Rare $B^0_{(s)}$ dileptonic decays at LHCb

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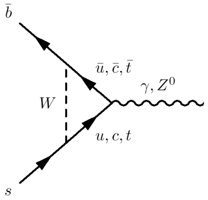
Outlook of the talk

- Motivations
- Experimental searches
  - $B^0_{(s)} \to \mu^+\mu^-$
  - $B^0_{(s)} \to e^\pm\mu^\mp$
- Conclusions and prospects

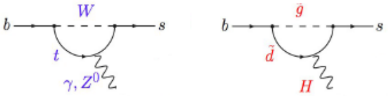
Why rare decays?

Dileptonic $B^0_{(s)}$ decays imply transition between b and d,s quarks *i.e.* a **Flavour Changing Neutral Currents** (FCNC)

In Standard Model (SM) FCNC forbidden at tree level ⇒ very rare decays.



An ideal place where to see NP at work!



New Physics (NP) particles may appear inside the loops or at the tree level in the interaction: **indirect probes of New Physics**

Dileptonic final states:

Additional sources of suppression

Very precise theoretical predictions

Clear experimental signature

Dileptonic decays: the "golden" channels $B^0_{(s)} \to \ell^+\ell^-$

$$BR(B^0_q \to \ell^+\ell^-) = \left(\frac{G_F^2\alpha^2}{64\pi^3}\right) \cdot |V^\star_{tb}V_{tq}|^2 \cdot \tau_{B_q} \cdot f^2_{B_q} \cdot M^3_{B_q} \cdot \sqrt{1 - 4\frac{m^2_\ell}{M^2_{B_q}}}$$
$$\times \left\{ \left|2\frac{m_\ell}{M_{B_q}}(C_{10} - C'_{10}) + (C_P - C'_P)\right|^2 + \left(1 - 4\frac{m^2_\ell}{M^2_{B_q}}\right)|C_S - C'_S|^2 \right\}$$

- **SM** case: $C^{(\prime)}_{S,P}, C'_{10} \simeq 0$
  - additional **helicity suppression**
  - only **one hadronic input**
- **BSM** scenarios:
  - $C^{(\prime)}_{S,P}, C'_{10} \neq 0,\ C^{SM}_{10} \to C^{SM}_{10} + \delta C^{NP}_{10}$
  - **still** only one hadronic input

Standard Model predictions for $\ell = \mu$ [Bobeth *et al.*, arXiv:1311.0903v1]

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

First evidence for $B^0_s \to \mu^+\mu^-$ @ 3.5σ with $2.1 fb^{-1}$ [LHCb, Phys. Rev. Lett. 110 021801]

$B^0_{(s)} \to \mu^+\mu^-$ [LHCb, Phys. Rev. Lett. 111 101805]

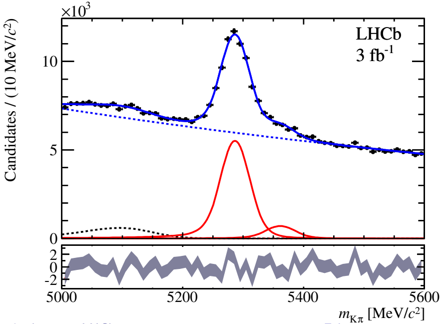
The dataset: $3.1 fb^{-1}$ collected during 2011 and 2012 at $\sqrt{s}$ =7 and 8 TeV

$$BR(B^0_q \to \mu^+\mu^-) = \underbrace{\frac{BR_{norm}}{N_{norm}} \cdot \frac{\epsilon^{SEL}_{norm}\epsilon^{SEL,REC}_{norm}}{\epsilon^{SEL}_{sig}\epsilon^{SEL,REC}_{sig}} \cdot \frac{\epsilon^{TRIG}_{norm}}{\epsilon^{TRIG}_{sig}} \cdot \frac{f_{norm}}{f_q}}_{\alpha_q} \cdot N_{B^0_q \to \mu^+\mu^-}$$

