Overview and prospects for rare charm decays at LHCb

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LPNHE (Paris)

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Outline

- Why charm rare decays?
- The LHCb detector
- 2-body decays
- 3-body decays
- 4-body decays
- Prospects
- Conclusions

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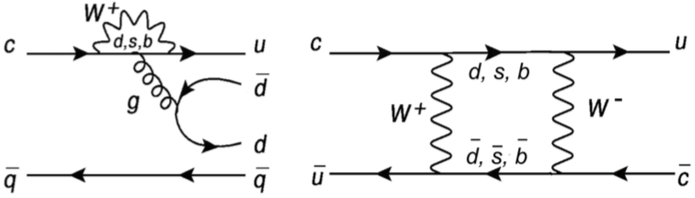
Why charm rare decays?

Mod. Phys. Lett. A 36 (2021) 2130002

- **Up-type quark** provides a unique laboratory in the flavour sector, complementary to studies in K and B systems
- Rare decays receive contributions from **flavor-changing neutral-current (FCNC) processes**
- **Very suppressed** in the SM due to GIM and CKM suppressions



- **Short distance** (SD) contributions to $c \to u\ell\ell$ tiny in the SM ($\mathcal{B} \sim 10^{-9}$), dominated by **long distance** (LD) contributions
- Precise theoretical predictions are difficult
- This does not exclude the possibility to perform **promising searches for New Physics** (NP)

Why charm rare decays?

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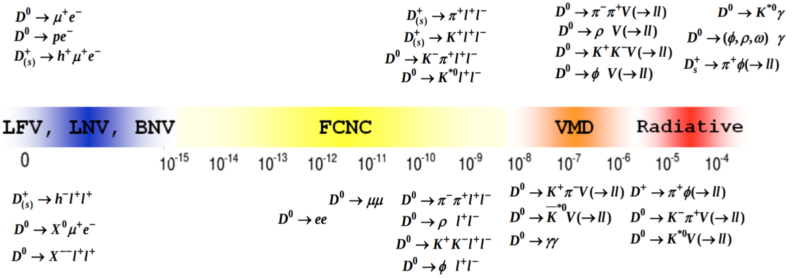
- Different type of physics channels, from forbidden to not-so-rare



- SM can be tested with **clean null-tests**
  - Searches for extremely rare and forbidden decays
  - Angular and CP asymmetries of resonance-dominated decays
  - Lepton flavour universality measurements

The LHCb experiment

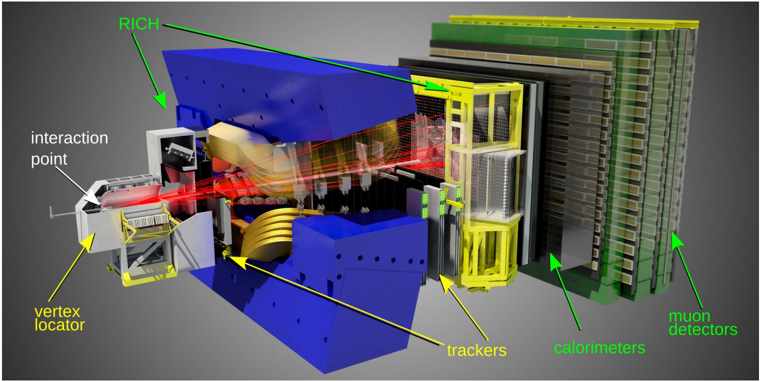
JINST 3 (2008) S080005

- Single arm forward spectrometer
- Optimized for *b*- and *c*-physics
- Good vertex resolution and tracking
- Excellent particle identification
- Fast, efficient and flexible high bandwidth trigger system

Large charm x-sec ($p_T < 8$ GeV$/c$, $2.0 < y < 4.5$)

$\sigma(c\bar{c}, \sqrt{s} = 7\text{ TeV}) = (1419 \pm 133)\mu\text{b}$ [Nucl.Phys.B 871(2013) 1-20]

