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Charm Physics with LHCb

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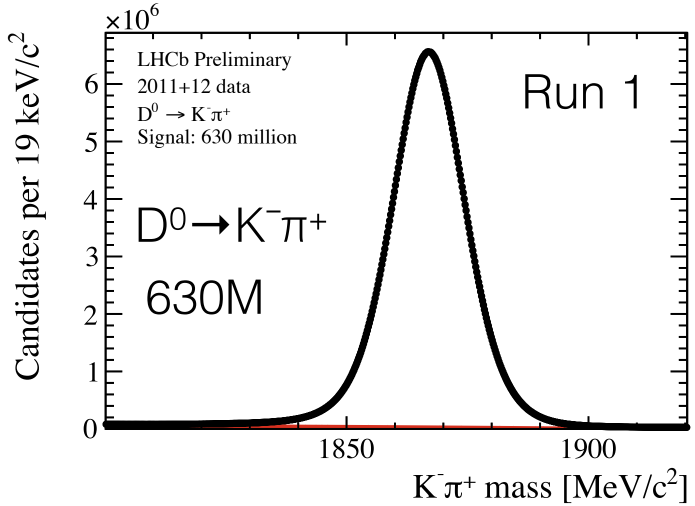
LHCb

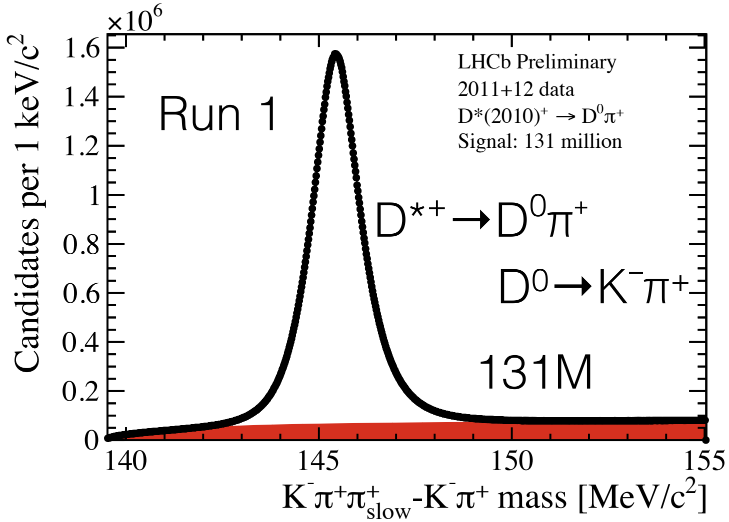
The role of charm physics

- Charm is the only up-type quark allowing full range of probes for mixing and CP Violation:
    - top quark decays too fast (no hadronizination),
    - π^0-π^0 oscillations not possible (particle and anti-particle are identical).
- CPV not yet observed in charm and predicted to be small within SM, since mixing and relevant amplitudes are described, to an excellent approximation, by the physics of the first two generations only.
    - From CKM scheme CPV ~ $O(V_{ub}V^*_{cb}/V_{us}V^*_{cs})$ ~ 10^{-3} or less,
- Charm transitions are a unique portal (complementarity wrt B and K mesons) for obtaining a novel access to flavor dynamics with the experimental situation being a priori favorable ("low SM background").
    - Caveat: need to keep under control QCD effects (long distance) and shrink theory uncertainties.
- Unprecedented huge samples of D decays are necessary (much larger than 10^6 events needed) in order to approach SM predictions.

Charm Physics with LHCb

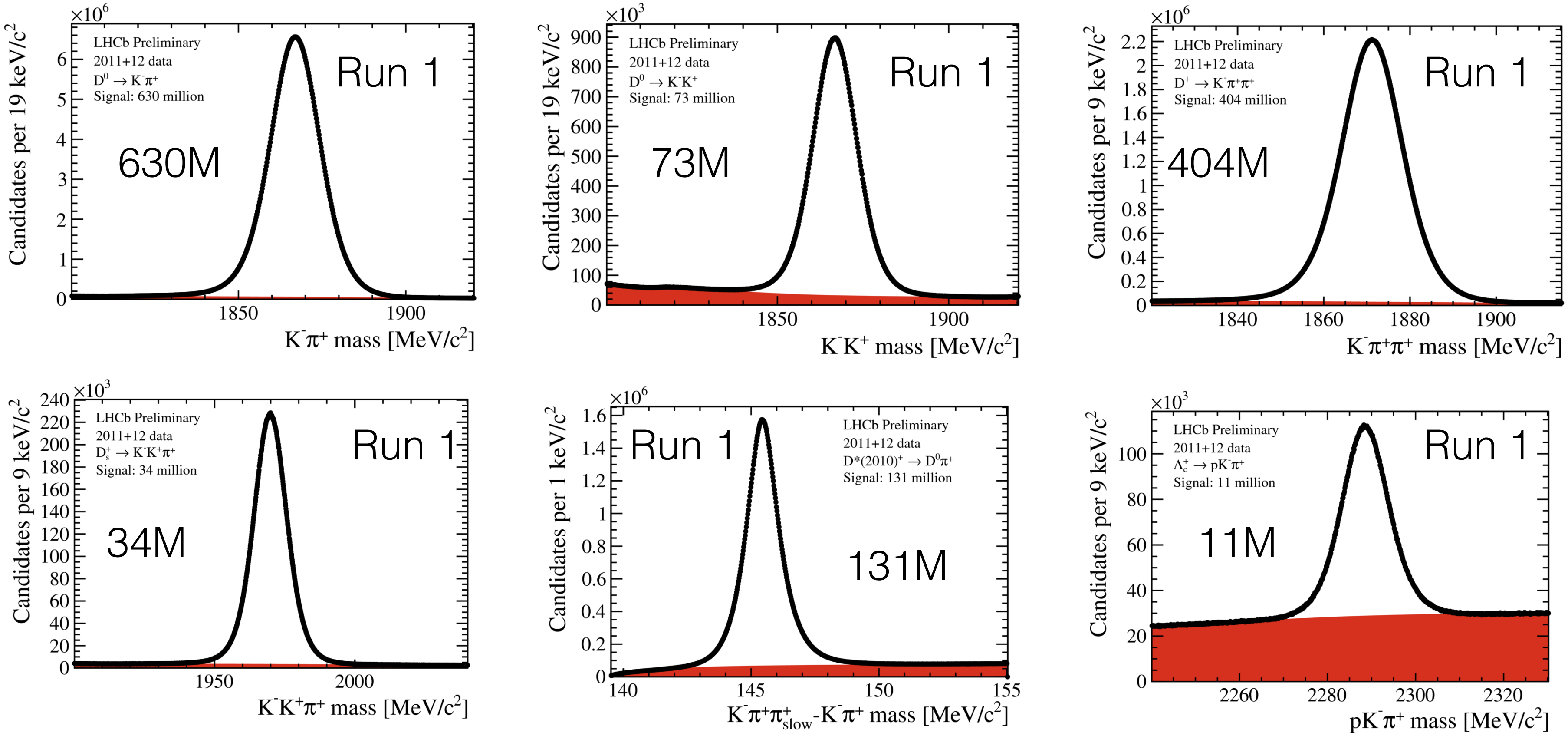
- All *c*-hadrons produced in *pp* collisions.
- Huge production cross-section $\boldsymbol{\sigma}(pp \to DX) \sim 1000$ μbarn at 13 TeV.
- Produced ~5×10^{12} D^0 and ~2×10^{12} D^{*+} mesons in only 3fb^{-1} (Run 1) of data at $L_{inst} = 4\times10^{32}\ cm^{-2}s^{-1}$.
- Final Run 1 sample about factor of 30 larger than samples collected by past experiments.





