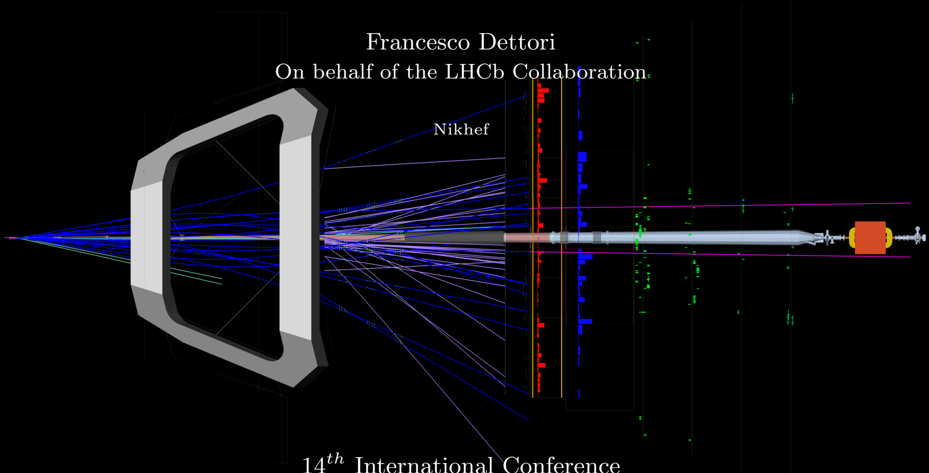
Very rare decays at LHCb



Francesco Dettori
On behalf of the LHCb Collaboration

Nikhef

14^{th} International Conference
on B-Physics at Hadron Machines
BEAUTY 2013
8-13 April - Bologna

Rare beauty decays

- Rare decays are fundamental tools for indirect searches of new physics
- Very rare decays here means $\mathcal{B} \lesssim 10^{-8}$
- Indirectly probing higher energy scales than directly accessible

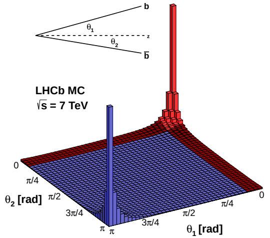
  ⋆ Flavour changing neutral currents
  highly suppressed in SM: only higher order diagrams plus GIM mechanism

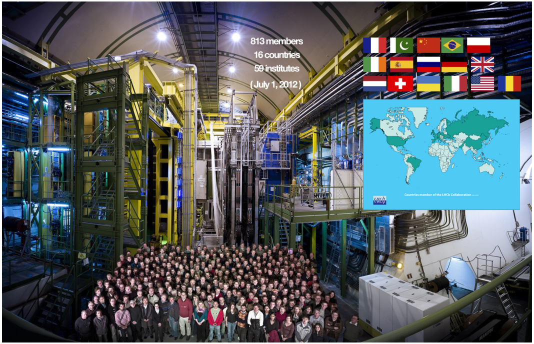
  ⋆ Forbidden decays:
  might be allowed by new particles at tree level or in the loops

The LHCb experiment

Large Hadron Collider
as flavour factory

- pp collisions at 7-8 TeV
- Large b-quark production in the forward region
- Full b-hadrons spectrum
- $\mathcal{L} = 3 - 4 \cdot 10^{32} \text{cm}^{-2}\text{s}^{-1}$
- $\int \mathcal{L} = 3.1 \text{fb}^{-1}$
  $\Rightarrow \mathcal{O}(10^{12})\ b\bar{b}$ pairs

