Rare charm decays at LHCb

Marianna Fontana
on behalf of the LHCb collaboration

LPNHE (Paris)

ICHEP conference 2022

Bologna, Italy, 06 - 13 July 2022

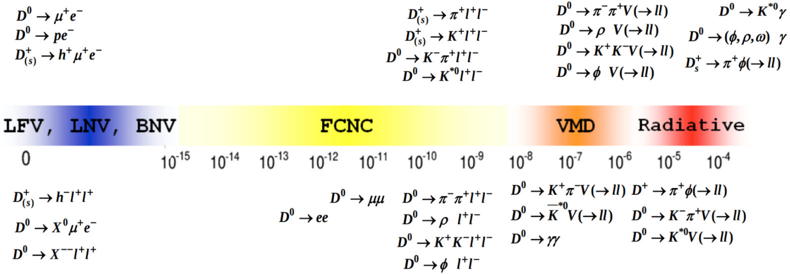
Outline

- Introduction
- Full angular analysis of $D^0 \to h^+h^-\mu^+\mu^-$ decays
  [Phys. Rev. Lett. 128 221801]
- Search for D^0 decays into two muons
  [LHCb-PAPER-2022-029 in preparation] **NEW**
- Conclusion

Rare charm decays

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

- Unique probe of up-type quark FCNC and complementary to B and K physics
- Very suppressed in the SM due to GIM and CKM suppressions
- Precise theoretical predictions are difficult
- SM can be tested exploiting (approximate) asymmetries with clean null-tests
    - Searches for extremely rare and forbidden decays
    - Angular and CP asymmetries of resonance-dominated decays
    - Lepton flavour universality measurements



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

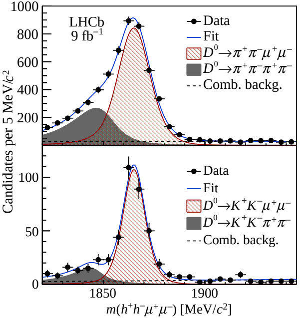
- 4-body decays have measurable BFs and rich set of observables
- First observation of the **rarest charm decays** to date using 2012 data (2fb^{-1})

$$\mathcal{B}(D^0 \to \pi^-\pi^+\mu^+\mu^-) \sim 9.6 \times 10^{-7}$$
$$\mathcal{B}(D^0 \to K^-K^+\mu^+\mu^-) \sim 1.5 \times 10^{-7}$$

[Phys. Rev. Lett. 119 (2017) 181805]

- First **full angular analysis** with Run 1+2 data
- The regions dominated by resonances can be used to perform SM null tests, due to interference between short- and long-distance contributions

[Phys. Rev. Lett. 128 221801]



$$N(D^0 \to \pi^+\pi^-\mu^+\mu^-) \sim 3500$$
$$N(D^0 \to K^+K^-\mu^+\mu^-) \sim 300$$

Observables

[Phys. Rev. Lett. 128 221801]

- The differential decay rate is expressed as the sum of nine angular coefficients I_{1-9}
- Measure p^2, $cos\theta_h$ integrated $< I_i >$ ($i = 2 - 9$) for D^0 and $\bar{D}^0$
- **Flavour average and CP asymmetries**

$$< S_i >= \frac{1}{2}[< I_i > +(-) < \bar{I}_i >] \quad < S^{SM}_{5,6,7} = 0 >$$
$$< A_i >= \frac{1}{2}[< I_i > -(+) < \bar{I}_i >] \quad < A^{SM}_i = 0 >$$

CP even (CP odd) coefficients

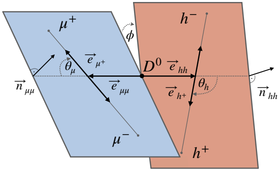
- **CP asymmetry**

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

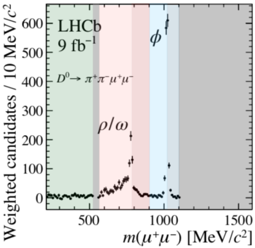
- Measurements in q^2 bins

Decay mode	low mass	η	ρ/ω		ϕ		high mass
			$m(\mu^+\mu^-)$ [MeV/c^2]				
$D^0 \to K^+K^-\mu^+\mu^-$	< 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



