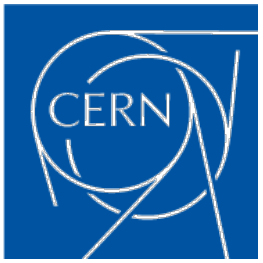


Mixing and Indirect CP Violation in Charm Decays at LHCb

Maurizio Martinelli (CERN)
on behalf the LHCb Collaboration

ICHEP 2018
Seoul, 06.07.2018

Motivation

Indirect Searches

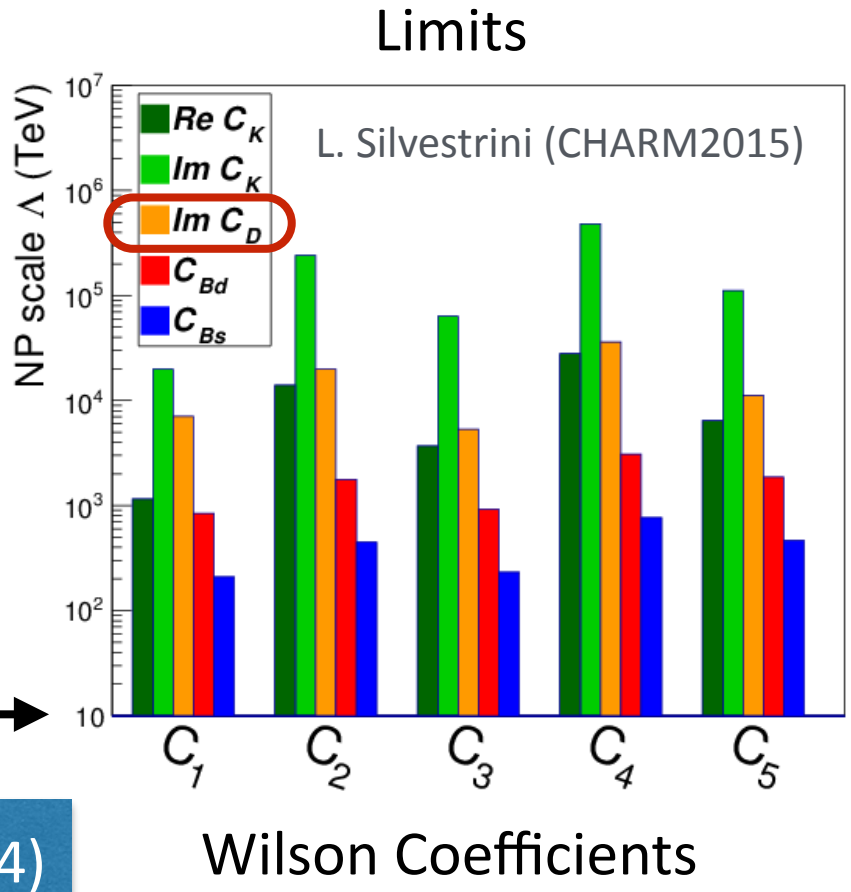
- **Indirect searches probe New Physics scenarios at higher energies than those directly accessible at LHC**
- **Complementary studies to direct searches**
  Scale depends on NP scenario
- **Often anomalies in well-known processes led to discovery**

BR($K^0_L \to \mu^+\mu^-$)

GIM (1970)

Charm Quark (1974)

LHC →



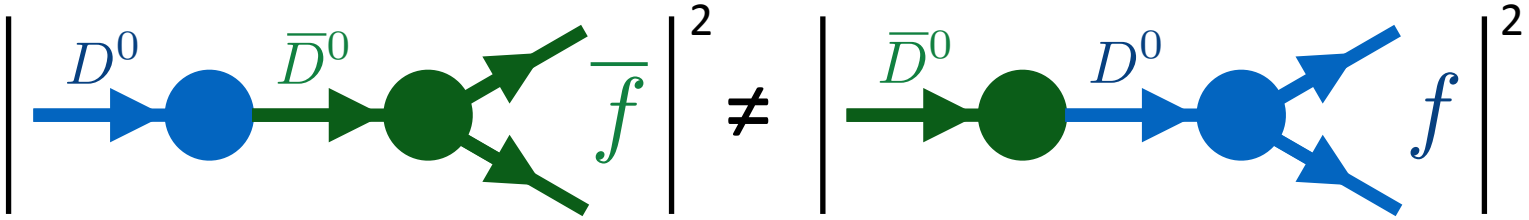
Indirect CP Violation

Mixing and Decay Amplitudes

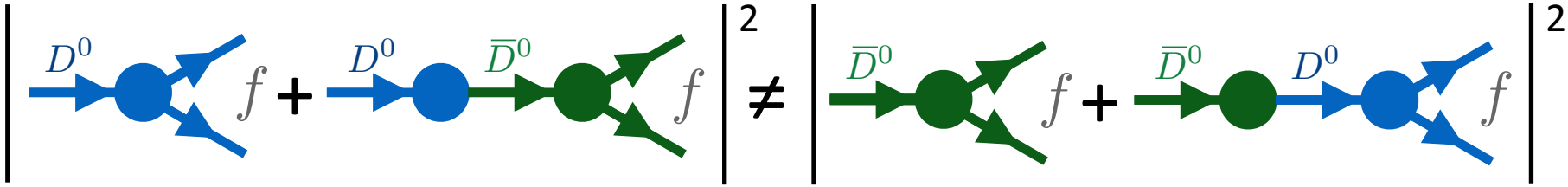
- $D_{1,2}$ mass eigenstates are superposition of D^0 and $\overline{D}^0$ flavour eigenstates
- The study of their oscillations in time provides insights into CPV in mixing
- …and interference between mixing and decay amplitudes

