LHCb results on *Mixing* and *CP violation* in Charm

Serena Maccolini

on behalf of the LHCb collaboration

Lake Louise Winter Institute - February 12th, 2019

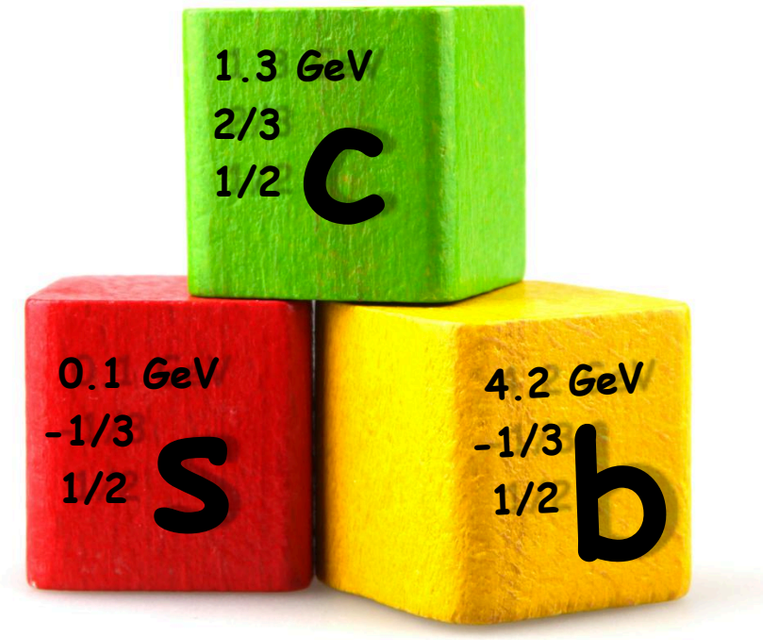
serena.maccolini@cern.ch

University of Bologna and INFN-BO

Why study charm physics?

- If new physics (**NP**) exists it should violate ***CP*** symmetry

- **Up-type** quark: unique probe of NP in the flavor sector, <u>complementary</u> to studies in K and B systems



- Small *CP* asymmetries expected **(0.1%÷1%)**
  - CKM/GIM suppression
  - Large uncertainties due to low-energy strong interaction effects
    [Phys.Lett. B222 (1989) 501-506]

- CP violation (CPV) in charm decays has not yet been observed

- Why at ***LHCb***? Huge $\mathbf{c\bar{c}}$ production cross-section:

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

[JHEP 03 (2016) 159]

Mixing of neutral D mesons

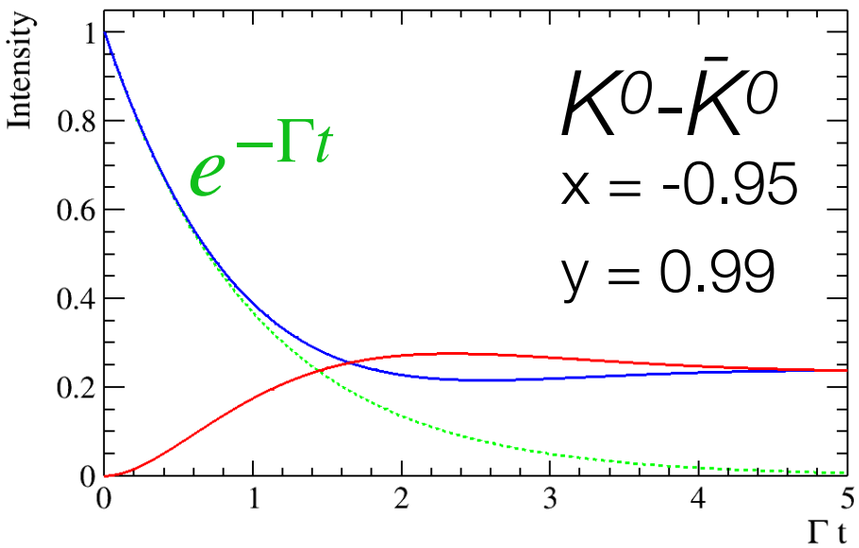
- *Mass* eigenstates are <u>not</u> the *flavor* eigenstates:

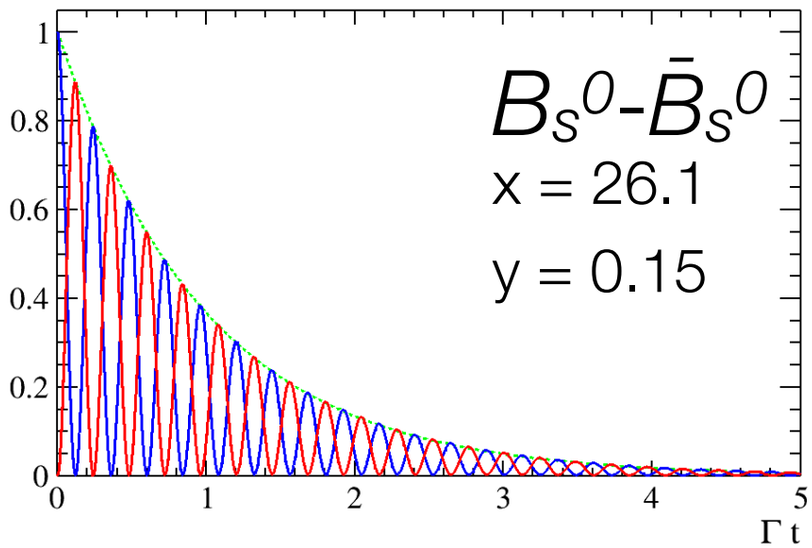
$$|D_{1,2}\rangle = p\left|D^0\right\rangle \pm q\left|\bar{D}^0\right\rangle$$

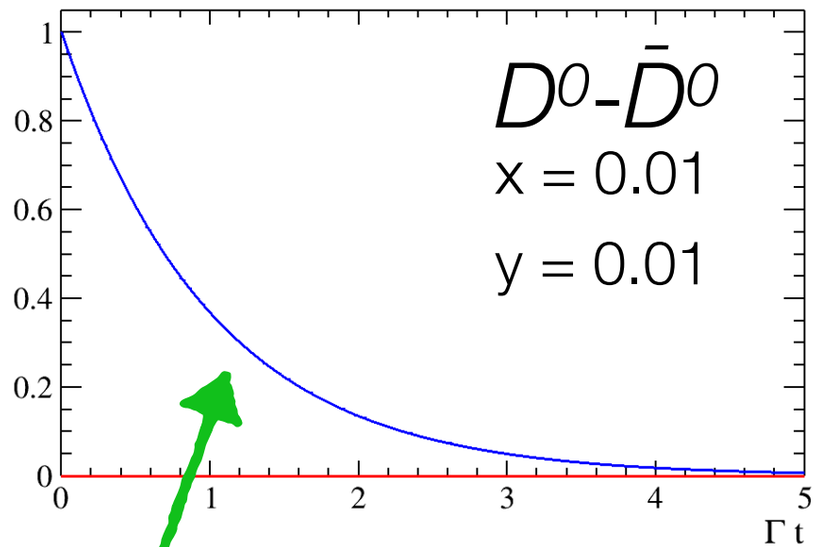
- This causes **D ↔ D̄** transitions described by

$$x = \frac{m_1 - m_2}{\Gamma}$$

$$y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$







$$|\langle P^0(0)|P^0(t)\rangle|^2 \propto e^{-\Gamma t}[\cosh(y\Gamma t) + \cos(x\Gamma t)]$$

$$|\langle P^0(0)|\bar{P}^0(t)\rangle|^2 \propto e^{-\Gamma t}[\cosh(y\Gamma t) - \cos(x\Gamma t)]$$