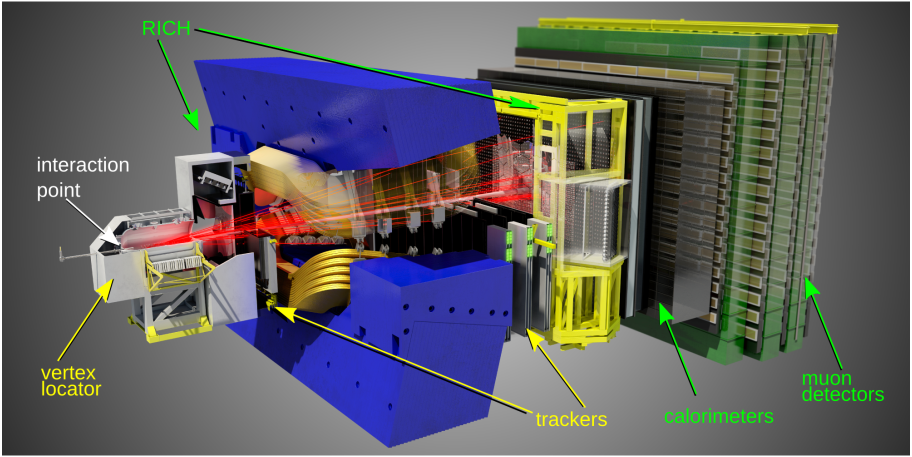




LHCb:

- Specialized B-physics experiment
- Forward single arm spectrometer
- Acceptance: $2 < \eta < 5$

The LHCb detector



Excellent vertex and IP resolution

- $\sigma(IP) \simeq 24\mu\text{m}$ at $p_{\text{T}} = 2$ GeV/c
- $\sigma_{\text{BV}} \simeq 16\mu\text{m}$ in x, y

Very good momentum resolution

- $\sigma(p)/p = 0.4\% - 0.6\%$ for $p \in (0, 100)$ GeV/c
- $\sigma(m_B) \sim 26$ MeV for two body decays

Muon identification

- $\varepsilon_\mu = 98\%$, $\varepsilon_{\pi\to\mu} = 0.6\%$, $\varepsilon_{K\to\mu} = 0.3\%$, $\varepsilon_{p\to\mu} = 0.3\%$

Trigger

- $\varepsilon_\mu = 90\%$

Outline

- Lepton and baryon number violation in τ decays
- Search for $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$ decays
- Updated search for $B^0_{d,s} \to \mu^+\mu^-$ decays

Lepton and baryon number violation in τ decays

$\tau^- \to \mu^-\mu^+\mu^-$, $\tau^- \to \bar{p}\mu^+\mu^-$, $\tau^- \to p\mu^-\mu^-$

Large inclusive τ production ($\sigma \sim 80\mu b$)

Selection

- Three tracks ($p_T > 300$ MeV/c, IP$\chi^2 > 9$) with mass around the τ
- Vertex $\chi^2 < 15$ and $c\tau > 100\mu$m
- Vetoes of $m_{\mu\mu} \sim m_\phi$ and $m_{\mu\mu} < 450 MeV/c^2$ to reject $D_s^- \to \eta(\mu^+\mu^-\gamma)\mu^-\bar{\nu}_\mu$

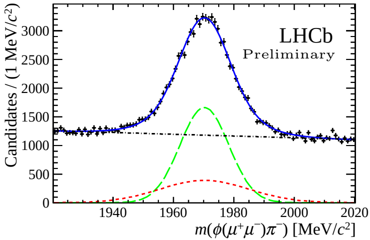
Normalisation

$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) = \mathcal{B}(D_s^- \to \phi(\to \mu\mu)\pi) \times \frac{f_\tau^{D_s}}{\mathcal{B}(D_s^- \to \tau\bar{\nu}_\tau)} \times \frac{\varepsilon_{cal}}{\varepsilon_{sig}} \times \frac{N_{sig}}{N_{cal}}$$

Background discrimination

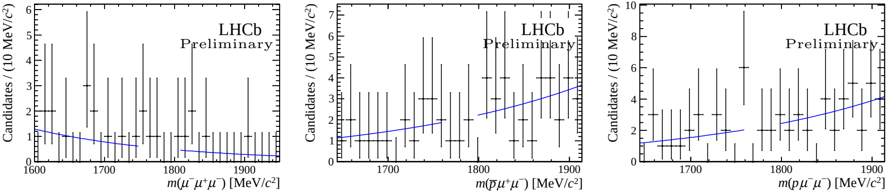
Three likelihoods

- $\mathcal{M}_{\text{3body}}$: multivariate topological variable to reject multi-body decays and combinatorial
- $\mathcal{M}_{\text{PID}}$: identification likelihood to reject mis-ID
- Invariant mass



Lepton and baryon number violation in τ decays

$\tau^- \to \mu^-\mu^+\mu^-$, $\tau^- \to \bar{p}\mu^+\mu^-$, $\tau^- \to p\mu^-\mu^-$



