Search for New Physics with Rare Charm decays at LHCb

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LPNHE (Paris)

Hadron

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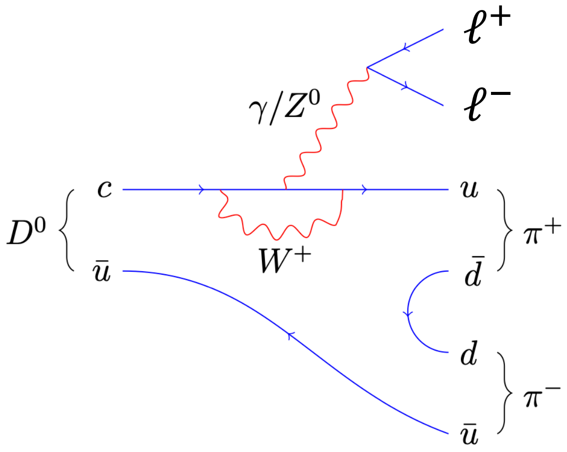
Why study Rare Charm decays?

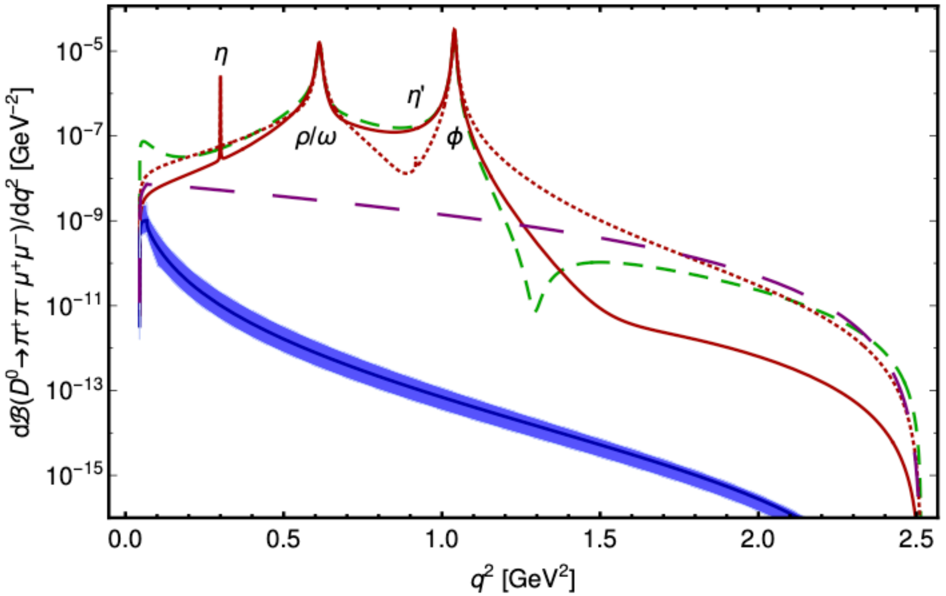
- Rare Charm decays receive contributions from flavor-changing neutral-current (FCNC) processes
- Decays containing the Charm quark are a unique up-type quark probe for these processes (complementary to the down-type quark studies in the K and B sectors)
- The FCNC transitions at tree level are forbidden in the SM, CKM and GIM suppressed (tiny SM prediction of $\mathcal{B} < 10^{-9}$) [J. High Energ. Phys. 2013, 135 (2013)]
- Some New Physics models predict large enhancement in rates and asymmetries



Challenges

- Rare Charm decays are dominated by Long Distance interactions (mesonic vector resonances) with tree-level dynamics
- Precise theoretical predictions are difficult on the Branching Fractions (the resonances contribution are dominated by QCD effects at very low energy and are evaluated with non-perturbative methods with high uncertainty)

[PRD 98 035041 (2018)]



