Rare charm decays at LHCb

Dominik Mitzel[1]
on behalf of the LHCb collaboration

[1]CERN

EPS-HEP
Ghent, Belgium
11 July 2019

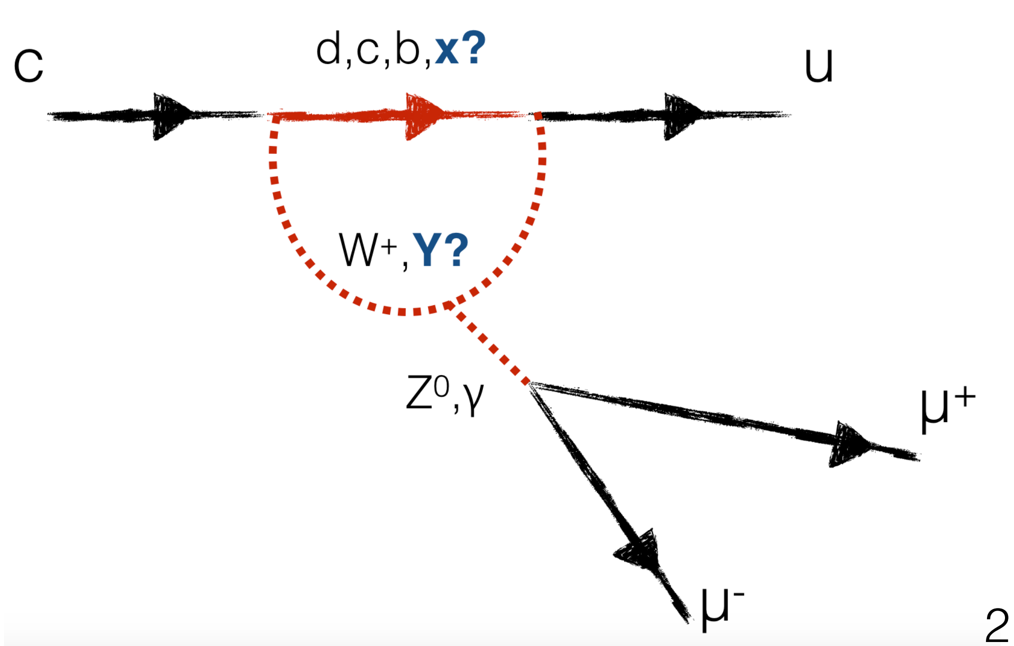
Why rare charm decays?

Promising to search for NP…

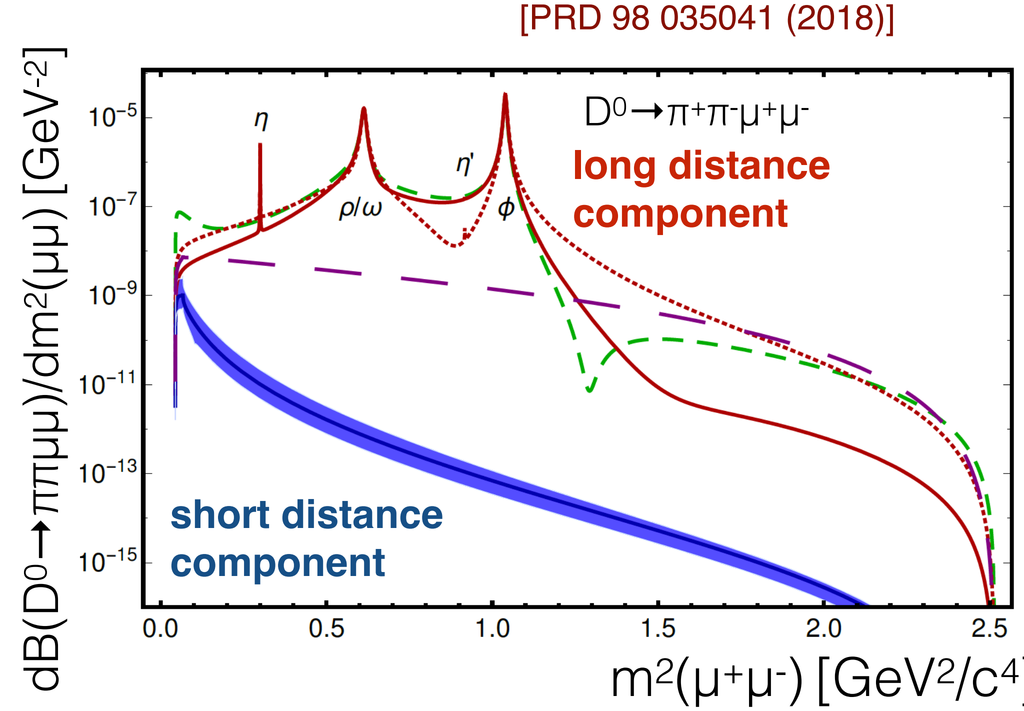
- rare charm decays involve FCNC $c \rightarrow u$ transitions at **short distances (SD)**
  - in SM only at loop level
- some NP models predict large enhancement in rates and asymmetries [PRD 83 114006 (2011)] [PRD 98 035041 (2018)]
- one of few occasions to investigate up-type quark FCNCs

…but also very challenging!

- SM short-distance contribution highly CKM & GIM suppressed
  - inclusive SM $D \rightarrow X\mu^+\mu^- \lesssim O(10^{-9})$
- processes dominated by **long distance (LD)** (tree-level) dynamics, shielding the FCNC processes
- theoretical description very hard



