Charm CPV and Rare Decays at LHCb

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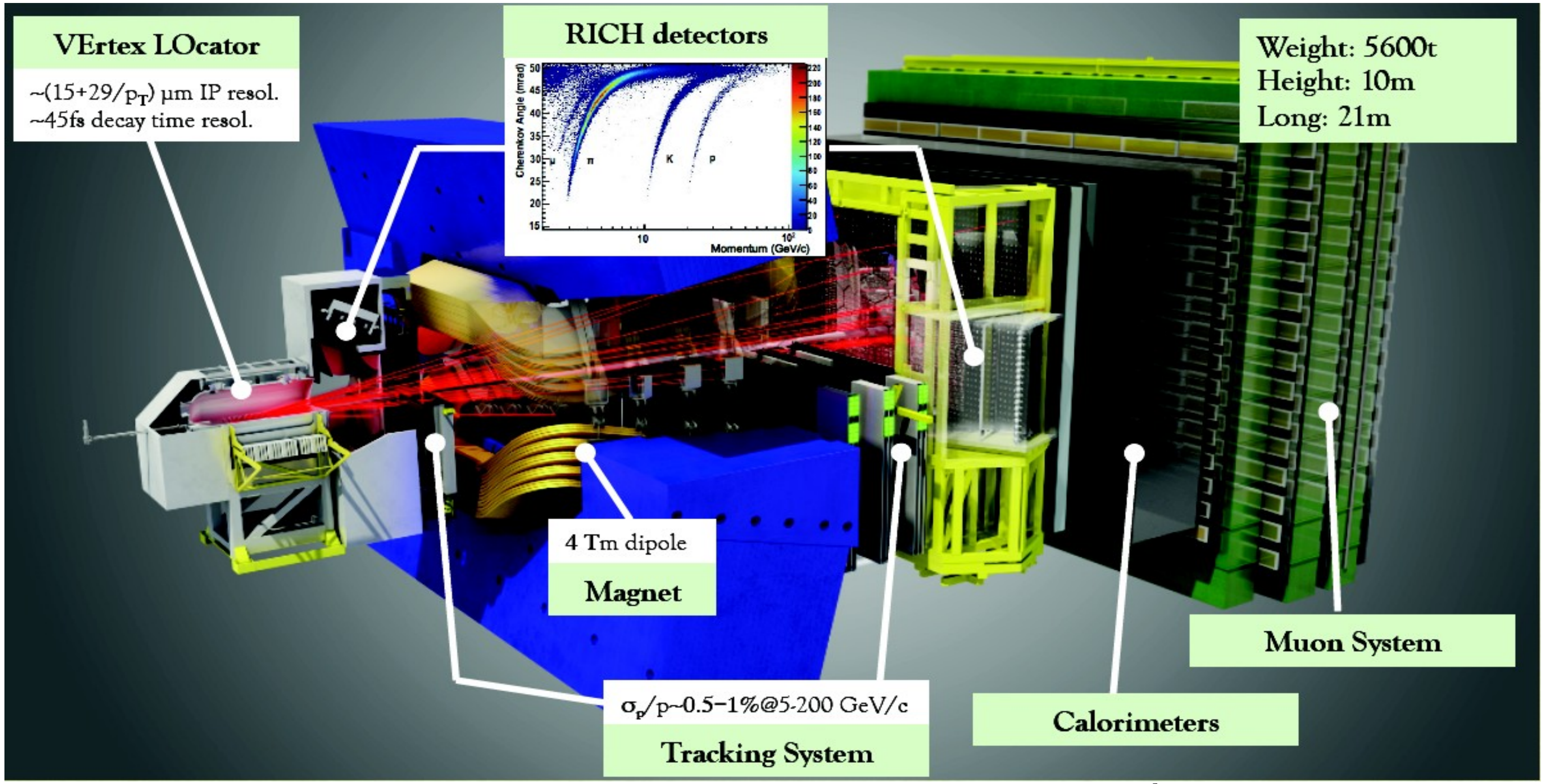
Outline

- Recent LHCb results:

  For a complete paper list on charm, see LHCb link

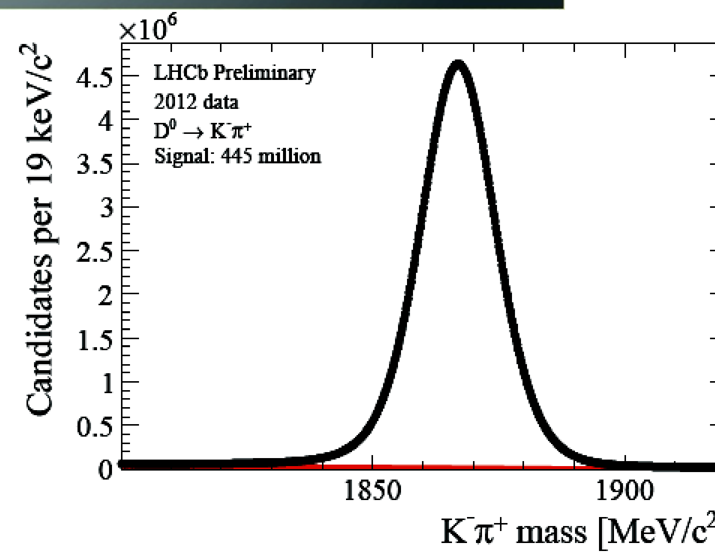
  - A_Γ in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ [PRL 118 (2017) 261803]
  - y_{CP} with $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$, and $D^0 \to K^-\pi^+$ [arXiv:1810.06874]
  - Mixing and CP violation in $D^0 \to K^\pm\pi^\mp$ [PRD 97 (2018) 031101(R)]
  - A_{CP} in $D^0 \to K_S^0 K_S^0$ with 2015-2016 data (2fb^{-1}) [arXiv:1806.01642]
  - ΔA_{CP} in $\Lambda_c^+ \to pK^-K^+$ and $\Lambda_c^+ \to p\pi^-\pi^+$ [JHEP 03 (2018) 182]
  - Angular and *CP* asymmetries in $D^0 \to K^+K^-(\pi^+\pi^-)\ \mu^+\mu^-$ [PRL 121 (2018) 091801]
  - Search for $\Lambda_c^+ \to p\mu^-\mu^+$ [PRD 97 (2018) 091101(R)]
- Summary & outlook

LHCb experiment



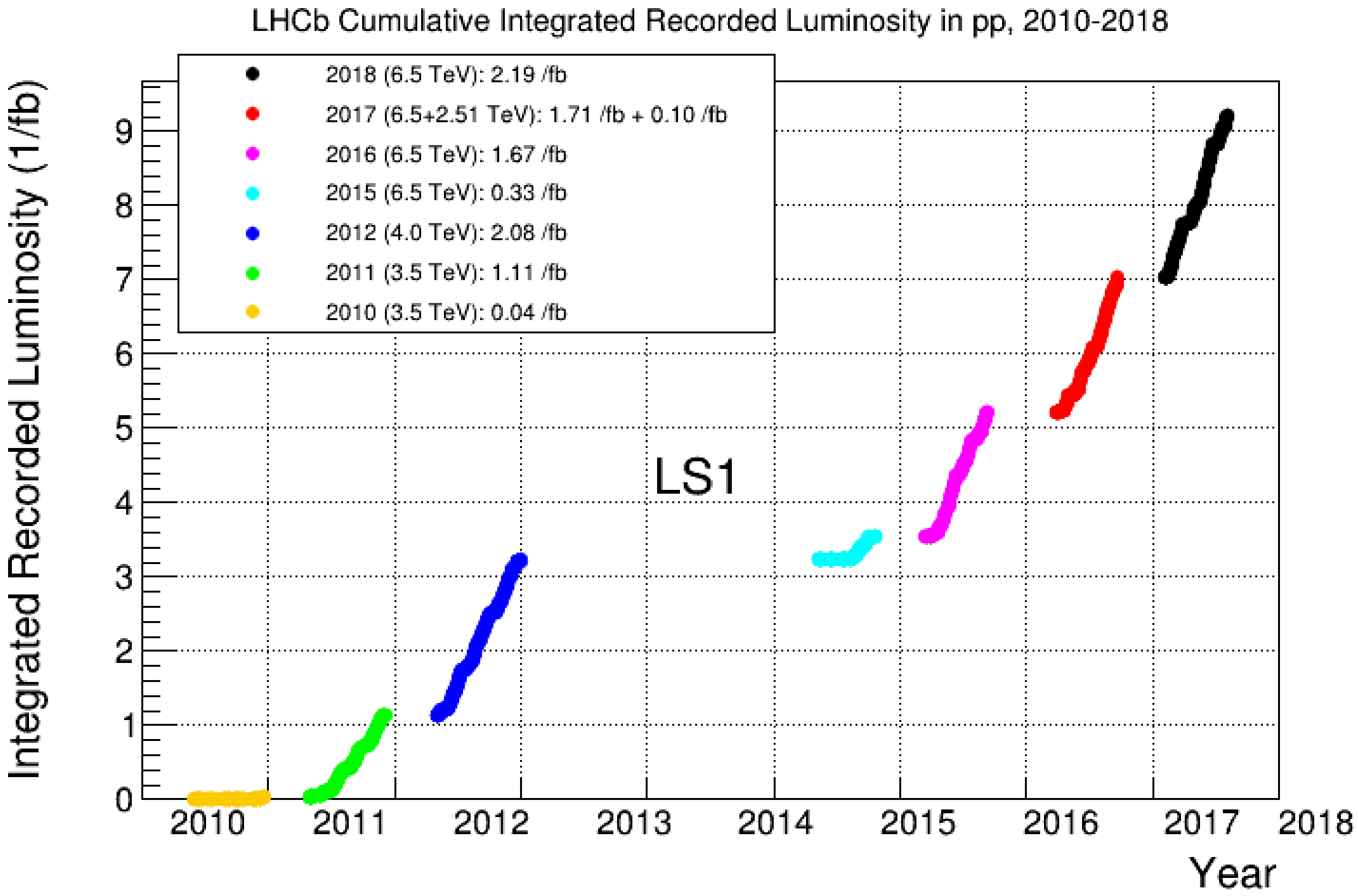
Int. J. Mod. Phys. A 30, 1530022 (2015)

