Searches for very rare decays to purely leptonic final states at LHCb

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Introduction

New physics searches in Heavy Flavour sector:

CP violation:
expected extra force

LFV:
- in the SM leptons do not change flavour
- possible symmetry between quarks and leptons
- $B^0_{(s)} \rightarrow e^+\mu^-$

Rare decays:
- small prediction in the SM and NP effects could arise a the same level
- $B^0_{(s)} \rightarrow \mu^+\mu^-$

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

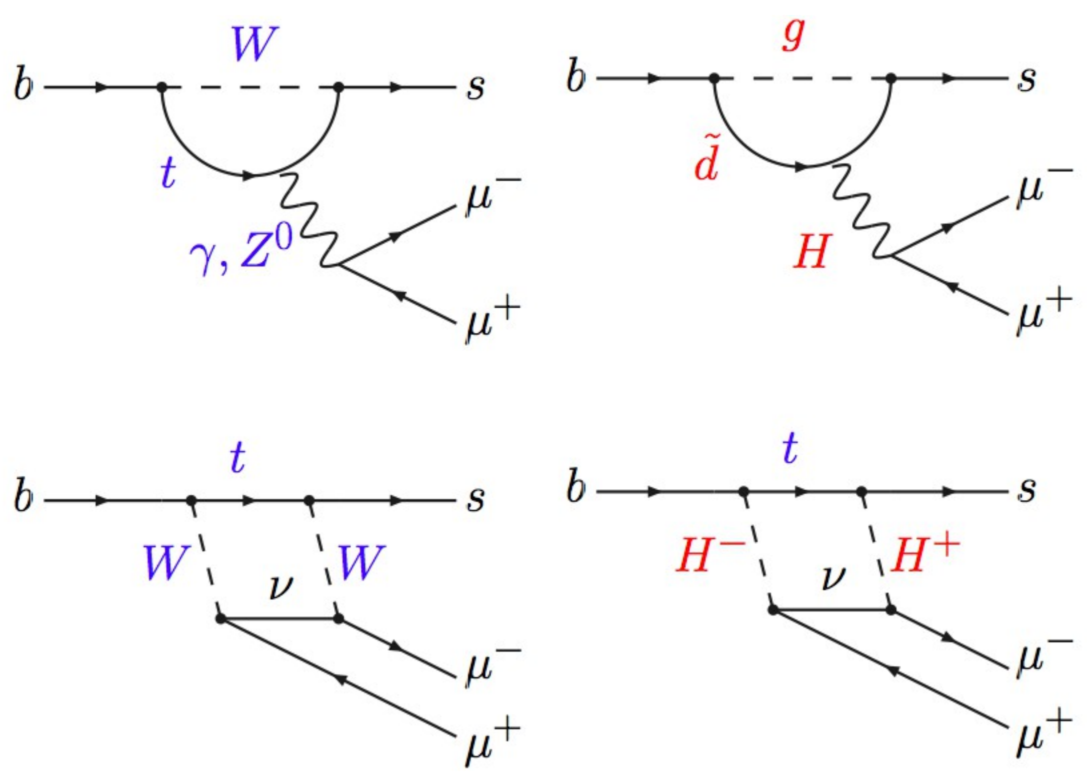
Branching fractions well predicted in the SM: [Eur. Phys. J. C72 (2012) 2172]

$$\mathcal{B}(B^0_s \to \mu^+\mu^-)^{CP} = (3.34 \pm 0.27) \cdot 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-)^{CP} = (1.07 \pm 0.05) \cdot 10^{-10}$$

Due the finite width of the B^0_s system the time integrated BF is:

$$\mathcal{B}(B^0 \to \mu^+\mu^-)^{\langle t \rangle} = (3.56 \pm 0.30) \cdot 10^{-9}$$ [arXiv:1207.1158]

Probe for models with an extended Higgs sector



Experimental Status

LHCb reported the first evidence of $B_s \to \mu^+\mu^-$ decay with a 3.5 σ significance:

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

[PRL 110, 021801 (2013)]

best upper limit on $B^0 \to \mu^+\mu^-$ (ATLAS+CMS+LHCb):

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 8.4 \cdot 10^{-10} \text{ @ } 95\% \text{ CL}$$

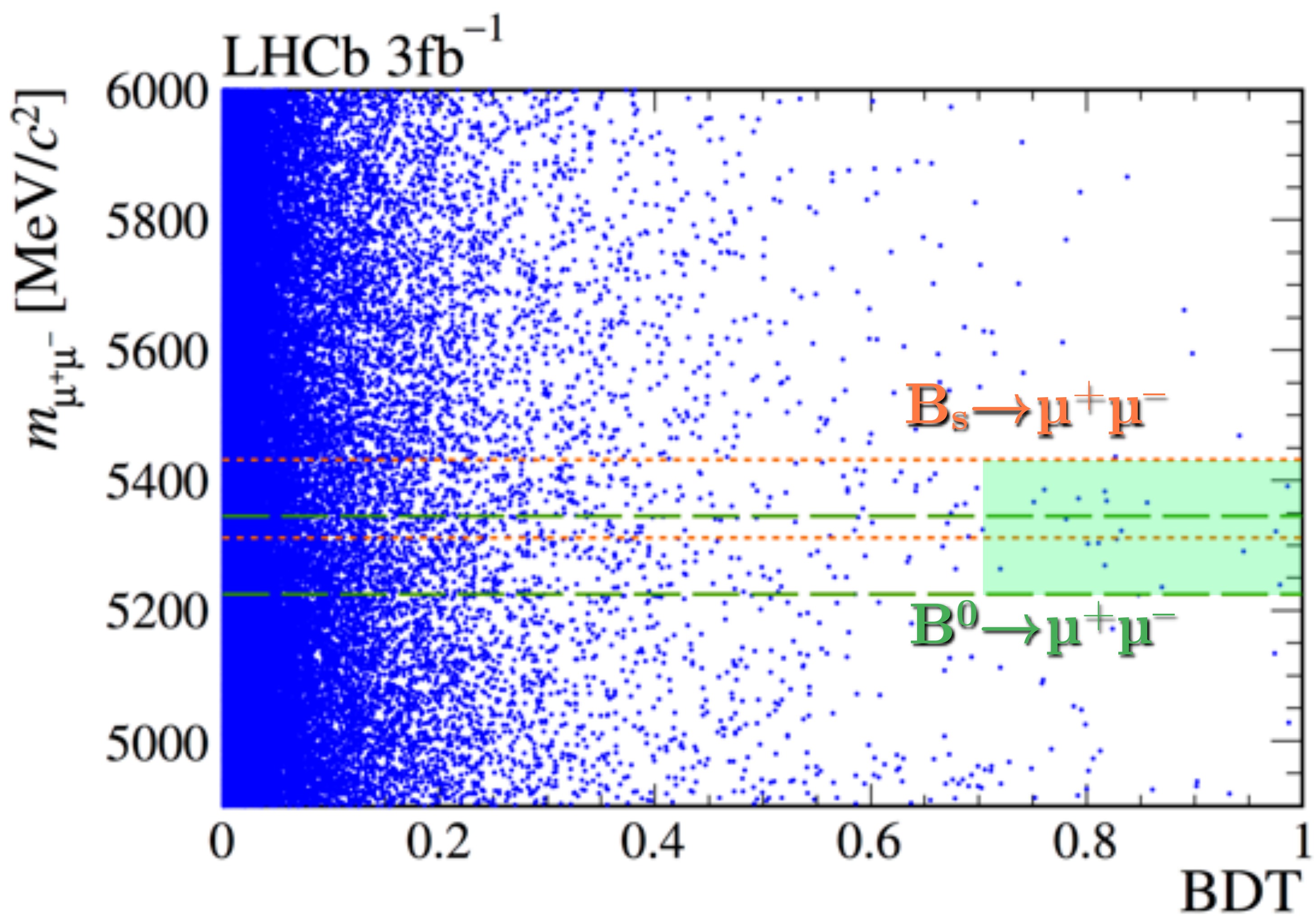
[LHCb-CONF-2012-017]

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

[LHCb-PAPER-2013-046]

- Blind analysis based on $3fb^{-1}$ of data recorded during 2011 and 2012
  - $2fb^{-1}$ of previous analysis included, re-reconstructed and re-analyzed

- Sig and bkg classification in $m_{\mu\mu}$ vs BDT plane:
- BDT (improved respect $2fb^{-1}$ analysis):
  - Based on kinematic and geometrical variables
  - trained with MC calibrated on data
- Data driven calibration