Upper limits with CLs method at the 90% (95%) CL

$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 8.0(9.8) \times 10^{-8}$$
$$\mathcal{B}(\tau^- \to \bar{p}\mu^+\mu^-) < 3.3(4.3) \times 10^{-7}$$
$$\mathcal{B}(\tau^- \to p\mu^-\mu^-) < 4.4(5.7) \times 10^{-7}$$

Phase space models used but efficiencies vary of 10 - 20% over the $\mu\mu$ mass.
Result on $\tau^- \to \mu^-\mu^+\mu^-$ compatible with previous limits
First limits on $\tau^- \to \bar{p}\mu^+\mu^-$ and $\tau^- \to p\mu^-\mu^-$ decays

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

Standard Model

- Main resonant component: $B^0_s \to J/\psi\phi$, with J/ψ and ϕ decaying in two muons. $[\mathcal{B} = (2.3 \pm 0.9) \times 10^{-8}]$
- SM non-resonant: $B^0_{(s)} \to \mu\mu\gamma(\to \mu\mu)$

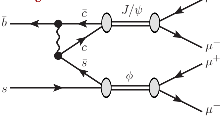
  $\mathcal{B} < 10^{-10}$ [Phys.Rev.D 70 (2004) 114028]

In NP models scalar and pseudoscalar particles can enhance the branching fraction via $B \to PS$ intermediate states.

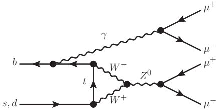
In particular it is sensitive to sgoldstino mediated decays decays in MSSM models.

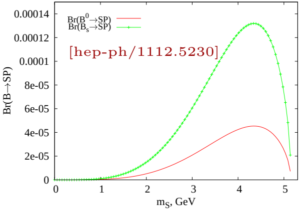
hypothesized pseudoscalar particle to explain HyperCP evidence in $\Sigma^+ \to p\mu\mu$ tested.

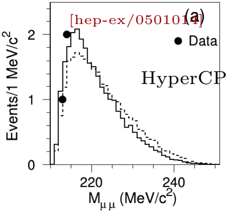
$B^0_s \to J/\psi\phi$



$B^0_{s,d} \to \mu^+\mu^-\mu^+\mu^-$







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

- Four muons with high IPχ^2 with good vertex ($\chi^2 < 30$)
- Tight muon PID criteria:
  $\varepsilon_\mu = 78.5\%$, $\varepsilon_{\pi\to\mu} = 1.4\%$
- Resonant component ($m_{\mu\mu} \in [950, 1090]$ and $[3000, 3200]$) excluded an used as control channel
- $N = 5.5 \pm 2.3$ expected $B^0_s \to J/\psi\phi$, 7 observed events
- Dominant background: combinatorial
- Peaking backgrounds negligible. Largest one $B \to \psi(2S)K^*$ with expected yield 0.44 events

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

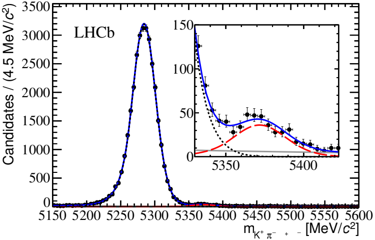
Normalisation

- $B^0 \to J/\psi(\to \mu^+\mu^-)K^{*0}(\to K^+\pi^-)$ with S-wave excluded
- Same selection (apart from PID)

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

$$\mathcal{B}(B^0 \to J/\psi K^{*0}) \frac{f_s}{f_d} \frac{\varepsilon_{J/\psi K^*}}{\varepsilon_{4\mu}} \frac{N_{B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-}}{N_{B^0 \to J/\psi K^{*0}}} \kappa$$

κ is a correction for the S-wave exclusion

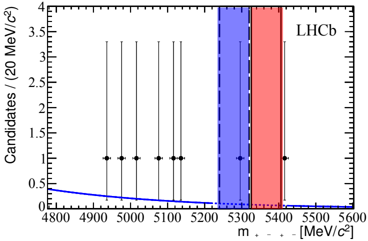


Upper limits at 90% (95%) CL for phase space decays:

- $\mathcal{B}(B^0_s \to \mu^+\mu^-\mu^+\mu^-) < 1.2(1.6) \times 10^{-8}$
- $\mathcal{B}(B^0 \to \mu^+\mu^-\mu^+\mu^-) < 5.3(6.6) \times 10^{-9}$

