New Physics Searches with $b \to s\ell^+\ell^-$ Transitions and Rare Decays at LHCb

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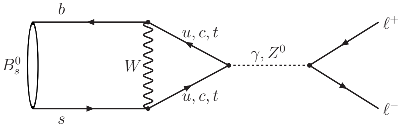
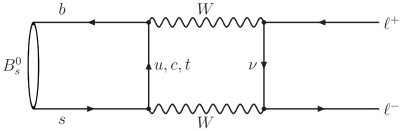
On behalf of the LHCb Collaboration

XXXI Rencontres de Physique de la Vallée d'Aoste
La Thuile – March 8th, 2017

$b \to s\ell^+\ell^-$ Transitions and Rare Decays

Standard Model





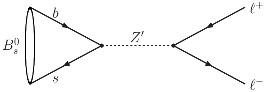
- Flavour Changing Neutral Current
- Forbidden at Tree level

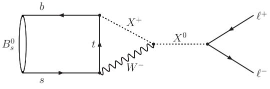
⇒ Loop suppressed

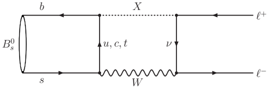
- Sensitive to new physics contributions

Beyond the SM Theories

- Z'/W' models, leptoquarks, 2HDM, . . .



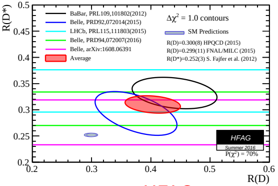




Puzzling Tensions in $b \to s\ell^+\ell^-$ Transitions

$B^0 \to D^{(*)-}\tau^+\nu_\tau$

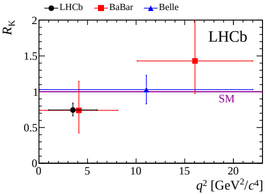
- $R(D^{(*)}) = \dfrac{\mathcal{B}(B^0 \to D^{(*)-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{(*)-}\mu^+\nu_\tau)}$



HFAG, arxiv:1612.07233

$B^+ \to K^+\ell^+\ell^-$

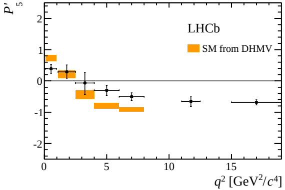
- $R_K = \dfrac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$



LHCb, PRL 113 (2014) 151601, arxiv:1406.6482

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

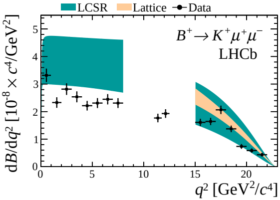
- Angular Observable P_5'



LHCb, JHEP02 (2016) 104, arxiv:1512.04442

$B^+ \to K^+\mu^+\mu^-$

- Differential branching fraction



LHCb, JHEP06 (2014) 133, arxiv:1403.8044

Hints for New Physics?

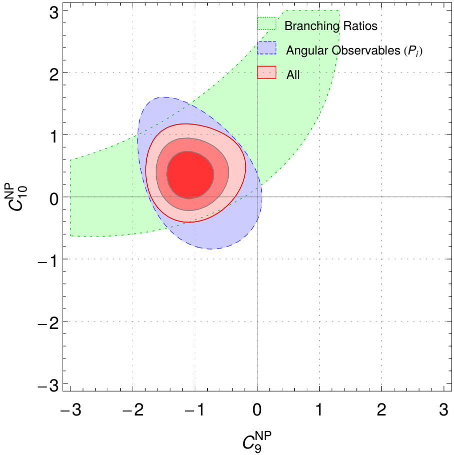
- Model-independent approach:
  Effective Hamiltonian
- Best fit model has Wilson coefficient
  $C_9^{\text{NP}} \approx -1$ (4 to 5σ)
- What can explain this?
  1. Statistical fluctuations
  2. Not-yet-understood SM effects
  3. New Physics

This Talk

1. Phase difference in $B^+ \to K^+\mu^+\mu^-$
2. Search for $B_s^0 \to \mu^+\mu^-\mu^+\mu^-$
3. $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ & Lifetime ← **New!**
4. Search for $B_s^0 \to \tau^+\tau^-$ ← **New!**

In Addition

- Talk on LFU tests at LHCb
  [Stefanie Reichert, Wednesday 16h50]
- YSF talk on $\Lambda_b^0 \to p\pi^-\mu^+\mu^-$
  [Eluned Smith, Tuesday 18h05]

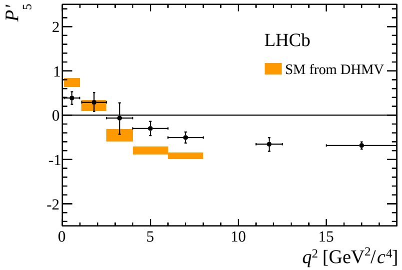


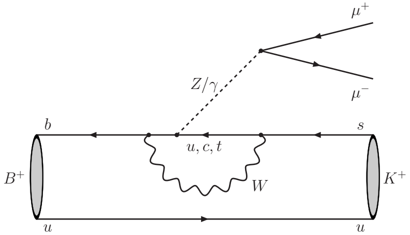
S.Descotes-Genon *et al.*, JHEP 06 (2016) 092
arxiv:1510.04239

Phase Difference in $B^+ \to K^+\mu^+\mu^-$ Decays

How Large are the $c\bar{c}$ Contributions?

q^2 Spectrum ($B^0 \to K^{*0}\mu^+\mu^-$)





- Short-distance effects: Electroweak penguins
- Long-distance effects from intermediate resonances: J/ψ, $\psi(2S)$, higher $c\bar{c}$ states
  - $\to$ Associated with large uncertainties: usually avoided
- Contribution from J/ψ can potentially extent all the way to $q^2 = 0$