LHCb-CONF-2016-005

A plenty of charm



LHCb-CONF-2016-005

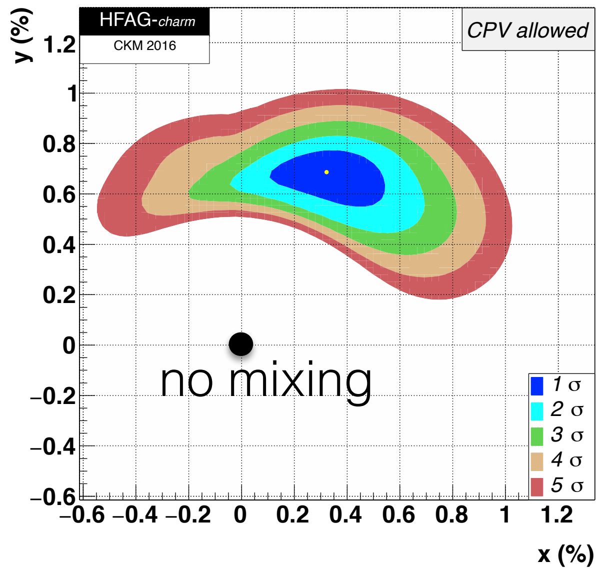
Today N_{sig}(Run 1 + Run 2) ~ 3.2 x N_{sig}(Run 1), and LHCb is taking data until the end of 2018, collecting about a total of 8fb^{-1} of data with the same efficiency and purity (yield per luminosity in 2015-16 increased by a factor of ~4 wrt Run 1).

Charm Mixing and CPV

D^0 mixing experimentally well established.
Very slow rate $x,y < 10^{-2}$

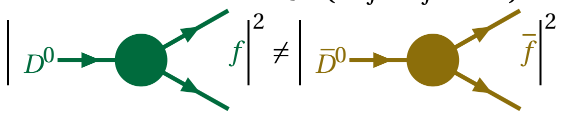
$$|D_{1,2}\rangle = q\,|D^0\rangle \pm p\,|\bar{D}^0\rangle \quad (|q|^2 + |p|^2) = 1, \phi = \arg\,(q/p)$$

$$\begin{aligned} x &\equiv 2(m_2 - m_2)/(\Gamma_1 + \Gamma_2) \\ y &\equiv (\Gamma_2 - \Gamma_1)/(\Gamma_1 + \Gamma_2) \end{aligned}$$

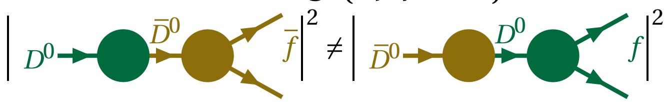


CPV not yet observed in the charm sector.
SM expectations are of the order of 10^{-3} or less.

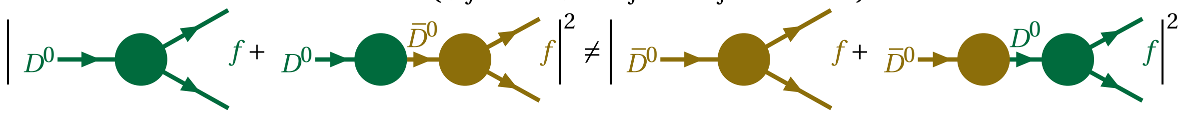
CPV in the decay $(|\bar{A}_f/A_f| \neq 1)$

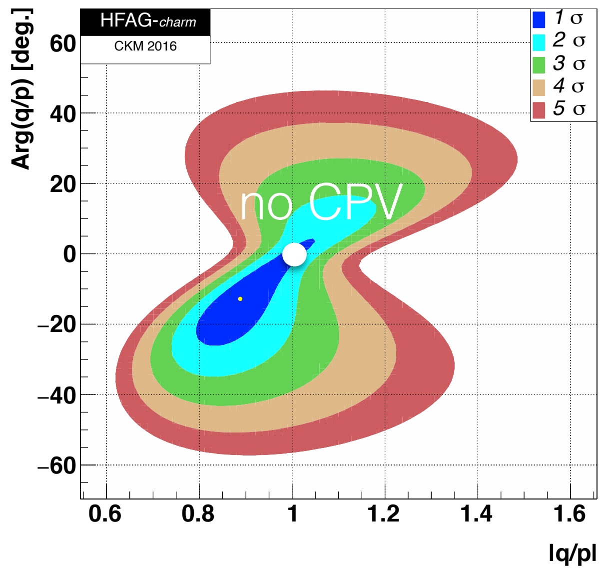


CPV in the mixing $(|q/p| \neq 1)$



CPV in the interference $(\phi_f = \arg(q\bar{A}_f/(pA_f)) \neq 0, \pi)$



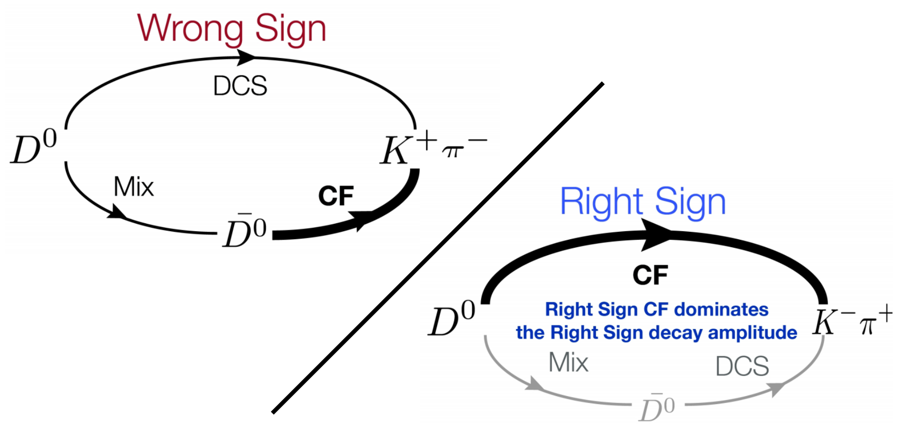


Charm mixing and CPV in $D^0 \to K^{\mp}\pi^{\pm}$(WS/RS)

Time-dependent measurement of the R(t)=WS/RS(t)

