Latest LHCb results on CPV in charm

Fabio Ferrari on behalf of the LHCb collaboration

University of Bologna and INFN

HQL2021 - The XV International Conference on Heavy Quarks and Leptons

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Setting the stage

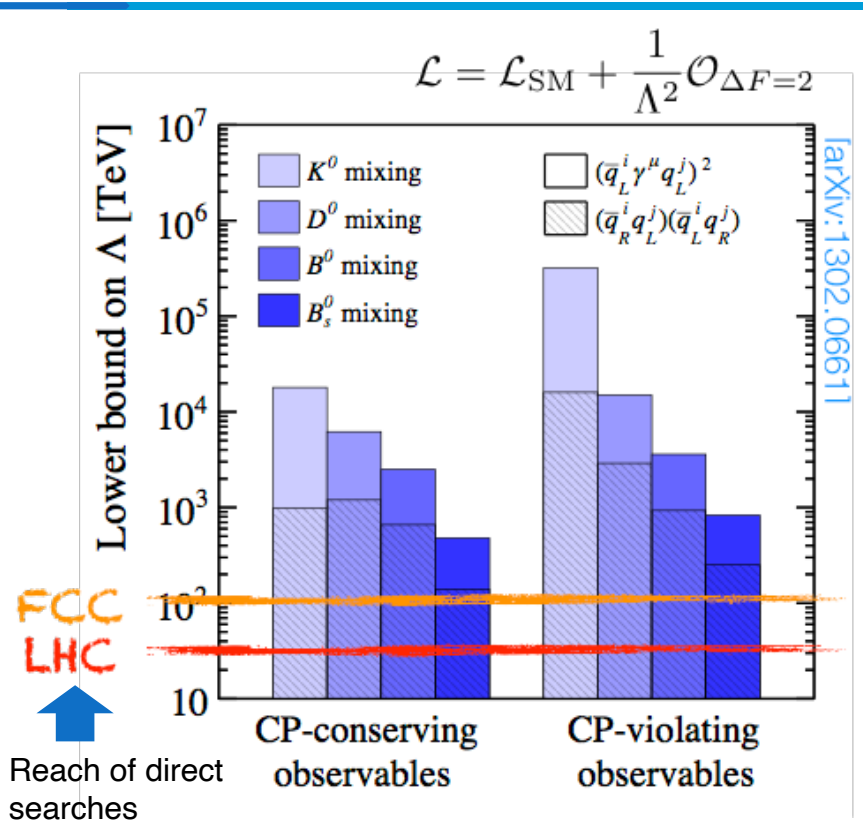
CPV in decay (direct CPV)

CPV in mixing (indirect CPV)

CPV in interference between mixing and decay

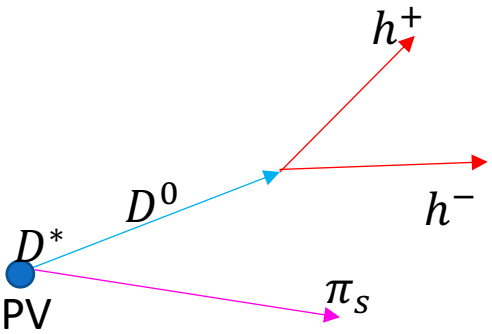
Power of charm physics

- Charm is the only up-type quark where we can look for flavor/CP violation
- **Large** production cross-section at LHC allows to perform **very high precision** measurements
- New Physics contributions could be hidden in the loops
- Assuming a generic NP scenario, **much larger scales** are accessible with respect to direct searches

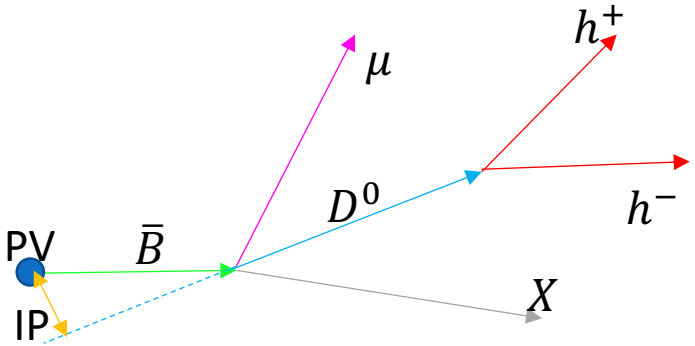


Tagging the decay

- The flavor of the D meson needs to be determined to perform mixing and CPV measurements
- Two possible tagging methods



Prompt tag – IP ~ 0



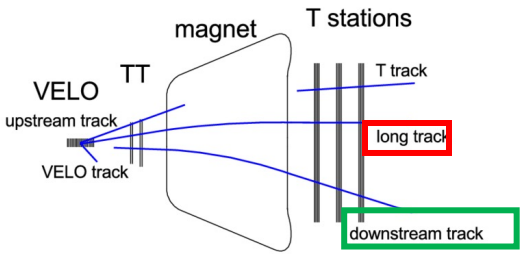
Semileptonic tag – IP > 0

- Prompt sample much bigger than semileptonic one, but semileptonic sample useful to extend the lifetime coverage

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

Phys. Rev. D 104, 031102 (2021)

- Since the observation of CPV in charm decays [PRL 122 (2019) 211803], a systematic search for it in several other charm hadrons decays has been carried out by the LHCb collaboration
- $D^0 \to K^0_S K^0_S$ is an interesting mode, since CPV could be **as large as 1%**
  - See [PRD 92, 054036 (2015)], [PRD 86, 036012 (2012)], [PRD 100, 093002 (2019)], [Phys. Rev. D 99, 113001 (2019)]
- Due to their lifetime, K^0_S are **difficult** to select at **trigger** level
- Use full Run 2 dataset and separate candidates in **three different categories**
  - LL sample: both K^0_S reconstructed as long tracks
  - LD sample: one K^0_S reconstructed as long and the other as downstream track
  - DD sample: both K^0_S reconstructed as downstream tracks



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

Phys. Rev. D 104, 031102 (2021)

- Want to measure the CP asymmetry

$$\mathcal{A}^{CP}(K^0_S K^0_S) = \frac{\Gamma(D^0 \to K^0_S K^0_S) - \Gamma(\overline{D}^0 \to K^0_S K^0_S)}{\Gamma(D^0 \to K^0_S K^0_S) + \Gamma(\overline{D}^0 \to K^0_S K^0_S)}$$

- Experimentally, measure raw asymmetry as difference between number of D^0 and $\overline{D}^0$ decays, using the $D^{*+} \to D^0 \pi^+$ mode to tag the flavour
- The number of D^0 and $\overline{D}^0$ is given by

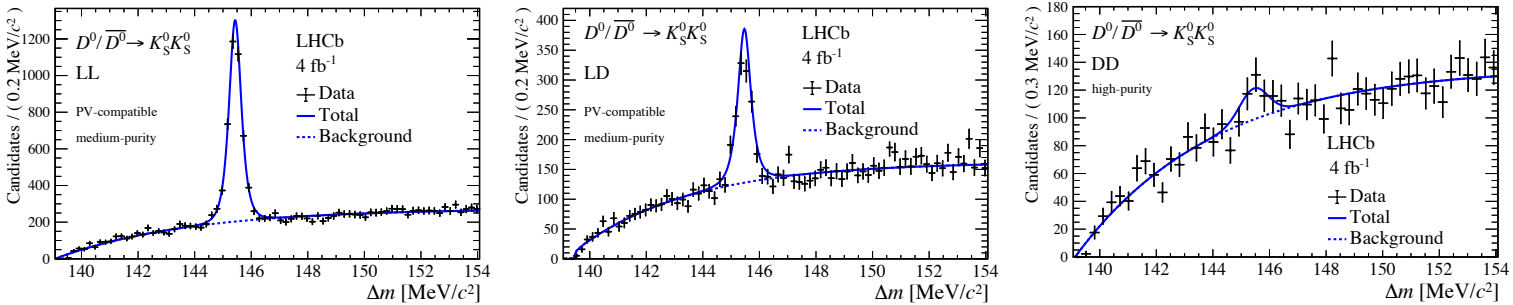
$$N(\overline{D}^{(0)} \to K^0_S K^0_S) \propto \sigma(D^{*\pm})\varepsilon^{\pm}\Gamma(\overline{D}^{(0)} \to K^0_S K^0_S)$$