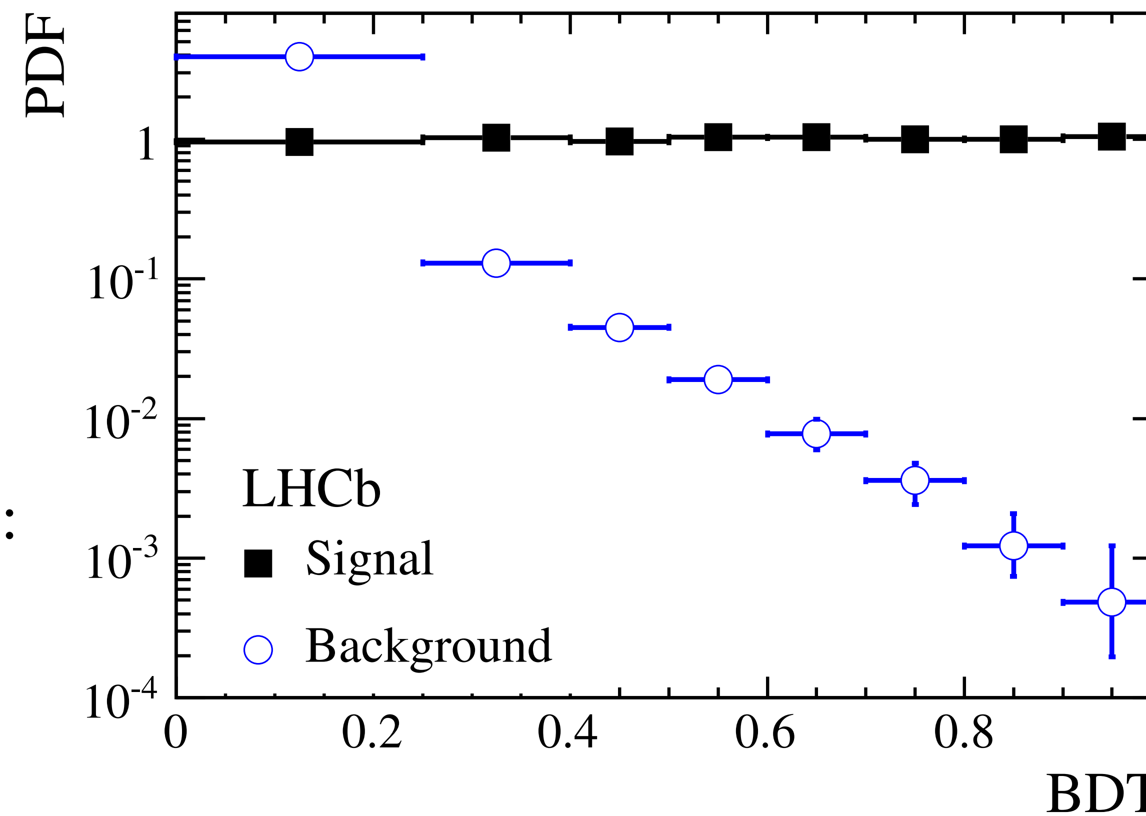
- Comparison between expectation and observed events:
  - Branching fraction from unbinned likelihood fit
  - Upper limit from CLs method

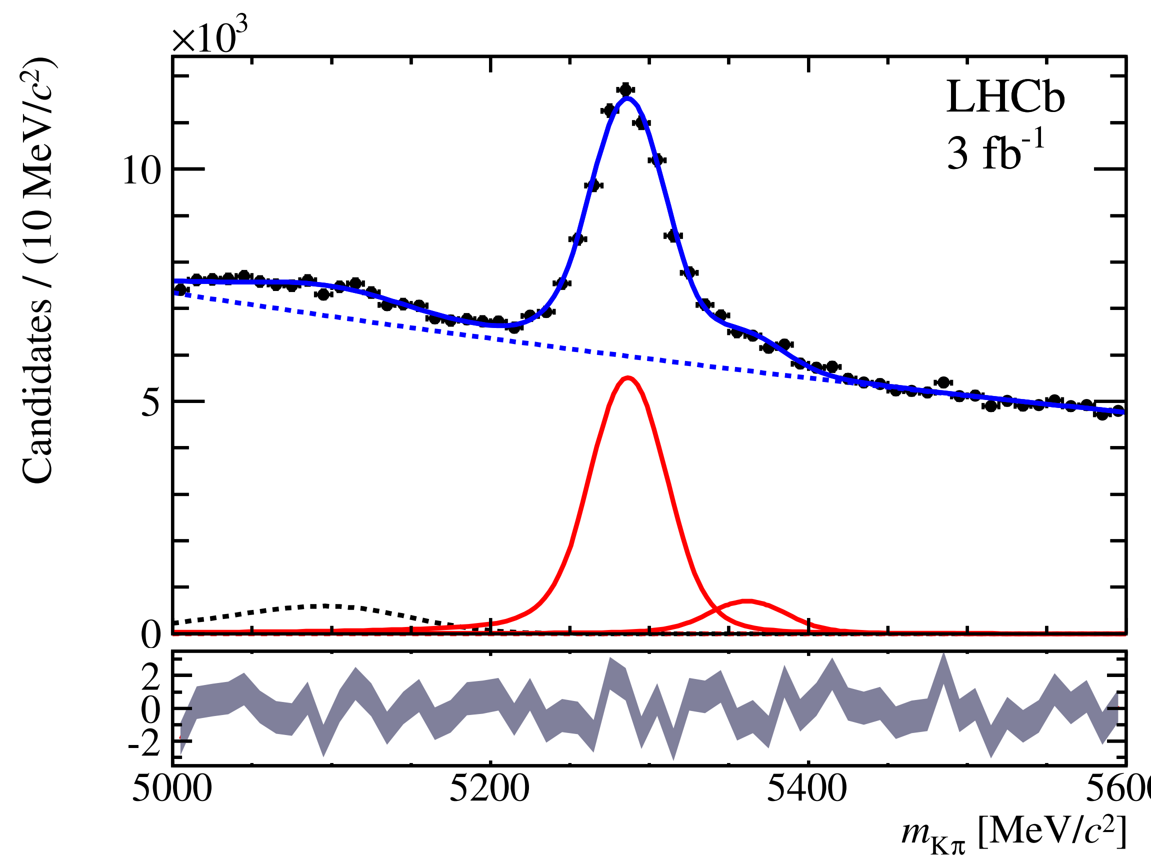
Calibrations

[LHCb-PAPER-2013-046]

- BDT classifier PDFs are calibrated using:
  - B→hh' events for signal
  - mass sidebands B→μμ candidates for bkg
- Invariant mass:
  - signal described by a Crystal Ball function:
    - mean value calibrated with exclusive B→hh' decays
    - resolution from di-μ resonance and exclusive B→hh'
  - background PDFs from data sidebands

$$\sigma_{B^0} = 22.8 \pm 0.4\,\mathrm{MeV}/c^2$$
$$\sigma_{B_s^0} = 23.2 \pm 0.4\,\mathrm{MeV}/c^2$$





Normalization

[LHCb-PAPER-2013-046]

- Two control channels used for the normalization: $B^+ \to J/\psi K^+$ and $B^0 \to K^+\pi^-$

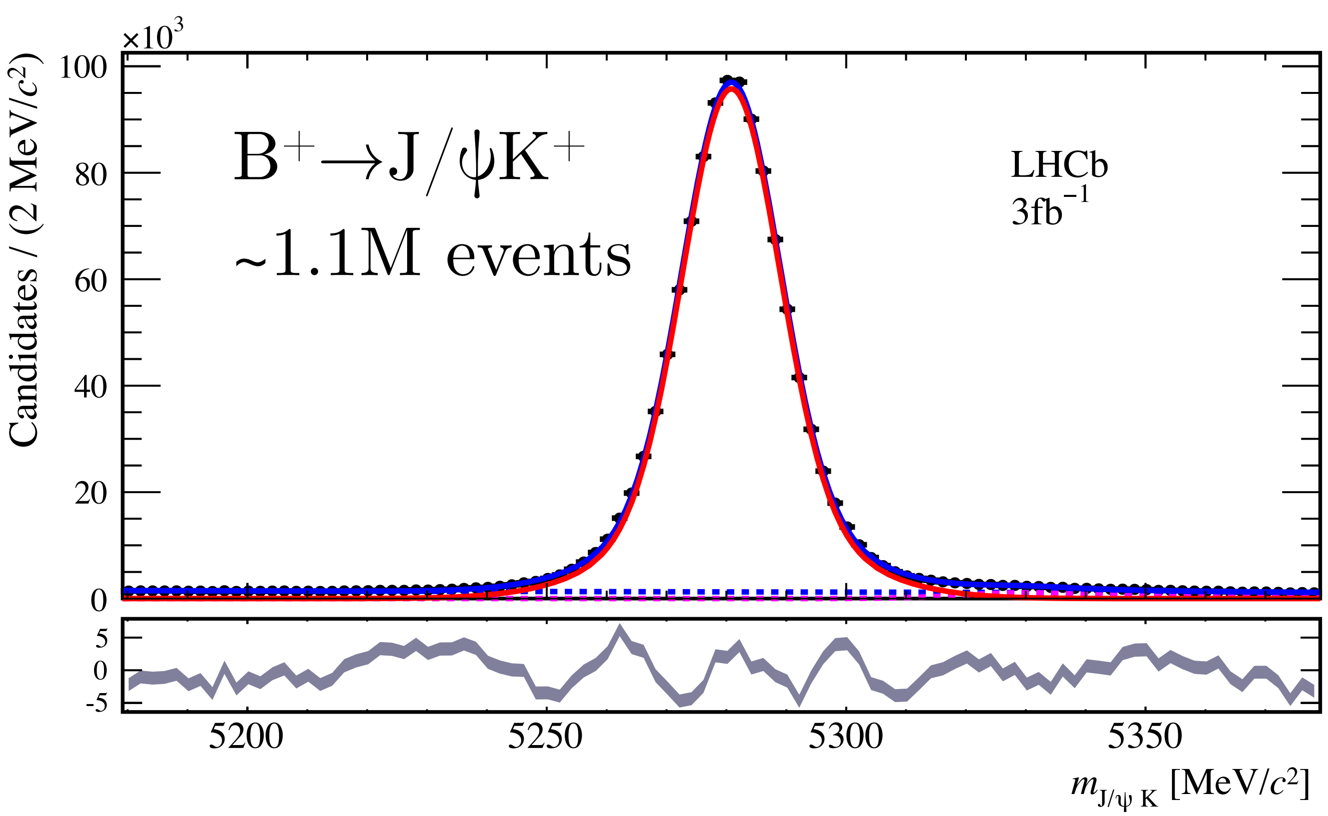
$$\mathrm{BR} = \mathrm{BR}_{\mathrm{cal}} \times \frac{\epsilon^{\mathrm{REC}}_{\mathrm{cal}}\epsilon^{\mathrm{SEL}}_{\mathrm{cal}}}{\epsilon^{\mathrm{REC}}_{\mathrm{sig}}\epsilon^{\mathrm{SEL}}_{\mathrm{sig}}} \times \frac{\epsilon^{\mathrm{TRIG}}_{\mathrm{cal}}}{\epsilon^{\mathrm{TRIG}}_{\mathrm{sig}}} \times \frac{f_{\mathrm{cal}}}{f_{d(s)}} \times \frac{N_{B^0_{(s)}\to\mu^+\mu^-}}{N_{\mathrm{cal}}} = \alpha_{(s)} \times N_{B^0_{(s)}\to\mu^+\mu^-}$$

