Recent Results and Prospect of Charm Physics @ LHCb

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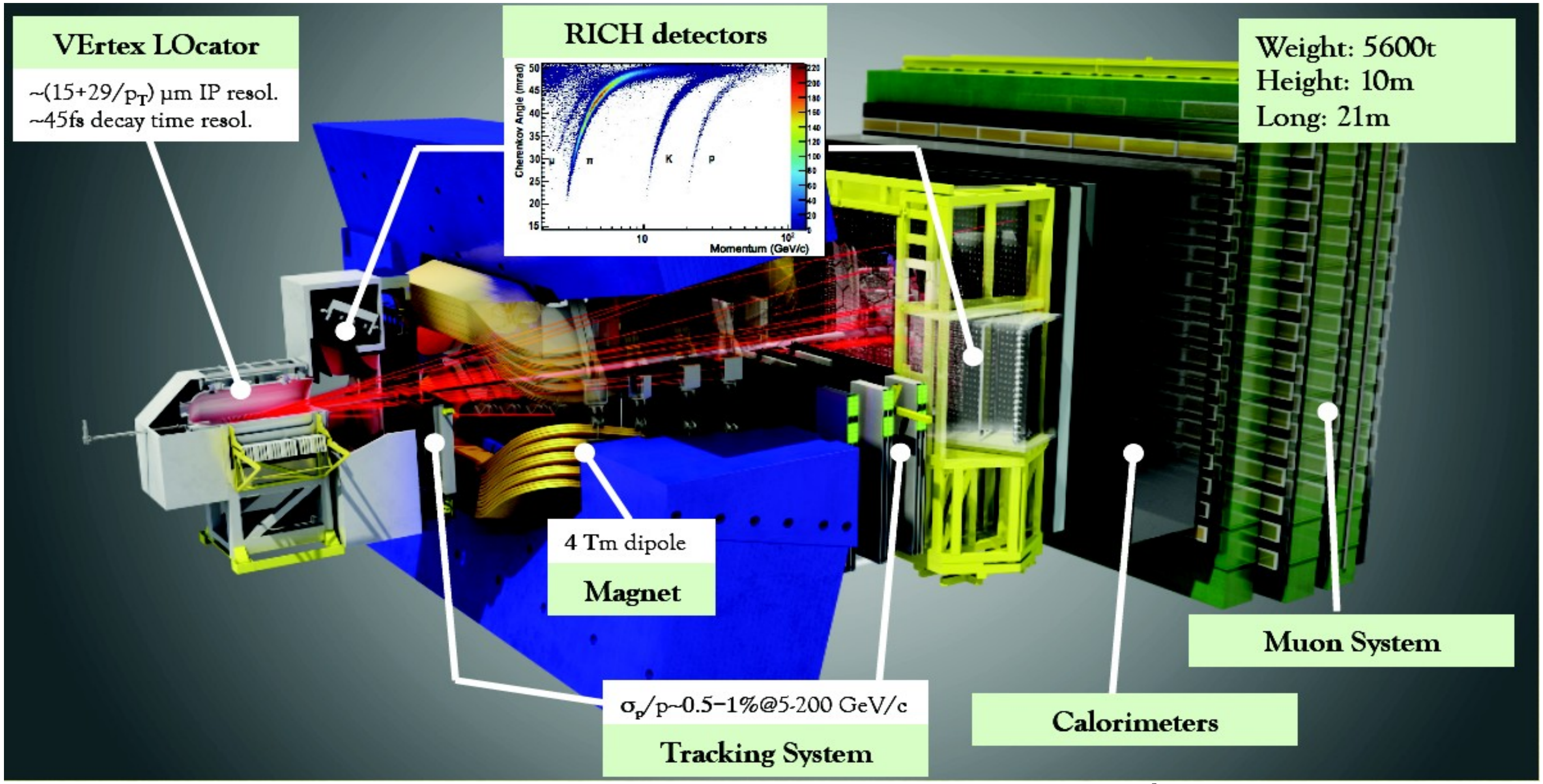
Outline

- Highlights of recent LHCb results:
  - CPV in two-body D decays
  - CPV in multi-body charm decays
  - Rare charm decays
  - Branching fractions

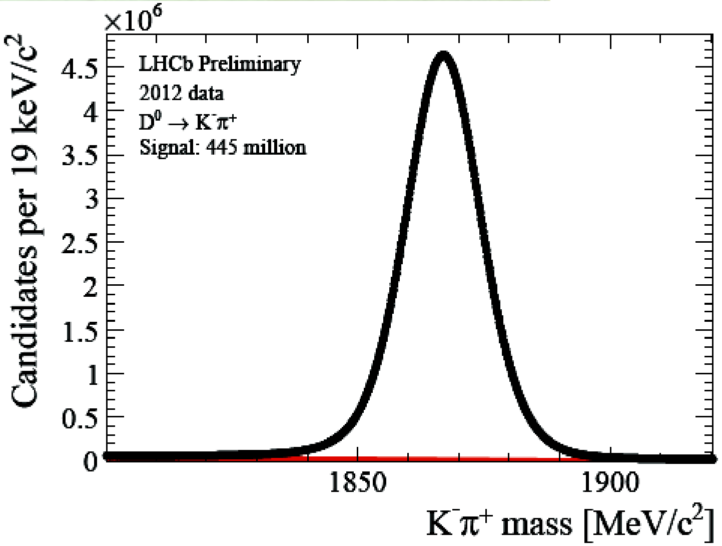
  For a complete paper list on charm, see LHCb link
- Ongoing LHCb work on charm
- Prospects

LHCb experiment



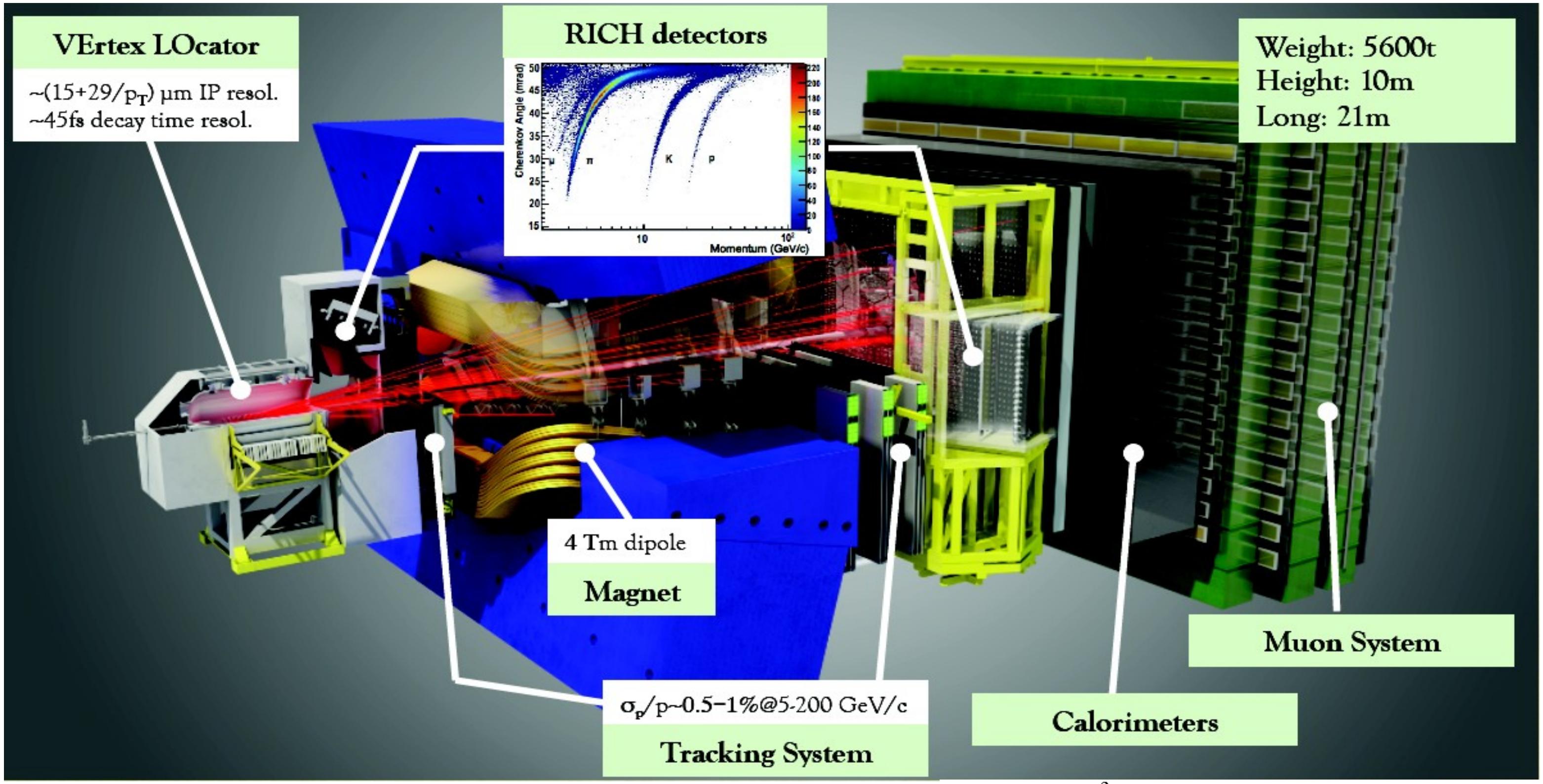
Int. J. Mod. Phys. A 30, 1530022 (2015)