- Need to account for different production rates of D^{*+} and D^{*-} as well as different interaction of particles and antiparticles with the detector
  - Solution: apply weight to each event proportional to the density of positively and negatively tagged events given by a kNN classifier trained on a control sample of $D^0 \to K^+K^-$ decays

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

Phys. Rev. D 104, 031102 (2021)

- Multidimensional fit to $\Delta m = m(D^*) - m(D^0)$ and the two K^0_S masses to extract A_{CP}

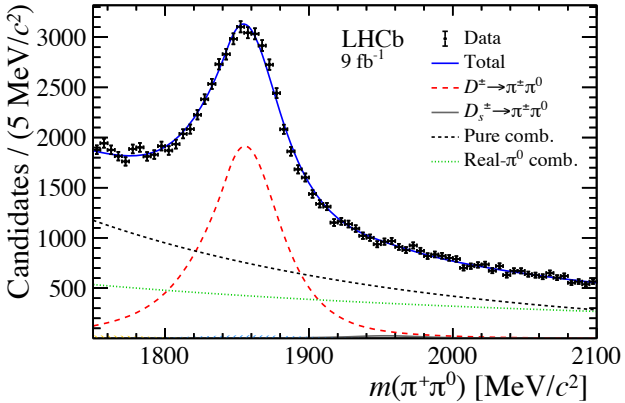


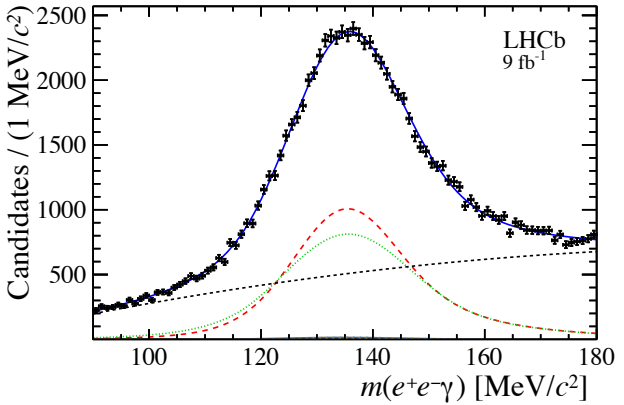
- Obtain: $\mathcal{A}^{CP}(K^0_S K^0_S) = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$
- **Best** measurement of this quantity to date and **competitive** with Belle
- Aim to improve it with more data and better K^0_S reconstruction efficiency in Run 3

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

JHEP 06 (2021) 019

- SM predicts $A_{CP}(D^+ \to \pi^+\pi^0) = 0$ due to isospin, so any deviation without violation of isospin sum rules means NP
- Two-body modes with neutrals challenging at LHCb, since it's **not possible** to reconstruct a **displaced vertex** with only one charged track
  - ☺ use $e^+e^-\gamma$ decays to form a vertex
  - ☹ BR is very low (BR($\pi^0 \to e^+e^-\gamma$) ~1%, BR(η → $e^+e^-\gamma$) ~ 0.7%)
- Measure raw asymmetry be means of 2D fits to reconstructed D and neutral particle masses
- Dataset: full Run 1 + 2 (9 fb^{-1})





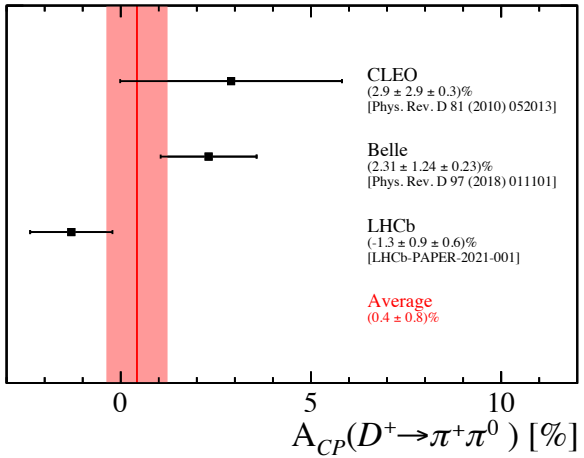
Search for CP violation in $D^+_{(s)} \to h^+\pi^0$ and $D^+_{(s)} \to h^+\eta$ decays

JHEP 06 (2021) 019

- Results consistent with **no CPV** hypothesis

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

World's best measurements



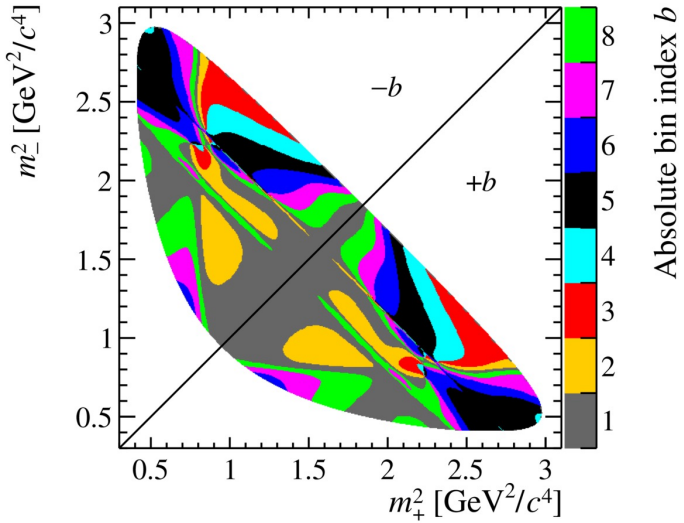
- $A_{CP}(D^+ \to \pi^+\pi^0)$ consistent with 0
  - Isospin sum rules verification updated
- Results **competitive** with b-factories

Slightly worse precision w.r.t. very recent Belle publication [Phys. Rev. D 103, 112005 (2021)]

Observation of the mass difference between neutral charm-meson eigenstates

arXiv:2106.03744, submitted to PRL

- Use $D^0 \to K^0_S \pi^+ \pi^-$ decays (both long and downstream)
  - Rich resonant structure
- Time-dependent Dalitz analysis performed with the **model independent "bin-flip" approach** [PRD99 (2019) 012007]
  - No need to have an accurate efficiency modelling
- Binning chosen to have about the **same strong phase difference** between D^0 and $\overline{D}^0$ amplitudes in each bin
- Dataset: 5.4 fb^{-1} of Run 2 prompt data (~30.6 M events)



$$m^2_\pm \equiv \begin{cases} m^2(K^0_S\pi^\pm) & \text{for } D^0 \to K^0_S\pi^+\pi^- \\ m^2(K^0_S\pi^\mp) & \text{for } \overline{D}^0 \to K^0_S\pi^+\pi^- \end{cases}$$