Normalization channels "similar" to signal:

- same trigger efficiency: $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$
- same topology: $B^0 \to K\pi$

$B^0 \to K^+\pi^-$: ∼38k events



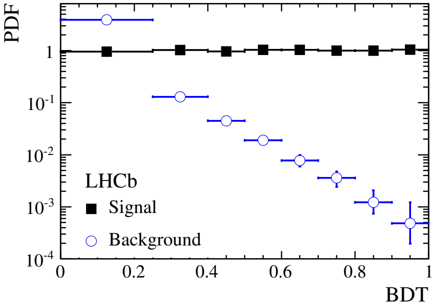
- extracted from data
- evaluated on MC & cross-checked on data
- measured from data
- ratio of hadronization probabilities [LHCb-CONF-2013-011]

Signal vs Background discrimination

Combinatorial $bb \to \mu^+\mu^- X$: main source of background in the signals mass windows

Boosted Decision Tree (BDT) algorithm to reject it:

- 12 kinematical & topological input variables
- trained on MC sig & bkg samples



Signal vs Background discrimination

Physical backgrounds:

- $\mathbf{B}^0_{(s)} \to hh^{(\prime)}$ ($h^{(\prime)} = K, \pi$) with double misID $h^{(\prime)} \to \mu$: peaks in the B^0 search window
- Other semi-leptonic b-hadron decays peaks in the sidebands $\Rightarrow$ bias combinatorial background shape

One misID hadron:

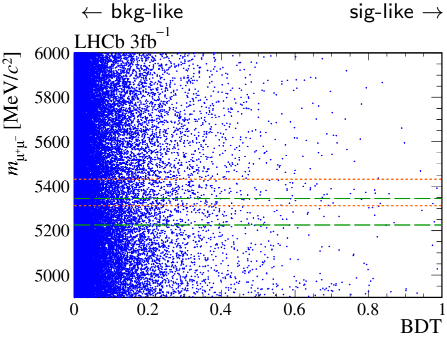
- $B^0 \to \pi^-\mu^+\nu_\mu$
- $B^0_s \to K^-\mu^+\nu_\mu$
- $\Lambda_b \to p\mu\nu_\mu$

Two μ from common vertex:

- $B^{0/+} \to \pi^{0/+}\mu^+\mu^-$
- $B_c \to J/\Psi(\mu^+\mu^-)\mu\nu_\mu$

- included as fit components
- taken into account in the systematics
- accounted for in the exponential mass sidebands fit

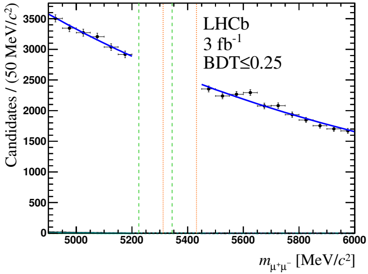
Events classification & PDF Calibration



Blinded region :
$[M_{B^0_d} - 60 \text{ MeV} \ , \ M_{B^0_s} + 60 \text{ MeV}]$

BDT PDF calibrated on data:

- Signal: $B^0 \to hh^{(\prime)}$
- Bkg: from $m_{\mu^+\mu^-}$ sidebands



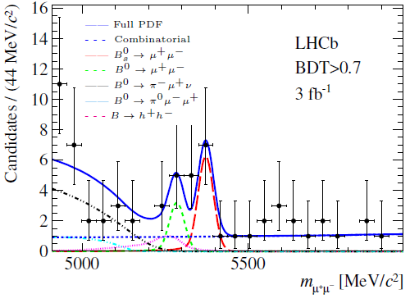
Mass PDF calibration:

- Signal: Crystal Ball function
  - mean from $B^0 \to hh^{(\prime)}$
  - resolution from di-μ resonances & $B^0 \to hh^{(\prime)}$
- Bkg: from $m_{\mu^+\mu^-}$ sidebands

