CP violation and CKM measurements with beauty decays at LHCb

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on behalf of the LHCb collaboration

12 January 2022

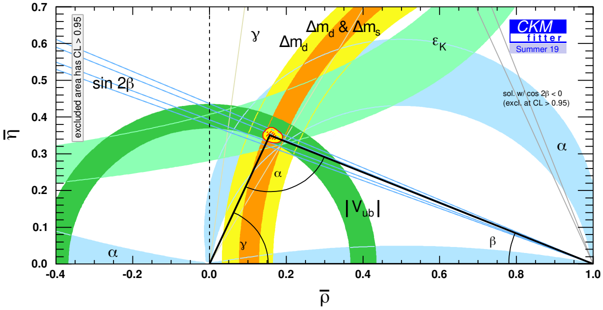
Introduction

- CKM matrix:
  - Link weak and mass eigenstates
  - Complex matrix
  - Unitary

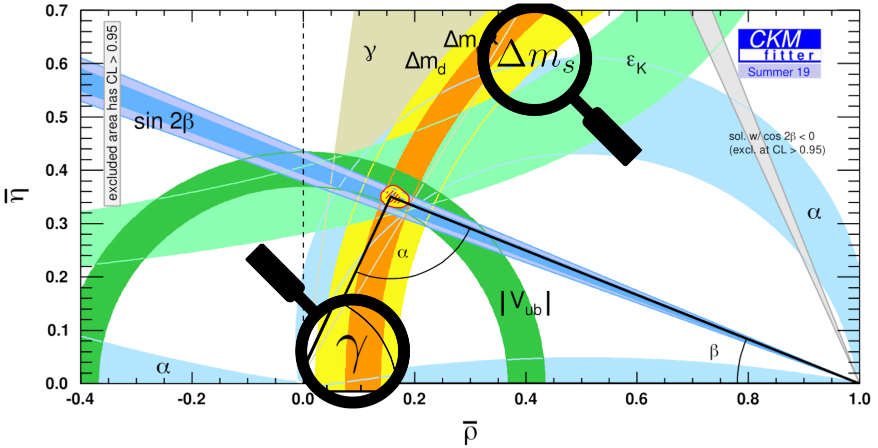
$$V_{CKM} \sim \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{-i\beta_s} & |V_{tb}| \end{pmatrix}$$

CKM angle γ

- Standard candle for SM
- Negligible theoretical uncertainty
- CKM fitter group:
  $\gamma = (65.7^{+0.9}_{-2.7})^\circ$
- UTfit:
  $\gamma = (65.8 \pm 2.2)^\circ$



[CKM fitter group]



0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
$\bar{\eta}$
$\bar{\rho}$
excluded area has CL > 0.95
sin 2β
γ
Δm_d
Δm_s
ε_K
CKM fitter
Summer 19
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
α
|V_ub|
β

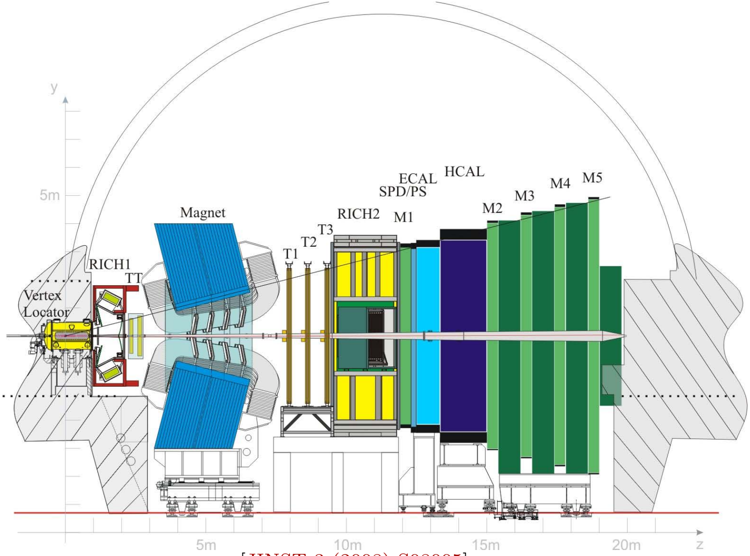
Outline

- LHCb γ combination [JHEP 12 (2021) 141]
- γ using $B^{\pm} \to Dh^{\pm}$, $(D \to h^{\pm}h'^{\mp}\pi^{0})$ [arXiv:2112.10617]
- CP asymmetry measurement using $\Lambda_b^0 \to DpK^-$ [Phys. Rev. D104 (2021) 112008]
- γ and Δm_s using $B_s^0 \to D_s^{\mp}h^{\pm}\pi^{\pm}\pi^{\mp}$ [JHEP 03 (2021) 137]
- Δm_s using $B_s^0 \to D_s^- \pi^+$ [Nature Physics (2022)]
- Branching fraction measurement $B^0 \to D_s^+ \pi^-$ [Eur. Phys. J. C81 (2021) 314]

