Decay-time-dependent analyses of the $B\to D\pi$ and $B_s\to D_sK$ channels at LHCb

Tim Gershon,
University of Warwick
on behalf of the LHCb collaboration

CKM2018, 20th September 2018

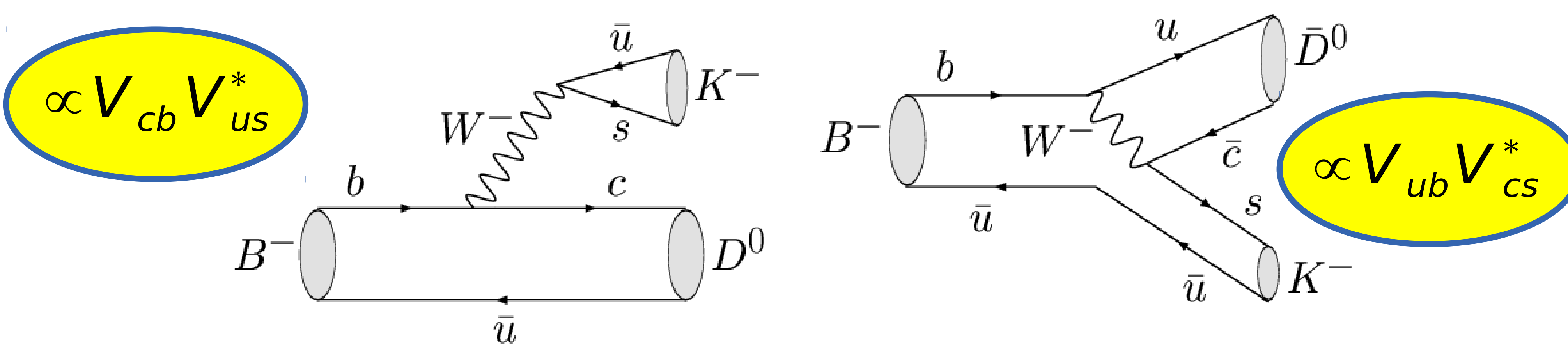
Importance of γ from B→DK

- γ plays a unique role in flavour physics

  the only CP violating parameter that can be measured through tree decays [(*)]

  (*) more-or-less

- A benchmark Standard Model reference point
  - doubly important after New Physics is observed



Variants use different B or D decays

require a final state common to both D^0 and $\overline{D}^0$

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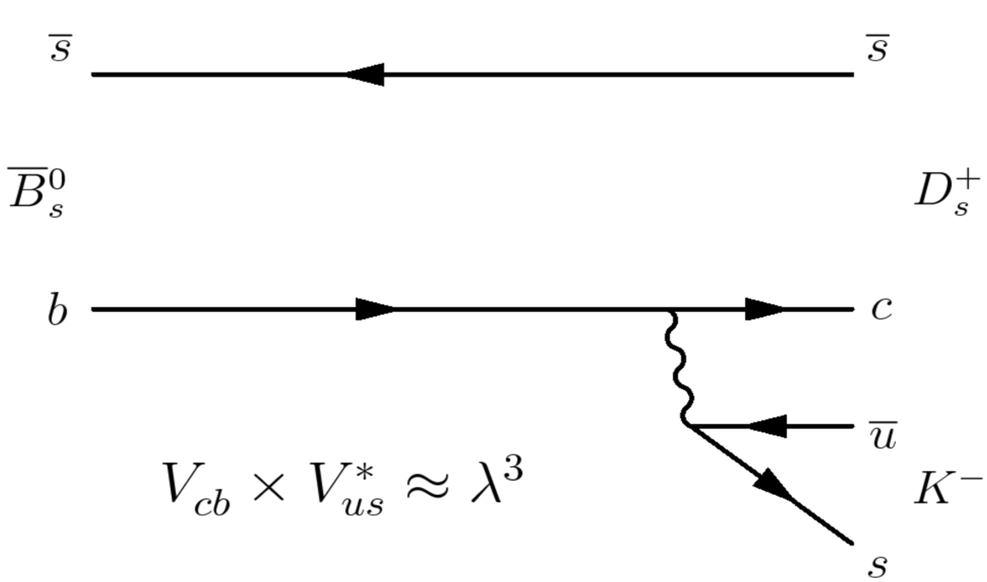
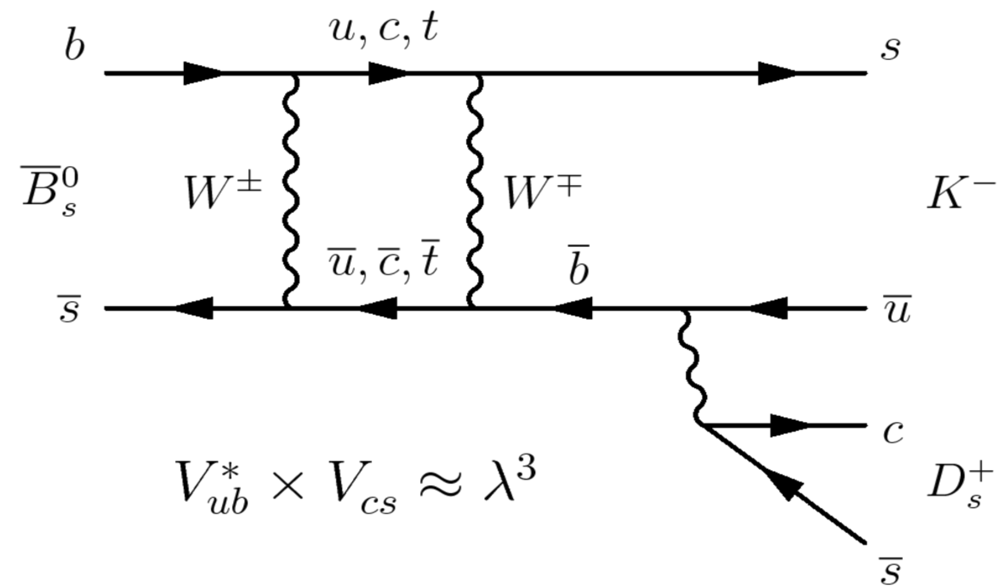
Decay-time-dependent analyses





- Interference of decays with and without mixing
  - No CP violation in decay, unlike “classic” B→DK methods
  - Need to resolve oscillations
- Sensitive to $\gamma-2\beta_s$ ($B_s \to D_s K$) or $\gamma+2\beta$ ($B^0 \to D\pi$)
  - Know $\beta_{(s)}$ independently → sensitivity to γ [or vice versa]

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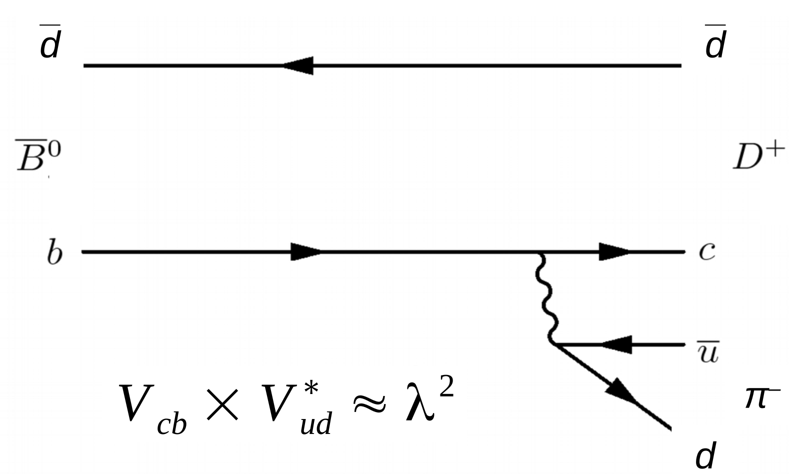
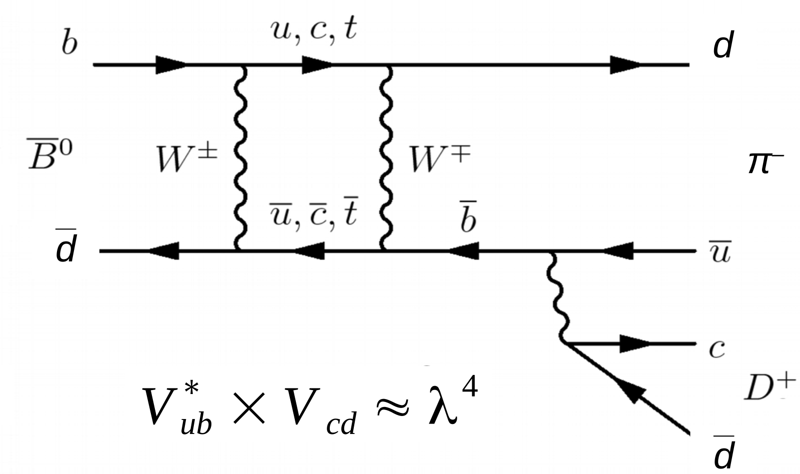
Pros and cons of $B_s \to D_s K$ and $B^0 \to D\pi$





$B_s \to D_s K$

- Smaller yields
  - background challenges
  - control samples available
- Fast oscillations
- Non-zero $\Delta\Gamma_s$
  - extra observables
- Large interference effects

$B^0 \to D\pi$

- Huge yields
  - little background
  - control sample challenges
- Slow oscillations
- Negligible $\Delta\Gamma_d$
  - fewer observables
- Small interference effects

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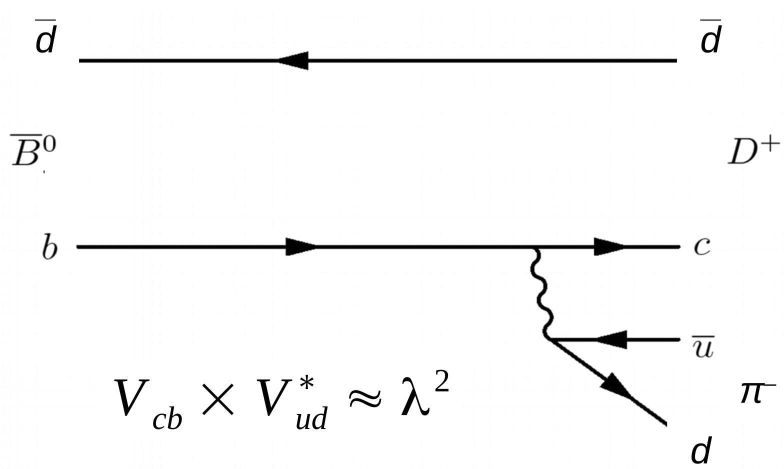
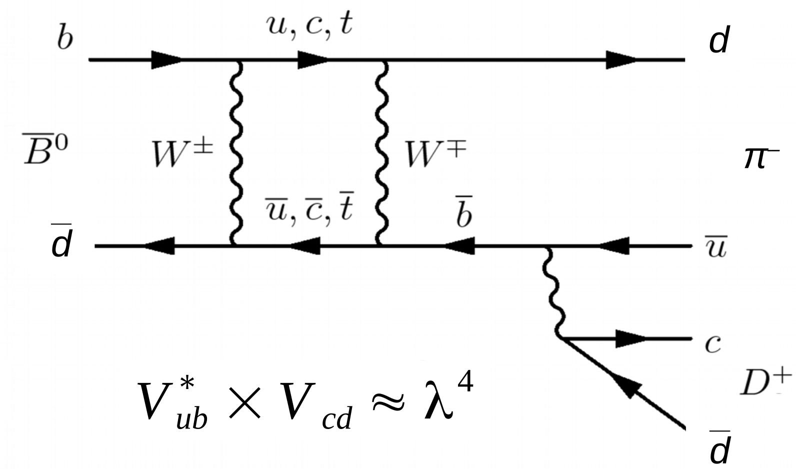
Pros and cons of $B_s \rightarrow D_s K$ and $B^0 \rightarrow D\pi$





$B_s \rightarrow D_s K$

- Smal
  - ges
  - ble
- ects

Golden mode for LHCb (excellent vertexing, particle identification & flexible trigger)