$$|D_1\rangle = p|D^0\rangle - q|\overline{D}^0\rangle$$
$$|D_2\rangle = p|D^0\rangle + q|\overline{D}^0\rangle$$

Mixing

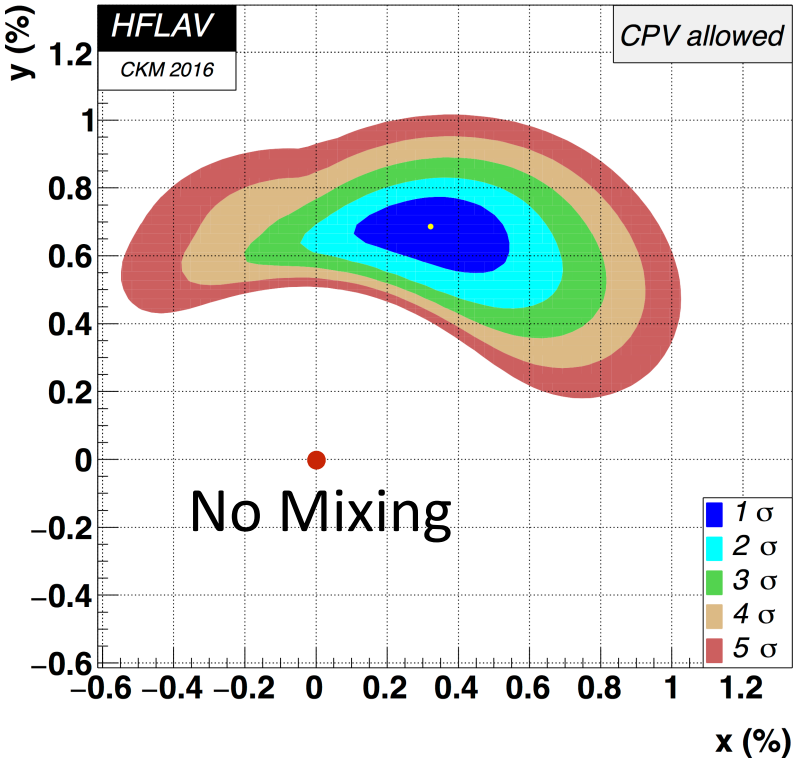


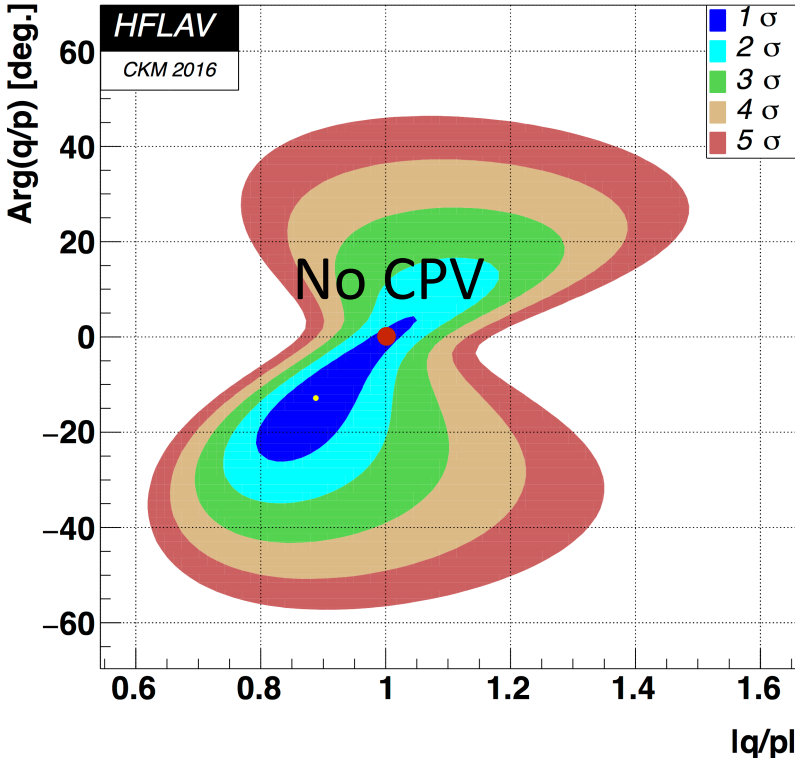
Interference Mixing and Decay



Observables

$$x \equiv \frac{m_1 - m_2}{\Gamma} \qquad y \equiv \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$





Mixing established with >11.5σ

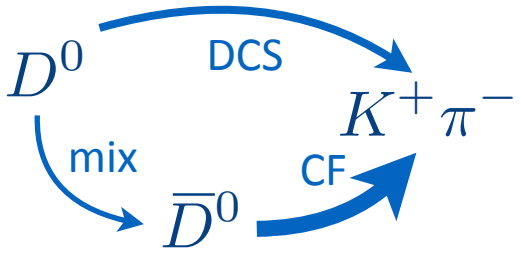
No CPV sign yet!