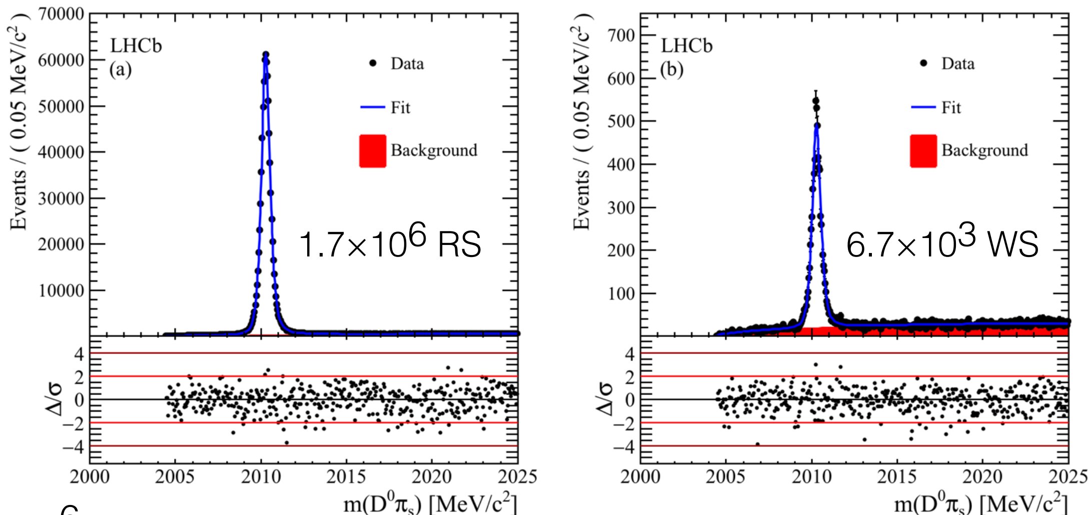
$$R(t)^{\pm} = \underbrace{R_D^{\pm}}_{DCS} + \underbrace{\sqrt{R_D^{\pm}}\,y'^{\pm}\left(\frac{t}{\tau}\right)}_{interference} + \underbrace{\frac{(x'^{\pm})^2 + (y'^{\pm})^2}{4}\left(\frac{t}{\tau}\right)^2}_{mixing}$$

$$x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi} \qquad y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$$



- Full Run 1 data sample (3fb^{-1}) .
- Use Doubly-Tagged (DT) D* decays ($B \to D^{*+}\mu^- X \to [D^0\pi^+]\mu^- X, D^0 \to K\pi$) resulting in a very pure sample.
- Much lower statistics than "prompt" decays ($D^{*+} \to D^0\pi^+, D^0 \to K\pi$), but it covers a complementary region in decay time.

arXiv:1611.06143v1 [hep-ex]. Submitted to PRD.

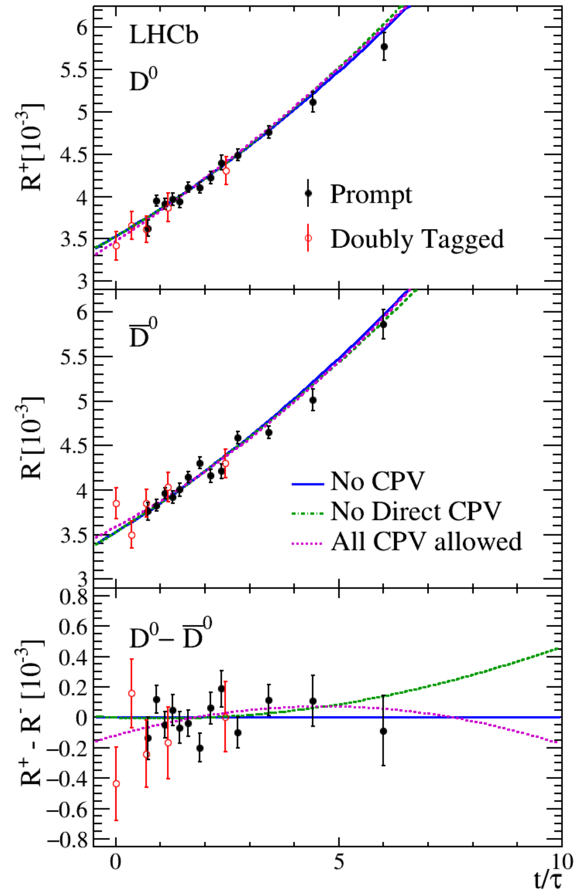


Charm mixing and CPV in $D^0 \rightarrow K^{\mp}\pi^{\pm}$(WS/RS)

- $R^+(t)$ and $R^-(t)$ for initially produced D^0 and antiD^0 mesons.
- Direct CPV occurs if $R_D^+ \neq R_D^-$.
- CPV in mixing and interference occurs if $x'^+ \neq x'^-$ and $y'^+ \neq y'^-$.

$$R(t)^{\pm} = \underbrace{R_D^{\pm}}_{DCS} + \underbrace{\sqrt{R_D^{\pm}}\, y'^{\pm} \left(\frac{t}{\tau}\right)}_{interference} + \underbrace{\frac{(x'^{\pm})^2 + (y'^{\pm})^2}{4} \left(\frac{t}{\tau}\right)^2}_{mixing}$$

Parameter	DT + Prompt	Prompt-only
	All CPV allowed	
$R_D^+[10^{-3}]$	3.474 ± 0.081	3.545 ± 0.095
$(x'^+)^2\,[10^{-4}]$	0.11 ± 0.65	0.49 ± 0.70
$y'^+[10^{-3}]$	5.97 ± 1.25	5.1 ± 1.4
$R_D^-[10^{-3}]$	3.591 ± 0.081	3.591 ± 0.090
$(x'^-)^2\,[10^{-4}]$	0.61 ± 0.61	0.60 ± 0.68
$y'^-[10^{-3}]$	4.50 ± 1.21	4.5 ± 1.4
χ^2/ndf	95.0/108	85.9/98



arXiv:1611.06143v1 [hep-ex]. Submitted to PRD.

World best measurement of charm mixing parameters. Results consistent with conservation of CP symmetry. Precision improves by 10-20% wrt prompt-only data sample.

Direct CPV: $\Delta A_{CP}(D^0 \rightarrow h^+h^-)$

- Effects of "direct" CP violation can be isolated by taking the difference between the time-integrated CP asymmetries in the K^+K^- and $\pi^+\pi^-$ modes:

$$
\begin{aligned}
\Delta A_{\mathrm{CP}} &\equiv A_{\mathrm{CP}}(D^0 \to K^+K^-) - A_{\mathrm{CP}}(D^0 \to \pi^+\pi^-) \\
&\approx \Delta A_{\mathrm{CP}}^{\mathrm{dir}} \left(1 + y_{\mathrm{CP}} \frac{\overline{\langle t \rangle}}{\tau}\right) + A_{\mathrm{CP}}^{\mathrm{ind}} \frac{\Delta \langle t \rangle}{\tau}
\end{aligned}
$$

- where a residual experiment-dependent contribution from indirect CP violation can be present, due to the fact that there may be a decay time dependent acceptance function that can be different for the K^+K^- and $\pi^+\pi^-$ channels.

- Well suited for LHCb because of cancellation of instrumental and production asymmetries. Measurement performed using both D*-tag *[PRL 116, 191601 (2016)]* and semi-leptonic $B \rightarrow D^0 \mu X$ *[JHEP 07 (2014) 041]* decays.

