



Rare decays of charm hadrons at LHCb

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LPNHE (Paris)

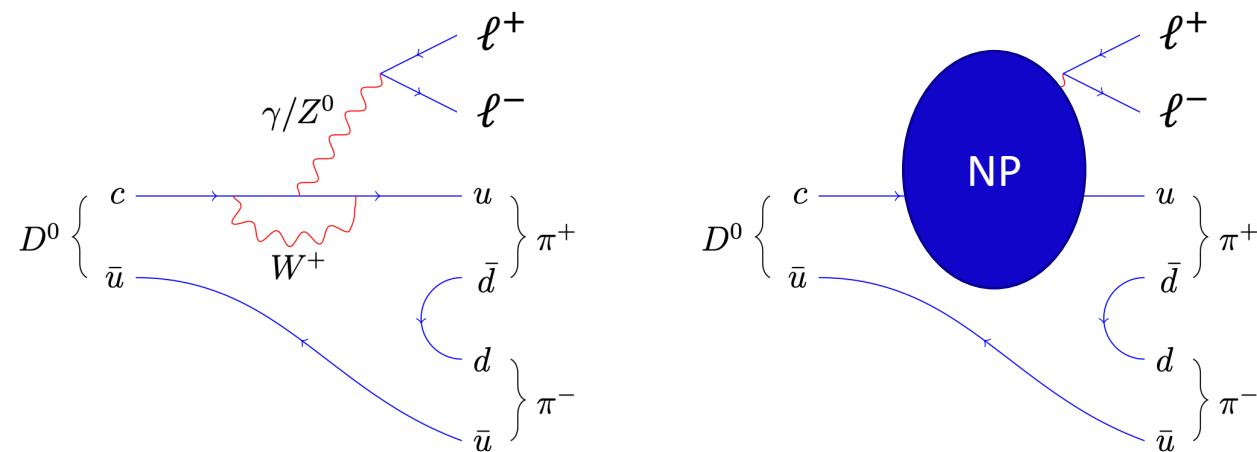


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Melbourne, Australia
17-21 July 2023



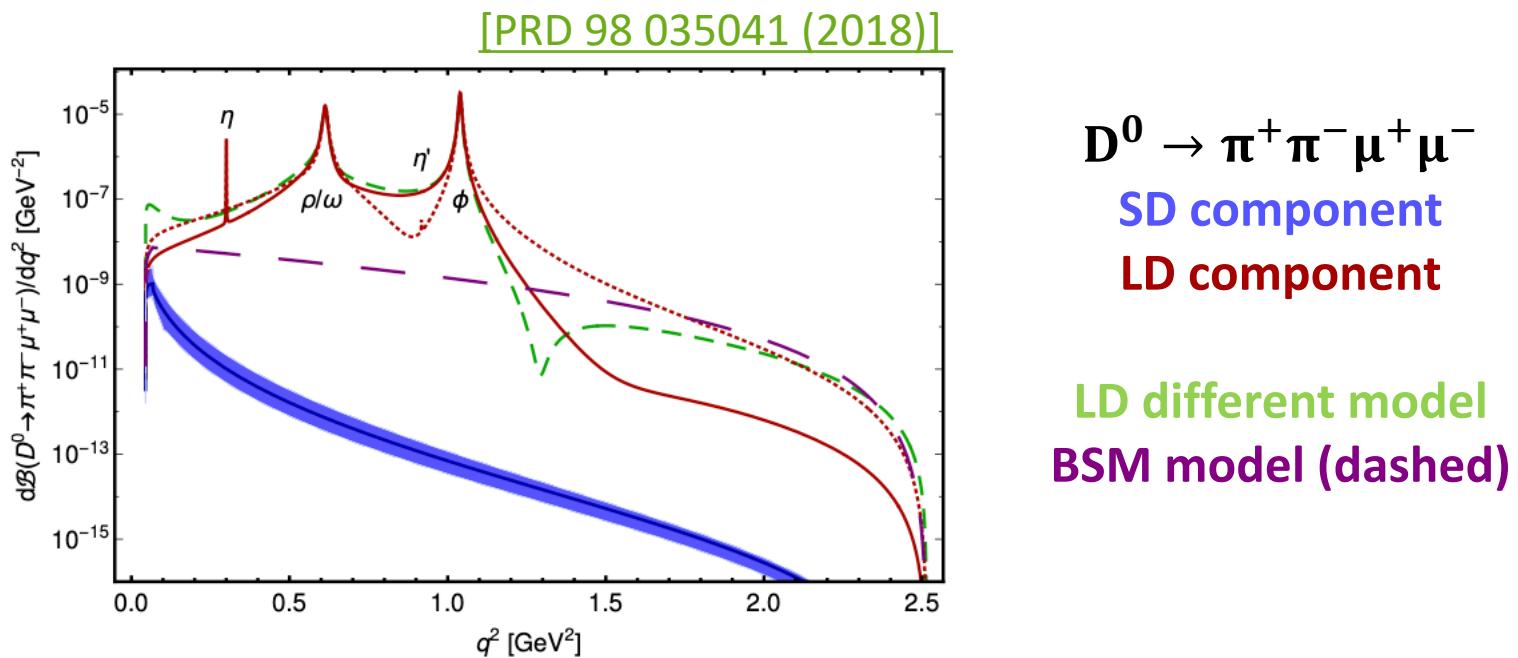
Why study rare charm decays?

