Study of rare heavy flavour decays at the LHC

Giulio Dujany
on behalf of the LHCb, CMS and ATLAS collaborations

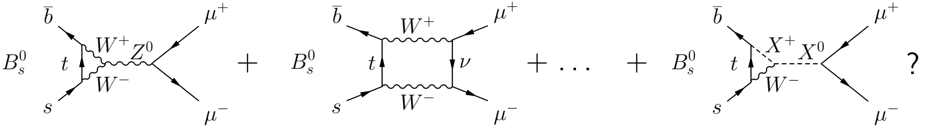
XXXII^{e} Rencontres de
Physique de la Vallée d'Aoste

Outline

1. Introduction
2. $B^0_{(s)} \to l^+ l^{(\prime)-}$
   - $B^0_{(s)} \to \mu^+\mu^-$
   - $B^0_{(s)} \to \tau^+\tau^-$
   - $B^0_{(s)} \to e^\pm\mu^\mp$
3. $B^0 \to K^{*0}\mu^+\mu^-$
4. Rare hadronic $B^0_{(s)}$ decays
   - $B^0_{(s)} \to p\bar{p}$
   - $B^0 \to D_s^+\phi$
5. Rare charm and baryon decays
   - $D^0 \to h^+h^-\mu^+\mu^-$
   - $\Lambda_c^+ \to p\mu^+\mu^-$
   - $\Sigma^+ \to p\mu^+\mu^-$
6. Conclusion

Introduction

- Rare heavy flavour decays are a good place to look for New Physics
- When Standard Model is suppressed New Physics contributions could become apparent
- Sensitive also to new mediators with masses inaccessible by direct production
- Interesting in particular:
  - Flavour changing neutral currents (FCNC), in the Standard Model proceeds only via loop diagrams, possible new particles in the loops
  - Lepton flavour violating (LFV) decays, practically forbidden in the Standard Model, an observation is a clear sign of New Physics



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

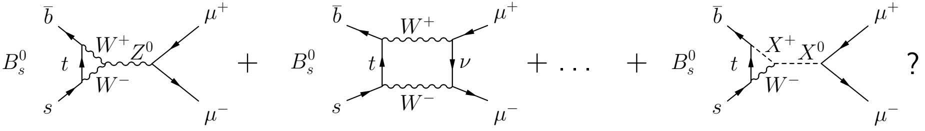
[Nature 522, 68-72 (04 June 2015)]
[Eur.Phys.J. C76 (2016) no.9, 513]
[Phys. Rev. Lett. 118, 191801 (2017)]

Motivations

- $B^0_{(s)} \to \mu^+\mu^-$ highly suppressed in the Standard Model
  - Proceeds only through loop
  - Helicity suppressed
- Robust Standard model calculation [Bobeth et al, Phys. Rev. Lett. 112, 101801 (2014)]

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

- Good place to look for New Physics and to constrain parameters of New Physics theories

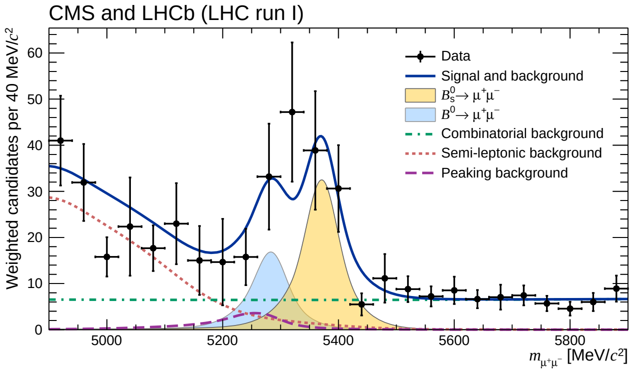


Run I: CMS+LHCb [Nature 522, 68-72 (04 June 2015)]

- Use Run I dataset: 3 fb^{-1} (LHCb) and 25 fb^{-1} (CMS) at 7 and 8 TeV
- simultaneous fit to 20 categories (experiment, value of BDT classifier and for CMS also region of the detector and period of data taking)

