Mixing and indirect CPV in charm decays at LHCb

Guillaume Pietrzyk on behalf of the LHCb collaboration

CHARM, 3rd June 2021

Mexico Virtual (UNAM)

CP-violation in the charm sector

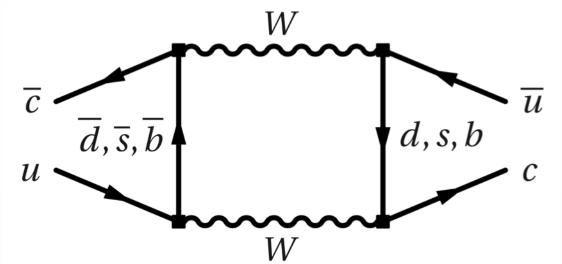
- The charm sector encompasses the only up-type quark decays of neutral mesons in which CP-violation (CPV) can be probed.
- CPV in SM is predicted to be small $(\sim 10^{-3} - 10^{-4})$.

  → Room for new physics enhancements.
- These predictions are dominated by long distance contributions.

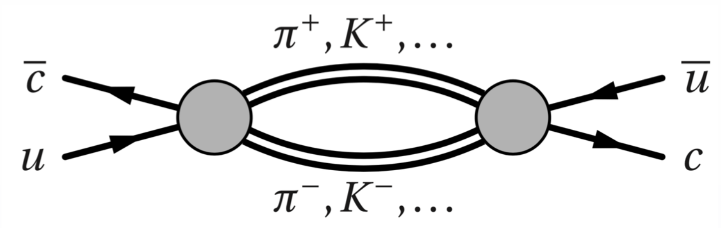
  → Experimental measurements are crucial to improve theoretical predictions.

	d	s	b
$\bar{d}$	-	K^0	B_0
$\bar{s}$	$\bar{K}^0$	-	B_s^0
$\bar{b}$	$\bar{B}^0$	$\bar{B}_s^0$	-

	u	c	t
$\bar{u}$	-	D^0	-
$\bar{c}$	$\bar{D}^0$	-	-
$\bar{t}$	-	-	-



Short Distance Contributions:
Heavily suppressed!



Long Distance Contributions:
Large theoretical uncertainties!

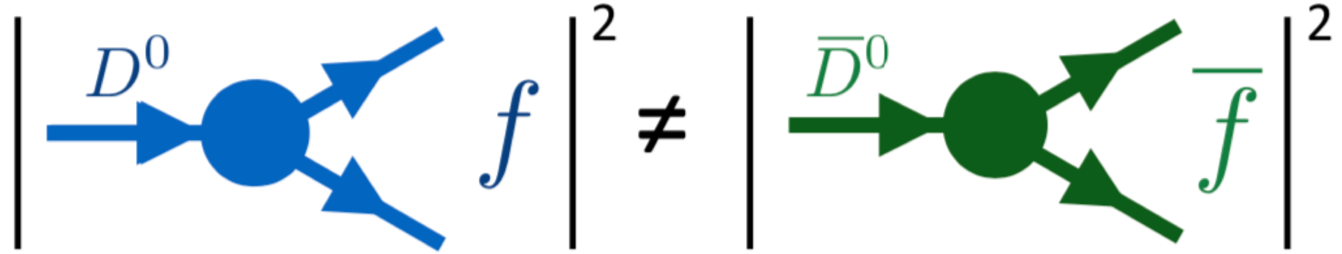
- Charm data samples are huge: ~ a few billion D^0 decays to be analysed at LHCb with Run 1 + Run 2 data.

CP-violation in the charm sector

DIRECT

Decay

$|A_f| \neq |\bar{A}_{\bar{f}}|$



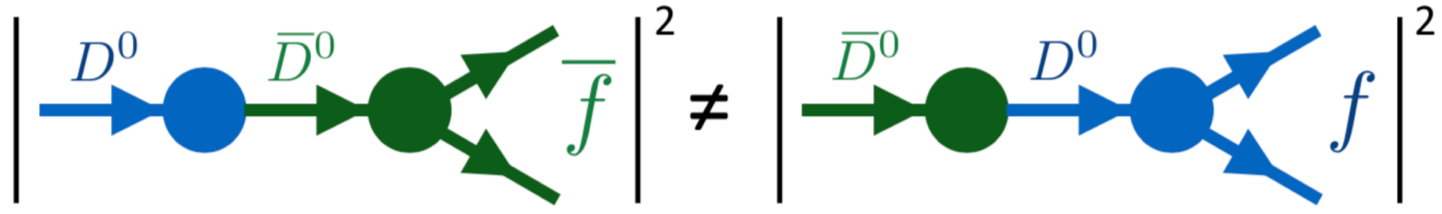
CPV in the decay observed at 5.3σ by the LHCb collaboration in March 2019!
[PhysRevLett.122.211803]

INDIRECT

THIS TALK!