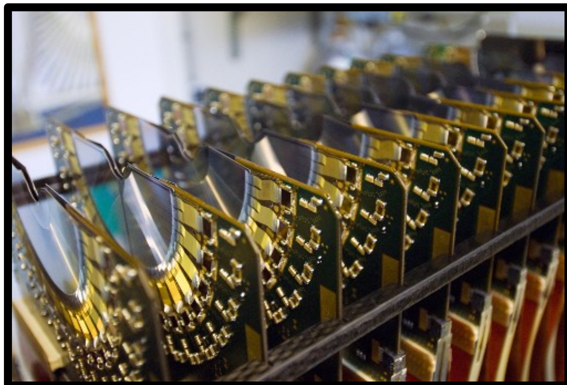
$B^0 \rightarrow D\pi$

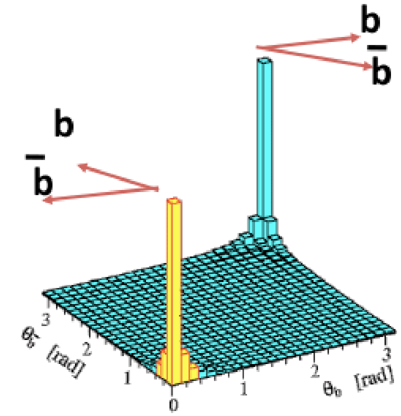
- Huge yi
  - lit
  - es
- S
- s

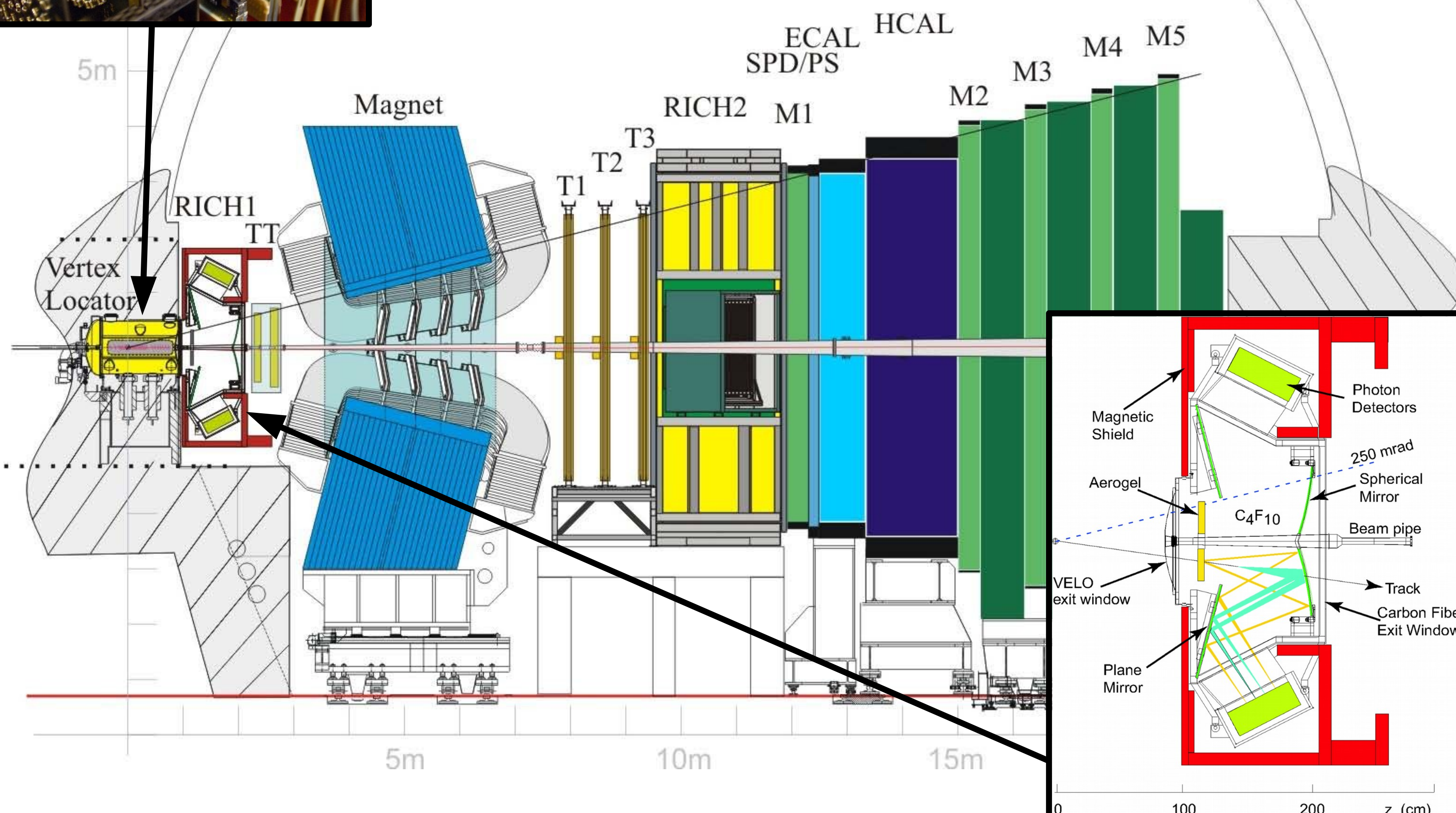
Challenging for LHCb but potentially excellent sensitivity

LHCb detector

JINST 3 (2008) S08005

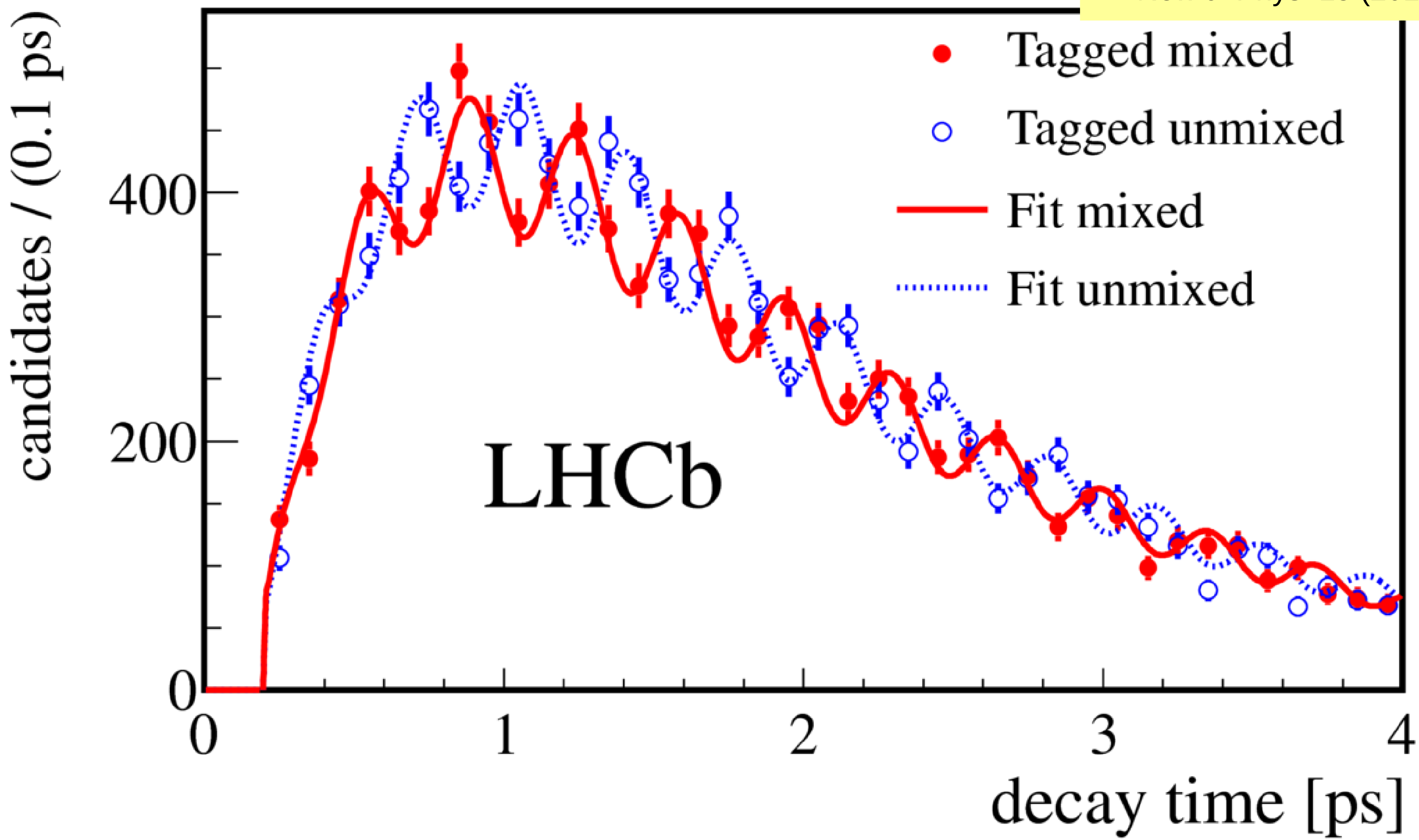






Measurement of Δm_s with $B_s \to D_s \pi$

LHCb-PAPER-2013-006, 1 fb^{-1}
New J. Phys. 15 (2013) 053021



Δm_s = 17.768 ± 0.023 (stat) ± 0.006 (syst) ps^{-1}

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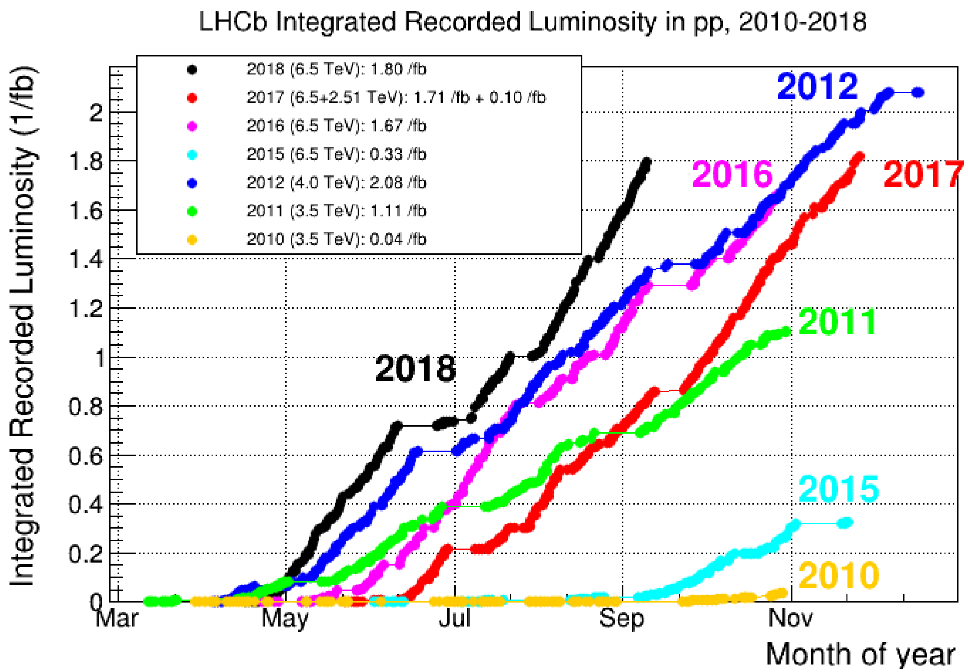
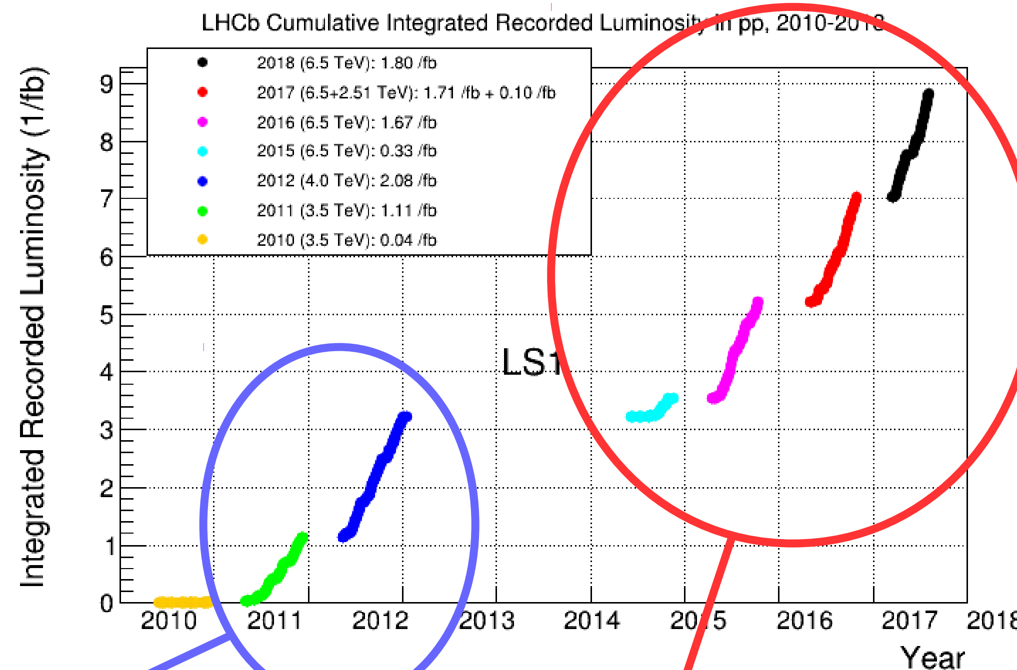
LHCb data samples





