Rare Charm decays at LHCb

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on behalf of the LHCb Collaboration

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Why rare charm decays?

- Rare charm decays proceed through highly suppressed loops in the SM; ideal probe of new physics.
  - s&d loop GIM suppressed $\sim (m_s^2-m_d^2)/m_W^2$;
  - b–loop CMK suppressed $V_{ub}V_{cb}(m_b/m_W)^2 \sim 10^{-6}$.

- Complementary to beauty and strange. Charm probes also couplings to up–type quarks.

- But … long–distance (tree–level) contributions are non–negligible and hard to calculate.
So far LHCb focused mostly on final states with 2 muons:

- Best limits on $D^0 \rightarrow \mu^+\mu^-$ [PLB 725 (2013) 15], $D_{(s)}^+ \rightarrow \pi^\pm \mu^\mp \mu^\mp$ [PLB 724 (2013) 203], $D^0 \rightarrow e^+\mu^-$ [PLB 754 (2016) 167], $\Lambda_c^+ \rightarrow p\mu^+\mu^-$ [PRD 97 (2018) 091101].

- First observation of $D^0 \rightarrow K^-\pi^+V(\rightarrow \mu^+\mu^-)$ [PLB 757 (2016) 558], $D^0 \rightarrow K^-K^+V(\rightarrow \mu^+\mu^-)$, $\pi^-\pi^+V(\rightarrow \mu^+\mu^-)$ [PRL 119 (2017) 181805], $\Lambda_c^+ \rightarrow pV(\rightarrow \mu^+\mu^-)$ [PRD 97 (2018) 091101]
Search for LFV decays $D^0 \rightarrow e^+\mu^-$

**Abstract**

A search for the lepton-flavour violating decay $D^0 \rightarrow e^+\mu^+$ is made with a dataset corresponding to an integrated luminosity of 3.0 fb$^{-1}$ of proton-proton collisions at centre-of-mass energies of 7 TeV and 8 TeV, collected by the LHCb experiment. Candidate $D^0$ mesons are selected using the decay $D^{*+} \rightarrow D^0 e^+$ and the $D^0 \rightarrow e^+\mu^-$ branching fraction is measured using the decay mode $D^0 \rightarrow K^-\pi^+$ as a normalisation channel. No significant excess of $D^0 \rightarrow e^+\mu^-$ candidates over the expected background is seen, and a limit is set on the branching fraction, $\mathcal{B}(D^0 \rightarrow e^+\mu^-) < 1.3 \times 10^{-3}$, at 90% confidence level. This is an order of magnitude lower than the previous limit and it further constrains the parameter space in some leptoquark models and in supersymmetric models with R-parity violation.
Search for LFV decays $D^0 \to e^+\mu^-$

- Forbidden in the SM $\Rightarrow$ Signal means NP.
- 3/fb of Run1 data. $D^0$ from $D^*+ \to D^0\pi^+$ decays to suppress combinatorial background.

$$B(D^0 \to e^+\mu^-) < 1.3(1.6) \times 10^{-8} \text{ @ 90(95)% CL}$$
- 10x better precision than Belle [PRD 81 091102 (2010)].
Search for \( \Lambda_{c}^{+} \rightarrow p\mu^{+}\mu^{-} \)

Search for the rare decay
\[ \Lambda_{c}^{+} \rightarrow p\mu^{+}\mu^{-} \]

LHCb collaboration

Abstract
A search for the flavor-changing neutral-current decay \( \Lambda_{c}^{+} \rightarrow p\mu^{+}\mu^{-} \) is reported using a data set corresponding to an integrated luminosity of 3.0 fb\(^{-1}\) collected by the LHCb collaboration. No significant signal is observed outside of the dimuon mass region around the \( \phi \) and \( \omega \) resonances and an upper limit is placed on the branching fraction of \( \mathcal{B}(\Lambda_{c}^{+} \rightarrow p\mu^{+}\mu^{-}) < 7.7 \times 10^{-3} \) at 68% (90%) confidence level. A significant signal is observed in the \( \omega \) dimuon mass region for the first time.

Published in Phys. Rev. D97 (2018) 091101(R)
Search for $\Lambda_c^+ \rightarrow p\mu^+\mu^-$

- Rare decay (SM FCNC BF $\sim 10^{-9}$) overwhelmed with resonant contributions (BF $\sim 10^{-6}$): $\rho^0/\omega, \varphi \rightarrow \mu^+\mu^-$.  

- Search performed with 3/fb (Run1 data) using $\Lambda_c^+ \rightarrow p\varphi(\rightarrow \mu^+\mu^-)$ as reference mode.