- Rare Charm decays receive contributions from flavor-changing neutral-current (FCNC) processes
- Decays containing the Charm quark are a unique up-type quark probe for these processes (complementary to the down-type quark studies in the K and B sectors)
- The FCNC transitions at tree level are forbidden in the SM, CKM and GIM suppressed (tiny SM prediction of $\mathcal{B} < 10^{-9}$) [\[J. High Energ. Phys. 2013, 135 \(2013\)\]](#)
- Some New Physics models predict large enhancement in rates and asymmetries



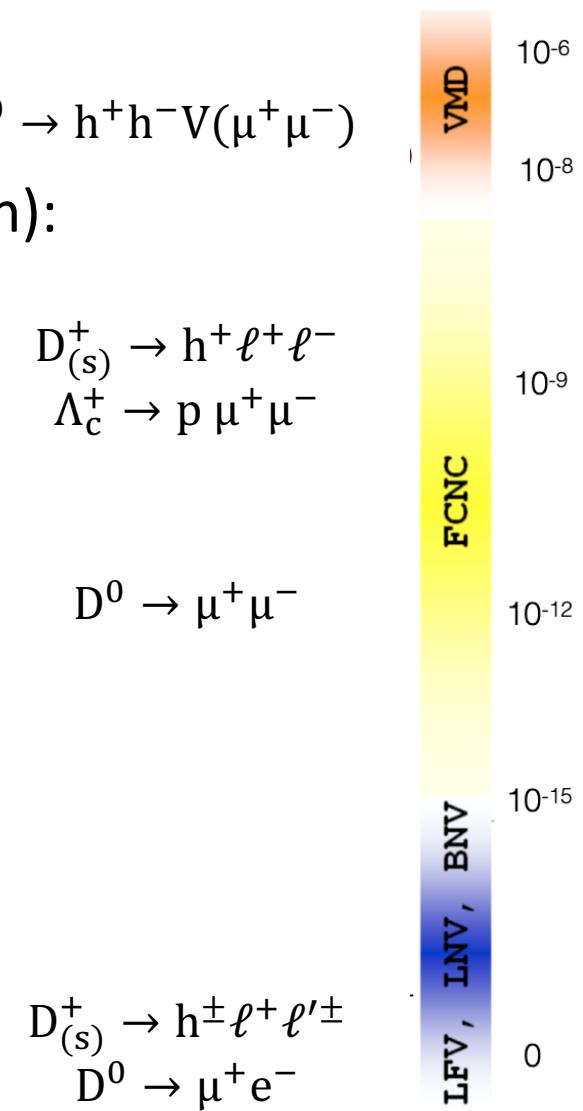
Challenges

- Rare Charm decays are dominated by Long Distance interactions (mesonic vector resonances) with tree-level dynamics
- Precise theoretical predictions are difficult on the Branching Fractions (the resonances contribution are dominated by QCD effects at very low energy and are evaluated with non-perturbative methods with high uncertainty)



Rare Charm decays at LHCb

- Exploit the LHC huge σ ($pp \rightarrow c\bar{c}X$) ~ 2.4 mb $\sim 20 \times \sigma$ ($pp \rightarrow b\bar{b}X$)
 - $\sim 10^{13}$ pairs produced up to now
- Branching fraction measurements (including lepton flavour violation):
 - Search for $D^0 \rightarrow \mu^+ \mu^-$ [[PLB 725 15-24 \(2013\), arXiv:2212.11203](#)]
 - Search for $D^{0*}(2007) \rightarrow \mu^+ \mu^-$ [[arXiv:2304.01981](#)]
 - Search for $\Lambda_c^+ \rightarrow p \mu^+ \mu^-$ [[PRD 97 091101 \(2018\)](#)]
 - Observation $D^0 \rightarrow h^+ h^- V(\mu^+ \mu^-)$ [[PRL 119 \(2017\) 181805](#)]
 - Search for $D^0 \rightarrow \mu^+ e^-$ [[PLB 754 167 \(2016\)](#)]
 - Search for $D_{(s)}^+ \rightarrow h^\pm \ell^\pm \ell'^\pm$ [[JHEP06\(2021\)044](#)]
- Angular and CP asymmetries tests:
 - Angular analysis and CP violation in $D^0 \rightarrow h^+ h^- \mu^+ \mu^-$ [[PRL 121 \(2018\) 091801, PRL 128 \(2022\) 221801](#)]

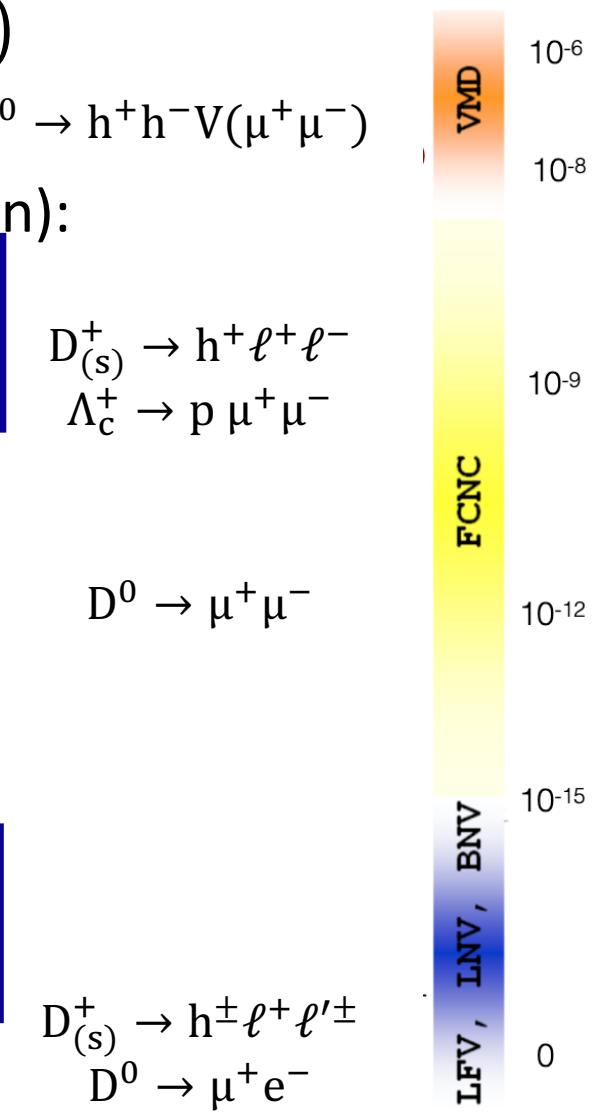


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Focus of the talk

- Search for $D_{(s)}^+ \rightarrow h^\pm \ell^\pm \ell'^\pm$ [[JHEP06\(2021\)044](#)]
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Search for $D^0 \rightarrow \mu^+ \mu^-$