Upper limits at 90% (95%) CL for the MSSM models ($m_{P(S)} = 214.3\text{MeV/c}^2(2.5\text{GeV/c}^2)$):

- $\mathcal{B}(B^0_s \to SP \to 4\mu) < 1.2(1.6) \times 10^{-8}$
- $\mathcal{B}(B^0 \to SP \to 4\mu) < 5.1(6.6) \times 10^{-9}$



Updated search for $B^0_{d,s} \to \mu^+\mu^-$ decays

- Standard Model prediction for CP averaged branching fractions at $t = 0$:

$$\mathcal{B}^{t=0}(B^0_s \to \mu^+\mu^-) = (3.25 \pm 0.17) \times 10^{-9}$$
$$\mathcal{B}^{t=0}(B^0 \to \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10}$$

[A. Buras et al. arXiv:1303.3820]
[Eur.Phys.J. C72 (2012) 2172]

To compare with experimental values, which are time integrated, a correction due to the finite $B^0_s - \bar{B}^0_s$ width difference has to be applied [De Bruyn et al. [PRL 109, 041801]]
[Phys.Rev.Lett.108 (2012) 101803]

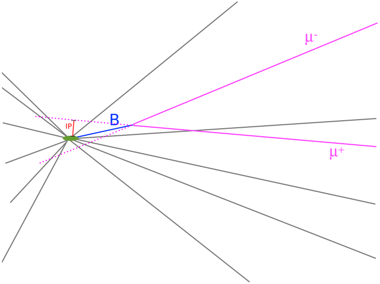
$$\mathcal{B}^{\langle t\rangle}(B^0_s \to \mu^+\mu^-) = \left(\frac{1 + \mathcal{A}_{\Delta\Gamma} y_s}{1 - y_s^2}\right) \mathcal{B}^{t=0}(B^0_s \to \mu^+\mu^-) \stackrel{SM}{=} (3.56 \pm 0.18) \times 10^{-9}$$

- New Physics models predict various and different enhancements
- Today: updated search including: 1fb^{-1} at 7 TeV and 1.1fb^{-1} at 8 TeV
  1 additional fb^{-1} on tape to be analysed soon!

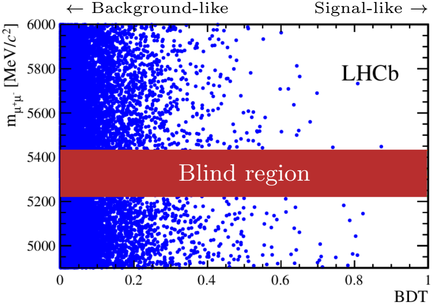
Analysis strategy

[Phys. Rev. Lett. 110, 021801 (2013)]

1. Loose selection:
   - ⋆ Pairs of opposite charged muons
   - ⋆ Vertex displaced with respect to interaction point
   - ⋆ $m_{\mu\mu} \in (4900, 6000)$
   - ⋆ p_{T}, IP and quality requirements



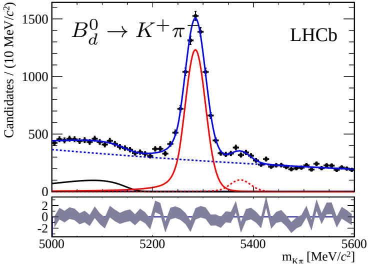
2. Search in a two dimensional plane of invariant mass and BDT

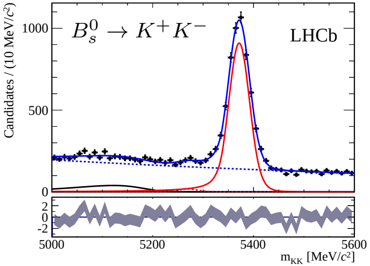


How to know where to look?

