Rare Charm Decays and asymmetries

Towards the Ultimate Precision in Flavour Physics
Durham - UK

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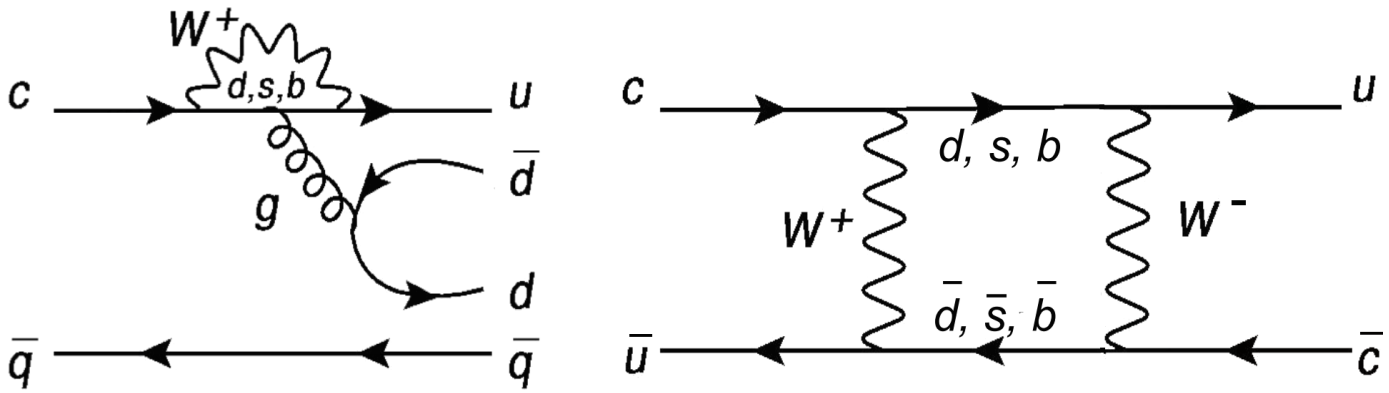
Why study rare charm processes?

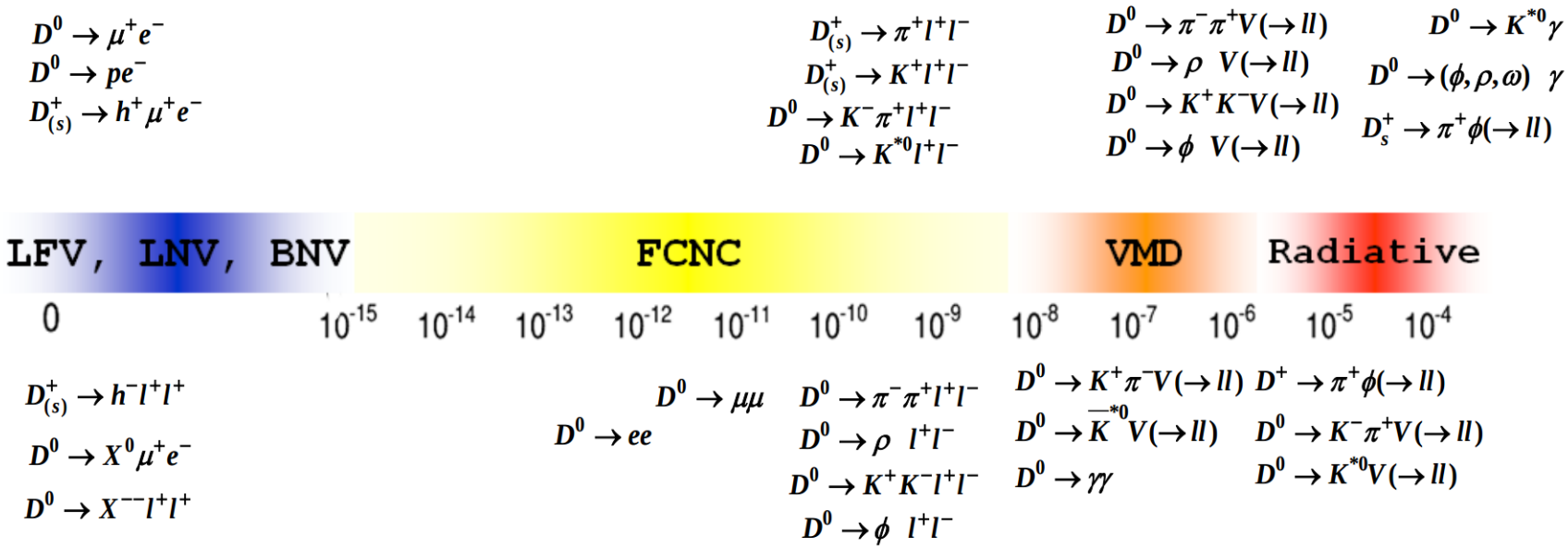
- Up-type quark: unique probe of NP in the flavour sector, complementary to studies in K and B systems
- Rare processes are very suppressed in the SM



- New Physics may be hidden in the loops
- Challenging due to large long-distance contributions, precise theoretical predictions are difficult

Charm Rare Decays

Wide variety of physics, ranging from forbidden to not-so-rare decays



[PRD 66 (2002) 014009]

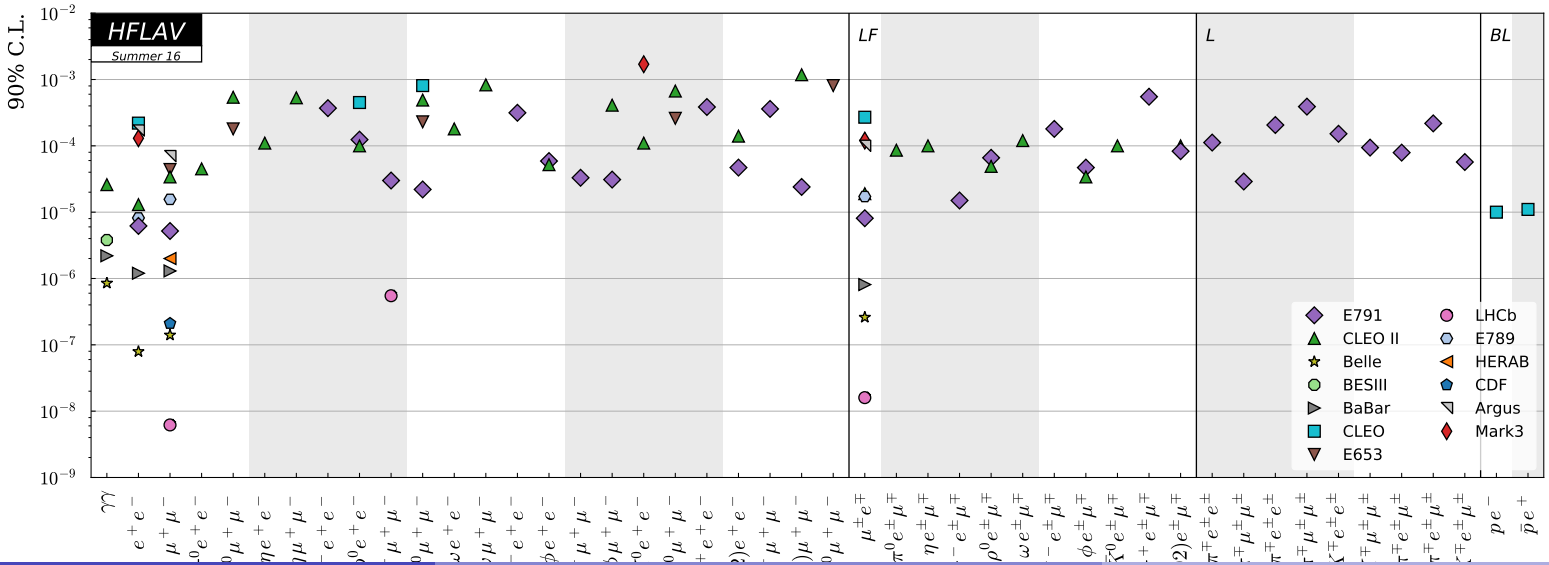
Short distance contributions to effective $c \to u$ transitions are tiny, branching fractions dominated by long distance contributions
SM predictions for the short distance part are normally $BF < 10^{-9}$, getting there...