[arXiv:2212.11203]

- FCNC contributions additionally helicity suppressed with minimal hadronic uncertainties: $\text{BF} \sim 10^{-18}$ expected in the SM [PRD 93, 074001 (2016)]
- Long distance contribution via intermediate two-photon state: $\text{BF} \sim 10^{-11}$
- At LHCb, Run1+2 dataset (9 fb^{-1})
- Tagged $D^{*+} \rightarrow D^0 \pi^+$ decays
- Main backgrounds:
 - Combinatorial: multivariate analysis (BDT)
 - Mis-identified $h^+ h^- \rightarrow \mu^+ \mu^-$: PID variables
- BF measured relatively to the normalisation channels $D^0 \rightarrow \pi^+ \pi^-$ and $D^0 \rightarrow K^- \pi^+$:

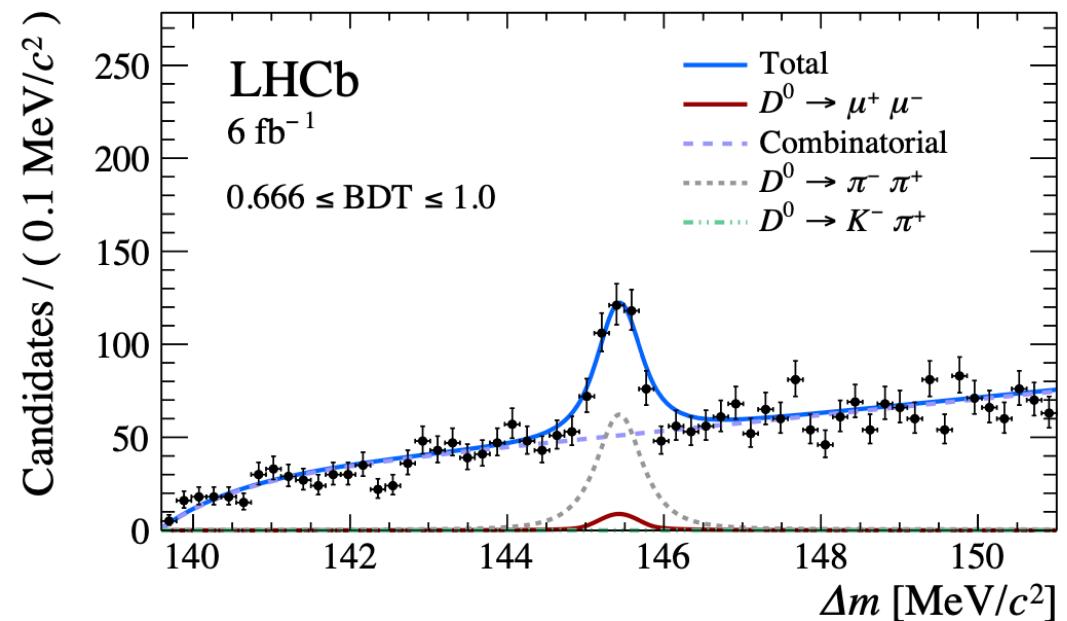
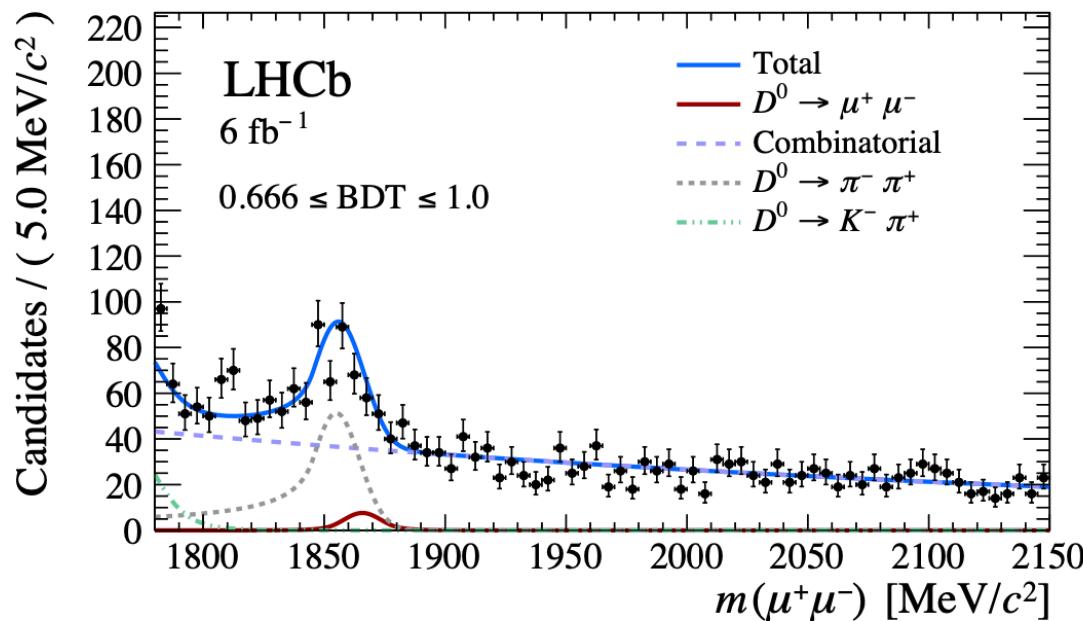
$$B(D^0 \rightarrow \mu^+ \mu^-) = \frac{N(D^0 \rightarrow \mu^+ \mu^-)}{N(D^0 \rightarrow h^+ h^-)} \frac{\epsilon(D^0 \rightarrow h^+ h^-)}{\epsilon(D^0 \rightarrow \mu^+ \mu^-)} B(D^0 \rightarrow h^+ h^-)$$

