Mixing and CPV in beauty and charm at LHCb

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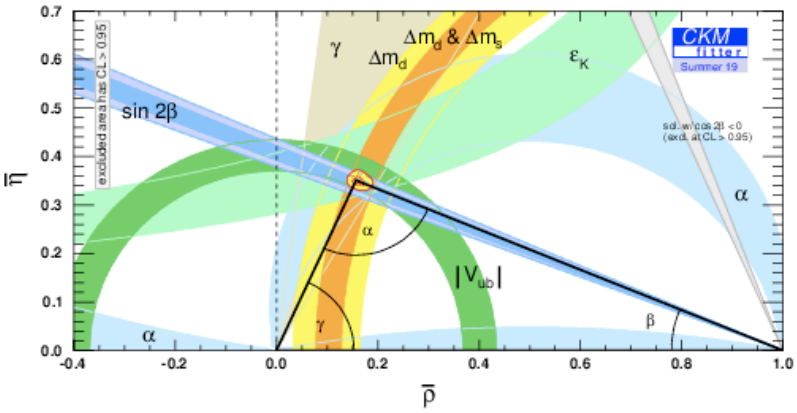
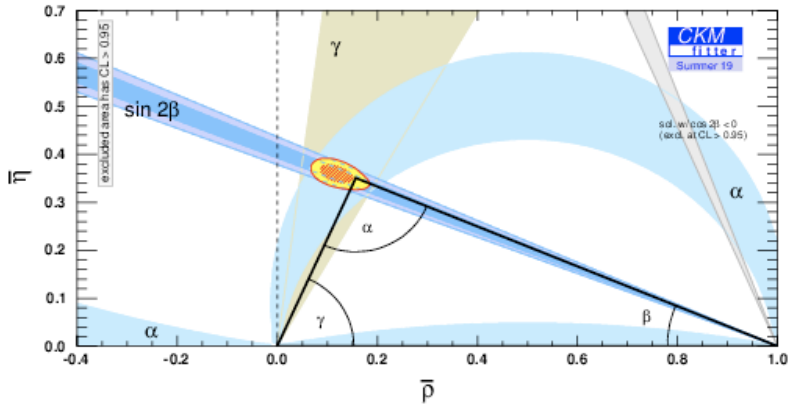
28th International Workshop on Weak Interactions and Neutrinos (WIN2021), University of Minnesota Virtual, June 7 – 11, 2021

Overview: CPV and mixing

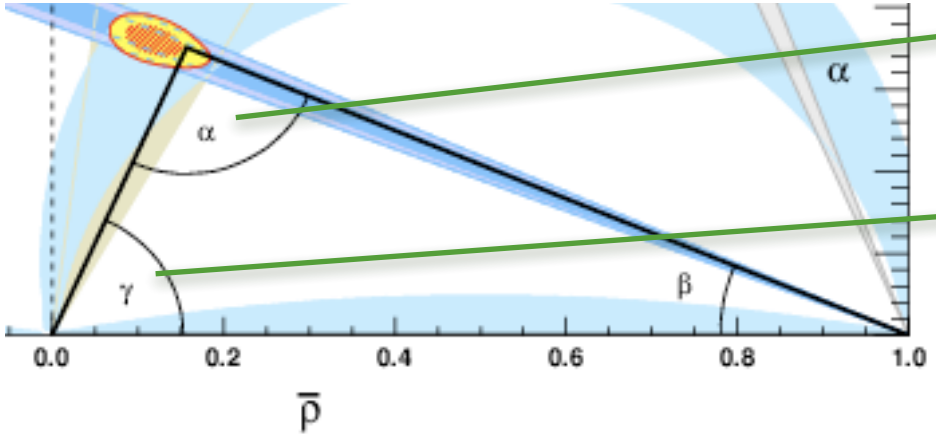




- The universe has more matter than antimatter…
- …but CPV in the SM is not enough to explain this asymmetry
- Precision measurements of CPV and mixing could discover extra asymmetry and new physics

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

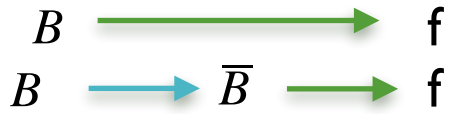
Overview: CPV and mixing in beauty



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

- α:
  - $B \to \pi\pi$ via isospin rules
- γ:
  - $B_{(s)} \to Dh(h)(h)$ type decays
  - Can be measured at tree level
- mixing phases $\phi_s = -2\beta_s$:
  - Interference between direct CPV and mixing
  - β_s is often measured in $B_s \to J/\psi K^+K^-$, $B_s \to D_sD_s$, etc

CPV from mixing:



$$A_{CP}(B \to f) = \frac{\Gamma(B \to f) - \Gamma(\overline{B} \to f)}{\Gamma(B \to f) + \Gamma(\overline{B} \to f)}$$

What about charm?

LHCb-PAPER-2019-006
PRL 122 (2019) 211803

- Reminder: observation of CPV in charm in 2019
  - Direct CPV: Difference in A_{CP} between $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$
- BSM CPV in charm may completely independent from the down-quark sector
  - New rich area of investigation for experiment and theory

Overview of recent results from LHCb

- BEAUTY:
  - The B_s^0 system and γ
    - Δm_s measurements
    - CKM γ with B_s^0
    - γ combinations for $B^+ \to Dh$
    - CP-violating phase β_s
  - The $K\pi$ puzzle
    - $B^0_{(s)} \to h^+h^-$
    - $B^+ \to K^+\pi^0$
  - Searches for CPV in baryons
    - $\Xi_b^- \to pK^-K^-$
- CHARM:
  - Time-dependent $D^0 \to h^+h^-$
  - Searches with neutral light mesons
    - $D^+_{(s)} \to h^+\pi^0$ or $\to h^+\eta$
    - $D^0 \to K^0_S K^0_S$
  - Measurement of the mass mixing parameters in neutral charm

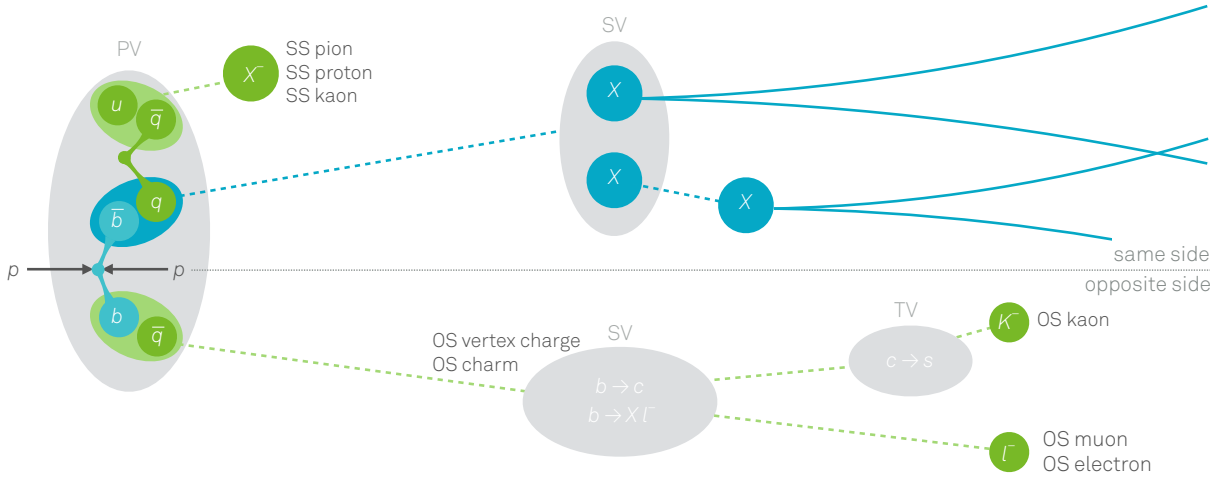
Other LHC experiments:
CPV results from ATLAS are available as a poster during WIN2021

