Searches for rare charm decays at LHCb

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on behalf of the LHCb collaboration

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The 9th International Workshop on Charm Physics
Novosibirsk
25 May 2018

GEFÖRDERT VOM

Bundesministerium
für Bildung
und Forschung

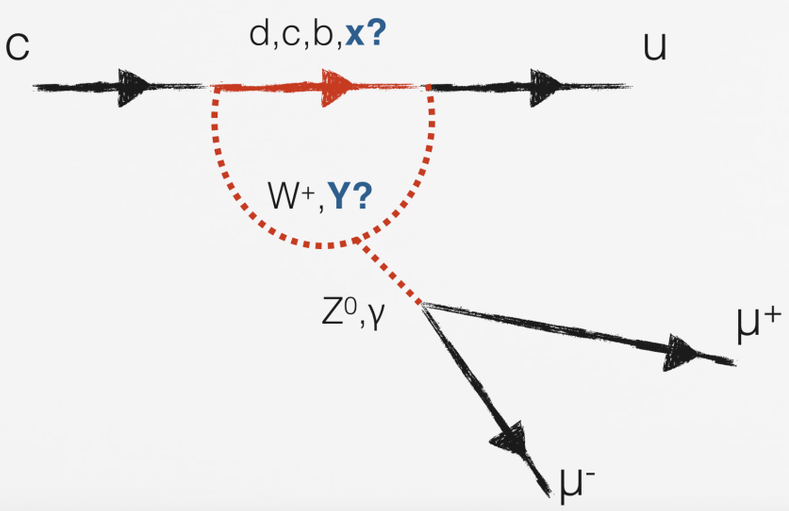
Why rare charm decays?

It is very promising…

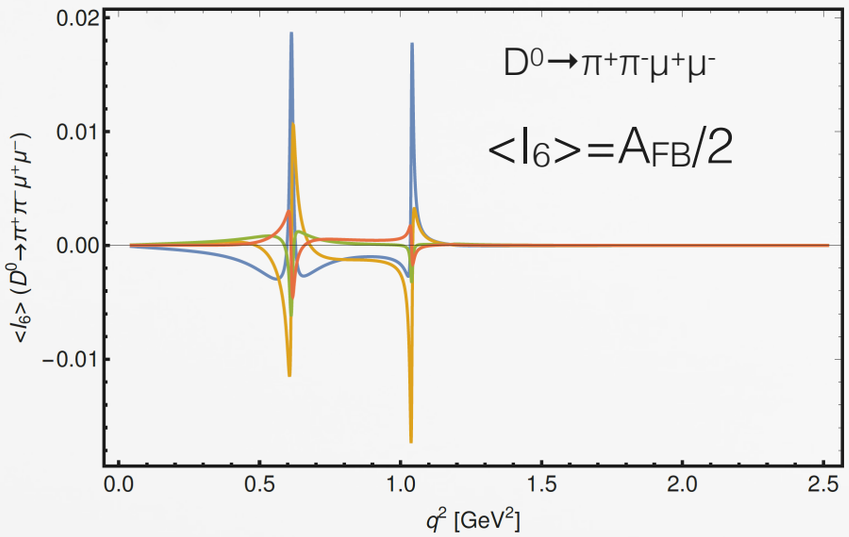
- rare charm decays involve FCNC c→u transitions (short distance)
  - in SM only at loop level
- some NP models predict large enhancement in rates and asymmetries [PRD 83 114006 (2011)] [arXiv:1805.08516]
- one of few occasions to investigate up-type quark FCNCs

…but also very challenging!

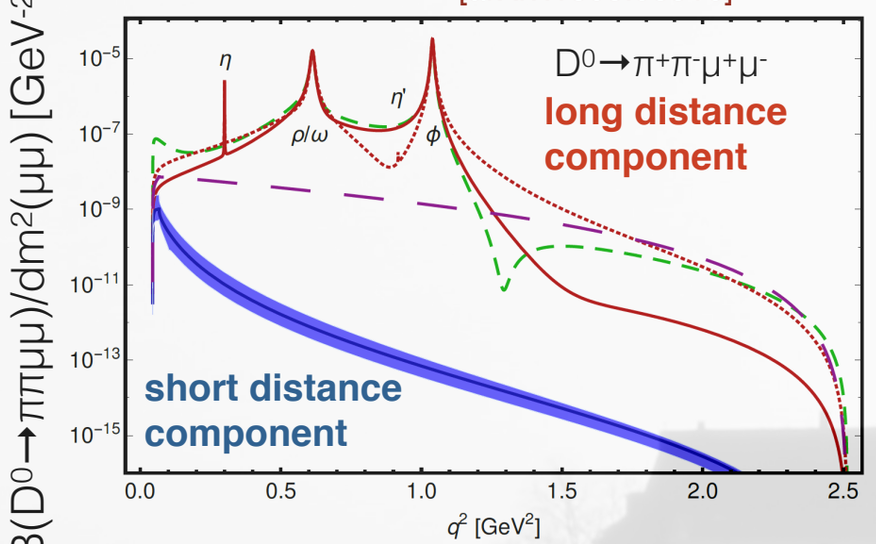
- SM short-distance contribution highly CKM & GIM suppressed
  - inclusive SM $D \to X\mu^+\mu^-$ $\lesssim O(10^{-9})$
- processes dominated by long distance (tree-level) dynamics, shielding the FCNC processes
- theoretical description very hard



[arXiv:1805.08516]



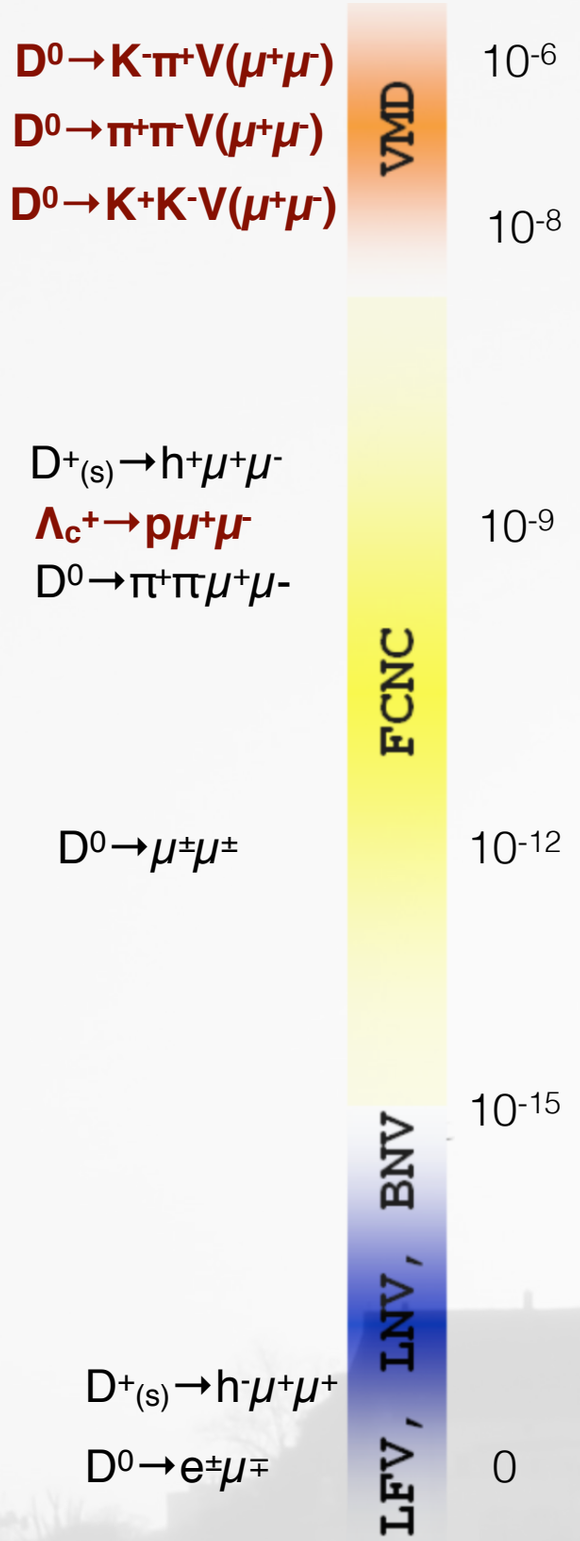
[arXiv:1805.08516]



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)] NEW
  - search for $D^0 \to \pi^+\pi^-\mu^+\mu^-$ [PLB 728 234-243 (2014)] NEW
  - 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 $D^0 \to h^+h^-\mu^+\mu^-$ [LHCb-PAPER-2018-020] in preparation BRAND NEW
  - lepton-universality [→future]



