Mixing and CP violation in charm

Louis Henry (IFIC, University of Valencia-CSIC)
On behalf of the LHCb collaboration
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Outline

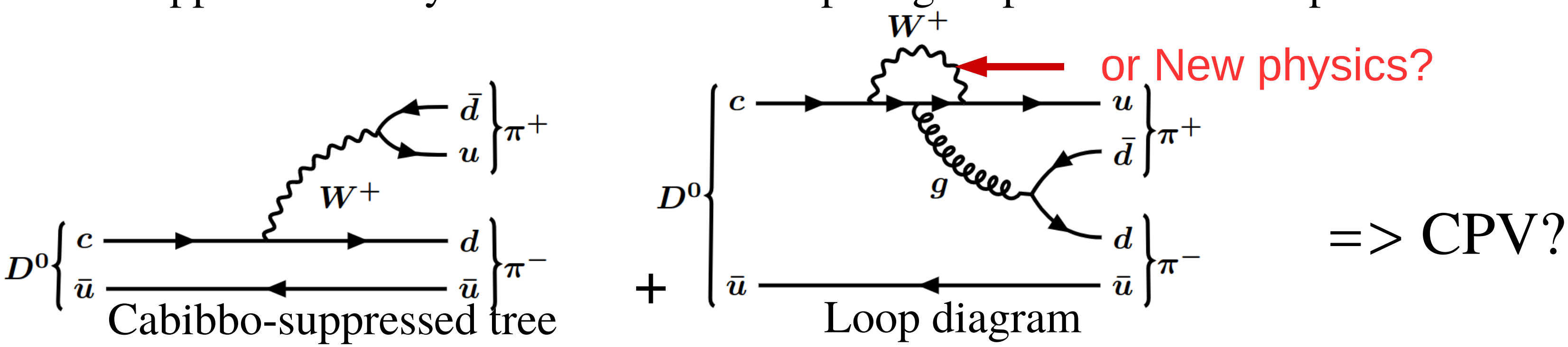
- Introduction

- Recent results
  - A measurement of the CP asymmetry difference in $\Lambda_c^+ \to pK^+K^-$ and $p\pi^+\pi^-$ decays [arxiv:1712.07051]
  - Measurement of CP asymmetries in $D^\pm \to \eta' \pi^\pm$ and $D_s^\pm \to \eta' \pi^\pm$ decays (Phys. Lett. B 771 (2017) 21-30)
  - Updated determination of D^0-$\overline{D}^0$ mixing and *CP* violation parameters with $D^0 \to K^+\pi^-$ decays [arxiv:1712.03220]

- Conclusion

CP violation and mixing in charm decays

- CP violation (CPV) observed in down-quark sector (kaons, $B_{(s)}$ mesons).
  - Leading order for charm in Standard Model is $(1/m_c)$ → non-observation is compatible with expectations.
  - However NP coupling solely to up-type quarks could enhance CPV effects.
- In the Standard Model (SM), no CPV in single amplitude processes.
  - Single-Cabibbo suppressed decays have different competing amplitudes → CPV possible

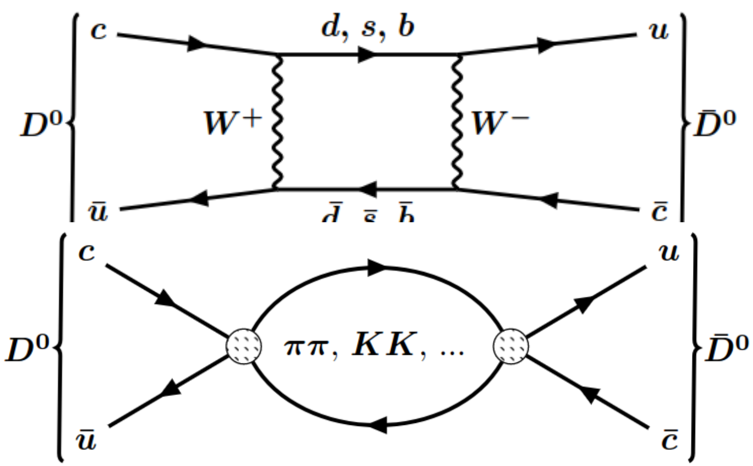


  - No CPV seen in charm as of yet.
- Charm mixing is very small in the SM

$$x = \Delta m/\Gamma, \; y = \Delta\Gamma/2\Gamma$$

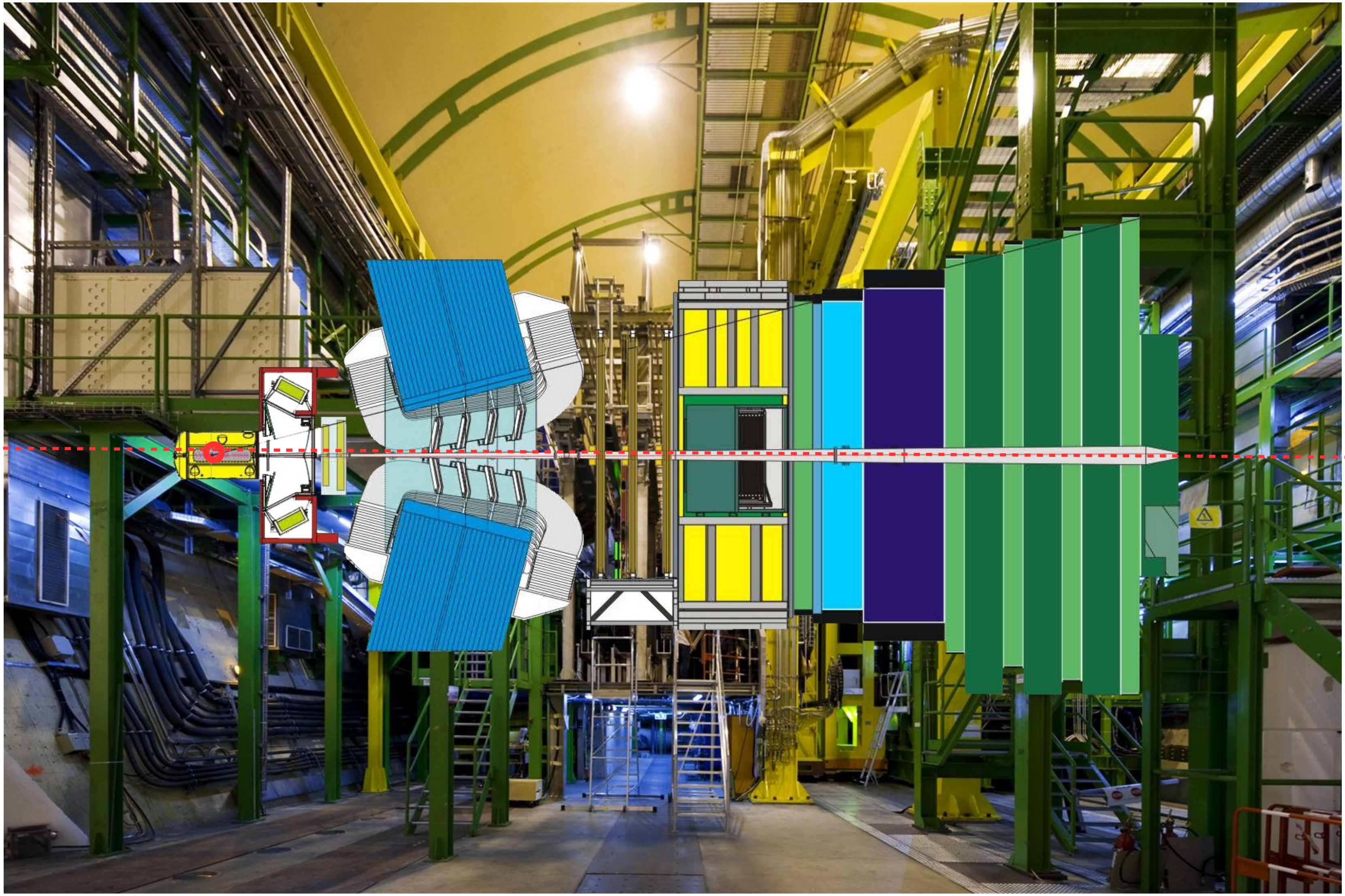
$$x = (4.6^{+1.4}_{-1.5}) \times 10^{-3} \text{ and } y = (6.2 \pm 0.8) \times 10^{-3}$$