Related talks:

- 11/01, 10:00 GMT - Mixing and CP violation in beauty and charm hadrons - Malcolm John
- Today, 11:40 GMT - CP violation and mixing in charm at LHCb - Joan Ruiz Vidal

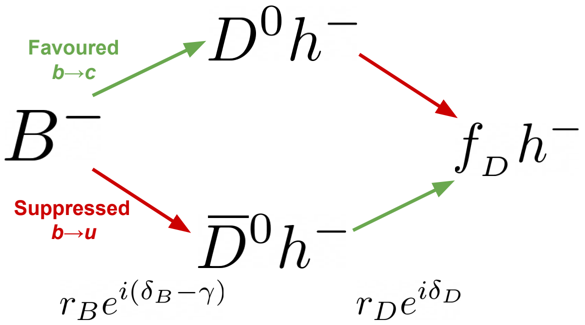
LHCb detector



[JINST 3 (2008) S08005]

Measuring γ through $B \to Dh$ decays

- Measure γ through interference between favoured $b \to c$ and suppressed $b \to u$ decay amplitudes
- Typically using $B^{\pm} \to Dh^{\pm}$ decays
  - D admixture D^0 and $\overline{D}^0$ decaying to same f_D
- Interference mixing and decay (TD analyses):
  - $B^0 \to D^{\mp}\pi^{\pm}$
  - $B_s^0 \to D_s^{\mp}K^{\pm}$
  - $B_s^0 \to D_s^{\mp}K^{\pm}\pi^+\pi^-$



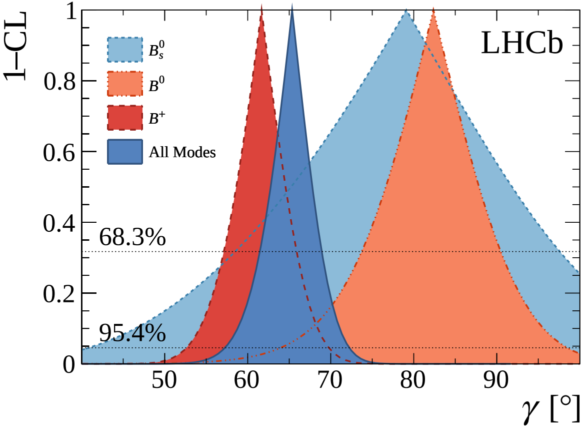
- New feature: combination of results from the beauty **and** charm sectors
  - Precision in γ and δ_B is enables us to constrain $\delta_D^{K\pi}$ a factor 2 better than world average
  - Therefore, improvement in charm mixing knowledge
- External constraints
  - Mainly hadronic parameters and coherance factors in multi-body B and D decays
- Frequentist approach

B decay	D decay	Ref.	Dataset	Status since Ref. [24]
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[27]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[28]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[29]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	[26]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	[30]	Run 1&2	**Updated**
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	[27]	Run 1&2	**Updated**
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[31]	Run 1&2(*)	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[31]	Run 1&2(*)	As before
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[32]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[33]	Run 1&2(*)	**Updated**
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[33]	Run 1&2(*)	**New**
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	[34]	Run 1	As before
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[35]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	[36]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm\pi^+\pi^-$	$D^+_s \to h^+h^-\pi^+$	[37]	Run 1&2	**New**
–	$D^0 \to h^+h^-$	[38,39,40]	Run 1&2	**New**
–	$D^0 \to h^+h^-$	[41]	Run 1	**New**
–	$D^0 \to h^+h^-$	[42,43,44,45]	Run 1&2	**New**
–	$D^0 \to K^+\pi^-$	[46]	Run 1	**New**
–	$D^0 \to K^+\pi^-$	[47]	Run 1&2(*)	**New**
–	$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	[48]	Run 1	**New**
–	$D^0 \to K^0_S\pi^+\pi^-$	[49,50]	Run 1&2	**New**
–	$D^0 \to K^0_S\pi^+\pi^-$	[51]	Run 1	**New**