D*-tag: $\Delta A_{CP} = (-0.10 \pm 0.08\ (\mathrm{stat}) \pm 0.03\ (\mathrm{syst}))\ \%$

μ-tag: $\Delta A_{CP} = (+0.14 \pm 0.16\,(\mathrm{stat}) \pm 0.08\,(\mathrm{syst}))\%$

LHCb dominates the world average with systematics well below statistical uncertainty.

Time-integrated $A_{CP}(D^0 \to K^+K^-)$

Full Run 1 data sample (3fb-1).
D^0 flavor inferred with strong $D^{*+} \to D^0\pi^+$ decay chain.
CPV in calibration channels assumed negligible

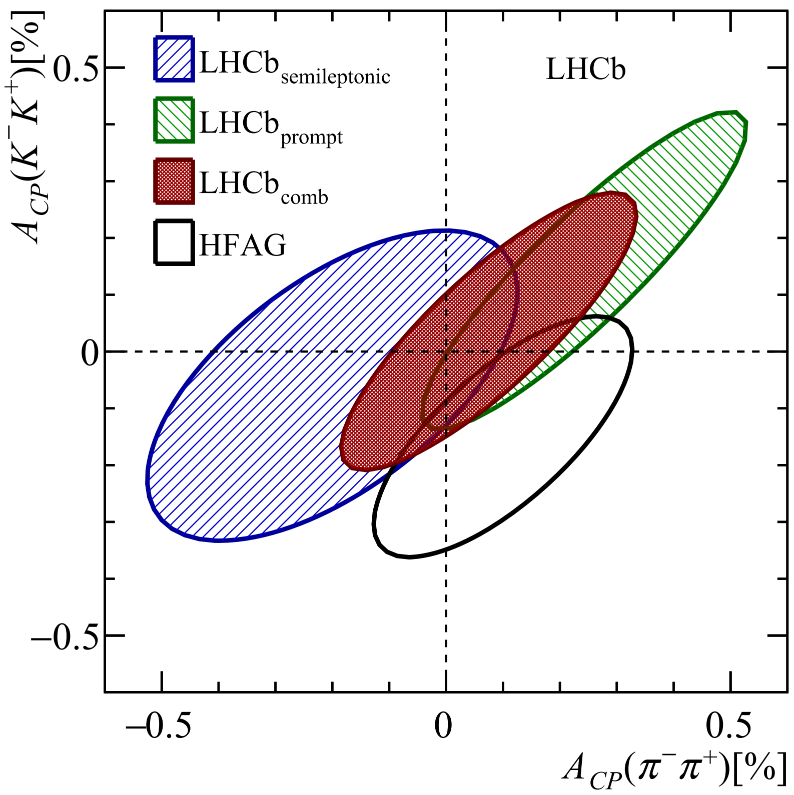
$$
\begin{aligned}
A_{CP}(D^0 \to K^-K^+) \\
&= A_{\mathrm{raw}}(D^0 \to K^-K^+) - A_{\mathrm{raw}}(D^0 \to K^-\pi^+) \\
&\quad + A_{\mathrm{raw}}(D^+ \to K^-\pi^+\pi^+) - A_{\mathrm{raw}}(D^+ \to \overline{K}^0\pi^+) \\
&\quad + A_D(\overline{K}^0).
\end{aligned}
$$

$$A_{CP}(K^-K^+) = (0.14 \pm 0.15\,(\mathrm{stat}) \pm 0.10\,(\mathrm{syst}))\%$$

A combination with other LHCb measurements yields

$$A_{CP}(K^-K^+) = (0.04 \pm 0.12\,(\mathrm{stat}) \pm 0.10\,(\mathrm{syst}))\%$$
$$A_{CP}(\pi^-\pi^+) = (0.07 \pm 0.14\,(\mathrm{stat}) \pm 0.11\,(\mathrm{syst}))\%$$

Phys.Lett. B767 (2017) 177-187



Most precise measurements from a single experiment. No evidence of CP asymmetry.

Time-dependent CPV in $D^0 \to h^+h^-$

Because of the slow mixing rate of charm mesons ($x,y \sim 10^{-2}$) the time-dependent asymmetry is approximated at first order as the sum of two terms:

$$A_{CP}(h^+h^-;t) \approx A_{CP}^{\mathrm{dir}}(h^+h^-) + \frac{t}{\tau} A_{CP}^{\mathrm{ind}}(h^+h^-)$$

$$A_{CP}^{\mathrm{ind}}(h^+h^-) = \frac{\eta_{CP}}{2}\left[\underbrace{y\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\cos\varphi}_{\text{CPV in the mixing } |q/p| \neq 1} - \underbrace{x\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\sin\varphi}_{\text{CPV in the interference } \varphi_f \neq 0,\pi}\right],$$

$$A_\Gamma \approx -A_{\mathrm{CP}}^{\mathrm{ind}}$$

defined as the asymmetry between D^0 and antiD^0 effective lifetimes

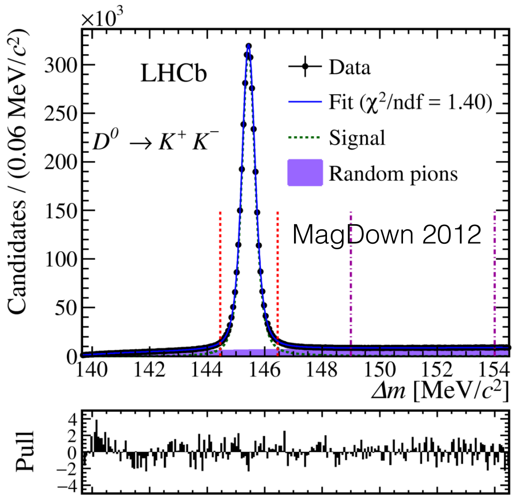
Neglecting subleading amplitudes A_Γ is independent of the final state f. Furthermore, in the absence of CP violation in mixing, it can be found that $A_\Gamma = -x \sin\varphi$ —> $|A_\Gamma| \leq |x| < 5\times10^{-3}$.

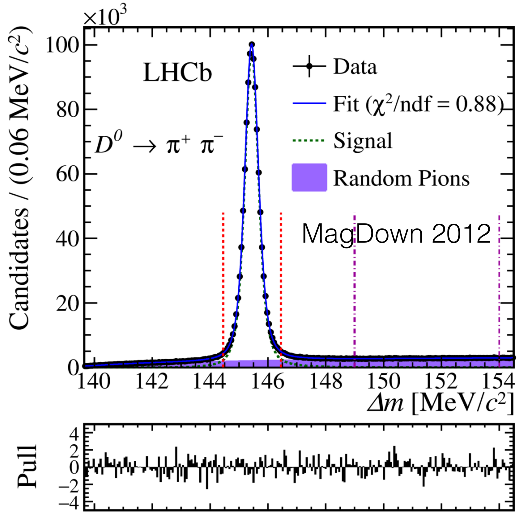
Full Run 1 data sample (3fb-1).

D^0 flavor inferred with strong $D^{*+} \to D^0\pi^+$ decay.

Subsample [10^6]	$D^0 \to K^-\pi^+$	$D^0 \to K^+K^-$	$D^0 \to \pi^+\pi^-$
2011 *MagUp*	10.7	1.2	0.4
2011 *MagDown*	15.5	1.7	0.5
2012 *MagUp*	30.0	3.3	1.0
2012 *MagDown*	31.3	3.4	1.1
Total	87.5	9.6	3.0

arXiv:1702.06490 [hep-ex]. Submitted to PRL.





