Rare Decays at LHCb

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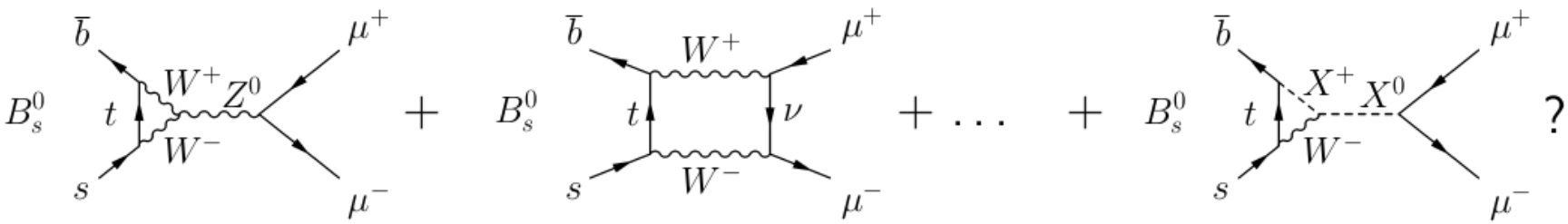
Introduction

Rare decays: mediated by electroweak flavour-changing neutral current (FCNC) processes in the Standard Model (SM)

- SM: forbidden at **tree level**. Occurs via **electroweak penguin** or box diagrams ⇒ **strongly suppressed**
  - NP contributions could become apparent
- Beyond the Standard Model (BSM) Physics entering these decays ⇒ **large deviations** from SM predictions



- **Complementary approach to direct searches**
  - higher energy ranges than directly accessible can be probed (virtual particles)

Introduction

Forbidden decays: if oberved, clear sign of New Physics

Covered today

- ★ $\mathbf{B_s^0 \to l^+ l^{(\prime)-}}$: $B^0_{(s)} \to \mu^+\mu^-$, $B^0_{(s)} \to \tau^+\tau^-$, $B^0_{(s)} \to e^\pm\mu^\mp$
- ★ $B^0 \to K^{*0}\mu^+\mu^-$, $B^0_s \to \bar{K}^{*0}\mu^+\mu^-$
- ★ **Rare charm, baryon and strange decays:** $D^0 \to h^+h^-\mu^+\mu^-$, $\Lambda_c^+ \to p\mu^+\mu^-$, $\Sigma^+ \to p\mu^+\mu^-$, $K_S^0 \to \mu^+\mu^-$

Covered in the next talk (Vinicius)

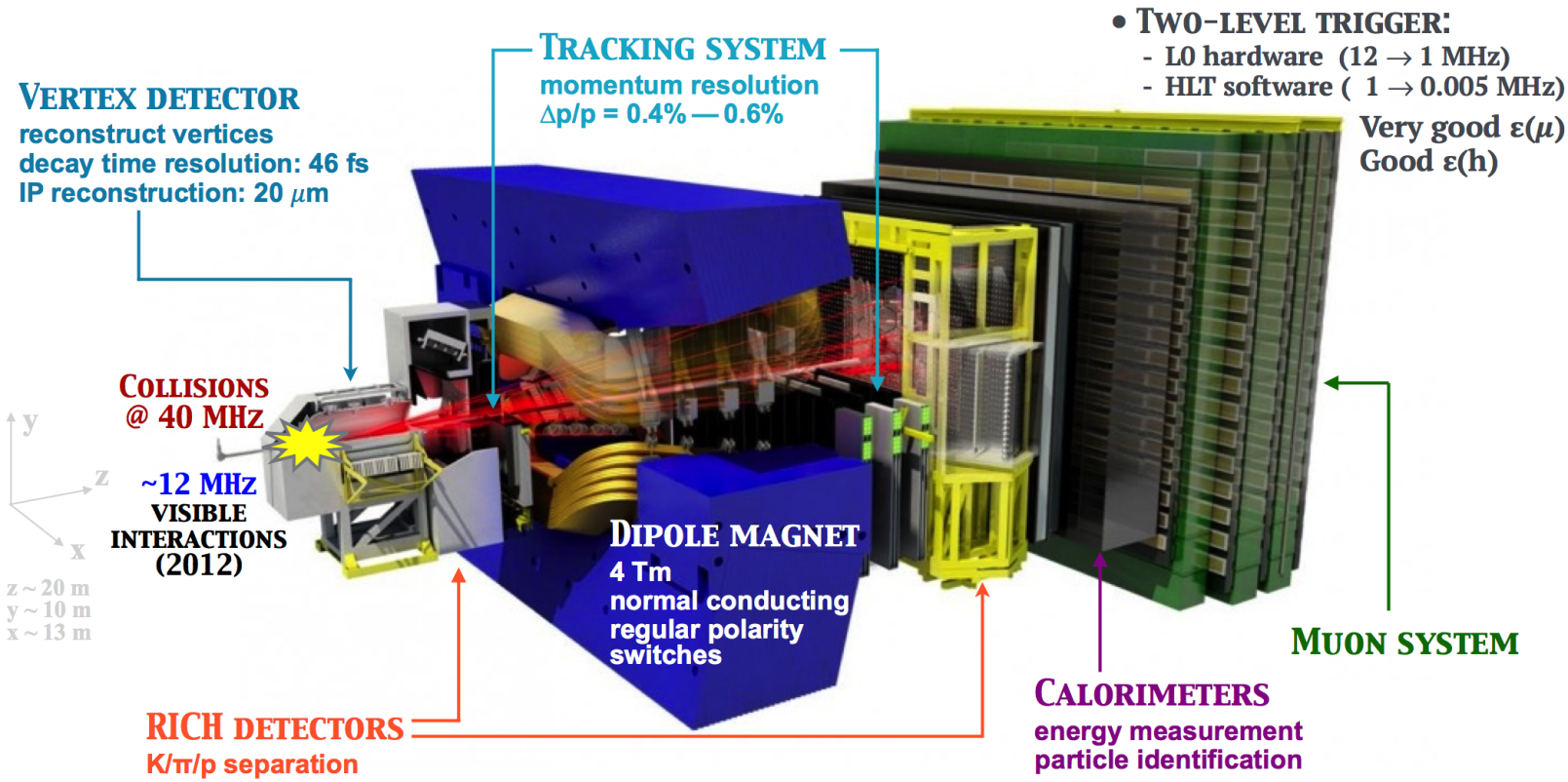
Lepton Flavour Universality tests:

- ★ **Tree-level:** $R(J/\psi)$, $R(D^*)$ (semileptonic), $R(D^*)$ (hadronic)
- ★ **Loop-level:** $R(K)$, $R(K^*)$

$\mathbf{B^+ \to K^+\mu^+\mu^+}$

LHCb [Int J Mod Phys A30 (2015) 1530022]