Results shown today based on Run 1
1 (2) fb^{-1} @ $\sqrt{s}$ = 7 (8) TeV

Larger sample accumulated in Run 2
~6 fb^{-1} @ $\sqrt{s}$ = 13 TeV

- higher $b\bar{b}$ production rate
- better trigger efficiency
- stable data-taking conditions

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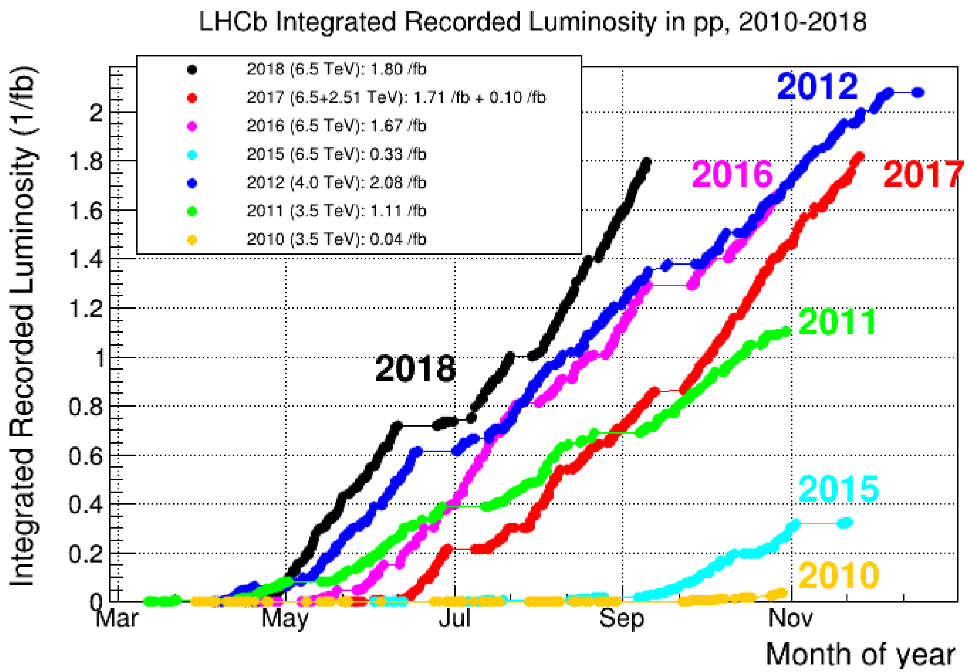
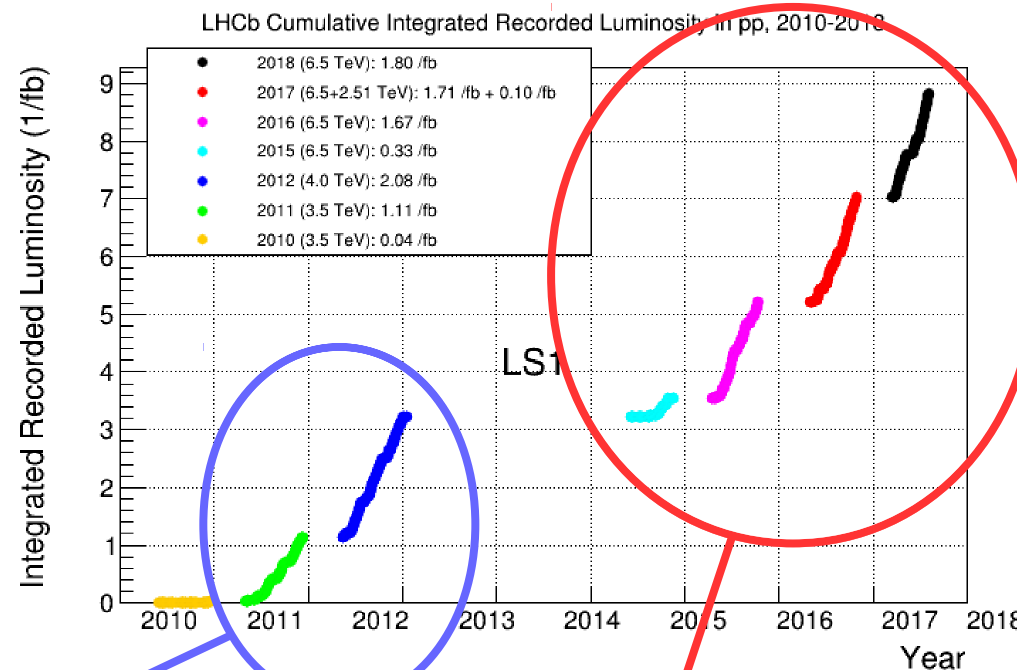
LHCb data samples





Results shown today based on Run 1
1 (2) fb^{-1} @ $\sqrt{s}$ = 7 (8) TeV

Larger sample accumulated in Run 2
~6 fb^{-1} @ $\sqrt{s}$ = 13 TeV
- higher $b\bar{b}$ production rate
- better trigger efficiency
- stable data-taking conditions

… and
exciting prospects for Run 3

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$B_s \to D_s K$ – formalism

$$\frac{\mathrm{d}\Gamma_{B_s^0\to f}(t)}{\mathrm{d}t} = \frac{1}{2}|A_f|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \underline{A_f^{\Delta\Gamma}}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right.$$
$$\left. + \underline{C_f}\cos\left(\Delta m_s t\right) - \underline{S_f}\sin\left(\Delta m_s t\right)\right],$$
$$\frac{\mathrm{d}\Gamma_{\overline{B}_s^0\to f}(t)}{\mathrm{d}t} = \frac{1}{2}|A_f|^2\left|\frac{p}{q}\right|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \underline{A_f^{\Delta\Gamma}}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right.$$
$$\left. - \underline{C_f}\cos\left(\Delta m_s t\right) + \underline{S_f}\sin\left(\Delta m_s t\right)\right],$$

… and similar equations for $\bar{f}$ (e.g. $f = D_s^- K^+$, $\bar{f} = D_s^+ K^-$)

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$B_s \to D_s K$ – formalism

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$$\frac{d\Gamma_{\bar{B}_s^0\to f}(t)}{dt} = \frac{1}{2}|A_f|^2\left|\frac{p}{q}\right|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \underline{A_f^{\Delta\Gamma}}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \underline{C_f}\cos(\Delta m_s t) + \underline{S_f}\sin(\Delta m_s t)\right],$$

… and similar equations for $\bar{f}$ (e.g. $f = D_s^- K^+$, $\bar{f} = D_s^+ K^-$)

Five independent observables assuming no CP violation in mixing or in decay

$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} = -C_{\bar{f}} = -\frac{1-|\lambda_{\bar{f}}|^2}{1+|\lambda_{\bar{f}}|^2},$$

$$S_f = \frac{2\mathcal{I}m(\lambda_f)}{1+|\lambda_f|^2}, \quad A_f^{\Delta\Gamma} = \frac{-2\mathcal{R}e(\lambda_f)}{1+|\lambda_f|^2},$$

$$S_{\bar{f}} = \frac{2\mathcal{I}m(\lambda_{\bar{f}})}{1+|\lambda_{\bar{f}}|^2}, \quad A_{\bar{f}}^{\Delta\Gamma} = \frac{-2\mathcal{R}e(\lambda_{\bar{f}})}{1+|\lambda_{\bar{f}}|^2}.$$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

$$|\lambda_f| = |\lambda_{\bar{f}}| \equiv r_{D_s K} \sim 0.4$$

$B_s \rightarrow D_s K$ – formalism

$$\frac{d\Gamma_{B_s^0\to f}(t)}{dt} = \frac{1}{2}|A_f|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \underline{A_f^{\Delta\Gamma}}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \underline{C_f}\cos(\Delta m_s t) - \underline{S_f}\sin(\Delta m_s t)\right],$$

$$\frac{d\Gamma_{\bar{B}_s^0\to f}(t)}{dt} = \frac{1}{2}|A_f|^2\left|\frac{p}{q}\right|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \underline{A_f^{\Delta\Gamma}}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \underline{C_f}\cos(\Delta m_s t) + \underline{S_f}\sin(\Delta m_s t)\right],$$

Five observables for three unknowns → measure $\gamma-2\beta_s$ (up to ambiguity)

… and similar equations for $\bar{f}$ (e.g. $f = D_s^- K^+$, $\bar{f} = D_s^+ K^-$)

$$C_f = \frac{1-r_{D_sK}^2}{1+r_{D_sK}^2},$$

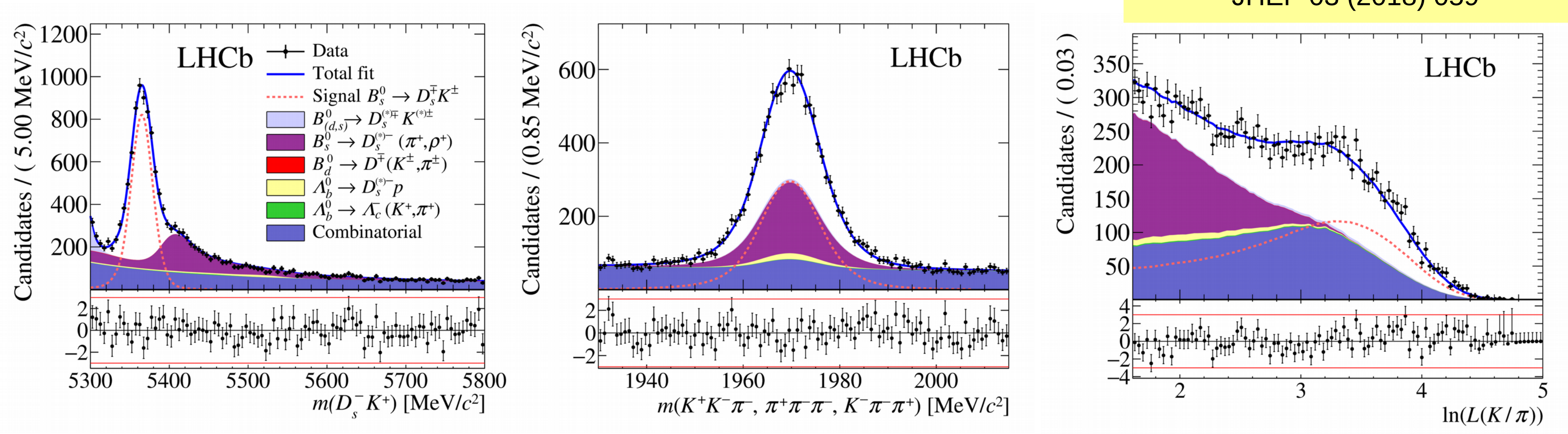
Also determine strong phase difference δ

$$A_f^{\Delta\Gamma} = \frac{-2r_{D_sK}\cos(\delta-(\gamma-2\beta_s))}{1+r_{D_sK}^2}, \qquad A_{\bar{f}}^{\Delta\Gamma} = \frac{-2r_{D_sK}\cos(\delta+(\gamma-2\beta_s))}{1+r_{D_sK}^2},$$

$$S_f = \frac{2r_{D_sK}\sin(\delta-(\gamma-2\beta_s))}{1+r_{D_sK}^2}, \qquad S_{\bar{f}} = \frac{-2r_{D_sK}\sin(\delta+(\gamma-2\beta_s))}{1+r_{D_sK}^2}.$$

$B_s \to D_s K$ – selection & background

LHCb-PAPER-2017-047, 3 fb^{-1}
JHEP 03 (2018) 059



- Increase signal yields by combining three D_s decays
  - πππ, Kππ and KKπ (latter subdivided into φπ, K*K & NR)
- Improve signal-background separation by 3D fit
  - B_s candidate mass, D_s candidate mass & K/π likelihood
- control sample $B_s \to D_s \pi$ selected in same way