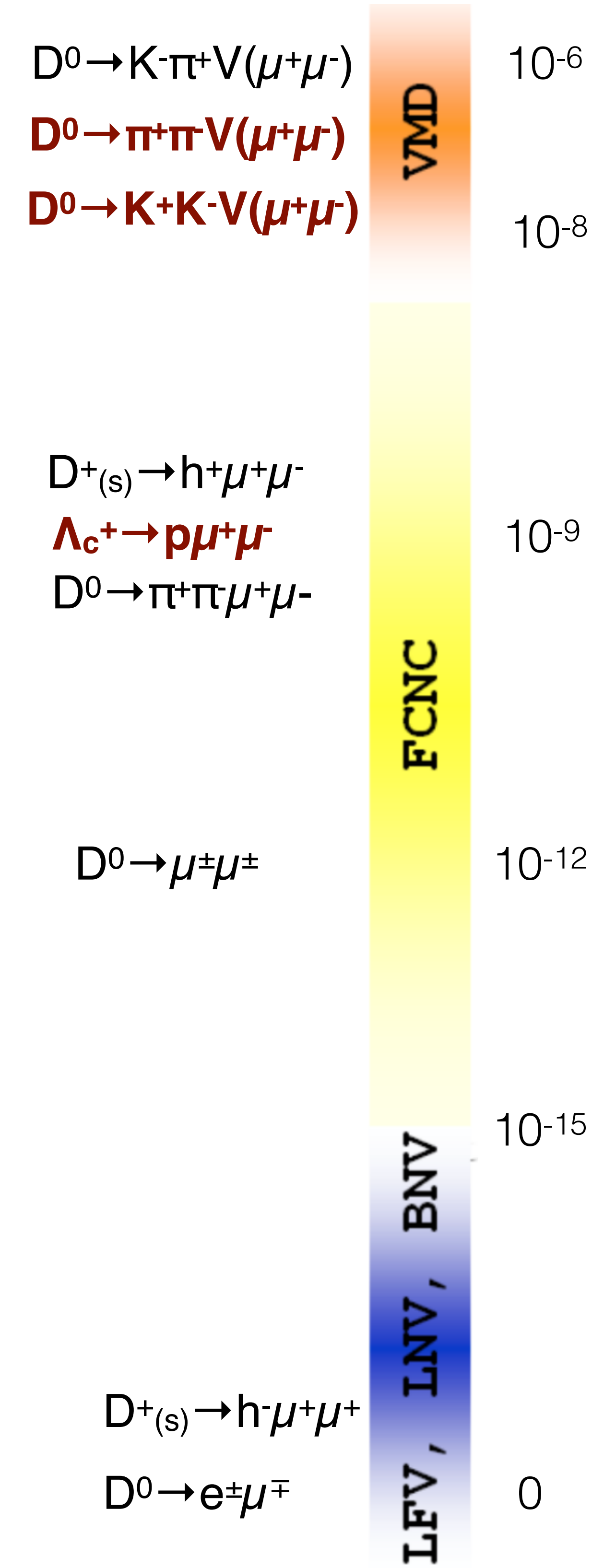
[PRD 98 035041 (2018)]



How to search for BSM physics?

- branching ratios, especially regions away from the resonances
  - search for $D^0 \to \mu^+\mu^-$ [PLB 725 15-24 (2013)]
  - search for $D^+_{(s)} \to \pi^+\mu^+\mu^-$ [PLB 724 203-212 (2013)]
  - search for $\Lambda_c^+ \to p\mu^+\mu^-$ [PRD 97 091101 (2018)]
  - search for $D^0 \to \pi^+\pi^-\mu^+\mu^-$ [PLB 728 234-243 (2014)]
  - observation of $D^0 \to h^-h^{(\prime)+} V(\mu^+\mu^-)$ [PRL 119, 181805 (2017)] [PLB 757 558-567 (2016)]

- null tests based on (approximate) symmetries
  - lepton-flavor/number-violation
    - search for $D^0 \to \mu^+e^-$ [PLB 754 167 (2016)]
    - search for $D^+_{(s)} \to \pi^-\mu^+\mu^+$ [PLB 724 203-212 (2013)]
  - angular and CP asymmetries
    - asymmetries in $D^0 \to h^+h^-\mu^+\mu^-$ [PRL 121 091801 (2018)]
  - lepton-universality [→future]

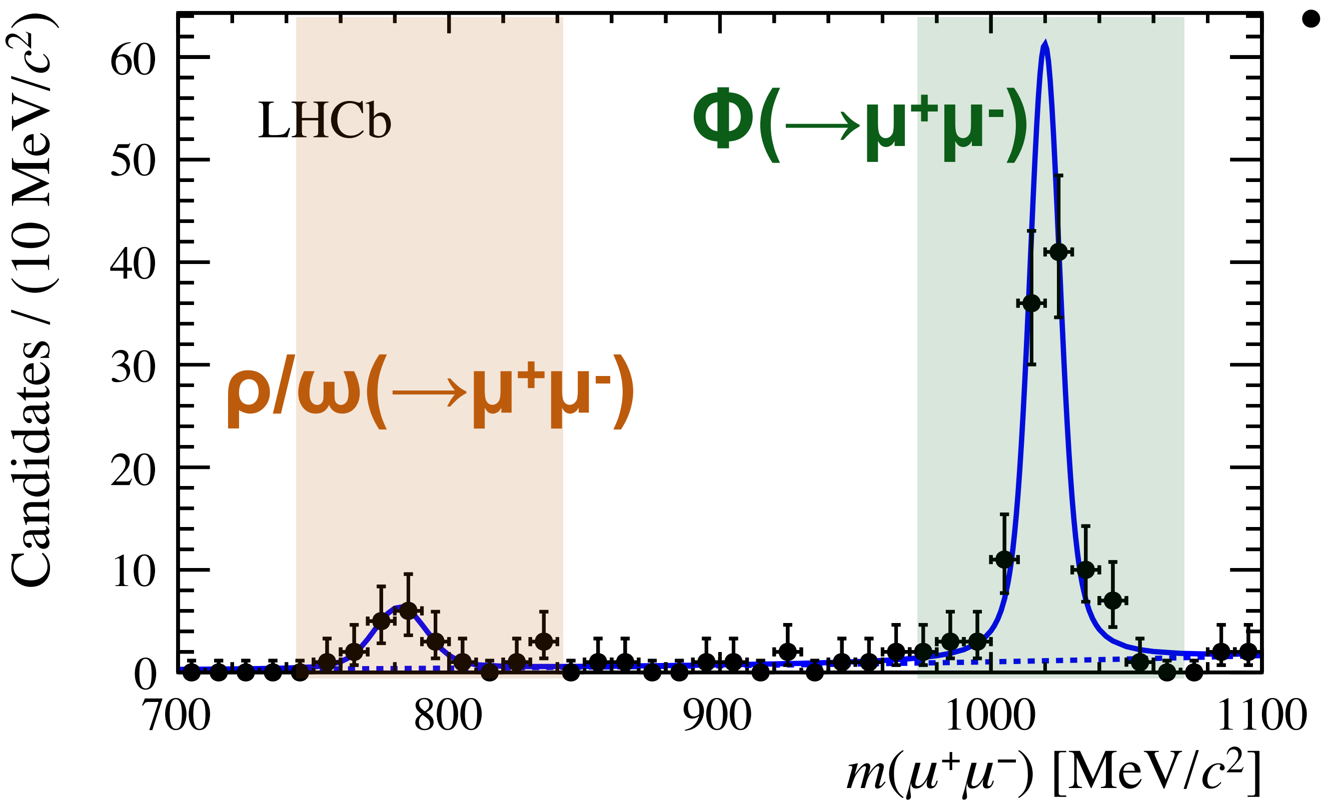


Search for the rare decay $\Lambda_c^+ \rightarrow p\mu^+\mu^-$

PRD 97, 091101 (2018)

Search for the rare decay $\Lambda_c^+ \to p\mu^+\mu^-$

PRD 97, 091101 (2018)



- first measurement of rare decays of charmed baryons at LHCb
  - total BF dominated by resonant **LD** contributions:
    - $\Lambda_c^+ \to p\Phi(\to\mu^+\mu^-)$
    - $\Lambda_c^+ \to p\rho/\omega(\to\mu^+\mu^-)$
  - sensitivity to **SD** physics away from resonances in dimuon mass