With N the yields, ϵ the efficiencies and $B(D^0 \rightarrow h^+ h^-)$ the normalisation BF

Search for $D^0 \rightarrow \mu^+ \mu^-$

[arXiv:2212.11203]

- Signal yield extracted from a simultaneous fit on $m(D^0)$ and $\Delta m = m(D^{*+}) - m(D^0)$ in three different BDT intervals



- No significant signal is observed $N(D^0 \rightarrow \mu^+ \mu^-) = 79 \pm 45$ and an upper limit on the BF is set:
 $B(D^0 \rightarrow \mu^+ \mu^-) < 2.94 (3.25) \times 10^{-9}$ @ 90 (95)% C.L.
- Most stringent limit of FCNC on charm sector

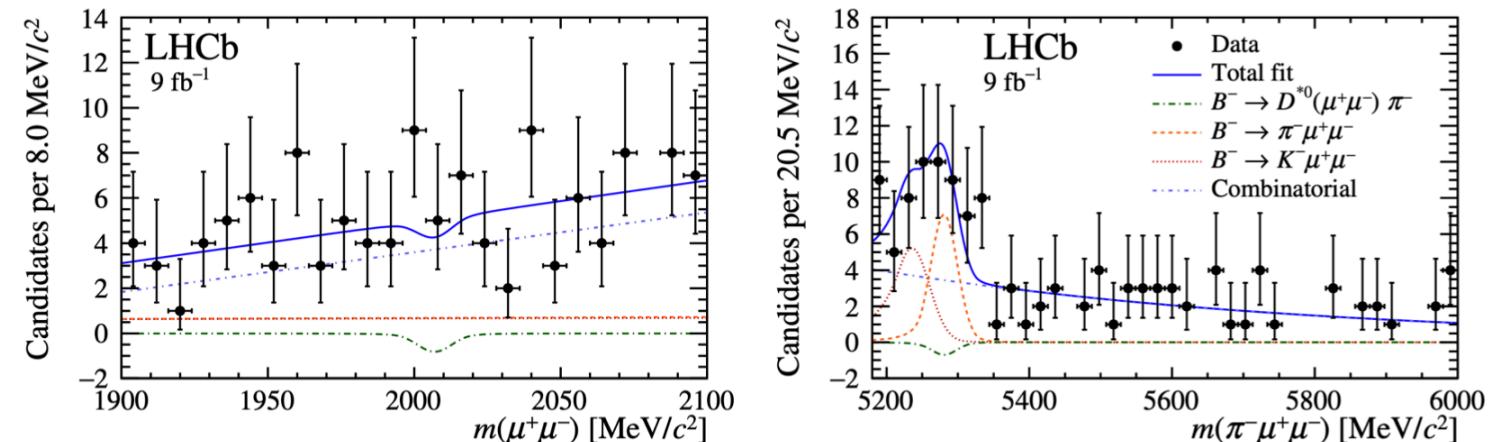
Search for $D^{*0}(2007) \rightarrow \mu^+ \mu^-$

[arXiv:2304.01981]

- SM predictions $BF \sim 10^{-19}$ [JHEP 11 (2015), 142]
- Looking for $B^- \rightarrow D^{*0} \pi^-$ decays: greatly helps background reduction
- First rare charm study exploiting B production
- As normalisation channel $B^- \rightarrow J/\psi(\rightarrow \mu^+ \mu^-) K^-$:

$$B(D^{*0} \rightarrow \mu^+ \mu^-) = \frac{N(D^{*0} \rightarrow \mu^+ \mu^-)}{N(J/\psi \rightarrow \mu^+ \mu^-)} \frac{\epsilon(J/\psi \rightarrow \mu^+ \mu^-)}{\epsilon(D^{*0} \rightarrow \mu^+ \mu^-)} \frac{B(B^- \rightarrow J/\psi K^-)}{B(B^- \rightarrow D^{*0} \pi^-)} B(J/\psi \rightarrow \mu^+ \mu^-)$$

- Simultaneous fit $m(\mu^+ \mu^-)$ and $m(\pi^- \mu^+ \mu^-)$ spectra
- No excess with respect to the bkg-only hypothesis
- Most stringent limit on leptonic D^{*0} decays:



$$B(D^{*0} \rightarrow \mu^+ \mu^-) < 2.6 (3.4) \times 10^{-8} @ 90 (95)\% C.L.$$

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

- First observed by LHCb with Run1 data

[PRL 119 (2017) 181805]

$$\mathcal{B}(D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 1.16) \times 10^{-7}$$

$$\mathcal{B}(D^0 \rightarrow K^+K^-\mu^+\mu^-) = (1.54 \pm 0.32) \times 10^{-7}$$

- Full angular analysis with Run1+2 data:

- $N(D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-) = 3579 \pm 71$

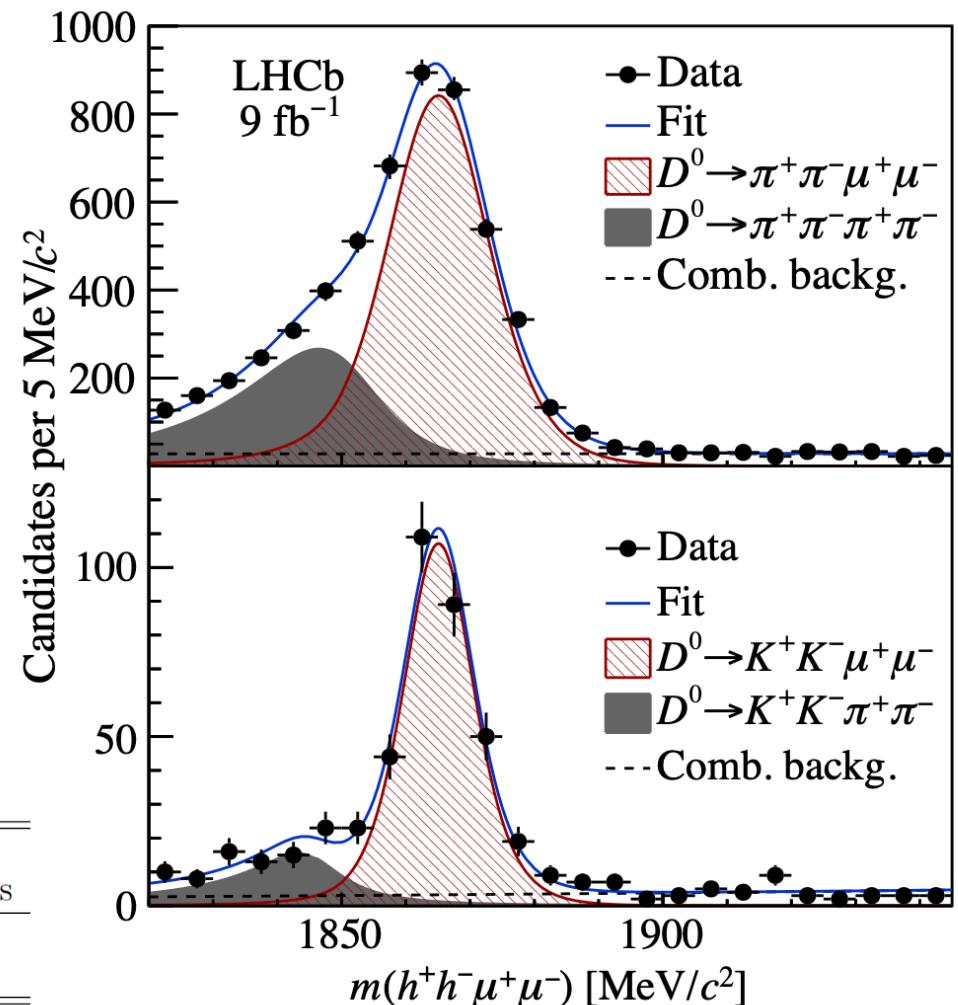
- $N(D^0 \rightarrow K^+K^-\mu^+\mu^-) = 319 \pm 19$

- Perform SM null tests in the resonant regions, testing the possible interference between long-distance and BSM contributions

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

NA = not available, NS = no signal

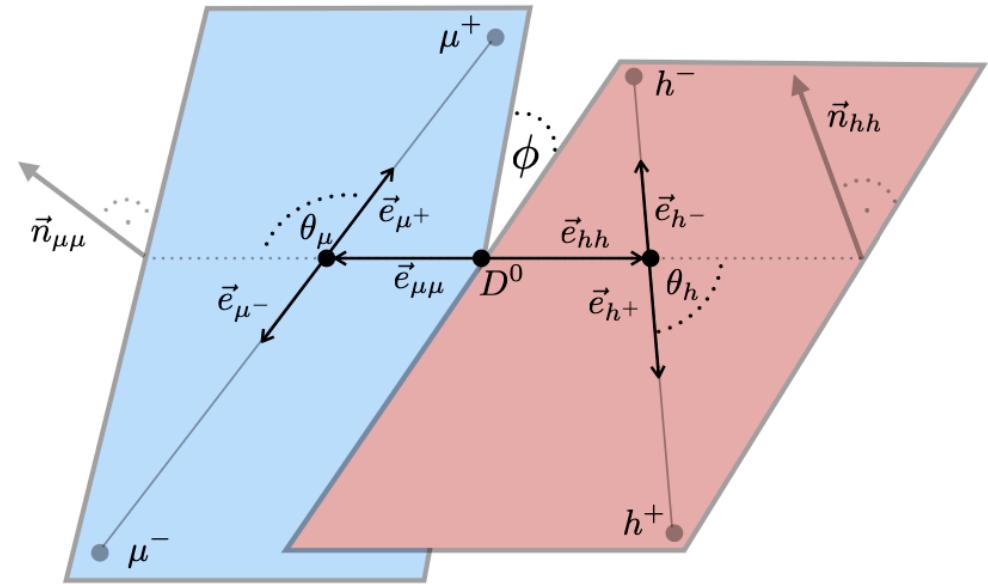
[PRL 128 (2022) 221801]



Angular analysis: $D^0 \rightarrow h^+ h^- \mu^+ \mu^-$

[PRL 128 (2022) 221801]

- Differential decay rate expressed as a sum of nine angular coefficients I_{1-9} function of:
 - $q^2 = m^2(\mu^+ \mu^-)$ and $p^2 = m^2(h^+ h^-)$
 - Three angles: θ_μ , θ_h and ϕ
- Define $\langle I_i \rangle$ integrated over p^2 , θ_h , for D^0 and \bar{D}^0
- For example, the forward-backward asymmetry:
 - $\langle I_6 \rangle = A_{FB} = \frac{\Gamma(\cos\theta_\mu > 0) - \Gamma(\cos\theta_\mu < 0)}{\Gamma(\cos\theta_\mu > 0) + \Gamma(\cos\theta_\mu < 0)}$
- The CP averaged $\langle S_i \rangle$ and asymmetries $\langle A_i \rangle$:
 - $\langle S_i \rangle = \frac{1}{2} [\langle I_i \rangle + (-)\langle \bar{I}_i \rangle] \rightarrow \langle S_{5,6,7}^{SM} \rangle = 0$ CP even
 - $\langle A_i \rangle = \frac{1}{2} [\langle I_i \rangle - (+)\langle \bar{I}_i \rangle] \rightarrow \langle A_i^{SM} \rangle = 0$ CP odd