- LHCb acceptance: 2 < η < 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

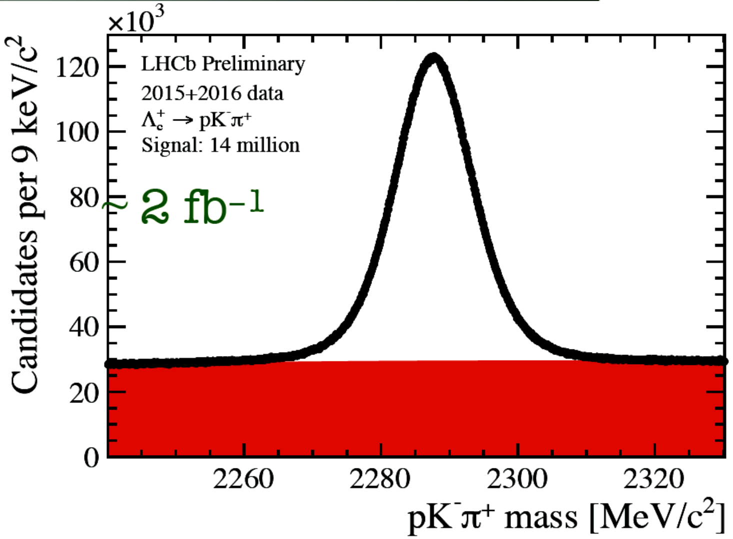
LHCb experiment



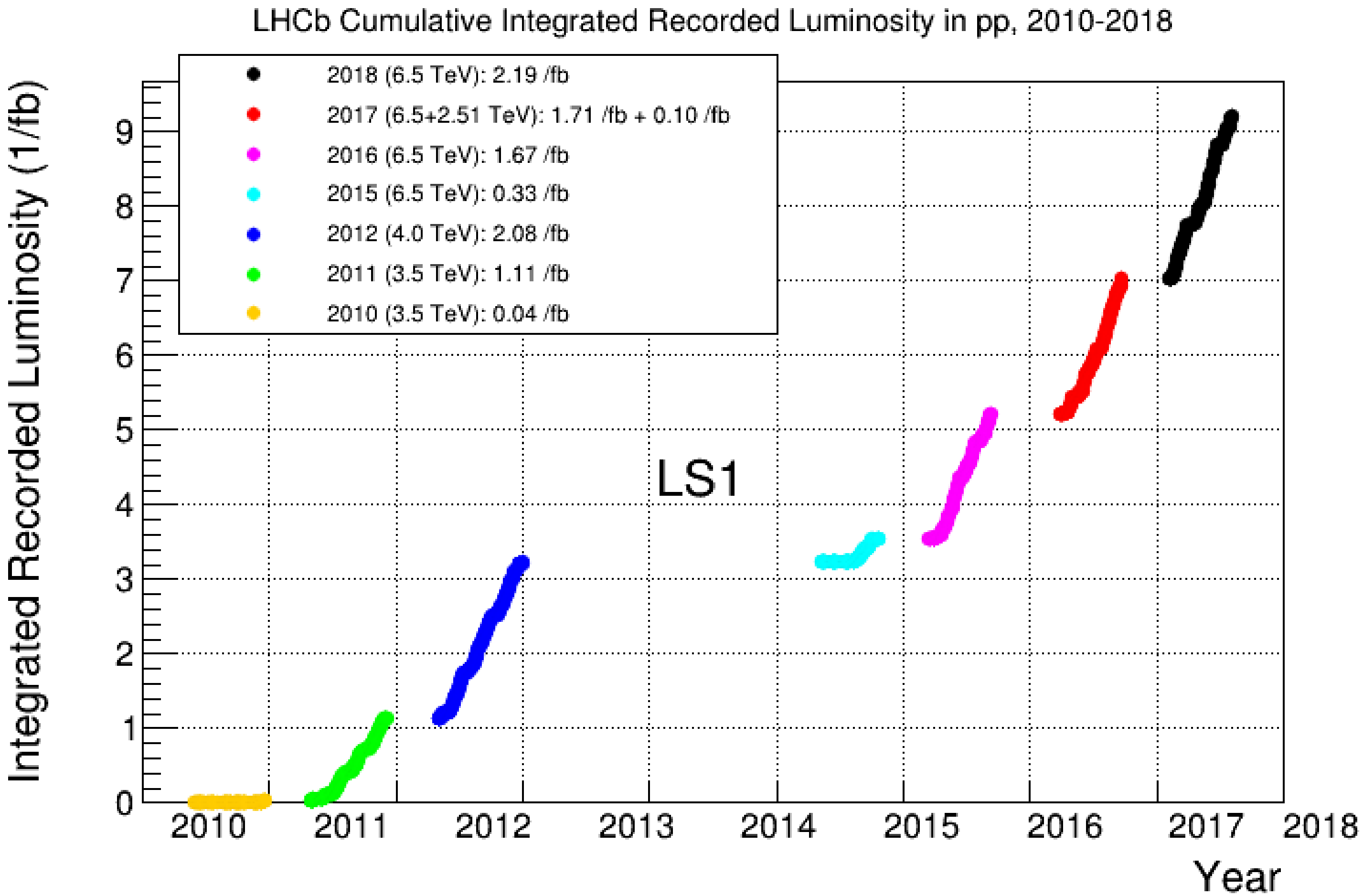
Int. J. Mod. Phys. A 30, 1530022 (2015)

Also large samples of charm baryon decays

- ~7M $\Lambda_c^+ \rightarrow pK^-\pi^+$ decays / fb^{-1} directly from the trigger



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 observed
- CPV in charm sector yet to be found

Unitarity triangle for charm

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

$$\sim\lambda \qquad \sim\lambda \qquad \sim\lambda^{5}$$

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

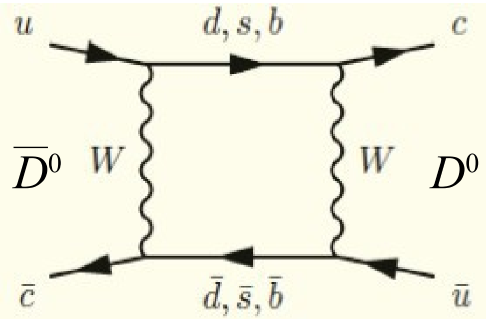
Expected CPV very small in charm

- 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 $\left|\frac{\overline{A}_f}{A_f}\right|^{\pm 2} \approx 1 \pm A_d$ ➔ $a_{CP}^{dir} \approx -\frac{1}{2} A_d$



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

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

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:

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

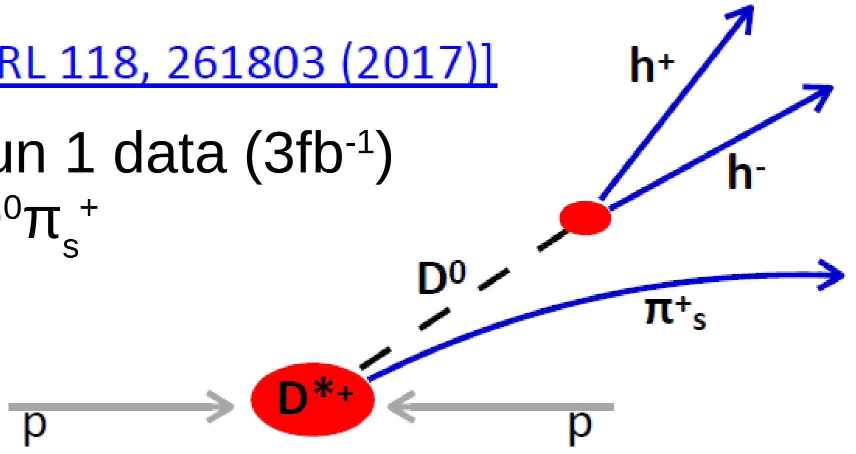
$$A_\Gamma = \frac{1}{2}\left[\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y\cos\phi + \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x\sin\phi\right] \approx y\left(\left|\frac{q}{p}\right| - 1\right) - x\phi$$

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)]

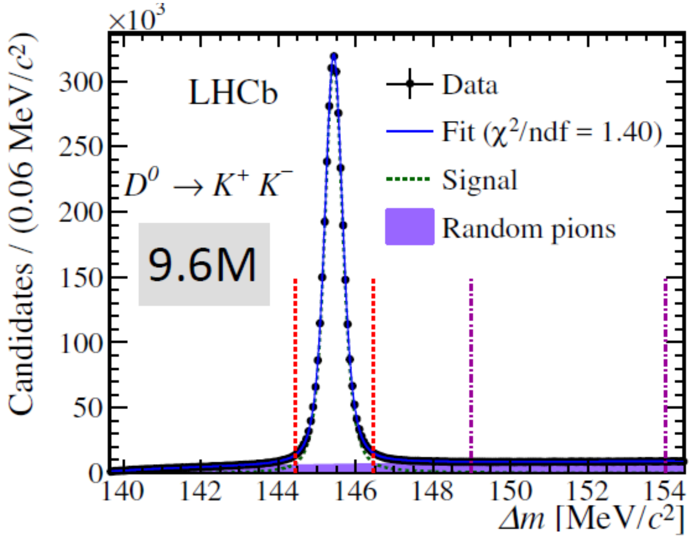
- At LHCb: measurement performed with Run 1 data ($3 fb^{-1}$)
- D^0 flavor tagged from strong decay $D^{*+} \rightarrow D^0\pi_s^+$