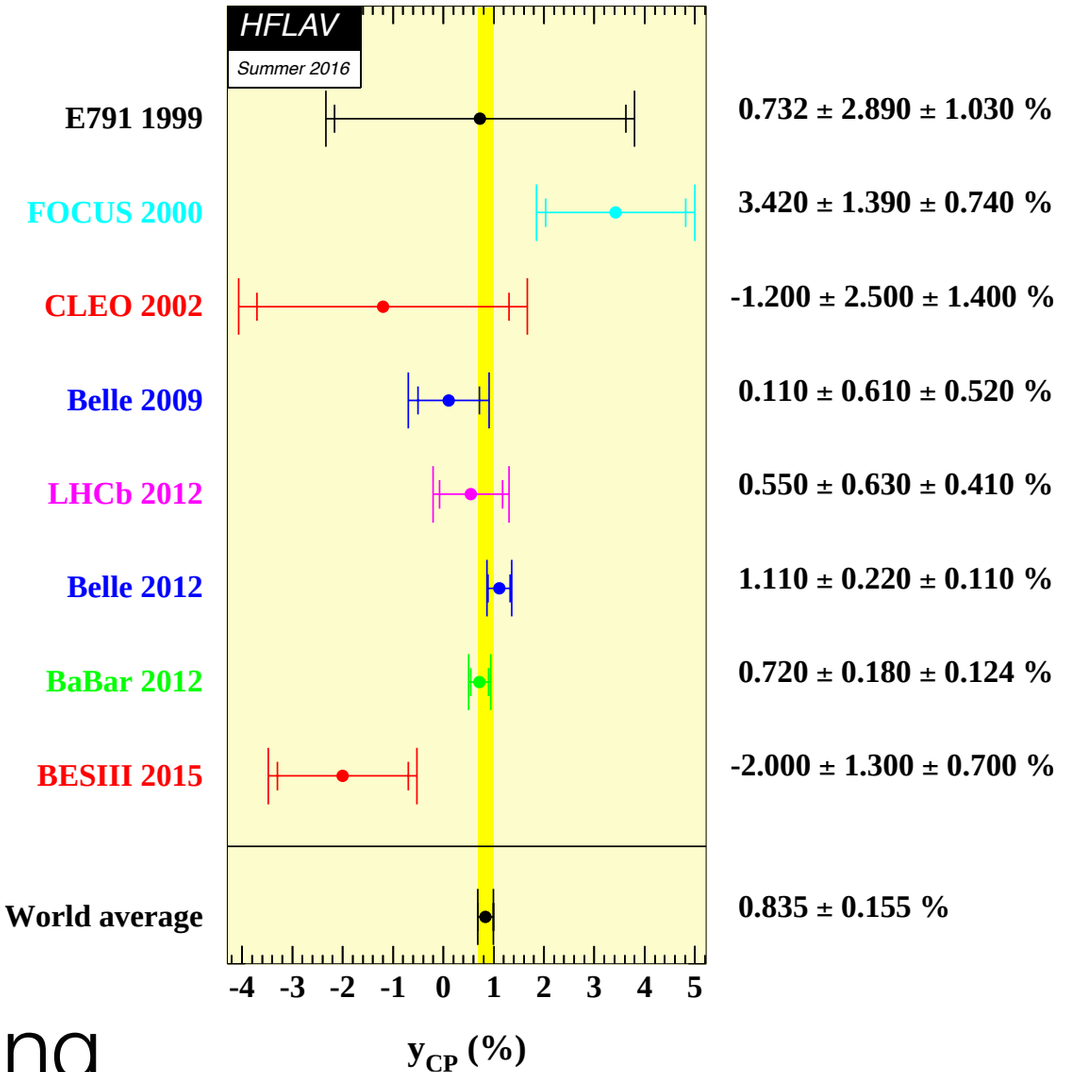
Tiny mixing in charm!

Measurement of the charm-mixing parameter y_{CP}

- Compare decay widths of D^0 decaying to *CP*-eigenstates ($\mathbf{\Gamma^{CP}}$) and to *CP*-mixed states ($\mathbf{\Gamma}$):

$$y_{CP} = \frac{\Gamma^{CP}}{\Gamma} - 1 = \Delta_\Gamma \tau$$

$$\Delta_\Gamma = \Gamma^{CP} - \Gamma$$



- Use $\mathbf{K^+K^-}$ and $\mathbf{\pi^+\pi^-}$ (*CP*-even) and $\mathbf{K^-\pi^+}$ (*CP*-mixed) states

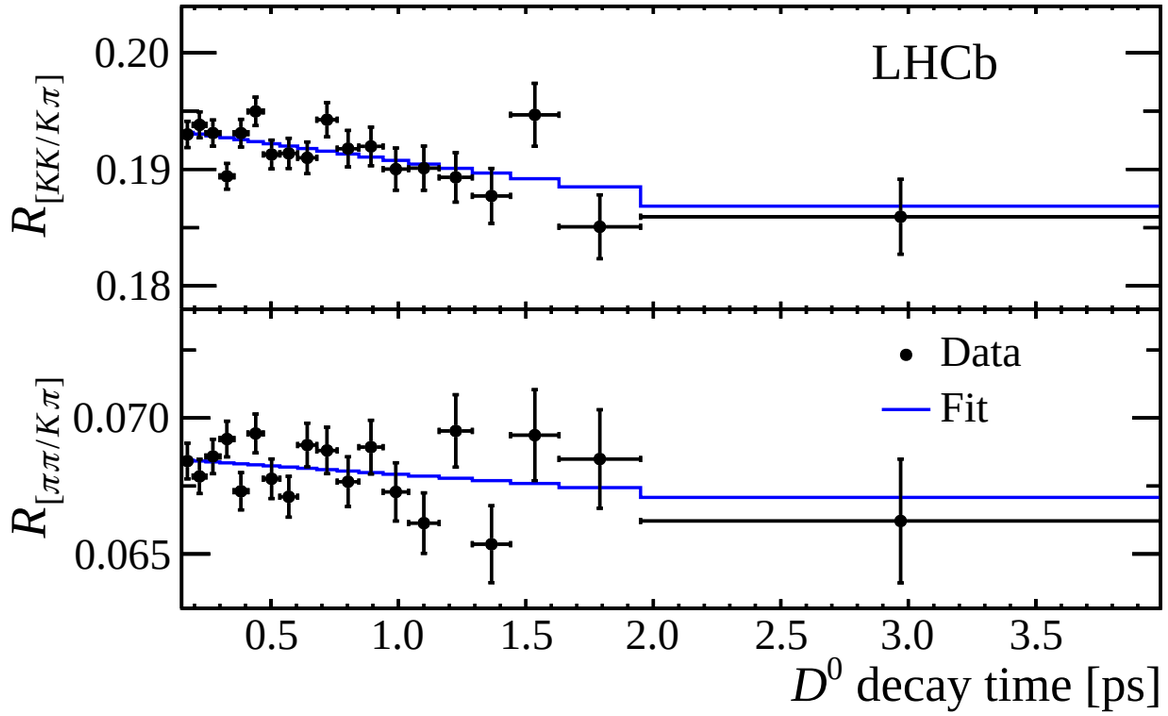
- y_{CP} differs from 0 because of mixing