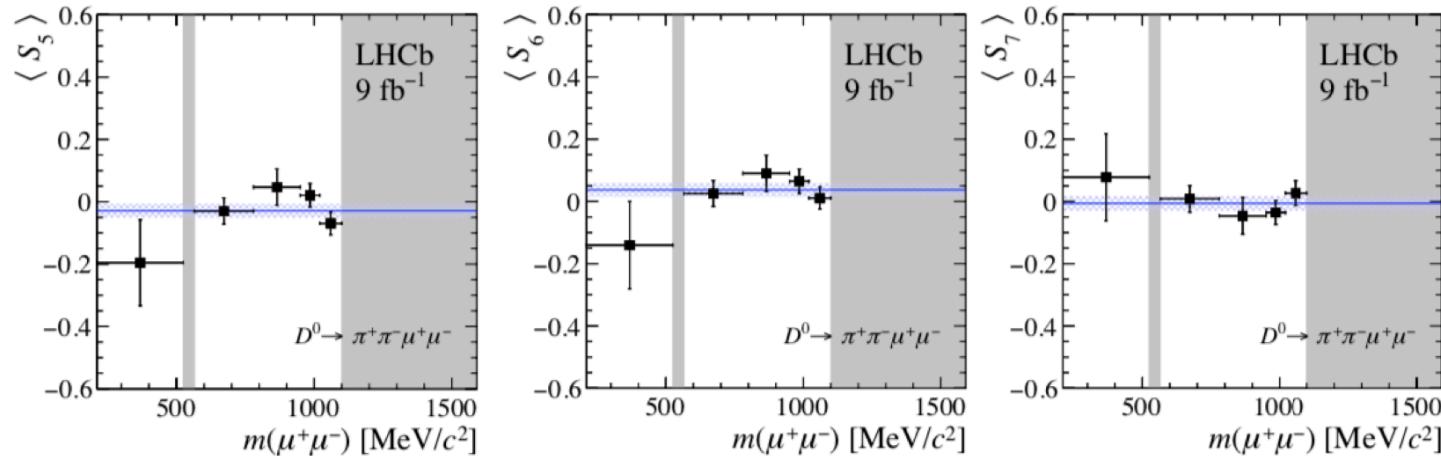
CP asymmetry:

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

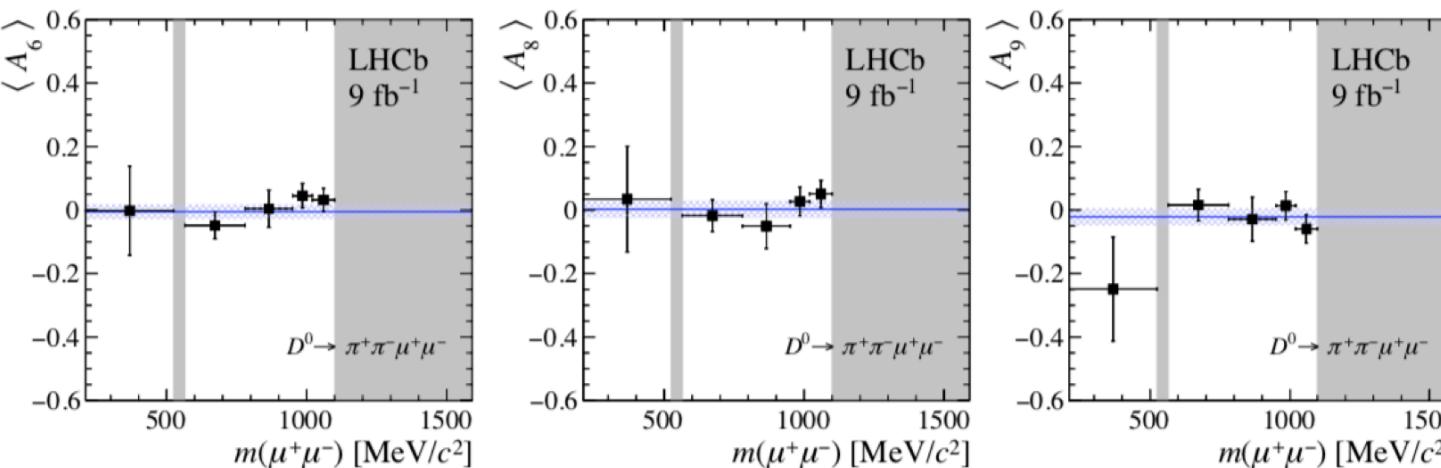
Angular analysis: $D^0 \rightarrow h^+h^-\mu^+\mu^-$

[PRL 128 (2022) 221801]

- Examples of SM null tests with $\langle S_{5,6,7} \rangle$ ($\langle S_6 \rangle \sim A_{FB}$)

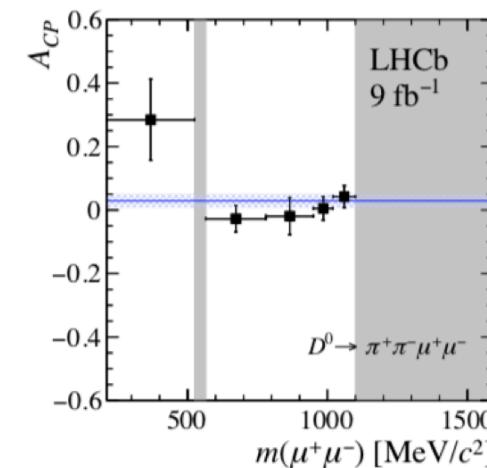


- $\langle A_6 \rangle \sim A_{FB}^{CP}$, $\langle A_{7-8} \rangle \sim$ triple product asymmetry and A_{CP}



Compatible with
the SM predictions:
 $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$: 0.3 σ
 $D^0 \rightarrow K^+K^-\mu^+\mu^-$: 2.7 σ

[JHEP 04 135 (2013), PRD 98, 035041(2018)]



Prospects for the LHCb Upgrades

[Physics Case Upgrade2](#)

- Limits on BFs for Run3-4 (Upgrade1 2022-2030) and Run5 (Upgrade2 2030-...):

