# Overview of time-integrated CP violation in *b*-hadron decays

## Workshop Italiano Fisica Alta Intensità 2023

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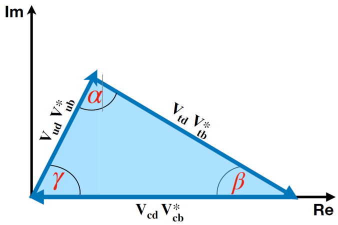
# CP violation (CPV) in the Standard Model

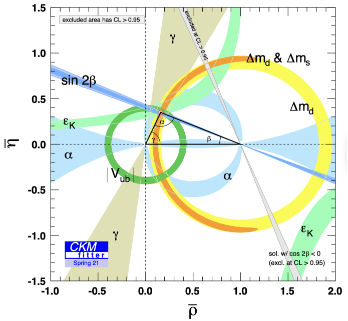
- CKM matrix describe quark charged current weak interactions
- Key test of the Standard Model (SM): verify unitary of CKM matrix
  - **Magnitudes**: measuring branching fractions or mixing frequencies
  - **Phase**: measure *CPV*

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

- Sensitivity to BSM effects from global consistency of various measurements




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



## CP violation (CPV) in the Standard Model

- Direct *CPV* arises from the interference between amplitudes with different weak and strong phases leading to the same final state:
  - Strong phase: short-distance penguin contributions, hadronic final-state-interactions(FSI)
  - Weak phase: CKM matrix elements
- Example of at least 2 competitive amplitudes:

$$A(B \to f) = |A_1|e^{i(\delta_1+\gamma_1)} + |A_2|e^{i(\delta_2+\gamma_2)} \qquad A(\bar{B} \to \bar{f}) = |A_1|e^{i(\delta_1-\gamma_1)} + |A_2|e^{i(\delta_2-\gamma_2)}$$

$$A_{CP} = \frac{|A(B \to f)|^2 - |A(\bar{B} \to \bar{f})|^2}{|A(B \to f)|^2 + |A(\bar{B} \to \bar{f})|^2} = \frac{2|A_2/A_1|\sin(\delta_1 - \delta_2)\sin(\gamma_1 - \gamma_2)}{1 + |A_2/A_1|^2 + |A_2/A_1|\cos(\delta_1 - \delta_2)\cos(\gamma_1 - \gamma_2)}$$

- *CPV* predicted for baryons within the SM but never observed
- In contrast with the *CPV* in *b*-meson decays, *b*-baryons sector remains almost unexplored
- Thanks to the large production cross-section of *b*-baryons in pp collisions at the LHC, LHCb is the only experiment capable of expanding our knowledge in this sector
- The first observation of *CPV* in a baryon decay is already within the reach of LHCb with the data collected during the Run 2 of the LHC
  - first hint for *CPV* in baryon decays has been reported in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays

## CKM angle $\gamma$

- $\gamma$ is the phase between $b \to c$ and $b \to u$
- Theoretically clean measurement at $10^{-7}$ level [arXiv:1308.5663]
- Determined from tree-level decays $\Longrightarrow$ SM benchmark
- $\gamma$ accessed in many ways using $b \to c \to u$ transitions

**B decays**

- $B^0 \to DK^{*0}$, $B^0 \to D^{\mp}\pi^{\pm}$
- $B_s \to D_s^{\mp}K^{\pm}$, $B_s \to D_s^{\mp}K^{\pm}\pi^+\pi^-$
- $B^+ \to Dh^+$, $B^+ \to D^*h^+$, $B^+ \to DK^{*+}$, $B^+ \to Dh^+\pi^+\pi^-$

**D decays**

- $D^0 \to K^+\pi^-$, $D^0 \to h^+h^-$
- $D^0 \to K_s h^+ h'^-$, $D^0 \to h^+h'^-\pi^0$
- $D^0 \to K^-\pi^+\pi^-\pi^+$, $D^0 \to K^+K^-\pi^+\pi^-$, $D^0 \to K_s\pi^+\pi^-\pi^0$, $D^0 \to \pi^-\pi^+\pi^-\pi^+$

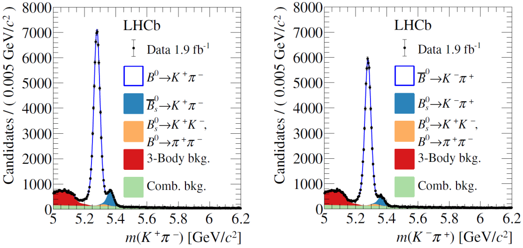
- Close sensitivity gap:
  - Direct measurement: $\gamma = (71.1^{+4.1}_{-4.5})^\circ$ [HFLAV20]
  - Indirect measurement: $\gamma = (65.7^{+0.9}_{-2.7})^\circ$ [CKMFitter19]
- BaBar and Belle achieved precision of around $15^\circ$. LHCb has achieved $4^\circ$ precision
- Important role for BESIII (Quantum correlated measurements at the $\psi(3770)$)

