Rare Charm and Strange Decays in LHCb

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Rare decays in Charm & Strange

- Similarities:
  - Transitions that are highly suppressed or forbidden by SM, mostly FCNCs (also LFV).
  - BSM scenarios could contribute at tree & loop level.
  - Usually involve leptonic final states $\rightarrow$ from an experimental point of view, muon signatures are usually easier to detect.
- Differences:
  - Different quarks involved (up & down-type $\rightarrow$ complementary).
  - Strange decays are quite detached from PV, not charm.
- Latest developments

	Charm	Strange
Published	$D^0 \rightarrow h^+h^-\mu^+\mu^-$ [PRL 128 (2022) 221801]	$K^0_S \rightarrow \mu^+\mu^-$ [PRL 125 (2020) 231801]
Preliminary	$D^0 \rightarrow \mu^+\mu^-$ [LHCb-PAPER-2022-029]	$K^0_S \rightarrow \mu^+\mu^-\mu^+\mu^-$ [LHCb-PAPER-2022-035]

Rare charm decays at LHCb

$D^0 \to h^+h^-\mu^+\mu^-$ [PRL 128 (2022) 221801]

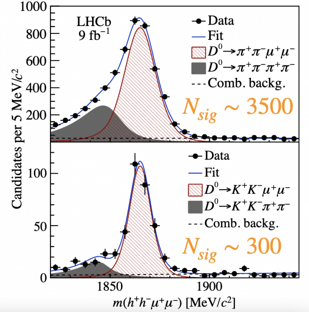
- Sensitive to FCNCs.
- Final state observed by LHCb with 2012 data $\to$ Compatible with SM. [PRL 119 (2017) 181805]
- First full angular analysis in a rare charm decay. (Run 1 + 2)
- Five kinematic variables: $q^2 \equiv m^2(\mu^+\mu^-)$, $p^2 \equiv m^2(h^+h^-)$, θ_μ, θ_h, ϕ.
- Differential decay rate:

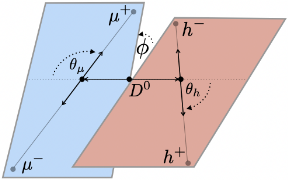
$$\frac{d^5\Gamma}{dq^2dp^2d\Omega} = \frac{1}{2\pi}\sum_{i=1}^{9} c_i I_i$$

$c_{1-9} \to$ angular basis

$I_{1-9} \to$ angular coefficients

[PRL 128 (2022) 221801]





$D^0 \to h^+h^-\mu^+\mu^-$ [PRL 128 (2022) 221801]

- Coefficients measured integrating out the hadronic system.
- The analysis measures the normalized observables $\langle I_{2-9}\rangle$.
- Experimentally, they are computed as the decay-rate asymmetries of the data split by angular tags, for example:

$$\langle I_2\rangle = \frac{1}{\Gamma}\big(\Gamma(|\cos\theta_\mu| > 0.5) - \Gamma(|\cos\theta_\mu| < 0.5)\big)$$

- Measured separately for D^0 and $\overline{D}^0$.
- Flavor average and CP asymmetries:

$$\langle S_i\rangle = \frac{1}{2}\big(\langle I_i\rangle \pm \langle \bar{I}_i\rangle\big) \qquad + \to \text{CP even}$$

$$- \to \text{CP odd}$$

$$\langle A_i\rangle = \frac{1}{2}\big(\langle I_i\rangle \mp \langle \bar{I}_i\rangle\big) \qquad I_i(\bar{I}_i) \to \text{ coefficient for } D^0(\overline{D}^0)$$

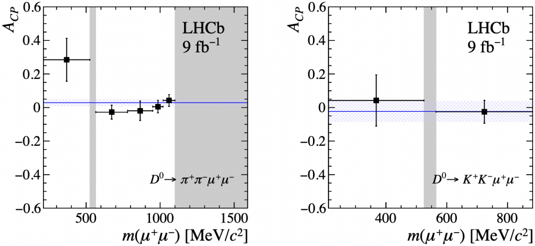
- CP asymmetry of the decay angular integrated rate:

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

$D^0 \to h^+h^-\mu^+\mu^-$ Results [PRL 128 (2022) 221801]