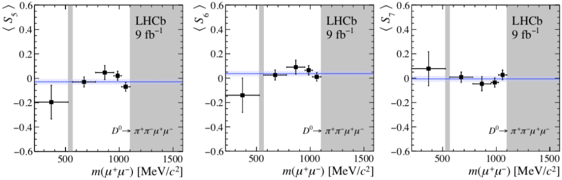
$p^2 = m^2(h^+h^-)$
$q^2 = m^2(\mu^+\mu^-)$



Results

[Phys. Rev. Lett. 128 221801]

- Examples of SM null tests $< S_{5,6,7} >$ $[< S_6 >\sim A_{FB}]$



Compatible with SM predictions

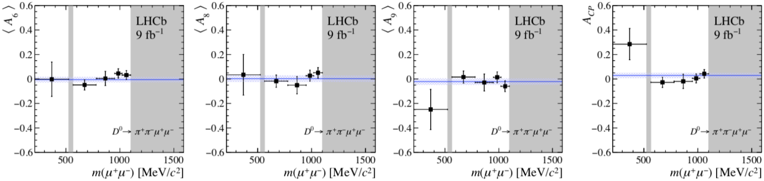
$D^0 \to \pi^+\pi^-\mu^+\mu^-$: 0.3 σ

$D^0 \to K^+K^-\mu^+\mu^-$: 2.7 σ

[JHEP 04 135 (2013)]

[PRD 98, 035041(2018)]

- Examples of $< A_6 >$ $[< A_6 >\sim A_{FB}^{CP}]$, $< A_{8,9} >$ (Triple Product Asym.), A_{CP}



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

LHCb-PAPER-2022-029
in preparation

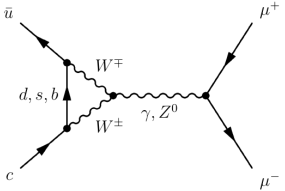
- Very rare decay: FCNC + helicity suppression
- Very clean experimental signature
- Minimal hadronic uncertainties
- Key in constraining NP: different kind of leptoquarks explaining the B anomalies contribute at loop level for B but tree for D

- Receives two contributions within the SM
  - Short Distance: $\mathcal{B}(D^0 \to \mu^+\mu^-) \sim 10^{-18}$
  - Long Distance: $\mathcal{B}(D^0 \to \mu^+\mu^-) \sim 10^{-11}$
  [arXiv: 1510.00311]

- Current upper limit (1 fb^{-1})

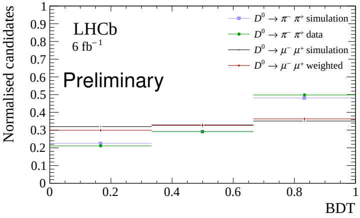
$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9} \text{ @ 90\% CL}$$

[Phys. Lett. B (2013) 725]



Analysis strategy

- Run 1 (2011-2012)+2 (2015-2018) (9 fb^{-1})
- Tagged $D^{*+} \to D^0\pi^+$ decay
- BDT against combinatorial background
- PID to suppress $hh \to \mu\mu$ misID
- Fit simultaneously in three BDT intervals



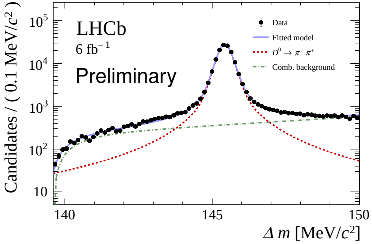
Normalisation

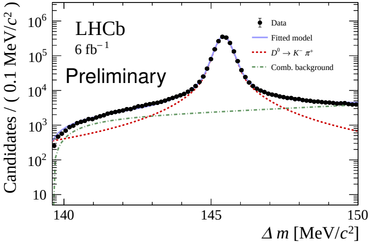
LHCb-PAPER-2022-029
in preparation

- Normalisation to $D^0 \to \pi^-\pi^+,\ K^-\pi^+$ decays

$$\mathcal{B}(D^0 \to \mu^+\mu^-) = \frac{N_{D^0\to\mu^+\mu^-}}{N_{D^0\to h^+h^-}} \cdot \frac{\varepsilon_{h^+h^-}}{\varepsilon_{\mu^+\mu^-}} \cdot p \cdot \mathcal{B}(D^0 \to h^+h^-) \equiv \alpha N_{D^0\to\mu^+\mu^-}$$