- Sensitivity to short distance contributions away from the resonances, even if tails can be significant [PRD 97 034511 (2018)]. BF is not the optimal observable for NP.
Search for $\Lambda_c^+ \rightarrow p\mu^+\mu^-$

- Upper limit on non-resonant component:
  \[ B(\Lambda_c^+ \rightarrow p\mu^+\mu^-) < 9.6 \times 10^{-8} \text{ at 95\% CL} \]
  
  \( 10^3 \times \) better than BaBar for integrated \( m(\mu^+\mu^-) \)
  
  [PRD 84 072006 (2011)]

- First observation of $\Lambda_c^+ \rightarrow p\omega (\rightarrow \mu^+\mu^-)$:
  \[ B(\Lambda_c^+ \rightarrow p\omega) = (9.4 \pm 3.2 \pm 1.0 \pm 2.0) \times 10^{-4} \]

  Uncertainties are: statistical, systematic and due to the BF of the normalisation mode.

[PRD 97 091101 (2018)]
Observation and asymmetries of $D^0 \rightarrow h^+ h^- \mu^+ \mu^-$ decays

Observation of $D^0$ meson decays to $\pi^+ \pi^- \mu^+ \mu^-$ and $K^+ K^- \mu^+ \mu^-$ final states

The LHCb collaboration

Abstract
The first observation of the $D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ and $D^0 \rightarrow K^+ K^- \mu^+ \mu^-$ decays is reported using a sample of proton-proton collisions collected by LHCb at a center-of-mass energy of 8 TeV, and corresponding to 2.0 fb$^{-1}$ of integrated luminosity. The corresponding branching fractions are measured using as normalization the decay $D^0 \rightarrow K^+ \pi^- \mu^+ \nu_{\mu}$, where the two masses are consistent with coming from the decay of a $D^0$ or $\omega$ meson. The results are $B(D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.07) \times 10^{-7}$ and $B(D^0 \rightarrow K^+ K^- \mu^+ \mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}$, where the uncertainties are statistical, systematic, and due to the limited knowledge of the normalization branching fraction. The dependence of the branching fraction on the dimuon mass is also investigated.

Measurement of angular and CP asymmetries in $D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ and $D^0 \rightarrow K^+ K^- \mu^+ \mu^-$ decays

LHCb collaboration

Abstract
The first measurements of the forward-backward asymmetry of the dimuon pair ($A_{FB}$), the triple-product asymmetry ($A_{TP}$), and the charge-parity-conjugation asymmetry ($A_{CP}$), in $D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ and $D^0 \rightarrow K^+ K^- \mu^+ \mu^-$ decays are reported. They are performed using data from proton-proton collisions collected with the LHCb experiment from 2011 to 2016, corresponding to a total integrated luminosity of 5.0 fb$^{-1}$. The asymmetries are measured to be

$A_{FB}(D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-) = (-3.3 \pm 3.7 \pm 0.0)\%$,
$A_{TP}(D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-) = (-0.6 \pm 3.7 \pm 0.0)\%$,
$A_{CP}(D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-) = (4.9 \pm 3.8 \pm 0.7)\%$,
$A_{FB}(D^0 \rightarrow K^+ K^- \mu^+ \mu^-) = (0 \pm 11 \pm 2)\%$,
$A_{TP}(D^0 \rightarrow K^+ K^- \mu^+ \mu^-) = (9 \pm 1.1 \pm 1)\%$,
$A_{CP}(D^0 \rightarrow K^+ K^- \mu^+ \mu^-) = (0 \pm 11 \pm 2)\%$,

where the first uncertainty is statistical and the second systematic. The asymmetries are also measured as a function of the dimuon invariant mass. The results are consistent with the Standard Model predictions.

Published in Phys. Rev. Lett. 119 (2017) 181805

The richness of $D^0 \rightarrow h^+ h^- \mu^+ \mu^-$

- Overwhelming contribution from long-distance amplitudes proceeding through intermediate vector resonances in the $\mu^+ \mu^-$ spectrum.

- However, rich and diverse dynamic of a four-body decay compensate such penalty [JHEP 04 135 (2013), PRD 87 054026 (2013)].
Observation of $D^0 \rightarrow h^+h^-\mu^+\mu^-$

- Search of $D^0 \rightarrow h^+h^-\mu^+\mu^-$ decays using 2/fb of Run1 data.
- Reference mode: $D^0 \rightarrow K^-\pi^+\mu^+\mu^-$.
- Use $D^{*+} \rightarrow D^0\pi^+$ decays to greatly suppress combinatorial background.
- Misreconstructed decays are the main source of background.
- BF measured in $m(\mu^+\mu^-)$ bins.

<table>
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<th>$\rho/\omega$</th>
<th>$\phi$</th>
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<td>$D^0 \rightarrow K^+K^-\mu^+\mu^-$</td>
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</tr>
</tbody>
</table>

[PLR 119 181805 (2017)]
Signal in bins of $m(\mu^+\mu^-)$

$D^0 \rightarrow K^+K^-\mu^+\mu^-$

- Low-$m(\mu^+\mu^-)$: 3.1σ
- High-$m(\mu^+\mu^-)$: 8.1σ

$D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$

- Low-$m(\mu^+\mu^-)$: 5.4σ
- High-$m(\mu^+\mu^-)$: 2.5σ

Pietro Marino – Rare Charm

[PRl 119 181805 (2017)]
Branching fraction results

- Rarest charm decay ever observed:
  \[
  B(D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7}
  \]
  \[
  B(D^0 \rightarrow K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}
  \]
  Uncertainties are statistical, systematic, and due to the BF of the reference mode, respectively.

