Measurement of the CKM angle γ with $B_s^0 \to D_s^{\mp} K^{\pm}$ decays

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on behalf of the LHCb collaboration

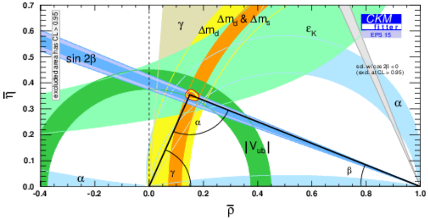
CERN, Geneva

CKM, Mumbai, 01.12.2016

Motivation: CKM matrix

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

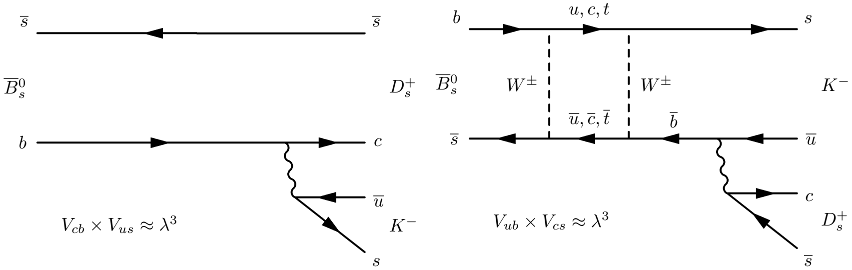
$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



- Amplitudes of weak interactions depend on 4 parameters in the CKM matrix.
- One goal in flavor physics is to thoroughly test whether these 4 parameters really do describe both the magnitudes and phases of quark transitions associated with many decay processes
- The weak phase $\gamma \propto Arg(V_{ub})$ is the least well measured of the CKM angles .
  trees: $\gamma = (73^{+6}_{-7})^\circ$
- Any discrepancy in the position of the apex of the Unitarity Triangle from the different measurements would indicate physics beyond Standard Model.

Motivation

- Tree level process.
- Theoretically clean measurement $O(\delta\gamma/\gamma) < 10^{-7}$.
- No sensitivity to New Physics.
- Measure CP violation in the interference of mixing and decay



Advantage: Both decay amplitudes are $O(\lambda^3) \rightarrow$ LARGE INTERFERENCE

Similarly it is possible to measure: $B^0 \rightarrow D^\mp \pi^\pm$, see Alex Birnkraut talk!

Motivation: Time dependent CP asymmetries

$$\frac{\Gamma(B_s^0(t)\rightarrow D_s^- K^+)-\Gamma(\overline{B_s^0}(t)\rightarrow D_s^- K^+)}{\Gamma(B_s^0(t)\rightarrow D_s^- K^+)+\Gamma(\overline{B_s^0}(t)\rightarrow D_s^- K^+)} =$$

$$\frac{-C(B_s^0(t)\rightarrow D_s^- K^+)cos(\Delta m_s t)+S(B_s^0(t)\rightarrow D_s^- K^+)sin(\Delta m_s t)}{cosh(\Delta\Gamma_s t/2)+A^{\Delta\Gamma}(B_s^0(t)\rightarrow D_s^- K^+)sinh(\Delta\Gamma_s t/2)}$$

[arXiv:hep-ph/0304027v2]

- oscillation terms
- sensitivity comes only from events with known initial flavour
- flavour tagging detects, if B_s^0 or $\overline{B_s^0}$ was produced
- requires knowledge about Δm_s (oscillation in B_s system)

- hyperbolics terms
- sensitivity comes from all events
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Motivation: from CP parameters to γ angle