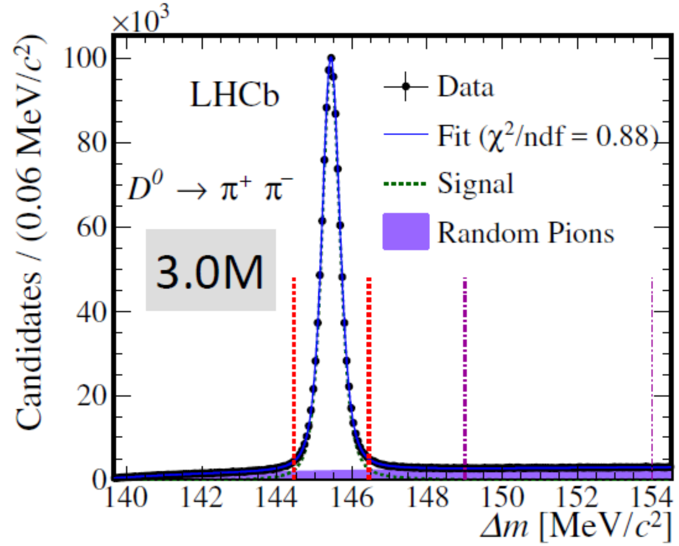


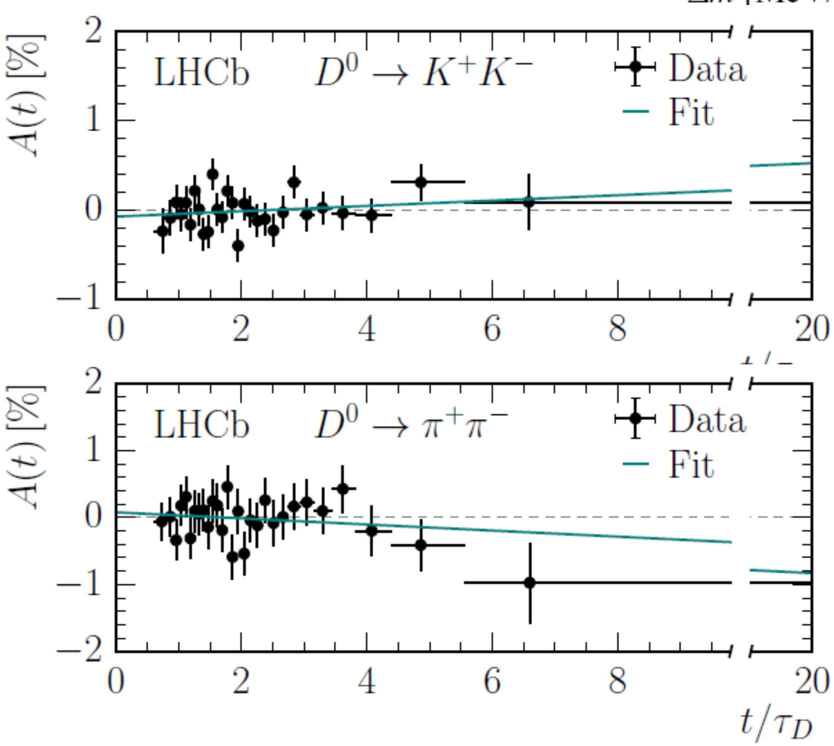
A_Γ results

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

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







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

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

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}

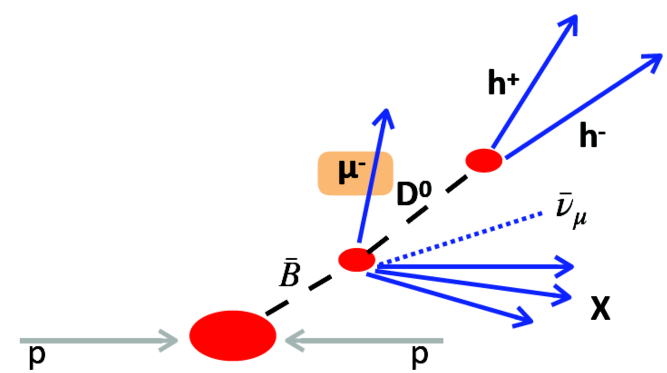
Search for CPV: measuring y_{CP}

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

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

- 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, $|q/p|-1$

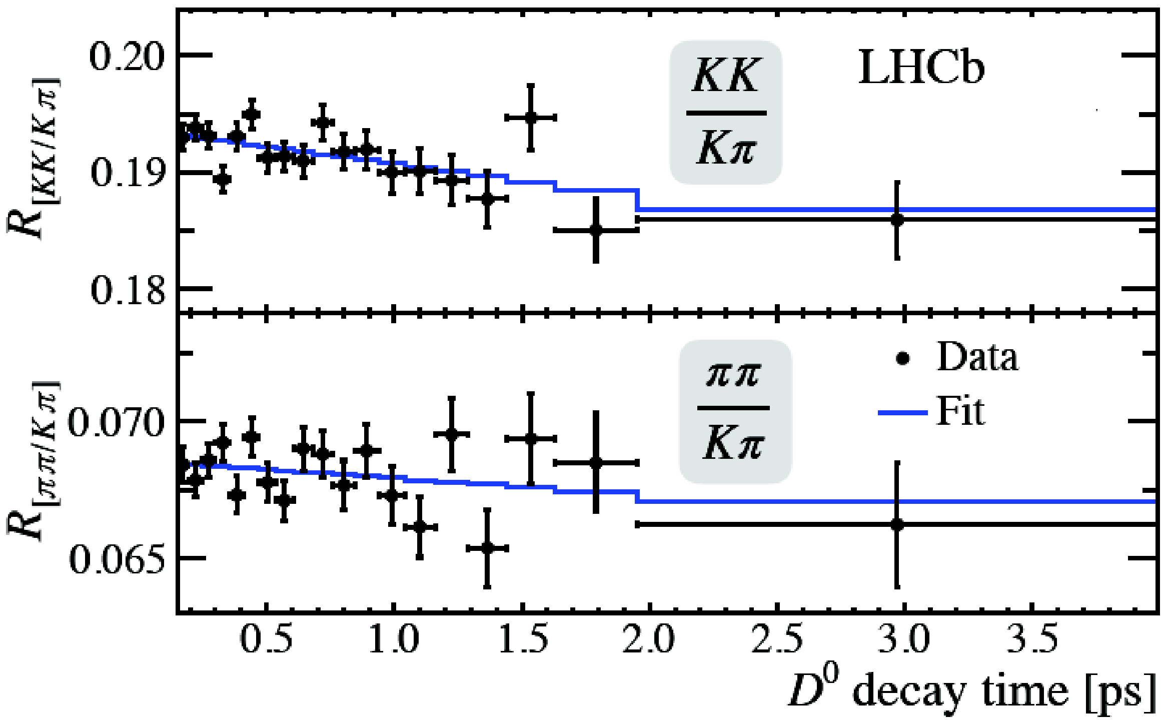
  } 5% of y or less



- 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 $\overline{B} \to D^0 \mu X$
- 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)



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

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

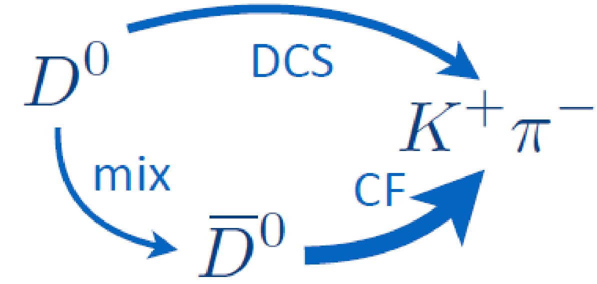
$$y_{CP} = (0.57 \pm 0.13 \pm 0.09)\,\%$$

- 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

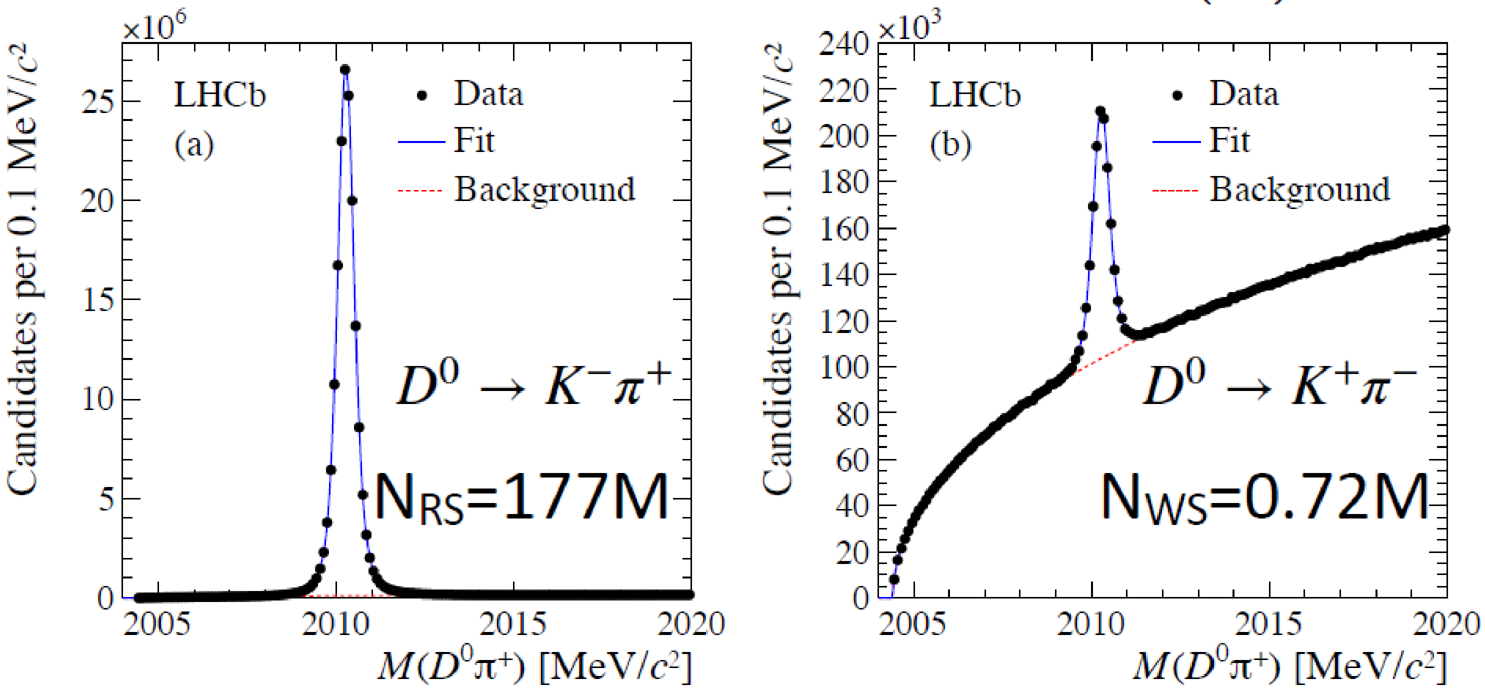
- Mixing parameters measured separately for D^0 and $\bar{D}^0$ decays
- Any different oscillation pattern between D^0 and $\bar{D}^0$ decays indicates CPV



