CP violation in beauty with the LHCb experiment

A. Bertolin on behalf of the LHCb collaboration

Outlook:

- short introduction
- LHCb results:
  - Δm_s mass difference: LHCb individual measurements and LHCb combination
  - CKM γ : LHCb individual measurements and LHCb combination
  - CPV in 2-body neutral B meson (Bd/Bs) decays
  - CPV for baryons in LHCb
- take home message

CPV in the SM

CPV is one of the requirements for explaining the baryon asymmetry we observe today

in the SM the CKM matrix, V, 3 x 3, fulfilling V V* = I, is describing quark charged current weak interactions
⇔ 3 angles and 1 phase (or 3 reals and 1 imaginary parameters)

$$V = \begin{array}{c} \\ u \\ c \\ t \end{array}\begin{array}{c} d & s & b \\ \left(\begin{array}{ccc} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5\left[1-2(\rho+i\eta)\right] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3\left[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)\right] & -A\lambda^2+\frac{1}{2}A\lambda^4\left[1-2(\rho+i\eta)\right] & 1-\frac{1}{2}A^2\lambda^4 \end{array}\right) \end{array} + \mathcal{O}\left(\lambda^6\right) \qquad \lambda \approx 0.22$$

the term $\rho + i\,\eta$ gives the CKM phase: **only** source of CPV in the SM quark sector
"intrinsic" connection between CPV in the beauty and charm sectors
however the imaginary part of:
$V_{cd} \propto \lambda^5$
$V_{ub} \propto \lambda^3$
expect CPV suppression in charm w.r.t beauty …

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

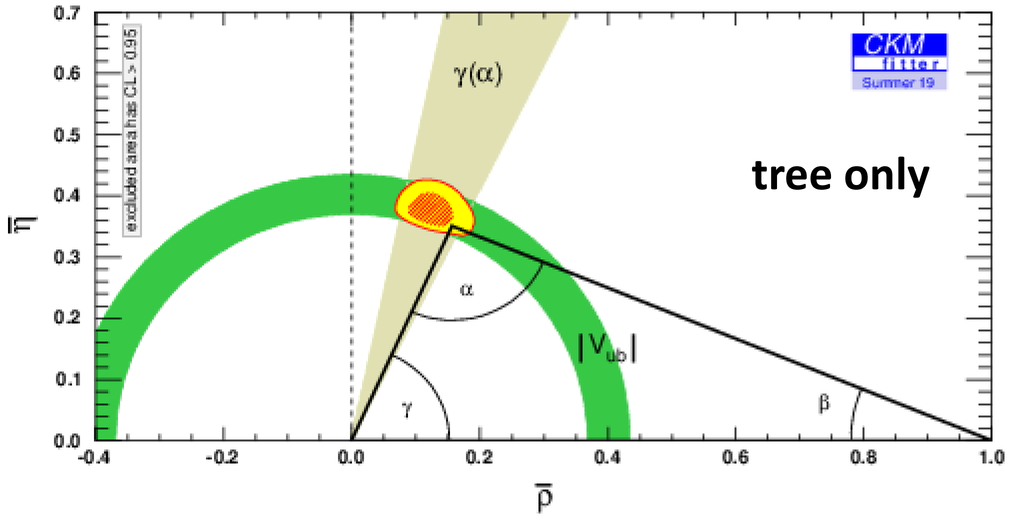
unitary condition relevant for beauty decays
can be represented as a triangle in a complex plane, with angles α, β and γ

$$\gamma \equiv \arg\left[-\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}}\right]$$

a.k.a. ϕ_3

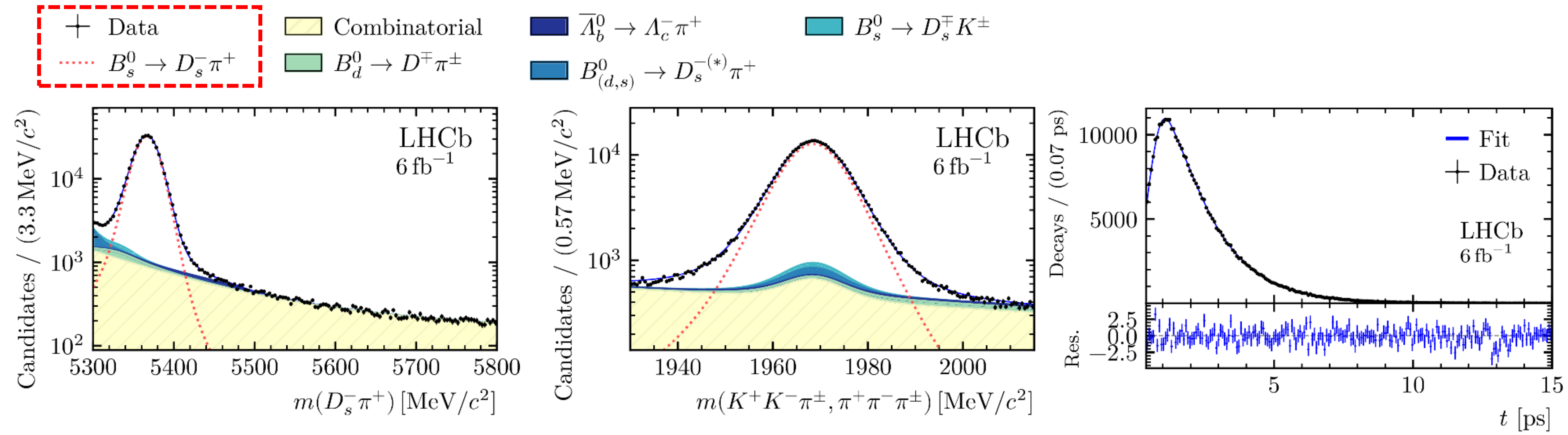
- only CKM angle easily accessible in tree-level decays
- assuming no new physics in tree-level decays, has negligible theoretical uncertainty

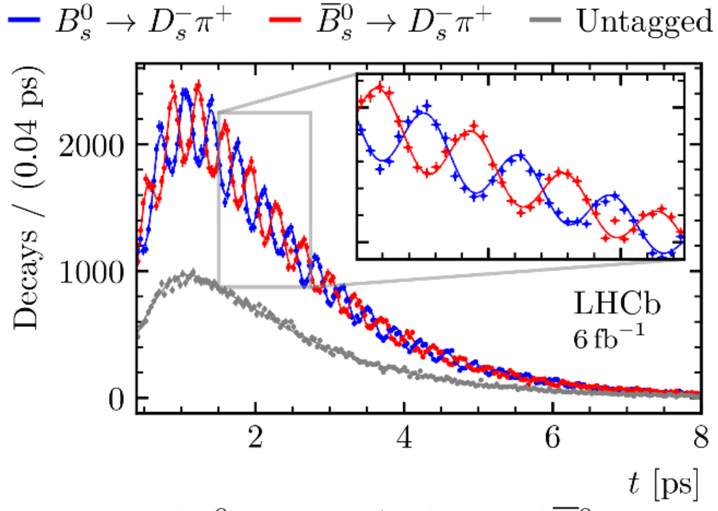
http://ckmfitter.in2p3.fr/www/results/plots_summer19/ckm_res_summer19.html



LHCb Δm_s mass difference update

arXiv:2104.04421
LHCb-PAPER-2021-005
submitted to Nature Physics





$$A(t) = \frac{N(B_s^0 \to D_s^- \pi^+, t) - N(\overline{B}_s^0 \to D_s^- \pi^+, t)}{N(B_s^0 \to D_s^- \pi^+, t) + N(\overline{B}_s^0 \to D_s^- \pi^+, t)}$$

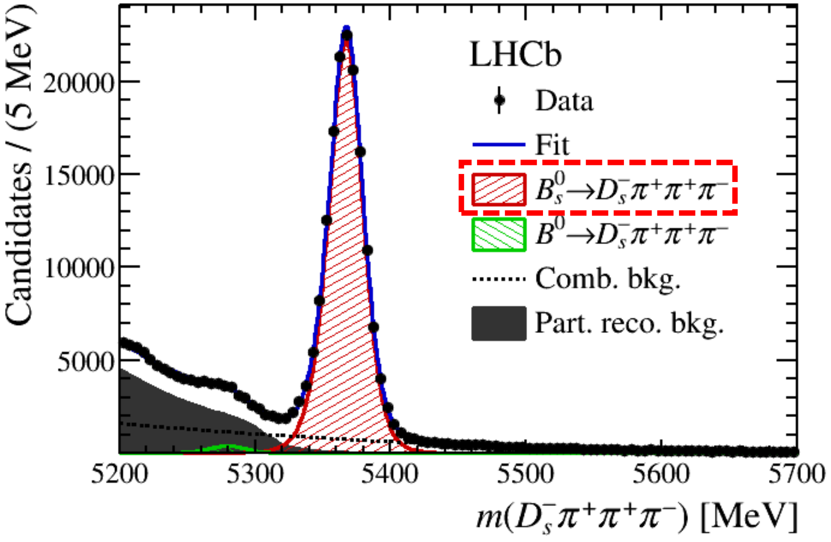
- exploit the flavor specific nature of this decay i.e. just oscillations
- full Run 2 statistic (6 /fb), partial Run 1 (1 /fb) result already published
- signal yield for a simultaneous fit to the beauty and charm mass distributions: **378.7 k events**
- Δm_s from a fit to the background subtracted decay time distribution

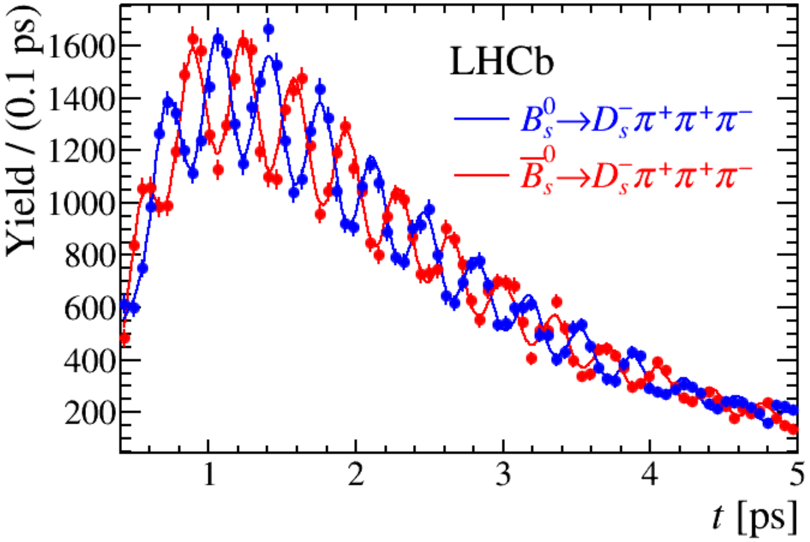
$$\Delta m_s = 17.7683 \pm 0.0051\,(\mathrm{stat}) \pm 0.0032\,(\mathrm{syst})\ \mathrm{ps}^{-1}$$