Mode	Run1-2 (1-6 fb ⁻¹)	Upgrade1 (50 fb ⁻¹)	Upgrade2 (300 fb ⁻¹)
$D^0 \rightarrow \mu^+ \mu^-$	6.2×10^{-9}	4.2×10^{-10}	1.3×10^{-10}
$D^+ \rightarrow \pi^+ \mu^+ \mu^-$	6.7×10^{-8}	10^{-8}	3×10^{-9}
$D_s^+ \rightarrow K^+ \mu^+ \mu^-$	2.6×10^{-8}	10^{-8}	3×10^{-9}
$\Lambda_c^+ \rightarrow p \mu^+ \mu^-$	9.6×10^{-8}	1.1×10^{-8}	4.4×10^{-9}
$D^0 \rightarrow e^\pm \mu^\mp$	1.3×10^{-8}	10^{-9}	4.1×10^{-9}

- Statistical precision on asymmetries:

Mode	Run1-2 (1-6 fb ⁻¹)	Upgrade1 (50 fb ⁻¹)	Upgrade2 (300 fb ⁻¹)
$D^+ \rightarrow \pi^+ \mu^+ \mu^-$		0.2 %	0.08 %
$D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$	3.8 %	1 %	0.4 %
$D^0 \rightarrow K^- \pi^+ \mu^+ \mu^-$		0.3 %	0.13 %
$D^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$		12 %	5 %
$D^0 \rightarrow K^+ K^- \mu^+ \mu^-$	11 %	4 %	1.7 %

[A. Contu - Towards ultimate precision in Flavor Physics, Durham \(2-4 April 2019\)](#)

Conclusion and prospects

- Rare Charm decays constitutes a unique environment to look for new physics, either with BF measurements or as SM null tests
- LHCb gave major contributions in the field and will continue to exploit the data collected during Run2:
 - Update on the $D^0 \rightarrow \mu^+ e^-$ search
 - Update on the $\Lambda_c^+ \rightarrow p \mu^+ \mu^-$ search
 - Search for $D^0 \rightarrow h^+ h^- e^+ e^-$
 - Search for $D^0 \rightarrow h^+ h^- \mu^\pm e^\mp$
 - Asymmetries study for $D_{(s)}^+ \rightarrow h^+ \ell^+ \ell^-$
 - Asymmetries study for $\Lambda_c^+ \rightarrow p \mu^+ \mu^-$
- ... and many more to come with Run3 data!