$\mathbf{D^0 \to \pi^+\pi^-\mu^+\mu^-}$

SD component

LD component

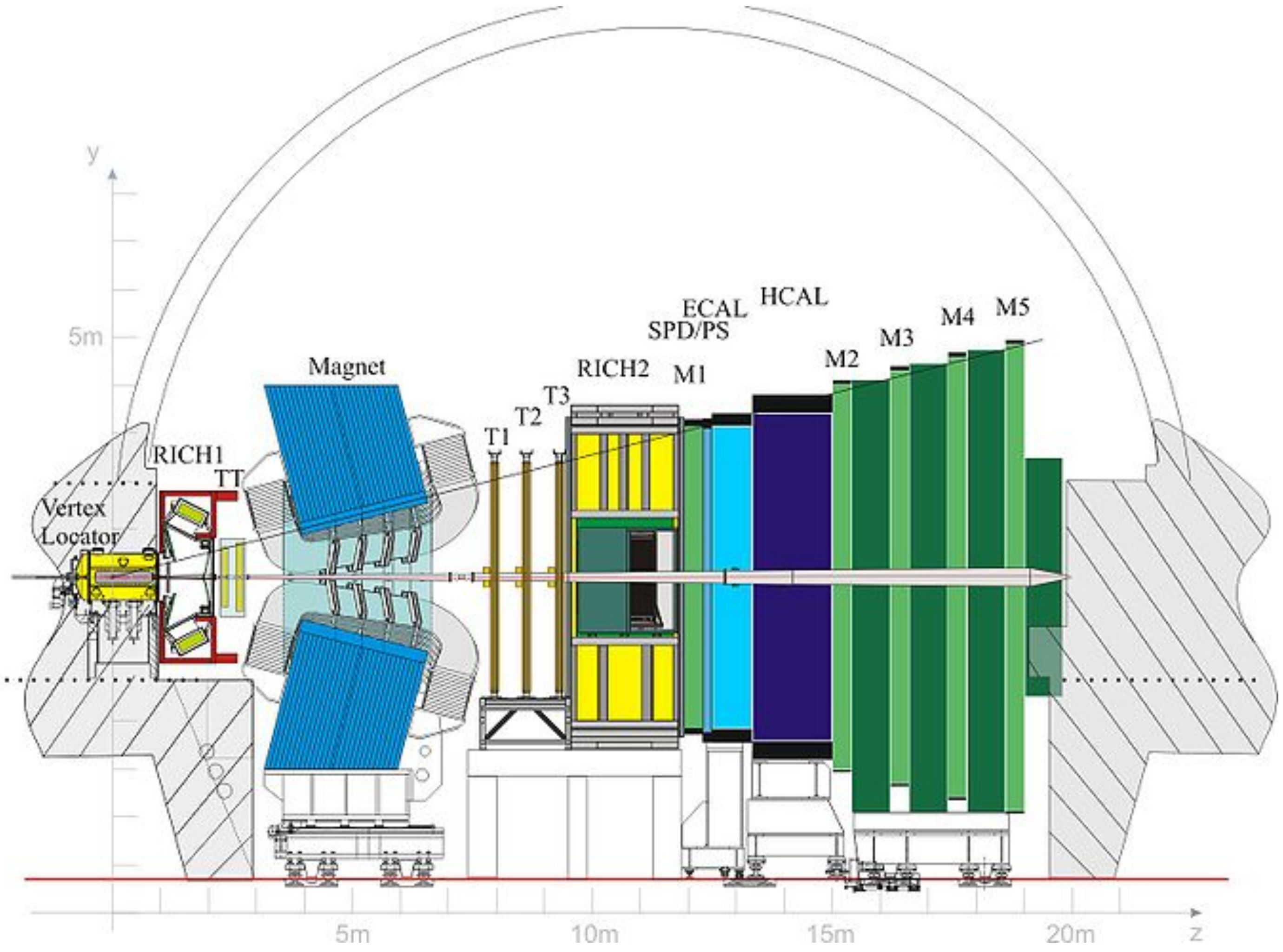
LD different model

BSM model (dashed)

The LHCb experiment

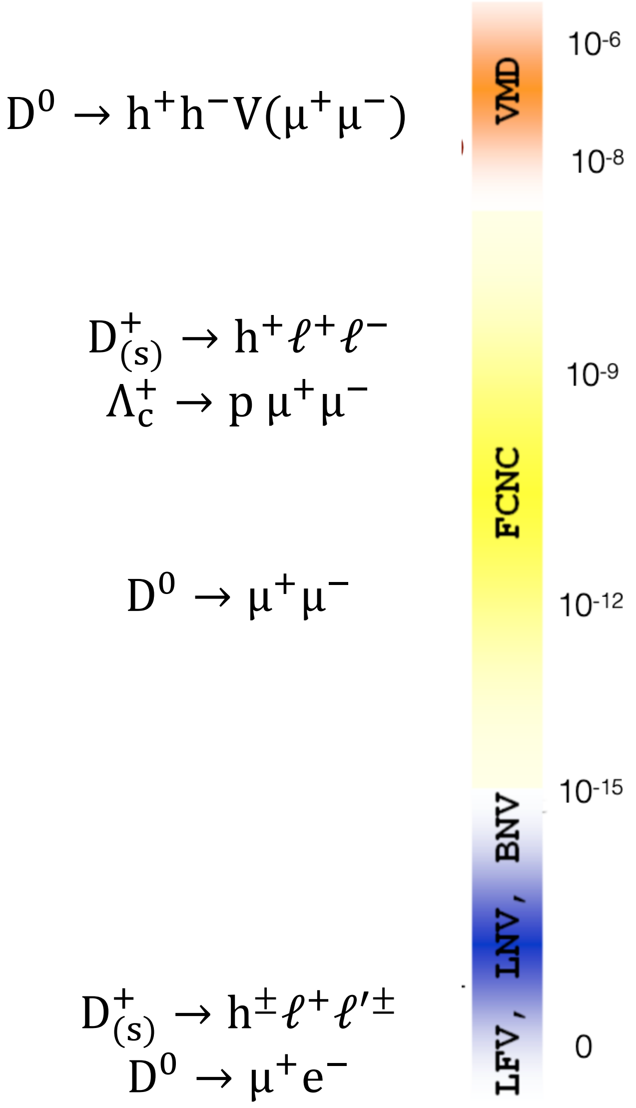
- LHCb is a single arm forward spectrometer optimized for b and c physics
- Good vertex/momentum resolution and excellent particle identification
- LHCb has the world's largest sample of charm decays
- $\sigma\,(pp \rightarrow c\bar{c}) \sim O(\mathrm{mb})$
  → $\sim 10^{13}$ pairs produced up to now

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



Rare Charm decays at LHCb

- Branching ratios:
  - Search for $D^0 \to \mu^+\mu^-$ [PLB 725 15-24 (2013)]
  - Search for $\Lambda_c^+ \to p\,\mu^+\mu^-$ [PRD 97 091101 (2018)]
  - Observation $D^0 \to h^+h^-V(\mu^+\mu^-)$ [PRL 119 (2017) 181805]
- Null tests (Lepton Flavor Violation and Asymmetries):
  - Search for $D^0 \to \mu^+e^-$ [PLB 754 167 (2016)]
  - Search for $D_{(s)}^+ \to h^\pm\ell^+\ell'^\pm$ [JHEP06(2021)044]
  - Asymmetries in $D^0 \to h^+h^-\mu^+\mu^-$ [PRL 121 (2018) 091801]



