CP violation and mixing in heavy flavor at LHCb

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on behalf of the LHCb Collaboration

Outline of the Talk

- **Observation of CP violation in charm decays:**
  - Measure CPV asymmetries in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays

- **Time-dependent *CP* –violating observables in** $B_s^0 \to J/\psi K^- K^+$

- **Time-dependent CPV measurement in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$**

- **Mass difference between neutral c-meson eigenstates** $(D^0 - \bar{D}^0)$

Observation of CP violation in charm decays

- Observation of CPV in the charm sector has not been achieved yet, despite decades of experimental searches.
- Charm hadrons provide an unique opportunity to measure CPV, with particles containing only up-quarks

The first observation of CPV in the decay of charm hadrons

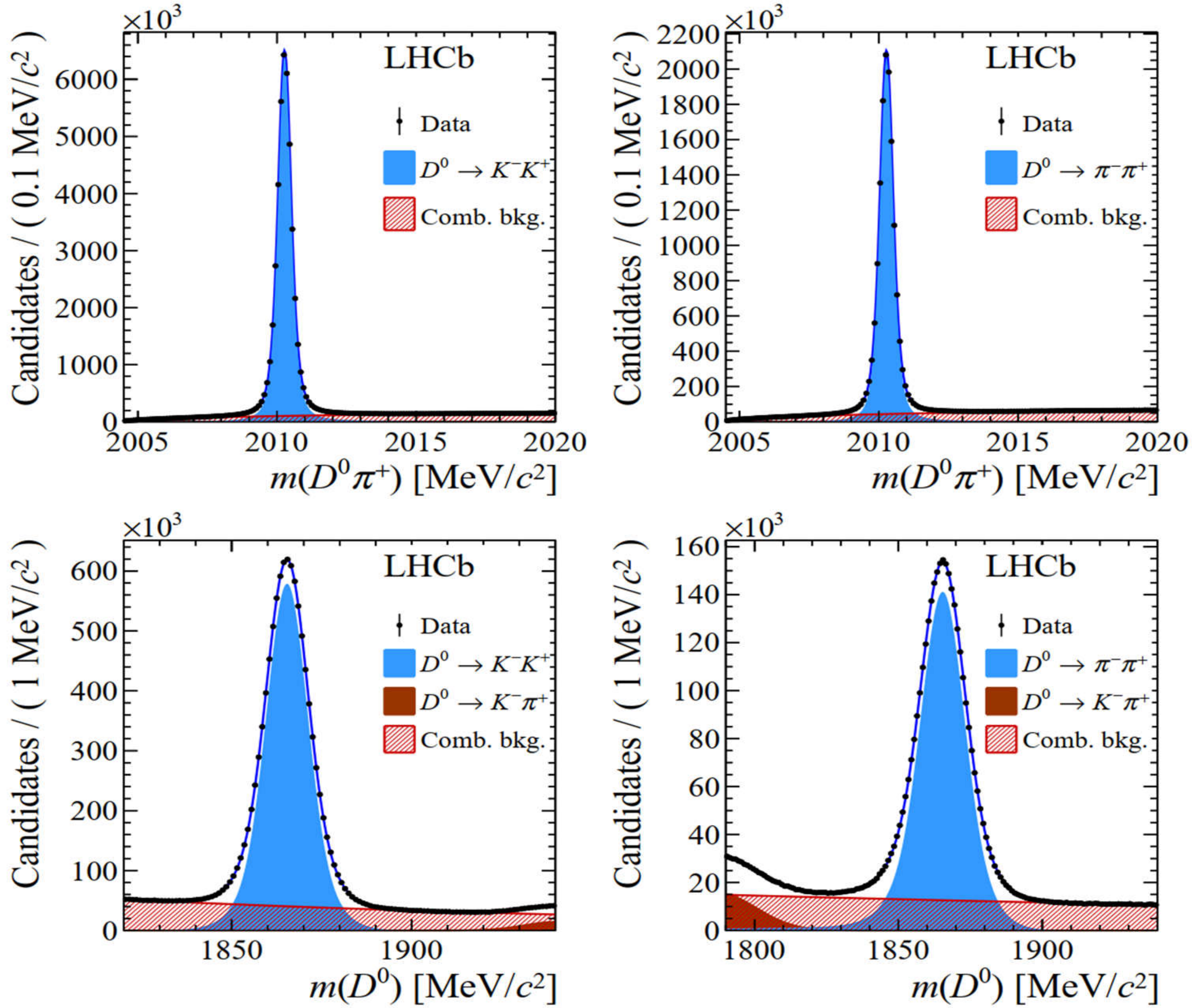
- Measurement of CP-violating asymmetries in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays
- In order to identify the D^0:
  - **π-tagged**: $D^{*+} \to D^0\pi^+$
  - **μ-tagged:** $\bar{B} \to D^0\mu^-\bar{\nu}_\mu X$
- Define: $\Delta A_{CP} = A_{raw}(K^-K^+) - A_{raw}(\pi^-\pi^+)$ to cancel production and detection asymmetries