- LHCb acceptance: $2 < \eta < 5$ (forward region)
- Large $c\bar{c}$ production cross-section [JHEP 03 (2016) 159]
  - $\sigma(pp \rightarrow c\bar{c}) = (2369 \pm 3 \pm 152 \pm 118)\,\mu b\, @\, 13\, TeV$
- About ~790M $D^0 \rightarrow K^- \pi^+$ collected by LHCb between 2011 and 2016



LHCb-CONF-2016-005

LHCb data-taking



- Run I: 1.0 fb^{-1} @ 7 TeV (2011) + 2.0 fb^{-1} @ 8 TeV (2012)
- Run II: 0.3 fb^{-1} (2015) + 1.7 fb-1 (2016) + 1.7 fb^{-1} (2017) + 2.2 fb^{-1} (2018) @ 13 TeV

CP Violation in Charm

- Only way to probe CP violation in up-type quark
- Complementary to K and B mesons with observed CPV
- Difficult to calculate SM predictions, but small (~10^{-3}) CP asymmetry is expected → hints of NP if higher values are expected
- CPV in charm sector yet to be found

Unitarity triangle for charm

$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0$$

$$\sim\lambda \qquad \sim\lambda \qquad \sim\lambda^5$$

$$\lambda = \sin(\theta_C) \sim 0.23$$

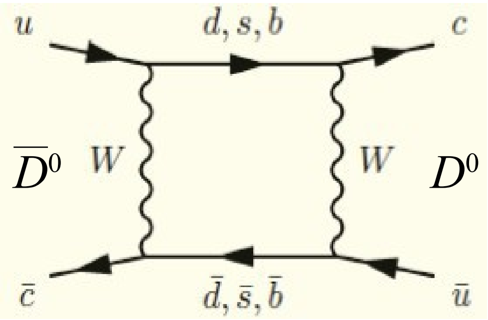
Expected CPV very small in charm

- Effectively 2-generation system
- 3rd generation and CPV enter through loops

Mixing and CPV in $D^0 – \overline{D}^0$

- Charm mixing: a well-established fact:
  - Mass eigenstates are related to their flavor eigenstates via $|D_{1,2}\rangle \equiv p|D^0\rangle \pm q|\overline{D}^0\rangle$, with $|q|^2 + |p|^2 \equiv 1$
  - Mixing parameters based on the mass and width differences: $x \equiv (m_2 - m_1)/\Gamma$, $y \equiv (\Gamma_2 - \Gamma_1)/2\Gamma$, with $\Gamma \equiv (\Gamma_2 + \Gamma_1)/2$
- *CP* violation contributions:
  - In decays: amplitudes for a process and its conjugate differ

Direct *CP* violation $\quad \left|\frac{\overline{A}_f}{A_f}\right|^{\pm 2} \approx 1 \pm A_d \quad \rightarrow \quad a_{CP}^{dir} \approx -\frac{1}{2} A_d$



  - In mixing: rates of $D^0 \to \overline{D}^0$ and $\overline{D}^0 \to D^0$ differ

Indirect *CP* violation $\quad \left|\frac{q}{p}\right|^{\pm 2} \approx 1 \pm A_m \quad \rightarrow \quad a_{CP}^{ind} = -\frac{A_m}{2} y\cos\phi + x\sin\phi$

ϕ: weak phase,
A_m: *CPV from mixing*

  - In interference between mixing and decay diagrams

Search for CPV: measuring A_Γ

- Measure of indirect CPV in D^0 SCS decays to *CP* eigenstates:

$$A_{CP}(t) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)} \approx A_{CP}^{\mathrm{dir}} - A_\Gamma \left(\frac{t}{\tau}\right), \qquad f = K^+K^-, \pi^+\pi^-$$

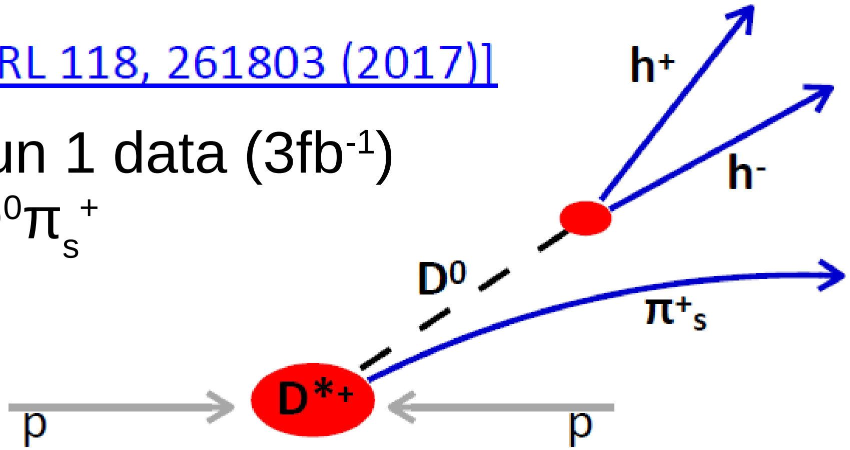
$$A_\Gamma = \frac{1}{2}\left[\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y\cos\phi + \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x\sin\phi\right] \approx y\left(\left|\frac{q}{p}\right| - 1\right) - x\phi$$

with $\phi = \arg\left(-\frac{q}{p}\frac{\bar{A}_f}{A_f}\right)$

- If $A_\Gamma \neq 0 \rightarrow$ indirect CPV

[PRL 118, 261803 (2017)]

- At LHCb: measurement performed with Run 1 data ($3\mathrm{fb}^{-1}$)
- D^0 flavor tagged from strong decay $D^{*+} \to D^0\pi_s^+$

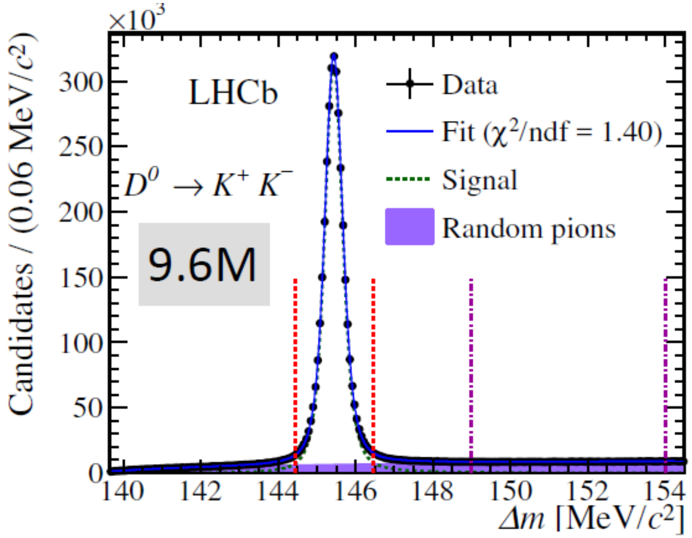


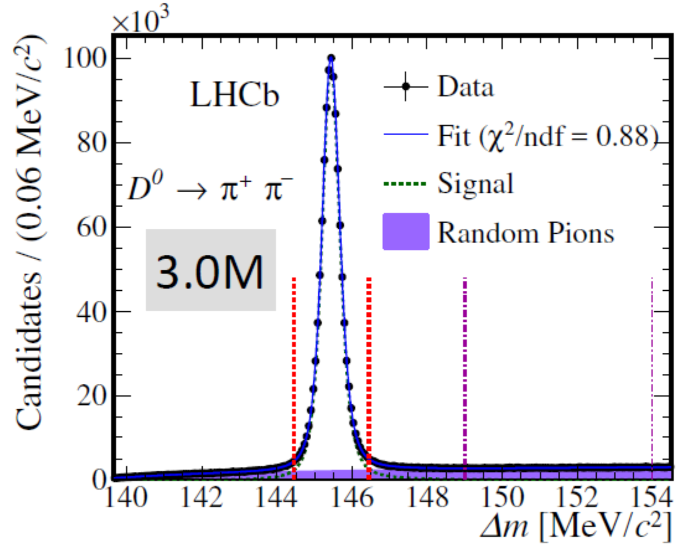
[PRL 118 (2017) 261803]