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

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

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

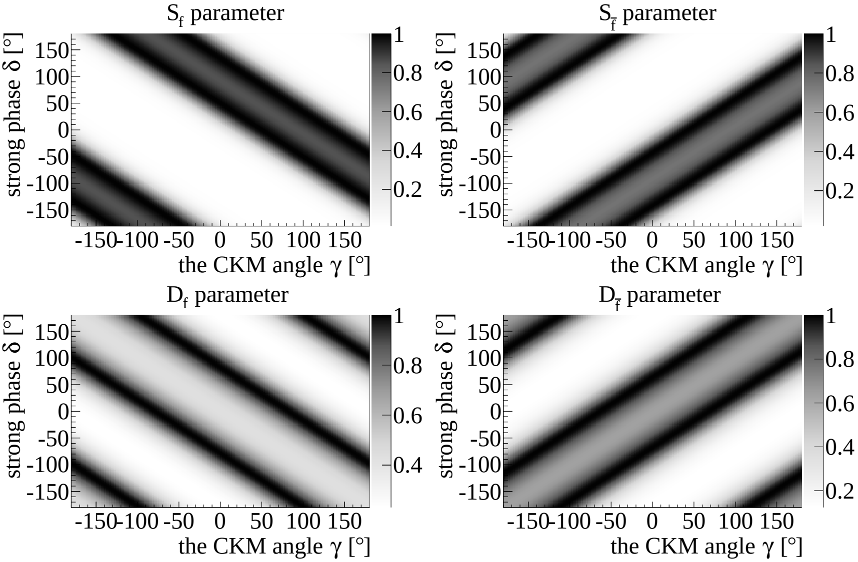
where r_{D_sK} - ratio of the amplitudes, δ - strong phase, γ - weak phase, $2\beta_s$- weak phase in mixing.

Assuming no penguin pollution and no BSM contribution in these decays: $\phi_s = -2\beta_s$.
In this measurement we used as input:

$$\phi_s = -0.010 \pm 0.039 \text{ rad}$$

[Phys. Rev. Lett. 114, 041801 (2015)].

Motivation: from CP parameters to γ angle



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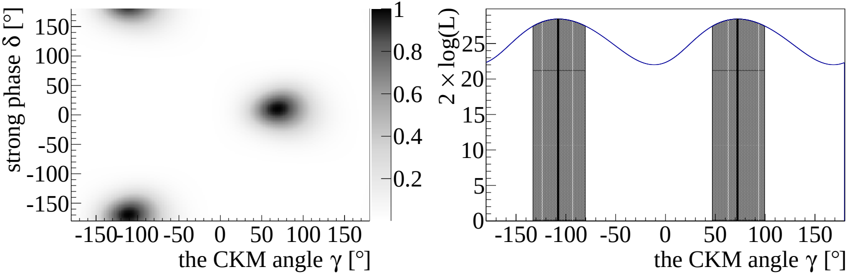
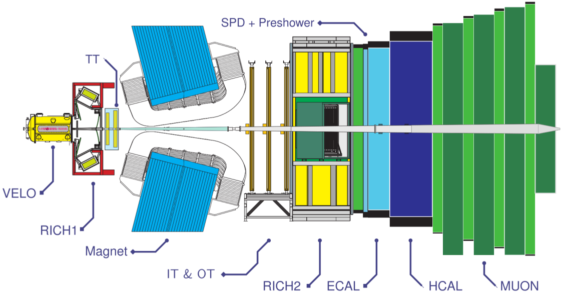
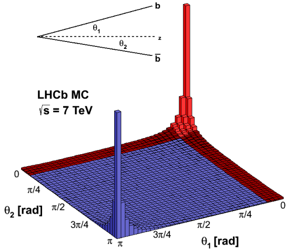


Feature of the $B_s^0 \to D_s^{\mp} K^{\pm}$ decays:
Only one solution for the CKM angle γ in (0,180)$^\circ$

The LHCb experiment



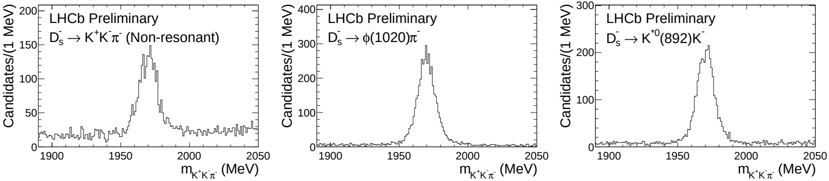


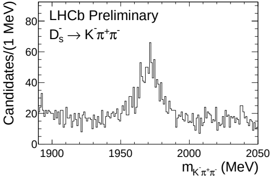
Decay-time resolution:
$\sim 45 - 55$ fs
$\Delta p/p = 0.5 - 1.0\%$
Tracking efficiency $> 95\%$

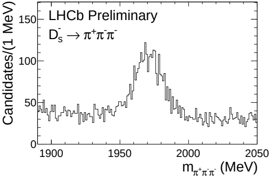
Precise π/K identification
$\epsilon(K \to K) \sim 95\%$
$misID(\pi \to K) \sim 5\%$

JINST 3 (2008) S08005
Int. J. Mod. Phys. A 30, 1530022 (2015)

The analysis is based on pp collision data sample of 3 fb^{-1} collected the LHCb detectorin 2011 (2012) at the center-of-mass energy $\sqrt{s} = 7(8)\,TeV$ (LHCb-CONF-2016-015).