arXiv:1612.07233 (Eur. Phys. J. C77 (2017) 895)



The LHCb detector

Beam
pipe



Single-arm forward spectrometer [JINST 3(2008) S08005.]

Recent results on CPV and mixing in charm decays at LHCb

ΔA_{CP} in $\Lambda_c^+ \to pK^+K^-$ and $p\pi^+\pi^-$ decays (Run 1)

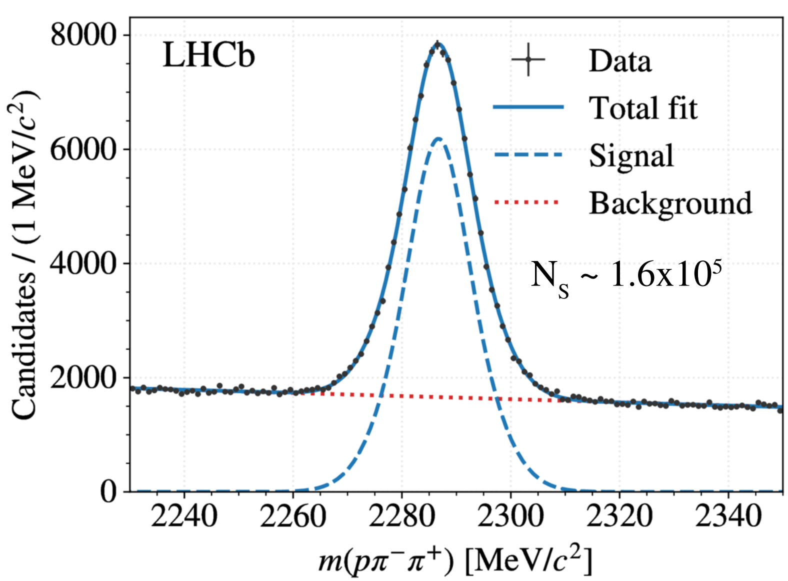
arxiv:1712.07051, submitted to JHEP

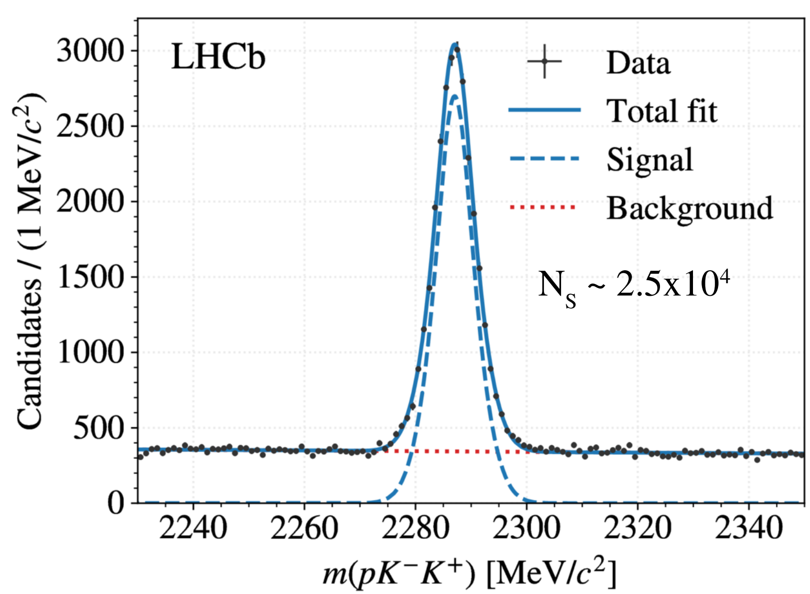
- Both modes are selected as part of the $\Lambda_b^0 \to \Lambda_c^+ \mu^- X$ decay chain.
- We measure A_{raw} as:

$$A_{raw}(f) = \frac{N(f\mu^-) - N(\bar{f}\mu^+)}{N(f\mu^-) + N(\bar{f}\mu^+)}$$ related to A_{CP} by: $A_{raw} = A_{CP} + A_{detection} + A_{production}$

Large source of systematic uncertainties

- Measure A_{raw} for two modes and correct for kinematical differences in order to access to ΔA_{CP}.