Time-dependent CPV in $D^0 \to h^+h^-$

$$A_\Gamma(K^+K^-) = (-0.30 \pm 0.32 \pm 0.10) \times 10^{-3}$$
$$A_\Gamma(\pi^+\pi^-) = (0.46 \pm 0.58 \pm 0.12) \times 10^{-3}$$

Precision approaches the level of 10^{-4}. No evidence for CP violation and improve on the precision of the previous best measurements by nearly a factor of 2.

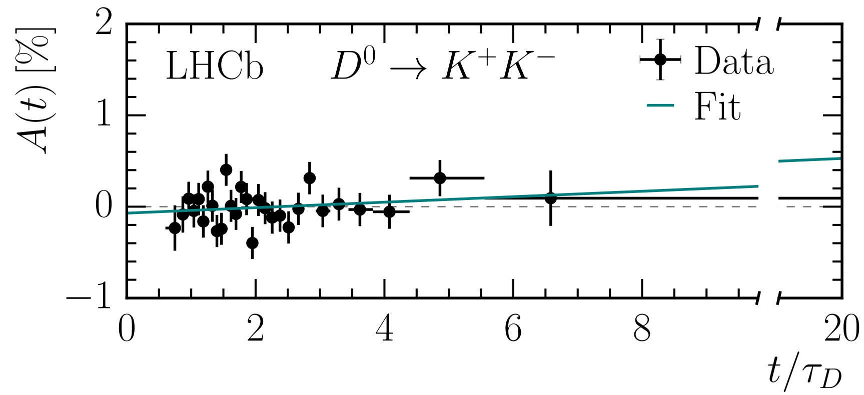
Assuming that only indirect CP violation contributes to A_Γ, the two values, can be averaged to yield a single value:

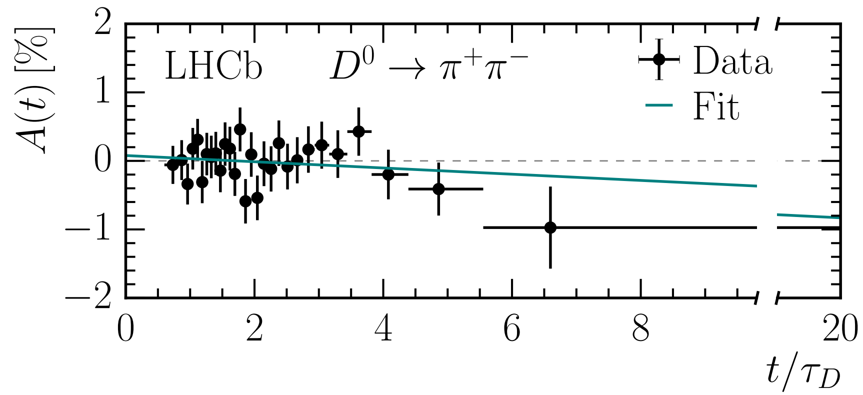
$$A_\Gamma = (-0.13 \pm 0.28 \pm 0.10) \times 10^{-3}$$

Consistent with the result obtained by LHCb in a muon-tagged sample [*JHEP 1504 (2015) 043*], which is statistically independent. The two results are therefore combined to yield an overall LHCb Run 1 value:

$$A_\Gamma = (-0.29 \pm 0.28) \times 10^{-3}$$

arXiv:1702.06490 [hep-ex]. Submitted to PRL.





Most precise measurement of CPV in the charm sector.

The impact on LHCb on CP Violation of $D^0 \to h^+h^-$ decays in Run 1

From HFAG 2016 the world average values are:

$$A_{\rm CP}^{\rm ind} = (\ \ 0.30 \pm 0.26) \times 10^{-3}$$
$$\Delta A_{\rm CP}^{\rm dir} = (-1.34 \pm 0.70) \times 10^{-3}$$

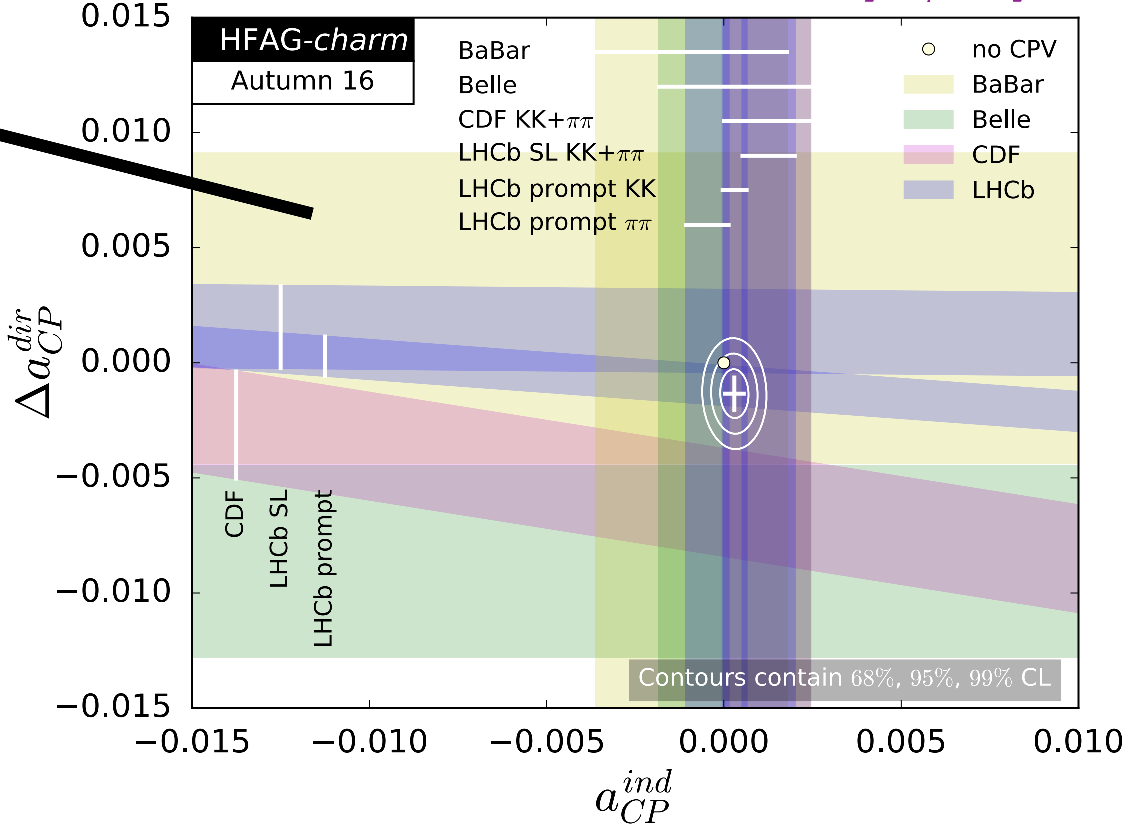
Consistent with the hypothesis of CP symmetry with a p-value of 9.3% (1.7$\boldsymbol{\sigma}$)

My "unofficial" LHCb-only average:

$$A_{\rm CP}^{\rm ind} = (\ \ 0.29 \pm 0.28) \times 10^{-3}$$
$$\Delta A_{\rm CP}^{\rm dir} = (-0.56 \pm 0.76) \times 10^{-3}$$

Consistent with the hypothesis of CP symmetry with a p-value of 79%.