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

Phys. Rev. D 97, 091101 (2018)

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

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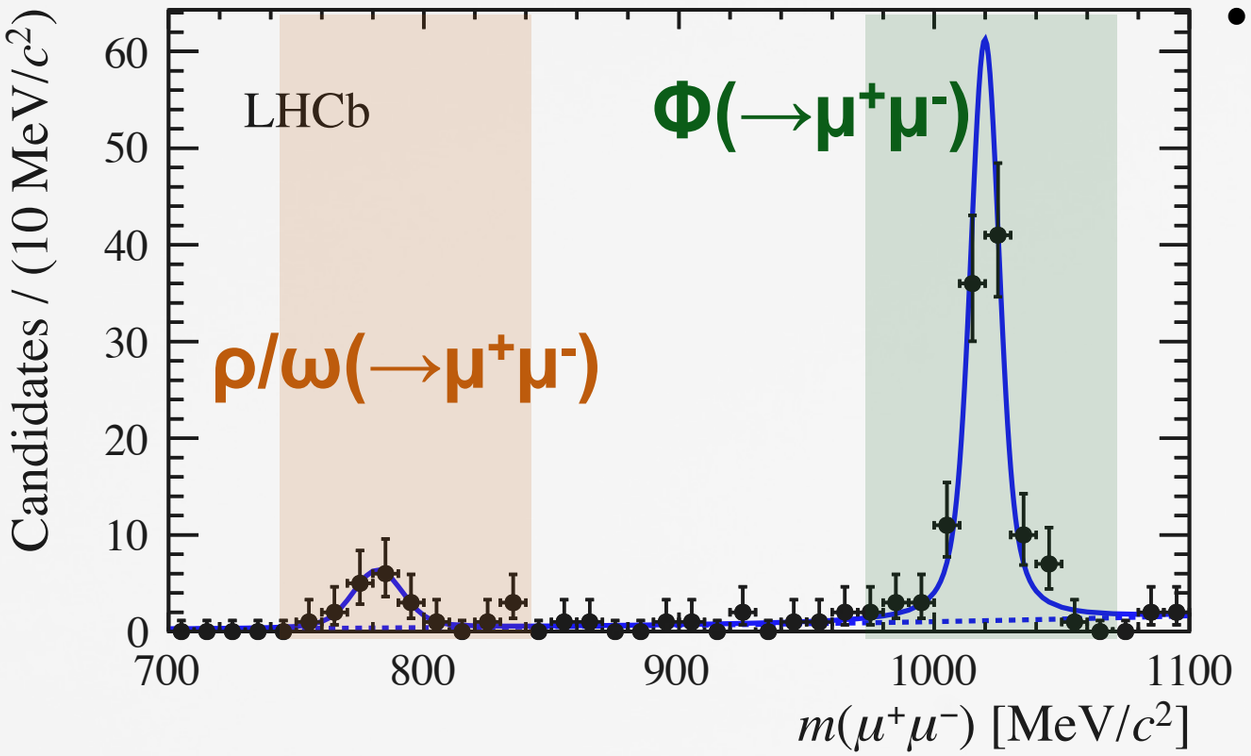


- first measurement of rare decays of charmed baryons at LHCb
  - total BF dominated by resonant **LD** contributions:
    - $\Lambda_c \to p\Phi(\to \mu^+\mu^-)$
    - $\Lambda_c \to p\rho/\omega(\to \mu^+\mu^-)$
- sensitivity to **SD** physics away from resonances in dimuon mass

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 $\Lambda_c \to p\mu^+\mu^-$

Phys. Rev. D 97, 091101 (2018)

- upper limit on non-resonant component

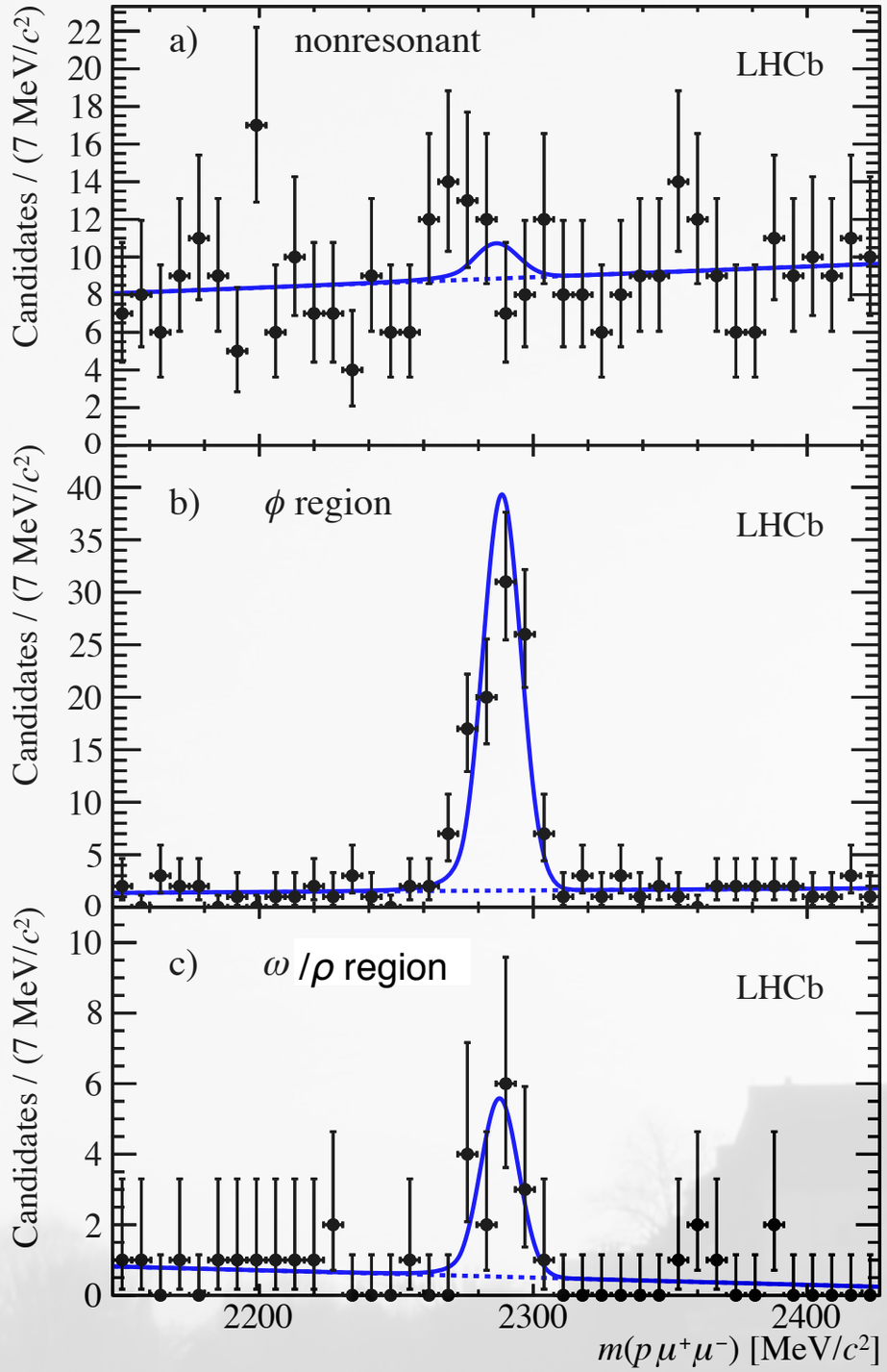
$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 9.6 \times 10^{-8} \text{ at } 95\% \text{ CL}$$

  - ~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



First observation of the decay $D^0 \to K^-\pi^+\mu^+\mu^-$ in the ρ^0–ω region of the dimuon mass spectrum

PLB 757 558-567 (2016)

Observation of the decay $D^0 \to K^-\pi^+\mu^+\mu^-$

PLB 757 558-567 (2016)