$$A_{\text{raw}}^{\pi\text{-tagged}}(f) \equiv \frac{N\left(D^{*+} \to D^0(f)\pi^+\right) - N\left(D^{*-} \to \overline{D}^0(f)\pi^-\right)}{N\left(D^{*+} \to D^0(f)\pi^+\right) + N\left(D^{*-} \to \overline{D}^0(f)\pi^-\right)},$$

$$A_{\text{raw}}^{\mu\text{-tagged}}(f) \equiv \frac{N(\overline{B} \to D^0(f)\,\mu^-\bar{\nu}_\mu X) - N(B \to \overline{D}^0(f)\,\mu^+\nu_\mu X)}{N(\overline{B} \to D^0(f)\,\mu^-\bar{\nu}_\mu X) + N(B \to \overline{D}^0(f)\,\mu^+\nu_\mu X)},$$

PRL 122 (2019) 211803; 5.9 fb^{-1} at 13 TeV

$m(D^0\pi^+)$ and $m(D^0)$



$\pi^{\pm}$-tagged

$\mu^{\pm}$-tagged

Measurements

- **The results:**

$$\Delta A_{CP}^{\pi\text{-tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4},$$
$$\Delta A_{CP}^{\mu\text{-tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}.$$

- **Combine with previous measurements:**

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4},$$

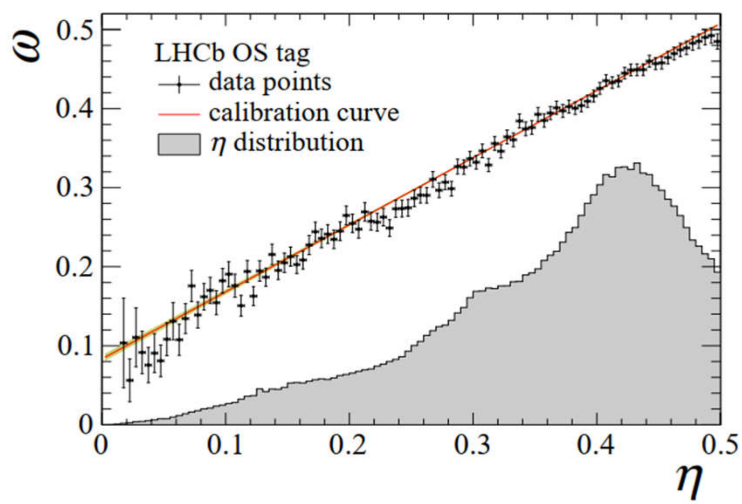
- **Consistent with (in magnitude at the upper end) SM**
  - SM: 10^{-4}-10^{-3}
  - Further measurements + possible theoretical improvements, will clarify the picture (SM or new dynamics in the up-quark sector)

