Charm (Semi-)leptonic Decays at LHCb

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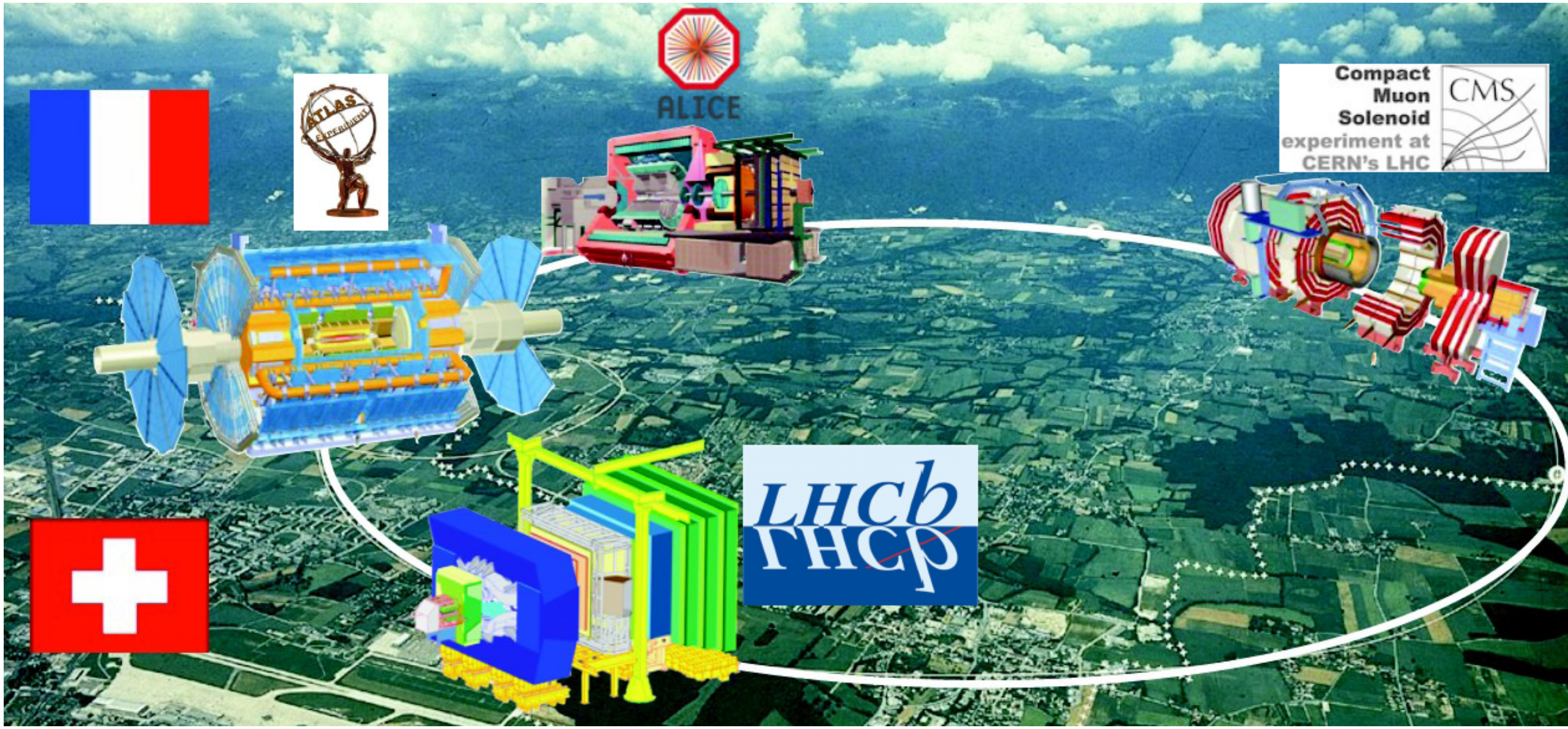
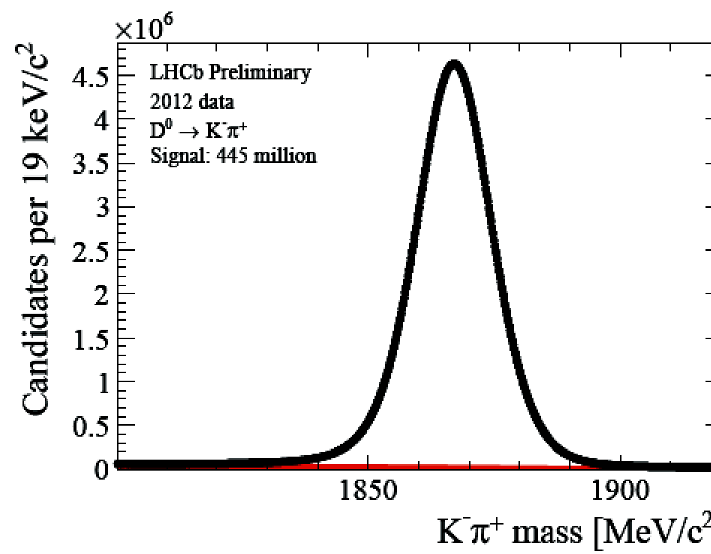
Outline

- Recent LHCb results on charm rare decays
  - $D^0 \to K^+K^-$ $(\pi^+\pi^-)$ $\mu^+\mu^-$
  - $D^0 \to K^-\pi^+$ $\mu^+\mu^-$ in ρ/ω region of dimuon mass
  - $D^0 \to \mu^+\mu^-$, $D_{(s)}^+ \to \pi^+ \mu^+\mu^-$ / $D_{(s)}^+ \to \pi^- \mu^+\mu^+$
  - $D^0 \to e^+ \mu^-$
- Charm semileptonic decays: prospects
- Summary

LHCb experiment



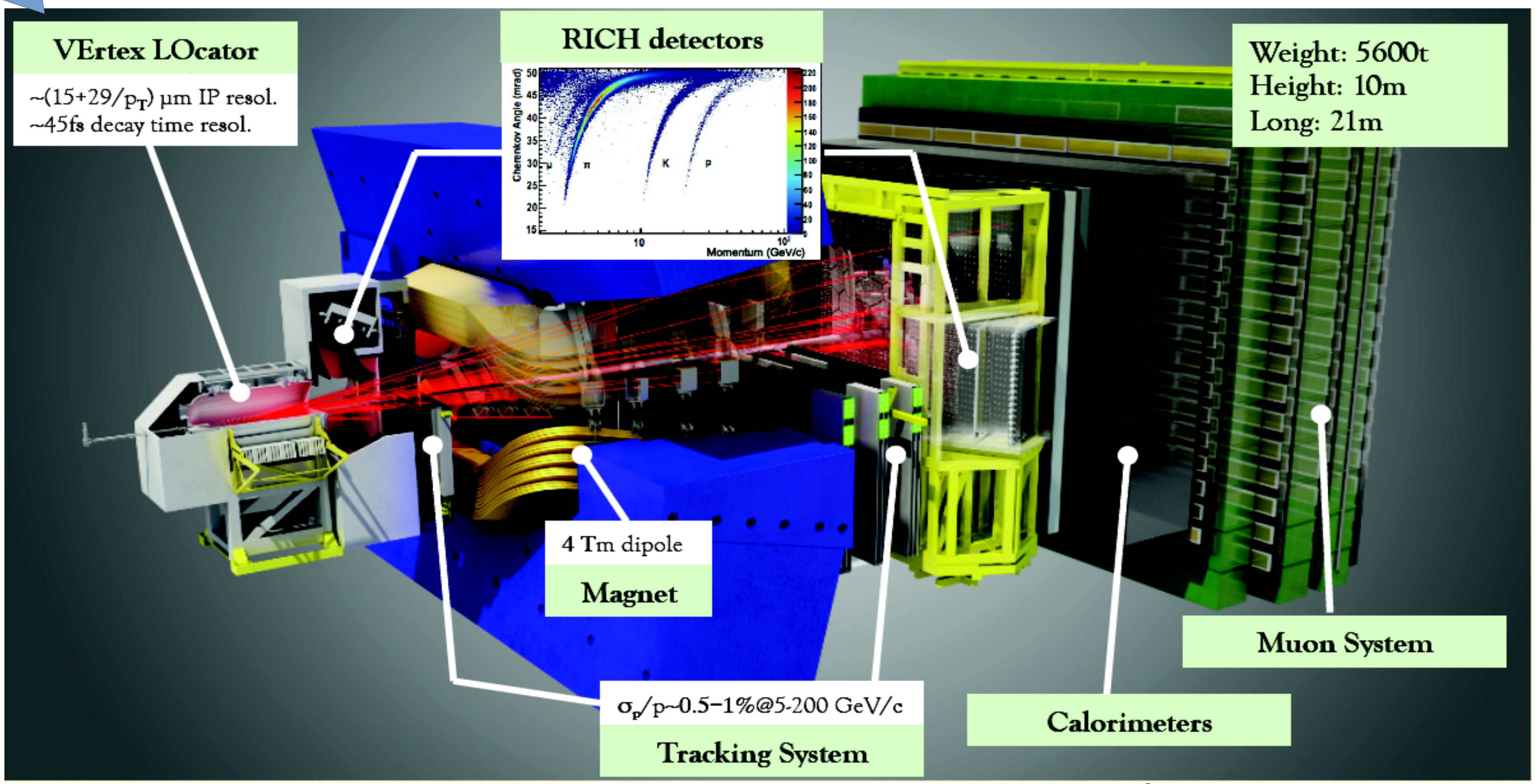
- LHCb acceptance: $2 < \eta < 5$ (forward region)
- All the results presented today are based on (a subset of) $3fb^{-1}$ Run1 data of LHCb collected within 2011-2012
- 1.15 billion charm hadron decays reconstructed in Run1



LHCb-CONF-2016-005

Superb!