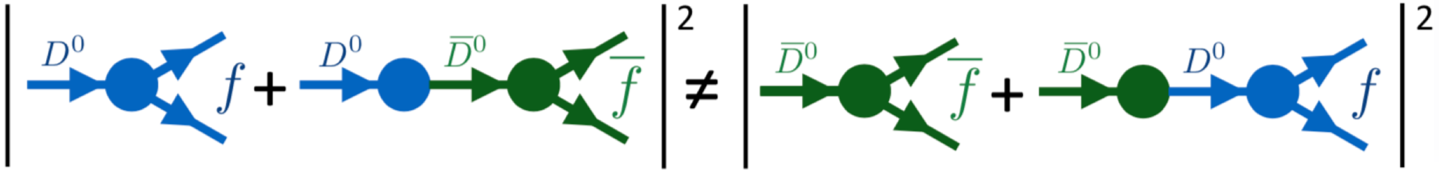
Mixing

$|q| \neq |p|$



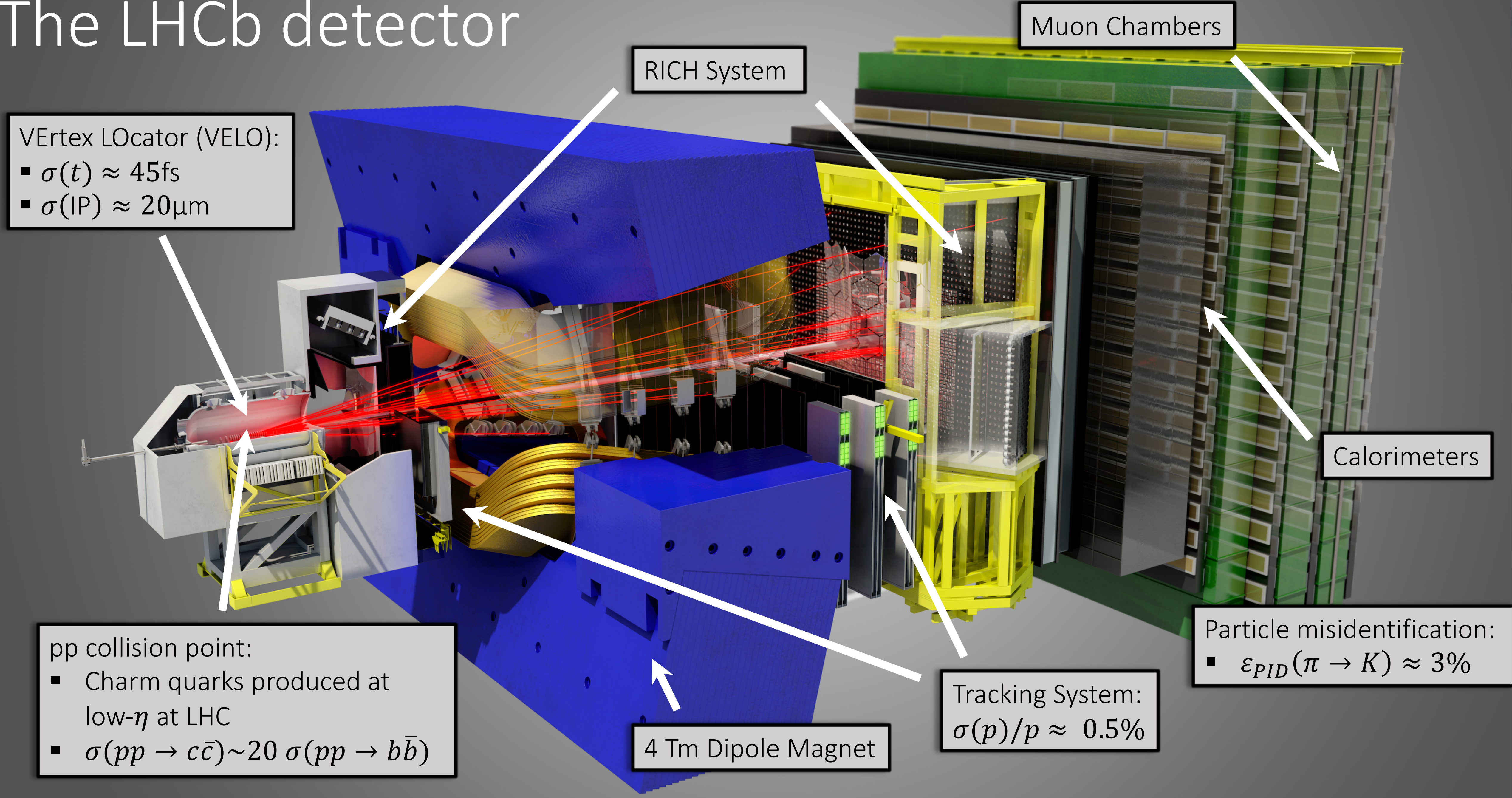
Interference mixing-decay

$$\phi_{\lambda_f} = \arg\left(\frac{q\bar{A}_f}{pA_f}\right) \neq 0$$



Still no evidence of CPV

The LHCb detector



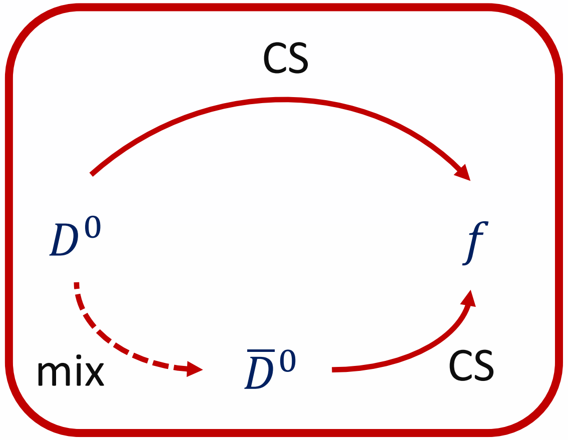
Search for time-dependent CPV in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays

arXiv:2105.09889

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

- Search for indirect CPV using the slope of the time-dependent $D^0 - \bar{D}^0$ asymmetry $\Delta Y_f \approx -A_\Gamma$:

$f = K^+K^-, \pi^+\pi^-$



$$A_{raw}(f,t) = \frac{N(D^0 \to f,t) - N(\bar{D}^0 \to f,t)}{N(D^0 \to f,t) + N(\bar{D}^0 \to f,t)}$$

$$= A_{CP}^{\text{decay}}(f) + \Delta Y_f \frac{t}{\tau_{D^0}} + \underbrace{A_D^{\text{flav-id}}(f,t) + A_P(f,t)}$$

Time-dependent nuisance asymmetries which need to be carefully dealt with (biggest challenge of the analysis!)

$$\Delta Y_f \approx x\phi_{\lambda_f} - y\left(\left|\frac{q}{p}\right| - 1\right) + yA_{CP}^{\text{decay}}(f)$$

CPV in the mixing-decay interference

CPV in the mixing

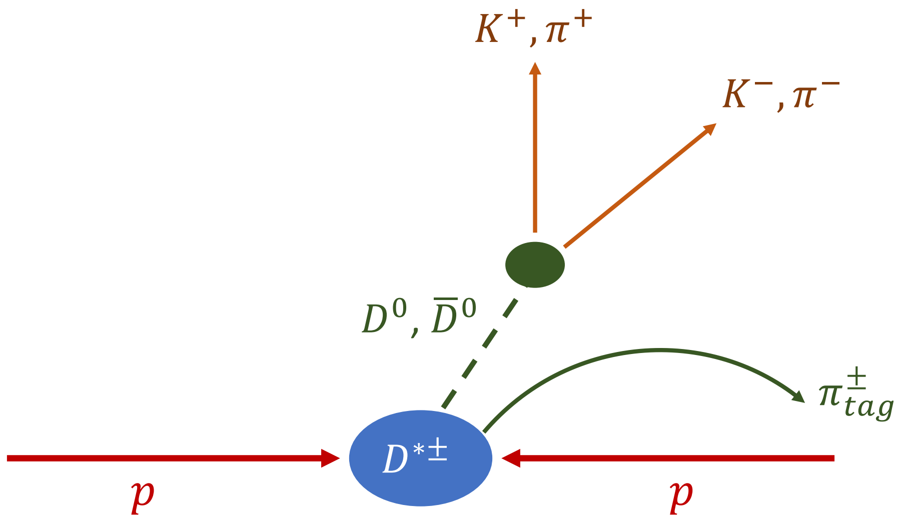
CPV in the decay ($\leq 1\times10^{-5}$)

- If $\Delta Y_f \neq 0$ → CP violation in charm decays!
- SM expectation: $\mathcal{O}(2\times10^{-5})$ Kagan, Silvestrini (2020), Li, Umeeda, Xu, Yu (2020)
- Current best experimental precision: $\sim 2\times10^{-4}$ HFLAV

Measurement of ΔY_f: Analysis strategy

arXiv:2105.09889

- Analysis performed using the full Run 2 data (2015-2018, 6fb^{-1}).
- $D^0 \to f$ candidates obtained from prompt $D^{*+} \to D^0\pi^{\pm}_{tag}$ candidates. The charge of $\pi^{\pm}_{tag}$ tags the flavour of the D^0 meson.
- Combinatorial background present in the $m(D^0\pi^{\pm}_{tag})$ distribution removed with a sideband subtraction procedure.



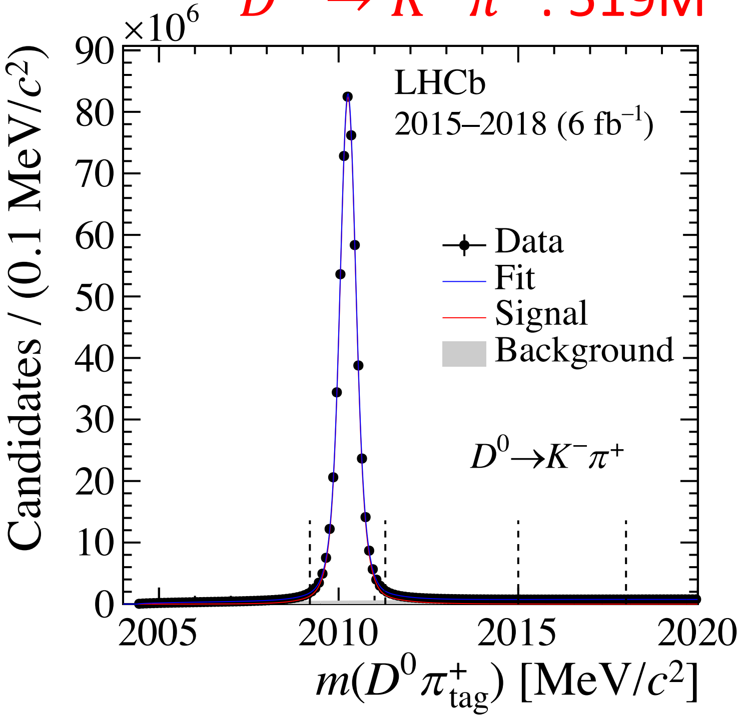
- Time-dependent nuisance asymmetries removed by equalising the kinematics of D^0 and $\overline{D}^0$ candidates.
- Significant background contribution from D^{*+} candidates coming from B-mesons (called *secondary decays*): treated by studying and then subtracting their corresponding asymmetry.
- The analogue of ΔY_f for $D^0 \to K^-\pi^+$ decays is known to be $\leq 0.3\times10^{-4}$ at 90% CL (from experimental results) and is used to cross-check the analysis method (benefiting from huge $D^0 \to K^-\pi^+$ yields!)

arXiv:2105.09889

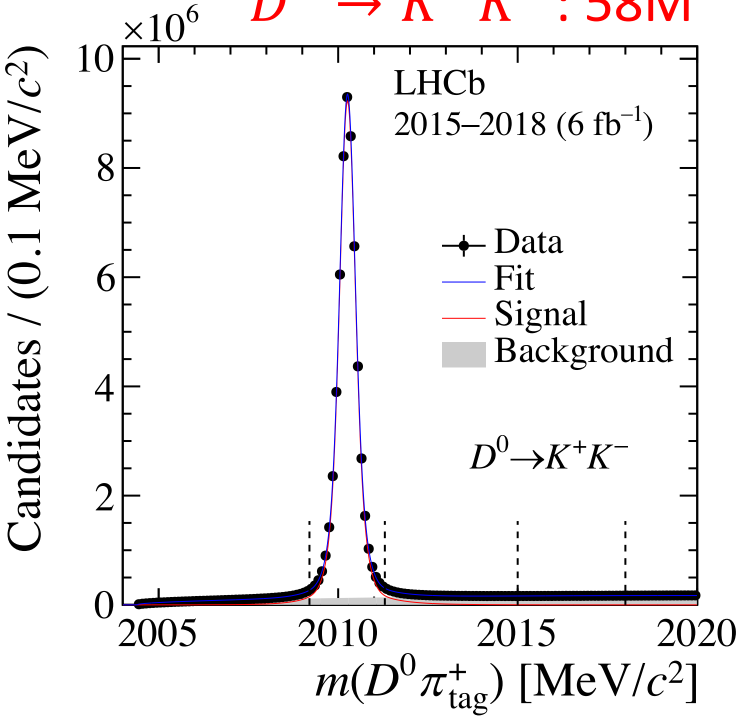
Removal of the $m(D^0\pi^{\pm}_{tag})$ background

- The small combinatorial background present in the $m(D^0\pi^{\pm}_{tag})$ distribution comes mainly from the association of a D^0 with a random $\pi^{\pm}$ from the pp interactions.
- This background source is removed with a sideband subtraction procedure by fitting in each bin of D^0 decay time the background and the signal of the $m(D^0\pi^{\pm}_{tag})$ distribution.