Wrong Sign Ratio in $D^0 \to K^+\pi^-$ Decays

PHYS. REV. D 97, 031101 (2018)

Charm Mixing Measurement

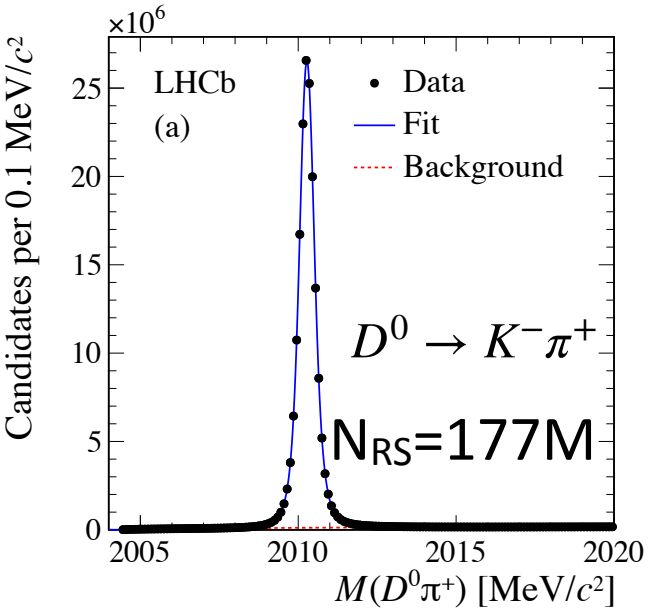
- Mixing parameters are measured separately to D^0 and $\overline{D}^0$ decays
- Any different oscillation pattern between D^0 and $\overline{D}^0$ decays indicates CPV

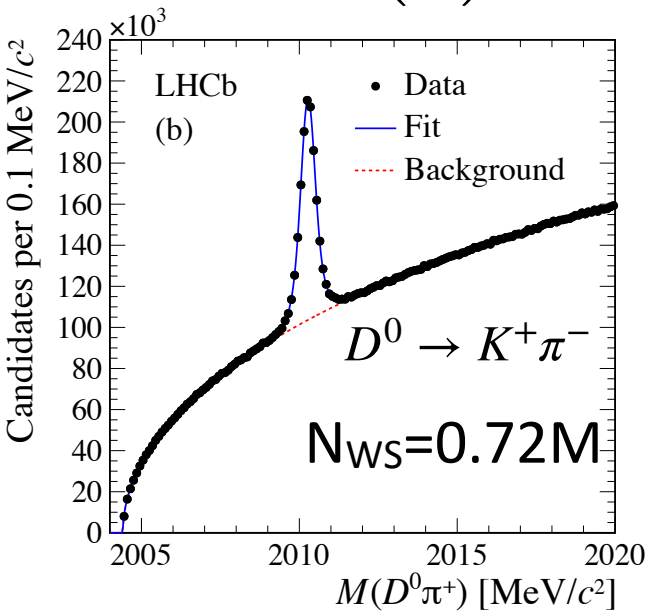


decay *mixing/decay* *mixing*

$$R^{\pm}(t) = \frac{N^{\pm}_{WS}(t)}{N^{\pm}_{RS}(t)} \approx R^{\pm}_D + \sqrt{R^{\pm}_D}\, y'^{\pm}\, \frac{t}{\tau} + \frac{x'^{\pm 2} + y'^{\pm 2}}{4} \left(\frac{t}{\tau}\right)^2$$

- 2011-2016: 5/fb
- $D^{*+} \to D^0\pi^+$
- Cut on D^0 mass, fit Δm
- Measure ratio in intervals of decay time up to $20\tau_{D0}$





Wrong Sign Ratio in $D^0 \to K^+\pi^-$ Decays - Results

Challenges

- **Contamination from D^0 decays from B**
  Bias D^0 lifetime towards higher values
- **Instrumental asymmetries $\epsilon(K^-\pi^+)/\epsilon(K^+\pi^-)$**