- if *CP* symmetry is violated y_{CP} differs from y

[Phys. Rev. Lett. 122 (2019) 011802]

Strategy and results

- Use D^0 from semi-leptonic B decays (Run-1 data)
- Determine the **K^+K^-**, **$\pi^+\pi^-$** and **$K^+\pi^-$** signal yields in bins of D^0 decay time
- Fit the *acceptance-corrected* ratio of **$K^+K^-/K^+\pi^-$** and **$\pi^+\pi^-/K^+\pi^-$** to measure **y_{CP}**

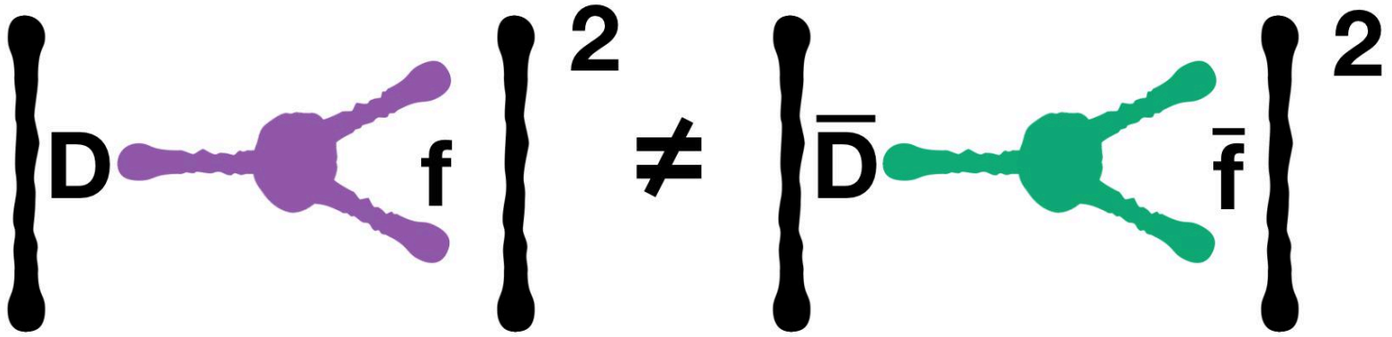


- Results are consistent between modes, and combined give:

$$y_{CP} = (0.57 \pm 0.13\,(\text{stat}) \pm 0.09\,(\text{syst}))\%,$$

- Consistent and, as precise as, the world average
- Consistent with world average value of y = (0.62 ± 0.07) %

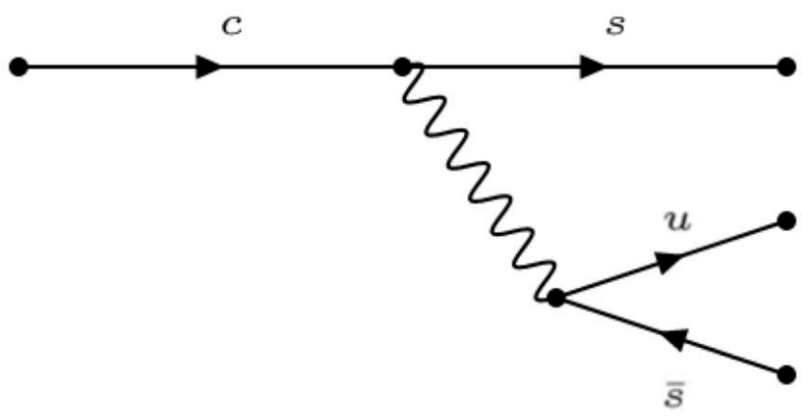
Direct *CP* violation

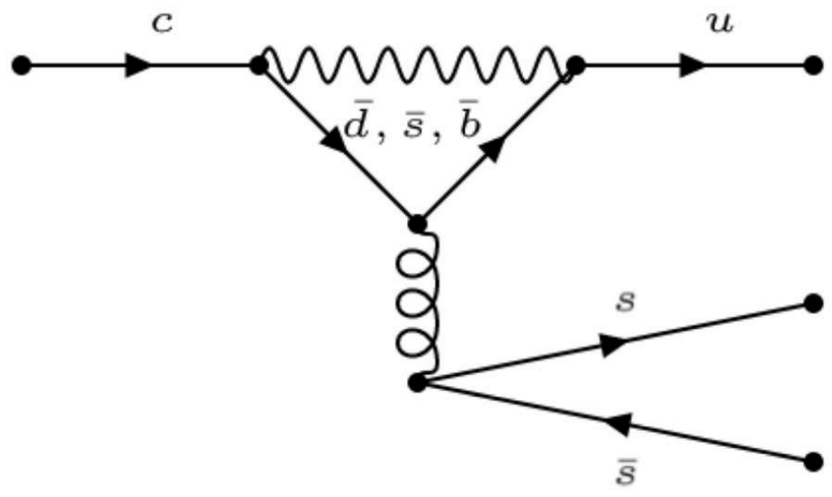


- Corresponds to

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

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





Experimentally…

- *Raw asymmetry* between the observed yields:

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

- Contributions other than $\mathbf{A_{CP}}$:

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

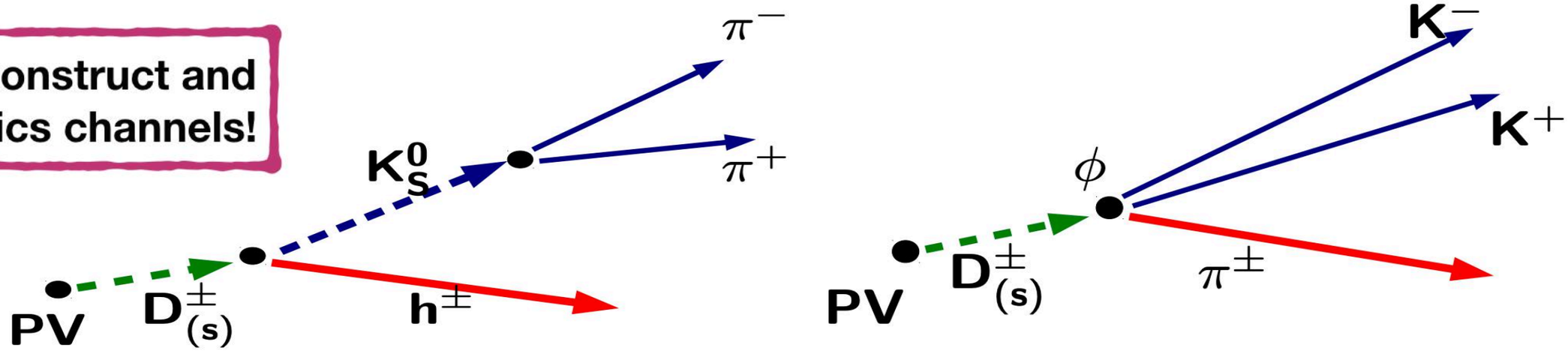
$$A_D(f) = \frac{\epsilon(f) - \epsilon(\bar{f})}{\epsilon(f) + \epsilon(\bar{f})}$$

Production asymmetry

Detection and reconstruction asymmetry

CP asymmetries in the CS $D_s^+ \to K_S\pi^+$, $D^+ \to K_S K^+$ and $D^+ \to \phi\pi^+$ decays

Easy-to-reconstruct and high-statistics channels!



- Best measurements to date are from LHCb Run-1: [JHEP 06 (2013) 112] and [JHEP 1410 (2014) 025]

Channel	$\mathcal{A}_{CP}$ (%)	Dataset
$D_s^+ \to K_S^0\pi^+$	$+0.38 \pm 0.46$ (stat) ± 0.17 (syst)	2011-2012 (3.2/fb)
$D^+ \to K_S^0 K^+$	$+0.03 \pm 0.17$ (stat) ± 0.14 (syst)	
$D^+ \to \phi\pi^+$	-0.04 ± 0.14 (stat) ± 0.14 (syst)	2011 (1.1/fb)

NEW

- Today, updated results using 3.8/fb of **Run-2** data collected during 2015-2017

Strategy

- Correct *raw asymmetries A* using kinematically weighted samples of Cabibbo-favored $D_{(S)}^+$ decays (where CPV can be neglected)

Production and detection asymmetries cancel out !

$$A_{CP}(D_s^+ \to K_S^0\pi^+) = [A(D_s^+ \to K_S^0\pi^+) - A_D(K^0)] - A(D_s^+ \to \phi\pi^+)$$

$$A_{CP}(D^+ \to K_S^0K^+) = [A(D^+ \to K_S^0K^+) - A_D(\bar{K}^0)] - [A(D^+ \to K_S^0\pi^+) - A_D(\bar{K}^0)] - [A(D_s^+ \to K_S^0K^+) - A_D(\bar{K}^0)] + A(D_s^+ \to \phi\pi^+)$$

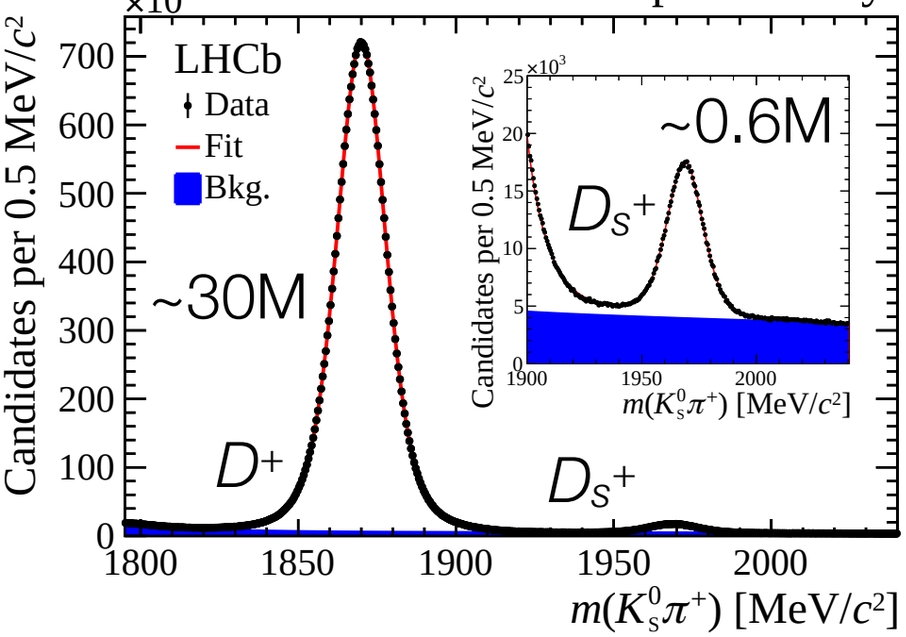
$$A_{CP}(D^+ \to \phi\pi^+) = A(D^+ \to \phi\pi^+) - [A(D^+ \to K_S^0\pi^+) - A_D(\bar{K}^0)]$$

where $K_S \to \pi^+\pi^-$ *and* $A_D(K^0) = -A_D(\bar{K}^0)$ is the detection asymmetry of neutral kaons, which includes mixing and CPV effects