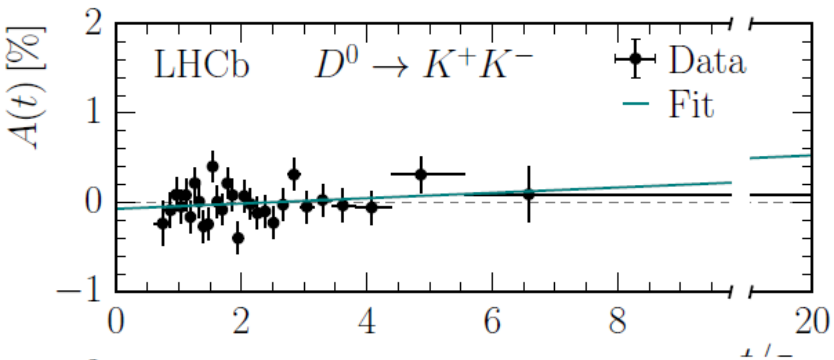
A_Γ results

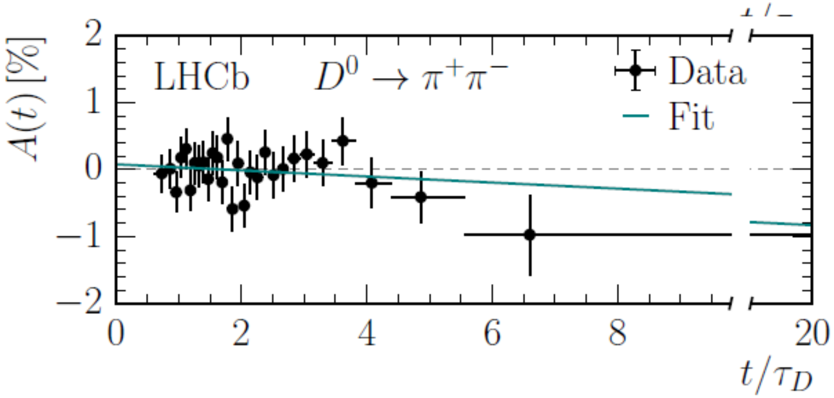
$$\Delta m = m(h^+h^-\pi_s^\pm) - m(h^+h^-)$$

$$A_\Gamma \equiv \frac{\hat{\Gamma}_{D^0\to f} - \hat{\Gamma}_{\overline{D}^0\to f}}{\hat{\Gamma}_{D^0\to f} + \hat{\Gamma}_{\overline{D}^0\to f}}$$









$$A_\Gamma^{KK} = (-3.0 \pm 3.2 \pm 1.0) \cdot 10^{-4}$$

$$A_\Gamma^{\pi\pi} = (\;\;4.6 \pm 5.8 \pm 1.2) \cdot 10^{-4}$$

Combination with the smaller independent sample $\overline{B} \to D^0 \mu X$ [JHEP 04 (2015) 043]:

$$A_\Gamma = (-2.9 \pm 2.8) \cdot 10^{-4}$$

- Dominating world average
- Compatible with zero within 3×10^{-4}

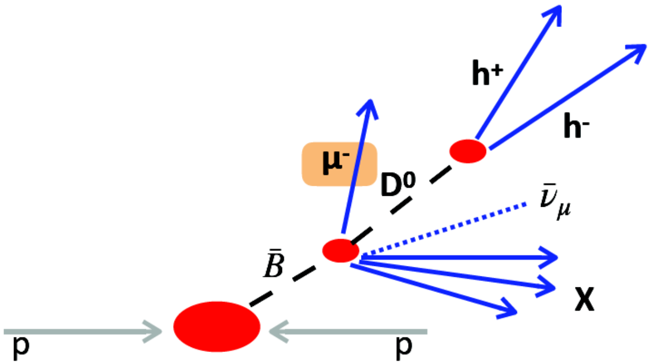
Search for CPV: measuring y_{CP}

$$y_{CP} = \frac{\hat{\Gamma}(D^0 \to h^+h^-) + \hat{\Gamma}(\bar{D}^0 \to h^+h^-)}{2\Gamma} - 1 \qquad f = K^+K^-,\ \pi^+\pi^- \ \text{(CP-even)}$$

$$= \frac{1}{2}\left[\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) y\cos\phi - \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) x \sin\phi\right] \approx y + \boxed{y\left[\frac{1}{2}\left(\left|\frac{q}{p}\right| - 1\right)^2 - \frac{\phi^2}{2}\right] - x\phi\left(\left|\frac{q}{p}\right| - 1\right)}$$

- y_{CP} is equal to y in the limit of no CPV ($|q/p| = 1$ and $\phi = 0$)
- Differences are:
  - Linear in mixing parameters
  - Quadratic in ϕ, $|q/p|-1$

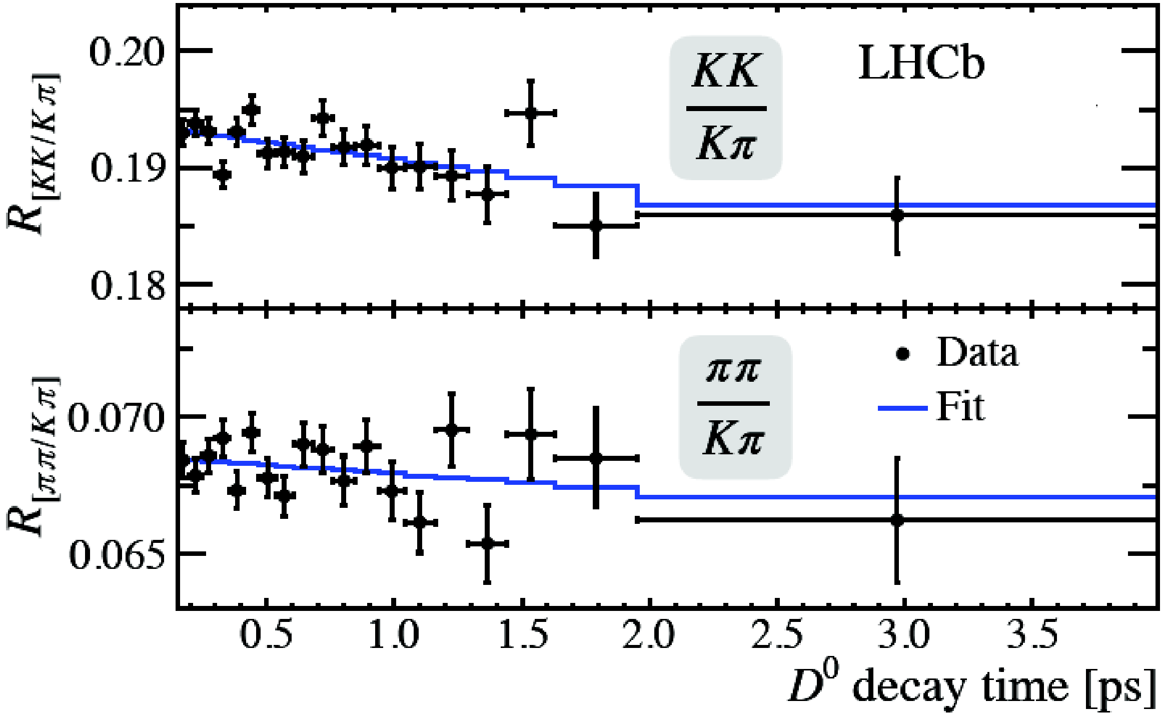
  } 5% of y or less



- Current precision not as competitive as A_Γ for CPV searches
- It is a measurement of y independent of $R(t) = Br(D^0 \to K^+\pi^-)/Br(D^0 \to K^-\pi^+)$
- At LHCb: measurement performed with Run 1 data (3 fb^{-1}) tagged with $\bar{B} \to D^0 \mu X$
- Extract y_{CP} from the time-dependent ratio between h^+h^- and $K^-\pi^+$ yields

y_{CP} result

[LHCb-PAPER-2018-038] (arXiv:1810.06874)



$$y_{CP}^{KK} = (0.63 \pm 0.15 \pm 0.11)\,\%$$

$$y_{CP}^{\pi\pi} = (0.38 \pm 0.28 \pm 0.15)\,\%$$

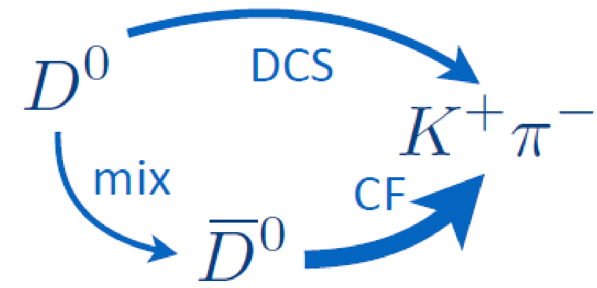
$$y_{CP} = (0.57 \pm 0.13 \pm 0.09)\,\%$$