  - ε is the efficiency
  - N yield of a given channel
  - p is the trigger prescale of the normalisation channel
  - $\alpha = (2.15 \pm 0.34) \times 10^{-11}$ is the single event sensitivity
- Normalisation yield extracted through a ML fit to $\Delta m = m(D^{*+}) - m(D^0)$ distribution

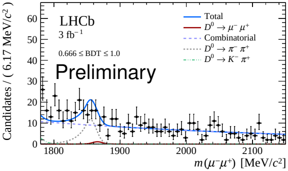


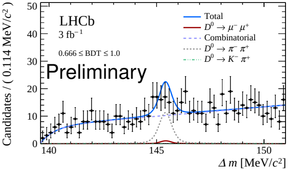


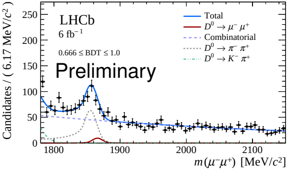
Fit

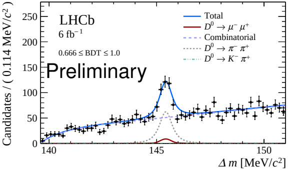
LHCb-PAPER-2022-029
in preparation

- Signal yield extracted with a ML fit to $m(D^0)$ and Δm distributions
- Fit simultaneously in three BDT intervals
- Constraints on the expected number of misID backgrounds decays
- Systematic uncertainties related to the normalisation, and the background shapes and yields, are included in the fit as Gaussian constraints to the relevant parameters
- Dominant systematic uncertainty coming from the calibration of the hadronic trigger efficiency





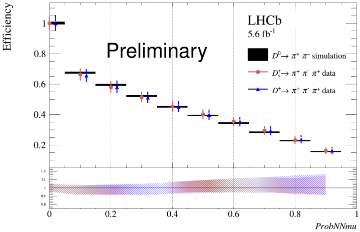




Cross-check and results

LHCb-PAPER-2022-029
in preparation

- $\pi\pi \to \mu\mu$ PID efficiency obtained from simulation, cross-checked using control samples in data
- Agreement over the full range of the muon identification discriminant variable



- No significant signal observed
- Upper limit put on the branching fraction

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 2.9\ (3.3) \times 10^{-9} \text{ @ } 90\ (95)\%\ \text{CL}$$

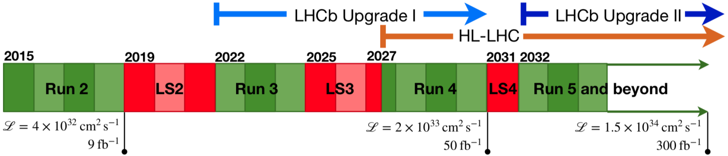
- Improvement of more than a factor two with respect to the previous LHCb result

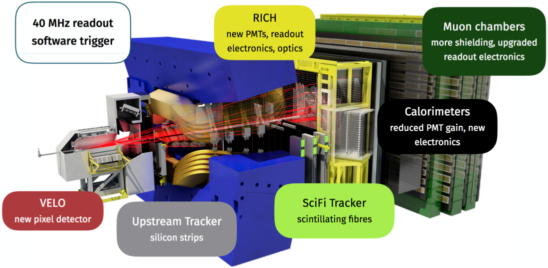
Most stringest limit of FCNC in the charm sector

Towards ultimate precision

Physics case for an LHCb Upgrade II
arXiv:1808.08865

- The charm rare analyses are statistically limited
- The LHCb upgrades will largely improve many measurements
- Upgrade I: 40 MHz software trigger replaced 1 MHz Run 2 trigger





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 charm 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 ($\Lambda_c^+ \to p\mu^+\mu^-$, ..)
  - Dielectron modes will also follow soon
  - Radiative decays should be possible as well, although background rejection is non-trivial
- LHCb Upgrade I (Run 3-4) is currently taking data and many new measurements will come in the next few years
- The full potential of the detector in flavour physics will be exploited with the Upgrade II (Run 5 and beyond)

Thanks for your attention!