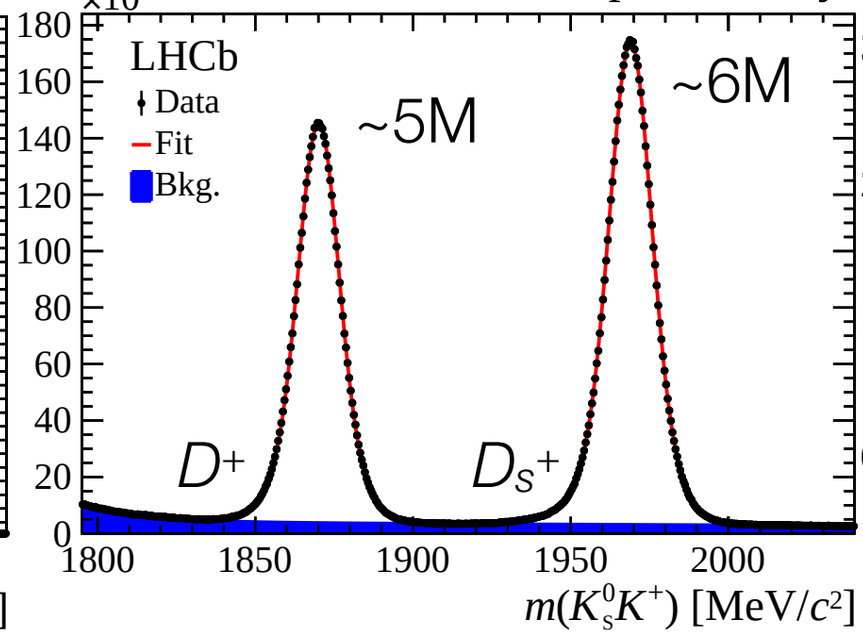
[LHCB-PAPER-2019-002] in preparation

Determination of raw asymmetries

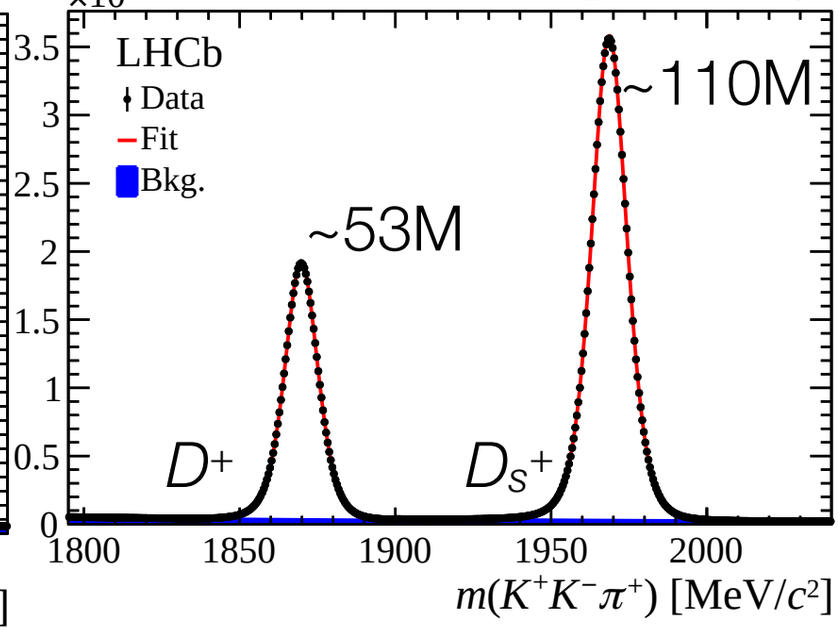
$K_S\pi^+$ LHCb preliminary



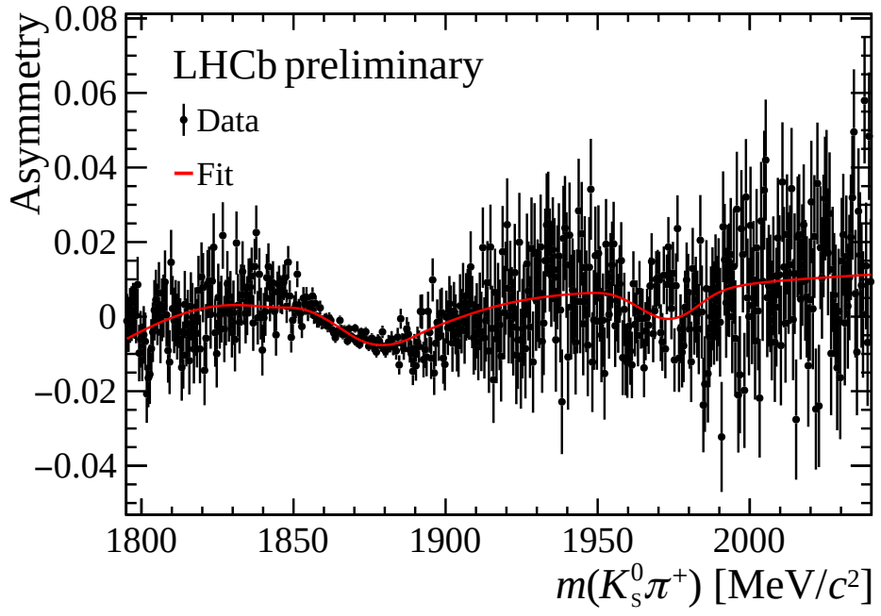
K_SK^+ LHCb preliminary

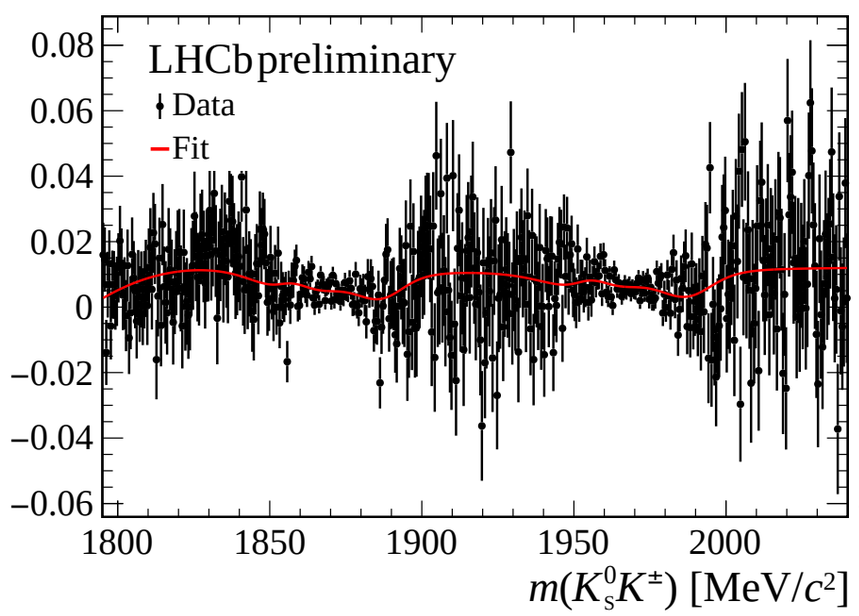


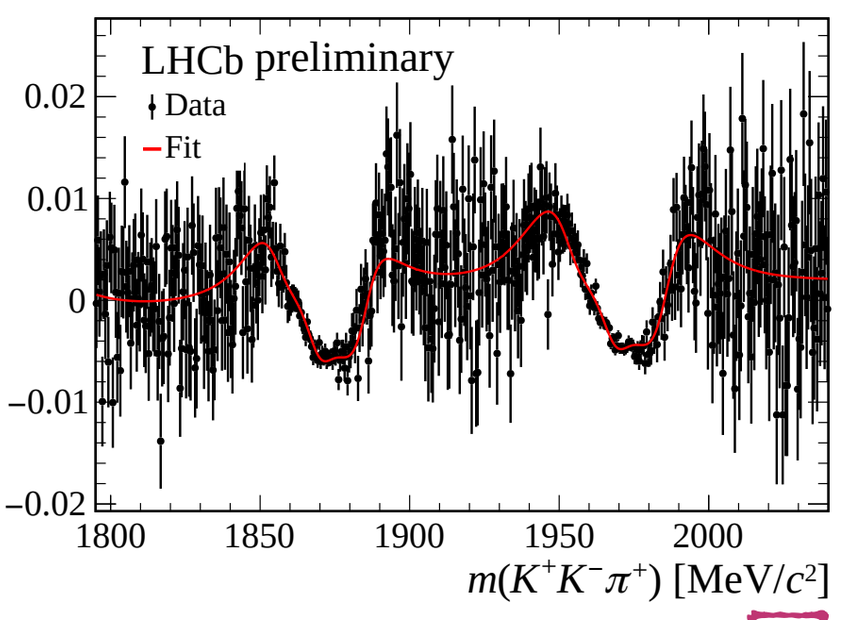
$\phi\pi^+$ LHCb preliminary



Raw asymmetries projection:







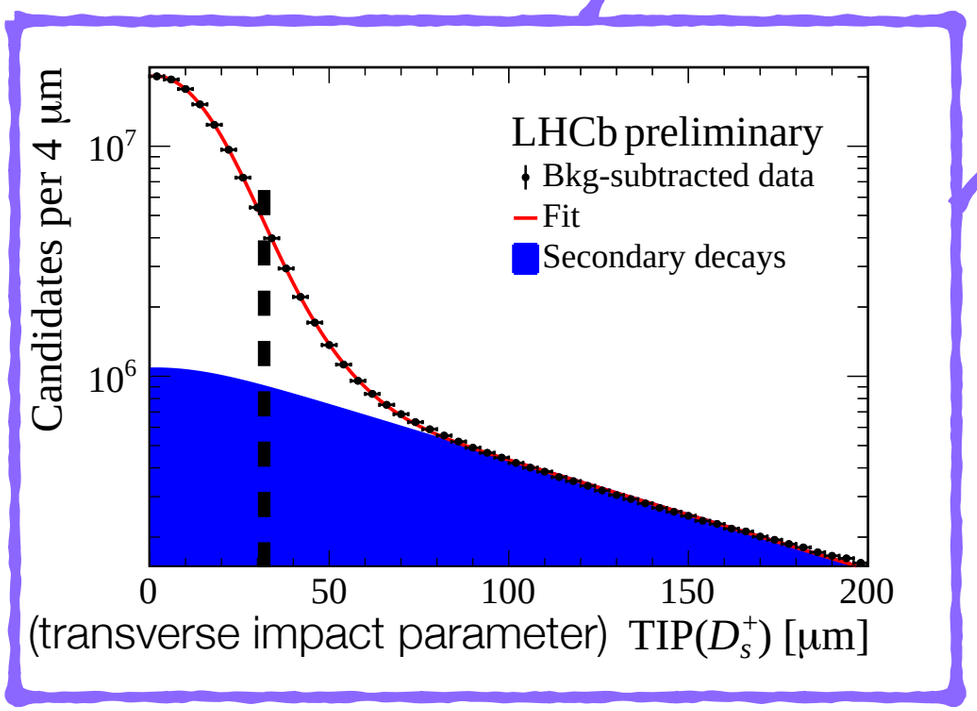
[LHCB-PAPER-2019-002] in preparation

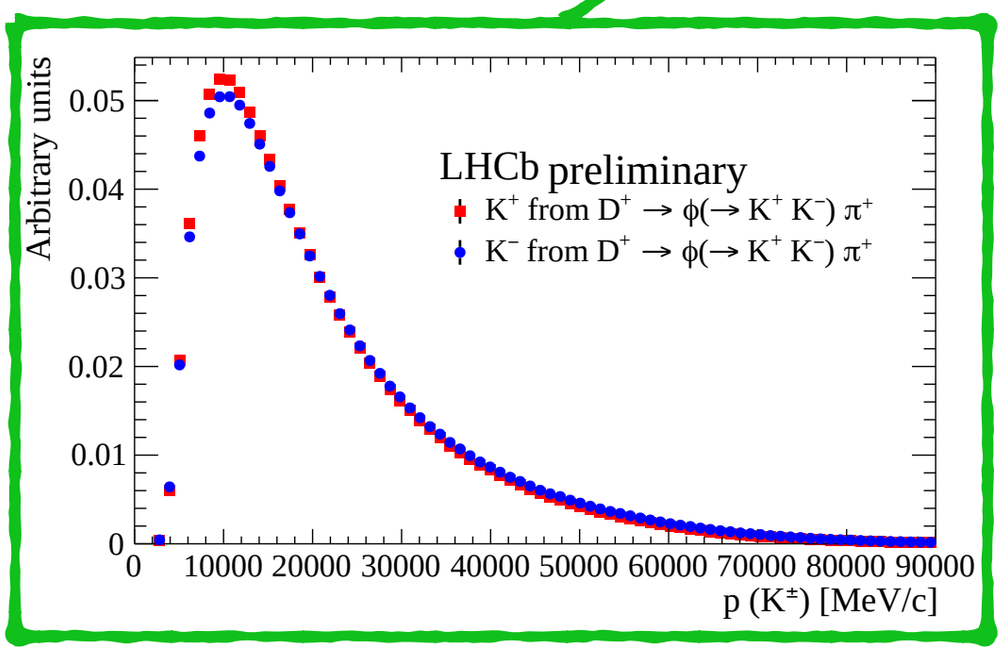
Systematics

Table 1: Summary of the systematic uncertainties (in units of 10^{-3}) on the measured quantities. The total is the sum in quadrature of the different sources.

LHCb preliminary

Source	$\mathcal{A}_{CP}(D_s^+ \to K_S^0\pi^+)$	$\mathcal{A}_{CP}(D^+ \to K_S^0K^+)$	$\mathcal{A}_{CP}(D^+ \to \phi\pi^+)$
Fit model	0.39	0.44	0.24
Secondary decays	0.30	0.12	0.03
Kinematic diff.	0.09	0.09	0.04
Neutral kaon asym.	0.05	0.05	0.04
Charged kaon asym.	0.08	0.09	0.15
Total	0.51	0.48	0.29





Results

- *CP* asymmetries:

LHCb preliminary

$$\mathcal{A}_{CP}(D_s^+ \to K_S^0\pi^+) = (\ \ 1.3\ \ \pm 1.9\ \ (\text{stat}) \pm 0.5\ \ (\text{syst})) \times 10^{-3},$$
$$\mathcal{A}_{CP}(D^+ \to K_S^0 K^+) = (-0.09 \pm 0.65\,(\text{stat}) \pm 0.48\,(\text{syst})) \times 10^{-3},$$
$$\mathcal{A}_{CP}(D^+ \to \phi\pi^+) = (\ \ 0.05 \pm 0.42\,(\text{stat}) \pm 0.29\,(\text{syst})) \times 10^{-3}.$$