$\sigma(c\bar{c}, \sqrt{s} = 13\text{ TeV}) = (2940 \pm 240)\mu\text{b}$ [JHEP03(2016)159]



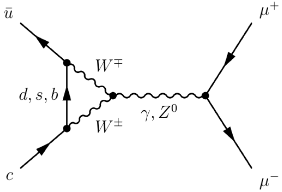
The $D^0 \to \mu^+\mu^-$ decay

Phys. Lett. B (2013) 725

- Very rare decay: FCNC + helicity suppression
- Very clean experimental signature
- Minimal hadronic uncertainties
- Key in constraining NP: many different kind of leptoquarks which contribute at loop level for B but tree for D [Phys. Rev. Lett. 116 no. 14, (2016) 141802]

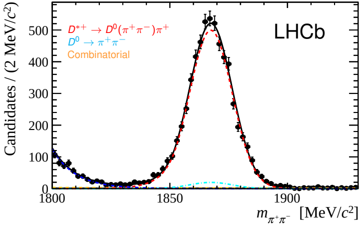
- Receives two contributions within the SM
  - SM SD: $\mathcal{B}(D^0 \to \mu^+\mu^-) \sim 10^{-18}$
  - SM LD: $\mathcal{B}(D^0 \to \mu^+\mu^-) \sim 10^{-11}$

  [arXiv: 1510.00311]



Analysis strategy

- 2011 dataset (1 fb^{-1})
- Tagged $D^{*+} \to D^0\pi^+$ decay
- Use of MVA and PID to suppress the main backgrounds:
  - combinatorial
  - $hh \to \mu\mu$ misID
- Normalisation to $D^0 \to \pi^+\pi^-$ decay

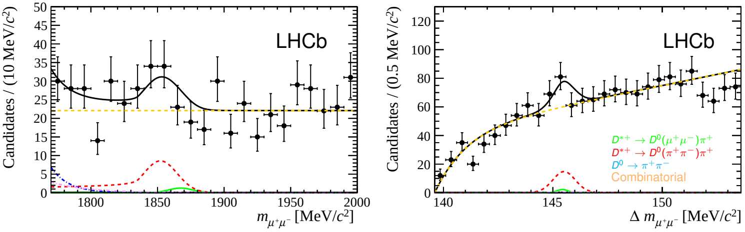


The $D^0 \to \mu^+\mu^-$ decay

Phys. Lett. B (2013) 725

- Signal yield extracted with a ML fit to D^0 and $\Delta m = m(D^*+) - m(D^0)$
- Current upper limit set to

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9} \text{ @ } 90\% \text{ CL}$$



Update is being worked on with full Run 1 + 2 data

- Run 1 (2011-2012): 3 fb^{-1}, $\sqrt{s} = 7(8)$ TeV
- Run 2 (2015-2018): 6 fb^{-1}, $\sqrt{s} = 13$ TeV
- Scaling with the same efficiency and signal-to-background ratio

$$\mathcal{B}(D^0 \to \mu^+\mu^-) \sim \text{fewer } 10^{-9}$$

- This could be further improved with a better muon identification

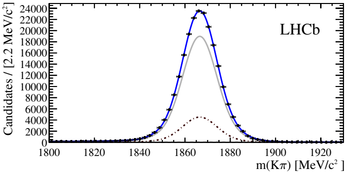
$D^0 \to e^\pm \mu^\mp$

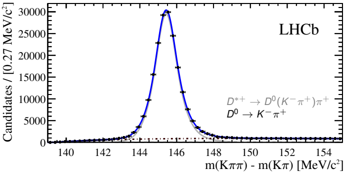
PLB 754 (2016) 167

- Branching fraction predictions given in beyond the SM theories [PRD 66 (2002) 014009]
  - MSSM with R-parity: $\mathcal{O}(10^{-6})$
  - Multiple Higgs doublets: $< 7 \times 10^{-10}$
  - Extra fermions: $< \mathcal{O}(10^{-14})$