- Compatible and with similar precision of world average (0.835 ± 0.155)%
- Compatible with $y = \left(0.67^{+0.06}_{-0.13}\right)\%$ within 1σ [HFAG CHARM18]

[PRD 97, 031101 (2018)]

Search for CPV: the $D^0 \to K^+\pi^-$ case

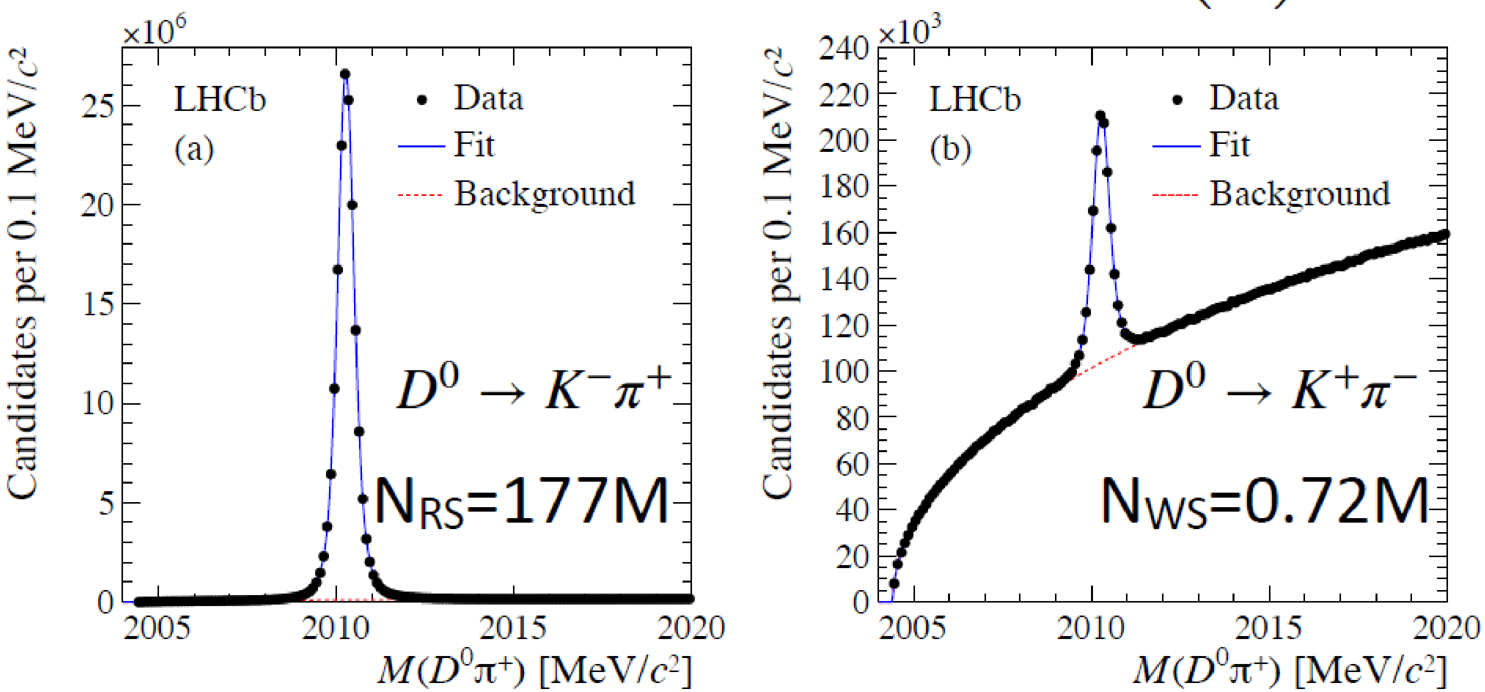
- Mixing parameters measured separately for D^0 and $\overline{D}^0$ decays
- Any different oscillation pattern between D^0 and $\overline{D}^0$ decays indicates CPV



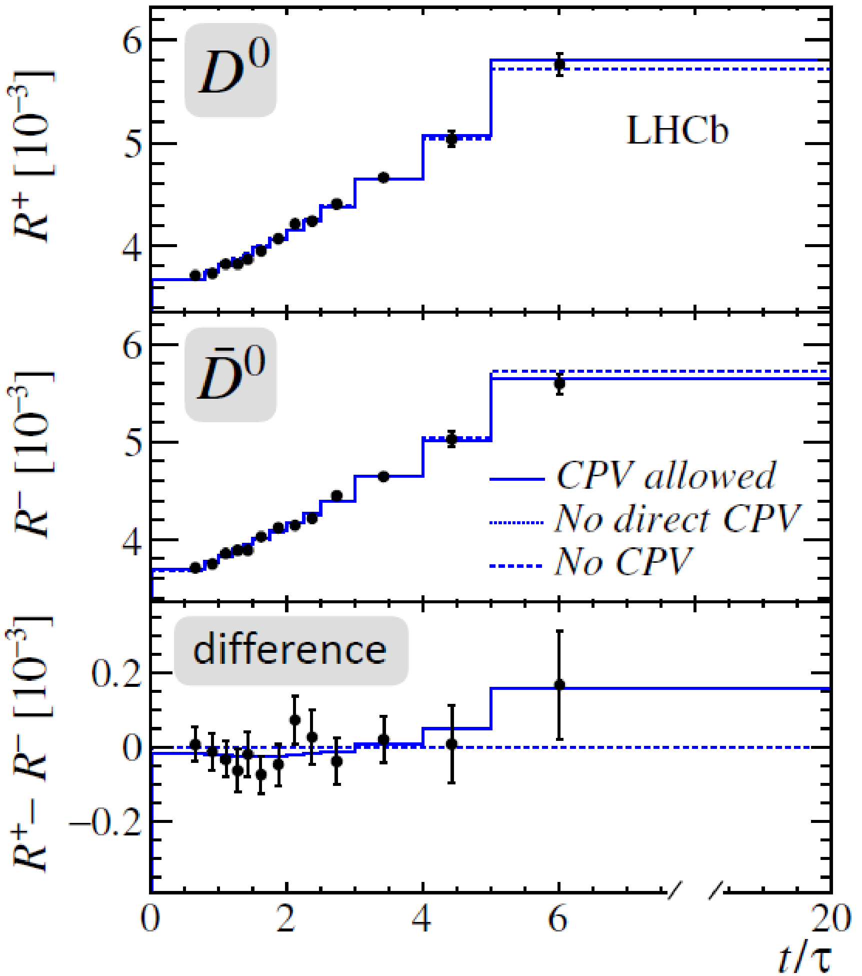
decay — mixing/decay — mixing

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

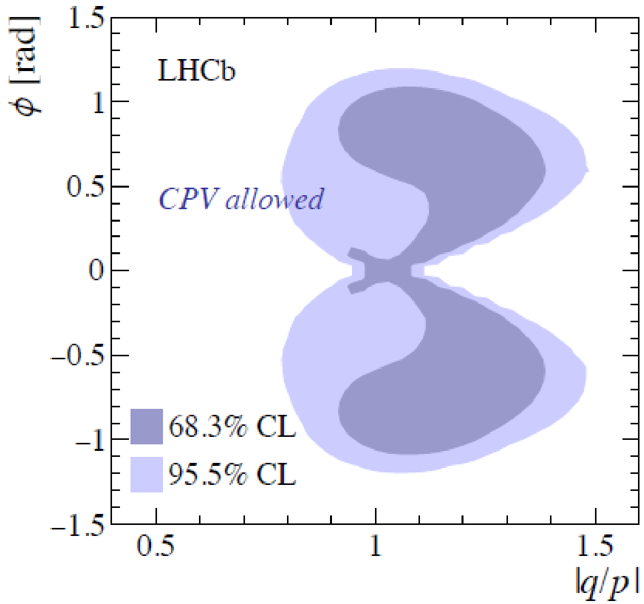
- 2011-2016: 5/fb
- Production mode: $D^{*+} \to D^0 \pi_s^+$
- Requirement on $K\pi$ invariant mass
- Ratios measured in intervals of decay time



Mixing & CPV results in $D^0 \to K^+\pi^-$



- No evidence for CPV



- If no CPV is assumed:

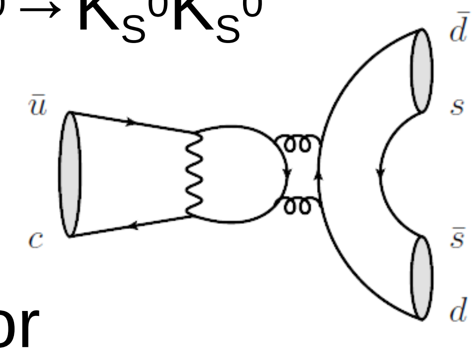
$$x'^2 = (0.039 \pm 0.023 \pm 0.014) \cdot 10^{-3}$$
$$y' = (5.28 \pm 0.45 \pm 0.27) \cdot 10^{-3}$$

- Twice as precise as previous superseded LHCb measurement [PRL 111 (2013) 251801]

[arXiv:1806.01642]