Calibration of signal PDFs: mass

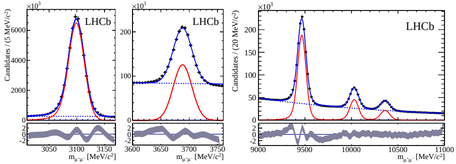
Mass central value

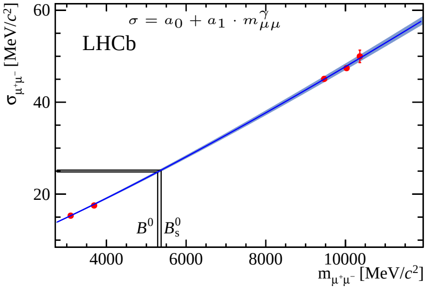




[Phys. Rev. Lett. 110, 021801 (2013)]

Mass resolution



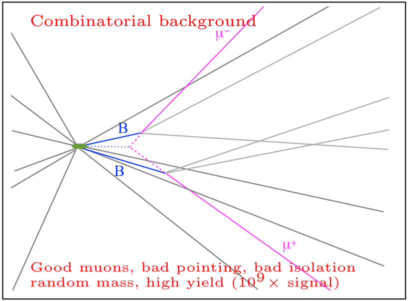


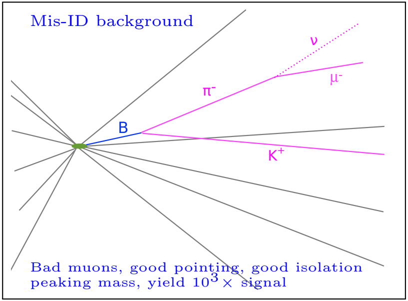
$$\sigma_{B^0} = (24.6 \pm 0.4)\ \mathrm{MeV/c^2}$$

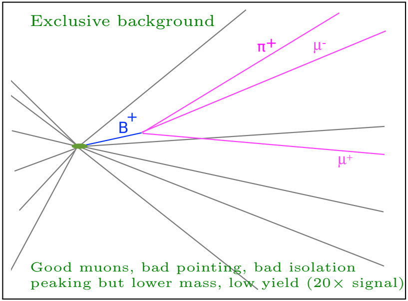
$$\sigma_{B_s^0} = (25.0 \pm 0.4)\ \mathrm{MeV/c^2}$$

[Phys. Rev. Lett. 110, 021801 (2013)]

Backgrounds







Hadronic	$B \to h^+ h'^-$ with $h = \pi, K$
Semileptonic	$B^0 \to \pi^- \mu^+ \nu$ $B_s^0 \to K^- \mu^+ \nu$ $\Lambda_b^0 \to \bar{p} \mu^+ \nu$ $B_c^+ \to J/\psi \mu^+ \nu_\mu$ $B_s^0 \to D_s^- (\to \mu^- \nu) \mu^+ \nu$
Rare decays	$B^{+(0)} \to \pi^{+(0)} \mu^+ \mu^-$ $B_s^0 \to \mu^+ \mu^- \gamma$

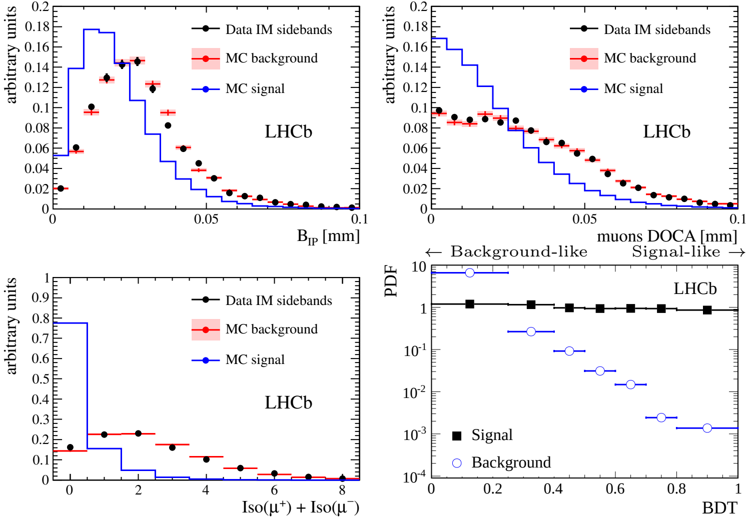
In red the ones added as separate component
Various others considered but found to be negligible.

[Phys. Rev. Lett. 110, 021801 (2013)]

BDT = Beauty Detection Tool?