decay *mixing/decay* *mixing*

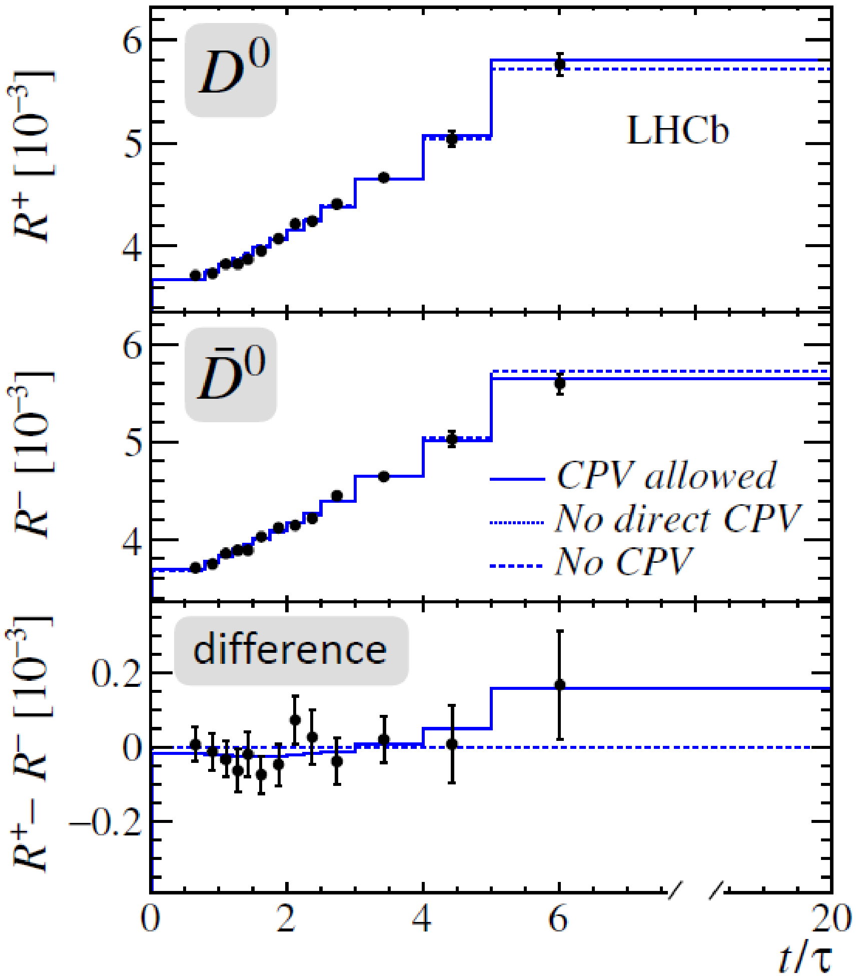
$$R^{\pm}(t) = \frac{N^{\pm}_{WS}(t)}{N^{\pm}_{RS}(t)} \approx R^{\pm}_{D} + \sqrt{R^{\pm}_{D}}\, y'^{\pm}\frac{t}{\tau} + \frac{x'^{\pm 2} + y'^{\pm 2}}{4}\left(\frac{t}{\tau}\right)^2$$

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

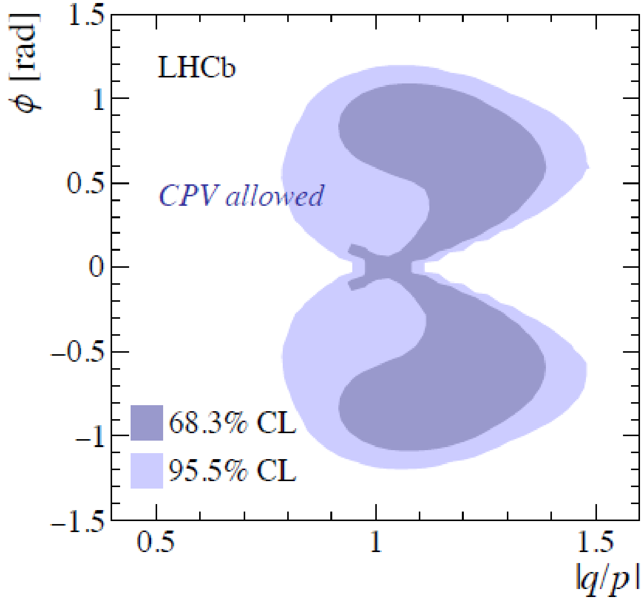


[PRD 97, 031101 (2018)]

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



- No evidence for CPV



- If no CPV is assumed:

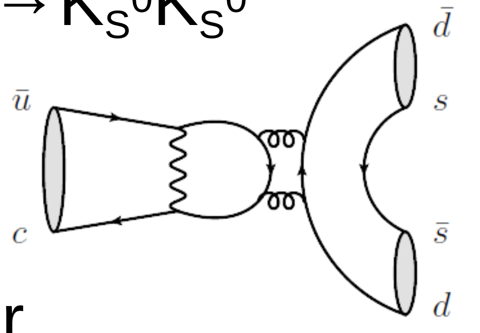
$$x'^2 = (0.039 \pm 0.023 \pm 0.014) \cdot 10^{-3}$$
$$y' = (5.28 \pm 0.45 \pm 0.27) \cdot 10^{-3}$$

- 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 π_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:

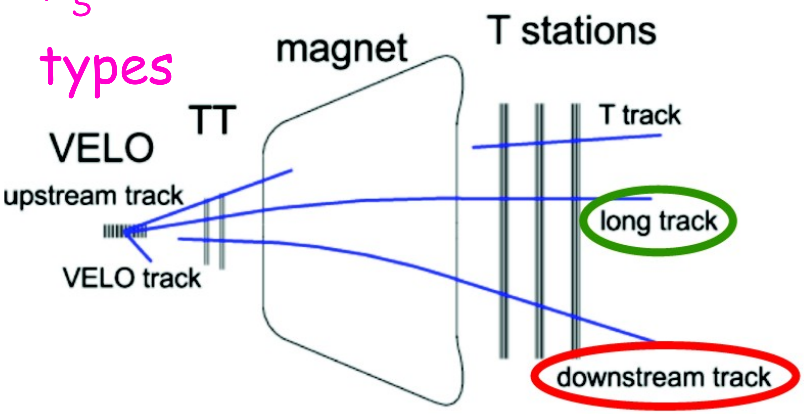
$$\begin{aligned} \Delta A_{CP} &= A_{\text{raw}}(K_S^0 K_S^0) - A_{\text{raw}}(K^+ K^-) \\ &= A_{CP}(K_S^0 K_S^0) - A_{CP}(K^+ K^-) \end{aligned}$$

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

[arXiv:1806.01642]

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

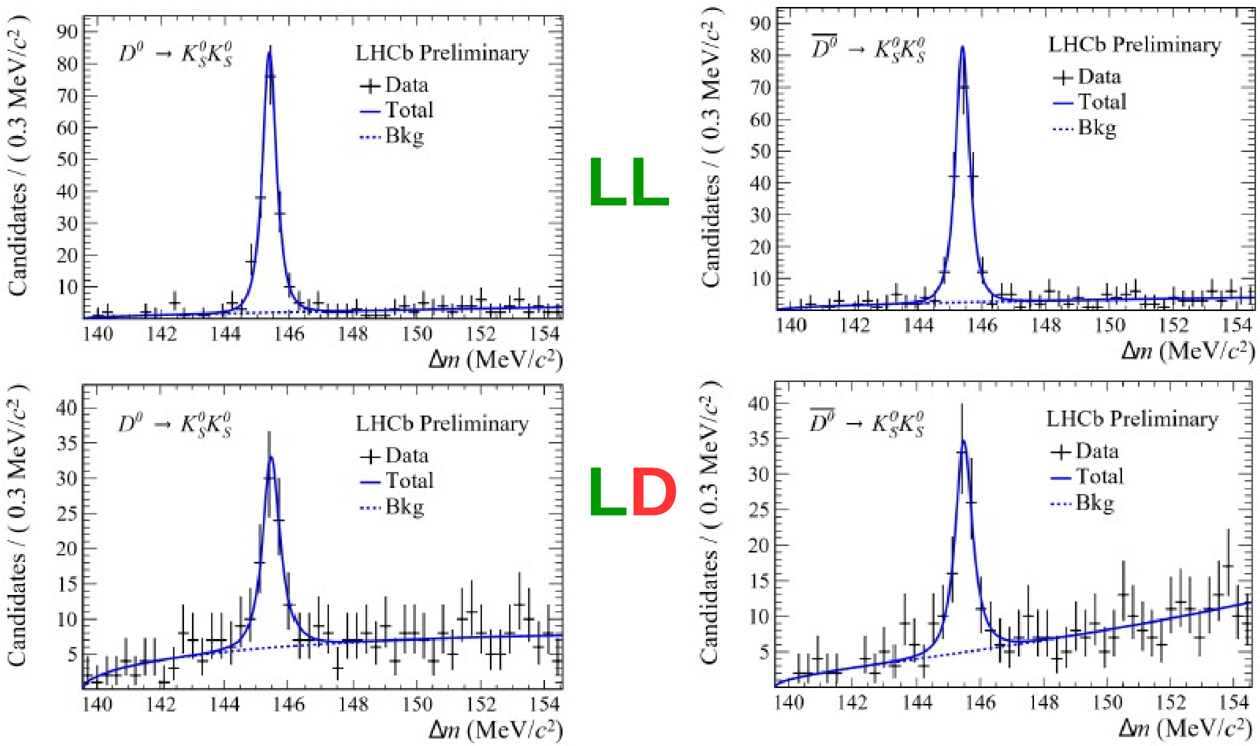
K_S^0 reconstruction types



LL: $N_{sig} = 759 \pm 32$

LD: $N_{sig} = 308 \pm 26$

$D^0 \to K_S^0 K_S^0$ $\qquad$ $\overline{D}^0 \to K_S^0 K_S^0$



Results

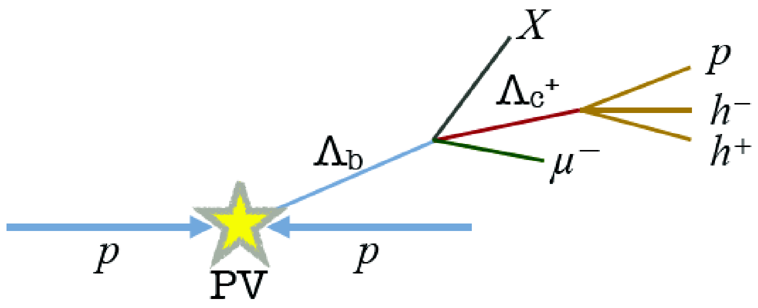
- $A_{CP} = (4.2 \pm 3.4 \pm 1.0)\%$
- Compatible with Run 1 result: $A_{CP} = (-2.9 \pm 5.2 \pm 2.2)\%$ [JHEP 10 (2015) 055]
- Average : $A_{CP} = (2.0 \pm 2.9 \pm 1.0)\%$

→ 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



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

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

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

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

➡ Assuming same kinematics for the two final states

[JHEP 03 (2018) 182]