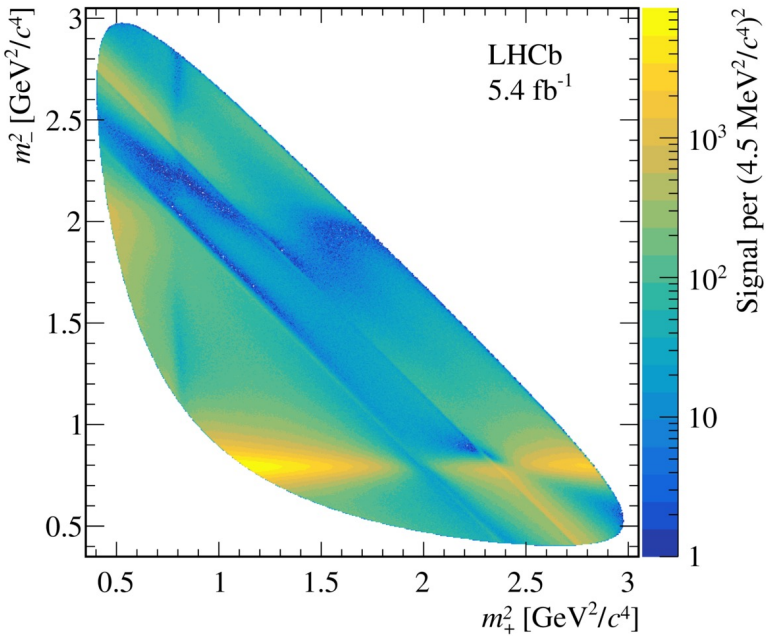
Observation of the mass difference between neutral charm-meson eigenstates

arXiv:2106.03744, submitted to PRL

- Observables: measure yield ratio (R), between *b* and *–b* bins, as a function of decay time. This is a function of

$$z_{CP} \pm \Delta z = -(q/\mathrm{p})^{\pm 1}(\mathrm{y} \pm ix)$$
$$x_{CP} = -Im(z_{CP}), y_{CP} = -Re(z_{CP})$$
$$\Delta x = -Im(\Delta z), \Delta y = -Re(\Delta z)$$
Δy often referred to as A_Γ

- Perform least-squares minimization that compares the decay-time evolution of signal yields in the Dalitz bins *b* and *–b*

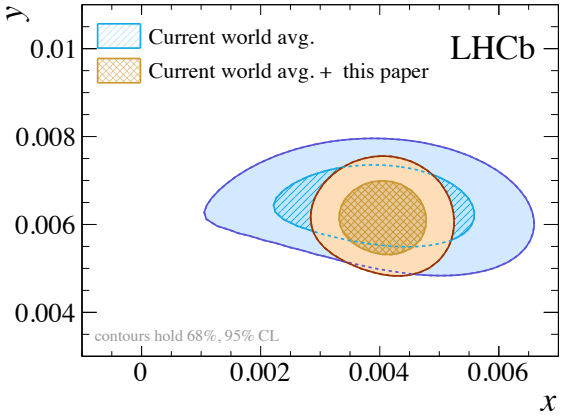


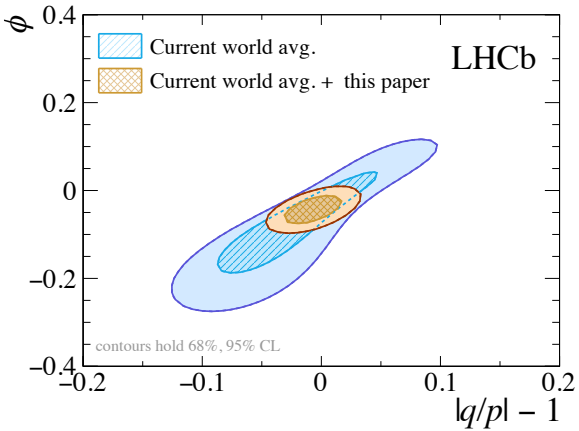
Observation of the mass difference between neutral charm-meson eigenstates

arXiv:2106.03744, submitted to PRL

- Fit results compatible with CP symmetry hypothesis ($\Delta x = \Delta y = 0,\ x_{CP} = x, y_{CP} = y$)

Parameter	Value $[10^{-3}]$
x_{CP}	$3.97 \pm 0.46 \pm 0.29$
y_{CP}	$4.59 \pm 1.20 \pm 0.85$
Δx	$-0.27 \pm 0.18 \pm 0.01$
Δy	$0.20 \pm 0.36 \pm 0.13$





- **First observation** of a **nonzero value** of the mass difference of neutral charm meson mass eigenstate at more than 7σ
- Measurement still **statistically limited**: aim to improve it with Run 3 dataset together with better K_S^0 reconstruction efficiency!
- BESIII inputs are about half of statistical uncertainty for x_{CP} and y_{CP} : will need to improve these measurements as the LHCb dataset increases

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

arXiv:2105.09889, submitted to PRD

- Complementary test of SM w.r.t. measurement of direct CPV
- SM expectations still ~ **1 order of magnitude below experimental precision** → need to improve
- Measure time-dependent CP asymmetry of D^0 mesons to K^+K^- and $\pi^+\pi^-$ final states with full Run 2 dataset

$$A_{CP}(f,t) \equiv \frac{\Gamma(D^0 \to f, t) - \Gamma(\overline{D}^0 \to f, t)}{\Gamma(D^0 \to f, t) + \Gamma(\overline{D}^0 \to f, t)}$$

Since: $x, y \ll 1$

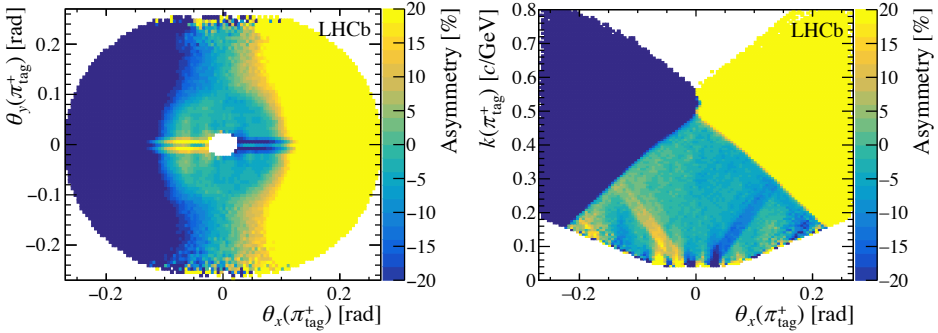
$$A_{CP}(f,t) \approx a_f^d + \Delta Y_f \frac{t}{\tau_{D^0}}$$

- Perform linear fit to the values of the CP asymmetry in bins of D^0 decay time to measure the slope parameter ΔY_f

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

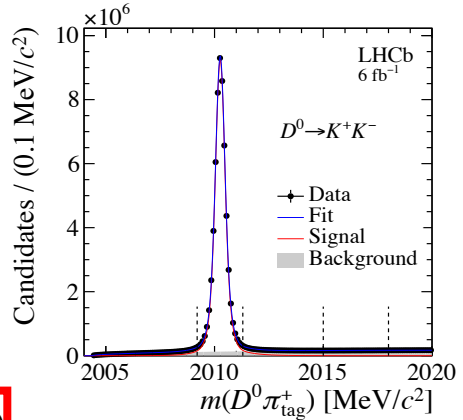
arXiv:2105.09889, submitted to PRD

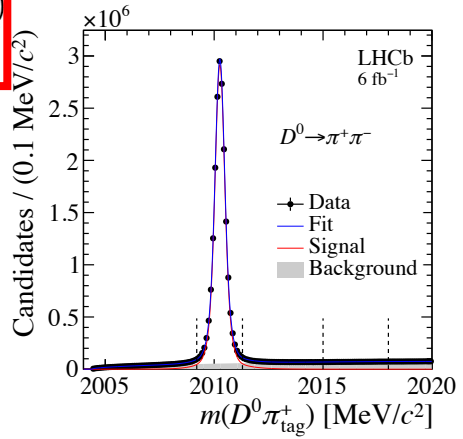
- Parameter ΔY_f determined from linear fit to time-dependent asymmetry in 21 bins of decay time
- **Momentum-dependent charge asymmetries** arise from the pion used to tag the D^0 flavor



$$\theta_{x(y)} \equiv \arctan(p_{x(y)}/p_z)$$
$$k \equiv 1/\sqrt{p_x^2 + p_z^2}$$