Signal yield of 5955 ± 90

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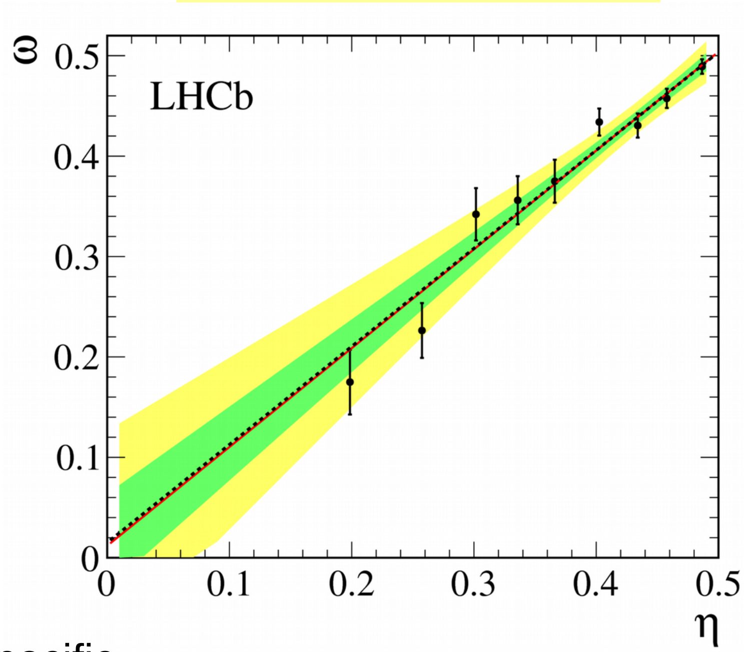
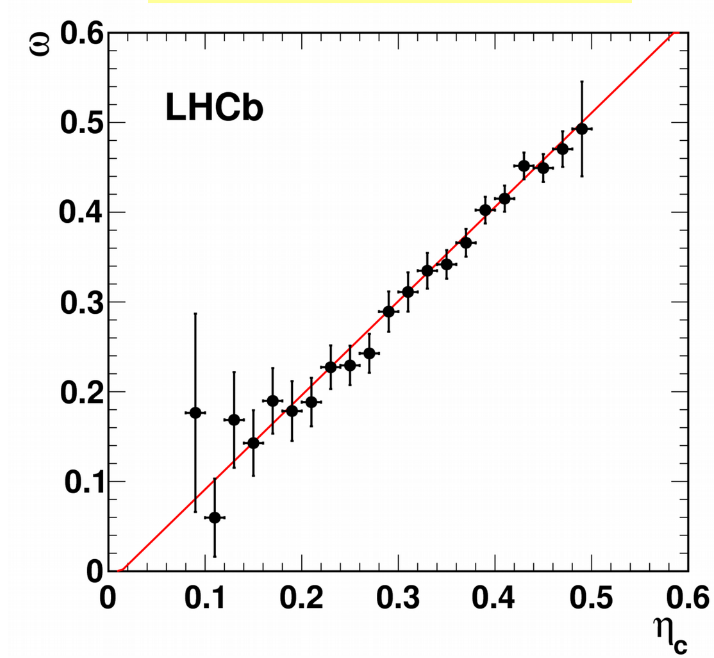
$B_s \rightarrow D_s K$ – flavour tagging

Same side kaon
LHCb-PAPER-2015-056
JINST 11 (2016) P05010

Opposite side taggers
LHCb-PAPER-2011-027
EPJ C72 (2012) 2022





Analysis-specific calibration:

$B_s^0 \rightarrow D_s^- \pi^+$	$\varepsilon_{\rm tag}$ [%]	$\varepsilon_{\rm eff}$ [%]
OS only	12.94 ± 0.11	1.41 ± 0.11
SS only	39.70 ± 0.16	1.29 ± 0.13
Both OS and SS	24.21 ± 0.14	3.10 ± 0.18
Total	76.85 ± 0.24	5.80 ± 0.25

LHCb-PAPER-2017-047, 3 fb^{-1}
JHEP 03 (2018) 059

$$\epsilon_{eff} = \epsilon_{tag} (1 - 2\langle \omega \rangle)^2$$

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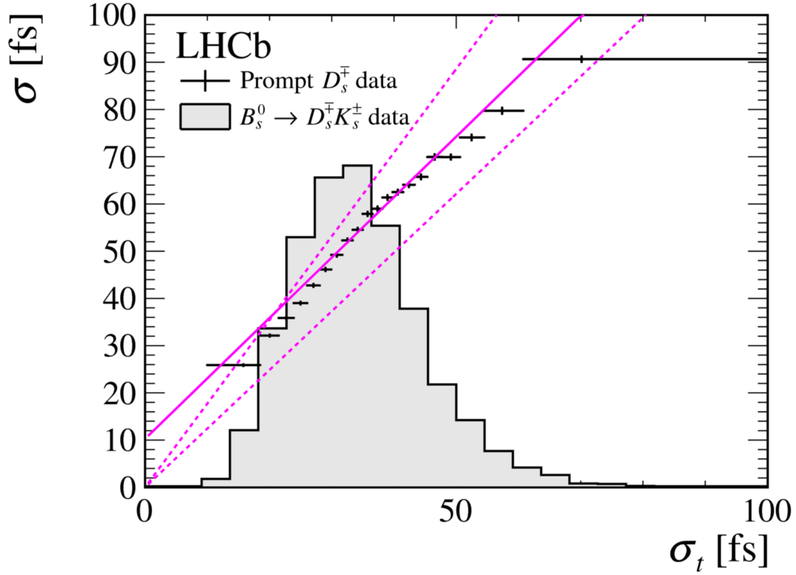
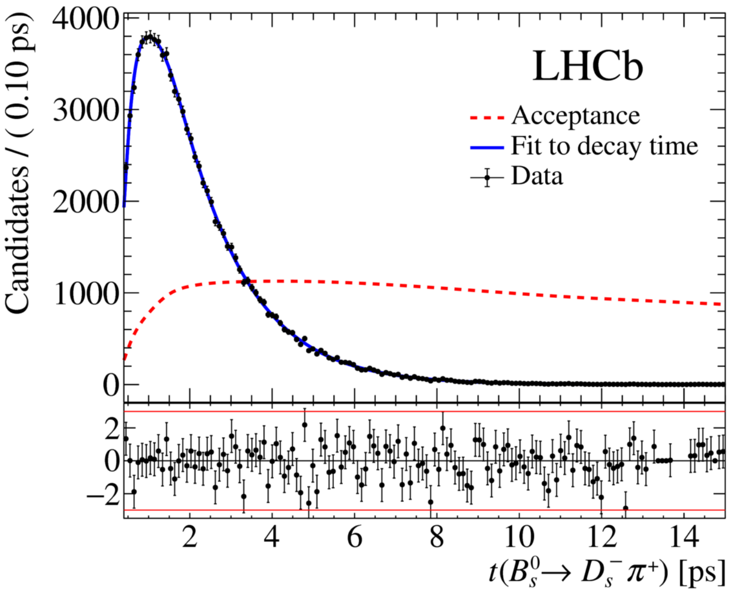
$B_s \to D_s K$ – decay-time resolution and acceptance

LHCb-PAPER-2017-047, 3 fb^{-1}
JHEP 03 (2018) 059





- Candidate-by-candidate resolution used to improve sensitivity
  - Vertex fit gives good estimate (σ_t); calibrated with prompt D_s mesons
- Known lifetime of $B_s \to D_s\pi$ used to obtain acceptance function
  - Corrections for $B_s \to D_sK/B_s \to D_s\pi$ differences obtained from MC
  - Important source of systematic uncertainty on $A^{\Delta\Gamma}$ observables

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$B_s \to D_sK$ – results

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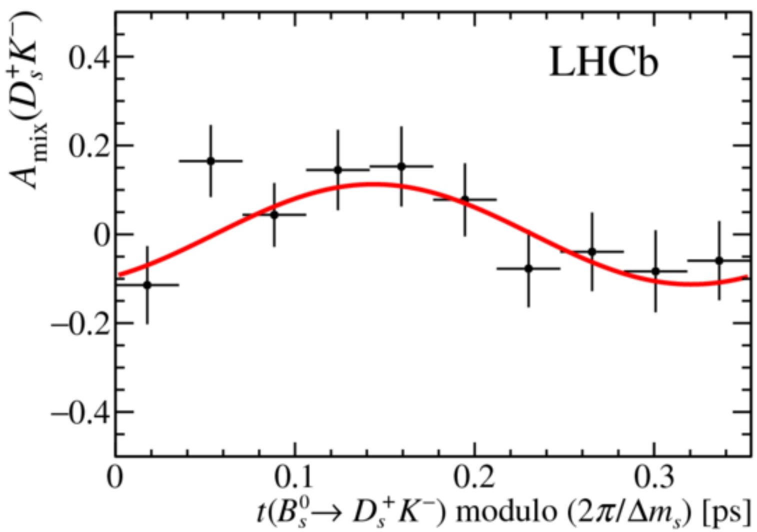

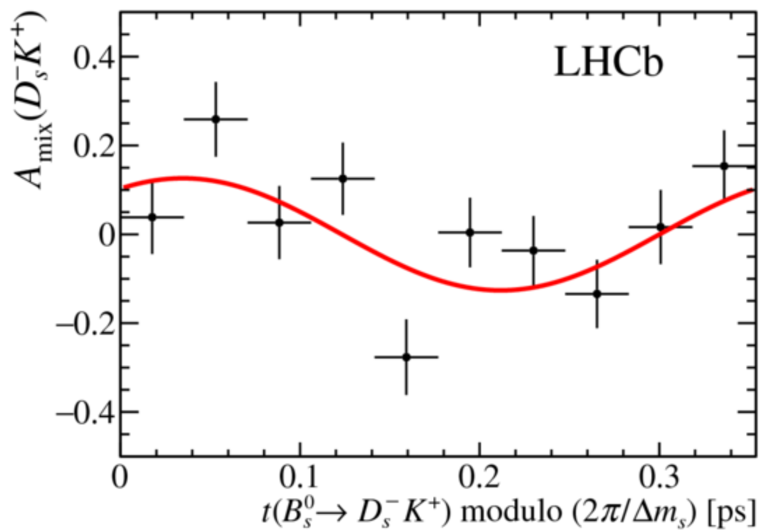

Parameter	Value
C_f	$0.730 \pm 0.142 \pm 0.045$
$A_f^{\Delta\Gamma}$	$0.387 \pm 0.277 \pm 0.153$
$A_{\bar{f}}^{\Delta\Gamma}$	$0.308 \pm 0.275 \pm 0.152$
S_f	$-0.519 \pm 0.202 \pm 0.070$
$S_{\bar{f}}$	$-0.489 \pm 0.196 \pm 0.068$

Statistical+systematic correlations

C_f	$A_f^{\Delta\Gamma}$	$A_{\bar{f}}^{\Delta\Gamma}$	S_f	$S_{\bar{f}}$
1	0.092	0.078	0.008	−0.057
	1	0.513	−0.083	−0.004
		1	−0.042	−0.003
			1	0.001
				1

1	0.05	0.03	0.03	−0.01
	1	0.42	0.02	0.02
		1	0.03	0.03
			1	0.01
				1

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$B_s \rightarrow D_s K$ – systematic uncertainties

LHCb-PAPER-2017-047, 3 fb^{-1}
JHEP 03 (2018) 059

Quoted relative to the statistical uncertainty

Source	C_f	$A_f^{\Delta\Gamma}$	$A_{\overline{f}}^{\Delta\Gamma}$	S_f	$S_{\overline{f}}$
Detection asymmetry	0.02	0.28	0.29	0.02	0.02
Δm_s	0.11	0.02	0.02	0.20	0.20
Tagging and scale factor	0.18	0.02	0.02	0.16	0.18
Tagging asymmetry	0.02	0.00	0.00	0.02	0.02
Correlation among observables	0.20	0.38	0.38	0.20	0.18
Closure test	0.13	0.19	0.19	0.12	0.12
Acceptance, simulation ratio	0.01	0.10	0.10	0.01	0.01
Acceptance data fit, Γ_s, $\Delta\Gamma_s$	0.01	0.18	0.17	0.00	0.00
Total	0.32	0.55	0.55	0.35	0.35

Mainly from control samples – will scale with statistics
Others also appear reducible