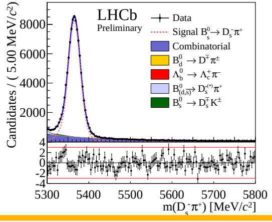




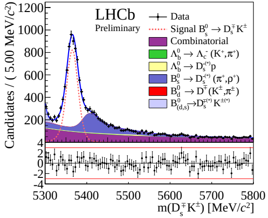
- We consider three D_s^- final states:
  $KK\pi(\phi\pi^-, K^{*0}K^-, NonResonant)$, $K\pi\pi$, $\pi\pi\pi$.
- Normalization mode: $B_s^0 \rightarrow D_s^-\pi^+$ - topologically identical.

$D_s h$ mass

$B_s^0 \to D_s^- \pi^+$



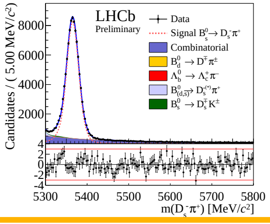
$B_s^0 \to D_s^{\mp} K^{\pm}$

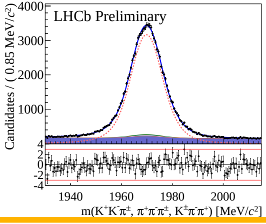


LHCb-CONF-2016-015

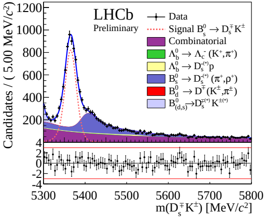
$D_s h$ mass — $KK\pi, K\pi\pi, \pi\pi\pi$ mass

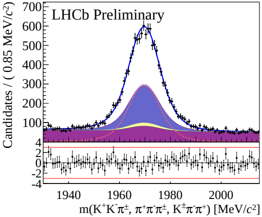
$B_s^0 \to D_s^- \pi^+$





$B_s^0 \to D_s^\mp K^\pm$





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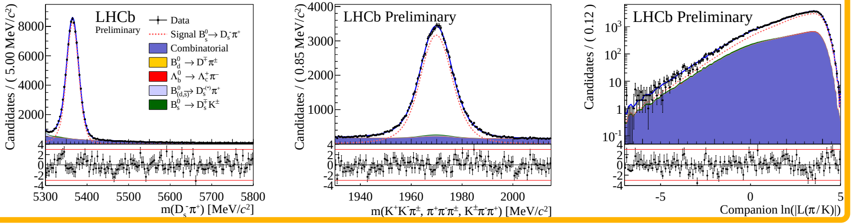
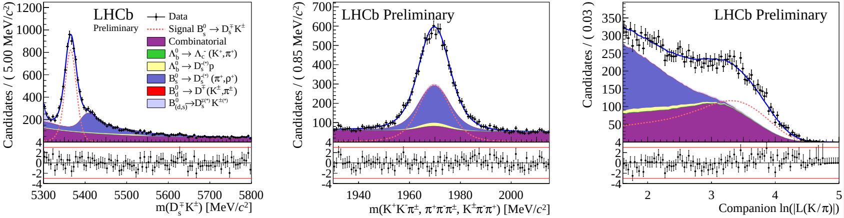
$D_s h$ mass | $KK\pi, K\pi\pi, \pi\pi\pi$ mass | bachelor ID

$B_s^0 \to D_s^- \pi^+$



$B_s^0 \to D_s^\mp K^\pm$



Signal $B_s^0 \to D_s^- \pi^+ = 96942 \pm 345$

Signal $B_s^0 \to D_s^\mp K^\pm = 5955 \pm 90$

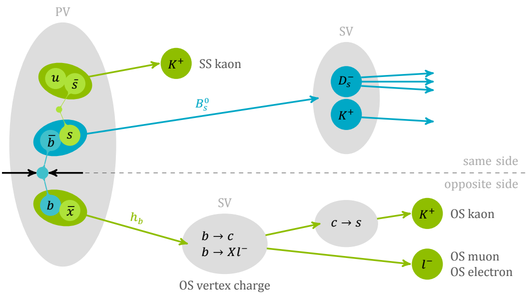
Tagging: identification of flavour at $t = 0$