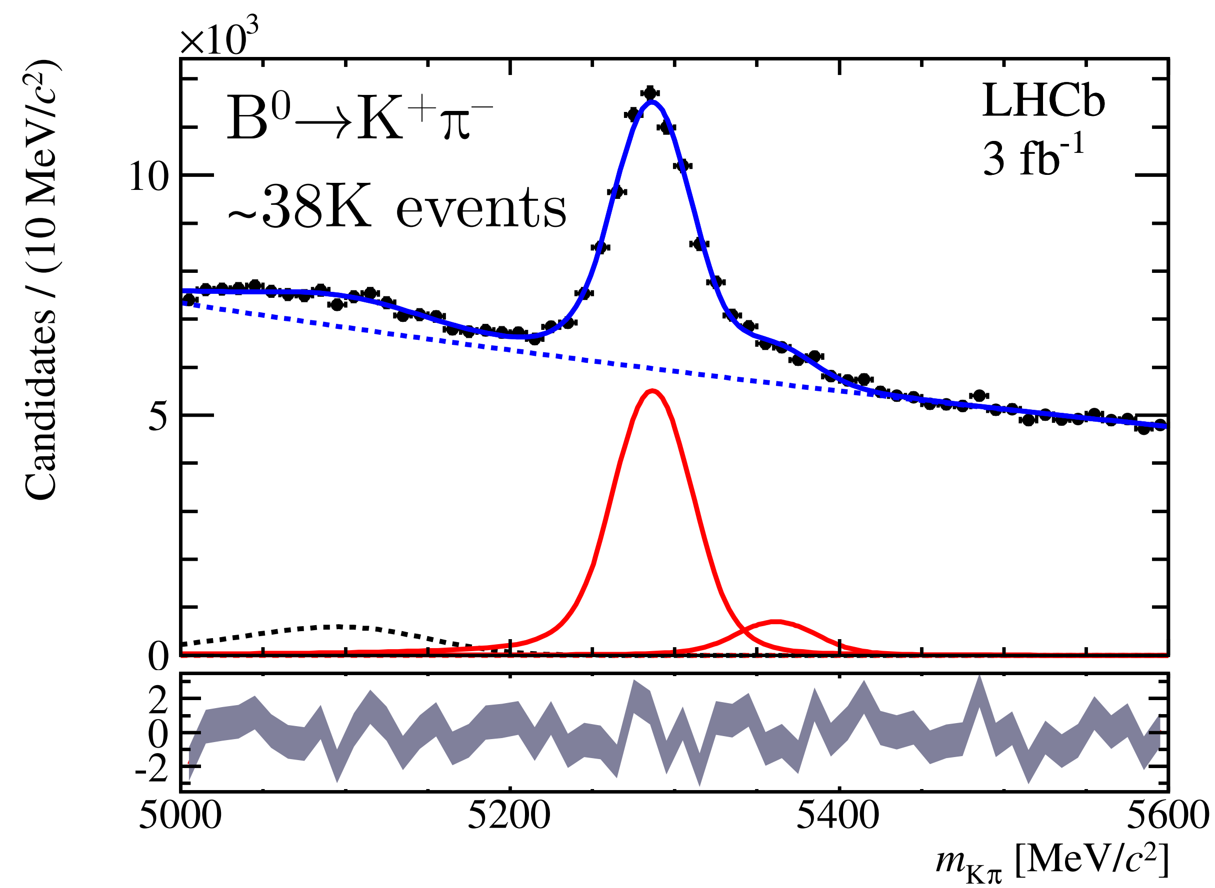
- **From MC and x-checked on data**
- **Trigger efficiency from $J/\psi \to \mu\mu$ data**
- **fs/fd from LHCb measurement (next slide)**

$\alpha_s = (9.41 \pm 0.65) \cdot 10^{-11}$

$\alpha = (2.40 \pm 0.09) \cdot 10^{-11}$

- Using the SM signal we expect 39.5 ± 4.3 $B_s \to \mu^+\mu^-$ and 4.5 ± 0.4 $B^0 \to \mu^+\mu^-$





b fragmentation f_s/f_d

[LHCb-CONF-2013-011]

- LHCb used semileptonic decays: ratio of $B^0_s \to D_s \mu X$ to $B \to D^+ \mu X$
- Combined with hadronic results: ratio of $B^0_s \to D^-_s \pi^+$ to $B^0 \to D^- K^+$

- Recently updated using new BF($D_s \to K^+ K^- \pi^+$) from CLEO, BaBar and Belle
- Updated B lifetime measurements

New

$$\frac{f_s}{f_d} = 0.259 \pm 0.015$$

- PT dependence negligible for $B^0_{(s)} \to \mu^+ \mu^-$. Checked the variation as a function of $\sqrt{s}$ with $B^+ \to J/\psi K^+$ and $B^0_s \to J/\psi \phi$

Time dependent acceptance

- $B_s \to \mu^+\mu^-$ time dependent width:

$$\Gamma(B_s^0(t) \to \mu^+\mu^-) = (R_H + R_L)e^{-\Gamma_s t}\left[\cosh\frac{y_s t}{\tau_{B_s}} + \mathcal{A}_{\Delta\Gamma}\sinh\frac{y_s t}{\tau_{B_s}}\right]$$

where:

$$y_s = \frac{\Gamma_L - \Gamma_H}{\Gamma_L + \Gamma_H} = 0.01615 \pm 0.0085 \qquad \mathcal{A}_{\Delta\Gamma} = \frac{\Gamma_{B^0_{s,H}\to\mu\mu} - \Gamma_{B^0_{s,L}\to\mu\mu}}{\Gamma_{B^0_{s,H}\to\mu\mu} + \Gamma_{B^0_{s,L}\to\mu\mu}} \overset{SM}{=} 1$$

- So the time integrated efficiency is model dependent: $\varepsilon = \frac{\int \varepsilon(t)\Gamma_{\mathcal{A},y_s}(t)dt}{\int \Gamma_{\mathcal{A},y_s}(t)dt}$

- Normalization to be corrected to take into account this effect:

$$\delta_\epsilon = \frac{\epsilon^{\mathcal{A}_{\Delta\Gamma},y_s}}{\epsilon^{MC}} = \frac{\int_0^\infty \Gamma(B_s^0(t) \to \mu^+\mu^-, \mathcal{A}_{\Delta\Gamma}, y_s)\epsilon(t)\mathrm{d}t}{\int_0^\infty \Gamma(B_s^0(t) \to \mu^+\mu^-, \mathcal{A}_{\Delta\Gamma}, y_s)\mathrm{d}t} \cdot \frac{\int_0^\infty e^{-\Gamma_{MC}t}\mathrm{d}t}{\int_0^\infty e^{-\Gamma_{MC}t}\epsilon(t)\mathrm{d}t}$$

