Rare Charm Decays at LHCb

Joint BESIII/LHCb workshop - Bejing, China

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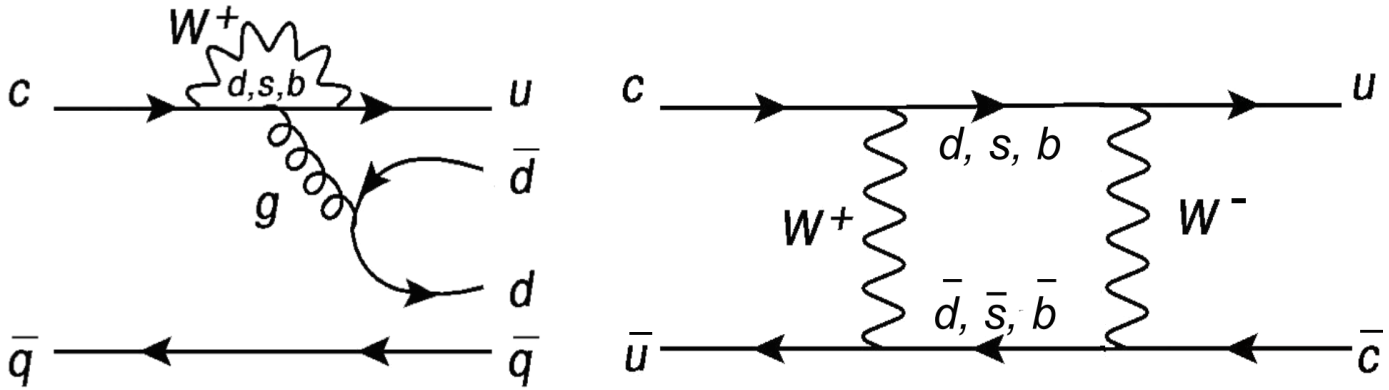
Outline

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



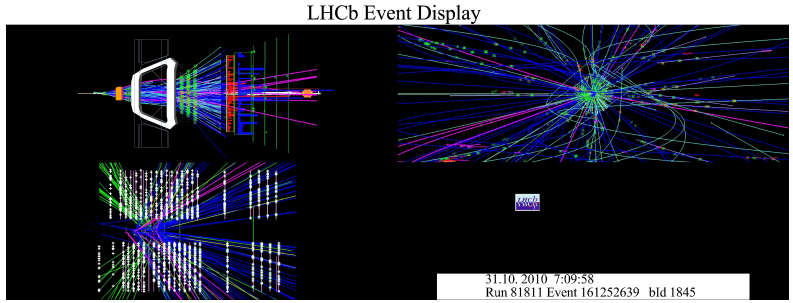
- New Physics may be hidden in the loops
- Long-distance contributions are non-negligible and precise theoretical predictions are difficult
- Charm is more of a "discovery tool"

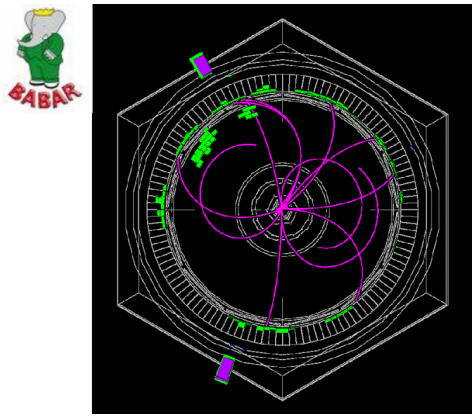
Charm samples

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	2/fb +	2.6 mb	4.4×10^{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