Time-dependent CPV observables in $B_s^0 \to J/\psi K^- K^+$

- In decays of B_s^0 to a *CP* eigenstate, *CPV* can originate from the interference of the amplitude and that of the adjoint decay preceded by B_s^0-$\bar{B}_s^0$ oscillation.
  - It manifests itself through a nonzero value of the phase ϕ_s
- a measurement of ϕ_s different from the SM prediction would provide clear evidence for NP
- **Most sensitive channel to NP** is $B_s^0 \to J/\psi(\mu\mu)K^- K^+$: clean, large statistics

Tagging the B_s^0 meson flavour:

- Opposite-side tagging: use $B^+ \to J/\psi K^+$
- Same-side tagging: use $B_s^0 \to D_s^- \pi^+$



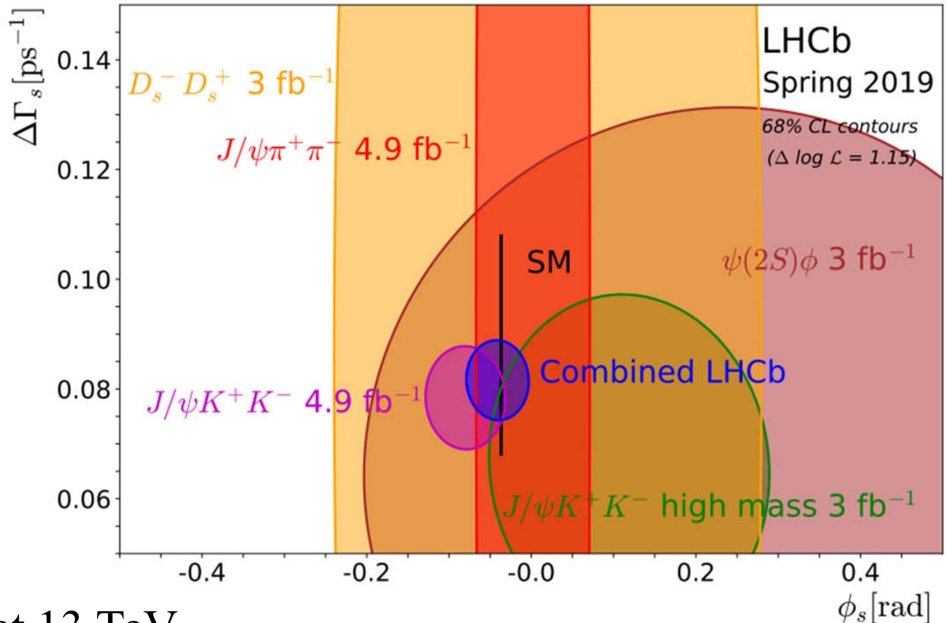
EUR. PHYS. J. C 79 (2019) 706, 1.9 fb^{-1} at 13 TeV

Time-dependent CPV observables in $B_s^0 \to J/\psi K^- K^+$

- Further combine with Run−II $B_s^0 \to J/\psi(\mu\mu)\pi^-\pi^+$ (**PLB 797 (2019)**) .
- And Run-I $J/\psi(\mu\mu)\pi^-\pi^+$, $B_s^0 \to J/\psi K^- K^+$ for the $K^- K^+$ invariant mass > 1.05 GeV, $B_s^0 \to \varphi(2S)\phi$ and $B_s^0 \to D_s^+ D_s^-$

$$\phi_s = -0.041 \pm 0.025\,\text{rad},\ |\lambda| = 0.993 \pm 0.010,\ \Gamma_s = 0.6562 \pm 0.0021\,\text{ps}^{-1}$$

- ϕ_s is consistent with a non-zero *CPV* predicted within the SM and with no *CPV* in the interference of B_s^0 meson mixing and decay.
- $|\lambda|$ is consistent with unity, implying no evidence for direct *CPV*