Goal

- Provide additional insights using the ground-state system $B^+ \to K^+\mu^+\mu^-$
  - $\to$ Allows precise Lattice calculations
  - $\to$ Can still use branching fraction to constrain Wilson coefficients

Study of $B^+ \to K^+\mu^+\mu^-$

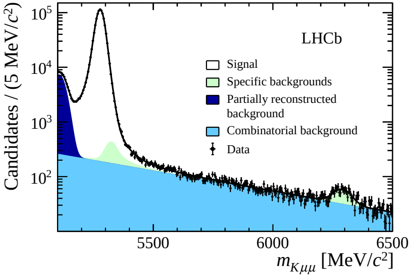
LHCb-PAPER-2016-045, to appear in EPJC, arxiv:1612.06764

Objectives

- Phase difference between J/ψ, $\psi(2S)$ and the penguin contribution
- Wilson coefficients C_9 and C_{10}
- $\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$

Strategy

- Select $B^+ \to K^+\mu^+\mu^-$ candidates with $m_{K\mu\mu}$ in 80 MeV$/c^2$ window around B^+
- Model $m_{\mu\mu}$ over full range, including the resonance regions
  - → J/ψ and $\psi(2S)$ are modelled using a Breit-Wigner
  - → Penguin is modelled using Wilson coefficients and form factors

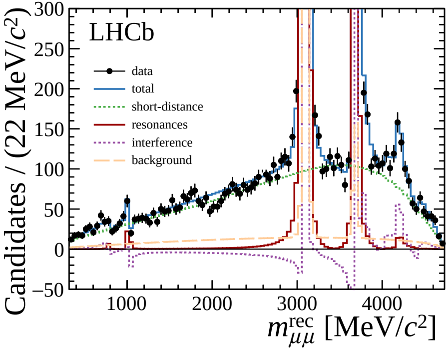


Main Results

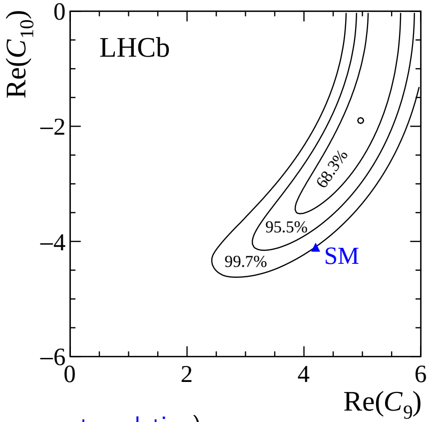
LHCb-PAPER-2016-045, to appear in EPJC, arxiv:1612.06764

- 4-fold degenerate solution: phases of J/ψ and $\psi(2S)$ can be $+$ or $-$

$\varphi_{J/\psi} < 0$ and $\varphi_{\psi(2S)} < 0$ Solution



Wilson Coefficients



Branching Ratio

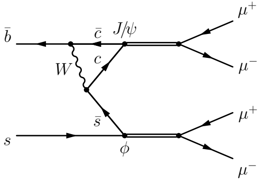
- Short-distance component (full $m_{\mu\mu}$ range, no extrapolation)

$$\mathcal{B}(B^+ \to K^+\mu^+\mu^-) = (4.37 \pm 0.15\,(\text{stat}) \pm 0.23\,(\text{syst})) \times 10^{-7}$$

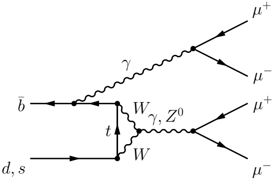
Search for $B_s^0 \to \mu^+\mu^-\mu^+\mu^-$ and $B^0 \to \mu^+\mu^-\mu^+\mu^-$

Search for the Rare Decays $B \to \mu^+\mu^-\mu^+\mu^-$

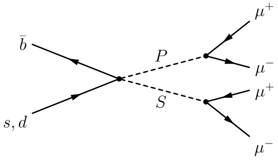
Resonant



Non-Resonant



New Physics



4 Muon Final State:

1. Intermediate J/ψ, $\psi(2S)$ and ϕ resonances
   - → Most abundant: $B_s^0 \to J/\psi\phi$ with $\mathcal{B}(B_s^0 \to J/\psi\phi) = (1.83 \pm 0.18) \times 10^{-8}$
2. Non-resonant component (Signal)
   - → SM expectation: $\mathcal{B}(B_s^0 \to \mu^+\mu^-\mu^+\mu^-) \overset{\text{SM}}{\sim} 3.5 \times 10^{-11}$

     Y. Dincer and L. Sehgal, PLB 556 (2003) 169, arxiv:hep-ph/0301056
3. New physics contributions
   - → For example, MSSM model with scalar (S) +pseudo-scalar (P) sgoldstino interactions
   - → Motivated by excess seen by HyperCP collaboration: $\Sigma^+ \to P(\to \mu^+\mu^-)p$

     HyperCP, PRL 94 (2005) 021801, arxiv:hep-ex/0501014

Analysis Strategy

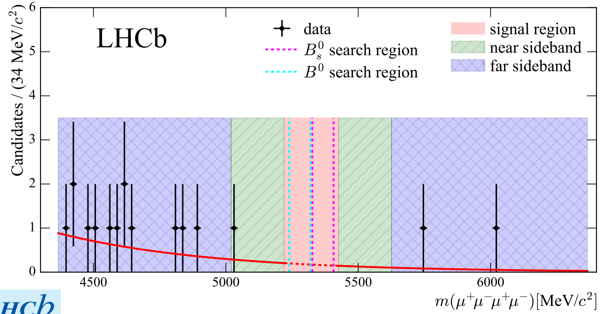
LHCb-PAPER-2016-043, to appear in JHEP, arxiv:1611.07704