LHCb analysis strategy

- define three dimuon mass regions: Φ,ρ/ω and non-resonant (NR)
  - measurement/limit of the BF in ρ/ω and NR region relative to $\Lambda_c^+ \to p\Phi(\to\mu^+\mu^-)$
- full Run 1 data (3/fb)

Search for the rare decay $\Lambda_c^+ \to p\mu^+\mu^-$

PRD 97, 091101 (2018)

- upper limit on non-resonant component

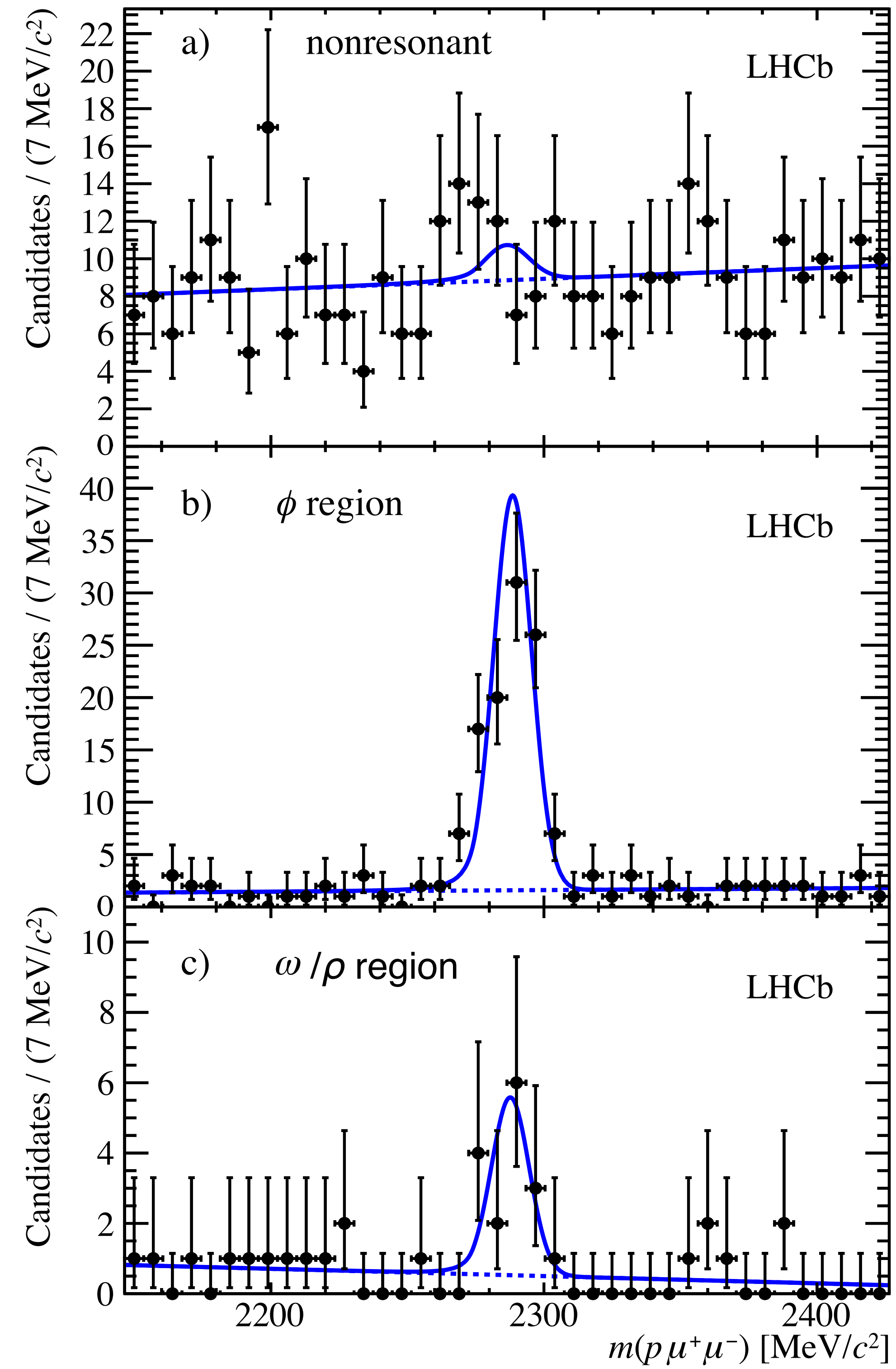
$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 9.6 \times 10^{-8} \text{ at } 95\% \text{ CL}$$

  - ~1000x better than previous result from BaBar [PRD 84 072006 (2011)]

- first observation of $\Lambda_c^+ \to p\mu^+\mu^-$ in the ρ/ω region of the dimuon mass spectrum

$$\mathcal{B}(\Lambda_c^+ \to p[\mu^+\mu^-]_{\rho/\omega}) = (9.4 \pm 3.2 \pm 1.0 \pm 2.0) \times 10^{-8}$$

- uncertainties are statistical, systematic and due to the BF of normalization mode



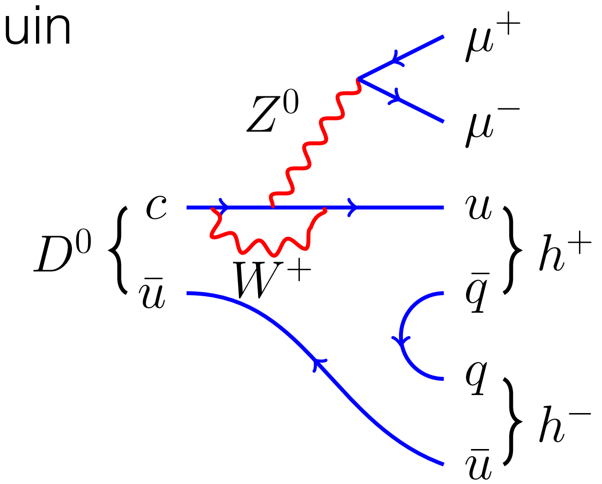
Study of rare four-body $D^0 \to h^+h^-\mu^+\mu^-$ decays ($h=\pi,K$)

PRL 119 181805 (2017), PRL 121 091801 (2018)

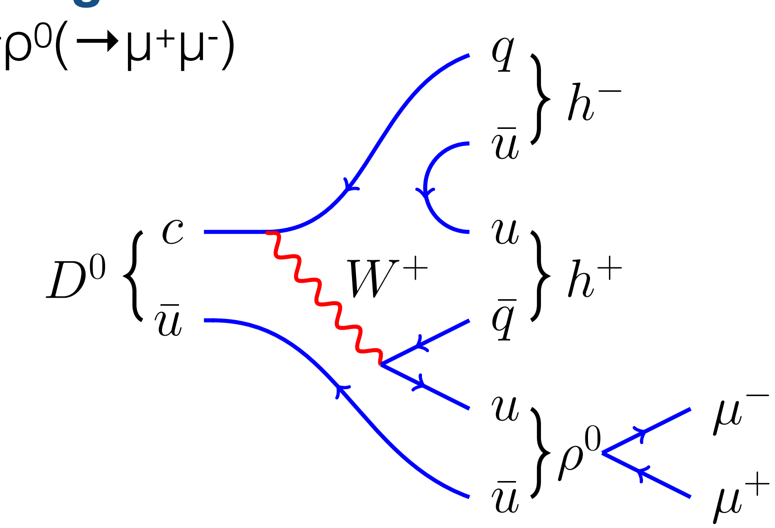
The richness of $D^0 \to h^+h^-\mu^+\mu^-$ decays