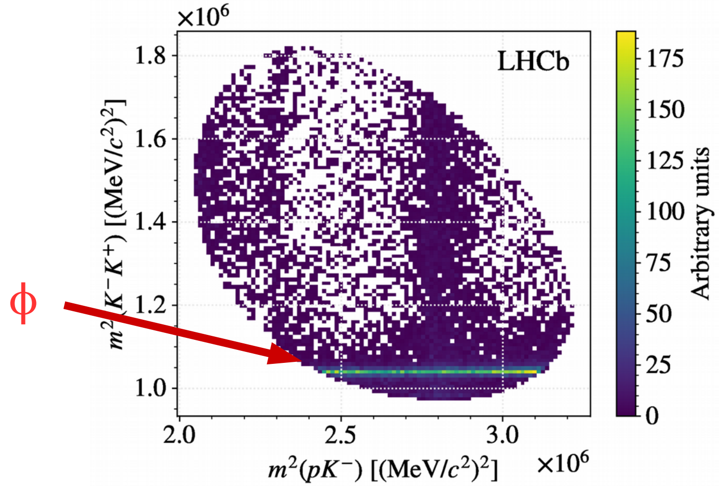


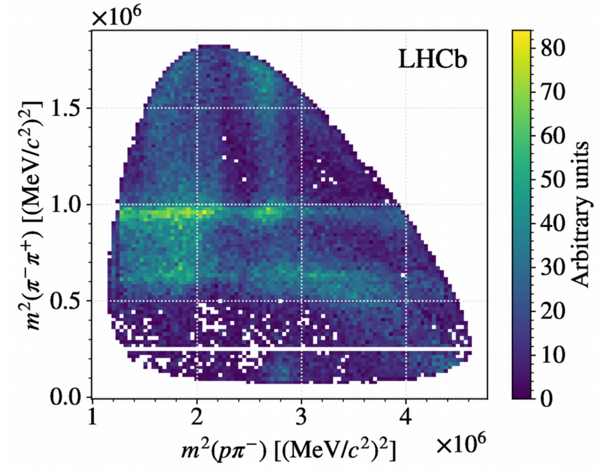


ΔA_{CP} in $\Lambda_c^+ \to pK^+K^-$ and $p\pi^+\pi^-$ decays (Run 1)

arxiv:1712.07051, submitted to JHEP

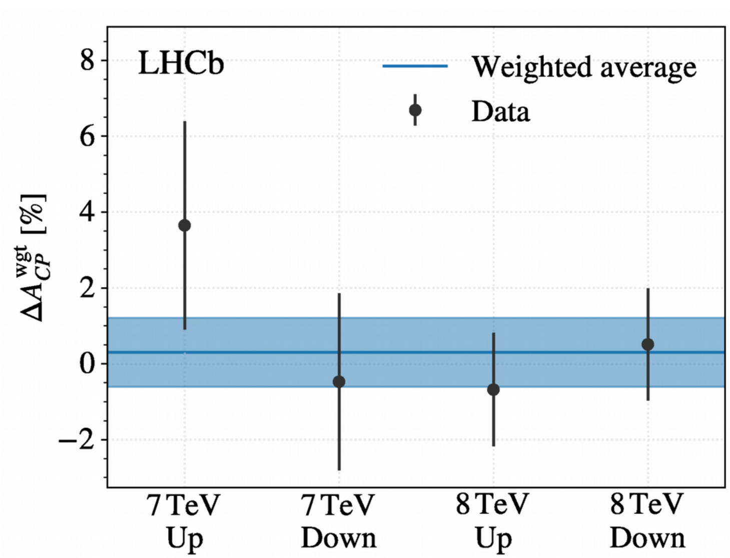
- 5-D efficiencv and kinematic differences taken into account.





- Main systematics arise from the size of the simulated samples but measurement is statistically limited.

Source	Uncertainty [%]
Fit signal model	0.20
Fit background model	—
Residual asymmetries	0.10
Limited simulated sample size	0.57
Prompt Λ_c^+	—
Total	0.61



$A_{raw}(pK^+K^-)$	$(3.72 \pm 0.78)\%$
$A_{raw}(p\pi^+\pi^-)$	$(3.42 \pm 0.47)\%$
ΔA_{CP}	$(0.30 \pm 0.91 \pm 0.61)\%$

First measurement of CPV parameter in 3-body Λ_c^+ decays!

CPV in $D^{\pm} \to \eta' \pi^{\pm}$ and $D_s^{\pm} \to \eta' \pi^{\pm}$ decays (Run 1)

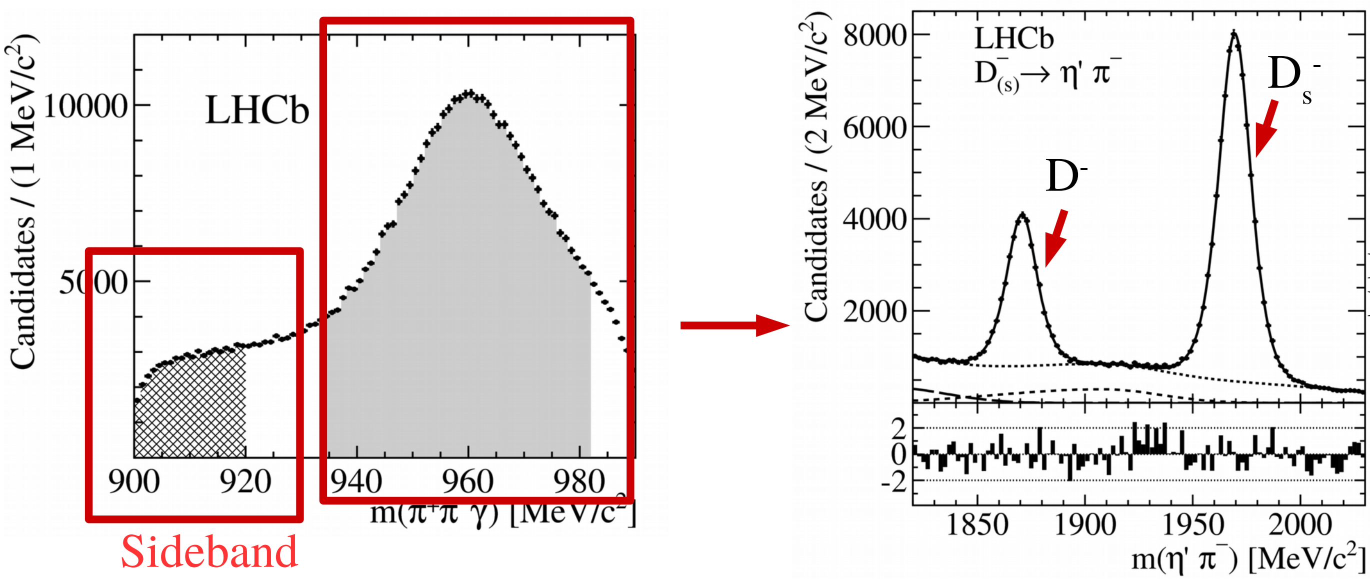
Phys. Lett. B 771 (2017) 21-30

- We measure the difference in A_{CP} between the studied modes and modes where A_{CP} is already measured precisely.

$$\Delta\mathcal{A}_{CP}(D^{\pm} \to \eta'\pi^{\pm}) \equiv \mathcal{A}_{CP}(D^{\pm} \to \eta'\pi^{\pm}) - \mathcal{A}_{CP}(D^{\pm} \to K_S^0\pi^{\pm})$$
$$= \mathcal{A}_{\rm raw}(D^{\pm} \to \eta'\pi^{\pm}) - \mathcal{A}_{\rm raw}(D^{\pm} \to K_S^0\pi^{\pm}) + \mathcal{A}(\overline{K}^0 - K^0),$$
$$\Delta\mathcal{A}_{CP}(D_s^{\pm} \to \eta'\pi^{\pm}) \equiv \mathcal{A}_{CP}(D_s^{\pm} \to \eta'\pi^{\pm}) - \mathcal{A}_{CP}(D_s^{\pm} \to \phi\pi^{\pm})$$
$$= \mathcal{A}_{\rm raw}(D_s^{\pm} \to \eta'\pi^{\pm}) - \mathcal{A}_{\rm raw}(D_s^{\pm} \to \phi\pi^{\pm}).$$

$\eta' \to \pi^+\pi^-\gamma$
$\varphi \to K^+K^-$
$K_s^0 \to \pi^+\pi^-$

- Three different trigger requirements:
  - Energy deposit in hadronic calorimeter from decay particle (T1)
  - Energy deposit in hadronic calorimeter from unrelated particle (T2)
  - Energy deposit in electromagnetic calorimeter or high-pT muon from unrelated particle (T3).