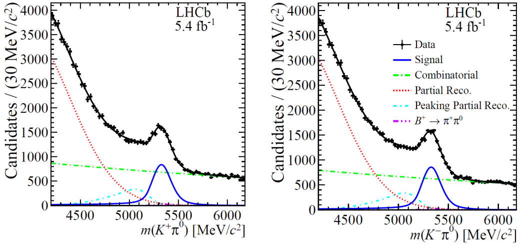
## The B $\to K\pi$ puzzle

- Time-integrated *CP* asymmetry in $B^0 \to K^+\pi^-$ and $B_s \to \pi^+K^-$
- Direct *CP* in $B^+ \to K^+\pi^0$ decays, 5.4 $\text{fb}^{-1}$ (first analysis of a one-track decay at a hadron collider)

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

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




$$A_{CP}^{B^0} = (-8.24 \pm 0.03_{stat} \pm 0.03_{syst})\%$$
$$A_{CP}^{B^0_s} = (23.6 \pm 1.3_{stat} \pm 1.1_{syst})\%$$

[JHEP2103(2021)075]

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

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

# $K\pi$ isospin sum rules @ Belle II [arXiv:2105.04111]

- Isospin sum-rule relation for $B \to K\pi$ provides a stringent SM test [Phys. Lett. B627 82-8]

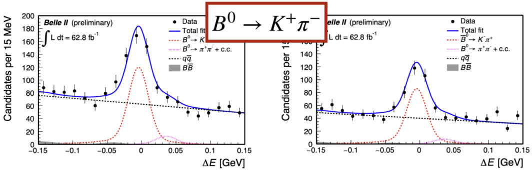
$$I_{K\pi} = A_{K^+\pi^-} + A_{K^0\pi^+} + \frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

- WA: $I_{K\pi} = (13 \pm 11)\%$, precision limited by $K^0_s\pi^0$

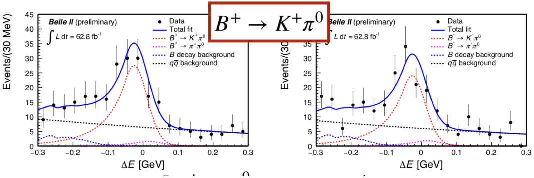
$$A_{CP}^{B^0\to K^+\pi^-} = (-0.16 \pm 0.05_{stat} \pm 0.01_{syst})$$
$$A_{CP}^{B^+\to K^0\pi^+} = (-0.01 \pm 0.08_{stat} \pm 0.05_{syst})$$
$$A_{CP}^{B^+\to K^+\pi^0} = (-0.09 \pm 0.09_{stat} \pm 0.03_{syst})$$
$$A_{CP}^{B^0\to K^0\pi^0} = (-0.01 \pm 0.12_{stat} \pm 0.05_{syst})$$
$$I_{K\pi} = -0.03 \pm 0.13_{stat} \pm 0.05_{syst}$$

[$A_{CP}^{B^0\to K^0\pi^0}$ requires a TD analysis]

Belle II is the only experiment that accesses to all channels



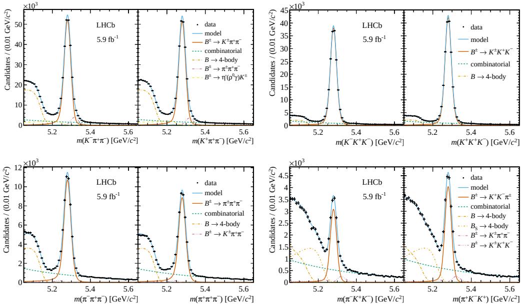

Probes tracking.



- Invariant mass fit:
  - signal: Gaussian + two Crystal Balls
  - combinatorial: exponential
  - part. reco.: Argus convolved with a Gaussian
- Asymmetry determined from signal yields:

$$A_{raw} = \frac{N^{-} - N^{+}}{N^{-} + N^{+}}$$

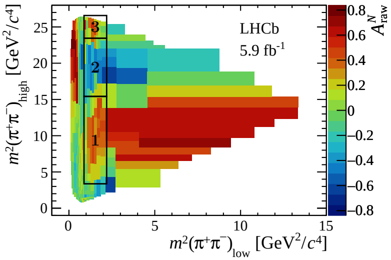
- $A_{raw}$ corrected by efficiency & production asym. determined on $B^{\pm} \to J/\psi K^{\pm}$



