CP violation in the beauty sector at LHCb

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Outline

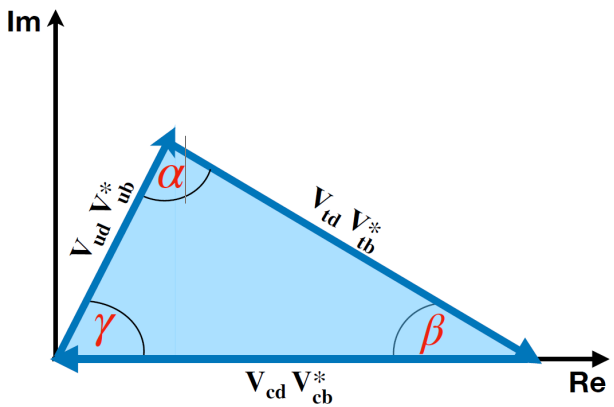
- **Short introduction**
- **LHCb results**:
  - **CKM γ: LHCb individual measurements and LHCb combination**
  - **Δm_s mass difference: LHCb individual measurements and combination**
  - **CPV in 2-body neutral $B^0_{(s)}$ meson decays**
  - **CPV for baryons in LHCb**
- **Conclusions**

CP violation (CPV) in the Standard Model

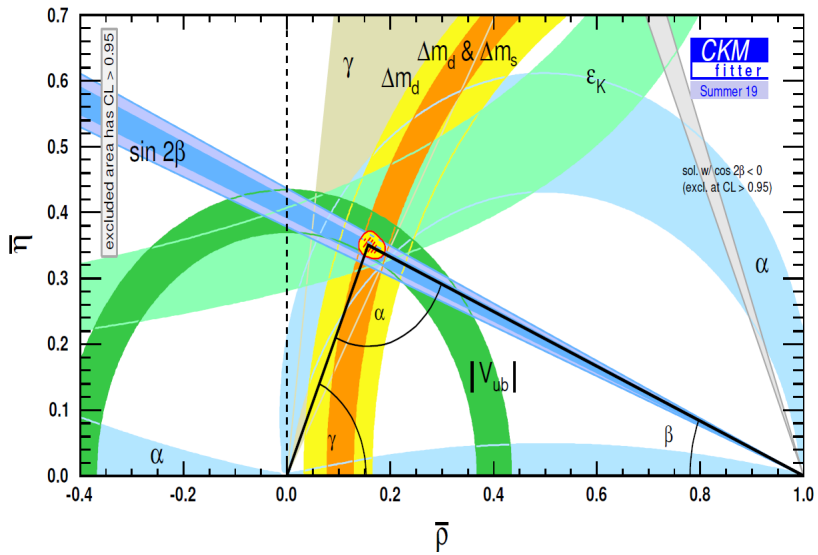
- CKM matrix describe quark charged current weak interactions:

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

- Key test of the Standard Model (SM): verify unitary of CKM matrix
  - **Magnitudes**: measuring branching fractions or mixing frequencies
  - **Phase**: measure *CPV*
- Sensitivity to BSM effects from global consistency of various measurements



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

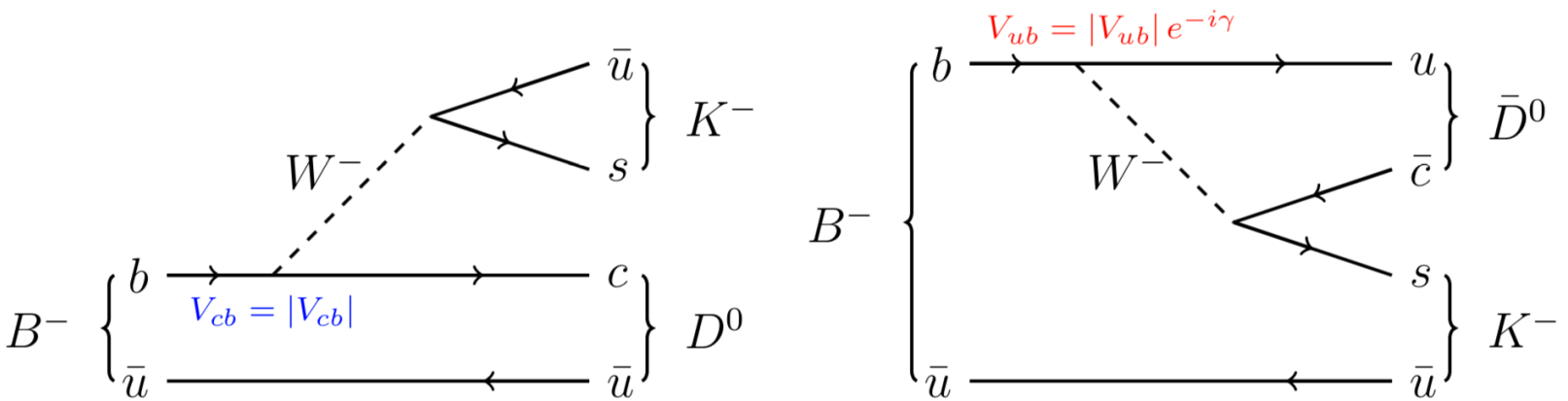


CKM angle γ

- γ is the phase between $b \to c$ and $b \to u$
- Determined from tree-level decays $\Longrightarrow$ SM benchmark
- Close sensitivity gap:
  - Direct measurement: $\gamma = (71.1^{+4.1}_{-4.5})^\circ$ [HFLAV20]
  - Indirect measurement: $\gamma = (65.7^{+1.0}_{-2.5})^\circ$ [CKMFitter19]
- **Tree-level** measurements:
  - CP-asymmetric rates in $B^\pm \to DK^\pm$:
    $D \to hh$ [JHEP04(2021)081]
    $D \to K^0_s hh$ [JHEP02(2021)169]
  - Time-dependent *CPV* in $B^0_s \to D^\mp_s K^\pm \pi^\pm \pi^\mp$ [JHEP03(2021)137]
- **Loop-level** measurements $B^0_s \to K^+K^-$ [JHEP03(2021)075]

CKM angle γ: direct CPV in $B^{\pm} \to DK^{\mp}(D \to K^{\pm}\pi^{\mp})$

- Update measurement to the full Run 1+2 data (9 fb^{-1}) [JHEP04(2021)081]
- Many *CP* observables are measured:
  - 9 from fully reconstructed decays
  - 19 from partially reconstructed decays (missing neutral particle)



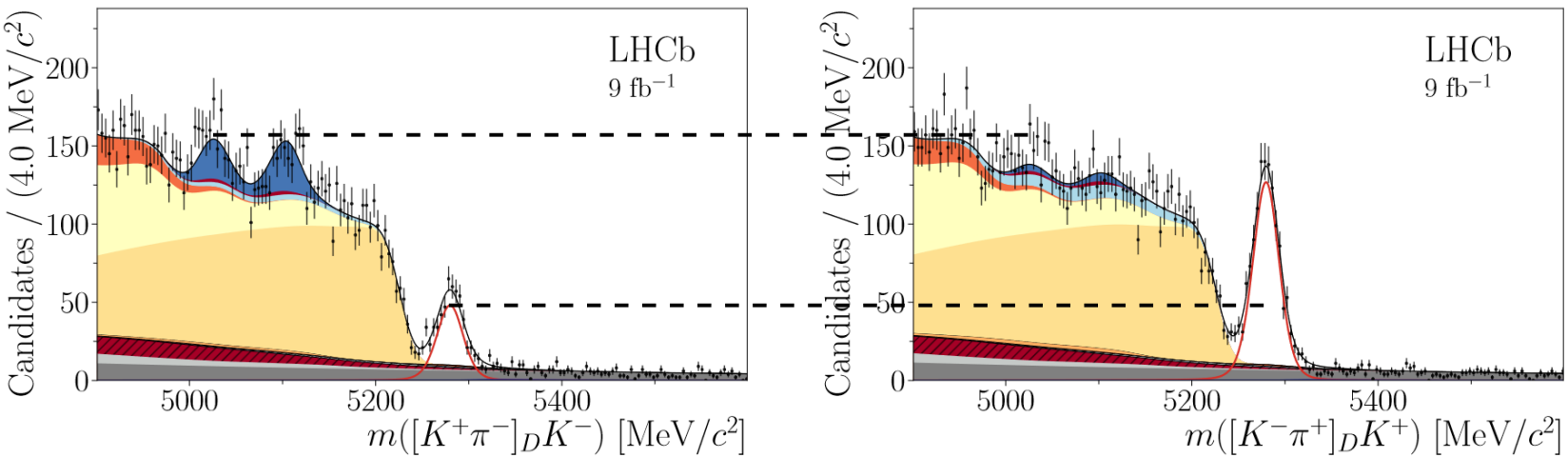
CKM angle γ: direct CPV in $B^{\pm} \to DK^{\mp}(D \to K^{\pm}\pi^{\mp})$ [JHEP04(2021)081]