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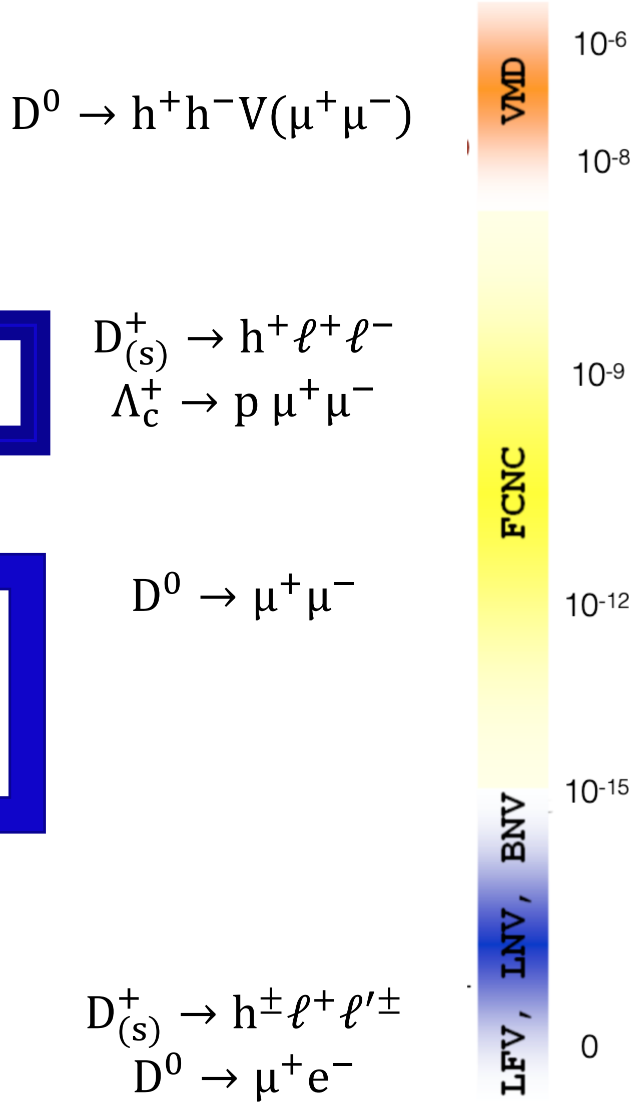
Focus of the talk



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

[JHEP06(2021)044]

- Search of 25 decays of the form $\mathrm{D}^+_{(s)} \to \mathrm{h}^\pm \ell^+ \ell'^\pm$ with $\mathrm{h} = \pi, \mathrm{K}$ and $\ell = \mathrm{e}, \mu$
- The analysis included also Lepton Flavor Violating (LFV) and Lepton Number Violating (LFN) decays with similar topology to the allowed decays

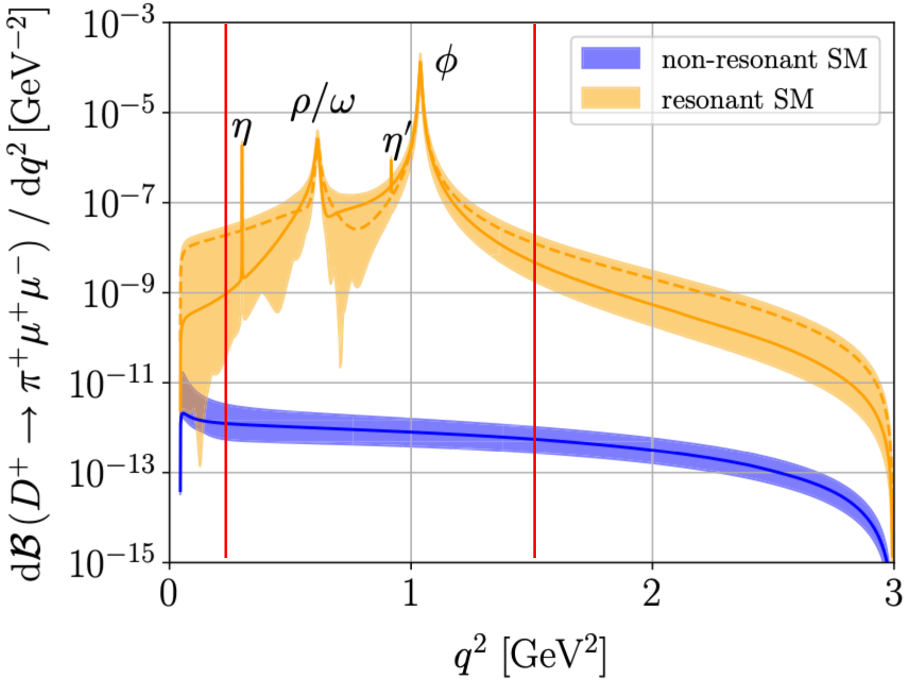
$D^+ \to \pi^+\mu^+\mu^-$	$D^+ \to \pi^+e^+e^-$	$D^+ \to K^+e^+e^-$	$D_s^+ \to \pi^+e^+\mu^-$	$D_s^+ \to K^+\mu^+e^-$
$D^+ \to \pi^-\mu^+\mu^+$	$D^+ \to \pi^-e^+e^+$	$D_s^+ \to \pi^+\mu^+\mu^-$	$D_s^+ \to \pi^+e^+e^-$	$D_s^+ \to K^-\mu^+e^+$
$D^+ \to \pi^+\mu^+e^-$	$D^+ \to K^+\mu^+\mu^-$	$D_s^+ \to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