- Single-arm forward spectrometer, $2 < \eta < 5$
- **General purpose experiment in the forward region**, initially designed to study of b and c-hadrons



$B^0_{(s)} \to \mu^+\mu^-$ [PRL 118 (2017) 191801]

- **Golden channel:** very rare decay, **helicity suppressed**
  - Within the SM only through loop diagrams [PRL 112 (2014) 10180]:
    $\mathcal{B}_{SM}(B^0_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$,
    $\mathcal{B}_{SM}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$
- Previous measurement: LHCb and CMS combination, 2011 + 2012 data: [Nature 522 (2015) 68]

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9},\ \mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06^{+1.6}_{-1.4}) \times 10^{-10}$$

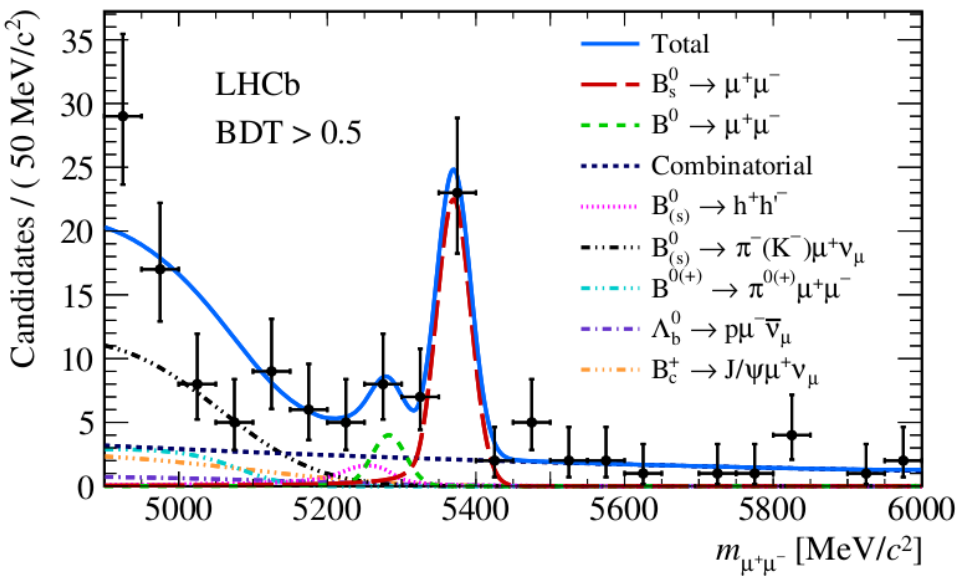
- Complementary measurement of **effective lifetime** can help disentangle B^0_s and $\bar{B}^0_s$ contribution to the decay

$$\tau_{\mu^+\mu^-} = \frac{\tau_{B^0_s}}{1-y_s^2}\left[\frac{1+2A^{\mu^+\mu^-}_{\Delta\Gamma} y_s + y_s^2}{1+A^{\mu^+\mu^-}_{\Delta\Gamma} y_s}\right],\ y_s \equiv \tau_{B^0_s}\frac{\Delta\Gamma}{2}$$

$A^{\mu^+\mu^-}_{\Delta\Gamma}$ = 1 in the SM, [-1,1] in NP scenarios

$B^0_{(s)} \to \mu^+\mu^-$ [PRL 118 (2017) 191801]

Measurement of the time-integrated branching fractions



Optimisation

- Better rejection of misidentified b-hadron decays
- Improved isolation variables $\Rightarrow$ Improved boosted decision tree (separate signal from combinatorial background)

Run1 + part Run2 (2015 and 2016) data (4.4 fb^{-1})

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9},\ 7.8\sigma \text{ excess}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10},\ 95\ \%\ \text{CL}$$

Results **compatible** with SM

$B_s^0 \to \mu^+\mu^-$ [PRL 118 (2017) 191801]

Lifetime determination

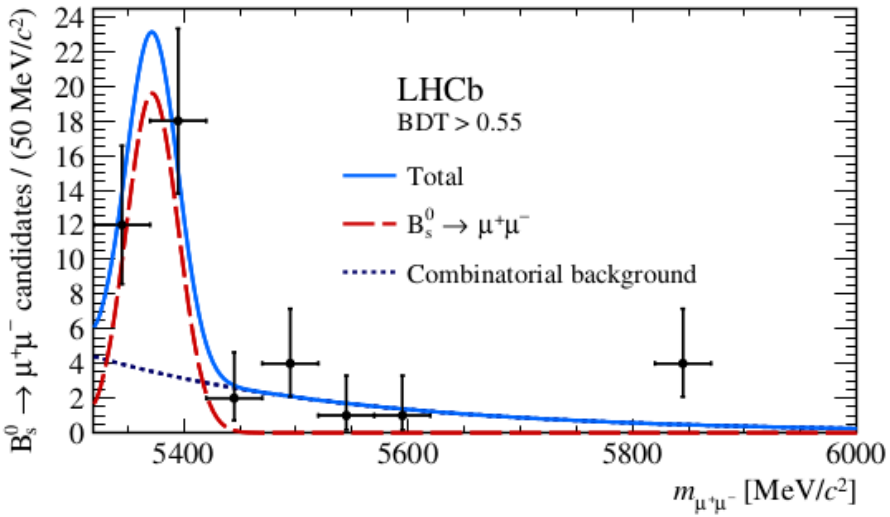
Fit details

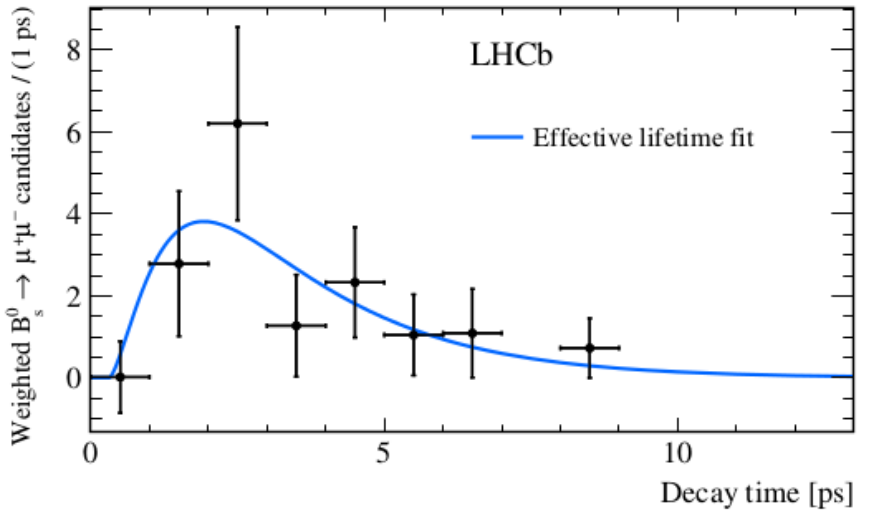
- Background-subtracted data
- Reduced $\mu^+\mu^-$ mass window
- Looser particle identification requirements for the muons
- Decay-time cut at 13.5 ps to remove bkg with $\tau >> \tau(B_s^0 \to \mu^+\mu^-)$
- Fit to acceptance(t)*exp(t)