LHCb combination of CKM angle γ

[JHEP 12 (2021) 141]

- $\gamma = (65.4^{+3.8}_{-4.2})^\circ$
  - Most precise determination by single experiment
- Charm mixing parameters:
  - $x = (0.400^{+0.052}_{-0.053})\%$
  - $y = (0.630^{+0.033}_{-0.030})\%$ factor 2 improvement
- Reminder:
  - $x = \Delta m/\Gamma$, $y = \Delta\Gamma/2\Gamma$
  - Mass difference in charm only recently observed [Phys. Rev. Lett. 127 (2021) 111801]
- Beauty part cross-checked using Bayesian approach
- Charm results validated by reproducing HFLAV results



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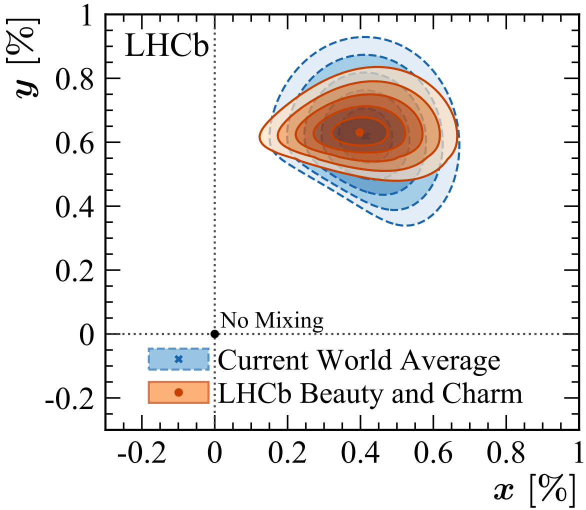


γ using $B^{\pm} \to Dh^{\pm}$, $(D \to h^{\pm}h'^{\mp}\pi^0)$

Overview

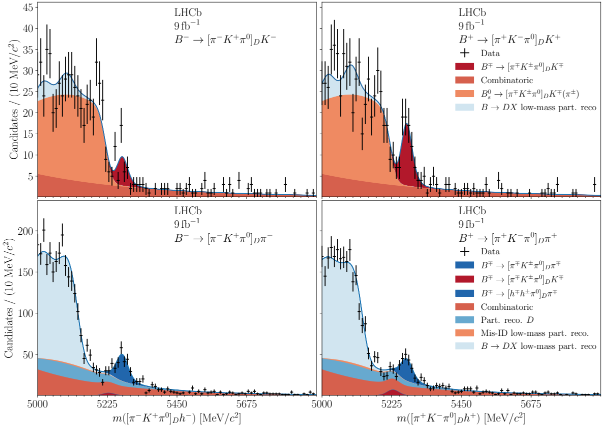
[arXiv:2112.10617][1], submitted to JHEP

Dataset: 2011-2018

- Study 8 final states:

Mode ($h^- = \{\pi^-, K^-\}$)	Analysis type
$B^- \to [K^-\pi^+\pi^0]_D h^-$	quasi-ADS (fav.)
$B^- \to [\pi^-K^+\pi^0]_D h^-$	quasi-ADS (sup.)
$B^- \to [K^-K^+\pi^0]_D h^-$	quasi-GLW
$B^- \to [\pi^-\pi^+\pi^0]_D h^-$	quasi-GLW

- Discovery of $B^- \to [\pi^-K^+\pi^0]_D K^-$ (7.8σ!)
- Invariant-mass fit performed to 16 sub-samples



[1] This paper is dedicated to our friend and colleague Bernhard Spaan

[arXiv:2112.10617][1], submitted to JHEP

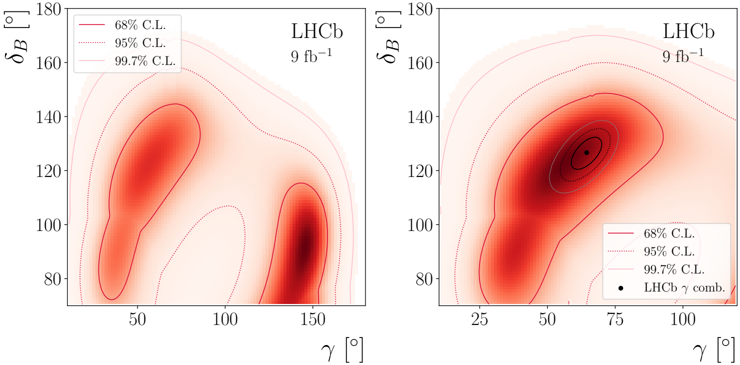
- Fit performed to 11 ratios/asymmetries
- Interpret in terms of γ, r_B and δ_B