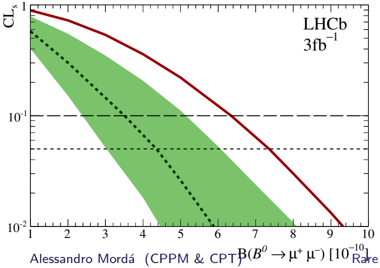
Yields and results

Event yields determination:

- simultaneous unbinned likelihood fit in 8 BDT bins
- B^0, B^0_s and combinatorial background yields free
- yields & PDF shapes of exclusive backgrounds constrained



$B^0 \to \mu^+\mu^-$ bkg-only expectation, **observed**



$BR(B^0_s \to \mu^+\mu^-) = 2.9^{+1.1}_{-1.0} \times 10^{-9}$ @ 4σ,

$BR(B^0 \to \mu^+\mu^-) = 3.7^{+2.4}_{-2.1} \times 10^{-10}$ @ 2σ

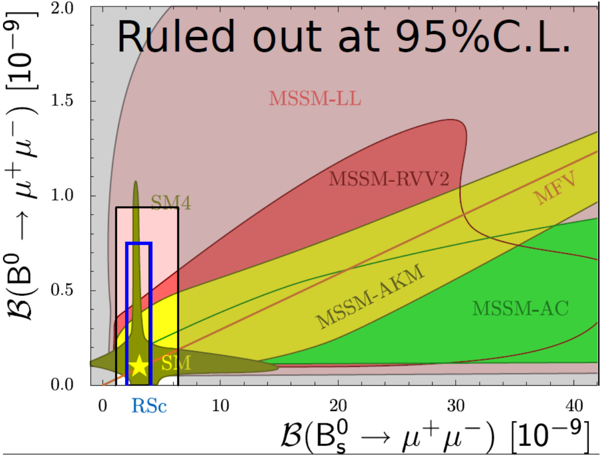
No evidence for $B^0 \Rightarrow$ upper limit:

$BR(B^0 \to \mu^+\mu^-) < 6.3(7.4) \times 10^{-10}$ @ 90(95)% CL

Implications of measurements

Measured values of $BR(B^0_{(s)} \to \mu^+\mu^-)$ are consistent with SM predictions.

Updated from [Straub, ArXiv:1205.6094]



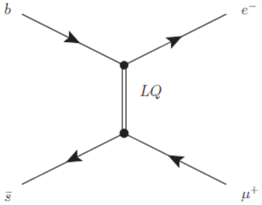
Indicative only: LHCb $2.1 fb^{-1}$, $3.1 fb^{-1}$

Dileptonic decays: $B^0_{(s)} \to \ell^{\pm}\ell'^{\mp}$

Lepton Flavour Violation

- In **SM** only flavour conserving currents in the leptonic sector $\Rightarrow$ Lepton Flavour Violation (LFV) modes $B^0_{s,d} \to \ell^{\pm}\ell'^{\mp}$ are forbidden.

- **NP models** (*e.g.* Pati-Salam model [Phys. Rev. D 10 275]):
  - gauge symmetry between quarks and leptons requires the existence of a spin-1 gauge boson Leptoquark (LQ)
  - quark-lepton interaction allowed at tree level



Status before LHCb measurements: CDF ($2fb^{-1}$) [CDF, Phys. Rev. Lett. 102 201901]

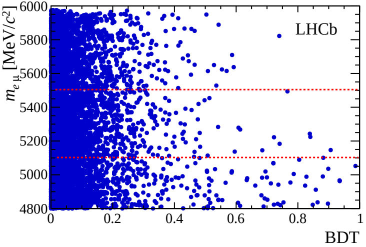
$$BR(B^0_s \to e\mu) < 20.0(20.6) \cdot 10^{-8} \text{ @ } 90(95)\% \ CL$$

$$BR(B^0 \to e\mu) < 64.0(79.0) \cdot 10^{-9} \text{ @ } 90(95)\% \ CL$$

$B^0_{(s)} \to e^{\pm}\mu^{\mp}$ [Phys. Rev. Lett. 111 141801]