- Measured decay rates:

$$\Gamma \propto |r_D e^{i\delta_D} + r_B e^{i(\delta_B - \gamma)}|^2 \qquad \bar{\Gamma} \propto |r_D e^{i\delta_D} + r_B e^{i(\delta_B + \gamma)}|^2$$

- Measured CP asymmetries:

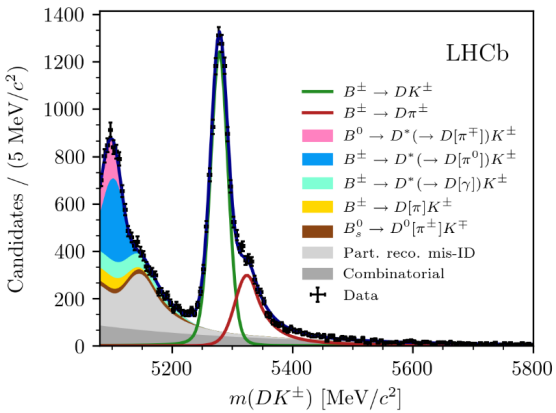
$$A_{CP} = \frac{2 r_B r_D \sin(\delta_B + \delta_D)\sin(\gamma)}{r_B^2 + r_D^2 + 2 r_B + r_D \cos(\delta_B + \delta_D)\cos(\gamma)}$$

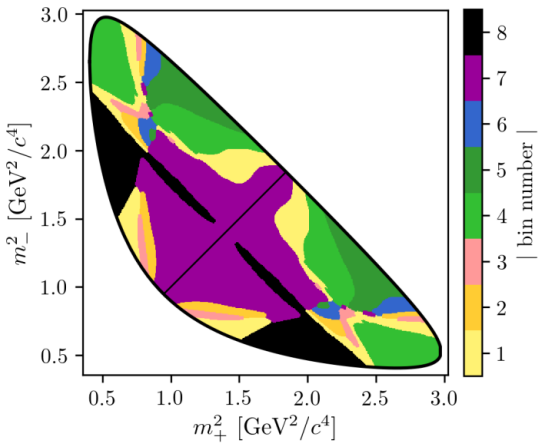


- Significant difference in peaks height!
- $A_{CP} = (45.1 \pm 2.6)\%$ fully rec., $A_{CP} = (71.7 \pm 28.6)\%$ partially rec.

CKM angle γ: $B^{\pm} \to DK^{\mp}(D \to K^0_S h^+ h^-)$

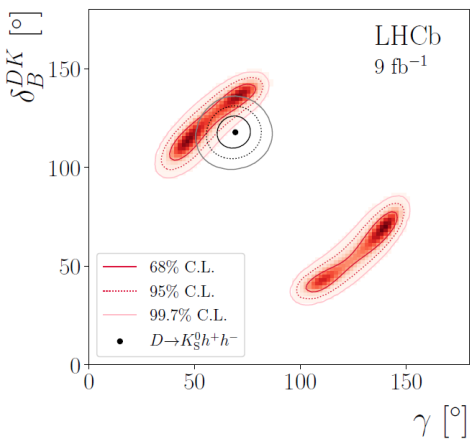
- Full Run 1+2 data (9 fb^{-1}) [JHEP02(2021)169]
- Measured *CPV* parameters from the distribution of events in Dalitz plot
- External input: from CLEO and BESIII combined data
  - strong-phase $\delta_D = arg(A_{D^0}) - arg(A_{\bar{D}^0})$ [PRD101, 112002(2020)]
- **Most precise γ measurement from a single analysis!**

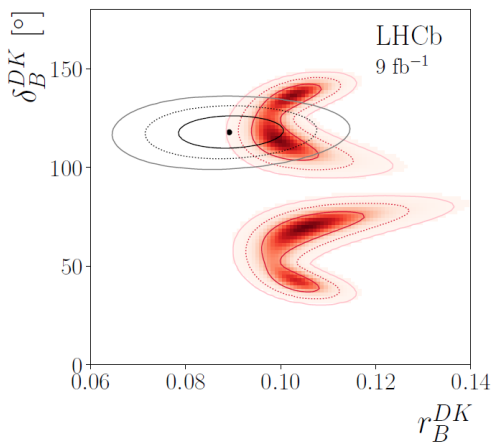




$$\gamma = (68.7^{+5.2}_{-5.1})^\circ$$
$$r_B^{DK^{\pm}} = 0.0904^{+0.0077}_{-0.0075}$$
$$\delta_B^{DK^{\pm}} = (118.3^{+5.5}_{-5.6})^\circ$$
$$r_B^{D\pi^{\pm}} = 0.0050 \pm 0.0017$$
$$\delta_B^{D\pi^{\pm}} = (291^{+24}_{-26})^\circ$$

- Combining results with previous analysis [JHEP04(2021)081]
- All *CP* observables measured with world-best precision
- Two-fold ambiguity solved!

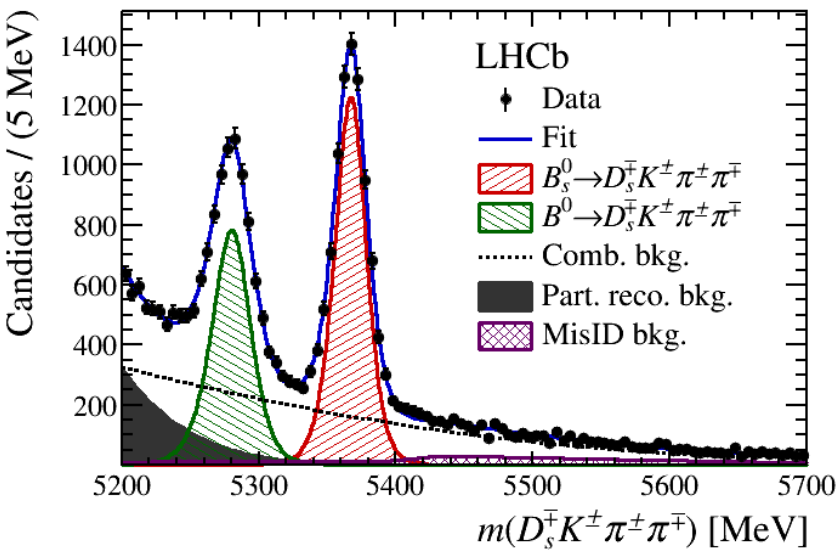


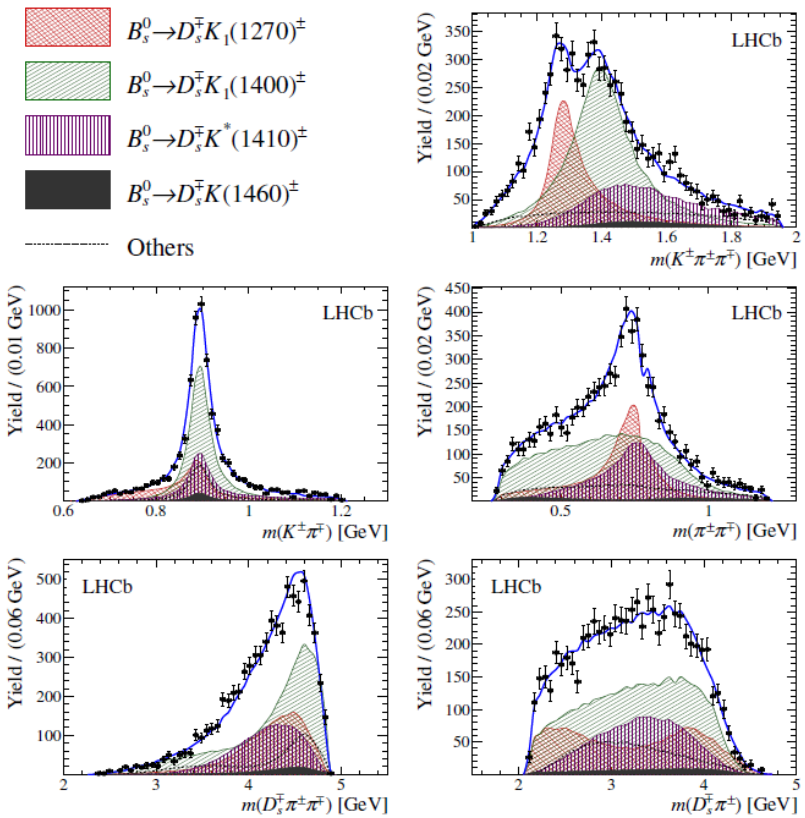


CKM angle γ: Time-dependent measurement on $B_s^0 \to D_s^{\mp} K^{\pm} \pi^{\pm} \pi^{\mp}$

- Full Run 1+2 data ~ 9 fb^{-1} [JHEP03(2021)137]
- *CPV* due to interference between mixing and decay
- Many contributions from different channels $\Longrightarrow$ amplitude analysis

- Two different strategies:
  - model-dependent: describe resonance with amplitude model
  - model-independent: integrate over the phase-space





CKM angle γ: Time-dependent measurement on $B_s^0 \to D_s^{\mp} K^{\pm} \pi^{\pm} \pi^{\mp}$ (II)