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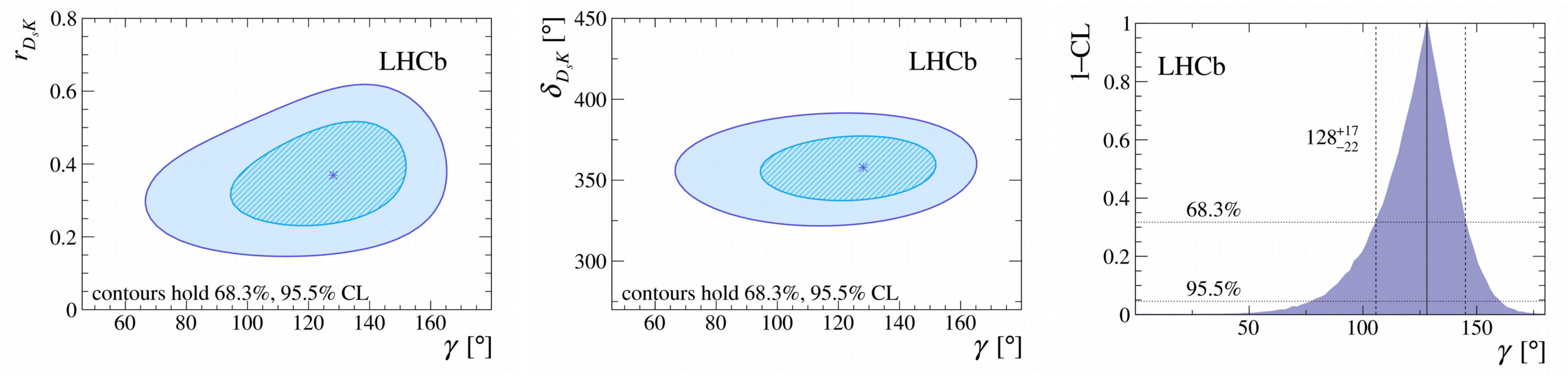
Constraint on γ

LHCb-PAPER-2017-047, 3 fb^{-1}
JHEP 03 (2018) 059



Measurements of five observables converted to constraints on three parameters using *GammaCombo* (LHCb-PAPER-2016-032, LHCb-CONF-2018-002)

$\gamma - 2\beta_s$ converted to γ using $-2\beta_s$ from $B_s \to J/\psi\phi$

$$\gamma = (128\,^{+17}_{-22})^\circ\,,$$
$$\delta = (358\,^{+13}_{-14})^\circ\,,$$
$$r_{D_sK} = 0.37\,^{+0.10}_{-0.09}\,,$$

3.8σ evidence for CP violation

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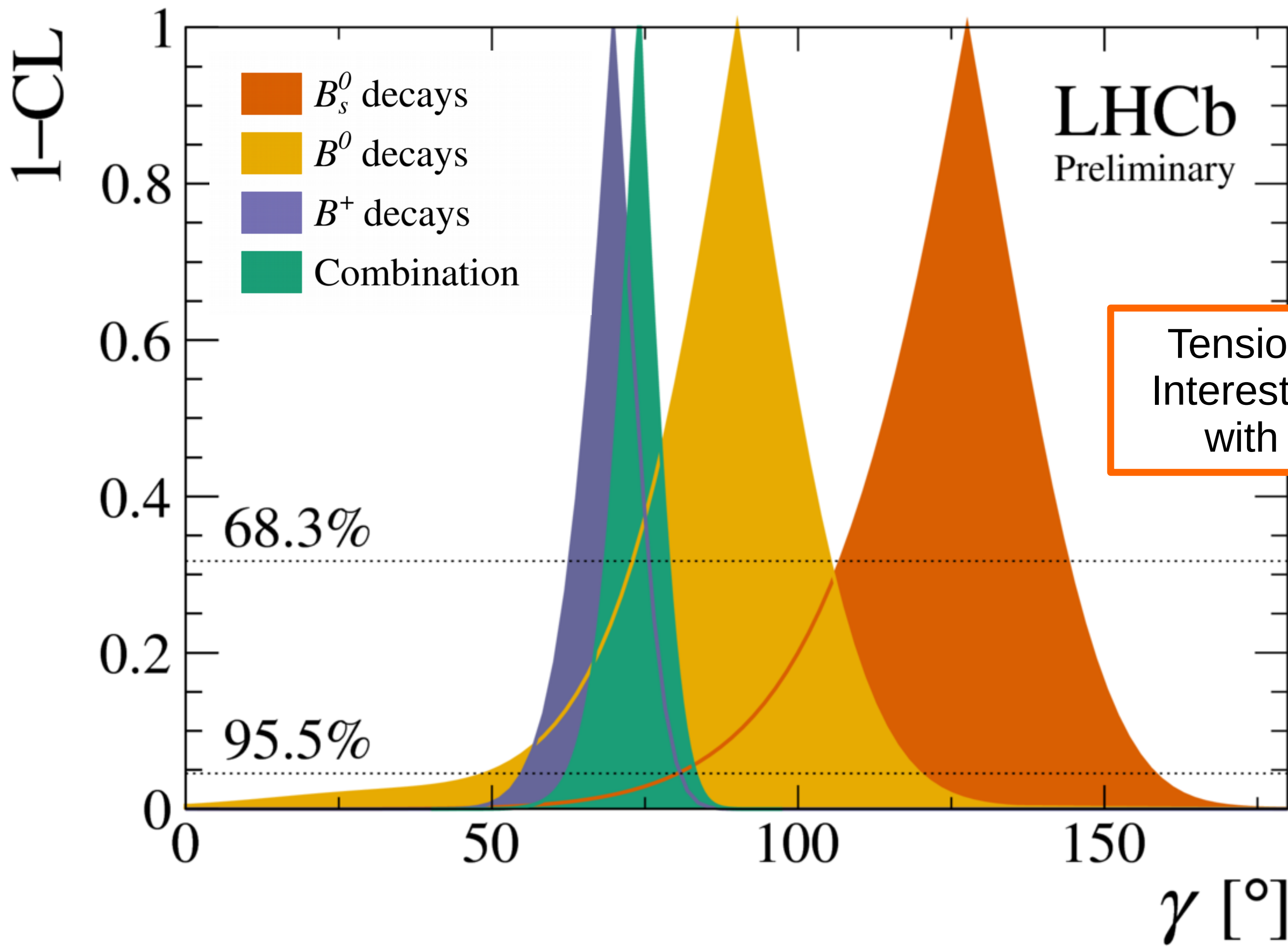
Comparison with γ from B → DK

LHCb-CONF-2018-002



Tension at 2σ level
Interesting to update with more data

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$B \to D\pi$ – formalism

$$\frac{\mathrm{d}\Gamma_{B^0 \to f}(t)}{\mathrm{d}t} = \frac{1}{2}|A_f|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[1 + 0 \pm 1\cos(\Delta m_d t) - S_f \sin(\Delta m_d t)\right],$$

$$\frac{\mathrm{d}\Gamma_{\bar{B}^0 \to f}(t)}{\mathrm{d}t} = \frac{1}{2}|A_f|^2\left|\frac{p}{q}\right|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[1 + 0 - (\pm 1)\cos(\Delta m_d t) + S_f \sin(\Delta m_d t)\right],$$

… and similar equations for $\bar{f}$ (e.g. $f = D^-\pi^+$, $\bar{f} = D^+\pi^-$)

Two observables for three unknowns → need external input to measure $\gamma+2\beta$

$$S_f = -\frac{2r_{D\pi}\sin[\delta - (2\beta+\gamma)]}{1+r_{D\pi}^2},$$

$$S_{\bar{f}} = \frac{2r_{D\pi}\sin[\delta + (2\beta+\gamma)]}{1+r_{D\pi}^2},$$

Expect $r_{D\pi} \sim 0.02$
→ |C| indistinguishable from unity

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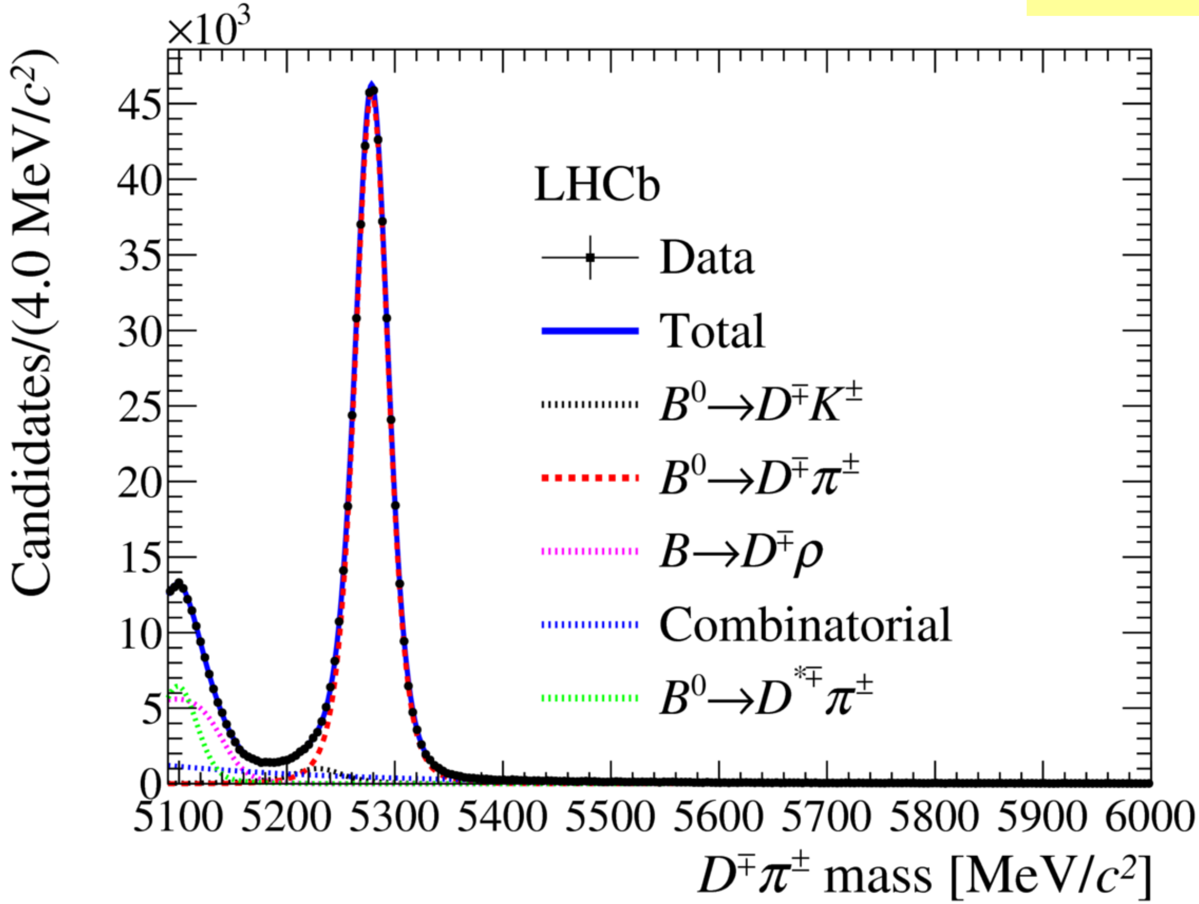
B→Dπ – selection & background

