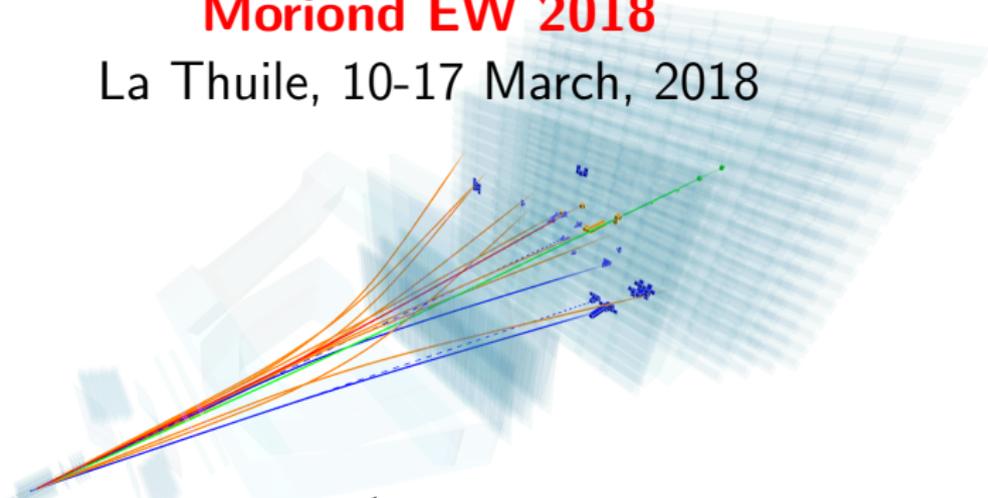# Very rare decays at LHC

Moriond EW 2018
La Thuile, 10-17 March, 2018

Maarten van Veghel[1] (Nikhef, the Netherlands)
on behalf of the ATLAS, CMS and LHCb[1] collaborations

Why look for very rare decays?

Rare decays

- Small Standard Model (SM) branching fractions $\rightarrow$ relatively large hypothetical **new physics** (NP) contributions
- Sensitive to higher energy than direct searches due to virtual contributions
- Often Flavour Changing Neutral Currents (FCNCs), which are not possible at tree level in SM
- **Anomalies** seen in $b \rightarrow s\ell^+\ell^-$ FCNCs
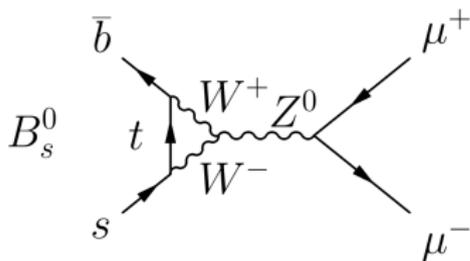 - See *e.g.* F. Dettori's and C. Langenbruch's talks for $b \rightarrow s\ell^+\ell^-$

Forbidden decays

- If you see SM forbidden decays, obviously new physics

Note: will only discuss a selection of recent results

# $B^0_{(s)} \rightarrow \mu^+\mu^-$: the flagship of very rare decays

Standard Model

- $b \rightarrow s\ell^+\ell^-$ and $b \rightarrow d\ell^+\ell^-$ like FCNC
- Both loop diagrams and helicity suppression, so **heavily suppressed**
  - In SM[a]: $\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) \approx 4 \times 10^{-9}$ and $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) \approx 1 \times 10^{-10}$
- **Theoretically clean** and experimentally favourable