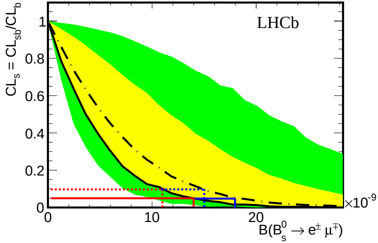
Strategy *à la* $B^0_{(s)} \to \mu^+\mu^-$

- Dataset: 1 fb^{-1} collected in 2011 at $\sqrt{(s)}$= 7 TeV
- $B^0 \to K\pi$ as normalization channel
- events classification in $m_{e\mu}$ - BDT plane



No excess over background is seen ⇒ upper limit on $BR(B^0_{(s)} \to e\mu)$ is obtained using the CL_s method

$B^0_s \to e\mu$, background-only expectation



Results

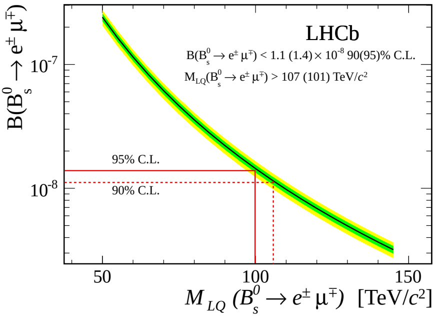
$BR(B^0_s \to e\mu) < 1.1(1.4) \cdot 10^{-8}$ @ 90(95)% CL

$BR(B^0 \to e\mu) < 2.8(3.7) \cdot 10^{-9}$ @ 90(95)% CL

$\sim$ 20 times more stringent than previous limits

Implications of measurements

From limits on $BR(B^0_{(s)} \to e\mu)$ lower bounds on Pati-Salam LeptoQuark masses are inferred (formula from [Phys. Rev. D 50 6843])

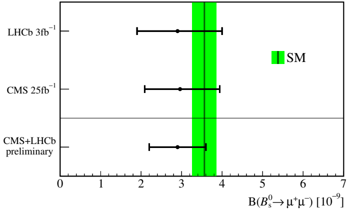


$$m_{LQ_s}(B^0_s \to e\mu) > 107(101)\, TeV/c^2 \text{ @ } 90(95)\% \; CL$$
$$m_{LQ_d}(B^0 \to e\mu) > 135(126)\, TeV/c^2 \text{ @ } 90(95)\% \; CL$$

Conclusions & Prospects

- $\mathbf{B}^0_{(s)} \to \mu^+\mu^-$: from a discovery regime to a precision test of Standard Model
  - BR measurements compatible with SM predictions
  - LHCb & CMS are combining their results.

A preliminary combination has already been done [LHCb-CONF-2013-012]



  - Efforts to improve the sensitivity for the $BR(B^0 \to \mu^+\mu^-)$
  - Fit the ratio $\frac{BR(B^0_s \to \mu^+\mu^-)}{BR(B^0 \to \mu^+\mu^-)}$ (relevant to constrain MFV NP models)

- $\mathbf{B}^0_{(s)} \to e^\pm\mu^\mp$:
  - First LHCb measurements improve the previous limits
  - Still $\sim 2fb^{-1}$ to be analized

Thanks for your attention !