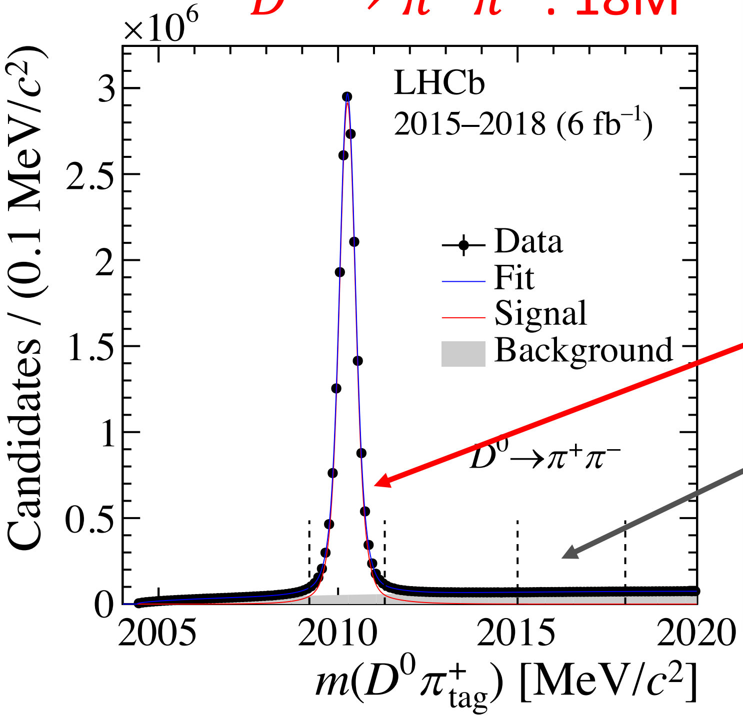
$D^0 \to K^-\pi^+$: 519M



$D^0 \to K^+K^-$: 58M



$D^0 \to \pi^+\pi^-$: 18M



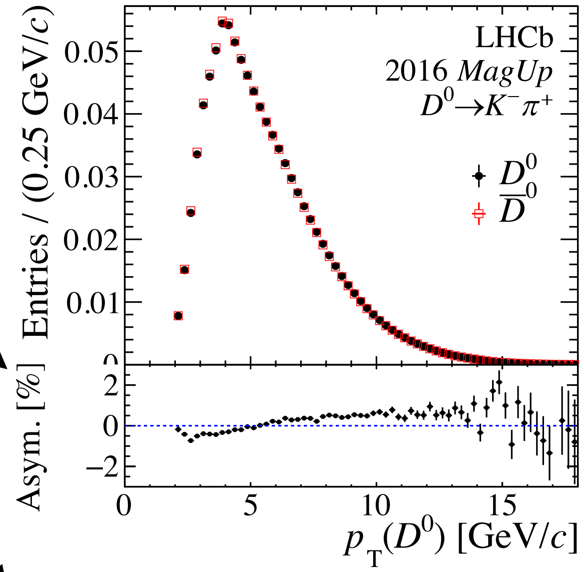
Signal region

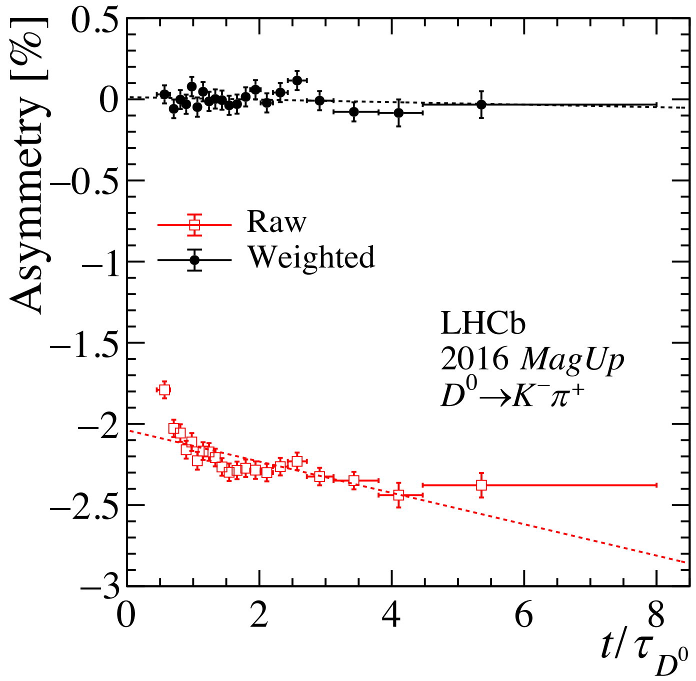
Sideband region

Treatment of the time-dependent nuisance asymmetries

arXiv:2105.09889

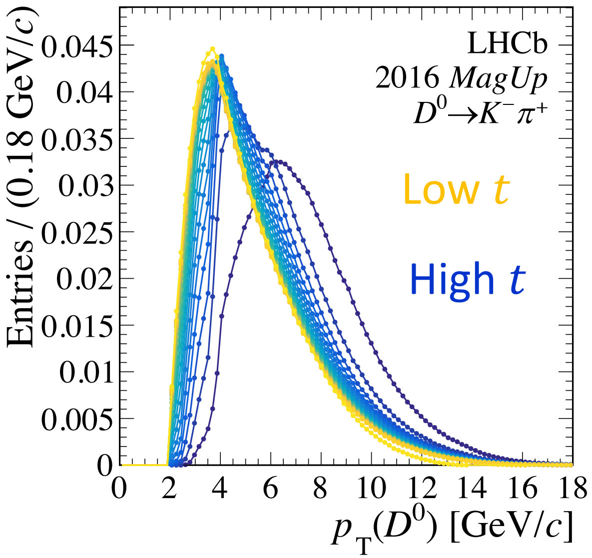
- The LHCb dipole magnet can point upwards (*MagUp*) or downwards (*MagDown*).
- For a given magnet polarity, this induces large $D^0 - \overline{D}^0$ momentum-dependent detection asymmetries alongside the horizontal plane (especially from the $\pi^{\pm}_{tag}$ that have low momenta).
- These asymmetries (+ $D^{*\pm}$ production asymmetries) reflect into D^0 momentum asymmetries.
- Trigger requirements correlate D^0 kinematics and D^0 decay time, these nuisance asymmetries becomes time-dependent. This biases the measurement.
- Strategy: equalise the kinematics of D^0 and $\overline{D}^0$ decays with a kinematic weighting procedure.





After kinematic weighting: $\Delta Y_{K^-\pi^+} = 0$ (as expected inside control sample).