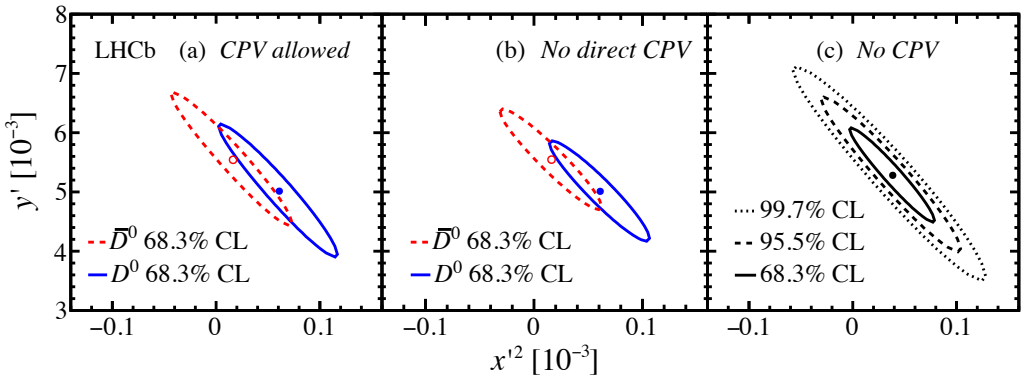
Results

- **No measurable CPV observed**

$$-1.00 < |q/p| < 1.35 \text{ @ } 68.3\% \text{ CL}$$

- **Improved determination of mixing parameter by a factor 2**

$$x'^2 = (3.9 \pm 2.7) \times 10^{-5}$$
$$y' = (5.28 \pm 0.52) \times 10^{-3}$$



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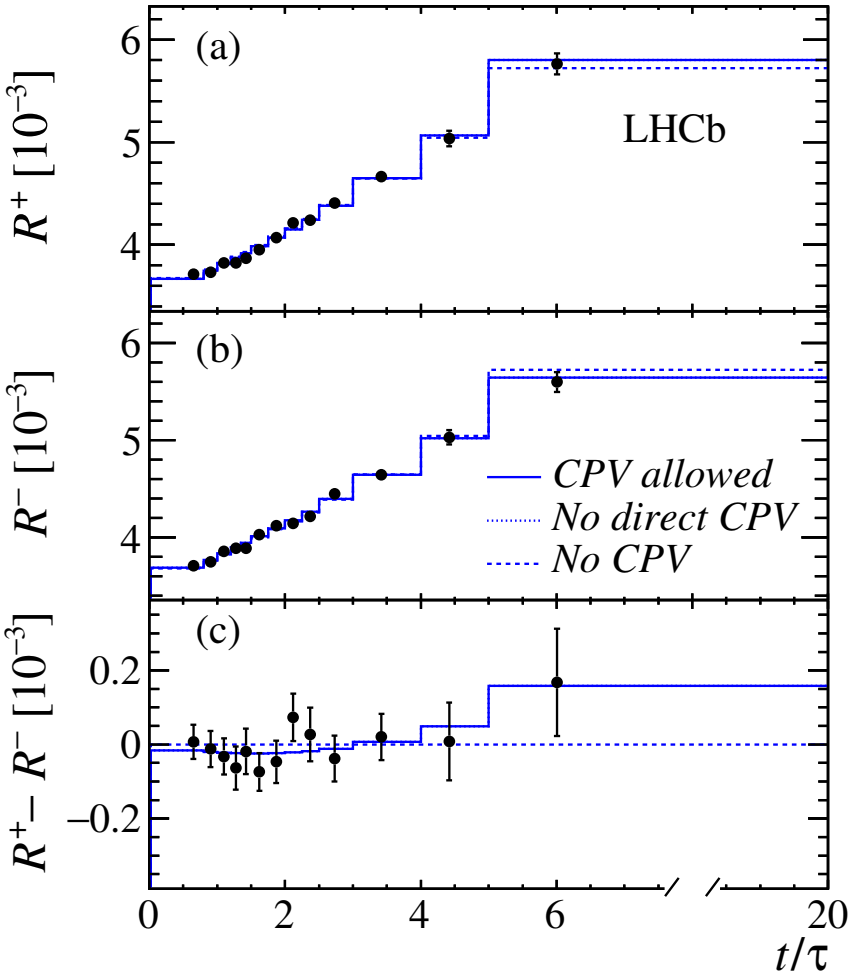
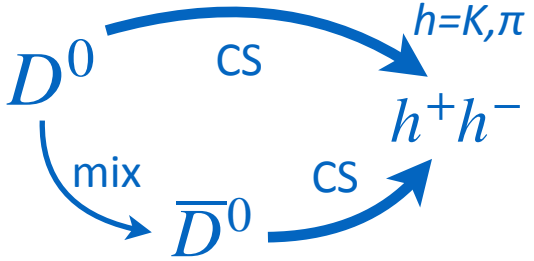


A_Γ with $D^0 \to hh$ decays

PHYS. REV. LETT. 118, 261803 (2017)

CP Violation in Time-Dependent Rate

- **Decay to same CP eigenstate**
  CPV leads to different time-dependent rate between D^0 and $\overline{D}^0$