Analysis strategy

- Run 1 data (3 fb^{-1})
- Using $D^{*+} \to D^0\pi^+$ decay chain
- $D^0 \to K^-\pi^+$ is the normalisation
- Most important bkg is the $D^0 \to \pi^+\pi^-$
- Electron momentum corrected for bremsstrahlung effects

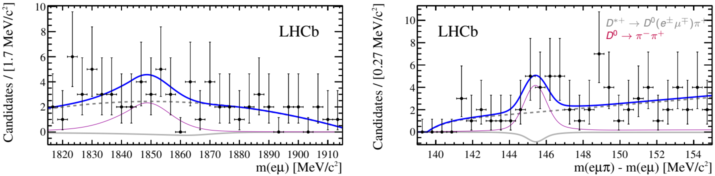




$D^0 \to e^\pm \mu^\mp$

PLB 754 (2016) 167

- Signal yield extracted with a ML fits simultaneously in the BDT bins (shown only the most signal-like)



- The branching fraction is extracted directly from the fits
- No evidence seen and upper limit set with CL_s method

$$\mathcal{B}(D^0 \to e^\pm \mu^\mp) < 1.3\ (1.6) \times 10^{-8}\ @90\ (95)\%\ \mathrm{CL}$$

- Order of magnitude lower than the previous limit

Extrapolation to full Run 1 + 2 data

- Scaling with the same efficiency and signal-to-background ratio

$$\mathcal{B}(D^0 \to e^\pm \mu^\mp) \sim 0.8 \times 10^{-8}$$

Search for $D^+_{(s)} \to h^\pm \ell^+ \ell^-$ decays

LHCB-PAPER-2020-007
arxiv 2011.00217

- Analysed 25 decays $D^+_{(s)} \to h\ell\ell$
  - h is a charged kaon or pion
  - ℓ is an electron or muon
  - Includes LFV and LNV decays

$D^+ \to \pi^+\mu^+\mu^-$	$D^+ \to \pi^+e^+e^-$	$D^+ \to K^+e^+e^-$	$D_s^+ \to \pi^+e^+\mu^-$	$D_s^+ \to K^+\mu^+e^-$
$D^+ \to \pi^-\mu^+\mu^+$	$D^+ \to \pi^-e^+e^+$	$D_s^+ \to \pi^+\mu^+\mu^-$	$D_s^+ \to \pi^+e^+e^-$	$D_s^+ \to K^-\mu^+e^+$
$D^+ \to \pi^+\mu^+e^-$	$D^+ \to K^+\mu^+\mu^-$	$D_s^+ \to \pi^-\mu^+\mu^+$	$D_s^+ \to \pi^-e^+e^+$	$D_s^+ \to K^+e^+\mu^-$
$D^+ \to \pi^-\mu^+e^+$	$D^+ \to K^+\mu^+e^-$	$D_s^+ \to \pi^+\mu^+e^-$	$D_s^+ \to K^+\mu^+\mu^-$	$D_s^+ \to K^+e^+e^-$
$D^+ \to \pi^+e^+\mu^-$	$D^+ \to K^+e^+\mu^-$	$D_s^+ \to \pi^-\mu^+e^+$	$D_s^+ \to K^-\mu^+\mu^+$	$D_s^+ \to K^-e^+e^+$

Allowed in the SM, Forbidden in the SM

- SM allowed decays involve FCNC or Weak Annihilation
- Forbidden at tree level in the SM and CKM suppressed
- Dominated by LD tree level contributions
- Wide range of null tests of the SM [Eur. Phys. J. C80(2020) 65]