Mixing and CPV in beauty at LHCb

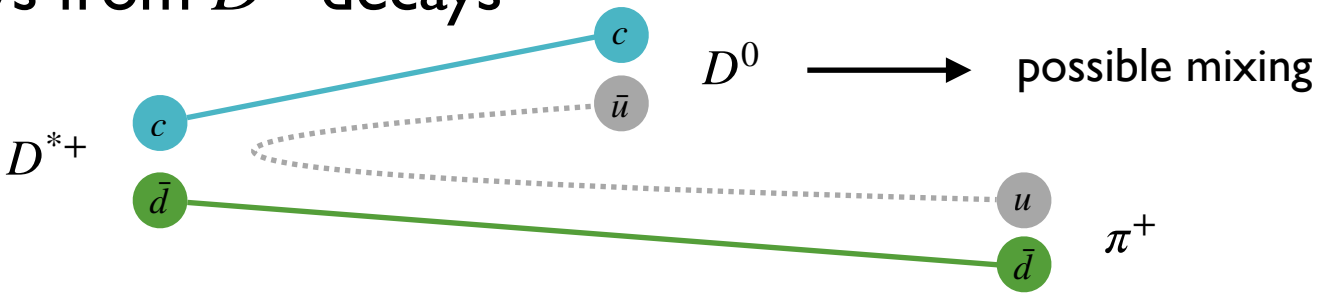
- The B_s^0 system and γ
- The $K\pi$ puzzle
- Searches for CPV in baryons

How do we measure mixing?

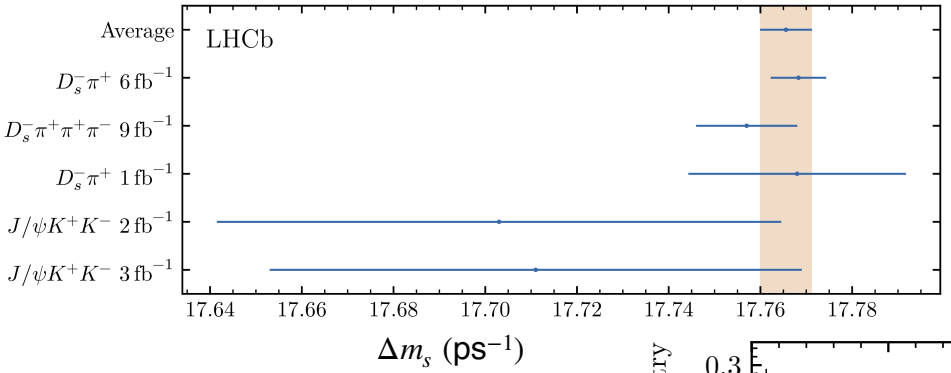
- Flavour tagging is needed to identify the initial state of the b -hadron, especially if both B and $\overline{B}$ decay to the same final state



- In charm, flavour is often identified by choosing D^0 or $\overline{D^0}$ decays from D^* decays



Summary of Δm_s results at LHCb



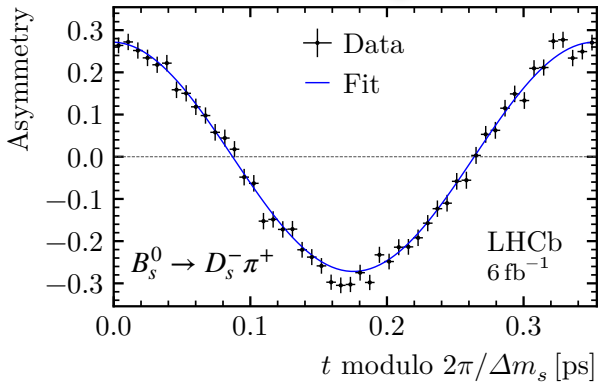
LHCb-PAPER-2021-005
http://arxiv.org/abs/2104.04421
Data: 2015-2018 (6 fb^{-1})

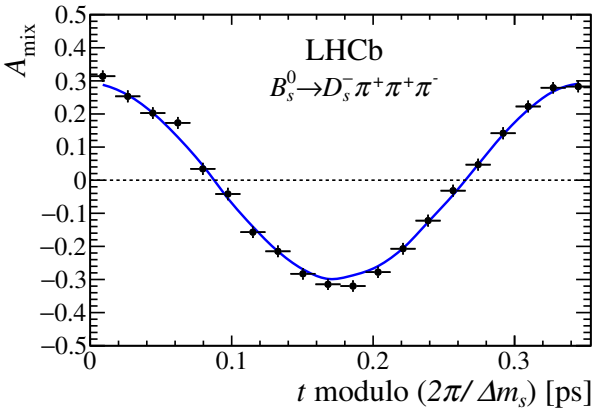
LHCb-PAPER-2020-030
JHEP 03 (2021) 137
Data: 2011-2018 (9 fb^{-1})

Flavour-specific final state: simplifies calculation of time dependent shape

$$P(t) \sim e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + C\cdot\cos(\Delta m_s t)\right]$$

$$C = \begin{cases} -1 & \text{if mixing occurs} \\ 1 & \text{if not mixed} \end{cases}$$

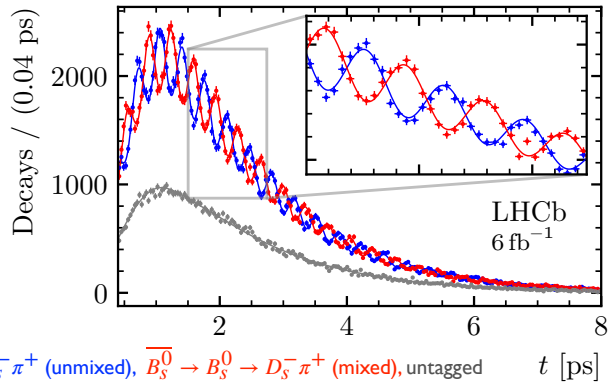


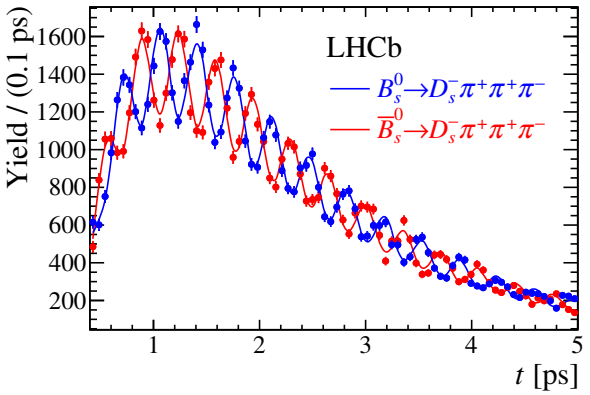


RESULT:

Most precise Δm_s to date from $D_s^-\pi^+$

$$\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032 \text{ ps}^{-1}$$



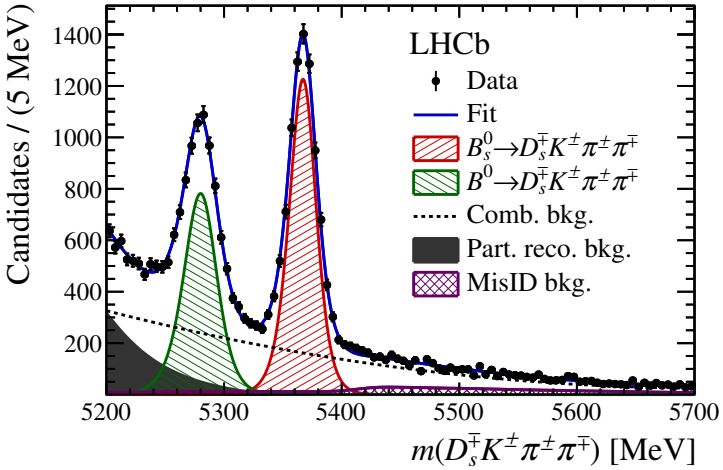


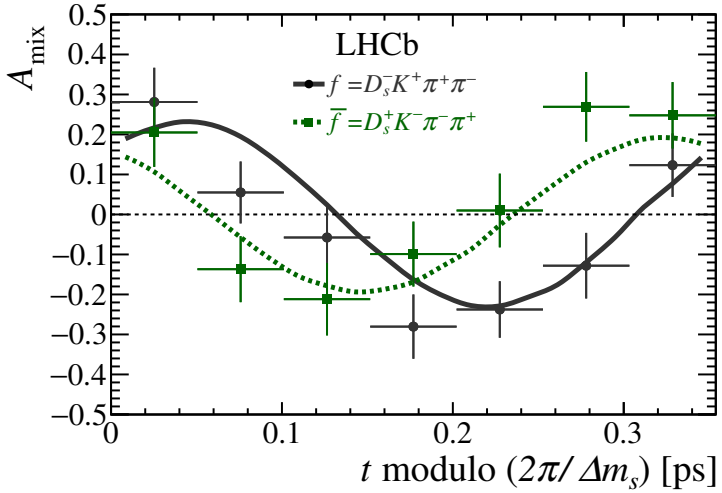
Measuring γ: recent results for B_s^0

- γ measured in the same $B_s^0 \to D_s^- h^+ \pi^+ \pi^-$ study as Δm_s
- Two different fits to CP parameters:
  - Model-independent fit:
    - fit to decay time distributions
    - separation of the two final states from mixing-induced CPV
  - Model-dependent analysis: simultaneous fit to 5 mass combinations using amplitude of the form

$$|A^{\text{eff}}(\mathbf{x})|^2 = |A^c(\mathbf{x})|^2 + r^2 |A^u(\mathbf{x})|^2$$

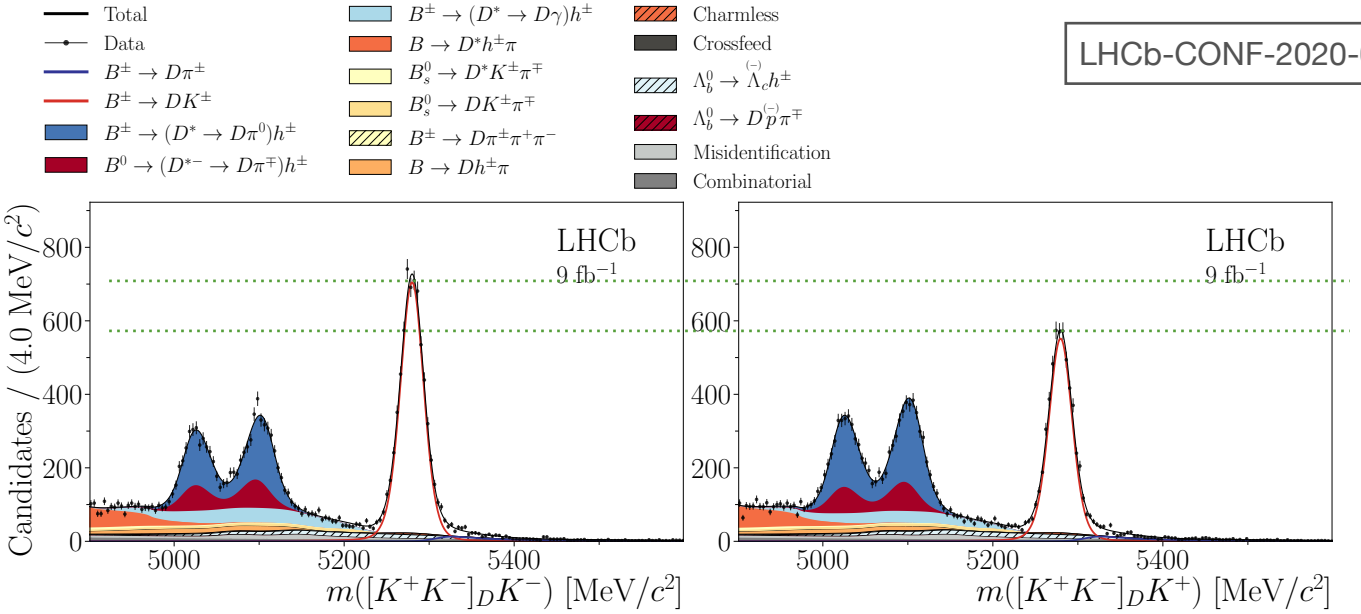
LHCb-PAPER-2020-030
JHEP 03 (2021) 137
Data: 2011-2018 (9 fb^{-1})