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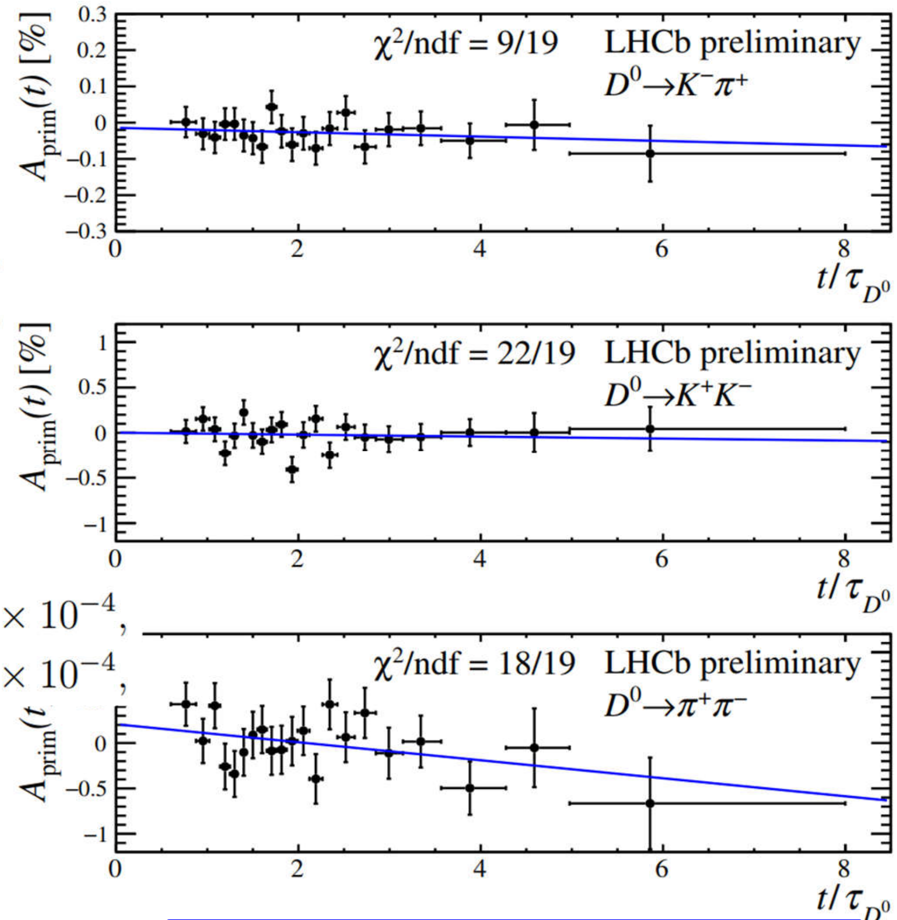
Time-dependent CPV in $D^0 \to K^-K^+, D^0 \to \pi^-\pi^+$

- The asymmetries of the time-dependent decay rates of D^0, $\overline{D}^0$:
  - Sensitive to CPV in the mixing and in the interference between mixing and decay



- With 2015-2016 data:

$$A_\Gamma(D^0 \to K^+K^-) = (\ 1.3 \pm 3.5 \pm 0.7) \times 10^{-4},$$
$$A_\Gamma(D^0 \to \pi^+\pi^-) = (11.3 \pm 6.9 \pm 0.8) \times 10^{-4},$$

- With 2011-2016 data, and combine both channels :

$$A_\Gamma(K^+K^- + \pi^+\pi^-,\ 2011\text{–}2016) = (\ \ 0.9 \pm 2.1 \pm 0.7) \times 10^{-4},$$
$$\Delta A_\Gamma(2011\text{–}2016) = (-8.6 \pm 5.0 \pm 0.5) \times 10^{-4},$$

the linear fit slope is equal to $-A_\Gamma$

LHCB-CONF-2019-001

Mass difference between neutral c-meson eigenstates

- Unknown particles can contribute as virtual particles in the amplitude
  - Possibly enhance the average oscillation rate or the difference between the rates of mesons and antimesons ($D^0 - \overline{D}^0$).
- This makes flavor oscillations sensitive to non-SM dynamics