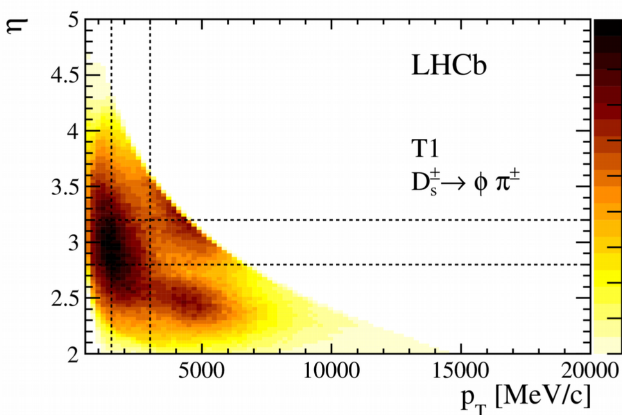


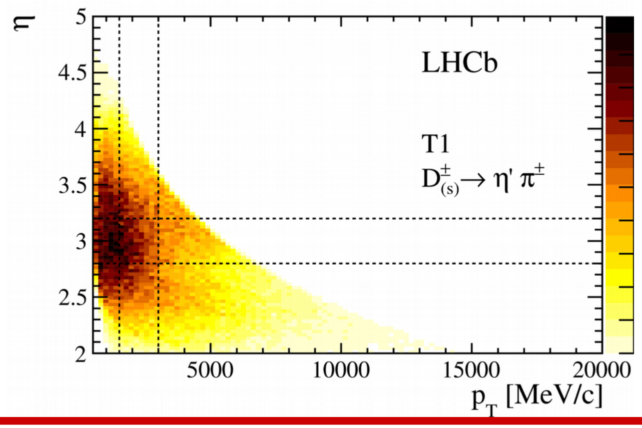
$N(D) \sim 6.3 \times 10^4$ candidates
$N(D_s) \sim 1.5 \times 10^5$ candidates

CPV in $D^\pm \to \eta' \pi^\pm$ and $D_s^\pm \to \eta' \pi^\pm$ decays (Run 1)

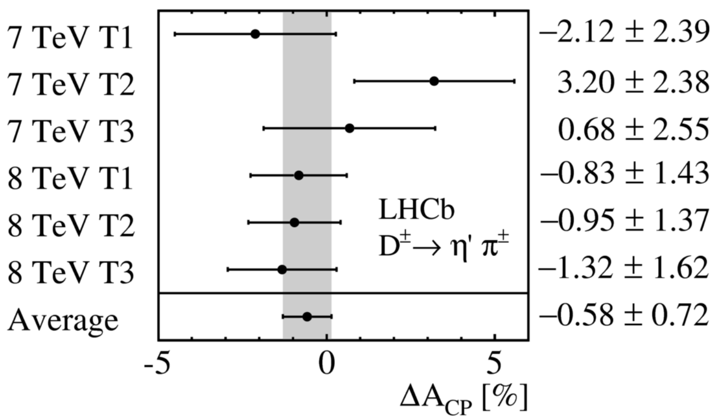
Phys. Lett. B 771 (2017) 21-30

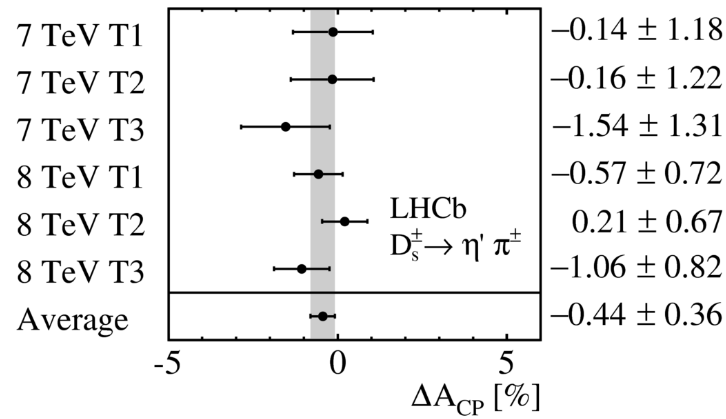
- Fits are performed in nine bins of (p_T-η), then A_{raw} are combined using a weighted average.





Source	$\delta[\Delta\mathcal{A}_{CP}(D^\pm)]$	$\delta[\Delta\mathcal{A}_{CP}(D_s^\pm)]$
Non-prompt charm	0.03	0.03
Trigger	0.09	0.09
Background model	0.50	0.19
Fit procedure	0.08	0.04
Sideband subtraction	0.03	0.02
K^0 asymmetry	0.08	–
$\pi^\pm$ detection asymmetry	0.06	0.01
$D_{(s)}^\pm$ production asymmetry	0.07	0.02
Total	0.53	0.22





Consistent measurements through data-taking conditions and trigger requirements.

$$\Delta\mathcal{A}_{CP}(D^\pm \to \eta'\pi^\pm) = (-0.58 \pm 0.72 \pm 0.53)\%,$$
$$\Delta\mathcal{A}_{CP}(D_s^\pm \to \eta'\pi^\pm) = (-0.44 \pm 0.36 \pm 0.22)\%.$$

→

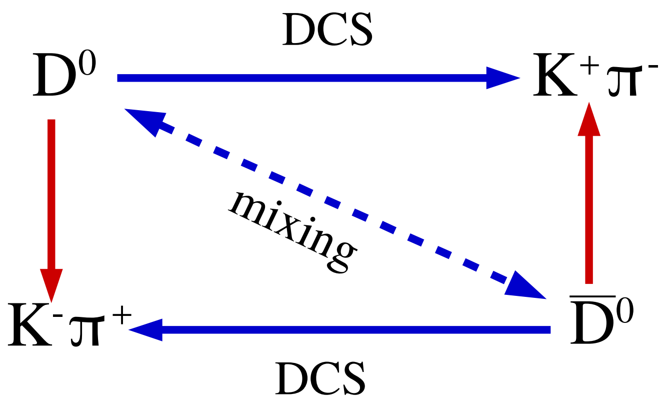
$$\mathcal{A}_{CP}(D^\pm \to \eta'\pi^\pm) = (-0.61 \pm 0.72 \pm 0.53 \pm 0.12)\%,$$
$$\mathcal{A}_{CP}(D_s^\pm \to \eta'\pi^\pm) = (-0.82 \pm 0.36 \pm 0.22 \pm 0.27)\%,$$