Charm samples

Type	Exp	$\sqrt{s}$	L_{int}	$\sigma(c\bar{c})$	$N(c\bar{c})$
		prompt $c\bar{c}$			
Hadron colliders	LHCb	7, 8 TeV	3/fb	1.4 mb	3.6×10^{12}
		13 TeV	6/fb	2.6 mb	13.2×10^{12}
	CDF	2 TeV	10/fb	0.1 mb	2.3×10^{11}
		$c\bar{c}$ from continuum			
e^+e^- collider	Belle	10.6 GeV	1/ab	1.3 nb	1.3×10^9
	BaBar	10.6 GeV	550/fb	1.3 nb	0.7×10^9
		Charm factories at $D\bar{D}$ threshold			
	BESIII	3.7 GeV	3/fb	3 nb	20×10^6
	Cleo-c	3.7 GeV	0.8/fb	3 nb	5×10^6

Where do we stand?

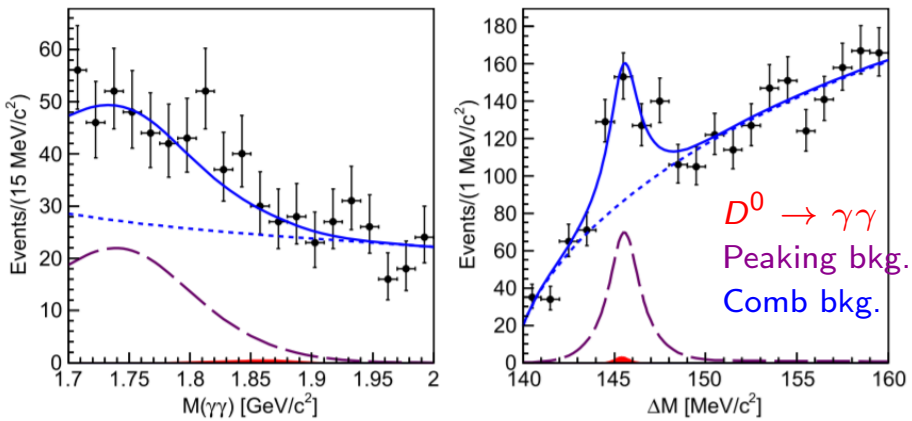
- **LHCb:**
  - Rarest accessible modes are decays into two muons + ≥ 0 charged hadrons
  - Final state with e/γ harder but not impossible
  - Large production cross section ensures every measurement is likely a world best
- **BaBar/Belle/BelleII:**
  - Best for $D^0 \to V\gamma$ and electron modes
  - Only hope for $D^0 \to \gamma\gamma$



$D^0 \to \mu^+\mu^-$ and $D^0 \to \gamma\gamma$

- NP could appear in BF enhancements
- Only limits so far:
  - $D^0 \to \gamma\gamma \sim 10^{-8}$ in the SM but up to 10^{-6} in NP scenarios. Best limit from Belle at $\mathcal{B}(D^0 \to \gamma\gamma) < 8.5 \times 10^{-7}$ at 90% CL

[PRD 93, 051102 (2016)]



- $D^0 \to \mu^+\mu^-$ is also helicity suppressed. In the SM is actually constrained by the limit above to about 10^{-12} (main contribution to the BF comes from a long distance $\gamma\gamma$ recombination)
  Best limit from LHCb at 7.6×10^{-9} at 90% CL, 1/fb only [PLB 725 (2013) 15-24]. Update is being worked on!

Thinking differently...

Search for $e^+e^- \to D(2007)^{0\star}$

We are trying to probe also charm-physics

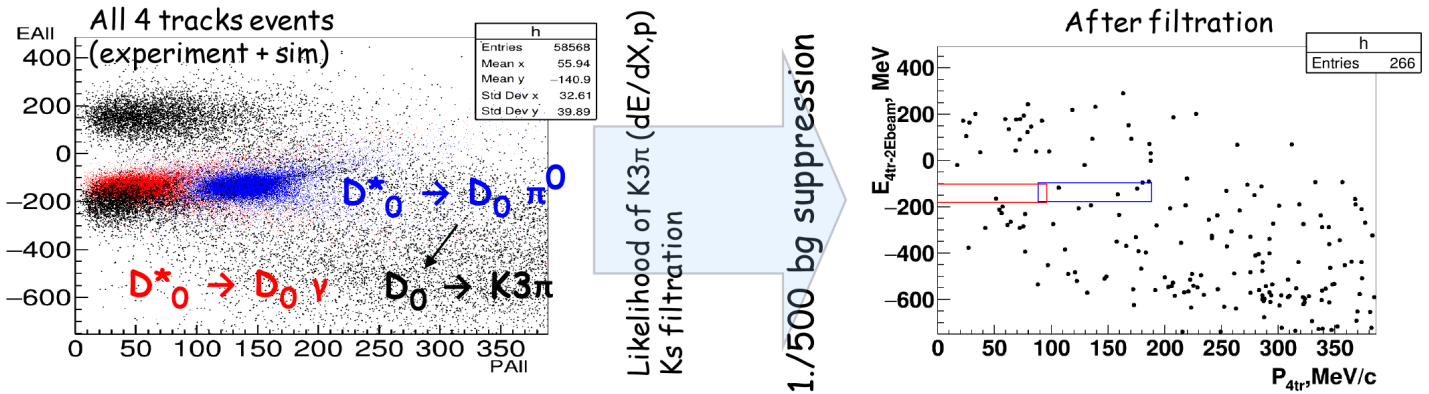
motivation

A. Khodjamirian et al, JHEP11(2015)142 :
SM: Br($D^* \to e^+e^-$) >= $5. \times 10^{-19}$
New Physics with Z' : Br($D^* \to e^+e^-$) < 2.5×10^{-11}