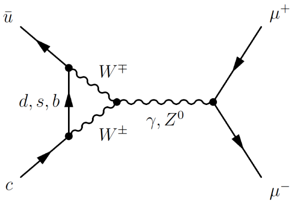
- If only SM contributions: $\langle S_{5-7} \rangle = 0$
- $\langle A_{2-9} \rangle, A_{\rm CP} \to$ Expected to be below current sensitivity.
- Results: SM null tests consistent with zero within $\sim 1\%$.
- Global p-value $\sim 79\%$ for $D^0 \to \pi^+\pi^-\mu^+\mu^-(0.3\sigma)$
- Global p-value $\sim 0.8\%$ for $D^0 \to K^+K^-\mu^+\mu^-(2.7\sigma)$

[PRL 128 (2022) 221801]



$D^0 \to \mu^+\mu^-$ Overview [LHCb-PAPER-2022-029]

- FCNC + helicity suppression
- Current world-best limit ($1\,\text{fb}^{-1}$): $\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9}$ (90% C.L.) [PLB 725 (2013) 15]
- Short distance contribution [PRD 66 (2002) 014009]:
  - Perturbatively calculable amplitudes
  - Cannot proceed at tree level.
  - $\mathcal{B}^{s.d.}(D^0 \to \mu^+\mu^-) \sim 10^{-18}$



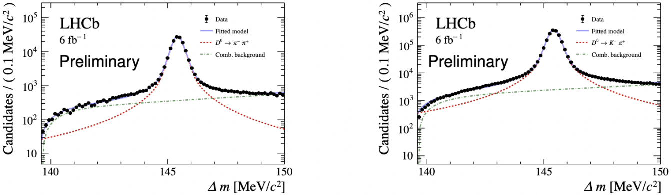
- Long distance contribution [PRD 66 (2002) 014009]:
  - Single-particle intermediate state
  - Two-photon intermediate state. Upper limit would be $\mathcal{B}^{(\gamma\gamma)}(D^0 \to \mu^+\mu^-) < 2.3 \times 10^{-11}$
- Leptoquark models explainig B anomalies contribute at tree level for D [PRD 79 (2009) 114030]

$D^0 \to \mu^+\mu^-$ Strategy [LHCb-PAPER-2022-029]

- Full Run 1 + 2 analysis ($9\,\text{fb}^{-1}$).
- D^0 coming from $D^{*+} \to D^0\pi^+$ ($\mathcal{B} \sim 68\%$).
- Blind analysis → Normalization mode ($D^0 \to h^-\pi^+$)

$$\mathcal{B}(D^0 \to \mu^+\mu^-) = \alpha N_{D^0\to\mu^+\mu^-}, \quad \alpha \sim \frac{\mathcal{B}(D^0\to h^-\pi^+)}{N_{D^0\to h^-\pi^+}} \frac{\varepsilon_{D^0\to h^-\pi^+}}{\varepsilon_{D^0\to\mu^+\mu^-}} \sim 2\times 10^{-11}$$

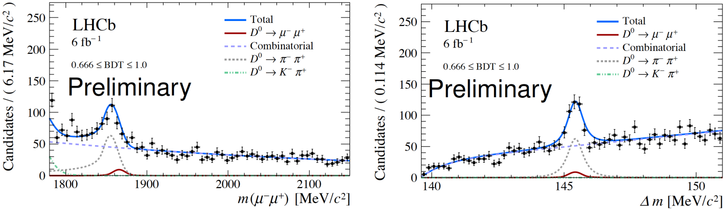
- $N_{D^0\to h^-\pi^+}$ determined via a fit to $\Delta m = m(D^{*+}) - m(D^0)$



- Selection strategy chosen to minimise the combinatorial + misID backgrounds: BDT + PID

$D^0 \to \mu^+\mu^-$ Fit model & Results [LHCb-PAPER-2022-029]

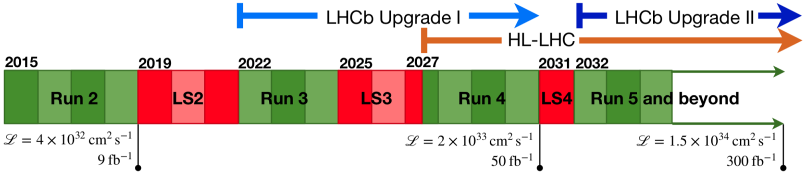
- Signal yield measured from a 2D unbinned ML fit to $m(D^0)$ and Δm.
- Simultaneous to 3 BDT bins per Run.
- No significant $D^0 \to \mu^+\mu^-$ contribution $\to$ peak is mostly $D^0 \to \pi^+\pi^-$ misIDs.
- Main systematic uncertainty comes from normalization mode trigger.