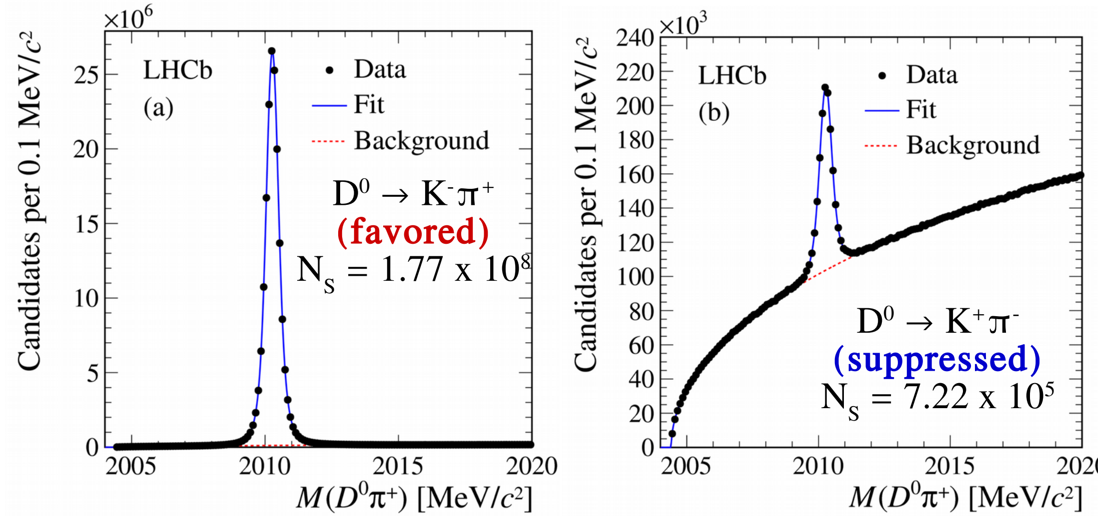
Most precise measurement to date

Charm mixing and CPV with $D^0 \to K^\pm \pi^\mp$ decays

arxiv:1712.03220, submitted to PRD

- D^0 decay to $K^+\pi^-$ is doubly Cabibbo-suppressed (DCS) → interfere with $D^0 \to \overline{D}^0$ mixing.





- Analysis on Run 1 + 2015 + 2016
- D^0 flavor tagged at production by using D^0 from $D^{*\pm}$
- Ratio of suppressed-to-favored decay rates approximated as:

$$R^{\pm}(t) = R_D^{\pm} + \sqrt{R_D^{\pm}}\, y'^{\pm} t + \frac{(x'^{\pm})^2 + (y'^{\pm})^2}{4}\, t^2,$$

+(-) refers to the decay from a D^0 ($\overline{D}^0$).
x' = xcos(δ) + ysin(δ), **y'** = ycos(δ) - xsin(δ),
δ: strong-phase difference between the suppressed and favored amplitudes (CLEO-c, BESIII)
(Phys. Rev. D86 (2012) 112001, Phys. Lett. B734 (2014) 227)

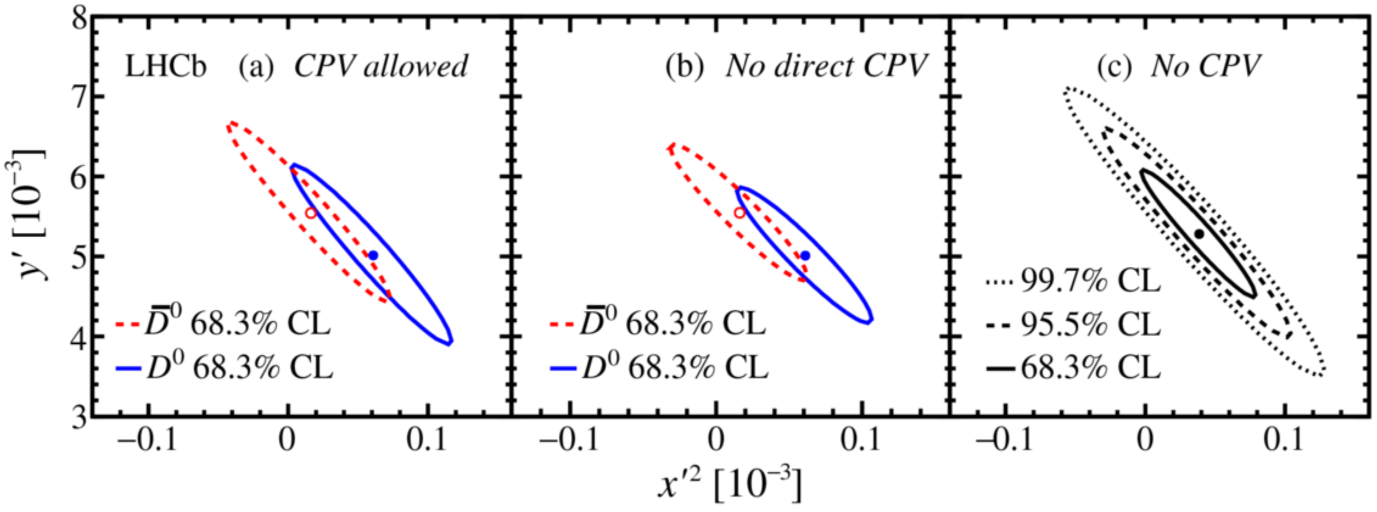
CPV if and only if $(x',y',R_D)^\pm$ are different.