Results

$$\gamma = (56^{+24}_{-19})^\circ$$

$$\delta_B = (122^{+19}_{-23})^\circ$$

$$r_B = (9.3^{+1.0}_{-0.9}) \times 10^{-2}$$



- Global minimum: $\gamma = (145^{+\ 9}_{-39})^\circ$
- Second solution closer to LHCb γ combination (see slide 7)

[1] This paper is dedicated to our friend and colleague Bernhard Spaan

Dataset: 2011-2018

- Observation of $\Lambda_b^0 \to [K^+\pi^-]_D pK^-$
- Two parameters of interest:

$$R = \frac{\mathcal{B}(\Lambda_b^0 \to [K^-\pi^+]_D pK^-)}{\mathcal{B}(\Lambda_b^0 \to [K^+\pi^-]_D pK^-)}$$

$$A = \frac{\mathcal{B}(\Lambda_b^0 \to [K^+\pi^-]_D pK^-) - \mathcal{B}(\overline{\Lambda}_b^0 \to [K^-\pi^+]_D K^+)}{\mathcal{B}(\Lambda_b^0 \to [K^+\pi^-]_D pK^-) + \mathcal{B}(\overline{\Lambda}_b^0 \to [K^-\pi^+]_D K^+)}$$

- More data needed to extract γ

Results

Parameter	Phase space	
	Full	Restricted
R	$7.1 \pm 0.8\,^{+0.4}_{-0.3}$	$8.6 \pm 1.5\,^{+0.4}_{-0.3}$
A	$0.12 \pm 0.09^{+0.02}_{-0.03}$	$0.01 \pm 0.16^{+0.03}_{-0.02}$

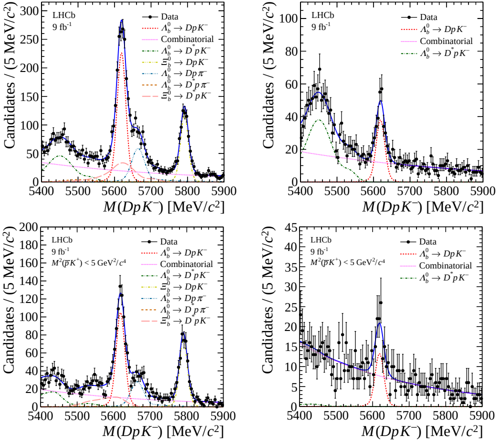
Favoured $\Lambda_b^0 \to [K^-\pi^+]_D pK^-$

Suppressed $\Lambda_b^0 \to [K^+\pi^-]_D pK^-$

Full phase space

Restricted phase space

$M^2(pK^-) < 5\,\mathrm{GeV}^2/c^4$



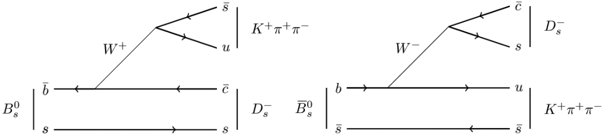
γ and Δm_s using $B_s^0 \to D_s^{\mp} h^{\pm}\pi^{\pm}\pi^{\mp}$

Brief overview

[JHEP 03 (2021) 137]

Dataset: 2011-2018

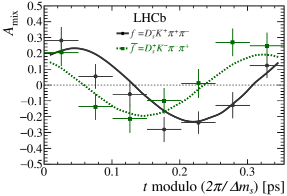
- $B_s^0 \to D_s^- \pi^+\pi^+\pi^-$
  - Extract Δm_s
  - Calibrate detector induced effects
- $B_s^0 \to D_s^{\mp} K^{\pm}\pi^{\pm}\pi^{\mp}$
  - Sensitive to $\gamma - 2\beta_s$
  - 4-body decay $\to$ strong-phase variation over phase space

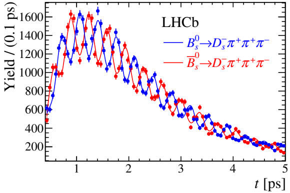


Results

$$\gamma = (44 \pm 12)^\circ$$

$$\Delta m_s = 17.757 \pm 0.007 \pm 0.008\,\text{ps}^{-1}$$





- Cross-check: integrated phase space: $\gamma = (44^{+20}_{-13})^\circ$

Precise determination of Δm_s using $B_s^0 \to D_s^- \pi^+$

Strategy and invariant-mass fit

[arXiv:2104.04421], [Nature Physics (2022)]