A_{CP} in $D^0 \to K_S{}^0 K_S{}^0$ decay

- Penguin annihilation diagrams contribute to $D^0 \to K_S{}^0 K_S{}^0$
  - Hint of NP if significant time-integrated A_{CP} found



- LHCb dataset: 2.0/fb, 2015-2016
- Reconstruct $D^{*+} \to D^0 \pi_s{}^+$, with $\pi_s{}^+$ to tag D^0 flavor
- Raw asymmetry:

$$A_{\text{raw}}(K_S^0 K_S^0) = A_{CP}(K_S^0 K_S^0) + A_P(D^{*+}) + A_{\text{tag}}(\pi^+)$$

- Control channel $D^0 \to K^+K^-$ to remove production & tagging asymmetries:

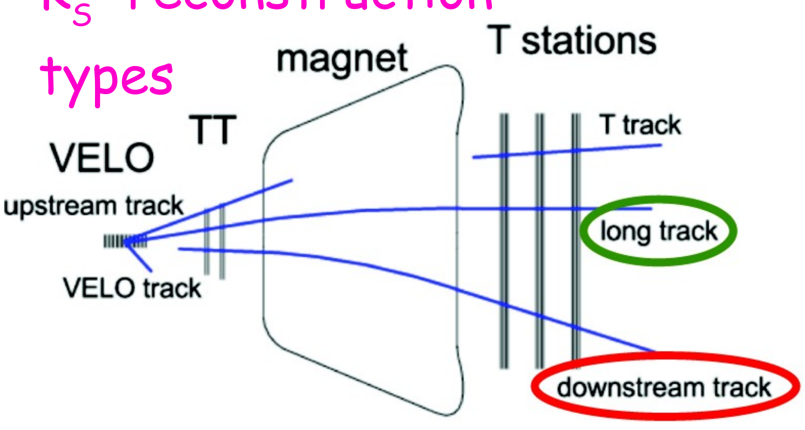
$$\begin{aligned} \Delta A_{CP} &= A_{\text{raw}}(K_S^0 K_S^0) - A_{\text{raw}}(K^+K^-) \\ &= A_{CP}(K_S^0 K_S^0) - A_{CP}(K^+K^-) \end{aligned}$$

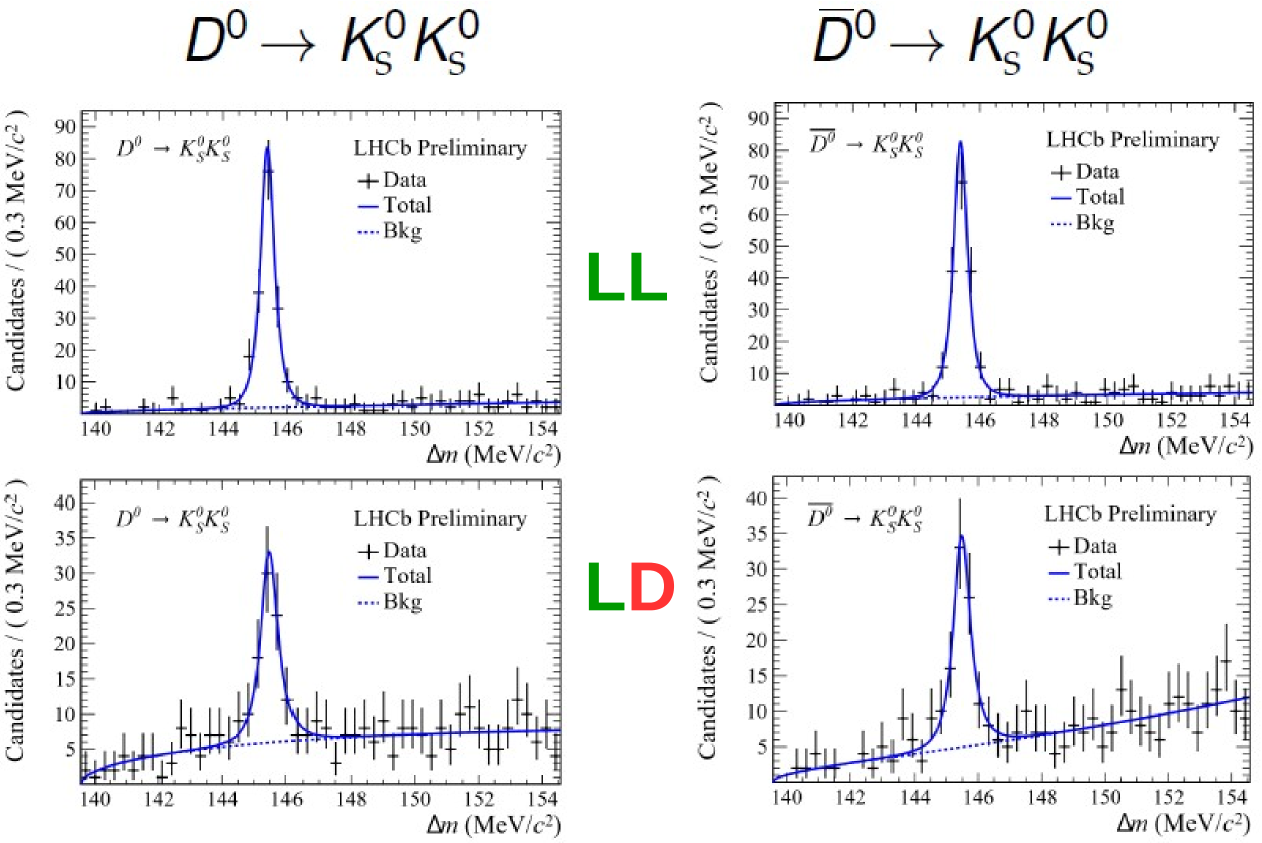
$A_{CP}(K^+K^-) = (0.04 \pm 0.12 \pm 0.10)\%$ measured by LHCb PLB 767 (2017) 177

[arXiv:1806.01642]

Result of $A_{CP}(D^0 \to K_S^0 K_S^0)$

K_S^0 reconstruction types





LL: N_{sig} = 759 ± 32
LD: N_{sig} = 308 ± 26

Results

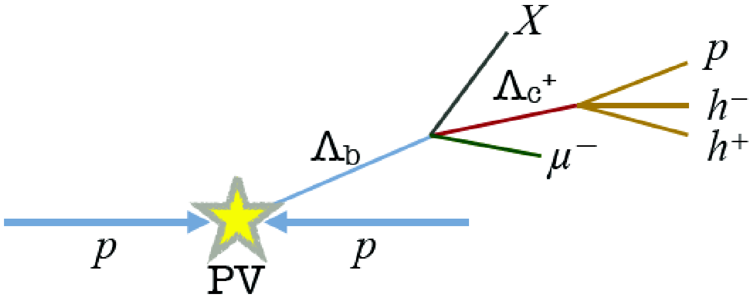
- $A_{CP} = (4.2 \pm 3.4 \pm 1.0)\%$
- Compatible with Run 1 result: $A_{CP} = (-2.9 \pm 5.2 \pm 2.2)\%$ [JHEP 10 (2015) 055]
- Average : $A_{CP} = (2.0 \pm 2.9 \pm 1.0)\%$

→ Catching up with the Belle result [PRL 119 (2017) 171801]

[JHEP 03 (2018) 182]

ΔA_{CP} in $\Lambda_c^+ \to ph^+h^-$ decays

- LHCb dataset: 3.0 fb^{-1}, Run 1
- Production mode: $\Lambda_b^0 \to \Lambda_c^+ \mu^- X$
- Raw asymmetry



$$A_{\text{raw}}(f) = A_{CP}(f) + A_P(\Lambda_b^0) + A_{\text{tag}}(\mu) + A_D(f)$$

where f = pK^+K^-, $p\pi^+\pi^-$

- Removing experimental asymmetries by taking the difference between the two final states

$$\Delta A_{\text{CP}}^{\text{wgt}} \equiv A_{\text{raw}}(\Lambda_c^+ \to pK^-K^+) - A_{\text{raw}}^{\text{wgt}}(\Lambda_c^+ \to p\pi^-\pi^+)$$
$$\approx A_{\text{CP}}(\Lambda_c^+ \to pK^-K^+) - A_{\text{CP}}^{\text{wgt}}(\Lambda_c^+ \to p\pi^-\pi^+)$$

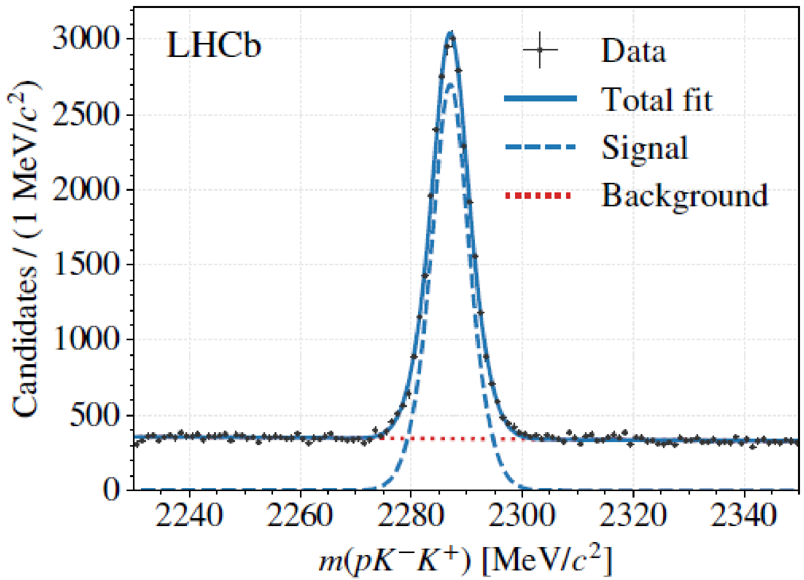
➡ Assuming same kinematics for the two final states