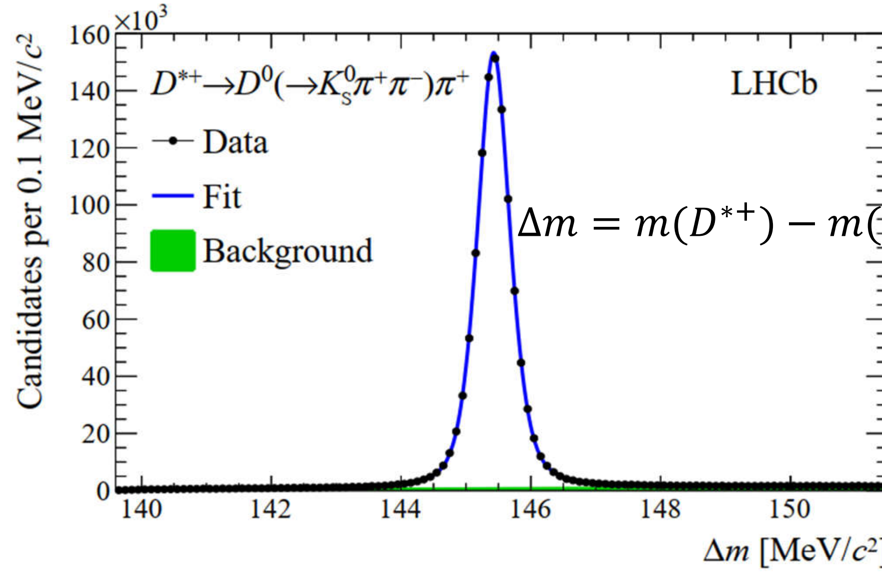
Yield the first evidence that the masses of the neutral charm-meson eigenstates differ

- A novel model-independent approach: the bin-flip method
  - Relies on ratios between charm decays reconstructed in similar kinematic and decay-time conditions
  - Avoiding the need for an accurate modeling of the efficiency variation across phase space and decay time.

PRL 122 (2019) 231802; 5.9 fb^{-1} at 13 TeV

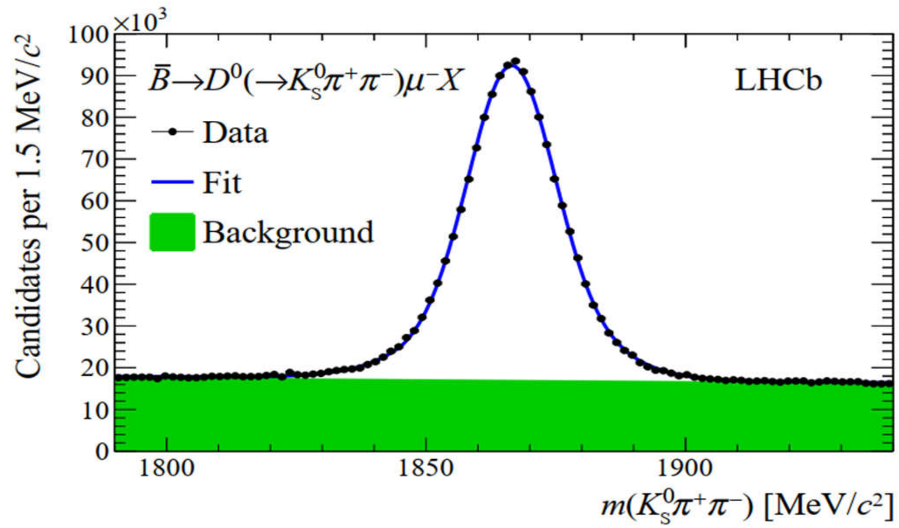
The analysis

- **For $(D^{*+} \to D^0(\to K_S^0\pi^+\pi^-)\pi^+$:**
  - The prompt sample contains 1.3×10^6 signals
  - And a small background dominated by genuine $D^0(\to K_S^0\pi^+\pi^-)$ decays associated to random soft pions



$\Delta m = m(D^{*+}) - m(D^0)$

- **The semileptonic sample:**
  - 1.0×10^6 signals
  - And a sizable background dominated by unrelated $K_S^0\pi^+\pi^-$ combinations.
  - Genuine D^0 decays associated with random muons contribute <1%