Allowed in the SM, Forbidden in the SM

Search for $\mathbf{D}^+_{(s)} \rightarrow \mathbf{h}^{\pm}\ell^+\ell'^{\pm}$

[JHEP06(2021)044]

- $\mathrm{D}^+_{(s)} \rightarrow \mathrm{h}^{\pm}\ell^+\ell'^{\pm}$ decays receive contributions from FCNC and Weak Annihilation processes decays
- Normalised to $\mathrm{D}^+_{(s)} \rightarrow \pi^{\pm}\phi(\rightarrow \ell^+\ell^-)$ dominant resonance
- Dilepton mass regions dominated by resonances are vetoed (in q^2 $[0.27, 1.56]\ \mathrm{GeV}^2$)

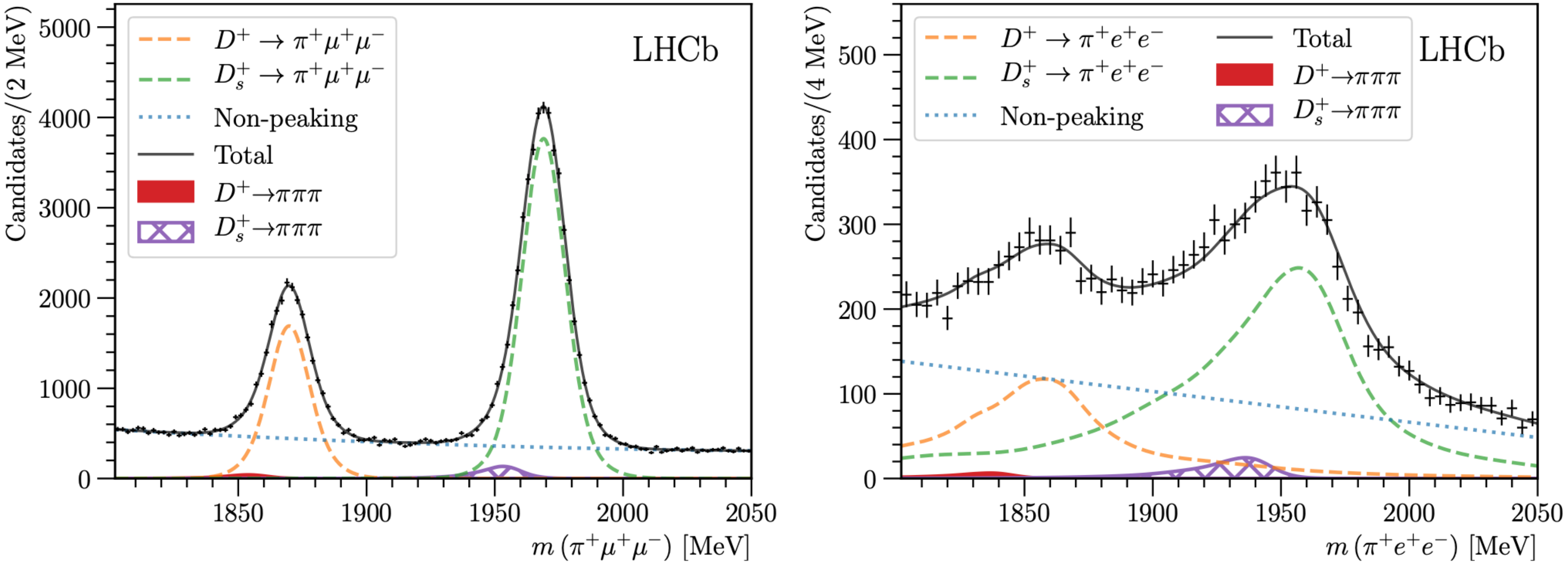


Search for $\mathbf{D}^+_{(s)} \to \mathbf{h}^\pm \ell^+ \ell'^\pm$

[JHEP06(2021)044]

- Analysis performed with LHCb's 2016 dataset (1.7 fb^{-1})
- Electrons lose momentum due to bremsstrahlung radiation and worsen the D mass resolution (long tail in the left-hand side)

$D^+_{(s)} \to \pi^\pm \phi(\to \ell^+\ell^-)$ normalization mode fit

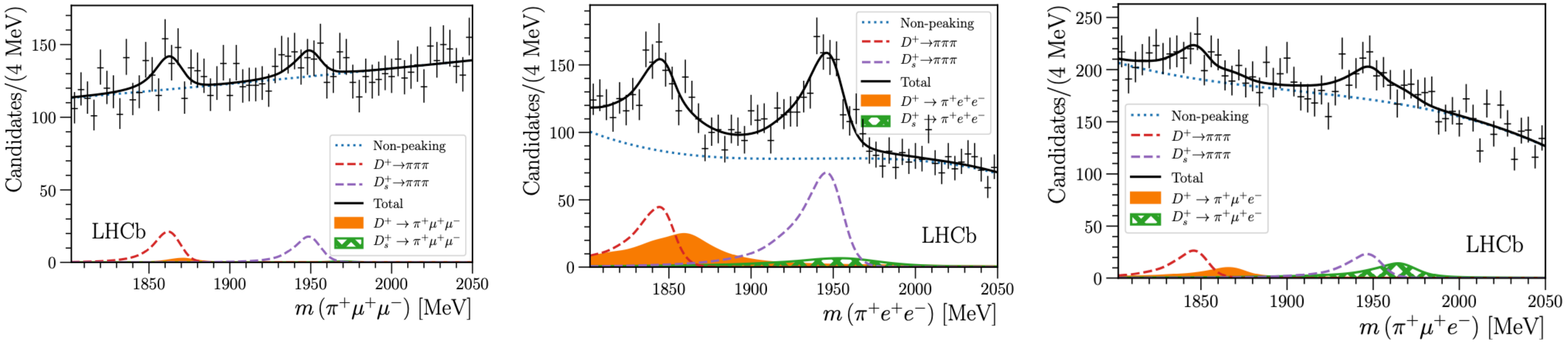


Search for $\mathbf{D}^{+}_{(s)} \rightarrow \mathbf{h}^{\pm}\ell^{+}\ell'^{\pm}$