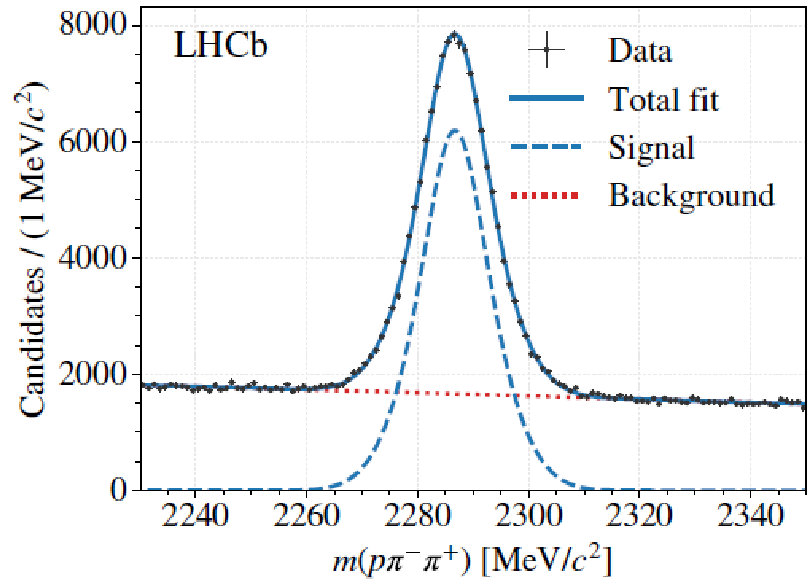
[JHEP 03 (2018) 182]

$\Delta A_{CP}(\Lambda_c^+ \rightarrow ph^+h^-)$ result

Yields $\Lambda_c^+ \to pK^-K^+$ $\Lambda_c^+ \to p\pi^-\pi^+$

$N_{\rm sig} = 25190 \pm 200$ $N_{\rm sig} = 161390 \pm 580$



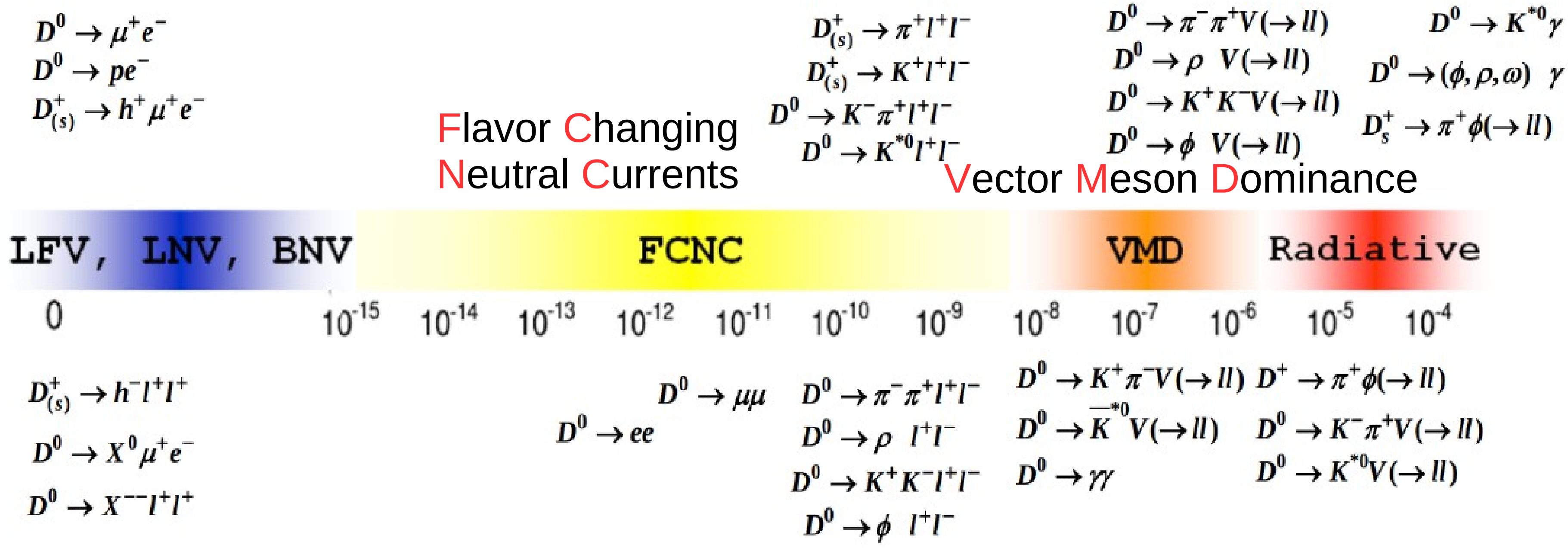


Results

$$\Delta A_{CP}^{\rm wgt} = (3.0 \pm 9.1 \pm 6.1) \times 10^{-3}$$

- First measurement of CPV parameters in 3-body Λ_c^+ decays
- No CPV observed

Overview of charm rare decays

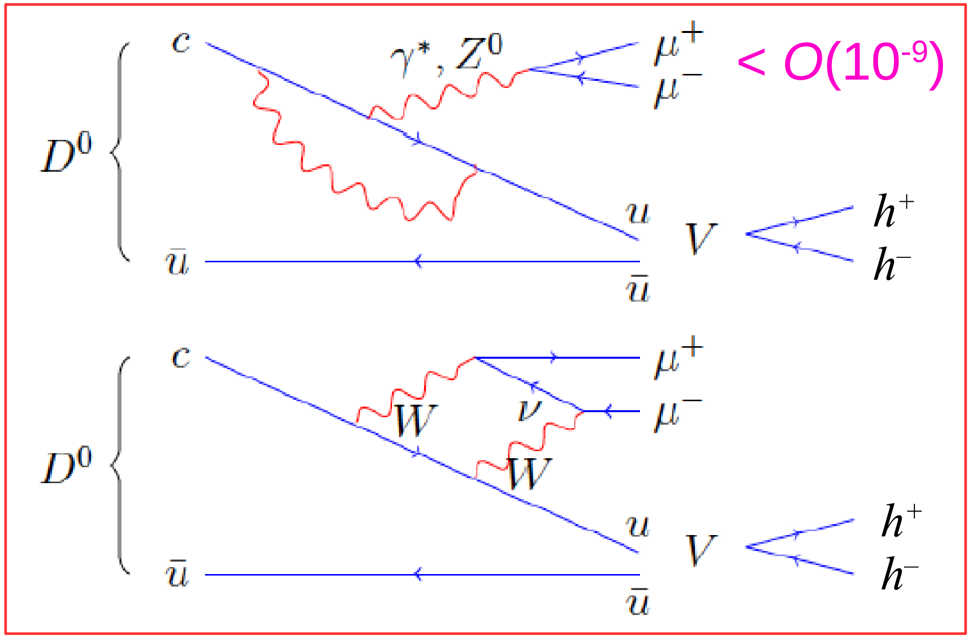


[PRD 66 (2002) 014009]

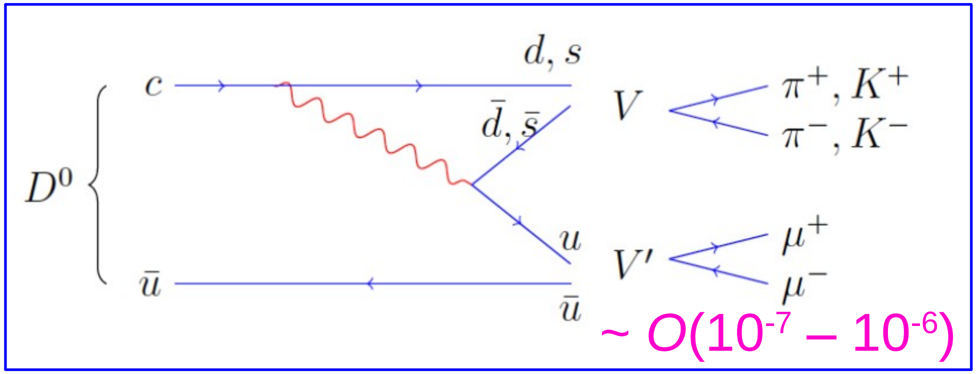
- Short-distance FCNC contributions to c → u processes are tiny < 10^{-9}
  - Only possible at the loop level
  - More suppressed than *B* decays due to GIM mechanism
  - Up-type quark FCNCs complementary to those in B and K sectors
- Branching fractions of D → X$\ell^+\ell^-$ are dominated by resonant long-distance VMD contributions