Results

$\tau(B_s^0 \to \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05$ ps

- **Consistent** with SM at 1.0σ
- **Consistent** with $A_{\Delta\Gamma}^{\mu^+\mu^-} = -1$ at $1.4\ \sigma$





$B^0_{(s)} \to \tau^+\tau^-$ [PRL 118 (2017) 251802]

- Complementary search to $B^0_{(s)} \to \mu^+\mu^-$(less helicity supressed), very interesting in view of the latest LFU results (see talk by Vinicius)
- $\mathcal{B}_{SM}(B^0_s \to \tau^+\tau^-) = (7.73 \pm 0.49) \times 10^{-7}$ [PRL 112 (2014) 101801]
  $\mathcal{B}_{SM}(B^0 \to \tau^+\tau^-) = (2.22 \pm 0.19) \times 10^{-8}$ [PRL 112 (2014) 101801]
  - BSM Physics explaining latest LFU results could enhance these values by several orders of magnitude

Previous measurements

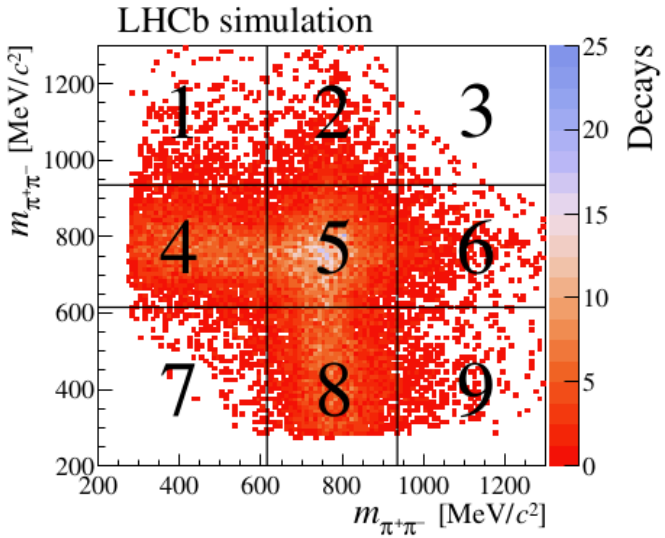
$\mathcal{B}(B^0 \to \tau^+\tau^-) < 4 \times 10^{-3}$ at 90% CL (Babar, [PRL 96 (2006) 241802])
$\mathcal{B}(B^0_s \to \tau^+\tau^-) < 3\%$ at 90% CL (indirect constraints, [PRD 82 (2010) 031502])

τ reconstruction [Phys. Rept. 421 (2005) 191]

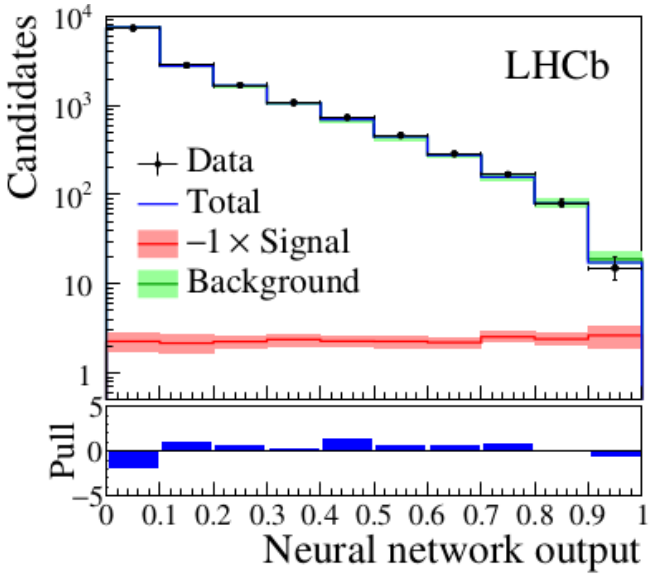
- $\tau^- \to \pi^+\pi^-\pi^+\nu_\tau$ [$\tau^- \to a_1(1260)^-\nu_\tau, a_1(1260)^- \to \rho(770)^0\pi^-$]
- **Final-state neutrinos** $\to m_{\tau^+\tau^-}$ cannot be used to distinguish between $B^0_s$and B^0

$B^0_{(s)} \to \tau^+\tau^-$ [PRL 118 (2017) 251802]

- Exploit the $\rho(770)^0$ resonance
- **Signal region:** both τ in 5 (signal yield)
- **Signal-depleted region:** at least one τ in 1,3,7 or 9 (bkg when optimising the selection, first Neural-Network)
- **Control region:** one τ in 4,5 or 8, the other in 4 or 8 (bkg model)



Fit to a second Neural-Network:



Run1 data (3 fb^{-1})

$\mathcal{B}(B^0_s \to \tau^+\tau^-) < 6.8 \times 10^{-3}$, 95% CL
(**first** direct limit)
$\mathcal{B}(B^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3}$, 95 % CL
(**world's best** limit)

(*) assuming no crossed-contributions

$B^0_{(s)} \to e^\pm \mu^\mp$ [JHEP 1803 (2018) 078]

- Lepton-Flavour Violating decay, **forbidden** in the SM $\to$ sensitive to new mediators
  - Not present in the SM, allowed in nature (at least) through neutrino mixing [PRL 81 (1998) 1562]
- Large LFV expected in numerous NP scenarios (e.g. leptoquarks, supersymmetric models) $\to \mathcal{B}(B^0 \to e^\pm \mu^\mp)$, $\mathcal{B}(B^0_s \to e^\pm \mu^\mp)$ enhancement [PRD 92 (2015) 054013], [PRD 94 (2016) 115021], [JHEP 06 (2015) 072]

Previous measurements: LHCb $1\,\mathrm{fb}^{-1}$ (PRL 111 (2013) 141801)

$\mathcal{B}(B^0 \to e^\pm \mu^\mp) < 3.7 \times 10^{-9}$, $\mathcal{B}(B^0_s \to e^\pm \mu^\mp) < 1.4 \times 10^{-8}$ at 95% CL

Improvements

- Larger data sample
- Improved selection (multivariate classifier)

Categories:

1. Bremsstrahlung γ associated with the $e^\pm$
2. No bremsstrahlung γ associated with the $e^\pm$

$B^0_{(s)} \to e^\pm \mu^\mp$ [JHEP 1803 (2018) 078]

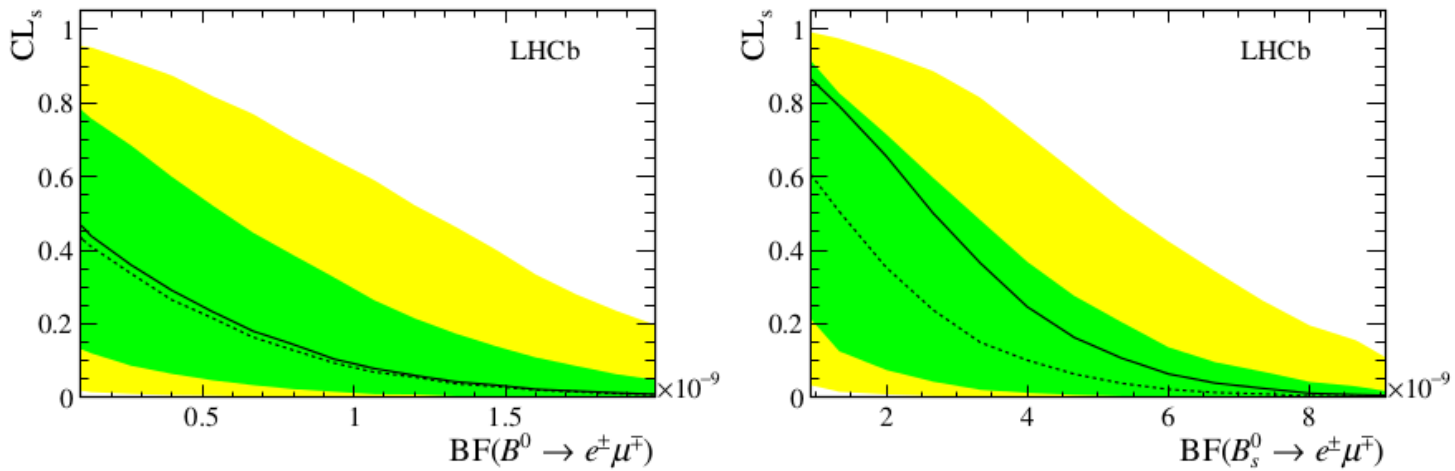
Unbinned maximum likelihood fit to the $m_{e^\pm\mu^\mp}$ distributions:

- 7 bins of BDT (uniform) response $\in$ [0.25,1.0]
  - **Signal:** simulated $B^0_s \to e^\pm \mu^\mp$, **Background:** data with $e^\pm \mu^\pm$

Run1 data ($3\ \mathrm{fb}^{-1}$)

$$\mathcal{B}(B^0_s \to e^\pm \mu^\mp) < 5.4(6.3) \times 10^{-9},\ 95\%\ \mathrm{CL}\ (*)$$
$$\mathcal{B}(B^0 \to e^\pm \mu^\mp) < 1.0(1.3) \times 10^{-9},\ 95\ \%\ \mathrm{CL}$$

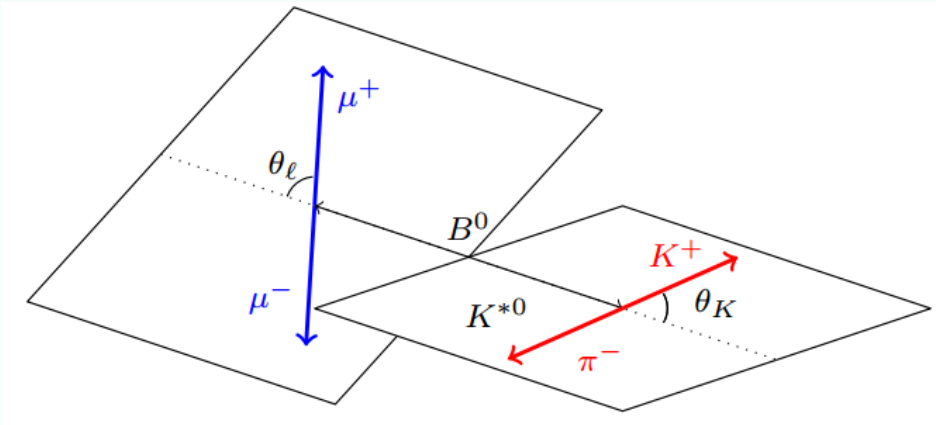
(*) assuming only contribution from heavy mass eigenstate



Strongest limits on these decays consistent with **background-only** hypothesis

$B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 02 (2016) 104]

- $b \to s$ Flavour-Changing Neutral Current transition
- Measurement of **CP-averaged angular observables** and **CP-asymmetries** (**full** angular distribution)
  - **Angular observables:** less affected by hadronic uncertainties ($B^0 \to K^{*0}$)
- Previous measurements by LHCb [PRL 111 (2013) 191801], Babar [PRD 73 (2006) 092001], Belle [PRL 103 (2009) 171801], CDF [PRL 108 (2012) 081807], CMS [PRB 727 (2013) 77]



- Final state: $(\theta_l, \theta_K, \phi)$, $m(K^+\pi^-)$ and q^2 $(m^2_{\mu^+\mu^-})$
- S-wave contribution included

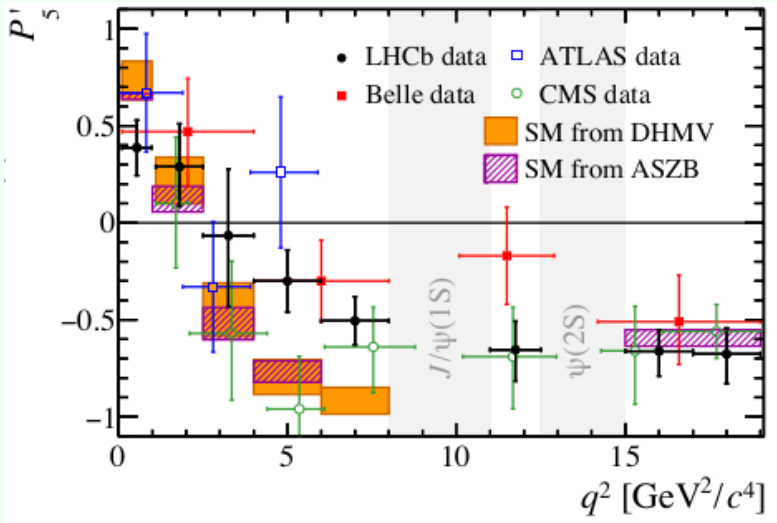
$B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 02 (2016) 104]

