Rare charm decays at LHCb

Marco Colonna, on behalf of **LHCb collaboration**.

Discrete2024, Ljubljana

December 4, 2024

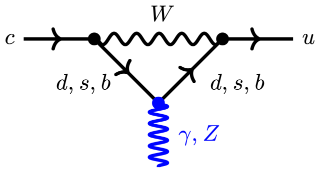
Introduction: why do we study charm rare decays?

The $c \to u\ell^+\ell^-$ transitions are **heavily suppressed**: may allow to **observe of New Physics**.

- Tree level **flavor-changing neutral-current** (FCNC) is not in the Standard Model (SM).
- Amplitude $A(c \to u)$ depends on CKM elements ($\lambda_i = V_{ci}^* V_{ui}$) and loop functions ($f_i$):

$$A(c \to u) = \sum_{i=d,s,b} \lambda_i f_i = \lambda_s \left((f_s - f_d) + \frac{\lambda_b}{\lambda_s}(f_b - f_d) \right)$$

CKM suppression and **Glashow-Iliopoulos-Maiani (GIM)** mechanism extremely suppress the branching fractions and CP asymmetries.



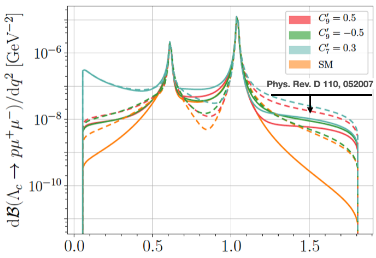
Introduction: complementary approaches to probe New Physics

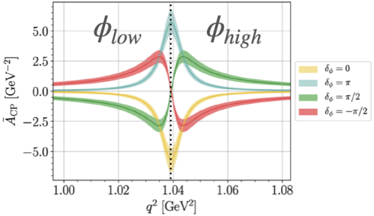
We have different strategies to probe New Physics:

- measure the branching fraction of the decays;
  - NP sensitive in the **non-resonance region**;
- *CP* and angular asymmetries (null tests);
  - NP sensitive in the **resonance region**;
- Lepton flavour universality tests;

$$R^D_{P_1,P_2} = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{dB(D\to P_1 P_2 \mu^+\mu^-)}{q^2}}{\int_{q^2_{min}}^{q^2_{max}} \frac{dB(D\to P_1 P_2 e^+ e^-)}{q^2}}$$

LHCb is providing **major contributions** in the field.
Today we discuss the **most recent results** at LHCb.





Hiller et al, JHEP09(2021)208

Search for $D^0 \to h^+h^-e^+e^-$ decays

(*LHCb-PAPER-2024-047, in preparation*)

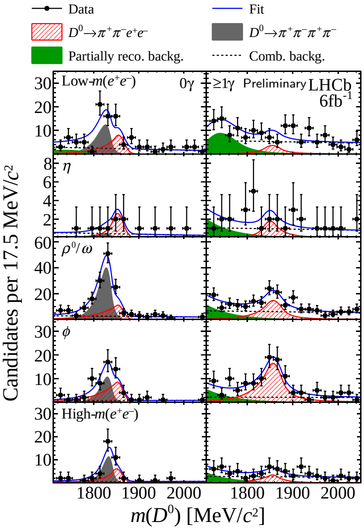
New!

Search for $D^0 \to h^+h^-e^+e^-$ decays (*LHCb-PAPER-2024-047, in preparation*)

$D^0 \to \pi^+\pi^-e^+e^-$

- LHCb **observed for the first time** the $D^0 \to \pi^+\pi^-e^+e^-$ in ρ/ω and ϕ dilepton mass regions.
- The current **best upper limits** on $\mathcal{B}$ in other regions have been established.
- The $\mathcal{B}$ in the electron mode is **compatible with the one of the muon mode**.