Selection

1. Resonant components: Veto ϕ, J/ψ and $\psi(2S)$ mass windows in all $\mu^+\mu^-$ comb.
2. Combinatorial background: Selection is based on a MatrixNet [JMLR Proc. 14 (2011) 63]
3. Background from $\pi \to \mu$ misidentification: Particle identification requirements

Event Yield

- Split data into Far Sideband, Near Sideband and Signal regions
- PID and MatrixNet cuts optimised using Near Sideband region
- Background yield in *Signal* region extrapolated from fit to Far Sideband



Signal Region

- Expected Bkg yields

$$N_{\text{bkg}}(B^0) = 0.55 \pm 0.31$$

$$N_{\text{bkg}}(B_s^0) = 0.47 \pm 0.29$$

Main Results

LHCb-PAPER-2016-043, to appear in JHEP, arxiv:1611.07704

- No events found in Signal region
- Set limit on braching ratio

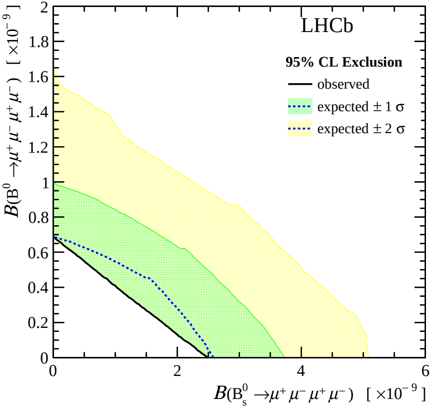
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\mu^+\mu^-) = \alpha^s \times N^{obs}_{\mu^+\mu^-\mu^+\mu^-}$$

- with normalisation mode $B^+ \to J/\psi K^+$

$$\alpha^s \equiv \frac{\epsilon^{J/\psi K^+} \times \mathcal{B}(B^+ \to J/\psi K^+)}{\epsilon^{4\mu} \times N_{J/\psi K^+}} \times \frac{f_u}{f_s}$$

- Single event sensitivity:

$$\alpha^s = (2.29 \pm 0.16) \times 10^{-10}$$
$$\alpha^d = (8.65 \pm 0.80) \times 10^{-10}$$



Branching Fraction Limits (CL$_s$ Method)

$$\mathcal{B}(B^0 \to \mu^+\mu^-\mu^+\mu^-) < 6.9 \times 10^{-10} \quad @\,95\,\%\text{ C.L.}$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\mu^+\mu^-) < 2.5 \times 10^{-9} \quad @\,95\,\%\text{ C.L.}$$

NEW

$B_s^0 \to \mu^+\mu^-$ Branching Ratio and Effective Lifetime

Search for the Rare Decays $B \to \mu^+\mu^-$

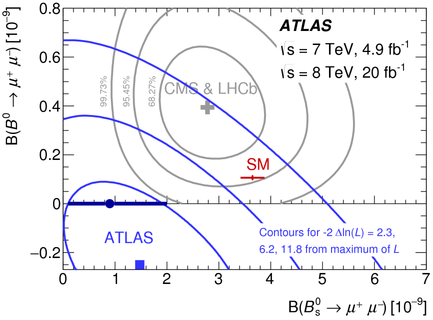
- Theoretically clean quantity → accurate SM prediction

$$\mathcal{B}(B^0 \to \mu^+\mu^-) \stackrel{\text{SM}}{=} (1.06 \pm 0.09) \times 10^{-10}$$

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) \stackrel{\text{SM}}{=} (3.66 \pm 0.23) \times 10^{-9}$$

Bobeth *et al.*, PRL 96 (2006) 241802, arxiv:hep-ex/0511015

Current Status



ATLAS, EPJC 76 (2016) 513, arxiv:1604.04263

CMS+LHCb, Nature 522 (2015) 68, arxiv:1411.4413

Analysis Strategy

LHCb-PAPER-2017-001

In a Nutshell

- Same strategy as for the Run 1 CMS+LHCb analysis
- Selection based on: BDT + particle identification (PID)
  - → BDT output is flat for signal, calibrated on $B^0 \to K^+\pi^-$
  - → BDT output peaks towards zero for background, calibrated on mass sidebands
- Fit the $m_{\mu^+\mu^-}$ mass in bins of BDT output

Improvements

- Larger data sample: $3\,\text{fb}^{-1}$ Run 1 + $1.4\,\text{fb}^{-1}$ of Run 2
- New and improved signal isolation
- New and improved BDT: 50% better background rejection
- Improved PID requirements: 50% less $B \to h^+h^-$ background

Normalisation

- Two control channels: $B^+ \to J/\psi K^+$ and $B^0 \to K^+\pi^-$
- Dependence of hadronisation fraction f_s/f_d on $\sqrt{s}$ evaluated comparing $B^+ \to J/\psi K^+$ and $B^0_s \to J/\psi\phi$