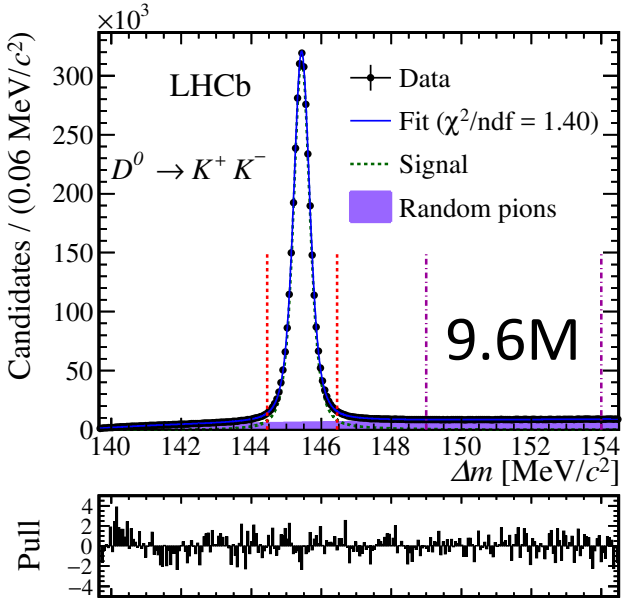


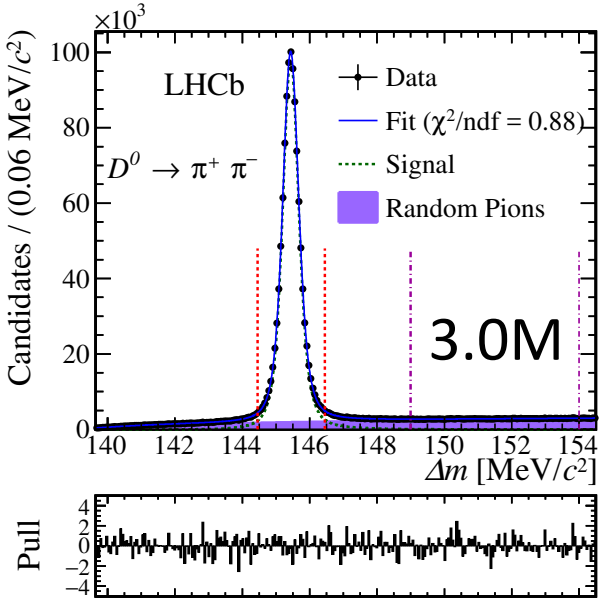
$$A_\Gamma \equiv \frac{\hat{\Gamma}(D^0 \to f) - \hat{\Gamma}(\overline{D}^0 \to f)}{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}(\overline{D}^0 \to f)} \approx \frac{1}{2}\left[\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y \cos\phi_f - \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x \sin\phi_f\right]$$

CPV mixing *CPV mixing/decay*

Dataset

- **Run1 (2011-2012): 3/fb**
- **$D^{*+} \to D^0\pi^+$**
- **Cut on D^0 mass, study Δm**
- **Combinatorial background sideband-subtracted**
- **Measured asymmetry in intervals of decay time $[0.6,20]\tau_{D0}$**





A_Γ with $D^0 \to hh$ decays - Challenges

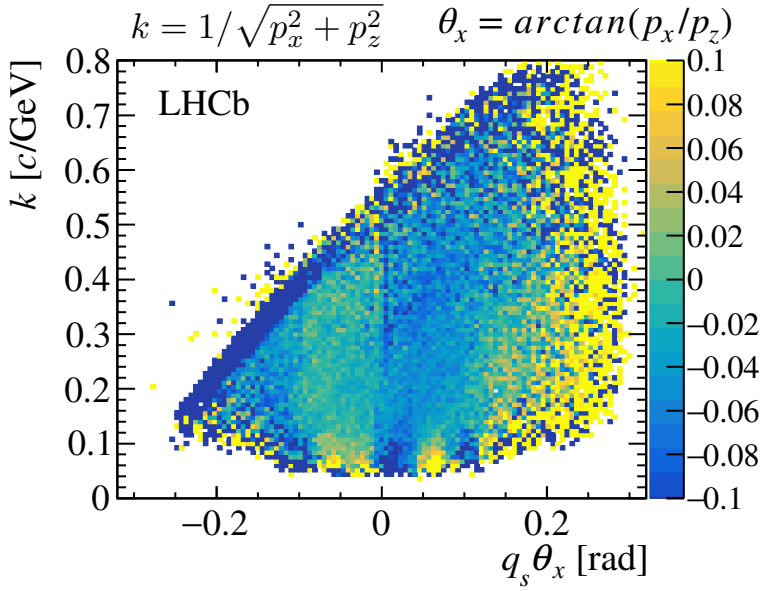
PHYS. REV. LETT. 118, 261803 (2017)

