\mathrm{hadrons}}$
  - Penguin-free $B^0 \to D_{CP}\pi^+\pi^-$

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    - $\epsilon_{\mathrm{eff}} = 8.1\%$!
    - Benefit from upgrade $\epsilon^{\mathrm{trigger}}_{\mathrm{hadrons}}$
  - Penguin-free $B^0 \to D_{CP}\pi^+\pi^-$
- Wide range of $b \to q\bar{q}q'$ transitions;
  - differing penguin roles: $B_s^0 \to \phi\phi$, $B_s^0 \to K^*\bar{K}^*$, $B_s^0 \to K_{\mathrm{S}}^0 K\pi$
  - improved calorimetry: $B_s^0 \to (J/\psi \to e^+e^-)\phi$, penguins in $B_{s,d}^0 \to J/\psi\,\pi^0$

The UT angles β, ϕ_s

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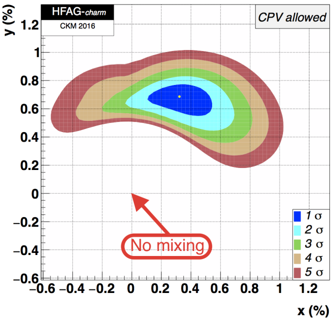
  - improved calorimetry: $B_s^0 \to (J/\psi \to e^+e^-)\phi$, penguins in $B_{s,d}^0 \to J/\psi \pi^0$
- In the $\sigma(\gamma) < 1^\circ$ era, $B_s^0 \to D_s^\pm K^\mp$ constrains β_s without penguin pollution

CP violation in Charm

CPV in charm

- SM predicts small mixing and $\mathcal{O}(10^{-3})$ CPV
- Mixing firmly established (significant $y \neq 0$ a good start for indirect CPV searches)
- CPV remains elusive:
  - **Direct:** charged $c-$hadrons or time-integrated D^0
  - **Indirect:** time-dependent D^0



- **LHCb competes with B-factories:**
  - time resolution
  - huge LHC $\sigma_{\mathrm{prod}}(c\bar{c})$

Evolution of LHCb sensitivity (beginning from the W.A.)

	$x(10^{-3})$	$y(10^{-3})$	$\lvert q/p\rvert(10^{-3})$	$\Phi(\mathrm{mrad})$
Run 1	1.2	0.5	59	89
Run 2	0.9	0.4	44	70
Upg.	**0.2**	**<0.1**	**8**	**14**
Phase2	**0.09**	**<0.05**	**4**	**6**

CPV in charm

Searching for direct CPV: focus on Cabibbo suppressed decays

1. Isolate $D^0 \to h^+h^-$ direct component & reduce systematics:

Approaching the SM threshold (PRL 116 191601)

$$\Delta A_{CP} = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) = (-0.10 \pm 0.08 \pm 0.03)\%$$

2. Charged $D^\pm$ and $D_s^\pm$ decays

Most precise results are (JHEP 10 025)

$$\Delta\mathcal{A}_{D^+\to K^0_S K^+} = (0.3 \pm 1.7 \pm 1.4)x10^{-3} \text{ and } \Delta\mathcal{A}_{D_s^+\to K^0_S \pi^+} = (3.8 \pm 4.6 \pm 1.7)x10^{-3}$$

In the Phase 2 era:

- Low momentum track reconstruction: significant statistics increase
- Improved calorimetry: searches for CPV in, e.g., $D^0 \to \phi\gamma$, $D^0 \to \rho\gamma$
- Continued need for high statistics PID calibration samples
- Reco. asymmetries: continued reliance on absence of CPV in CF modes? Magnetic field reversal? Partial/full reconstruction methods may provide solutions.

CPV in charm

Searching for **indirect** CPV

1. Small $x, y \Rightarrow$ simple modifications to D^0 decay rate parameters: y_{CP}, A_Γ

10^{-4} precision with well-controlled systematic uncertainties (arXiv:1702.06490)

$$A_\Gamma(D^0 \to K^- K^+) = (-3.0 \pm 3.2 \pm 1.4) \times 10^{-4},$$
$$A_\Gamma(D^0 \to \pi^+ \pi^-) = (4.6 \pm 5.8 \pm 1.6) \times 10^{-4}$$

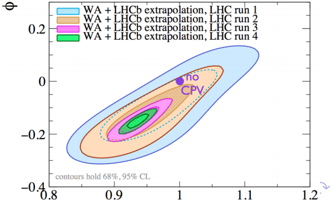
2. TD analysis of $D^0 \to K^0_S \pi^+ \pi^-$

Determines $x, y, |q/p|, \phi_D$ (JHEP 04 033)

Mixing analysis: $x = (-8.6 \pm 5.3 \pm 1.7) \times 10^{-3}$, $y = (0.3 \pm 4.6 \pm 1.3) \times 10^{-3}$

In the Phase 2 era:

- Golden $D^0 \to K^0_S \pi^+ \pi^-$ mode will be stats limited
- Any non-zero signal with current precision would indicate NP



Encore: Charm for Beauty

Charm inputs for model-independent γ at LHCb

Charm for Beauty in Phase 2

Where will γ become limited:

- Most[1] $B \to DK$ modes rely on CLEO strong phase measurements at the $\psi(3770)$
- Allows for model independence; crucial in the high-statistics era
- Current systematic due to CLEO inputs $\sim 2^\circ$
- Some D modes not analysed by CLEO; some would benefit from D-phasespace-binned analysis

Available now:

- Quadruplication of the CLEO dataset at BES III ($\to$ systematic $\sim 1^\circ$)
  - Measurement in $D \to K\pi$ (Int.J.Mod.Phys.Conf.Ser. 31 1460305)
  - Preliminary results in $D \to K^0_S\pi\pi$

[1] not, e.g., $B^0_s \to D^+_s K$

Charm for Beauty in Phase 2

Alternative sources of charm information?

- Additional BES III run at $\psi(3770)$ - under consideration - gives $\sigma(\gamma) \sim 0.5^\circ$
- Exploit enormous LHCb charm samples? Require ~ 1 LHCb-upgrade of charm to match already available BES III sample, though good prospects remain via mixing measurements
- Float the charm parameters in the γ combination?
  - Lose γ precision
  - Reduce ability to compare decay modes

Best outcome:

- Full suite of charm inputs measured with current **and future** BES III datasets

Conclusion

Beauty

- 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
- Vital role of BESIII in providing charm inputs
- Precise measurements of CPV in B-mixing; penguin pollution under control

Charm

- Direct and indirect CPV searches already probing SM territory
- No show-stoppers approaching Phase 2

Improvements in calorimetry and low-momentum track reconstruction will open up many little-explored modes