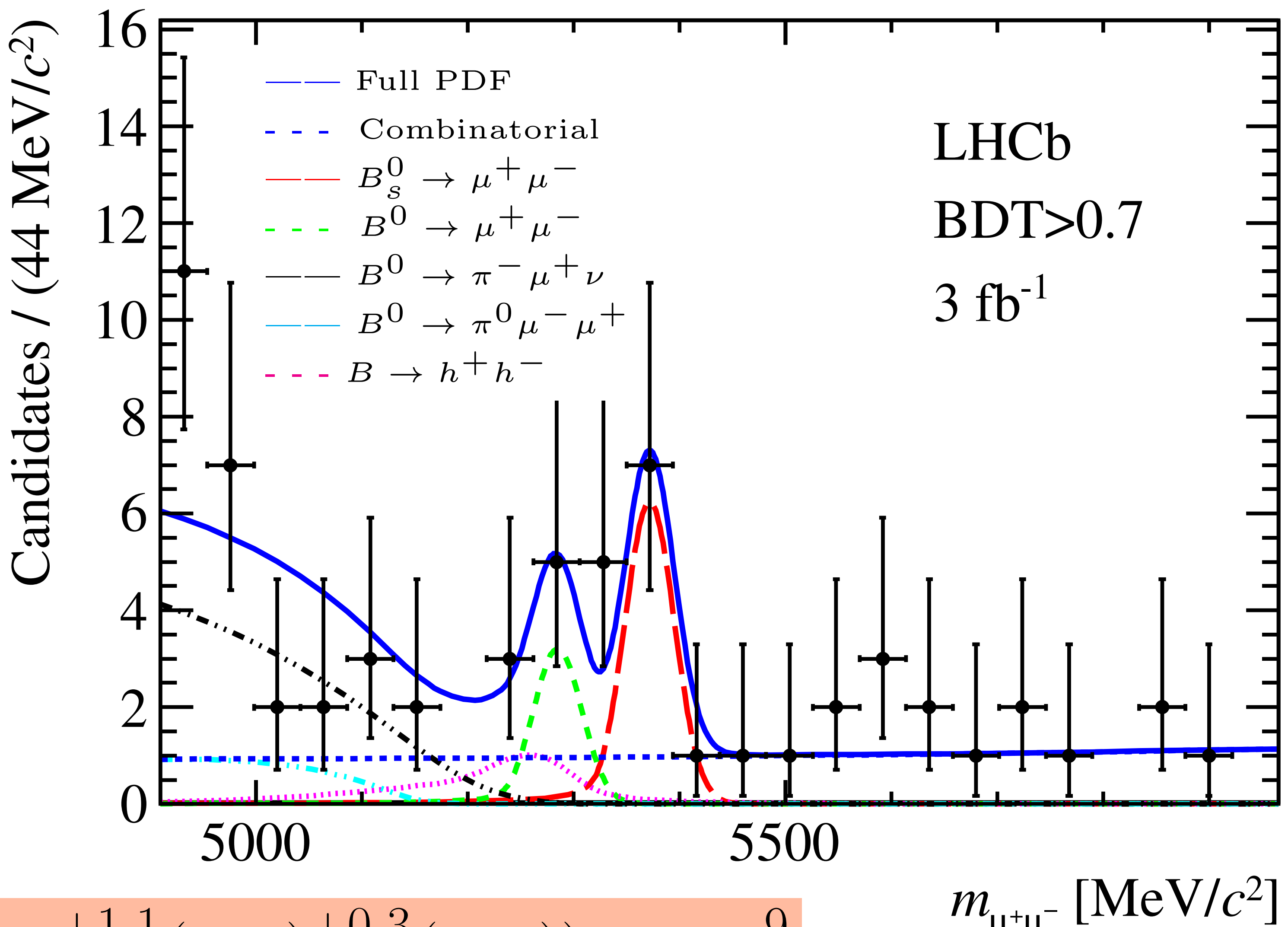
Correction for B_S = 4.50±0.03%
Correction for B^0 = 1.48±0.01%

- BDT PDF also corrected because time dependent

BF($B^0_s \to \mu^+\mu^-$)

[LHCb-PAPER-2013-046]

- A simultaneous unbinned likelihood fit to the mass spectra is performed on 8 BDT bins
- Combinatorial bkg, B_s and B^0 yields free
- yield and PDFs of exclusive backgrounds constrained to their expectations.



- For the B_s we obtain:

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}(\text{stat})^{+0.3}_{-0.1}(\text{syst})) \times 10^{-9}$$

- with a significance of **4.0 σ**
- For the B^0:

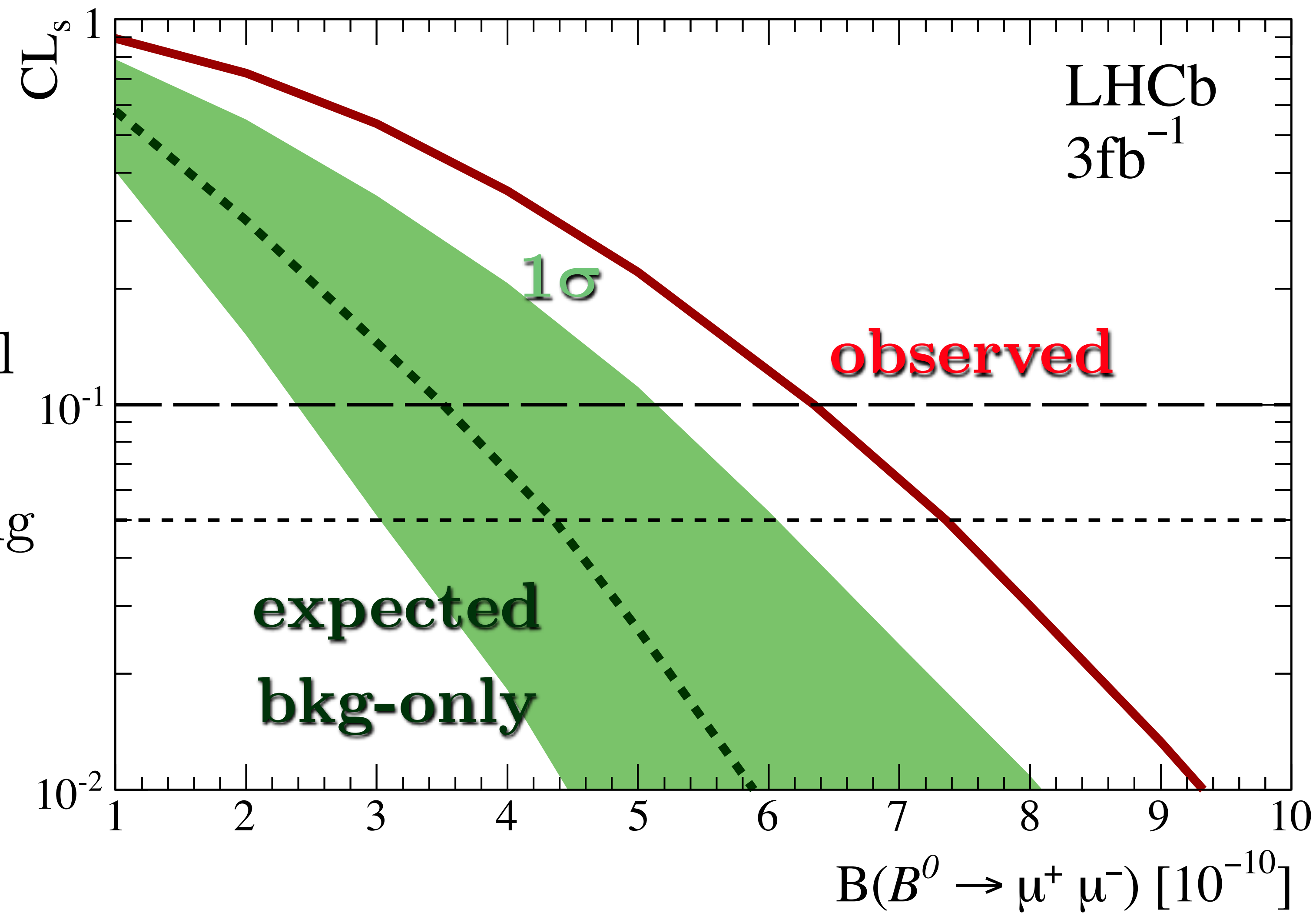
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}(\text{stat})^{+0.6}_{-0.4}(\text{syst})) \times 10^{-10}$$

- with a significance of 2.0 σ

$B^0 \to \mu^+\mu^-$ upper limit

[LHCb-PAPER-2013-046]

- No significant evidence of signal over background
- We quote an UL evaluated using CLs method.