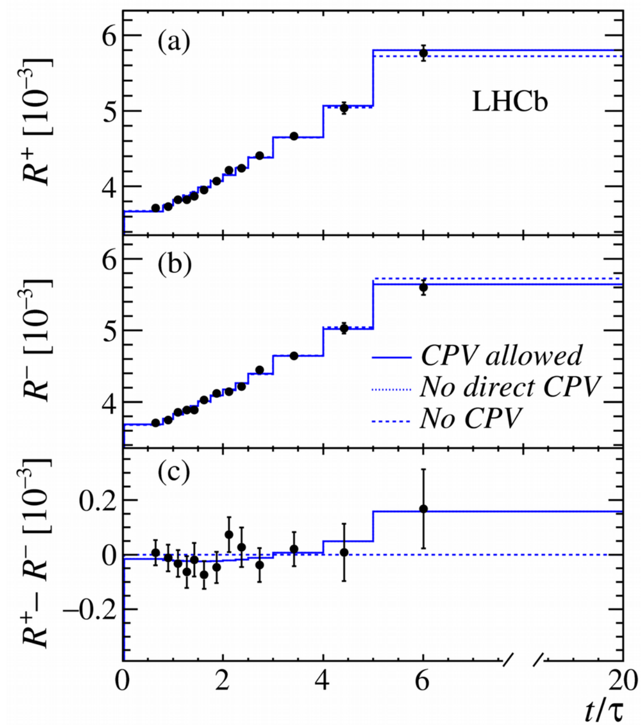
"Indirect" CPV **"Direct" CPV**

Charm mixing and CPV with $D^0 \to K^\pm \pi^\mp$ decays

arxiv:1712.03220, submitted to PRD

- Separated in 13 bins of lifetime.





- Statistical uncertainty dominates, main sources of systematic uncertainties are residual D^{*+} from B mesons and spurious soft pions → statistical in nature.

$$x'^2 = (3.9 \pm 2.7)\times 10^{-5}\ ,\ y' = (5.28 \pm 0.52)\times 10^{-3}$$
$$R_D = (3.454 \pm 0.031)\times 10^{-3}$$
$$A_D = (-0.1 \pm 9.1) \times 10^{-3} \text{ and } 1.00 < |q/p| < 1.35$$

Twice as precise as previous LHCb measurement (Phys. Rev. Lett. 111 (2013))
Most stringent limits to date on charm CPV

Conclusion and prospects

- A lot of activity in Charm physics in LHCb.
  - Could not present all of the recent results, for instance:
  - Measurement of CP asymmetry in $D^0 \to K^+K^-$ decays (Phys. Lett. B 767 (2017), 177-187)
  - Measurement of the CP violation parameter A_Γ in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays (Phys. Rev. Lett. 118, 261803 (2017))
  - Search for CP violation in the phase space of $D^0 \to \pi^+\pi^-\pi^+\pi^-$ decays (Phys. Lett. B 769 (2017) 345-356)
- Wealth of experience from Run 1 analyses → fast and improved analyses.
- Analysis of Run 2 data directly on trigger output! ("turbo" trigger).
- Systematic use of control modes, consistency checks and difference of observables allow to keep systematic uncertainties under control.

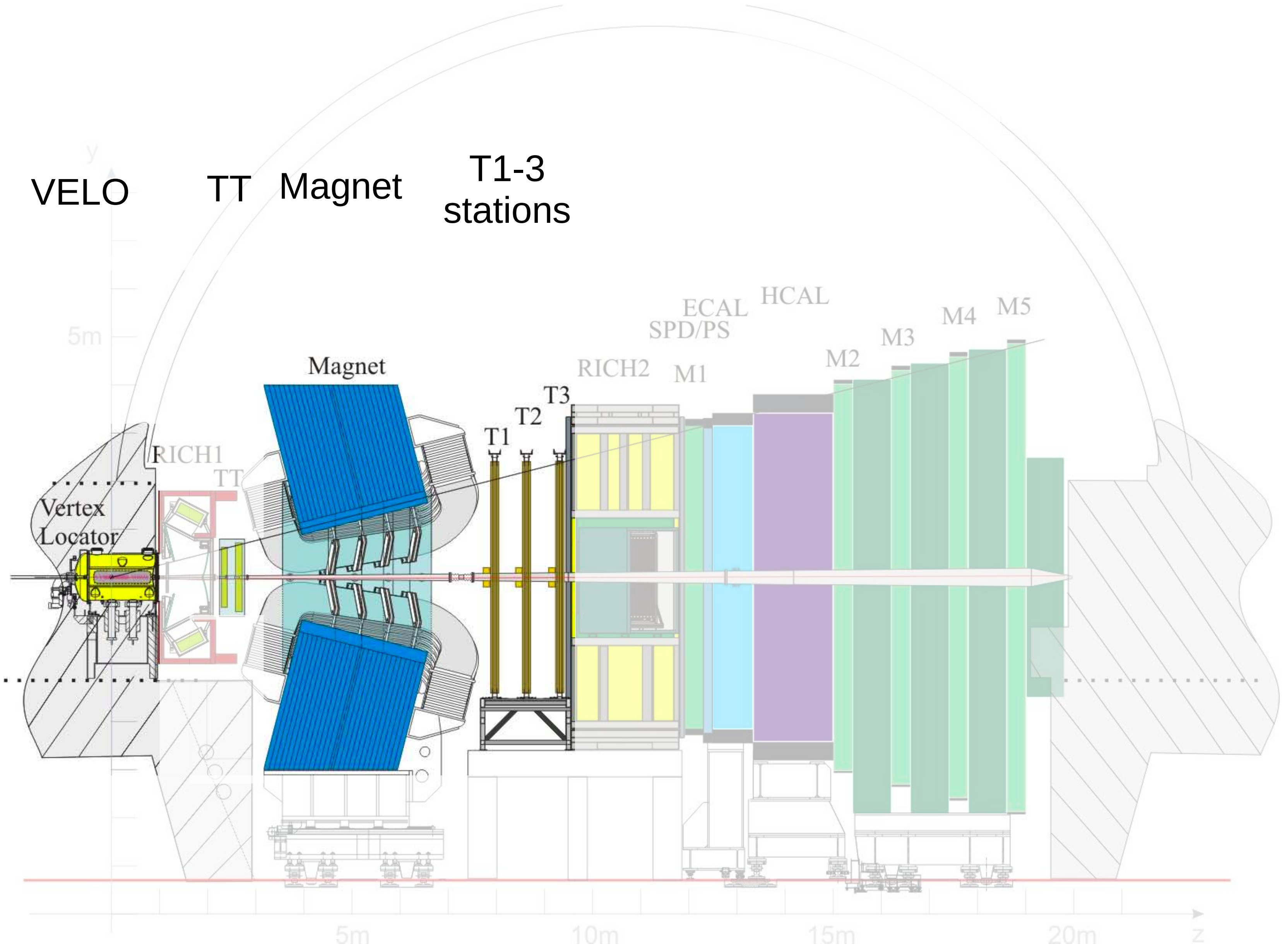
  → Despite often huge datasets (order 10^5-10^7 signal candidates), presented measurements are all statistically limited.

Stay tuned!

Thank you!