$D^0 \to h^+h^- \mu^+\mu^-$ decays

SD contributions, good for NP probes



LD contributions, hard to predict theoretically



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[PRL 121 (2018) 091801]

Asymmetries in $D^0 \to K^+K^-(\pi^+\pi^-)\mu^+\mu^-$

- Recent LHCb results[PRL 119 (2017) 191805]:

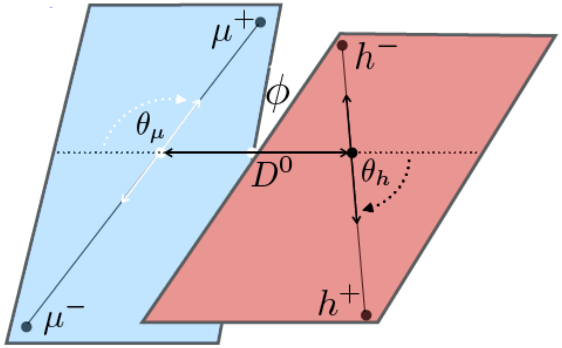
LHCb 2012 2 fb^{-1}

$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (96.4 \pm 4.8(stat) \pm 5.1(sys) \pm 9.7(\mathcal{B}_{norm})) \cdot 10^{-8}$$

$$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) = (15.4 \pm 2.7(stat) \pm 0.9(sys) \pm 1.6(\mathcal{B}_{norm})) \cdot 10^{-8}$$

  - Rarest charm decays observed so far

- Angular and CP asymmetries in SM are expected to be negligibly small



$$A_{FB} = \frac{\Gamma\left(\cos\theta_\mu > 0\right) - \Gamma\left(\cos\theta_\mu < 0\right)}{\Gamma\left(\cos\theta_\mu > 0\right) + \Gamma\left(\cos\theta_\mu < 0\right)}$$

Forward backward asymmetry

$$A_{2\phi} = \frac{\Gamma\left(\sin 2\phi > 0\right) - \Gamma\left(\sin 2\phi < 0\right)}{\Gamma\left(\sin 2\phi > 0\right) + \Gamma\left(\sin 2\phi < 0\right)}$$

Triple product asymmetry

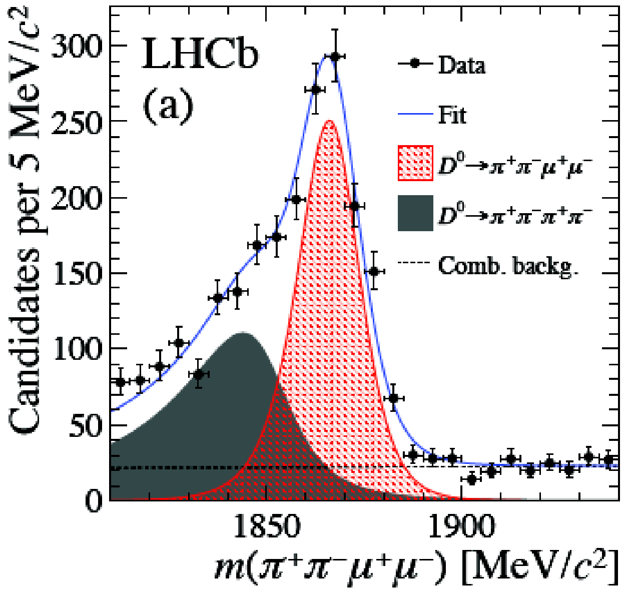
$$A_{CP} = \frac{\Gamma\left(D^0 \to h^+h^-\mu^+\mu^-\right) - \Gamma\left(\bar{D}^0 \to h^+h^-\mu^+\mu^-\right)}{\Gamma\left(D^0 \to h^+h^-\mu^+\mu^-\right) + \Gamma\left(\bar{D}^0 \to h^+h^-\mu^+\mu^-\right)}$$

CP asymmetry

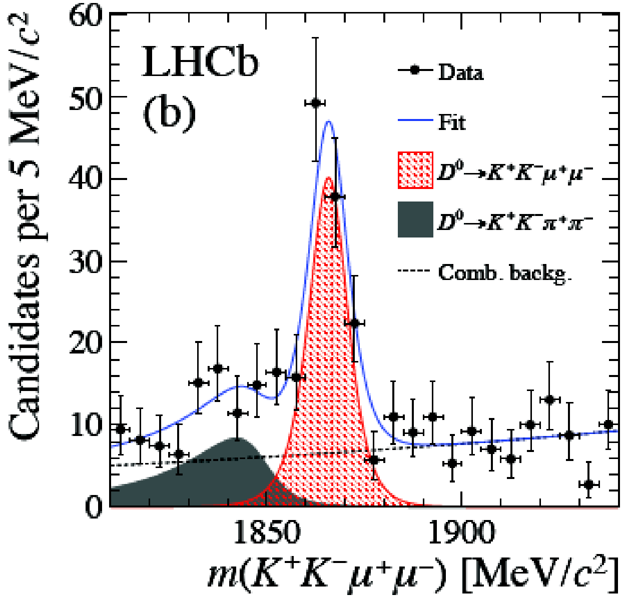
- LHCb dataset: 5/fb, 2011-2016
- Reconstruct $D^{*+} \to D^0\pi_s^+$, with π_s^+ to tag D^0 flavor

[PRL 121 (2018) 091801]

Results of asymmetries



N_{sig}: 1083 ± 41



N_{sig}: 110 ± 13

Results integrated across m($\mu^+\mu^-$)

$$A_{FB}\left(D^0 \to \pi^+\pi^-\mu^+\mu^-\right) = \left(3.3 \pm 3.7 \pm 0.6\right)\%$$

$$A_{2\phi}\left(D^0 \to \pi^+\pi^-\mu^+\mu^-\right) = \left(-0.6 \pm 3.7 \pm 0.6\right)\%$$

$$A_{CP}\left(D^0 \to \pi^+\pi^-\mu^+\mu^-\right) = (4.9 \pm 3.8 \pm 0.7)\%$$

$$A_{FB}\left(D^0 \to K^+K^-\mu^+\mu^-\right) = (0 \pm 11 \pm 2)\%$$

$$A_{2\phi}\left(D^0 \to K^+K^-\mu^+\mu^-\right) = (9 \pm 11 \pm 1)\%$$

$$A_{CP}\left(D^0 \to K^+K^-\mu^+\mu^-\right) = (0 \pm 11 \pm 2)\%$$

[PRL 121 (2018) 091801]

Results of asymmetries

$m(\mu^+\mu^-)$ [MeV/c^2]	Signal asymmetries A_{FB} [%]	$A_{2\phi}$ [%]	A_{CP} [%]
		$D^0 \to \pi^+\pi^-\mu^+\mu^-$	
<525	$2 \pm 20 \pm 2$	$-28 \pm 20 \pm 2$	$17 \pm 20 \pm 2$
525–565	...	...	...
565–780	$8.1 \pm 7.1 \pm 0.7$	$7.4 \pm 7.1 \pm 0.7$	$-12.9 \pm 7.1 \pm 0.7$
780–950	$7 \pm 10 \pm 1$	$-14 \pm 10 \pm 1$	$17 \pm 10 \pm 1$
950–1020	$3.1 \pm 6.5 \pm 0.6$	$1.2 \pm 6.4 \pm 0.5$	$7.5 \pm 6.5 \pm 0.7$
1020–1100	$0.9 \pm 5.6 \pm 0.7$	$1.4 \pm 5.5 \pm 0.6$	$9.9 \pm 5.5 \pm 0.7$
>1100	...	...	...
Full range	$3.3 \pm 3.7 \pm 0.6$	$-0.6 \pm 3.7 \pm 0.6$	$4.9 \pm 3.8 \pm 0.7$
		$D^0 \to K^+K^-\mu^+\mu^-$	
<525	$13 \pm 26 \pm 4$	$9 \pm 26 \pm 3$	$-33 \pm 26 \pm 4$
525–565	...	...	...
>565	$1 \pm 12 \pm 1$	$22 \pm 12 \pm 1$	$13 \pm 12 \pm 1$
Full range	$0 \pm 11 \pm 2$	$9 \pm 11 \pm 1$	$0 \pm 11 \pm 2$

Results integrated across $m(\mu^+\mu^-)$

$$A_{FB}\left(D^0 \to \pi^+\pi^-\mu^+\mu^-\right) = \left(3.3 \pm 3.7 \pm 0.6\right)\%$$

$$A_{2\phi}\left(D^0 \to \pi^+\pi^-\mu^+\mu^-\right) = \left(-0.6 \pm 3.7 \pm 0.6\right)\%$$

$$A_{CP}\left(D^0 \to \pi^+\pi^-\mu^+\mu^-\right) = (4.9 \pm 3.8 \pm 0.7)\%$$

$$A_{FB}\left(D^0 \to K^+K^-\mu^+\mu^-\right) = (0 \pm 11 \pm 2)\%$$

$$A_{2\phi}\left(D^0 \to K^+K^-\mu^+\mu^-\right) = (9 \pm 11 \pm 1)\%$$

$$A_{CP}\left(D^0 \to K^+K^-\mu^+\mu^-\right) = (0 \pm 11 \pm 2)\%$$

- All measured asymmetries are compatible with zero
- No observed dependency on dimuon mass