HFAG 2016 arXiv:1612.07233 [hep-ex]



LHCb dominates the world average and much more data are coming.

Today

- LHC is a super-duper charm-factory, and LHCb is doing an excellent job collecting the largest ever charm samples.

- In Run 1 (especially for two-body golden modes) :

  - achieved statistical precision below 10^{-3}, and systematics already close to 10^{-4}.

  - no hints of CP-violation found so far, just started to approach SM expectations.

- LHCb charm physics covers a broad program, with many world leading measurements not presented in this talk

  - on multi-body charm decays where CPV can be studied through the phase space (local asymmetries larger than integrated ones),

  - and on rare decays ($D^0 \to \mu^+\mu^-$, $D^0 \to \pi^-\pi^+\mu^-\mu^+$, $D^+_{(s)} \to \pi^+\mu^+\mu^-$, $D^0 \to e\mu$, etc..) where limits from other experiments were already improved by orders of magnitude with only Run 1 data.

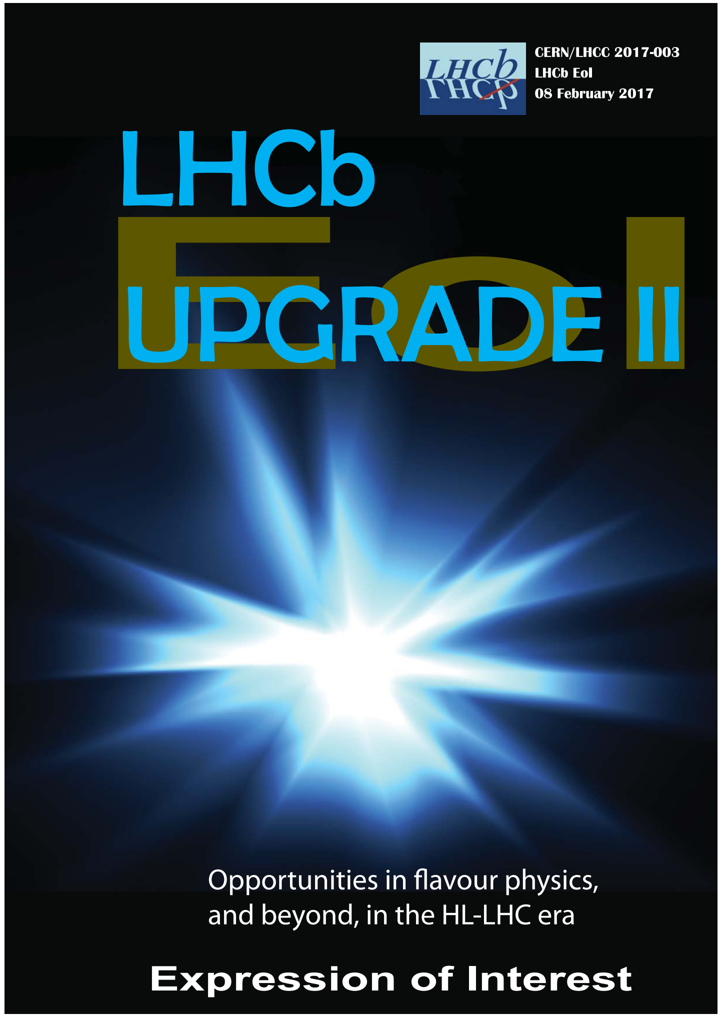
Future perspectives

- The Run 2 (2015-2018, ~8fb^{-1}) is currently ongoing and the size of LHCb samples already increased more than proportionally to the integrated luminosity.

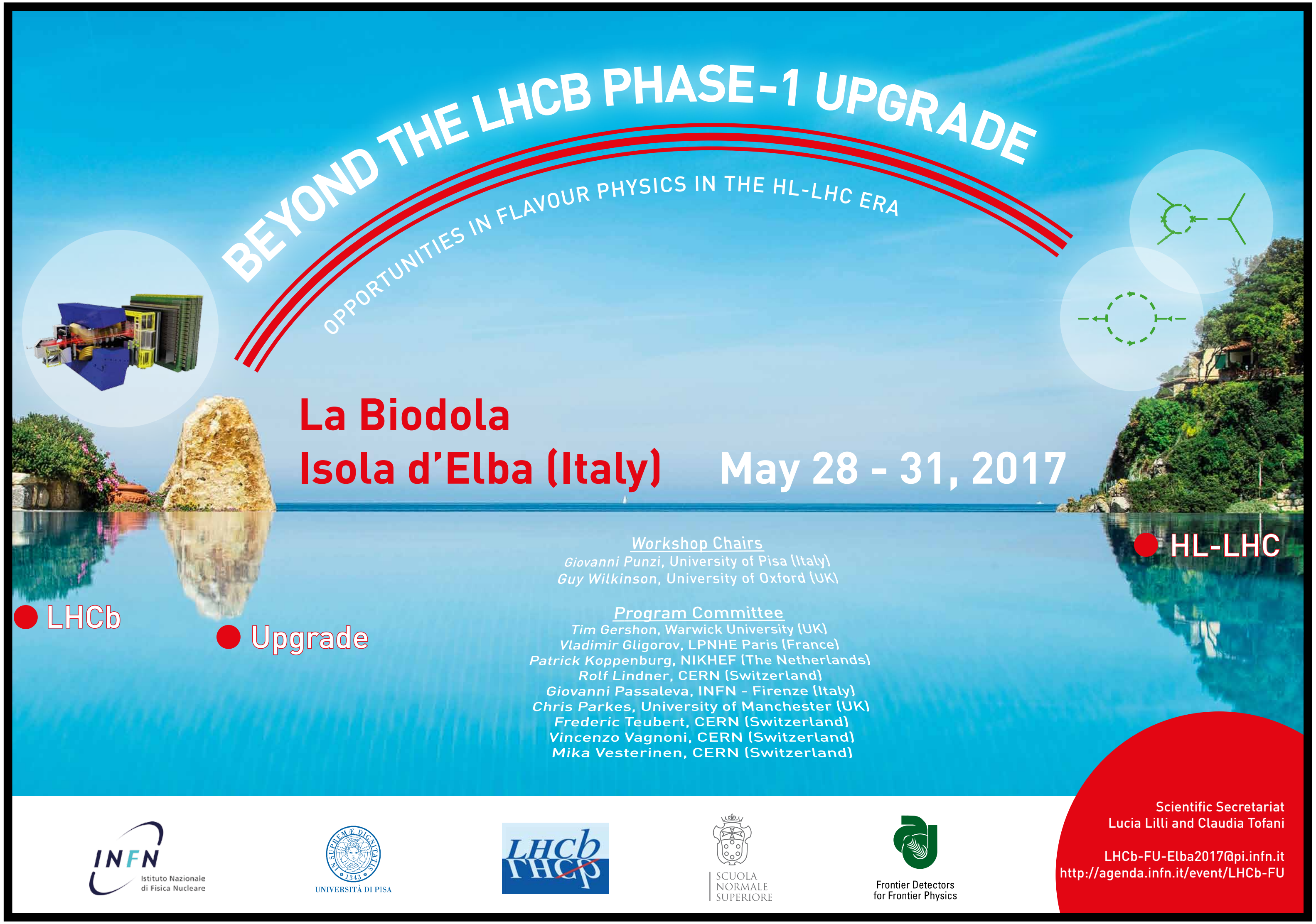
- Phase1 LHCb-Upgrade at L = 2x10^{33} cm^{-2}s^{-1}. (2020-29, ~50fb^{-1}) is behind the corner.