Analysis Strategy

LHCb-PAPER-2017-001

Mass Fit

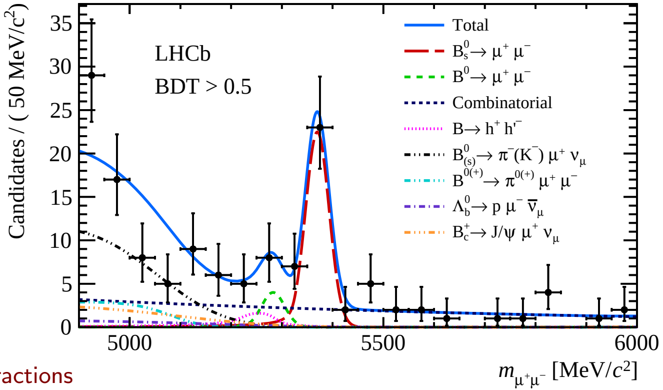
- Unbinned maximum likelihood fit in 4 bins of BDT output
- $m_{\mu^+\mu^-} \in [4900, 6000]$ MeV/c^2
- Exclude BDT< 0.25 (background dominated)
- Simultaneous fit of Run 1 and Run 2 data
- Free parameters: $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$, $\mathcal{B}(B^0 \to \mu^+\mu^-)$ and comb. bkg.
- Exclusive background yields are constrained in fit

Exclusive Backgrounds

- Decays with two real muons
  - $B_c^+ \to J/\psi\mu^+\nu_\mu$
  - $B^{0(+)} \to \pi^{0(+)}\mu^+\mu^-$
- Decays with hadrons misidentified as muons
  - $B \to h^+h^-$ (peaking in signal region)
  - $B^0 \to \pi^-\mu^+\nu_\mu$
  - $B_s^0 \to K^-\mu^+\nu_\mu$
  - $\Lambda_b^0 \to p\mu^+\nu_\mu$

A Nice Peak!

LHCb-PAPER-2017-001



Branching Fractions

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6\,(\text{stat})\,^{+0.3}_{-0.2}\,(\text{syst})) \times 10^{-9} \qquad (7.8\sigma)$$

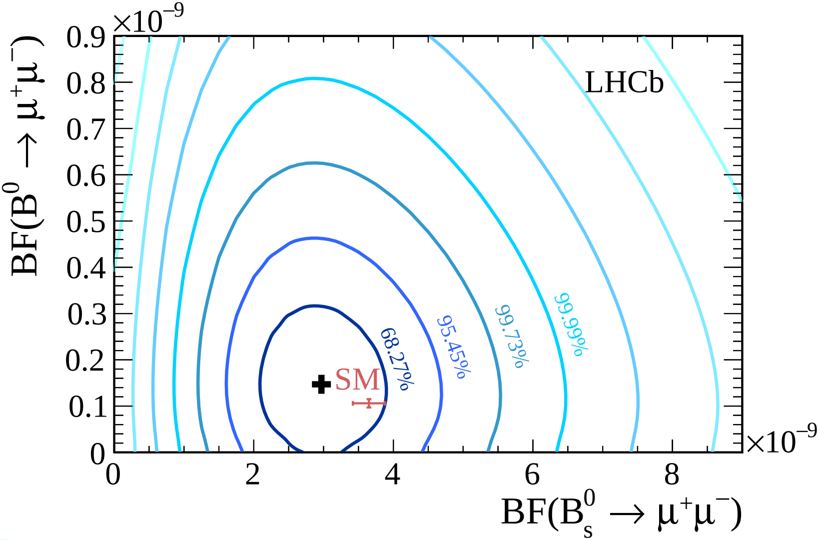
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.5\,^{+1.2}_{-1.0}\,(\text{stat})\,^{+0.2}_{-0.1}\,(\text{syst})) \times 10^{-10} \qquad (1.6\sigma)$$

Branching Fraction Limit (CL_s Method)

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

2D Contours

LHCb-PAPER-2017-001



$B_s^0 \to \mu^+\mu^-$ Effective Lifetime

- Even if $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\mathrm{SM}}$, NP can still hide in this decay
- Need a second, complementary observable to find it:
  either CP asymmetry parameter $\mathcal{A}_{\Delta\Gamma}^{\mu^+\mu^-}$ or effective lifetime $\tau_{\mu^+\mu^-}$
- Defined as

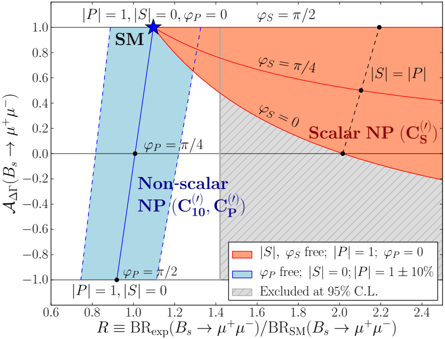
$$\tau_{\mu^+\mu^-} \equiv \frac{\int_0^\infty t\langle\Gamma(B_s(t) \to \mu^+\mu^-)\rangle \mathrm{d}t}{\int_0^\infty \langle\Gamma(B_s(t) \to \mu^+\mu^-)\rangle \mathrm{d}t}$$

- They are related

$$\tau_{\mu^+\mu^-} = \frac{\tau_{B_s}}{1-y_s^2}\left[\frac{1+2\mathcal{A}_{\Delta\Gamma}^{\mu^+\mu^-} y_s + y_s^2}{1+\mathcal{A}_{\Delta\Gamma}^{\mu^+\mu^-} y_s}\right]$$