Pros & Cons

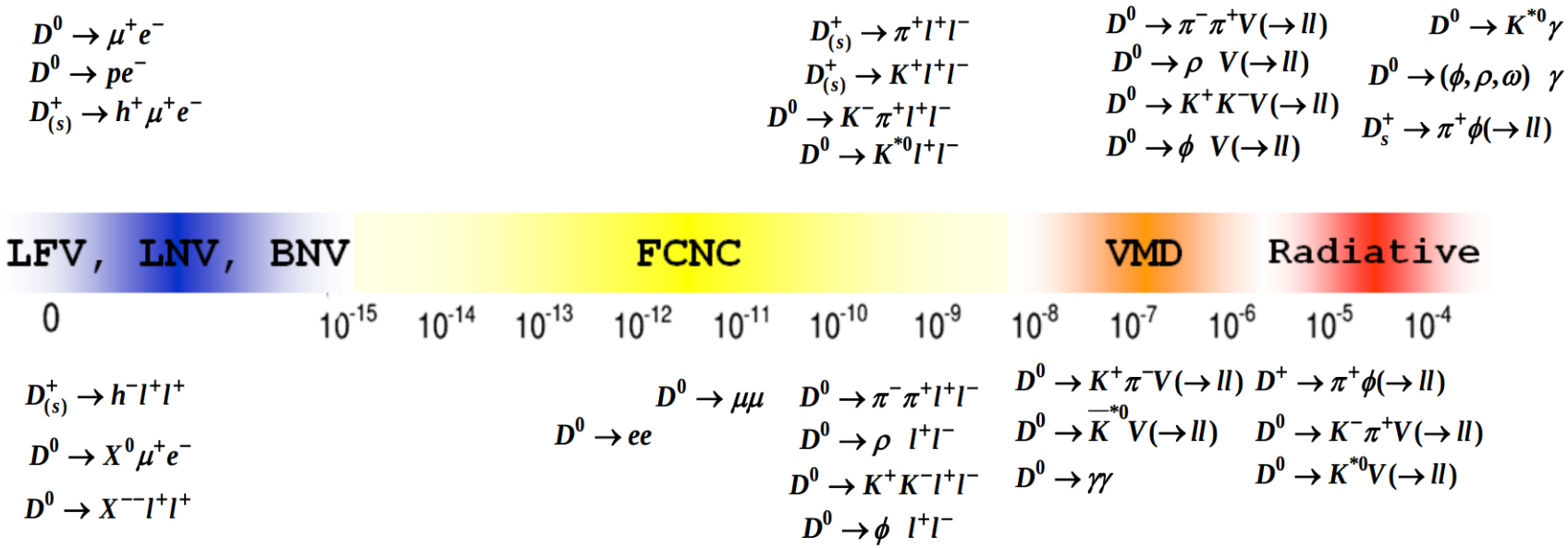
- LHCb
  - Large combinatorial backgrounds
  - Decays with neutrals and missing particles are difficult
  - Excellent lifetime resolution due to the boost, $\sim 0.1\tau_D$
  - Huge $c\bar{c}$ production cross sections
- Belle/BaBar
  - Lower boost, poorer lifetime resolution
  - Clean environment
  - Excellent performance when dealing with neutrals/neutrinos
- BESIII/CLEO-c
  - No boost, no lifetime measurement
  - Practically no background
  - $\psi(3770) \to DD$, quantum coherence (can measure strong phases!)