- **Two-step reweighting** procedure employed to mitigate this effect





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

arXiv:2105.09889, submitted to PRD

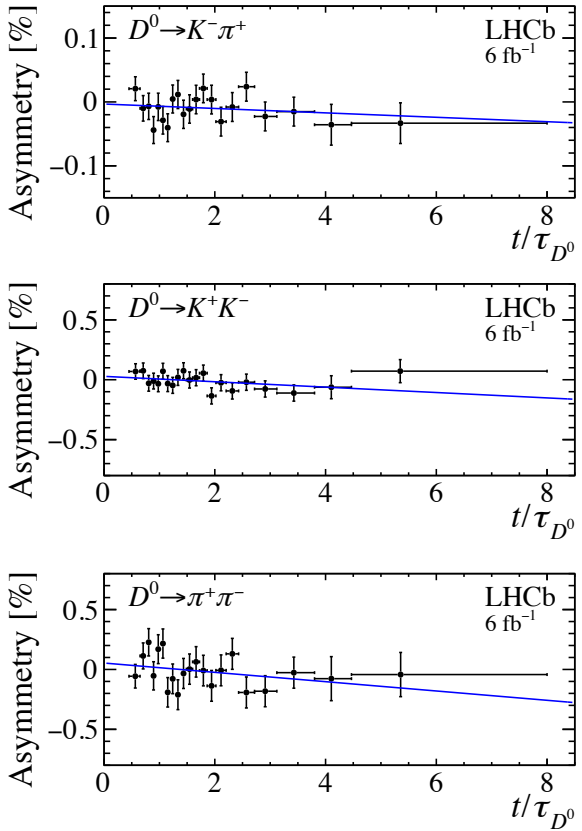
- Validate measurement on CF $D^0 \to K^-\pi^+$ decays → $\Delta Y_{K\pi}$ expected to be well below experimental precision
- Results

$$\Delta Y_{K^-\pi^+} = (-0.4 \pm 0.5 \pm 0.2) \times 10^{-4}$$
$$\Delta Y_{K^+K^-} = (-2.3 \pm 1.5 \pm 0.3) \times 10^{-4}$$
$$\Delta Y_{\pi^+\pi^-} = (-4.0 \pm 2.8 \pm 0.4) \times 10^{-4}$$

- Neglecting weak phases in the decay amplitude, ΔY_f does not depend on final state and the results can be combined

$$\Delta Y = (-2.7 \pm 1.3 \pm 0.3) \times 10^{-4}$$

LHCb Run 1+2 average: $\Delta Y = (-1.0 \pm 1.1 \pm 0.3) \times 10^{-4}$



Prospects

arXiv: 1808.08865

- LHCb estimates from Physics case for Upgrade 2

$D^0 \to K^0_S \pi^+ \pi^+$

Sample (lumi $\mathcal{L}$)	Tag	Yield	$\sigma(x)$	$\sigma(y)$	$\sigma(\lvert q/p \rvert)$	$\sigma(\phi)$
Run 1–2 (9 fb^{-1})	SL	10M	0.07%	0.05%	0.07	4.6°
	Prompt	36M	0.05%	0.05%	0.04	1.8°
Run 1–3 (23 fb^{-1})	SL	33M	0.036%	0.030%	0.036	2.5°
	Prompt	200M	0.020%	0.020%	0.017	0.77°
Run 1–4 (50 fb^{-1})	SL	78M	0.024%	0.019%	0.024	1.7°
	Prompt	520M	0.012%	0.013%	0.011	0.48°
Run 1–5 (300 fb^{-1})	SL	490M	0.009%	0.008%	0.009	0.69°
	Prompt	3500M	0.005%	0.005%	0.004	0.18°

No known systematic uncertainties will limit the ultimate precision

ΔY with $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$

Sample ($\mathcal{L}$)	Tag	Yield K^+K^-	$\sigma(A_\Gamma)$	Yield $\pi^+\pi^-$	$\sigma(A_\Gamma)$
Run 1–2 (9 fb^{-1})	Prompt	60M	0.013%	18M	0.024%
Run 1–3 (23 fb^{-1})	Prompt	310M	0.0056%	92M	0.0104 %
Run 1–4 (50 fb^{-1})	Prompt	793M	0.0035%	236M	0.0065 %
Run 1–5 (300 fb^{-1})	Prompt	5.3G	0.0014%	1.6G	0.0025 %

Finally reaching sub 10^{-4} level in Run 3

- $D^+_{(s)} \to h^+\pi^0$ and $D^+_{(s)} \to h^+\eta$ CPV measurements currently statistically limited
  - Room for large improvement with Run 3 (and beyond) datasets and with ECAL upgrades

Conclusions

- Several recent results have been presented today
  - Mass difference between neutral charm-meson eigenstates, ΔY, CPV in $D^0 \to K_S^0 K_S^0$, $D_{(s)}^+ \to h^+ \pi^0$ and $D_{(s)}^+ \to h^+ \eta$ decays
- **No CPV observed** in the presented analyses
- Since discovery of CPV in charm decays, searches are proceeding at full steam
  - **Many** new results expected for **winter** conferences
- Several analyses **still statistically limited**
  - **Run 3 and beyond** will allow to collect larger samples of charm decays
  - **Improvements** in the **detector** and **reconstruction** foreseen for Upgrade 1 and 2 (e.g. better efficiency for downstream K_S^0) will help to accumulate even larger datasets