Backup

Operator Product Expansion

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{\star} \sum_i C_i \cdot \mathcal{O}_i$$

For $B_s^0 \to \ell\bar{\ell}$, the relevant operators are $\left(P_{L,R} = \frac{1 \pm \gamma^5}{2}\right)$:

$\mathcal{O}_{10}^{(\prime)}$	$(\bar{b}\gamma^{\mu} P_{L,(R)} s)(\bar{\ell}\gamma_{\mu}\gamma^5 \ell)$
$\mathcal{O}_{S}^{(\prime)}$	$(\bar{b} P_{L,(R)} s)(\bar{\ell}\ell)$
$\mathcal{O}_{P}^{(\prime)}$	$(\bar{b} P_{L,(R)} s)(\bar{\ell}\gamma^5 \ell)$

Integrated BR [PhysRevD.86.014027]

- B_s^0 mesons are "affected" by the $B_s^0 - \overline{B}_s^0 \Longrightarrow$ sizable difference between decay widths of heavier lightest mass eigenstate, parametrized by

$$y_s \equiv \frac{\Gamma_H - \Gamma_L}{\Gamma_H + \Gamma_L} = 0.061 \pm 0.006$$

HFAG average measured experimentally looking at $B_s^0 \to J/\psi\phi$

- untagged BR

$$\langle \Gamma(B_s(t) \to f) \rangle \equiv \Gamma(B_s(t) \to f) + \Gamma(\overline{B}_s(t) \to f) = R_H^f e^{-\Gamma_H t} + R_H^f e^{-\Gamma_H t}$$
$$= (R_H + R_L)\, e^{-\Gamma t} \times [\cosh(y_s \Gamma t) + \mathcal{A}_{\Delta\Gamma} \cdot \sinh(y_s \Gamma t)]$$

with $\mathcal{A}_{\Delta\Gamma} \equiv \frac{R_H - R_L}{R_H + R_L}$

- the "experimental" BR

$$BR(B_s \to f)_{exp} \equiv \frac{1}{2} \int_0^\infty \langle \Gamma(B_s(t) \to f) \rangle dt = \frac{(R_H + R_L)}{2\Gamma} \times \left[\frac{1 + \mathcal{A}_{\Delta\Gamma} \cdot y_s}{1 - y_s^2} \right]$$

- the relation is

$$BR(B_s \to f)_{theo} = \left[\frac{1 - y_s^2}{1 + \mathcal{A}_{\Delta\Gamma} \cdot y_s} \right] \cdot BR(B_s \to f)_{exp}$$

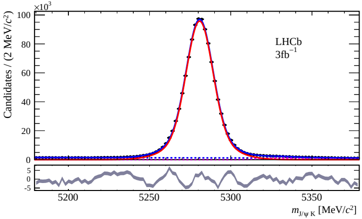
Hadronization fraction

$\frac{f_s}{f_d}$ is measured experimentally comparing the abundances of

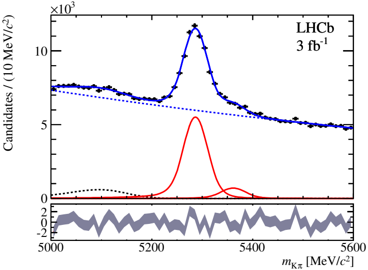
- $B_s^0 \to D_s^- \pi^+$ wrt $B^0 \to D^- K^+$ & $B^0 \to D^- \pi^+$
- $B_s^0 \to D_s^- \mu^+ X$ wrt $B_s^0 \to D_s^- \mu^+ X$

Normalisation channels

$B^+ \to J/\Psi K^+$: $\sim$ 1.1 Mevents



$B^0 \to K^+\pi^-$: $\sim$ 38K



Using the measured value of $\frac{f_s}{f_d}$ & the averaged value of the two channels we get

$$\alpha_s = (9.41 \pm 0.65) \times 10^{-11}$$
$$\alpha_d = (2.40 \pm 0.09) \times 10^{-11}$$

Using SM we expect:

- $39.5 \pm 4.3\ B_s^0 \to \mu^+\mu^-$
- $4.5 \pm 0.4\ B^0 \to \mu^+\mu^-$

BDT Standard variables

For the B:

- Proper times
- Impact parameter
- Transverse momentumn
- B isolation

For the 2 μ

- Distance Of Closest Approach (DOCA)
- Minimum IP significance
- Isolation of the 2 μ
- Polarization angle

BDT variables

- "other B angle": angle between the B candidate's momentum and the trust momentum of the B, defined as the sum of momenta of all the long tracks coming from the B PV and excluding those coming from long lived particles. If no such tracks is set to 0
- "angle wrt p_T": angle between the direction of the positive muon candidate in the rest frame of the B and the trust momentum in the B rest frame
- "$|\Delta\eta|$": absolute value of the difference between the pseudorapidity of the two muon candidates
- "$|\Delta\phi|$": absolute value of the difference between the sferical ϕ coordinate of the two muon candidates

BDT variables

- "B isolation": CDF definition [arXiv:0508036]

$$I_{CDF} = \frac{p_T(B)}{p_T(B) + \sum_{tracks} p_T(tracks)}$$

where the sum run over the *long* tracks, excluding the muon candidates, which satify $\sqrt{\delta\eta^2 + \delta\phi^2} < 1$, where $\delta\eta$ & $\delta\phi$ are the differences in pseudorapidity & polar angle between the track and the B candidate.

- "polarization angle": is the cos of the angle between the direction of the muon in the B_s^0 rest frame and the normal to the plane containing the B_s^0 momentum and the beam axis

Signal pdf

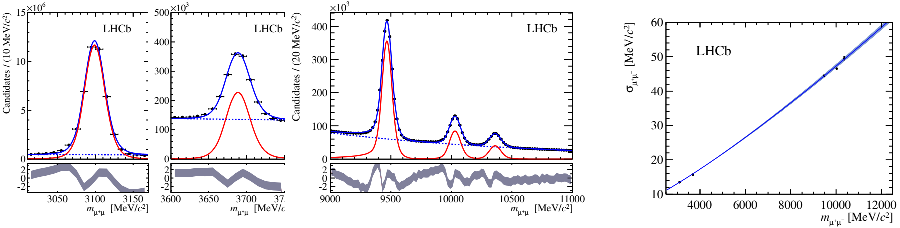
- BDT pdf calibrated on data $B \to hh$
- Mass pdf: Cristal ball

Mean extracted from $B^0_{(s)} \to hh^{(\prime)}$

- $m_{B^0} = 5284.90 \pm 0.10 \pm 0.20\ MeV$
- $m_{B^0_s} = 5371.85 \pm 0.17 \pm 0.19\ MeV$

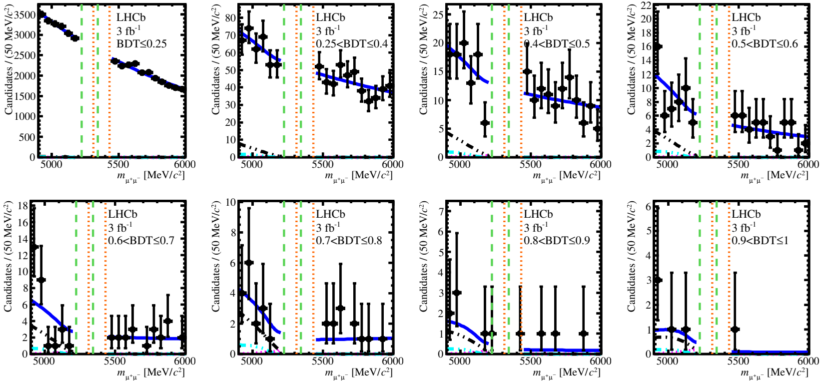
Resolution

- $\sigma_{B^0} = 22.8 \pm 0.4\ MeV/c^2$
- $\sigma_{B^0_s} = 23.2 \pm 0.4\ MeV/c^2$