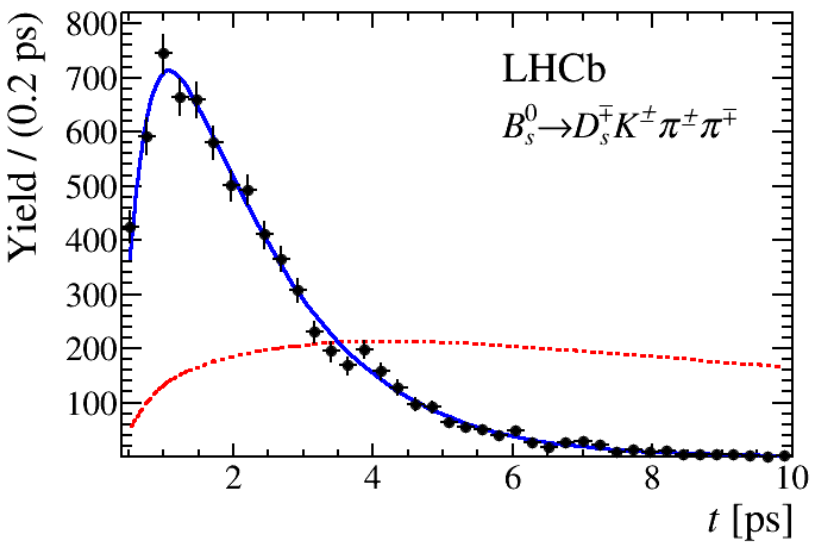
- Full time-dependent amplitude fit

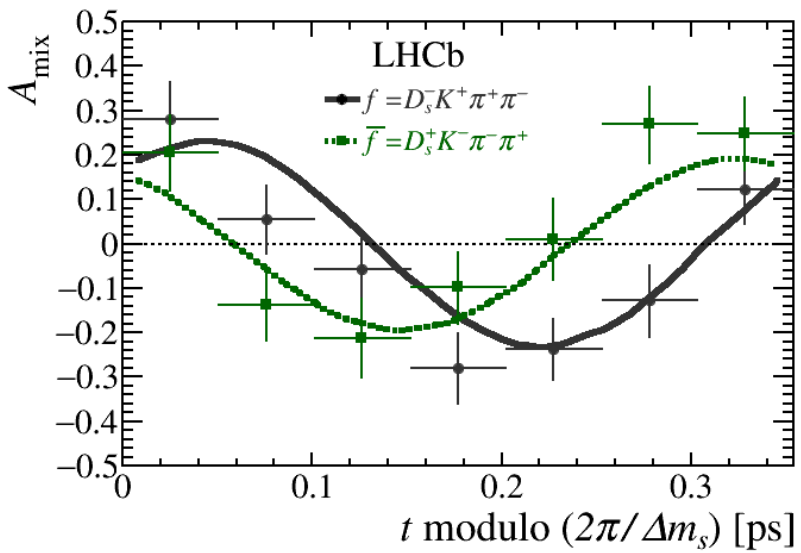
$$\gamma - 2\beta_s = 42 \pm 10(stat.) \pm 4(sys.) \pm 5(model)$$

- Model-independent fit:

$$\gamma - 2\beta_s = 42^{+19}_{-13}(stat.)^{+6}_{-2}(sys.)$$

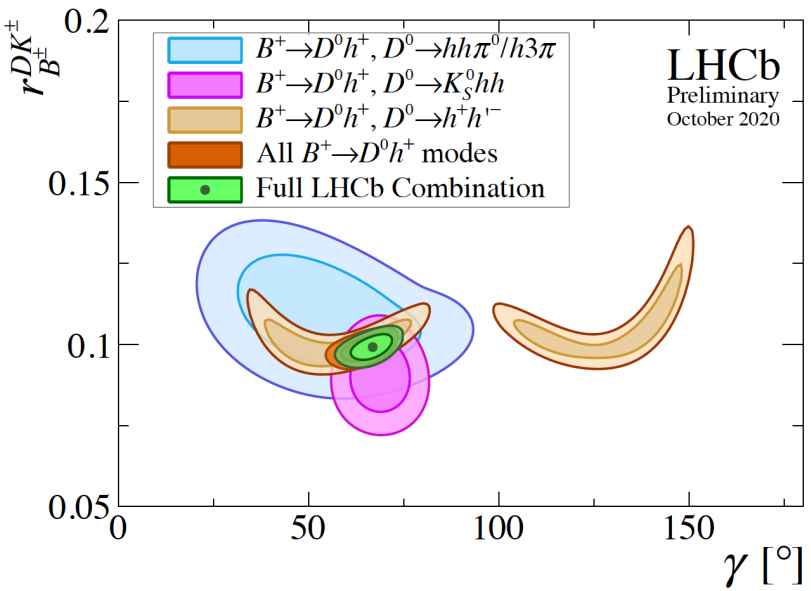
Good agreement between the two methods!

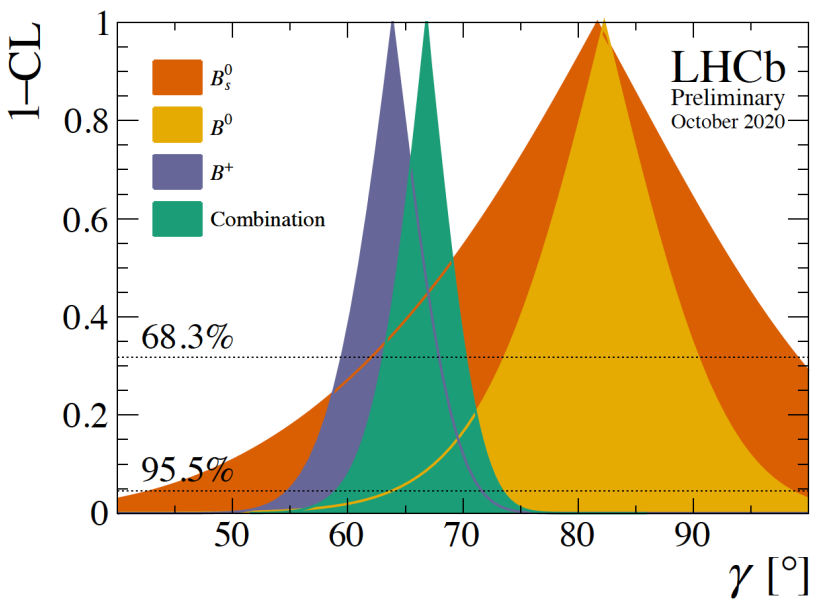




CKM angle γ: LHCb combination

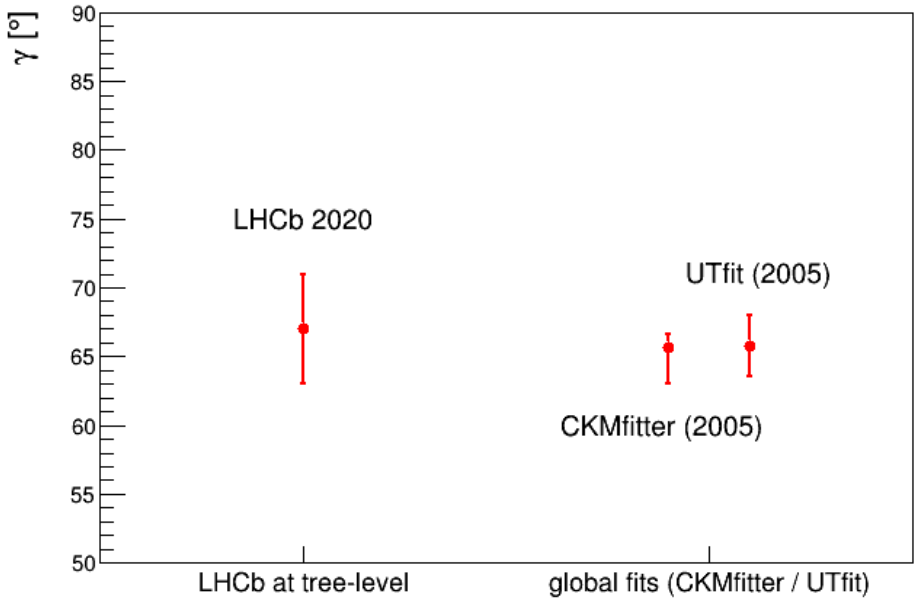
- Previous LHCb average: $\gamma = (74^{+5}_{-6})^\circ$ [LHCb-CONF-2018-002]
- New average $\gamma = (67 \pm 4)^\circ$
  - including the analysis presented in this talk
  - and more, see [LHCb-CONF-2020-003]





CKM angle γ: LHCb combination (II)

- LHCb is closing the sensitivity gap between direct meas. and global fits
- Δm_s is important input for *CPV* measurements in B_s decays [arXiv:2104.04421]
- New precise measurement of Δm_s and β_s [LHCB-PAPER-2020-042] are vital input for global CKM fits



