Direct CPV in charm hadrons at LHCb

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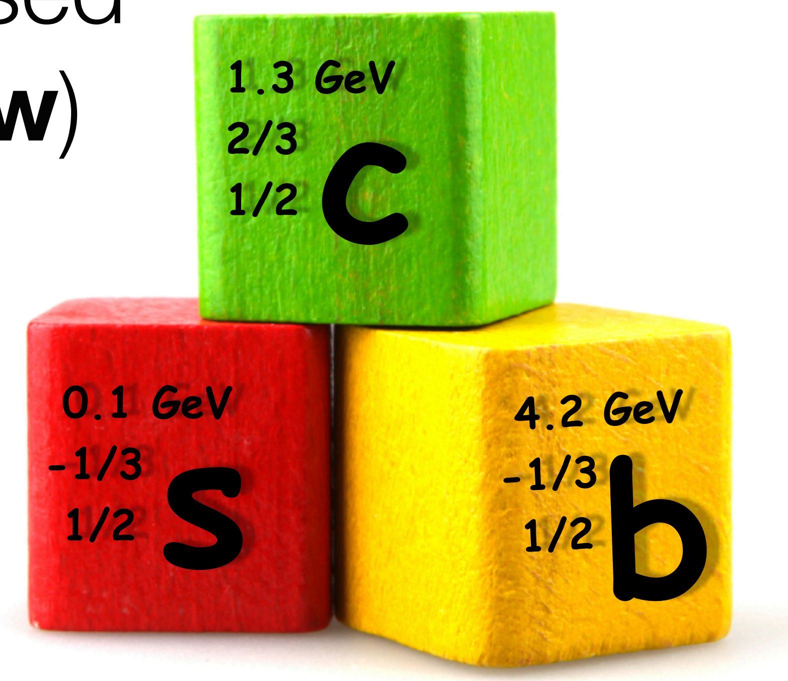
Why charm is charming?

- *CP* violation (CPV) in **charm** is suppressed (*asymmetries* expected **~0.1% or below**)
  - *Sensitive* to possible contributions of **physics beyond the SM**
  - **Up-type** quark: complementary to studies in ***K*** and ***B*** systems



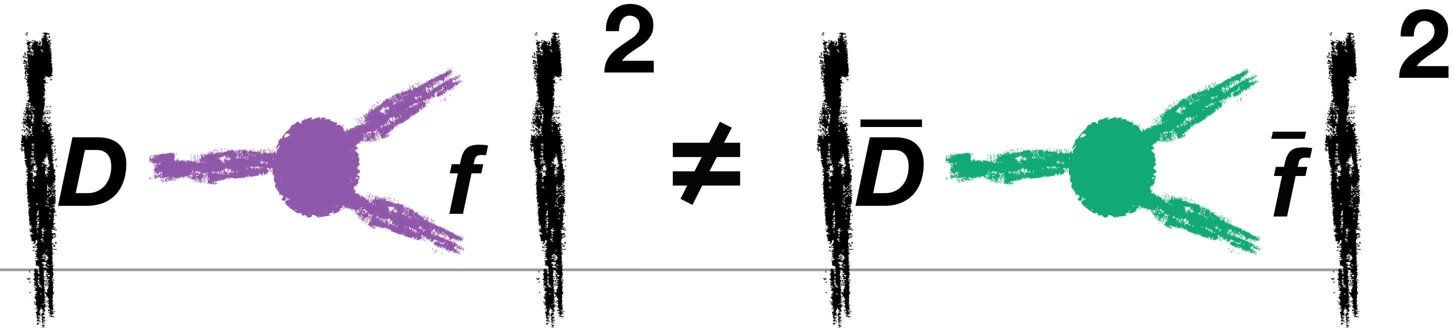
$\sigma(pp \to c\bar{c}X)_{\sqrt{s}\,=\,13\ \mathrm{TeV}} \cong 2.4\ \mathrm{mb}$

[JHEP 03 (2016) 159]

- ***LHCb*** is the main player in this quest

- CPV in charm has been searched for since decades, in **2019** the *LHCb* experiment **finally observed** in neutral meson decays!

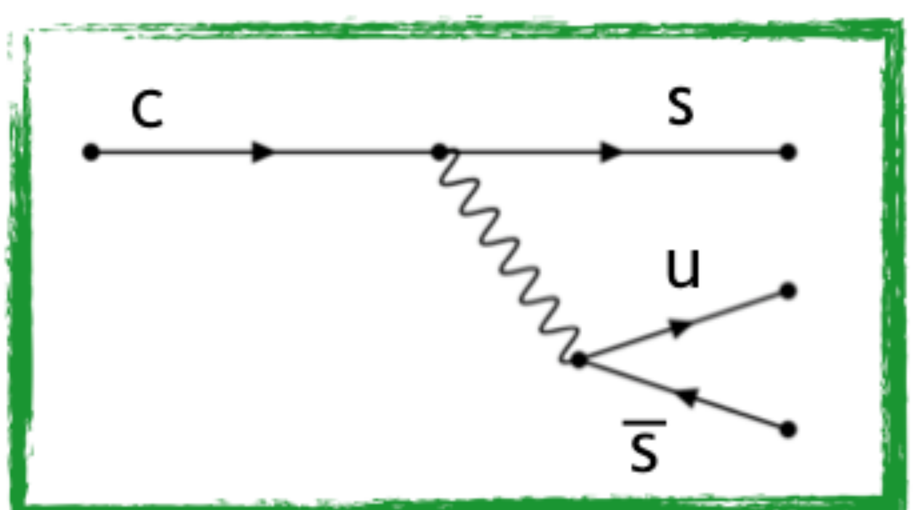
Direct *CP* violation



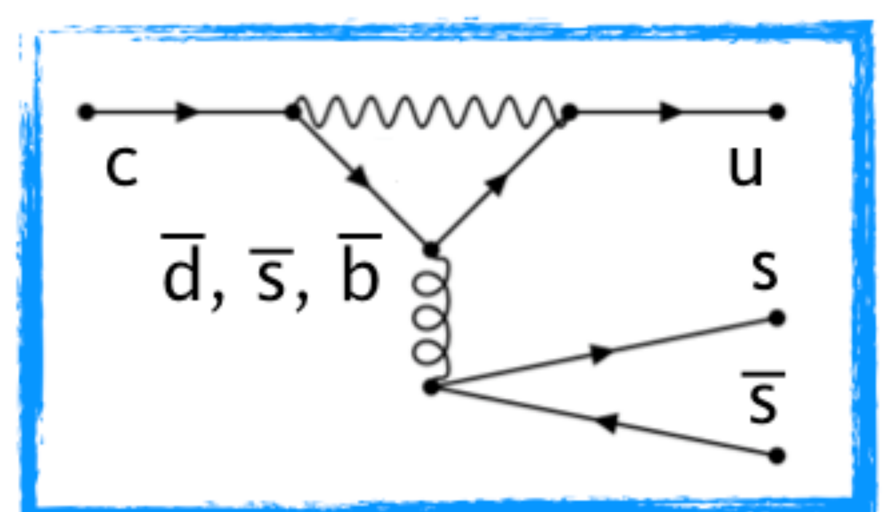
- Corresponds to

$$a_f^d = \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2} \neq 0$$

- Most promising channels are **Cabibbo-suppressed** (CS) decays because CPV may arise from the *interference* between the **tree** and the **penguin** amplitude



VS



Time-dependent *CP* violation

- In D^0 mesons, the ***time-integrated CP asymmetry*** between the decay rates

$$A_{CP}(f) = \frac{\int \epsilon(t)\Gamma(D^0 \to f)dt - \int \epsilon(t)\Gamma(\overline{D}^0 \to \bar{f})dt}{\int \epsilon(t)\Gamma(D^0 \to f)dt + \int \epsilon(t)\Gamma(\overline{D}^0 \to \bar{f})dt}$$

doesn't correspond to a_f^d but is affected by $D^0 - \overline{D}^0$ **mixing**:

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

$$\Delta Y_f \approx -x_{12} \sin \phi_f^M + y_{12} cos \phi_f^M a_f^d$$

[Phys. Rev. D 103, 053008]

where ΔY is related to the mixing parameters and $\langle t \rangle_f$ is the average (acceptance dependent) decay time of the D^0 mesons in the experimental sample.
This corresponds to a correction of few times **10^{-4}**.

NEW RESULT!

[LHCB-PAPER-2022-024] in preparation

Measurement of direct *CP* asymmetries in $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ decays

Presented
for the first time!