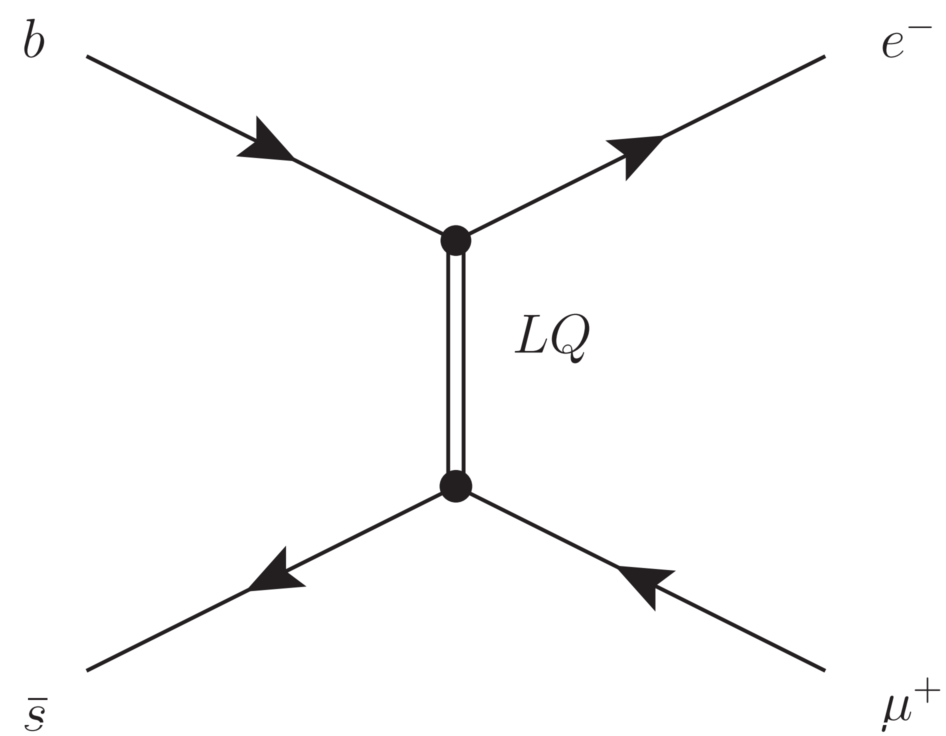


Limit at	90 % CL	95 % CL
Exp. bkg+SM	4.5×10^{-10}	5.4×10^{-10}
Exp. bkg	3.5×10^{-10}	4.4×10^{-10}
Observed	6.3×10^{-10}	7.4×10^{-10}

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

[LHCb-PAPER-2013-030]

- Charged LFV process are forbidden in the SM ($\sim 10^{-54}$)
- Decays like $B^0_{(s)} \to e\mu$ are allowed in model with a local gauge symmetry between leptons and quarks like the Pati-Salam model [Phys. Rev. D 10 (1974) 275.]
    - new interaction between lepton and quarks mediated by a spin-1 gauge boson (LQ)



- limits from CDF [Phys. Rev. Lett. 102 (2009) 201901]:

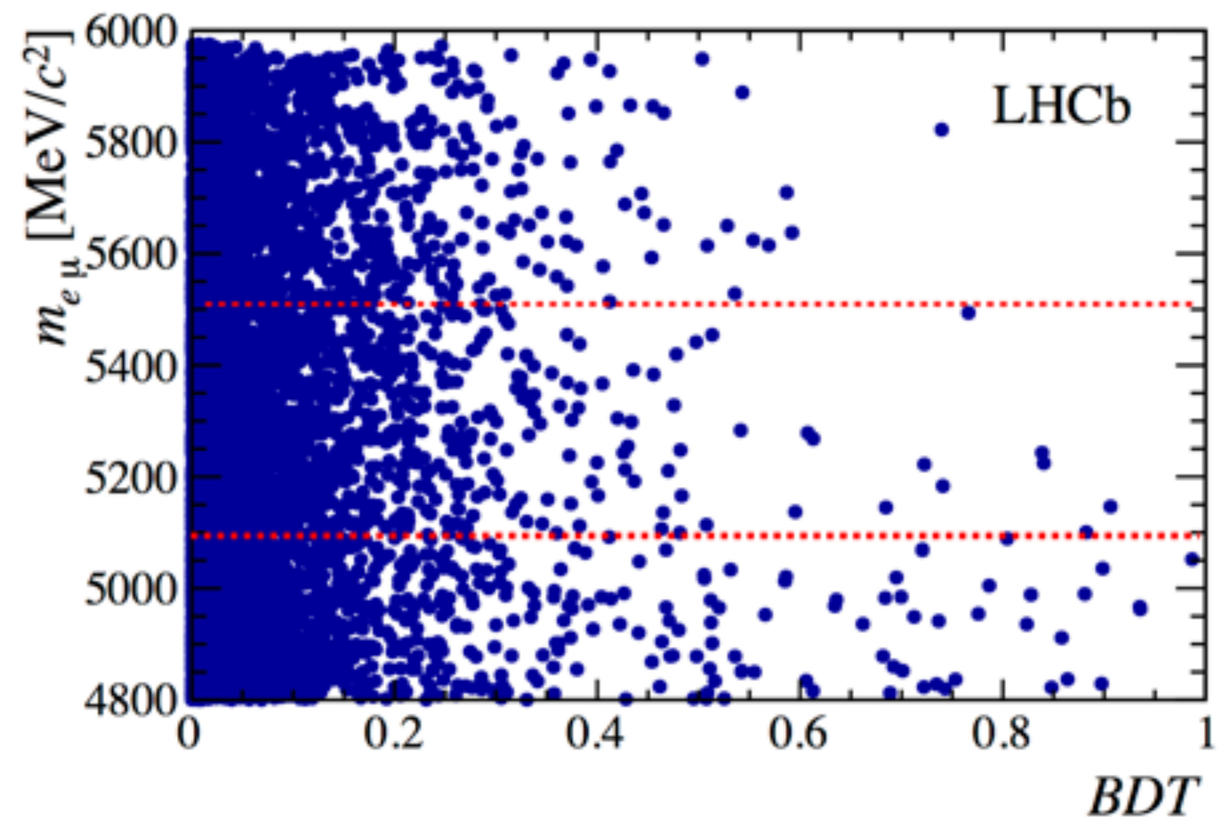
$$\mathcal{B}(B_s \to e^{\pm}\mu^{\mp}) < 2.0(2.6) \cdot 10^{-7} \text{ @ } 90(95)\% \text{ CL}$$

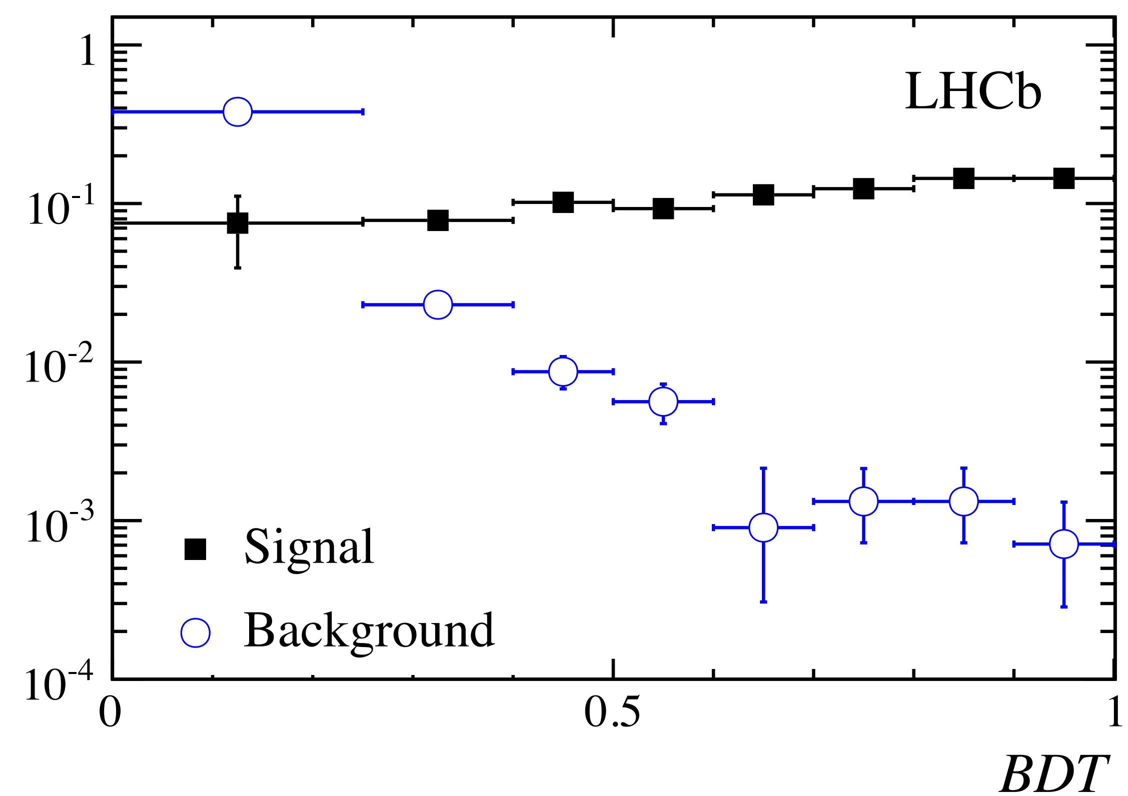
$$\mathcal{B}(B^0 \to e^{\pm}\mu^{\mp}) < 6.4(7.9) \cdot 10^{-8} \text{ @ } 90(95)\% \text{ CL}$$

Analysis strategy

[LHCb-PAPER-2013-030]