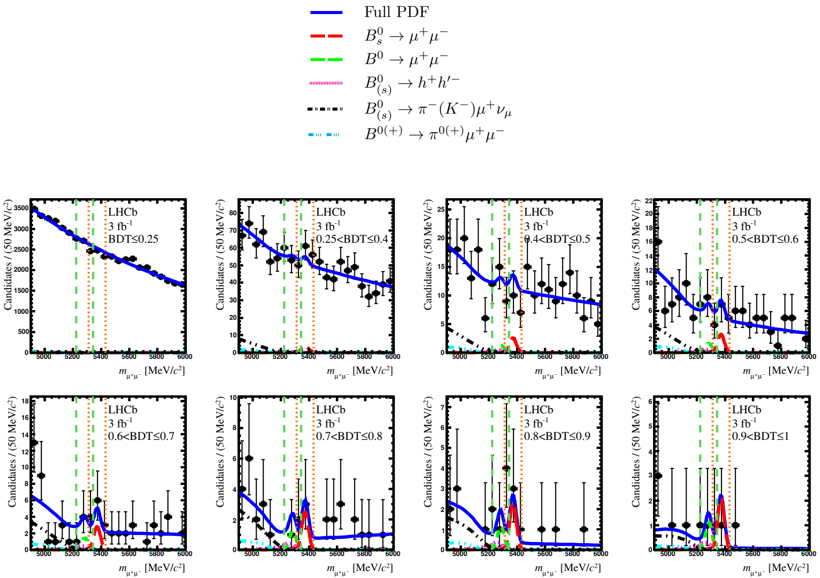


Bkg pdf

- Combinatorial: extrapolation from the data sidebands with an exponential
- Exclusive:
  - derive the misID probability $\pi, K \to \mu$ from data in bins of p & p_T
  - apply these probabilities to large MC samples
  - extract the mass & BDT probabilities from this weighted MC sample
  - normalize to $B^+ \to J/\psi K^+$