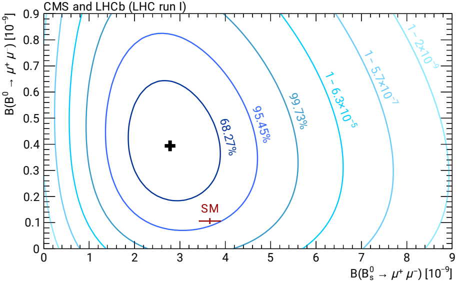
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9} \quad 6.2\sigma \quad (7.4\sigma \text{ expected})$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10} \quad 3.2\sigma \quad (0.8\sigma \text{ expected})$$

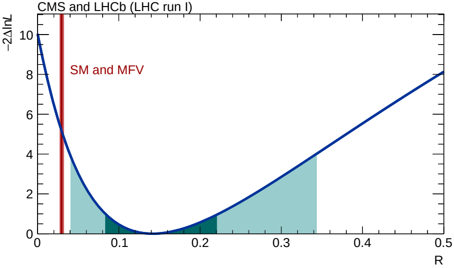


Run I: CMS+LHCb

[Nature 522, 68-72 (04 June 2015)]



- Likelihood scans performed with nuisance parameters profiled in the scans
- Compatible with Standard Model at 2σ



- Measured ratio between B^0 and B_s^0 where major part of theoretical uncertainties cancels

$$R = \frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)} = 0.14^{+0.08}_{-0.06}$$

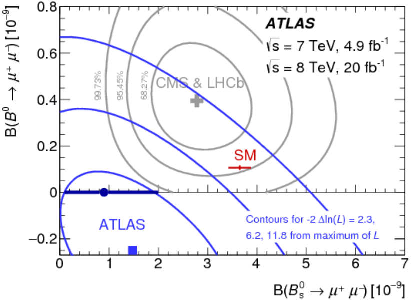
Run I: ATLAS

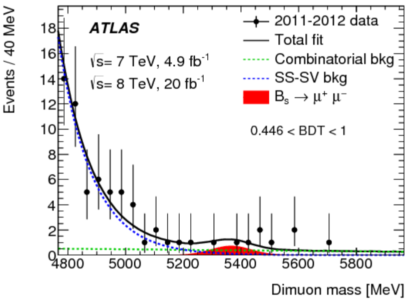
[Eur.Phys.J. C76 (2016) no.9, 513]

- Use Run I dataset: 25 fb^{-1} at 7 and 8 TeV
- No significant signal excess observed in both channels

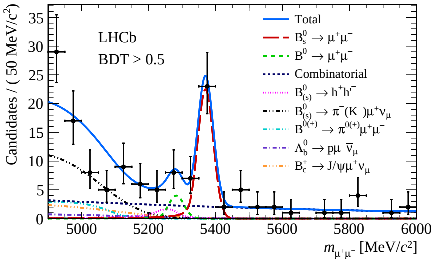
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (0.9^{+1.1}_{-0.8}) \times 10^{-9} (< 3.0 \times 10^{-9} \text{ @ } 95\% \text{ C.L.})$$

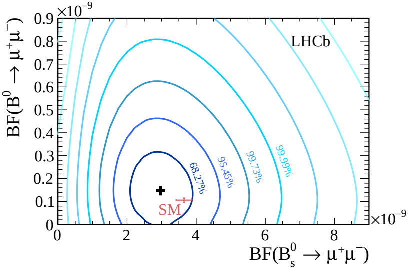
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10} \text{ @}95\% \text{ C.L.}$$





- Analyse Run I + Run II dataset ($4.4\ \text{fb}^{-1}$)
- Unbinned maximum likelihood simultaneous fit to 4 BDT categories for Run I and 4 for Run II
- Consistent with Standard Model prediction and previous measurement