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

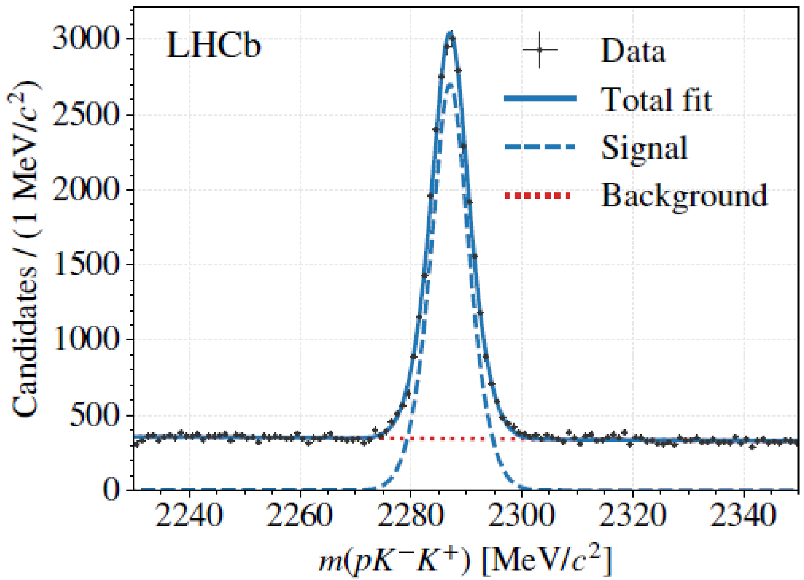
Yields

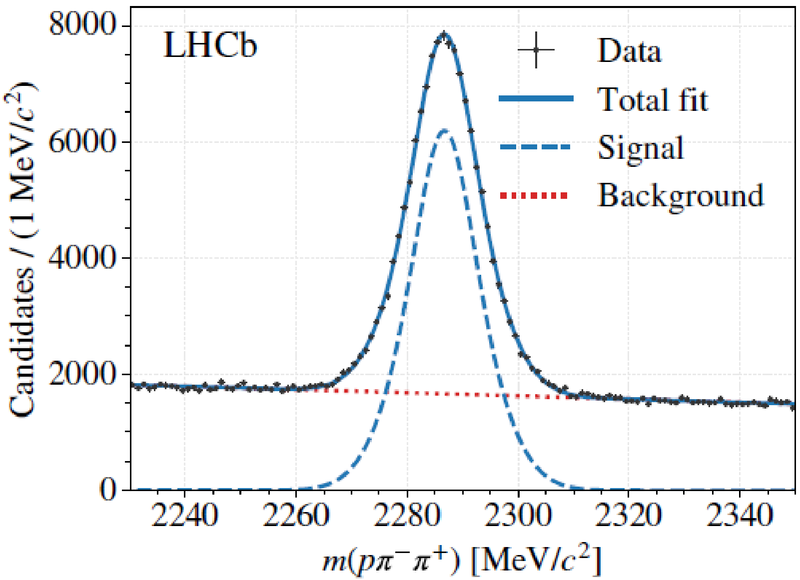
$\Lambda_c^+ \to pK^-K^+$

$N_{\text{sig}} = 25190 \pm 200$

$\Lambda_c^+ \to p\pi^-\pi^+$

$N_{\text{sig}} = 161390 \pm 580$





Results

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

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

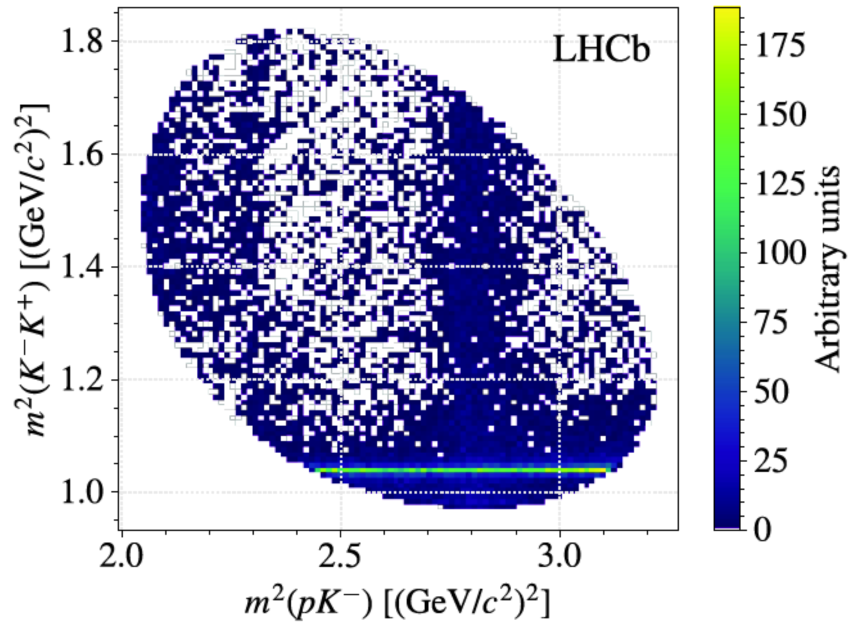
[JHEP 03 (2018) 182]

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

Yields

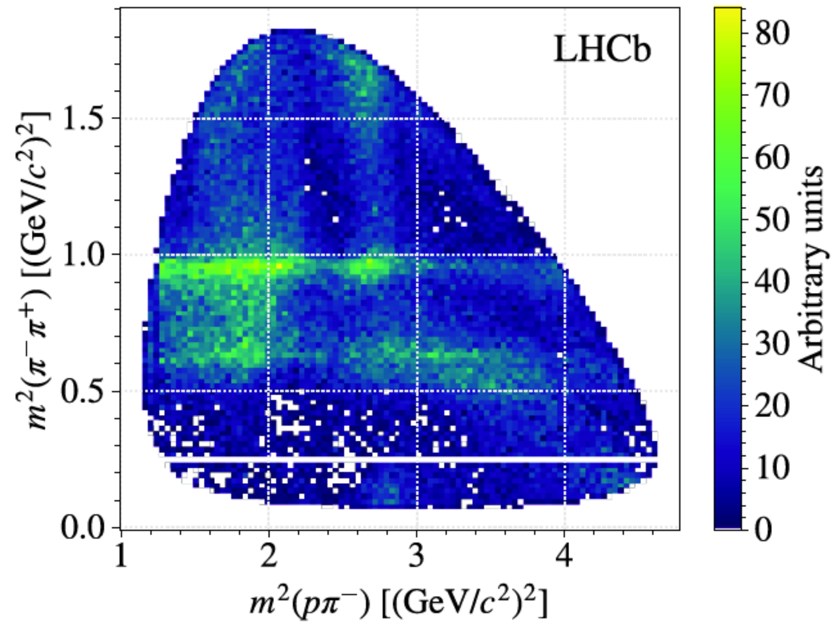
$\Lambda_c^+ \to pK^-K^+$

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



$\Lambda_c^+ \to p\pi^-\pi^+$

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



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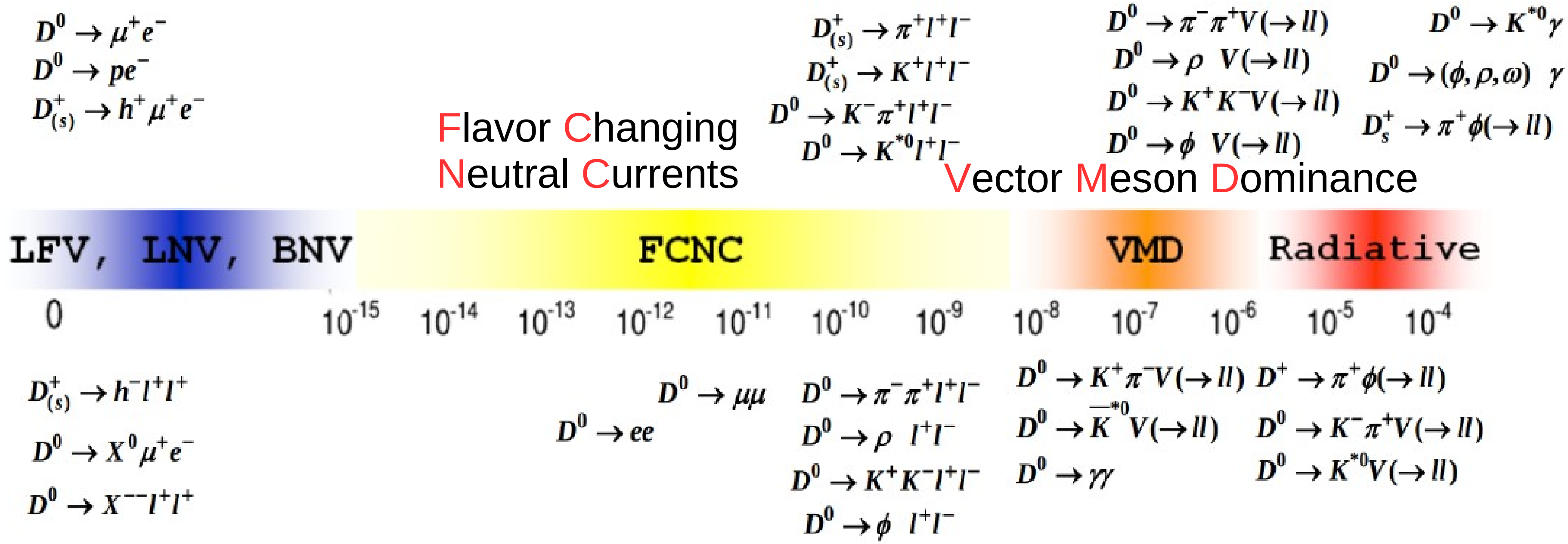
Overview of charm rare decays