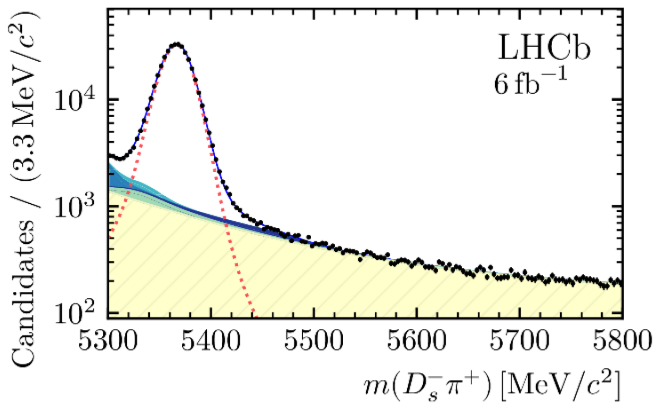
- Any disagreement between the values obtained with the two fit methods would imply physics beyond the SM:
  - new particles or mediators exchanged in loops

Measurement of Δm_s at LHCb

- Exploiting the flavour specific nature of this decay, i.e. just oscillations
- Two decay modes: $B_s^0 \to D_s^- \pi^+$ and $B_s^0 \to D_s^- \pi^+ \pi^- \pi^+$

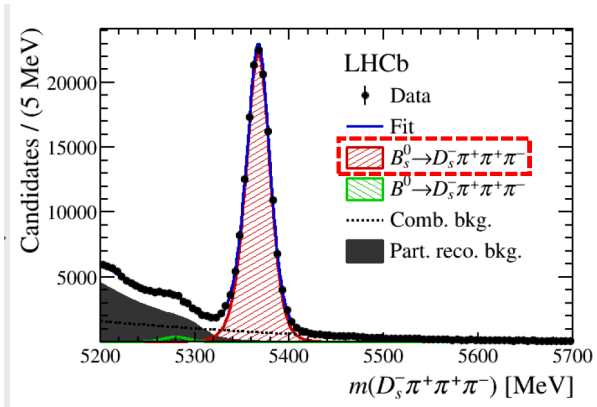
$$\mathbf{B_s^0 \to D_s^- \pi^+}$$

- Using full Run2 statistic (6 fb^{-1}) [arXiv:2104.04421]
  - partial Run 1 (1 fb^{-1}) analysis already published [New J.Phys. 15(2013)053021]
- Signal yield: 378.7 k events



$$\mathbf{B_s^0 \to D_s^- \pi^+ \pi^- \pi^+}$$

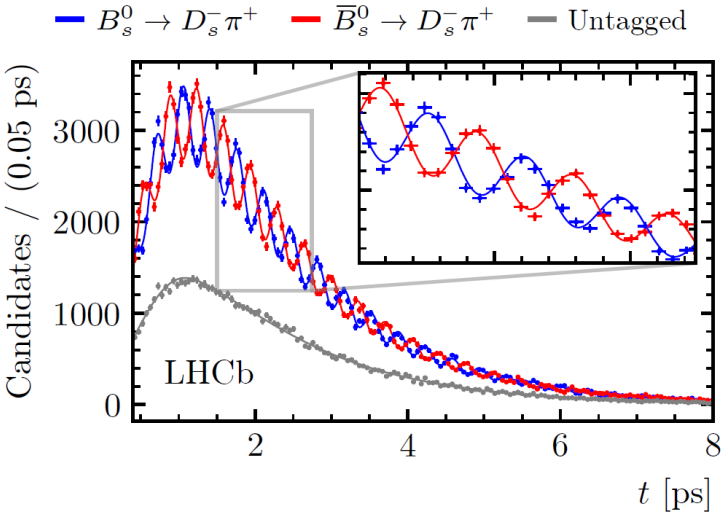
- Using full Run 1+2 statistic (9 fb^{-1}) [JHEP03(2021)137]
- Signal yield: 148 k events



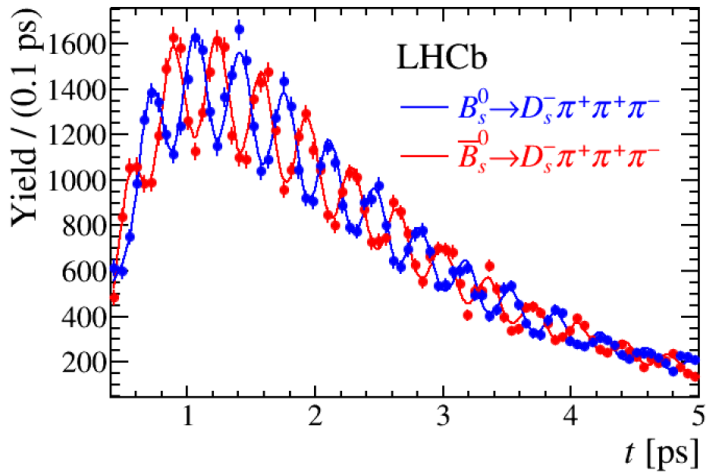
Measurement of Δm_s at LHCb (II)

- Δm_s from a fit to the background subtracted decay-time distribution
- Spectacular decay time asymmetry distribution

[arXiv:2104.04421]



[JHEP03(2021)137]

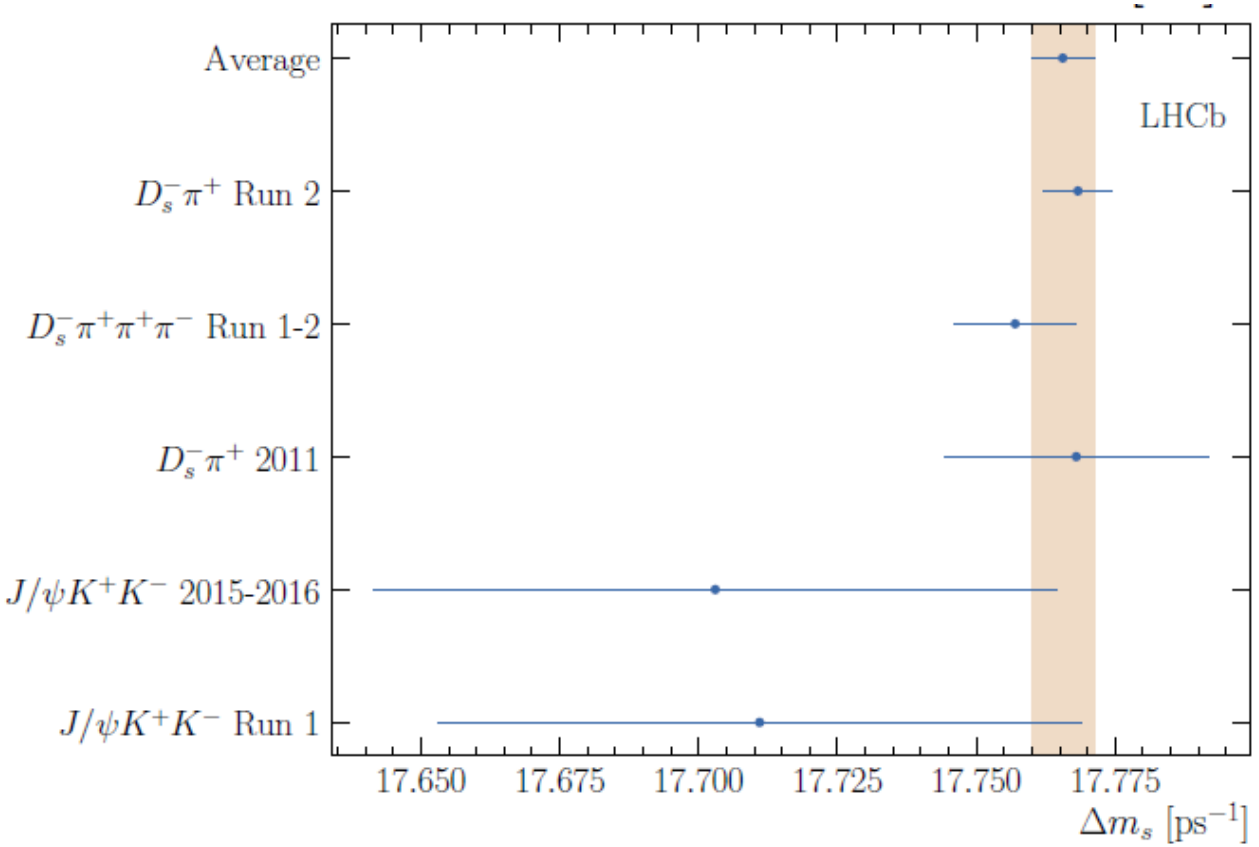


Decay mode	Data sample	Δm_s ps^{-1}
$B_s^0 \to D_s^- \pi^+$ [New J.Phys. 15(2013)053021]	2011	$17.768 \pm 0.023 \pm 0.006$
$B_s^0 \to D_s^- \pi^+ \pi^- \pi^+$ [JHEP03(2021)137]	2011-2018	$17.757 \pm 0.007 \pm 0.008$
$B_s^0 \to D_s^- \pi^+$ [arXiv:2104.04421]	2015-2018	$17.7683 \pm 0.0051 \pm 0.0032$
Average		17.7666 ± 0.0057