LHCb experiment



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

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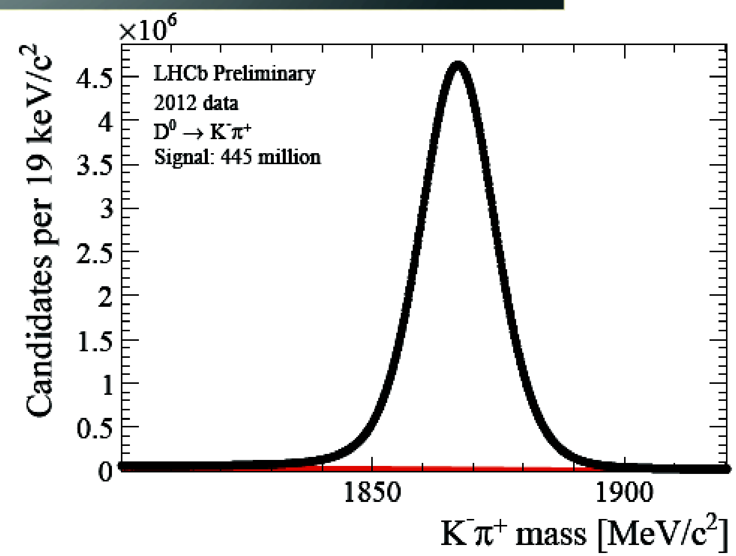

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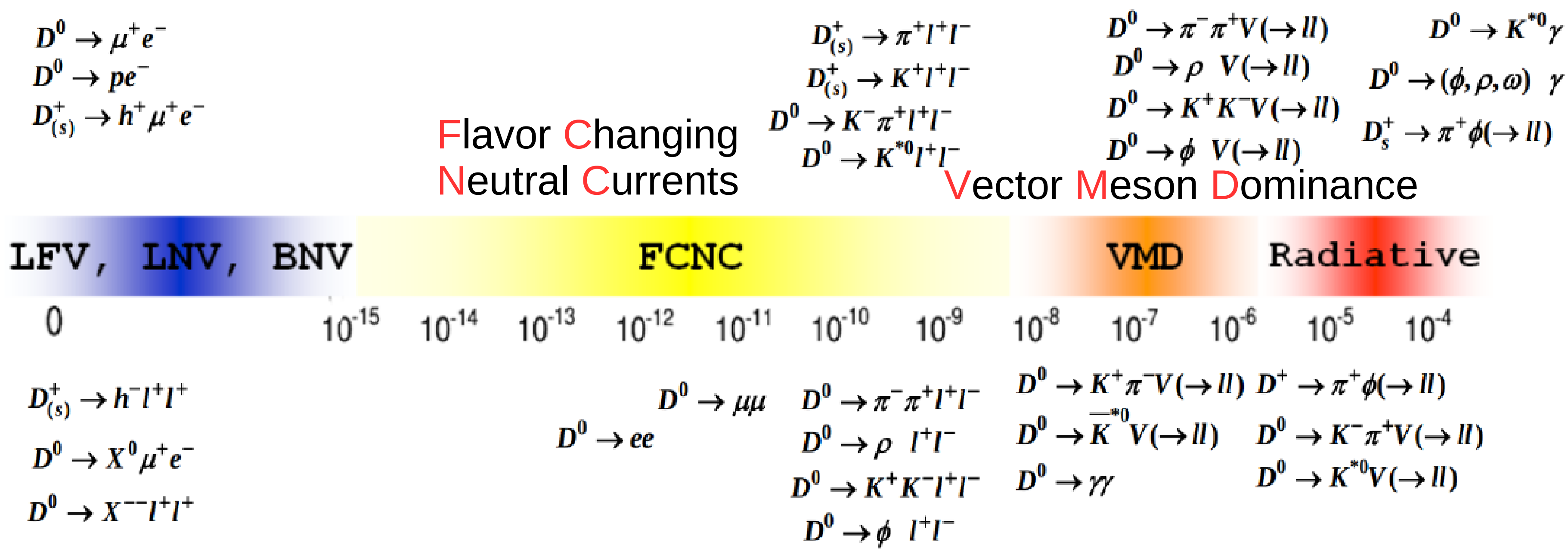
Overview of charm rare decays

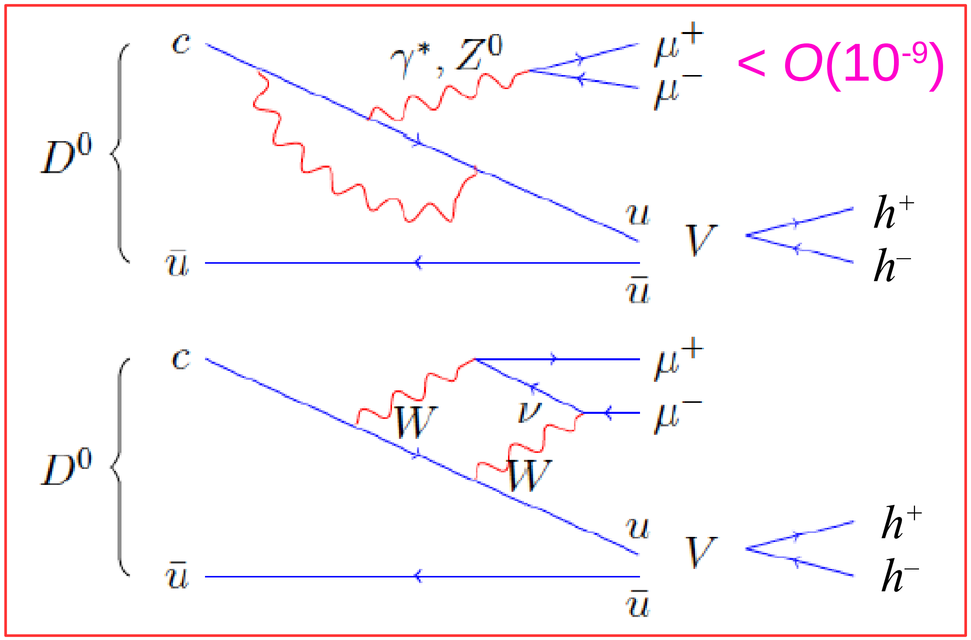


[PRD 66 (2002) 014009]

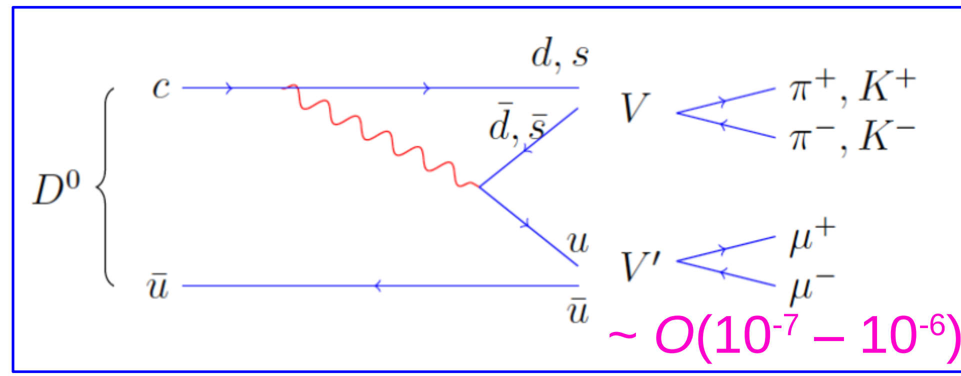
- Short-distance FCNC contributions to c → u processes are tiny < 10^{-9}
  - Only possible at the loop level
  - More suppressed than *B* decays due to GIM mechanism
  - Up-type quark FCNCs complementary to those in B and K sectors
- Branching fractions of D → X$\ell^+\ell^-$ are dominated by resonant long-distance VMD contributions