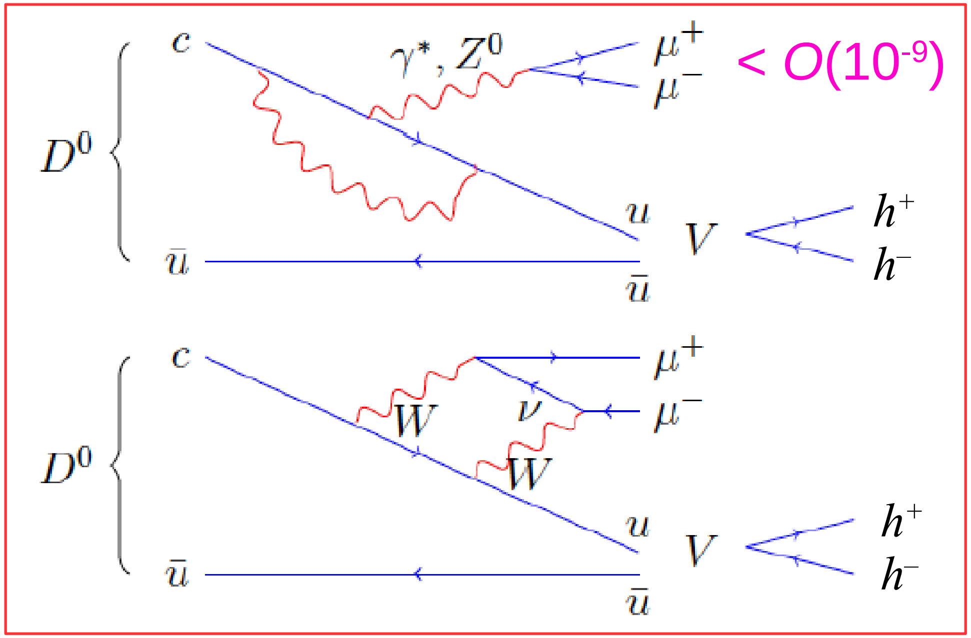


[PRD 66 (2002) 014009]

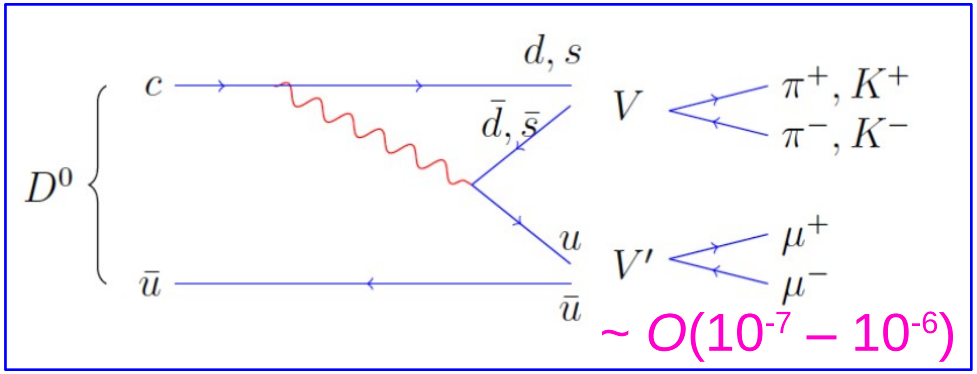
- Short-distance FCNC contributions to c→u processes are tiny < 10^{-9}
  - Only possible at the loop level
  - More suppressed than *B* decays due to GIM mechanism
  - Up-type quark FCNCs complementary to those in B and K sectors
- Branching fractions of D → X$\ell^+\ell^-$ are dominated by resonant 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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Asymmetries in $D^0 \to K^+K^-(\pi^+\pi^-)\mu^+\mu^-$

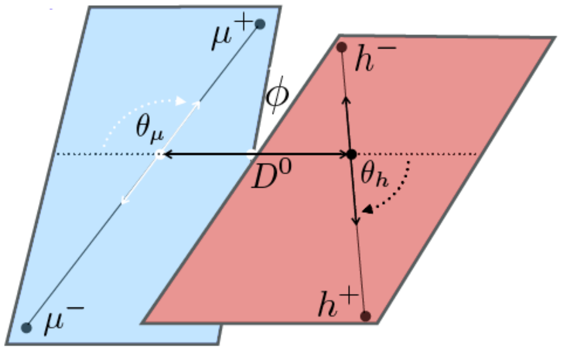
- Recent LHCb results[PRL 119 (2017) 191805]:

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

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

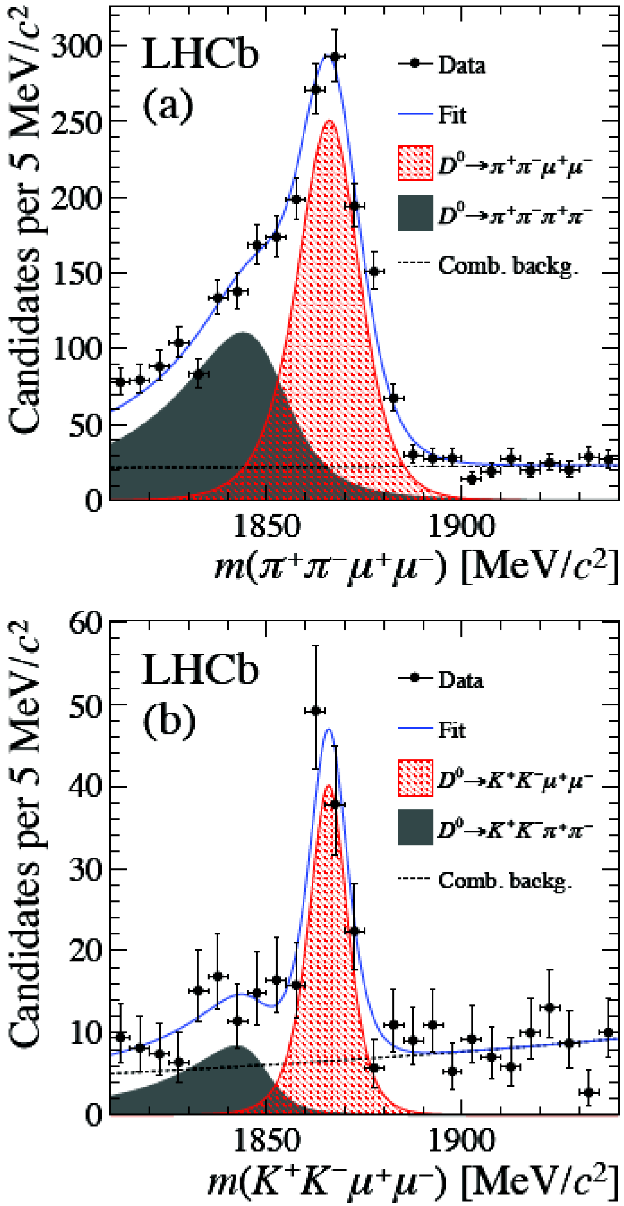
Triple product asymmetry

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

CP asymmetry

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

Results of asymmetries



N_{sig}: 1083 ± 41

N_{sig}: 110 ± 13

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

$$A_{FB}\left(D^0\to\pi^+\pi^-\mu^+\mu^-\right) = \left(3.3\pm3.7\pm0.6\right)\%$$

$$A_{2\phi}\left(D^0\to\pi^+\pi^-\mu^+\mu^-\right) = \left(-0.6\pm3.7\pm0.6\right)\%$$

$$A_{CP}\left(D^0\to\pi^+\pi^-\mu^+\mu^-\right) = (4.9\pm3.8\pm0.7)\%$$

$$A_{FB}\left(D^0\to K^+K^-\mu^+\mu^-\right) = (0\pm11\pm2)\%$$

$$A_{2\phi}\left(D^0\to K^+K^-\mu^+\mu^-\right) = (9\pm11\pm1)\%$$

$$A_{CP}\left(D^0\to K^+K^-\mu^+\mu^-\right) = (0\pm11\pm2)\%$$

[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 $\Lambda_c^+ \rightarrow p\mu^+\mu^-$

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

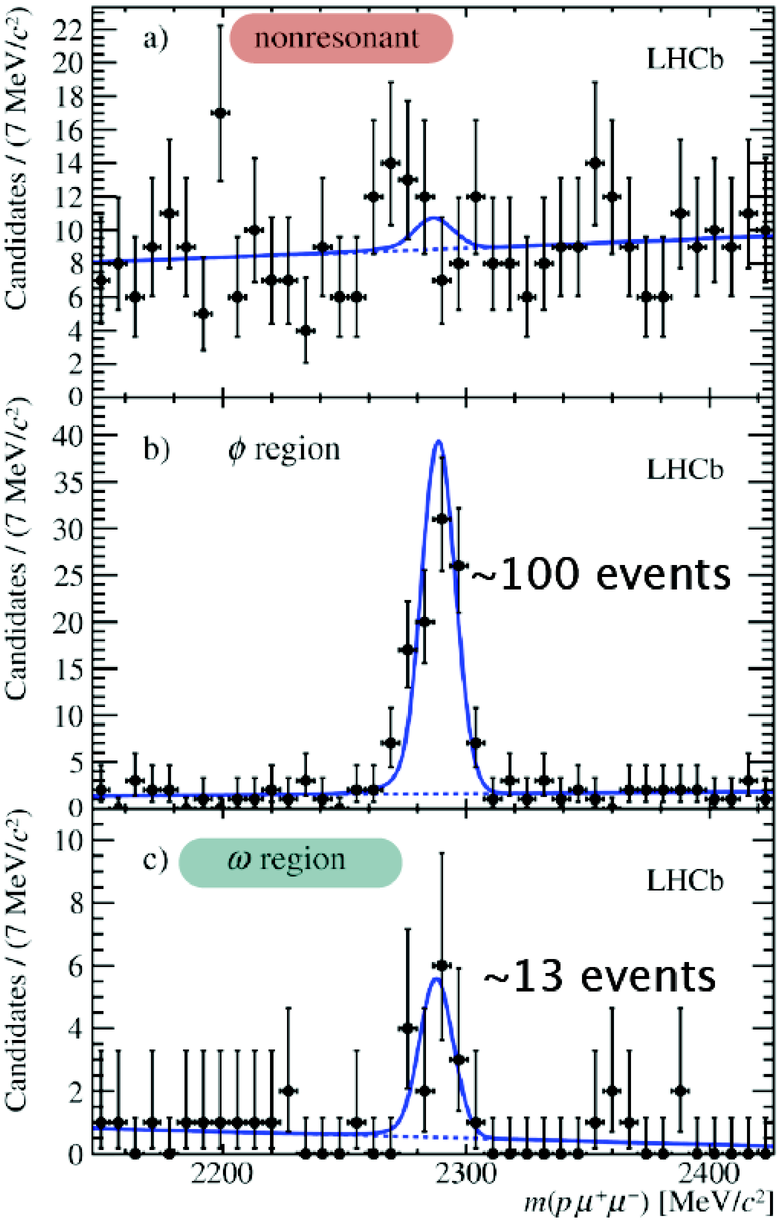
$B(\Lambda_c^+ \rightarrow p\mu^+\mu^-) < 9.6 \times 10^{-8}$ at 95% CL