- A proposal of a Phase 2 LHCb-Upgrade at L >10^{34} cm^{-2}s^{-1} (2031-??, >300fb^{-1}) is currently under discussion.

CERN-LHCC-2017-003



An extreme-flavour experiment



http://agenda.infn.it/event/LHCb-FU

Backup

$A_{CP}(t)(D^0 \to h^+h^-)$ h=K,π

Because of the slow mixing rate of charm mesons (x,y~10^{-2}) the time-dependent asymmetry is approximated at first order as the sum of two terms:

$$A_{CP}(h^+h^-;t) \approx A_{CP}^{\text{dir}}(h^+h^-) + \frac{t}{\tau} A_{CP}^{\text{ind}}(h^+h^-)$$

$$A_{CP}^{\text{dir}}(h^+h^-) \equiv A_{CP}(t=0) = \frac{|\mathcal{A}(D^0 \to h^+h^-)|^2 - |\mathcal{A}(\bar{D}^0 \to h^+h^-)|^2}{|\mathcal{A}(D^0 \to h^+h^-)|^2 + |\mathcal{A}(\bar{D}^0 \to h^+h^-)|^2}$$

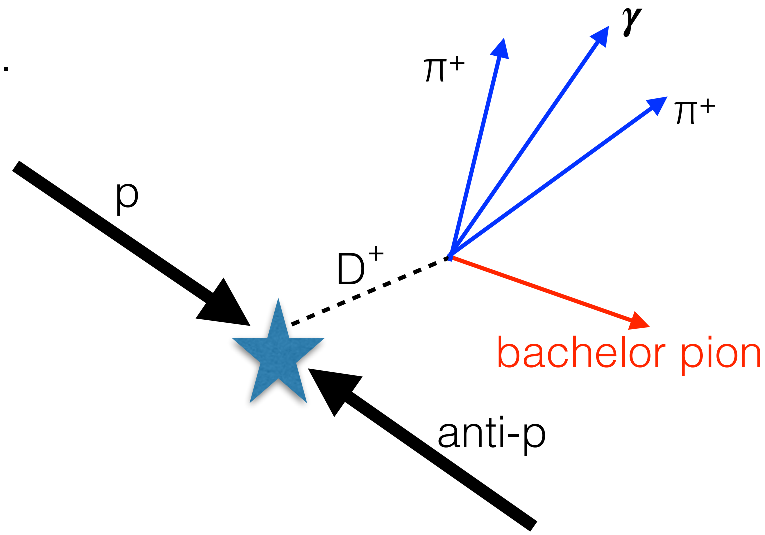
$$A_{CP}^{\text{ind}}(h^+h^-) = \frac{\eta_{CP}}{2}\left[y\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\cos\varphi - x\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\sin\varphi\right],$$

The time-integrated asymmetry is then the time integral of A_{CP}(t) over the experimental observed distribution of proper decay time D(t):

$$A_{CP}(h^+h^-) = A_{CP}^{\text{dir}}(h^+h^-) + A_{CP}^{\text{ind}}(h^+h^-)\int_0^\infty \frac{t}{\tau} D(t)dt = A_{CP}^{\text{dir}}(h^+h^-) + \frac{\langle t \rangle}{\tau} A_{CP}^{\text{ind}}(h^+h^-).$$

Still on CPV hunting: $D^+_{(s)} \rightarrow \eta'\pi^+$

First time measurement of CPV in charm with neutrals at LHCb.

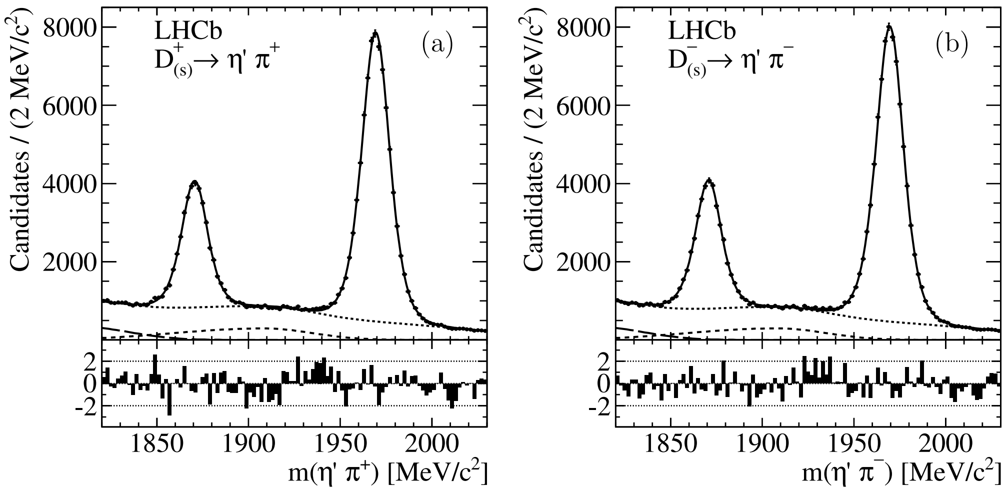


Full Run 1 data sample, $N(D^{\pm})$=63k and $N(D_s^{\pm})$=152k.
Measurement with respect to reference channels in order to cancel production and detection asymmetries.

$$\mathcal{A}_{CP}(D^{\pm} \to \eta'\pi^{\pm}) \approx \Delta\mathcal{A}_{CP}(D^{\pm} \to \eta'\pi^{\pm}) + \mathcal{A}_{CP}(D^{\pm} \to K^0_S\pi^{\pm}).$$

$$\mathcal{A}_{CP}(D_s^{\pm} \to \eta'\pi^{\pm}) \approx \Delta\mathcal{A}_{CP}(D_s^{\pm} \to \eta'\pi^{\pm}) + \mathcal{A}_{CP}(D_s^{\pm} \to \phi\pi^{\pm}).$$

arXiv:1701.01871v1 [hep-ex]