- spectacular decay time asymmetry distribution

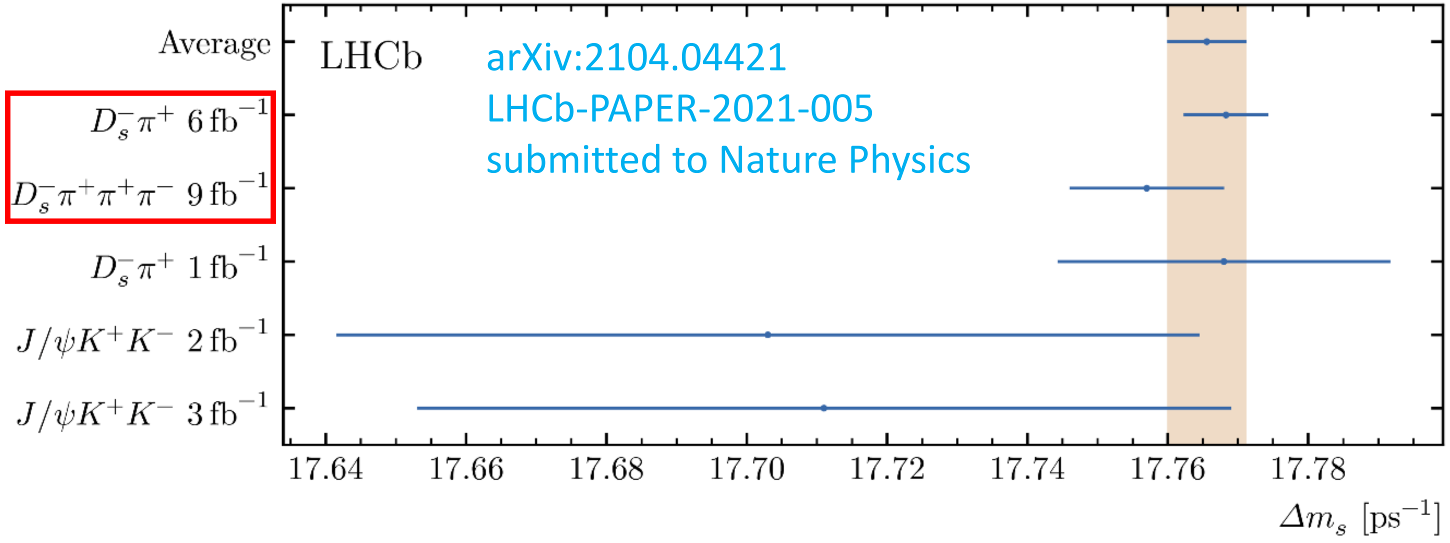
LHCb Δm_s mass difference update (cont.)

JHEP03(2021)137





- full Run 1+2 statistic (9 /fb)
- procedure as in the previous analysis
- signal yield: **148 k events**
- spectacular decay time asymmetry distribution



arXiv:2104.04421
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submitted to Nature Physics

LHCb average: 17.7656 ± 0.0057 ps^{-1}

lattice QCD + sum rule: $18.4^{+0.7}_{-1.2}$ ps^{-1}

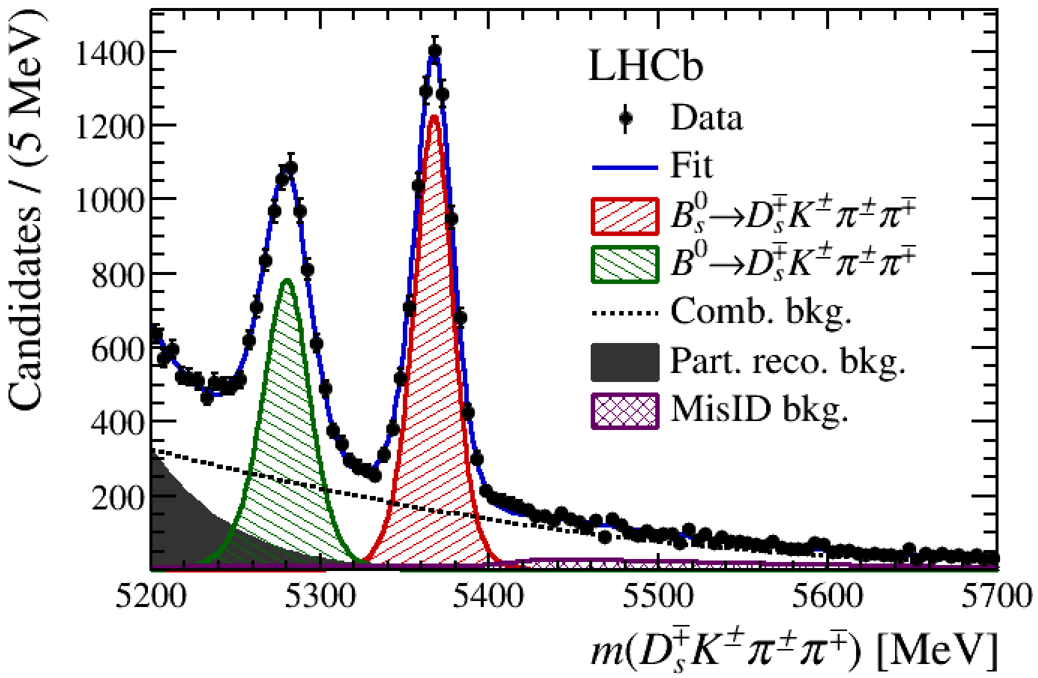
JHEP 12 (2019) 009

- interesting measurement on its own
- key input for many LHCb analyses: γ in primis

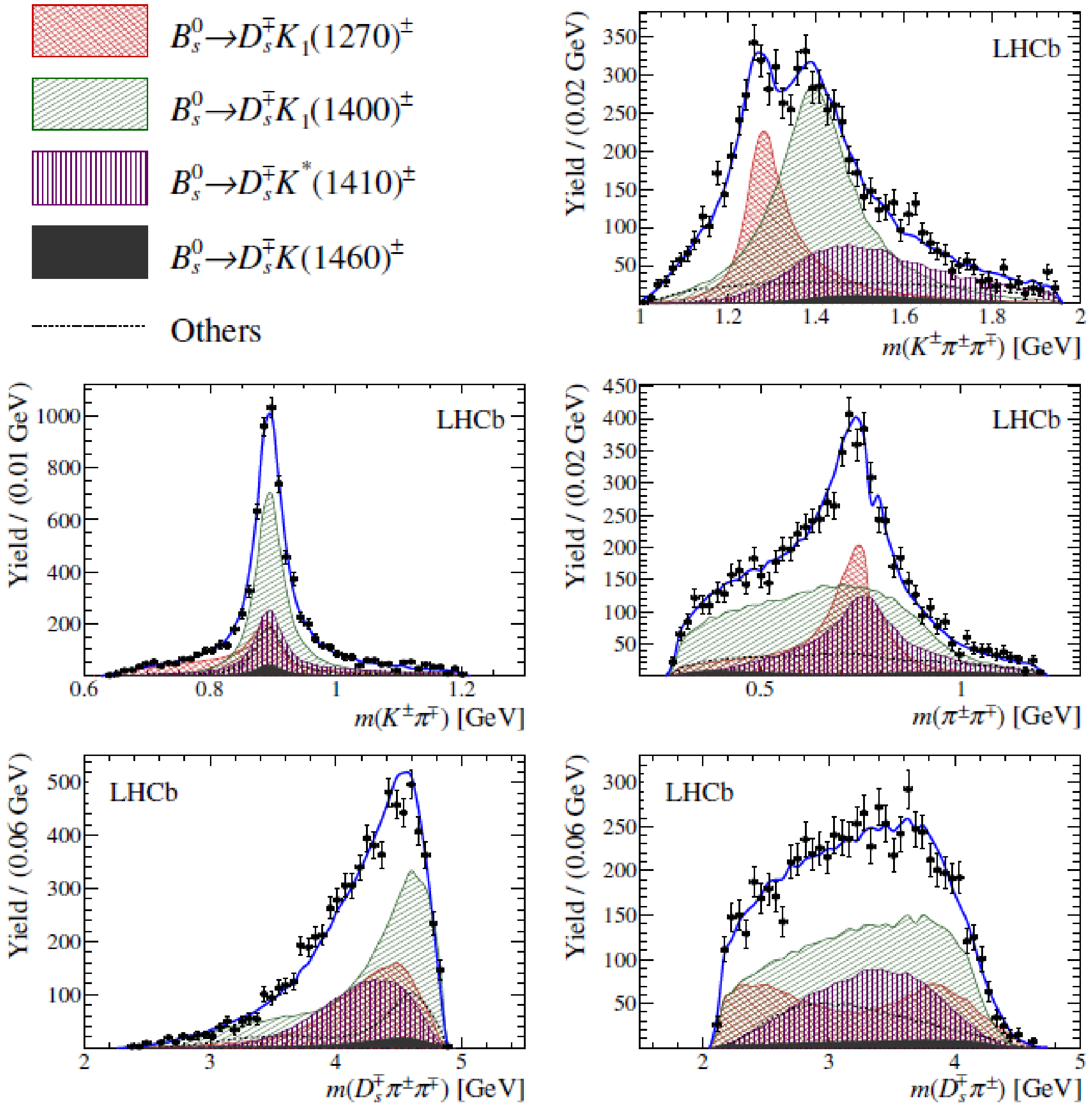
recent LHCb results on CMK γ: a TD measurement

JHEP03(2021)137

- replace a π with a K in the previous analysis
- CPV due to interference between mixing and decay to the same final state
- several contributing final states: amplitude analysis
- full Run 1+2 statistic (9 /fb)



- model-dependent approach:
describe resonance contributions, 4, with an amplitude model
- model-independent approach:
integrate over phase-space space



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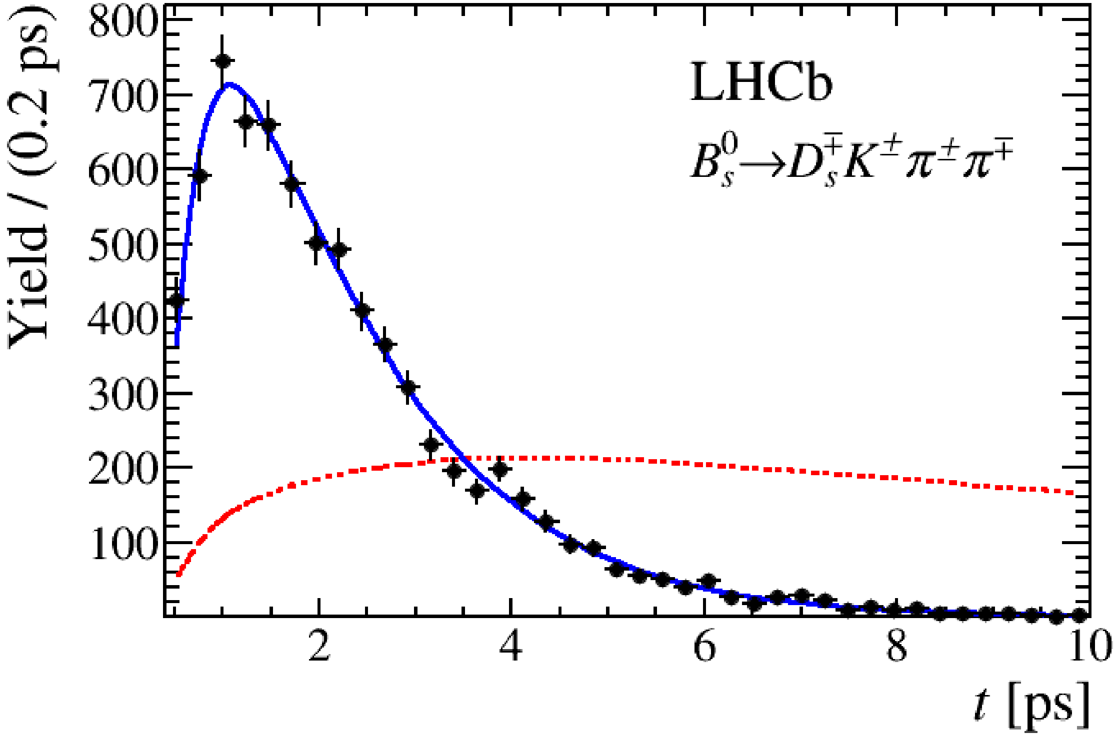
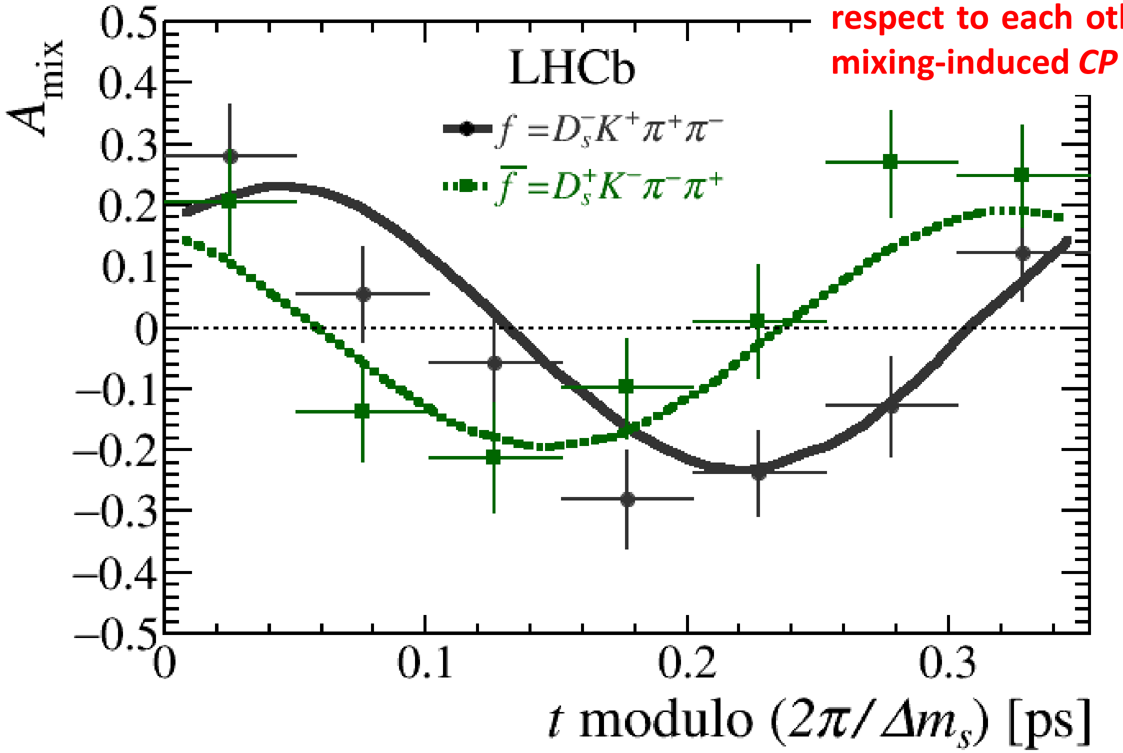
model dependent result