Charm Rare Decays

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

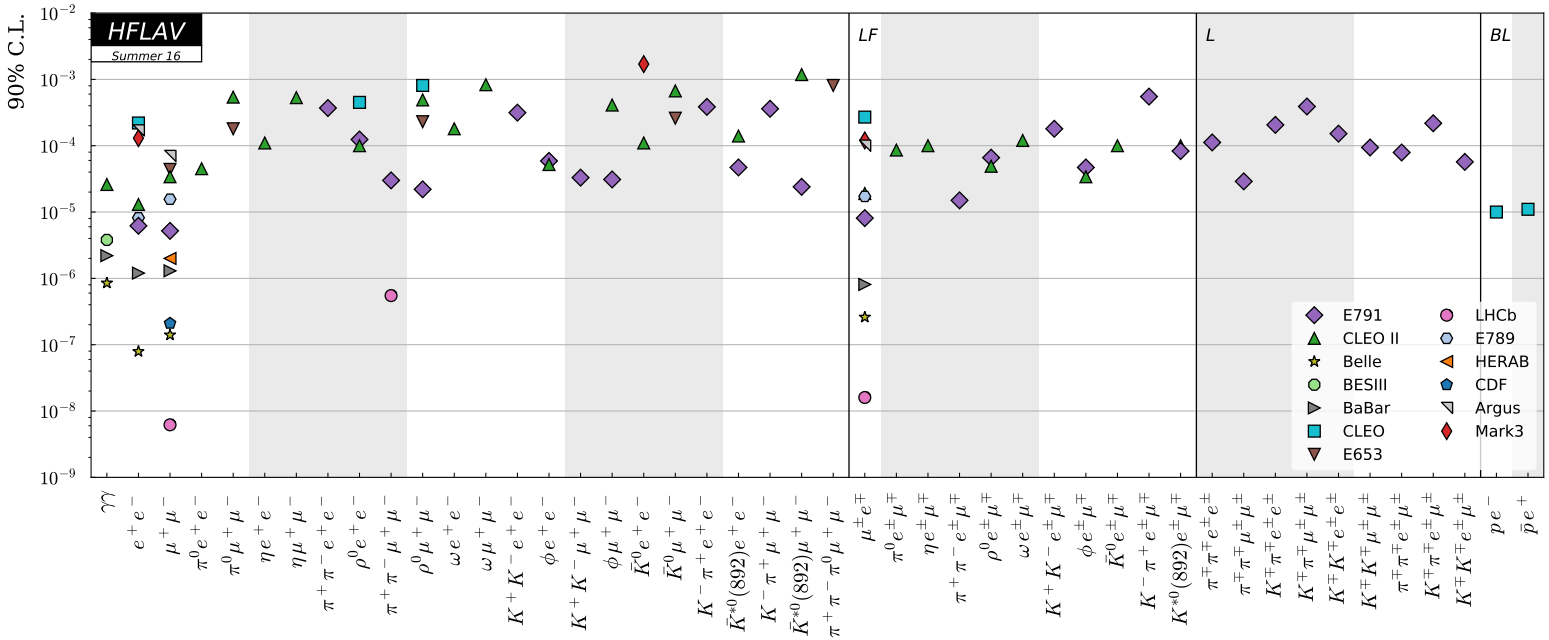


[PRD 66 (2002) 014009]

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 $BF < 10^{-9}$, not yet there

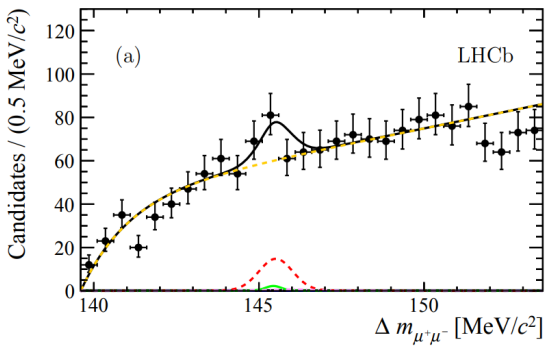
Where do we stand?

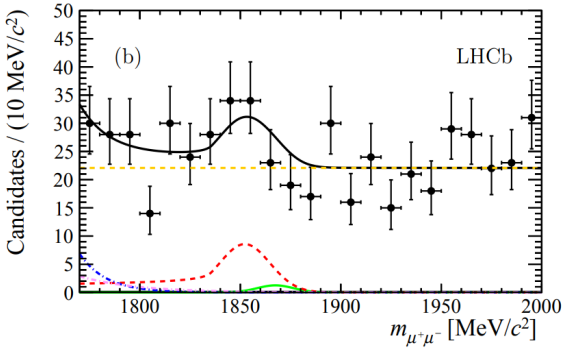
- Focused on decays into two muons + ≥ 0 charged hadrons
  - Relatively high trigger efficiency
  - Combinatorial under control, we D^* tag neutral D^0 to get additional suppression.
  - Irreducible background from hadronic decays $D \to N\pi^{\pm}$, where $N = 2, 3, 4$. Reduced by tight muonID by a factor $10^{-5} - 10^{-6}$ but cannot go beyond.
- Large production cross section ensures every measurement is likely a world best

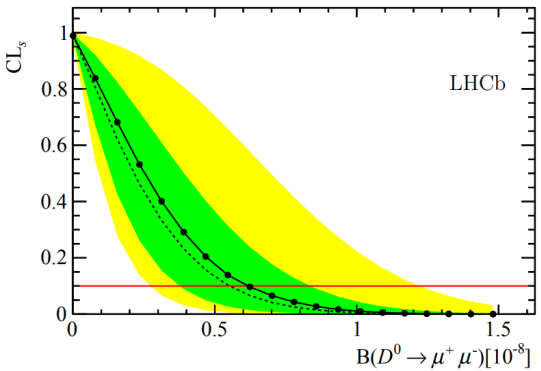


$D^0 \to \mu^+\mu^-$ [PLB 725 (2013) 15-24]

- Helicity suppressed. In the SM is constrained by limit on $\mathcal{B}(D^0 \to \gamma\gamma)$ from Belle [PRD 93, 051102 (2016)] to about 10^{-12} (main contribution to the BF comes from a long distance $\gamma\gamma$ recombination)
- Hope to see NP in BF enhancements
- Best limit from LHCb at 7.6×10^{-9} at 90% CL, 1/fb only. Update is being worked on!