But, they didn't take into account 10^2 - 10^4 factor: detection efficiency and beam energy spread

They did estimation
for e+e- collider with $\int L = 1 fb^{-1}$: Br($D^* \to e^+e^-$) > 4×10^{-13}

VEPP-2000 was able to jump above 2 GeV design machine limit:
At 2017 scan: E=2007 МэВ, L=3.4 πb^{-1}



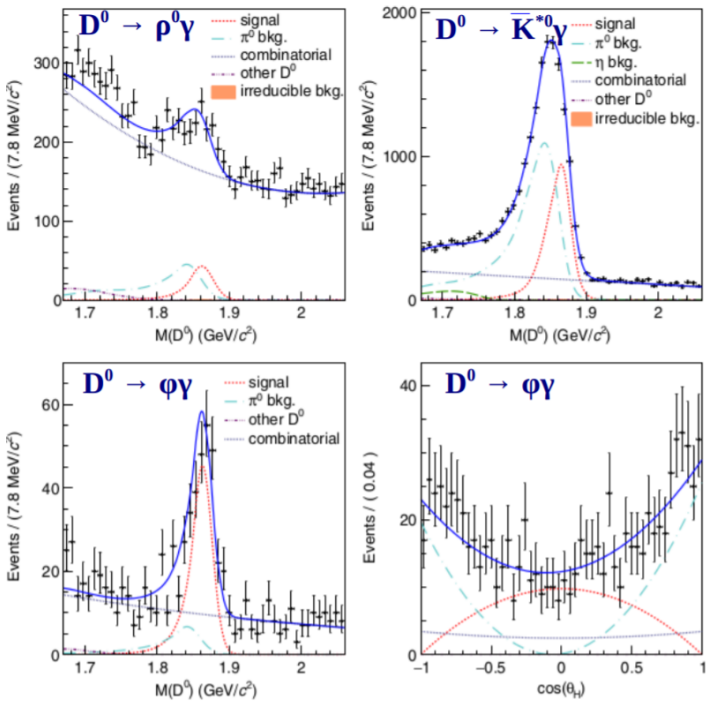
$D^*_0 \to D_0 \gamma$: Br($D^* \to ee$) < $5.2*10^{-6}$
$D^*_0 \to D_0 \pi^0$: Br($D^* \to ee$) < $1.7*10^{-6}$

First time UL measurement

from E. Solodov, Moriond QCD 2019

Radiative charm decays [PRL 118, 051801 (2017)]

- Measuring the BFs tests QCD based calculations of long distance dynamics
- Can probe New Physics when measuring A_{CP} (around 10^{-3} in the SM, up to several percent in NP scenarios)
- Belle measured BF and A_{CP} for all these modes



First observation

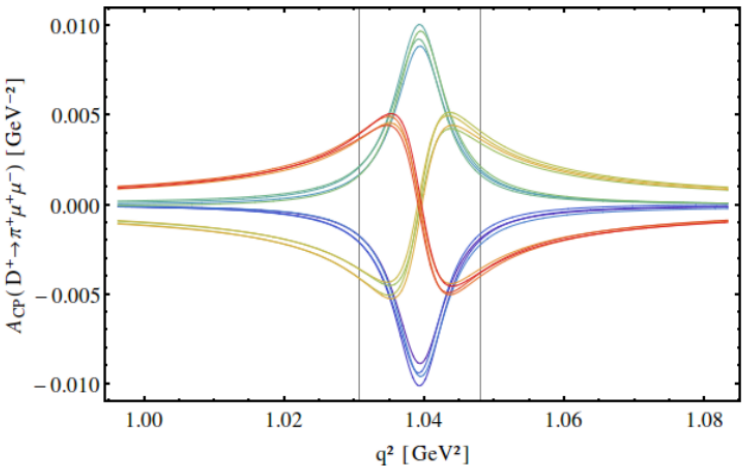
$$\mathcal{B}(D^0 \to \rho^0\gamma) = (1.77 \pm 0.30 \pm 0.07) \times 10^{-5},$$
$$\mathcal{B}(D^0 \to \phi\gamma) = (2.76 \pm 0.19 \pm 0.10) \times 10^{-5},$$
$$\mathcal{B}(D^0 \to \bar{K}^{*0}\gamma) = (4.66 \pm 0.21 \pm 0.21) \times 10^{-4}.$$

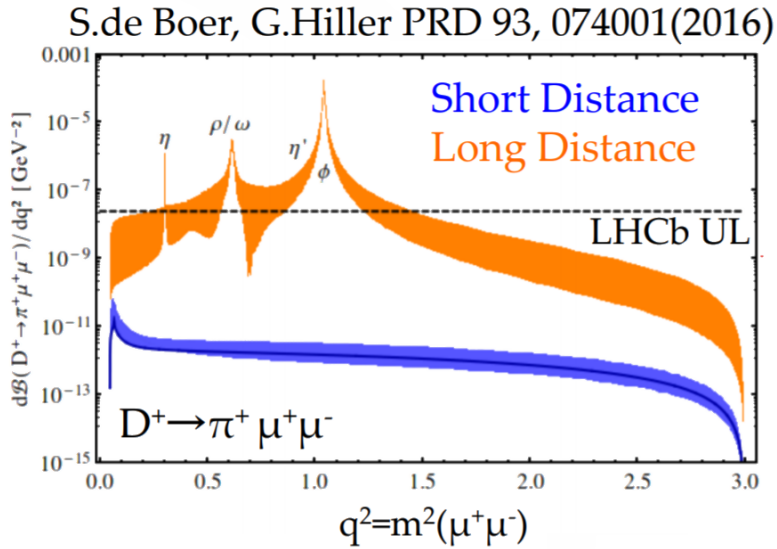
$$\mathcal{A}_{CP}(D^0 \to \rho^0\gamma) = +0.056 \pm 0.152 \pm 0.006,$$
$$\mathcal{A}_{CP}(D^0 \to \phi\gamma) = -0.094 \pm 0.066 \pm 0.001,$$
$$\mathcal{A}_{CP}(D^0 \to \bar{K}^{*0}\gamma) = -0.003 \pm 0.020 \pm 0.000$$

- Expect some competition from LHCb...