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

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

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

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

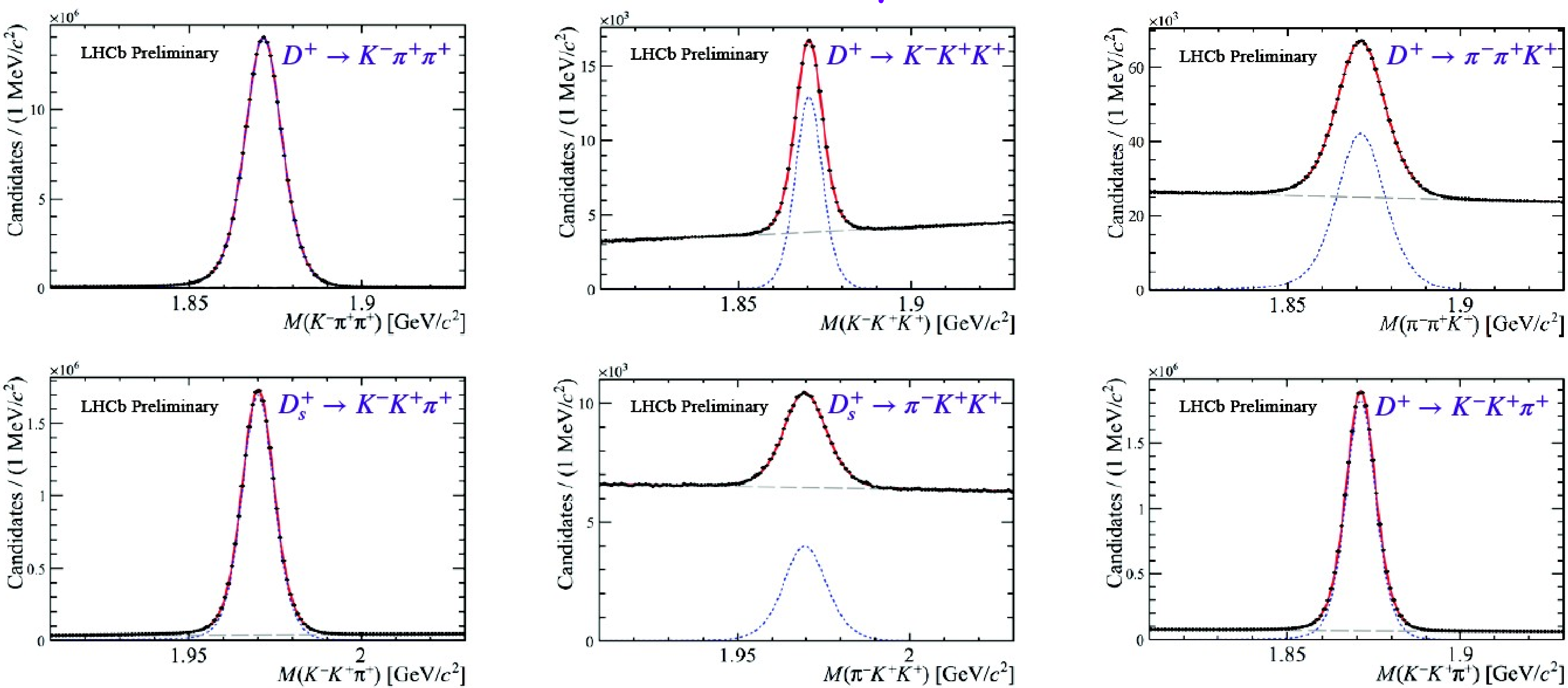


[arXiv:1810.03138]

Branching fractions of $D_{(s)}^{+} \to hhh$

DCS decays:

$2fb^{-1}$ @ 8TeV



[arXiv:1810.03138]

Branching fractions of $D_{(s)}^+ \to hhh$

DCS decays:

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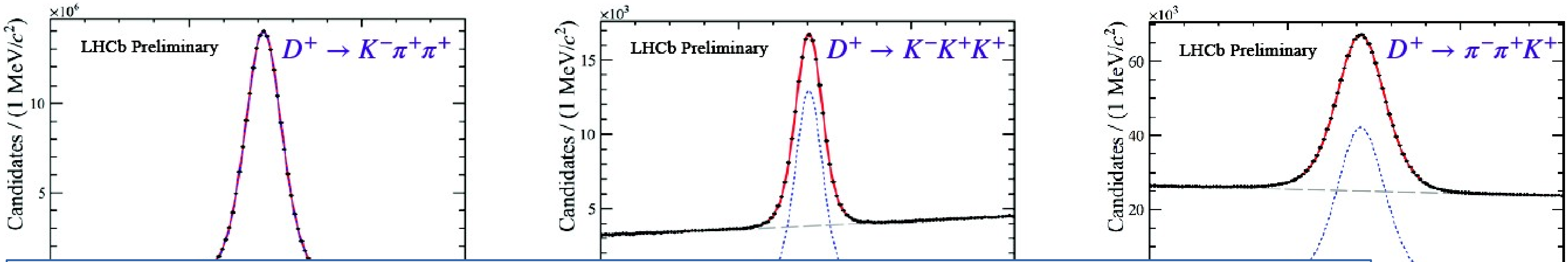
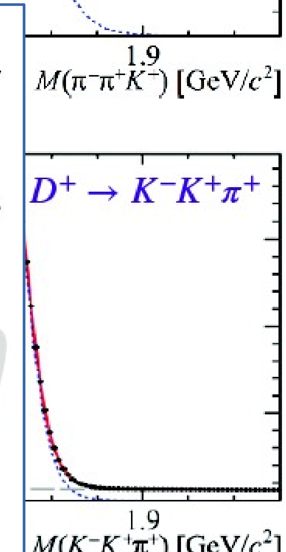


	Yields [$\times 10^3$]		
Channel	*MagDown*	*MagUp*	Total
$D^+ \to K^-K^+K^+$	67.61 ± 0.33	66.69 ± 0.33	134.30 ± 0.47
$D^+ \to \pi^-\pi^+K^+$	401.22 ± 0.99	393.72 ± 0.98	794.9 ± 1.4
$D_s^+ \to \pi^-K^+K^+$	33.68 ± 0.38	33.56 ± 0.38	67.24 ± 0.54
$D^+ \to K^-K^+\pi^+$	$11\,657.1 \pm 3.6$	$11\,482.0 \pm 3.6$	$23\,139.1 \pm 5.1$
$D^+ \to K^-\pi^+\pi^+$ (†)	$103\,282 \pm 10$	$101\,008 \pm 10$	$204\,290 \pm 14$
$D^+ \to K^-\pi^+\pi^+$ (††)	$80\,197.3 \pm 9.0$	$78\,530.2 \pm 8.9$	$158\,727 \pm 13$
$D_s^+ \to K^-K^+\pi^+$	$11\,629.4 \pm 3.5$	$11\,414.3 \pm 3.5$	$23\,043.7 \pm 5.0$



[arXiv:1810.03138]

Branching fractions of $D_{(s)}^+ \rightarrow hhh$

- World's best measurements in all cases

Ratio	PDG 2018	This analysis	Improvement
$\frac{\mathcal{B}(D^+ \to K^-K^+K^+)}{\mathcal{B}(D^+ \to K^-\pi^+\pi^+)}$	$(9.5 \pm 2.2) \times 10^{-4}$	$(6.541 \pm 0.025 \pm 0.042) \times 10^{-4}$	45
$\frac{\mathcal{B}(D^+ \to \pi^-\pi^+K^+)}{\mathcal{B}(D^+ \to K^-\pi^+\pi^+)}$	$(5.77 \pm 0.22) \times 10^{-3}$	$(5.231 \pm 0.009 \pm 0.023) \times 10^{-3}$	9
$\frac{\mathcal{B}(D_s^+ \to \pi^-K^+K^+)}{\mathcal{B}(D_s^+ \to K^-K^+\pi^+)}$	$(2.33 \pm 0.23) \times 10^{-3}$	$(2.372 \pm 0.024 \pm 0.025) \times 10^{-3}$	6.5
$\frac{\mathcal{B}(D^+ \to K^-K^+\pi^+)}{\mathcal{B}(D^+ \to K^-\pi^+\pi^+)}$	$(10.59 \pm 0.18)\ \%$	$(10.282 \pm 0.002 \pm 0.068)\ \%$	2.5

Branching fractions of $D_{(s)}^+ \rightarrow hhh$

- Combining with PDG2018 for the denominator:

$$\mathscr{B}\left(D^+ \rightarrow K^- K^+ K^+\right) = \left(5.87 \pm 0.02 \pm 0.04 \pm 0.18\right) \times 10^{-5}$$

$$\mathscr{B}\left(D^+ \rightarrow \pi^- \pi^+ K^+\right) = \left(4.70 \pm 0.01 \pm 0.02 \pm 0.15\right) \times 10^{-4}$$

$$\mathscr{B}\left(D_s^+ \rightarrow \pi^- K^+ K^+\right) = (1.293 \pm 0.013 \pm 0.014 \pm 0.040) \times 10^{-4}$$

$$\mathscr{B}\left(D^+ \rightarrow K^- K^+ \pi^+\right) = \left(9.233 \pm 0.002 \pm 0.061 \pm 0.288\right) \times 10^{-3}$$

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}.