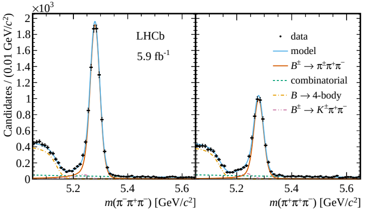

| Decay mode | Total yield | $A_{raw}$ [%] | $A_{CP}$ [%] | std. dev. |
|---|---|---|---|---|
| $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ | $499\,200 \pm 900$ | $+0.6 \pm 0.2$ | $+1.1 \pm 0.2_{stat} \pm 0.3_{syst} \pm 0.3_{J/\psi K}$ | $2.4\sigma$ |
| $B^{\pm} \to K^{\pm}K^{+}K^{-}$ | $365\,000 \pm 1000$ | $-5.2 \pm 0.2$ | $-3.7 \pm 0.2_{stat} \pm 0.2_{syst} \pm 0.3_{J/\psi K}$ | $8.5\sigma$ |
| $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ | $101\,000 \pm 500$ | $+9.0 \pm 0.4$ | $+8.0 \pm 0.4_{stat} \pm 0.3_{syst} \pm 0.3_{J/\psi K}$ | $14.1\sigma$ |
| $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ | $32\,470 \pm 300$ | $-13.2 \pm 0.7$ | $-11.4 \pm 0.7_{stat} \pm 0.3_{syst} \pm 0.3_{J/\psi K}$ | $13.6\sigma$ |

**First observation in $B^{\pm} \to K^{\pm}K^{+}K^{-}$ & $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$**

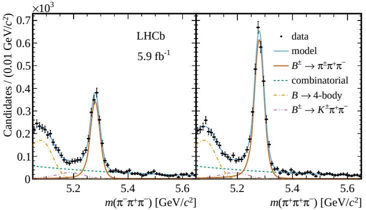
- Histogram created by an adaptive binning algorithm
- The asymmetry is calculated from the number of events in the bin
- Localized asymmetry within the range $\pm 80\%$
- Example for the $\pi^{\pm}\pi^{+}\pi^{-}$ final state



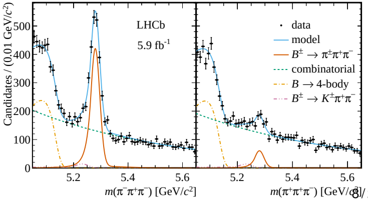

Region 1 $A_{CP}$ $(+30.3 \pm 0.9_{stat} \pm 0.4_{syst} \pm 0.3_{J/\psi K})\%$




Region 2 $A_{CP}$ $(-28.4 \pm 1.7_{stat} \pm 0.7_{syst} \pm 0.3_{J/\psi K})\%$




Region 3 $A_{CP}$ $(+74.5 \pm 2.7_{stat} \pm 1.8_{syst} \pm 0.3_{J/\psi K})\%$



## $B^{\pm}$ decays into a vector + scalar resonance @ LHCb [Phys. Rev. D108 (2023) 012013]

- Asymmetry $\propto$ amplitude squared:

$$|\mathcal{M}_{\pm}|^2 = \boxed{p_0^{\pm}} + \boxed{p_1^{\pm}\cos\theta(m_V^2, s_{\perp})} + \boxed{p_2^{\pm}\cos^2\theta(m_V^2, s_{\perp})}$$

Direct scalar $A_{CP}$ — Scalar & vector interference — Direct vector $A_{CP}$

- Amplitude parameters determined as a quadratic function in $\cos\theta$

$$A_{CP}^{V} = \frac{|M_-|^2 - |M_+|^2}{|M_-|^2 + |M_+|^2} = \frac{p_2^- - p_2^+}{p_2^- + p_2^+}$$

$B^{\pm} \to (V \to h^+h^-)h^{\pm}$ **contributions:**

- $B^{\pm} \to (\rho(770)^0 \to \pi^+\pi^-)\pi^{\pm}$
- $B^{\pm} \to (\rho(770)^0 \to \pi^+\pi^-)K^{\pm}$
- $B^{\pm} \to (K^*(892)^0 \to K^+\pi^-)\pi^{\pm}$
- $B^{\pm} \to (K^*(892)^0 \to K^+\pi^-)K^{\pm}$
- $B^{\pm} \to (\phi(1020) \to K^+K^-)K^{\pm}$

- Data selected in a narrow region around a vector resonance

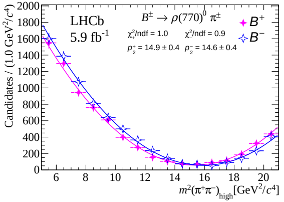
## $B^{\pm}$ decays into a vector + scalar resonance @ LHCb [Phys. Rev. D108 (2023) 012013]

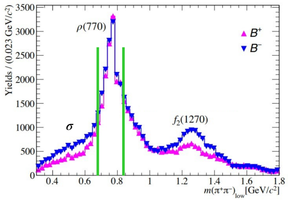
$B^{\pm} \to \rho(770)^0 \pi^{\pm}$

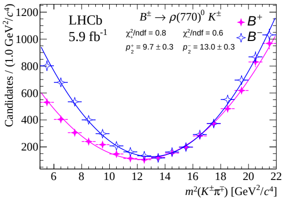
$A_{CP} = (-0.4 \pm 1.7_{stat} \pm 0.9_{syst})\%$