$D^0 \to \pi^+\pi^-e^+e^-$		
$m(e^+e^-)$ region	$[\text{MeV}/c^2]$	$\mathcal{B}\ [10^{-7}]$
Low mass	211–525	$< 4.8\,(5.4)$
η	525–565	$< 2.3\,(2.7)$
ρ^0/ω	565–950	$4.5 \pm 1.0 \pm 0.7 \pm 0.6$
ϕ	950–1100	$3.8 \pm 0.7 \pm 0.4 \pm 0.5$
High mass	> 1100	$< 2.0\,(2.2)$
Total	–	$13.3 \pm 1.1 \pm 1.7 \pm 1.8$

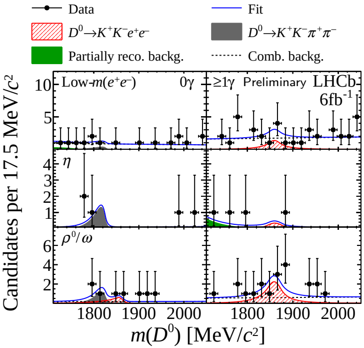


Search for $D^0 \to h^+h^-e^+e^-$ decays (*LHCb-PAPER-2024-047, in preparation*)

$$D^0 \to K^+K^-e^+e^-$$

- No evidences with the current precision.
- The current **best upper limits** on the $\mathcal{B}$ have been established.

$D^0 \to K^+K^-e^+e^-$		
$m(e^+e^-)$ region	[MeV/c^2]	$\mathcal{B}$ [10^{-7}]
Low mass	211–525	$< 1.0\,(1.1)$
η	525–565	$< 0.4\,(0.5)$
ρ^0/ω	> 565	$< 2.2\,(2.5)$

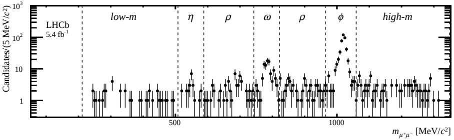


Search for $\Lambda_c^+ \to p\mu^+\mu^-$ decays

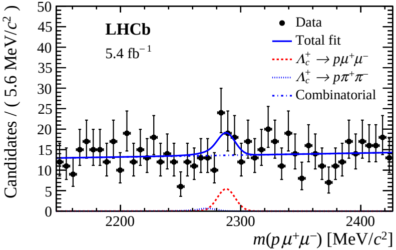
(*Phys. Rev. D 110, 052007*)

Study the **resonant and non resonant dimuon regions** with LHCb RUN2 (5.4 fb^{-1}).

- Measure the $\mathcal{B}$:
  - ρ, ω and η resonant regions;
- **Search in the non resonant region**;
- uses the ϕ resonant region **as normalization**.



No signal evidence in the non-resonant region:



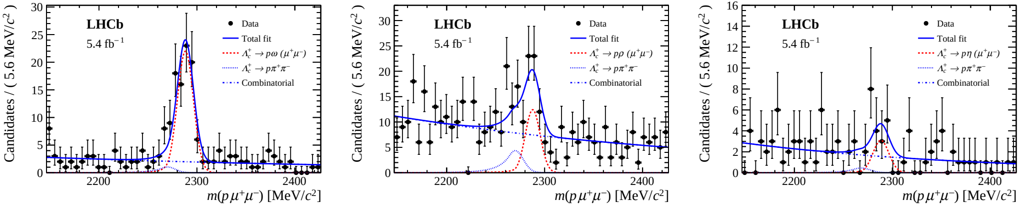
- The **best upper limits** on the $\mathcal{B}$ has been established:

$$\mathcal{B}\left(\Lambda_c^+ \to p\mu^+\mu^-\right) < 2.9(3.2) \times 10^{-8} \text{ at } 90\%(95\%) \text{ CL.}$$

Search for $\Lambda_c^+ \to p\mu^+\mu^-$ decays (*Phys. Rev. D 110, 052007*)

- The $\mathcal{B}$ in the **resonant regions** have been measured:

$\Lambda_c^+ \to p\rho(\to \mu^+\mu^-)$	$\Lambda_c^+ \to p\omega(\to \mu^+\mu^-)$	$\Lambda_c^+ \to p\eta(\to \mu^+\mu^-)$
$> 7\sigma$	$> 5.6\sigma$	$> 3.0\sigma$



$$\mathcal{B}\left(\Lambda_c^+ \to p\rho\right) = (1.52 \pm 0.34(\text{stat}) \pm 0.14(\text{syst}) \pm 0.24(\text{ext})) \times 10^{-3}$$
$$\mathcal{B}\left(\Lambda_c^+ \to p\omega\right) = (9.82 \pm 1.23(\text{stat}) \pm 0.73(\text{syst}) \pm 2.79(\text{ext})) \times 10^{-4}$$
$$\mathcal{B}\left(\Lambda_c^+ \to p\omega\right) = (1.67 \pm 0.69(\text{stat}) \pm 0.23(\text{syst}) \pm 0.34(\text{ext})) \times 10^{-3}$$

Search for resonance enhanced asymmetries on the $\Lambda_c^+ \to p\mu^+\mu^-$ channel

(*LHCb-PAPER-2024-051, in preparation*)

How to access the asymmetries (*LHCb-PAPER-2024-051, in preparation*)

CP asymmetry

We cannot access A_{CP} directly, we only can measure the so called raw-asymmetry (A_{CP}^{raw}):

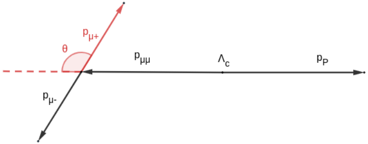
$$A_{CP}^{raw} = \frac{N\left(\Lambda_c^+\right) - N\left(\bar{\Lambda}_c^-\right)}{N\left(\Lambda_c^+\right) + N\left(\bar{\Lambda}_c^-\right)} = A_{CP} + A_P\left(\Lambda_c^+\right) + A_D\left(p\right) + \left(A_D\left(\mu^+\mu^-\right) = 0\right)$$

- a control sample of $\Lambda_c^+ \to pK_s^0$ is used to estimate the nuisance asymmetries:

FB asymmetry

The A_{FB} is defined with respect to $\theta-$angle:

$$A_{FB} = \frac{N\left(\cos\theta > 0\right) - N\left(\cos\theta < 0\right)}{N\left(\cos\theta > 0\right) + N\left(\cos\theta < 0\right)}$$



It is also possible to evaluate the relevant combinations:

$$\Sigma A_{FB} = \frac{1}{2}\left(A_{FB}^{\Lambda_c^+} + A_{FB}^{\bar{\Lambda}_c^-}\right) \qquad \Delta A_{FB} = \frac{1}{2}\left(A_{FB}^{\Lambda_c^+} - A_{FB}^{\bar{\Lambda}_c^-}\right)$$

Acceptance corrections

(*LHCb-PAPER-2024-051, in preparation*)

The detector and the offline selection may have different efficiencies in different regions of the $(m_{\mu\mu}, \cos\theta)$-phase space.

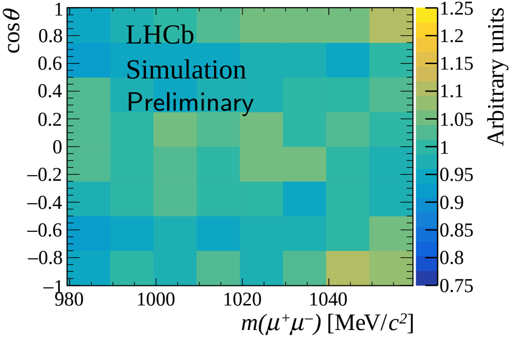
The distributions **at generation level** and **after the offline selection** are compared.