LHCb-PAPER-2018-009, 3 fb^{-1}
JHEP 06 (2018) 084



Signal yield of 479,000 ± 700

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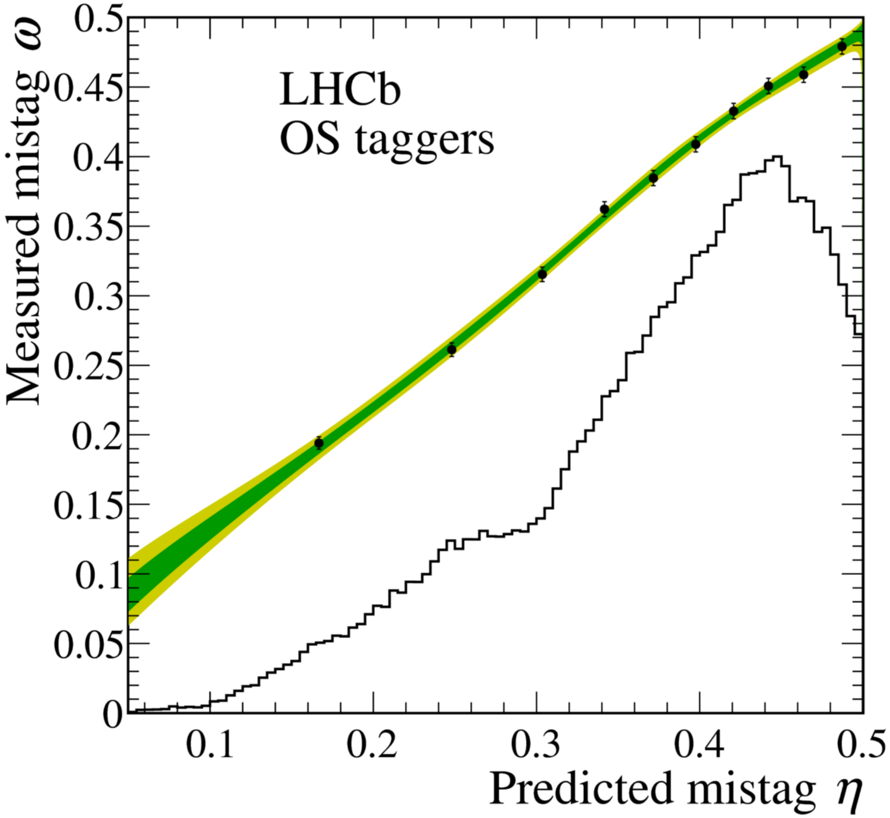
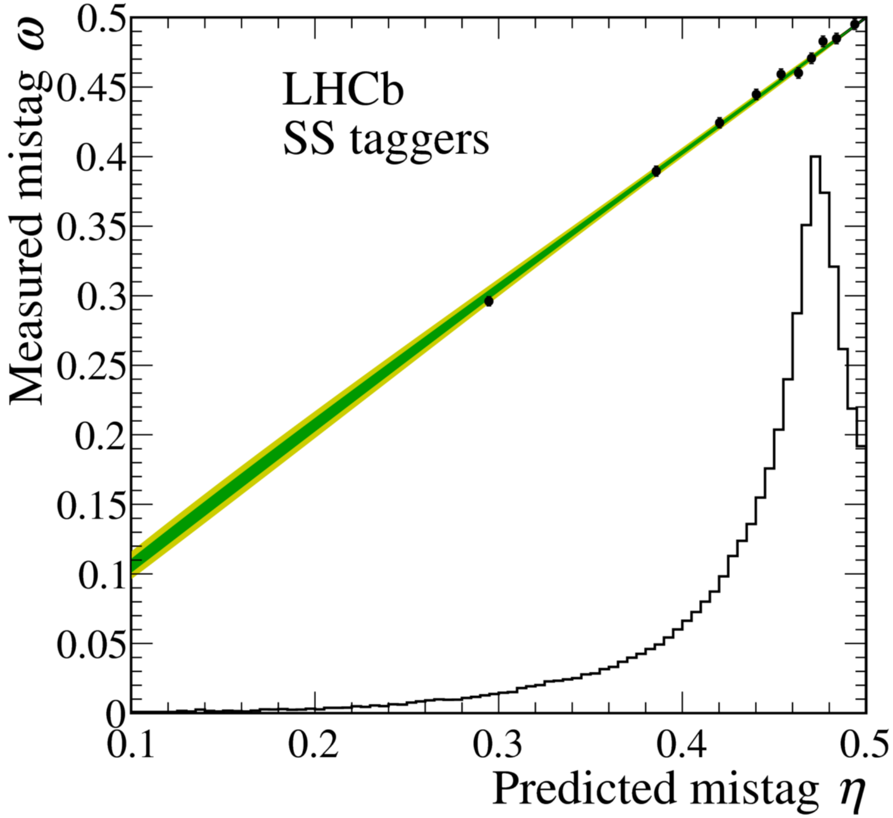
B → Dπ – flavour tagging

LHCb-PAPER-2018-009, 3 fb^{-1}
JHEP 06 (2018) 084





Exploit fact that |C|=1 to calibrate tagging with signal channel

ε_{eff} = (5.59 ± 0.01)%

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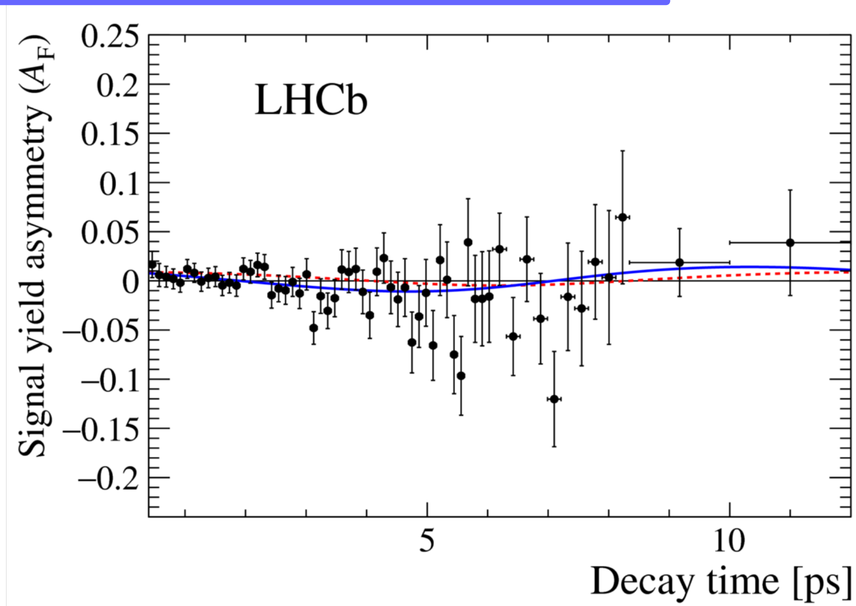
$B \rightarrow D\pi$ – results

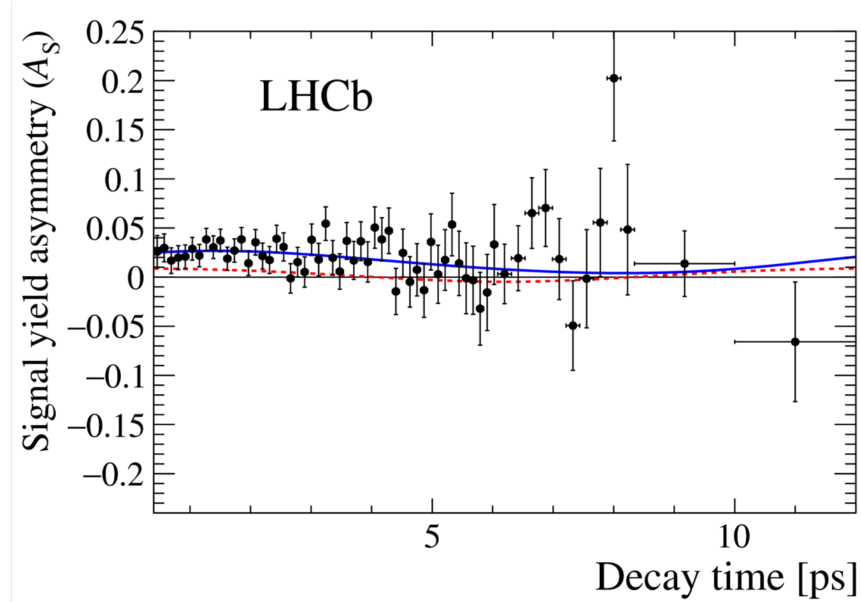
LHCb-PAPER-2018-009, 3 fb^{-1}
JHEP 06 (2018) 084

$$S_f = 0.058 \pm 0.020\,(\text{stat}) \pm 0.011\,(\text{syst}),$$
$$S_{\bar{f}} = 0.038 \pm 0.020\,(\text{stat}) \pm 0.007\,(\text{syst}),$$

CP violation @ 2.7σ

correlations of 60% (−41%) for statistical (systematic) uncertainties





Illustrated through asymmetries between favoured (A_F) and suppressed (A_S) decay modes

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B→Dπ – systematic uncertainties

LHCb-PAPER-2018-009, 3 fb^{-1}
JHEP 06 (2018) 084

Quoted as absolute uncertainties

Source	S_f	$S_{\bar{f}}$
uncertainty of Δm	0.0073	0.0061
fit biases	0.0068	0.0018
background subtraction	0.0042	0.0023
PID efficiencies	0.0008	0.0008
flavour-tagging models	0.0011	0.0015
flavour-tagging efficiency asymmetries	0.0012	0.0015
$\epsilon(t)$ model	0.0007	0.0007
assumption on $\Delta\Gamma$	0.0007	0.0007
decay-time resolution	0.0012	0.0008
assumption on C	0.0006	0.0006
total	0.0111	0.0073
statistical uncertainty	0.0198	0.0199

Largest sources expected to be reducible with more data

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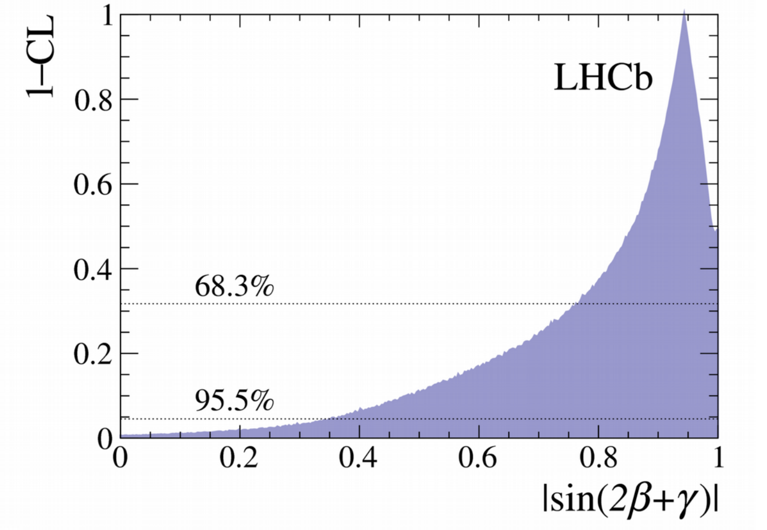
Constraints on sin(2β+γ) and γ

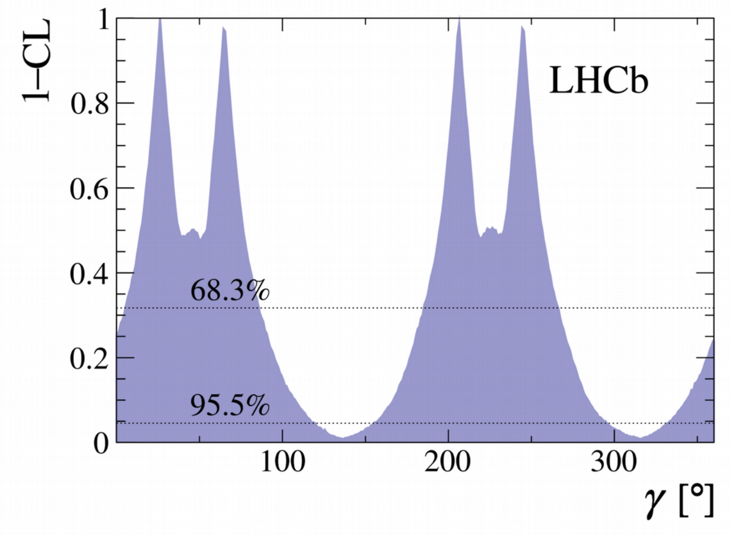
LHCb-PAPER-2018-009, 3 fb^{-1}
JHEP 06 (2018) 084

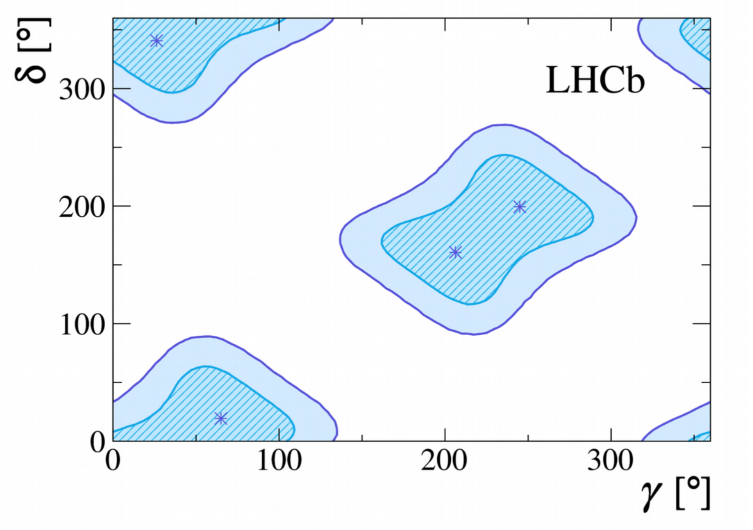
Use:

$$r_{D\pi} = \tan\theta_c \frac{f_{D^+}}{f_{D_s}} \sqrt{\frac{\mathcal{B}(B^0 \to D_s^+\pi^-)}{\mathcal{B}(B^0 \to D^-\pi^+)}},$$
$$= 0.0182 \pm 0.0012 \pm 0.0036$$