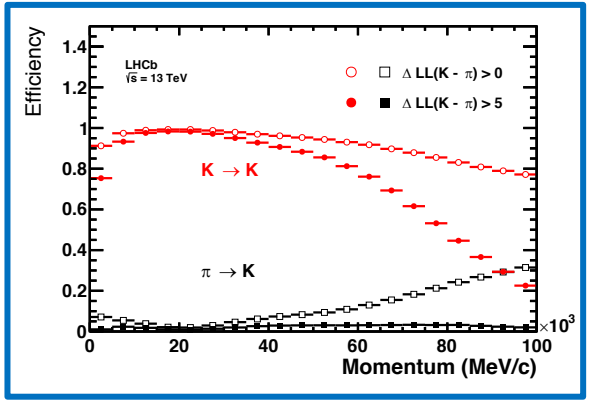
Backup

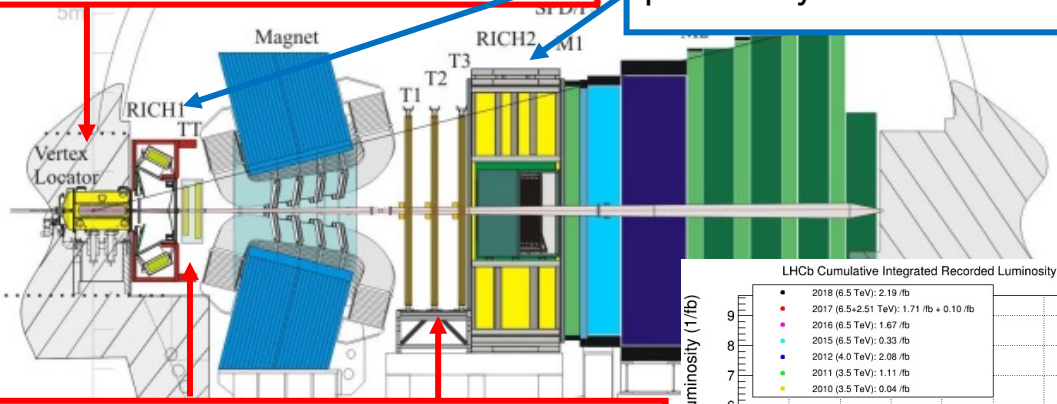
The LHCb detector

J. Instrum. 3 (2008) S08005
*Nucl.Phys. B871 (2013) 1-20
**J. High Energ. Phys. (2017) 74

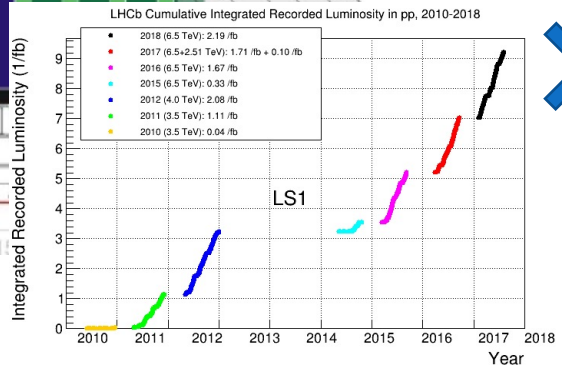
Silicon Vertex Locator (VELO)
$20\ \mu m$ impact parameter resolution, corresponding to $\sim 0.1\tau$ decay-time resolution for a 2-body charm decay

RICH 1 & 2
Provide discrimination between kaons, pions and protons between 5 and 150 GeV/c. Typical kaon ID $\sim 95\ \%$ for $\sim 5\ \%\ \pi \to K$ mis-ID probability





Tracking systems
$\Delta p/p = 0.4 - 0.6\%$ at $5 - 100\ GeV/c$, corresponding to $\sim 8\ MeV/c^2$ mass resolution for a 2-body charm decay



$\sigma(pp \to ccX) = 1419 \pm 134\ \mu b\ @\ \sqrt{s} = 7\ TeV^*$
$\sigma(pp \to ccX) = 2840 \pm 226\ \mu b\ @\ \sqrt{s} = 13\ TeV^{**}$

Unprecedented amount of charm decays collected during Run 1 and 2

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

Phys. Rev. D 104, 031102 (2021)

This table summarises the yields and CP asymmetries for different categories of K^0_S and years of data taking

Sample	$2015 + 2016$ $(2\ \text{fb}^{-1})$		$2017 + 2018$ $(4\ \text{fb}^{-1})$	
	Yield	$\mathcal{A}^{CP}$ [%]	Yield	$\mathcal{A}^{CP}$ [%]
LL PV-comp.	1388 ± 41	$0.3 \pm 2.5 \pm 0.6$	4056 ± 77	$-4.3 \pm 1.6 \pm 0.4$
LL PV-incomp.	178 ± 31	$-11 \pm 17 \pm 2$	430 ± 41	$-3.0 \pm 7.9 \pm 1.1$
LD PV-comp.	411 ± 25	$-7.2 \pm 5.8 \pm 1.1$	1145 ± 49	$-2.9 \pm 3.8 \pm 0.7$
LD PV-incomp.	58 ± 18	$-10 \pm 31 \pm 4$	349 ± 64	$-5 \pm 17 \pm 2$
DD	–	–	87 ± 28	$-35 \pm 47 \pm 6$

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

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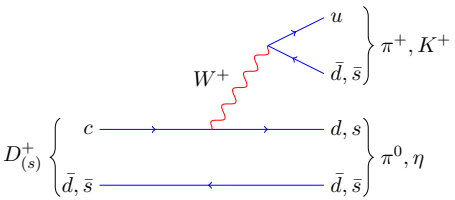
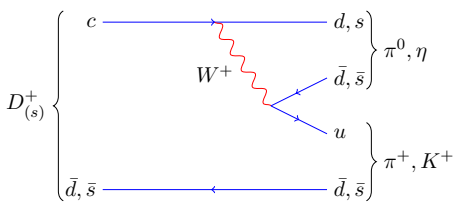
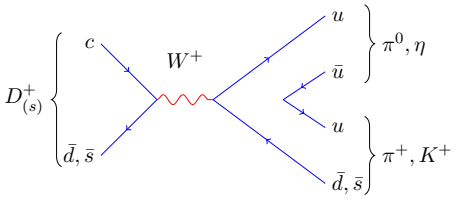
Feynman diagrams of the contributing processes

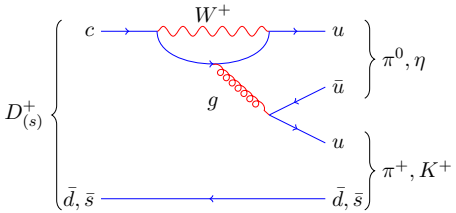
Tree level







Loop level



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

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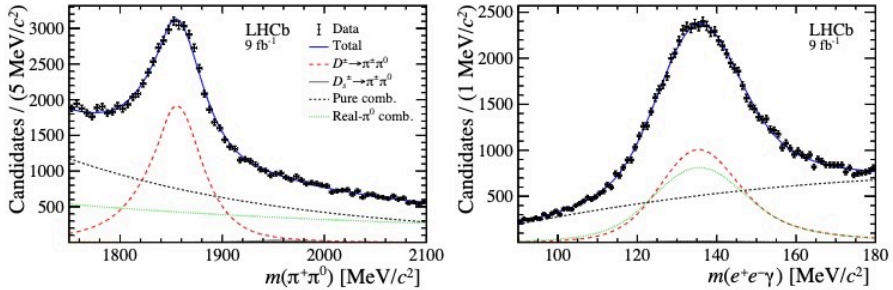
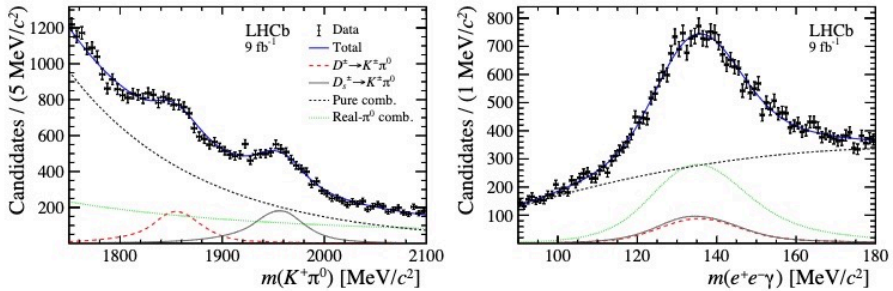
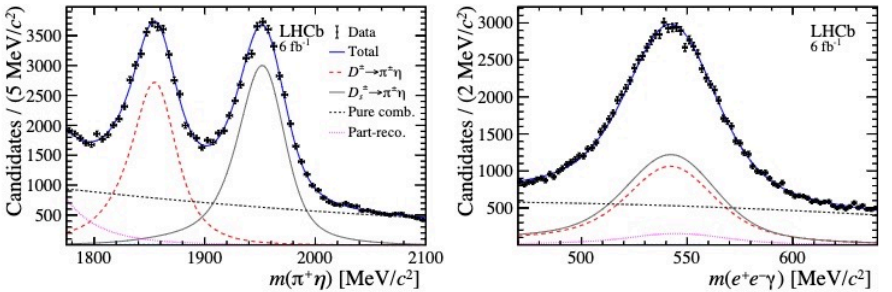
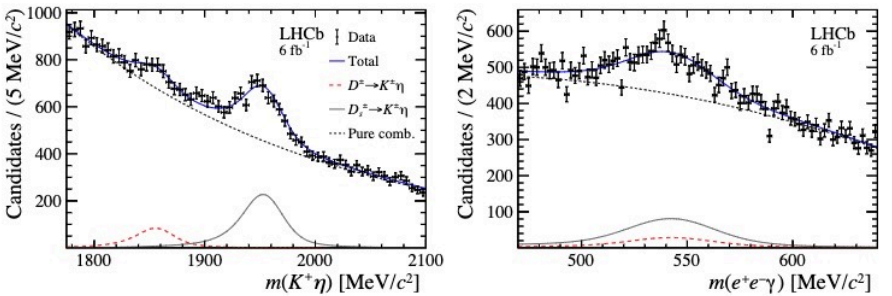
Fit projections of signal modes