- where

$$y_s \equiv \tau_{B_s}\Delta\Gamma_s/2 = 0.062 \pm 0.006$$



K. De Bruyn *et al.*, PRL 109 (2012) 041801
arxiv:1204.1737

$B_s^0 \to \mu^+\mu^-$ Effective Lifetime

LHCb-PAPER-2017-001

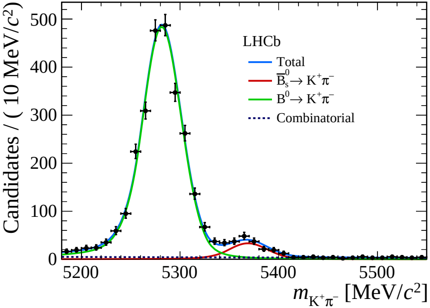
Analysis Strategy

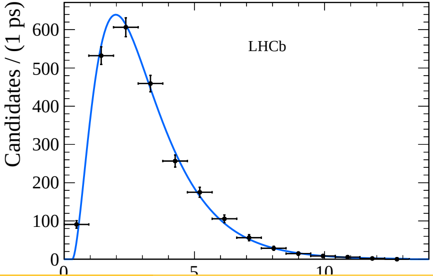
- Apply same selection, but looser cuts
- Reduces mass window $m_{\mu^+\mu^-} \in [5320, 6000]$ MeV/c^2
- Step 1: Mass fit to derive weights (sPlot technique)
- Step 2: Fit to weighted decay time distribution
- Strategy validated on $B^0 \to K^+\pi^-$

$$\tau_{B^0} = 1.52 \pm 0.03\,(\text{stat})\text{ ps}$$

- Compare to

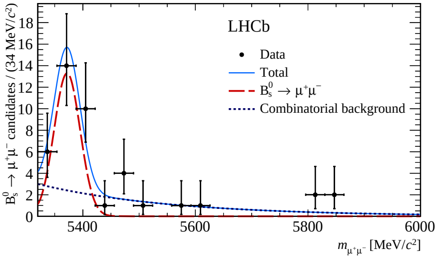
$$\tau_{B^0}^{\text{PDG}} = 1.520 \pm 0.004\text{ ps}$$

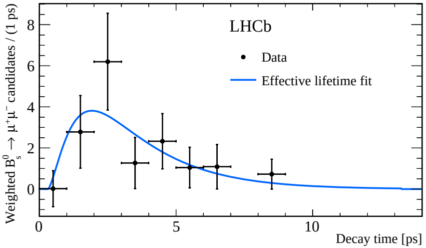




$B_s^0 \to \mu^+\mu^-$ Effective Lifetime

LHCb-PAPER-2017-001





Results

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

- Consistent with both $\mathcal{A}_{\Delta\Gamma}^{\mu^+\mu^-} = 1$ (1σ) and $\mathcal{A}_{\Delta\Gamma}^{\mu^+\mu^-} = -1$ (1.4σ)
- Does not yet constrain any NP models

NEW

Search for $B_s^0 \to \tau^+\tau^-$ and $B^0 \to \tau^+\tau^-$

Search for the Rare Decays $B \to \tau^+\tau^-$

- In the SM, only difference between $B_s^0 \to \tau^+\tau^-$ and $B_s^0 \to \mu^+\mu^-$ is due to helicity suppression (lepton mass)
- Theoretically clean quantity $\to$ accurate SM prediction

$$\mathcal{B}(B^0 \to \tau^+\tau^-) \stackrel{\text{SM}}{=} (2.22 \pm 0.19) \times 10^{-8}$$

$$\mathcal{B}(B_s^0 \to \tau^+\tau^-) \stackrel{\text{SM}}{=} (7.73 \pm 0.49) \times 10^{-7}$$

Bobeth *et al.*, PRL 96 (2006) 241802, arxiv:hep-ex/0511015

- Current best limit:

$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 4.1 \times 10^{-3} \quad \text{@ 90\% C.L.}$$

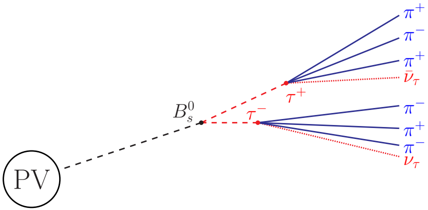
BaBar, PLB 687 (2010) 139, arxiv:1001.3221

LHCb Analysis for $B_s^0 \to \tau^+\tau^-$

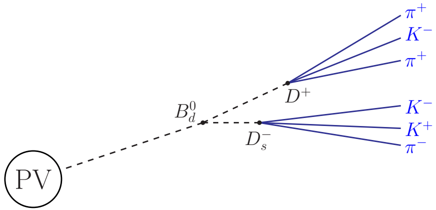
- Reconstructed in hadronic $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ mode (both τs)
  $\to$ Low efficiency: $\mathcal{B}(\tau^- \to \pi^-\pi^+\pi^-\nu_\tau) = (9.31 \pm 0.05)\%$
- Normalisation mode: $B^0 \to D^+(\to \pi^+K^-\pi^+)D_s^-(\to K^-K^+\pi^-)$

Experimental Signature

$B_s^0 \to \tau^+\tau^-$



$B^0 \to D^+D_s^-$



Challenges

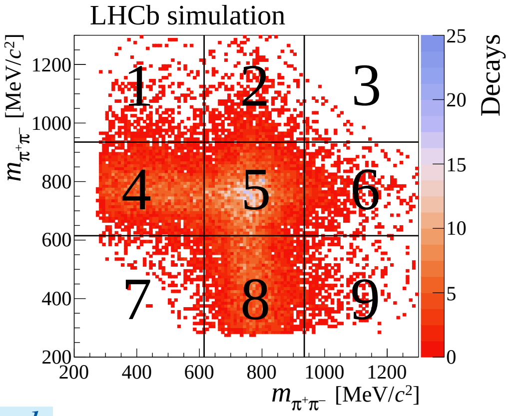
1. 2 missing neutrinos
   - No narrow (mass) peak to fit
   - Cannot differentiate B_s^0 from B^0
2. 6 pions = large combinatorial background
   - Use isolation variables to suppress background
   - Use decay geometry to approximately reconstruct the B and τ properties