Motivation

- *CP* Violation in Charm has been observed in the difference

$$\boxed{\begin{aligned}\Delta A_{CP} &= A_{CP}(D^0 \to K^-K^+) - A_{CP}(D^0 \to \pi^-\pi^+) \\ &= (-15.4 \pm 2.9)\times 10^{-4}\end{aligned}}$$

The measurement of $A_{CP}(D^0 \to K^-K^+)$ and $A_{CP}(D^0 \to \pi^-\pi^+)$ separately is necessary to understand the nature of CPV

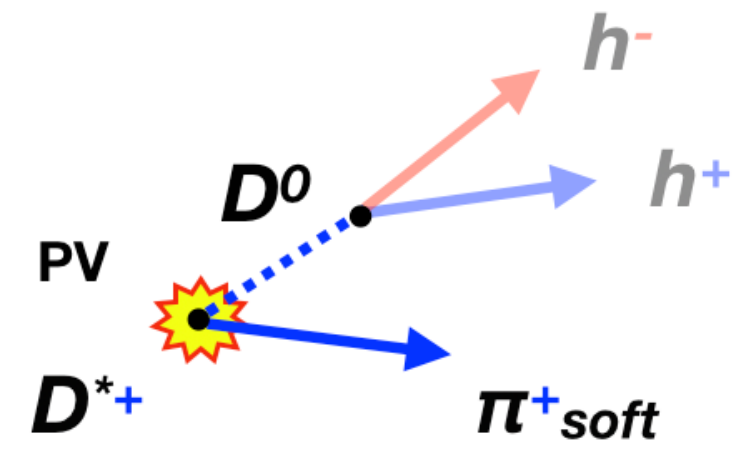
- The *strategy* consists in measuring $\mathbf{A_{CP}(D^0 \to K^-K^+)}$ and then retrieve a^d_{KK} and $a^d_{\pi\pi}$ from the combination with ΔA_{CP}

- Last measurement of $A_{CP}(D^0 \to K^-K^+)$ from LHCb using *Run-1* data:

$$A_{CP}(D^0 \to K^+K^+) = \left[14 \pm 15\ (\text{stat}) \pm 10\ (\text{syst})\right] \times 10^{-4}$$

[Phys. Lett. B 767 177-187]

Direct CPV measurements



- D^0 or $\bar{D}^0$ tagging: $D^{*+-} \to \overset{(-)}{D}{}^0 \pi^{+-}_{soft}$
  prompt (coming from primary vertex)

- The ***raw* asymmetry** (*A*) in $D^0 \to K^-K^+$ decays

$$A(D \to f) = \frac{N(D\to f) - N(\bar{D}\to\bar{f})}{N(D\to f) + N(\bar{D}\to\bar{f})}$$

  includes both physics and detector effects:

$$A = A_{CP} + A_P + A_D$$

CPV parameter

NUISANCE ASYMMETRIES:

Production asymmetry of D^{*+}

$$A_P(D) = \frac{\sigma(D) - \sigma(\bar{D})}{\sigma(D) + \sigma(\bar{D})}$$

Detection asymmetry of π^+_{soft}

$$A_D(f) = \frac{\epsilon(f) - \epsilon(\bar{f})}{\epsilon(f) + \epsilon(\bar{f})}$$

Strategy

$$A(D \to f) = \frac{N(D\to f) - N(\bar{D}\to\bar{f})}{N(D\to f) + N(\bar{D}\to\bar{f})}$$

- Prompt $D^0 \to K^- K^+$ collected during **Run-2**.
- Two methods to *cancel* **NUISANCE** asymmetries:
  - ***D*+** decays, same used in Run-1 analysis (***C*$_{D+}$**)
  - ***D*$_s$+** decays, *new!* (***C*$_{Ds+}$**)

particles with same color ("twin") must have identical kinematic distributions!

[backup]

- *Correct* raw asymmetry *A* using samples of Cabibbo-favoured $D^0/D_{(s)}^+$ decays (where CPV can be neglected):

***C*$_{D+}$:**

$$A_{CP}(D^0 \to K^-K^+) = +A(D^{*+} \to (D^0 \to K^-K^+)\,\pi^+_{soft}) - A(D^{*+} \to (D^0 \to K^-\pi^+)\,\pi^+_{soft})$$
$$+A(D^+ \to K^-\pi^+\pi^+) - \left[A(D^+ \to \overline{K}^0\,\pi^+) - A(\overline{K}^0)\right]$$

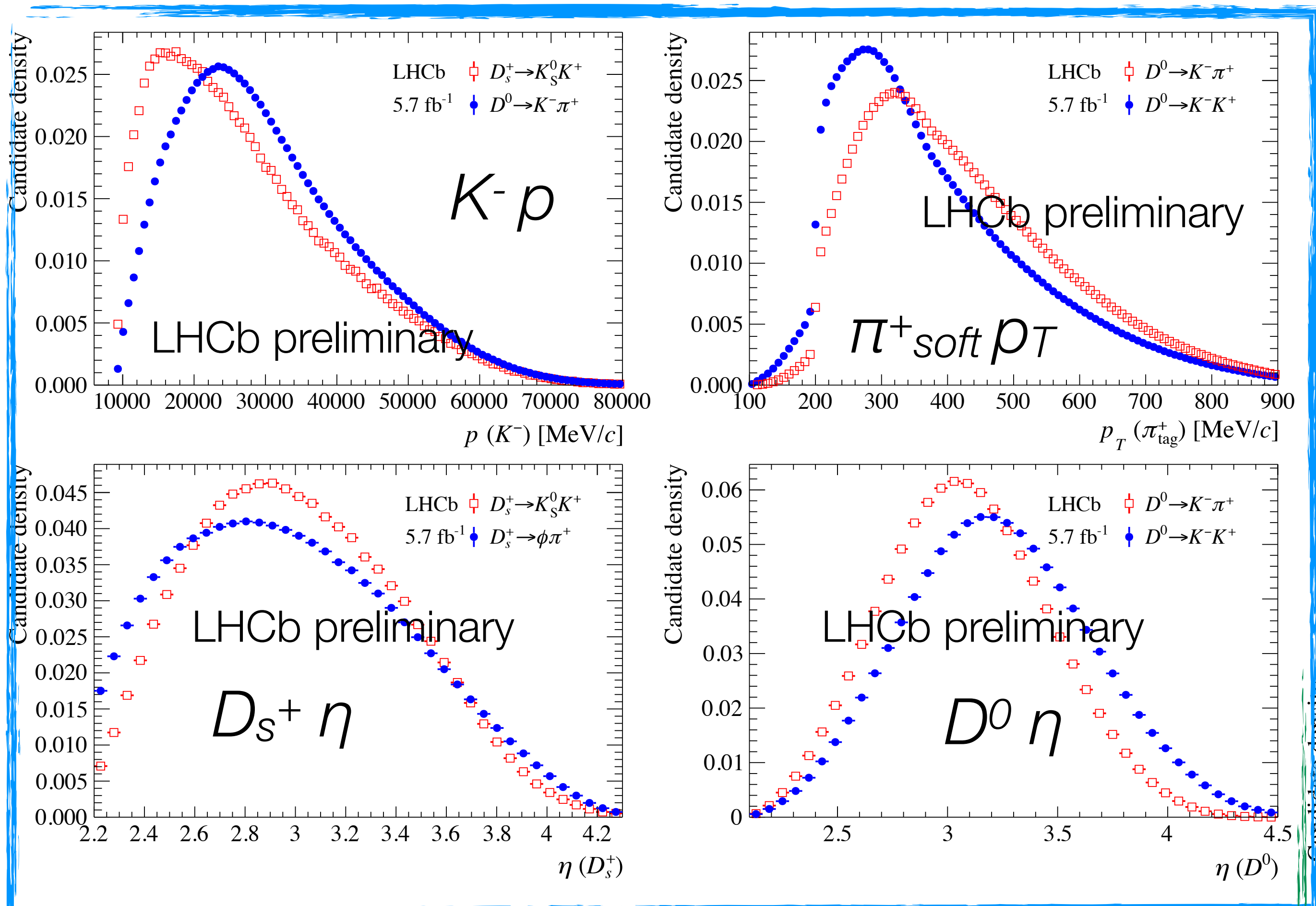
***C*$_{Ds+}$:**

$$A_{CP}(D^0 \to K^-K^+) = +A(D^{*+} \to (D^0 \to K^-K^+)\,\pi^+_{soft}) - A(D^{*+} \to (D^0 \to K^-\pi^+)\,\pi^+_{soft})$$
$$+A(D_s^+ \to \phi\pi^+) - \left[A(D_s^+ \to \overline{K}^0\,K^+) - A(\overline{K}^0)\right]$$

where $A(\bar{K}^0)$ includes the detection asymmetry of *neutral kaons*, mixing and *CP*-violating effects.