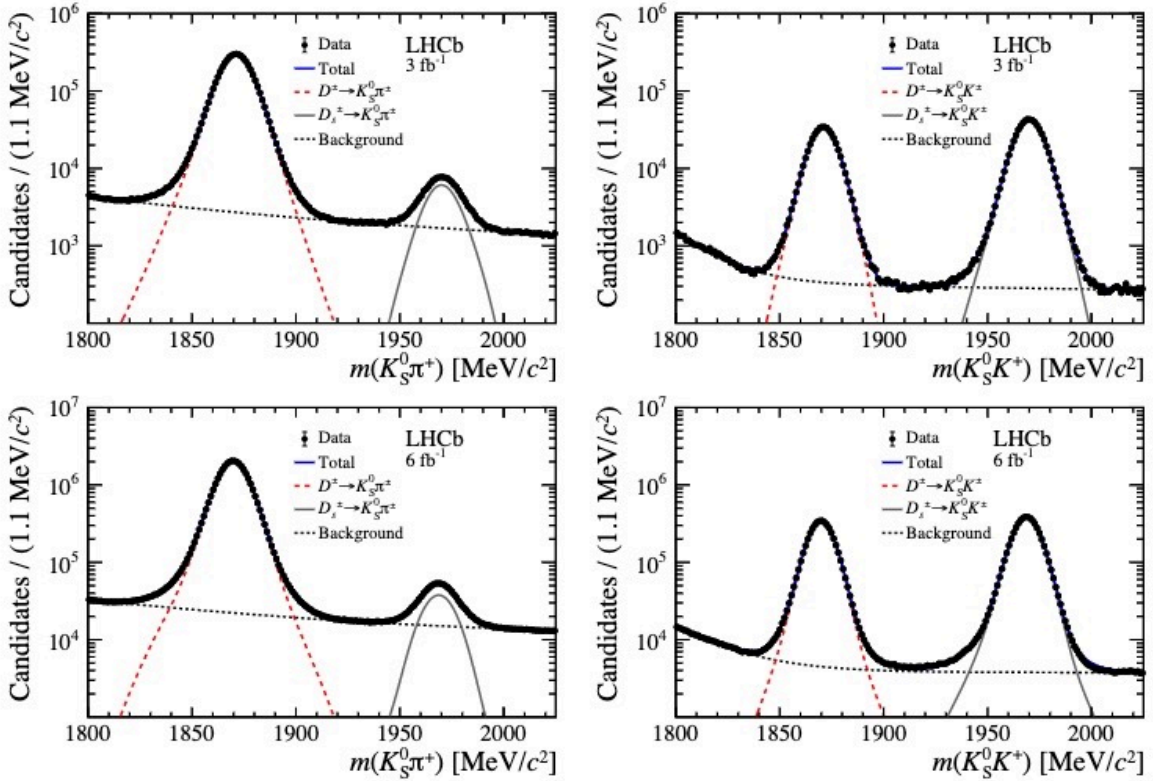




Search for CP violation in $D^+_{(s)} \to h^+\pi^0$ and $D^+_{(s)} \to h^+\eta$ decays

JHEP 06 (2021) 019

Fit projections of control modes



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

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Table 3: Absolute systematic uncertainties (%) on the *CP* asymmetries for $D^+_{(s)} \to h^+\pi^0$ decays.

Source	$D^+ \to \pi^+\pi^0$	$D^+ \to K^+\pi^0$	$D_s^+ \to K^+\pi^0$
Fit model	0.59	1.55	1.01
PID asymmetry	0.06	0.27	0.15
Secondary decays	< 0.01	0.01	0.02
Combined $A_{\rm Raw}$ Run 1 and Run 2	0.23	0.65	0.30
Control modes	0.03	1.18	0.59
$A_{\rm Mix}(K^0)$	< 0.01	< 0.01	< 0.01
$\mathcal{A}_{CP}(D^+_{(s)} \to K^0_S h^+)$	0.12	0.08	0.26
Total	0.65	2.07	1.24

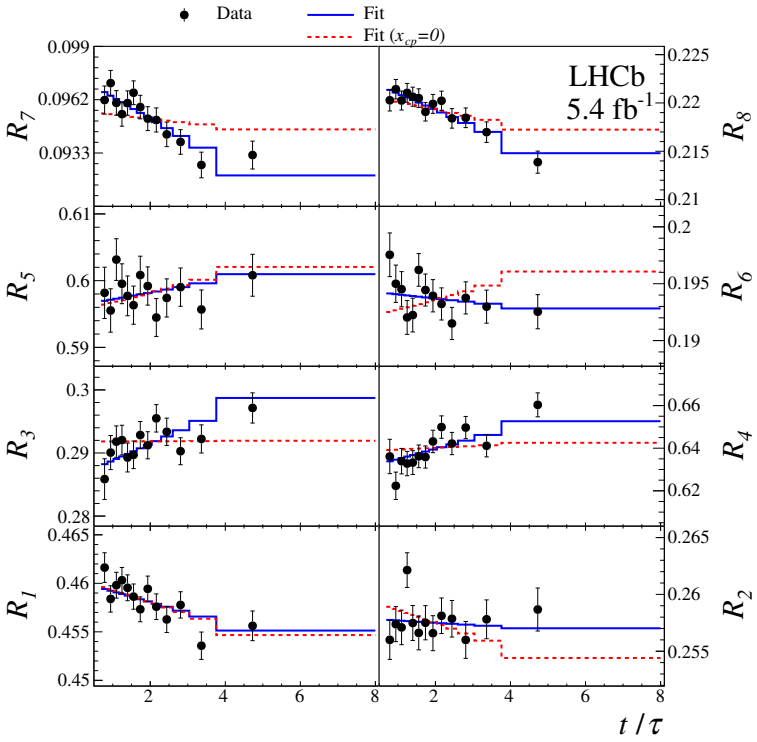
Table 4: Absolute systematic uncertainties (%) on the *CP* asymmetries for $D^+_{(s)} \to h^+\eta$ decays.

Source	$D^+ \to \pi^+\eta$	$D_s^+ \to \pi^+\eta$	$D^+ \to K^+\eta$	$D_s^+ \to K^+\eta$
Fit model	0.35	0.15	4.04	1.08
PID asymmetry	0.06	0.01	0.87	0.16
Secondary decays	< 0.01	0.02	0.01	0.04
Control modes	0.05	0.39	0.14	0.12
$A_{\rm Mix}(K^0)$	< 0.01	< 0.01	< 0.01	< 0.01
$\mathcal{A}_{CP}(D^+_{(s)} \to K^0_S h^+)$	0.12	0.20	0.08	0.26
Total	0.38	0.46	4.13	1.13