More precise than WA!! (PDG20: $\Delta m_s = (17.756 \pm 0.021)$ ps^{-1})

Measurement of Δm_s at LHCb (III) [arXiv:2104.04421]

- Combination of all the LHCb results: 17.7666 ± 0.0057 ps^{-1}
- Interesting measurement on its own and crucial input for future time-dependent *CP* analyses



CPV in two body neutral B meson decays [JHEP2103(2021)075]

- Unbinned likelihood fit to invariant mass, decay-time and mistag probability for the three different final states: $K^{\pm}\pi^{\mp}$, $\pi^+\pi^-$ and K^+K^-

- **Time-integrated *CP* asymmetry** in $B^0 \to K^+\pi^-$ and $B_s \to \pi^+K^-$

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

- **Time-dependent *CP* asymmetry** in $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$

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

$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \qquad S_f = \frac{2Im\lambda_f}{1+|\lambda_f|^2} \qquad A_f^{\Delta\Gamma} = \frac{2Re\lambda_f}{1+|\lambda_f|^2}$$

direct *CPV* — mixing induced *CPV*

$$|C_f|^2 + |S_f|^2 + |A_f^{\Delta\Gamma}|^2 = 1$$

constraint not imposed

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

CPV in two body neutral B meson decays (II) [JHEP2103(2021)075]

- Two alternative strategies: ”Simultaneous” and ”Per-candidate”
- Using the 2015-2016 data: ~ 1.9 fb^{-1}
- Results are consistent and in agreement with previous measurements
- Most precise result from single experiment to date

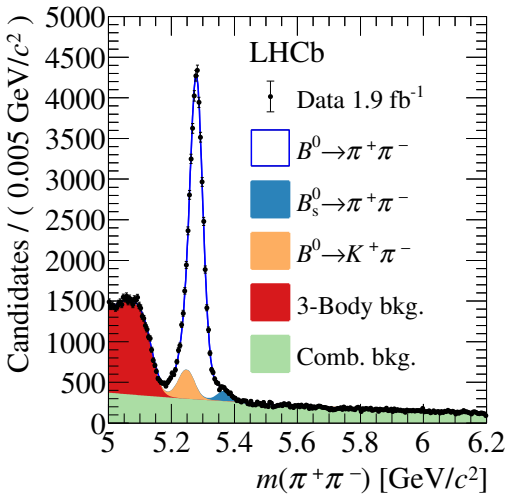
Final results

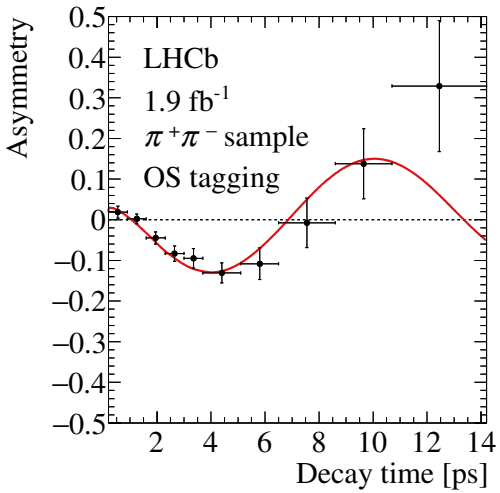
$$
\begin{aligned}
C_{\pi\pi} &= -0.311 \pm 0.045 \\
S_{\pi\pi} &= -0.706 \pm 0.042 \\
A_{CP}^{B^0} &= -0.0824 \pm 0.0033 \\
A_{CP}^{B_s^0} &= 0.236 \pm 0.013 \\
C_{KK} &= 0.164 \pm 0.034 \\
S_{KK} &= 0.123 \pm 0.034 \\
A_{KK}^{\Delta\Gamma} &= -0.833 \pm 0.054
\end{aligned}
$$

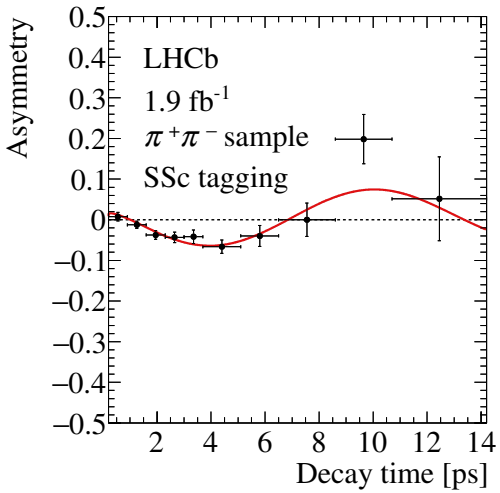
Fixed parameters

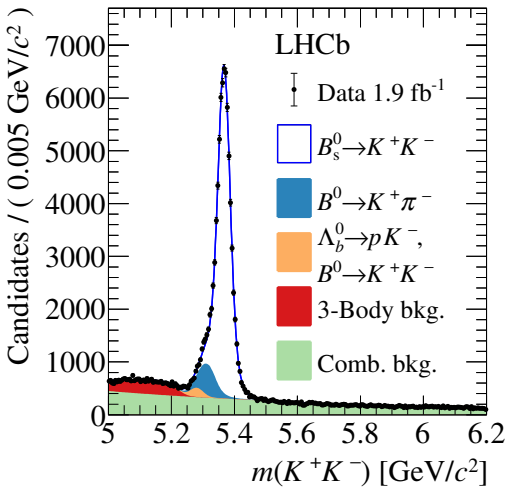
Parameter	Value
Δm_d	$0.5065 \pm 0.0019\ ps^{-1}$
Γ_d	$0.6579 \pm 0.0017\ ps^{-1}$
$\Delta\Gamma_d$	$0\ ps^{-1}$
Δm_s	$17.757 \pm 0.021\ ps^{-1}$
Γ_s	$0.6562 \pm 0.0021\ ps^{-1}$
$\Delta\Gamma_s$	$0.082 \pm 0.005\ ps^{-1}$
$\rho(\Gamma_s, \Delta\Gamma_s)$	-0.170

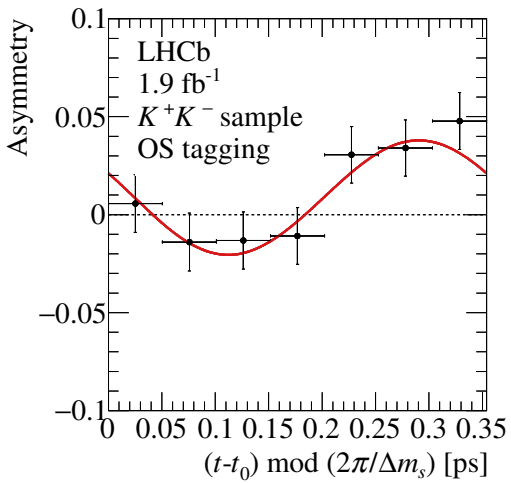
CPV in two body neutral B meson decays (III) [JHEP2103(2021)075]