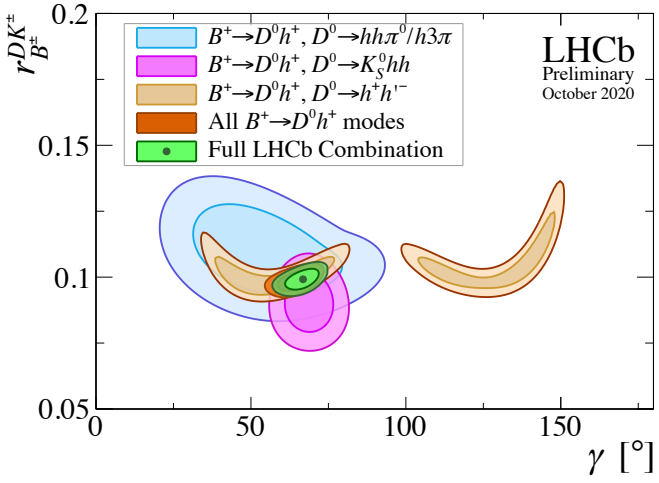
Parameter	Model-independent	Model-dependent
r	$0.47^{+0.08}_{-0.08}{}^{+0.02}_{-0.03}$	$0.56 \pm 0.05 \pm 0.04 \pm 0.07$
κ	$0.88^{+0.12}_{-0.19}{}^{+0.04}_{-0.07}$	$0.72 \pm 0.04 \pm 0.06 \pm 0.04$
δ (°)	$-6^{+10}_{-12}{}^{+2}_{-4}$	$-14 \pm 10 \pm 4 \pm 5$
$\gamma - 2\beta_s$ (°)	$42^{+19}_{-13}{}^{+6}_{-2}$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

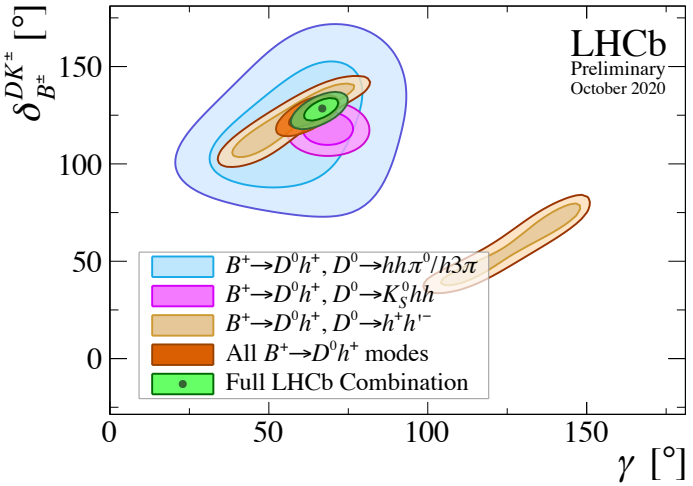
Measuring γ: $B \to D^{(*)}h$ decays



LHCb-CONF-2020-003

LHCb-PAPER-2020-036
JHEP 04 (2021) 081
Data: 2011-2018 (9 fb^{-1})





- Measurement of multiple neutral D modes:
  - GLW: $D \to K^+K^-, \pi^+\pi^-$
  - ADS: $D^0 \to K^+\pi^-$
- A_{CP} and other CPV results:
  - 9 CPV parameter results for D
  - 19 results for D^*
- RESULT:

$$\gamma \text{ from } B^+ : (64^{+4}_{-5})^\circ$$

$$\gamma \text{ from } B^+, B^0, B^0_s : (67 \pm 4)^\circ$$

LHCb Combination, 68.3% CL

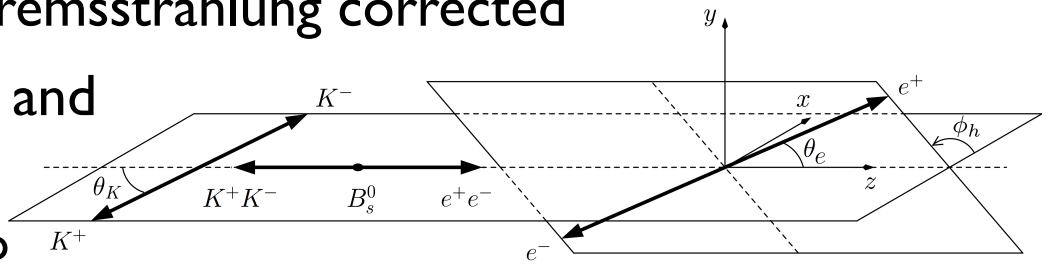
First measurement of the CP-violating phase in $B_s^0 \to J/\psi(e^+e^-)\phi$ decays

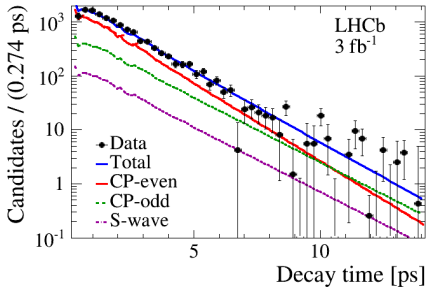
LHCb-PAPER-2020-042
https://arxiv.org/abs/2105.14738
Data: 2011-2012 (3 fb^{-1})

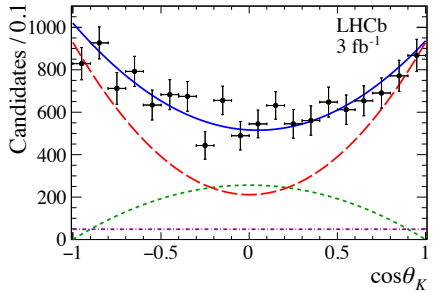
- Different systematic uncertainties compared to same decay with $J/\psi \to \mu\mu$: independent check
- Mass fit for $J/\psi\phi$ is divided into three categories based on whether the electrons are Bremsstrahlung corrected
- Unbinned 4D fit: Bs decay time and 3 helicity angles
  - $B_s^0 \to J/\psi\phi$ is a mixture of two CP-even components and one CP-odd component
- RESULTS:

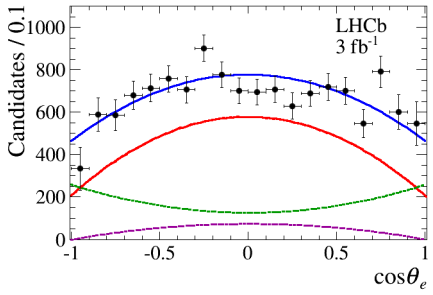
$$\phi_s = 0.00 \pm 0.28 \pm 0.05 \text{ rad}$$
$$\Delta\Gamma_s = 0.115 \pm 0.045 \pm 0.011 \text{ ps}^{-1}$$
$$\Gamma_s = 0.608 \pm 0.018 \pm 0.011 \text{ ps}^{-1}$$

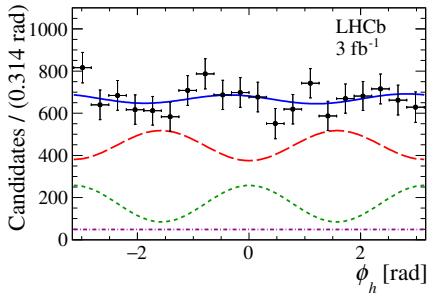
- Consistent with $J/\psi \to \mu\mu$ result and with SM