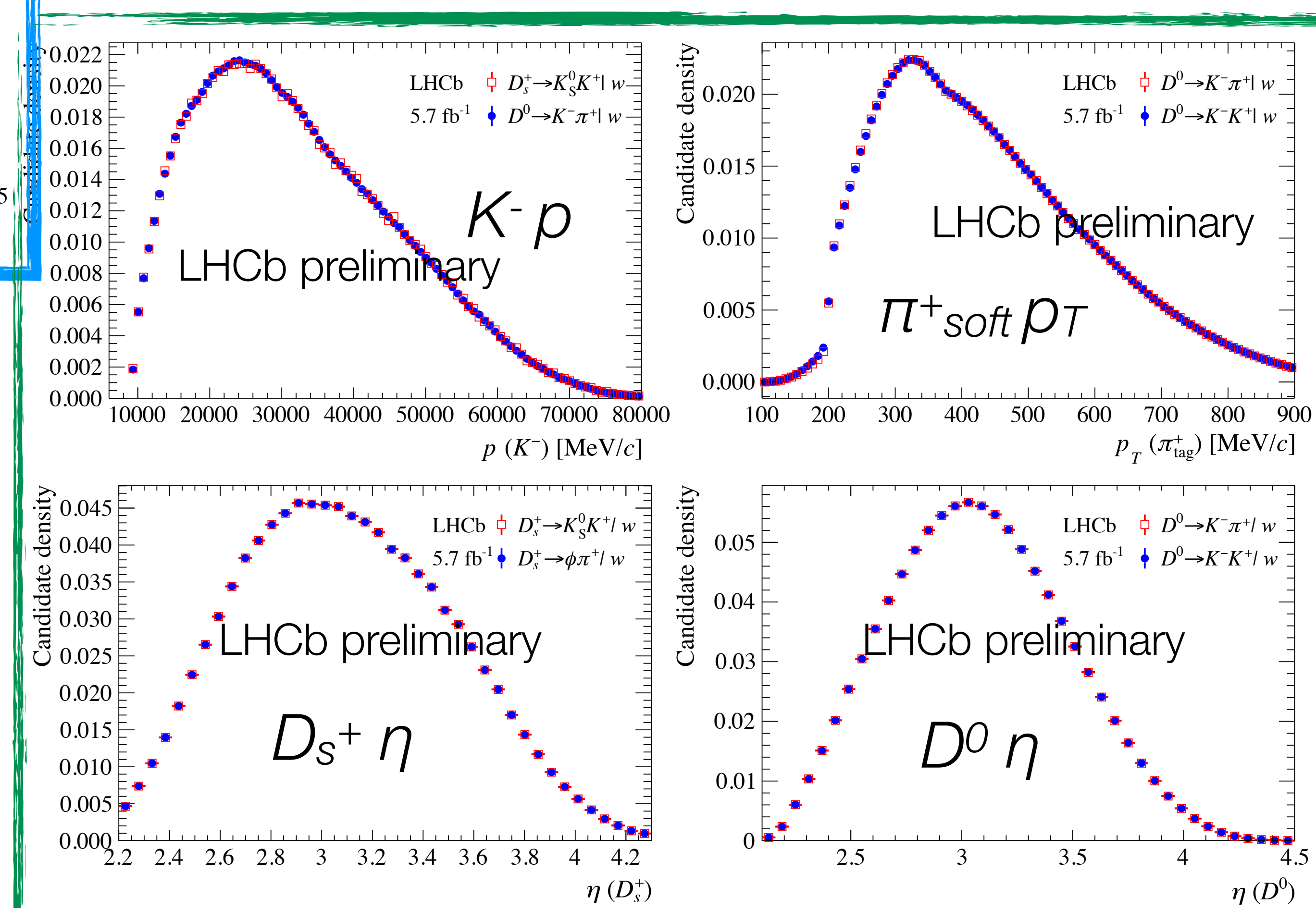
- For each *kinematically weighted* sample, the raw asymmetry *A* is determined with a *simultaneous* fit to the *positive* and *negative* final state invariant-mass distributions

Weighting procedure



BEFORE

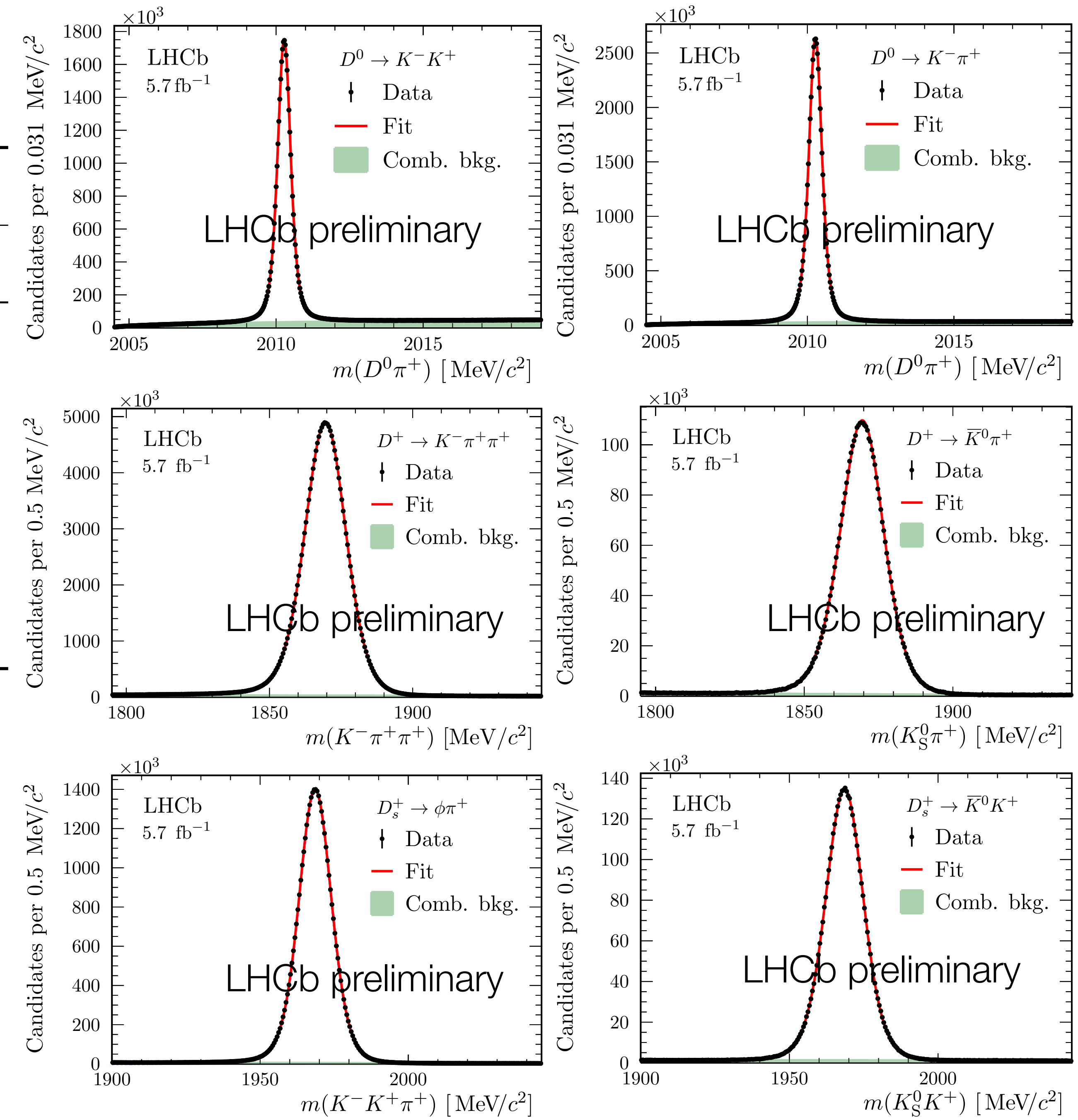
AFTER



Signal yields

Decay mode	Signal yield $[10^6]$		Reduction factor	
	C_{D^+}	$C_{D_s^+}$	C_{D^+}	$C_{D_s^+}$
$D^0 \to K^-K^+$	45	40	0.75	0.75
$D^0 \to K^-\pi^+$	60	55	0.35	0.75
$D^+ \to K^-\pi^+\pi^+$	192	–	0.25	–
$D_s^+ \to \phi\pi^+$	-	83	–	0.55
$D^+ \to \overline{K}^0\pi^+$	8	–	0.25	
$D_s^+ \to \overline{K}^0K^+$	–	6	–	0.40

- Statistical precision on A_{CP} of **8.8×10^{-4}** and **6.7×10^{-4}** for C_{D+} and C_{Ds+}, respectively