- overwhelming contribution from **LD** amplitudes proceeding through intermediate vector resonances screening the **SD** physics

example **short-distance** contribution
EW Penguin



example **long-distance** contribution
$D^0 \to h^+h^-\rho^0(\to\mu^+\mu^-)$



- **first step:** BF measurement (binned in dimuon mass and total BF)
  - (limited) sensitivity to **SD** contribution in regions away from resonances
    - **total BF**:

$$\mathcal{B}(D^0 \to \pi^-\pi^+\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7}$$

$$\mathcal{B}(D^0 \to K^-K^+\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}$$

[PRL 119 181805 (2017)]

- **second step:** measure asymmetries with sensitivity to **SD** in full range
  - O(few%) predictions for some NP models [JHEP 1304 135 (2013), PRD 87 054026 (2013)]

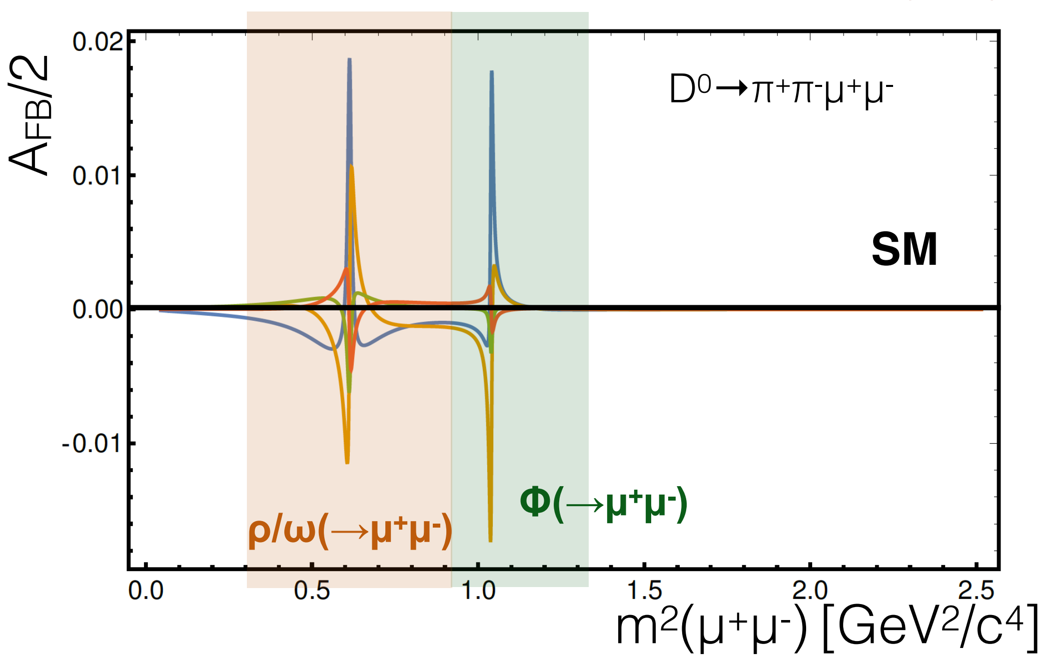
Asymmetries in $D^0 \to \pi^+\pi^-(K^+K^-)\mu^+\mu^-$

PRL 121 091801 (2018)

- for the first time, measurements of angular and CP asymmetries in these decays
  - conceptual new and complementary to BF measurements
- asymmetries are sensitive to **SD** in full range due to **SD**-**LD** interference
  - observables are SM null tests
  - O(few%) predictions for some NP models

[JHEP 1304 135 (2013), PRD 87 054026 (2013), PRD 93, 074001 (2016), PRD 98, 035041 (2018)]

[PRD 98, 035041 (2018)]

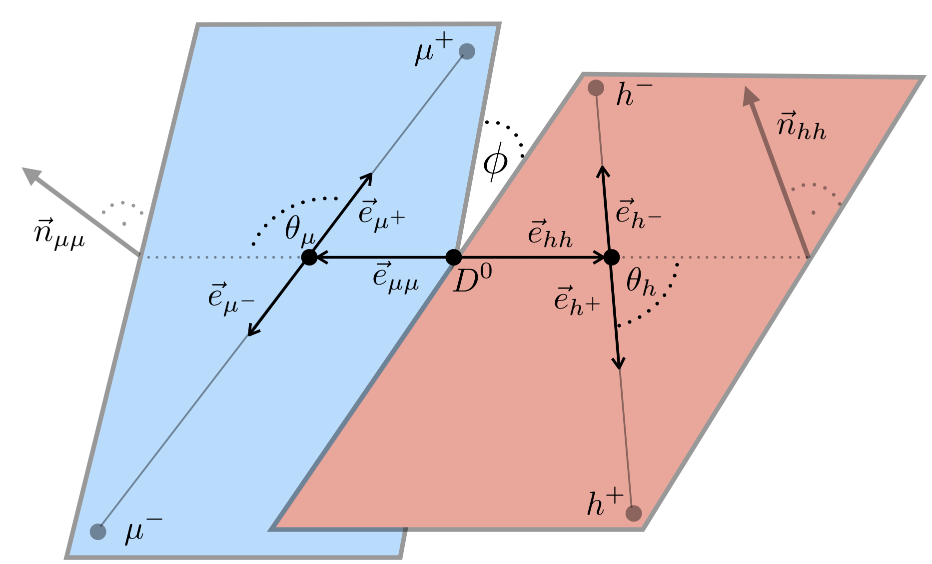


- angular asymmetries
  - forward backward asymmetry

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

  - 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 $D^0 \rightarrow \pi^+\pi^-(K^+K^-)\mu^+\mu^-$

PRL 121 091801 (2018)