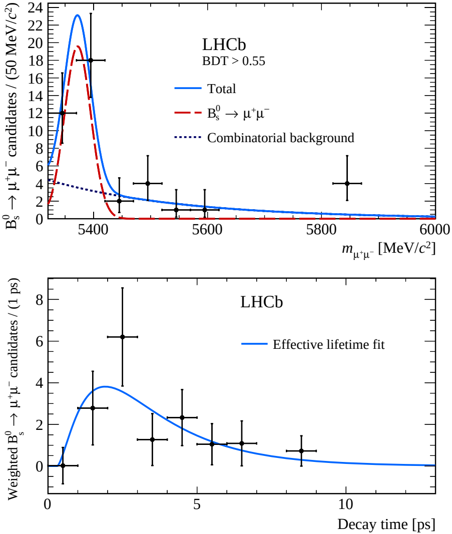
First observation of $B_s^0 \to \mu^+\mu^-$ by a single experiment (7.8σ)

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

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \text{ @ } 95\% \text{ C.L.}$$

Effective lifetime of $B_s^0 \to \mu^+\mu^-$ [Phys. Rev. Lett. 118, 191801 (2017)]

- In the Standard Model only the heavy B_s^0 eigenstate decay to $\mu^+\mu^-$ but this can be false in New Physics models
- New Physics can be found measuring the effective lifetime also if the branching fraction agrees with the Standard Model
- Selection uses looser particle identification requirements and a single cut on BDT
- Result consistent both with Standard Model (1σ) and most extreme New Physics scenario (1.4σ), more data needed



$$\tau(B_s^0 \to \mu^+\mu^-) = 2.04 \pm 0.44\,(\text{stat.}) \pm 0.05\,(\text{syst.})\,\text{ps}$$

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

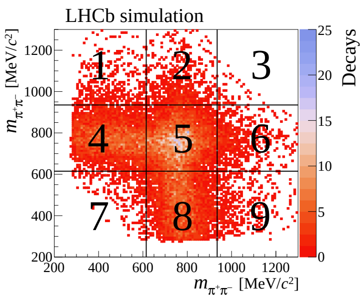
[Phys. Rev. Lett. 118, 251802 (2017)]

$B^0_{(s)} \to \tau^+\tau^-$ [Phys. Rev. Lett. 118, 251802 (2017)]

- More abundant than $B^0_{(s)} \to \mu^+\mu^-$ (less helicity suppressed)
- Theoretically clean
- Experimentally challenging

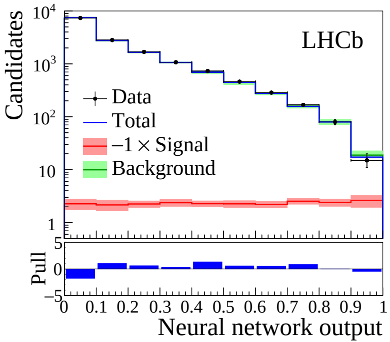
Reconstruct τ as $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ $(\mathcal{B} = (9.31 \pm 0.05)\%)$

- Dominant decay chain is
  $\tau^- \to \nu_\tau a1(1260)^-$; $a1(1260)^- \to \pi^-\rho(770)^0$; $\rho(770)^0 \to \pi^+\pi^-$
- Exploit it to define
  - Signal region (both τ in 5) to determine signal yield
  - Control region (one τ in 4,5,8 and the other in 4,8) Background model for fit
  - Signal depleted region (one τ in 1,3,7,8) background in neural network training



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

- Selection with neural network trained with signal Monte Carlo and background from signal depleted region
- Missed neutrinos make $m_{\tau^+\tau^-}$ not discriminating enough
- Instead perform fit to second neural network classifier
- Best World's upper limits.