Light hadrons, the $K\pi$ puzzle and CPV

- $B \to h_1 h_2$ decays can be useful for many CPV parameters:
  - $B^0 \to \pi^+\pi^-$ contributes to measurements of α
  - Combined U-spin measurements of $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ can measure γ and β_s
- The $K\pi$ puzzle:
  - Isospin arguments imply $A_{CP}(B^0 \to K^+\pi^-) = A_{CP}(B^+ \to K^+\pi^0)$, but current average of the difference is nonzero at 5.5σ

$$A_{CP}(\mathrm{K}^+\pi^-) + A_{CP}(\mathrm{K}^0\pi^+)\frac{\mathcal{B}(\mathrm{K}^0\pi^+)}{\mathcal{B}(\mathrm{K}^+\pi^-)}\frac{\tau_0}{\tau_+} = A_{CP}(\mathrm{K}^+\pi^0)\frac{2\mathcal{B}(\mathrm{K}^+\pi^0)}{\mathcal{B}(\mathrm{K}^+\pi^-)}\frac{\tau_0}{\tau_+} + A_{CP}(\mathrm{K}^0\pi^0)\frac{2\mathcal{B}(\mathrm{K}^0\pi^0)}{\mathcal{B}(\mathrm{K}^+\pi^-)}$$

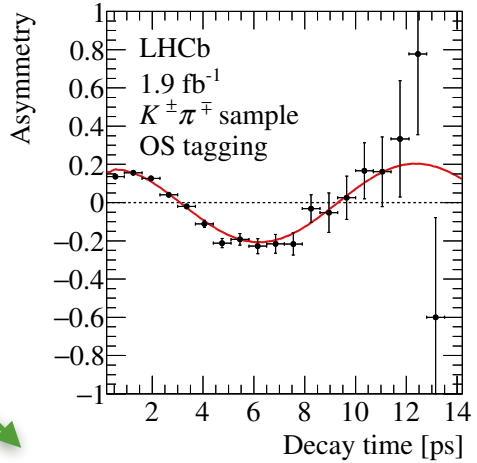
- New results for $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$ are now available

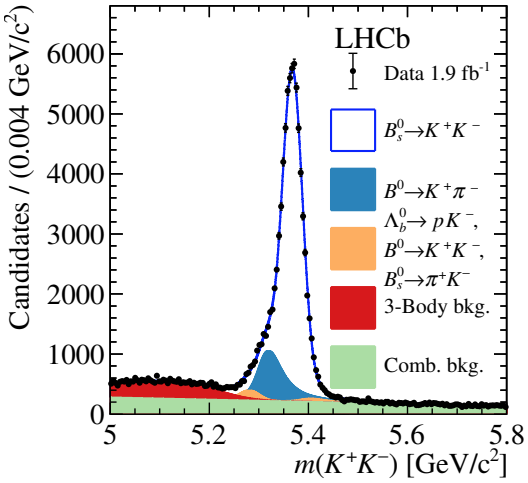
Observation of CP violation in two-body $B^0_{(s)}$-meson decays to charged pions and kaons

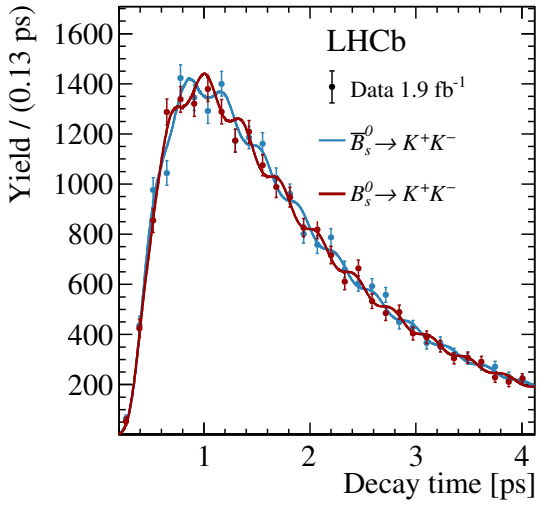
- Time-integrated A_{CP} of $K^{\pm}\pi^{\mp}$: calculated from time-dependent asymmetry with integrated PID, detector efficiency
- Time-dependent study in K^+K^- and $\pi^+\pi^-$:
  - Comparison of two methods of calculating asymmetries
  - First observation of time-dependent CPV in B_s (>6σ)

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

LHCb-PAPER-2020-029
JHEP 03 (2021) 075
Data: 2015-2016 (1.9 fb^{-1})