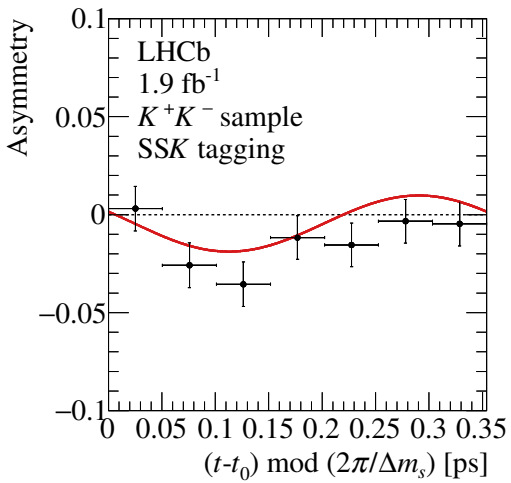






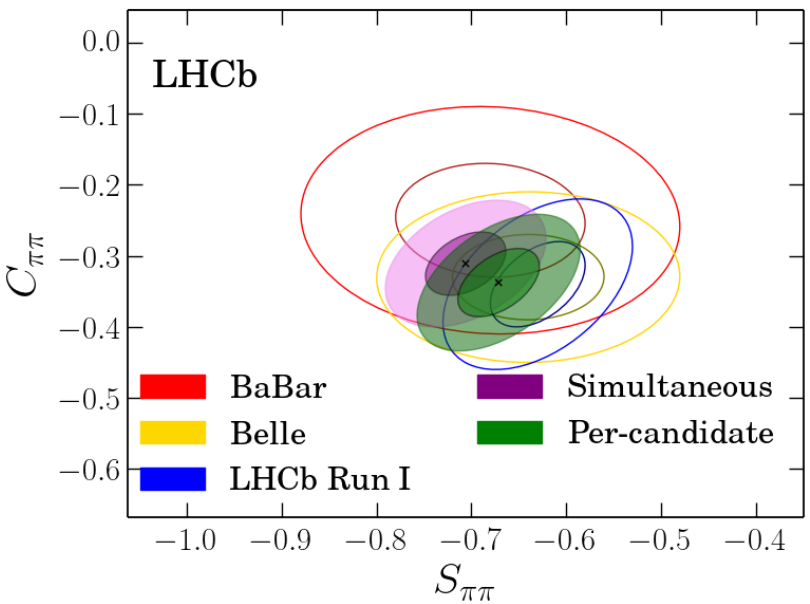


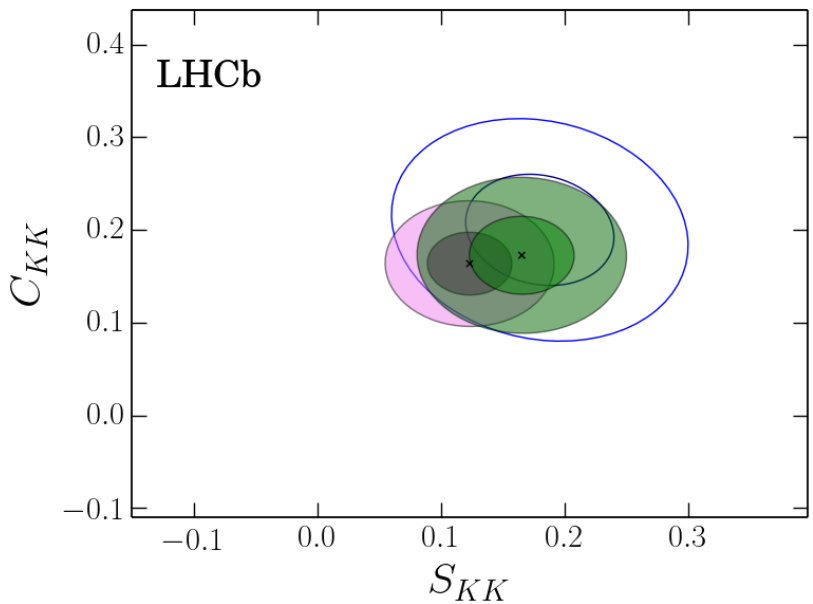




CPV in two body neutral B meson decays (IV) [JHEP2103(2021)075]

- Sensible to α, β, γ, β_s
- KK mixing parameter differs from (0, 0, -1) by 6.5 standard deviations:
  $\Longrightarrow$ first observation of time-dependent *CP* violation in B_s^0 decays



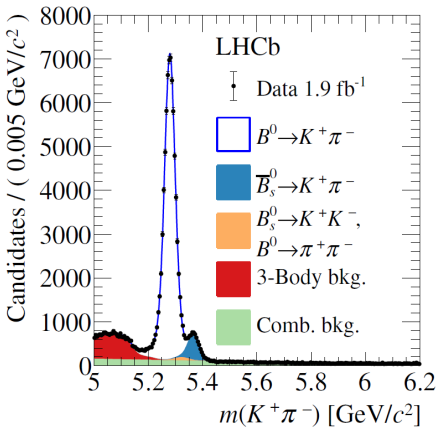


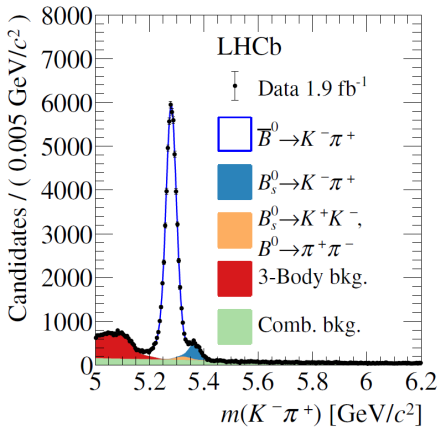
The B $\to$ Kπ puzzle

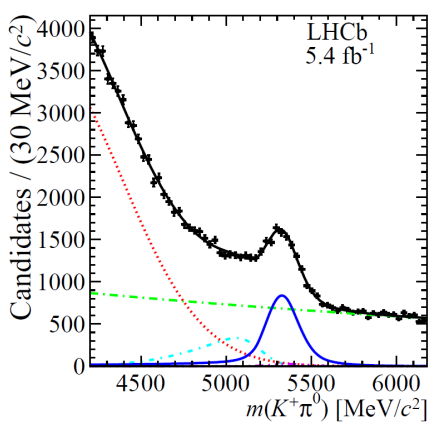
- Direct *CP* in $B^+ \to K^+\pi^0$ decays, 5.4 fb^{-1}
- First analysis of a one-track decay at a hadron collider
- Expected isospin symmetry but

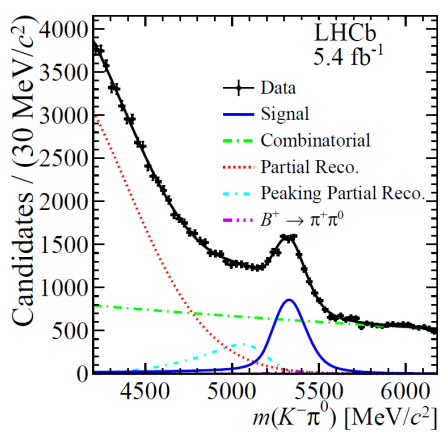
$$\Delta A_{CP}(K\pi) \equiv A_{CP}(B^+ \to K^+\pi^0) - A_{CP}(B^0 \to K^\pm\pi^\mp) \neq 0 \text{ by } 8.8\sigma!$$

Isospin symmetry breaking









$$A_{CP}^{B^0} = (-8.24 \pm 0.03 \pm 0.03)\%$$
$$(stat, syst)$$

[JHEP2103(2021)075]

$$A_{CP}^{B^+} = (2.5 \pm 1.5 \pm 0.6 \pm 0.3)\%$$
$$(stat, syst, ext.inputs)$$

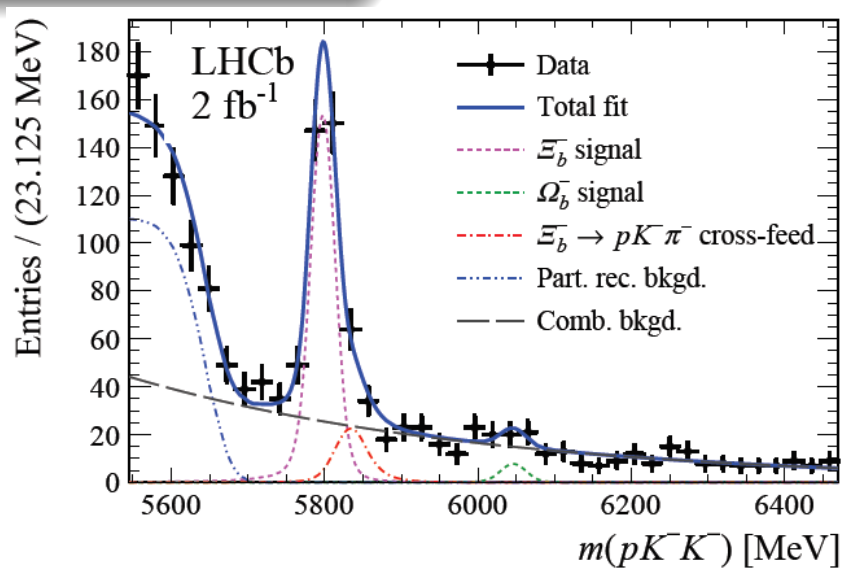
[Phys. Rev. Lett. 126(2021)091802]

CPV from baryons decays [arXiv:2104.15074]

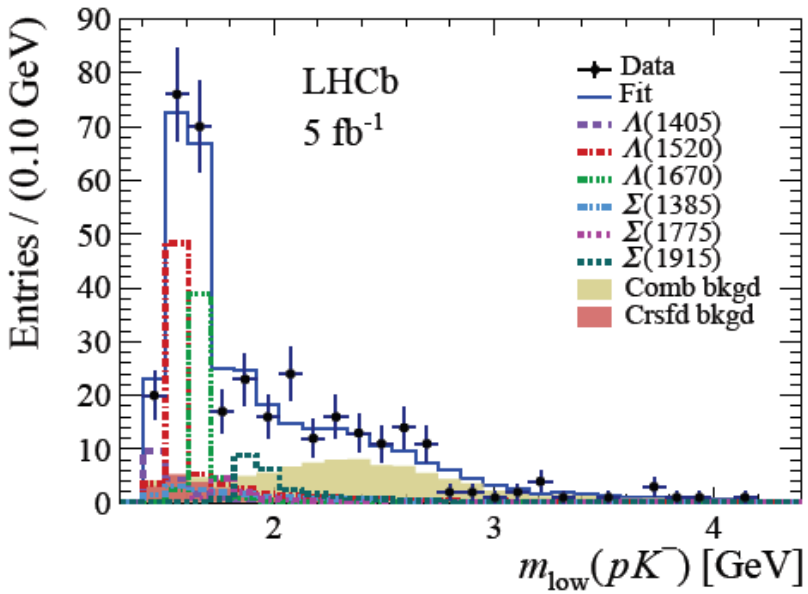
- *CPV* should also appear in baryons decays
- Using $\Xi_b^- \to pK^-K^-$, Run 1 + partial Run 2 $\sim$ 500 events [5 fb^{-1}]
- Many contributions from resonances $\Longrightarrow$ amplitude analysis
- *CP* asymmetry determined for each component
- Results consistent with 0, expected significant improvements in Run 3 due to a large boost in stat.