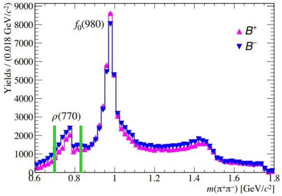
$B^{\pm} \to \rho(770)^0 K^{\pm}$

$A_{CP} = (+15.0 \pm 1.9_{stat} \pm 1.1_{syst})\%$




- First observation of *CP* asymmetry in $B^{\pm} \to \rho(770)^0 K^{\pm}$ decays at $7.9\sigma$
- No asymmetry observed in the other three decay modes

**previous results:**

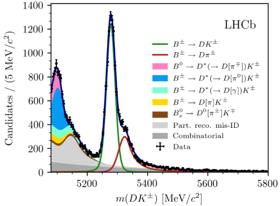
- LHCb: $A_{CP} = (+0.7 \pm 1.1 \pm 1.6)\%$ [PRL 124 031801]

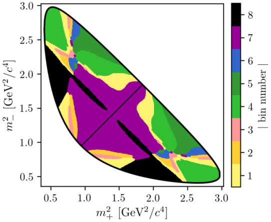
**Previous results:**

- Babar: $A_{CP} = (44 \pm 10 \pm 4^{+5}_{-13})\%$ [PRD 78 012004].
- Belle: $A_{CP} = (30 \pm 11 \pm 2^{+11}_{-4})\%$ [PRL 96 251803]

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

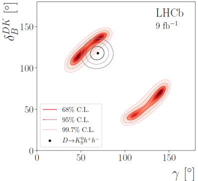
- Full Run 1+2 data (9 $fb^{-1}$) [JHEP02(2021)169]
- Measured *CPV* parameters from the distribution of events in Dalitz plot
- External input: from CLEO and BESIII combined data
  - strong-phase $\delta_D = arg(A_{D^0}) - arg(A_{\bar{D}^0})$ [PRD101, 112002(2020)]
- **Most precise $\gamma$ measurement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

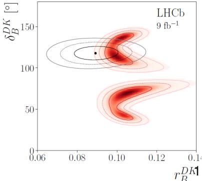



$$\begin{aligned}
\gamma &= (68.7^{+5.2}_{-5.1})^{\circ} \\
r_B^{DK^{\pm}} &= 0.0904^{+0.0077}_{-0.0075} \\
\delta_B^{DK^{\pm}} &= (118.3^{+5.5}_{-5.6})^{\circ} \\
r_B^{D\pi^{\pm}} &= 0.0050 \pm 0.0017 \\
\delta_B^{D\pi^{\pm}} &= (291^{+24}_{-26})^{\circ}
\end{aligned}$$

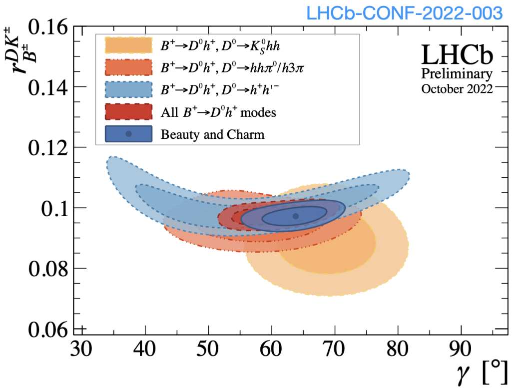
- Combining results with previous analysis [JHEP04(2021)081]
- All *CP* observables measured with world-best precision
- Two-fold ambiguity solved!

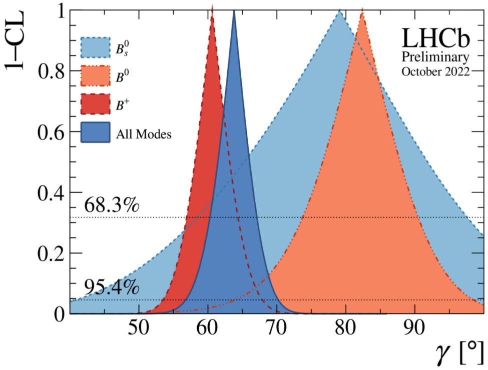


## CKM angle $\gamma$: LHCb combination [??LHCb-CONF-2022-003]

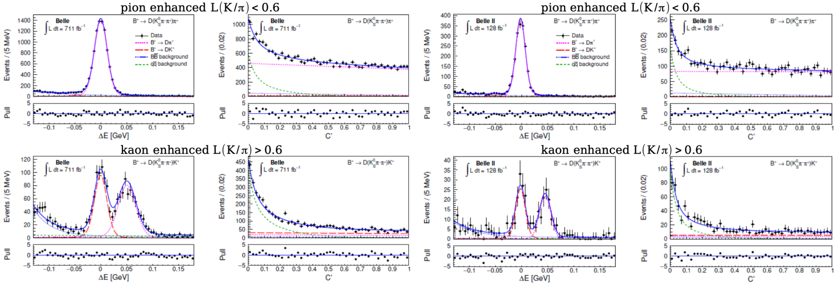
- New combination of the LHCb results: $\gamma = (63.8^{+3.5}_{-3.7})^\circ$
- Compatible with indirect determinations:
  - $\gamma = (65.7^{+0.9}_{-2.7})^\circ$ CKMfitter
  - $\gamma = (65.8 \pm 2.2)^\circ$ UTfit