[JHEP06(2021)044]

- Two different kind of backgrounds are dominating
- A classifier is used to reduce the background originated from random combination of tracks
- Particle Identification (PID) is used to suppress hadronic mis-identified backgrounds (which can have up to 7 orders of magnitude higher BF than the signal)

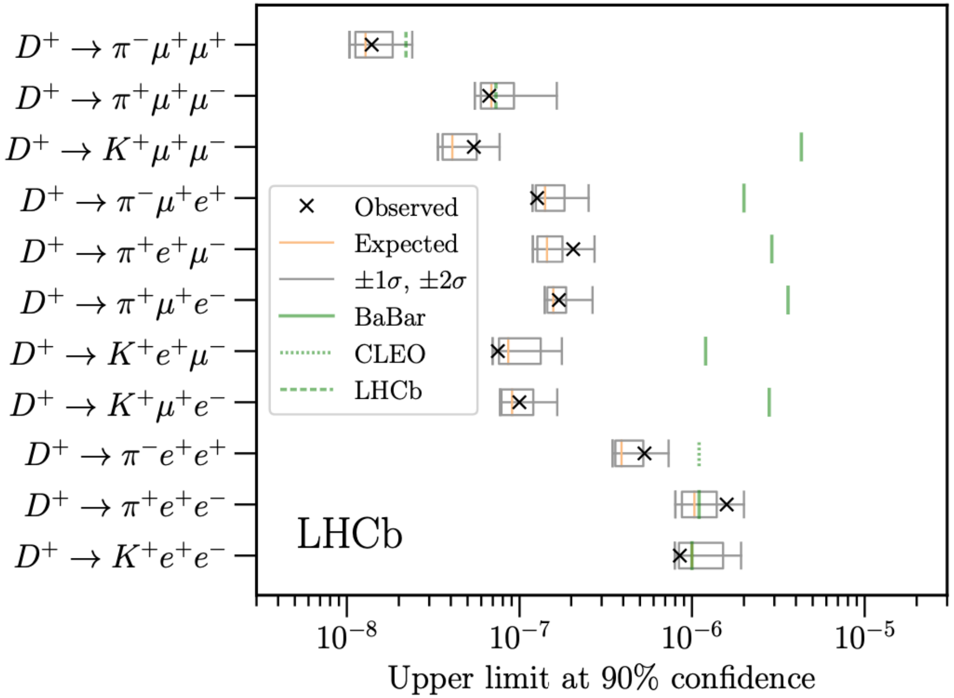
$\mathrm{D}^{+}_{(s)} \rightarrow \mathrm{h}^{\pm}\ell^{+}\ell'^{\pm}$ signal fits

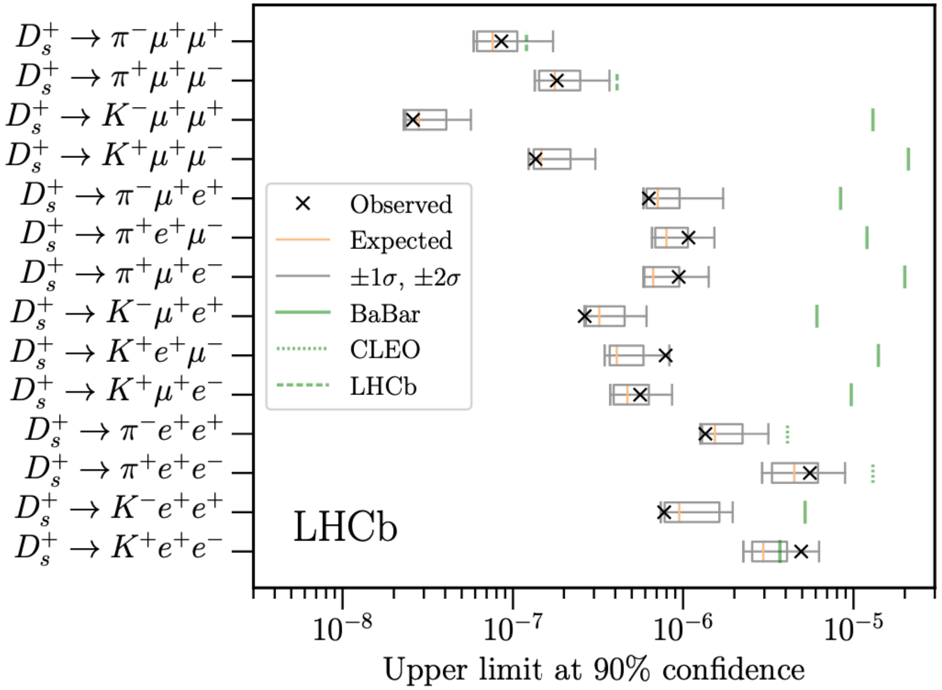


Search for $\mathbf{D}^+_{(s)} \to \mathbf{h}^\pm \ell^+ \ell'^\pm$

[JHEP06(2021)044]