New physics scenarios

- New particles in loops
- Sensitive to (pseudo)scalars (no helicity suppression)
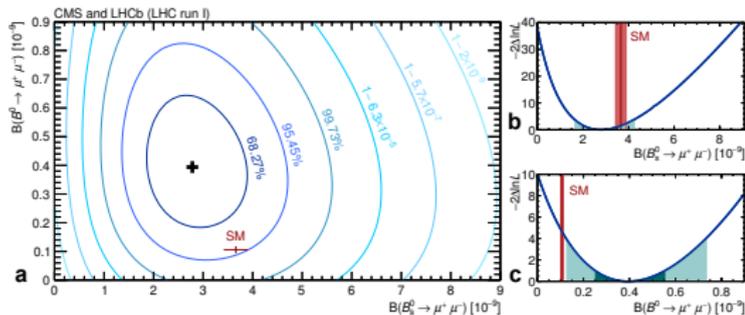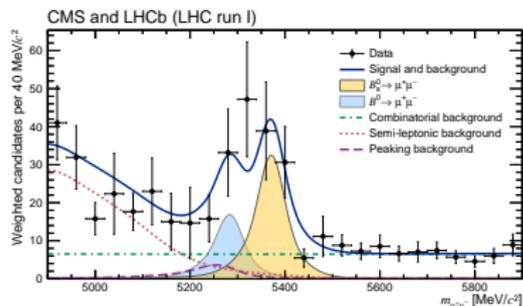- Specific: *e.g.* certain **SUSY** models, multiple Higgs models
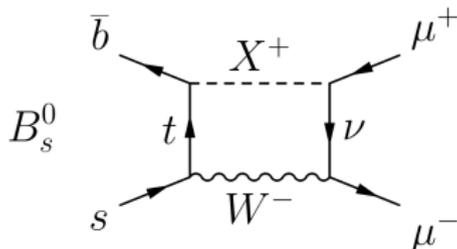
[a][Phys. Rev. Lett. 112, 101801 (2014)]

$B^0_{(s)} \to \mu^+\mu^-$: CMS+LHCb, [Nature 522, 68-72 (04 June 2015)]

- **First observation** of $B^0_s \to \mu^+\mu^-$ with CMS+LHCb **combined analysis** from full LHC Run 1 dataset published in 2015
- First evidence of $B^0 \to \mu^+\mu^-$ (slight enhancement from SM)
- Although **compatible** with SM

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$$
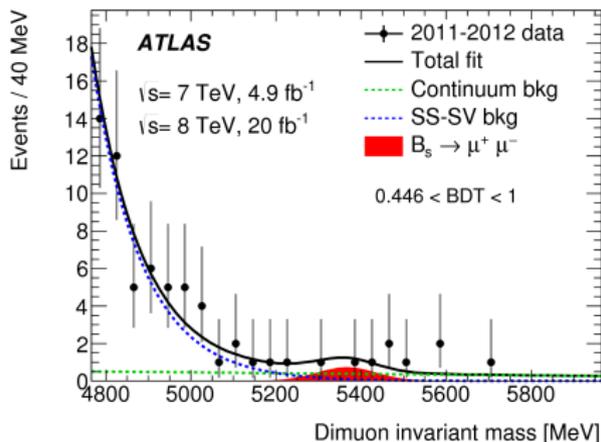
$B^0_{(s)} \to \mu^+\mu^-$: ATLAS, [Eur.Phys.J. C76 (2016) no.9, 513]

- Data from full Run 1 dataset
- No significant signal, but **consistent** with SM with 2.0σ
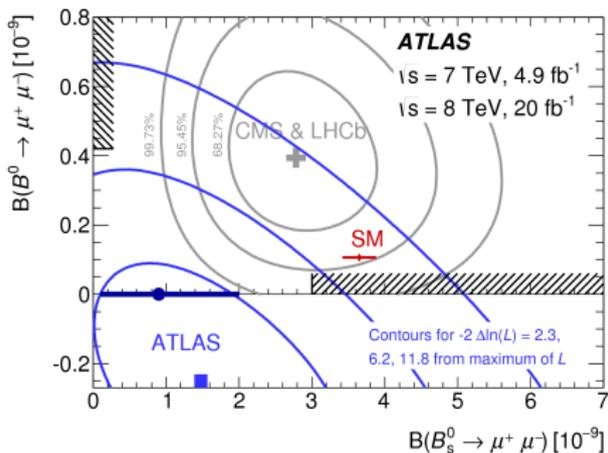- Result in **agreement** with CMS+LHCb results

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = 0.9^{+1.1}_{-0.8} \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10} \text{ [95\% CL]}$$

High BDT[1] region

Limits

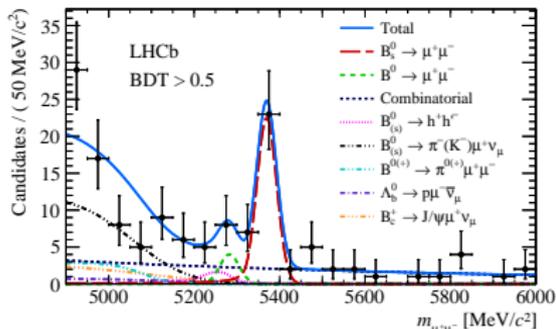[1][Multivariate classifier (Boosted Decision Tree)]