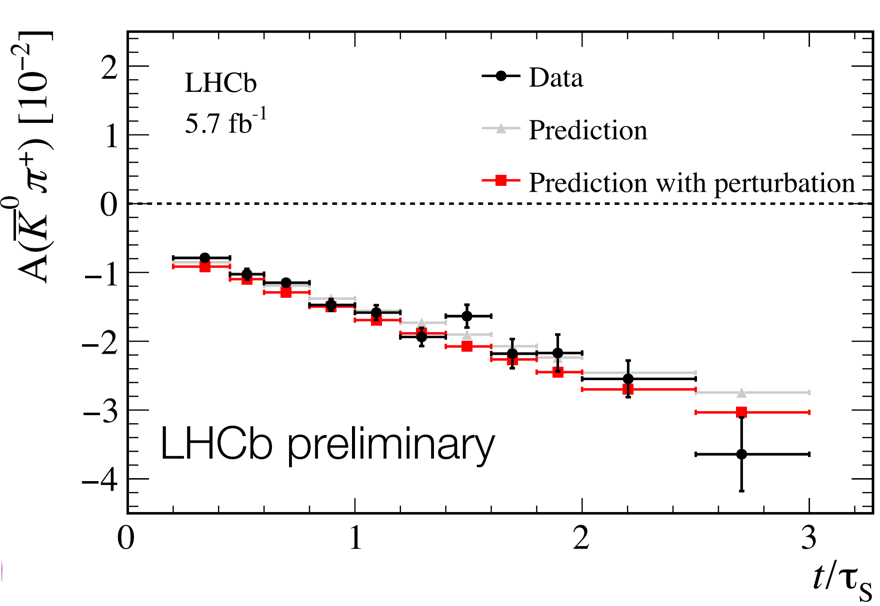


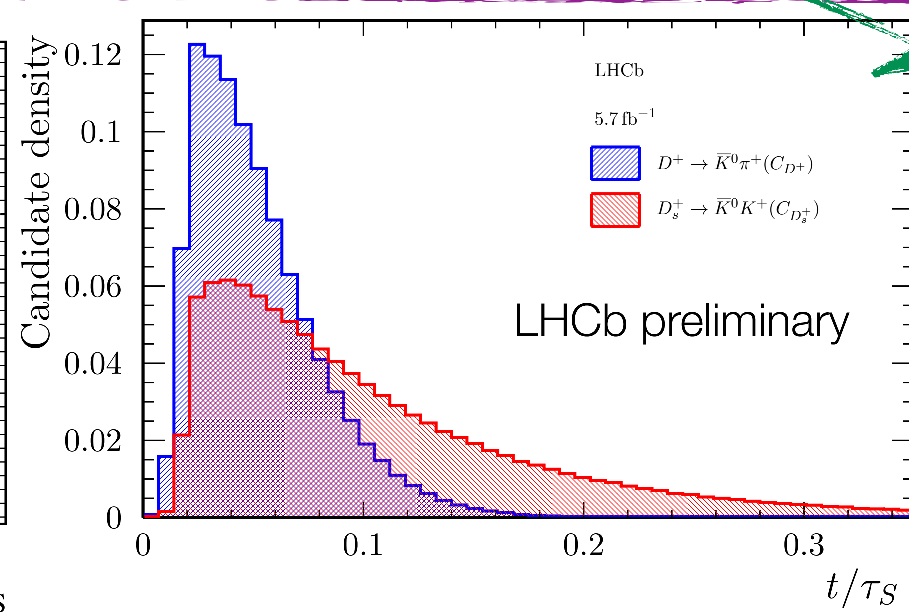
Systematic uncertainties

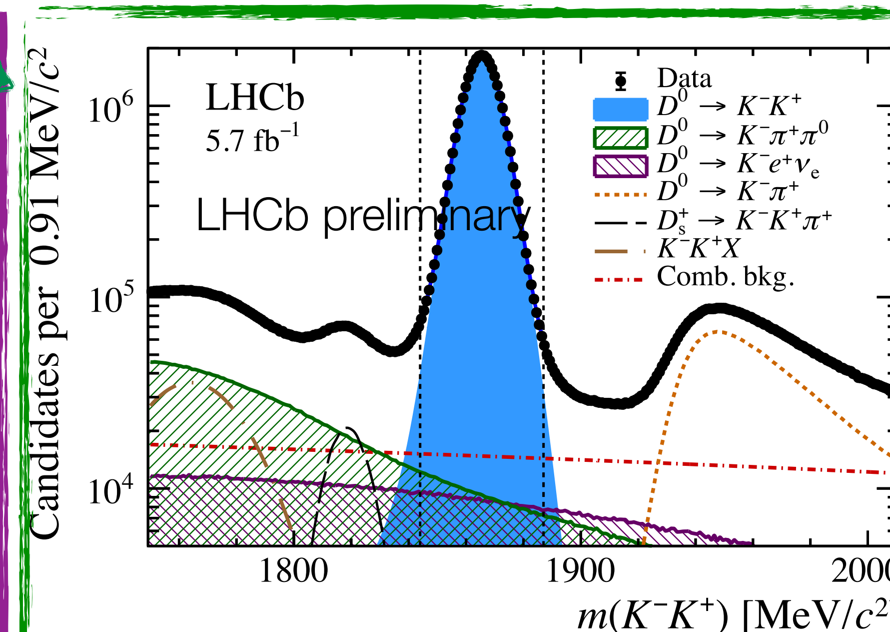
LHCb preliminary

Source	C_{D^+} $[10^{-4}]$	$C_{D_s^+}$ $[10^{-4}]$	ρ
Neutral kaon asym. [backup]	0.6	1.3	1.00
Secondary decays	0.6	0.3	/
Peaking backgrounds	0.3	0.4	0.74
Fit model	1.1	1.0	0.05
Kinematic diff.	0.8	0.4	/
Charged kaon asym.	/	1.0	/
Total systematic	1.6	2.0	0.28
Statistical	8.8	6.7	0.05

- neutral kaon asymmetry: accuracy tested with a data-driven approach
- secondary decays: presence of D meson from semi-leptonic B decays estimated
- peaking backgrounds: impact estimated by fits to the $m(KK)$ invariant mass
- fit model: alternative signal and background shapes evaluated
- kinematic difference: residual difference from weighting procedure
- charged kaon asymmetry: K^-K^+ asymmetries from $D_s^+ \to \phi\pi^+$ decays







Final results for $A_{CP}(K^-K^+)$ and combination

- Final results for $A_{CP}(K^-K^+)$ are:

$$\mathrm{C}_{D^+}: \ \mathcal{A}_{CP}(K^-K^+) = [13.6 \pm 8.8\,(\mathrm{stat}) \pm 1.6\,(\mathrm{syst})] \times 10^{-4},$$
$$\mathrm{C}_{D_s^+}: \ \mathcal{A}_{CP}(K^-K^+) = [\ 2.8 \pm 6.7\,(\mathrm{stat}) \pm 2.0\,(\mathrm{syst})] \times 10^{-4}.$$

with an overall correlation coefficient $\rho = 0.06$ and are found to be compatible within 1 standard deviation.

- The combination yields

$$\mathcal{A}_{CP}(K^-K^+) = [6.8 \pm 5.4\,(\mathrm{stat}) \pm 1.6\,(\mathrm{syst})] \times 10^{-4},$$

$$\Delta Y = \left[-1.04 \pm 1.17\right] \times 10^{-4}$$

[Phys. Rev. D 104, 072010]

From $A_{CP}(K^-K^+)$ to a^d_{KK} and $a^d_{\pi\pi}$

- **Direct *CP* violation parameters** a^d_{KK} and $a^d_{\pi\pi}$ in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ are calculated from the **combination** of $A_{CP}(K^-K^+)$ with ΔA_{CP} and accounting for possible *time-dependent CP* violation considering

$$A_{CP}(K^-K^+) = a^d_{KK} + \frac{\langle t \rangle_{KK}}{\tau_{D^0}} \Delta Y$$