Semileptonic D decays @ LHCb

- Reconstruction of missing neutrino momentum in a hadron machine is hard, but not possible
  - For example, LHCb measurement of $|V_{ub}|$ from $\Lambda_b \to p\mu\nu$ [Nature Physics 10 (2015) 1038]
- Ongoing LHCb efforts on $D^{*+} \to D^0\pi^+$, aiming for a number of observables:
  - FFxCKM elements with

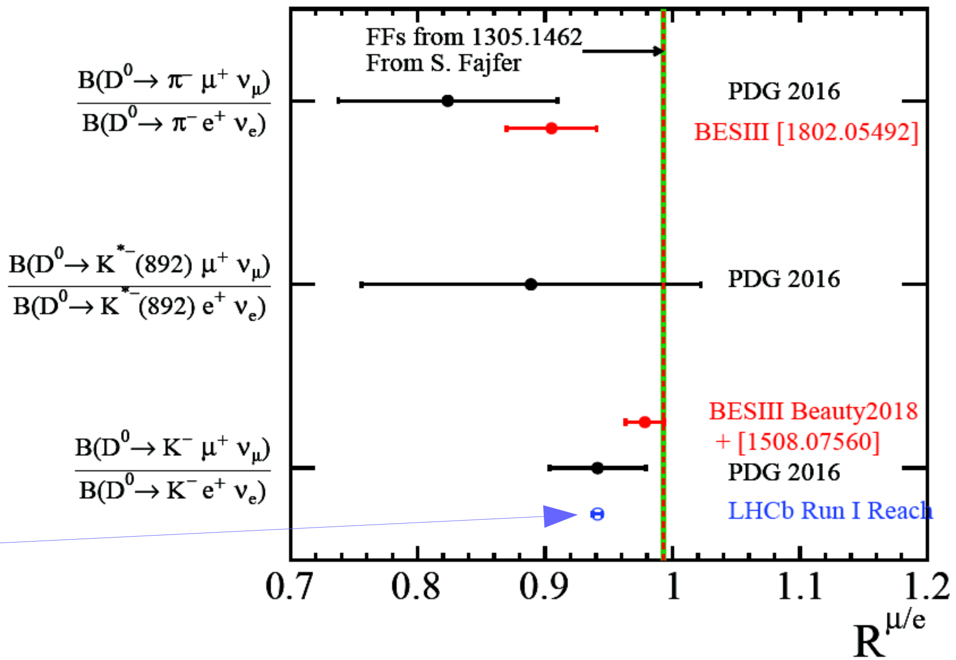
$$\frac{d\mathcal{B}(D^0 \to \pi^-\mu^+\nu)/dq^2}{d\mathcal{B}(D^0 \to K^-\mu^+\nu)/dq^2} \propto \frac{|V_{cd}|^2}{|V_{cs}|^2}\frac{|f^{D\to\pi}(q^2)|^2}{|f^{D\to K}(q^2)|^2}$$

  - CPV/mixing with

$$\frac{\mathcal{P}(D^0 \to K^+\mu^-\nu_\mu)}{\mathcal{P}(D^0 \to K^-\mu^+\nu_\mu)} \propto \frac{x^2+y^2}{4}\left(\frac{t}{\tau}\right)^2 \to \frac{x^2+y^2}{2}$$

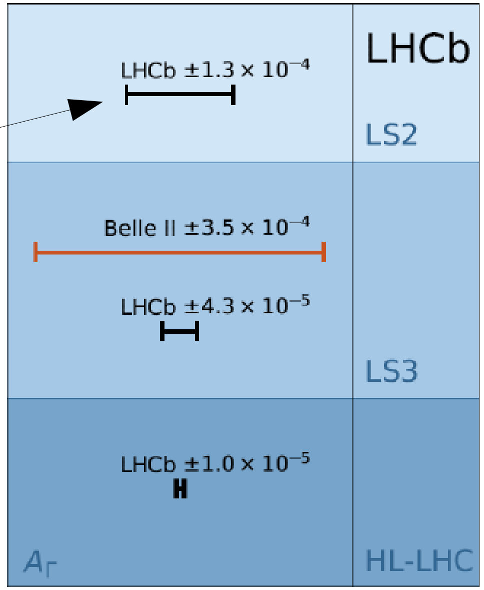
  - Lepton universality test
- All could be the best on the market!

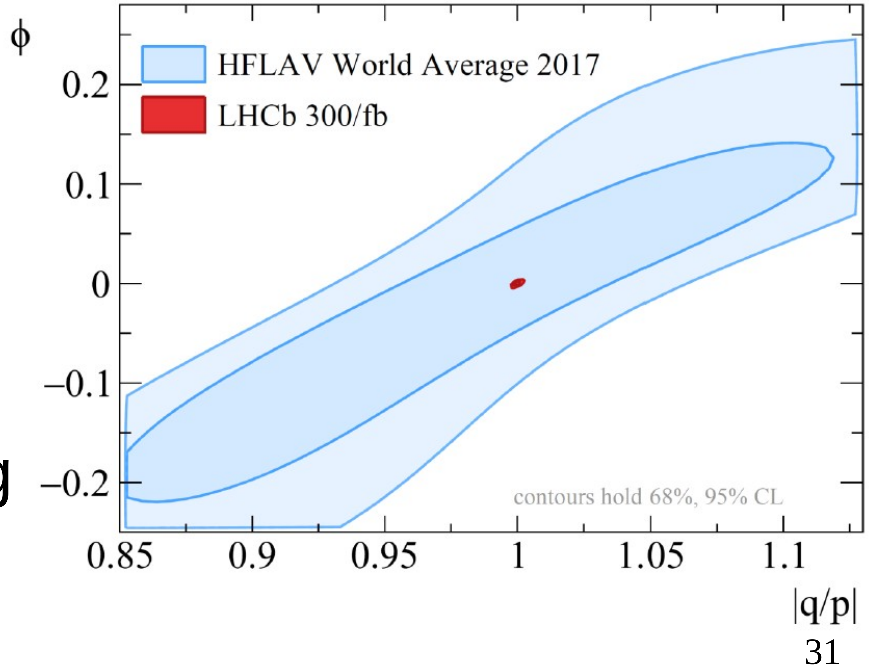
adapted from PoS CKM2016 (2017) 025



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





Summary

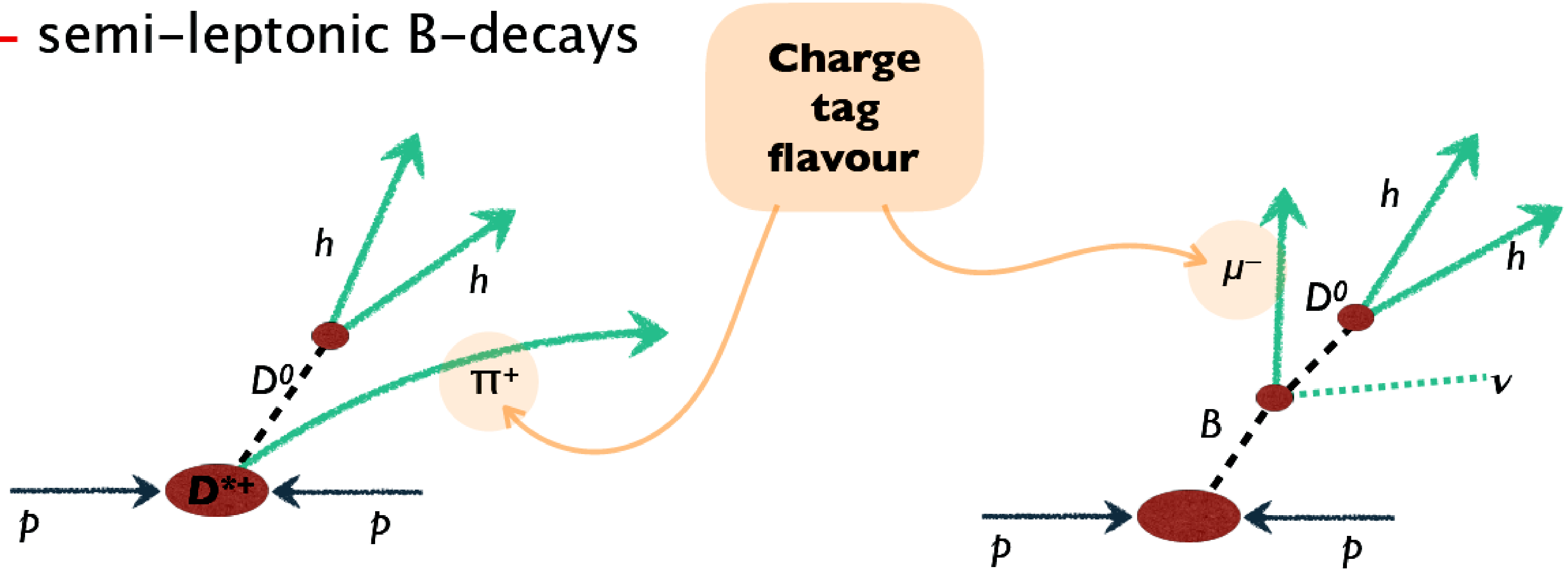
- LHCb is a charm factory and has the world's largest sample of charm decays
- High statistics and superb detector performance allow for high precision measurements on A_{CP} parameters and search for rare decays
- Many more charm results in the pipeline using Run 1 and Run 2 data, stay tuned!
- Longer 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！

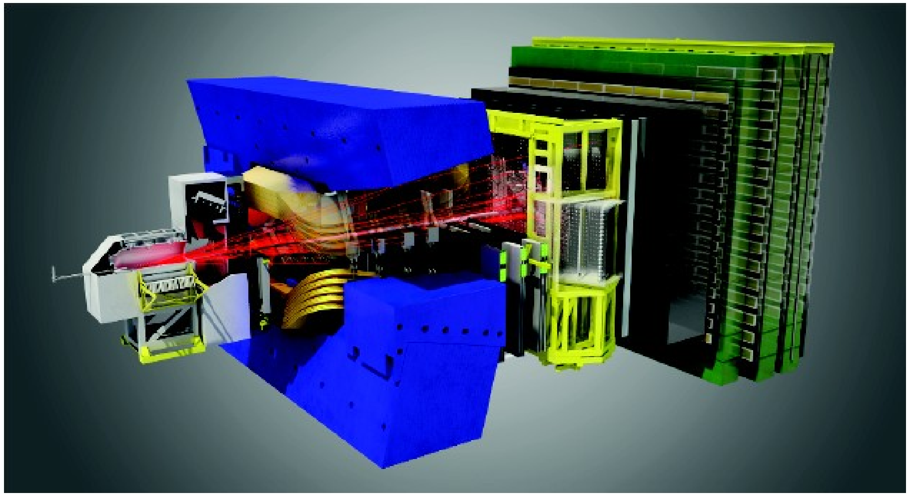
Backup Slides

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



Charm decays at LHCb



- **Pros**
  - Huge cross-section O(mb).
  - Excellent tracking and particle identification (muonID: $\varepsilon \sim 97\%$, 1–3% $\mu \rightarrow \pi$ misID probability).
  - Boosted production ⇒ good decay time resolution.
- **Cons**
  - Busy environment at hadron collider.
  - Asymmetric production of charm and anti-charm ⇒ issue for CP studies.
  - Non-trivial triggers ⇒ distortion of acceptance.