Usage of **optimised** obervables (cancellation of leading form-factor uncertainties), $P_i^{(\prime)}$ [arXiv:1207.2753]:

$$P_5^{\prime} = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

Run1 data ($3\ \mathrm{fb}^{-1}$)

Tension with SM prediction [JHEP 1412 (2014) 125], [Eur. Phys. J. C75 (2015) 382] in two bins of $P_5^{\prime}$



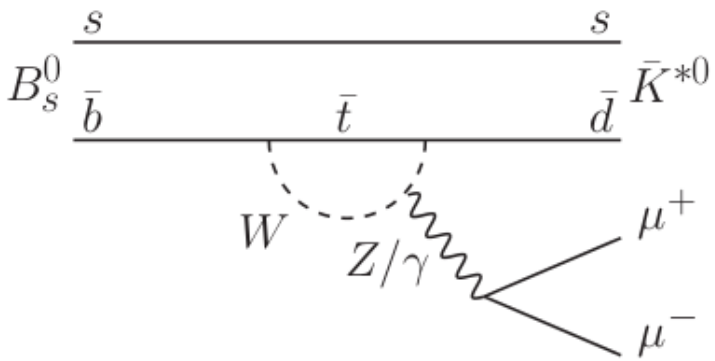
Combined significance of 3.4σ:

1. BSM physics (see upcoming talks)
2. Underestimated QCD uncertainties (see upcoming talks)

Correlations between observables are computed $\Rightarrow$ possibility of performing **global fits** to theoretical models

$B_s^0 \to \bar{K}^{*0}\mu^+\mu^-$ [LHCb-PAPER-2018-004]

- $b \to d$ Flavour-Changing Neutral Current transition
- **Never observed**, $\mathcal{B}_{SM}(B_s^0 \to \bar{K}^{*0}\mu^+\mu^-) \sim \mathcal{O}(10^{-8})$ (CKM suppressed)
  [JHEP 08 (2016) 098], [PoS LATTICE2014 (2015) 372]
- Complementary to $B^0 \to K^{*0}\mu^+\mu^-$. Can be used to compute $|V_{td}/V_{ts}|$



Unbinned maximum likelihood fit to $m(K^-\pi^+\mu^+\mu^-)$

- $m(K^-\pi^+)$ within $\pm$ 70 $\mathrm{MeV/c^2}$of the $\bar{K}^*(892)^0$
- $0.1 < q^2 = m^2_{\mu^+\mu^-} < 19.0\mathrm{GeV}^2/\mathrm{c}^4$
  - $12.5 < q^2 < 15.0\mathrm{GeV}^2/\mathrm{c}^4$ excluded ($\psi(2S)$ resonance)
  - $8.0 < q^2 < 11.0\mathrm{GeV}^2/\mathrm{c}^4$ treated separately (J/ψ resonance)

$B_s^0 \to \bar{K}^{*0}\mu^+\mu^-$ [LHCb-PAPER-2018-004]

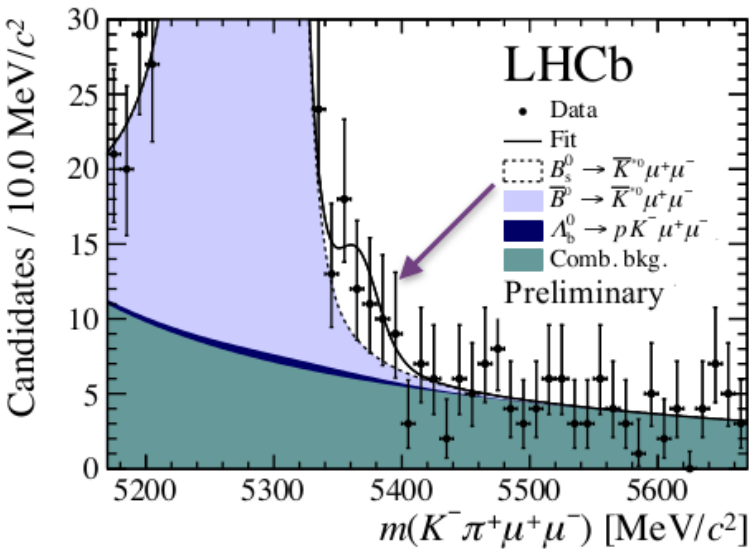
Run1 + part Run2 (2015 and 2016) data (4.6 fb^{-1})

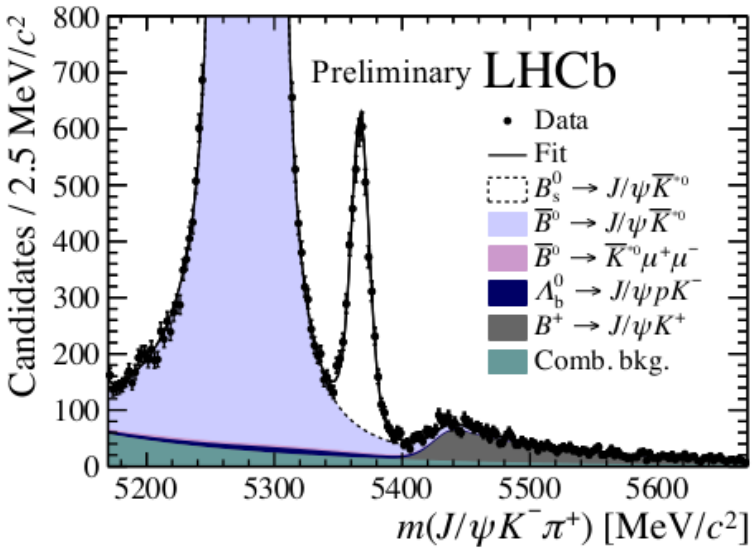
$$N(B_s^0 \to \bar{K}^{*0}\mu^+\mu^-) = 38 \pm 12,\ 3.4\sigma \text{ above bkg-only hypothesis}$$

(first evidence)

$$\mathcal{B}(B_s^0 \to \bar{K}^{*0}\mu^+\mu^-) = [2.9 \pm 1.0(\mathrm{stat}) \pm 0.2(\mathrm{syst}) \pm 0.3(\mathrm{norm})] \times 10^{-8}$$

(first measurement)

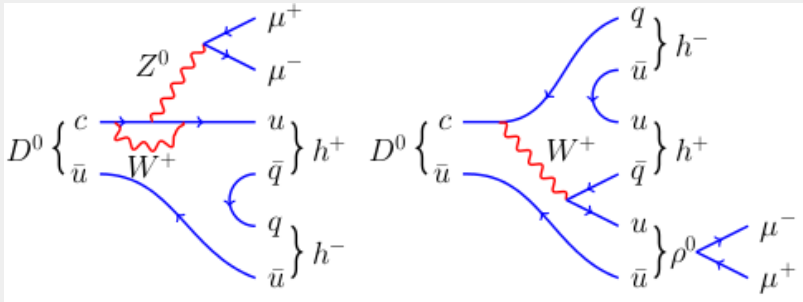




$D^0 \to h^+h^-\mu^+\mu^-$ [PRL 119 (2017) 181805]