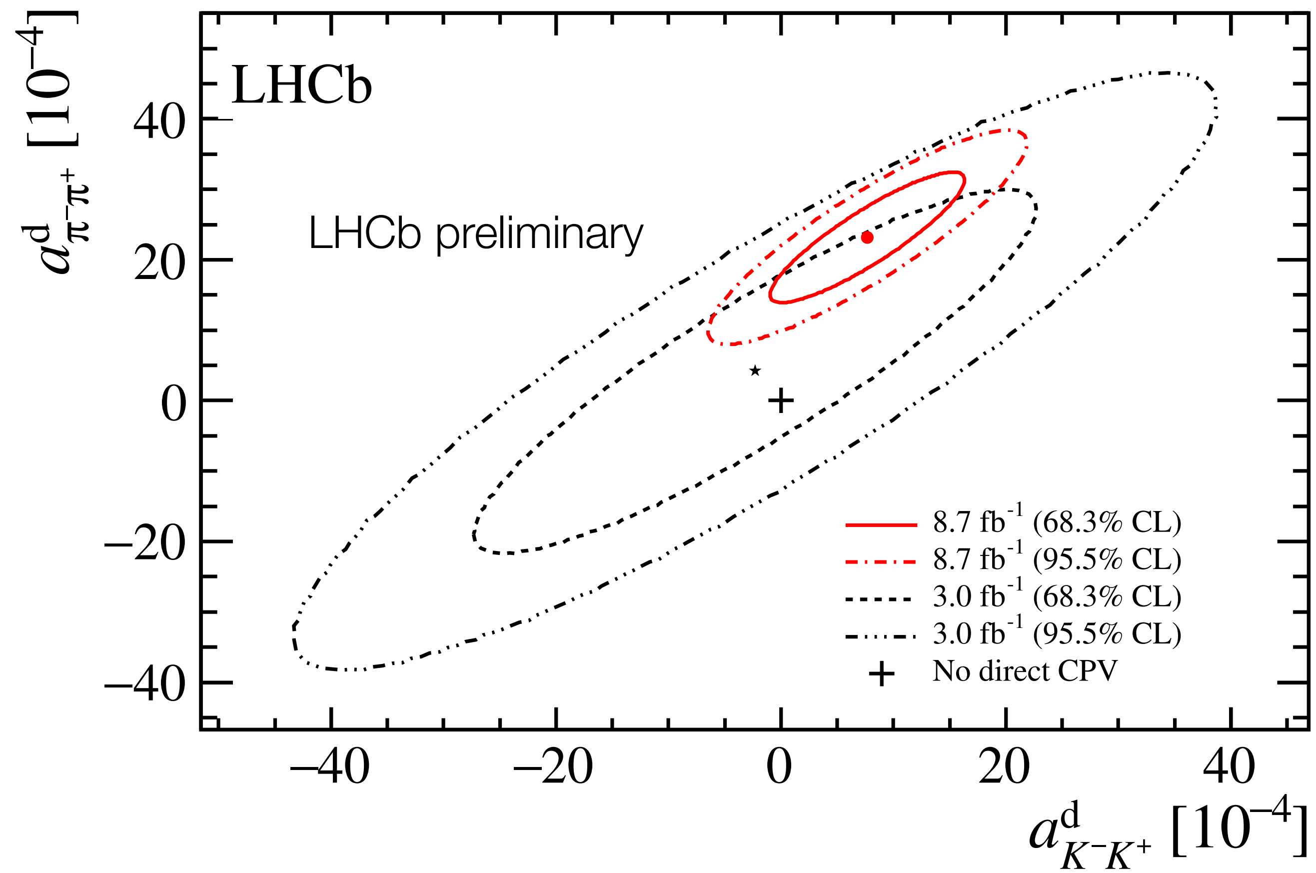
$$\Delta A_{CP} = a^d_{KK} - a^d_{\pi\pi} + \frac{\langle t \rangle_{KK} - \langle t \rangle_{\pi\pi}}{\tau_{D^0}} \Delta Y$$

- All Run-1 and Run-2 measurements are embedded in a **global χ^2**, taking into account *correlations*.

First evidence for direct *CP* violation

$$a^d_{K^-K^+} = (\ \ 7.7 \pm 5.7) \times 10^{-4}$$
$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4}$$

with $\rho(a^d_{KK}, a^d_{\pi\pi}) = 0.88$

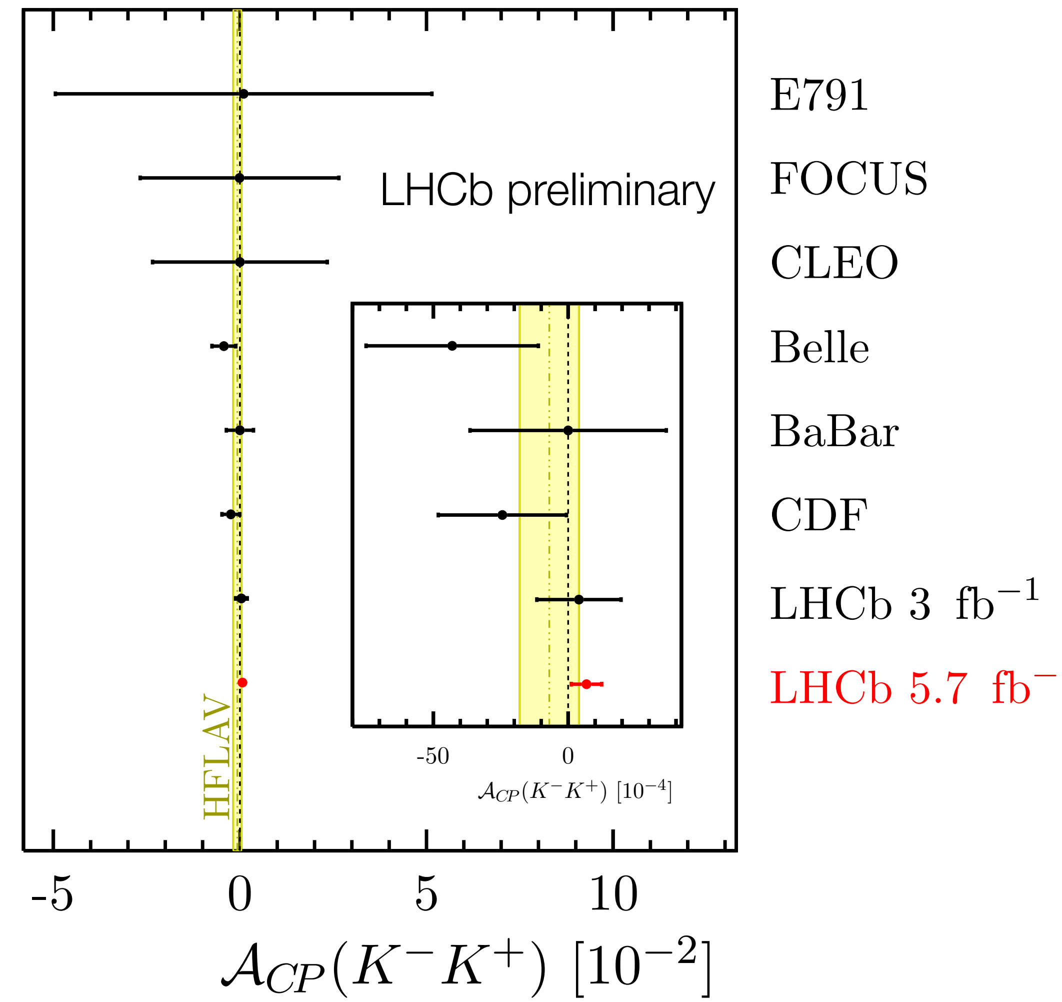


- They report the <u>first evidence</u> for **direct *CP* violation** in ***$D^0 \to \pi^-\pi^+$*** decays at the level of **3.8σ**.

- *U-spin* breaking in CP asymmetries: $a^d_{KK} + a^d_{\pi\pi} \neq 0$ at the level of 2.7σ.

Conclusions

- A measurement of $\boldsymbol{A_{CP}(D^0 \to K^- K^+)}$, using *prompt* decays collected during *Run-2*, has been presented
- A precision of **6x10^{-4}** has been obtained combining D^+ and D_s^+ decays to cancel nuisance asymmetries.
- The measurement is the most *accurate* in the **world** and is still *statistically* dominated.



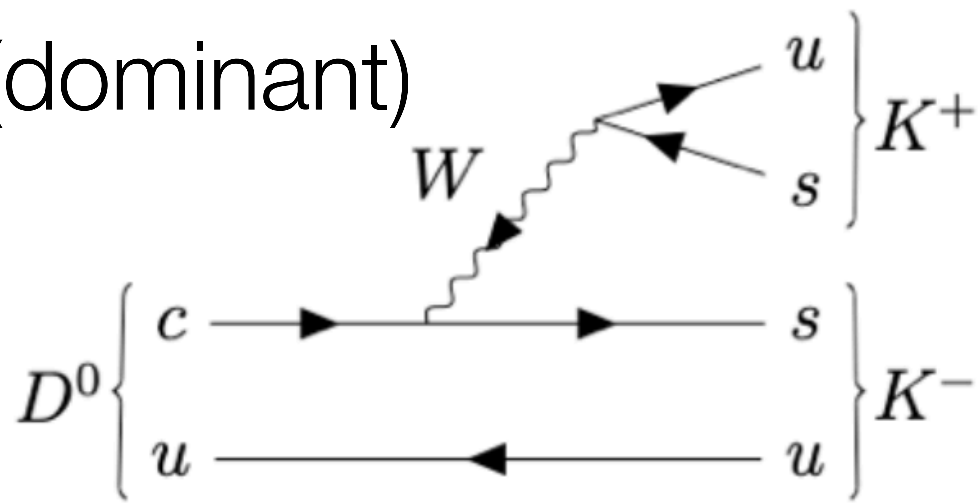
- **Direct *CP* violation** asymmetries a^d_{KK} and $a^d_{\pi\pi}$ are calculated from the combination of A_{CP} with previous LHCb measurements, revealing the **first evidence** for direct *CP* violation in $\boldsymbol{D^0 \to \pi^- \pi^+}$ decays

Thanks!