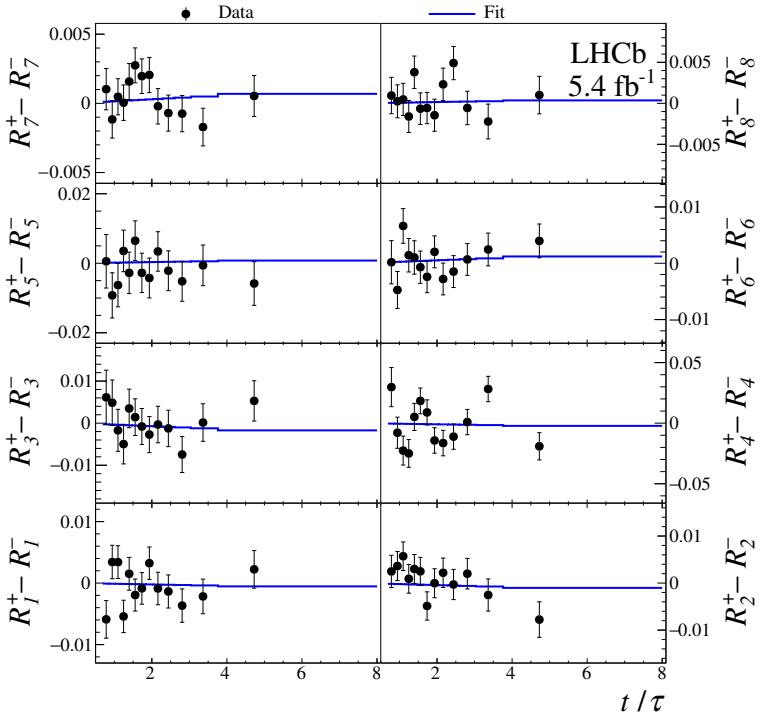
Observation of the mass difference between neutral charm-meson eigenstates

arXiv:2106.03744, submitted to PRL

CP-averaged yields ratios



Differences of D^0 and $\overline{D}^0$ yield ratios



Observation of the mass difference between neutral charm-meson eigenstates

arXiv:2106.03744, submitted to PRL

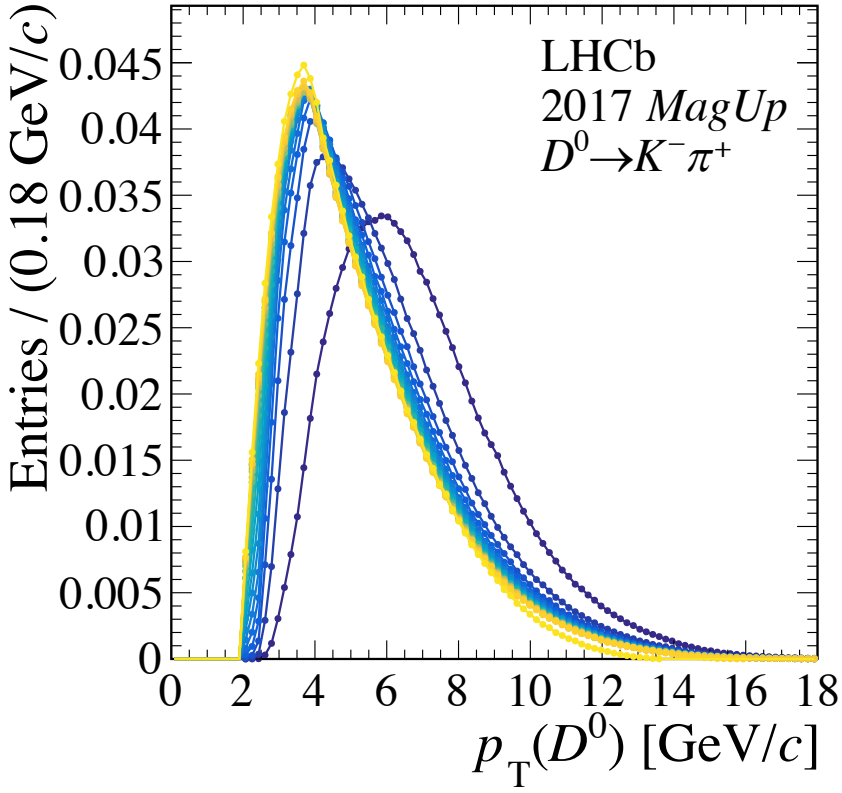
Systematic and statistical uncertainty on parameters $x_{CP}, y_{CP}, \Delta x$ and Δy. Strong phase inputs contribution is added in quadrature to the statistical uncertainty.

Source	x_{CP}	y_{CP}	Δx	Δy
Reconstruction and selection	0.199	0.757	0.009	0.044
Secondary charm decays	0.208	0.154	0.001	0.002
Detection asymmetry	0.000	0.001	0.004	0.102
Mass-fit model	0.045	0.361	0.003	0.009
Total systematic uncertainty	0.291	0.852	0.010	0.110
Strong phase inputs	0.23	0.66	0.02	0.04
Detection asymmetry inputs	0.00	0.00	0.04	0.08
Statistical (w/o inputs)	0.40	1.00	0.18	0.35
Total statistical uncertainty	0.46	1.20	0.18	0.36

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

arXiv:2105.09889, submitted to PRD

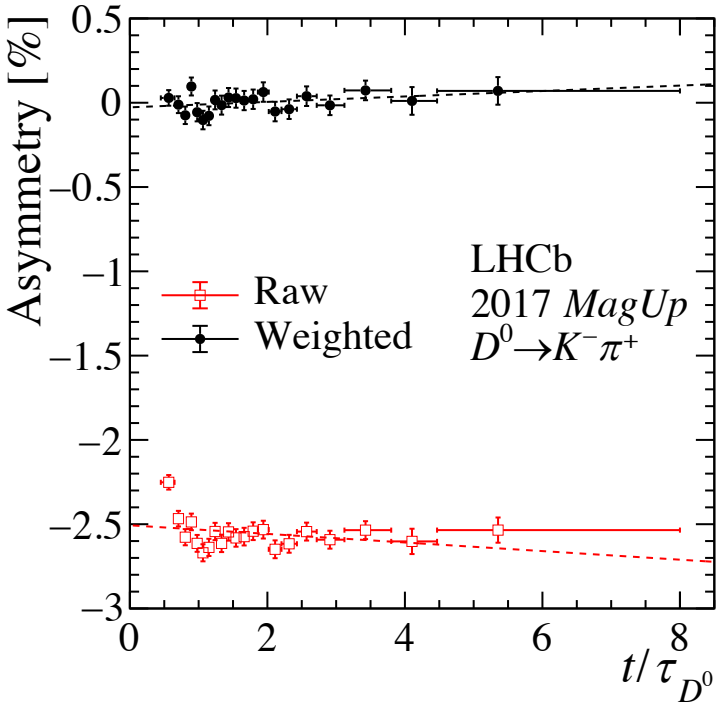
Normalised distributions of the D^0 transverse momentum divided by D^0 decay-time bin (lighter: lower decay-time, darker: higher decay-time)



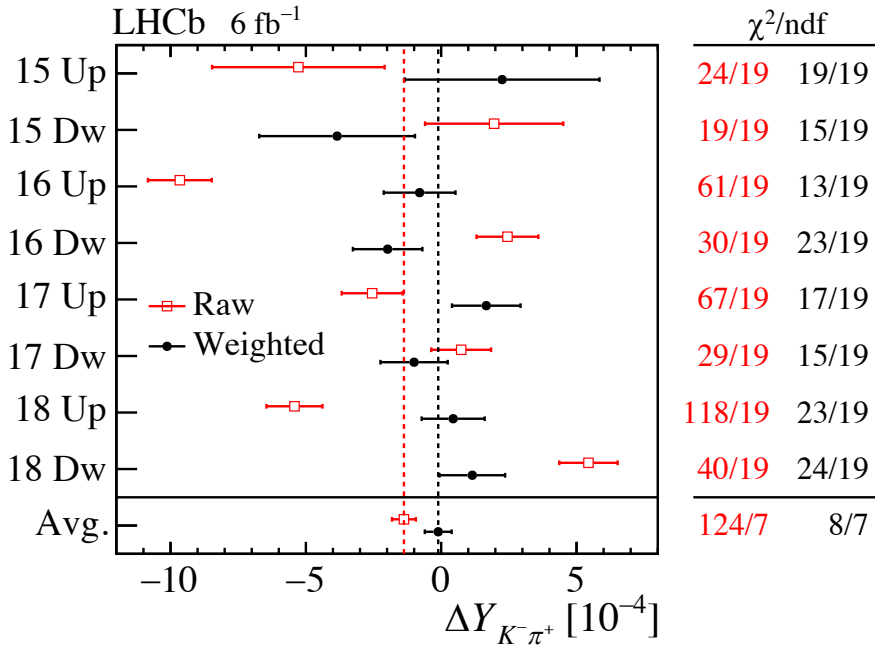
Search for time-dependent CPV in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays

arXiv:2105.09889, submitted to PRD

Effect of reweight procedure on asymmetry of the control sample in different decay-time bins