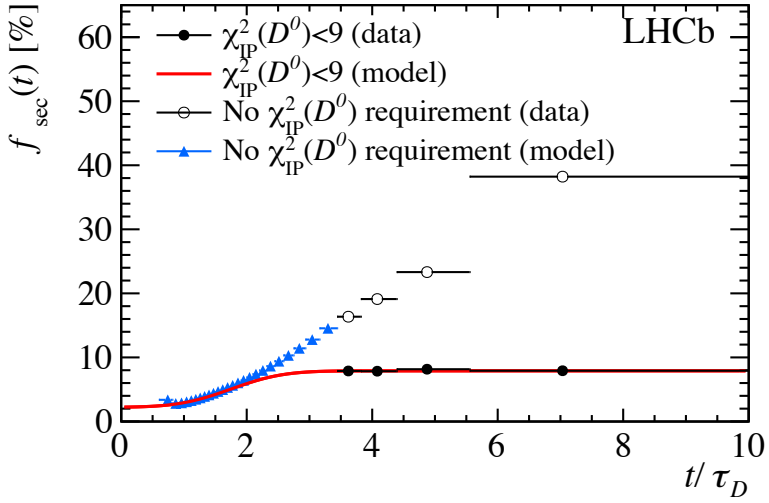
Instrumental Asymmetries

- **Soft pion charge reconstruction asymmetry**
  Time dependent correction due to correlation between soft pion kinematics and D^0 decay time
- **Reweighed the soft pion kinematic to recover left-right asymmetry of the detector**
  Validated on $D^0 \to K^-\pi^+$ decays

D^0 from B decays (Secondaries)

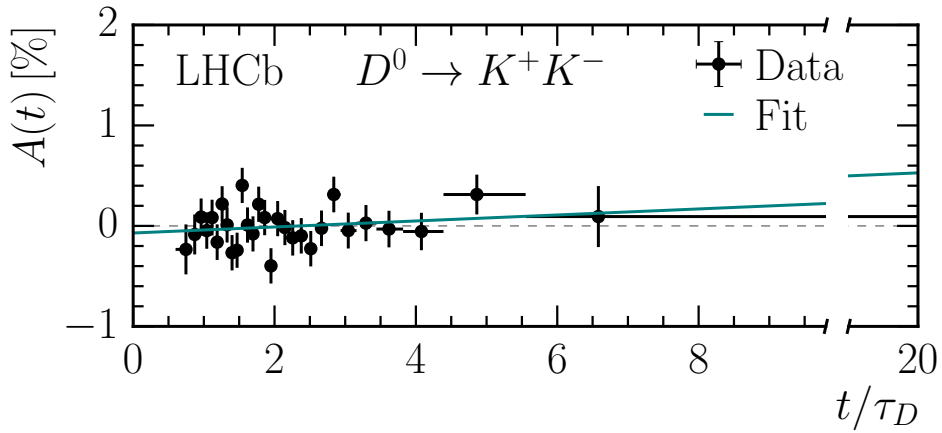
- **Undetected B decays mimic a larger D^0 decay time**
  Dilutes the asymmetry
- **Applied requirement of the D^0 pointing to PV**
  Residual background from B decays estimated with a model calibrated by the yield of secondaries at higher decay time

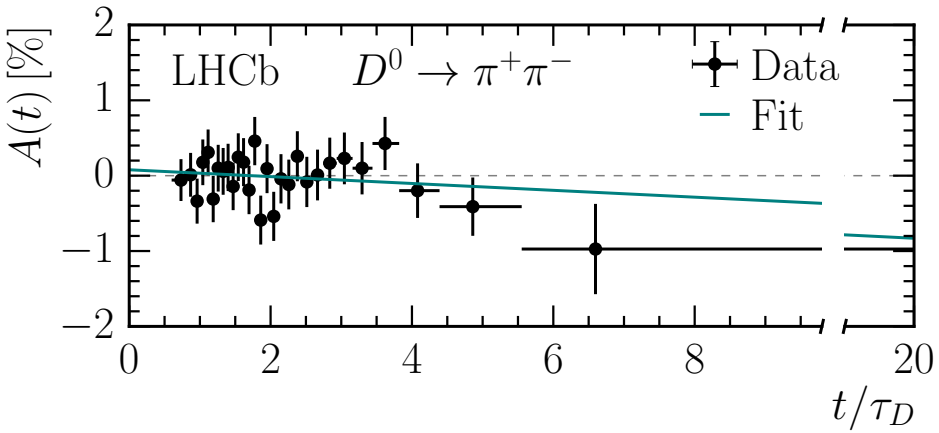




A_Γ with $D^0 \to hh$ decays - Results

PHYS. REV. LETT. 118, 261803 (2017)
JHEP 04 (2015) 043





No CPV

- **Compatible to CP conservation up to 3×10^{-4} sensitivity**

  $A_\Gamma(KK) = (-3.0\pm3.2\pm1.0)\times10^{-4}$

  $A_\Gamma(\pi\pi) = (4.6\pm5.8\pm1.2)\times10^{-4}$

- **A complementary measurement yields compatible results**
  Based on data-driven per-event acceptance calculation

- **Combination with statistically independent muon-tagged sample ($B \to D^0\mu^- X$)**