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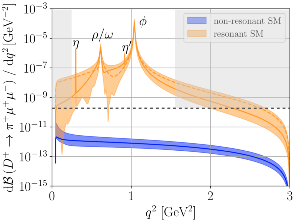
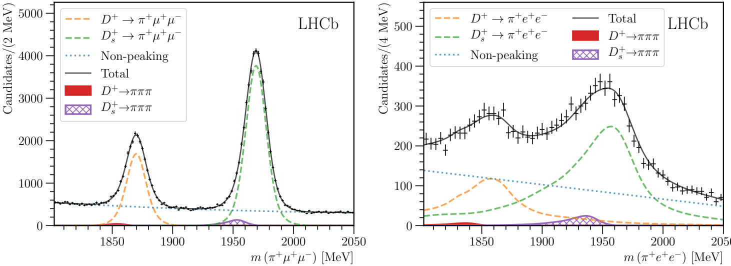


Analysis strategy

LHCB-PAPER-2020-007
arxiv 2011.00217

- Analysis performed with 2016 dataset (1.7 fb^{-1})
- Normalisation with $D_{(s)}^+ \to \phi(\ell\ell)\pi^+$
- Regions dominated by resonances in dilepton mass are vetoed when fitting for the signal

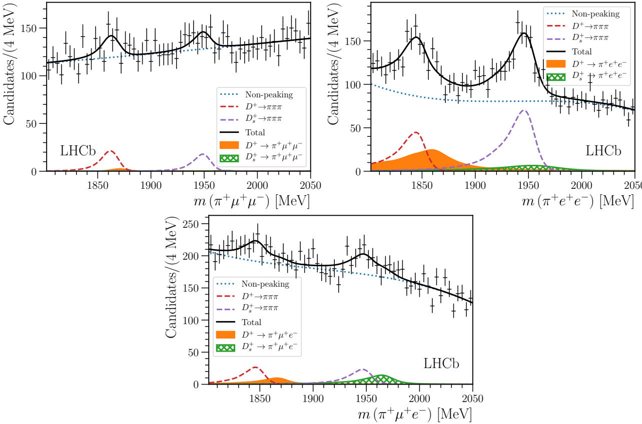


Channel	Fitted yield
$D^+ \to (\phi \to \mu^-\mu^+)\ \pi^+$	$18\,100 \pm 340$
$D^+ \to (\phi \to e^-e^+)\ \pi^+$	2160 ± 180
$D_s^+ \to (\phi \to \mu^-\mu^+)\ \pi^+$	$42\,000 \pm 400$
$D_s^+ \to (\phi \to e^-e^+)\ \pi^+$	5320 ± 180

Analysis strategy

LHCB-PAPER-2020-007
arxiv 2011.00217

- PID is used to suppress the hadronic misidentified backgrounds
- Fit to the three-body invariant mass to measure signal yields
- Peaking background modelled using fast simulation [Comput. Phys. Comm. 214C (2017) pp. 239-246]



Results

LHCB-PAPER-2020-007
arxiv 2011.00217

- Results consistent with background only hypothesis
- Limits set between 1.4×10^{-8} and 6.4×10^{-6}
- Results improve upon the prior world's best constraints by up to a factor of 500

Decay	Branching fraction upper limit $[10^{-9}]$					
	D^+			D_s^+		
	SES	90 % CL	95 % CL	SES	90 % CL	95 % CL
$D_{(s)}^+ \to \pi^+\mu^+\mu^-$	0.6	67	74	2.4	180	210
$D_{(s)}^+ \to \pi^-\mu^+\mu^+$	0.3	14	16	1.8	86	96
$D_{(s)}^+ \to K^+\mu^+\mu^-$	1.2	54	61	3.8	140	160
$D_{(s)}^+ \to K^-\mu^+\mu^+$	-	-	-	1.2	26	30
$D_{(s)}^+ \to \pi^+e^+\mu^-$	0.6	210	230	3.1	1100	1200
$D_{(s)}^+ \to \pi^+\mu^+e^-$	0.4	220	220	2.2	940	1100
$D_{(s)}^+ \to \pi^-\mu^+e^+$	0.4	130	150	2.0	630	710
$D_{(s)}^+ \to K^+e^+\mu^-$	0.7	75	83	3.7	790	880
$D_{(s)}^+ \to K^+\mu^+e^-$	0.5	100	110	2.5	560	640
$D_{(s)}^+ \to K^-\mu^+e^+$	-	-	-	2.4	260	320
$D_{(s)}^+ \to \pi^+e^+e^-$	1.9	1600	1800	8.1	5500	6400
$D_{(s)}^+ \to \pi^-e^+e^+$	0.9	530	600	4.1	1400	1600
$D_{(s)}^+ \to K^+e^+e^-$	4.4	850	1000	14.8	4900	5500
$D_{(s)}^+ \to K^-e^+e^+$	-	-	-	4.1	770	840