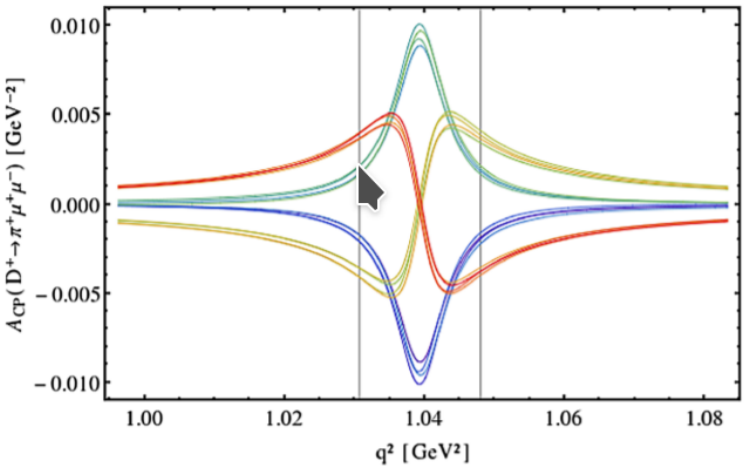


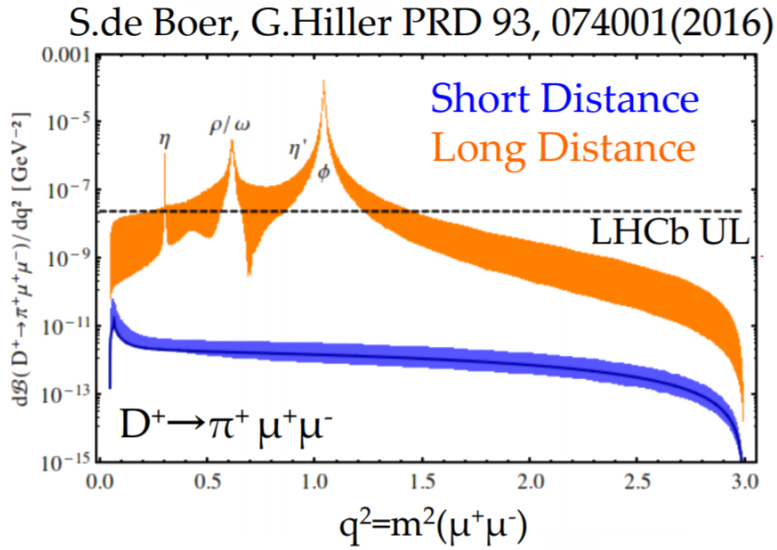




Multibody decays with a dilepton pair

- 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

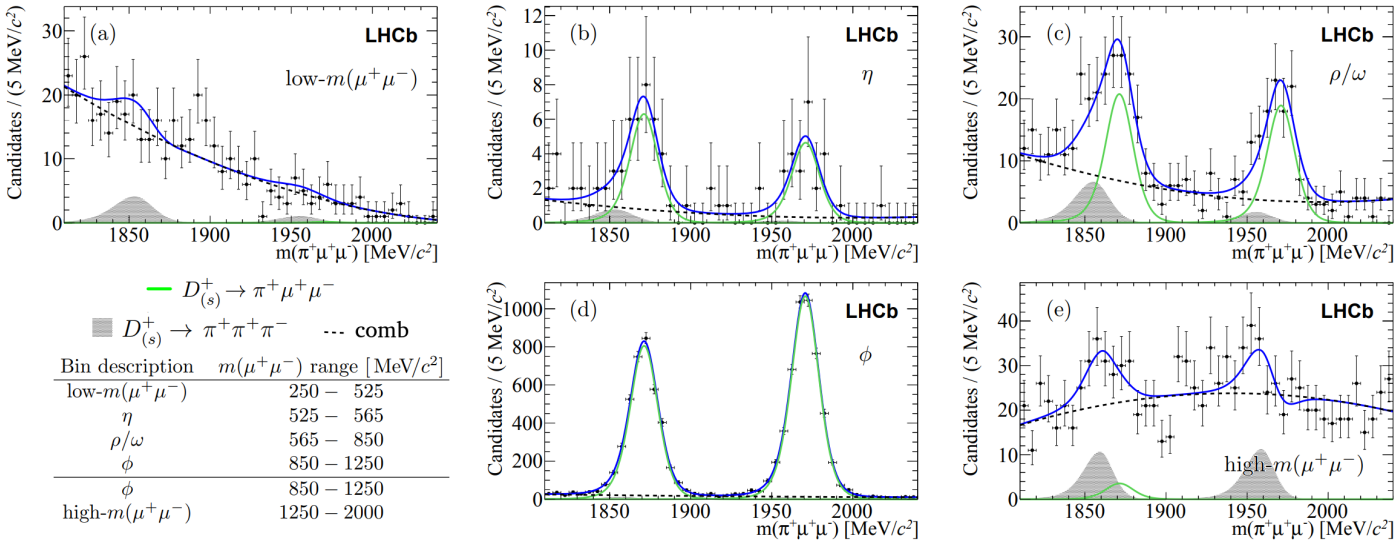




- Unlikely that NP could show up in the branching fraction
- But the richer dynamics allows to investigate A_{CP}, A_{FB} which can be up to a few percents in some NP scenarios

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.