- Goal: obtain B_s^0–$\overline{B}_s^0$ oscillation frequency Δm_s
- Use $D_s^- \to K^- K^+ \pi^-$ and $D_s^- \to \pi^- \pi^+ \pi^-$ decay modes

1. Invariant-mass fit

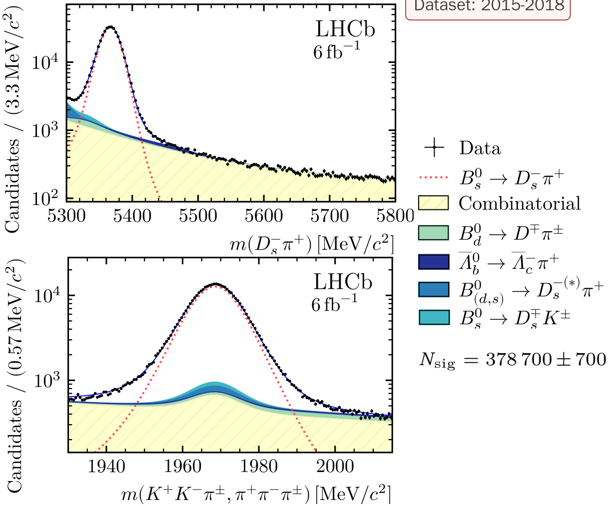
- Two-dimensional fit to B_s^0 and D_s^- invariant mass
- Statistically remove backgrounds using the sPlot method
- This is the input for decay-time fit

2. Decay-time fit

- Perform decay-time fit to background subtracted data to obtain Δm_s

See next slide

Dataset: 2015-2018



Precise determination of Δm_s using $B_s^0 \rightarrow D_s^- \pi^+$

Decay-time fit

[arXiv:2104.04421], [Nature Physics (2022)]

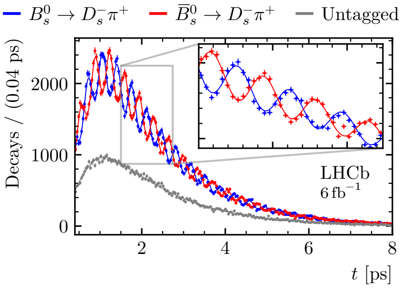
Ingredients for the decay-time fit:

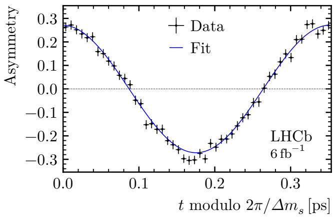
- Background subtracted data
- Flavour tagging
- Decay-time acceptance
- Decay-time error calibration
- Decay-time bias correction

Δm_s result from the decay-time fit

$$\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032\,\text{ps}^{-1}$$

- Main systematics: detector misalignment and length scale



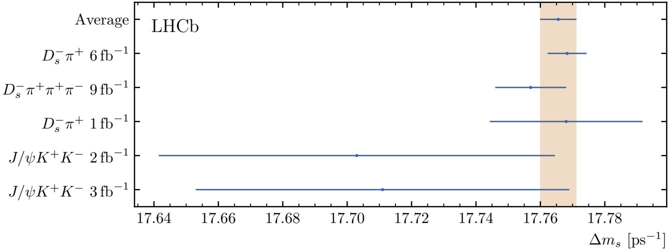


Precise determination of Δm_s using $B_s^0 \to D_s^- \pi^+$

LHCb Δm_s combination [arXiv:2104.04421], [Nature Physics (2022)]

Main LHCb measurements Δm_s

	Method	Dataset	$\Delta m_s (\text{ps}^{-1})$	Ref.
	$B_s^0 \to D_s^- \pi^+$	2011	$17.768 \pm 0.023 \pm 0.006$	[1]
	$B_s^0 \to J/\psi K^+ K^-$	Run1+2015+2016	17.694 ± 0.042	[2]
See slide 12 →	$B_s^0 \to D_s^- \pi^+ \pi^+ \pi^-$	Run1+Run2	$17.757 \pm 0.007 \pm 0.008$	[3]
	$B_s^0 \to D_s^- \pi^+$	Run2	$17.7683 \pm 0.0053 \pm 0.0037$	[4]
	Average		$\mathbf{17.7656 \pm 0.0057}$	