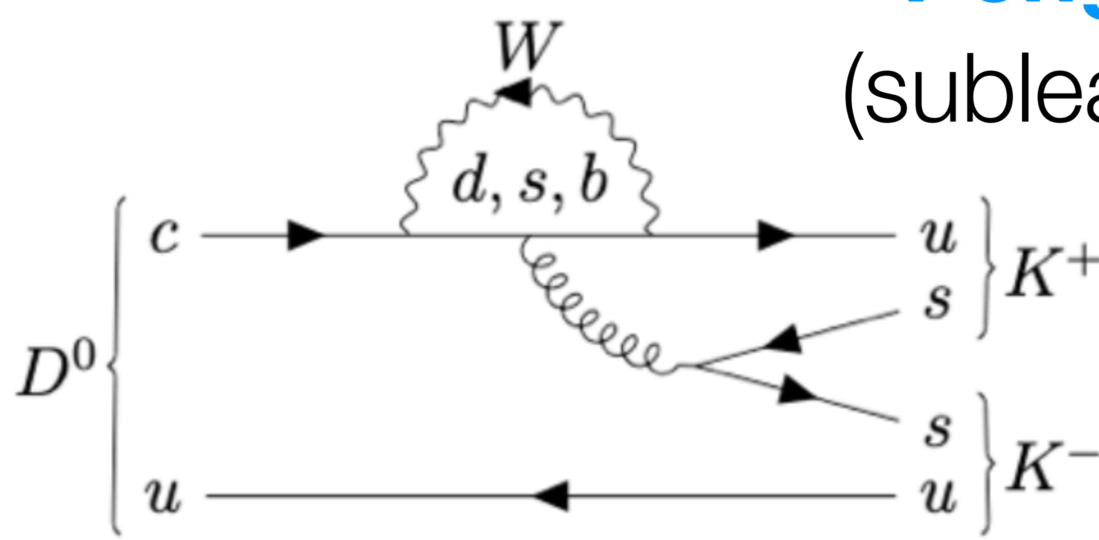
Back-up slides →

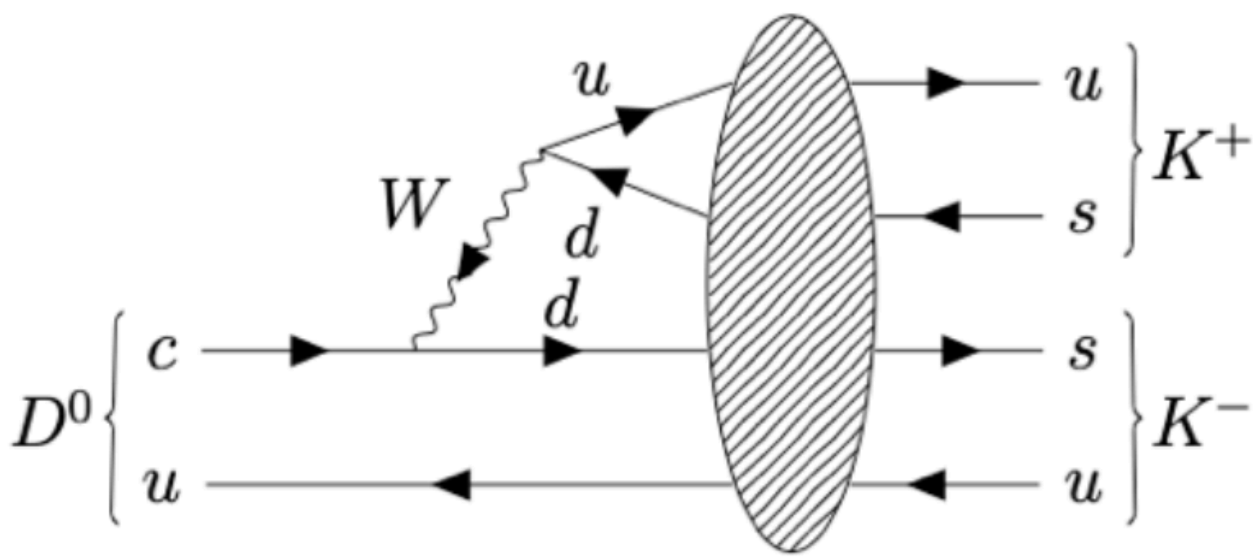
$D^0 \to K^- K^+$ processes (as an example)

Tree
(dominant)



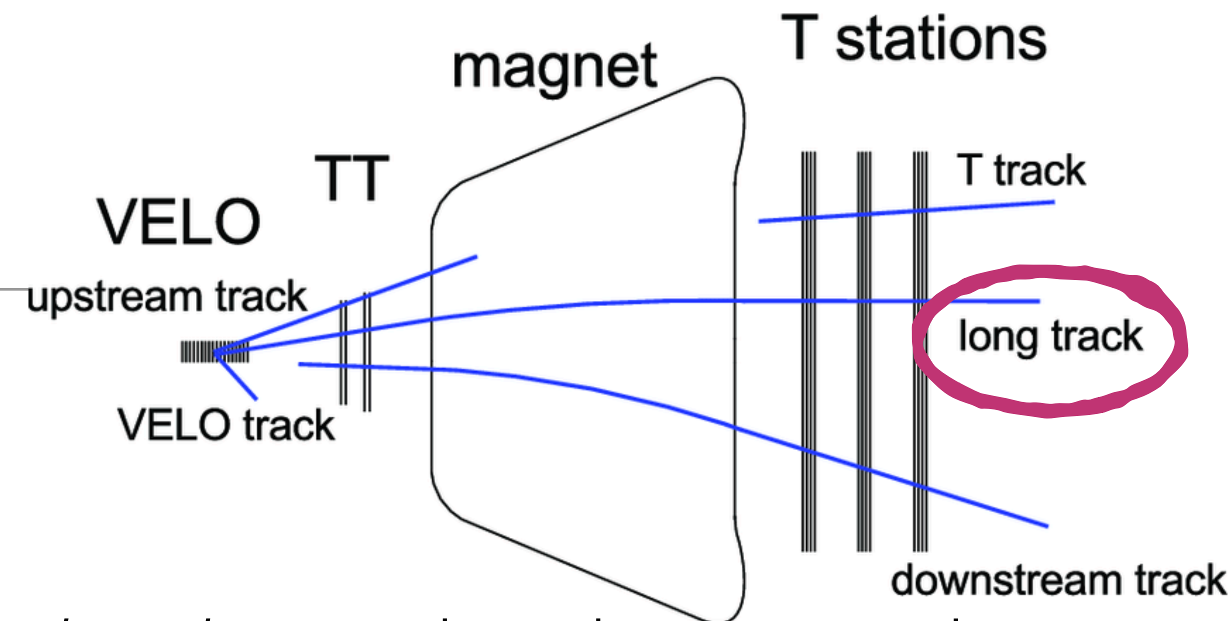
Penguin
(subleading)





Rescattering
(subleading)

Selection



- Data collected in ***Run-2*** with exclusive **online trigger lines** have been used

- $\overline{K}^0$ candidates reconstructed as $\boldsymbol{K_S \to \pi^- \pi^+}$ using *long-long* tracks to better control neutral kaon asymmetry

- For simplicity, the $D^0 \to K^- \pi^+$ sample is **split in 2** subsamples to be used in the D^+ and D_s^+ methods.

- $D^{*+}/D_{(s)}^+$ meson has to be ***prompt*** to avoid production asymmetries from B meson decays → cut on the impact parameter (IP)

- *Kinematic regions* with very large values of *raw asymmetries* need to be **removed**

- *T*ight particle-ID cuts to reduce ***mis-ID*** backgrounds

- The **"harmonization" rule**: every kinematic, PID and trigger requirement applied to a particle must be applied to the other "*twin*" particle. This simplifies the weighting procedure and avoids any possible final-state induced asymmetries.