Before kinematic weighting: $\Delta Y_{K^-\pi^+} \neq 0$



Cross-check: Measurement of $\Delta Y_{K^-\pi^+}$ using full Run 2 data

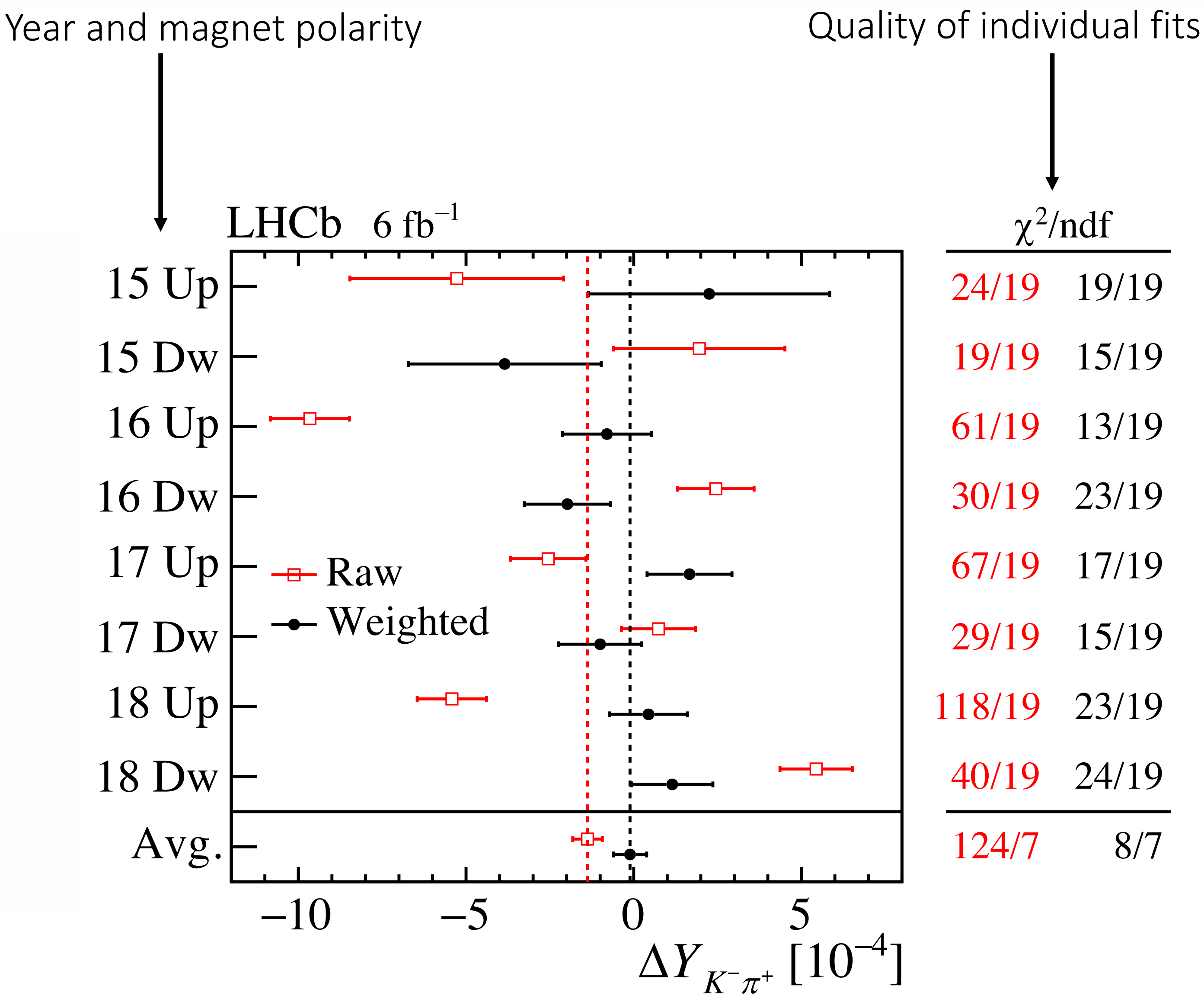
arXiv:2105.09889

- Before the kinematic weighting (raw condition): $\Delta Y_{K^-\pi^+} \neq 0$ with poor fit qualities and a bad compatibility among all years and magnet polarities.
- After the kinematic weighting: time-dependent asymmetries are removed. Good fit qualitites and good compatibility among each year and magnet polarity.

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

(includes correction from secondary B decays + systematics presented in next slides)

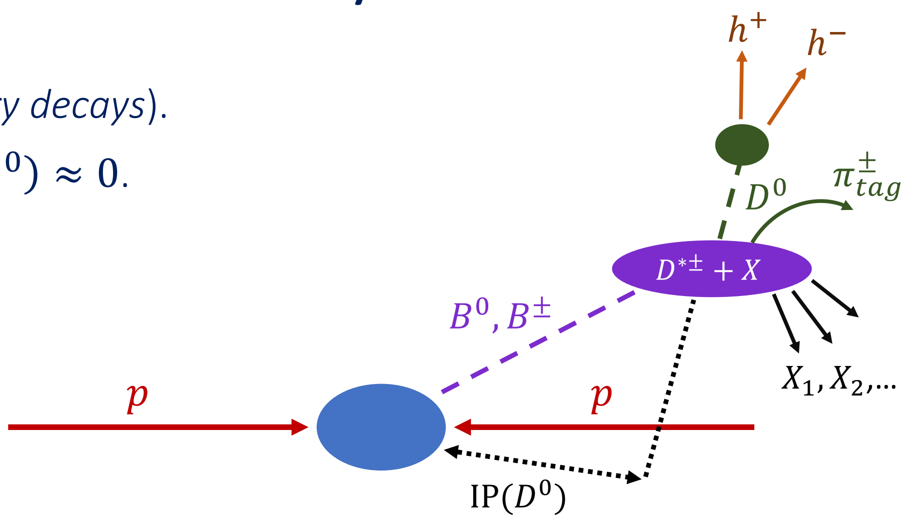
- An extremely precise and powerful cross-check measurement!



ΔY measurement – Contamination from B decays

arXiv:2105.09889

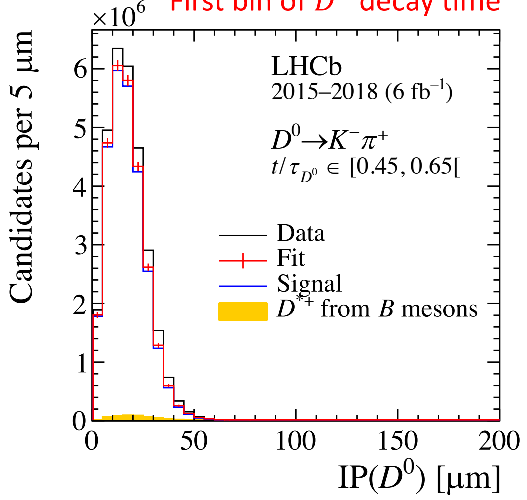
- Important nuisance from $D^{*\pm}$ candidates produced from B^0 or $B^\pm$ mesons (*secondary decays*).
- These secondary D^0 have large impact parameters (IP), unlike prompt D^0 where IP$(D^0) \approx 0$.
- We apply IP$(D^0) < 60$µm to remove a large fraction of secondary decays.



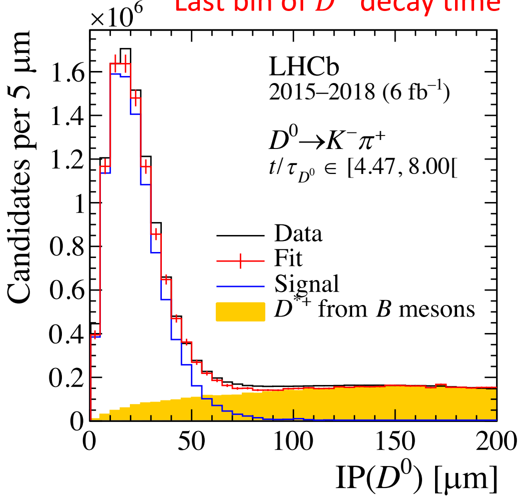
$$A_{\text{tot}}(t) = A_{\text{prompt}}(t) + f_{\text{sec}}(t)\left[A_{\text{sec}}(t) - A_{\text{prompt}}(t)\right]$$

- By measuring the fraction of secondary decays $f_{\text{sec}}(t)$ and the difference $A_{\text{sec}}(t) - A_{\text{prompt}}(t)$, we can subtract the secondary contribution.
- $f_{\text{sec}}(t)$ is measured in each bin of D^0 decay time by fitting real data to templates obtained from Monte Carlo samples of prompt and secondary candidates.

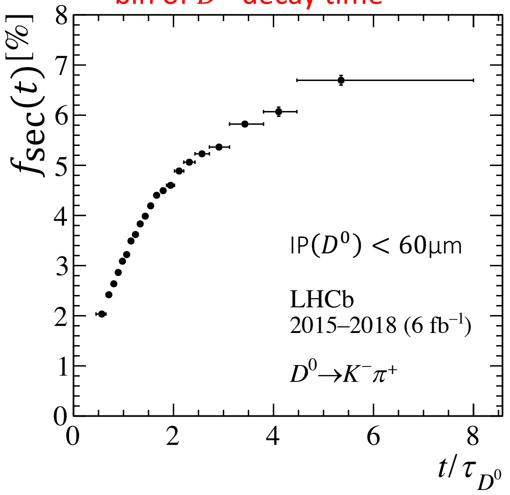
First bin of D^0 decay time



Last bin of D^0 decay time



Measured fraction in each bin of D^0 decay time



- $A_{\text{sec}}(t) - A_{\text{prompt}}(t)$ is measured from data with IP$(D^0) > 100$µm:

$$A_{\text{sec}}(t) - A_{\text{prompt}}(t) = (2.2 \pm 0.4)\times 10^{-3}$$

(and seen to be independent of decay time)

- Subtracted secondary contribution:

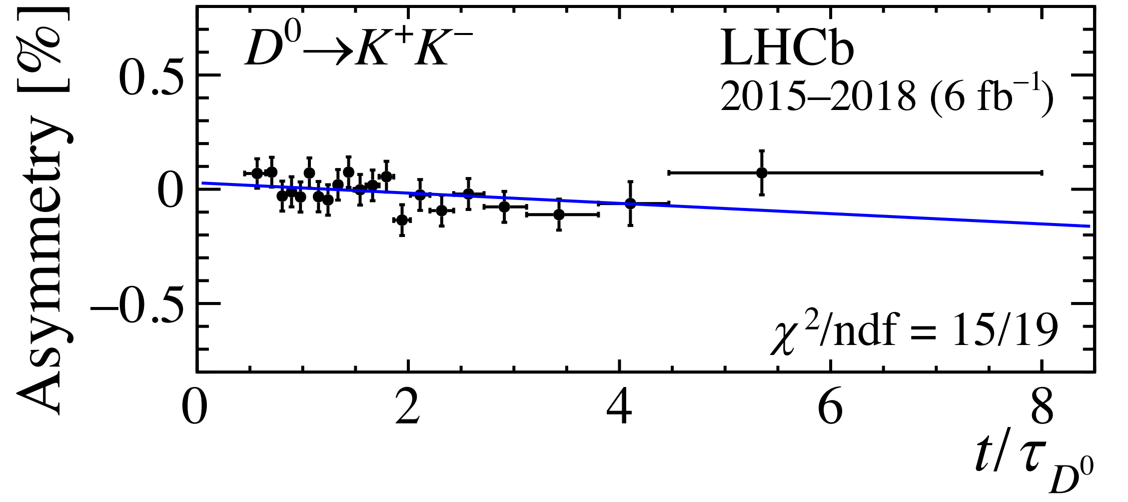
$$\Delta A = 0.26\times 10^{-4}$$

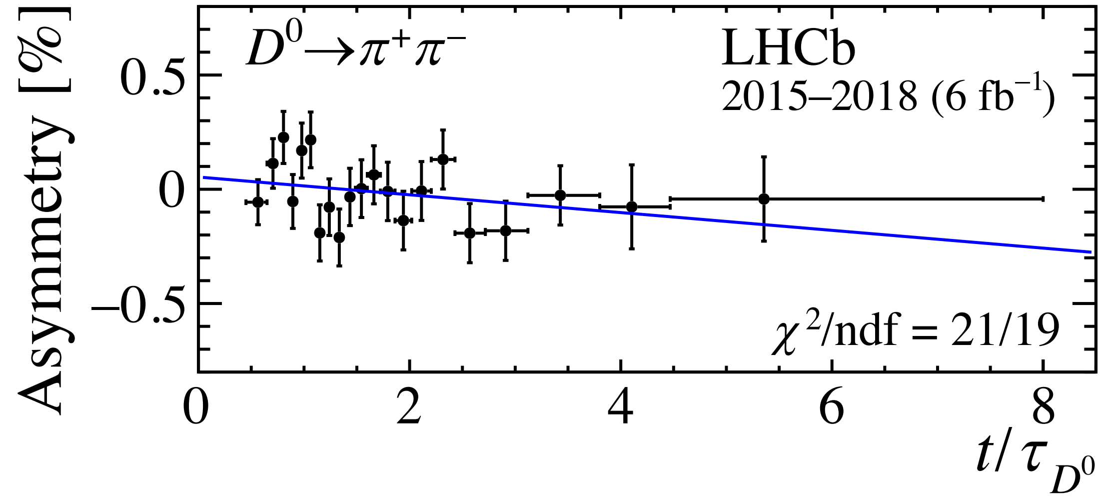
Final results using $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays

arXiv:2105.09889

$\Delta Y_{K^+K^-} = (-2.3 \pm 1.5 \pm 0.3)\times 10^{-4}$

$\Delta Y_{\pi^+\pi^-} = (-4.0 \pm 2.8 \pm 0.4)\times 10^{-4}$



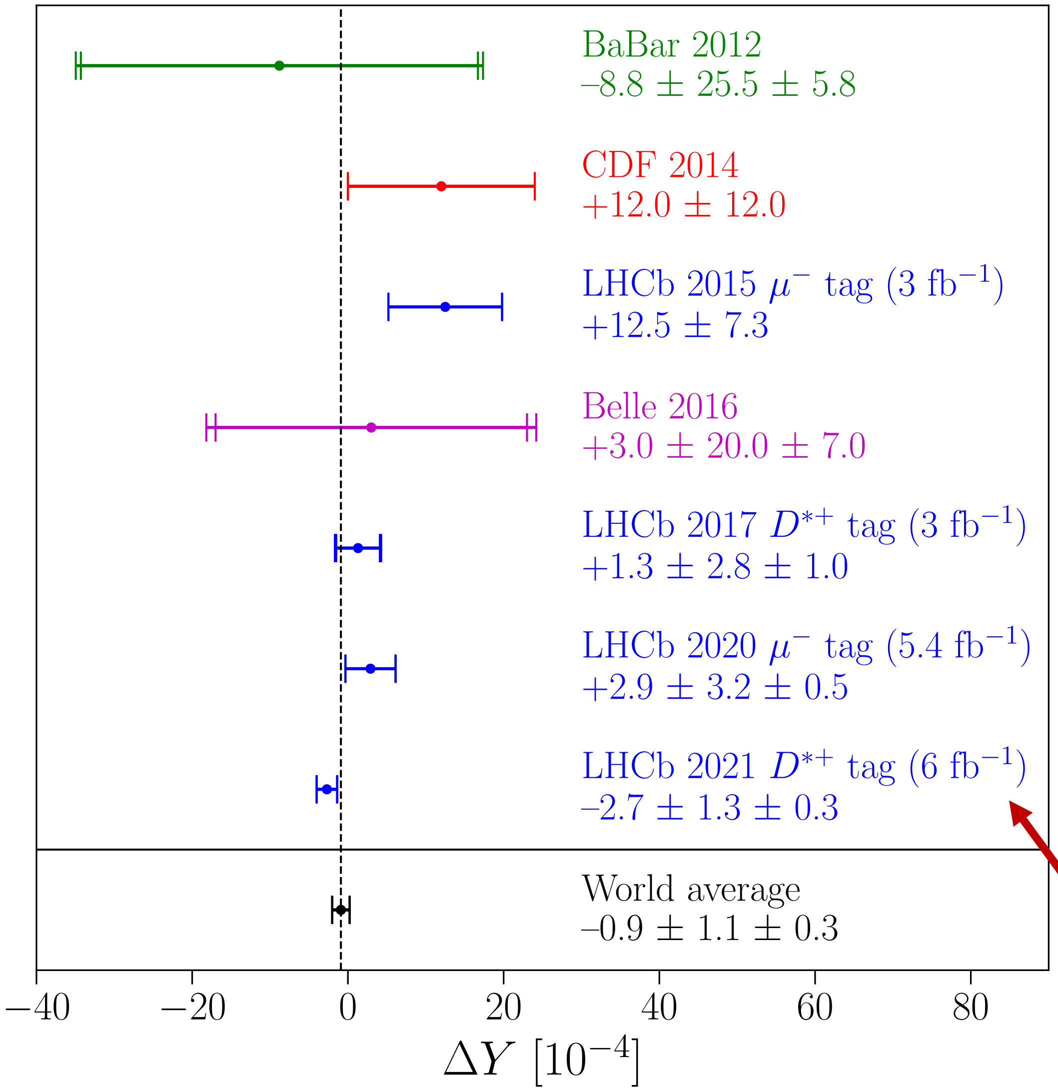


Systematic uncertainties (units of 10^{-4})

Source	$\Delta Y_{K^+K^-}$	$\Delta Y_{\pi^+\pi^-}$
Subtraction of the $m(D^0\pi^+_{\text{tag}})$ background	0.2	0.3
Flavour-dependent shift of $m(D^{*+})$ 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	0.3	0.4
Statistical	1.5	2.8

- $\Delta Y_{K^+K^-}$ and $\Delta Y_{\pi^+\pi^-}$ agree with each other within 0.5σ and are compatible with zero within 2σ.
- Systematic uncertainties are at the level of a few 10^{-5}: less than 20% of the statistical uncertainty. Very promising for future LHCb measurements!

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



This measurement!

Previous world average value: $\Delta Y = (+3.1 \pm 2.0 \pm 0.5) \times 10^{-4}$

HFLAV

Our estimated new world average value:

$$\Delta Y = (-0.9 \pm 1.1 \pm 0.3) \times 10^{-4}$$

Compatible with CP conservation hypothesis

Standard Model prediction:

$$\Delta Y \approx \mathcal{O}(2 \times 10^{-5})$$

Kagan & Silvestrini 2020

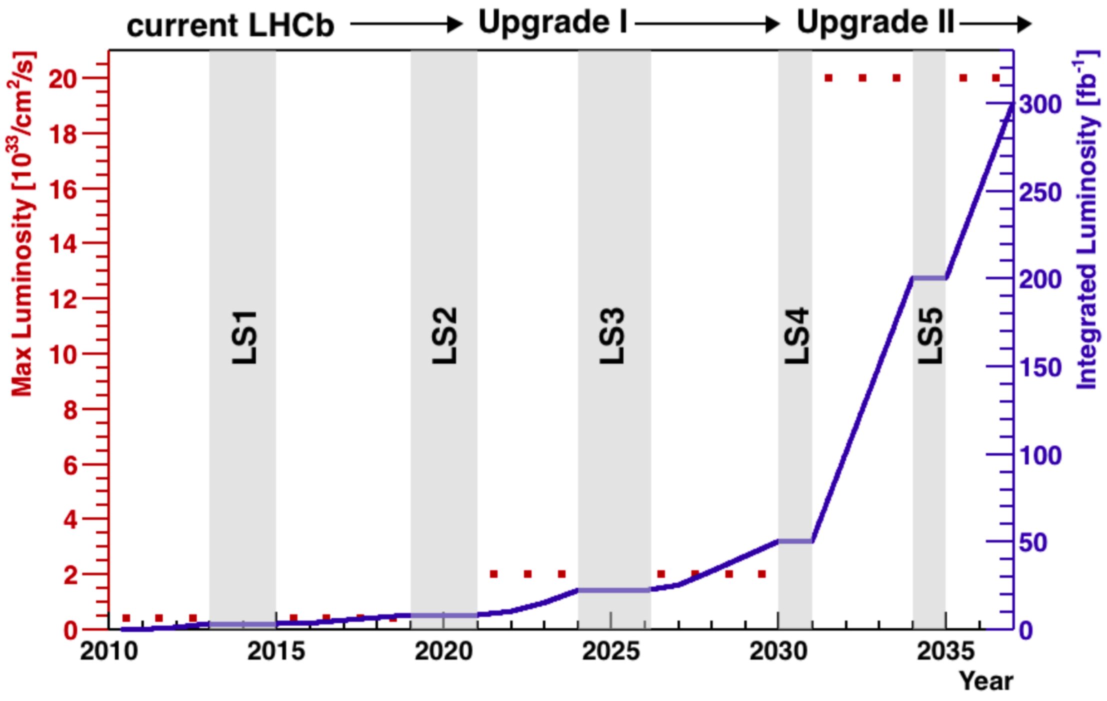
Li, Umeeda, Xu, Yu 2020

Projected sensitivities for LHCb Run 1+2 charm mixing measurements

Parameter(s)/observable(s)	Channel(s)	Current public results	Projected sensitivities with full Run 1+2 ($9\mathrm{fb}^{-1}$)
Charm mixing parameters from two-body RS/WS decay time ratios	$D^0 \to K^-\pi^+$ $D^0 \to K^+\pi^-$	$x'^2 = (3.9 \pm 2.7)\times10^{-5}$ $y' = (5.28 \pm 0.52)\times10^{-3}$ $R_D = (3.454 \pm 0.031)\times10^{-3}$ $A_D = (-0.1 \pm 9.1))\times10^{-3}$ Prompt D^0 (Run 1 + 2015-2016 ($5\mathrm{fb}^{-1}$)) Phys. Rev. D 97, 031101(R)	$\sigma(x'^2)\sim2\times10^{-5}$ $\sigma(y')\sim0.3\times10^{-3}$ $\sigma(R_D)\sim0.02\times10^{-3}$ $\sigma(A_D)\sim6\times10^{-3}$
Charm mixing parameters from bin-flip analysis [arXiv:1811.01032]	$D^0 \to K_S^0\pi^+\pi^-$	$x = (0.27^{+0.17}_{-0.15})\times10^{-2}$ $y = (0.74 \pm 0.37)\times10^{-2}$ $\lvert q/p\rvert = 1.05^{+0.22}_{-0.17}$ $\phi = -0.09^{+0.11}_{-0.16}$ Prompt D^0 (2012, $2\mathrm{fb}^{-1}$) and D^0 from semileptonic B decays (Run 1, $3\mathrm{fb}^{-1}$) Phys. Rev. Lett. 122, 231802	$\sigma(x)\sim0.05\times10^{-2}$ $\sigma(y)\sim1.5\times10^{-2}$ $\sigma(\lvert q/p\rvert)\sim0.04$ $\sigma(\phi)\sim0.04$
Charm mixing parameter y_{CP}	$D^0 \to K^-\pi^+$ $D^0 \to K^+K^-$ $D^0 \to \pi^+\pi^-$	$y_{CP} = (0.57 \pm 0.16)\times10^{-2}$ D^0 from semileptonic B decays (Run 1, $3\mathrm{fb}^{-1}$) Phys. Rev. Lett. 122, 011802	$\sigma(y_{CP})\sim0.02\times10^{-2}$ Using prompt D^0 + D^0 from semileptonic B decays

Charm mixing and indirect CPV: prospects for future LHCb measurements

arXiv:1808.08865



*Current plan shifted by a year due to Covid-19

Prospects for Run 4 and Run 5 at LHCb

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 %

300fb^{-1} predictions reach the SM expectations of $A_\Gamma \approx \mathcal{O}(2 \times 10^{-5})$

Charm mixing parameters

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°

Recap: $\Delta Y \approx -A_\Gamma$

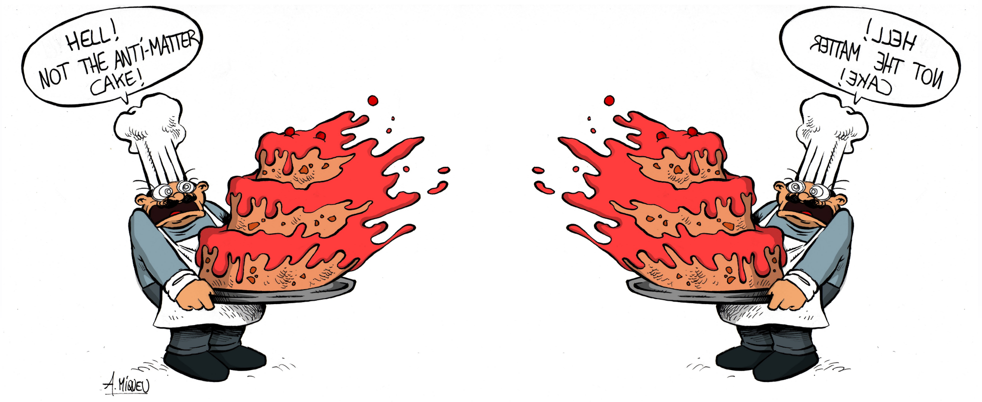
Summary

- The ΔY measurement reaches an impressive precision of $\sim 1 \times 10^{-4}$! But still no sign of indirect CPV in charm decays.

- We are working hard to finalise other charm measurements with the full Run 2 dataset.

- All results are limited by statistics: room for improvement in the next data-taking periods.

- Tune in tomorrow to Angelo Carbone's plenary talk *CPV and Oscillations in the Charm Sector at LHCb* 😉



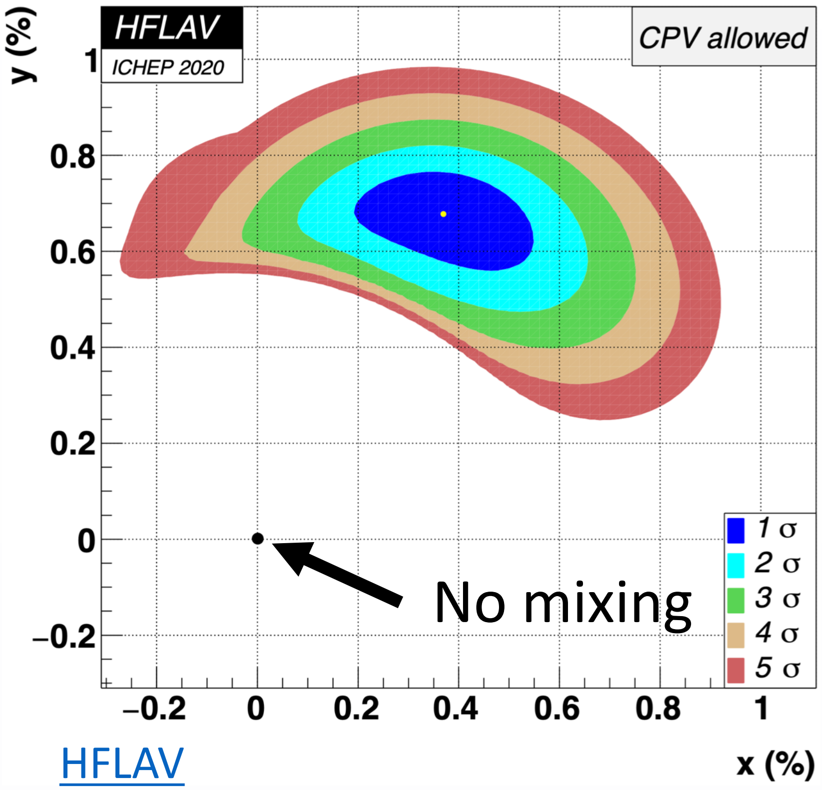
Back-up slides

Charm-mixing and CP-violation

- Flavour-mixing leads to a distinction between mass eigenstates and flavour eigenstates:

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

Charm mixing is well-established: no-mixing hypothesis excluded at $\gg 5\sigma$!