- When averaged with previous LHCb measurements they yield

$$\mathcal{A}_{CP}(D_s^+ \to K_S^0\pi^+) = (\ \ 1.6\ \ \pm 1.7\ \ (\text{stat}) \pm 0.5\ \ (\text{syst})) \times 10^{-3},$$
$$\mathcal{A}_{CP}(D^+ \to K_S^0 K^+) = (-0.04 \pm 0.61\,(\text{stat}) \pm 0.45\,(\text{syst})) \times 10^{-3},$$
$$\mathcal{A}_{CP}(D^+ \to \phi\pi^+) = (\ \ 0.03 \pm 0.40\,(\text{stat}) \pm 0.29\,(\text{syst})) \times 10^{-3}.$$

- No evidence of CPV is found

Summary

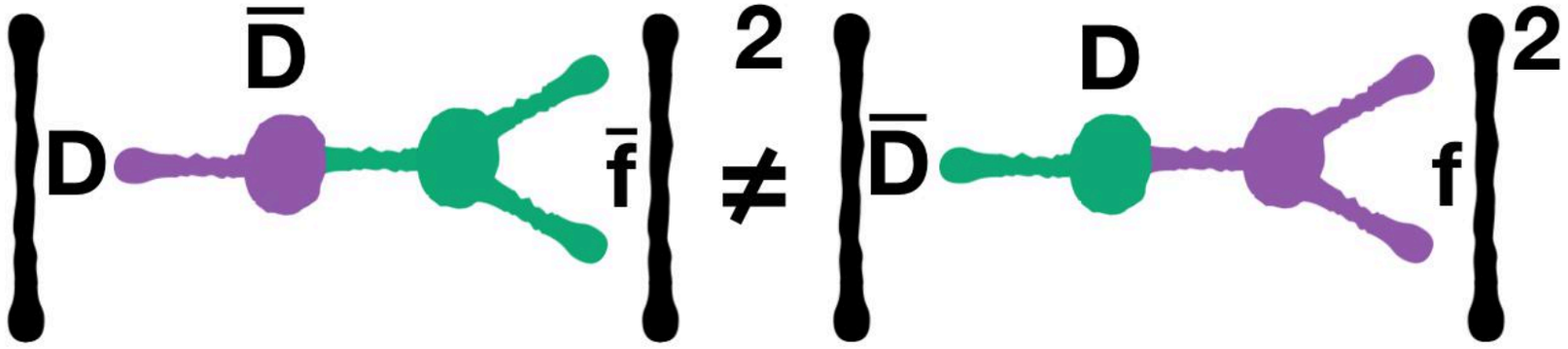
- Presented new results in Charm physics at LHCb
  - Measurement of mixing parameter y_{CP} as precise as the World average
  - For the first time: a search for direct *CP* violation in $D_{(s)}^+ \to K_S h^+$ and $D^+ \to \phi\pi^+$ decays
    In $\boldsymbol{D^+ \to \phi\pi^+}$ measured the most precise $\boldsymbol{A_{CP}}$ in charm hadrons!
- All results so far are *consistent* with *CP* symmetry
- However they are limited by *statistics*, and a large amount of data remains to be analyzed

Thanks for your attention!

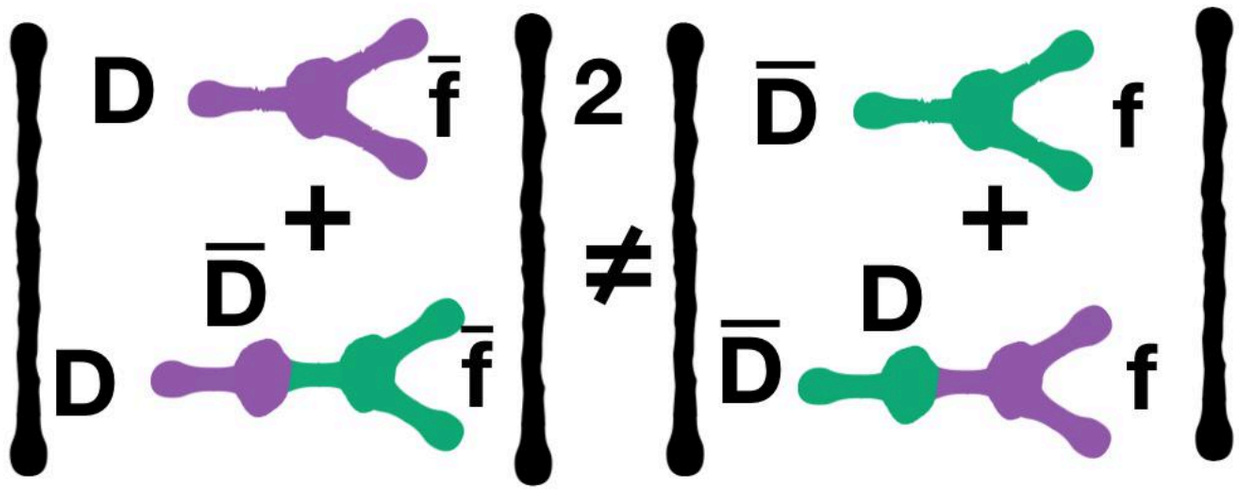
Back-up slides

Mixing and *CP* violation

- CPV in **mixing**
  Occurs if **|q/p| ≠ 1**



- CPV in **interference** between mixing and decay
  Occurs if
  $\phi \stackrel{\text{def}}{=} \arg(q\bar{A}_{\bar{f}} / pA_f) \neq 0$