$B^0_{(s)} \to \mu^+\mu^-$: LHCb, update [Phys. Rev. Lett. 118, 191801 (2017)]

Updated $\mathcal{B}$ measurement

- Run 1 + part Run 2 (2015/2016; 1.4 fb^{-1}) data
- Improved BDT and $B \to h^+h^-$ rejection
- Result **compatible** with SM
- $B^0 \to \mu^+\mu^-$ fluctuated down

High BDT region
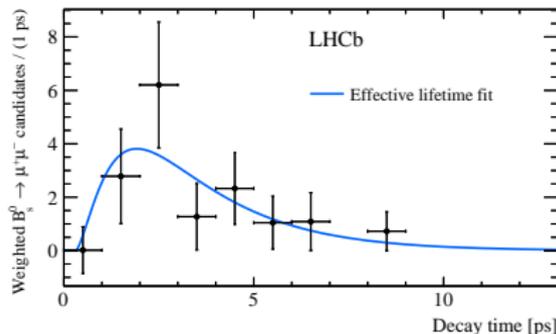

$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$

Effective lifetime measurement

- Possible **NP orthogonal to $\mathcal{B}$** contribution in effective lifetime
- Disentangle CP-odd versus CP-even contribution
- First measurement, as proof of principle, compatible with SM

Decay time distribution

$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}$ [95% CL]

$B^0_{(s)} \to \tau^+ \tau^-$

- **Lepton Flavour Universality tensions** hint to new physics with τ's
- Similar to $B^0_{(s)} \to \mu^+ \mu^-$, but **less helicity suppressed**
  - In SM[1]: $\mathcal{B}(B^0_s \to \tau^+ \tau^-) \approx 8 \times 10^{-7}$ and $\mathcal{B}(B^0 \to \tau^+ \tau^-) \approx 2 \times 10^{-8}$
- Experimentally much more **difficult**
  - Neutrinos in final state

Previous limit from BaBar [Phys. Rev. Lett. 96, 241802 (2006)]

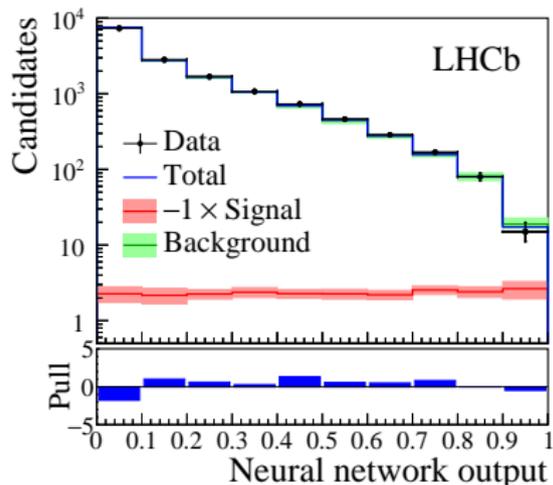$$\mathcal{B}(B^0 \to \tau^+ \tau^-) < 4.1 \times 10^{-3} \text{ [90\% CL]}$$

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[1][Phys. Rev. Lett. 112, 101801 (2014)]

$B^0_{(s)} \to \tau^+\tau^-$: LHCb,

Neural net for signal region

- Run 1 data
- τ reconstruction with $\tau^+ \to \pi^+\pi^-\pi^+\nu$
- No clear mass peak due to neutrinos, **fit neural net output**[a]
- Different Dalitz regions of τ decay and control decay channels to determine/verify neural net response

New best limits

$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3} \text{ [95\% CL]}$$
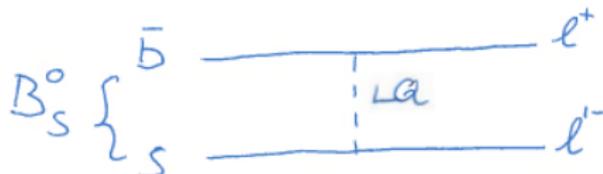$$\mathcal{B}(B^0_s \to \tau^+\tau^-) < 6.8 \times 10^{-3} \text{ [95\% CL]}$$

[a][Neural net used as multivariate classifier]