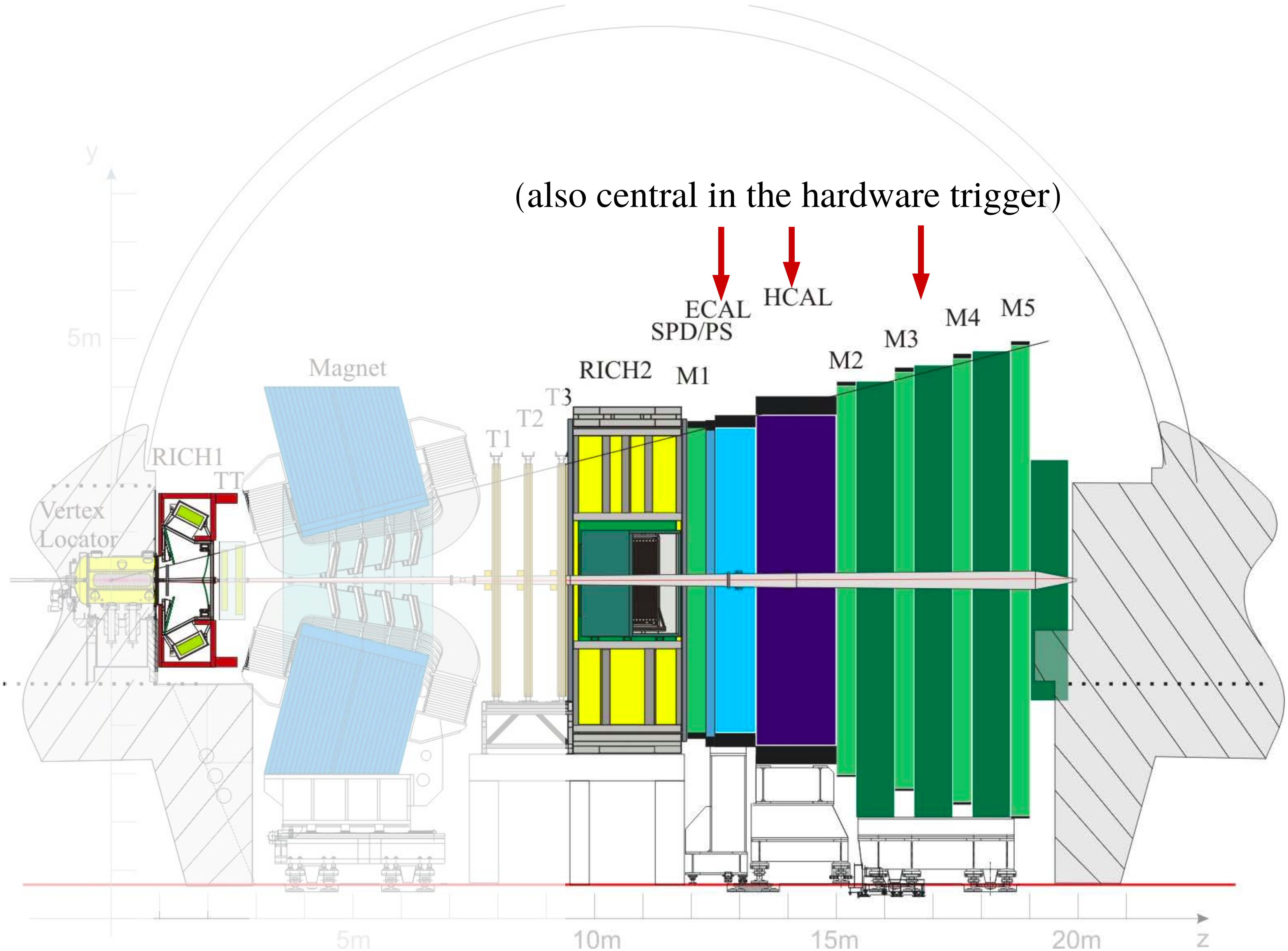
The LHCb detector

The LHCb detector: tracking subsystems

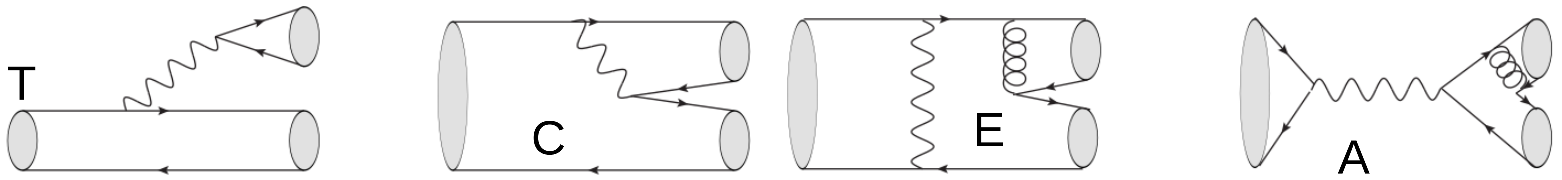


The LHCb detector: particle identification

(also central in the hardware trigger)



CPV in $D^{\pm}\to\eta'\pi^{\pm}$ and $D_s^{\pm}\to\eta'\pi^{\pm}$ decays (Run 1)

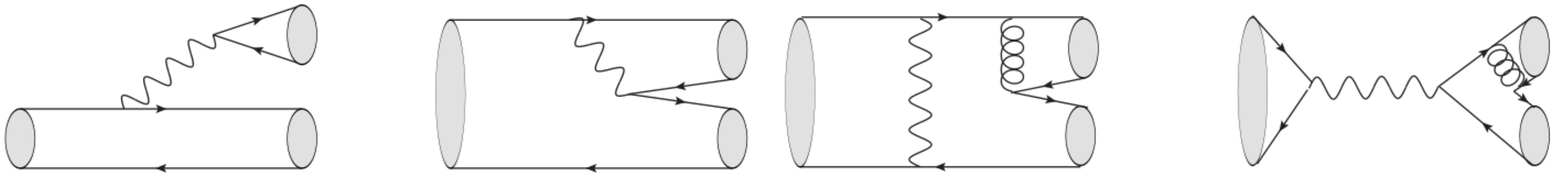


- Eta or eta': 30% of the BR
- CPV expected at the < 1% level.
- Tree-level:

  (phi: eta-eta' mixing = -11°)