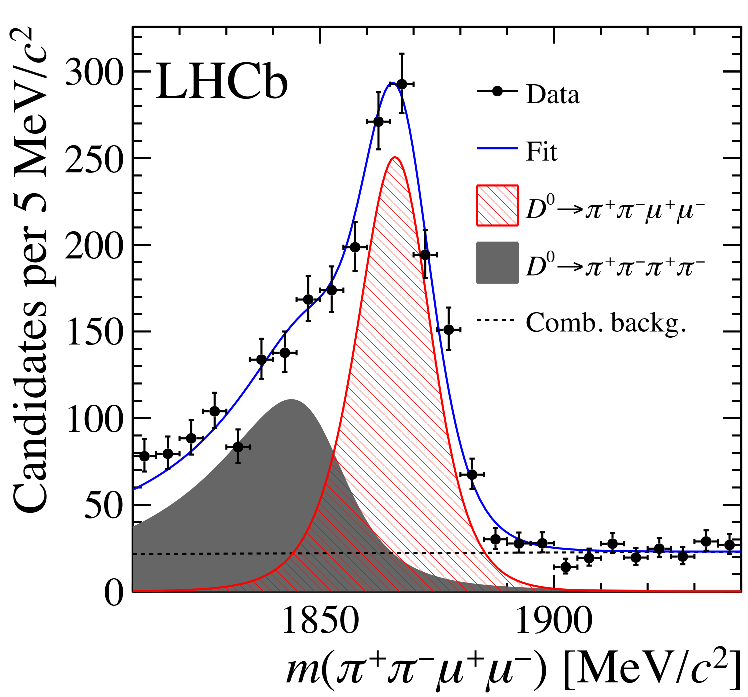
Measurement strategy

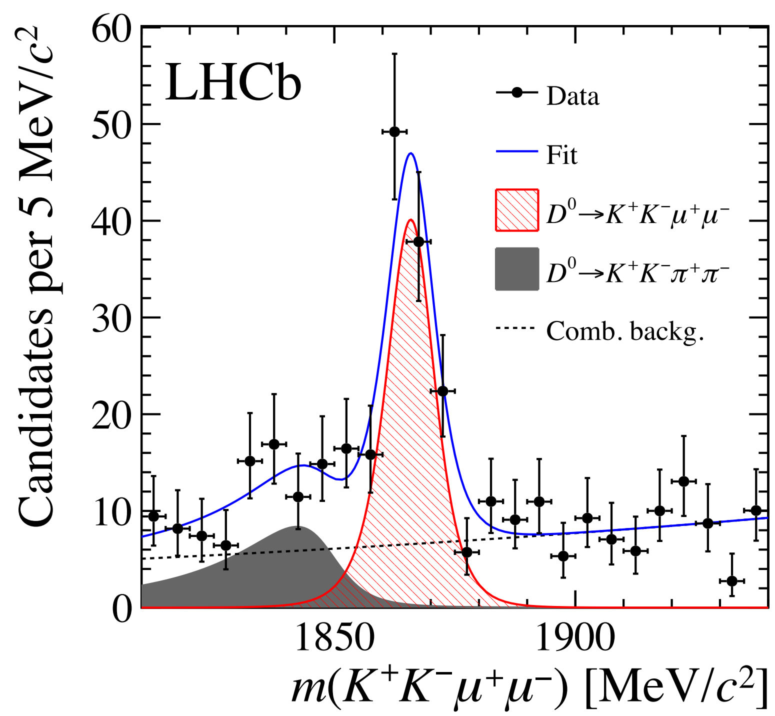
- measure A_{FB}, A_Φ and A_{CP} binned and integrated in dimuon mass
- select D^0 from flavour sepecific $D^{*+} \rightarrow D^0\pi^+$ decays
- 5/fb recorded 2011-2016

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

NA = not available
NS = no signal

- total yields
  - $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$: 1.1k
  - $D^0 \rightarrow K^+K^-\mu^+\mu^-$: 110
- sensitivity on asymmetries of a few %



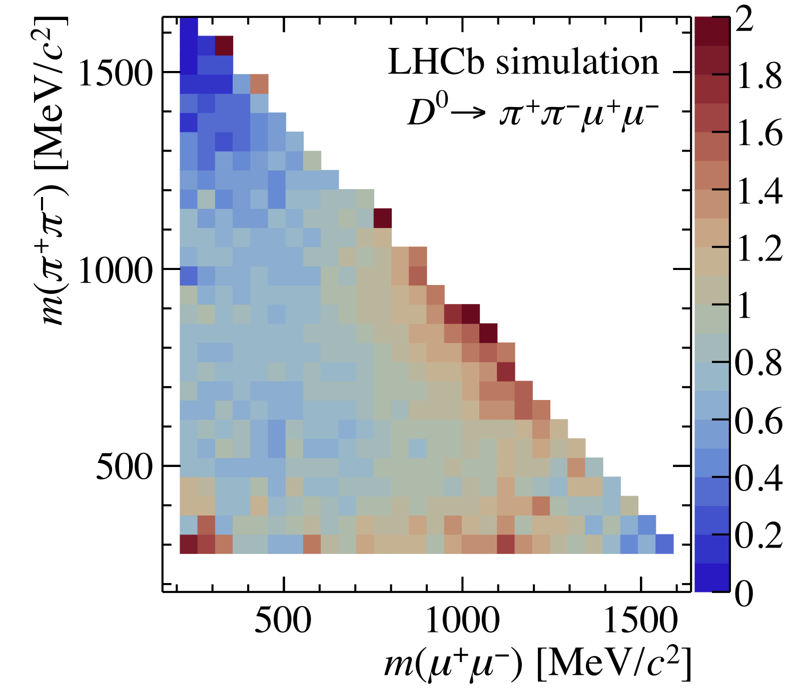


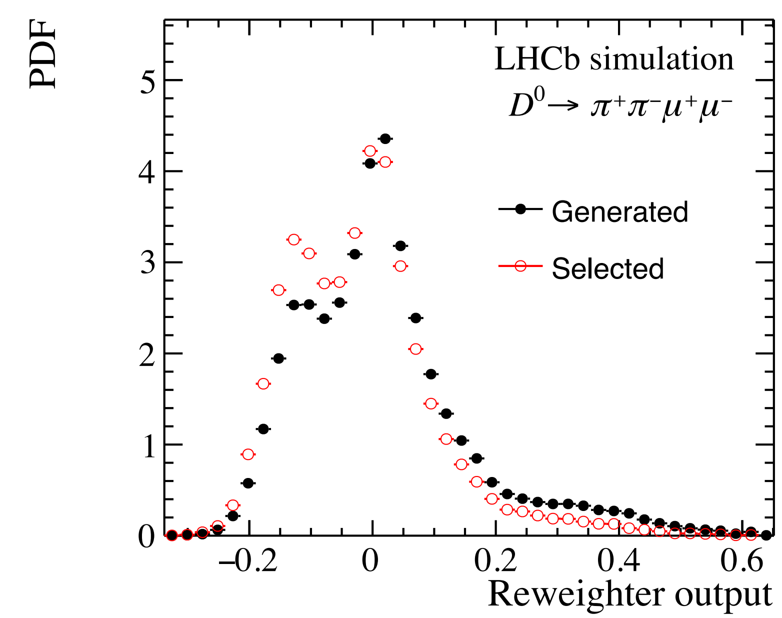
Asymmetries in $D^0 \to \pi^+\pi^-(K^+K^-)\mu^+\mu^-$