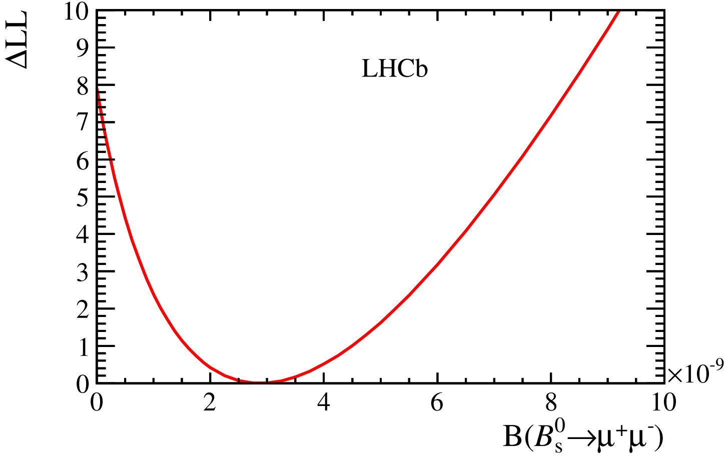


Fit results

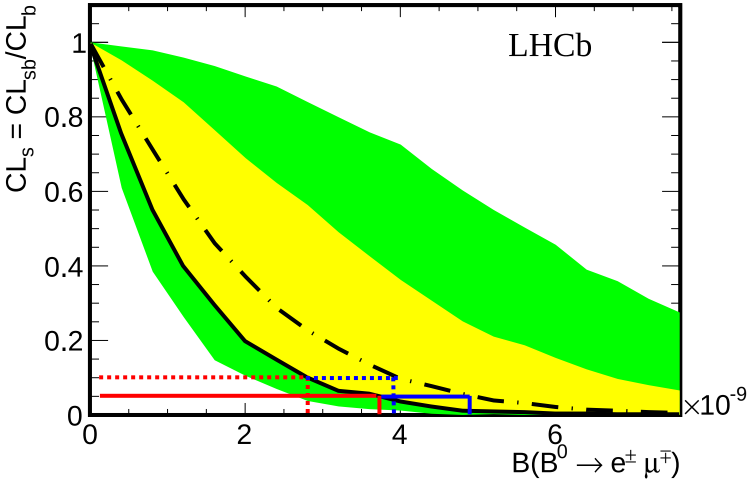


Full PDF
$B_s^0 \to \mu^+\mu^-$
$B^0 \to \mu^+\mu^-$
$B_{(s)}^0 \to h^+h'^-$
$B_{(s)}^0 \to \pi^-(K^-)\mu^+\nu_\mu$
$B^{0(+)} \to \pi^{0(+)}\mu^+\mu^-$
LHCb
3 fb^{-1}
BDT≤0.25
0.25<BDT≤0.4
0.4<BDT≤0.5
0.5<BDT≤0.6
0.6<BDT≤0.7
0.7<BDT≤0.8
0.8<BDT≤0.9
0.9<BDT≤1
Candidates / (50 MeV/c^2)
$m_{\mu^+\mu^-}$ [MeV/c^2]

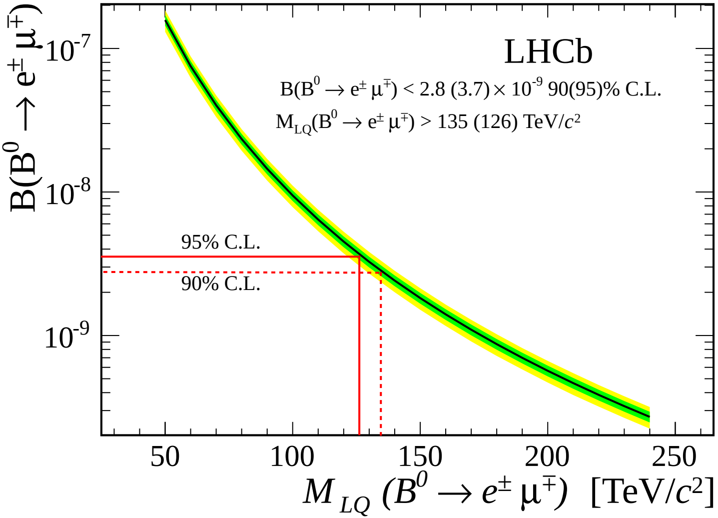
Likelihood scan



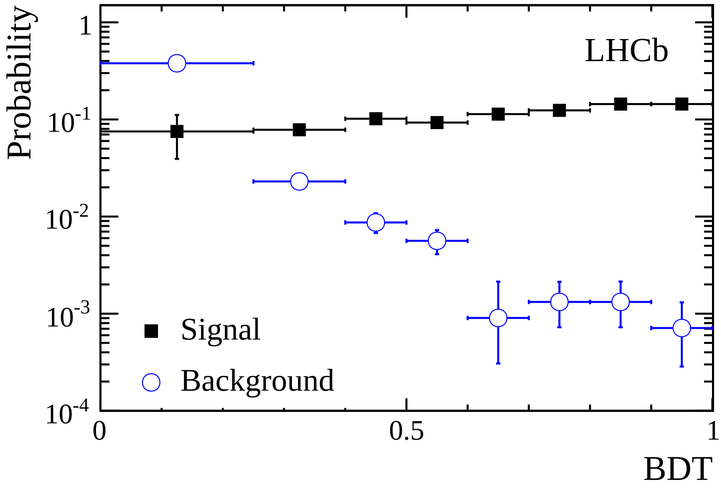
$B^0 \to e^{\pm}\mu^{\mp}\ CL_s$



$B^0 \to e^\pm\mu^\mp$ LQ mass lower bound



$B^0 \to e^{\pm}\mu^{\mp}$ BDT



LHCB & CMS combinations [LHCb-CONF-2013-012]