- In agreement with the SM. [JHEP 04 135 (2013)]
Asymmetries in $D^0 \to \pi^+\pi^-\mu^+\mu^-$, $D^0 \to K^+K^-\mu^+\mu^-$

- Short–distance physics can be accessed through angular and CP asymmetries [JHEP 04 135 (2013), PRD 87 054026 (2013)].

  - Observables are SM null tests.
  - Predictions for NP up to few %.

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

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

$$A_{\phi} = \frac{\Gamma(\sin 2\phi > 0) - \Gamma(\sin 2\phi < 0)}{\Gamma(\sin 2\phi > 0) + \Gamma(\sin 2\phi < 0)}$$
Asymmetries in $D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$, $D^0 \rightarrow K^+ K^- \mu^+ \mu^-$

Table 1: Variables (candidates integrated in asymmetries. Figure 2 shows the first uncertainty is statistical and the second systematic. Measurements are reported only in and (bottom) includes also the regions where no yields are reported.

For $D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$:

- $A_{FB} = (3.3 \pm 3.7 \pm 0.6)\%$
- $A_\phi = (-0.6 \pm 3.7 \pm 0.6)\%$
- $A_{CP} = (4.9 \pm 3.8 \pm 0.7)\%$

For $D^0 \rightarrow K^+ K^- \mu^+ \mu^-$:

- $A_{FB} = (0 \pm 11 \pm 2)\%$
- $A_\phi = (9 \pm 11 \pm 1)\%$
- $A_{CP} = (0 \pm 11 \pm 2)\%$

2/fb Run1 + 3/fb Run2

Pietro Marino - Rare Charm decays at LHCb
Asymmetries in $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$, $D^0 \rightarrow K^+K^-\mu^+\mu^-$ as function of $m(\mu^+\mu^-)$

No $m(\mu^+\mu^-)$ invariant-mass dependency.
Summary

- Not just **beautiful**: rare decays at LHCb are also **charming**.
  - Possible thanks to the world’s largest charm data sample.

- Steady progress of rare charm decays at LHCb:
  - Seen signal of 4–body charm decays into two muon and two hadrons. First measurement of angular and CP asymmetries, already with a sensitivity of few %.
  - First studies of baryonic decays $\Lambda_c^+ \rightarrow p\mu^+\mu^-$, probing BF up to $10^{-8}$.

- Hoping for exciting results to come ...
Rare Charm decays at LHCb

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Backup
The LHCb detector

Weight: 5600t
Height: 10m
Long: 21m

~(15+29/p_T)µm IP resolution
~45fs decay time resolution

4 Tm dipole

σ_p/p ~ 0.5-1%@ 5-200 GeV/c

Calorimeters

Muon system

Figure 38: Reconstructed Cherenkov angle for isolated tracks, as a function of track momentum in the C4F10 radiator [81]. The Cherenkov bands for muons, pions, kaons and protons are clearly visible. The ring will generally overlap with several neighbouring rings. Solitary rings from isolated tracks, where no overlap is found, provide a useful test of the RICH performance, since isolated rings can be cleanly and unambiguously associated with a single track. Figure 38 shows the Cherenkov angle as a function of particle momentum using information from the C4F10 radiator for isolated tracks selected in data (∼2% of all tracks). As expected, the events populate distinct bands according to their mass.

4.2.2 Photoelectron yield

The average number of detected photons for each track traversing the Cherenkov radiator media, called the photoelectron yield (N_{pe}), is another important measure of the performance of a RICH detector. The yields for the three radiators used in LHCb are measured in data using two different samples of events [81]. The first sample is representative of normal LHCb data taking conditions, and consists of the kaons and pions originating from the decay D^0 → K^+\phi, where the D^0 is selected from D^+_s → D^0 φ decays. The second sample consists of low detector occupancy pp → ppμ+μ− events, which provide a clean track sample with very low background levels. In both samples, only high-momentum tracks are selected, to ensure that the Cherenkov angle is close to saturation.
Charm decays at LHCb

**Pros**

- Huge cross-section O(mb).
- Excellent tracking and particle identification (muonID: ε~97%, 1–3% $\mu \rightarrow \pi$ misID probability).
- Boosted production $\Rightarrow$ good decay time resolution.

**Cons**

- Busy environment at hadron collider.
- Asymmetric production of charm and anti-charm $\Rightarrow$ issue for CP studies.
- Non-trivial triggers $\Rightarrow$ distortion of acceptance.
Charm flavour tagging

- In order to measure mixing and CPV, it is necessary to identify the flavour of the $D^0$ meson.
- LHCb exploits two decays:
  - $D^{*+} \rightarrow D^0 \pi^+$ decays
  - semi–leptonic $B$–decays