Multibody decays with a dilepton pair

- Decays such as $D^{\pm}_{(s)} \to h^{\pm} l^+ l^-$, $D^0 \to h^+ h^- l^+ l^-$ have an overwhelming contribution from long-distance processes, through intermediate vector resonances in the dimuon spectrum

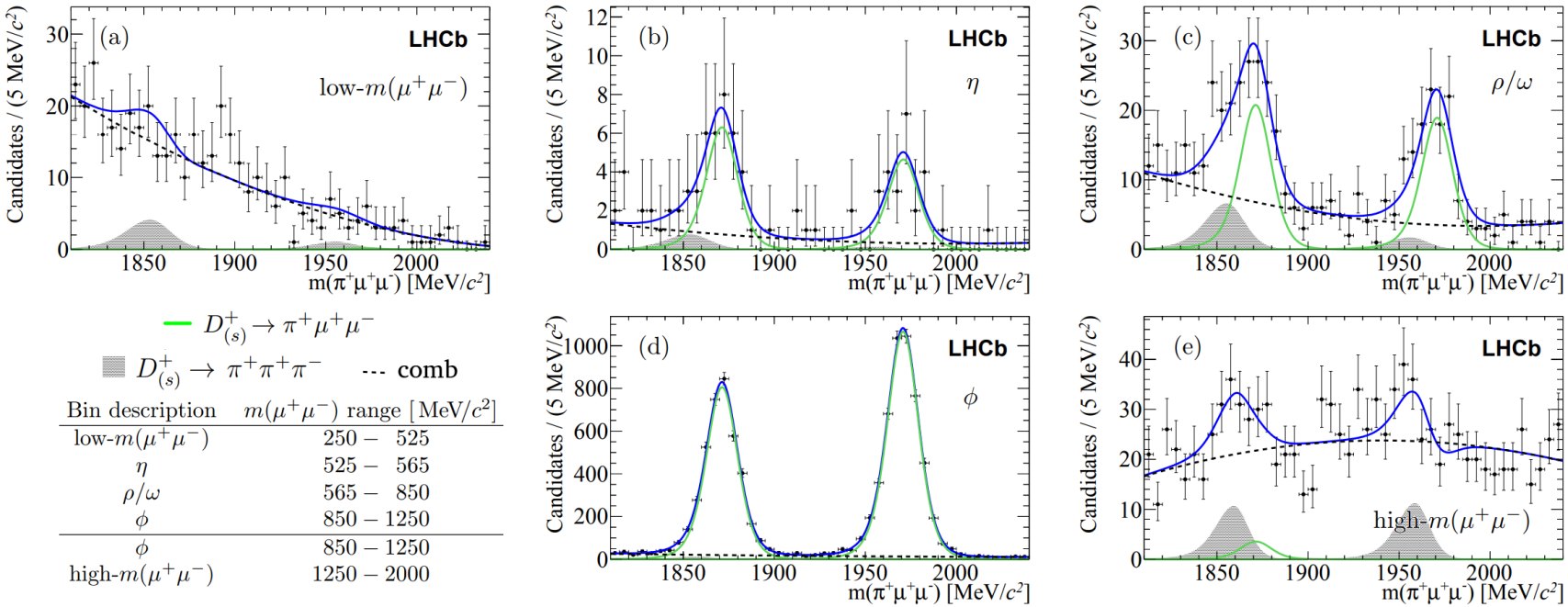




- Unlikely that NP could show up in the branching fraction
- But the richer dynamics allows to investigate A_{CP}, A_{FB} which can be up to a few percents in some NP scenarios

Search for non-resonant $D^{\pm}_{(s)} \to \pi^{\pm}\mu^{-}\mu^{+}$ [PLB724(2013)203-212]

- Limit on non resonant fraction determined from low and high q^2 bins normalised to $D^{+}_{(s)} \to \pi^{\pm}\phi(\to \mu\mu)$
- LHCb results: $\mathcal{B}(D^{\pm}_{(s)} \to \pi^{\pm}\mu^{-}\mu^{+}) < 0.83(4.8) \times 10^{-7}$, $\mathcal{B}(D^{\pm}_{(s)} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}) \times 10^{-7}$ at 95% C.L.

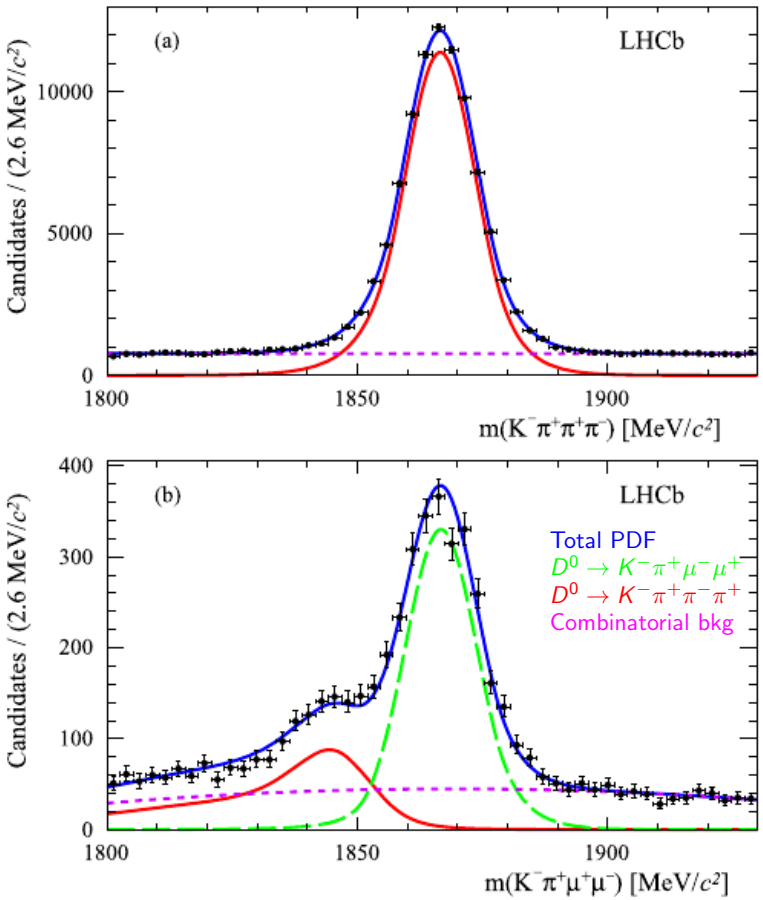


Bin description	$m(\mu^+\mu^-)$ range [MeV/c^2]
low-$m(\mu^+\mu^-)$	250 – 525
η	525 – 565
ρ/ω	565 – 850
ϕ	850 – 1250
ϕ	850 – 1250
high-$m(\mu^+\mu^-)$	1250 – 2000

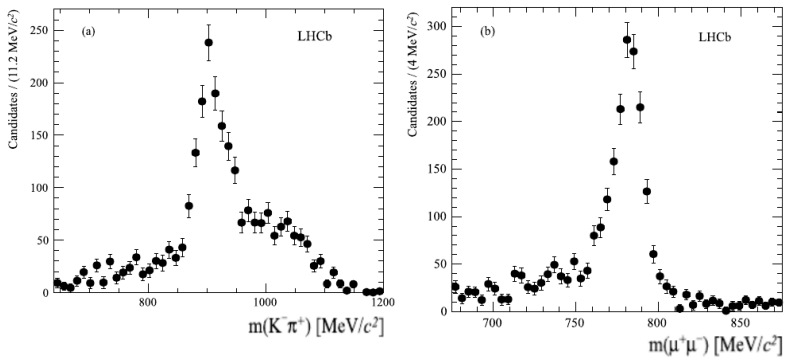
- Update including electron modes is being worked on