- Blind analysis based on $1 fb^{-1}$ of data recorded in 2011 ($\sqrt{s} = 7$TeV)
- Analysis inherited from $B^0_{(s)} \to \mu^+\mu^-$
- Events studied in $m_{e\mu}$ vs BDT plane
- Normalized to $B_d \to K\pi$ yield in data
- Upper limit on BF evaluated using the CLs method

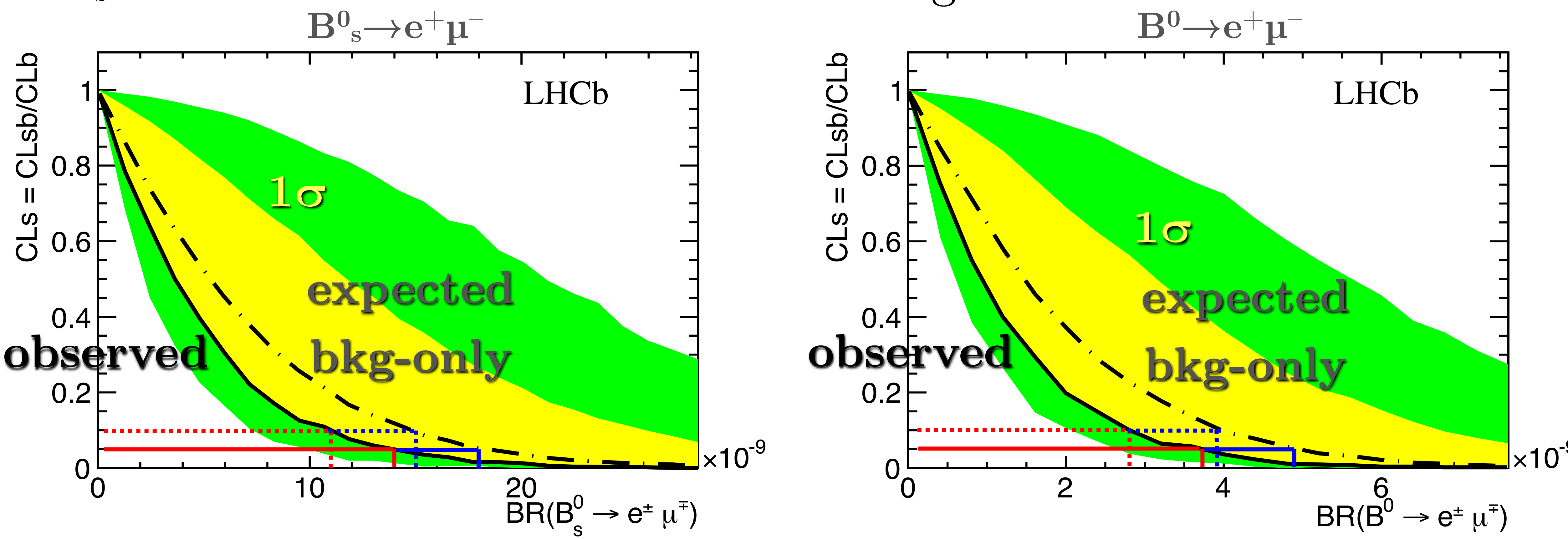




Results

[LHCb-PAPER-2013-030]

CL_s method to set limits on the branching fractions



	$B^0_s \to e^+\mu^-$ at 90%(95%) CL	$B^0 \to e^+\mu^-$ at 90%(95%) CL
Expected (LHCb 1fb^{-1})	**1.5 (1.8) 10^{-8}**	**3.8 (4.8) 10^{-9}**
Observed (LHCb 1fb^{-1})	**1.1 (1.4) 10^{-8}**	**2.8 (3.7) 10^{-9}**
Current (CDF 2fb^{-1})	20.0 (20.6) 10^{-8}	64.0 (79.0) 10^{-9}

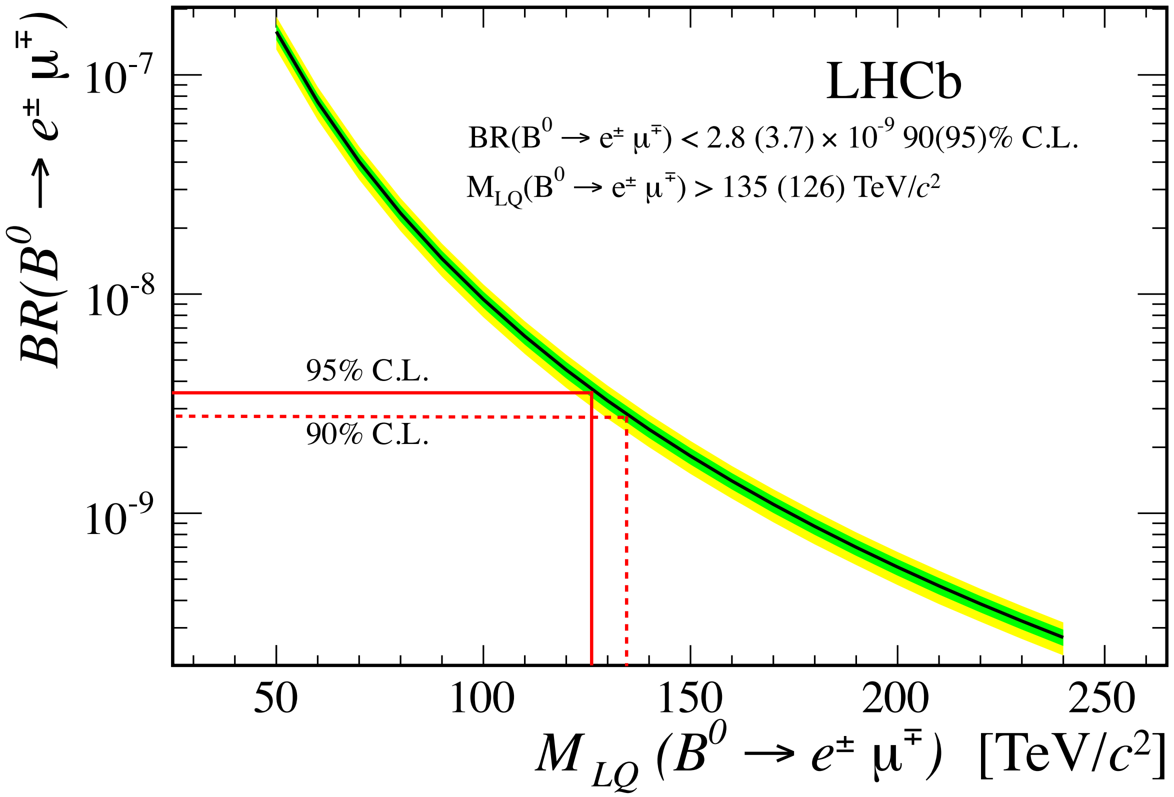
New world best limits ~20 times more stringent than limits previously reported.

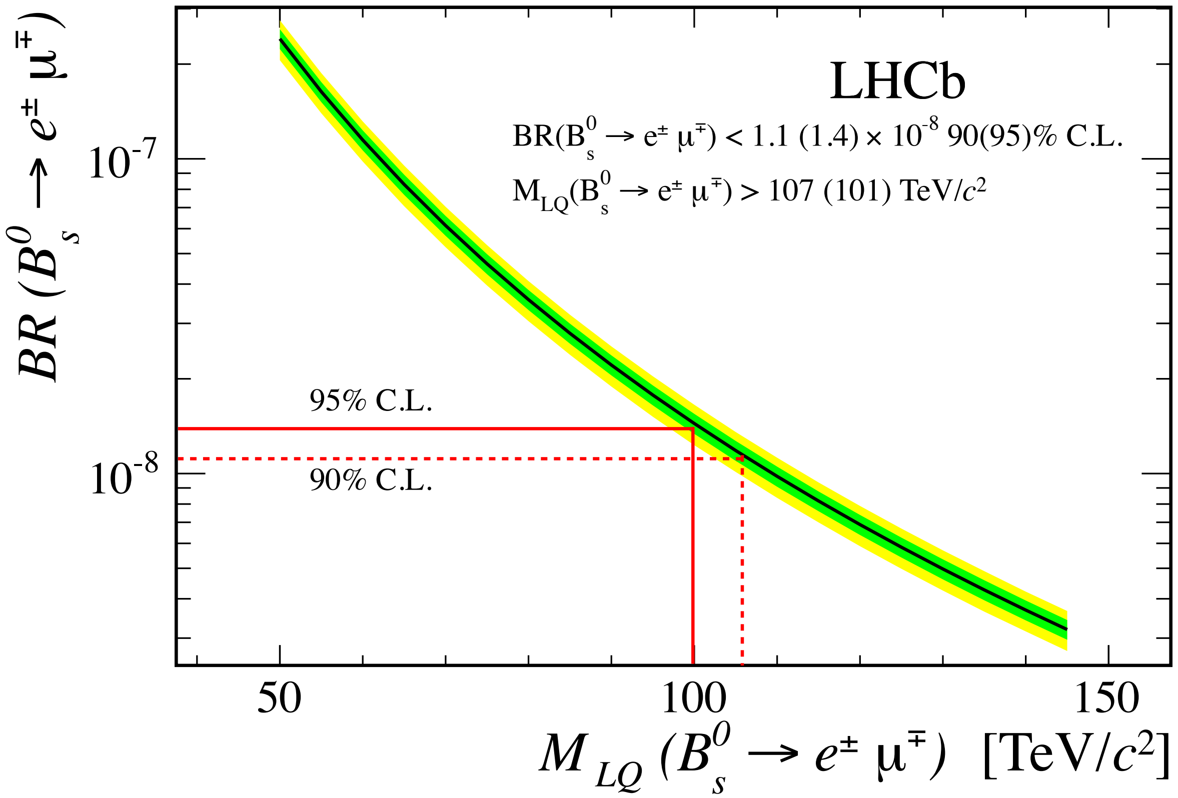
lepto-quark mass bounds

[LHCb-PAPER-2013-030]

UL on branching fractions set lower bounds to the Pati-Salam lepto-quark mass.