The "harmonization" rule

- In the formula, *"twin"* particles must induce the exact amount of nuisance asymmetry

$$\mathbf{C_{D+}}: \quad A_{CP}(D^0 \to K^- K^+) = +A(D^{*+} \to (D^0 \to K^- K^+)\,\pi^+_{soft}) - A(D^{*+} \to (D^0 \to K^- \pi^+)\,\pi^+_{soft})$$
$$+A(D^+ \to K^- \pi^+ \pi^+) - \left[A(D^+ \to \overline{K}^0\, \pi^+) - A(\overline{K}^0)\right]$$

$$\mathbf{C_{Ds+}}: \quad A_{CP}(D^0 \to K^- K^+) = +A(D^{*+} \to (D^0 \to K^- K^+)\,\pi^+_{soft}) - A(D^{*+} \to (D^0 \to K^- \pi^+)\,\pi^+_{soft})$$
$$+A(D_s^+ \to \phi \pi^+) - \left[A(D_s^+ \to \overline{K}^0\, K^+) - A(\overline{K}^0)\right]$$

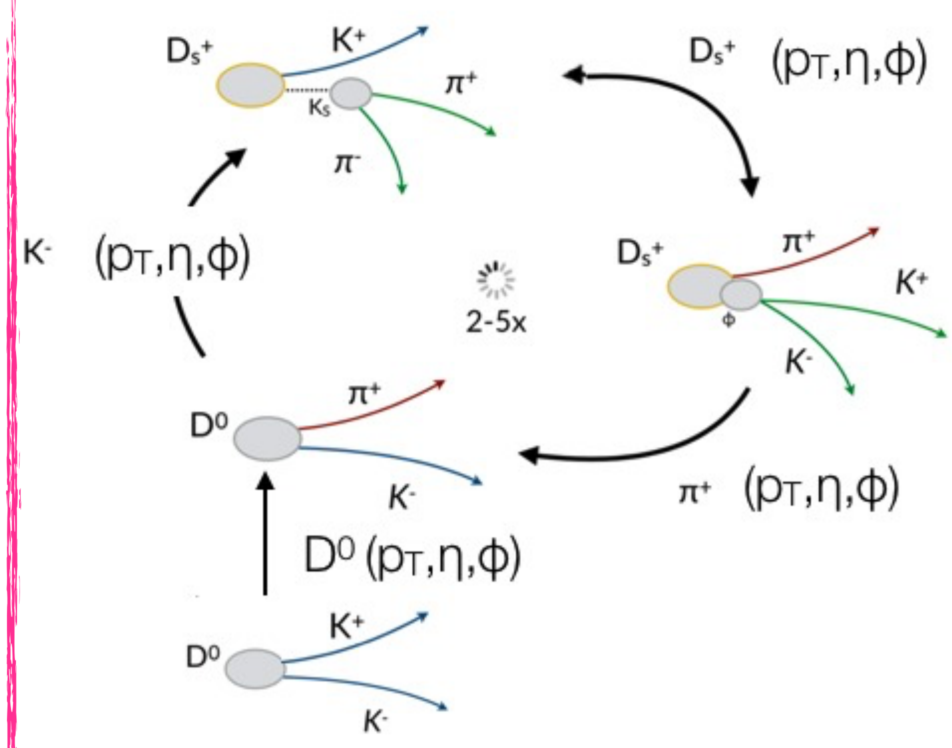
- Every kinematic, PID and trigger requirement applied to a particle must be applied to the other *"twin"* particle

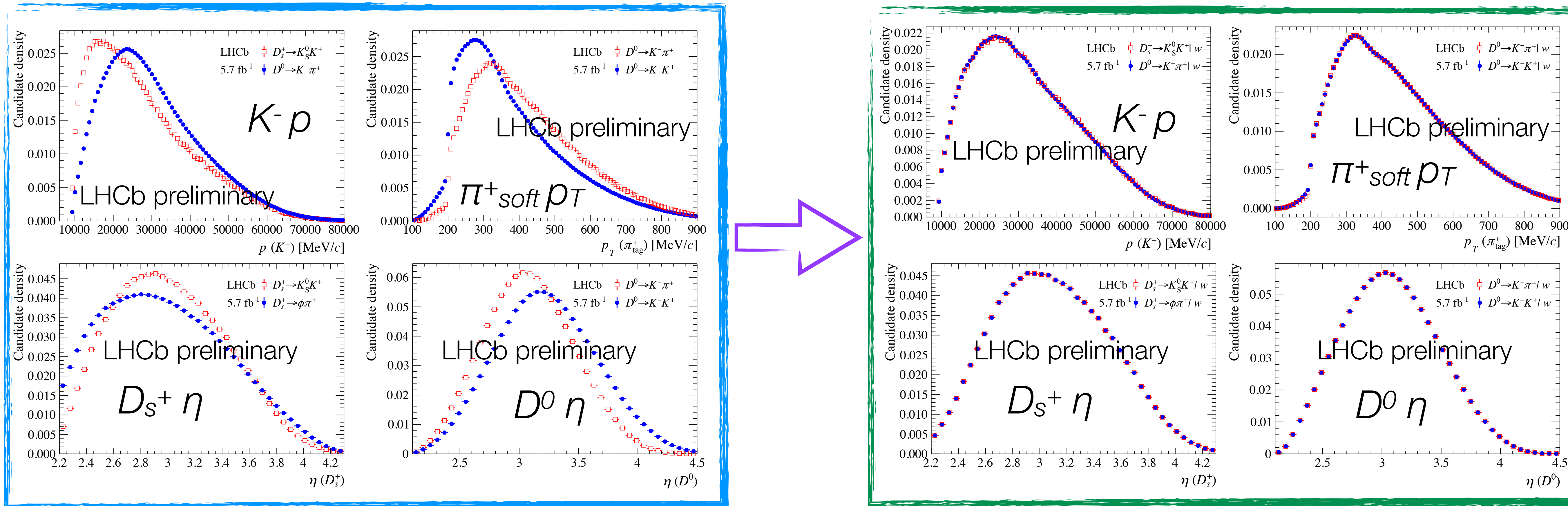
- This simplifies the *weighting* procedure and avoids any possible final-state induced asymmetries

Weighting procedure

- For each method, an *iterative* weighting approach has been used on the *four* decay modes.
- This is done until a satisfactory *agreement* of all kinematic distributions is obtained.

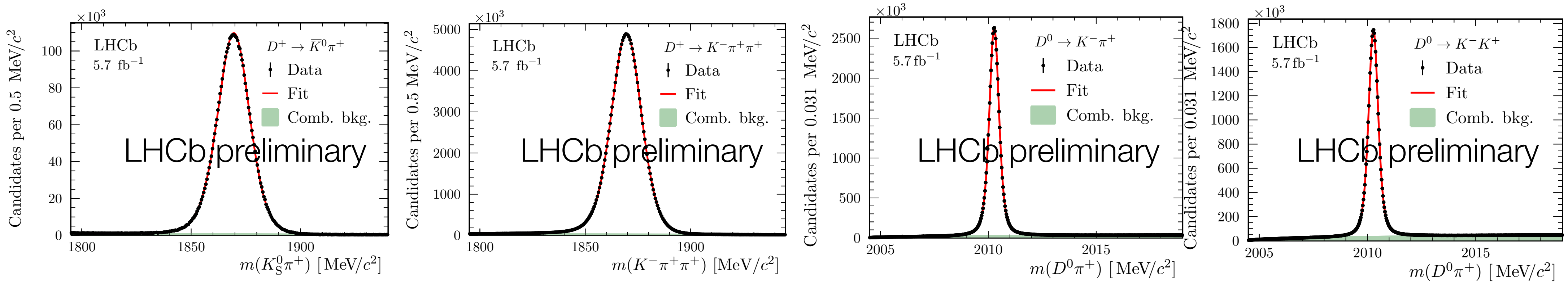
Strategy in $\boldsymbol{C_{D_s^+}}$ method:



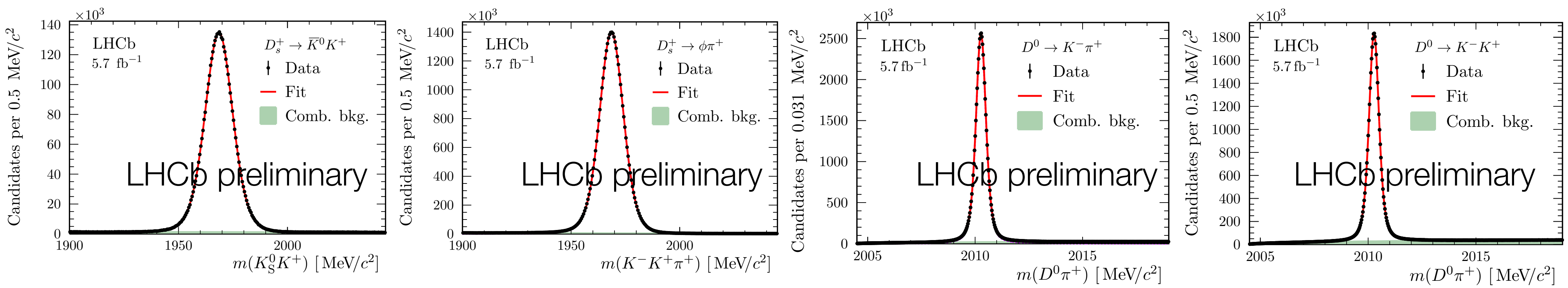


Fit results

C_{D+}:



C_{Ds+}:



Neutral kaon asymmetry

- Different interaction cross-sections of K^0 and $\bar{K}^0$ mesons with matter, including effects due to mixing and CPV induce an asymmetry.