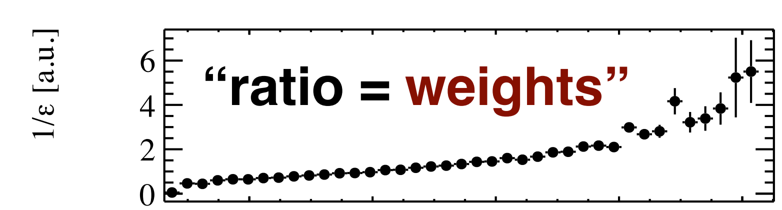
PRL 121 091801 (2018)

Efficiency correction

- efficiency across phase space sculpted due to kinematical cuts in selection/reconstruction. This can cause a bias!
- exploit MVA techniques to correct for efficiency variation
  - train a BDT using the samples of simulated decays before and after selection
  - input: $|\cos(\theta_\mu)|$, $|\cos(\theta_H)|$, $m(\mu^+\mu^-)$ and $m(h^+h^-)$
  - 4D problem reduced to a one dimensional variable
- assign per-event weights as function of reweighter output
- perform fit to efficiency corrected candidates to determine asymmetries







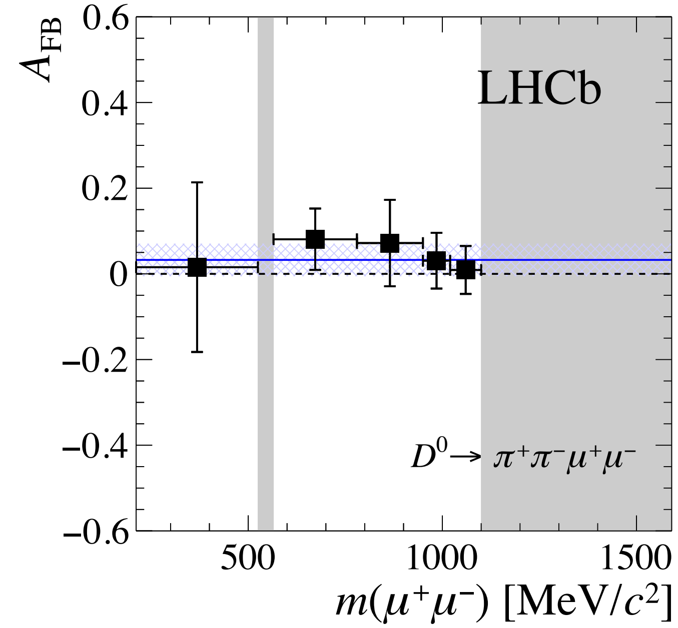
Asymmetries in $D^0 \to \pi^+\pi^-(K^+K^-)\mu^+\mu^-$

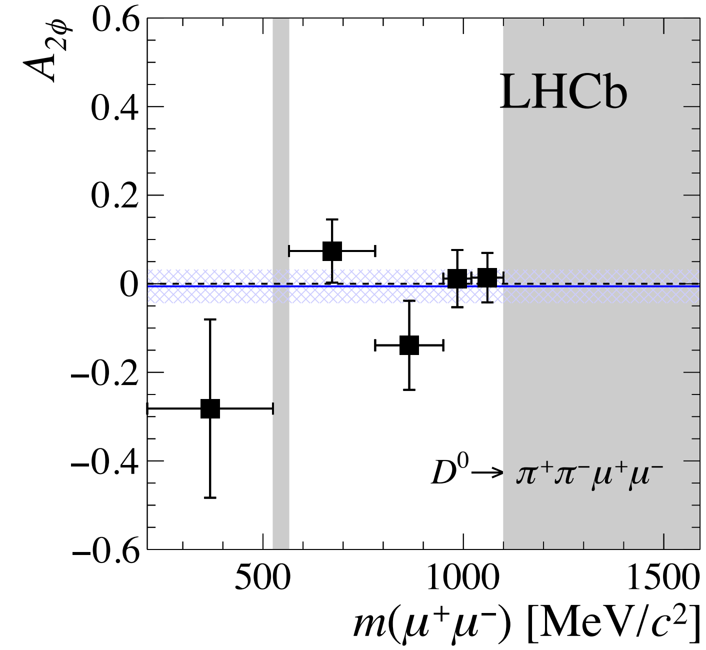
PRL 121 091801 (2018)

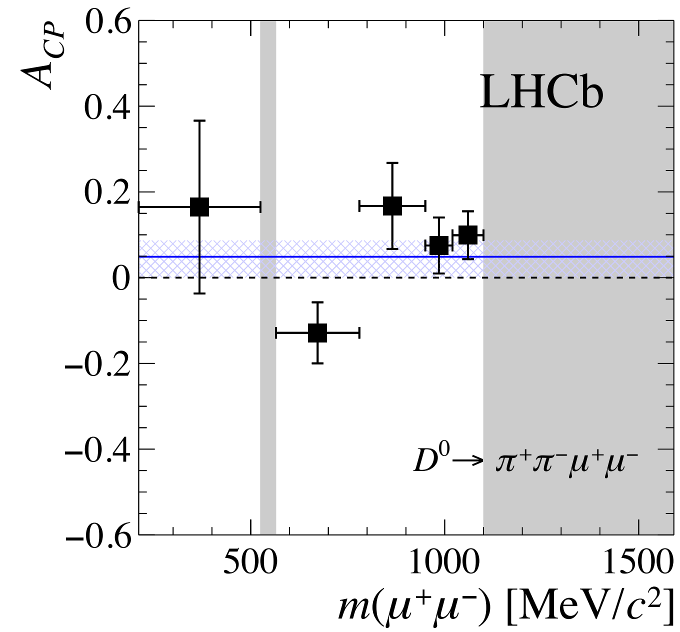
Total asymmetries

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

uncertainties are statistical and systematic







compatible with SM predictions
[JHEP 04 135 (2013), PRD 98, 035041(2018)]

- all asymmetries consistent with zero
- no dependency on dimuon mass observed (also true for $D^0 \to K^+K^-\mu^+\mu^-$)

What comes next?

Many updates will come in the near future…

- two-body decays
  - updated search for $D^0 \to \mu^+\mu^-$
  - updated search for $D^0 \to e^+\mu^-$