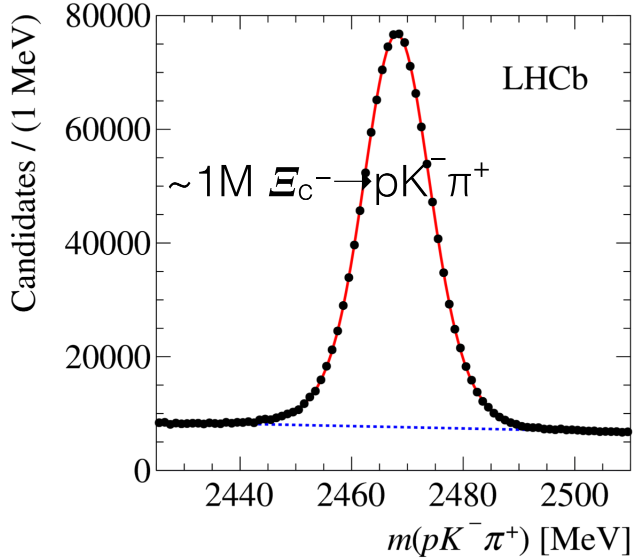


$$\mathcal{A}_{CP}(D^{\pm} \to \eta'\pi^{\pm}) = (-0.61 \pm 0.72 \pm 0.55 \pm 0.12)\%,$$
$$\mathcal{A}_{CP}(D_s^{\pm} \to \eta'\pi^{\pm}) = (-0.82 \pm 0.36 \pm 0.24 \pm 0.27)\%,$$

Most precise measurement of CP asymmetries in $D^+_{(s)} \rightarrow \eta'\pi^+$ decays to date. Previous measurements at e^+e^- machines error>1%.

Observation of new narrow states $\Omega^0_c \to \Xi_c^- K^+$

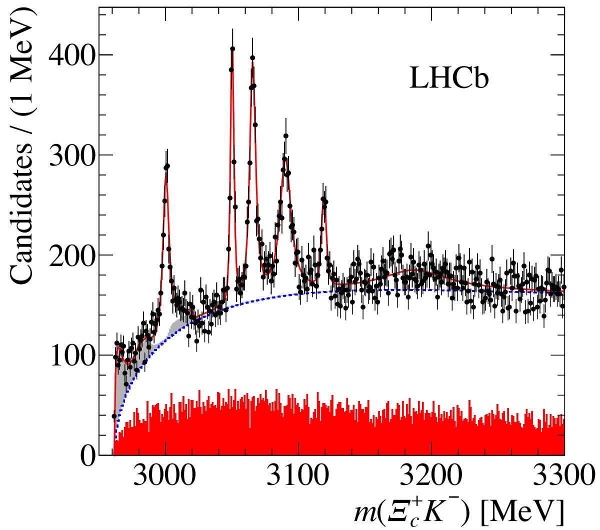
Run 1 + 2015 data ~ $3.3 fb^{-1}$



Spectroscopy of singly charmed baryons cqq' is intricate (many states are expected), but it provides a natural way both to understand the spectrum and improve accuracy of theory (i.e HQET).

arXiv:1703.04639 [hep-ex]. Submitted to PRL.

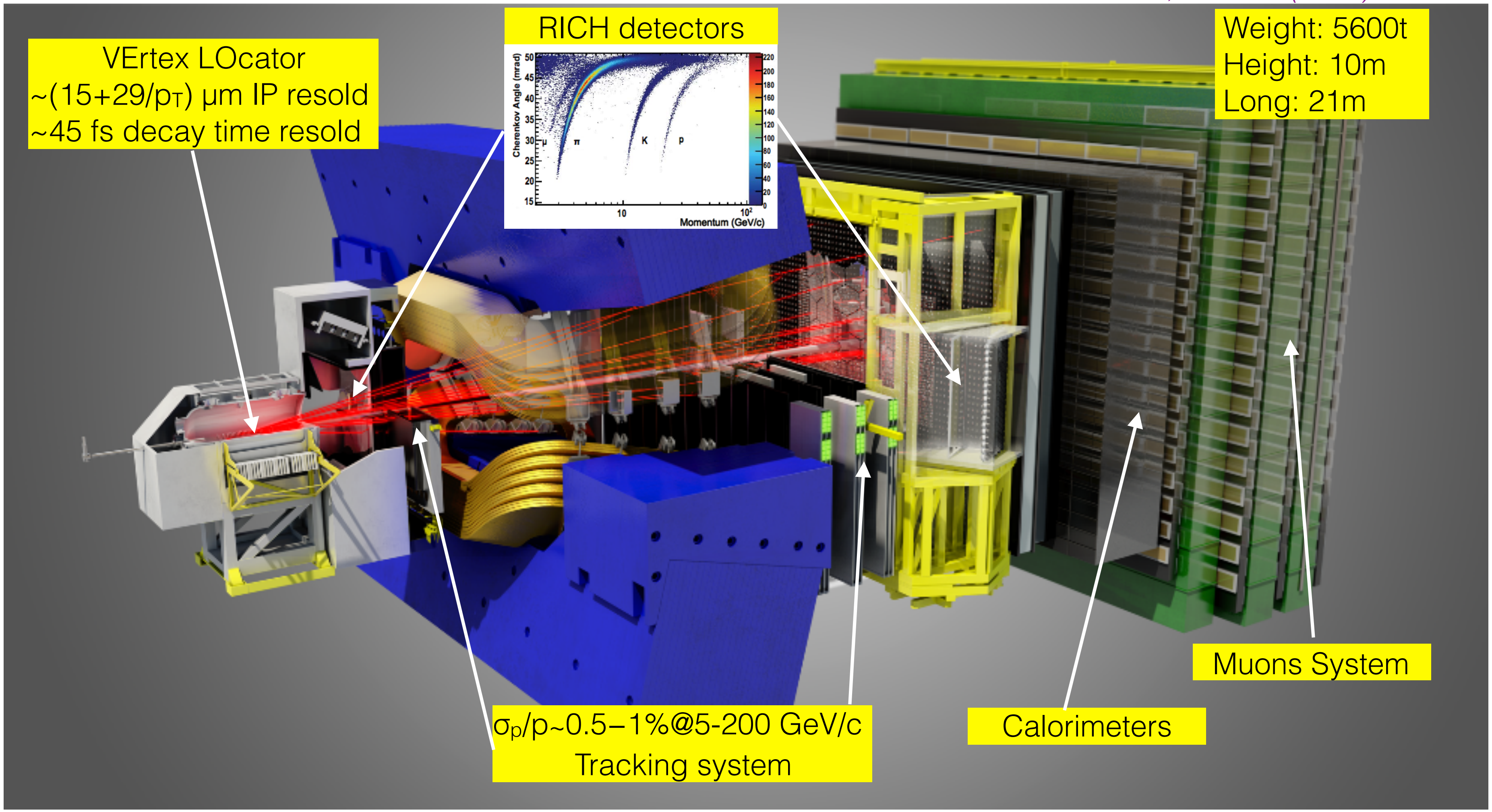
Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$	20.4
		< 1.2 MeV, 95% CL		
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	$480 \pm 70 \pm 30$	10.4
		< 2.6 MeV, 95% CL		



See talk from R. Cardinale on "Hadron spectroscopy at LHCb"

The LHCb detector

The LHC detector at LHC, JINST 3 (2008) S08005



Excellent trigger capabilities (Level-0 of custom electronics + HLT of commercial CPUs) to handle 11MHz of visible physics collisions. Events written on tape extremely fast at 2.5KHz, where typical event size is 60-100KBytes in Run 1 (2011-2012). In Run 2 (2015-2016) performances are even better. [LHCb-PROC-2015-011]