First observation of the decay $D^0 \to K^-\pi^+\rho^0/\omega(\to \mu^-\mu^+)$

[PLB 757 (2016) 558-567]



- Measurement restricted to $675 < m_{\mu\mu} < 875\,\mathrm{MeV}/c^2$
- $BF(D^0 \to K^-\pi^+\mu^-\mu^+) = (4.12 \pm 0.12_{stat} \pm 0.38_{syst}) \times 10^{-6}$
- In agreement with SM predictions [JHEP 04 (2013) 135]
- Ideal normalisation mode for $D^0 \to h^+h^-\mu^+\mu^-$

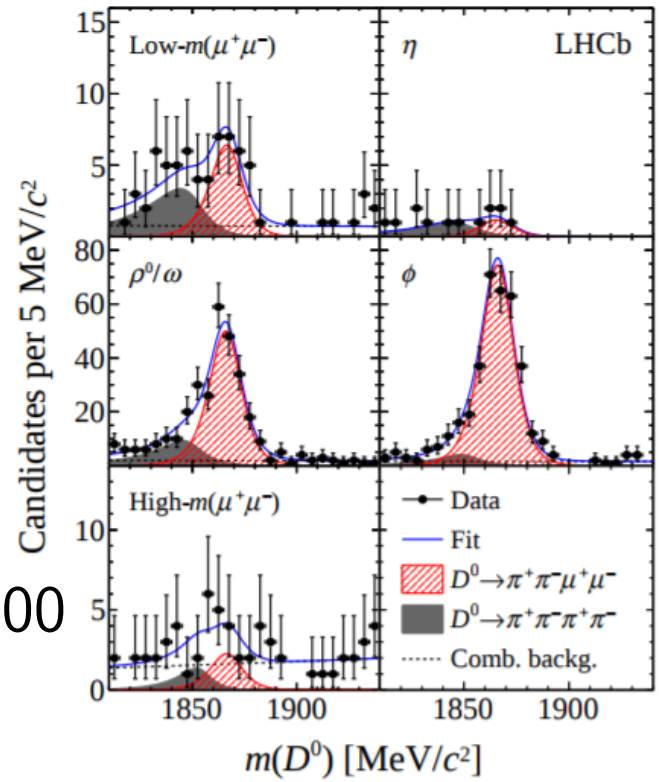


Observation of D^0 mesons decaying into $h^+h^-\mu^+\mu^-$

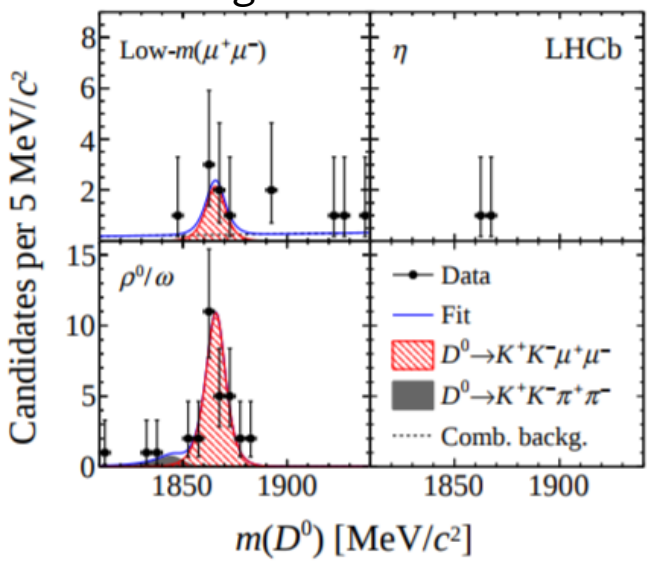
[PRL 119 (2017)181805]

- Using 2/fb LHCb made the first observation of $D^0 \to \pi^+\pi^-\mu^+\mu^-$, $D^0 \to K^+K^-\mu^+\mu^-$

$N_{sig} \geq 500$



$N_{sig} \geq 30$



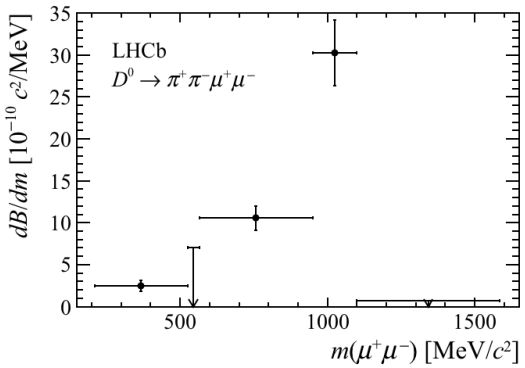
- No attempt is made to distinguish between long and short distance

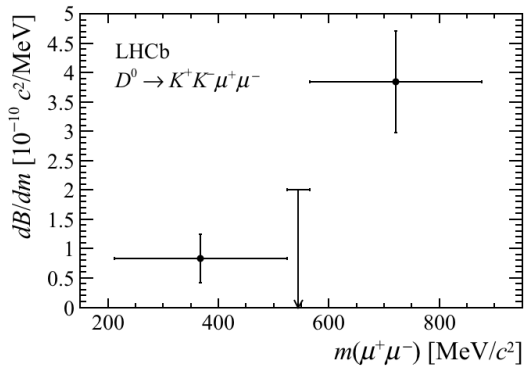
Observation of D^0 mesons decaying into $h^+h^-\mu^+\mu^-$

[PRL 119 (2017)181805]

- Measure differential and total BF
  (normalised to $\mathcal{B}(D^0 \to K^-\pi^+[\mu^+\mu^-]_{\rho^0/\omega})$ [PLB 757 (2016) 558-567])

$D^0 \to \pi^+\pi^-\mu^+\mu^-$		
$m(\mu^+\mu^-)$ 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	$< 2.4\,(2.8)$
ρ^0/ω	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	$< 2.8\,(3.3)$
$D^0 \to K^+K^-\mu^+\mu^-$		
$m(\mu^+\mu^-)$ 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	$< 0.7\,(0.8)$
ρ^0/ω	> 565	$12.0 \pm 2.3 \pm 0.7 \pm 1.2$





- Total branching fractions:

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

Rarest charm decays! Compatible with SM predictions [JHEP 04(2013)135]

- Statistics is enough to perform first asymmetry measurements!