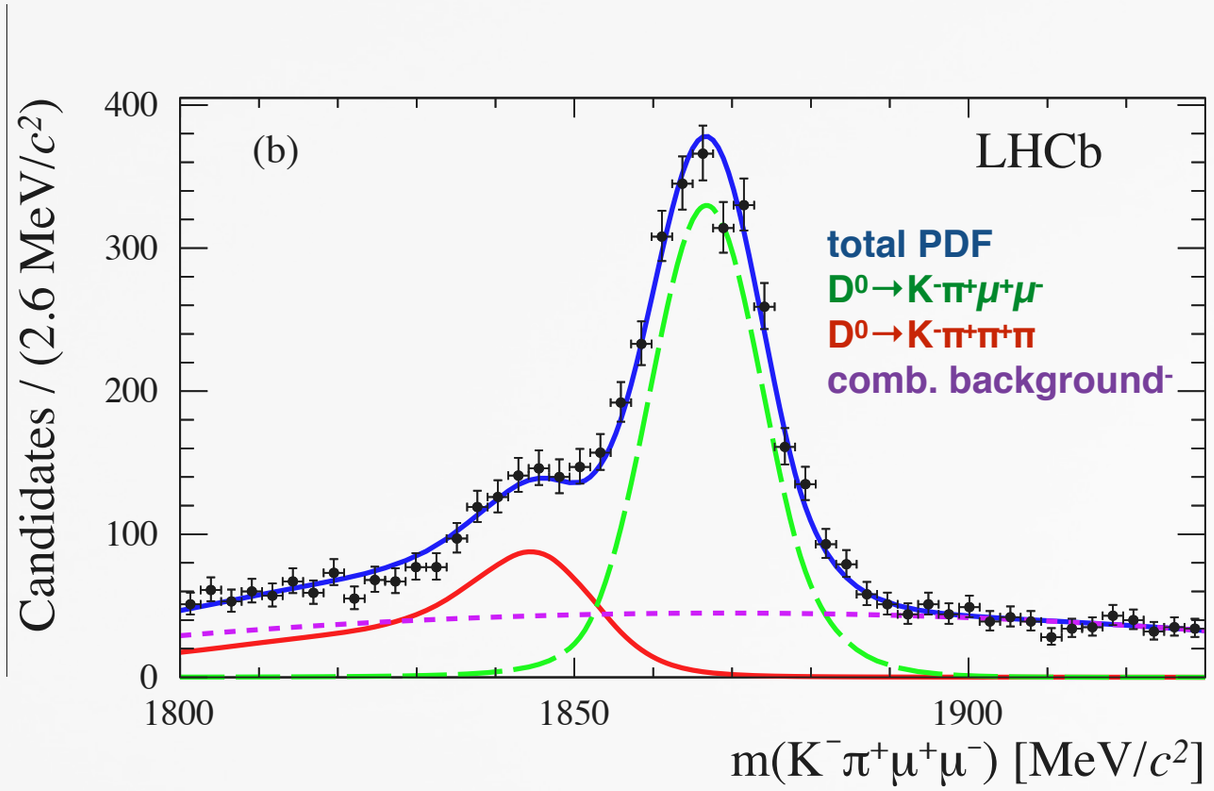
- $m(\mu^+\mu^-) \in$ [675-875] MeV/c^2 consistent with muons coming from ρ^0/ω resonance
- tree level dominated, still a rare decay and perfect normalization mode for $D^0 \to h^+h^-\mu^+\mu^-$
- most stringent limit so far: E791

$$\mathcal{B}(D^0 \to K^-\pi^+\mu^+\mu^-) < 3.6 \times 10^{-5} \text{ at } 90\% \text{ CL}$$

[PRL 86 (2001) 3969]

LHCb analysis details

- data: 2/fb from 2012
- prompt D^0 (primary pp interaction)
- normalization channel $D^0 \to K^-\pi^+\pi^+\pi^-$



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

[PLB 757 558-567 (2016)]

First observation! compatible with SM predictions

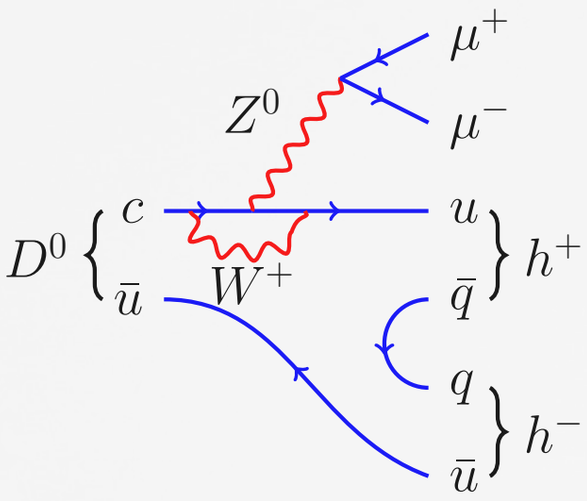
[JHEP 04 135 (2013)]

Observation of D^0 meson decays into $\pi^+\pi^-\mu^+\mu^-$ and $K^+K^-\mu^+\mu^-$ final states

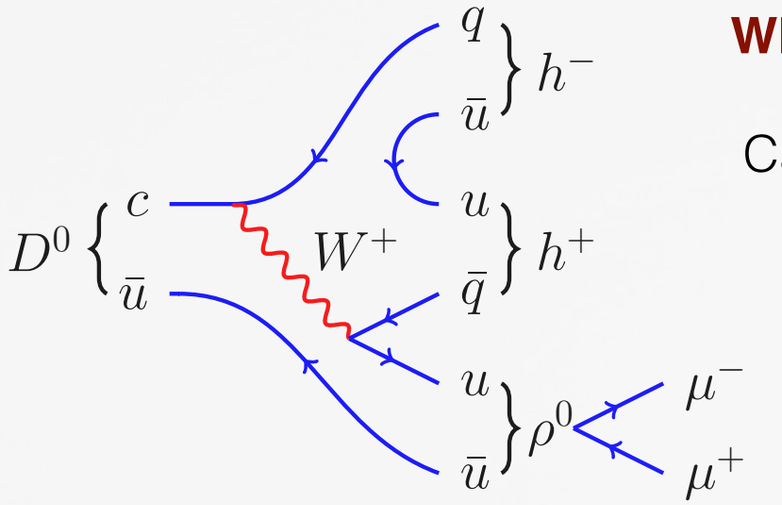
PRL 119 181805 (2017)

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

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



example **short-distance** contribution
EW Penguin



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

Why another channel?

Cappiello et al. about $D^0 \to h^+h^-\mu^+\mu^-$ decays:

"In a nutshell, the penalty of small branching fractions (…) is overly compensated by the diversity (and the size) of the asymmetries one can build."

[JHEP 04 135 (2013)]

- **First step:** BF measurement binned in dimuon mass [PRL 119 181805 (2017)]
  - (usual limited) sensitivity to **SD** contribution in regions away from resonances

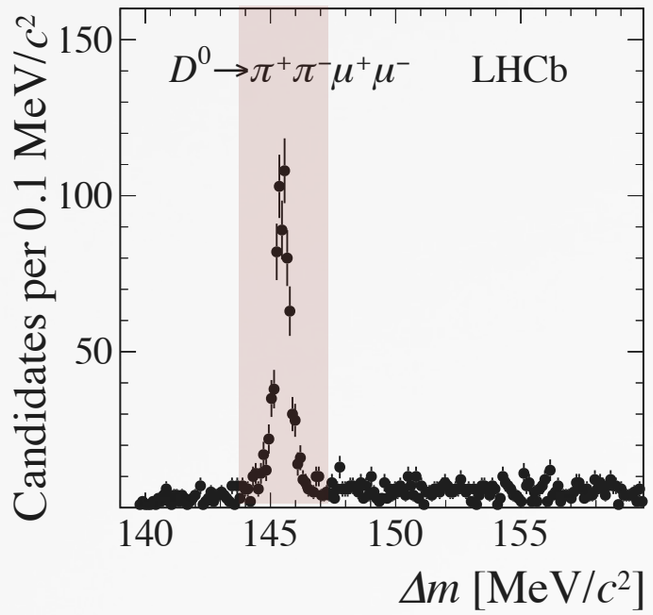
- **NEW:** measure asymmetries with sensitivity to **SD** in full range [LHCb-PAPER-2018-020](in preparation)
  - O(few%) predictions for some NP models [JHEP 1304 135 (2013), PRD 87 054026 (2013)]

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

PRL 119 181805 (2017)

Experimental details

- data: 2/fb from 2012
- normalization channel: $D^0 \to K^-\pi^+\mu^+\mu^-$
- D^0 from $D^{*+} \to D^0\pi^+$ decays
  - efficient suppression of combinatorial background



Dimuon mass binning scheme

bin	low mass	η	ρ/ω	ϕ	high mass
$m(\mu^+\mu^-)[MeV/c^2]$	< 525	$525 - 565$	$565 - 950$	$950 - 1100$	> 1100
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	✓	✓	✓	✓	✓
$D^0 \to K^+K^-\mu^+\mu^-$	✓	✓	✓		