$$\mathcal{B}(B^0_s \to \tau^+\tau^-) < 6.8 \times 10^{-3} \text{ @95\% C.L.}$$

$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3} \text{ @95\% C.L.}$$

assuming no contribution from the other

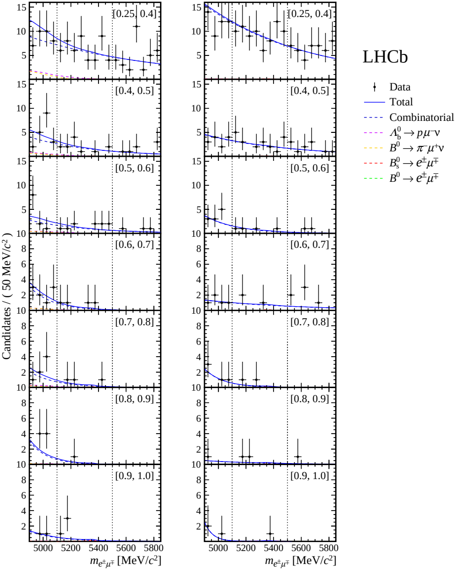
$$B^0_{(s)} \to e^\pm \mu^\mp$$

[LHCb-PAPER-2017-031, accepted by JHEP]

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

- LFV decay forbidden in the Standard Model but can be up to $\mathcal{O}(10^{-11})$ in lepton non-universality scenarios
- Searches uses full Run I sample (follows [Phys.Rev.Lett. 111 (2013) 141801] performed with 1 fb^{-1})
- Candidates selected with improved BDT (trained with signal MC and same sign $e^\pm\mu^\pm$ background)
- Uses two normalisation channels ($B^+ \to J/\psi K^+$ and $B^0 \to K^+\pi^-$)

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



- Candidates split by number of Bremsstrahlung photons (0 left; $\geqslant$ 1 right)
- Simultaneous fit to 7 bins of BDT classifier
- Best World's limits set

$$\mathcal{B}(B_s^0 \to e^\pm\mu^\mp) < 5.4(6.3) \times 10^{-9} \quad @90\%(95\%)\ \text{C.L.}$$

$$\mathcal{B}(B^0 \to e^\pm\mu^\mp) < 1.0(1.3) \times 10^{-9} \quad @90\%(95\%)\ \text{C.L.}$$

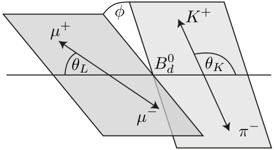
B_s^0 limit assumes only heavy mass eigenstate to contribute

$$B^0 \to K^{*0} \mu^+ \mu^-$$

[JHEP 02 (2016) 104]
[ATLAS-CONF-2017-023]
[CMS-BPH-15-008, arXiv:1710.02846]

$B^0 \to K^{*0}\mu^+\mu^-$

- The $B^0 \to K^{*0}\mu^+\mu^-$ proceeds via FCNC process: can be sensitive to New Physics
- Study of angular distribution allows different quantities to be studied as a function of q^2



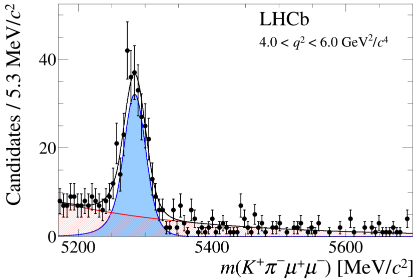
$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_L\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Bigg[\frac{3(1-F_L)}{4}\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1-F_L}{4}\sin^2\theta_K\cos 2\theta_L$$
$$-F_L\cos^2\theta_K\cos 2\theta_L + S_3\sin^2\theta_K\sin^2\theta_L\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_L\cos\phi + S_5\sin 2\theta_K\sin\theta_L\cos\phi$$
$$+S_6\sin^2\theta_K\cos\theta_L + S_7\sin 2\theta_K\sin\theta_L\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_L\sin\phi + S_9\sin^2\theta_K\sin^2\theta_L\sin 2\phi\Bigg].$$

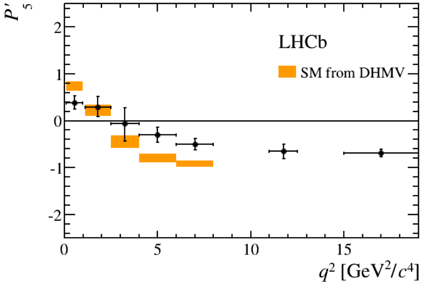
Use variables that cancel leading order form factor uncertainties