Measurements

- **The results:**

Parameter	Value $[10^{-3}]$	Stat. correlations y_{CP}	Stat. correlations Δx	Stat. correlations Δy	Syst. correlations y_{CP}	Syst. correlations Δx	Syst. correlations Δy
x_{CP}	$2.7 \pm 1.6 \pm 0.4$	-0.17	0.04	-0.02	0.15	0.01	-0.02
y_{CP}	$7.4 \pm 3.6 \pm 1.1$		-0.03	0.01		-0.05	-0.03
Δx	$-0.53 \pm 0.70 \pm 0.22$			-0.13			0.14
Δy	$0.6 \pm 1.6 \pm 0.3$						

- Most precise from a single experiment, as are the determinations of the CPV parameters.
- Consistent with x = 0 within 2σ; combined with the current global knowledge, yields $x = 3.9^{+1.1}_{-1.2} \times 10^{-3}$
- Strongly contributing to the emerging evidence for a nonzero (positive) mass difference
- The global constraints on CPV in the $D^0 - \overline{D}^0$ system are greatly improved

Summary

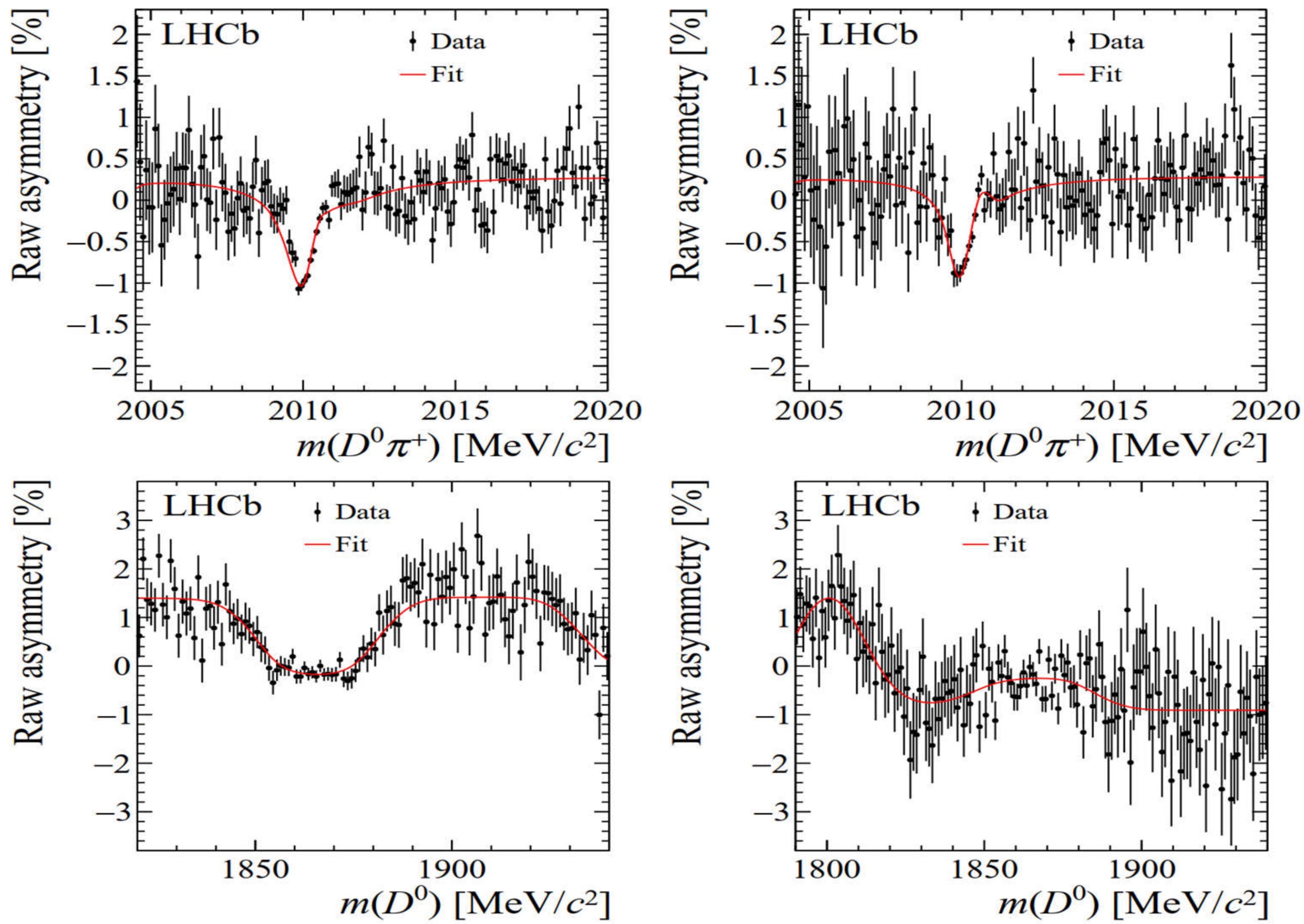
- CP violation is a key physics topic at LHCb. Numerous new results are out sincd PIC 2018, only part of them are shown today.
- We have much more Run2 data to analyze, more results are coming