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

SD contributions, good for NP probes



LD contributions, hard to predict theoretically



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PLB 757 (2016) 558-567

$D^0 \to K^-\pi^+\mu^-\mu^+$ BF in ρ^0/ω region of dimuon mass

- Not related to the FCNCs, still this decay mode provides an excellent normalization for all the other 4 body modes
- Analysis overview (2012 data, $2fb^{-1}$):
  - Dimuon mass in the ρ^0/ω region: [675, 875] MeV
  - $D^0 \to K^-\pi^+\pi^-\pi^+$ as the normalization channel, also the major background source
  - Careful estimation of peaking backgrounds due to misID or $\pi^+ \to \mu^+\nu_\mu$

$$\mathcal{B}(D^0 \to K^-\pi^+\mu^+\mu^-) = \frac{N_{D^0 \to K^-\pi^+\mu^+\mu^-}}{N_{D^0 \to K^-\pi^+\pi^+\pi^-}} \times \frac{\varepsilon_{D^0 \to K^-\pi^+\pi^+\pi^-}}{\varepsilon_{D^0 \to K^-\pi^+\mu^+\mu^-}} \times \mathcal{B}(D^0 \to K^-\pi^+\pi^+\pi^-)$$

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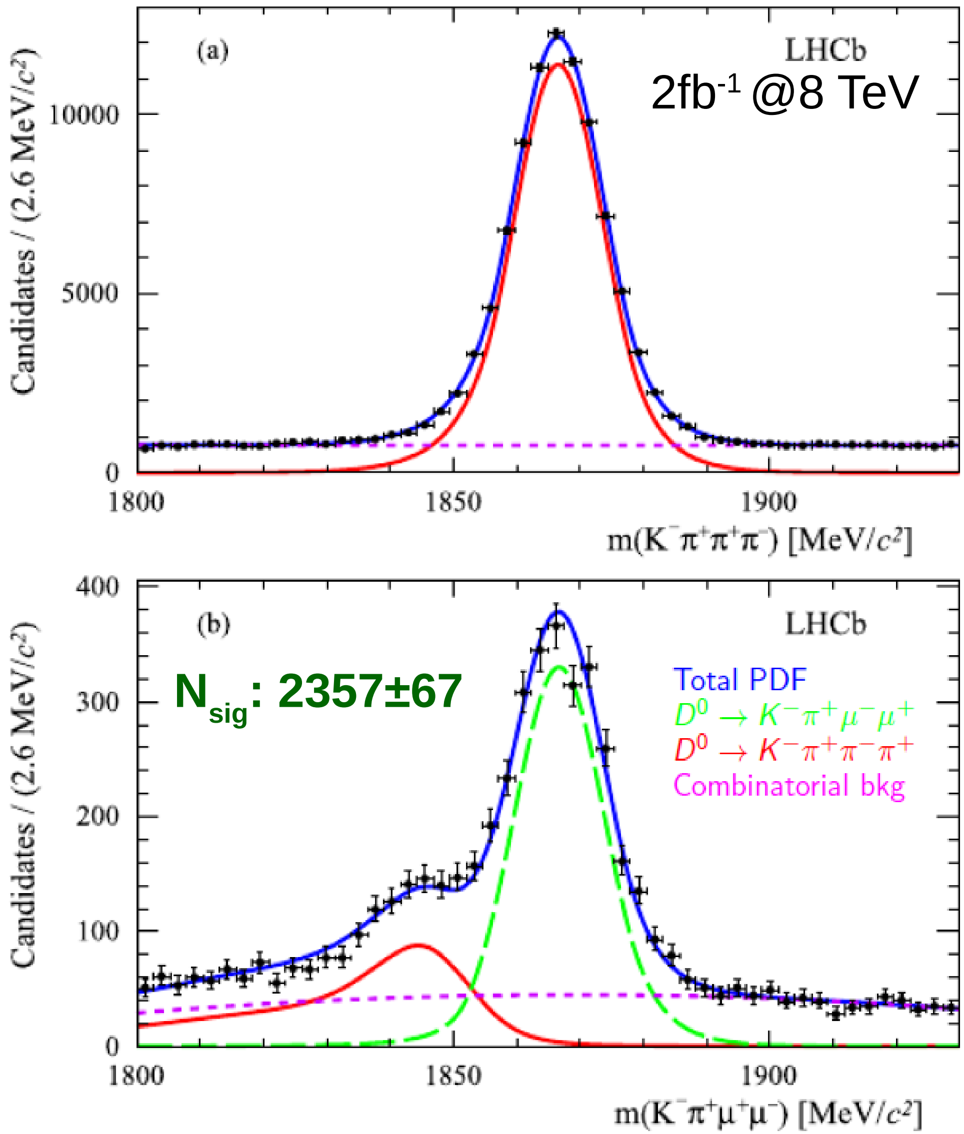
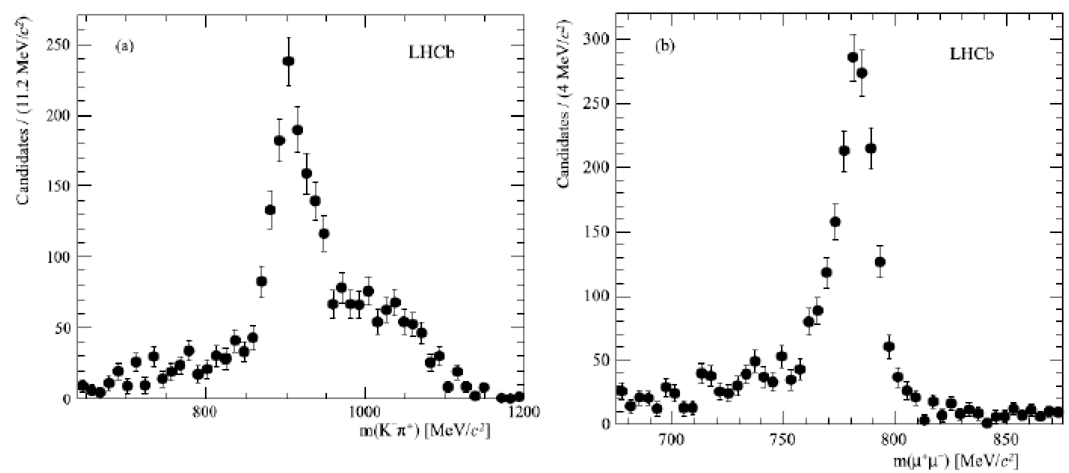
$D^0 \to K^-\pi^+ \rho^0/\omega(\to \mu^-\mu^+)$: First observation



$$\mathcal{B}(D^0 \to K^-\pi^+\mu^+\mu^-) = (4.17 \pm 0.12\,(\text{stat}) \pm 0.40\,(\text{syst})) \times 10^{-6}$$

- $D^0 \to K^-\pi^+\pi^+\pi^-$ as the normalization channel
- Compatible with SM expectation [JHEP 04(2013)135]