[Descotes-Genon, Hurth, Matias, Virto, JHEP '13, Descotes-Genon, Matias, Ramon, Virto, JHEP '13]

$$P'_{4,5,6,8} = \frac{S_{4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

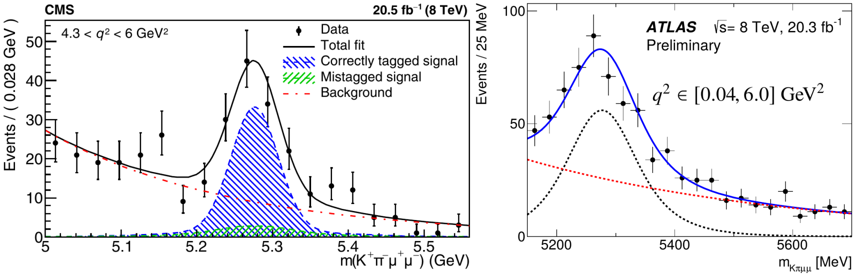
- Use 3 fb^{-1} from Run I
- Reconstruct clear signals in bins of q^2 to be used in angular analysis
- Tension Standard Model prediction from [Descotes-Genon, Hurth, Matias, Virto, JHEP '13] in two bins P'_5 (2.8σ for $4 < q^2 < 6$ GeV and 3.0σ for $6 < q^2 < 8$ GeV) and agreement in other distributions



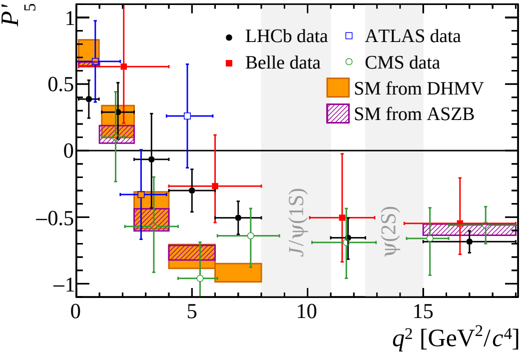


Atlas and CMS [ATLAS-CONF-2017-023, CMS - arXiv:1710.02846]

- Measure distribution of angular parameters using 20 fb^{-1} of 2012
- Use best mass assignment to separate $K^{*0}(K^+\pi^-)$ from $\bar{K}^{*0}(K^-\pi^+)$
  - Mistag rates of 10% (ATLAS) and 14% (CMS) vs (0.05 ± 0.05)% in LHCb thanks to RICH detectors
- Both fold the signal model based on the symmetries to reduce the number of free parameters in the fit
  - ATLAS fit all 6 remaining parameters
  - CMS fixes 3 from [Phys. Lett. B 753 (2016) 424] and estimate with pseudoexperiments the corresponding uncertainty

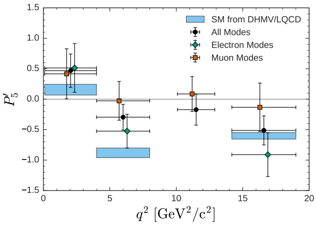


Together



LHCb [JHEP 02 (2016) 104]
Belle [Phys.Rev.Lett. 118 (2017) no.11, 111801]
ATLAS [ATLAS-CONF-2017-023]
CMS [CMS-BPH-15-008, arXiv:1710.02846]
DHMV [Descotes-Genon, Hurth, Matias, Virto, JHEP '13]
ASZB [Bharucha, Straub, Zwicky, JHEP '16, Altmannshofer, Straub, EPJC '15]

- Tension between the Standard Model prediction and ATLAS, Belle and LHCb in $4 < q^2 < 8$ GeV^2
- Belle compares also with $B^0 \to K^{*0} e^+ e^-$



$$B^0_{(s)} \to p\bar{p}$$

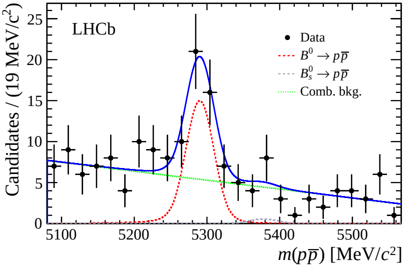
[Phys. Rev. Lett. 119, 232001 (2017)]