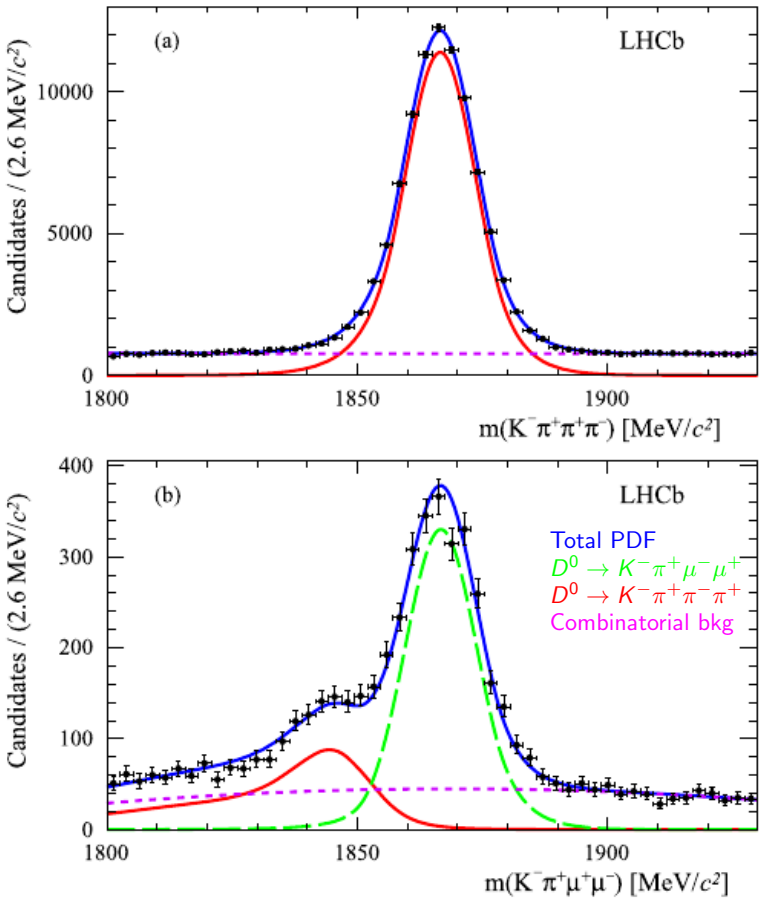


Bin description	$m(\mu^+\mu^-)$ range [MeV/c^2]
low-$m(\mu^+\mu^-)$	250 – 525
η	525 – 565
ρ/ω	565 – 850
ϕ	850 – 1250
ϕ	850 – 1250
high-$m(\mu^+\mu^-)$	1250 – 2000

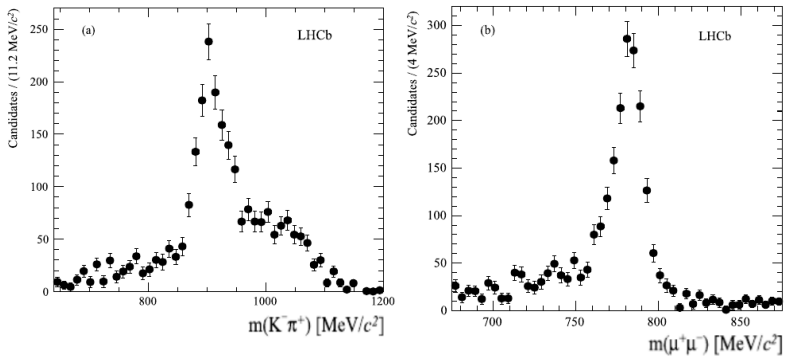
- Similar approach also adopted for $D^0 \to \pi^+\pi^-\mu^+\mu^-$ decay yielding $BF(D^0 \to \pi^+\pi^-\mu^+\mu^-) < 5.5 \times 10^{-7}$ at 90% CL (world's best) [PLB 728 (2014) 234-243] $\to$ dropped in favour of a model independent one..

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

[PLB 757 (2016) 558-567]



- $BF(D^0 \to K^-\pi^+\mu^-\mu^+) = (4.12 \pm 0.12_{stat} \pm 0.38_{syst}) \times 10^{-6}$
- In agreement with SM predictions [JHEP 04 (2013) 135]
- Ideal normalisation mode for $D^0 \to h^+h^-\mu^+\mu^-$