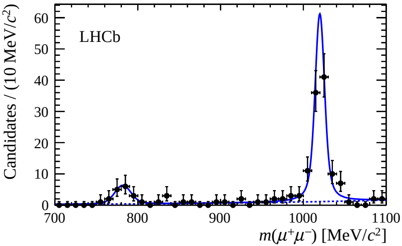
SES = single event sensitivities, i.e. the BF corresponding to a single observed signal event

$\Lambda_c^+ \to p\mu^+\mu^-$ decay

PRD97 091101 (2018)

- First measurement of rare decays of charmed baryons at LHCb
- BF dominated by LD contributions (10^{-6})
  - $\Lambda_c^+ \to p\rho/\omega(\mu^+\mu^-)$
  - $\Lambda_c^+ \to p\phi(\mu^+\mu^-)$

  Nucl. Phys. Proc. Supp. 115 (2003) 93
- SD sensitivity away from dimuon mass resonances

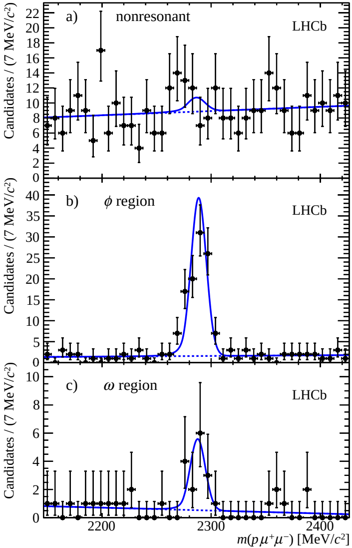


Analysis strategy

- Run 1 data (3 fb^{-1})
- Look for signals in three bins of dimuon mass: ϕ, ρ/ω and non-resonant (NR)
- Normalisation decay: $\Lambda_c^+ \to p\phi(\mu^+\mu^-)$

$\Lambda_c^+ \to p\mu^+\mu^-$ decay

PRD97 091101 (2018)



UL on non-resonant component

$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-)_{NR} < 9.6 \times 10^{-8} \text{ @ 95\% CL}$$

Improvement of two orders of magnitude with respect to the previous measurement by BaBar [PRD 84 072006 (2011)]

First observation (5σ) in the ρ/ω region

$$\mathcal{B}(\Lambda_c^+ \to p[\mu^+\mu^-]_{\rho/\omega}) = (9.4 \pm 3.2 \pm 1.9 \pm 2.0) \times 10^{-8}$$

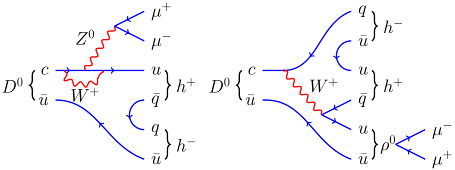
Extrapolation to full Run 1 + 2 data

Scaling with the same efficiency and signal-to-background ratio

$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-)_{NR} \sim 6 \times 10^{-8}$$

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

- 4-body decays have higher BFs and rich set of observables
- Unlikely that NP could show up in the branching fraction
- The richer dynamics allows to investigate asymmetries, which can be up to a few percents in some NP scenarios [Phys. Rev. D93 (2016) 074001]



- Complementary approach wrt $D_s^+ \to h\ell^+\ell^-$:
  - resonance-dominated regions are not vetoed
  - Total BF measurement and binned in dimuon mass regions
  - The sensitivity to SD contribution in regions away from resonances is limited
  - Signal decays in resonance-dominated regions can be used to perform SM null tests