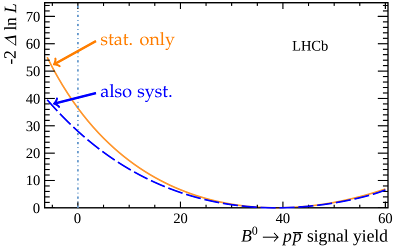
$B^0_{(s)} \to p\bar{p}$ [Phys. Rev. Lett. 119, 232001 (2017)]

- Two-body baryonic *B* decays rather suppressed
- Not seen at the *B* factories
- First two-body mode observed: $B^+ \to p\overline{\Lambda}(1520)$ [Phys. Rev. Lett. 113, 141801 (2014)]
- First evidence of $B^0 \to p\bar{p}$ with 1 fb^{-1}, no B^0_s signal [J. High Energy Phys. 10 (2013) 005]

$$\mathcal{B}(B^0 \to p\bar{p}) = (1.47^{+0.62}_{-0.51}{}^{+0.35}_{-0.14}) \times 10^{-8} \qquad \text{at } 68.3\% \text{ C.L.}$$
$$\mathcal{B}(B^0_s \to p\bar{p}) = (2.84^{+3.57}_{-2.12}{}^{+2.00}_{-0.21}) \times 10^{-8} \qquad \text{at } 90\% \text{ C.L.}$$

- Important to improve knowledge of these very rare decays $B^0_{(s)} \to p\bar{p}$
- New analysis with full Run I dataset (3 fb^{-1})





$$N(B^0 \to p\bar{p}) = 39 \pm 8 \qquad N(B^0_s \to p\bar{p}) = 2 \pm 4$$

- First observation of $B^0 \to p\bar{p}$ at 5.3 σ

$$\mathcal{B}(B^0 \to p\bar{p}) = (1.25 \pm 0.27 \pm 0.18) \times 10^{-8}$$

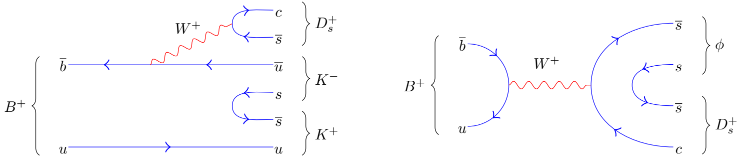
- Use Feldman-Cousin method to set upper limit on $B^0_s \to p\bar{p}$

$$\mathcal{B}(B^0_s \to p\bar{p}) < 1.5 \times 10^{-8} \quad \text{at } 90\% \text{ C.L.}$$

$B^0 \to D_s^+ \phi$

[JHEP 01 (2018) 131]

- Search for pure annihilation decay (large branching fraction possible in New Physics scenarios)
- Update with Run I + Run II dataset ($4.8\ \text{fb}^{-1}$) of previous measurement [JHEP 02(2013) 043] done with $1\ \text{fb}^{-1}$
- Search at the same time for $B^0 \to D_s^+ K^+ K^-$ and $B^0 \to D_s^+ \phi$
- Normalise with $B^0 \to D_s^+ (D^0 \to K^+ K^-)$



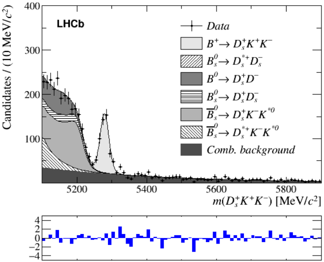
$B^0 \to D_s^+ \phi$ [JHEP 01 (2018) 131]