*remark: low and high mass bins also affected by tails of resonances

Measurement strategy

- BF measurement in $m(\mu^+\mu^-)$ bins if local signal significance > 3σ
- upper limit on signal BF if local significance <3σ

- quote total BF of the decays

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

PRL 119 181805 (2017)

Computation of the signal branching fraction

- in the ratio, cancellation of production cross section, luminosity, many systematic effects

$$\mathcal{B}(D^0 \to h^+h^-\mu^+\mu^-) = \frac{N(D^0 \to h^+h^-\mu^+\mu^-)}{N(D^0 \to K^-\pi^+\mu^+\mu^-)} \cdot \frac{\epsilon(D^0 \to K^-\pi^+\mu^+\mu^-)}{\epsilon(D^0 \to h^+h^-\mu^+\mu^-)} \cdot \mathcal{B}(D^0 \to K^-\pi^+\mu^+\mu^-)$$

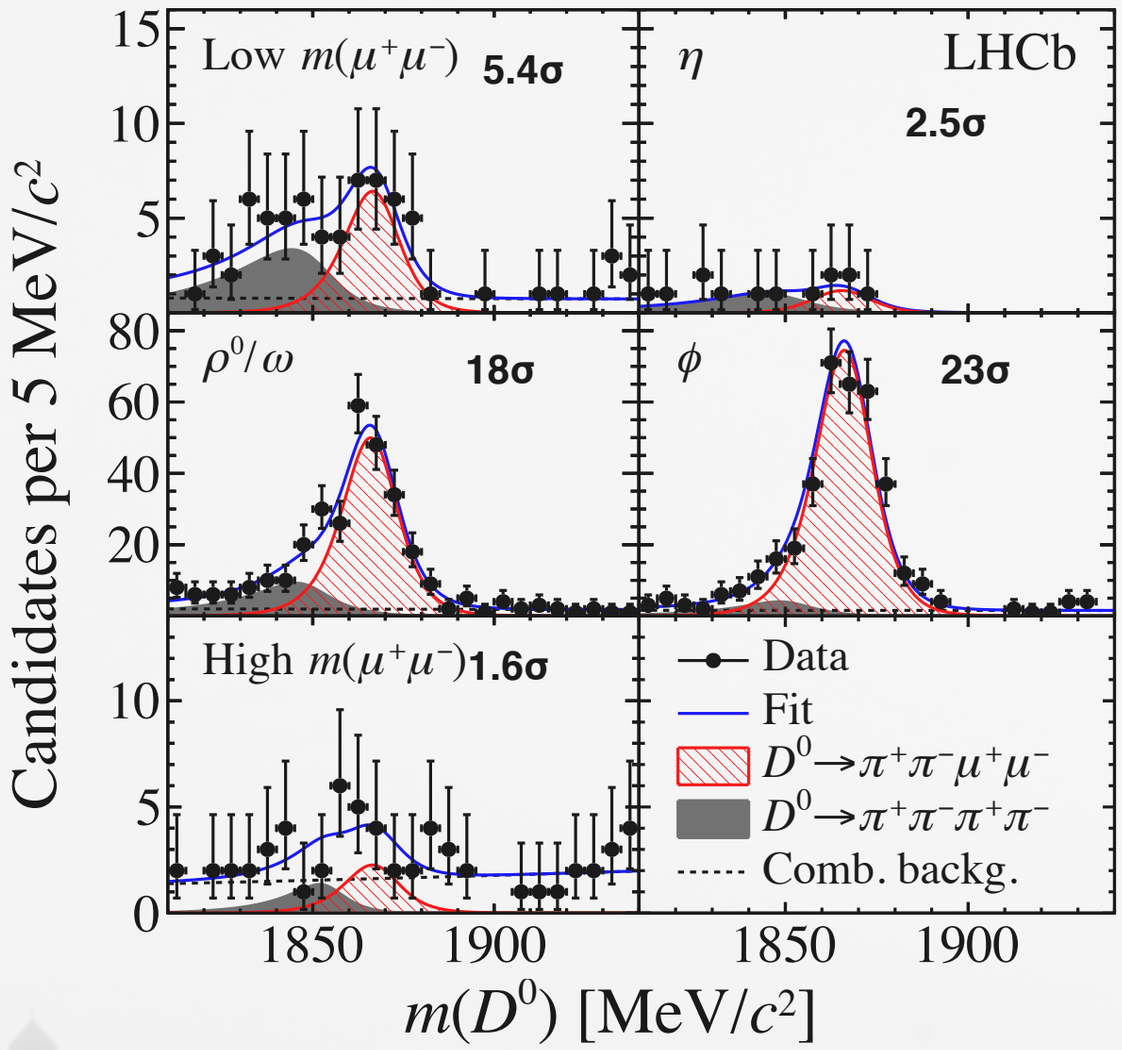
- **ratio of signal yields**
  - signal yield determination through maximum likelihood fits to D^0 mass
- **ratio of efficiencies**
  - mainly from simulations
    - unknown decay model dominant systematic uncertainty
  - data driven methods for trigger and PID efficiency
- **normalization mode BF**
  - from an independent measurement [PLB 757 558-567 (2016)]

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

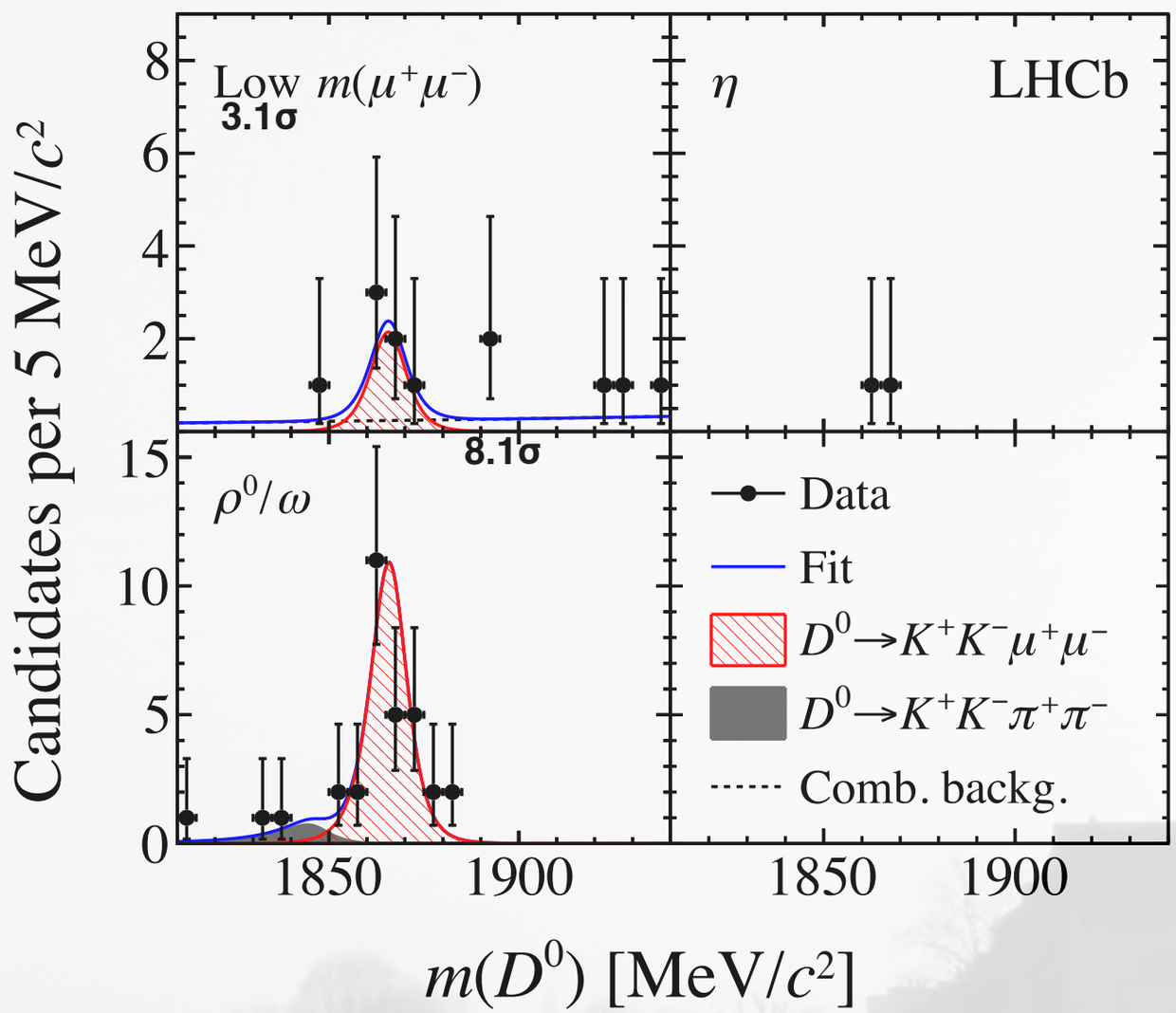
PRL 119 181805 (2017)