mixing asymmetries shifted with respect to each other is indicating mixing-induced *CP* violation

Parameter	Model-independent	Model-dependent
r	$0.47\,^{+0.08}_{-0.08}\,^{+0.02}_{-0.03}$	$0.56 \pm 0.05 \pm 0.04 \pm 0.07$
κ	$0.88\,^{+0.12}_{-0.19}\,^{+0.04}_{-0.07}$	$0.72 \pm 0.04 \pm 0.06 \pm 0.04$
δ [°]	$-6\,^{+10}_{-12}\,^{+2}_{-4}$	$-14 \pm 10 \pm 4 \pm 5$
$\gamma - 2\beta_s$ [°]	$42\,^{+19}_{-13}\,^{+6}_{-2}$	$42 \pm 10 \pm 4 \pm 5$

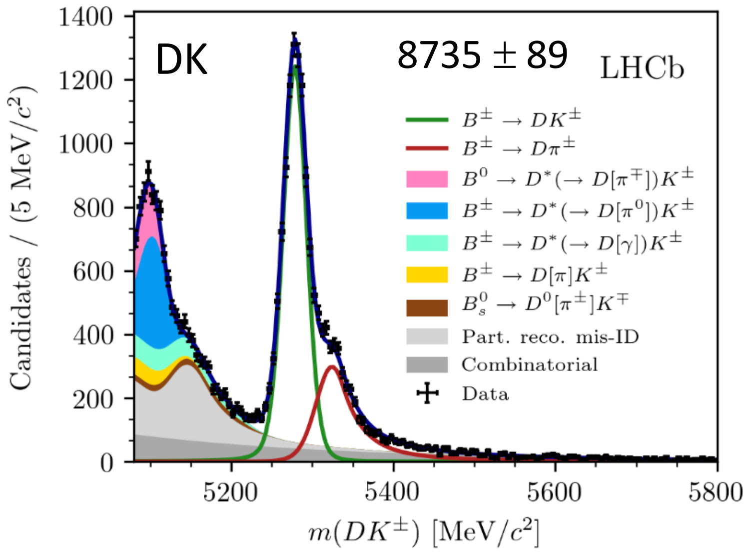
→ alternative amplitude models considered

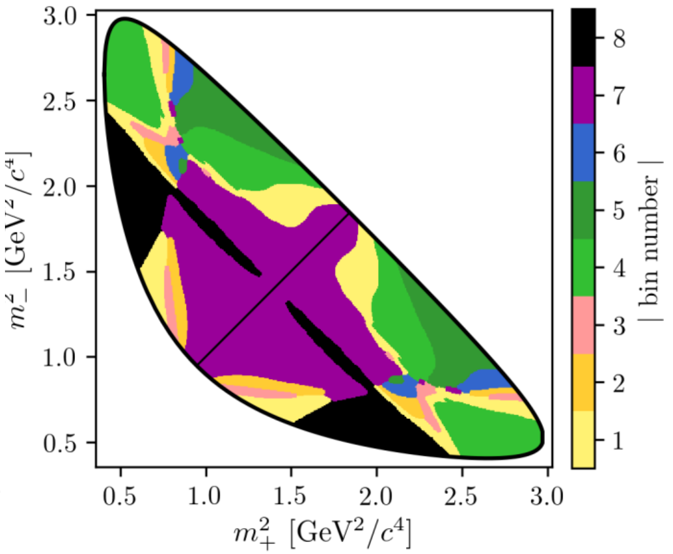
- ratio of the decay amplitudes to the same final state
- coherence factor, fitted (computed) in M-i (M-d)
- strong phase difference
- weak phase difference

LHCb CKM γ: time integrated measurements

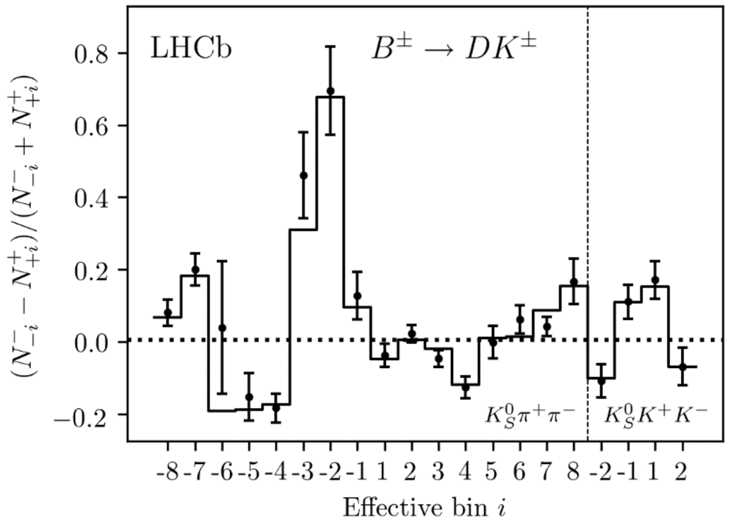
JHEP02(2021)169

$$B^- \to D^0(\to K^0_S h^+ h^-)K^- \propto V_{cb}$$
$$B^- \to \overline{D}^0(\to K^0_S h^+ h^-)K^- \propto V_{ub}$$
$$m^2_{\pm} = m(K^0_S, h^{\pm})$$





- full Run 1+2 statistic (9 /fb)
- external input: strong-phase difference between the D decay amplitudes at any given point of the Dalitz plot from CLEO and BESIII combined data
- CPV parameters from the distribution of events in the Dalitz plot: very large asymmetries in bins population
- most precise γ measurement from a single analysis



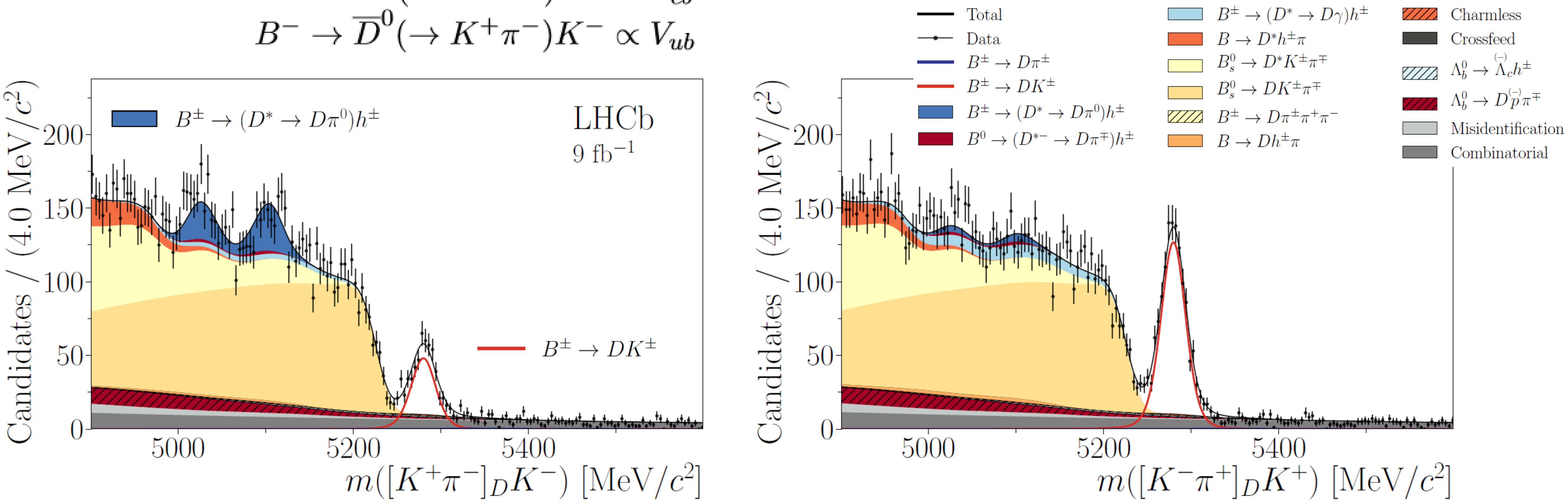
no CPV expectation

$$\gamma = (68.7^{+5.2}_{-5.1})^\circ,$$
$$r_B^{DK^\pm} = 0.0904^{+0.0077}_{-0.0075},$$
$$\delta_B^{DK^\pm} = (118.3^{+5.5}_{-5.6})^\circ,$$
$$r_B^{D\pi^\pm} = 0.0050 \pm 0.0017,$$
$$\delta_B^{D\pi^\pm} = (291^{+24}_{-26})^\circ.$$

LHCb CMK γ: time integrated measurements

JHEP04(2021)081

$$B^- \to D^0(\to K^+\pi^-)K^- \propto V_{cb}$$
$$B^- \to \overline{D}^0(\to K^+\pi^-)K^- \propto V_{ub}$$



- full Run 1+2 statistic (9 /fb)
- partial decay rates are related to the underlying physical parameters
- spectacular differences in peaks height
- 9 CP observables related to fully reconstructed decays
- 19 CP observables related to partially reconstructed decays (missing neutral particle)