HFLAV

- The oscillations depend on parameters x and y:

$$x = 2\frac{M_2 - M_1}{\Gamma_1 + \Gamma_2} \qquad y = \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2}$$

- The following CP-violating mixing parameters probe indirect CPV:

$$x_{CP} = \frac{1}{2}\left[x\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) + y\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right]$$

$$\Delta x = \frac{1}{2}\left[x\cos\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) + y\sin\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\right]$$

$$y_{CP} = \frac{1}{2}\left[y\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right]$$

$$\Delta y = \frac{1}{2}\left[y\cos\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\right]$$

if no CPV $\longrightarrow$

$$\phi = \arg\left(\frac{q\bar{A}_f}{pA_f}\right) = 0$$

and $\left|\frac{q}{p}\right| = 1$

$$x_{CP} = x$$

$$\Delta x = 0$$

$$y_{CP} = y$$

$$\Delta y = 0$$

ΔY measurement: Theoretical parametrisation

- The *phenomenological parametrisation* depends on: $x = \frac{M_2 - M_1}{\Gamma}, y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}, \lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$

- We can also use the *theoretical parametrisation* depending on:

$$x_{12} = \frac{2|M_{12}|}{\Gamma}, \qquad y_{12} = \frac{2|\Gamma_{12}|}{\Gamma}, \qquad \lambda_f^M = \frac{M_{12}}{|M_{12}|}\frac{\bar{A}_f}{A_f}, \qquad \lambda_f^\Gamma = \frac{\Gamma_{12}}{|\Gamma_{12}|}\frac{\bar{A}_f}{A_f}$$

- With the theoretical parametrisation, one can write ΔY_f as

$$\Delta Y_f \approx -x_{12}\sin\phi_2^M + y_{12}a_f^d\left(1 + \frac{x_{12}}{y_{12}}\cot\delta_f\cos\phi_f^M\right)$$

Universal part (independent of final state)

Dependent on final state

- Since $y_{12}a_f^d \lesssim 0.13\times10^{-4}$ and that our current experimental precision is $\sim 1\times10^{-4}$, we have

$$\Delta Y_f \approx \Delta Y \approx -x_{12}\sin\phi_2^M$$

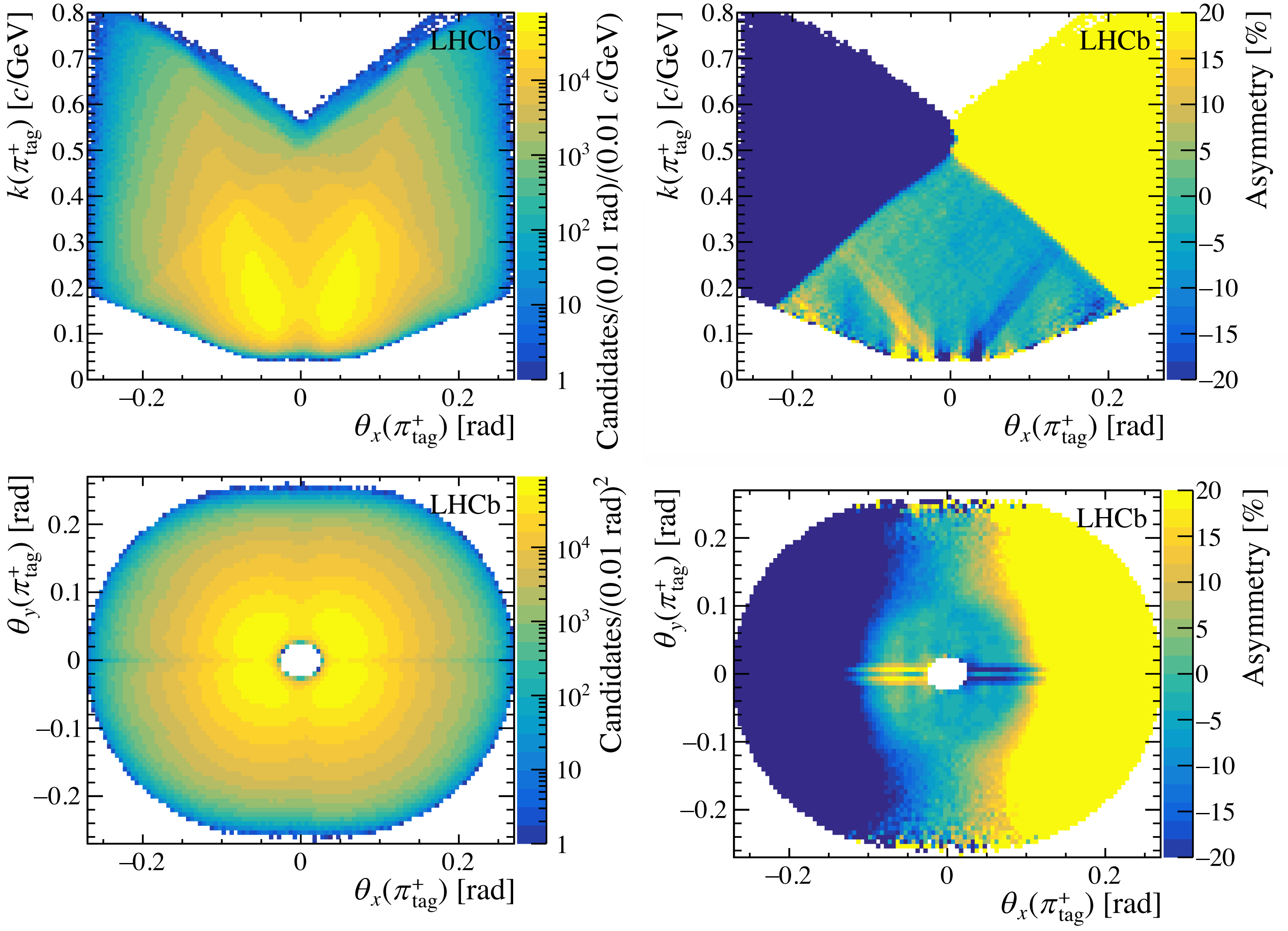
ΔY measurement: Nuisance asymmetries

- We study the topological quantities:

$$\theta_{x(y)} = \arctan(p_{x(y)}/p_z)$$

$$k = 1/\sqrt{p_x^2 + p_y^2}$$

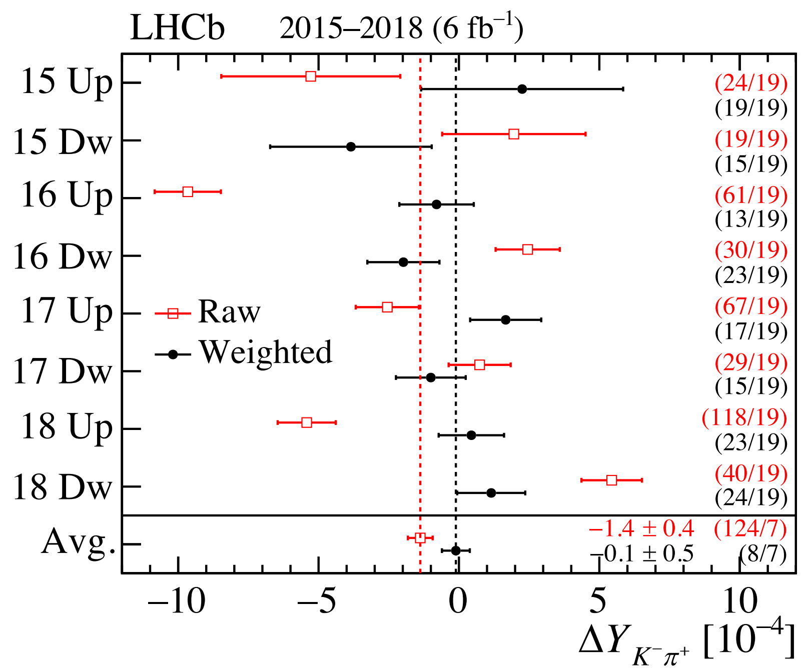
- (Left) sum and (right) asymmetry of the distributions of the momentum of $\pi_{tag}^{\pm}$ candidates, projected on the (top) k vs θ_x and (bottom) θ_y vs θ_x planes, for the $D^0 \to K^-\pi^+$ candidates collected in 2017 with the MagUp polarity.
- The asymmetries during the other data-taking years are similar, and opposite in sign for the data collected with the MagDown polarity. The regions of the distributions with asymmetries whose magnitude is larger than 20% are discarded from the data sample after the kinematic weighting.