- Preliminary result: New upper limit set (improvement of more than a factor two),

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

Rare Charm Future Prospects

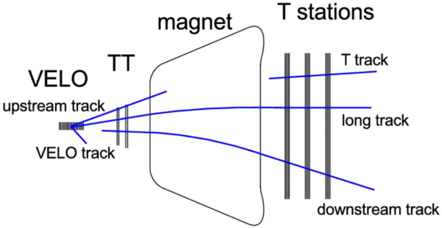


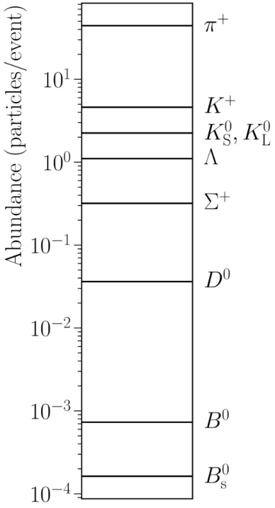
- Expectations for the Upgrade:
  - Upgrade I (50 fb^{-1}): $\mathcal{B}(D^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10}$
  - Upgrade II (300 fb^{-1}): $\mathcal{B}(D^0 \to \mu^+\mu^-) < 1.3 \times 10^{-10}$
- New studies are expected for Run 2 data
  - Update the current search measurements ($\Lambda_c^+ \to p\mu^+\mu^-$, $D \to hll$,...)
  - Dielectron modes will follow soon.
  - Radiative decays should be possible too, though background rejection is non-trivial.

Rare strange decays at LHCb

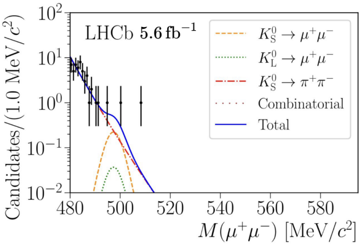
Strange decays at LHCb

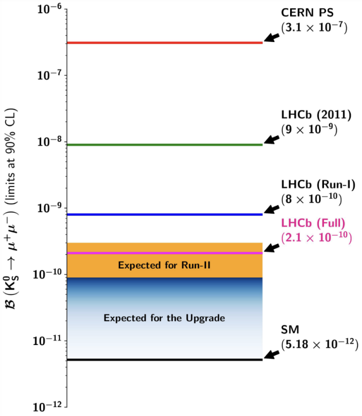
- LHCb was originally optimised for *b* physics.
- Huge production of strange hadrons at the LHC.
- Around 22% of the K_S^0 decay inside the VELO.
- This translates into $\mathcal{O}(10^{13}) K_S^0 / \text{fb}^{-1}$





- Flagship of rare strange decays at LHCb.
- Last publication uses full Run 2 data sample combined with Run 1.
- It improved over an order of magnitude with respect to the previous limit. [PRL 125 (2020) 231801]





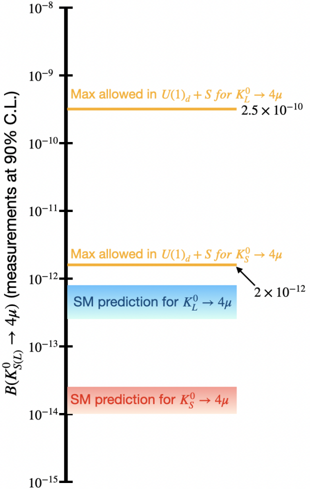
- SM prediction [Eur. Phys. J. C 73 (2013) 2678]:

$$\mathcal{B}(K^0_{S(L)} \to \mu^+\mu^-\mu^+\mu^-) \sim 10^{-14}(10^{-13})$$

- K^0_L escapes the detector acceptance.
- No existing measurements.
- Highly constrained by phase space, very low background.
- Dark photons models like $U(1)_d + S$ can enhance the SM branching fraction prediction up to two orders of magnitude. [arXiV:2201.07805]:

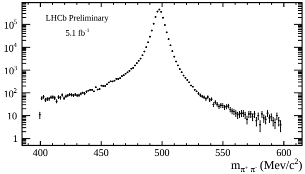
$$\mathcal{B}(K^0_S \to \mu^+\mu^-\mu^+\mu^-) \simeq 2.2 \times 10^{-12}$$

$$\mathcal{B}(K^0_L \to \mu^+\mu^-\mu^+\mu^-) \simeq 2.5 \times 10^{-10}$$



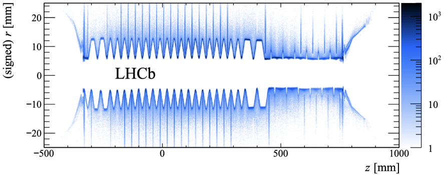
$K^0_{S(L)} \to \mu^+\mu^-\mu^+\mu^-$ Strategy [LHCb-PAPER-2022-035]

- 2016 – 2018 data (5.1 fb^{-1}).
- $K^0_{S(L)}$ coming from PV.
- Blind analysis → Control mode ($K^0_S \to \pi^+\pi^-$)



$$\mathcal{B}(K^0_{S(L)} \to \mu^+\mu^-\mu^+\mu^-) = \alpha N_{sig}, \quad \alpha \sim \frac{\mathcal{B}(K^0_S \to \pi^+\pi^-)}{N_{norm}} \frac{\varepsilon_{norm}}{\varepsilon_{sig}} \sim 2 \times 10^{-12}$$

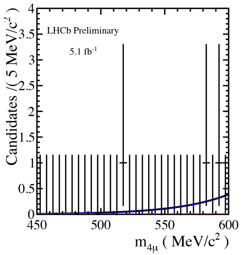
- N_{norm} easily obtained after soft selection (no fit required).
- Background contributions (combinatorial + inelastic collisions with material) minimized through BDT training.

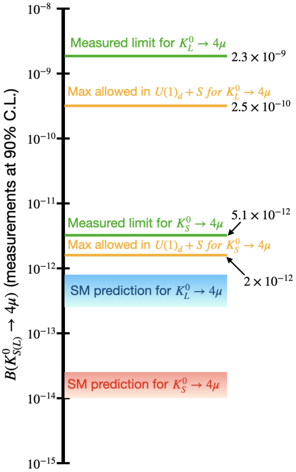


$K^0_{S(L)} \to \mu^+\mu^-\mu^+\mu^-$ Fit & Results [LHCb-PAPER-2022-035]

- BDT classifier removes most of the background
- Main source of systematic uncertainty comes from trigger.
- Both K^0_S and K^0_L decays are independently studied, assuming negligible contributions from the other.
- No significant signal observed.
- Preliminary results: first upper limits set for both decays at 90% C.L.:

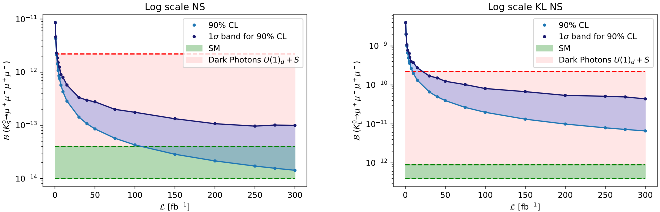
$$\mathcal{B}(K^0_S \to \mu^+\mu^-\mu^+\mu^-) < 5.1 \times 10^{-12}$$
$$\mathcal{B}(K^0_L \to \mu^+\mu^-\mu^+\mu^-) < 2.3 \times 10^{-9}$$





Rare Strange Future prospects

- Expect to gain an order of magnitude in $\mathcal{B}(K^0_{S(L)} \to \mu^+\mu^-\mu^+\mu^-)$ after Upgrade I (also $K^0_S \to \mu^+\mu^-$).



- Interesting channels:
  - $K^0_S \to \pi^+\pi^-\mu^+\mu^- \to$ highly constrained by phase space
  - $K^0_S \to \pi^+\pi^-e^+e^- \to$ very low electron efficiencies. Key to explore $K^0_S \to \mu^+\mu^-e^+e^-$ and $K^0_S \to e^+e^-e^+e^-$
  - $\Lambda \to p\mu^-\overline{\nu}_\mu$ (in progress)
  - $K^0_S \to e\mu$, $K^+ \to \pi^+e\mu \to$ Lepton flavor violation