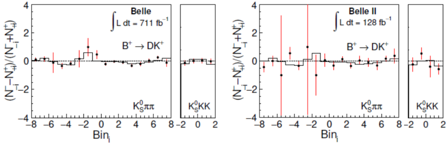


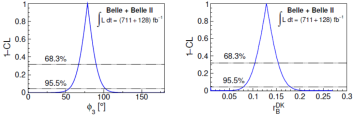



## BPGGSZ study on $B \to D(K_s^0 h^+ h^-)h^-$ (h=$\pi$, K) @Belle II [JHEP 02 (2022) 63]

- Analysis performed with 711 fb$^{-1}$ Belle data & 128 fb$^{-1}$ Belle II data
- Unbinned 2D simultaneous fit of $\Delta E$ versus $C'$



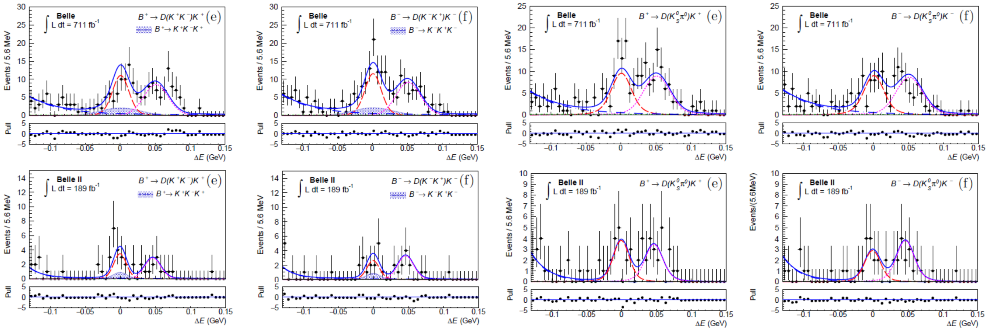




$$\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ,$$
$$r_B^{DK} = 0.129 \pm 0.024 \pm 0.001 \pm 0.002,$$
$$\delta_B^{DK} = (124.8 \pm 12.9 \pm 0.5 \pm 1.7)^\circ,$$
$$r_B^{D\pi} = 0.017 \pm 0.006 \pm 0.001 \pm 0.001,$$
$$\delta_B^{D\pi} = (341.0 \pm 17.0 \pm 1.2 \pm 2.6)^\circ.$$

## GLW study for $B \to D(KK)K$ & $D(K_s\pi^0)K$ @ Belle II [JHEP 09 (2023) 146]

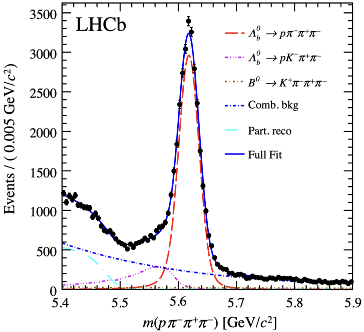
- Fitting simultaneously the $B \to D\pi$ and $B \to DK$ samples
- In GLW , $CP$-odd state accessible only to $B$-factories
- Direct evidence of opposite $A_{CP}$ for even and odd states

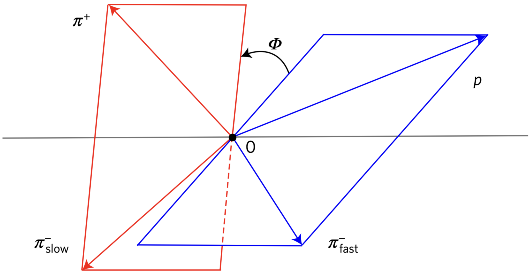
$$A_{CP+} = (+12.5 \pm 5.8 \pm 1.4)\%$$
$$A_{CP-} = (-16.7 \pm 5.7 \pm 0.6)\%$$



## Search for $CPV$ and observation of P violation in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ [Phys. Rev. D 102 051101]

- Dataset corresponding to an integrated luminosity of 6.6 $\text{fb}^{-1}$ (2011-17) at $\sqrt{s}$ = 7, 8 and 13 TeV
- The measurement is performed using two different independent techniques:
  - **Studying Triple Product Asymmetries** (TPA)
  - **Unbinned energy test method**
- The search for $CPV$ is performed by separating the P-odd and P-even contributions
- $CP$ asymmetry depends on the absolute value of the angle between the planes defined by the $p\pi^-_{fast}$ and $\pi^+\pi^-_{slow}$ systems in the $\Lambda_b^0$ rest frame
- $\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\pi^-$ decays used to assess experimental biases and systematics



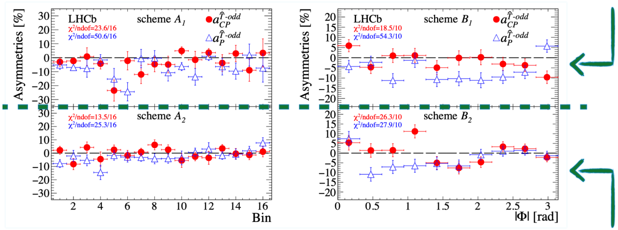
## Search for *CPV* and observation of P violation in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ [Phys. Rev. D 102 051101]