(theoretical formula here: Phys. Rev. D 50 (1994) 6843)





- CDF measurements:
  $m_{LQ}(B_s \to e^+\mu^-) > 47.8(44.9)\ TeV/c^2$ @ 90(95)%CL,
  $m_{LQ}(B_d \to e^+\mu^-) > 59.3(56.3)\ TeV/c^2$ @ 90(95)%CL
- LHCb new constraints:
  $m_{LQ}(B_s \to e^+\mu^-) > 107(101)\ TeV/c^2$ @ 90(95)%CL,
  $m_{LQ}(B_d \to e^+\mu^-) > 135(126)\ TeV/c^2$ @ 90(95)%CL

Conclusions

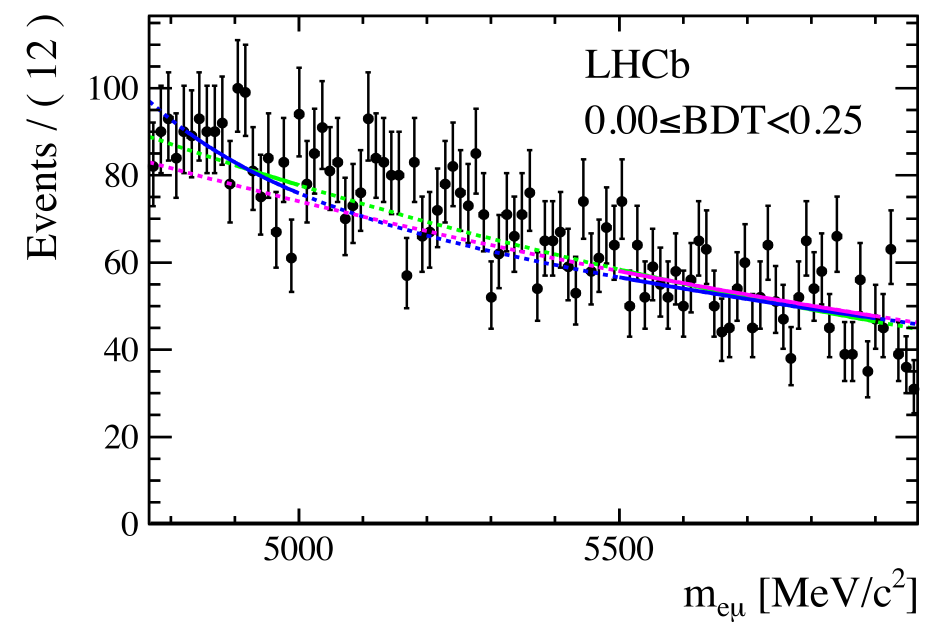
- Rare decays powerful probe to search NP beyond the SM
- LHCb is demonstrating its power in search for rare decays in Heavy Flavour sector
- New world's best limit on $B^0_{(s)} \rightarrow e\mu$ is presented
- Brand new results for $B^0_{(s)} \rightarrow \mu^+\mu^-$ using the full LHCb sample of $3fb^{-1}$
  - Confirmed evidence for $B_s \rightarrow \mu^+\mu^-$ with a significance of $4.0\ \sigma$
  - New world best limit on $B^0 \rightarrow \mu^+\mu^-$ branching fraction

Spares

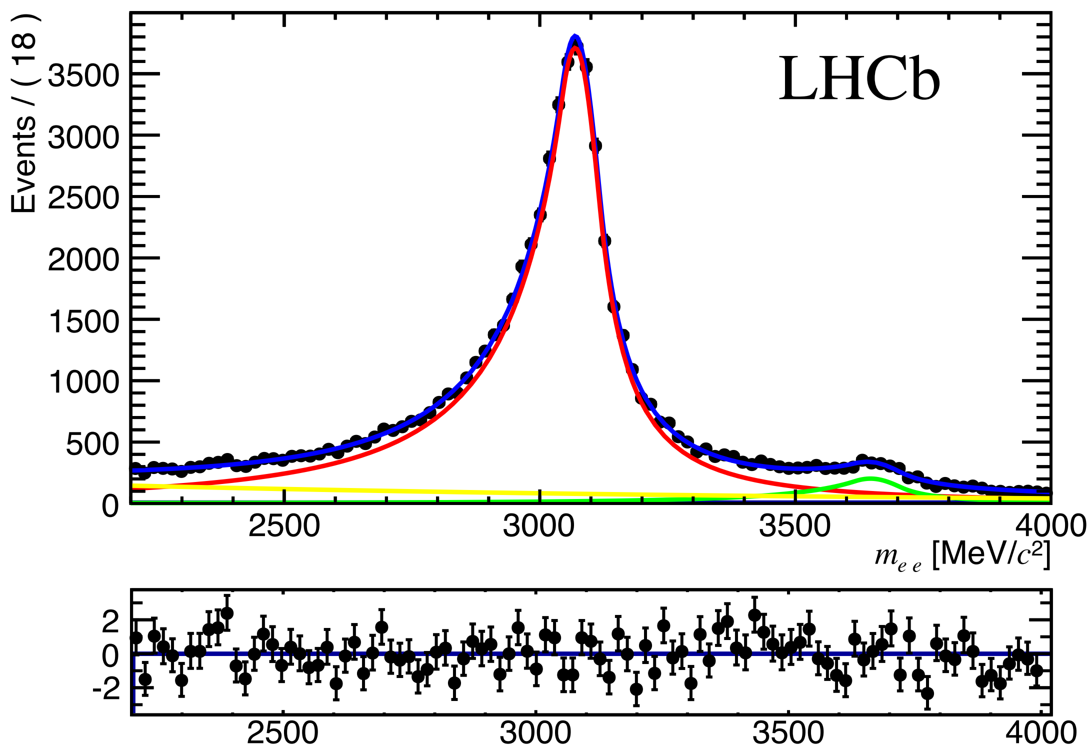
BDT Calibration $B^0_{(s)} \to e\mu$

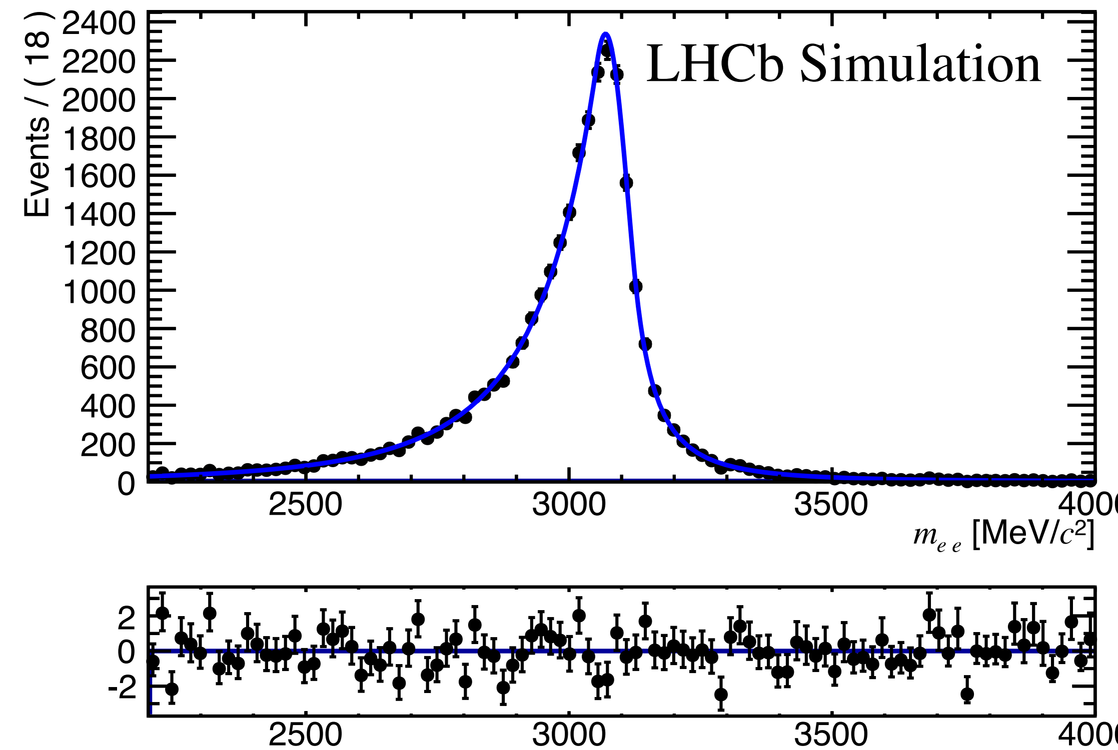
The BDT PDFs trained on MC are calibrated using:

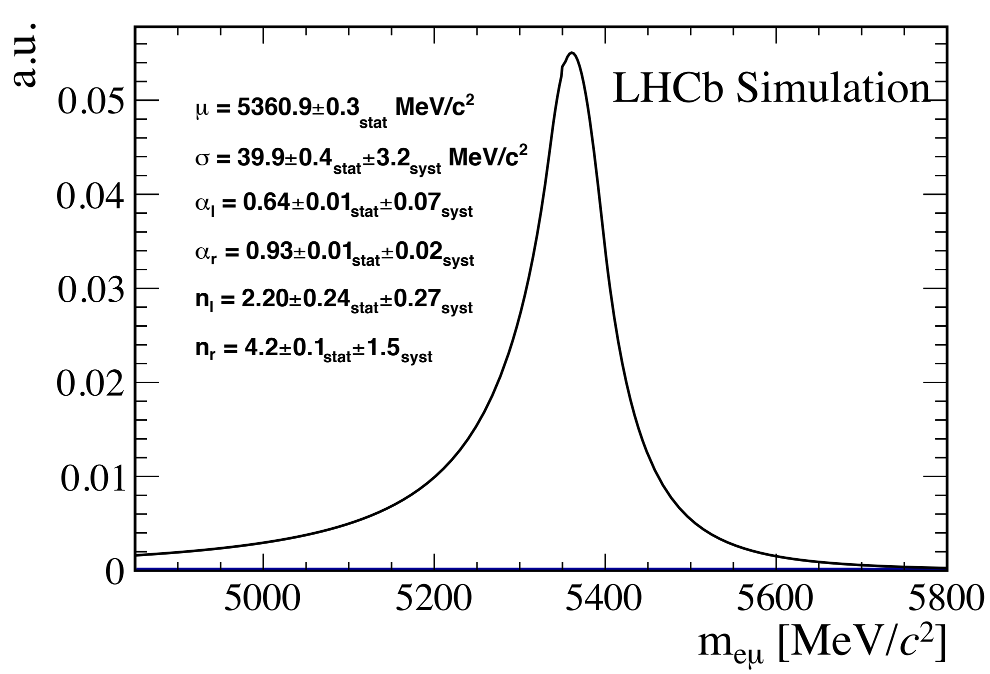
- $B \to hh$ for signal:
    - same topology and kinematics
    - correction introduced for the presence of an electron in the final state
- Data Sidebands for the calibration of the background



Mass Calibration $B^0_{(s)} \to e\mu$







- No proxy channel to calibrate the mass PDF
- J/psi->ee used for MC validation

Mass window		
	$\epsilon_{mass}(B_s)$	$(85.0 \pm 0.1_{\rm stat} \pm 4.5_{\rm syst})\%$
[5.1 – 5.5] GeV/c^2	$\epsilon_{mass}(B_d)$	$(82.1 \pm 0.1_{\rm stat} \pm 3.6_{\rm syst})\%$

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

$$\mathrm{BR}_{B^0_{(s)}\to e^+\mu^-} = \mathrm{BR}_{\mathrm{cal}} \times \frac{f_d}{f_q} \times \frac{\epsilon_{cal}^{SEL|REC}\,\epsilon_{cal}^{TRIG|SEL}}{\epsilon_{sig}^{SEL|REC}\,\epsilon_{sig}^{TRIG|SEL}}\,\frac{1}{\epsilon_{SIG}^{PID}} \times \frac{N_{B^0_{(s)}\to e^+\mu^-}}{N_{\mathrm{cal}}}$$

$$= \alpha \times N_{B^0_{(s)}\to e^+\mu^-}$$

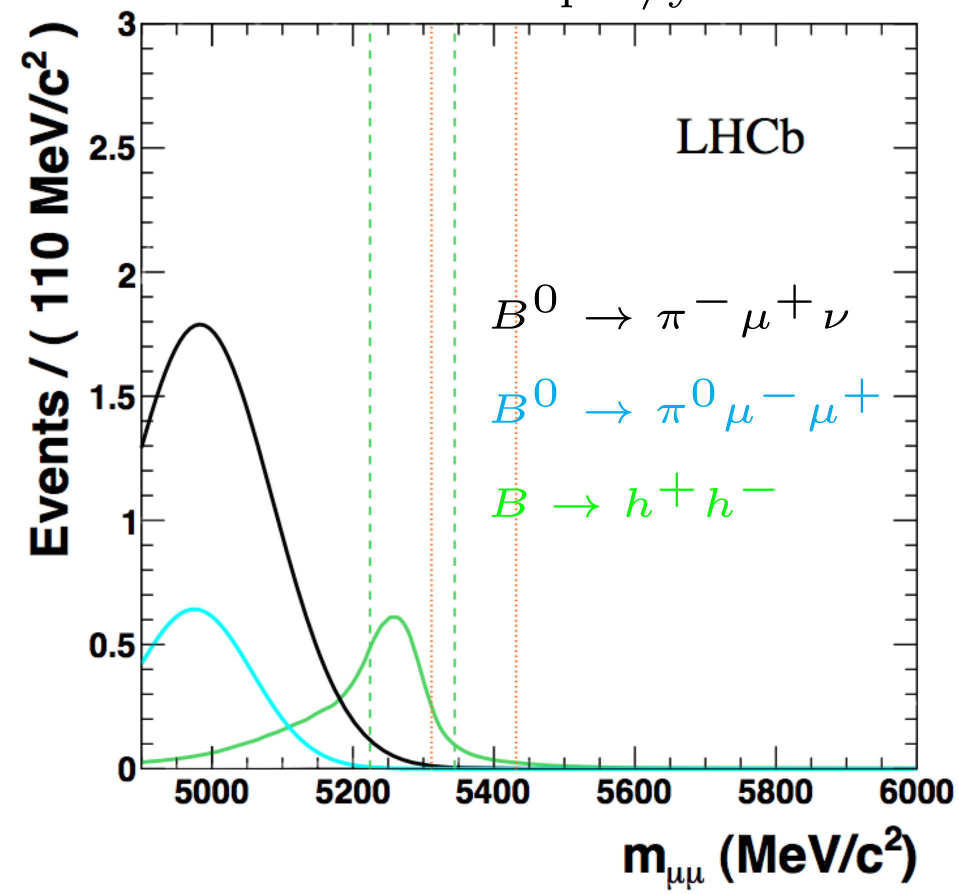
$BR(B_d \to K^+\pi^-)$	$(1.94 \pm 0.96) \cdot 10^{-5}$ [a]
f_d/f_s	3.91 ± 0.29 [b]
$\epsilon_{cal}^{SEL\|REC}/\epsilon_{sig}^{SEL\|REC}$	Take from MC, x-check in data
$\epsilon_{cal}^{TRIG\|SEL}/\epsilon_{sig}^{TRIG\|SEL}$	Data driven
ϵ_{SIG}^{PID}	Data driven
N_{cal}	10124 ± 916 [c]
$\alpha_{B^0_s\to e^+\mu^-}$ $\alpha_{B^0\to e^+\mu^-}$	$(1.1 \pm 0.2) \times 10^{-9}$ $(2.8 \pm 0.5) \times 10^{-10}$

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

- The main background is the combinatorial from $bb \to \mu^+\mu^-$ events extrapolated from mass sidebands

- Decays from partially reconstructed and/or misidentified decays:
  - contributing to the signal region: $B \to h^+h^- \to \mu^+\mu^-$
  - modifying the sidebands composition:
    - Semileptonics: $B^0 \to \pi^+\mu^-\nu$, $B^0_s \to K^+\mu^-\nu$, $\Lambda_b \to p\mu^-\nu$, $B^+_c \to J/\psi\mu^+\nu$
    - Rare decays: $B^+ \to \pi^+\mu^-\mu^+$, $B^0 \to \pi^0\mu^-\mu^+$
    - Many others considered and found negligible

Demonstrative plot
not actual shapes/yields



	Yield	Fraction for BDT> 0.7 [%]
$B^0_{(s)} \to h^+h'^-$	14.6 ± 1.3	28
$B^0 \to \pi^-\mu^+\nu_\mu$	115 ± 6	15
$B^0_s \to K^-\mu^+\nu_\mu$	10 ± 4	21
$B^{0(+)} \to \pi^{0(+)}\mu^+\mu^-$	28 ± 8	15
$\Lambda^0_b \to p\mu^-\bar{\nu}_\mu$	68 ± 30	11

Expected background yields from b-hadron decays, with dimuon mass $m_{\mu\mu} \in [4900, 6000]$ MeV/c^2