- No significant signal is observed in any of the 25 channels
- Upper limits on the branching fractions are set between 1.4×10^{-8} to 6.4×10^{-6}
- Results improve upon the prior world's best constraints by up to a factor 500

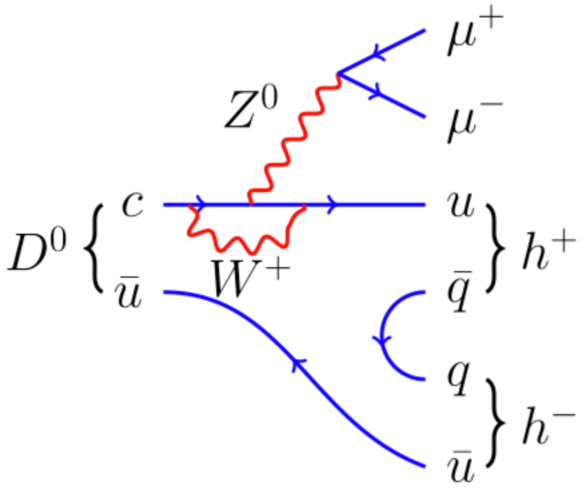




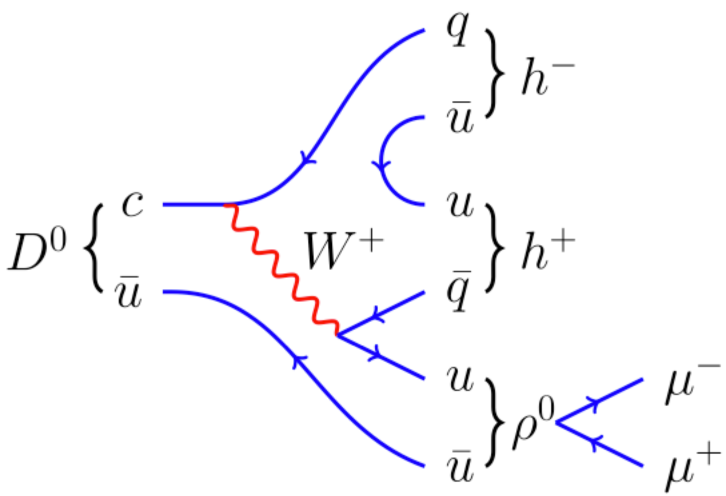
$D^0 \to h^+h^-\mu^+\mu^-$ decays

- First step: Branching Fraction measurements (binned in dimuon mass and integrated value) [PRL 119 (2017) 181805]
- The sensitivity to **SD** contributions is limited because of the **LD** domination
- Second Step: measure angular and CP asymmetries with sensitivity to SD in the full range [PRL 121 (2018) 091801]

SD contribution example



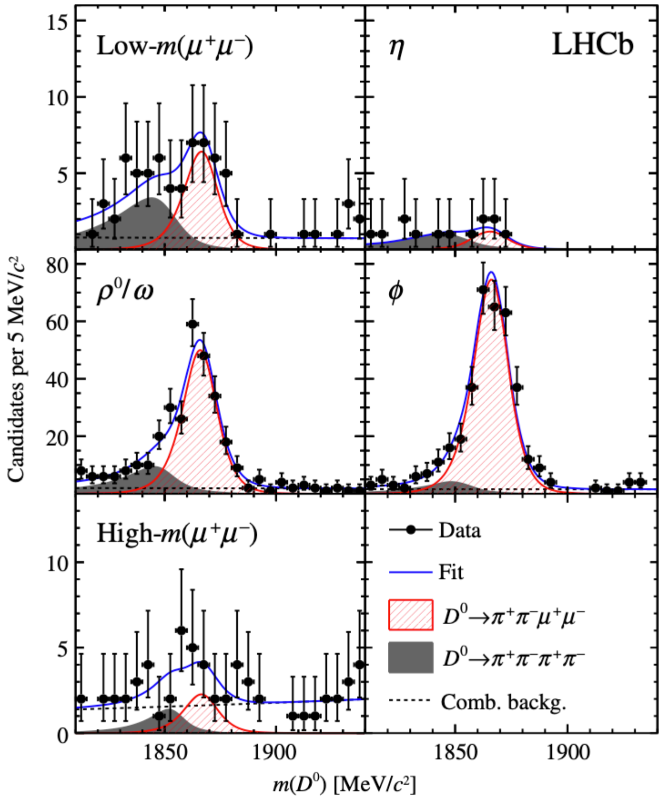
LD contribution example

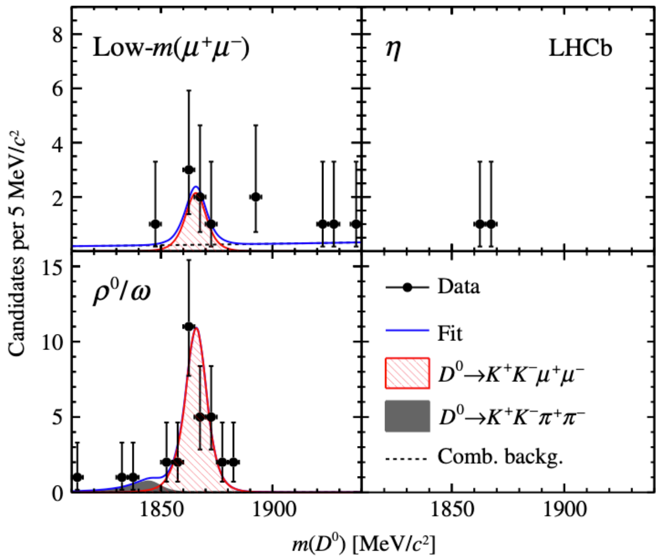


Observation of $\mathbf{D^0 \to h^+h^-\mu^+\mu^-}$

[PRL 119 (2017) 181805]