$B^0_{(s)} \to e^{\pm}\mu^{\mp}$: forbidden lepton flavour violating decays

Lepton flavour violation linked to lepton universality[2]

- SM has no charged lepton flavour violation
- For example **leptoquark** model could **explain** seen **tensions**
- Opens up possibilities for lepton flavour violation (like $B^0_{(s)} \to e^{\pm}\mu^{\mp}$)
- Previous limits for $B^0_{(s)} \to e^{\pm}\mu^{\mp}$ at about 10^{-8} to 10^{-9}

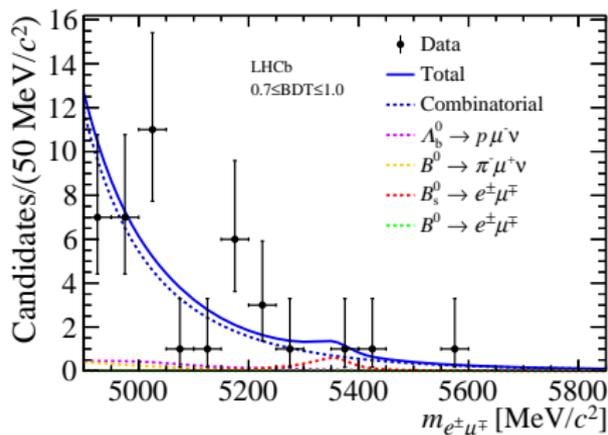$$B^0_s \to \ell'^{+}\ell^{-} \text{ (like } B^0_{(s)} \to e^{\pm}\mu^{\mp})$$

[2][Phys.Rev.Lett. 114 (2015) 091801]

$B_{(s)}^0 \to e^{\pm}\mu^{\mp}$: LHCb, [LHCb-PAPER-2017-031] (accepted by JHEP)

- Previous best limit set by LHCb with 2011 data [Phys.Rev.Lett. 111 (2013) 141801]
- **New limits** factor **2 to 3 improvement** on limit

High BDT region

Improvements

- Increased BDT performance
- Higher trigger efficiency
- Full Run 1 dataset

Limits

$\mathcal{B}(B^0 \to e^{\pm}\mu^{\mp}) < 1.3 \times 10^{-9}$ [95% CL]

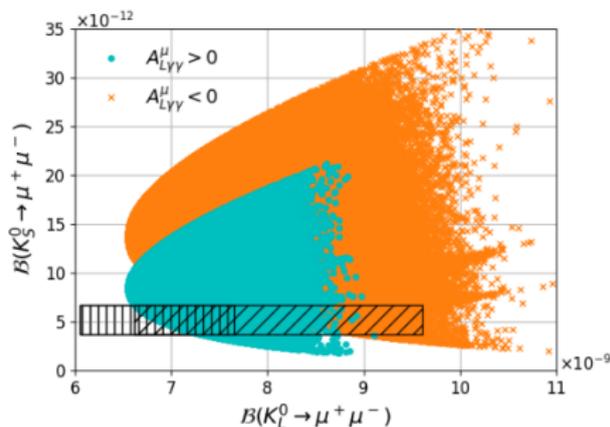$\mathcal{B}(B_s^0 \to e^{\pm}\mu^{\mp}) < 6.3 \times 10^{-9}$ [95% CL]

$K_S^0 \to \mu^+\mu^-$

- Similar to $B_{(s)}^0 \to \mu^+\mu^-$: also a FCNC, but $s \to d\ell^+\ell^-$
- $K_S^0 \to \mu^+\mu^-$ requires CP violation for s-wave SM component, which is small, so more suppressed, at level 5×10^{-12} in SM
- Model-independent bounds on CP violation phase of $s \to d\ell^+\ell^-$