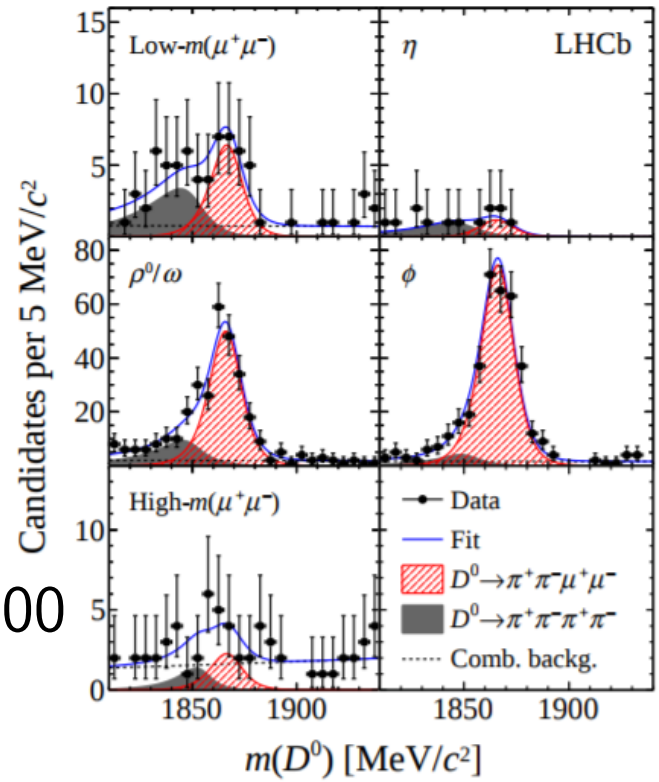


Observation of D^0 mesons decaying into $h^+h^-\mu^+\mu^-$

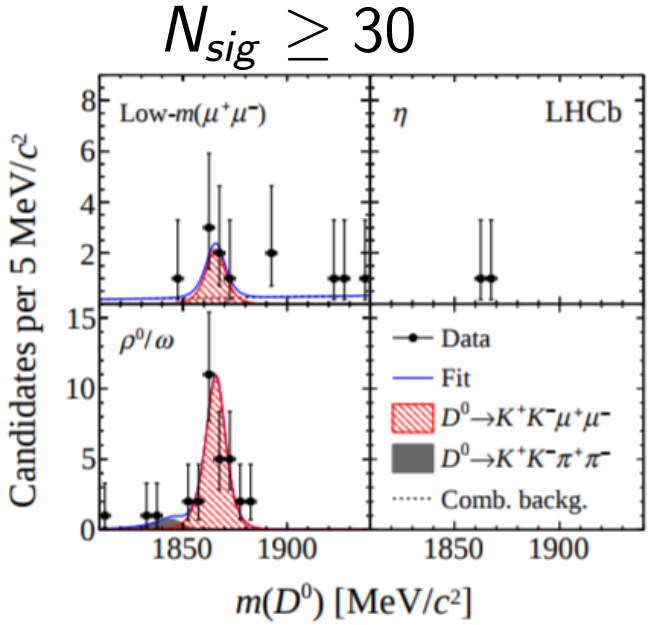
[PRL 119 2017)181805]

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

$N_{sig} \geq 500$



$N_{sig} \geq 30$



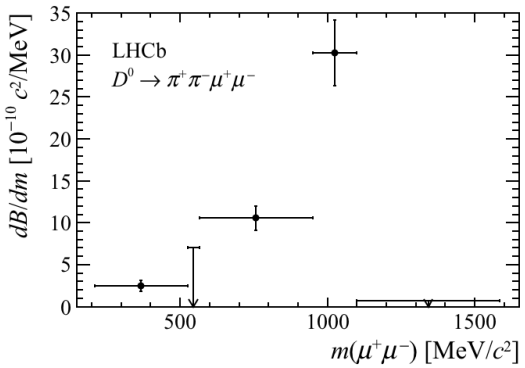
- No attempt is made to distinguish between long and short distance

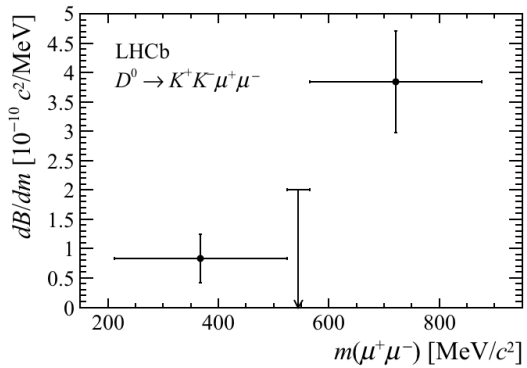
Observation of D^0 mesons decaying into $h^+h^-\mu^+\mu^-$

[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:

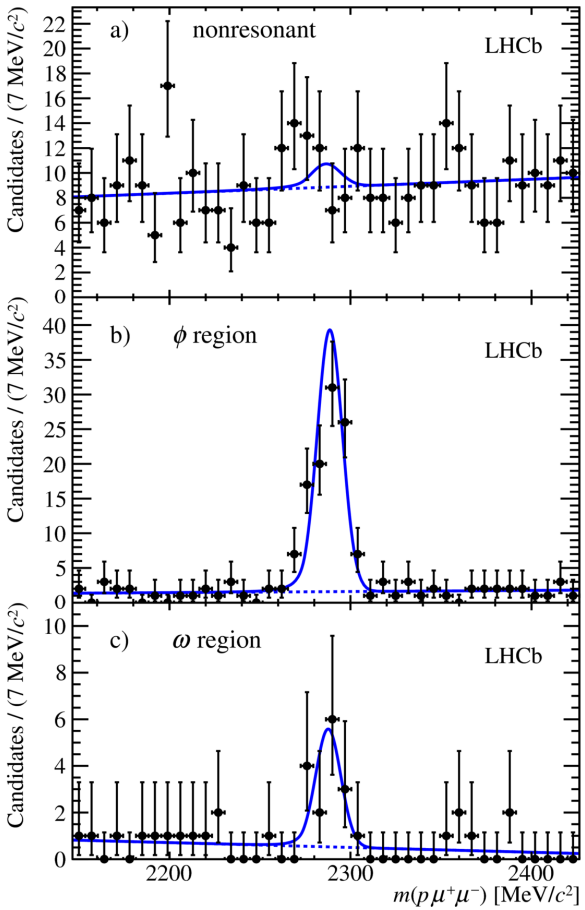
$$\mathcal{B}(D^0 \to \pi^-\pi^+\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7}$$
$$\mathcal{B}(D^0 \to K^-K^+\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}$$

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

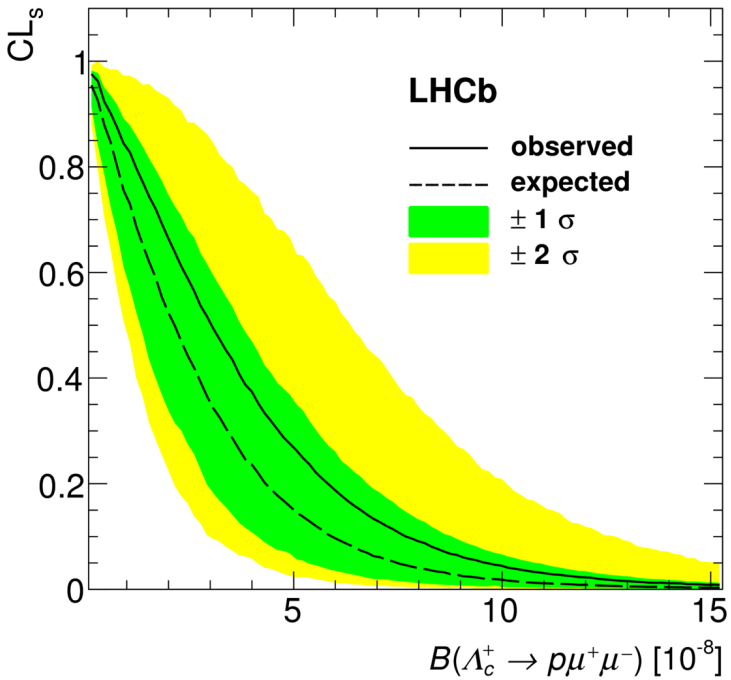
- Statistics is enough to perform first asymmetry measurements!

Search for $\Lambda_c \to p\mu^+\mu^-$ arXiv:1712.07938, submitted to PRL

- Similar approach to other 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