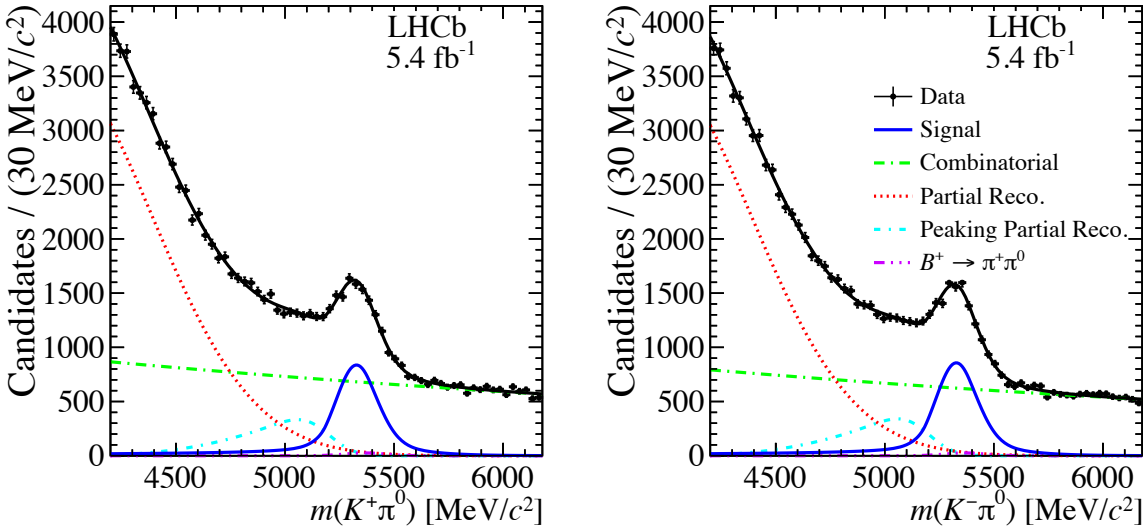




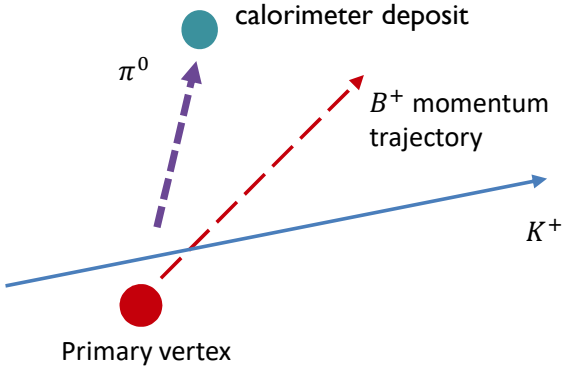
$$\begin{aligned}
C_{\pi\pi} &= -0.311 \pm 0.045 \pm 0.015, \\
S_{\pi\pi} &= -0.706 \pm 0.042 \pm 0.013, \\
A_{CP}^{\mathrm{B}^0} &= -0.0824 \pm 0.0033 \pm 0.0033, \\
A_{CP}^{\mathrm{B}_s^0} &= 0.236 \pm 0.013 \pm 0.011, \\
C_{\mathrm{KK}} &= 0.164 \pm 0.034 \pm 0.014, \\
S_{\mathrm{KK}} &= 0.123 \pm 0.034 \pm 0.015, \\
\mathcal{A}_{\mathrm{KK}}^{\Delta\Gamma} &= -0.83 \pm 0.05 \pm 0.09,
\end{aligned}$$

Result for 2015+2016

Measurement of CP Violation in the decay $B^+ \to K^+\pi^0$



LHCb-PAPER-2020-040
PRL 126 (2021) 091802
Data: 2016-2018 (5.4 fb^{-1})



- Compared to $B^0 \to K^+\pi^-$: extra contribution from colour-suppressed diagrams
- Measured:

$$A_{CP}(\mathrm{B}^+ \to \mathrm{K}^+\pi^0) = A_{\mathrm{raw}}(\mathrm{B}^+ \to \mathrm{K}^+\pi^0) - A^B_{\mathrm{prod.}} - A^K_{\mathrm{det.}}$$

where A_{prod} and A_{det} are calculated from $B^+ \to J/\psi K^+$

- RESULT:

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

$$A_{CP}(B^+ \to K^+\pi^0) - A_{CP}(B^0 \to K^+\pi^-) = 0.115 \pm 0.014$$

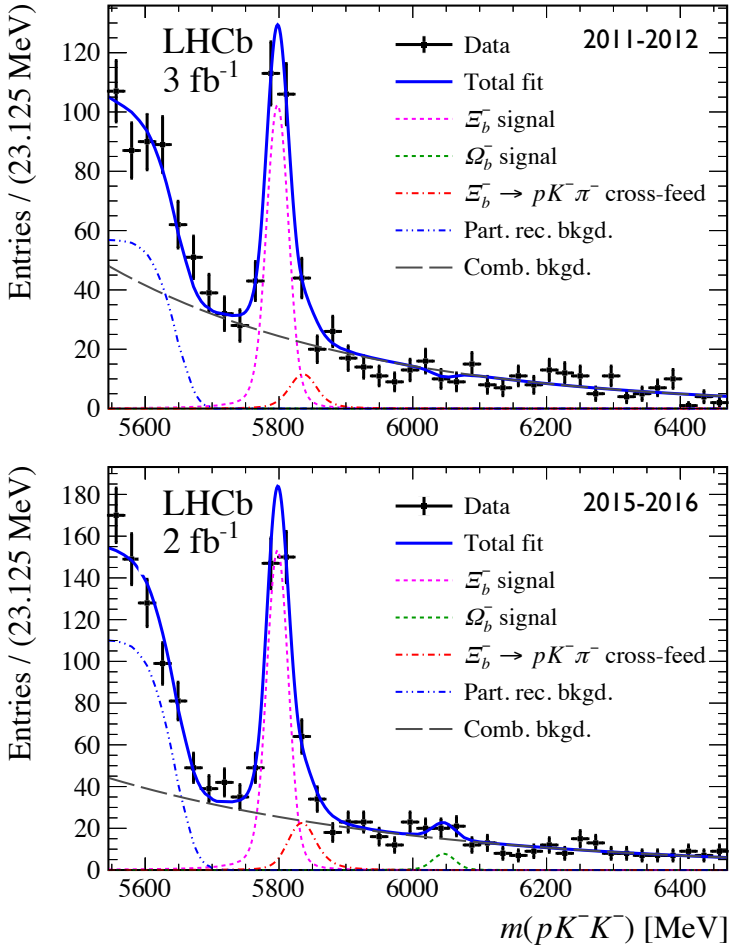
- World average difference in A_{CP} is now at 8σ

Search for CP violation in $\Xi_b^- \to pK^-K^-$ decays

- CP symmetry breaking has not been observed in the baryon sector (Λ_b^0)
- Large CPV is present in $B \to 3h$ decays
- Dalitz analysis is used to identify resonances in the pK^-K^- decay products
- CPV is consistent with zero

LHCb-PAPER-2020-017
https://arxiv.org/abs/2104.15074
Data: 2011-2016 (5 fb^{-1})

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)



Mixing and CPV in charm at LHCb

- Time-dependent $D^0 \to h^+h^-$
- Searches with neutral light mesons
- Measurement of mass mixing in neutral charm

Search for time-dependent CP violation in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$

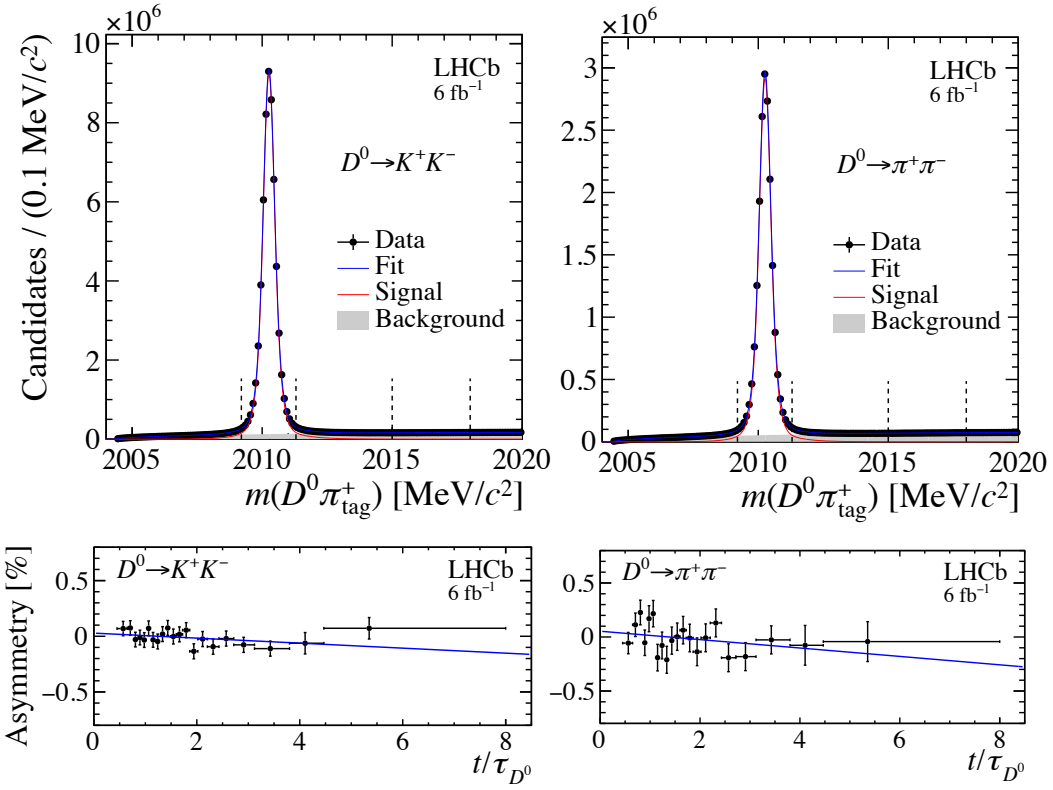
LHCb-PAPER-2020-045
http://arxiv.org/abs/2105.09889
Data: 2015-2018 (6 fb^{-1})