$K_L^0 \to \mu^+\mu^-$

- Observed: $(6.84 \pm 0.11) \times 10^{-9}$ [PDG 2017]
- Excellent agreement with SM: $(6.85 \pm 0.32) \times 10^{-9}$ [arXiv:hep-ph/9411439]
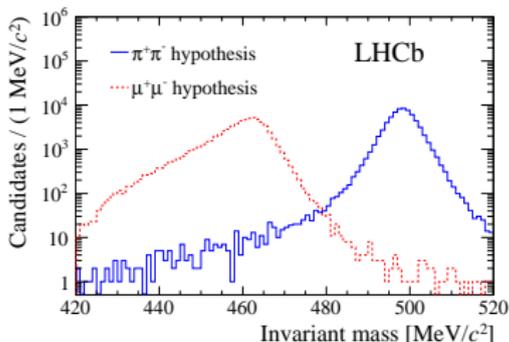
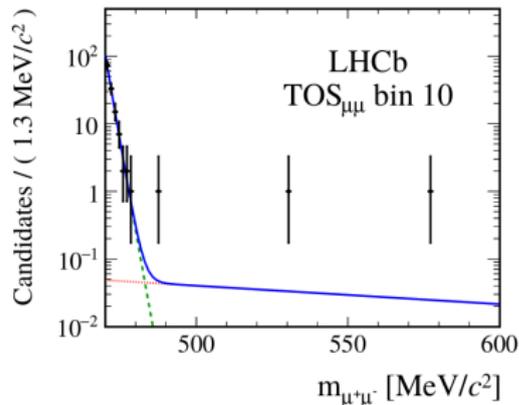### Example of New Physics range
[arXiv:1711.11030]

$K_S^0 \to \mu^+\mu^-$: LHCb, Eur. Phys. J. C, 77 10 (2017) 678

- Challenge for LHCb: high backgrounds and low trigger efficiencies
- **Improved trigger** and **more data**: full Run 1
- Main background: $K_S^0 \to \pi^+\pi^-$
- Specific BDTs for muon ID and against combinatorial

$$K_S^0 \to \pi^+\pi^-$$

Part signal region (high BDT bin)

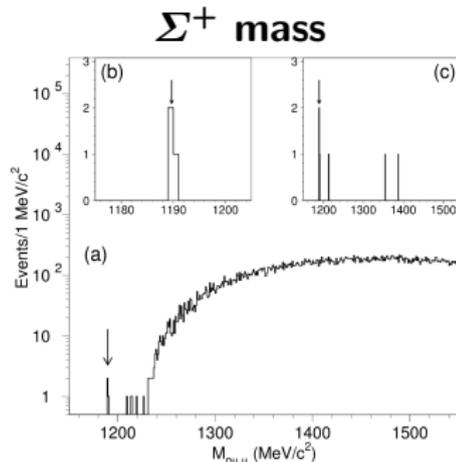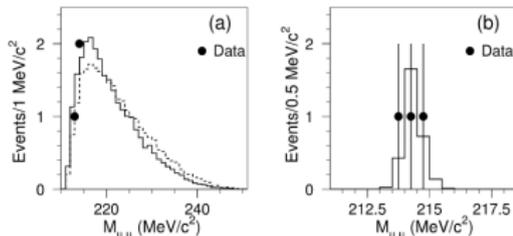$\mathcal{B}(K_S^0 \to \mu^+\mu^-) < 1.0 \times 10^{-9}$ [95% CL]

- **Improvement** of **factor 11** from previous result on limit

$\Sigma^+ \rightarrow p\mu^+\mu^-$

- Similar $s \rightarrow d\ell^+\ell^-$ transition as $K_S^0 \rightarrow \mu^+\mu^-$
- SM $\mathcal{B}$ prediction higher, due to long-distance contributions, at 10^{-8} to 10^{-7}
- Non-resonant SM $\mathcal{B}$ at about 10^{-12}

HyperCP

Σ^+ mass

- Evidence from HyperCP experiment [Phys.Rev.Lett.94:021801,2005]
- **All 3 events at dimuon mass of $\approx 214\,\mathrm{MeV}/c^2$**