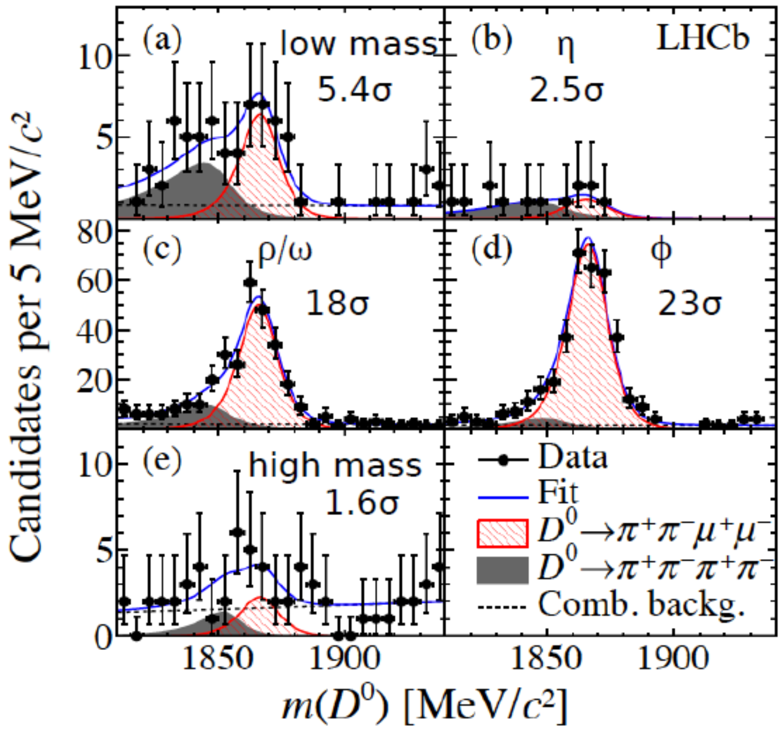
arXiv:1707.08377

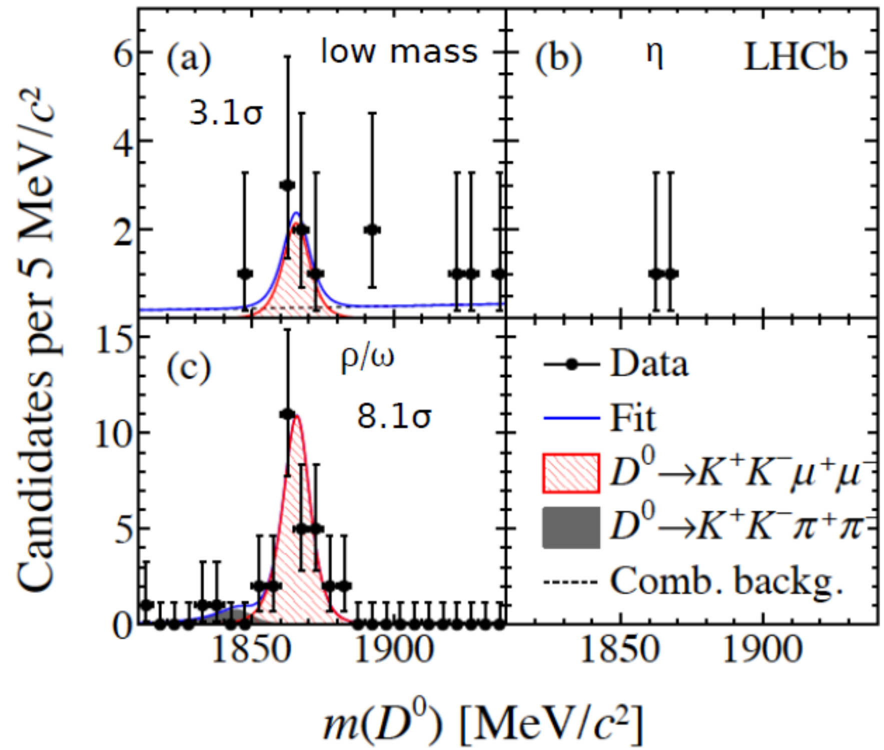
$D^0 \to K^+K^-/\pi^+\pi^-\ \mu^+\mu^-$ decays

- Previous LHCb search for the decay $D^0 \to \pi^+\pi^-\mu^+\mu^-$ published in 2013 with 1 fb^{-1} data [PLB 728 (2014) 234-243]
  - Best upper limits at the time
- Overview of this analysis (2012 data, 2fb-1):
  - $D^0 \to K^-\pi^+\ \rho^0/\omega(\to\mu^-\mu^+)$ as the perfect normalization channel
  - Binned measurement in m(μμ) to separate resonant and nonresonant contributions
  - Signal extraction in signal and normalization mode by a fit to D^0 mass

$$BF(D^0 \to hh\mu\mu) = BF(D^0 \to K\pi\mu\mu) \cdot \frac{N_{D^0\to hh\mu\mu}}{N_{D^0\to K\pi\mu\mu}} \cdot \frac{\epsilon_{D^0\to K\pi\mu\mu}}{\epsilon_{D^0\to hh\mu\mu}}$$

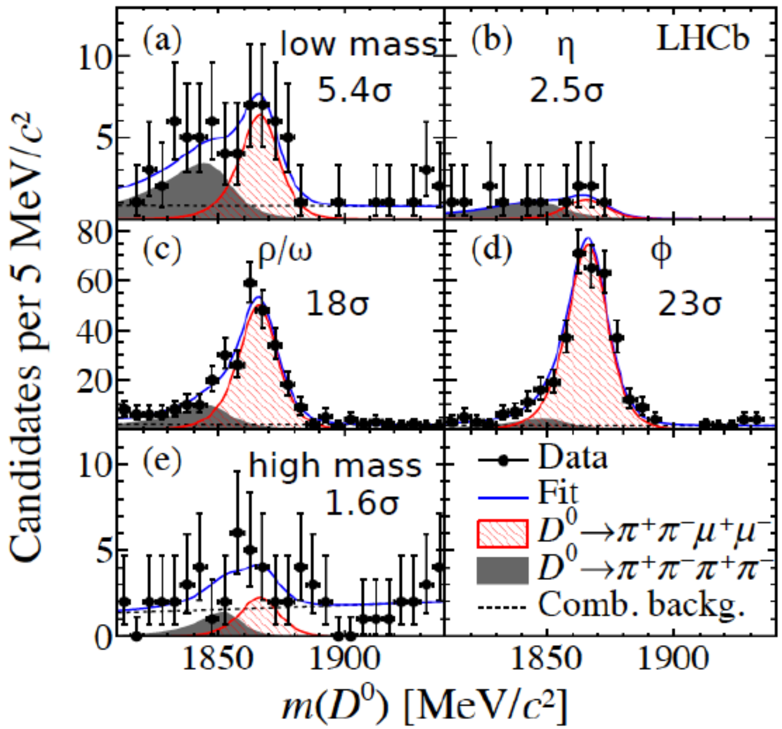
First observation of $D^0 \to K^+K^-/\pi^+\pi^- \mu^+\mu^-$

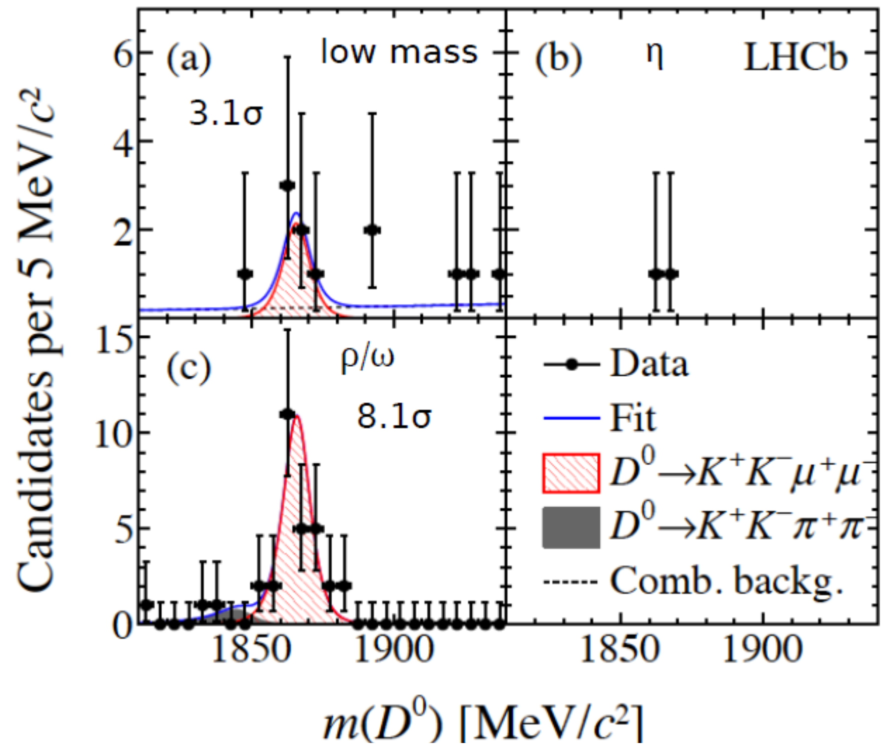




Dimuon-mass region $m(\mu^+\mu^-)$ [MeV/c^2]	low mass < 525	η 525–565	ρ^0/ω 565–950	ϕ 950–1100	high mass > 1100
$N^{\text{sig}}(D^0 \to \pi^+\pi^-\mu^+\mu^-)$	27 ± 6	5 ± 3	208 ± 17	312 ± 20	9 ± 6
Signal significance	5.4σ	2.5σ	18σ	23σ	1.6σ
$R^\epsilon(D^0 \to \pi^+\pi^-\mu^+\mu^-)$	0.73 ± 0.04	0.84 ± 0.07	1.08 ± 0.05	1.45 ± 007	1.5 ± 0.1
$N^{\text{sig}}(D^0 \to K^+K^-\mu^+\mu^-)$	5 ± 3	–	29 ± 5	–	–
Signal significance	3.1σ	–	8.1σ	–	–
$R^\epsilon(D^0 \to K^+K^-\mu^+\mu^-)$	0.49 ± 0.03	0.53 ± 0.04	0.55 ± 0.03	–	–

First observation of $D^0 \to K^+K^-/\pi^+\pi^- \mu^+\mu^-$





Rarest charm decays measured to date:

$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (96.4 \pm 4.8(stat) \pm 5.1(sys) \pm 9.7(\mathcal{B}_{norm})) \cdot 10^{-8}$$
$$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) = (15.4 \pm 2.7(stat) \pm 0.9(sys) \pm 1.6(\mathcal{B}_{norm})) \cdot 10^{-8}$$