- Mixing is small: allows a linear expansion in A_{CP}
- Cross-checks using $D^0 \to K^-\pi^+$
  - Corrections for momentum-dependent asymmetries from D* tag
  - Removing contaminations from B decays
- RESULTS:

$$\Delta Y_f \approx -A_\Gamma^f$$
$$A_{CP}(f,t) \approx a_f + \Delta Y_f \frac{t}{\tau_{D^0}}$$

$$\Delta Y_{K^+K^-} = (-0.3 \pm 1.3 \pm 0.3) \times 10^{-4}$$
$$\Delta Y_{\pi^+\pi^-} = (-3.6 \pm 2.4 \pm 0.4) \times 10^{-4}$$
$$\Delta Y = (-1.0 \pm 1.1 \pm 0.3) \times 10^{-4}$$
$$\Delta Y_{K^+K^-} - \Delta Y_{\pi^+\pi^-} = (+3.3 \pm 2.7 \pm 0.2) \times 10^{-4}$$

Combined results with previous measurement



Search for CP violation in $D^+_{(s)} \to h^+\pi^0$ and $D^+_{(s)} \to h^+\eta$ decays

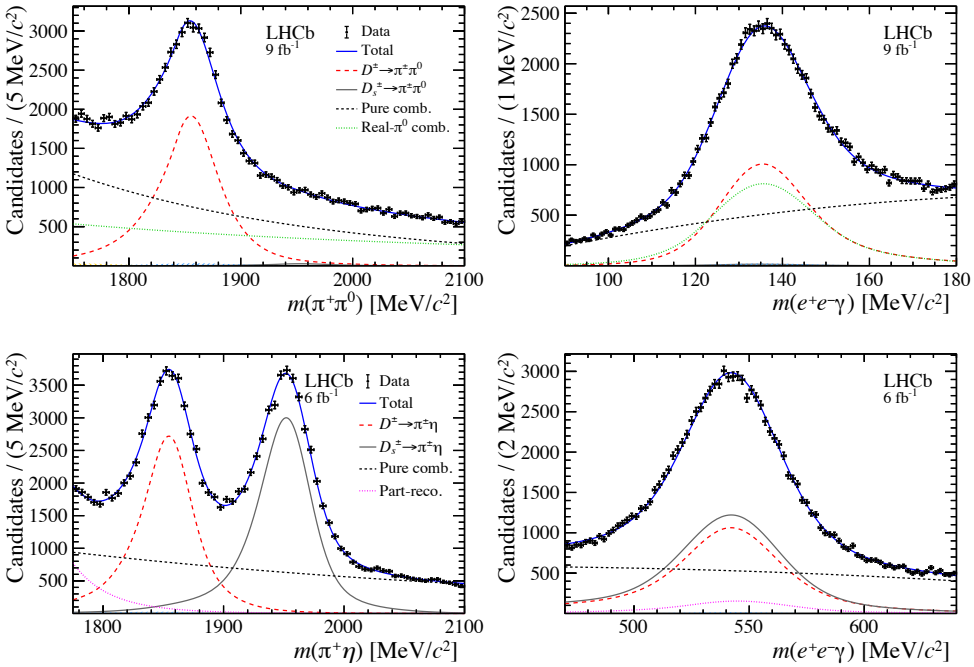
LHCb-PAPER-2021-036
http://arxiv.org/abs/2103.11058
π^0: 2011-2018 (9 fb^{-1})
η: 2015-2018 (6 fb^{-1})

- Looking for cross-checks of isospin sum rules
  - In SM, $A_{CP}(D^+_{(s)} \to \pi^+\pi^0)$ is expected to be 0
- RESULTS:

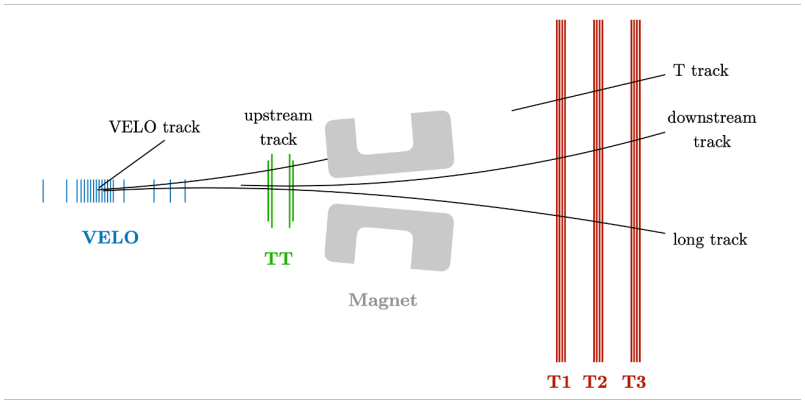
$$\mathcal{A}_{CP}(\mathrm{D}^+ \to \pi^+\pi^0) = (-1.3 \pm 0.9 \pm 0.6)\%,$$
$$\mathcal{A}_{CP}(\mathrm{D}^+ \to \mathrm{K}^+\pi^0) = (-3.2 \pm 4.7 \pm 2.1)\%,$$
$$\mathcal{A}_{CP}(\mathrm{D}^+ \to \pi^+\eta) = (-0.2 \pm 0.8 \pm 0.4)\%,$$
$$\mathcal{A}_{CP}(\mathrm{D}^+ \to \mathrm{K}^+\eta) = (-6 \pm 10 \pm 4)\%,$$
$$\mathcal{A}_{CP}(\mathrm{D}_\mathrm{s}^+ \to \mathrm{K}^+\pi^0) = (-0.8 \pm 3.9 \pm 1.2)\%,$$
$$\mathcal{A}_{CP}(\mathrm{D}_\mathrm{s}^+ \to \pi^+\eta) = (0.8 \pm 0.7 \pm 0.5)\%,$$
$$\mathcal{A}_{CP}(\mathrm{D}_\mathrm{s}^+ \to \mathrm{K}^+\eta) = (0.9 \pm 3.7 \pm 1.1)\%,$$