LHCb-CONF-2016-015

We use:

- combination of opposite side (OS) taggers (Eur. Phys. J. C72 (2012) 2022)
- same side kaon (SSK) tagger (JINST 11 (2015) P05010)

The sensitivity to C, S_f and $S_{\bar{f}}$ scales with $1/\sqrt{\epsilon_{eff}}$

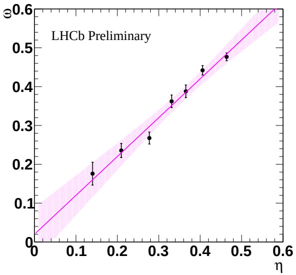


Event type	ϵ_{tag} [%]
OS-only	11.95 ± 0.11
SSK-only	34.47 ± 0.15
OS-SSK	19.27 ± 0.13
Total	65.69

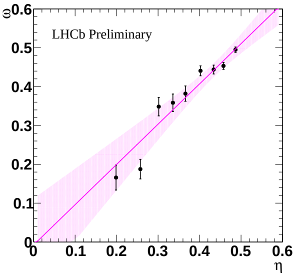
$$\epsilon_{eff} = \epsilon_{tag}(1 - 2\omega)^2$$

Event type	ϵ_{eff} [%]
OS-only	1.28 ± 0.12
SSK-only	1.19 ± 0.14
OS-SSK	2.51 ± 0.18
Total	4.98

Tagging calibration



Opposite side combinations



Same Side Kaon

Calibration performed using the $B_s^0 \to D_s^- \pi^+$ decay.
Mistag estimate (η) has to be calibrated on data: $\omega(\eta) = p_0 + p_1 * (\eta - <\eta>)$
The mistag calibration:

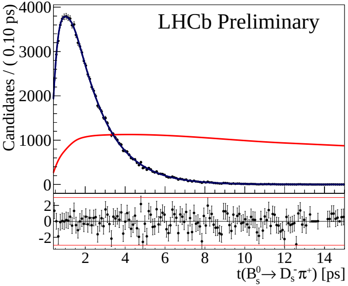
Tagger	p_0	p_1	$\langle\eta\rangle$	ε_{tag} [%]	ε_{eff} [%]
OS	$0.377 \pm 0.007 \pm 0.001$	$1.12 \pm 0.08 \pm 0.01$	0.370	37.15 ± 0.17	3.55 ± 0.33
SS	$0.441 \pm 0.005 \pm 0.000$	$1.09 \pm 0.08 \pm 0.01$	0.437	63.93 ± 0.17	1.92 ± 0.22

Other ingredients

We use per event decay time errors with average resolution 56 *fs*.

Decay time acceptance is taken from $B_s^0 \to D_s^- \pi^+$ and corrected by acceptances $B_s^0 \to D_s^\mp K^\pm / B_s^0 \to D_s^- \pi^+$ ratio from simulation.

$B_s^0 \to D_s^- \pi^+$ decay-time



$\Gamma_s = (0.6643 \pm 0.0020) ps^{-1}$ [HFAG]

$\Delta\Gamma_s = (0.083 \pm 0.006) ps^{-1}$ [HFAG]

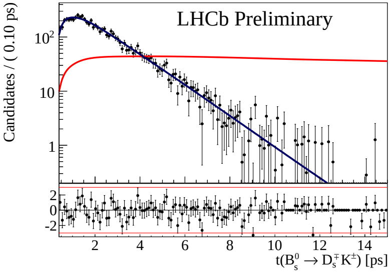
$\rho(\Gamma_s, \Delta\Gamma_s) = -0.239$ [Phys. Rev.D87 (2013) 112010]

$\Delta m_s = (17.757 \pm 0.021) ps^{-1}$ [HFAG]

$A_{det}(K\pi) = (1 \pm 1)\%$ JHEP 07 (2014) 041

$A_{prod}(B_s^0) = (1.1 \pm 2.7)\%$ Phys. Lett. B739 (2014) 218

Decay-time fit



The CP parameters obtained for the decay-time sFit to $B_s^0 \to D_s^{\mp} K^{\pm}$ sample.