20% SU(3)-breaking uncertainty







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Comparison with B factories

LHCb-PAPER-2018-009, 3 fb^{-1}
JHEP 06 (2018) 084

$$S_f = 0.058 \pm 0.020\,(\text{stat}) \pm 0.011\,(\text{syst}),$$
$$S_{\bar{f}} = 0.038 \pm 0.020\,(\text{stat}) \pm 0.007\,(\text{syst}),$$

correlations of 60% (−41%) for
statistical (systematic) uncertainties

BaBar, 232 $B\overline{B}$
PRD 73 (2006) 111101

$$a^{D\pi} = -0.010 \pm 0.023 \pm 0.007\ ,$$
$$c^{D\pi}_{\text{lep}} = -0.033 \pm 0.042 \pm 0.012\ ,$$

$a = -(S_+ + S_-)/2$
$c = -(S_+ - S_-)/2$
(lepton tags only for c)

Belle, 386M $B\overline{B}$
PR D73 (2006) 092003

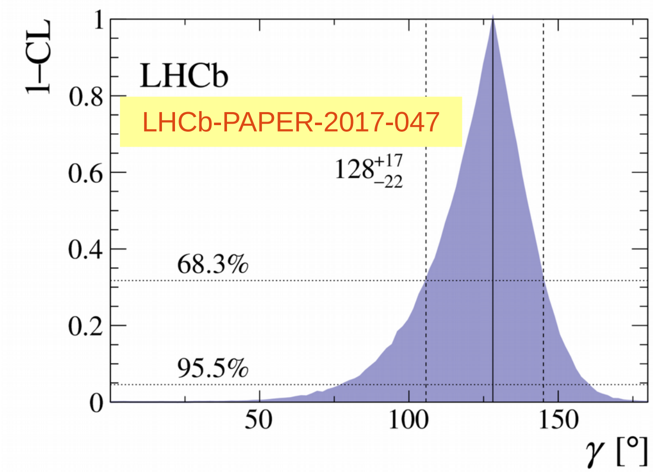
$$S^+(D\pi) = 0.031 \pm 0.030 \pm 0.012,$$
$$S^-(D\pi) = 0.068 \pm 0.029 \pm 0.012$$

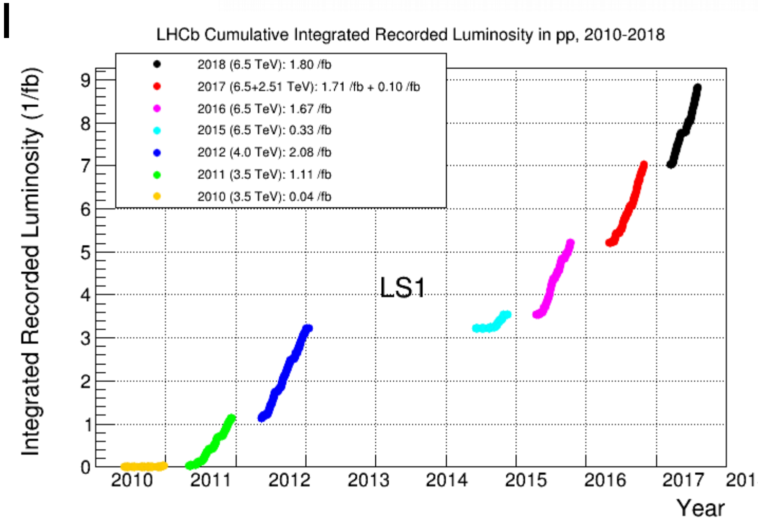
BaBar and Belle results have
essentially zero correlation

LHCb results in agreement with, and more precise than, measurements from BaBar and Belle

Summary

- Decay-time-dependent analyses provide powerful method to measure γ
  - CP violation in interference between mixing and decay
  - complementary to B → DK methods (CPV in decay)
- $B_s \to D_s K$ particularly powerful at LHCb
  - five observables depending on three parameters
  - large interference effects
- Interesting sensitivity also with B → Dπ
- Results presented today based on Run I data
  - expect significant improvement with Run II
    - and even more in Run III and beyond
  - can also add more modes (D_s^*K, $D^*\pi$)





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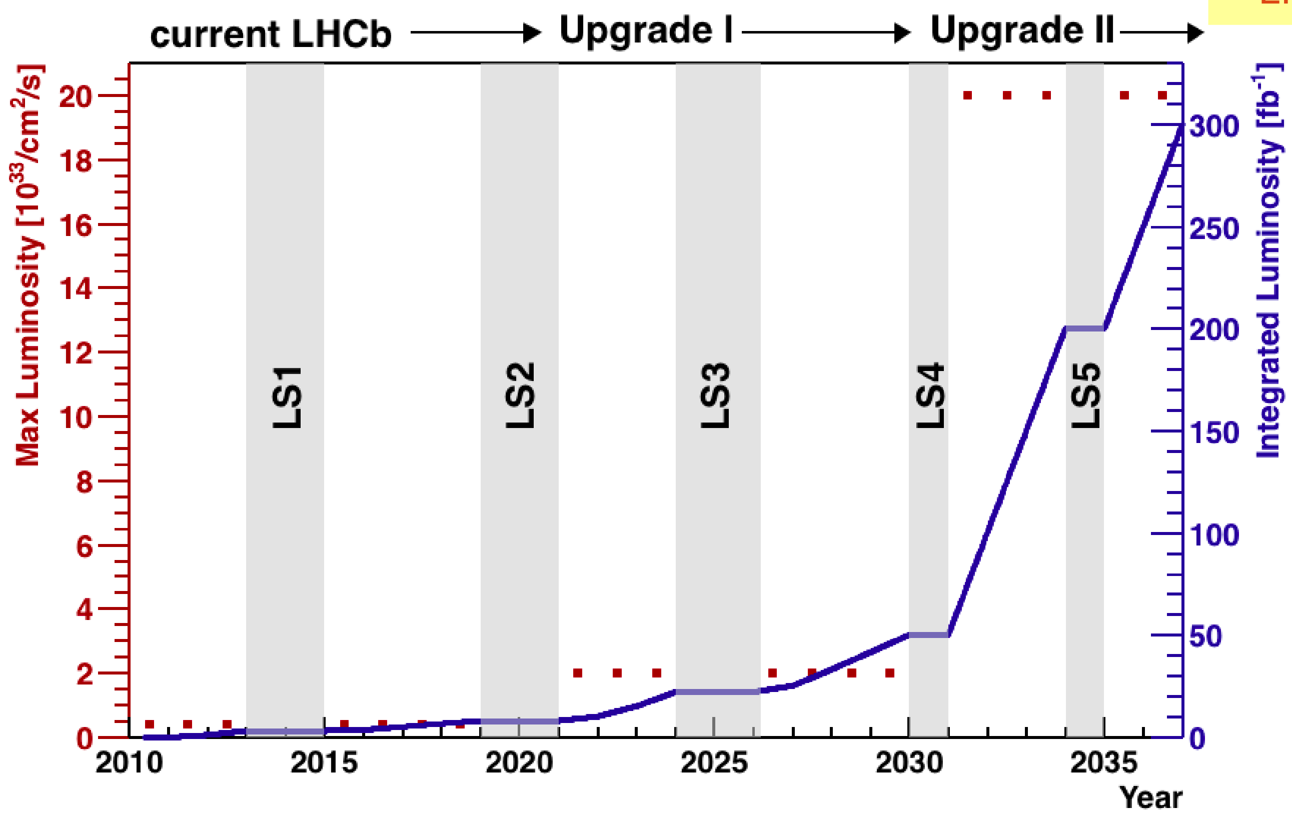


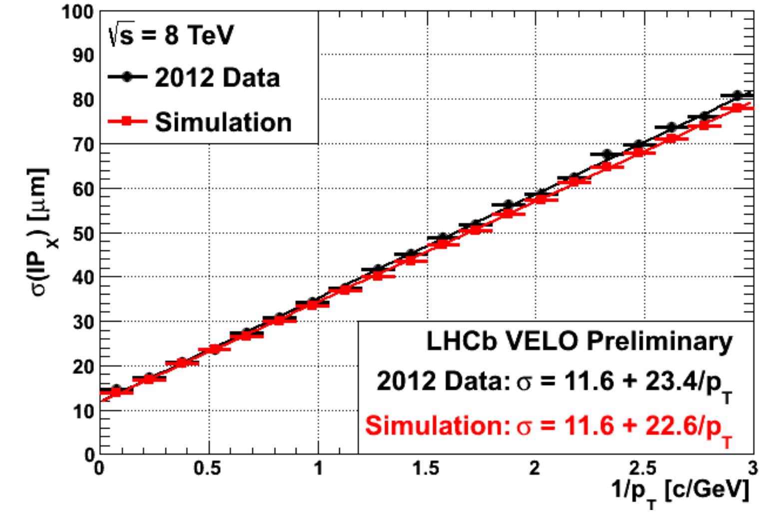
	$B_s^0 \to D_s^\mp K^\pm$				$B^0 \to D^\mp \pi^\pm$			
Parameters	Run 1	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}	Run 1	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
S_f, $S_{\bar{f}}$	0.20	0.043	0.027	0.011	0.02	0.0041	0.0026	0.0010
$A_f^{\Delta\Gamma}$, $A_{\bar{f}}^{\Delta\Gamma}$	0.28	0.065	0.039	0.016	–	–	–	
C_f	0.14	0.030	0.017	0.007	–	–	–	
γ	20°	4°	2.5°	1°				

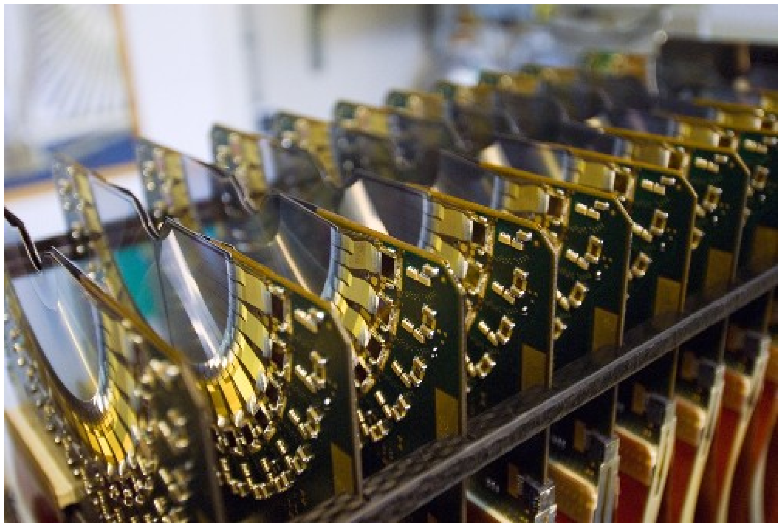
projections assume systematic uncertainties scale

Just getting started ...

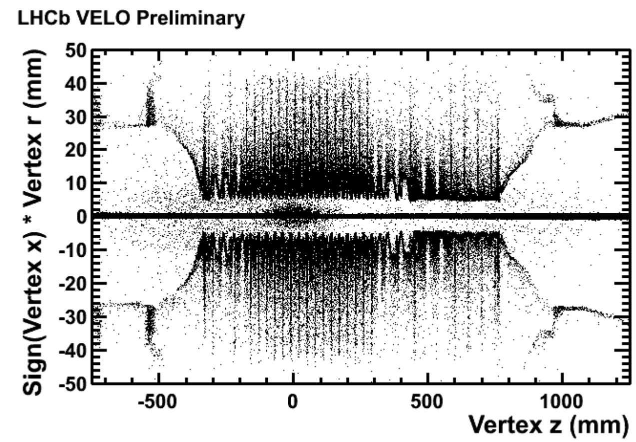

BACK UP!