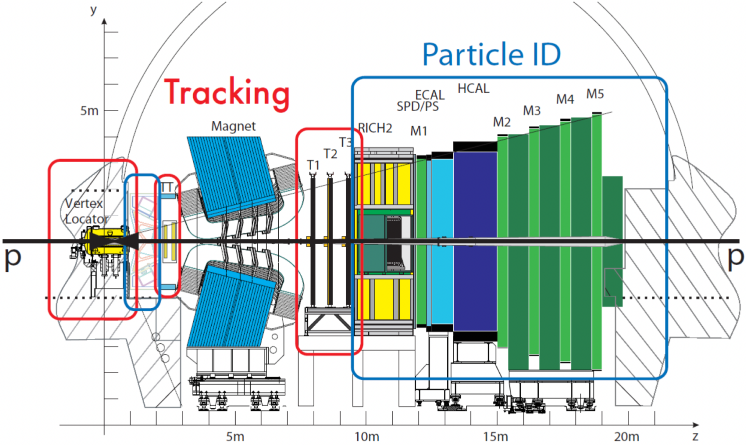
Conclusions

- Rare charm and strange decays are unique places to look for new physics.
- LHCb is giving major contributions in the charm rare sector, rare strange is not falling behind.
- More analysis to come from Run 2 data, including dielectron modes on both charm and strange.
- Upgrades of existing measurements are to be expected as the LHCb continues to take data (Run 3 + 4).
- The rare charm & strange physics program kept and even expanded with new topologies and decay channels thanks to the upgraded trigger, any further ideas to explore?

Thank you for your attention!

Backup

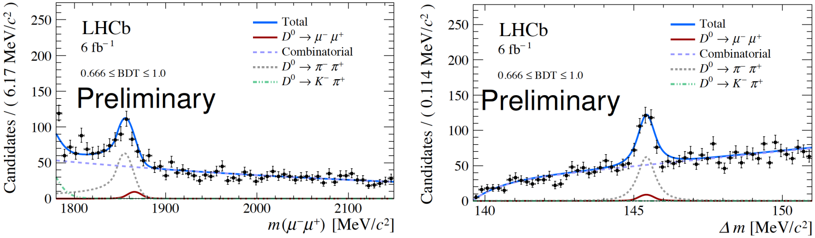
The LHCb detector



BDT Input variables

$D^0 \to \mu^+\mu^-$	$K^0_{S(L)} \to \mu^+\mu^-\mu^+\mu^-$
μ $\cos\theta$	VeloMatterVeto
$\log(1-\cos\gamma)$	$\min(\mu\text{IP})$
D^0 DOCA	K^0_S IP
D^0 IPχ^2	K^0_SFDT
$\min(\mu\text{IP}\chi^2)$	K^0_SDOCA
$\min(\mu p_T)$	$\min(\log(1-\cos\theta_{ij}))$
D^0 Vertex χ^2	
D^* DTF χ^2	
$D^0 \cos\theta$	
D^0 FDχ^2	
πp_T	
DTF D^0 p_T	

$D^0 \to \mu^+\mu^-$ Fit components



Component	$m(D^0)$ PDF	Δm PDF
Signal	Crystal Ball + 2 Gaussian	Johnson SU + 2 Gaussian
Untagged signal	Crystall Ball + 2 Gaussian	RooDstD0BG
Combinatorial	Cheby	RooDstD0BG
$\pi\pi$ misID	Crystal Ball	Johnson + Gaussian
Untagged $\pi\pi$ misID	Crystal Ball	RooDstD0BG
$K\pi$ misID	Johnson	3 Gaussian

Prospects for charm measurements

	Mode	Upgrade (50 fb^{-1})	Upgrade II (300 fb^{-1})
Limits on BFs	$D^0 \to \mu^+\mu^-$	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}
	$D^0 \to e\mu$	10^{-9}	4.1×10^{-9}
Stat. precision on asymmetries	$D^+ \to \pi^+\mu^+\mu^-$	0.2%	0.08%
	$D^0 \to \pi^+\pi^-\mu^+\mu^-$	1%	0.4%
	$D^0 \to \pi^+K^-\mu^+\mu^-$	0.3%	0.13%
	$D^0 \to K^+\pi^-\mu^+\mu^-$	12%	5%
	$D^0 \to K^+K^-\mu^+\mu^-$	4%	1.7%

$D^0 \to h^+h^-\mu^+\mu^-$ [PRL 128 (2022) 221801]