Observable	Definition
A_K^{CP}	$\frac{\Gamma(B^-\to[h^+h^-]_D K^-) - \Gamma(B^+\to[h^+h^-]_D K^+)}{\Gamma(B^-\to[h^+h^-]_D K^-) + \Gamma(B^+\to[h^+h^-]_D K^+)}$
A_π^{CP}	$\frac{\Gamma(B^-\to[h^+h^-]_D \pi^-) - \Gamma(B^+\to[h^+h^-]_D \pi^+)}{\Gamma(B^-\to[h^+h^-]_D \pi^-) + \Gamma(B^+\to[h^+h^-]_D \pi^+)}$
$A_K^{K\pi}$	$\frac{\Gamma(B^-\to[K^-\pi^+]_D K^-) - \Gamma(B^+\to[K^+\pi^-]_D K^+)}{\Gamma(B^-\to[K^-\pi^+]_D K^-) + \Gamma(B^+\to[K^+\pi^-]_D K^+)}$

3 out of 9 CP observables …

LHCb CMK γ: time integrated measurements

JHEP02(2021)169
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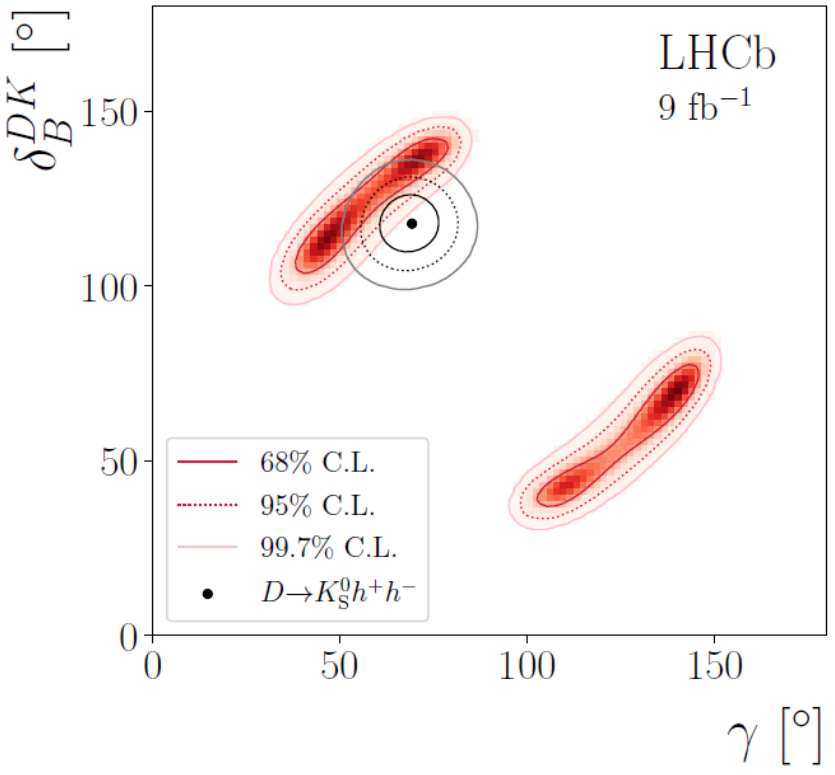
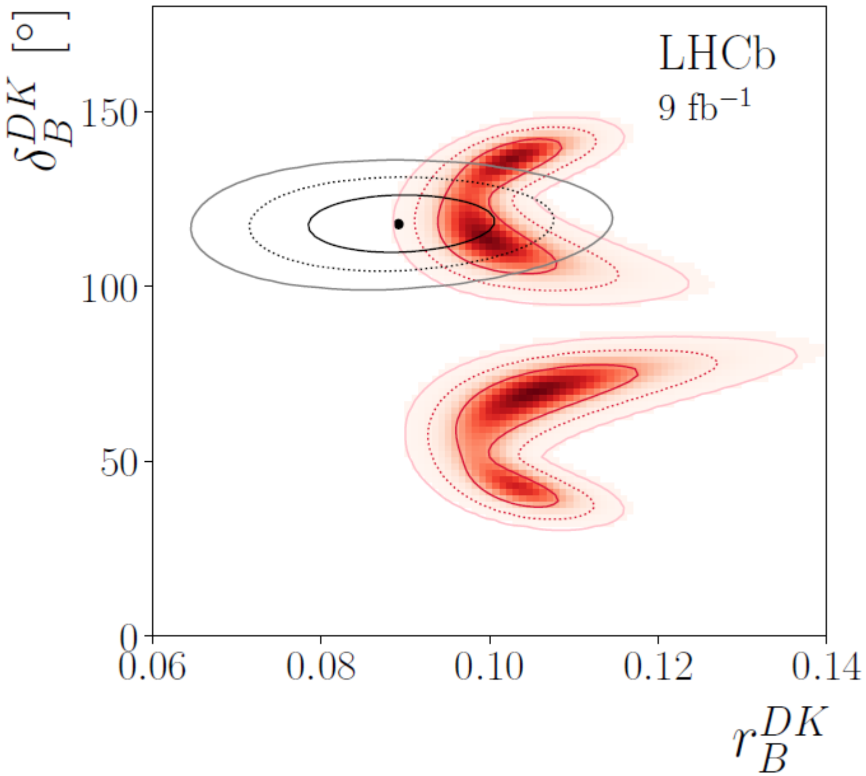
JHEP04(2021)081





- measurements on partially reconstructed decays are the first of their kind
- all CP observables are measured with world-best precision
- two-fold ambiguity solved combining results with the previous analysis

$$\gamma = (68.7^{+5.2}_{-5.1})^o \to (61.8 \pm 4.0)^o$$

LHCb CMK γ combination

LHCb input data:

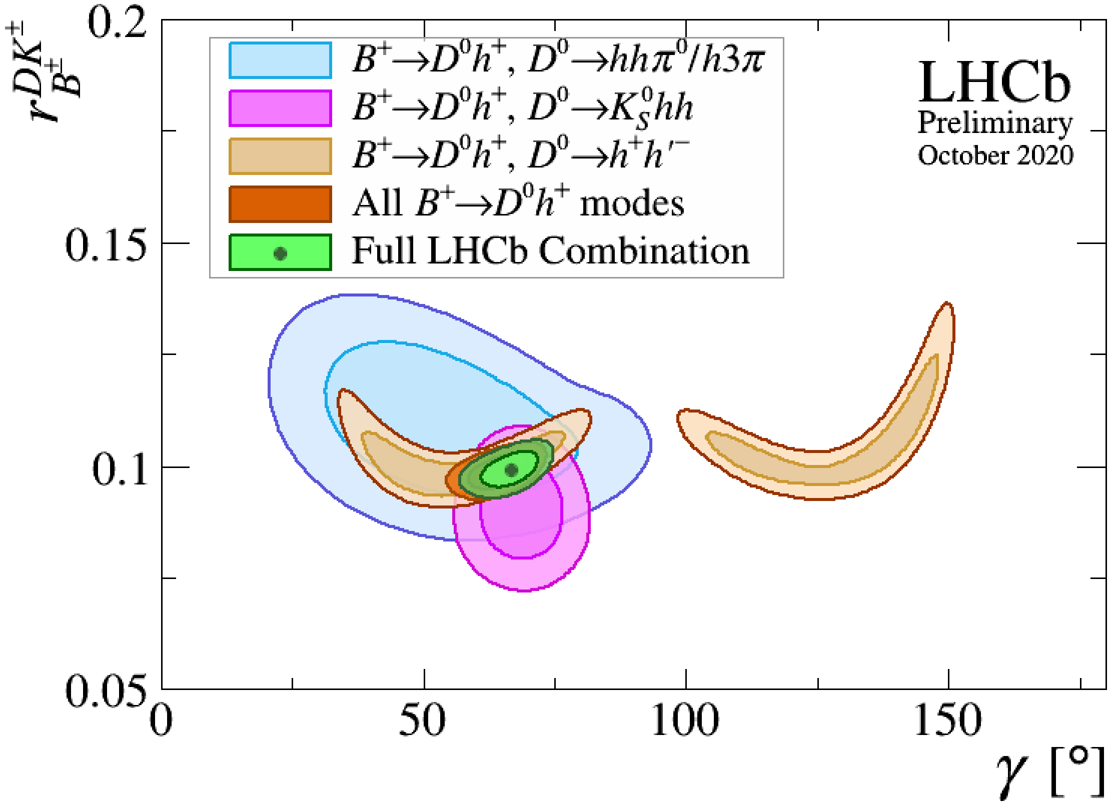
B decay	D decay	Method	Ref.	Dataset	Status since Ref. [3]
$B^+ \to Dh^+$	$D \to h^+h^-$	GLW/ADS	[16]	Run 1+2	**Updated**
$B^+ \to Dh^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[24]	Run 1	As before
$B^+ \to Dh^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[25]	Run 1	As before
$B^+ \to Dh^+$	$D \to K^0_S h^+h^-$	BPGGSZ	[17]	Run 1+2	**Updated**
$B^+ \to Dh^+$	$D \to K^0_S K^\pm\pi^\mp$	GLS	[20]	Run 1+2	**Updated**
$B^+ \to D^*h^+$	$D \to h^+h^-$	GLW/ADS	[16]	Run 1+2	**Updated**
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[26]	Run 1+2(*)	As before
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[26]	Run 1+2(*)	As before
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[27]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	GLW/ADS	[21]	Run 1+2(*)	**Updated**
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[21]	Run 1+2(*)	**New**
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[22]	Run 1	**Superseded**
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	BPGGSZ	[28]	Run 1	As before
$B^0 \to D^\mp\pi^\pm$	$D^\pm \to K^\mp\pi^\pm\pi^\pm$	TD	[29]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm$	$D^\pm_s \to h^\pm h^\mp\pi^\pm$	TD	[30]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm\pi^\pm\pi^\mp$	$D^\pm_s \to h^\pm h^\mp\pi^\pm$	TD	[23]	Run 1+2	**New**

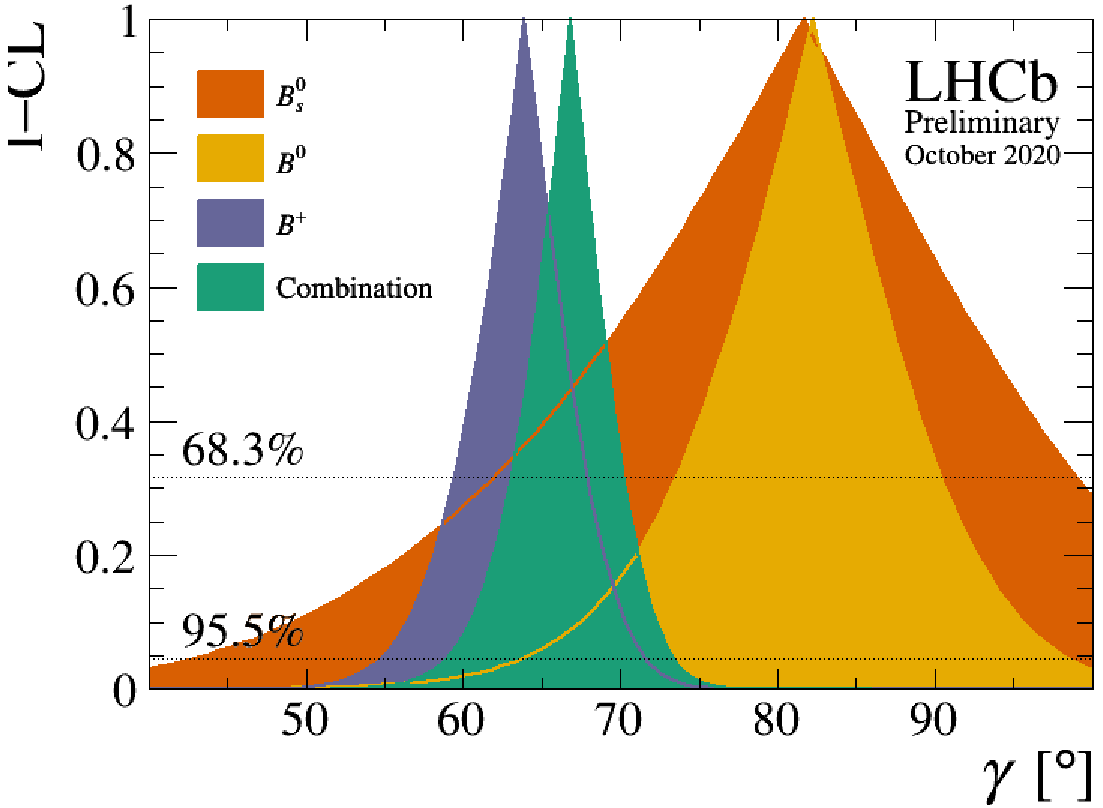
auxiliary inputs:

Decay	Parameters	Source	Ref.
D^0–$\overline{D}^0$-mixing	x_D, y_D	HLFAV	[29]
$D \to K^+\pi^-$	$r_D^{K\pi}$, $\delta_D^{K\pi}$	HLFAV	[29]
$D \to h^+h^-$	$A_{CP}^{\rm dir}(KK)$, $A_{CP}^{\rm dir}(\pi\pi)$	HLFAV	[29]
$D \to K^\pm\pi^\mp\pi^+\pi^-$	$\delta_D^{K3\pi}$, $\kappa_D^{K3\pi}$, $r_D^{K3\pi}$	CLEO+LHCb	[30]
$D \to \pi^+\pi^-\pi^+\pi^-$	$F_{\pi\pi\pi\pi}$	CLEO	[31]
$D \to K\pi\pi^0$	$\delta_D^{K2\pi}$, $\kappa_D^{K2\pi}$, $r_D^{K2\pi}$	CLEO+LHCb	[30]
$D \to h^+h^-\pi^0$	$F_{\pi\pi\pi^0}$, $F_{KK\pi^0}$	CLEO	[31]
$D \to K^0_S K^+\pi^-$	$\delta_D^{K_SK\pi}$, $\kappa_D^{K_SK\pi}$, $r_D^{K_SK\pi}$	CLEO	[32]
$D \to K^0_S K^+\pi^-$	$r_D^{K_SK\pi}$	LHCb	[33]
$B^0 \to DK^{*0}$	$\kappa_B^{DK^{*0}}$, $\bar{R}_B^{DK^{*0}}$, $\bar{\Delta}_B^{DK^{*0}}$	LHCb	[23]
$B^+ \to DK^{*+}$	$\kappa_B^{DK^{*+}}$	LHCb	[20]
$B^0_s \to D^\mp_s K^\pm$	ϕ_s	HFLAV	[29]
$B^0 \to D^\mp\pi^\pm$	β	HFLAV	[29]
$B^0 \to D^\mp\pi^\pm$	$r_B^{D^\mp\pi^\pm}$	See text	[26]

- whenever possible from experiment
- often from LHCb

LHCb-CONF-2020-003

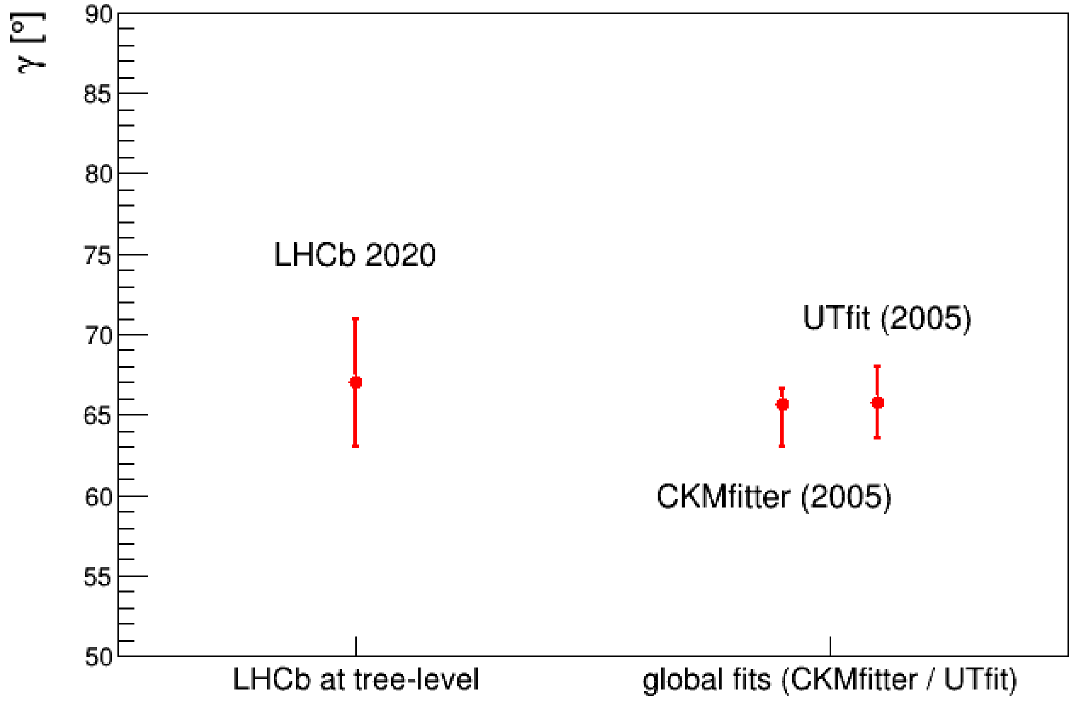




- complementarity between the different results
- most of the sensitivity from $B^\pm$
- LHCb unique sensitivity from B^0_s

$$\gamma = (67 \pm 4)^o$$

CMK γ: from trees vs global fits



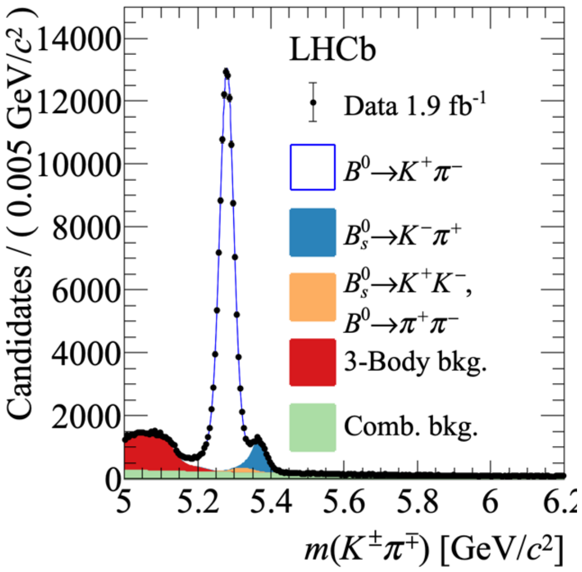
- **any disagreement between tree-level determinations and the value inferred from global CKM fits would indicate physics beyond the SM** due for example to new particles / mediators being exchanged in loops
- LHCb is nicely closing the sensitivity gap between direct measurements and global fits
- much more to come from LHCb:
    - extend already used channels to full Run 1 + 2 data
    - add new channels
- no show stopper on γ accuracy from the experimental side (importance of BESIII data)
- outstanding experimental task but LHCb will reach accuracies < 1 deg. already with 50 /fb

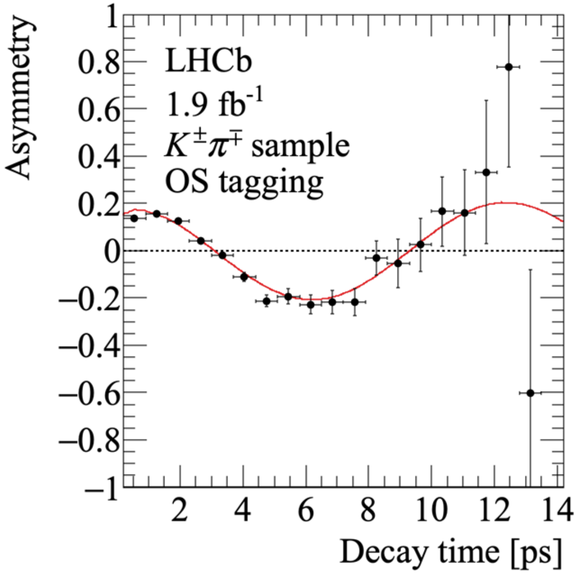
CPV from 2-body neutral B meson (Bd/Bs) decays

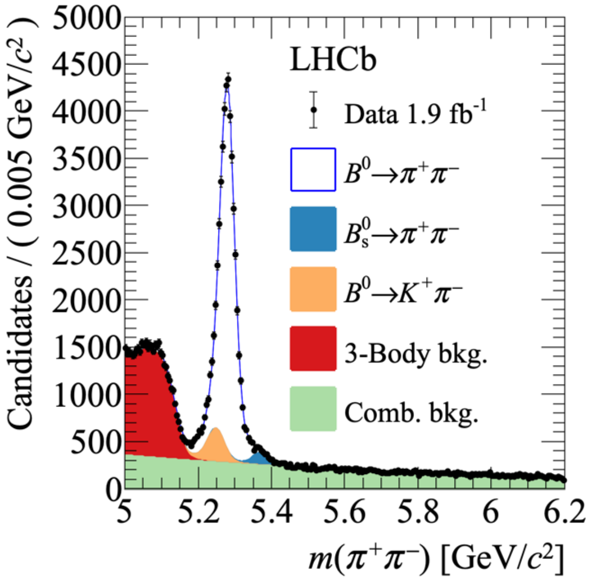
JHEP03(2021)075

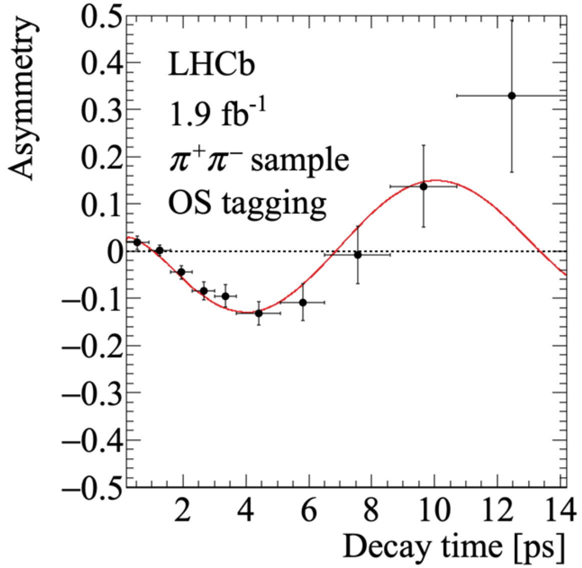
CPV from the interference between decay (to the same final state) and mixing

$$A_{CP}(t) = \frac{\Gamma_{\overline{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\overline{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{-C_f \cos(\Delta m_{d(s)} t) + S_f \sin(\Delta m_{d(s)} t)}{\cosh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right)}$$