### TPA results

- Two phase space binning schemes: *A* & *B*
- Main systematics are selection criteria, reconstruction and detector acceptance

$$a_{CP}^{\hat{T}-odd} = (-0.7 \pm 0.7 \pm 0.2)\%$$
$$a_{P}^{\hat{T}-odd} = (-4.0 \pm 0.7 \pm 0.2)\%$$

$m(p\pi^+\pi^-_{\rm slow}) > 2.8\,{\rm GeV}/c^2$




$m(p\pi^+\pi^-_{\rm slow}) < 2.8\,{\rm GeV}/c^2$

### Energy test results

- Energy Test method is insensitive to global asymmetries:
  $\Longrightarrow$ not affected by differences between $\Lambda_b^0$ and $\bar{\Lambda}_b^0$ production rates

| Distance scale $\delta$ | 1.6 $GeV^2/c^4$ | 2.7 $GeV^2/c^4$ | 13 $GeV^2/c^4$ |
|---|---|---|---|
| *p*-value (*CP* conservation, *P* even) | $3.1 \times 10^{-2}$ | $2.7 \times 10^{-3}$ | $1.3 \times 10^{-2}$ |
| *p*-value (*CP* conservation, *P* odd) | $1.5 \times 10^{-1}$ | $6.9 \times 10^{-2}$ | $6.5 \times 10^{-2}$ |
| *p*-value (*P* conservation) | $1.3 \times 10^{-7}$ | $4.0 \times 10^{-7}$ | $1.6 \times 10^{-1}$ |

## Future perspectives

- Huge improvements in statistical sensitivities of all key physics channels are expected in the next 1-2 decades

  $\Longrightarrow$ tests of the *CP* violation performed at a new regime of precision
- Main contribution expected by the Upgraded LHCb and the new Belle || experiments
- Two different but highly complementary physics program:

**LHCb Upgrade1**

- 50 $fb^{-1}$ in pp collisions at 13-14 TeV
- larger statistics in charged-track decay modes of all *b*-hadron species

**Belle 2**

- 50 $ab^{-1}$ in $e^+e^-$ collisions at the $\Upsilon(4S/5S)$
- unique capability to reconstruct $B^{0,+}_{(s)}$ decays with neutral or missing particles in final state

- Additional contributions will come in the HL-LHC era:
  - the phase-2 upgrade of ATLAS & CMS (Run4) with *b*-decays to final state containing muons
  - LHCb Upgrade2 will reach an instantaneous luminosity up to $2^{34} cm^{-2} s^{-1}$, collecting $\sim$ 300 $fb^{-1}$
- The knowledge of the angle $\gamma$ will be improved by an order or magnitude at least,

  $\Longrightarrow$ reaching a sub degree precision

# Future perspectives (II)

- Upgrade phases of the various experiments will enhance significantly the statistics available in all *b*-decay channels, allowing
  - high precision measurements in the decay modes we already studied
  - investigation of high-multiplicity or suppressed decay modes (with complementary experimental systematic uncertainties)

  $\Longrightarrow$ improving the constrains of the $\gamma$ angle
- These high-multiplicity modes will play an important role in the future determination of $\gamma$, e.g. $B^0 \to D[\to K_s^0\pi^+\pi^-]K^+\pi^-$ decays
- The sensitivity to $\gamma$ comes mainly from the difference in rates of the $B$ and $\bar{B}$ processes

  $\Longrightarrow$ a precise control of the charged-particle identification & detection asymmetries is fundamental
- Both Belle2 & LHCb Upgrade are going to reduce these uncertainty thanks to the improvements in the detectors
- Control samples have to be used for a precise determination
- $\gamma$ measurements often requires external strong-phase inputs (from CLEO & BESIII)

  new precise measurements with data from BESIII can reduce their uncertainty by $\sim$ 50% but further analysis with larger datasets will be vital for not compromising the sensitivity to $\gamma$

# Future perspectives: methods comparison

- $\gamma$ angle can be determined though different methods obtaining very precise results..
- ... but what are the main limitations of these methods?