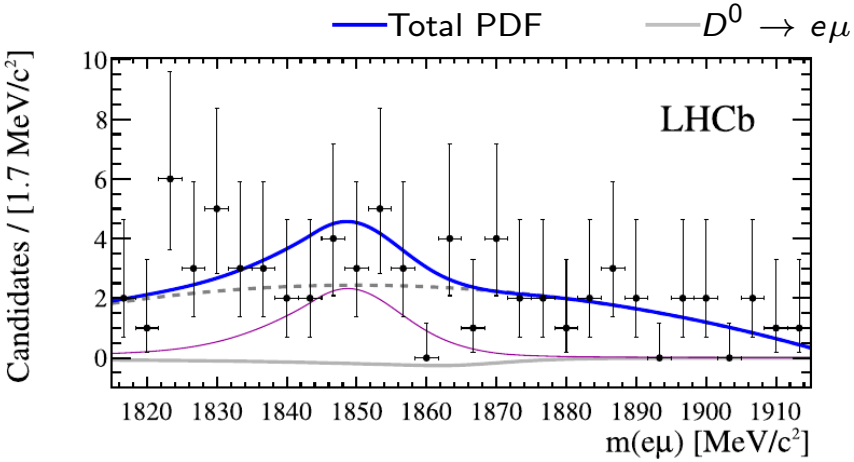


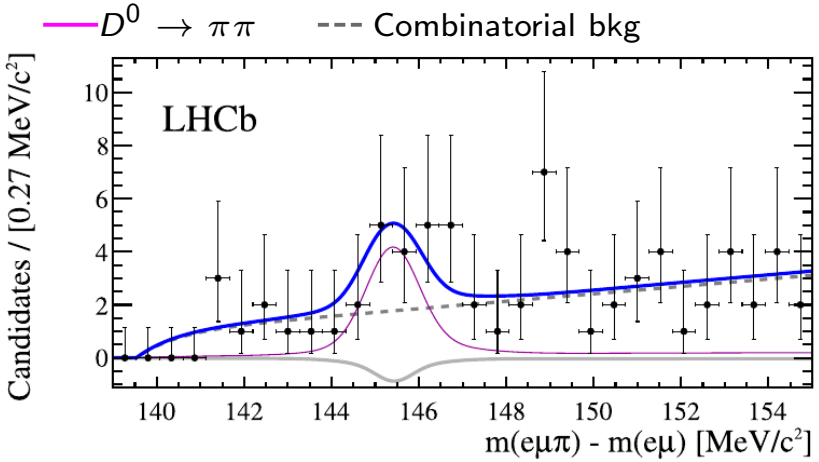
Radiative charm decays

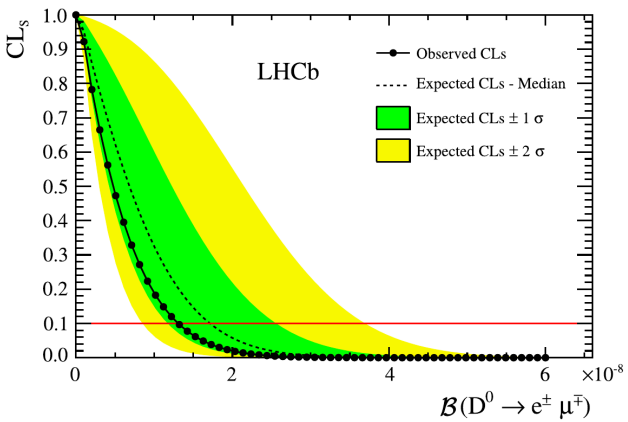
- Decays of the type $D^0 \to \{\phi/\rho/K^*\}\,\gamma$ are dominated by long-distance
- Measuring the BFs tests QCD based calculations of long distance dynamics
- Can probe New Physics when measuring A_{CP} (around 10^{-3} in the SM, up to several percent in NP scenarios)
- Belle recently measured BF and A_{CP} for all these modes [PRL 118, 051801 (2017)]
- Challenging to compete for LHCb due to neutral energy resolution and γ/π^0 separation, but not impossible...
- Our Run2 signal yield should exceed those from Belle, stay tuned!

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

Moving forward

- Continuing pushing down limits/measuring branching fractions on muonic channels
- Measure asymmetries (A_{CP}, A_{FB}...) in multibody decays with muons. Already some activity on $D^0 \to hh\mu^+\mu^-$
- Include electrons both in dielectron and LFV multibody decays. Ongoing activity in three-body $D^+_{(s)} \to hll'$
- Investigate LU violation following results on the B sector by measuring $\mathcal{B}(D \to Xee)/\mathcal{B}(D \to X\mu\mu)$. If not for NP, at least as a null test
- In the LHCb upgrade yields may be sufficient to perform angular/amplitude analyses

Prospects for existing measurements

Limits on BFs for the non-resonant part

Mode	Run I	Run II	Upgrade
$D^0 \to hh'\mu^+\mu^-$	few 10^{-7}	fewer 10^{-7}	10^{-8}
$D^0 \to \mu^+\mu^-$	few 10^{-9}	fewer 10^{-9}	10^{-10}
$D^+ \to \pi^+\mu^+\mu^-$	few 10^{-8}	fewer 10^{-8}	10^{-9}
$D_s^+ \to K^+\mu^+\mu^-$	few 10^{-7}	fewer 10^{-7}	10^{-8}
$\Lambda \to p\mu\mu$	few 10^{-7}	fewer 10^{-7}	10^{-8}
$D^0 \to e\mu$	few 10^{-8}	fewer 10^{-8}	10^{-9}

Statistical precision on A_{CP}

Mode	Run II	Upgrade
$D^+ \to \pi^+\mu^+\mu^-$	0.6%(30K events)	0.2%(300K events)
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	3%(1500 events)	1%(15K events)
$D^0 \to K^-\pi^+\mu^+\mu^-$	1%(10K events)	0.3%(100K events)
$D^0 \to K^+\pi^-\mu^+\mu^-$	40%(30 events)	12%(300 events)
$D^0 \to K^+K^-\mu^+\mu^-$	11%(150 events)	4%(1500 events)

Summary and Conclusions

- Steady progress over the years, not NP yet
- Orders of magnitude better than previous experiments on fully charged final states
- Signal seen on multibody decays, now moving to asymmetries!
- Expect some results on radiative decays and electron modes
- The future of rare charm decays at LHCb (upgrade in particular) looks very bright!
- BESIII is complementary for decays which are difficult for LHCb, missing neutrinos, neutrals, etc.