...or Boosted Decision Tree

Multivariate discriminant combining 9 variables



Plus:

B isolation, B p_T, B τ, μ IP , min(μp_T), μ to B angle

- Training with MC
- Calibration with data

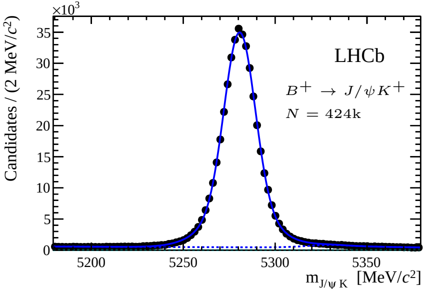
Normalisation

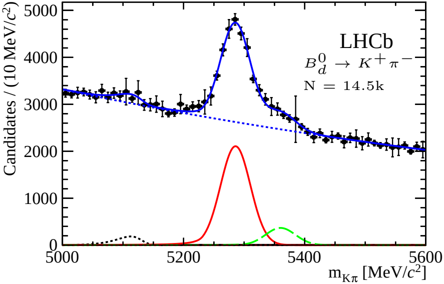
$$\mathcal{B} = \frac{\epsilon_{cc}}{\epsilon_{sig}} \cdot \frac{f_{cc}}{f_q} \cdot \frac{N_{B_q^0 \to \mu^+\mu^-}}{N_{cc}} \cdot \mathcal{B}_{cc} = \alpha_q \cdot N_{B_q^0 \to \mu^+\mu^-}$$

- Two control channels: $B^+ \to J/\psi K^+$ and $B^0 \to K^-\pi^+$
  Results compatible with each other and averaged for final result
- Reconstruction and selection efficiencies from MC but cross-checked with data
- Trigger efficiency from data ($\varepsilon_{B_s^0 \to \mu^+\mu^-} \simeq 90\%$)
- Hadronisation fractions from updated LHCb measurement
  $f_s/f_d = 0.256 \pm 0.020$ [hep-ph:1301.5286]

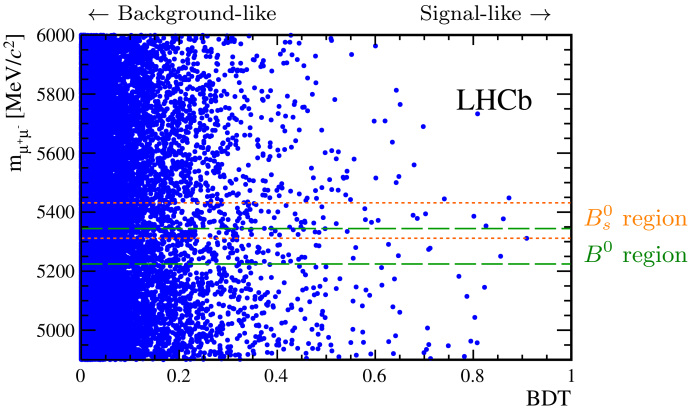
2011 and 2012 data normalised separately. Results for $1.1 fb^{-1}$ at 8 TeV (2012):

$$\alpha_{B_s^0 \to \mu^+\mu^-} = 2.80 \times 10^{-10} \qquad \alpha_{B^0 \to \mu^+\mu^-} = 7.16 \times 10^{-11}$$

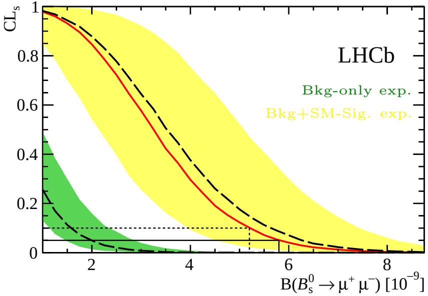




Open the box


← Background-like
Signal-like →
$m_{\mu^+\mu^-}$ [MeV/c^2]
6000
5800
5600
5400
5200
5000
LHCb
B_s^0 region
B^0 region
0
0.2
0.4
0.6
0.8
1
BDT