Intermediate Resonances

- Predominantly proceeds through

$$\tau^- \to a_1^-(1260)\nu_\tau \to \rho^0(770)\pi^-\nu_\tau \ .$$

- Exploit this in analysis



Subsamples:

- Signal Region [SR]:
  $(\tau^+ \in 5)$ & $(\tau^- \in 5)$
- Signal-Depleted Region:
  $(\tau^+ \in 1,3,7,9) || (\tau^- \in 1,3,7,9)$
- Control Region [CR]:
  $(\tau^\pm \in 4,5,8)$ & $(\tau^\mp \in 4,8)$

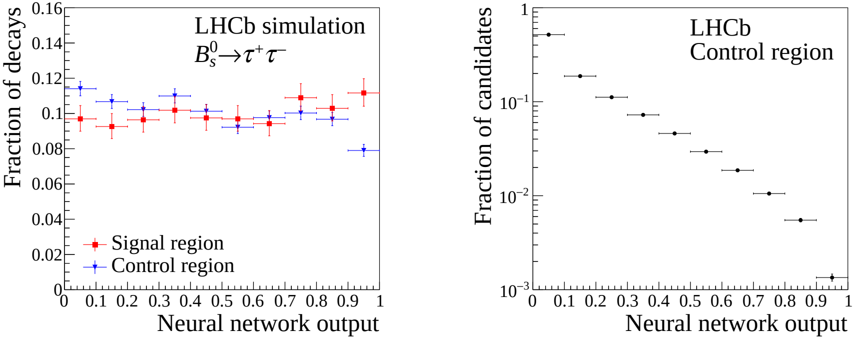
Selection:

- Cut-based loose selection
- Two-stage neural network

Fit Strategy

LHCb-PAPER-2017-003, arxiv:1703.02508

- Perform a 1-dimensional histogram fit to the output of a neural network
- Output is remapped such that signal is flat
- The Signal templates are taken from simulation
- The Background template is taken from data control region



Fit Model

LHCb-PAPER-2017-003, arxiv:1703.02508

Events:

Signal: 16% $B_s^0 \to \tau^+\tau^-$ Simulation versus 7% data

Sig.-Depleted: 13% $B_s^0 \to \tau^+\tau^-$ Simulation versus 37% data

Control: 58% $B_s^0 \to \tau^+\tau^-$ Simulation versus 47% data

- ...so the data control region might also contain signal.

Model:

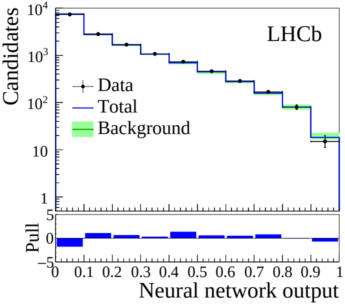
$$\mathcal{N}_{\text{data}}^{\text{SR}} = s \times \widehat{\mathcal{N}}_{\text{sim}}^{\text{SR}} + f_b \times \left(\mathcal{N}_{\text{data}}^{\text{CR}} - s \cdot \frac{\epsilon_{\text{CR}}}{\epsilon_{\text{SR}}} \times \widehat{\mathcal{N}}_{\text{sim}}^{\text{CR}} \right)$$

- s: signal yield (free parameter)
- f_b: scaling factor for background template (free parameter)
- ϵ_i: efficiencies, taken from simulation
- $\widehat{\ }$: indicates normalised distributions

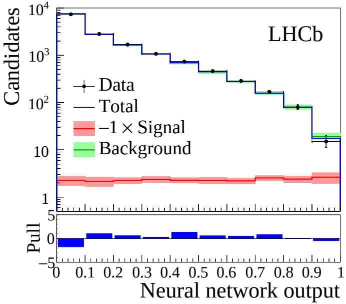
Fit to Data

LHCb-PAPER-2017-003, arxiv:1703.02508

Background-Only Model



Nominal Fit Model



$$N^{\text{obs}}_{\tau^+\tau^-} = s = -23 \pm 71$$

- Compatible with the background-only hypothesis

→ Set an upper limit

From Yield to Branching Ratio

LHCb-PAPER-2017-003, arxiv:1703.02508

$$\mathcal{B}(B_s^0 \to \tau^+\tau^-) = \alpha^s \times N^{\text{obs}}_{\tau^+\tau^-} ,$$

- Assume all signal comes from $B_s^0 \to \tau^+\tau^-$, i.e. ignore $B^0 \to \tau^+\tau^-$ completely
- Determine α^s using $B^0 \to D^- D_s^+$ normalisation mode

$$\alpha^s = \frac{\epsilon^{D^- D_s^+} \times \mathcal{B}(B^0 \to D^- D_s^+) \times \mathcal{B}(D^+ \to \pi^+ K^- \pi^+) \times \mathcal{B}(D_s^+ \to K^+ K^- \pi^+)}{N^{\text{obs}}_{D^- D_s^+} \times \epsilon^{\tau^+\tau^-} \times [\mathcal{B}(\tau^- \to \pi^-\pi^+\pi^-\nu_\tau)]^2} \times \frac{f_d}{f_s}$$

- Fit to data, Efficiencies from simulation, External Input

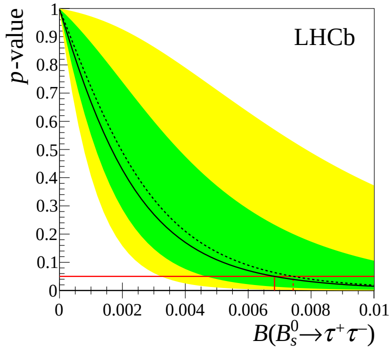
$$\alpha^s = (4.07 \pm 0.70) \times 10^{-5} \quad \to \quad N^{\text{SM}}_{\tau^+\tau^-} = 0.019$$

$$\alpha^d = (1.16 \pm 0.19) \times 10^{-5} \quad \to \quad N^{\text{SM}}_{\tau^+\tau^-} = 0.002$$