- $A_{CP}(D^+ \to \pi^+\pi^0)$ is consistent with SM
- All A_{CP} consistent with 0

- π^0 and η reconstructed in $e^+e^-\gamma$ mode (including $\gamma\gamma$ with $\gamma \to e^+e^-$)
- Simultaneous fit to $h = \pi$ and $h = K$ to account for misID

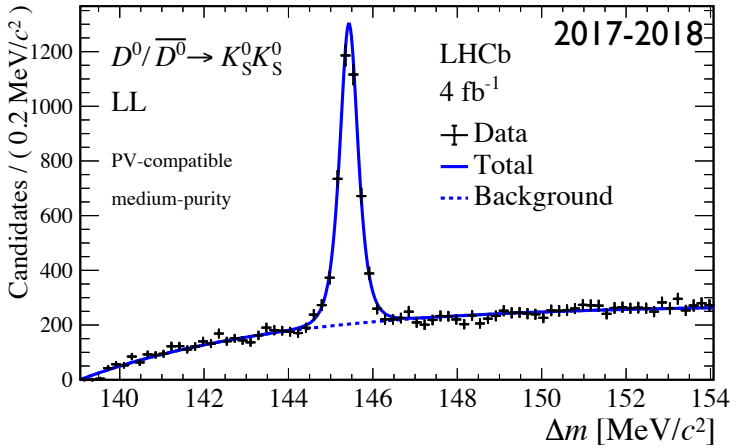


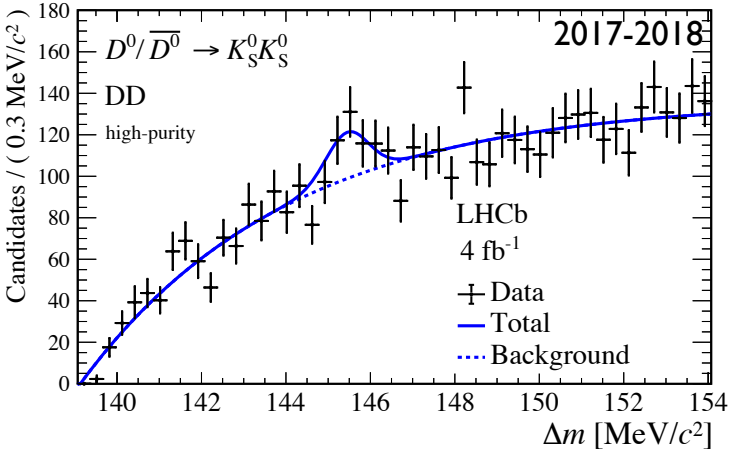
Measurement of CP asymmetry in $D^0 \to K^0_S K^0_S$ decays



each K^0_S is reconstructed from pion pairs: two long pions (L) or two downstream (D)

LHCb-PAPER-2020-047
http://arxiv.org/abs/2105.01565
Data: 2015-2018 (6 fb^{-1})





- $K^0_S K^0_S$ decay channel is sensitive to different amplitudes than h^+h^- modes
- Independent data categories:
  - depending on track types for the K^0_S
  - depending on whether D^* is from PV or not
- Simultaneous fit to $m(D^*) - m(D^0)$ and each $m(K^0_S)$
- RESULT:

$$A_{CP}(\mathrm{K^0_S K^0_S}) = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$$

Updated result for full Run 2

- Compatible with no CP at 2.4σ

Observation of the mass difference between neutral charm-meson eigenstates

- Measuring mixing parameters

$$x = \frac{(m_1 - m_2)c^2}{\Gamma}, \; y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

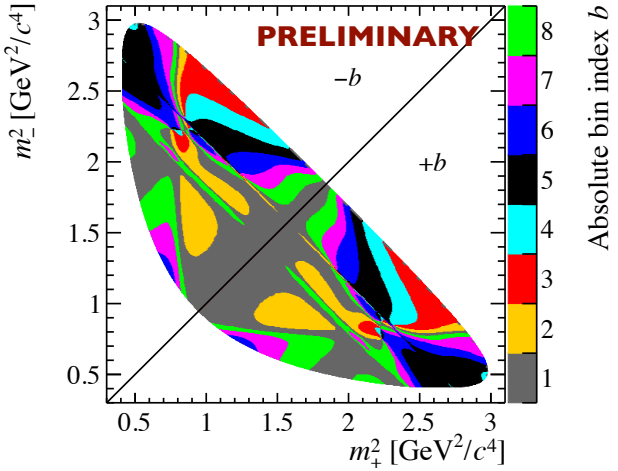
- 30.6 million $D^0 \to K^0_S \pi^+ \pi^-$ decays
- Analysis performed in Dalitz bins of similar strong phase, and in bins of decay time
- Simultaneous fit of 4 independent samples
  - 2 K^0_S types (long or downstream)
  - 2 types of π vertex requirement
- RESULTS:

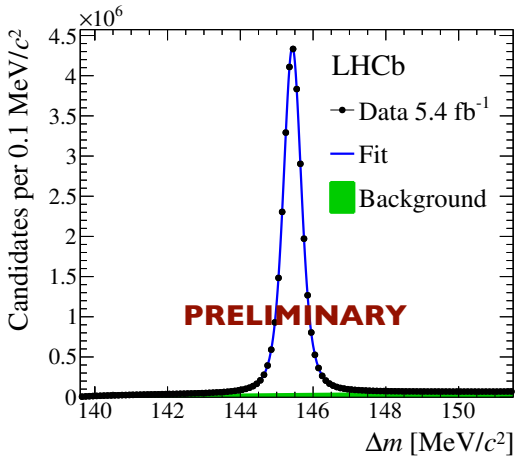
$$x_{CP} = (3.97 \pm 0.46 \pm 0.29) \times 10^{-3}$$
$$y_{CP} = (4.59 \pm 1.20 \pm 0.85) \times 10^{-3}$$
$$\Delta x = (-0.27 \pm 0.18 \pm 0.01) \times 10^{-3}$$
$$\Delta y = (0.20 \pm 0.36 \pm 0.13) \times 10^{-3}$$

PRELIMINARY

- x is not consistent with 0 at high significance!

LHCb-PAPER-2021-009
coming soon
Data: 2016-2018 (5.4 fb^{-1})





Summary and prospects

- Lots of exciting results in the past 6 months
- Newest results today (< 2 months old):
  - Most precise measurement to date of Δm_s
  - Search for CPV in $\Xi_b^- \to pK^-K^-$
  - First measurement of CPV phase in $B_s^0 \to J/\psi\phi$
  - Most precise $A_{CP}(D^0 \to K_S^0 K_S^0)$ to date
  - Improved precision in ΔY in $D^0 \to h^+h^-$
  - Mass difference observed in neutral D system

- LHC is currently working on an upgrade, more data at increased luminosity coming in the next few years
- Updates to these results with increased precision are possible!