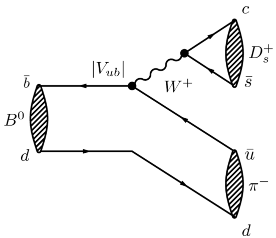
Measurement of the branching fraction of the $B^0 \to D_s^+ \pi^-$ decay

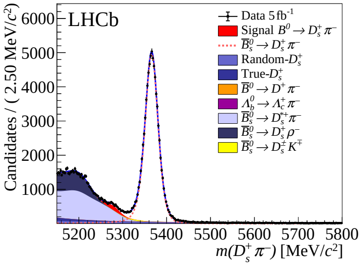
[Eur. Phys. J. C81 (2021) 314]

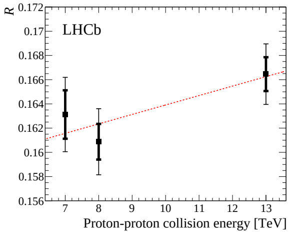
Dataset: 2011-2016

- Normalisation channel $B^0 \to D^- \pi^+$
- Most precise single measurement:
  $\mathcal{B}(B^0 \to D_s^+ \pi^-) = (19.4 \pm 1.8 \pm 1.3 \pm 1.2) \times 10^{-6}$
- Probe product $|V_{ub}|$ and non-factorisable QCD effects:
  $|V_{ub}||a_{\mathrm{NF}}| = (3.14 \pm 0.20 \pm 0.25) \times 10^{-3}$
- Can be used as input for CP violation in $B^0 \to D^\mp \pi^\pm$:

$$r_{D\pi} = \tan(\theta_c) \frac{f_{D^+}}{f_{D_s^+}} \sqrt{\frac{\mathcal{B}(B^0 \to D_s^+ \pi^-)}{\mathcal{B}(B^0 \to D^- \pi^+)}} = 0.0163 \pm 0.0007 \pm 0.0033$$





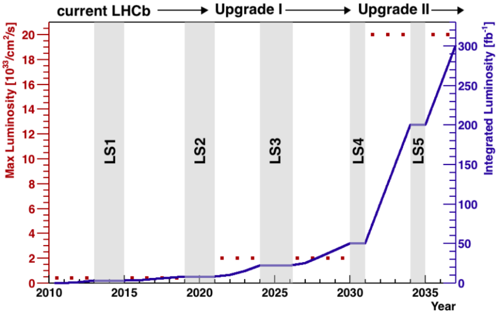


- Collision energy dependence ratio of hadronisation fractions

$$\frac{f_s}{f_d} \propto \mathcal{R} = \frac{N_{B_s^0 \to D_s^- \pi^+}}{N_{B^0 \to D^- \pi^+}} \frac{\epsilon_{B^0 \to D^- \pi^+}}{\epsilon_{B_s^0 \to D_s^- \pi^+}}$$

Conclusion

- Most precise γ determination by single experiment
  $\gamma = (65.4^{+3.8}_{-4.2})^{\circ}$
- LHCb legacy measurement Δm_s
  $\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032\,\mathrm{ps}^{-1}$ $(D_s^- \pi^+)$
  $\Delta m_s = 17.7656 \pm 0.0057\,\mathrm{ps}^{-1}$ (Comb.)
- Good prospects for LHCb upgrades



[CERN-LHCC-2018-027]

Conclusion

Thanks for your attention!

Backup Slides

Observation of the $B^0 \to \overline{D}^{*0} K^+ \pi^-$ and $B_s^0 \to \overline{D}^{*0} K^- \pi^+$ decays

Brief overview

[arXiv:2112.11428], submitted to Phys. Rev. D

Dataset: 2016-2018

- Source of potential background in γ determinations from $B^+ \to D K^+$ and $B^0 \to D K^+ \pi^-$ decays
- Normalisation channel: $B^0 \to \overline{D}^*(2007)^0 \pi^+ \pi^-$
- Results:

  $\mathcal{B}(B^0 \to \overline{D}^*(2007)^0 K^+ \pi^-) =$
  $(5.18 \pm 0.27 \pm 0.34 \pm 1.84) \times 10^{-5}$

  $\mathcal{B}(B_s^0 \to \overline{D}^*(2007)^0 K^- \pi^+) =$
  $(7.30 \pm 0.18 \pm 0.56 \pm 2.59 \pm 0.23) \times 10^{-4}$

  Uncertainties: stat, syst, BF and f_s/f_d, respectively

$\overline{D}^*(2007)^0 \to \overline{D}^0 \pi^0$ | $\overline{D}^*(2007)^0 \to \overline{D}^0 \gamma$

B^0

B_s^0