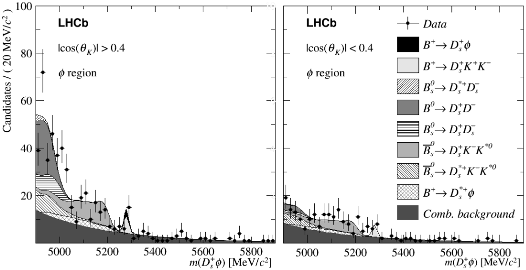
- For $B^0 \to D_s^+ K^+ K^-$ fit phase-space-efficiency-corrected yields

$$\mathcal{B}(B^0 \to D_s^+ K^+ K^-) = (7.1 \pm 0.5\,(\text{stat.}) \pm 0.6\,(\text{syst.}) \pm 0.7\,(\text{norm.})) \times 10^{-6}$$

- For $B^0 \to D_s^+ \phi$ candidates selected in narrow range around ϕ mass and with $|\cos(\theta_K)| > 0.4$
- No signal observed and upper limit set

$$\mathcal{B}(B^0 \to D_s^+ \phi) < 4.9 \times 10^{-7} \text{ @95\% C.L.}$$





Rare charm and baryon decays

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

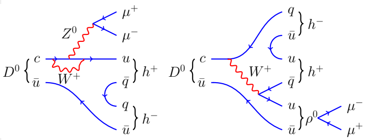
- FCNC $c \to ull$ transition
- Short-distance $\mathcal{B}_{SM} = \mathcal{O}(10^{-9})$ but possibly enached by New Physics
- Long-distance (ρ^0, ω, ϕ) $\mathcal{B}_{SM}$ up to $\mathcal{O}(10^{-6})$

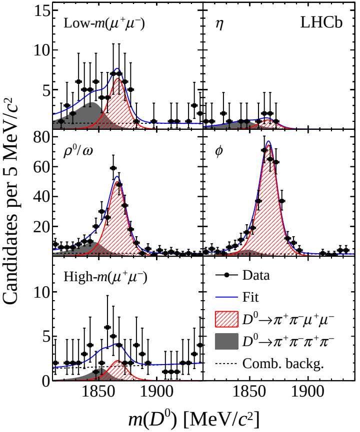
Search on 2012 data (2 fb^{-1})

- Select D^0 from $D^{*+} \to D^0\pi^+$
- Use $D^0 \to K^-\pi^+[\mu^+\mu^-]_{\rho^0/\omega}$ as normalisation mode
- Study signal in different regions of $m_{\mu^+\mu^-}$
- First observations of rarest measured charm decay to date

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

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





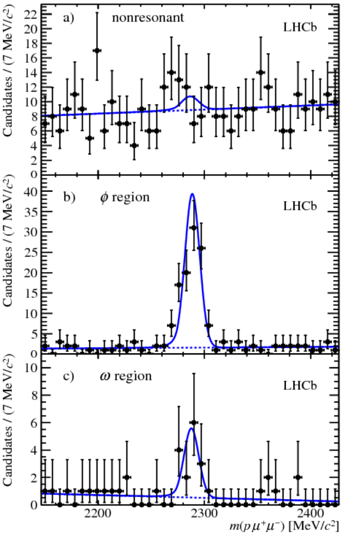
- FCNC $c \to ull$ transition less explored than $b \to sll$
- Short-distance $\mathcal{B}_{SM}(\Lambda_c^+ \to p\mu^+\mu^-) \sim 10^{-9}$
- Long-distance $\mathcal{B}_{SM}(\Lambda_c^+ \to p(V \to \mu^+\mu^-)$ up to 10^{-6}
- Could be enhanced also by New Physics

Search on Run I data (3 fb^{-1})

- 3 q^2 regions: a) nonresonant, b) ϕ, c) ω
- First observation in the ω region at 5σ

$$\mathcal{B}(\Lambda_c^+ \to p\omega) = (9.4 \pm 3.2\,(\text{stat.}) \pm 1.0\,(\text{syst.}) \pm 2.0\,(\text{ext.})) \times 10^{-4}$$

$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 7.7 \times 10^{-8}\ @\ 90\%\ \text{C.L.}$$