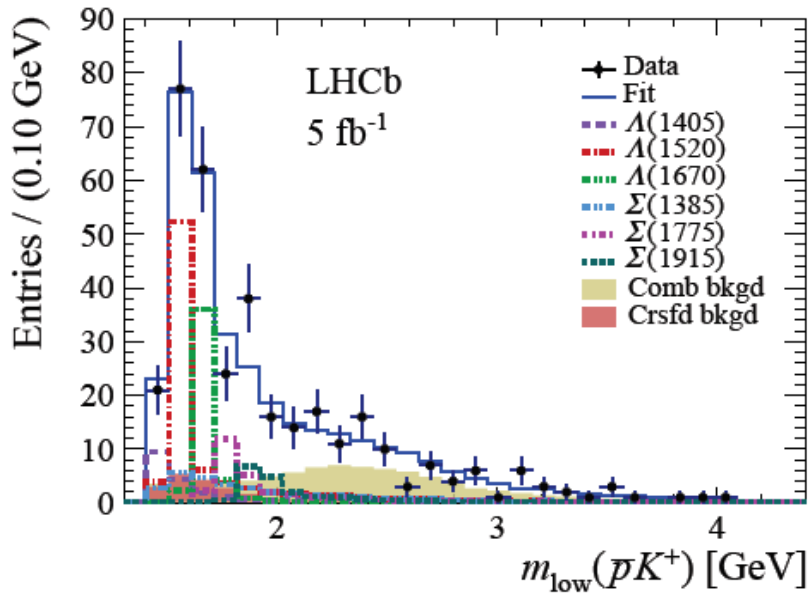
$$A^{CP} = \frac{\int_\Omega (d\Gamma_i^+/d\Omega - d\Gamma_i^-/d\Omega)d\Omega}{\int_\Omega (d\Gamma_i^+/d\Omega + d\Gamma_i^-/d\Omega)d\Omega}$$

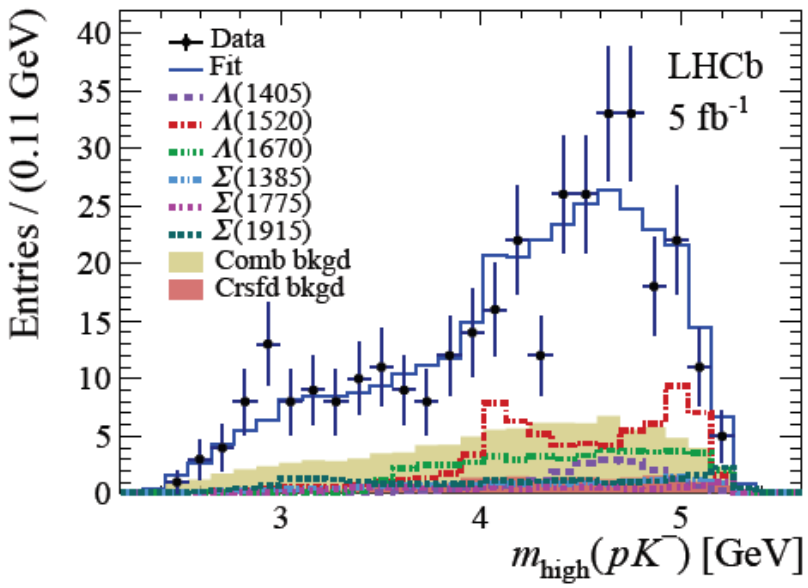
Component	$A^{CP}(10^{-2})$ (stat, syst)
$\Sigma(1385)$	$-27 \pm 34 \pm 73$
$\Lambda(1405)$	$-1 \pm 24 \pm 32$
$\Lambda(1520)$	$-5 \pm 9 \pm 8$
$\Lambda(1670)$	$3 \pm 14 \pm 10$
$\Sigma(1775)$	$-47 \pm 26 \pm 14$
$\Sigma(1915)$	$11 \pm 26 \pm 22$

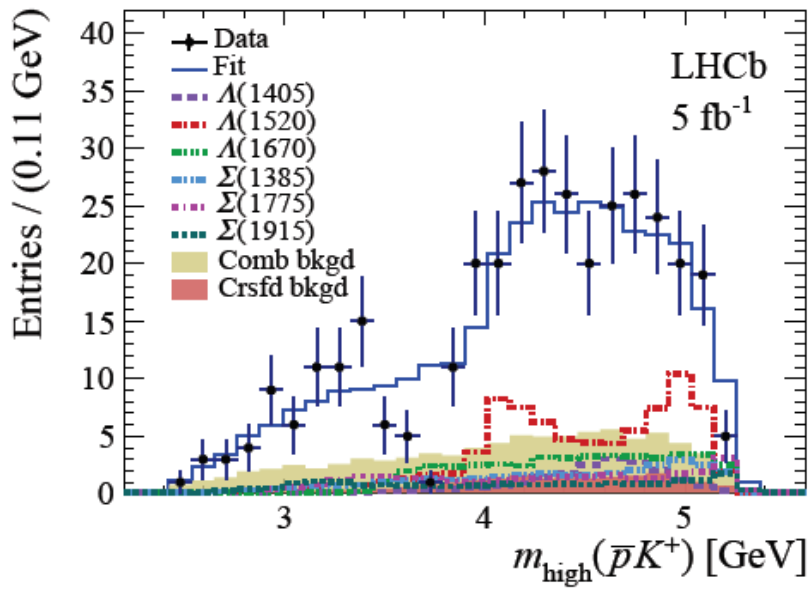


CPV from baryons decays (II) [arXiv:2104.15074]