[PRD 97 (2018) 091101(R)]

Search for $\Lambda_c^+ \to p\mu^+\mu^-$

- LHCb dataset: 3/fb Run1 data using $\Lambda_c^+ \to p\phi(\to \mu^+\mu^-)$ as reference mode
- Upper limit on non-resonant component:

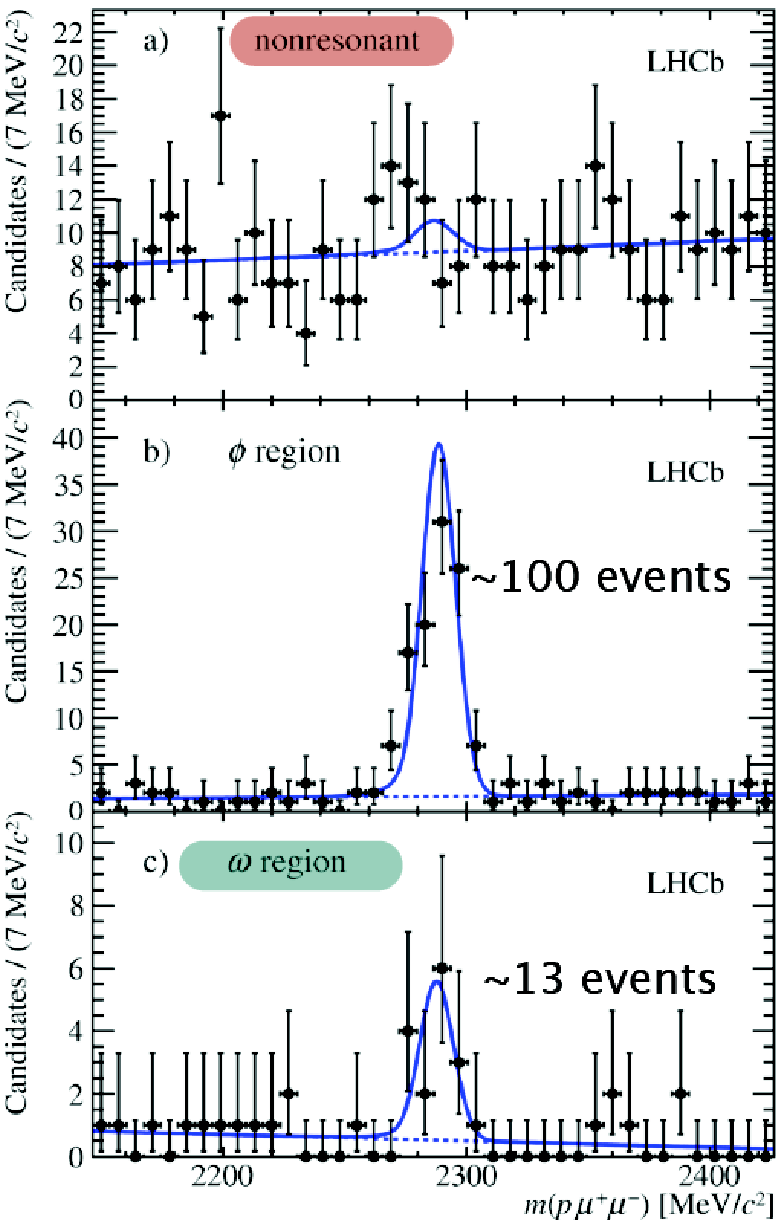
$B(\Lambda_c^+ \to p\mu^+\mu^-) < 9.6 \times 10^{-8}$ at 95% CL

10^3x better than BaBar for the integrated $m(\mu^+\mu^-)$ [PRD 84 (2011) 072006]

- First observation of $\Lambda_c^+ \to p\omega(\to \mu^+\mu^-)$:

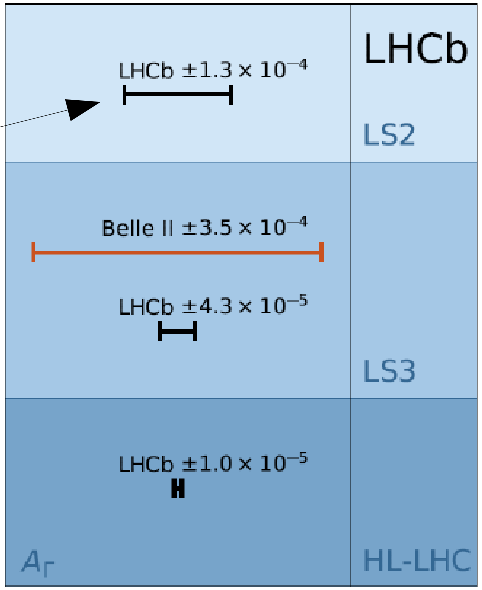
$B(\Lambda_c^+ \to p\omega) = (9.4 \pm 3.2 \pm 1.0 \pm 2.0) \times 10^{-4}$

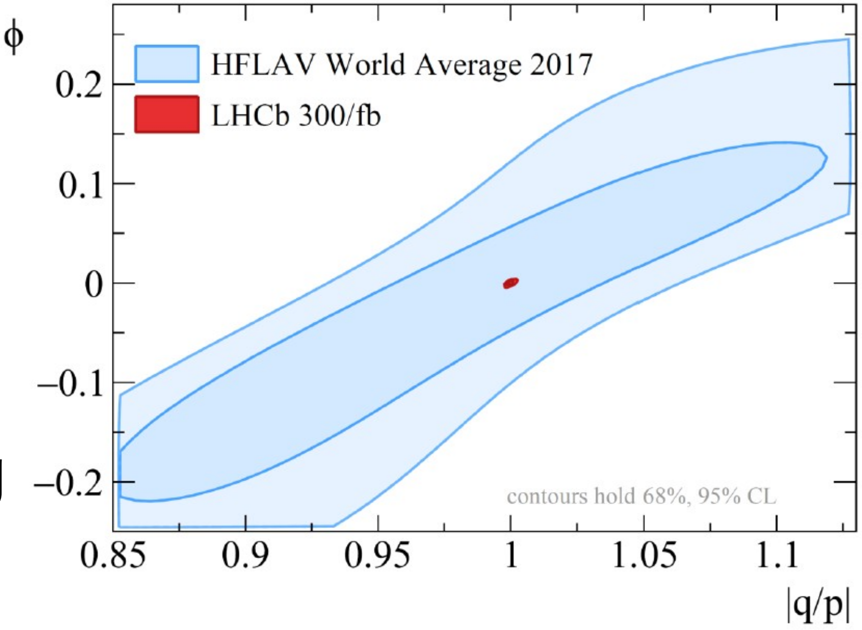
Uncertainties are: statistical, systematic and due to the BF of the normalization mode.



LHCb Run2 and Beyond

- Many more Run2 analysis are ongoing, and we are approaching 10^{-4} precision on A_Γ
- Upgrade (2020-2023) will provide 3x larger dataset, very similar to current experiment
  - Analysis strategies will follow what's done in LHCb
- Upgrade (2025-) will be for HL-LHC to collect 300/fb
  - Ambitious but extremely rewarding





CPV in $D_{(s)}$ decays involving K_s^0 @ LHCb

- CPV in charmed meson CF decays to Ks is theoretically suggested to be attributed to three parts:

$$A_{CP}(t) \simeq \left[A_{CP}^{\overline{K}^0}(t) + A_{CP}^{\rm dir}(t) + A_{CP}^{\rm int}(t)\right] / D(t).$$

The current precision of $O(10^{-3})$ has been pushed that interference part is not negligible, as suggested by Yu et al. [PRL, 119 (2017) 181802]

- The CP asymmetry difference $\Delta A_{CP}^{K^+,\pi^+}$ between $A_{CP}^{D^+\to\pi^+K_S}$ and $A_{CP}^{D_S^+\to K^+K_S}$ provide a mode-independent way to measure the interference part
  ➔ a more realistic way to test the better-controlled SM prediction
  ➔ NP can enhance the asymmetry
- LHCb will have a precision of sub-level of permillage
  ➔ search for the CP asymmetry difference at the level of 10^{-3}.

See Prof. Yu's talk this morning: link

Summary

- LHCb is a charm factory and has the world's largest sample of charm decays
- High statistics and superb detector performance allow for high precision measurements on A_{CP} parameters and search for rare decays
- Many more charm results in the pipeline using Run 1 and Run 2 data, stay tuned!
- Longer term: LHCb's first upgrade begins at the end of the year
  - Will allow for measurements with 10x larger samples
- Synergy with BESIII important for CPV searches in the charm sector

谢谢！

Backup Slides

Charm flavour tagging

- In order to measure mixing and CPV, it is necessary to identify the flavour of the D^0 meson.
- LHCb exploits two decays:
  - $D^{*+} \rightarrow D^0 \pi^+$ decays
  - semi-leptonic B-decays