$m(D^0\pi^+)$ and $m(D^0)$

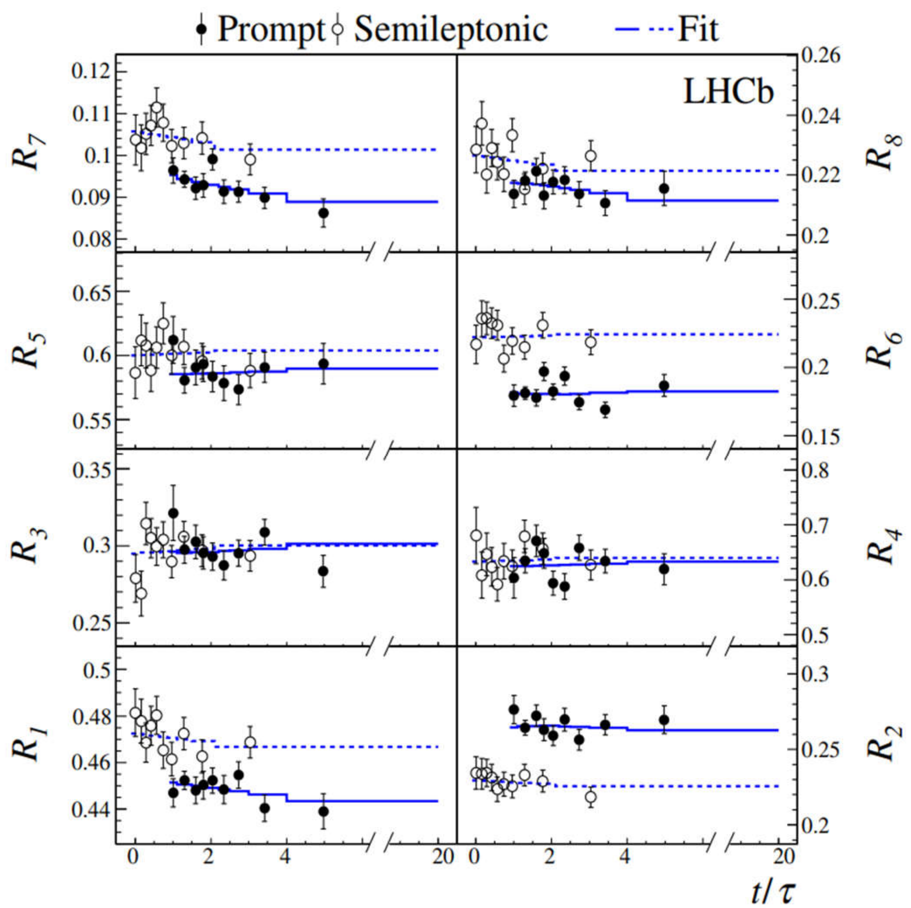
- **Raw asymmetry:**

$$A_{\text{raw}}^{\pi\text{-tagged}}(f) \equiv \frac{N\left(D^{*+} \to D^0(f)\pi^+\right) - N\left(D^{*-} \to \overline{D}^0(f)\pi^-\right)}{N\left(D^{*+} \to D^0(f)\pi^+\right) + N\left(D^{*-} \to \overline{D}^0(f)\pi^-\right)},$$