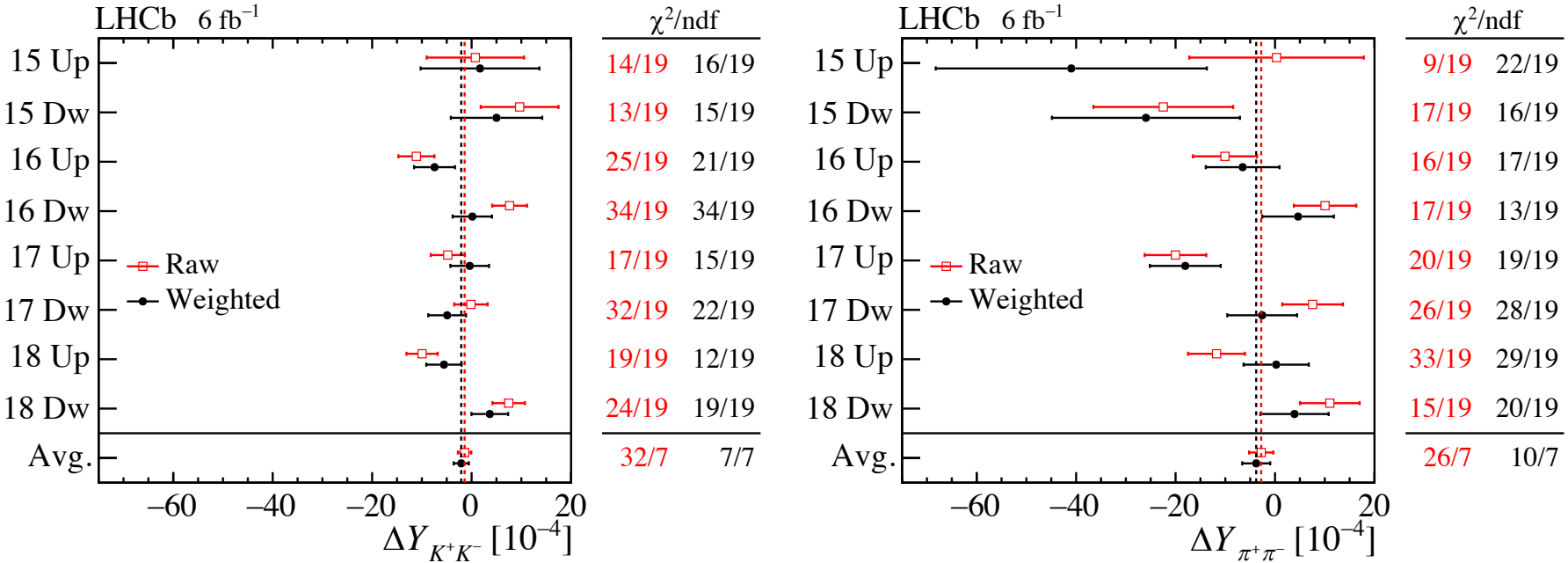
Results of the time-dependent fits on the $K\pi$ control sample divided by year and magnet polarity, before and after the reweight procedure



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

arXiv:2105.09889, submitted to PRD

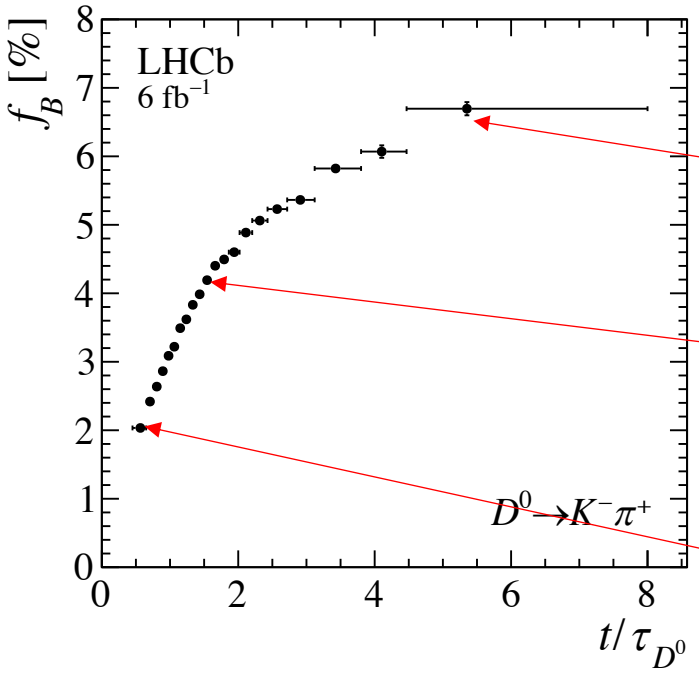
Results of the time-dependent fits on the (left) KK and (right) $\pi\pi$ sample divided by year and magnet polarity, before and after the reweight procedure

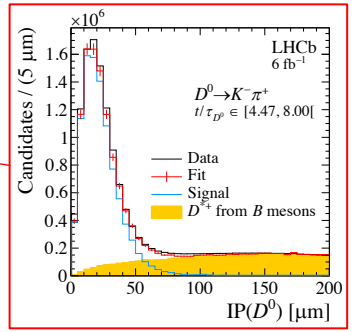


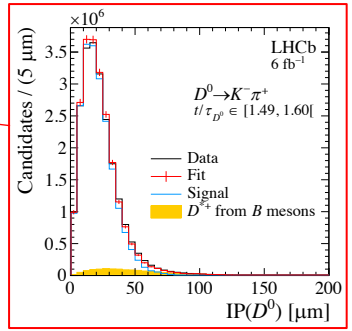
Search for time-dependent CPV in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays

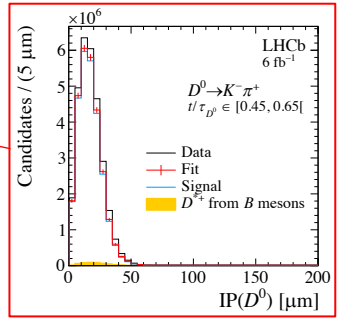
arXiv:2105.09889, submitted to PRD

Template fits to the IP(D^0) distribution. The templates are obtained from simulation and the fraction is floating









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

Summary of the systematic uncertainties and comparison with the statistical uncertainty

Source	$\Delta Y_{K^+K^-}$ $[10^{-4}]$	$\Delta Y_{\pi^+\pi^-}$ $[10^{-4}]$
Subtraction of the $m(D^0\pi^+_{\text{tag}})$ background	0.2	0.3
Flavour-dependent shift of D^* -mass peak	0.1	0.1
D^{*+} from B -meson decays	0.1	0.1
$m(h^+h^-)$ background	0.1	0.1
Kinematic weighting	0.1	0.1
Total systematic uncertainty	0.3	0.4
Statistical uncertainty	1.5	2.8