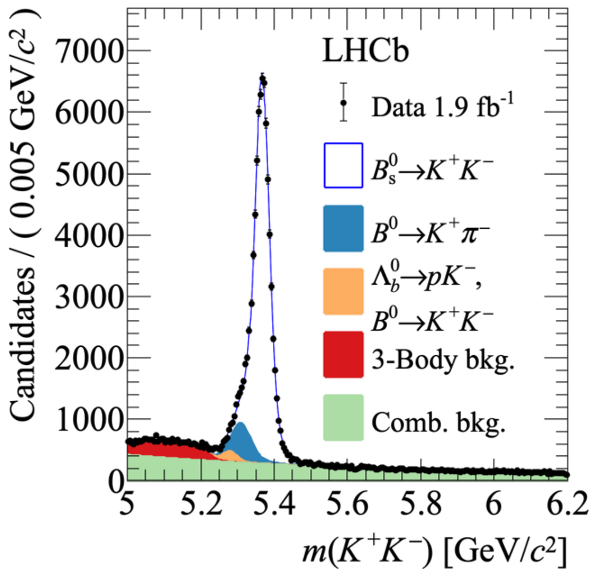


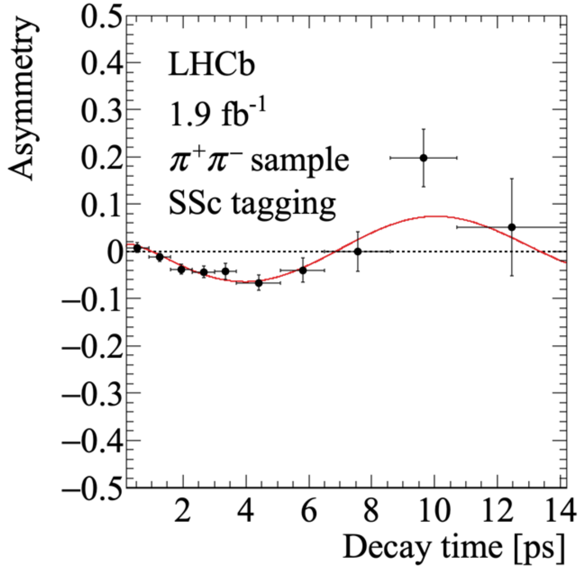


- 1.9 /fb (2015-2016)
- simultaneous fit to invariant mass, decay time, tagging decision, mistag probabilities distributions for Kπ ππ and KK samples

$$A_{CP} = \frac{|\overline{A}_{\overline{f}}|^2 - |A_f|^2}{|\overline{A}_{\overline{f}}|^2 + |A_f|^2}$$

time-integrated CP asymmetry





CPV from 2-body neutral B meson (Bd/Bs) decays (cont.)

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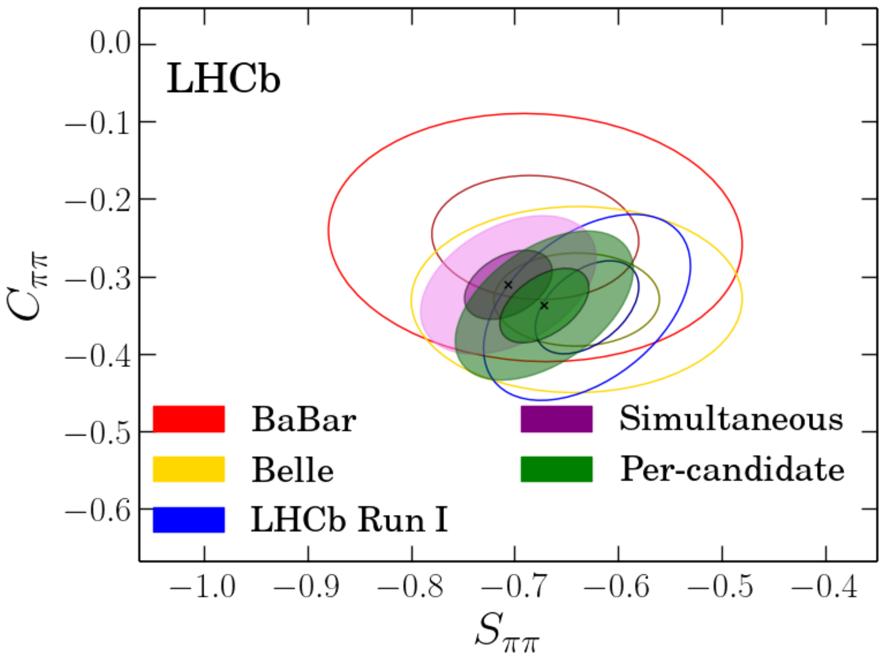
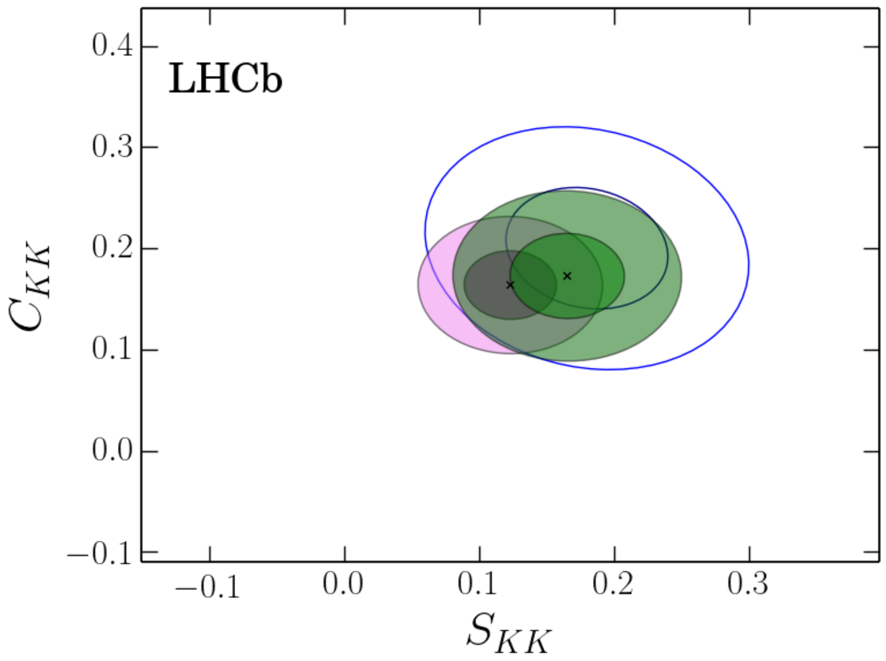


$$C_{\pi\pi} = -0.311 \pm 0.045,$$
$$S_{\pi\pi} = -0.706 \pm 0.042,$$
$$A_{CP}^{B^0} = -0.0824 \pm 0.0033,$$
$$A_{CP}^{B_s^0} = 0.236 \pm 0.013,$$
$$C_{KK} = 0.164 \pm 0.034,$$
$$S_{KK} = 0.123 \pm 0.034,$$
$$A_{KK}^{\Delta\Gamma} = -0.833 \pm 0.054,$$



- per-candidate is an alternative analysis technique applied to the same data set, results are consistent

- new results are in agreement with previous LHCb Run 1 measurements
- good agreement with BaBar / Belle (where applicable)
- most precise results from a single experiment to date
- the KK mixing parameters are differing from 0 0 -1 by 6.5 standard deviations

⇒ first observation of time-dependent CP violation in decays of the B^0_s meson

Parameter	Value
Δm_d	$0.5065 \pm 0.0019\,\mathrm{ps}^{-1}$
Γ_d	$0.6579 \pm 0.0017\,\mathrm{ps}^{-1}$
$\Delta\Gamma_d$	$0\,\mathrm{ps}^{-1}$
Δm_s	$17.757 \pm 0.021\,\mathrm{ps}^{-1}$
Γ_s	$0.6562 \pm 0.0021\,\mathrm{ps}^{-1}$
$\Delta\Gamma_s$	$0.082 \pm 0.005\,\mathrm{ps}^{-1}$
$\rho(\Gamma_s, \Delta\Gamma_s)$	-0.170

fixed inputs

CPV from 2-body neutral B meson (Bd/Bs) decays (cont.)

Phys. Rev. Lett. 126 (2021) 091802
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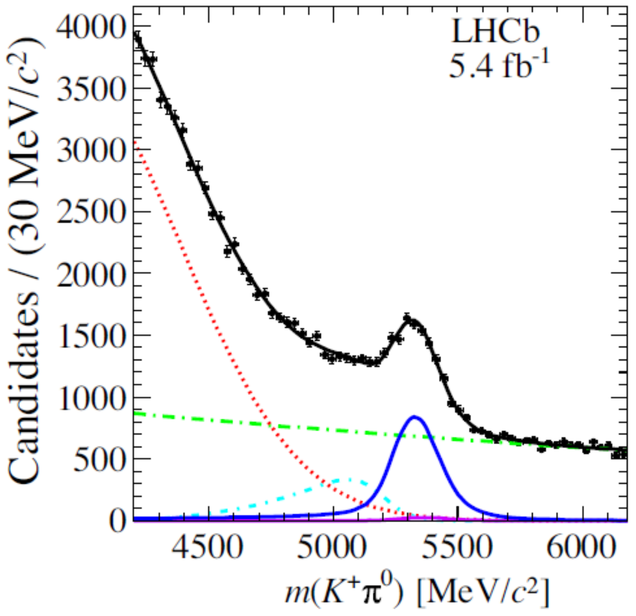
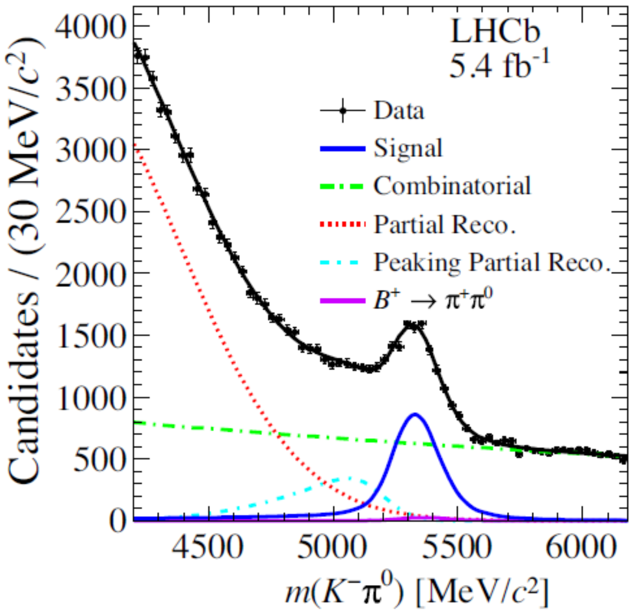
JHEP 03 (2021) 075





$B^+ \to K^+\pi^0$

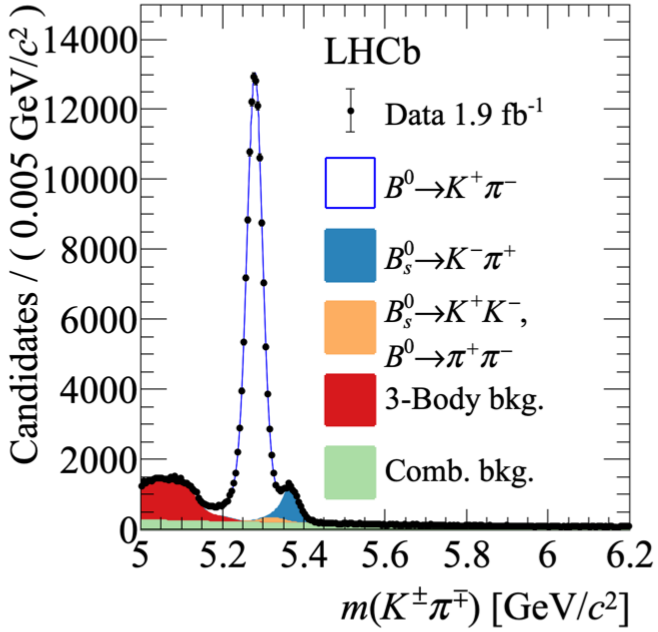
$$A_{CP} = \frac{\Gamma(B^- \to K^-\pi^0) - \Gamma(B^+ \to K^+\pi^0)}{\Gamma(B^- \to K^-\pi^0) + \Gamma(B^+ \to K^+\pi^0)}$$