Angular and *CP* asymmetries in $D^0 \to h^+h^-\mu^+\mu^-$ decays

[PRL 121, 091801 (2018)]

- Better suited for CP and NP searches than BF measurements since not restricted to non-resonant regions
- Observables are SM null tests. Asymmetry predictions for some NP model can be up to few % in the vicinity of resonances
  [JHEP 1304 135 (2013)], [PRD 87 054026 (2013)], [PRD 98, 035041 (2018)]

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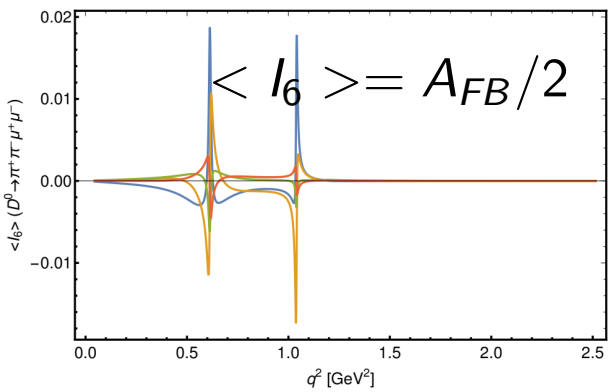
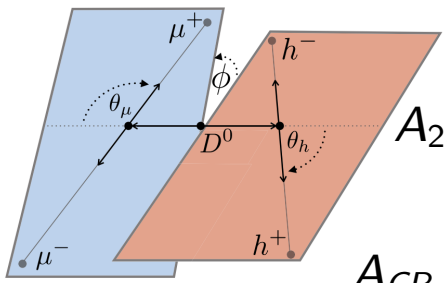




$$A_{\rm FB} = \frac{\Gamma(\cos\theta_\mu > 0) - \Gamma(\cos\theta_\mu < 0)}{\Gamma(\cos\theta_\mu > 0) + \Gamma(\cos\theta_\mu < 0)}$$

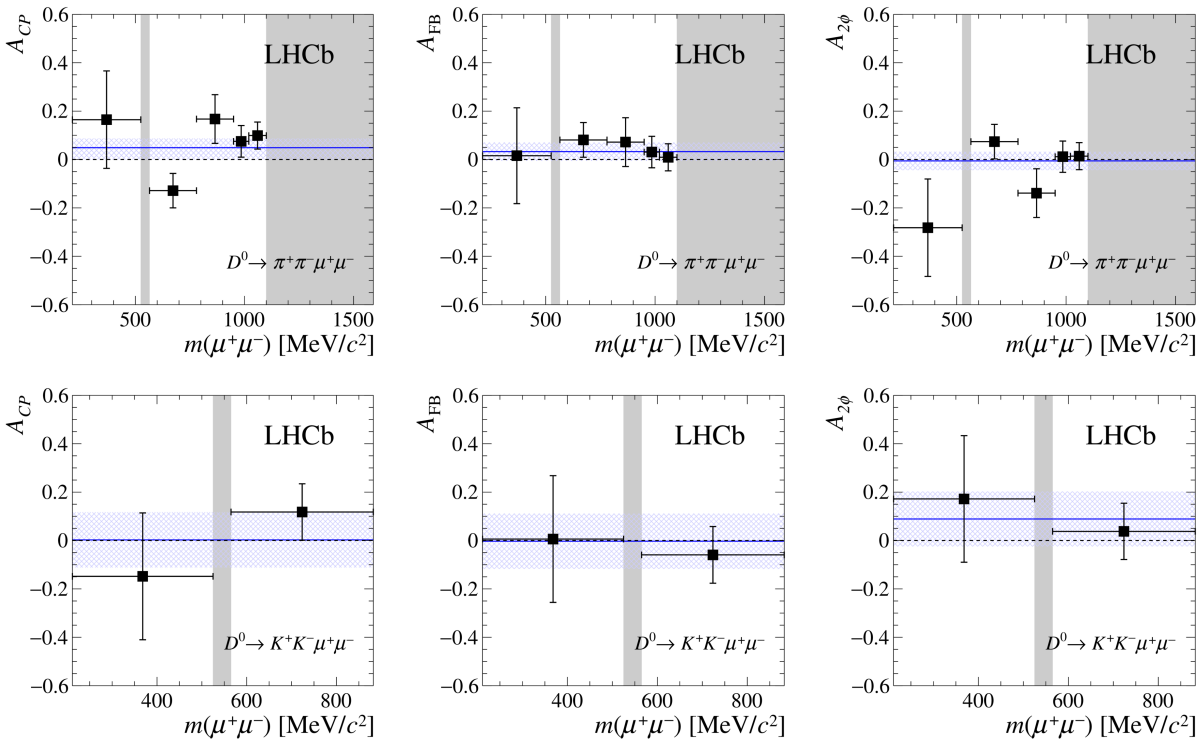
$$A_{2\phi} = \frac{\Gamma(\sin 2\phi > 0) - \Gamma(\sin 2\phi < 0)}{\Gamma(\sin 2\phi > 0) + \Gamma(\sin 2\phi < 0)}$$

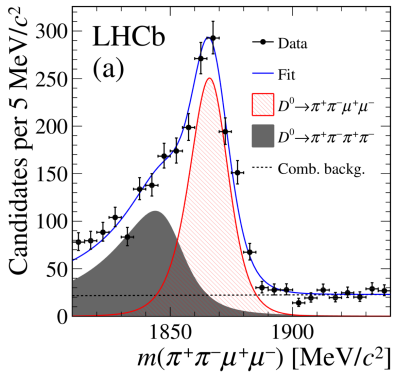
$$A_{CP} = \frac{\Gamma(D^0 \to hh\mu\mu) - \Gamma(\bar{D}^0 \to hh\mu\mu)}{\Gamma(D^0 \to hh\mu\mu) + \Gamma(\bar{D}^0 \to hh\mu\mu)}$$

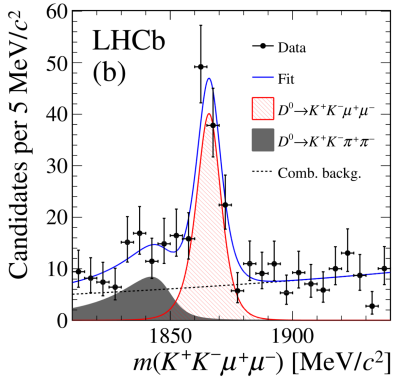
- Measurement performed using 2011-2016 data, both PS integrated and in bins of $m_{\mu\mu}$

Angular and *CP* asymmetries in $D^0 \to h^+h^-\mu^+\mu^-$ decays

[PRL 121, 091801 (2018)]