Backup

The LHCb experiment

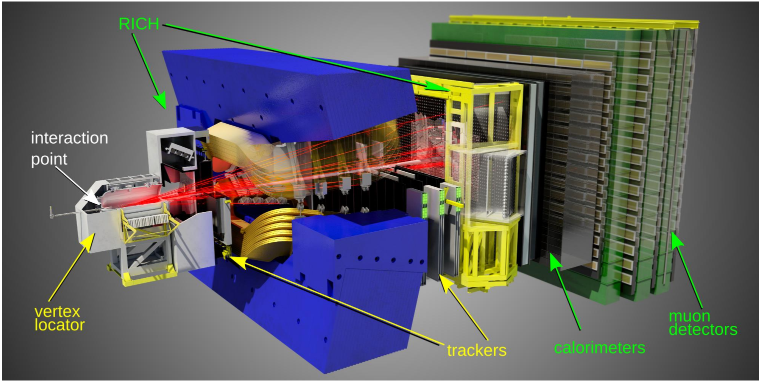
JINST 3 (2008) S080005

- 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$/c$, $2.0 < y < 4.5$)

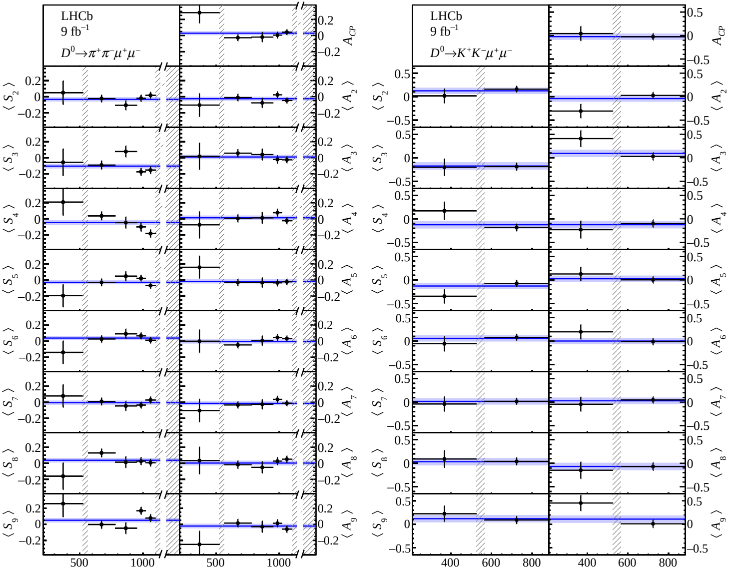
$\sigma(c\bar{c}, \sqrt{s} = 7\text{ TeV}) = (1419 \pm 133)\mu\text{b}$ [Nucl.Phys.B 871(2013) 1-20]

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



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

PAPER-2021-035
arXiv:2111.03327



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

JHEP 06 (2021) 044

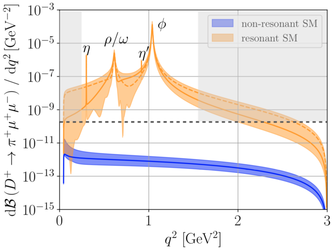
- Analysed 25 decays $D^+_{(s)} \to h\ell\ell$
  - h is a charged kaon or pion
  - ℓ is an electron or muon
  - Includes LFV and LNV decays

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

Allowed in the SM, Forbidden in the SM

- 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

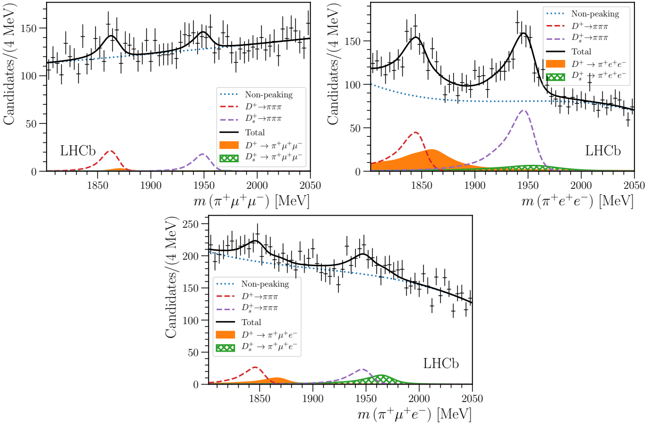
Mod. Phys. Lett. A 36 (2021) 2130002



Analysis strategy

JHEP 06 (2021) 044

- 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

JHEP 06 (2021) 044

- 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