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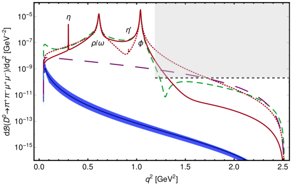
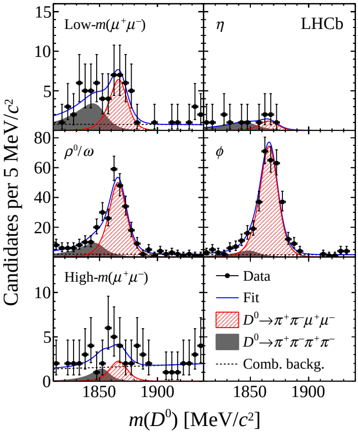
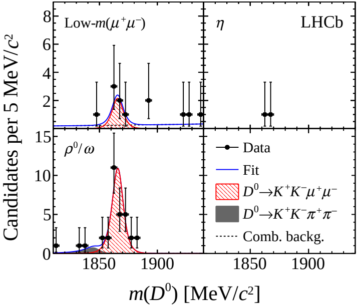


$D^0 \to h^+h^-\mu^+\mu^-$ decays

PRL 119 (2017) 181805

- First observation of the **rarest charm decays** to date using 2012 data (2fb^{-1})





$$\mathcal{B}(D^0 \to \pi^-\pi^+\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7}$$
$$\mathcal{B}(D^0 \to K^-K^+\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}$$

Asymmetries in $D^0 \to h^+h^-\mu^+\mu^-$

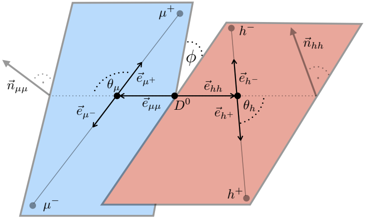
- Additional discrimination between SD and LD contributions can be gained by studying **Angular** and **CP asymmetries**
- Asymmetries are sensitive to SD in full range due to SD-LD interference
  - Null test for the SM
  - $\mathcal{O}$(few%) predictions for some NP models [JHEP 1304 135 (2013)] [PRD 87 054026 (2013)]

- Angular asymmetries
  - Forward backward asymmetry

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

  - Triple product asymmetry

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



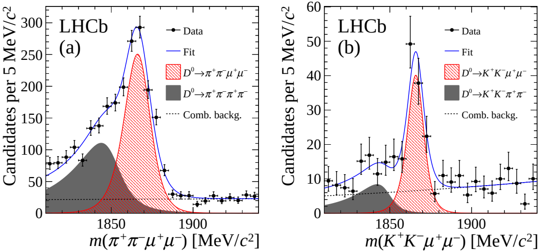
- CP asymmetry

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

Analysis strategy $D^0 \to h^+h^-\mu^+\mu^-$

PRL 119 (2017) 181805

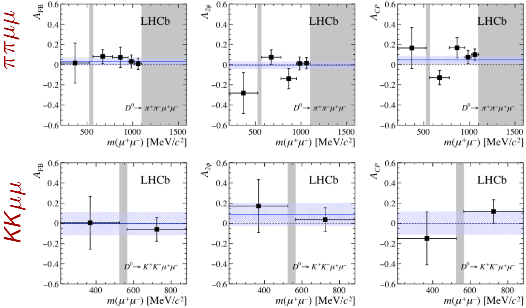
- Measurement of A_{FB}, $A_{2\phi}$ and A_{CP} in bins of dimuon mass and in the full range
- 2011-2016 dataset (5 fb^{-1})



- Possible efficiency variation across phase space due to selection cuts
- Correction exploiting a MVA technique
- Asymmetries determined with a fit to efficiency corrected candidates