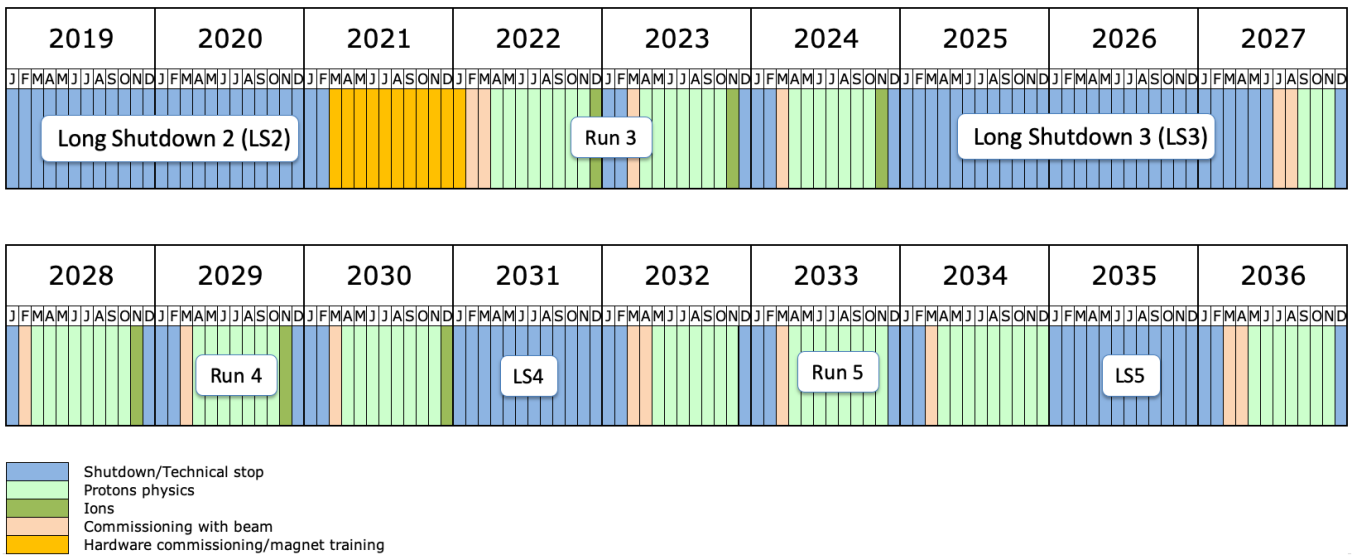


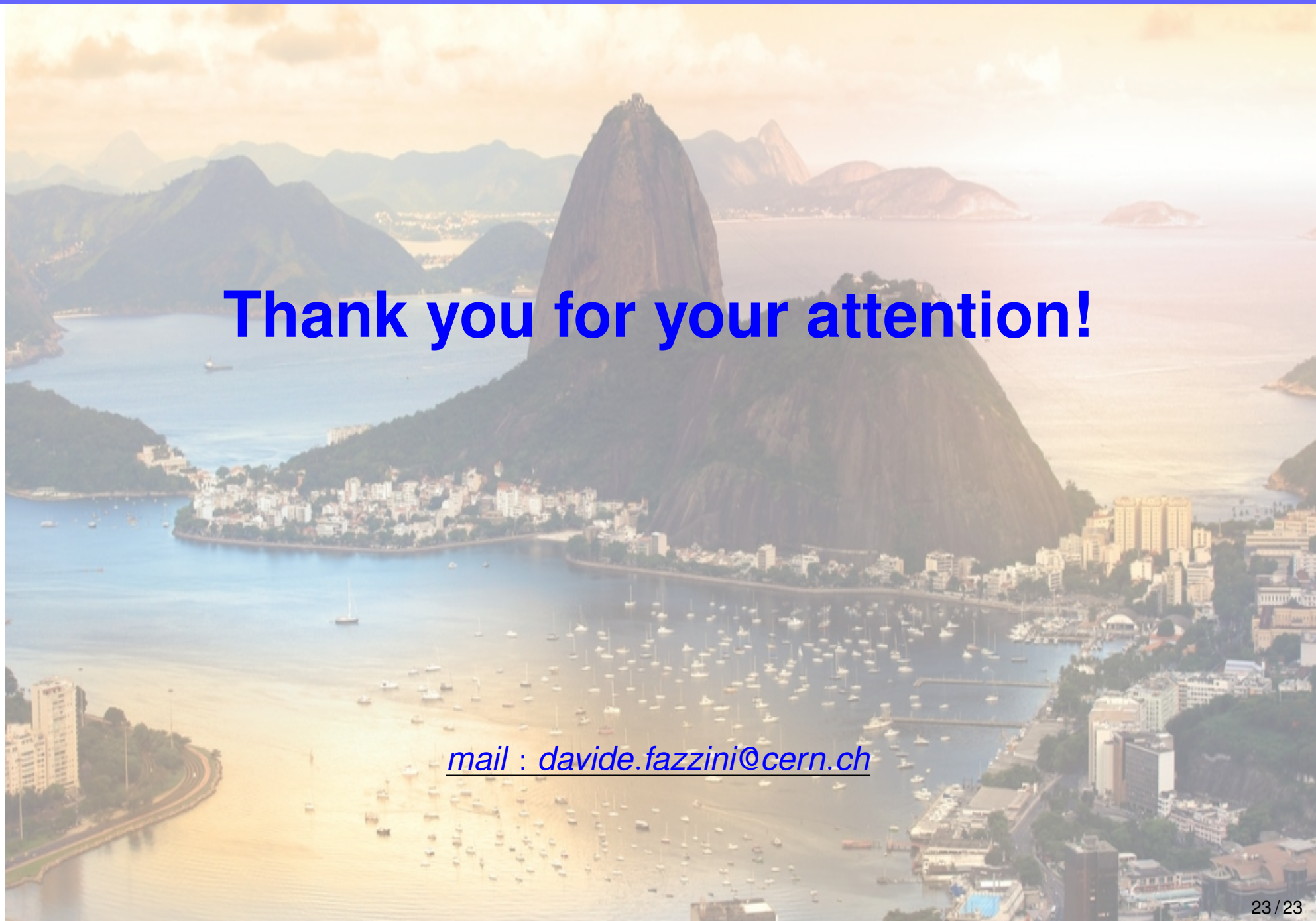
Conclusions

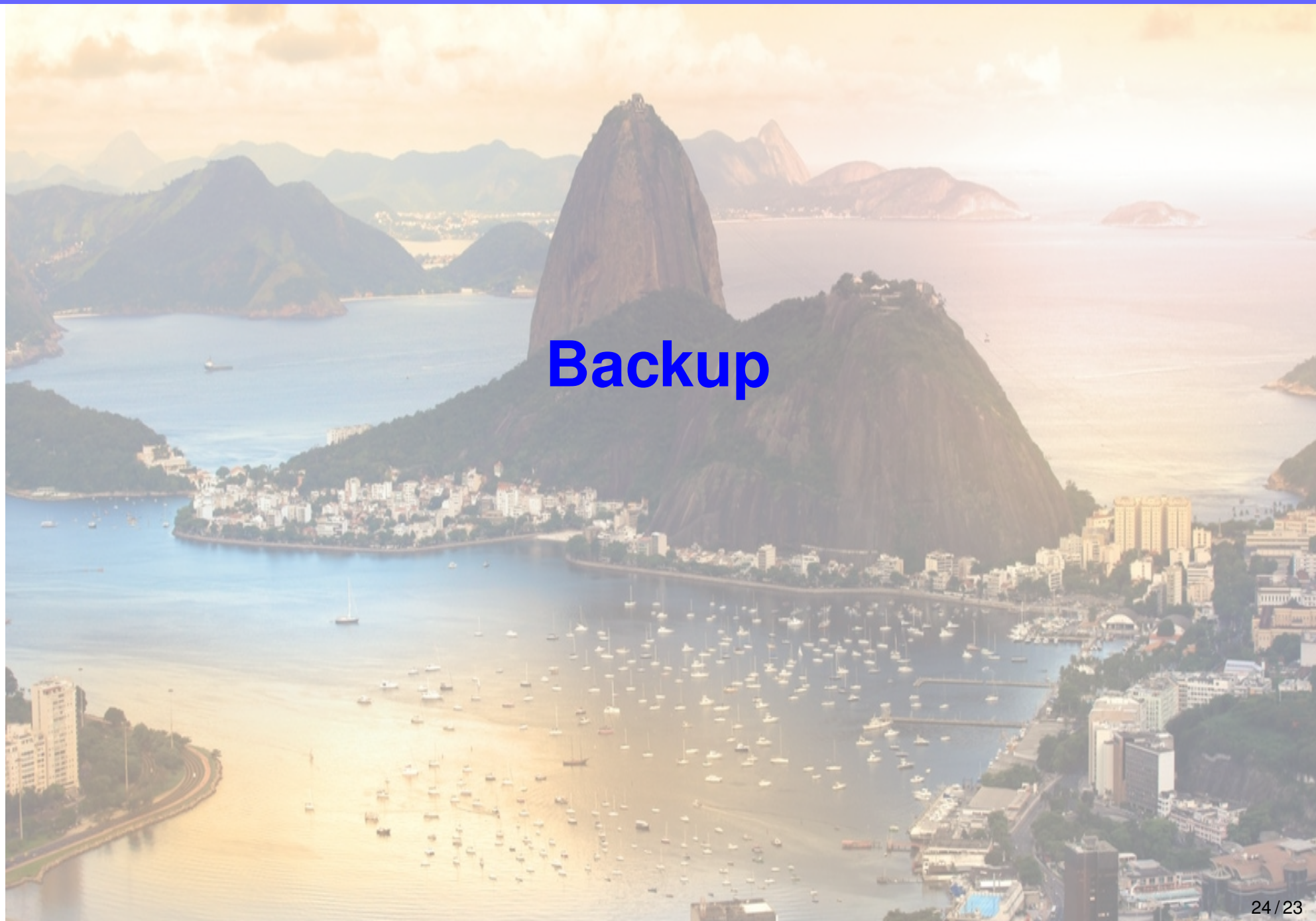
LHCb produced outstanding results on CPV and mixing in beauty sector

- Tree-level γ mesurements are approaching precision of global fits
- $\Delta m_s \Longrightarrow$ world best measurement
- first observation of TD *CPV* in B_s^0 sector
- deepening the $K\pi$ puzzle

More excited results are expected in the near future given the LHC/LHCb upcoming upgrade era




Thank you for your attention!
mail : davide.fazzini@cern.ch


Backup

The Large Hadron Collider beauty (LHCb) Experiment

- LHCb detector is a single-arm forward spectrometer optimised for b and c hadron physics
  - pseudorapidity range: [2,5] $\Longrightarrow \sim 25\%$ $b\bar{b}$ pairs in LHCb acceptance
- **High precision measurements** in flavour physics (e.g. CKM, beyond SM)
- Collected data:
  - Run1 (2010-2012) $\Longrightarrow \approx 3$ fb^{-1}
  - Run2 (2015-2018) $\Longrightarrow \approx 4$ (already taken) $+ 2$ (expected) fb^{-1}

- Excellent performances [Int. J. Mod. Phys. A 30, 1520022 (2015)]:
  - **Momentum resolution**: $\frac{\sigma_p}{p} \approx 0.5 - 0.8\%$ ($p < 100$ GeV/c)
  - **Impact Parameter (IP) resolution**: $\sigma_{IP} \approx 20$ μm (at high p_T)
  - **Decay time resolution**: $\sigma_t \approx 50$ fs
  - **Particle Identification (PID)**: $\varepsilon(K) \approx 95\%, \pi$ mis-ID $\approx 5\%$ ($p < 100$ GeV/c) $\varepsilon(\mu) \approx 97\%, \pi$ mis-ID $\approx$ 1-3%