$c \to u\mu^+\mu^-$ FCNC proccess (GIM suppressed)

- **Short-distance (SD) contributions:**
  $\mathcal{B}_{SM}(D^0 \to h^+h^-\mu^+\mu^-) \sim \mathcal{O}(10^{-9})$
  [PRD 83 (2011) 114006]
- **Long-distance (LD) contributions:**
  $\mathcal{B}_{SM}(D^0 \to h^+h^-\mu^+\mu^-) \sim \mathcal{O}(10^{-6})$
  [PRD 76 (2007) 074010]
  [JHEP 04 (2013) 135]



4 body-decay $\Rightarrow$ access to a variety of angular distributions $\Rightarrow$ **disentangle** LD and SD

Previous measurements: LHCb 1fb^{-1} (PLB 728 (2014) 234))

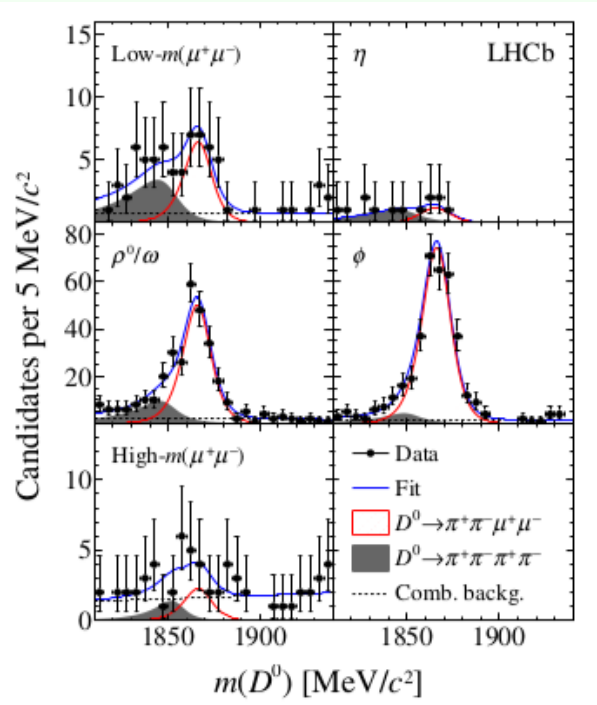
$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) < 5.5 \times 10^{-7} \text{ at 90\% CL}$$

- $D^0 \to h^+h^-\mu^+\mu^-$, h=π, K, $D^{*+} \to D^0\pi+$ (D^{*+} produced directly at PV)

$D^0 \to h^+h^-\mu^+\mu^-$ [PRL 119 (2017) 181805]

Run1 data (2 fb^{-1}; 8 TeV)

$\mathbf{m}_{\mu^+\mu^-}$ mass regions:
(low-mass) $< 525\ \mathrm{MeV/c^2}$
(η) $525 - 565\ \mathrm{MeV/c^2}$
(ρ^0/ω) $565 - 950\ \mathrm{MeV/c^2}$
(ϕ) $950 - 1100\ \mathrm{MeV/c^2}$
(high-mass) $< 525\ \mathrm{MeV/c^2}$



$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = [9.64 \pm 0.48(\mathrm{stat}) \pm 0.51(\mathrm{syst}) \pm 0.97(\mathrm{norm})] \times 10^{-7}$
$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) = [1.54 \pm 0.27(\mathrm{stat}) \pm 0.09(\mathrm{syst}) \pm 0.16(\mathrm{norm})] \times 10^{-7}$
(*) integrating over dimuon mass

Rarest charm-hadron decays ever observed, **consistent** with the SM

$\Lambda_c^+ \to p\mu^+\mu^-$ [arXiv:1712.07938]

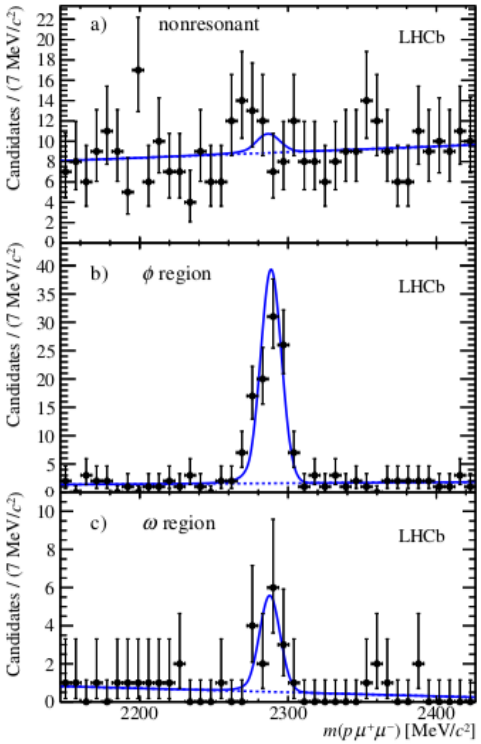
GIM-suppressed FCNC proccess

$\mathcal{B}_{SM}(\Lambda_c^+ \to p\mu^+\mu^-) \sim \mathcal{O}(10^{-9})$ (SD), $\mathcal{O}(10^{-6})$ (LD)
[PRD 73 (2006) 054026], [PRD 66 (2002) 014009]

BaBar (PRD 84 (2011) 072006)

$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 4.4 \times 10^{-5}$ at 90% CL

$m_{\mu^+\mu^-}$ mass regions: a) non-resonant, b) ϕ (normalization), c) ω



Run1 data (3 fb^{-1})

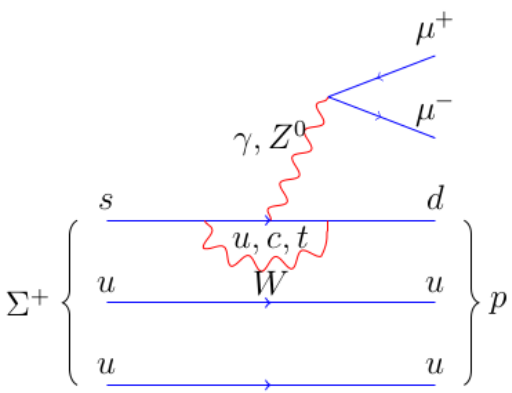
- **Excess** seen at ϕ and ω (5.0σ, **first** observation):
  $\mathcal{B}(\Lambda_c^+ \to p\omega) = [964 \pm 3.2(\mathrm{stat}) \pm 1.0(\mathrm{syst}) \pm 2.0(\mathrm{norm})] \times 10^{-4})$
- $\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 7.7(9.6) \times 10^{-8}$ at 90% (95 %) CL $\leftarrow 10^2$ improvement