Mass fits signal modes

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



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



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

PRL 119 181805 (2017)

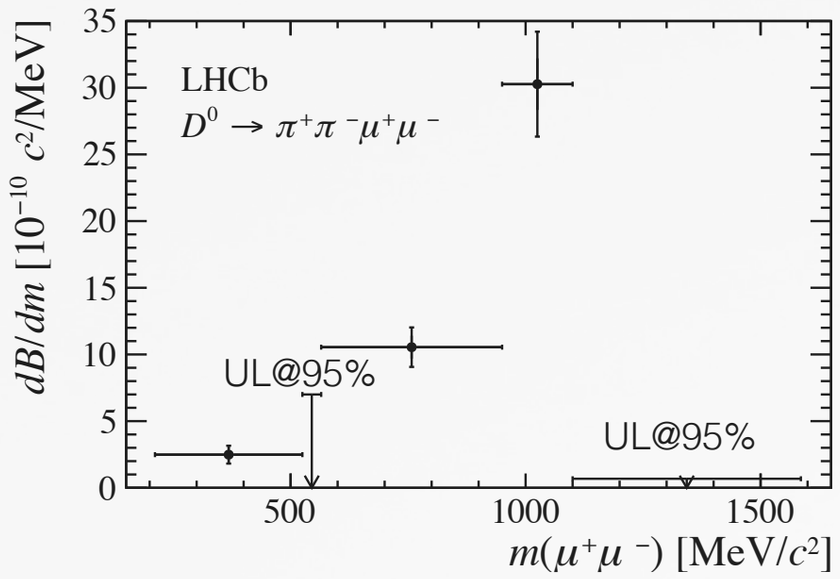
Binned measurement

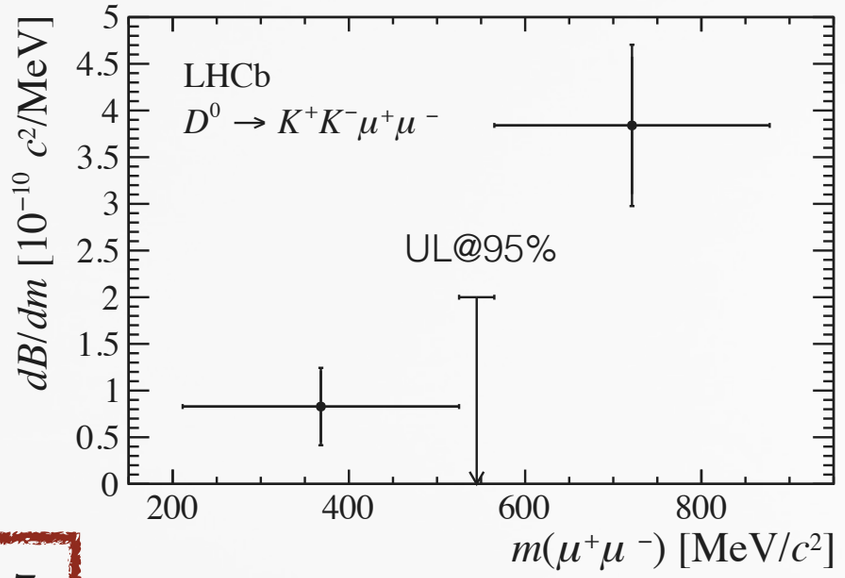
$D^0 \to \pi^+\pi^-\mu^+\mu^-$

$\mu^+\mu^-$ 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	$12.0 \pm 2.3 \pm 0.7 \pm 1.2$





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)]

Angular and CP asymmetries in $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$ decays

[LHCb-PAPER-2018-020]
in preparation

First time shown at this conference

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

[LHCb-PAPER-2018-020]

- 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)
D 93, 074001 (2016)
[arXiv:1805.08516]

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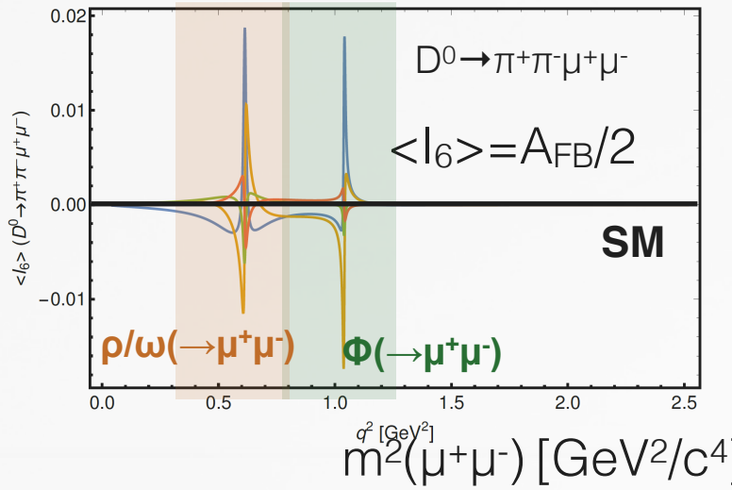
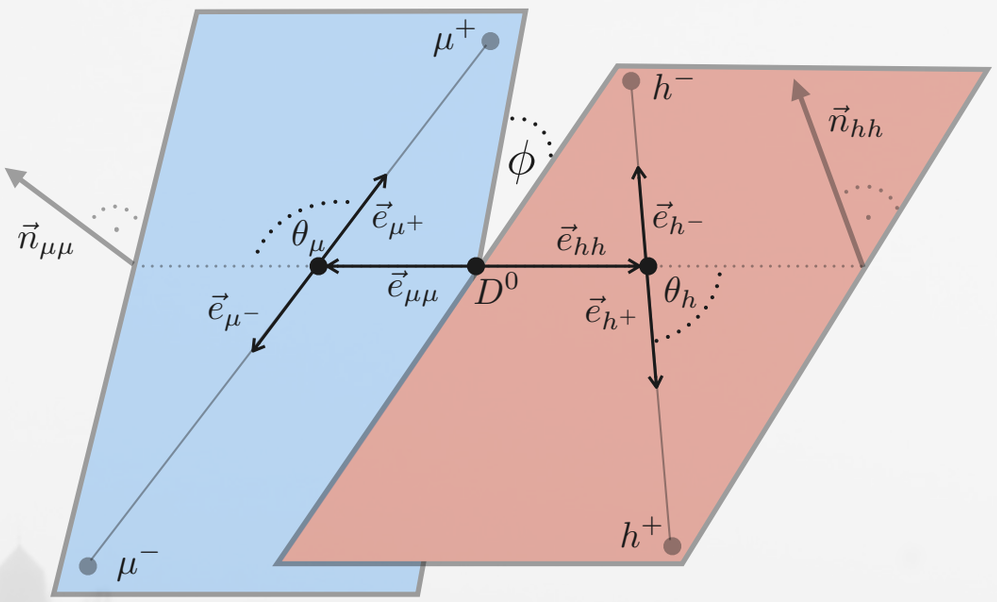