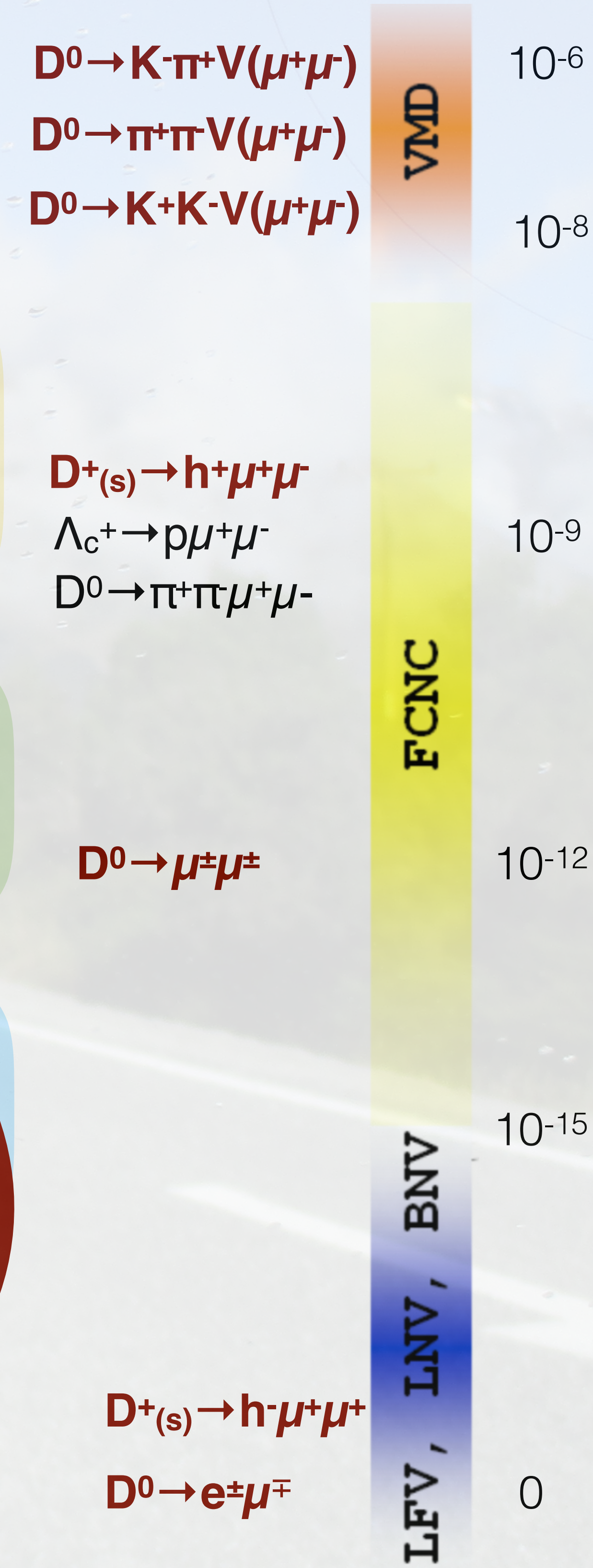
expected limits $O(10^{-10}\text{-}10^{-9})$

- three-body decays
  - search for $D^+_{(s)} \to h^- l^+ l^+$, $D^+_{(s)} \to h^+ l^+ l^-$

expected limits $O(10^{-8}\text{-}10^{-6})$

- four-body decays
  - angular analysis of $D^0 \to h^+h^-\mu^+\mu^-$

Stay Tuned!



Conclusions

- the low SM rates make the field a perfect place to look for physics beyond the SM
  - for many decay modes the SM predictions are way below current experimental sensitivities
- LHCb is making major contributions
  - most measurements report world's best result
    - we hold the record for the rarest charm decays to date…
    - …and even measured asymmetries in these decays!
  - new analyses and updates will come exploring the full Run 2 data set

Thank you

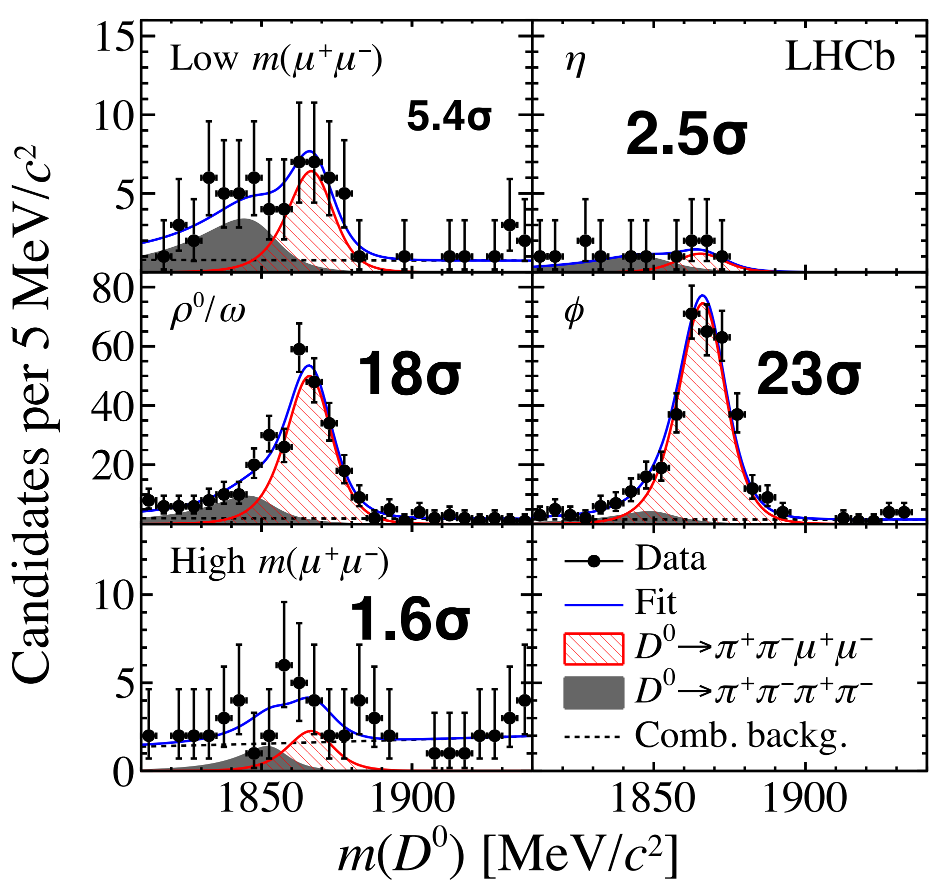
Observation of $D^0 \to \pi^+\pi^-(K^+K^-)\mu^+\mu^-$

PRL 119 181805 (2017)