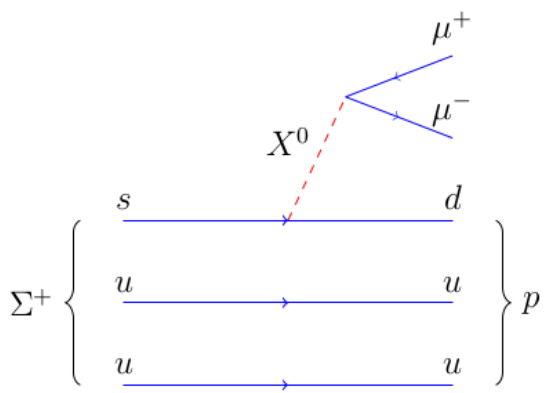
$\Sigma^+ \to p\mu^+\mu^-$ [arXiv:1712.08606]

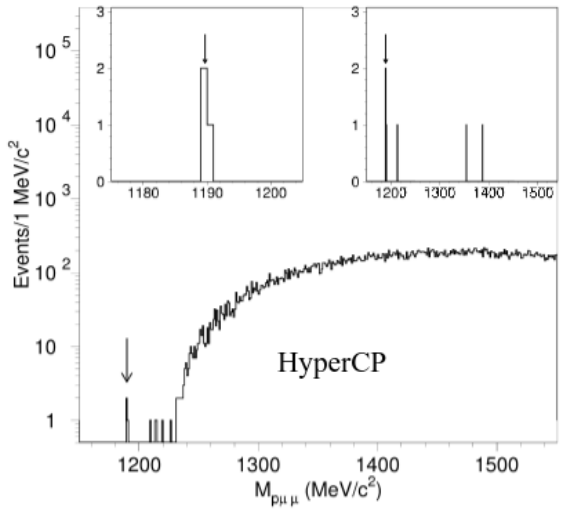
- $s \to d$ process, $1.6 \times 10^{-8} < \mathcal{B}_{SM}(\Sigma^+ \to p\mu^+\mu^-) < 9.0 \times 10^{-8}$ dominated by **LD** contributions [PRD 72 (2005) 074003]
- Hyperons are copiously produced at LHC

First evidence: HyperCP (PRL 94 (2005) 021801)

- $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (8.6^{+6.6}_{-5.4}) \times 10^{-8}$
- 3 observed signal events with almost the same $m_{\mu^+\mu^-} \Rightarrow$ possibility of a BSM intermediate resonance $\Sigma^+ \to pX^0(\to \mu\mu)$





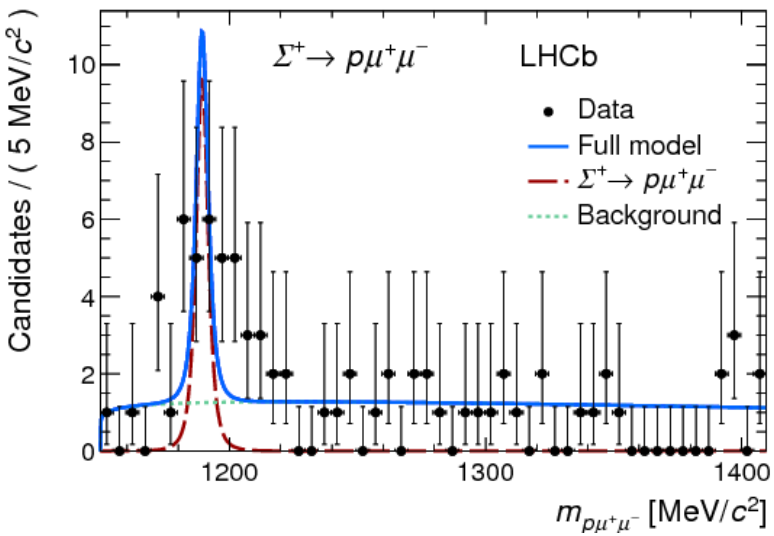


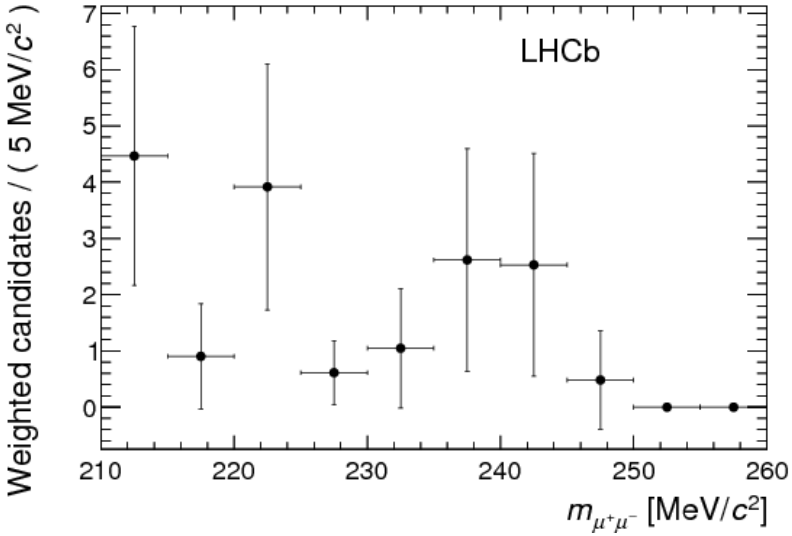
$\Sigma^+ \to p\mu^+\mu^-$ [arXiv:1712.08606]

- Relatively low p_T of the final-state particles
- $\left|m_{p\mu^+\mu^-} - m_{\Sigma^+}\right| < 500\ \mathrm{MeV/c^2}$
- Strategy optimized to search for a dimuon resonance

Run1 data ($3\ \mathrm{fb}^{-1}$)

- **Excess** of events observed, 4σ significance:
  $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (2.1^{+1.6}_{-1.2}) \times 10^{-8})$ ← **consistent** with the SM
- No significant structure in the dimuon invariant mass distribution





$K_S^0 \to \mu^+\mu^-$ [Eur. Phys. J. C77 10 (2017) 678]