- First observation of the decay with $\mathrm{h} = \pi, \mathrm{K}$ using LHCb 2012 data (2 fb^{-1})
- $\mathcal{B}(\mathrm{D}^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97)\times 10^{-7}$
- $\mathcal{B}(\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16)\times 10^{-7}$





Asymmetries in $\mathbf{D^0 \to h^+h^-\mu^+\mu^-}$ [PRL 121 (2018) 091801]

- Angular and CP asymmetries in these decays are sensitive to **SD** in the full dilepton range due to the **SD**-**LD** interference
- The observables are SM null tests and scenarios of physics beyond the SM predict effects of $\mathcal{O}(1\%)$ [JHEP 1304 135 (2013), PRD 87 054026 (2013), PRD 93, 074001 (2016)]
- Angular asymmetries:
  - Forward backward asymmetry

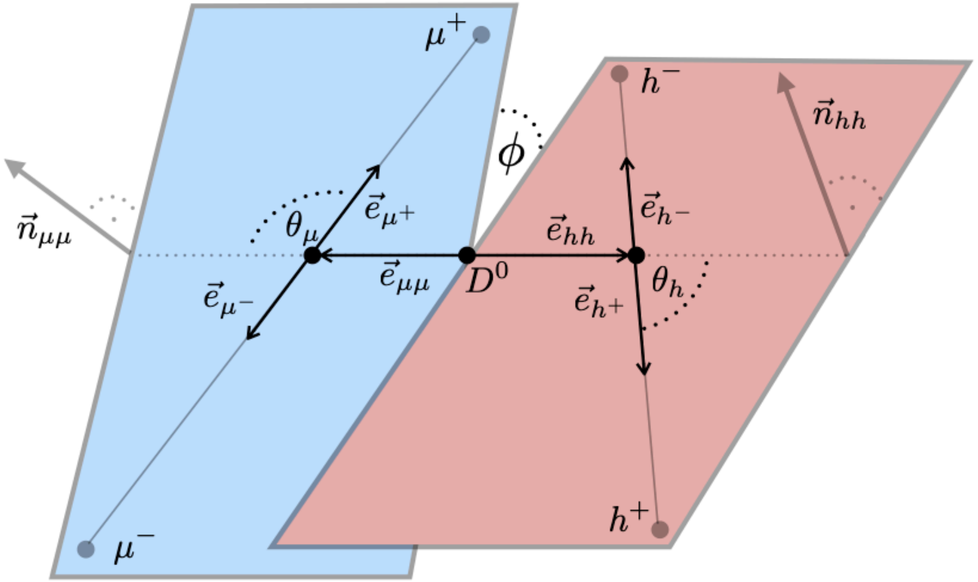
$$A_{FB} = \frac{\Gamma(\cos\theta_\mu > 0) - \Gamma(\cos\theta_\mu < 0)}{\Gamma(\cos\theta_\mu > 0) + \Gamma(\cos\theta_\mu < 0)}$$

  - 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

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



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

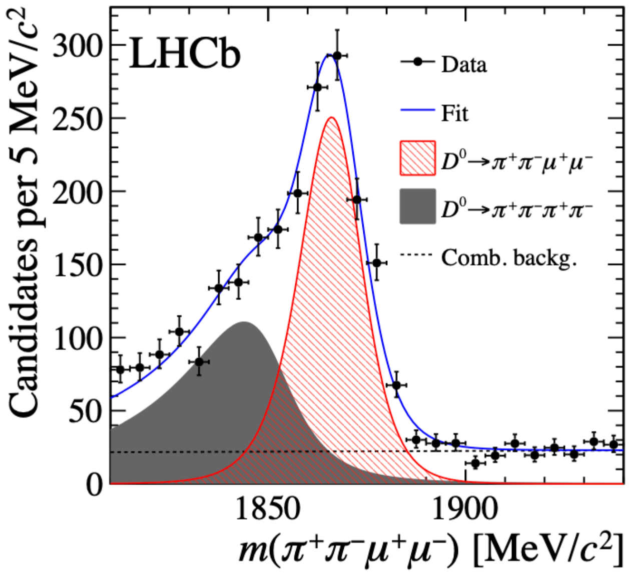
[PRL 121 (2018) 091801]

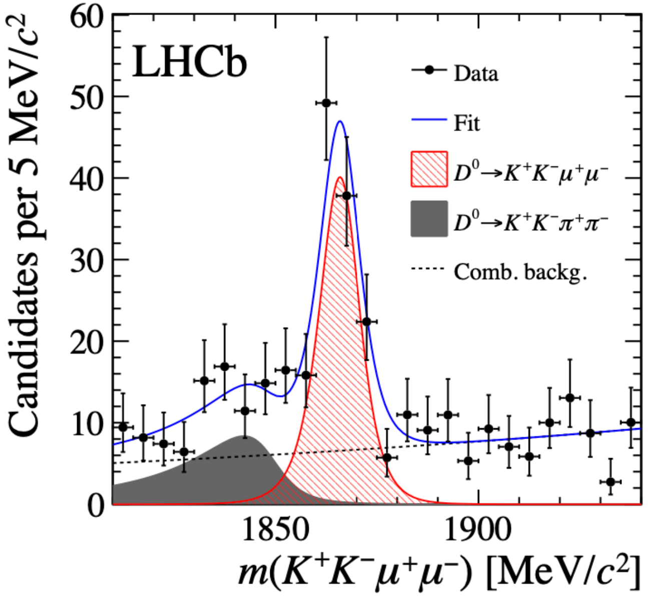
- Analysis performed with LHCb's 2011-2016 dataset (5 fb^{-1})
- The observables A_{FB}, $A_{2\phi}$ and A_{CP} are measured in bins of dimuon mass and in the full range