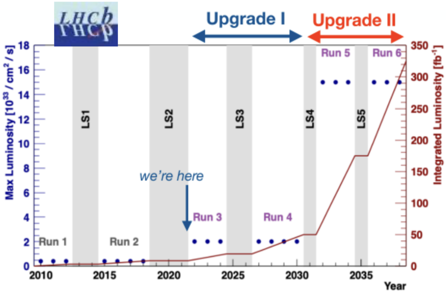
- $B \to DK$ **GLW/ADS**:
  - $D$ is reconstructed in two-charged tracks
  - sensitivity to $\gamma$ results from the ratio of the $B$ amplitudes
  - all measurements are currently statistically limited
  - systematics arise from sources that decrease with increasing data, e.g. detector asymmetry, $\Lambda_b$ & charmless backgrounds
- $B \to DK$ **GGSZ**:
  - $D$ is reconstructed in three-charged tracks, with self-conjugate final states
  - sensitivity to $\gamma$ obtained from the Dalitz plane for $B^{\pm}$ meson
  - systematics should in general scale with statistics, dominant are: strong-phase inputs & distribution of $D$ meson in the Dalitz plane
- **Decay modes with neutrals**:
  - excellent sensitivity to $\gamma$ given by the exact phase difference between the $D^{*0}$ modes
  - efficient distinction of $\pi^0$ and $\gamma$ is critical as the two $D^{*0}$ modes have opposite $CP$ asymmetries

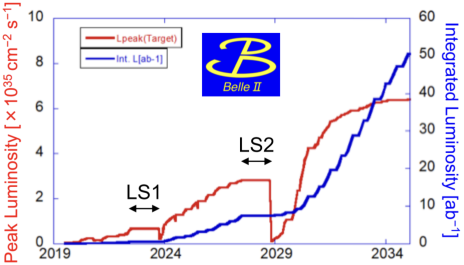
# Future perspectives: CP violation in baryons

- To date, most of the observed *CPV* has been in the meson sector
  - only LHCb has the opportunity to perform these measurements
  - low statistics available for each decay mode
- Theoretical calculations in the baryon sector are challenging due to the complex dynamics of strong interactions.
- An observation would have profound implications:
  - extend the realm of CP violation to a different category of particles
  - providing a more comprehensive view of this phenomenon
  - crucial test of the Standard Model
  - new constraints on the CKM matrix
  - sensitive probe for NP signs and potential deviations from SM predictions.
  - insights into the baryogenesis process
- Determination of production and detection asymmetries is more difficult wrt B mesons,
  - different interactions of baryons and antibaryons with the detector material are difficult to calibrate.
- Several quantities unaffected by experimental effects can be measured e.g.: the difference of *CPV* asymmetries of particles decaying to a similar final state, $\Delta A_{CP}$, triple-product asymmetries (TPA) and energy-test (ET)

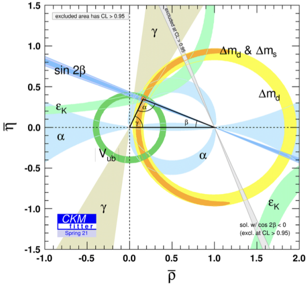
## Conclusions

- $\gamma$ known to better than 4°:
  - no longer the least precisely known CKM angle
  - aims to become the most precise standard candle of the UT
- Deepening the $K\pi$ puzzle
- Belle2: ramping up and producing wide range of interesting results
- A lot more to come in the next decades from LHCb Upgrade(s), ATLAS/CMS & Belle2
  - the unprecedented number of beauty baryons available with the data sample expected to be collected in the LHCb Upgrades, will allow a precision measurement programme of *CPV* observables in *b*-baryon decays to be pursued



# Conclusions



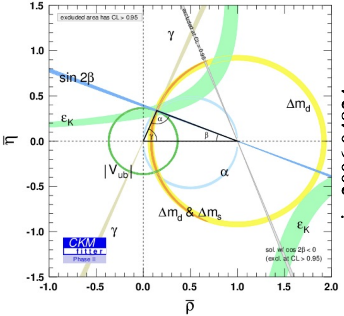

2021

$\sigma_\gamma \sim 4^\circ$

?

$\sigma_\gamma \sim 0.4^\circ$

2040




arxiv:2006.04824

# Thank you for your attention!

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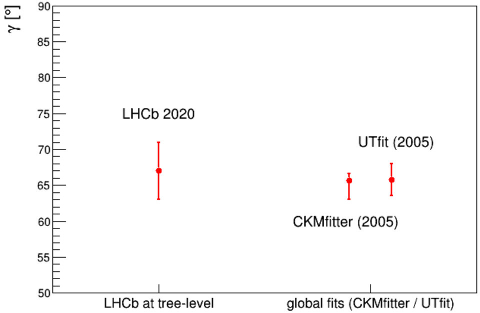
# Backup

# CKM angle $\gamma$: LHCb combination (II)

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



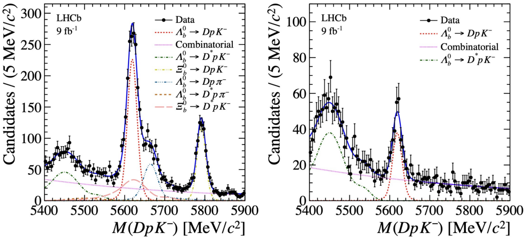

- Any disagreement between the values obtained with the two fit methods would imply physics beyond the SM:
  - new particles or mediators exchanged in loops