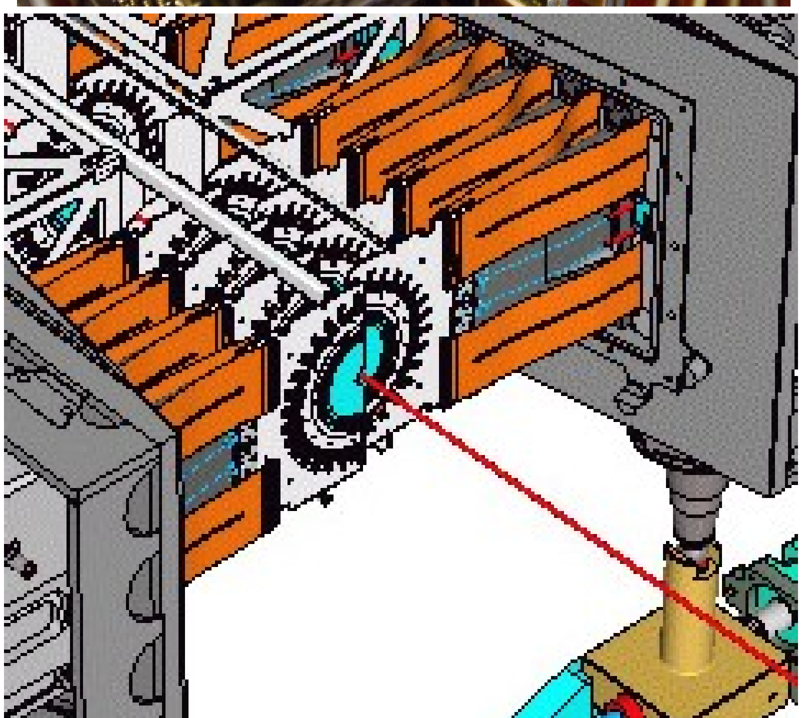
VELO

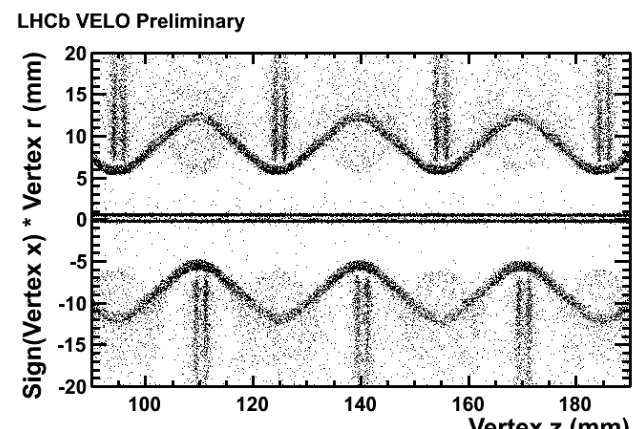




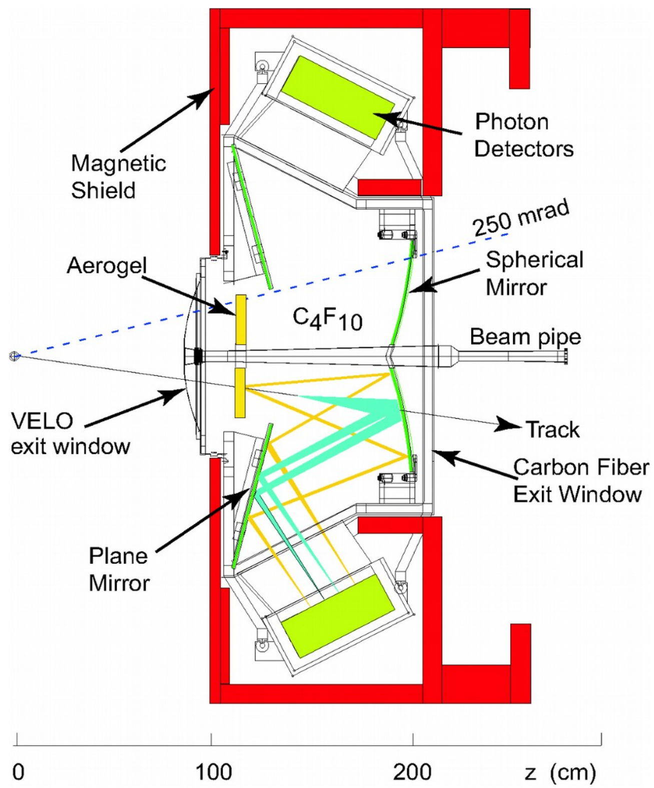
Material imaged used beam gas collisions



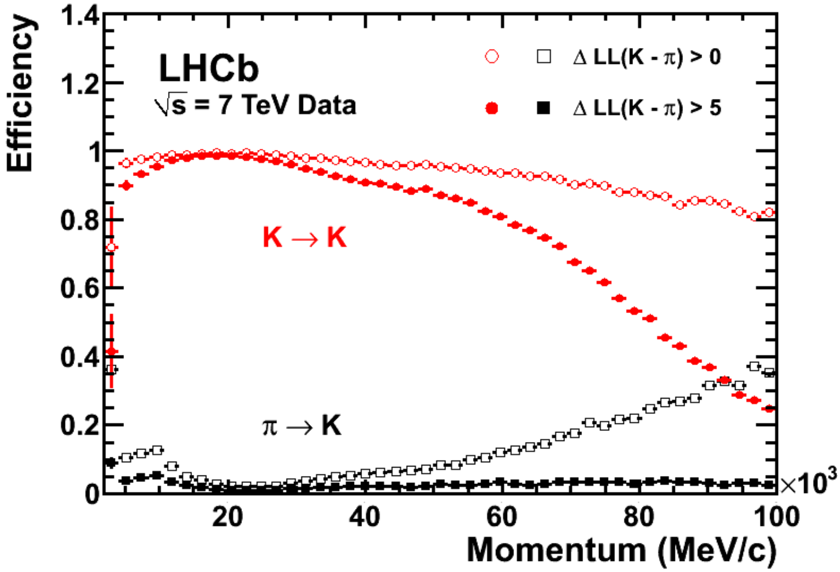




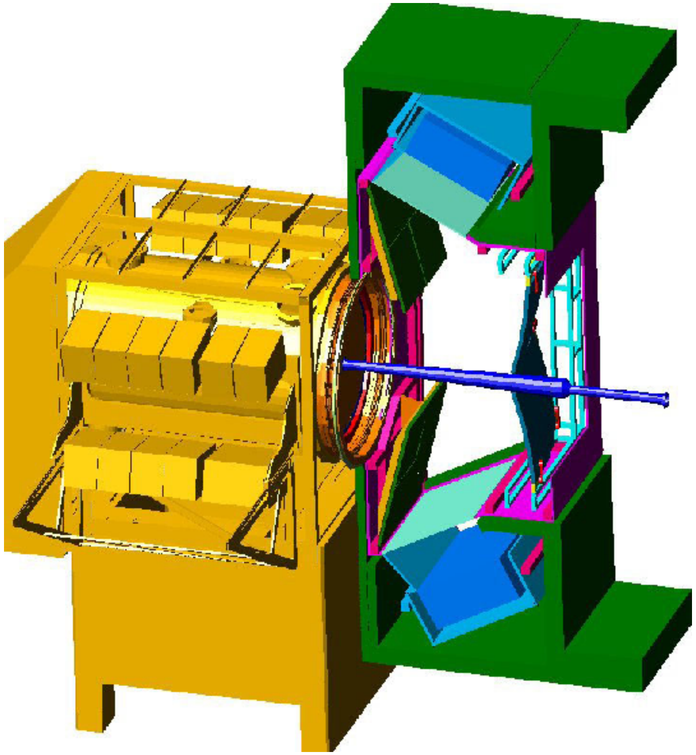
RICH



Magnetic Shield
Photon Detectors
250 mrad
Aerogel
Spherical Mirror
C_4F_{10}
Beam pipe
VELO exit window
Track
Carbon Fiber Exit Window
Plane Mirror
0
100
200
z (cm)

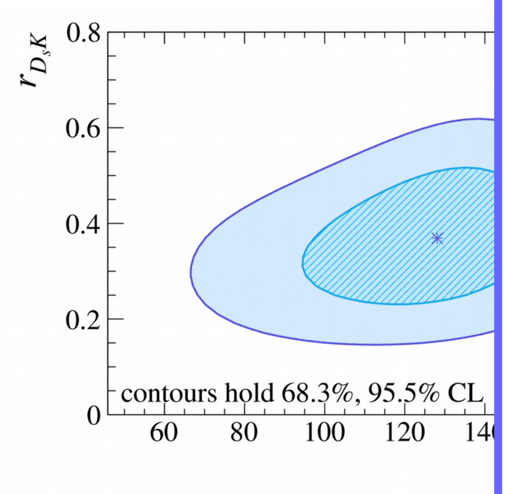


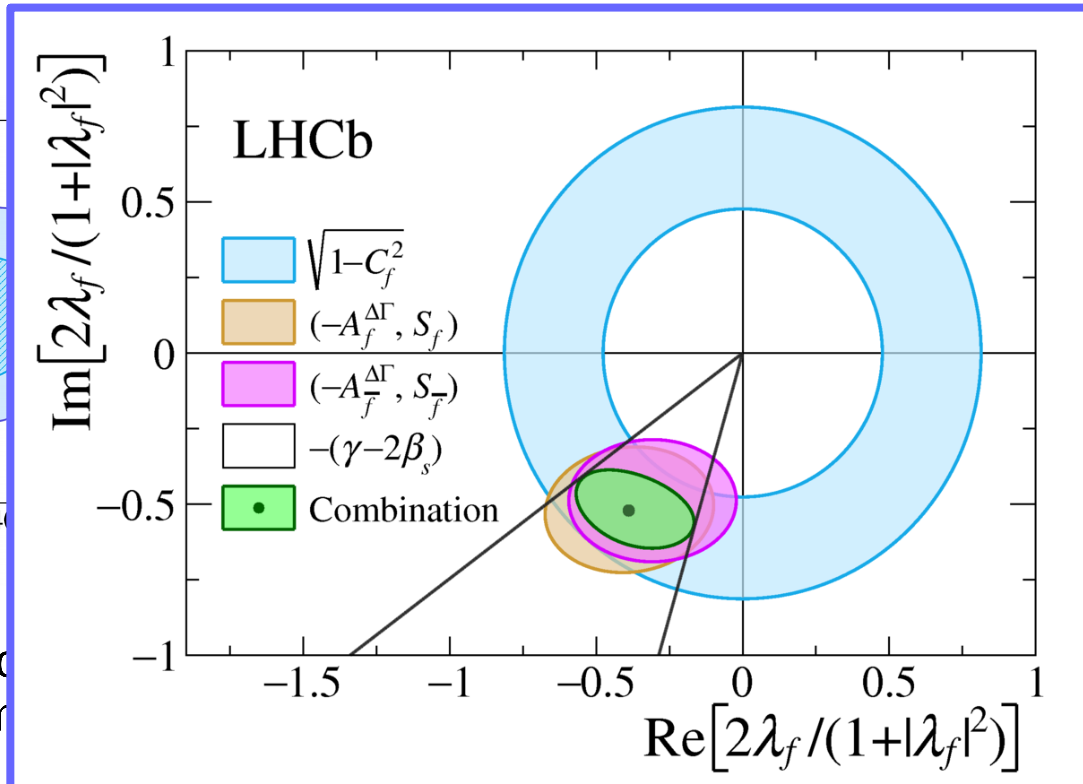
LHCb
$\sqrt{s}$ = 7 TeV Data
Δ LL(K - π) > 0
Δ LL(K - π) > 5
K → K
π → K
Efficiency
Momentum (MeV/c)
×10³
0
0.2
0.4
0.6
0.8
1
1.2
1.4
20
40
60
80
100

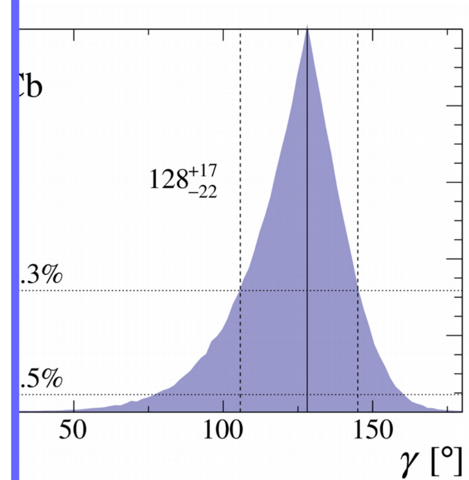


Constraint on γ

LHCb-PAPER-2017-047
Data sample: 3 fb^{-1}







Measurements c... Gamm...

...e parameters using ...018-002)

γ–2β_s converted to γ using –2β_s from $B_s \rightarrow J/\psi\varphi$

$$\gamma = (128\,^{+17}_{-22})^\circ\,,$$
$$\delta = (358\,^{+13}_{-14})^\circ\,,$$
$$r_{D_sK} = 0.37\,^{+0.10}_{-0.09}\,,$$

3.8σ evidence for CP violation

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