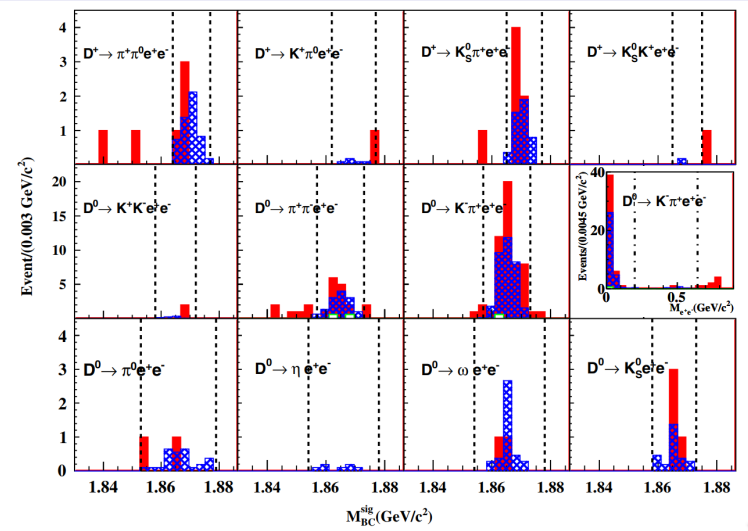
$$A_{FB}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (\ \ 3.3 \pm 3.7 \pm 0.6)\%$$
$$A_{2\phi}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (-0.6 \pm 3.7 \pm 0.6)\%$$
$$A_{CP}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (\ \ 4.9 \pm 3.8 \pm 0.7)\%$$
$$A_{FB}(D^0 \to K^+K^-\mu^+\mu^-) = (0 \pm 11 \pm 2)\%$$
$$A_{2\phi}(D^0 \to K^+K^-\mu^+\mu^-)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

All asym. consistent with zero

No dependency on dimuon mass

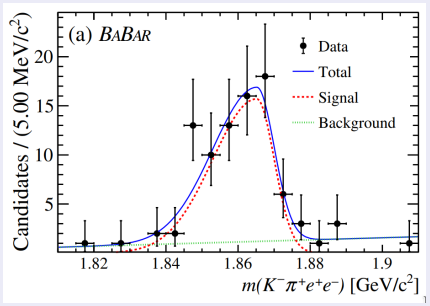
Studies of $D^0 \to (h(')) ^- h^+ e^+ e^-$ and Babar and BESIII

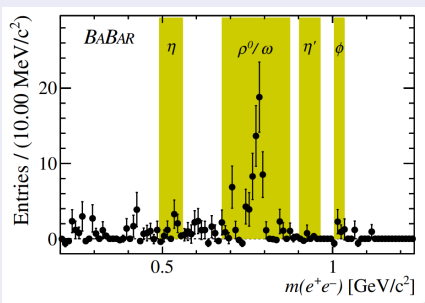
BESIII: Search for the rare decays $D^0 \to (h(')) ^- h^+ e^+ e^-$ [PRD 97 072015 (2018)]



Only limits at 10^{-5} level, still a big improvement

Babar: Observation of the decay $D^0 \to K^- \pi^+ e^- e^-$ [PRL 122 081802 (2019)]





Observation for $675 < m_{ee} < 875\,\mathrm{MeV}/c^2$

$BF(D^0 \to K^- \pi^+ e^- e^-) =$

$(4.0 \pm 0.5 \pm 0.2 \pm 0.1) \times 10^{-6}$

In agreement with LHCb's

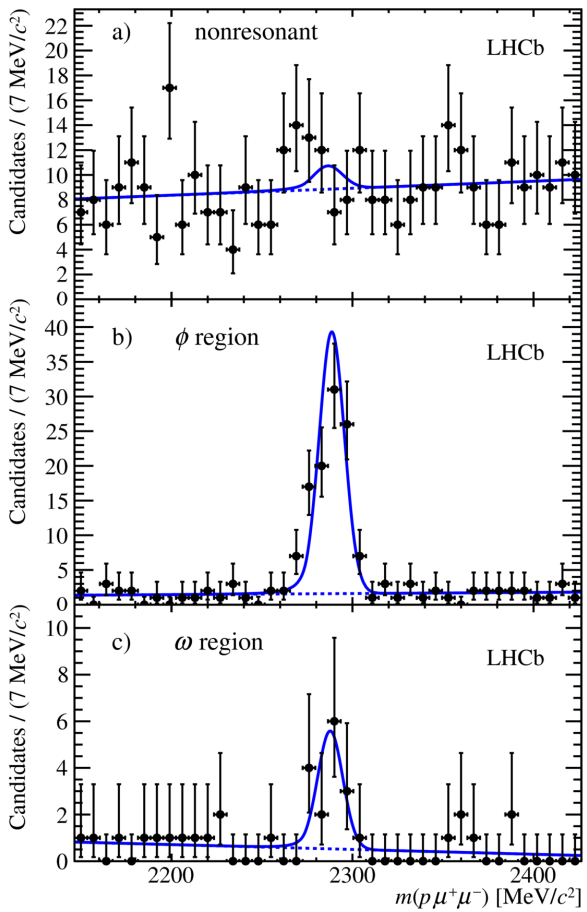
$D^0 \to K^- \pi^+ \mu^+ \mu^-$

Limits elsewhere at 10^{-6} level

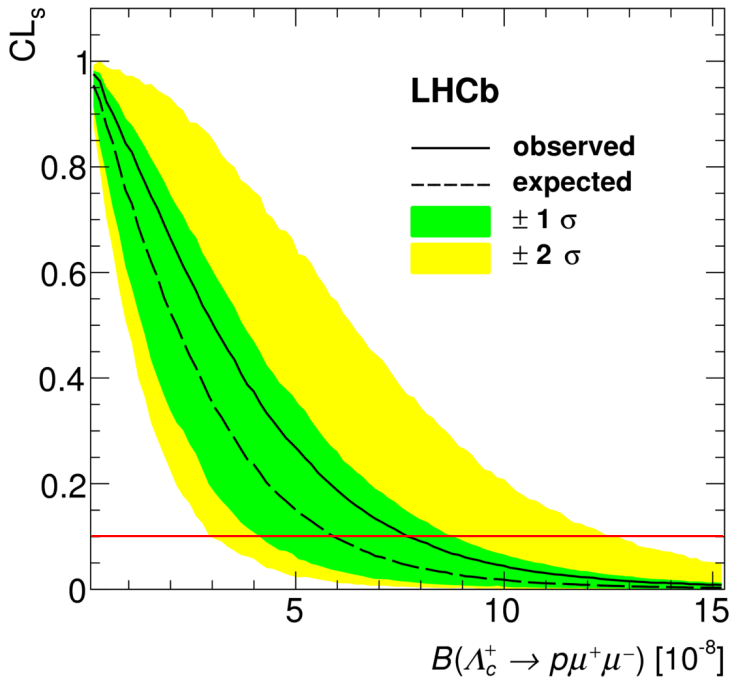
LHCb should be competitive, or hopefully better (modulo BelleII)

Search for $\Lambda_c \to p\mu^+\mu^-$ [PRD 97 091101 (2017)]

- Similar approach to $D_s^+ \to h^+\mu^+\mu^-$ search analysis (split in dimoun mass regions, normalise to ϕ region)