- angular asymmetries
  - forward backward asymmetry

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

  - triple product asymmetry

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

- CP asymmetry

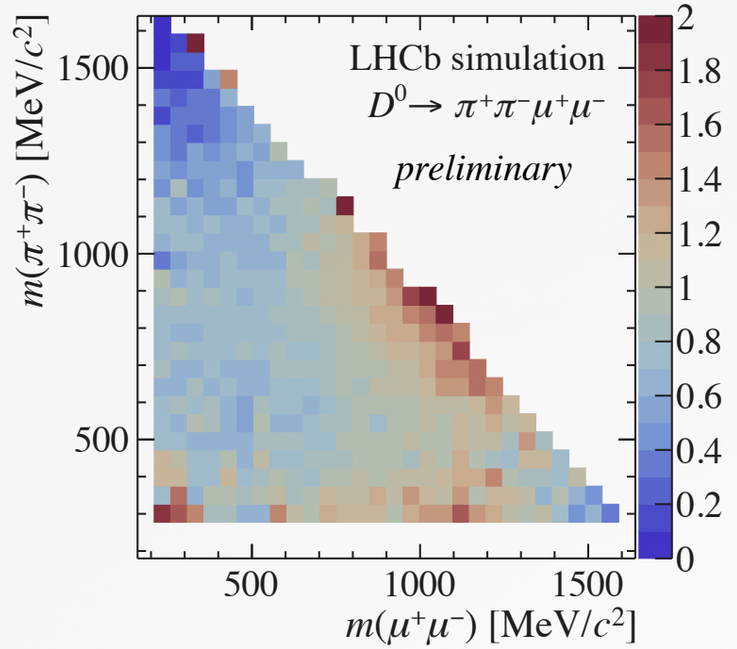
$$A_{CP} = \frac{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) - \Gamma(\overline{D}^0 \to h^+h^-\mu^+\mu^-)}{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) + \Gamma(\overline{D}^0 \to h^+h^-\mu^+\mu^-)}$$

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

[LHCb-PAPER-2018-020]

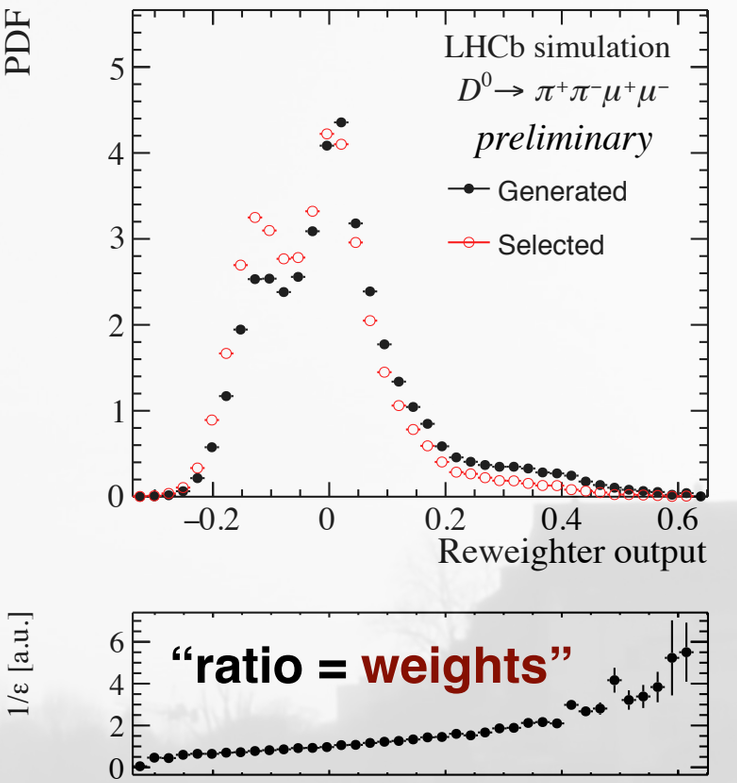
Experimental details

- select D^0 from flavour sepecific $D^{*+} \to D^0\pi^+$ decays
- increased data statistics: 5/fb recorded 2011-2016



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



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

[LHCb-PAPER-2018-020]

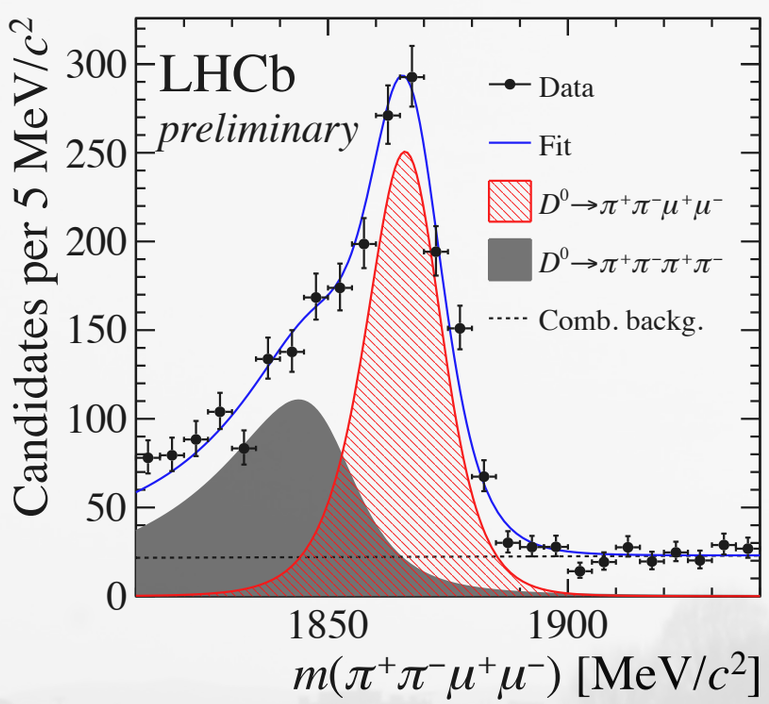
Measurement strategy

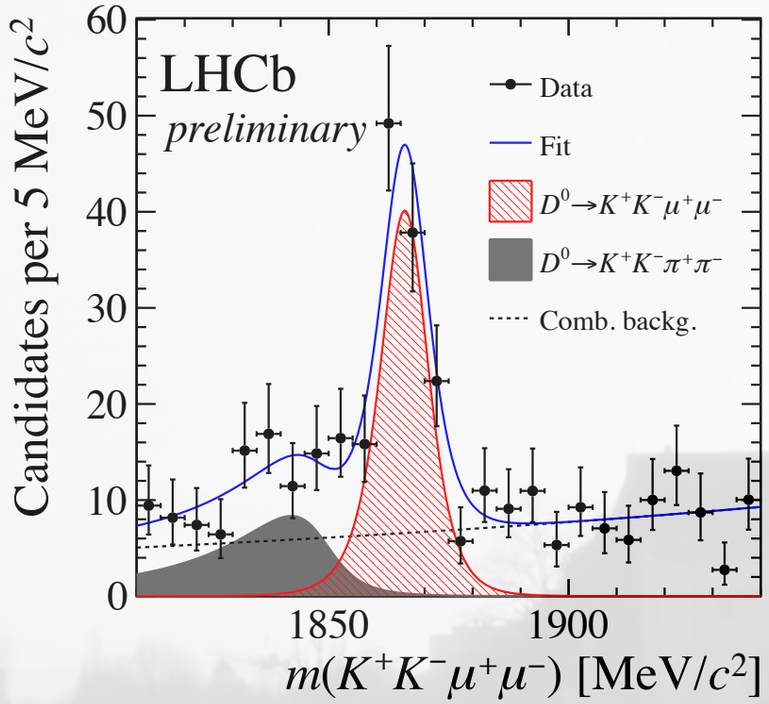
- measure A_{FB}, A_Φ and A_{CP} binned and integrated in dimuon mass
  - quote results where significant signal was observed in BF measurement
  - split bins at resonance peak positions (for $D^0 \to \pi^+\pi^-\mu^+\mu^-$)

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

- total yields
  - $D^0 \to \pi^+\pi^-\mu^+\mu^-$: 1.1k
  - $D^0 \to K^+K^-\mu^+\mu^-$: 110

- sensitivity on asymmetries of a few % already now!