  $A_\Gamma = (-2.9\pm2.8)\times10^{-4}$

$D^0 \to K^0_S \pi^+ \pi^-$ - The Golden Mode

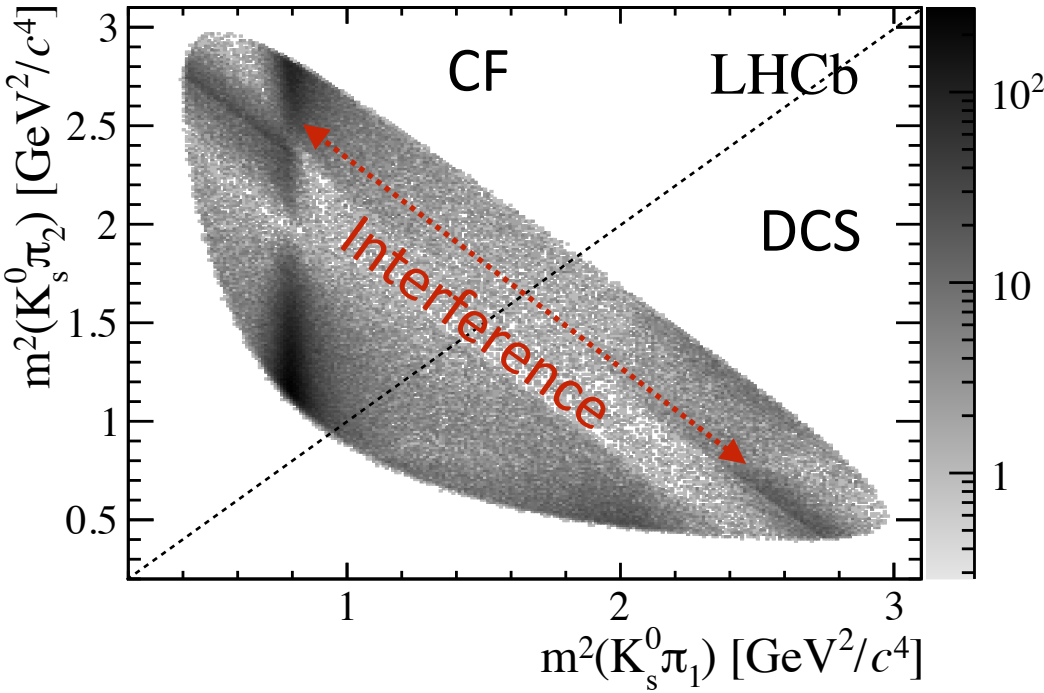
JHEP 04 (2016) 033

Direct Access to Mixing and CP Parameters

- Allows to measure directly x, y, |q/p|, ϕ
- Presence of multiple interfering amplitudes enhances sensitivity to mixing
- Coexistence of CF and DCS suppressed amplitudes in a CP eigenstate

Challenges

- Need a model to describe resonances



$D^0 \to K^0_S \pi^+ \pi^-$ at LHCb

LHCb: JHEP 04 (2016) 033
Belle: PRD 89 (2014) 091103
Babar: PRL 105 (2010) 081803

Semi-Unbinned

- To avoid the complication of performing a time-dependent amplitude analysis, we applied a semi-unbinned approach
- The phase-space is split in regions with slow variation of the strong phase following BaBar's 2008 model
- In each of these the D^0 decay time distribution is studied

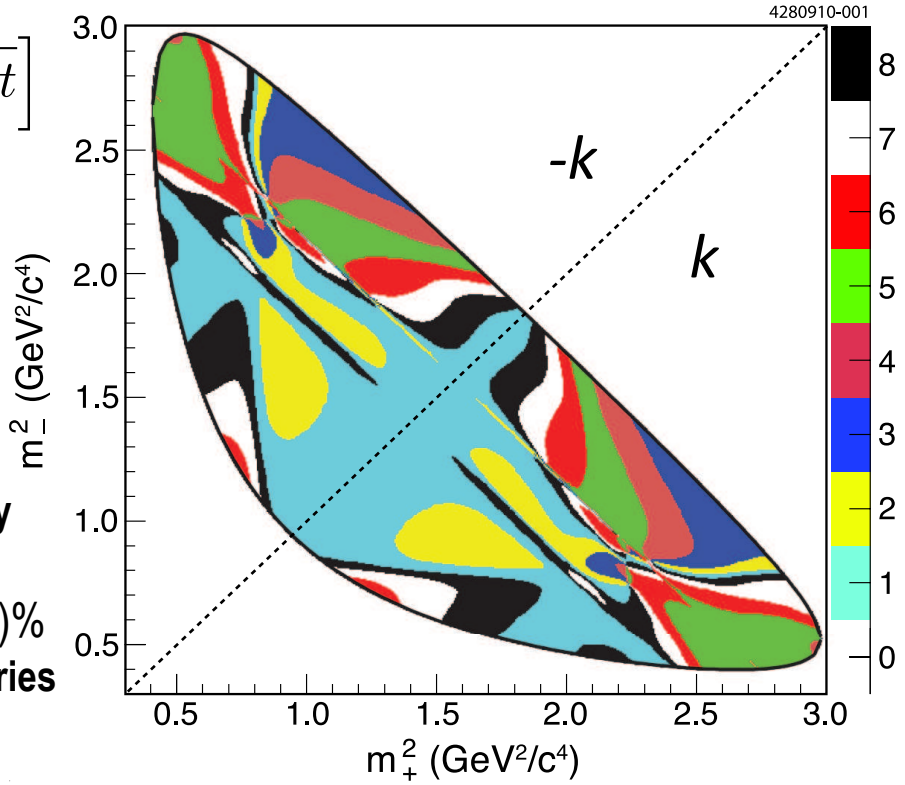
$$\mathcal{P}^k_{D^0} \propto e^{-\Gamma t}\left[T_k - \sqrt{T_k T_{-k}}(y c_k - x s_k)\Gamma t\right]$$