CP parameter	Value
C_f	$0.735 \pm 0.143 \pm 0.048$
$A_f^{\Delta\Gamma}$	$0.395 \pm 0.277 \pm 0.122$
$A_{\overline{f}}^{\Delta\Gamma}$	$0.314 \pm 0.274 \pm 0.107$
S_f	$-0.518 \pm 0.202 \pm 0.073$
$S_{\overline{f}}$	$-0.496 \pm 0.197 \pm 0.071$

The systematics are obtained using

- a large scale pseudoexperiments
- a large statistics simulation samples
- data fit

Systematics

We consider five uncorrelated sources of systematics due to

- fixed value of Δm_s,
- time resolution model and tagging,
- neglecting correlations among observables,
- the closure test (fitting high statistics fully simulated sample),
- the detection asymmetry.

Parameter	C_f	$A_f^{\Delta\Gamma}$	$A_{\overline{f}}^{\Delta\Gamma}$	S_f	$S_{\overline{f}}$
Detection asymmetry	0.01	0.23	0.26	0.02	0.03
Δm_s	0.06	0.01	0.01	0.17	0.18
Tagging and scale factor	0.15	0.06	0.06	0.22	0.16
Correlation among observables	0.27	0.25	0.18	0.20	0.23
Closure test	0.12	0.19	0.19	0.12	0.12

The systematic uncertainty is expressed as a fraction of statistical error.

- Many other sources of systematic have been checked, finding negligible impact to the measurement.

Systematics

We consider correlated systematics due to:

- decay-time acceptance,
- fixed value of $\Delta\Gamma_s$,
- fixed value of Γ_s.

Parameter	C_f	$A_f^{\Delta\Gamma}$	$A_{\overline{f}}^{\Delta\Gamma}$	S_f	$S_{\overline{f}}$
Contributions:					
Γ_s	0.02	0.16	0.18	0.01	0.01
$\Delta\Gamma_s$	0.01	0.07	0.11	0.00	0.00
Acceptance, MC ratio	0.04	0.09	0.10	0.01	0.01
Acceptance, data fit	0.07	0.18	0.20	0.01	0.02
Acceptance, Γ_s, $\Delta\Gamma_s$	0.07	0.19	0.06	0.01	0.02

The systematic uncertainty is expressed as a fraction of statistical error.

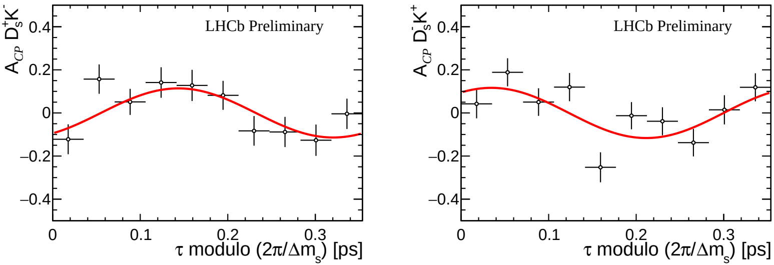
Total systematics:

Parameter	C_f	$A_f^{\Delta\Gamma}$	$A_{\overline{f}}^{\Delta\Gamma}$	S_f	$S_{\overline{f}}$
Total	0.34	0.44	0.39	0.36	0.36

The systematic uncertainty is expressed as a fraction of statistical error.

Folded asymmetry plots

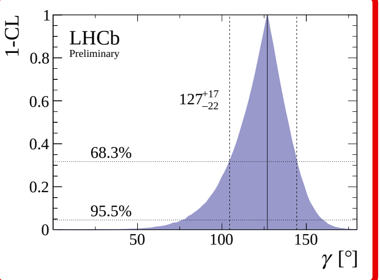
- the difference in the rates of B_s^0 and $\overline{B_s^0}$ tagged $D_s^+ K$ and $D_s^- K^+$ candidates
- plotted in slices of $2\pi/\Delta m_s$
- using data with subtracted backgrounds

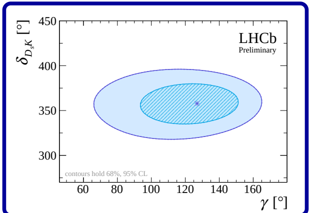


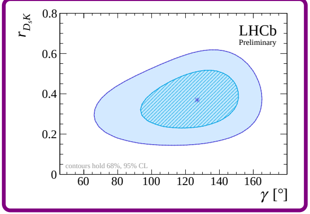
Evidence of oscillation!