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

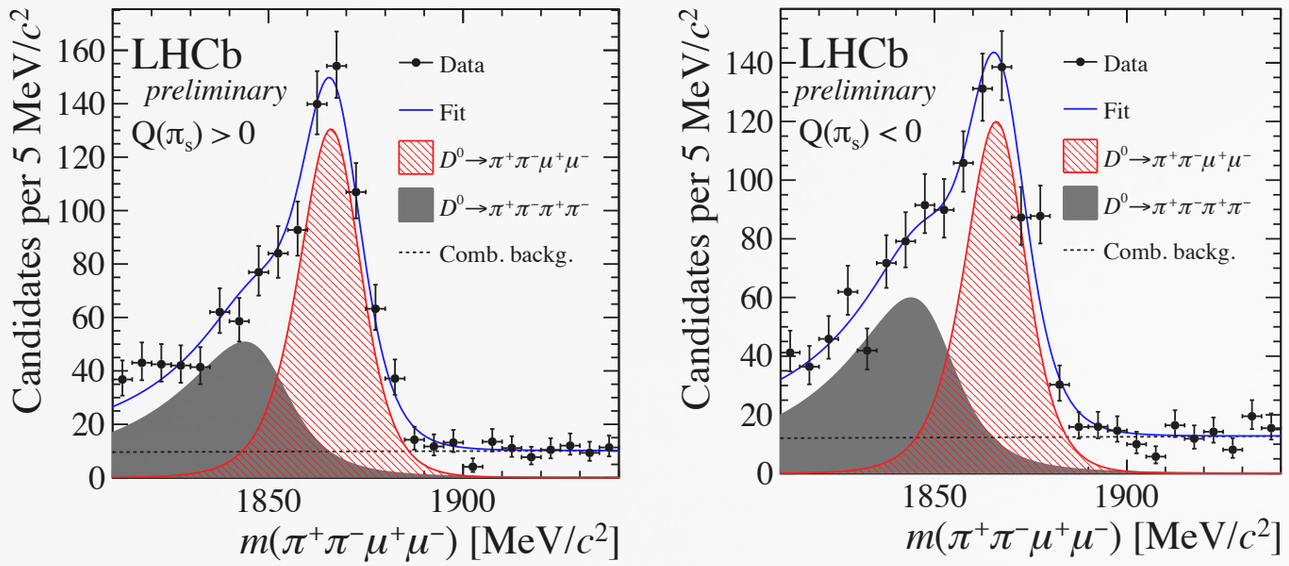
[LHCb-PAPER-2018-020]

Determination of the asymmetries

- split data set according to *tag*

A_{FB}	A_Φ	A_{CP}
$\cos(\theta_\mu) > 0$	$\sin(2\Phi)>0$	$Q(\pi^+) < 0$
$\cos(\theta_\mu) < 0$	$\sin(2\Phi)<0$	$Q(\pi^+) > 0$

- perform simultaneous fit to efficiency corrected m(D^0) with asymmetry as shared parameter



- use control samples of $D^{+*} \to D^0(\to K^+K^-)\pi_s^+$ decays to correct for production and charge dependent detection asymmetries

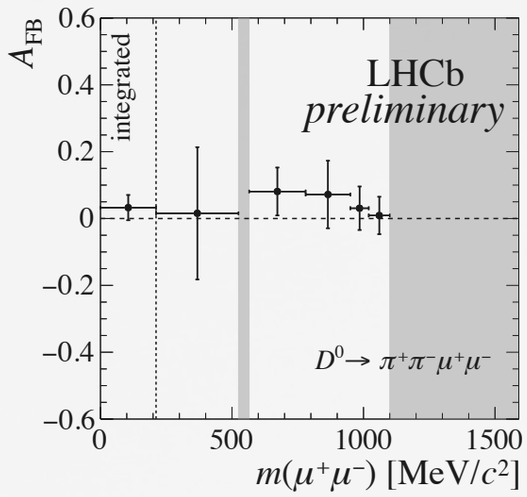
$$A_{CP}^{\text{raw}}(f) = \frac{N[D^{*+} \to D^0(\to f)\pi^+] - N[D^{*-} \to \overline{D}^0(\to f)\pi^-]}{N[D^{*+} \to D^0(\to f)\pi^+] + N[D^{*-} \to \overline{D}^0(\to f)\pi^-]} \approx A_{CP}(f) + A_d(\pi^+) + A_P(D^{*+})$$

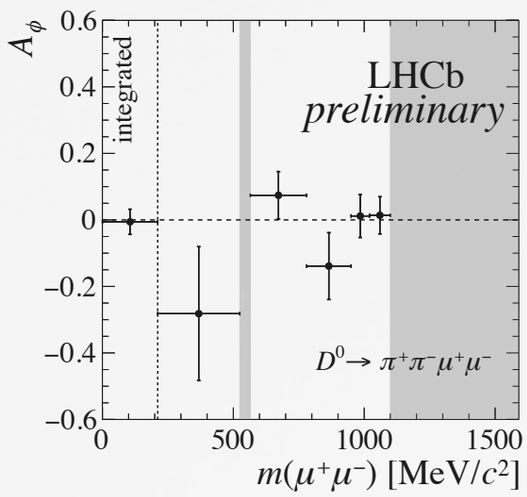
$$A_{CP}(h^+h^-\mu^+\mu^-) = A_{CP}^{\text{raw}}(h^+h^-\mu^+\mu^-) - A_{CP}^{\text{raw}}(K^+K^-) + A_{CP}(K^+K^-)$$

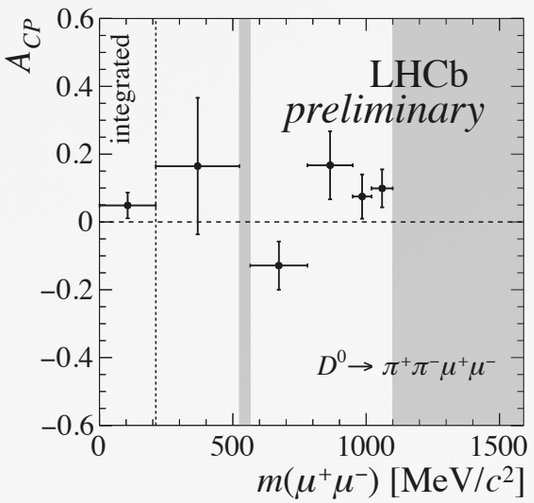
JHEP 07 041 (2014)

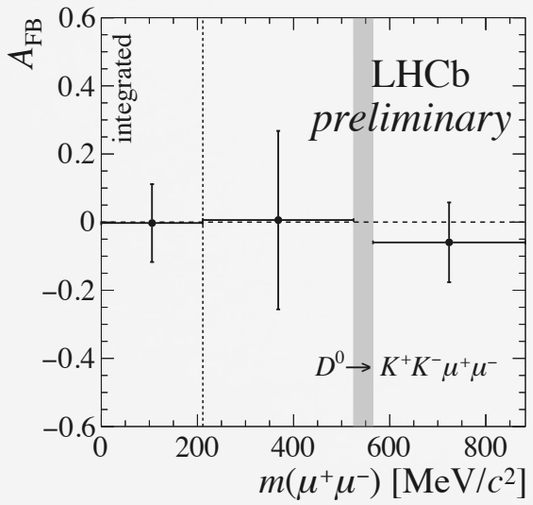
Asymmetries in $D^0 \to \pi^+\pi^-(K^+K^-)\mu^+\mu^-$

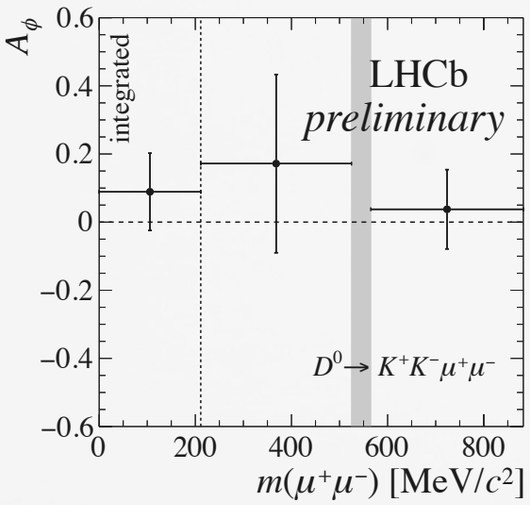
[LHCb-PAPER-2018-020]

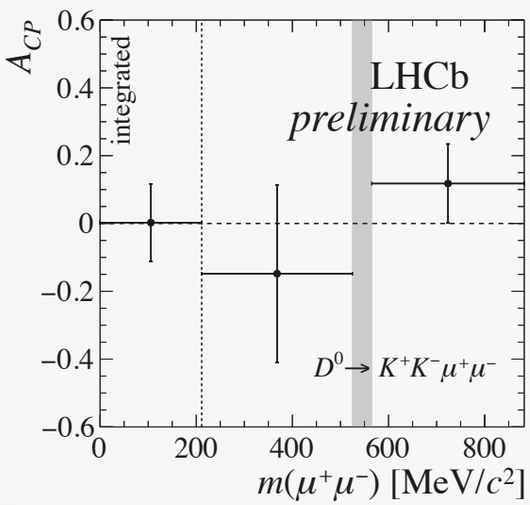












Total asymmetries

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

- uncertainties are statistical and systematic

- all asymmetries consistent with zero
- no dependency on dimuon mass observed

compatible with SM predictions
[JHEP 04 135 (2013)]

Conclusions

- the low SM rates make the field a perfect place to look for physics beyond the SM
    - for many decays 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 for Run 1 and Run 2 data

Mode	Run 2 ($9fb^{-1}$)	upgrade ($50fb^{-1}$)
$D^+ \to \pi^+\mu^+\mu^-$	0.5% (40k events)	0.2% (200k events)
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	2% (3.6k events)	1.0% (18.5k events)
$D^0 \to K^+K^-\mu^+\mu^-$	7% (380 events)	3% (1900 events)

Stay tuned!