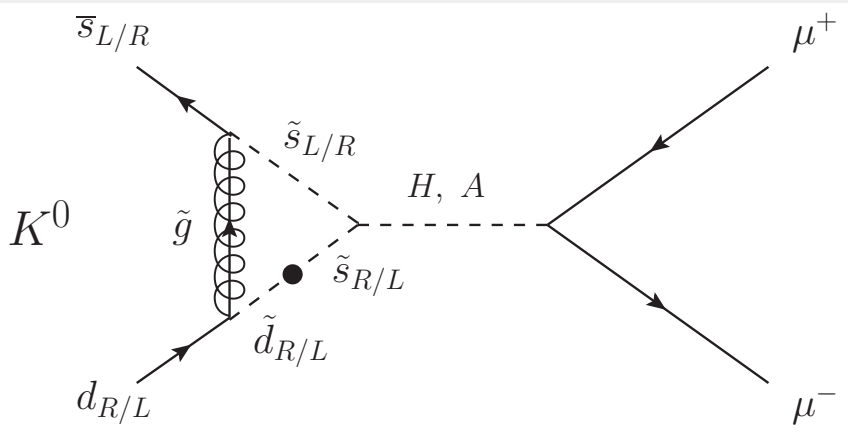
$$\mathcal{B}_{SM}(K_S^0 \to \mu^+\mu^-) = (5.0 \pm 1.5) \times 10^{-12} \text{ (LD dominated)}$$

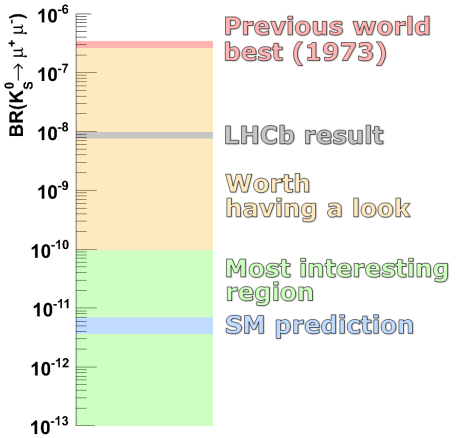
[Nucl. Phys. B366 (1991) 189], [JHEP 01 (2004) 009]

LHCb 1fb^{-1} (JHEP 01 (2013) 090)

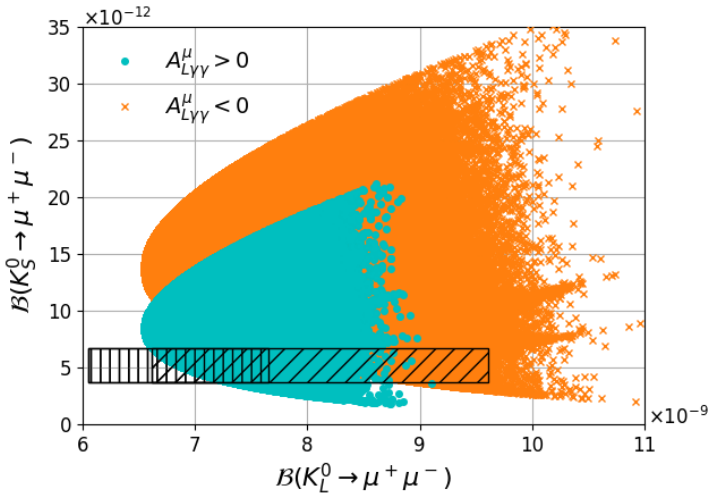
$$\mathcal{B}(K_S^0 \to \mu^+\mu^-) < 9 \times 10^{-9}, \text{ 90\% CL}$$

Very sensitive to BSM Physics (e.g. light scalars)





[arXiv:1711.11030]

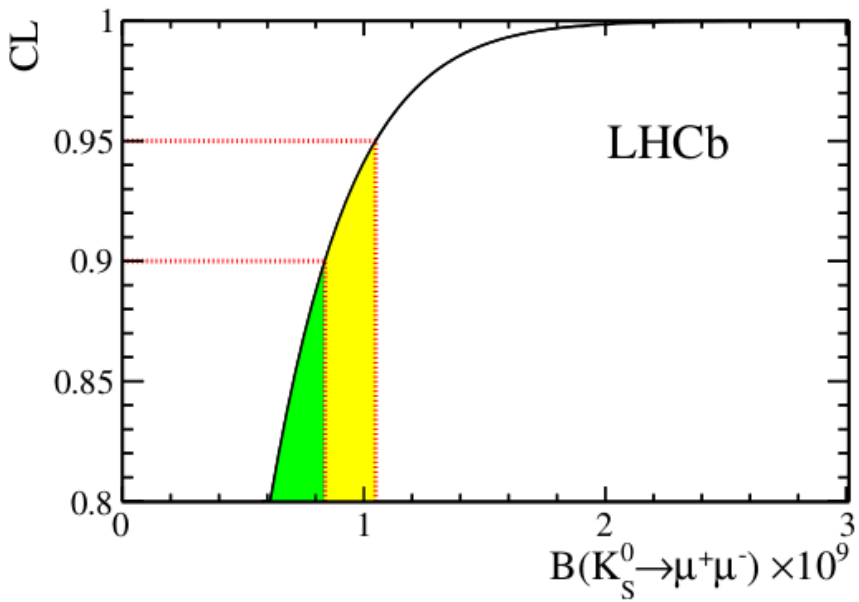


$K_S^0 \to \mu^+\mu^-$ [Eur. Phys. J. C77 10 (2017) 678]

- $\mathcal{O}(10^{13})$ of K_S^0 per fb^{-1} within the LHCb acceptance
- Main limitation is the low trigger efficiency
  - no mass requirements, lower p_T threshold $\Rightarrow$ factor **2.5** improvement wrt previous measurement
- 2 multivariate discriminants to remove background (**combinatorial** and from $\mathbf{K_S^0 \to \pi^+\pi^-}$)

Run1 data (3 fb^{-1})

$\mathcal{B}(K_S^0 \to \mu^+\mu^-) < 0.8(1.0) \times 10^{-9}$
90%, 95% CL
factor 11 improvement



- Good prospects to enter the most interesting region in the future

Conclusions

A lot of activity in rare decays @ LHCb :

- $B_s^0 \to \mu^+\mu^-$: **first observation** in a single experiment + **first measurement** of the effective lifetime
- **Improved(set) upper limits** for $B_{(s)}^0 \to \tau^+\tau^-$, $B_{(s)}^0 \to e^\pm\mu^\mp$, $K_S^0 \to \mu^+\mu^-$
- $B^0 \to K^{*0}\mu^+\mu^-$: **tension with SM** persists
- **First evidence** of $B_s^0 \to \bar{K}^{*0}\mu^+\mu^-$
- $D^0 \to h^+h^-\mu^+\mu^-$: **rarest charm-hadron decay observed**
- **First observation** of $\Lambda_c^+ \to p\mu^+\mu^-$ in the ω region
- **Evidence** of $\Sigma^+ \to p\mu^+\mu^-$, no resonance found in $m_{\mu^+\mu^-}$

Important constraints on New Physics

Thanks for your attention!