$$\mathcal{B}(\Sigma^+ \rightarrow pX^0(\rightarrow \mu^+\mu^-)) = (3.1^{+2.4}_{-1.9} \pm 1.5) \times 10^{-8}$$
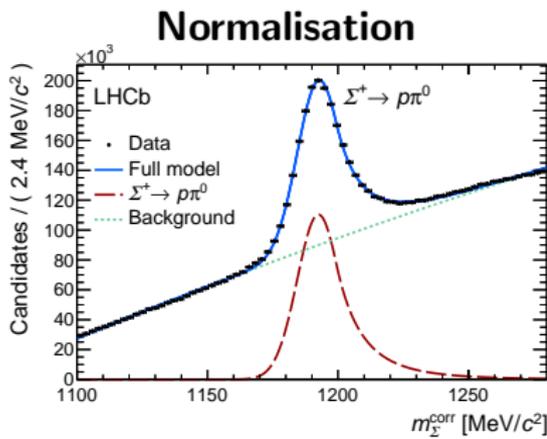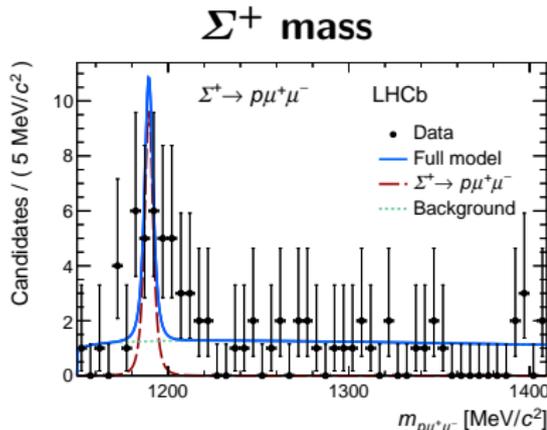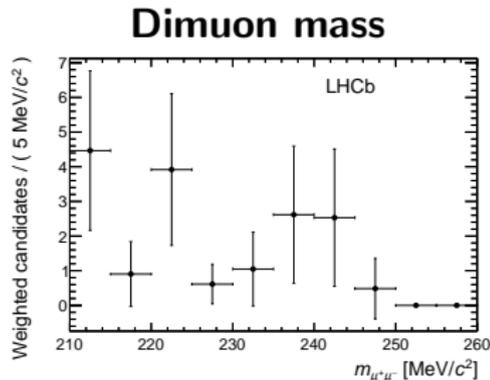
$\Sigma^+ \to p\mu^+\mu^-$: LHCb, [LHCb-PAPER-2017-049] (submitted to PRL)

- Full Run 1 dataset
- **Evidence** for the decay! (4.0σ)
- Consistent with SM
- **No visible structure** in **dimuon mass**

$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = 2.1^{+1.6}_{-1.2} \times 10^{-8}$$

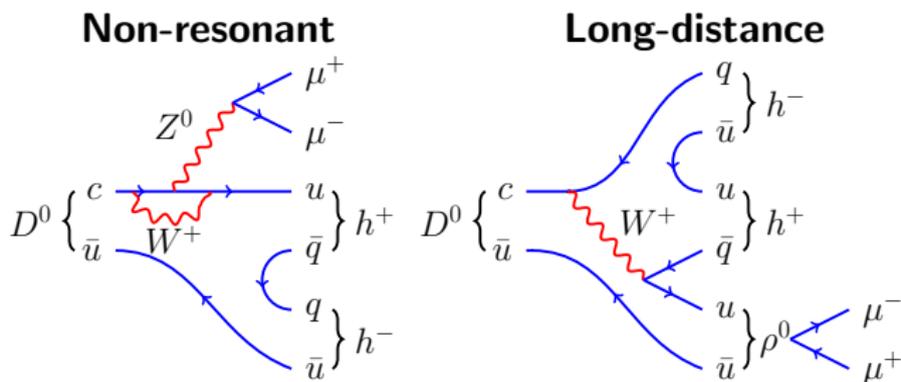**Limit on resonance at $214\,\mathrm{MeV}/c^2$**

$\mathcal{B}(\Sigma^+ \to pX^0(\to \mu^+\mu^-)) < 1.2 \times 10^{-8}$ [95% CL]
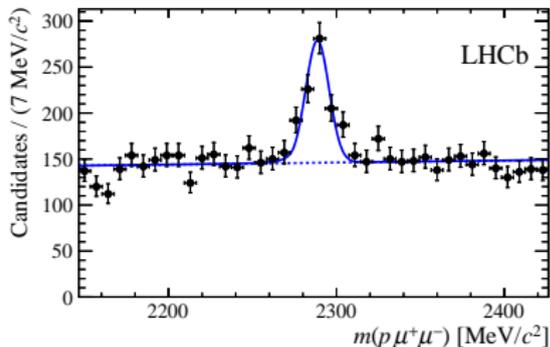
Dimuon mass