- 5.4 /fb
- first analysis of a one-track decay at a hadron collider

$$A_{CP}(B^+ \to K^+\pi^0) = 0.025 \pm 0.015 \pm 0.006 \pm 0.003$$

stat., syst., ext. inputs

- exceeding the precision of the current world average (HFLAV)



$$A_{CP}^{B^0} = -0.0831 \pm 0.0034$$

- average of Phys. Rev. D 98 (2018) 032004 (3 /fb, Run 1) and JHEP 03 (2021) 075 (1.9 /fb, 2016-2016)

$$\Delta A_{CP}(K\pi) \equiv A_{CP}(B^+ \to K^+\pi^0) - A_{CP}(B^0 \to K^+\pi^-)$$

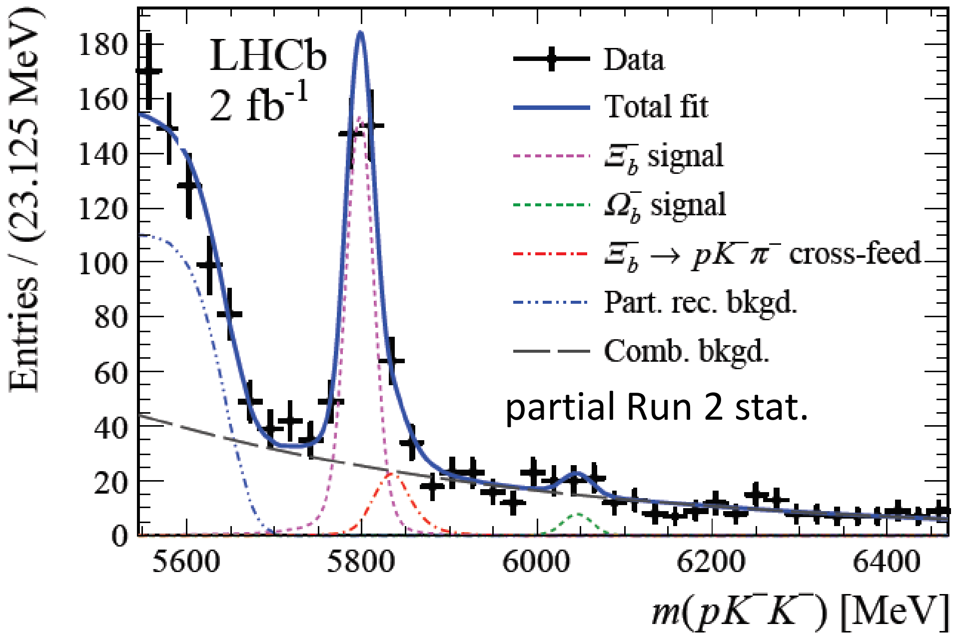
- is nonzero with a significance of more than 8 standard deviations (using the HFLAV averages updated with the above LHCb results) ⇒ isospin symmetry breaking
- accuracy substantially enhanced wrt previous measurement

B → K π puzzle

CPV from baryons decays

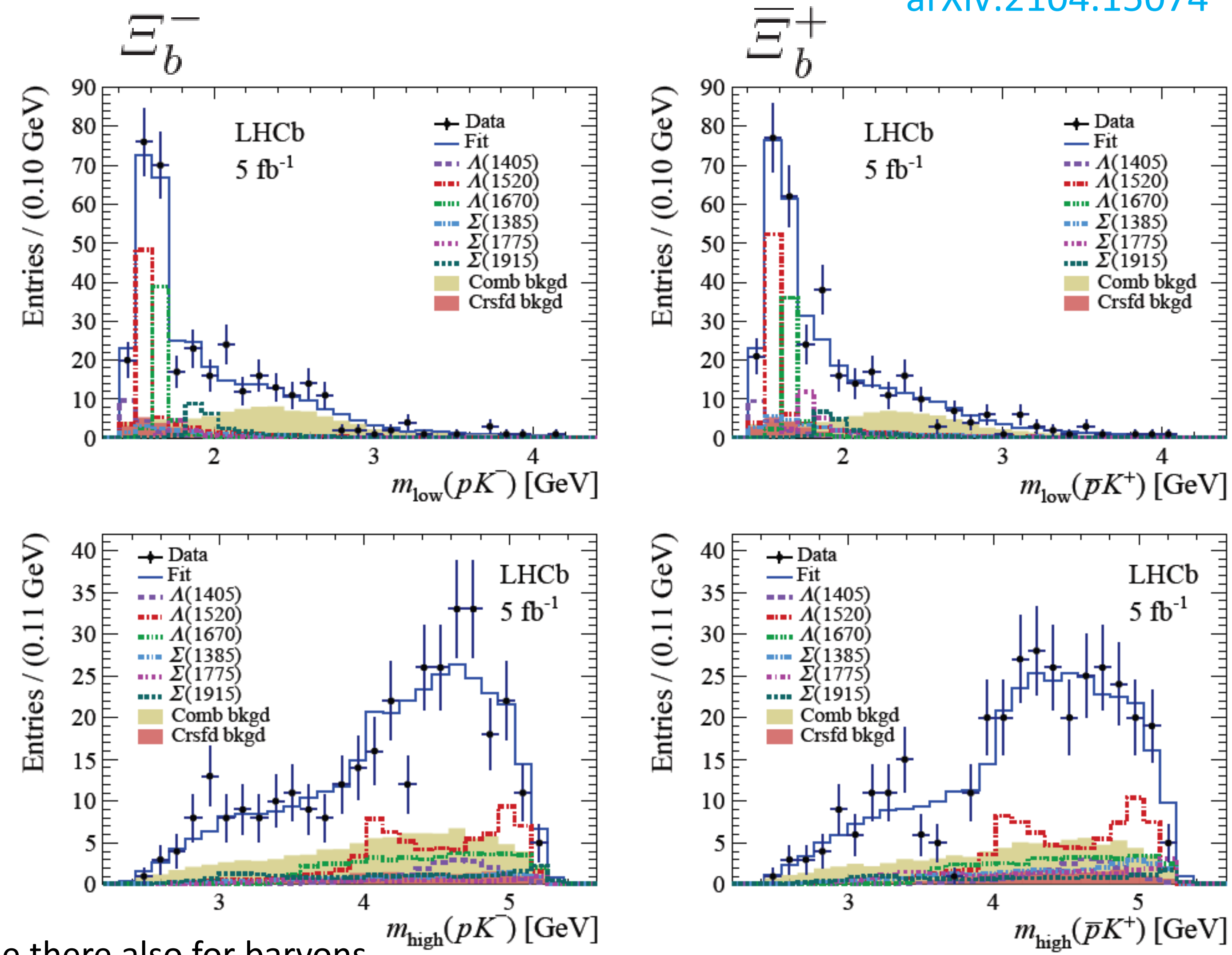
arXiv:2104.15074

$\Xi_b^- \to pK^-K^-$



$$A_i^{CP} = \frac{\int_\Omega (d\Gamma_i^+/d\Omega - d\Gamma_i^-/d\Omega) d\Omega}{\int_\Omega (d\Gamma_i^+/d\Omega + d\Gamma_i^-/d\Omega) d\Omega}$$

Component	A^{CP} (10^{-2})
$\Sigma(1385)$	-27 ± 34 (stat) ± 73 (syst)
$\Lambda(1405)$	-1 ± 24 (stat) ± 32 (syst)
$\Lambda(1520)$	-5 ± 9 (stat) ± 8 (syst)
$\Lambda(1670)$	3 ± 14 (stat) ± 10 (syst)
$\Sigma(1775)$	-47 ± 26 (stat) ± 14 (syst)
$\Sigma(1915)$	11 ± 26 (stat) ± 22 (syst)



- CPV should be there also for baryons
- Run 1 + partial Run 2 statistic (5 /fb overall)
- amplitude analysis: several, 6, contributing resonances
- CP asymmetry for each
- results consistent with 0, expect a large boost in stat. from Run 3 data

take home message

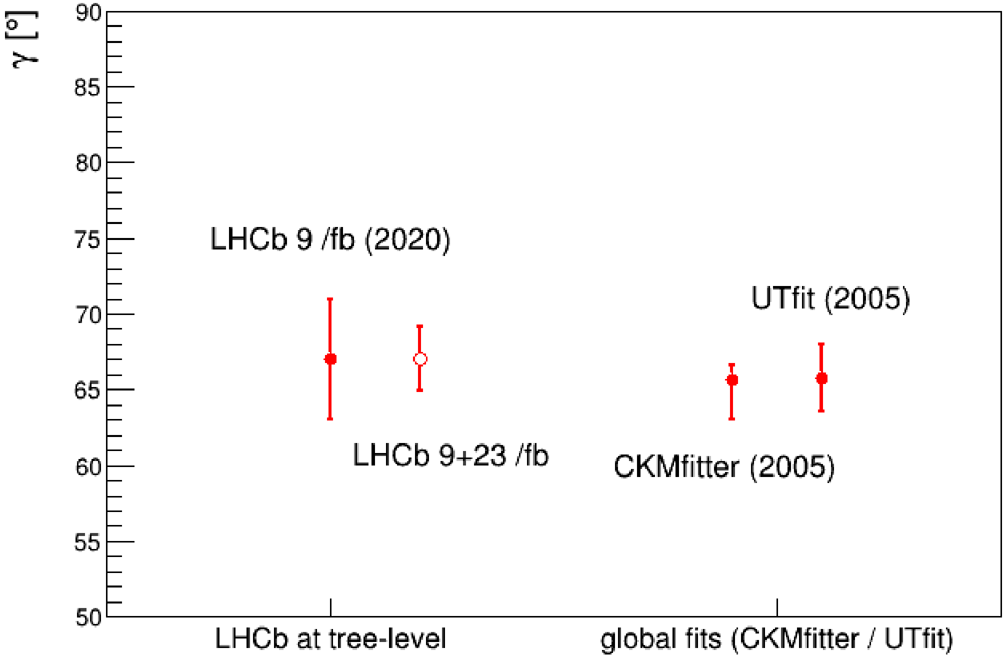
LHCb has performed outstanding measurements in beauty:

- Δm_s
- CKM γ
- CPV in 2-body neutral B meson (Bd/Bs) decays
- hunting CPV in the baryon sector

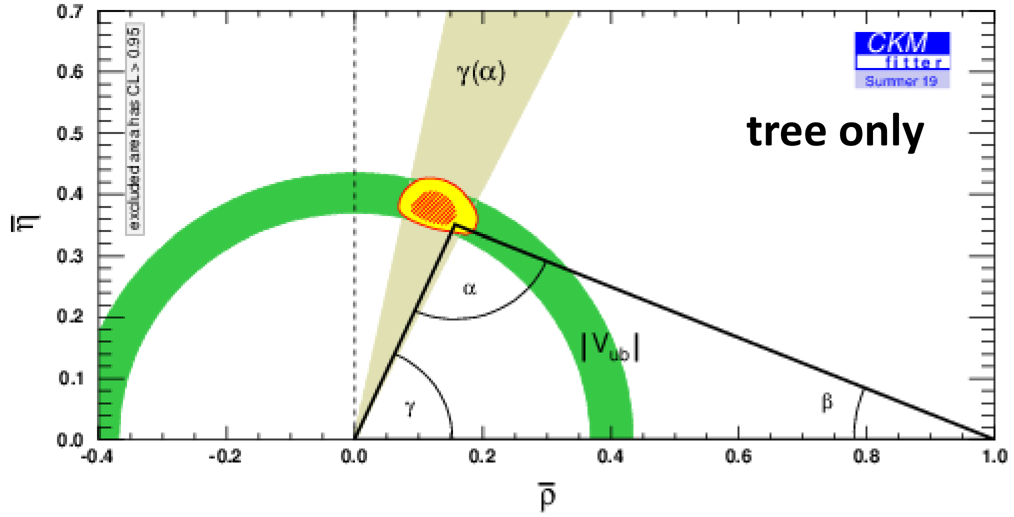
often:

- different and/or complementary decay channels
- different and/or complementary analysis techniques
- word best precision

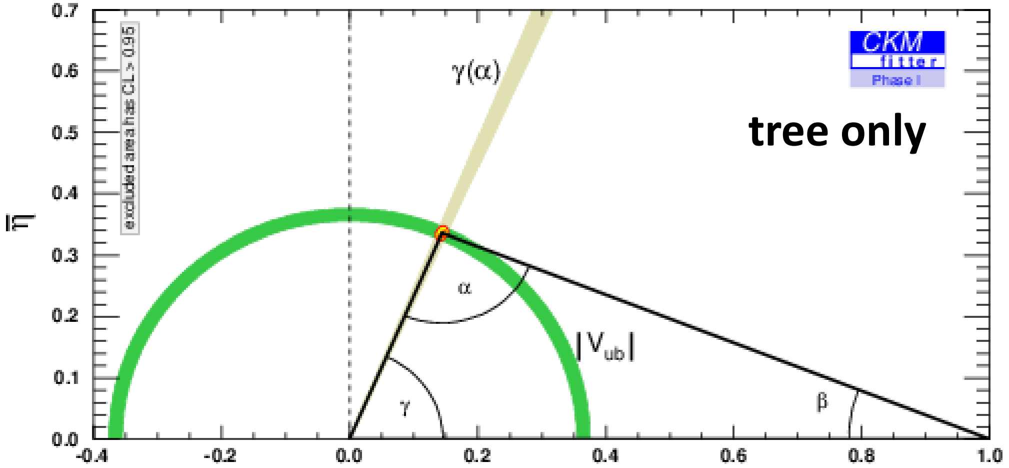
- given the LHC / LHCb upcoming upgrade era this was just an … **appetizer**
- expected to boost statistics far beyond 9 /fb on a relatively short time scale
- looking forward to contributions from Belle II



http://ckmfitter.in2p3.fr/www/results/plots_summer19/ckm_res_summer19.html



same plot after phase I: LHCb at 23 /fb, CMS/ATLAS at 300 /fb and Belle II at 50 /ab



http://ckmfitter.in2p3.fr/www/studies/plots_hllhc18/phase1/ckm_plots_hllhc18_phase1.html

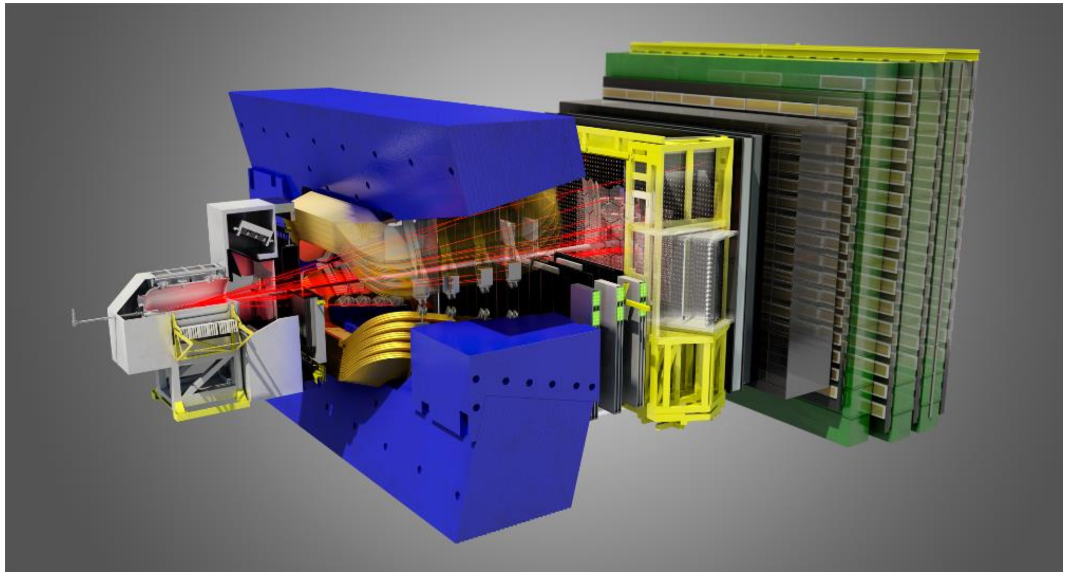
Thank you for your attention !

advertisement: **CPV and semileptonic in b-hadrons**, plenary session tomorrow , by my colleague Khanji Basem

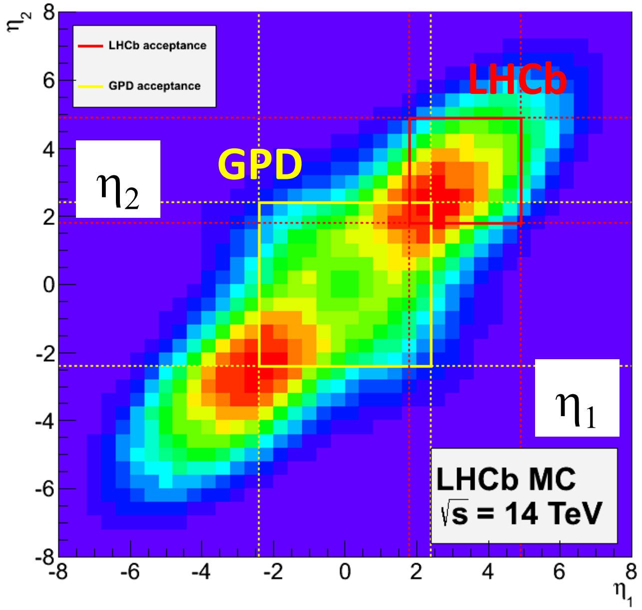
backups

LHCb: the detector and its performance so far

single-arm forward spectrometer at the LHC



b anti-b pairs produced



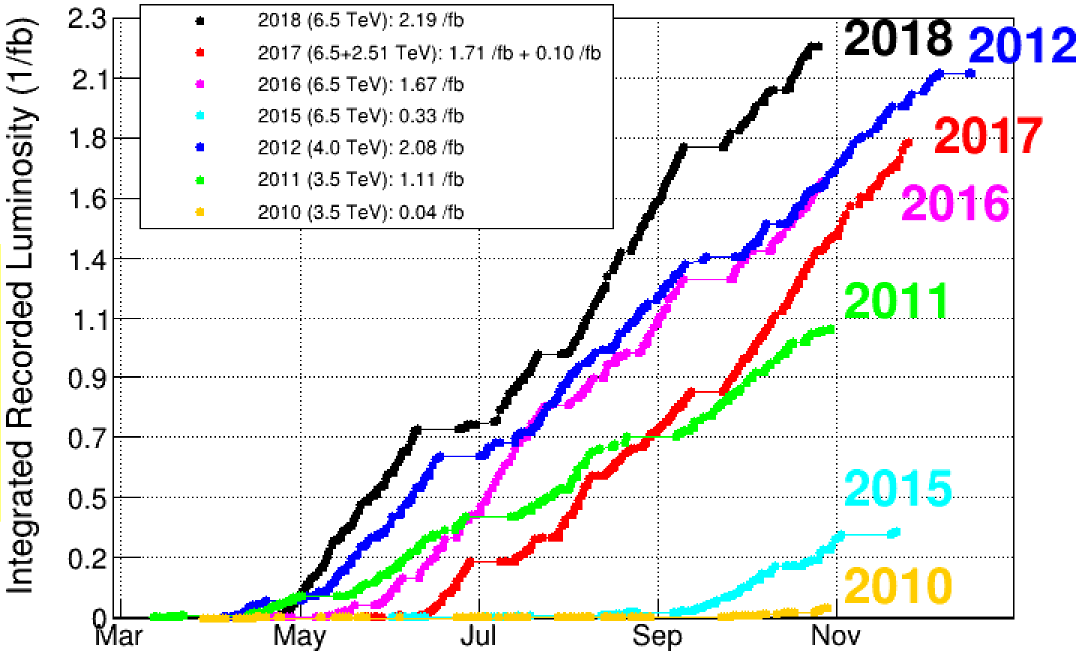
- detector paper:
JINST 3 (2008) S08005
- Run 1 performance:
Int. J. Mod. Phys. A30 (2015) 1530022
- Run 2 performance:
JINST 14 (2019) P04013

optimized for beauty and charm physics at $2 < \eta < 5$

key points:

- momentum resolution
  ($\sigma(p)/p \approx 0.5$ % (low momentum) to 1 % @ 200 GeV/c)
- impact parameter resolution
  ($\sigma(IP) \approx 15\ \mu m$ at high p_T)
- primary and secondary vertices reco.
- decay time resolution ($\sigma(t) \approx 50$ fs)
- 'global' PID: e / μ / π / K
  (K id ≈ 95 % π mis-id ≈ 5 %, p < 100 GeV/c)
- γ and π^0 reconstruction

recorded lumi.:
2011→ 2012 (Run 1): 3.19 /fb
~ 3 10^{11} b anti-b pairs prod.
2015 → 2018 (Run 2): 5.9 /fb
~ 2 x 6 10^{11} b anti-b pairs prod.



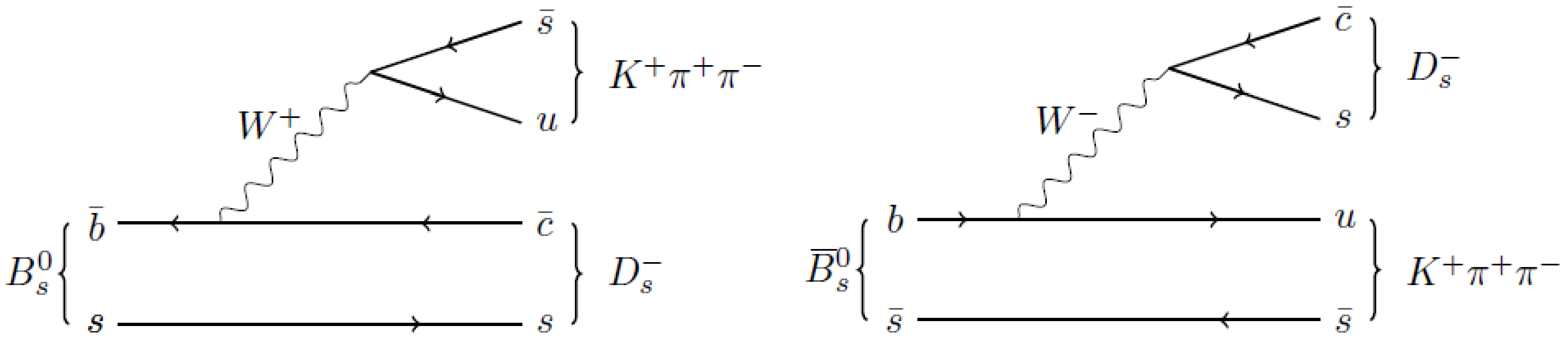


Figure 1. Leading-order Feynman diagrams for (left) B_s^0 and (right) $\overline{B}_s^0$ decays to the $D_s^- K^+\pi^+\pi^-$ final state, where the $\pi^+\pi^-$ subsystem exemplarily hadronises in conjunction with the kaon.

$$\frac{\mathrm{d}\Gamma(B_s^0 \to f)}{\mathrm{d}t} \propto \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_f \cos\left(\Delta m_s t\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - S_f \sin\left(\Delta m_s t\right)\right] e^{-\Gamma_s t},$$

$$\frac{\mathrm{d}\Gamma(\overline{B}_s^0 \to f)}{\mathrm{d}t} \propto \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - C_f \cos\left(\Delta m_s t\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + S_f \sin\left(\Delta m_s t\right)\right] e^{-\Gamma_s t}.$$

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

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

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