$\mathcal{B}(B^0_{d,s} \to \mu^+\mu^-)$: expected and observed upper limits

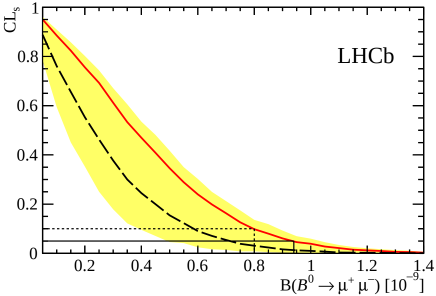


Upper limit at 95 % CL	$\mathcal{B}(B^0_s \to \mu^+\mu^-)$
Exp. bkg+SM	6.3×10^{-9}
Exp. bkg	2.0×10^{-9}
Observed	5.8×10^{-9}

Compatibility with background p-value (1-CL_b) is 5×10^{-4}

Excess of $B^0_s \to \mu^+\mu^-$ events with a significance of 3.5σ.

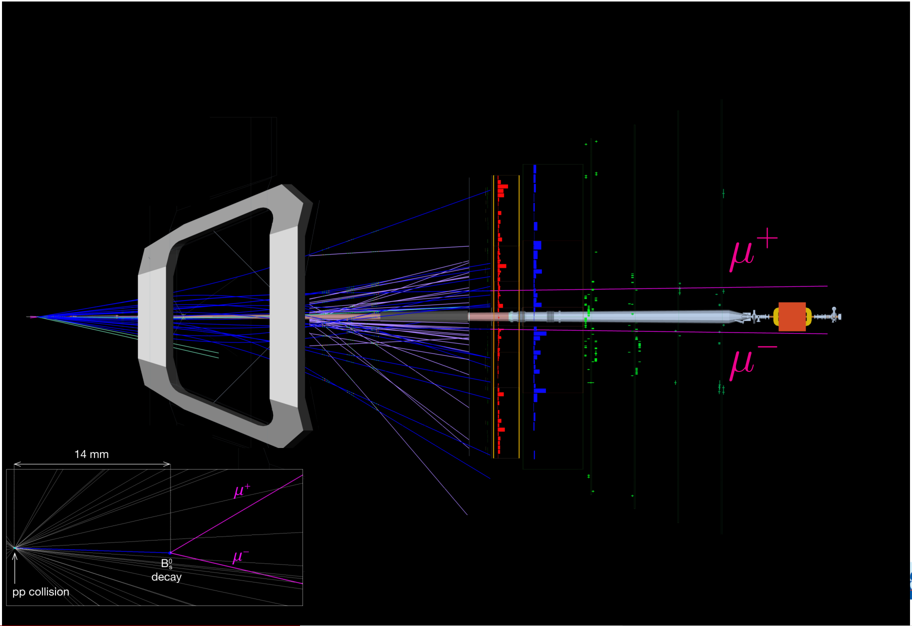
First evidence of $B^0_s \to \mu^+\mu^-$ decay



Upper limit at 95 % CL	$\mathcal{B}(B^0 \to \mu^+\mu^-)$
Exp. bkg+SM	7.1×10^{-10}
Exp. bkg	6.0×10^{-10}
Observed	9.4×10^{-10}

[Phys. Rev. Lett. 110, 021801 (2013)]