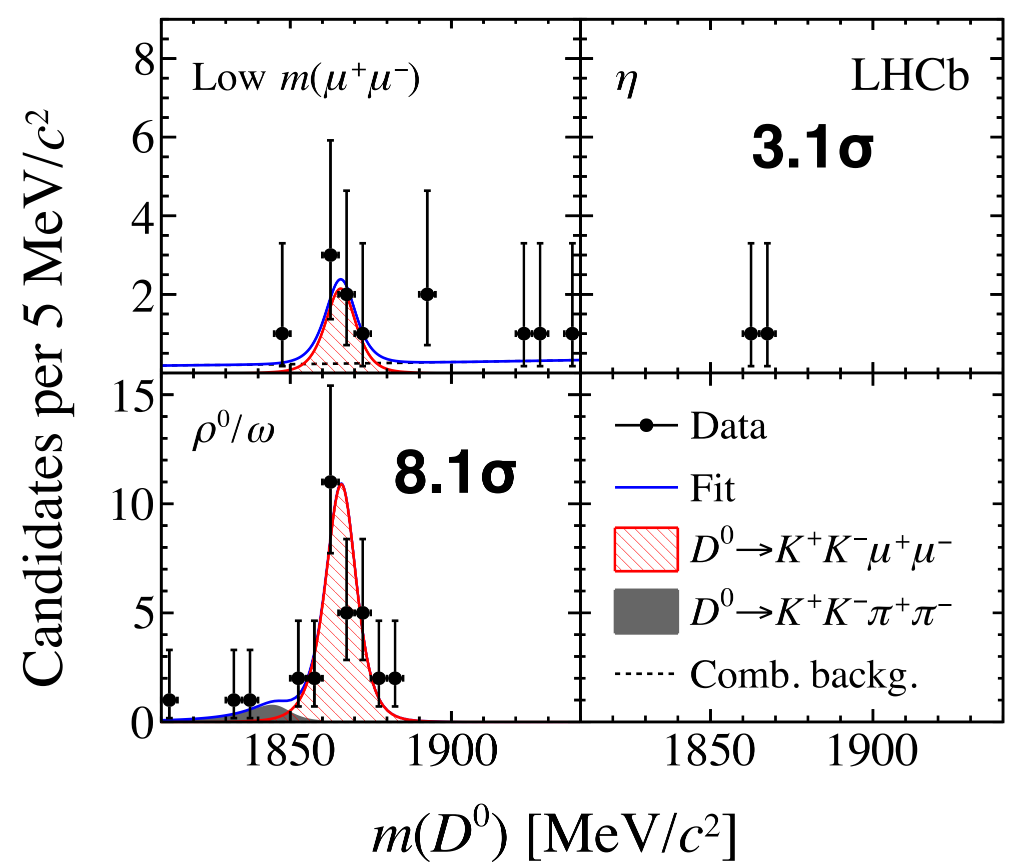
Experimental details

- data: 2/fb from 2012
- normalization channel: $D^0 \to K^-\pi^+\mu^+\mu^-$
- strategy: measure BF binned and integrated in dimuon mass

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



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



Observation of $D^0 \to \pi^+\pi^-(K^+K^-)\mu^+\mu^-$

PRL 119 181805 (2017)

Binned measurement

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

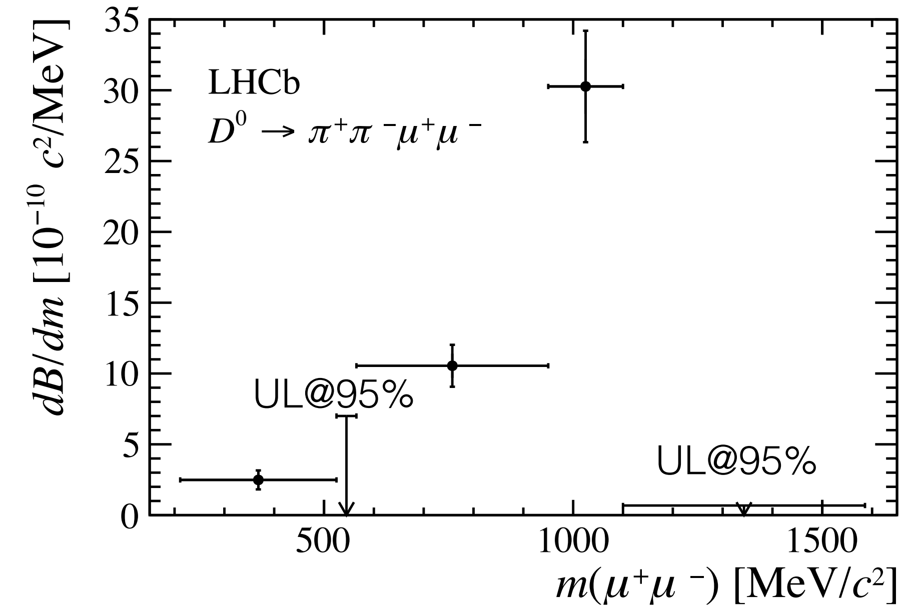
$\mu^+\mu^-$ region	$[MeV/c^2]$	$\mathcal{B}\ [10^{-8}]$
Low mass	< 525	$7.8 \pm 1.9 \pm 0.5 \pm 0.8$
η	525–565	$< 2.4\,(2.8)$ at 90%(95%) CL
ρ^0/ω^0	565–950	$40.6 \pm 3.3 \pm 2.1 \pm 4.1$
ϕ	950–1100	$45.4 \pm 2.9 \pm 2.5 \pm 4.5$
High mass	> 1100	$< 2.8\,(3.3)$ at 90%(95%) CL

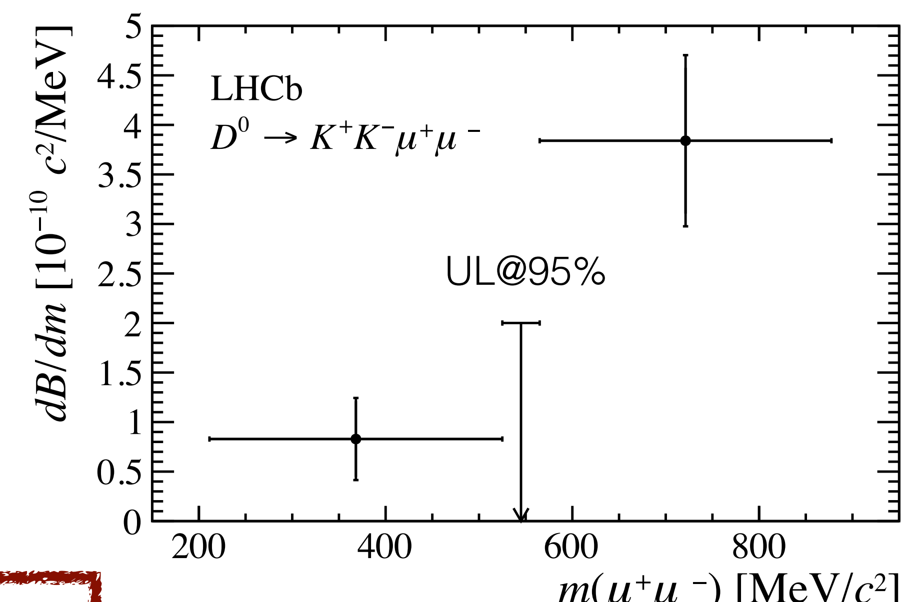
$D^0 \to K^+K^-\mu^+\mu^-$

$\mu^+\mu^-$ region	$[MeV/c^2]$	$\mathcal{B}\ [10^{-8}]$
Low mass	< 525	$2.6 \pm 1.2 \pm 0.2 \pm 0.3$
η	525–565	$< 0.7\,(0.8)$ at 90%(95%) CL
ρ^0/ω^0	> 565	$12.0 \pm 2.3 \pm 0.7 \pm 1.2$

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

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





Total branching fraction

$$\mathcal{B}(D^0 \to \pi^-\pi^+\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7}$$
$$\mathcal{B}(D^0 \to K^-K^+\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}$$

- uncertainties are statistical, systematic and due to the BF of normalization mode

Rarest charm decays so far! compatible with SM predictions
[JHEP 04 135 (2013)]