Measurement of γ angle

- Statistical and systematic uncertainties and correlations are taken into account.
- Constraint: $|C|^2 + |S_f|^2 + |A_f^{\Delta\Gamma}|^2 = 1$

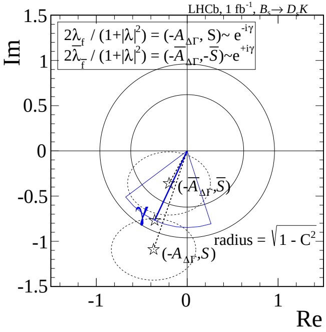


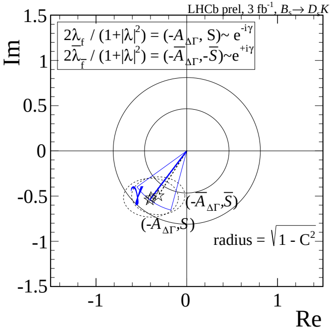




$$\gamma = (127^{+17}_{-22})^\circ$$
$$\delta_{D_sK} = (358^{+15}_{-16})^\circ$$
$$r_{D_sK} = 0.37^{+0.10}_{-0.09}$$

- The LHCb published 1 fb^{-1} paper (JHEP 11 (2014) 060).





$$\gamma = (115^{+28}_{-43})^\circ$$
$$\delta_{D_s K} = (3^{+19}_{-20})^\circ,$$
$$r_{D_s K} = 0.53^{+0.17}_{-0.16}$$

$$\gamma = (127^{+17}_{-22})^\circ$$
$$\delta_{D_s K} = (358^{+15}_{-16})^\circ,$$
$$r_{D_s K} = 0.37^{+0.10}_{-0.09}$$

Measurement of γ angle

- We observe 3.6σ evidence for CP violation in the $B_s^0 \to D_s^{\mp} K^{\pm}$ decays with the γ value:

$$\gamma = (127^{+17}_{-22})^{\circ}$$

- The LHCb collaboration provides its own γ combination:

See Conor Fitzpatrick talk!

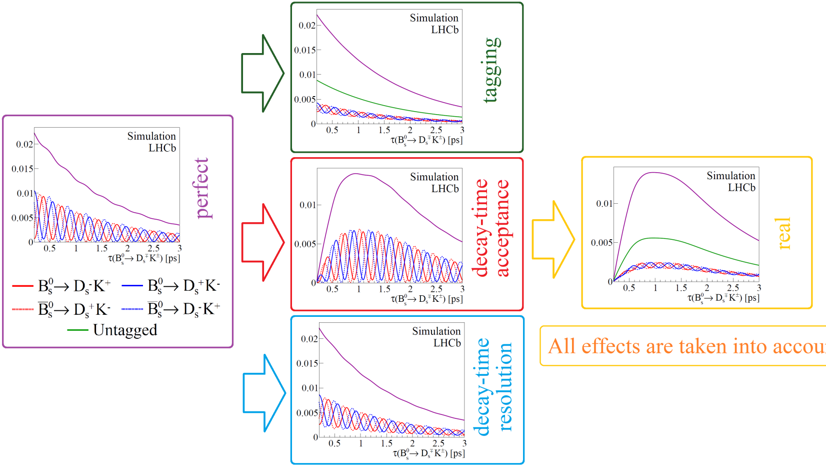
- The CKM angle γ (excluding previous $B_s^0 \to D_s^{\mp} K^{\pm}$ measurement) agrees with the LHCb γ average at the level of 2.15σ.

- Future prospects for sensitivity:
  $\sim 11^{\circ}$ at the end of Run II.
  $\sim 2^{\circ}$ at the end of Upgrade.

See Veronika Chobanova slides!

Thank You!

Detector effects



All effects are taken into account!

Influence of the detector effects to the decay rates.