- $D_s^+ \to \eta\pi^+$ (CF): $V_{cs}^* V_{ud}(\sqrt{2}A\cos\phi - T\sin\phi)$;
- $D_s^+ \to \eta'\pi^+$ (CF): $V_{cs}^* V_{ud}(\sqrt{2}A\sin\phi + T\cos\phi)$;
- $D^+ \to \eta\pi^+$ (SCS): $\frac{1}{\sqrt{2}} V_{cd}^* V_{ud}(T' + C' + 2A')\cos\phi - V_{cs}^* V_{us} C'\sin\phi$;
- $D^+ \to \eta'\pi^+$ (SCS): $\frac{1}{\sqrt{2}} V_{cd}^* V_{ud}(T' + C' + 2A')\sin\phi + V_{cs}^* V_{us} C'\cos\phi$;
- $D_s^+ \to \eta K^+$ (SCS): $V_{cs}^* V_{us}[\frac{1}{\sqrt{2}}A''\cos\phi - (T'' + C'' + A'')\sin\phi] + \frac{V_{cd}^* V_{ud}}{\sqrt{2}}C''\cos\phi$;
- $D_s^+ \to \eta' K^+$ (SCS): $V_{cs}^* V_{us}[\frac{1}{\sqrt{2}}A''\cos\phi + (T'' + C'' + A'')\sin\phi] + \frac{V_{cd}^* V_{ud}}{\sqrt{2}}C''\cos\phi$;
- $D^+ \to \eta K^+$ (DCS): $V_{cd}^* V_{us}[\frac{1}{\sqrt{2}}(T''' + A''')\cos\phi - A'''\sin\phi]$;
- $D^+ \to \eta' K^+$ (DCS): $V_{cd}^* V_{us}[\frac{1}{\sqrt{2}}(T''' + A''')\sin\phi + A'''\cos\phi]$;

CPV in $D^{\pm}\to\eta'\pi^{\pm}$ and $D_s^{\pm}\to\eta'\pi^{\pm}$ decays (Run 1)



- Signal form: Johnson distributions, tails shared between signals and (p_T-eta) bins

$$f(x;\mu,\sigma,\delta,\gamma) \propto \left[1+\left(\frac{x-\mu}{\sigma}\right)^2\right]^{-\frac{1}{2}} \exp\left\{-\frac{1}{2}\left[\gamma+\delta\sinh^{-1}\left(\frac{x-\mu}{\sigma}\right)\right]^2\right\}.$$

- Background: 4th order polynomial with parameters Gaussian-constrained by sideband fit.
- Peaking backgrounds: all suppressed except $D_s \to \phi(\to\pi^+\pi^-\pi^0)\pi$, A_{CP} from control sample.
- ACP computed as inverse-variance weighted average over the (p_T-eta) bins.
- Dominant systematic: background model.
  - Background → second-order polynomial, ARGUS
  - Fix parameters from sideband, change peaking background contribution
  - Neglected contributions, signal leaking in sidebands, remaining nonresonant (K^+K^-) in control sample
  - Independently assessed by lifting constraints and observing increase of statistical uncertainty.

Charm mixing and CPV with $D^0 \to K^{\pm}\pi^{\mp}$ decays: systematics

No *CP* violation			
Source	R_D $[10^{-3}]$	y' $[10^{-3}]$	x'^2 $[10^{-3}]$
Instrumental asymm.	< 0.001	< 0.01	< 0.001
Peaking background	± 0.003	± 0.04	± 0.002
Secondary D decays	± 0.010	± 0.21	± 0.011
Ghost soft pions	± 0.008	± 0.15	± 0.008
Total syst. uncertainty	± 0.014	± 0.27	± 0.014
Statistical uncertainty	± 0.028	± 0.45	± 0.023

No direct *CP* violation					
Source	R_D $[10^{-3}]$	y'^{+} $[10^{-3}]$	y'^{-} $[10^{-3}]$	x'^{2+} $[10^{-3}]$	x'^{2-} $[10^{-3}]$
Instrumental asymm.	< 0.001	± 0.08	± 0.08	± 0.003	± 0.004
Peaking background	± 0.003	± 0.04	± 0.04	± 0.002	± 0.002
Secondary D decays	± 0.010	± 0.21	± 0.21	± 0.011	± 0.012
Ghost soft pions	± 0.008	± 0.16	± 0.16	± 0.009	± 0.009
Total syst. uncertainty	± 0.014	± 0.29	± 0.29	± 0.016	± 0.016
Statistical uncertainty	± 0.028	± 0.48	± 0.48	± 0.026	± 0.026

Direct and indirect *CP* violation						
Source	R_D^{+} $[10^{-3}]$	R_D^{-} $[10^{-3}]$	y'^{+} $[10^{-3}]$	y'^{-} $[10^{-3}]$	x'^{2+} $[10^{-3}]$	x'^{2-} $[10^{-3}]$
Instrumental asymm.	± 0.006	± 0.006	± 0.04	± 0.03	± 0.002	± 0.001
Peaking background	± 0.003	± 0.003	± 0.04	± 0.04	± 0.002	± 0.002
Secondary D decays	± 0.014	± 0.014	± 0.29	± 0.29	± 0.015	± 0.015
Ghost soft pions	± 0.012	± 0.012	± 0.21	± 0.21	± 0.011	± 0.011
Total syst. uncertainty	± 0.020	± 0.020	± 0.38	± 0.38	± 0.019	± 0.020
Statistical uncertainty	± 0.040	± 0.040	± 0.64	± 0.64	± 0.032	± 0.033

Master formula

- What do we mean when we say that "asymmetries are small"?

$$A_{CP}^{\mathrm{Raw}}(f) = \frac{\mathcal{P}(\Lambda_b^0)\epsilon(\mu^-)\epsilon(f)\Gamma(f) - \mathcal{P}(\overline{\Lambda}_b^0)\epsilon(\mu^+)\epsilon(\bar{f})\Gamma(\bar{f})}{\mathcal{P}(\Lambda_b^0)\epsilon(\mu^-)\epsilon(f)\Gamma(f) + \mathcal{P}(\overline{\Lambda}_b^0)\epsilon(\mu^+)\epsilon(\bar{f})\Gamma(\bar{f})},$$

$$A_P^{\Lambda_b^0}(f) = \frac{\mathcal{P}(\Lambda_b^0) - \mathcal{P}(\overline{\Lambda}_b^0)}{\mathcal{P}(\Lambda_b^0) + \mathcal{P}(\overline{\Lambda}_b^0)},$$

$$A_D^{\mu}(f) = \frac{\epsilon(\mu^-) - \epsilon(\mu^+)}{\epsilon(\mu^-) + \epsilon(\mu^+)},$$

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

, using

$$x = \frac{1}{2}(x+y)(1+X),$$

$$y = \frac{1}{2}(x+y)(1-X).$$

$$A_{CP}^{\mathrm{Raw}}(f) = \frac{A_P^{\Lambda_b^0}A_D^{\mu}A_D^{f} + A_P^{\Lambda_b^0}A_D^{\mu}A_{CP} + A_P^{\Lambda_b^0}A_D^{f}A_{CP} + A_D^{\mu}A_D^{f}A_{CP} + A_P^{\Lambda_b^0} + A_D^{\mu} + A_D^{f} + A_{CP}}{1 + A_P^{\Lambda_b^0}A_D^{\mu} + A_P^{\Lambda_b^0}A_D^{f} + A_P^{\Lambda_b^0}A_{CP} + A_D^{\mu}A_D^{f} + A_D^{\mu}A_{CP} + A_D^{f}A_{CP} + A_P^{\Lambda_b^0}A_D^{\mu}A_D^{f}A_{CP}}.$$