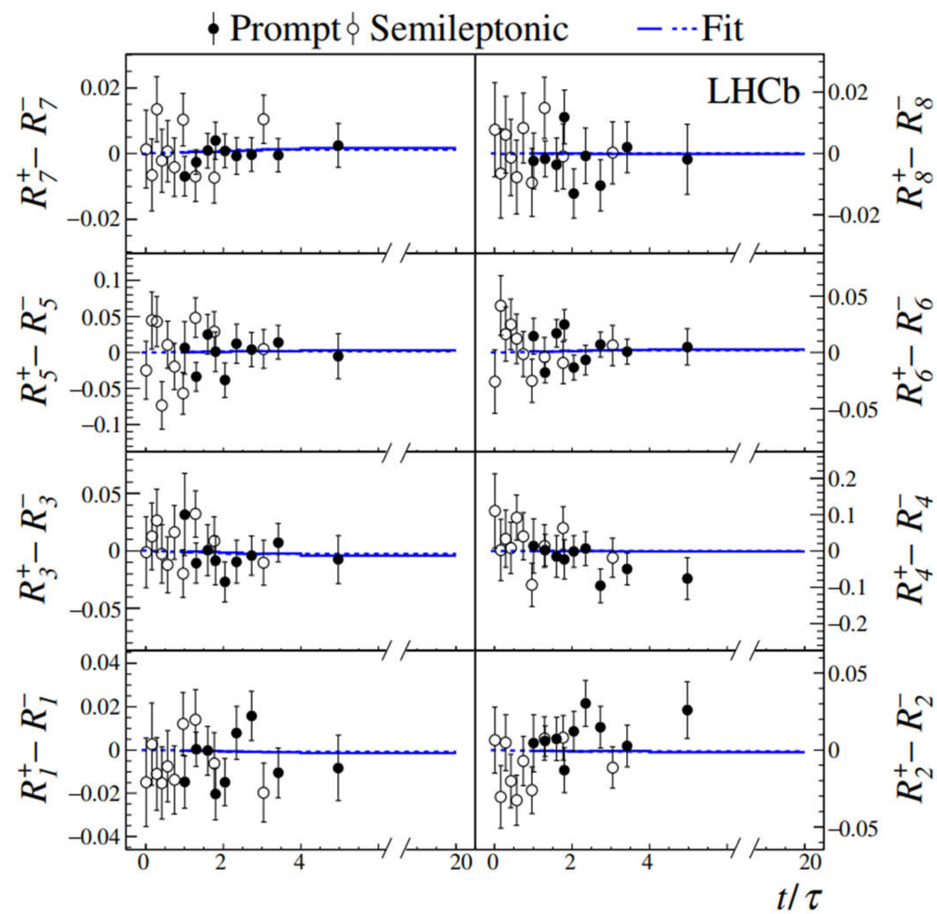
$$A_{\text{raw}}^{\mu\text{-tagged}}(f) \equiv \frac{N(\overline{B} \to D^0(f)\,\mu^-\bar{\nu}_\mu X) - N(B \to \overline{D}^0(f)\,\mu^+\nu_\mu X)}{N(\overline{B} \to D^0(f)\,\mu^-\bar{\nu}_\mu X) + N(B \to \overline{D}^0(f)\,\mu^+\nu_\mu X)},$$



The analysis



CP-averaged yield ratios bin



differences of D^0 and $\overline{D}^0$ yield ratios as functions of t/τ for each Dalitz bin