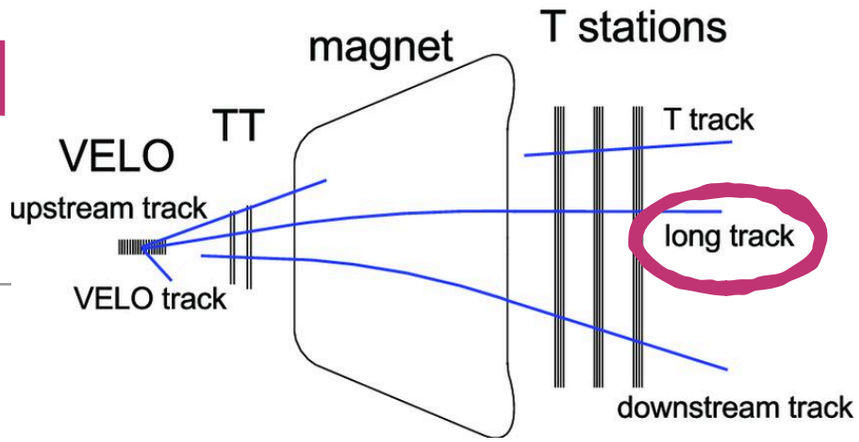


- Charm-mixing parameter **y_{CP}**

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

CPV in mixing — CPV in interference

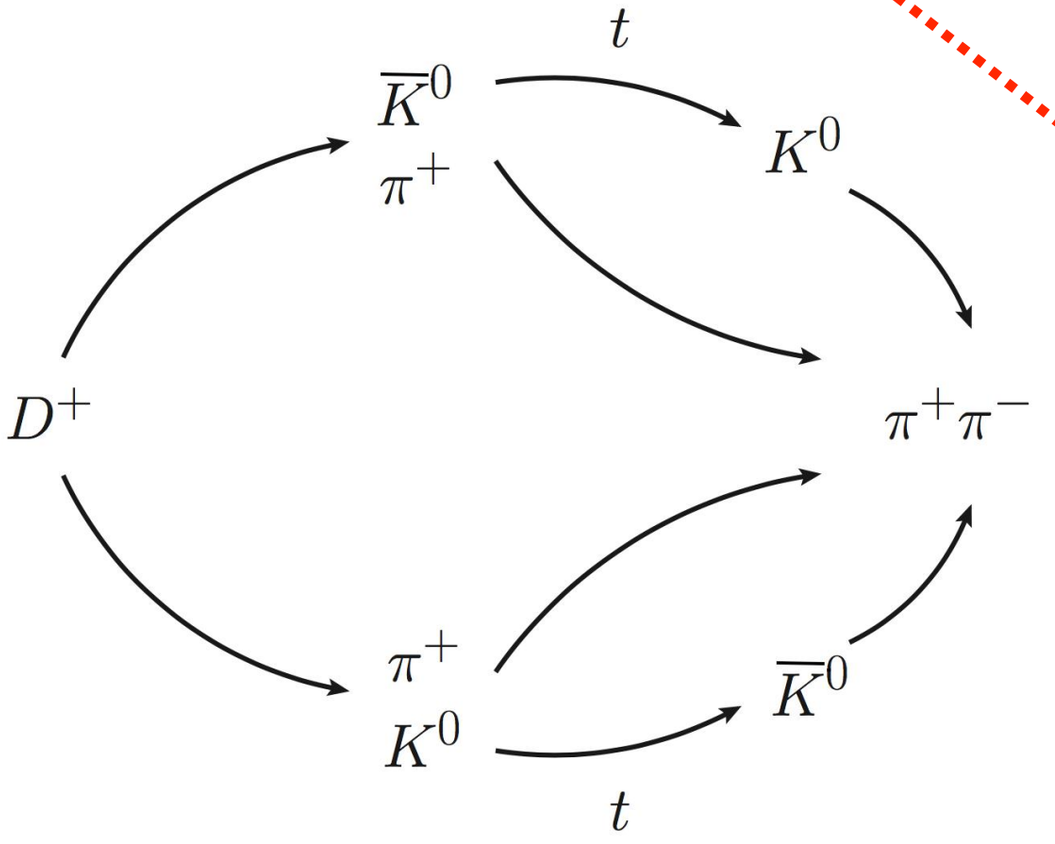
CP violation in Cabibbo-favored $D_{(s)}^+ \to K_S h^+$ decays

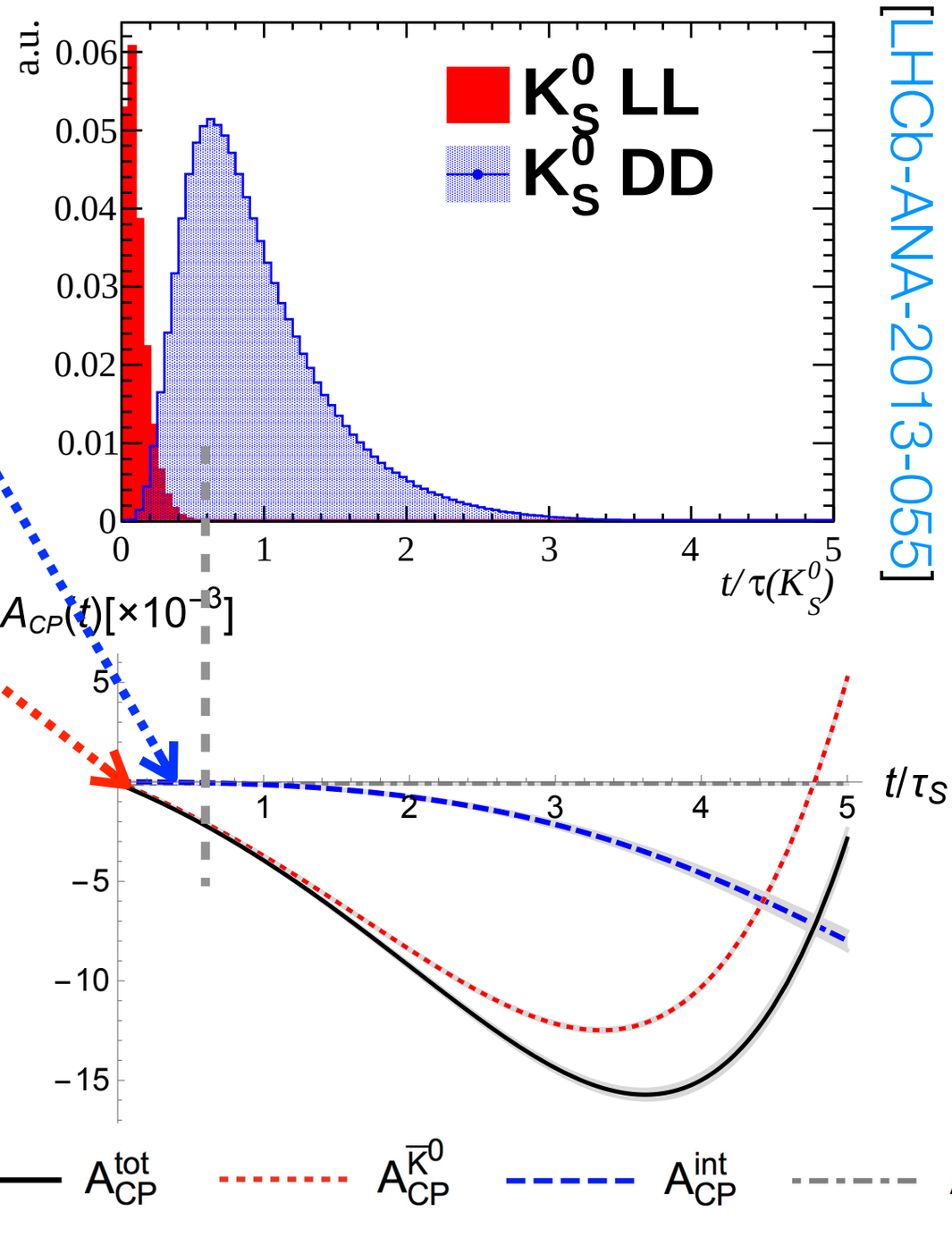


- K_S reconstructed from two long tracks (LL)

Effect that we ignore

Effect that we consider





[LHCb-ANA-2013-055]

[PRL 119 (2017) 181802]