## Observation of $\Lambda_b^0 \to D^0 pK^-$ decay and measurement of CP asymmetry [Phys. Rev. D 104 112008]

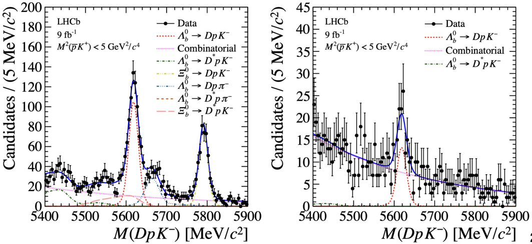
- Dataset corresponding to an integrated luminosity of 9 fb$^{-1}$ (2011-18) at $\sqrt{s}$ = 7, 8 and 13 TeV
- Study of $\Lambda_b^0 \to DpK^-$ with $D \to K^\pm\pi^\mp$, since $D$ is a superposition of $D^0$ and $\bar{D}^0$ states
- $\Lambda_b^0 \to [K^+\pi^-]_D pK^-$ is suppressed by a factor $R \approx \left|\frac{V_{cb}V_{us}^*}{V_{ub}V_{cs}^*}\right|^2 = 6.0$
- Branching fractions ratio $R$ and CP asymmetry $A_{CP}$ measured both in full phase space and in a restricted phase space region $m^2(K^-p) < 5\ GeV^2/c^4$ (enhanced sensitivity to $\gamma$ due to $D\Lambda^*$)

| Phase space | Favored yield | Suppressed yield | $\mathcal{B}$ ratio | $A_{CP}$ |
|---|---|---|---|---|
| Full | $1437 \pm 92$ | $241 \pm 22$ | $7.1 \pm 0.8^{+0.4}_{-0.3}$ | $0.12 \pm 0.09^{+0.02}_{-0.03}$ |
| Restricted | $664 \pm 36$ | $84 \pm 14$ | $8.6 \pm 1.5^{+0.4}_{-0.3}$ | $0.01 \pm 0.16^{+0.03}_{-0.02}$ |

**Full phase space**

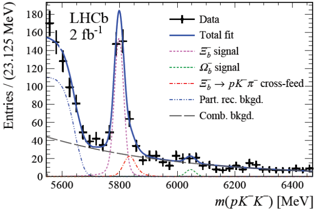


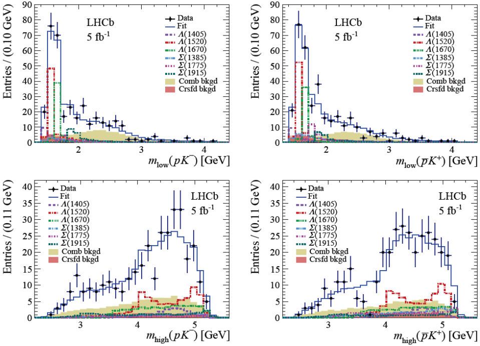

**Restricted phase space**



# Search for $CP$ violation in $\Xi_b^- \to pK^+K^-$ decays [Phys Rev D 104 052010]

- Dataset corresponding to an integrated luminosity of 5 $\text{fb}^{-1}$ (2011-16) at $\sqrt{s}$ = 7, 8 and 13 TeV
- **First amplitude analysis** of baryon decays allowing for $CPV$ effects
- Only candidates in the $m(pK^-K^-)$ signal region of $\pm$ 40 MeV around the $\Xi_b^-$ mass are retained for the amplitude analysis
- Results consistent with no $CPV$ effects

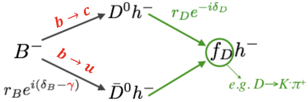


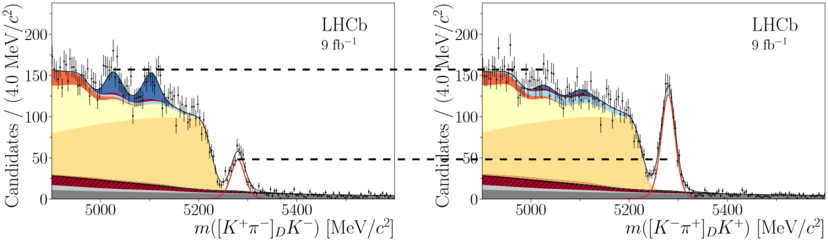

| Component | $A^{CP}(10^{-2})$ (stat, syst) |
|---|---|
| $\Sigma(1385)$ | $-27 \pm 34 \pm 73$ |
| $\Lambda(1405)$ | $-1 \pm 24 \pm 32$ |
| $\Lambda(1520)$ | $-5 \pm 9 \pm 8$ |
| $\Lambda(1670)$ | $3 \pm 14 \pm 10$ |
| $\Sigma(1775)$ | $-47 \pm 26 \pm 14$ |
| $\Sigma(1915)$ | $11 \pm 26 \pm 22$ |

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

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




- Measured decay rates: $\Gamma \propto |r_D e^{i\delta_D} + r_B e^{i(\delta_B - \gamma)}|^2$ $\quad \bar{\Gamma} \propto |r_D e^{i\delta_D} + r_B e^{i(\delta_B + \gamma)}|^2$
- 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.