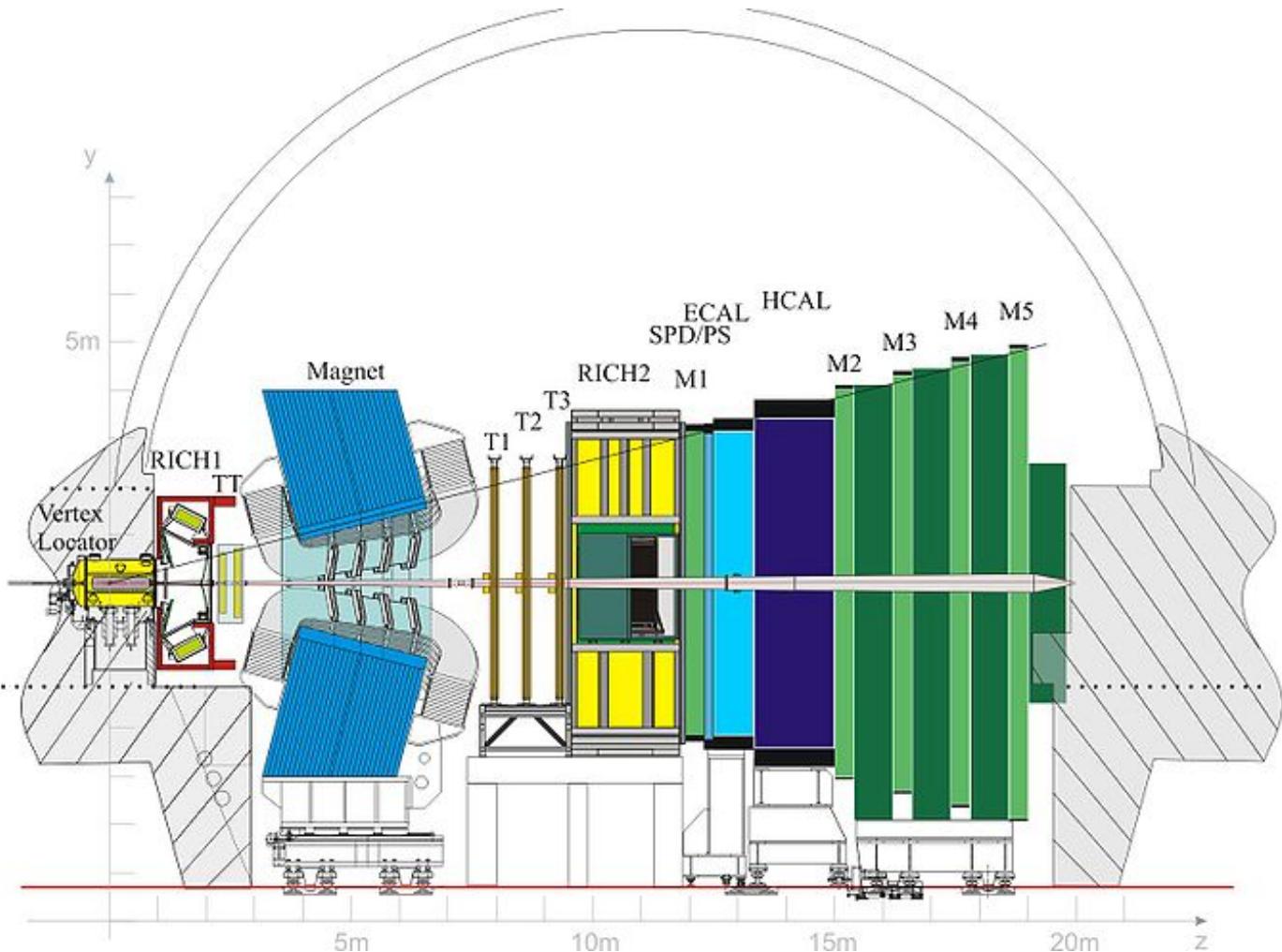


Backup

The LHCb experiment

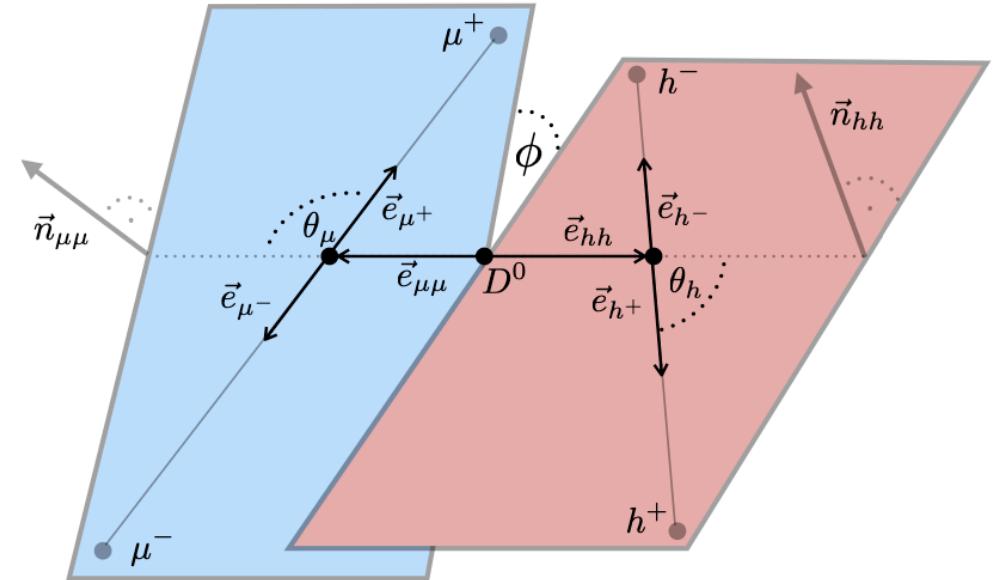
- LHCb is a single arm forward spectrometer optimized for b and c physics
- Good vertex/momentum resolution and excellent particle identification
- LHCb has the world's largest sample of charm decays
- $\sigma(p p \rightarrow c\bar{c}) \sim 0(\text{mb})$
 $\rightarrow \sim 10^{13}$ pairs produced up to now

[Int. J. Mod. Phys. A 30, 1530022 (2015)]



Decay rate model

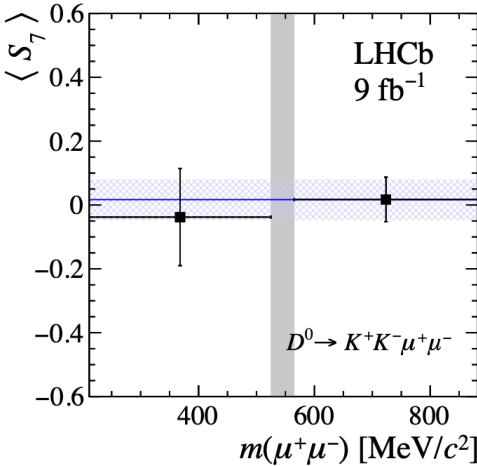
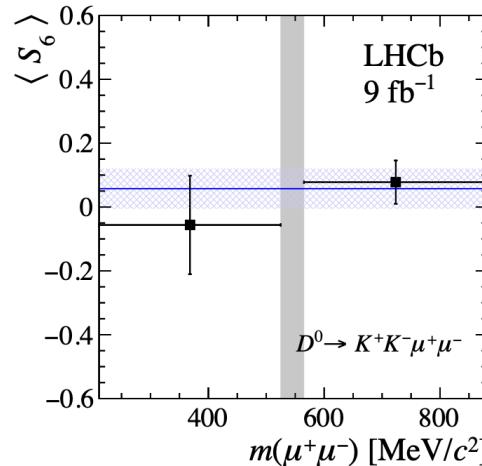
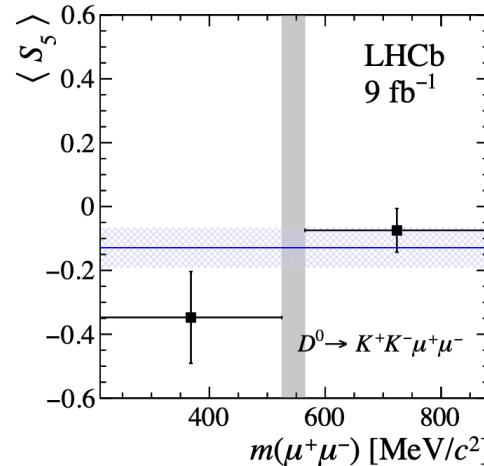
$$d^5\Gamma = \frac{1}{2\pi} \left[\sum c_i(\theta_\mu, \phi) I_i(q^2, p^2, \cos \theta_h) \right] \cdot dq^2 dp^2 d \cos \theta_h d \cos \theta_\mu d\phi .$$



$$\begin{aligned} c_1 &= 1, & c_2 &= \cos 2\theta_\mu, & c_3 &= \sin^2 \theta_\mu \cos 2\phi, & c_4 &= \sin 2\theta_\mu \cos \phi, & c_5 &= \sin \theta_\mu \cos \phi, \\ c_6 &= \cos \theta_\mu, & c_7 &= \sin \theta_\mu \sin \phi, & c_8 &= \sin 2\theta_\mu \sin \phi, & c_9 &= \sin^2 \theta_\mu \sin 2\phi. \end{aligned}$$

Angular analysis: $D^0 \rightarrow h^+ h^- \mu^+ \mu^-$

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