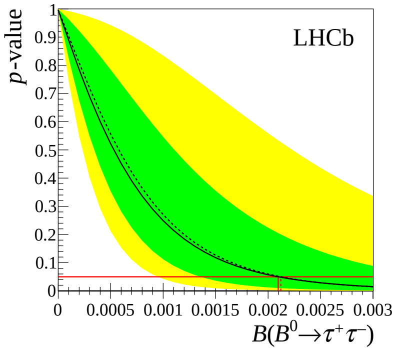
Branching Fraction Limit

LHCb-PAPER-2017-003, arxiv:1703.02508

$B_s^0 \to \tau^+\tau^-$



$B^0 \to \tau^+\tau^-$



Branching Fraction Limit ($\mathrm{CL_s}$ Method)

$$\mathcal{B}(B_s^0 \to \tau^+\tau^-) < 6.8 \times 10^{-3} \quad @\,95\,\%\ \text{C.L.}$$
$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3} \quad @\,95\,\%\ \text{C.L.}$$

Conclusion

- Study of the short and long-distance effects in $B^+ \to K^+\mu^+\mu^-$

$$\mathcal{B}(B^+ \to K^+\mu^+\mu^-) = (4.37 \pm 0.15\,(\text{stat}) \pm 23\,(\text{syst})) \times 10^{-7}$$

- Improved limits on the $B \to \mu^+\mu^-\mu^+\mu^-$ branching ratios

$$\mathcal{B}(B^0 \to \mu^+\mu^-\mu^+\mu^-) < 6.9 \times 10^{-10} \quad @\,95\,\%\ \text{C.L.}$$
$$\mathcal{B}(B^0_s \to \mu^+\mu^-\mu^+\mu^-) < 2.5 \times 10^{-9} \quad @\,95\,\%\ \text{C.L.}$$

- Improved measurement of $B^0_s \to \mu^+\mu^-$ branching ratio **New!**

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.0 \pm 0.6\,(\text{stat})\,^{+0.3}_{-0.2}\,(\text{syst})) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \quad @\,95\,\%\ \text{C.L.}$$

- First measurement of the $B^0_s \to \mu^+\mu^-$ effective lifetime **New!**

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

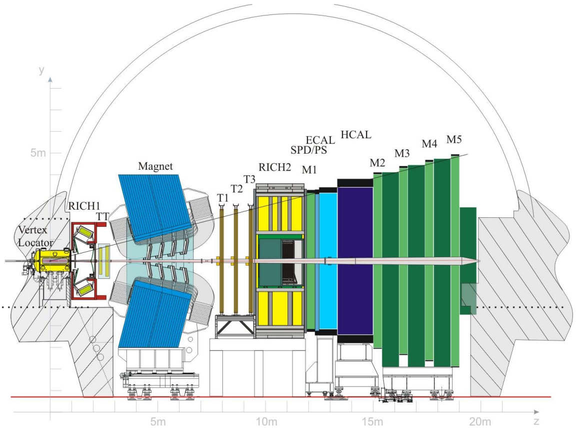
- First limit on the $B^0_s \to \tau^+\tau^-$ branching ratio **New!**

$$\mathcal{B}(B^0_s \to \tau^+\tau^-) < 6.8 \times 10^{-3} \quad @\,95\,\%\ \text{C.L.}$$
$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3} \quad @\,95\,\%\ \text{C.L.}$$

Supplementary Material

The LHCb Detector

JINST 3 (2008) S08005



Forward arm spectrometer to study b- and c-hadron decays

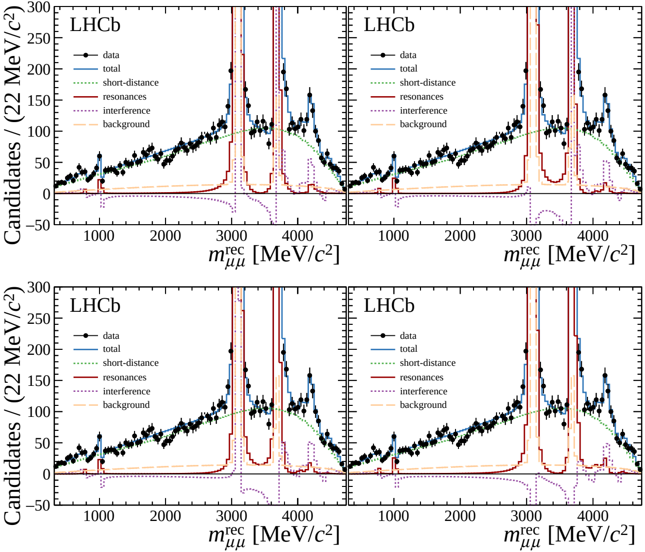
- Pseudo-rapidity coverage: $2 < \eta < 5$

- Good impact parameter resolution to identify secondary vertices: $(15 + 29/p_{\mathrm{T}})\ \mu\mathrm{m}$
- Invariant mass resolution: $8\ \mathrm{MeV}/c^2$ $(B \to J/\psi X)$ $22\ \mathrm{MeV}/c^2$ $(B \to hh)$
- Excellent particle identification: $95\,\%$ K ID efficiency ($5\,\%$ $\pi \to K$ mis-ID)
- Versatile & efficient trigger for b- and c-hadrons and forward EW signals