Σ^+ mass

Normalisation

$\Lambda_c^+ \rightarrow p\mu^+\mu^-$ and $D^0 \rightarrow h^+h^-\mu^+\mu^-$

- $c \rightarrow u\ell^+\ell^-$ FCNC
- Both $\Lambda_c^+ \rightarrow p\mu^+\mu^-$ and $D^0 \rightarrow h^+h^-\mu^+\mu^-$ have this transition
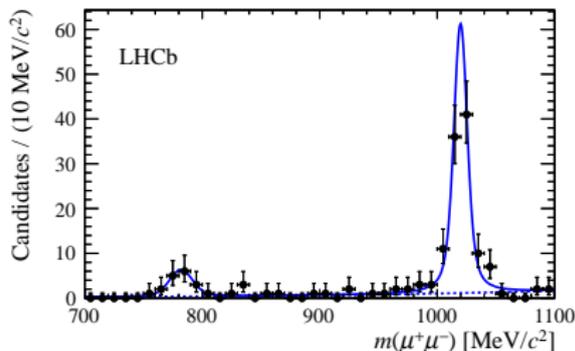- SM predicts both at around 10^{-9} for non-resonant contribution

$\Lambda_c^+ \rightarrow p\phi(\rightarrow \mu^+\mu^-)$

Dimuon mass

- Previous limit at about 4×10^{-5} [90% CL] from BaBar

This analysis

- Full Run 1 dataset
- Contributions seen from ϕ and ω
- No signal seen in non-resonant region
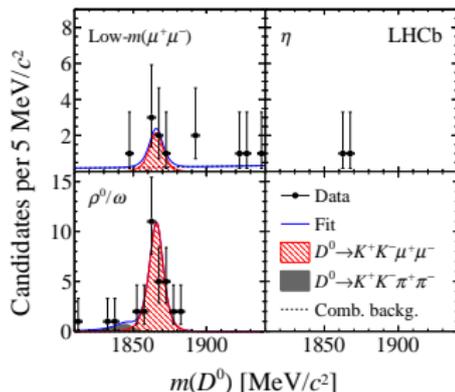- Near 10^3 **improvement** in limit!

Limit on non-resonant contribution

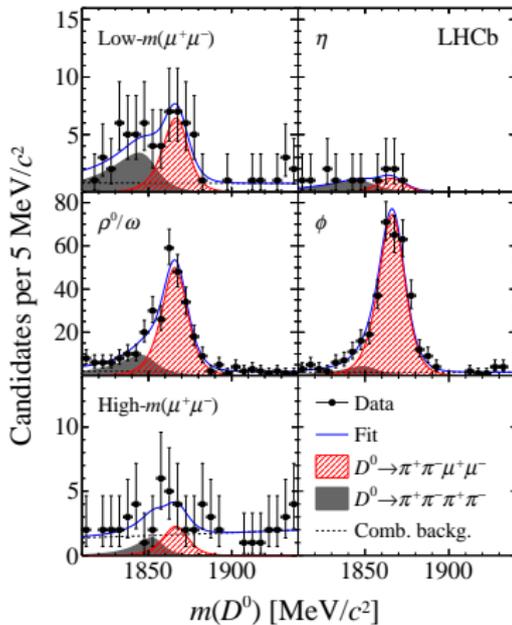$\mathcal{B}(\Lambda_c^+ \rightarrow p\mu^+\mu^-) < 9.6 \times 10^{-8}$ [95% CL]

$D^0 \to h^+ h^- \mu^+ \mu^-$: LHCb, [Phys. Rev. Lett. 119, 181805 (2017)]

- Part Run 1 (2012, $2\,\text{fb}^{-1}$) dataset
- **First observation!** of both decays
- Rarest charm decay so far!
- Both in agreement with SM (long-distance contributions)

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

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

$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48(\text{stat.}) \pm 0.51(\text{syst.}) \pm 0.97(\text{norm.})) \times 10^{-7}$

$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27(\text{stat.}) \pm 0.09(\text{syst.}) \pm 0.16(\text{norm.})) \times 10^{-7}$

Summary

- Very rare decays **good probe for new physics**
- Rich field, many results not shown
- Many improved limits and observations of decays with suppressed FCNC $b \to s\ell^+\ell^-$, $b \to d\ell^+\ell^-$, $s \to d\ell^+\ell^-$ and $c \to u\ell^+\ell^-$ transitions
- Improved limits on lepton flavour violating channels
- Help to **constrain possible new physics in B-anomalies**
- Stay tuned for (Run 2) updates and new analyses!