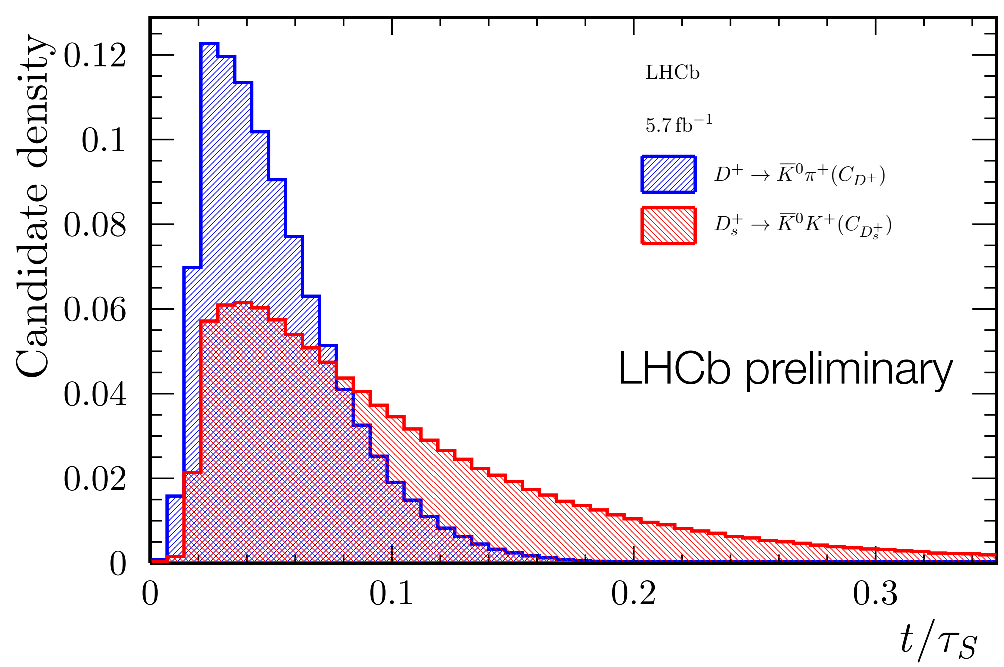
- Evaluated for each sample with a K_S in the final state using LHCb material map from simulation (Si,Al,vacuum), neutral-kaon cross-sections, forward scattering phase, mixing and CPV.

$A(\bar{K}^0)$

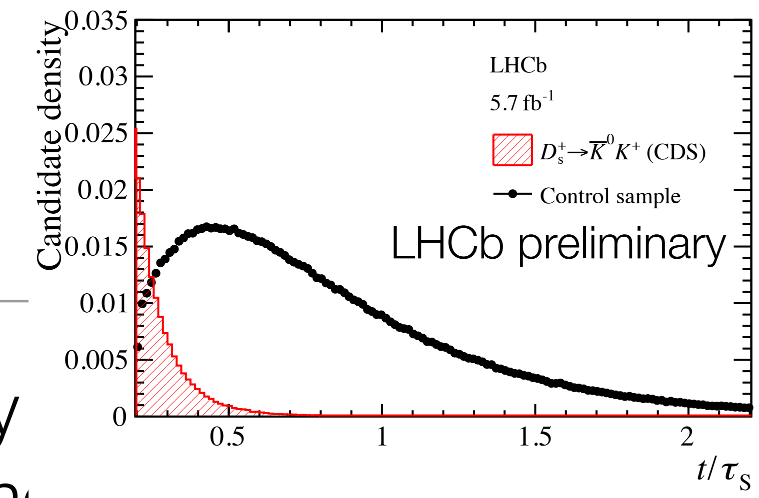
$D^+ \rightarrow K_S \pi^+$: [-5.1 ± 0.6 (syst)] x10^{-4}

$D_s^+ \rightarrow K_S K^+$: [-8.5 ± 1.3 (syst)] x10^{-4}

data driven approach using K_S control sample



Systematic

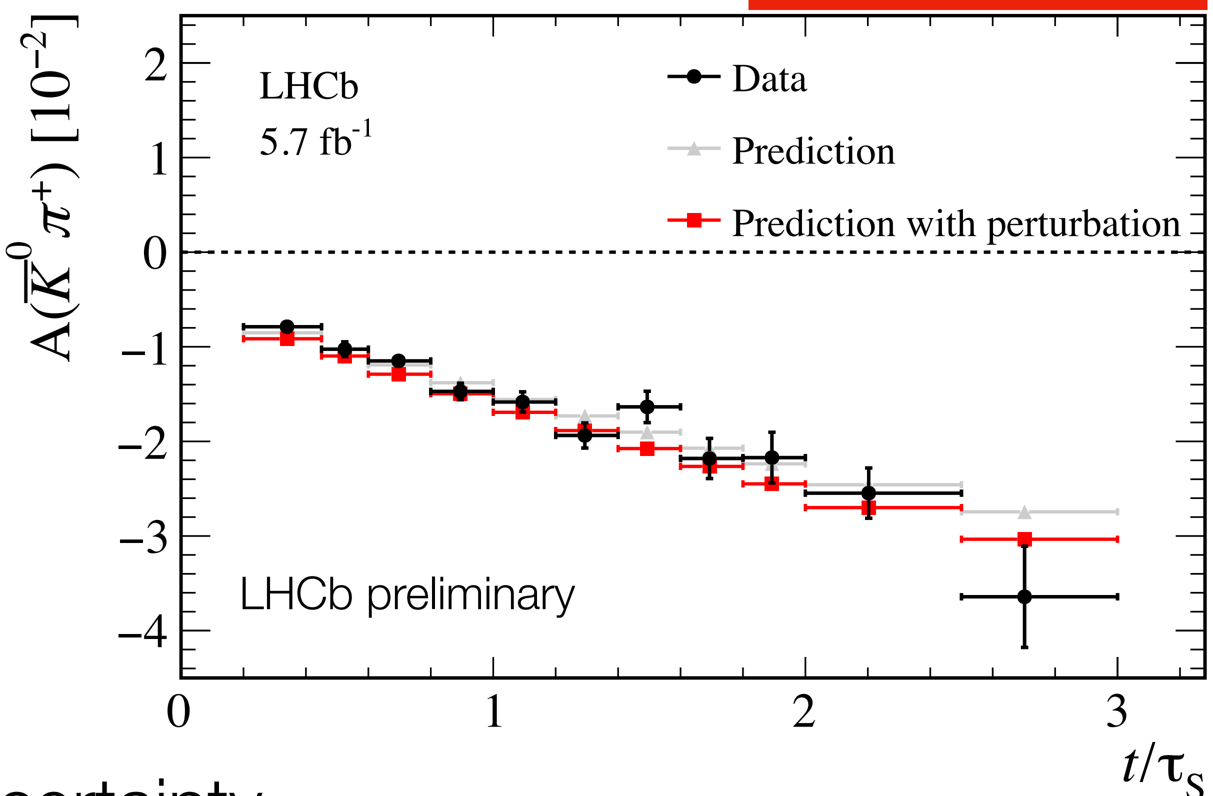


- Strategy: introduce an additional linear term in the decay time to approximate the first-order deviations from the model

$$A_{\text{raw}}(\tau) = A_{\text{nuisance}} + A_{\text{det}}^{\text{pred}}(\tau) + \delta A \qquad \delta A = c \cdot \tau$$

Capture, to first order, mis-modelling, including possible effects of additional K_S-lifetime-dependent *CP* violation.

(control sample)



- Fit slope term ***c*** on data
- Effect on the time-integrated raw asymmetry in long long sample:

$$\langle \delta A \rangle = c \, \langle \tau \rangle$$

Its RMS is assigned as systematic uncertainty.

Validation with MC and consistency checks

- The *weighting* procedure is verified by checking all the assumptions embedded in the cancellation of the nuisance asymmetries for A_{CP} using huge-statistics **particle-Gun** samples.

- Several **consistency checks** to verify that $A_{CP}(K^-K^+)$ does not depend on running conditions, kinematics, topology, PID and high-level trigger selection.