Asymmetries in $D^0 \to h^+h^-\mu^+\mu^-$

PRL 121 (2018) 091801



Asymmetries

$$A_{FB}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (\ \ 3.3 \pm 3.7 \pm 0.6)\%,$$
$$A_{2\phi}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (-0.6 \pm 3.7 \pm 0.6)\%,$$
$$A_{CP}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (\ \ 4.9 \pm 3.8 \pm 0.7)\%,$$
$$A_{FB}(D^0 \to K^+K^-\mu^+\mu^-) = (0 \pm 11 \pm 2)\%,$$
$$A_{2\phi}(D^0 \to K^+K^-\mu^+\mu^-) = (9 \pm 11 \pm 1)\%,$$
$$A_{CP}(D^0 \to K^+K^-\mu^+\mu^-) = (0 \pm 11 \pm 2)\%,$$

compatible with SM predictions
[JHEP 04 135 (2013)]

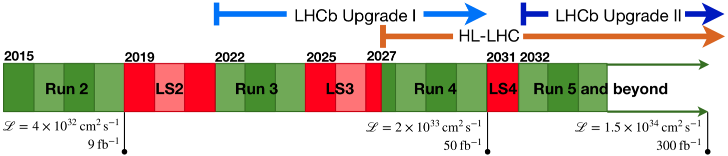
- Asymmetries compatible with zero
- No dependency on dimuon mass

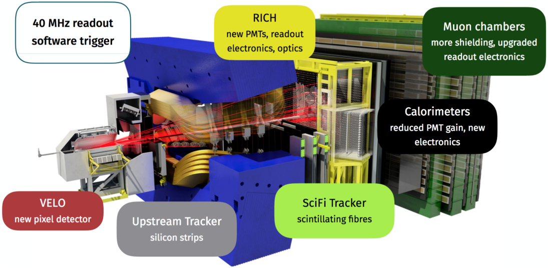
Towards ultimate precision

Physics case for an LHCb Upgrade II

arXiv:1808.08865

- The charm rare analyses are statistically limited
- Foreseen upgrades will largely improve many measurements
- Upgrade I: 40 MHz software trigger replaces current 1 MHz





Prospects for existing measurements

Limits on BFs (away from resonances for multibody)

Mode	Upgrade (50 fb^{-1})	Upgrade II (300 fb^{-1})
$D^0 \to \mu^+\mu^-$	4.2×10^{-10}	1.3×10^{-10}
$D^+ \to \pi^+\mu^+\mu^-$	10^{-8}	3×10^{-9}
$D_s^+ \to K^+\mu^+\mu^-$	10^{-8}	3×10^{-9}
$\Lambda_c \to p\mu^+\mu^-$	1.1×10^{-8}	4.4×10^{-9}
$D^0 \to e^\pm\mu^\mp$	10^{-9}	4.1×10^{-9}

Statistical precision on asymmetries (phase space integrated)

Mode	Upgrade (50 fb^{-1})	Upgrade II (300 fb^{-1})
$D^+ \to \pi^+\mu^+\mu^-$	0.2%	0.08%
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	1%	0.4%
$D^0 \to K^-\pi^+\mu^+\mu^-$	0.3%	0.13%
$D^0 \to K^+\pi^-\mu^+\mu^-$	12%	5%
$D^0 \to K^-K^+\mu^+\mu^-$	4%	1.7%

A. Contu - Towards ultimate precision in Flavor Physics, Durham (2-4 April 2019)

Conclusion

- Rare and forbidden decays constitutes a **unique environment to look for NP**
- LHCb is giving major contributions in the charm rare sector
- Many LHCb measurements are world's best, but there is still space for improvement wrt SM predictions and to reach NP sensitivity
- New studies are expected for Run 2 data
  - Update the current search measurements ($D^0 \to \mu^+\mu^-$, $\Lambda_c^+ \to p\mu^+\mu^-$, ..)
  - Signal already seen on multibody dimuonic decays $\to$ angular/amplitude analysis
  - Dielectron modes will also follow soon
  - Radiative decays should be possible as well, although background rejection is non-trivial
- The future upgrade is awaited and very promising!

Thanks for your attention!

Backup