Thank you

Search for the lepton-flavour violating decay $D^0 \rightarrow e^{\pm}\mu^{\mp}$

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Search for LFV decay $D^0 \to e^{\pm}\mu^{\mp}$

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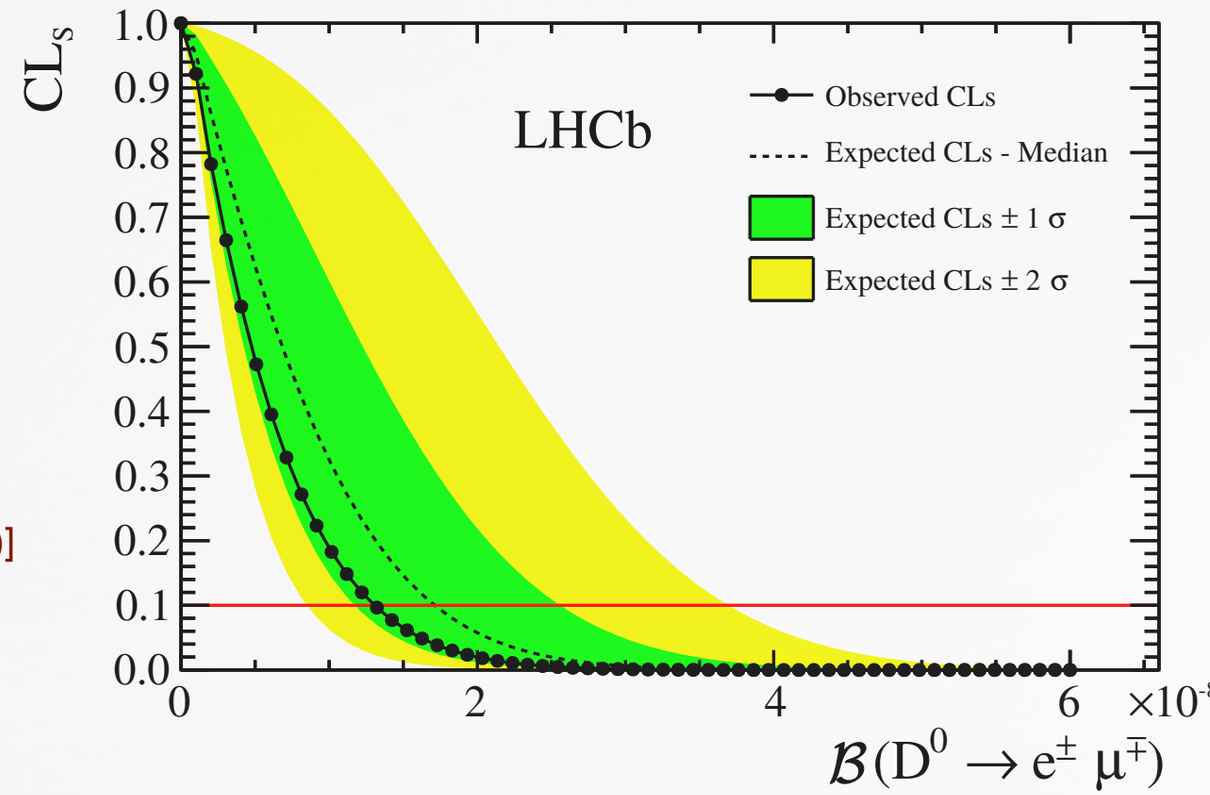
- strictly forbidden in the SM
  - SM extensions: rates in [10^{-14}-10^{-6}]

    [PRD 66 (2002) 014009]
  - any signal clear indication of NP
  - most stringent limit so far: Belle

    $\mathcal{B}(D^0 \to e^{\pm}\mu^{\mp}) < 2.6 \times 10^{-6}$ at 90% CL

    [PRD 81(2010) 091102(R)]



LHCb analysis details

- full Run 1 data (3/fb)
- D^0 from $D^{*+} \to D^0\pi^+$ decays
- measurement relative to normalization decay $D^0 \to K^-\pi^+$

$$\mathcal{B}(D^0 \to e^{\pm}\mu^{\mp}) < 1.3 \times 10^{-8} \text{ at } 90\% \text{ CL}$$

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world's best limit!

Search for the rare decay $D^0 \rightarrow \mu^{\pm}\mu^{\mp}$

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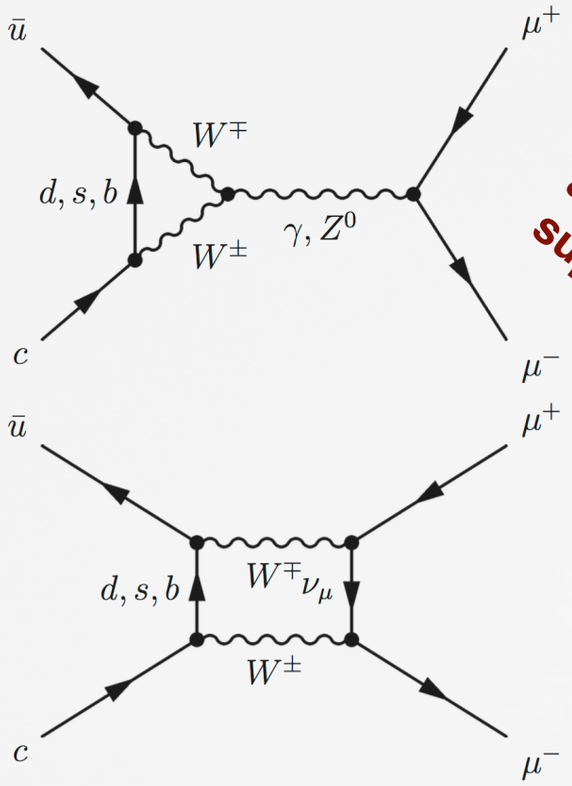
Search for the rare decay $D^0 \to \mu^\pm\mu^\mp$

PLB 725 (2013) 15-24



additional helicity suppression!

- very clean experimental and theoretical signature
- SM BF dominated by two-photon intermediate state ~O(10^{-13})
  - **SD** contribution ~O(10^{-19})

[Phys.Rev.D66:014009,2002
Phys.Rev.D79:114030,2009
Phys.Rev.D82:094006,2010
arxiv:1409.0181
Phys. Rev. D 93, 074001 (2016)
arXiv:1510.00965]

- in NP scenarios $BF_{NP} \lesssim BF_{EXP}$
- best limit so far: Belle

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 1.4 \times 10^{-7} \text{ at } 90\% \text{ CL}$$

[PLB 725 (2013) 15-24]

LHCb analysis details

- 1/fb recorded 2011
- D^0 from $D^{*+} \to D^0\pi^+$ decays
- measurement relative to normalization decay $D^0 \to \pi^-\pi^+$

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

PLB 725 (2013) 15-24

world's best limit!

Asymmetries in NP models

https://agenda.infn.it/getFile.py/accesscontribId=60&sessionId=16&resId=0&materialId=slides&confId=13986

... within BSM models

model	A_{CP}	A_{FB}
Leptoquark models	$\gtrsim A_{CP}^{\mathrm{SM}}$	$\lesssim 8 \times 10^{-1}$
Little Higgs model	$\lesssim \mathcal{O}(10^{-3})$	$\lesssim \mathcal{O}(5 \times 10^{-3})$
Minimal SUSY SM	$\lesssim \mathcal{O}(10^{-3})$	$\lesssim \mathcal{O}(10^{-1})$
Up vector-like quark singlet	–	$\lesssim 10^{-3}$
Warped extra dimension	$\lesssim \mathcal{O}(10^{-2})$	$\lesssim \mathcal{O}(5 \times 10^{-2})$
Z' boson	–	~ 0
SM	$< \mathcal{O}(10^{-3})$	~ 0

[Fajfer et al: 9805461, 0106333, 0511048, 0610032, 0706.1133, 0810.4858, 1510.00965, Burdman et al: 0112235, Paul et al: 1101.6053, 1212.4849, Bigi et al: 1110.2862, Delaunay et al: 1207.0474, Cappiello et al: 1209.4235, Wang et al: 1409.0181, SdB et al: 1510.00311, Guo et al: 1703.08799, Sahoo et al: 1705.02251]