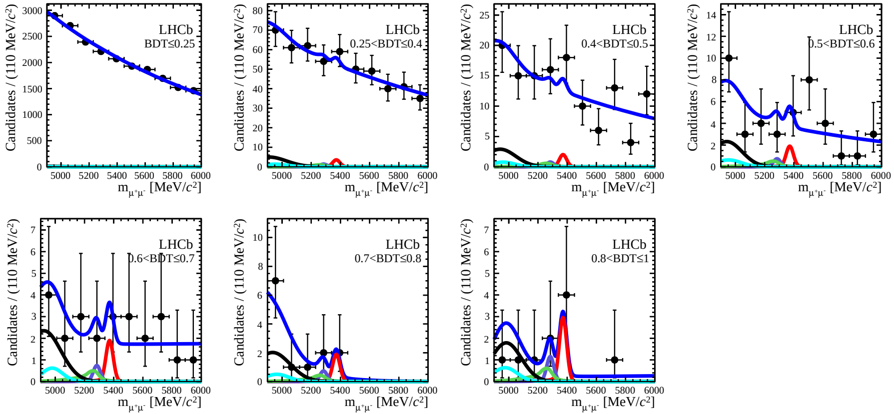
A good looking event



Full fit to combined dataset

- Simultaneous fit to the two years dataset
- Shared branching ratio parameters

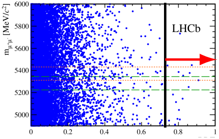
2012 dataset, 7 BDT bins

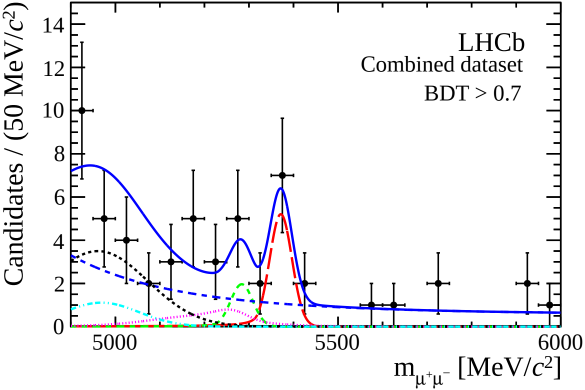


$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2^{+1.4}_{-1.2}(\text{stat})^{+0.5}_{-0.3}(\text{syst})) \times 10^{-9}$$

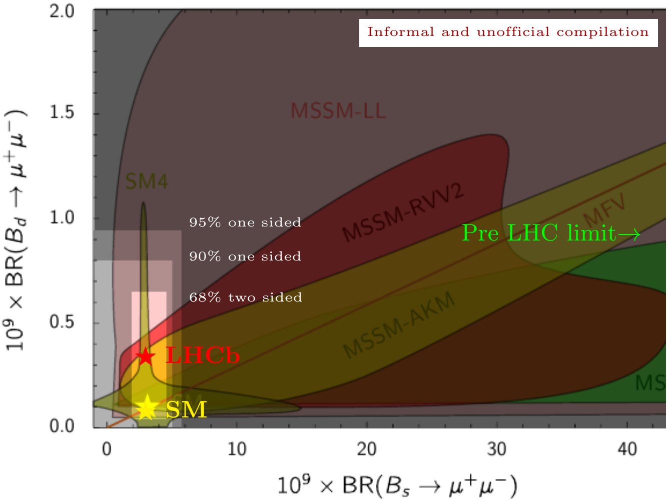
Invariant mass distribution

Full PDF
$B_s^0 \to \mu^+\mu^-$
$B^0 \to \mu^+\mu^-$
Comb. background
$B^0_{(s)} \to h^+h'^-$
$B^0 \to \pi^-\mu^+\nu_\mu$
$B^{0(+)} \to \pi^{0(+)}\mu^+\mu^-$





The parameter space and outlook



Original figure from D. Straub - Nuovo Cim. C035N1 (2012) 249-256

Other very rare decays results

- First observation of $B^+ \to \pi^+ \mu^+ \mu^-$

  LHCB-PAPER-2012-020 - JHEP 12 (2012) 125 [hep-ex/1210.2645]
- Search for the rare decay $K^0_S \to \mu^+ \mu^-$

  LHCB-PAPER-2012-023 - JHEP 01(2013) 090 [hep-ex/1209.4029]
- Searches for Majorana neutrinos in B^- decays

  LHCB-PAPER-2011-038 - Phys. Rev. D 85, 112004 (2012) [hep-ex/1201.5600]
- Search for the lepton number violating decays $B^+ \to \pi^- \mu^+ \mu^+$ and $B^+ \to K^- \mu^+ \mu^+$

  LHCB-PAPER-2011-009 - Phys.Rev.Lett. 108 (2012) 101601 [hep-ex/1110.0730]
- Search for the rare decay $D^0 \to \mu^+ \mu^-$
  ...see talk by Chris Thomas

Conclusions and outlook

- Very rare decays are probes of very tiny NP effects
- LHCb is exploring branching fractions in the 10^{-9} range
- First limits on $\tau^- \to \bar{p}\mu^+\mu^-$ and $\tau^- \to p\mu^-\mu^-$ and limit on $\tau^- \to \mu^-\mu^+\mu^-$ compatible with previous results
- First limit on $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$ decays
- First evidence of $B^0_s \to \mu^+\mu^-$ decay and tight limit on $B^0 \to \mu^+\mu^-$
- More data already on tape... Stay tuned!

Additional material

Lepton and baryon number violation in τ decays

CLs plots