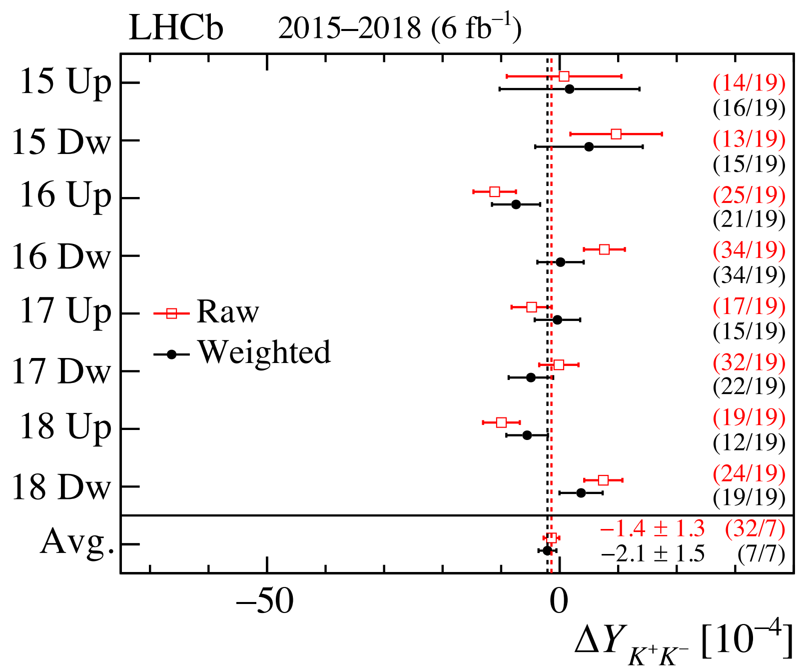
ΔY measurement – results for each year and magnet polarity

- ΔY fits for years 2015-2018 and *MagUp-MagDown* magnet polarities.
- Raw values in red and kinematically reweighted (to remove time-dependent experimental asymmetries) + secondary decays substracted values in black.

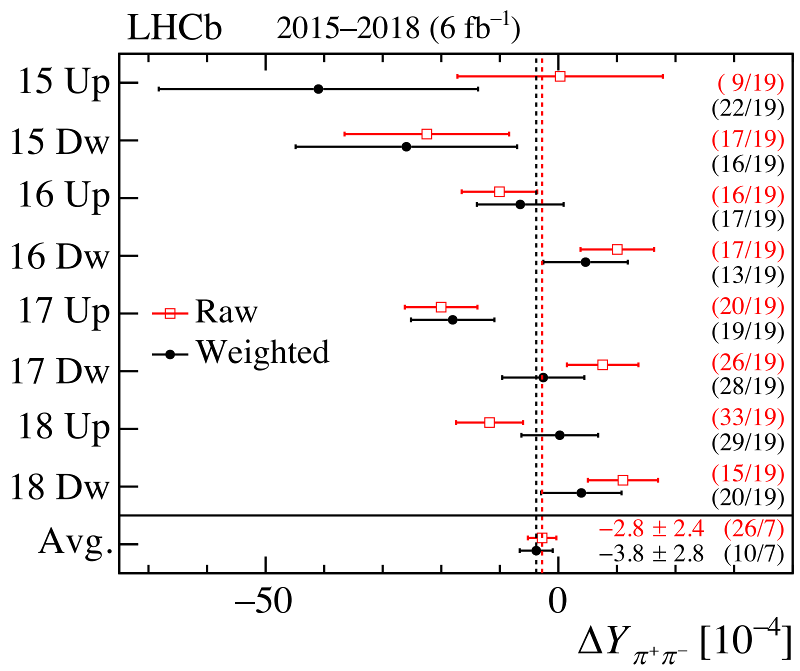
Cross check with $D^0 \rightarrow K\pi$ decays



Measurements of $\Delta Y_{K^+K^-}$

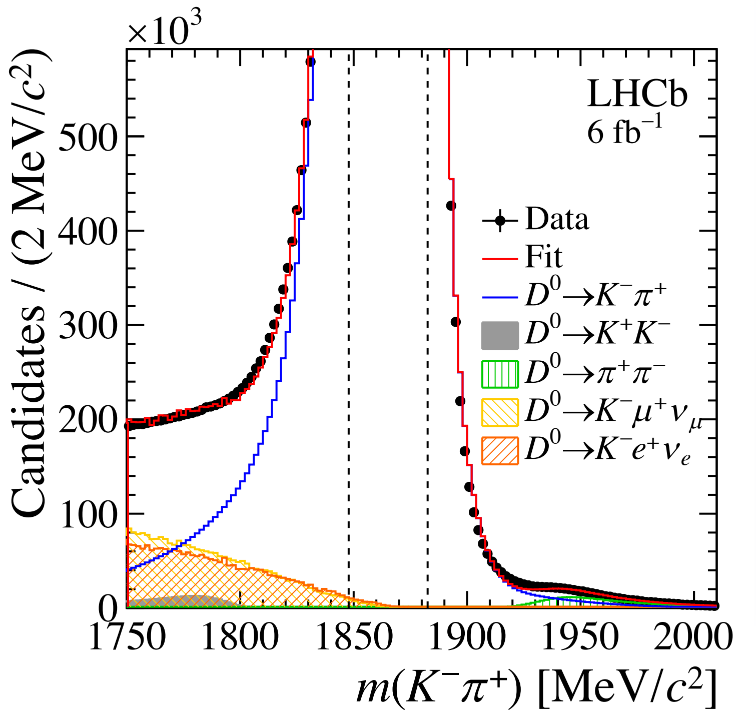


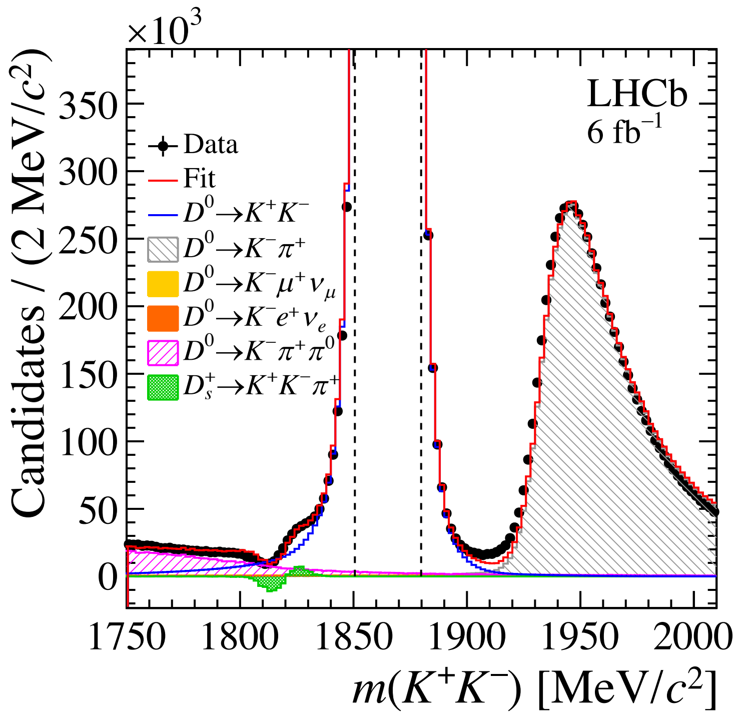
Measurements of $\Delta Y_{\pi^+\pi^-}$

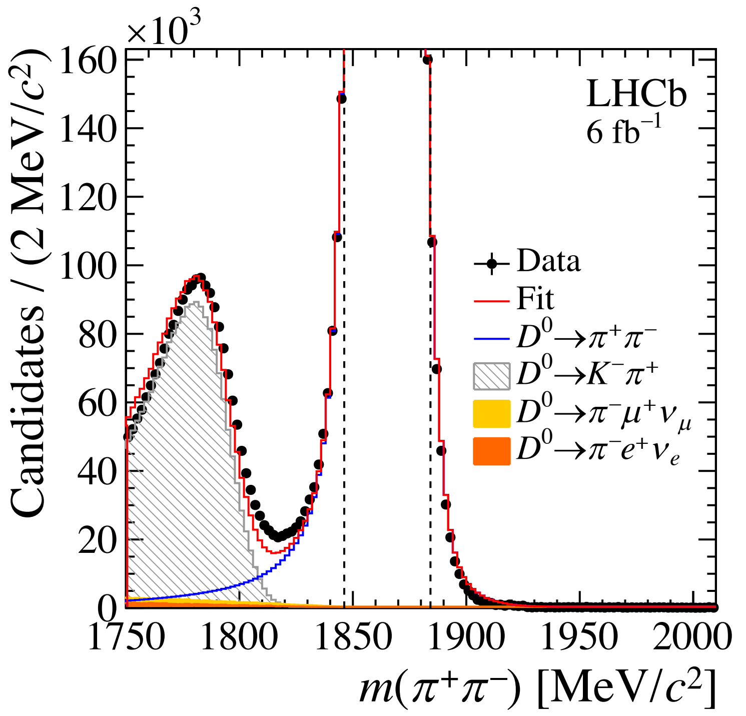


ΔY measurement – $m(h^+h^-)$ background (systematic uncertainty)

- There is a small background in the $m(h^+h^-)$ distribution coming from partially or misreconstructed $D^{*+} \rightarrow (D^0 \rightarrow h^+h^-)\pi^+_{tag}$ candidates.
- The background fractions amount to $10^{-3} - 10^{-4}$ for the different decay channels.
- The corresponding systematic uncertainties are $\sigma(\Delta Y_{K^-\pi^+}) = 0.00{\times}10^{-4}$, $\sigma(\Delta Y_{K^+K^-}) = 0.06{\times}10^{-4}$ and $\sigma(\Delta Y_{\pi^+\pi^-}) = 0.03{\times}10^{-4}$.







Improvements of ϕ_2^M and ϕ_2^Γ