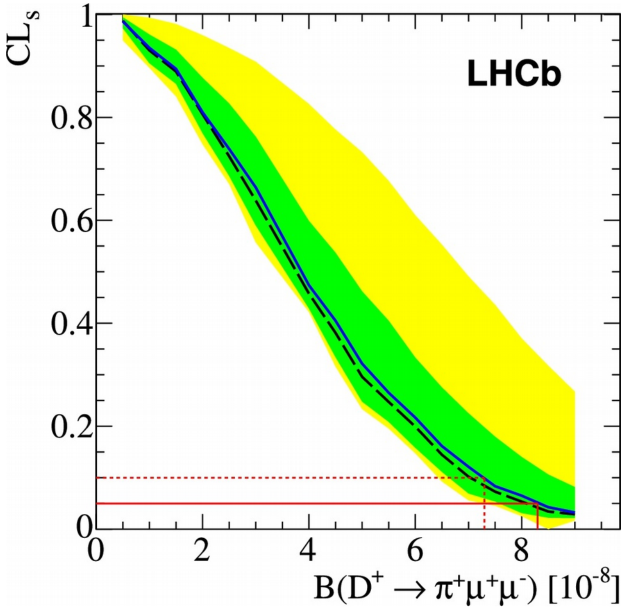
$m(\mu^+\mu^-)$ [MeV/c^2]	$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-)$ [10^{-8}]
< 525	$7.8 \pm 1.9 \pm 0.5 \pm 0.8$
525–565	$< 2.4\,(2.8)$ at 90% (95%) CL
565–950	$40.6 \pm 3.3 \pm 2.1 \pm 4.1$
950–1100	$45.4 \pm 2.9 \pm 2.5 \pm 4.5$
> 1100	$< 2.8\,(3.3)$ at 90% (95%) CL
$m(\mu^+\mu^-)$ [MeV/c^2]	$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-)$ [10^{-8}]
< 525	$2.6 \pm 1.2 \pm 0.2 \pm 0.3$
525–565	$< 0.7\,(0.8)$ at 90% (95%) CL
> 565	$12.0 \pm 2.3 \pm 0.1 \pm 0.1$

PLB 724 (2013) 558-567

LHCb upper limits based on 2011 data, 1 fb^{-1}:

$$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 7.3(8.3)\cdot 10^{-8} \text{ at } 90\%(95\%) \text{ CL}$$
$$\mathcal{B}(D_s^+ \to \pi^+\mu^+\mu^-) < 4.1(4.8)\cdot 10^{-7} \text{ at } 90\%(95\%) \text{ CL}$$
$$\mathcal{B}(D^+ \to \pi^-\mu^+\mu^+) < 2.2(2.5)\cdot 10^{-8} \text{ at } 90\%(95\%) \text{ CL}$$
$$\mathcal{B}(D_s^+ \to \pi^-\mu^+\mu^+) < 1.2(1.4)\cdot 10^{-7} \text{ at } 90\%(95\%) \text{ CL}$$

- Improved by a factor of 50

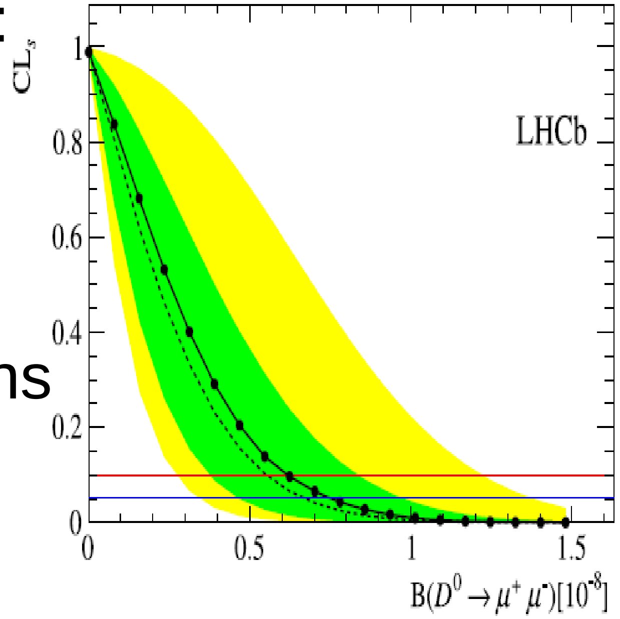


PLB 725 (2013) 15-24

LHCb upper limits based on 2011 data, 0.9 fb^{-1}:

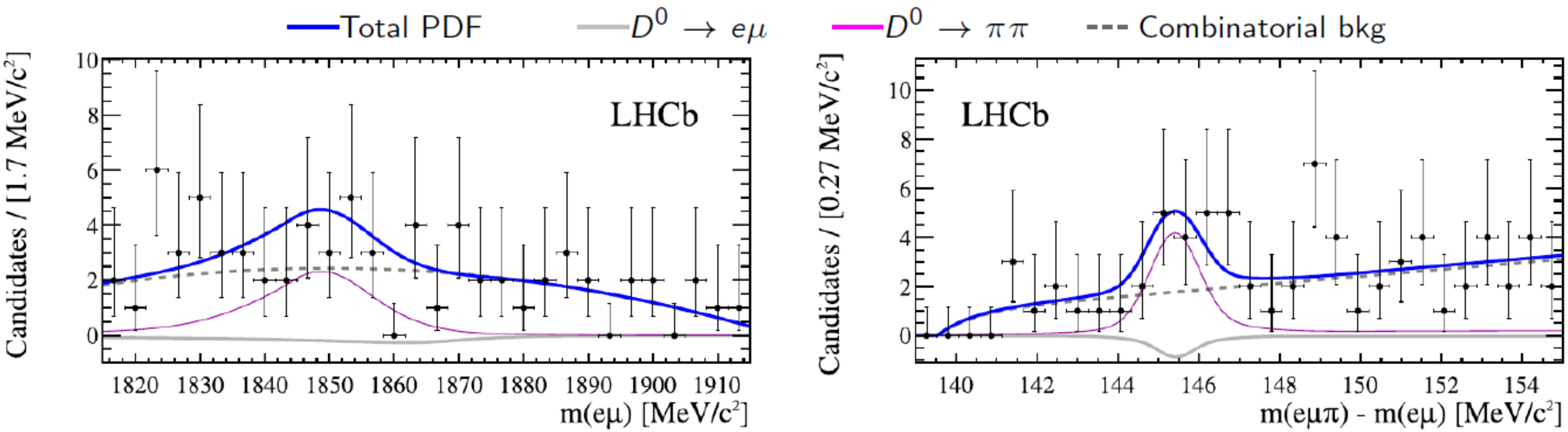
$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2(7.6)\cdot 10^{-9} \text{ at } 90\%(95\%) \text{ CL}$$