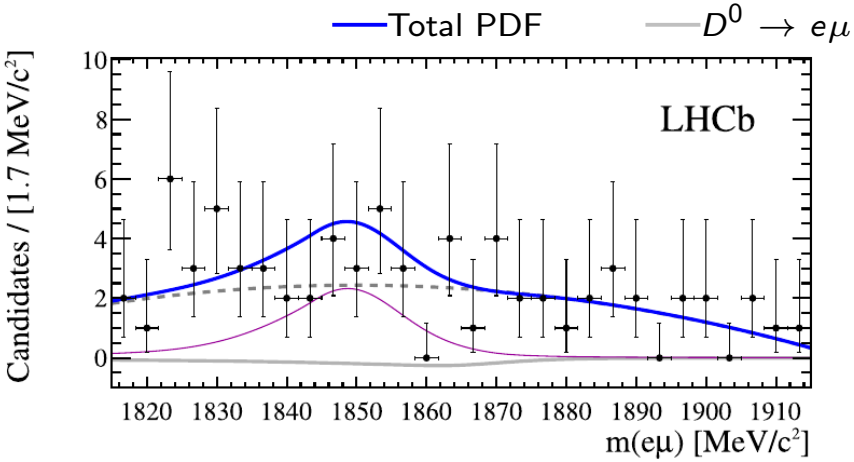


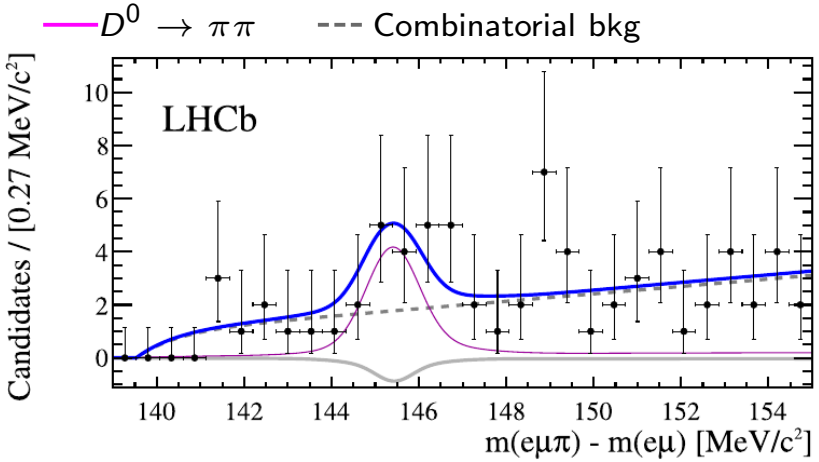
- Significant signal (5σ) in the ω region
- Best limit on the non-resonant component, $\mathcal{B}(\Lambda_c \to p\mu^+\mu^-) < 7.7 \times 10^{-8}$ at 90% CL

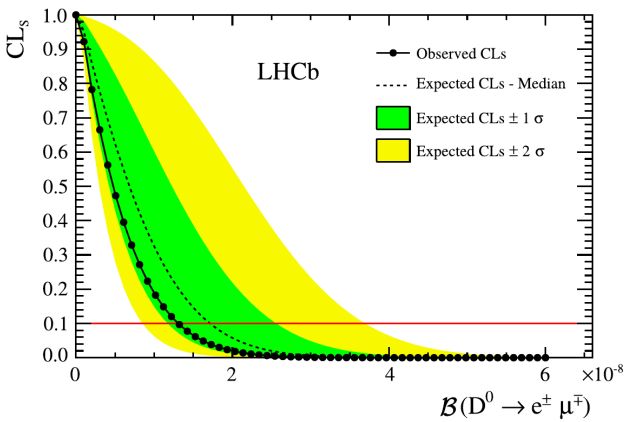


Lepton flavour violation: search for $D^0 \to e^+\mu^-$ decay

- LFV is effectively forbidden in the SM but predicted to occur in some NP scenarios







No evidence seen

Best limit from LHCb [PLB 754 (2016) 167]

$BF(D^0 \to e\mu) < 1.3(1.6) \times 10^{-8}$ at 90(95)%CL

Update is being worked on

LHCb prospects for existing measurements

(private extrapolations from existing measurements and arXiv:1808.08865)

Limits on BFs (away from resonances for multibody)

Mode	Upgrade ($50\,\mathrm{fb}^{-1}$)	Upgrade II ($300\,\mathrm{fb}^{-1}$)
$D^0 \to \mu^+\mu^-$	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}
$\Lambda \to p\mu\mu$	1.1×10^{-8}	4.4×10^{-9}
$D^0 \to e\mu$	10^{-9}	4.1×10^{-9}

Statistical precision on A_{CP} (PS integrated)

Mode	Upgrade ($50\,\mathrm{fb}^{-1}$)	Upgrade II ($300\,\mathrm{fb}^{-1}$)
$D^+ \to \pi^+\mu^+\mu^-$	0.2%	0.08%
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	1%	0.4%
$D^0 \to K^-\pi^+\mu^+\mu^-$	0.3%	0.13%
$D^0 \to K^+\pi^-\mu^+\mu^-$	12%	5%
$D^0 \to K^+K^-\mu^+\mu^-$	4%	1.7%

Prospects for radiative decays at Belle II [arXiv:1808.10567]

	Int. luminosity	$A_{CP}(D^0 \to \rho^0\gamma)$		
Belle result	1 ab^{-1}	$+0.056$	± 0.152	± 0.006
	5 ab^{-1}		± 0.07	
Belle II statistical error	15 ab^{-1}		± 0.04	
	50 ab^{-1}		± 0.02	
		$A_{CP}(D^0 \to \phi\gamma)$		
Belle result	1 ab^{-1}	-0.094	± 0.066	± 0.001
	5 ab^{-1}		± 0.03	
Belle II statistical error	15 ab^{-1}		± 0.02	
	50 ab^{-1}		± 0.01	
		$A_{CP}(D^0 \to \overline{K}^{*0}\gamma)$		
Belle result	1 ab^{-1}	-0.003	± 0.020	± 0.000
	5 ab^{-1}		± 0.01	
Belle II statistical error	15 ab^{-1}		± 0.005	
	50 ab^{-1}		± 0.003	

Some thoughts on systematics

- Muonic channels at LHCb should be statistically limited (proved by current analyses with hardonic channels)
- Same is true for radiative decays at BelleII
- Electron modes may see some competition between BelleII and LHCb (mass resolution vs cross section)
- Radiative decays should be possible at LHCb as well, although the neutral energy reco makes bkg rejection non-trivial

Conclusions

- Steady progress over the years, all modes one can think of should be covered in the near future
- Signal already seen on multibody dimuonic decays, first asymmetry measurements! Move to angular/amplitude analyses
- Modes with dielectron well hopefully follow soon
- The future of rare charm decays at LHCb Upgrade and BelleII looks promising!