$B^+ \to K^+\mu^+\mu^-$

LHCb-PAPER-2016-045, to appear in EPJC, arxiv:1612.06764

- 4-fold degenerate solution: phases of J/ψ and $\psi(2S)$ can be $+$ or $-$



$B^+ \to K^+\mu^+\mu^-$

LHCb-PAPER-2016-045, to appear in EPJC, arxiv:1612.06764

Resonance	J/ψ negative/$\psi(2S)$ negative Phase [rad]	Branching fraction	J/ψ negative/$\psi(2S)$ positive Phase [rad]	Branching fraction
$\rho(770)$	-0.35 ± 0.54	$(1.71 \pm 0.25) \times 10^{-10}$	-0.30 ± 0.54	$(1.71 \pm 0.25) \times 10^{-10}$
$\omega(782)$	0.26 ± 0.39	$(4.93 \pm 0.59) \times 10^{-10}$	0.30 ± 0.38	$(4.93 \pm 0.58) \times 10^{-10}$
$\phi(1020)$	0.47 ± 0.39	$(2.53 \pm 0.26) \times 10^{-9}$	0.51 ± 0.37	$(2.53 \pm 0.26) \times 10^{-9}$
J/ψ	-1.66 ± 0.05	–	-1.50 ± 0.05	–
$\psi(2S)$	-1.93 ± 0.10	$(4.64 \pm 0.20) \times 10^{-6}$	2.08 ± 0.11	$(4.69 \pm 0.20) \times 10^{-6}$
$\psi(3770)$	-2.13 ± 0.42	$(1.38 \pm 0.54) \times 10^{-9}$	-2.89 ± 0.19	$(1.67 \pm 0.61) \times 10^{-9}$
$\psi(4040)$	-2.52 ± 0.66	$(4.17 \pm 2.72) \times 10^{-10}$	-2.69 ± 0.52	$(4.25 \pm 2.83) \times 10^{-10}$
$\psi(4160)$	-1.90 ± 0.64	$(2.61 \pm 0.84) \times 10^{-9}$	-2.13 ± 0.33	$(2.67 \pm 0.85) \times 10^{-9}$
$\psi(4415)$	-2.52 ± 0.36	$(6.04 \pm 3.93) \times 10^{-10}$	-2.43 ± 0.43	$(7.10 \pm 4.48) \times 10^{-10}$

Resonance	J/ψ positive/$\psi(2S)$ negative Phase [rad]	Branching fraction	J/ψ positive/$\psi(2S)$ positive Phase [rad]	Branching fraction
$\rho(770)$	-0.26 ± 0.54	$(1.71 \pm 0.25) \times 10^{-10}$	-0.22 ± 0.54	$(1.71 \pm 0.25) \times 10^{-10}$
$\omega(782)$	0.35 ± 0.39	$(4.93 \pm 0.58) \times 10^{-10}$	0.38 ± 0.38	$(4.93 \pm 0.58) \times 10^{-10}$
$\phi(1020)$	0.58 ± 0.38	$(2.53 \pm 0.26) \times 10^{-9}$	0.62 ± 0.37	$(2.52 \pm 0.26) \times 10^{-9}$
J/ψ	1.47 ± 0.05	–	1.63 ± 0.05	–
$\psi(2S)$	-2.21 ± 0.11	$(4.63 \pm 0.20) \times 10^{-6}$	1.80 ± 0.10	$(4.68 \pm 0.20) \times 10^{-6}$
$\psi(3770)$	-2.40 ± 0.39	$(1.39 \pm 0.54) \times 10^{-9}$	-2.95 ± 0.14	$(1.68 \pm 0.61) \times 10^{-9}$
$\psi(4040)$	-2.64 ± 0.50	$(4.05 \pm 2.76) \times 10^{-10}$	-2.75 ± 0.48	$(4.30 \pm 2.86) \times 10^{-10}$
$\psi(4160)$	-2.11 ± 0.38	$(2.62 \pm 0.82) \times 10^{-9}$	-2.28 ± 0.24	$(2.68 \pm 0.81) \times 10^{-9}$
$\psi(4415)$	-2.42 ± 0.46	$(6.13 \pm 3.98) \times 10^{-10}$	-2.31 ± 0.48	$(7.12 \pm 4.94) \times 10^{-10}$

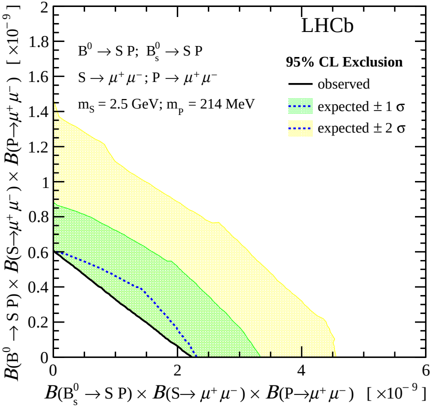
$B \to \mu^+\mu^-\mu^+\mu^-$

LHCb-PAPER-2016-043, to appear in JHEP, arxiv:1611.07704

HyperCP-inspired MSSM Scenario

- Single event sensitivity:

$$\alpha^s(\text{MSSM}) = (2.01 \pm 0.14) \times 10^{-10}$$
$$\alpha^d(\text{MSSM}) = (7.75 \pm 0.72) \times 10^{-10}$$



Branching Fraction Limits (CL_s Method)

$$\mathcal{B}(B^0 \to S(\to \mu^+\mu^-)P(\to \mu^+\mu^-)) < 6.9 \times 10^{-10} \quad @\,95\,\%\ \text{C.L.}$$
$$\mathcal{B}(B_s^0 \to S(\to \mu^+\mu^-)P(\to \mu^+\mu^-)) < 2.5 \times 10^{-9} \quad @\,95\,\%\ \text{C.L.}$$