- Improved by a factor of 20
- Two orders of magnitude above SM predictions

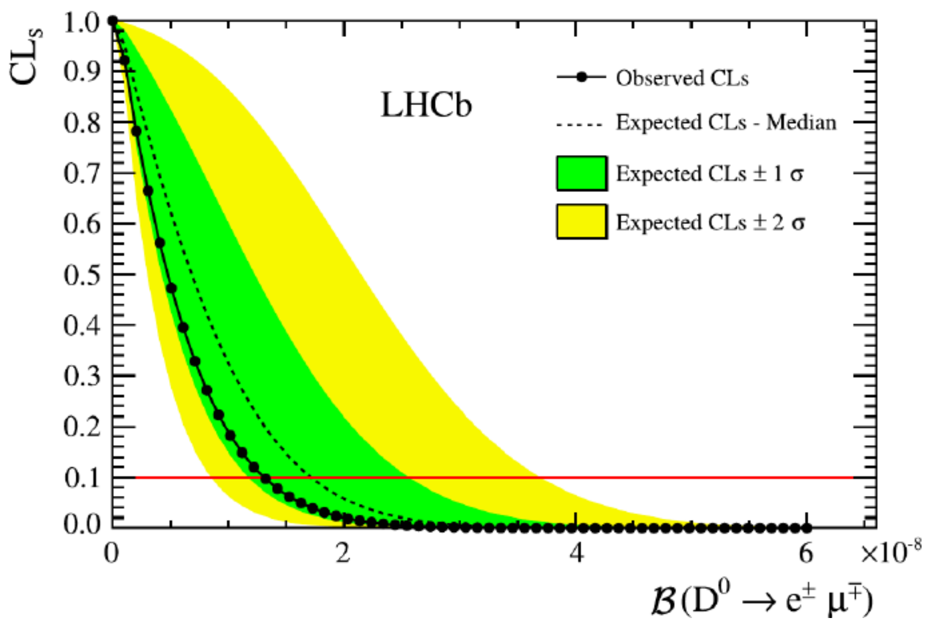


PLB 754 (2016) 167-175

Search for LFV decay $D^0 \to e^+\mu^-$



No evidence seen



- Use $D^{*\pm} \to D^0\pi^\pm$ decays
- Normalised to $D^0 \to K^-\pi^+$ mode

New world best limit

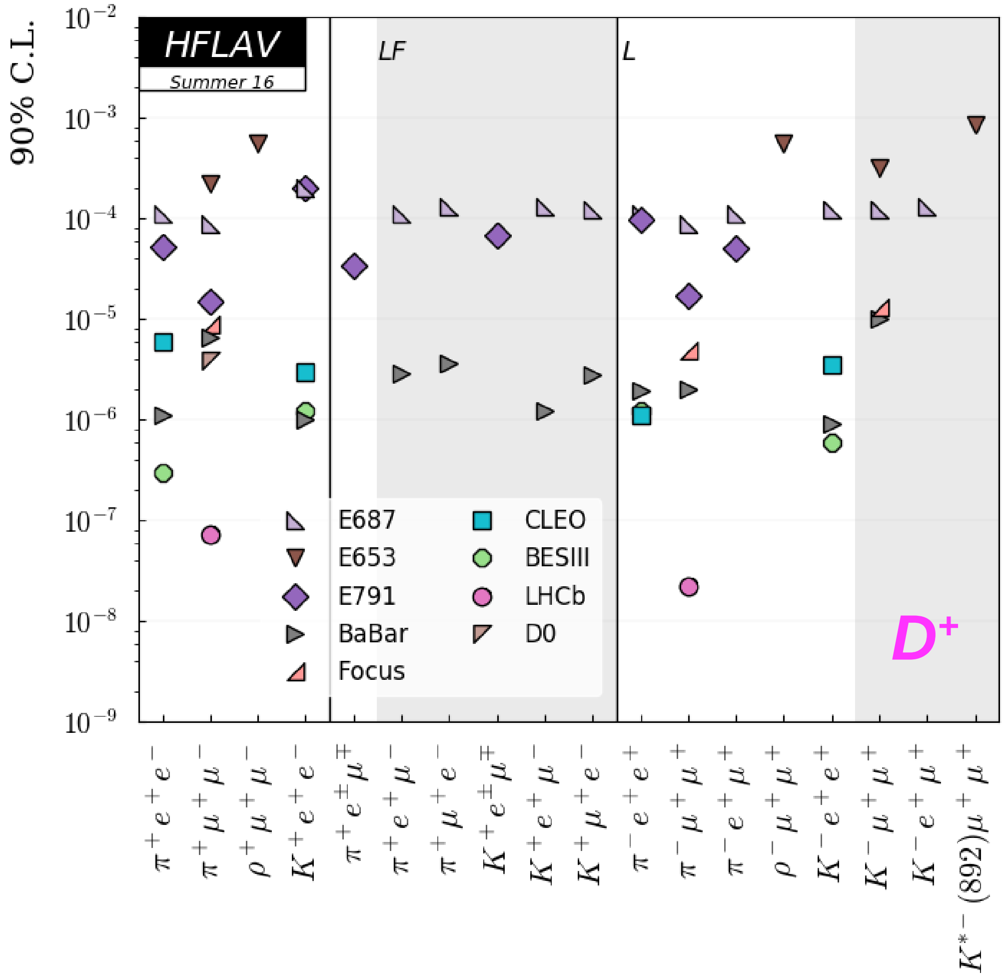
$$BF(D^0 \to e\mu) < 1.3(1.6) \times 10^{-8}$$

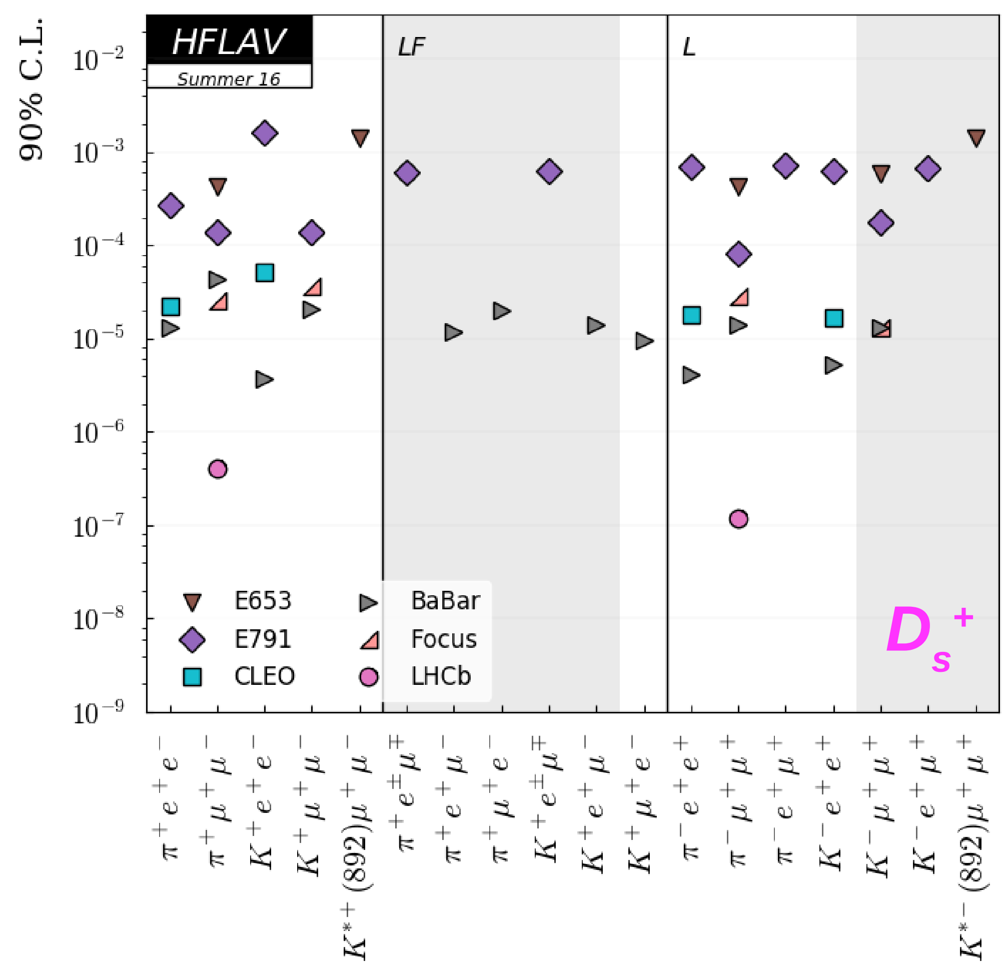
at 90(95)%CL

$$\mathcal{B}(D^0 \to e^\pm\mu^\mp) = \frac{N_{e\mu}/\epsilon_{e\mu}}{N_{K\pi}/\epsilon_{K\pi}} \times \mathcal{B}(D^0 \to K^-\pi^+)$$

Overview of results on D rare decays

Almost every LHCb measurement is the world's best

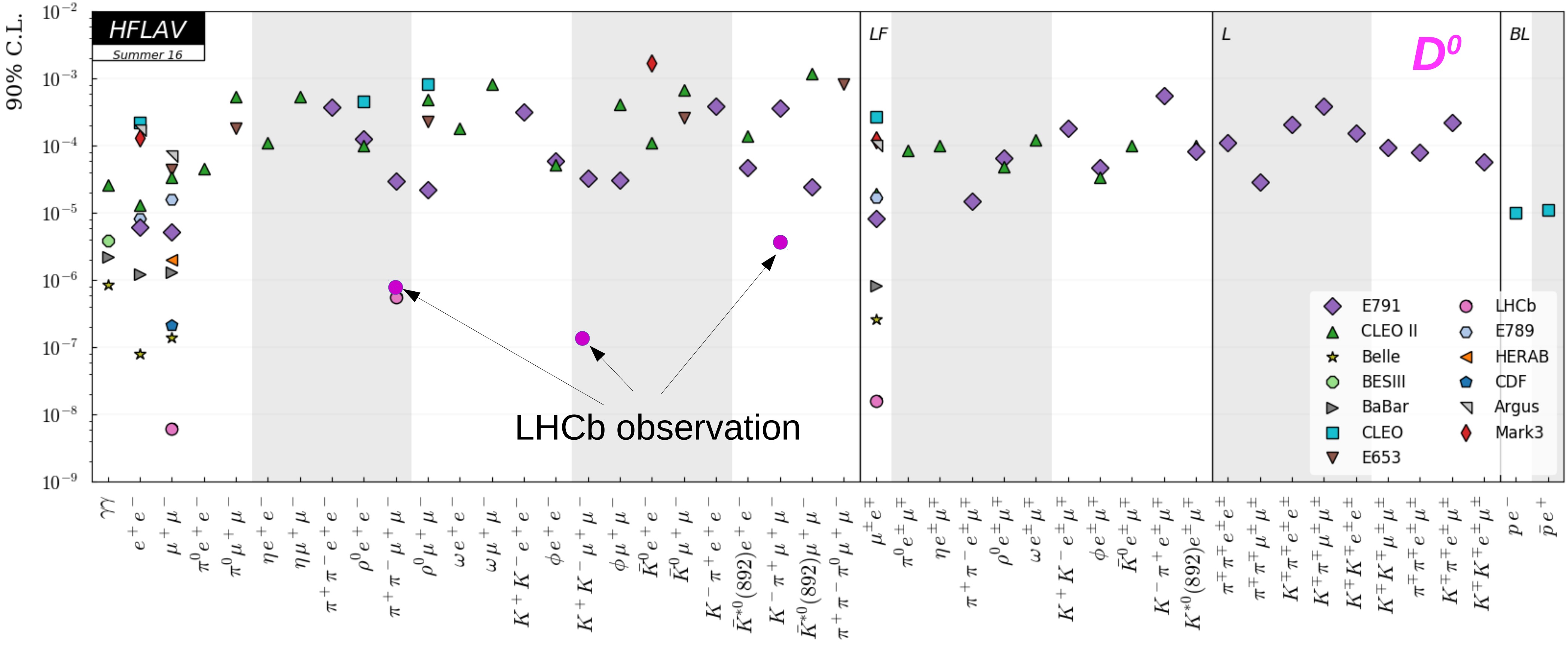




Overview of results on D rare decays

Almost every LHCb measurement is the world's best

Also first observations!