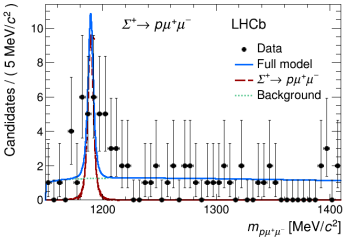
$\Sigma^+ \to p\mu^+\mu^-$ [LHCb-PAPER-2017-049, submitted to PRL]

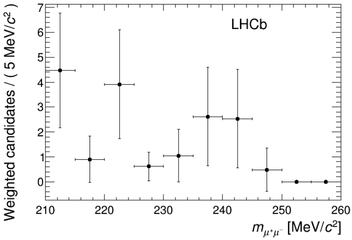
- FCNC $s \to dll$ transition
- $1.6 \times 10^{-8} < \mathcal{B}_{SM} < 9.0 \times 10^{-8}$ [He, Tandean, Valencia, PRD '05] dominated by long distance contributions
- Evidence from HyperCP [Phys.Rev.Lett.94:021801,2005]: three candidates with approximately same $\mu^+\mu^-$ mass close to lower kinematic limit (214.3 ± 0.5 MeV)
  - New intermediate particle?

Search on Run I data (3 fb^{-1})

$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (2.1^{+1.6}_{-1.2}) \times 10^{-8}$ (4σ)

No significant structure observed in $\mu^+\mu^-$ invariant mass distribution





Conclusion

Many rare heavy flavour decays studied by LHC experiments in the past year

- Effective lifetime of $B_s^0 \to \mu^+\mu^-$ measured for the first time
- World's best upper limit set on $B_{(s)}^0 \to \tau^+\tau^-$ and on the LFV decay $B_{(s)}^0 \to e^\pm\mu^\mp$
- Tension with the Standard Model in the $B^0 \to K^{*0}\mu^+\mu^-$ angular analysis still present. Contributions to this measurement from four different experiments
- $B_{(s)}^0 \to p\bar{p}$ observed for the first time: the rarest hadronic B decay observed to date
- First observation of rarest observed charm decay to date: $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$
- Updated limit on pure annihilation decay $B^0 \to D_s^+\phi$
- First observation of $\Lambda_c^+ \to p\mu^+\mu^-$ in the ω region
- Evidence for $\Sigma^+ \to p\mu^+\mu^-$ but no evidence for intermediate state decaying to $\mu^+\mu^-$

BACKUP

Analysis considerations $B^0_{(s)} \to \mu^+\mu^-$

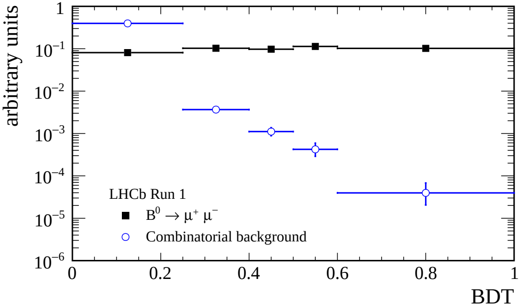
- Various possible sources of background (semileptonic B decays, peaking rare hadronic B decays e.g. $B^0 \to K^+\pi^-$)
- Essential to reduce background: muon identification, well-reconstructed secondary vertices, $\mu^+\mu^-$ mass resolution, isolation variables, pointing angle
- Event classification carried out by BDT including several topological and kinematical variables
- Calibrations/validations with $B^+ \to J/\psi K^+$, $B^0 \to K^+\pi^-$ and $B^0_s \to J/\psi \phi$
- Normalised with $B^+ \to J/\psi K^+$ (and LHCb also with $B^0 \to K^+\pi^-$)

Run I+II: LHCb

[Phys. Rev. Lett. 118, 191801 (2017)]

Several improvements to the analysis strategy:

- Improved isolation variables (combinatorial background reduced by $\sim 50\%$ for BDT> 0.25)
- Improved BDT classifier with uniform response on signal
- Improved muon particle identification (reduced main peaking background $B^0_{(s)} \to h^+ h'^-$ by $\sim 50\%$ with signal reduction of $\sim 10\%$)



$B^0 \to D_s^+ \phi$ [JHEP 01 (2018) 131]