The **relative efficiencies** in the phase space are:

$$\epsilon\left(m_{\mu\mu}, \cos\theta\right) = \frac{f_{selected}\left(m_{\mu\mu}, \cos\theta\right)}{f_{generated}\left(m_{\mu\mu}, \cos\theta\right)}$$

and the **acceptance weights**:

$$\lambda_{corr} = \frac{1}{\epsilon}$$



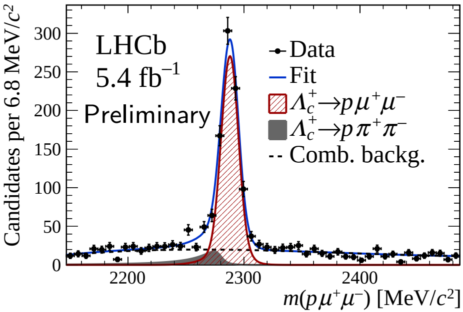
A total model to fit the **final selected mass distribution** has been studied:

$$f_{tot}(m; N_1, ..., N_n) = \sum_{i=1}^{n} N_i f_i(m; \vec{x_i})$$

The shapes of the different components ($\vec{x_i}$) have been **constrained by previous fits** on simulation and data control samples.

The **yields from the total fit** are:

$m(\mu^+\mu^-)$	Efficiency-weighted yields Signal	Misid. back.	Comb. back.
$\phi_{\rm low}$	346 ± 22	57 ± 21	437 ± 26
$\phi_{\rm high}$	435 ± 22	35 ± 17	390 ± 25



Final null test results! (*LHCb-PAPER-2024-051, in preparation*)

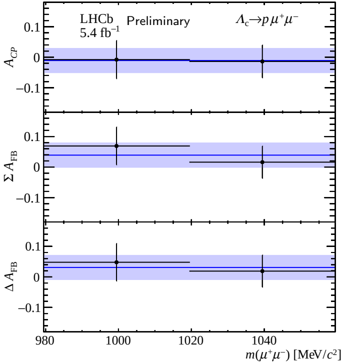
Finally the **values of the null tests**:

$m(\mu^+\mu^-)$	A_{CP}[%]	$A_{\rm FB}^{\Lambda_c^+}$ [%]	$A_{\rm FB}^{\bar{\Lambda}_c^-}$ [%]	$\Sigma A_{\rm FB}$ [%]	$\Delta A_{\rm FB}$ [%]
$\phi_{\rm low}$	$-0.8 \pm 6.2 \pm 0.6$	$11.7 \pm 8.5 \pm 1.1$	$2.2 \pm 8.7 \pm 1.4$	$6.9 \pm 6.1 \pm 1.0$	$4.8 \pm 6.1 \pm 0.8$
$\phi_{\rm high}$	$-1.4 \pm 5.3 \pm 0.6$	$3.5 \pm 7.2 \pm 0.9$	$-0.3 \pm 7.4 \pm 1.1$	$1.6 \pm 5.2 \pm 0.8$	$1.9 \pm 5.2 \pm 0.6$

We also **combine the two dilepton mass bins**:

$$A_{CP} = -1.1 \pm 4.0 \pm 0.5\%$$
$$\Sigma A_{\rm FB} = +3.9 \pm 4.0 \pm 0.6\%$$
$$\Delta A_{\rm FB} = +3.1 \pm 4.0 \pm 0.4\%$$

- **No significant deviation** from the SM are observed.
- At this precision the $\Lambda_c^+ \to p\mu^+\mu^-$ is a competitive channel for **setting constraints to BSM physics** (Hiller et al, arXiv 2410.00115).



Conclusions and outlook

Conclusions

- **Rare charm decays** are a powerful probe to investigate New Physics, complementary to the beauty-sector.
- LHCb is giving a **major contribution** in the field:
  - $D^0 \to h^+h^-e^+e^-$: **first observation** in $D^0 \to \pi^+\pi^-e^+e^-$ and **world's best upper limit** in $D^0 \to K^+K^-e^+e^-$ decays;
  - $\Lambda_c^+ \to p\mu^+\mu^-$: **world's best upper limit** in non resonant region;
  - $\Lambda_c^+ \to p\mu^+\mu^-$: **first null test measurement** in the ϕ-resonant region.

Outlook

- The electron mode will allow **future LFU tests**.
- $\Lambda_c^+ \to p\mu^+\mu^-$ is a powerful channel to **probe New Physics**.
- LHCb new data, with **improved trigger efficiency**, will provide **higher statistic dataset**.