Prospects on rare charm decays

- During Run2 and beyond, SM predictions can be reached for more dimuon modes

$\sigma_{c\bar{c}}(14\,\text{TeV}) \approx 2\sigma_{c\bar{c}}(7\,\text{TeV})$ & assuming same efficiency and S/B ratio

Mode	$8\,\text{fb}^{-1}$	$50\,\text{fb}^{-1}$	$300\,\text{fb}^{-1}$
$D^0 \to \mu^+\mu^-$	fewer 10^{-9}	few 10^{-10}	fewer 10^{-10}
$D^0 \to e^+\mu^-$	few 10^{-9}	fewer 10^{-9}	few 10^{-10}
$D^+ \to \pi^+\mu^+\mu^-$	fewer 10^{-8}	few 10^{-9}	fewer 10^{-9}
$D_s^+ \to K^+\mu^+\mu^-$	fewer 10^{-7}	few 10^{-8}	fewer 10^{-8}
$D^0 \to hh\mu^+\mu^-$	fewer 10^{-7}	few 10^{-8}	fewer 10^{-8}

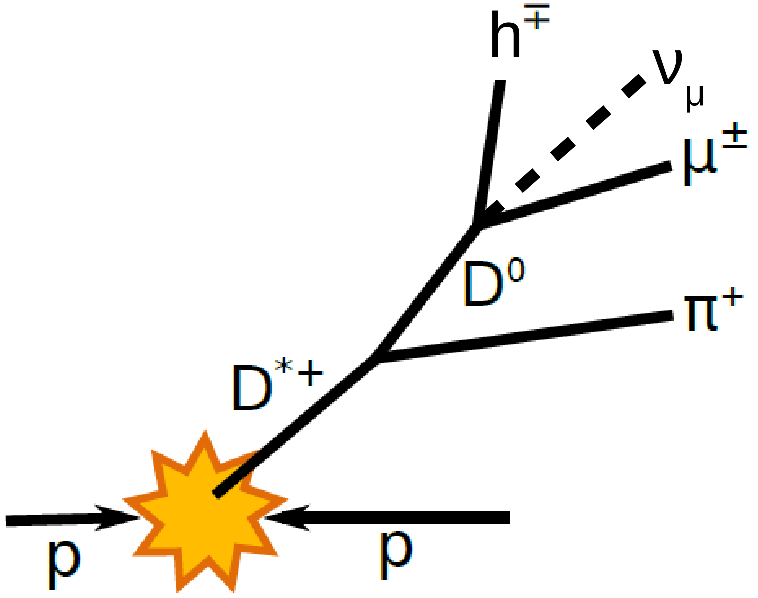
Prospects on rare charm decays

- During Run2 and beyond, SM predictions can be reached for more dimuon modes
- Promising for first investigation of angular/*CP* asymmetries in $D^0 \to h^+h^-\mu^+\mu^-$ decays including Run2 data
  - Precision possibly at tens of percent level by end of 2017

Mode	Run II 8 fb^{-1}	Upgrade 50 fb^{-1}
$D^+ \to \pi^+\mu^+\mu^-$	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)

Predictions on asymmetries' sensitivity by assuming the same efficiency and signal-to-background ratio

Charm semileptonic decays at LHCb: the prospects



See A. Davis's CKM2016 talk

Why charm SL decays?

- Well-known form of D^0 differential decay rate:

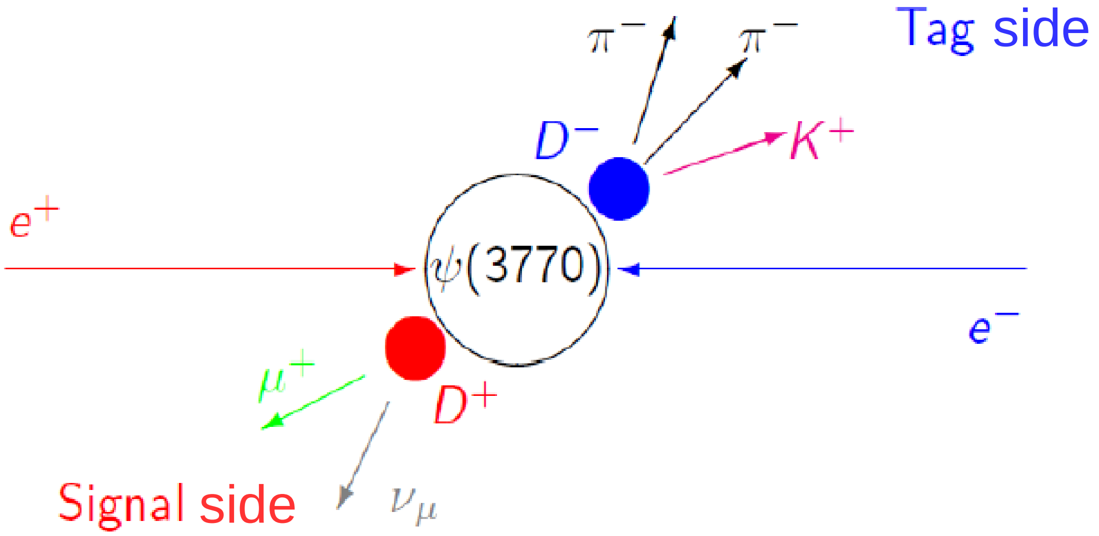
EPJC 77, no. 2, 112 (2017)

$$\frac{d\Gamma(D^0 \to P^- \ell^+ \nu_\ell)}{dq^2} = |V_{cQ}|^2 \frac{G_F^2}{24\pi^3} \frac{(q^2 - m_\ell^2)^2 \sqrt{E_P^2 - m_P^2}}{q^4 m_{D^0}^2} \times \left[\left(1 + \frac{m_\ell^2}{2q^2}\right) m_{D^0} (E_P^2 - m_P^2) |f_+(q^2)|^2 + \frac{3m_\ell^2}{8q^2} (m_{D^0}^2 - m_P^2)^2 |f_0(q^2)|^2 \right]$$

- With q^2 dependent rates, we can measure
  - CKM factor |VcQ|, useful for testing unitarity of the CKM matrix, or
  - The form factor dependence $|f_+(q^2)|$ and $|f_0(q^2)|$, useful input to Lattice QCD calculations, or
  - Lepton universality

Challenge for LHCb: missing neutrinos

- Only partially reconstructed final state: $D^0 \to h^- \mu^+$
- For e+e- machines, neutrino info could be deduced from the beam energy and the other side of the event: the missing 4-momentum
- Not possible at a hadron collider!



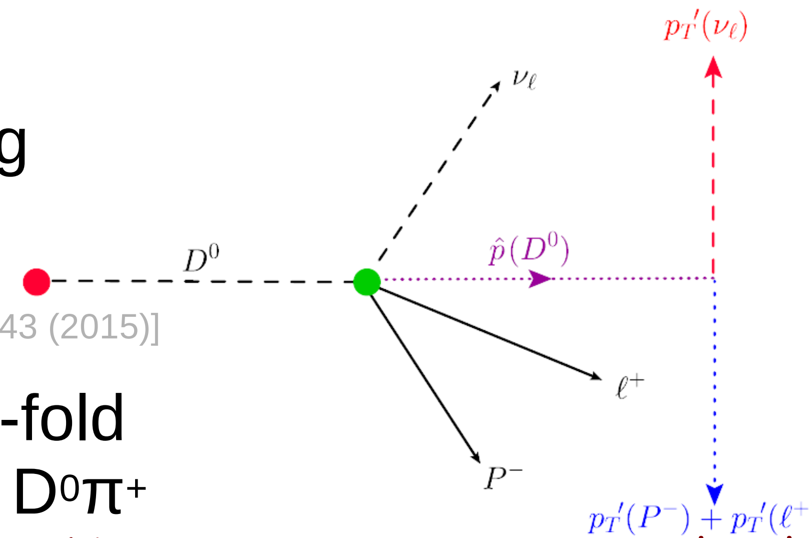
Neutrino and q^2 reco: possible solutions