Decay mode	$m(\mu^+\mu^-)$ [MeV/c^2] low mass	η	ρ/ω		ϕ		high mass
$D^0 \to K^+K^-\mu^+\mu^-$	< 525	NS	> 565		NA		NA
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	< 525	NS	565-780	780-950	950-1020	1020-1100	NS

NA = not available
NS = no signal

- Yields determined by the fit:
  - $D^0 \to \pi^+\pi^-\mu^+\mu^-$: 1326 ± 45 events
  - $D^0 \to K^+K^-\mu^+\mu^-$: 137 ± 14 events
- MVA techniques are used to correct for efficiency variation across the phase space



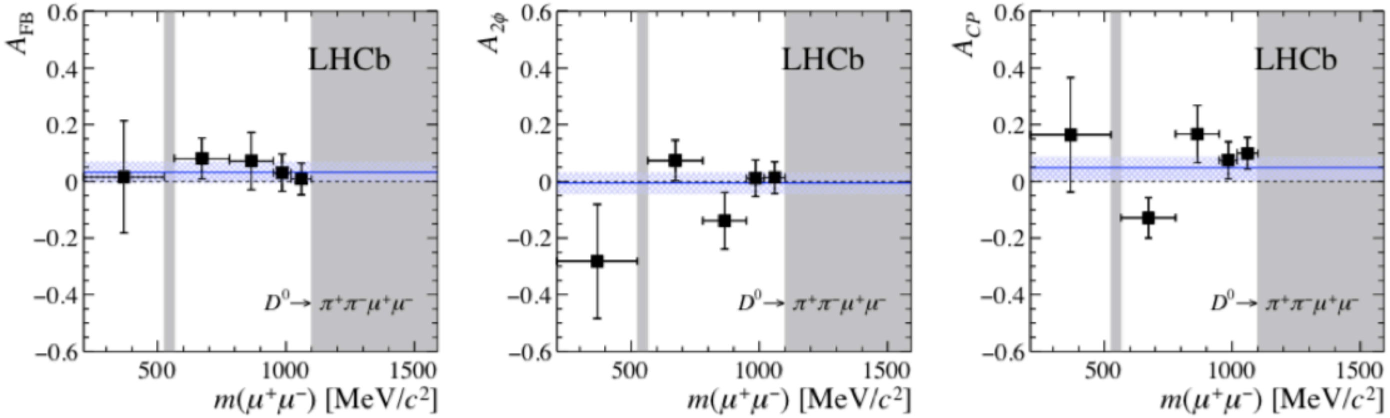


Asymmetries in $\mathbf{D^0 \to h^+h^-\mu^+\mu^-}$

[PRL 121 (2018) 091801]

- All asymmetries are consistent with zero (compatible with the SM predictions)
- No dependency on the dimuon mass is observed

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



Prospects for the LHCb Upgrades

Physics Case Upgrade2

- Limits on BFs for Run3-4 (Upgrade1 2022-2030) and Run5 (Upgrade2 2030-…):

Mode	Run1-2 (1-6 fb^{-1})	Upgrade1 (50 fb^{-1})	Upgrade2 (300 fb^{-1})
$D^0 \to \mu^+\mu^-$	6.2×10^{-9}	4.2×10^{-10}	1.3×10^{-10}
$D^+ \to \pi^+\mu^+\mu^-$	6.7×10^{-8}	10^{-8}	3×10^{-9}
$D_s^+ \to K^+\mu^+\mu^-$	2.6×10^{-8}	10^{-8}	3×10^{-9}
$\Lambda_c^+ \to p\mu^+\mu^-$	9.6×10^{-8}	1.1×10^{-8}	4.4×10^{-9}
$D^0 \to e^\pm\mu^\mp$	1.3×10^{-8}	10^{-9}	4.1×10^{-9}

- Statistical precision on asymmetries:

Mode	Run1-2 (1-6 fb^{-1})	Upgrade1 (50 fb^{-1})	Upgrade2 (300 fb^{-1})
$D^+ \to \pi^+\mu^+\mu^-$		0.2 %	0.08 %
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	3.8 %	1 %	0.4 %
$D^0 \to K^-\pi^+\mu^+\mu^-$		0.3 %	0.13 %
$D^0 \to K^+\pi^-\mu^+\mu^-$		12 %	5 %
$D^0 \to K^+K^-\mu^+\mu^-$	11 %	4 %	1.7 %

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

Conclusion and prospects

- Rare Charm decays constitutes a unique environment to look for New Physics, either with BF measurements or as SM null tests
- LHCb gave major contributions in the field and will continue to exploit the data collected during Run2:
  - Update on the $D^0 \to \mu^+\mu^-$ search
  - Update on the $D^0 \to \mu^+e^-$ search
  - Update on the $\Lambda_c^+ \to p\,\mu^+\mu^-$ search
  - Search for $D^0 \to h^+h^-e^+e^-$
  - Search for $D^0 \to h^+h^-\mu^\pm e^\mp$
  - Angular analysis and CP asymmetries of $D^0 \to h^+h^-\mu^+\mu^-$ decays

- … and many more to come with Run3 data!