$$T_k = \int_k |\mathcal{A}_{D^0}|^2 d\mathcal{D}$$

$$c_k - i s_k = \frac{1}{\sqrt{T_k T_{-k}}} \int_k \mathcal{A}^*_{D^0}\mathcal{A}_{\bar{D}^0} d\mathcal{D}$$

- T_k, c_k and s_k are hadronic parameters constrained from CLEO [PRD82(2010) 112006]
- First model-independent measurement of x and y with 2011 data (1/fb, N=178k)

  x=(0.86±0.53±0.17)% y=(0.03±0.46±0.13)%
- Compatible, but not yet competitive with B factories
  Their precision is ~0.2%



Interplay Between LHCb and BESIII

https://indico.ihep.ac.cn/event/7249/

Multibody Decays

- Especially in multi body decays, a synergy between LHCb and BESIII could be very advantageous
- BESIII could measure with good precision the variation of the strong phases in the Dalitz plot
- LHCb could use those phases as inputs to perform binned analysis of our data
- Precision is slightly degraded, but avoids the need of performing extremely complex time-dependent Dalitz plot analyses at LHCb
- Notable examples are $D^0 \to K^0_S \pi^+ \pi^-$ and $D^0 \to K^+ \pi^- \pi^+ \pi^-$

LHCb Run2 and Beyond

What to Expect?

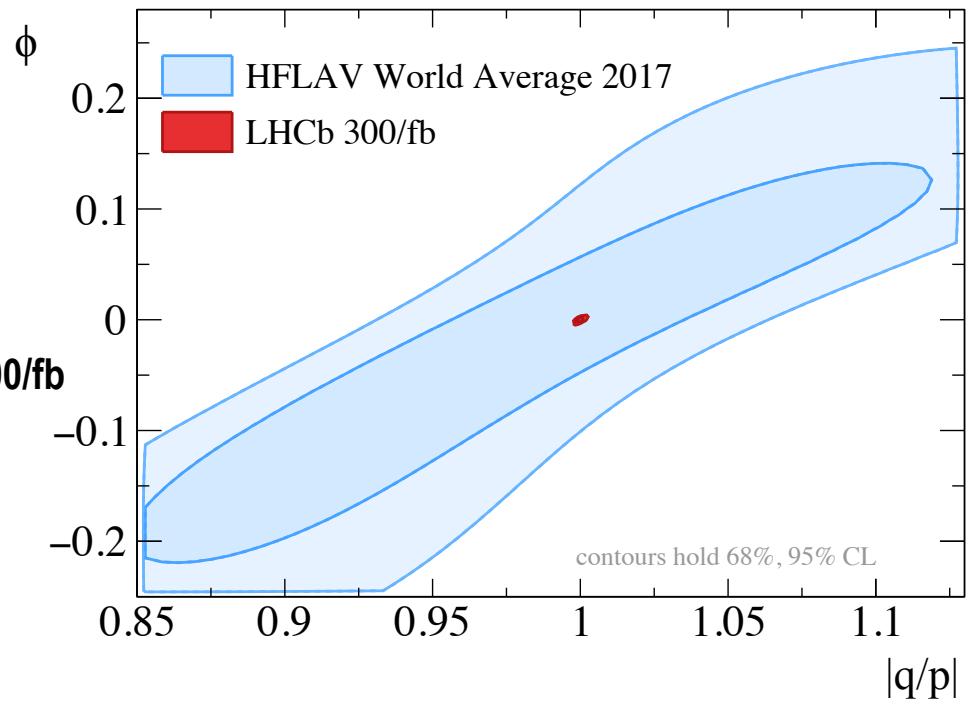
- **We have already started analysing Run2 data and already produced an update for the WS mixing analysis**
- **More analysis are in the pipeline, as we are approaching the 10^{-4} precision on CP observables (A_Γ)**

Upgrade (2020-2023)

- **Will provide a factor 3 larger dataset, very similar to current experiment**
  Analyses strategies should follow what's done in LHCb

Upgrade II (2025-)

- **A LHCb experiment for HL-LHC to collect 300/fb**
- **Ambitious but extremely rewarding**



Conclusions

Mixing

- We have the potential to measure x with Run2 data in $D^0 \to K^0_S \pi^+ \pi^-$

No CPV found yet

- Nevertheless, we are setting the stage for very interesting measurements in the future
- Precision levels approaching the SM predictions (10^{-4})

Future

- Synergy with BESIII
- Will the Upgrade(s) finally provide the answers to our questions?