- Still, a number of proven experimental techniques are out there…
- Flight direction of the *D* can be used to constrain p_T'
- New problem: two-fold ambiguity for total neutrino momentum
- Possible solutions:
  - Corrected *D* mass with one missing massless particle:

$$M_{corr} = \sqrt{m(K\ell)^2 + p_T'^2} + p_T'$$ [LHCb, Nature Phys. 11, 743 (2015)]

  - Cone-closure method to break two-fold ambiguity: requiring D^0 from $D^{*+} \to D^0\pi^+$ and enforcing D^* mass constraint

[E687, FERMILAB-THESIS-1995-05]



Neutrino momentum is completely constrained perpendicular to the D^0 flight direction:

$$p_T'(\nu) = -(p_T'(P) + p_T'(\ell))$$

Experimental opportunities: one example

- Measure

$$\frac{|V_{cs}|^2}{|V_{cd}|^2} \text{ using } \frac{\mathcal{B}(D \to K\mu\nu)}{\mathcal{B}(D \to \pi\mu\nu)}$$

Expecting ~4 M $D \to K\mu\nu$ events in Run1

- Analogous to measurement of $|V_{ub}|$ from $\Lambda_b \to p\mu\nu$ (Nature Physics 10 (2015) 1038)
- Experimental advantages:
  - Use $D^{*+} \to D^0\pi_s^+ \to$ gives access to Δm for background rejection, q^2 constraint
  - μ, π_s detection efficiencies cancel in ratio
  - K, π detection efficiencies known well from CP measurements
  - μ easily detectable
  - Use M_{corr} to reduce multibody/neutral backgrounds
- The hard parts
  - Trigger on the inclusive D event $\to$ possible biases vs q^2 depending on data-taking conditions
  - MC statistics will be a limiting factor
  - $f_+^K(q^2), f_+^\pi(q^2)$ knowledge will play a large role in the extraction

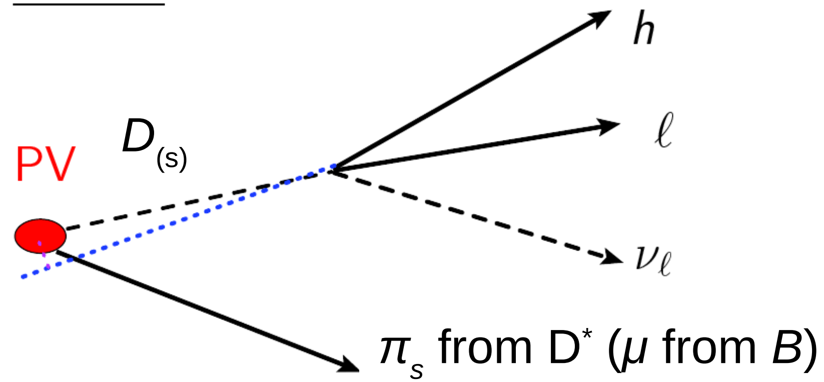
Estimation on the relative systematic uncertainty: **0.2%**
Comparable to the world average!

SL opportunities @ LHCb

D^0		D^+		D_s	
$D^0 \to \pi\mu\nu$	$(\mathcal{B} = 0.238 \pm 0.024\%)$	$D^+ \to K\pi\mu\nu$	$(\mathcal{B} = 3.9 \pm 0.4\%)$	$D_s^+ \to \phi\mu\nu$	$(\mathcal{B} =\sim 2\%)$
$D^0 \to K\mu\nu$	$(\mathcal{B} = 3.3 \pm 0.13\%)$	$D^+ \to K^0\mu\nu$	$(\mathcal{B} = 9.3 \pm 0.7\%)$	$D_s^+ \to K^0\mu\nu$	$(\mathcal{B} =\sim 0.3\%)$
$D^0 \to K^*(892)^-\mu\nu$	$(\mathcal{B} = 1.92 \pm 0.25\%)$	$D^+ \to K^{*0}\mu\nu$	$(\mathcal{B} = 5.3 \pm 0.15\%)$	$D_s^+ \to \eta^{(\prime)}\mu\nu$	$(\mathcal{B} =\sim 3\%)$
		$D^+ \to \eta\mu\nu$	$(\mathcal{B} =\sim 1\%)$		

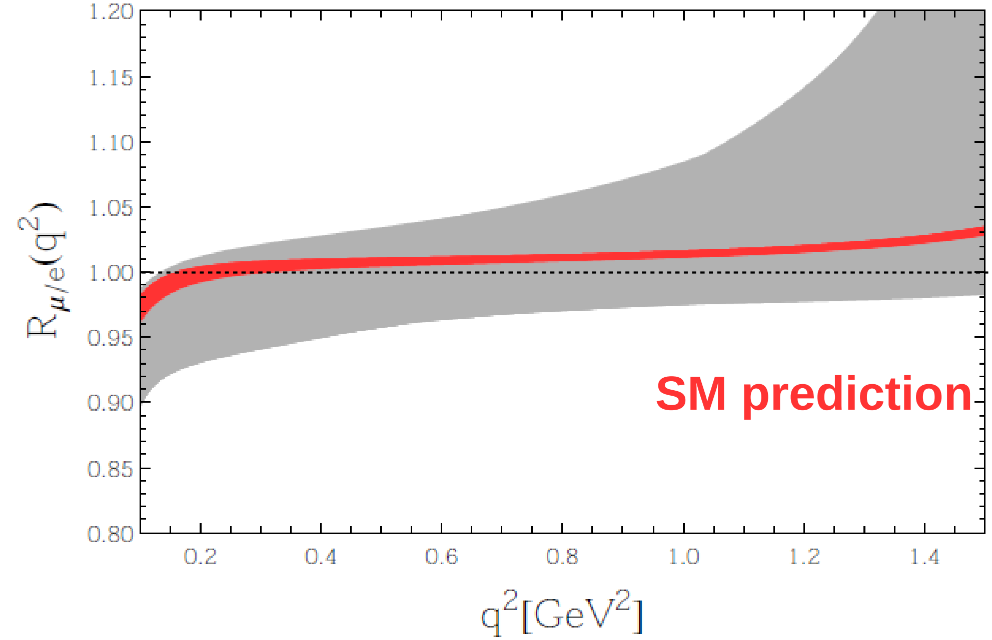
- Items in red are unlikely
- $D_{(s)}$ from D^* or B are possible
- A control channel is needed for each decay
- Λ_c will be more challenging due to its short lifetime ~0.5 $\tau(D^0)$

Prompt

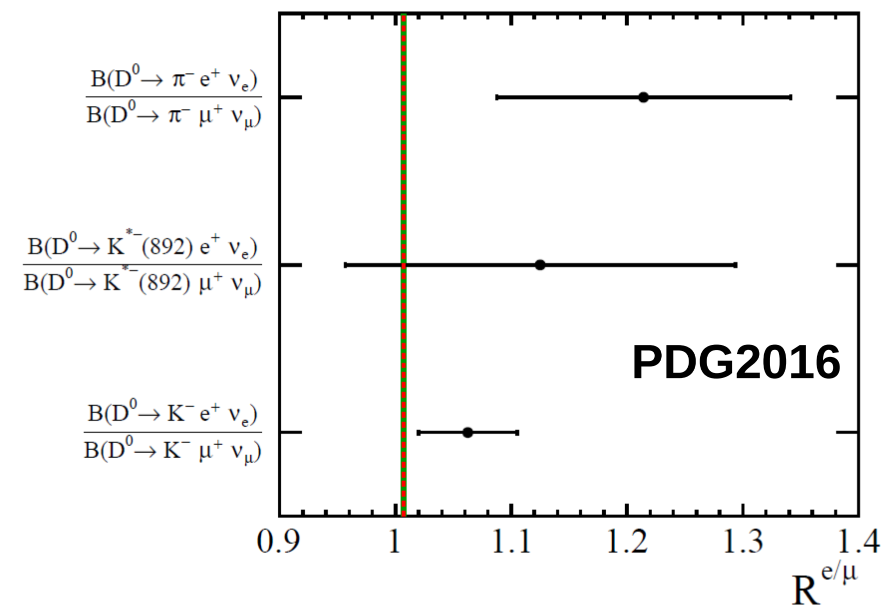


LU in SL D decays

arXiv:1502.07488



- Lepton universality a hot topic recently
- The decay ratio of D→Kμν to D→Keν could differ significantly from unity in the presence of NP
- Current PDG values for BFs of muon modes are rather inaccurate and hint μ/e ratios possibly below 1
- D→Keν is hard, but not impossible @ LHCb



Summary

- LHCb is more than a B factory, with a lot of charm opportunities
- Huge statistics is a blessing for rare charm decays
- First observations on a number of dimuon charm decays
- World's best upper limits on dimuon and LFV charm decays
- Ongoing work on charm SL decays
- More to come for LHCb in Run2 & upgrade, including NP searches in rare charm decays