Measurement of the $B_s \to \mu^+\mu^-$ branching fraction at LHC(b)

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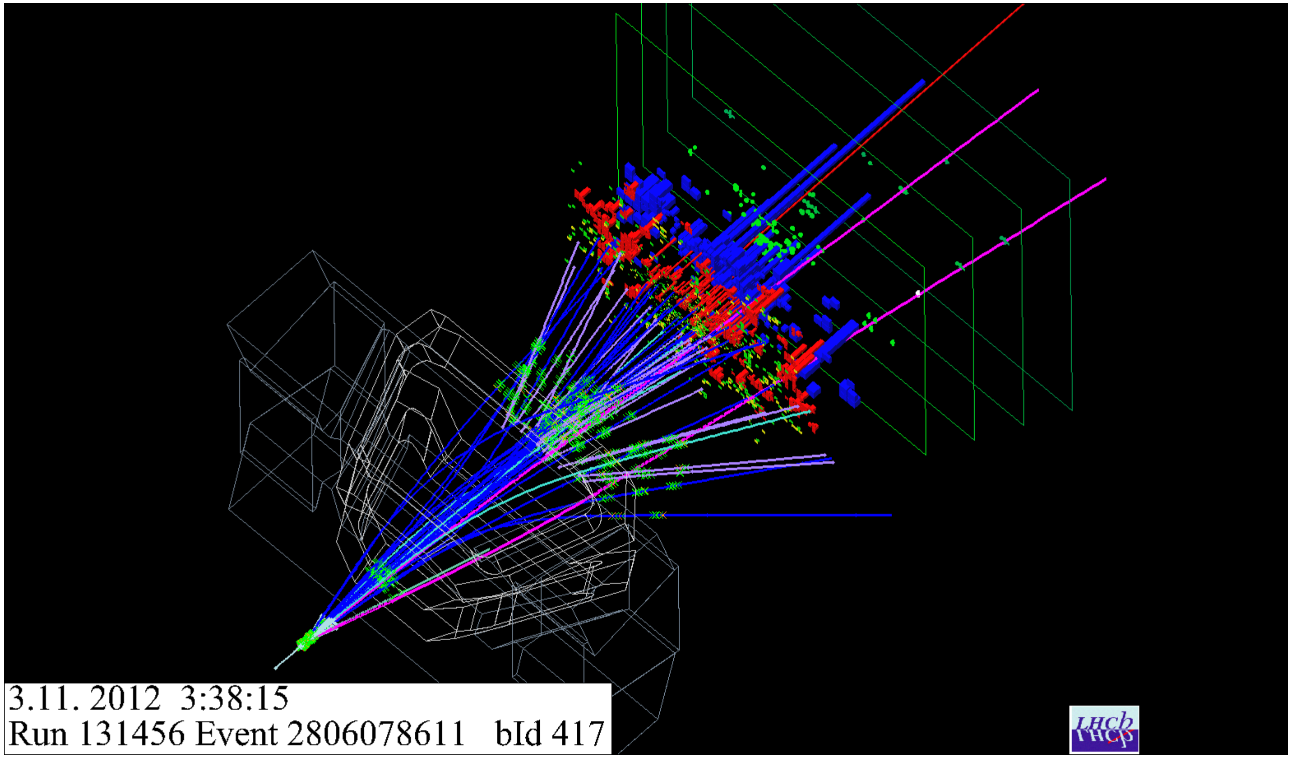
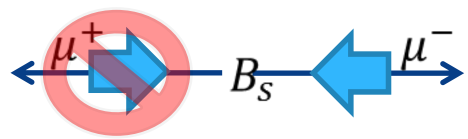


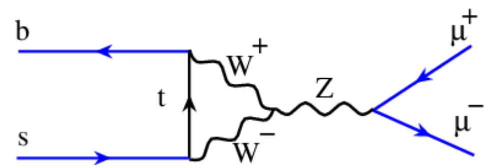
October 18th 2013, Annecy

Interest of $B_{s/d} \to \mu^+\mu^-$

- Flavour changing neutral current and helicity suppressed decays



- Precise SM prediction:



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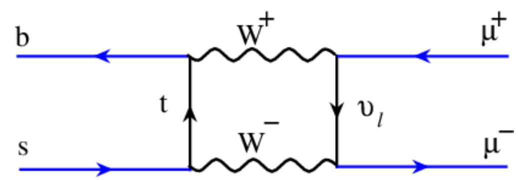


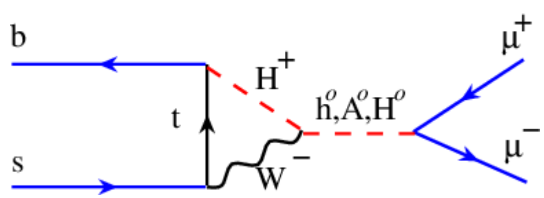
24%

  - $BR(B_s \to \mu^+\mu^-) = (3.35 \pm 0.28) \times 10^{-9}$
  - $BR(B_d \to \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10}$

A.J.Buras: arXiv:1208.0934 (updated Bs lifetime)

- Possible new particles in the loops

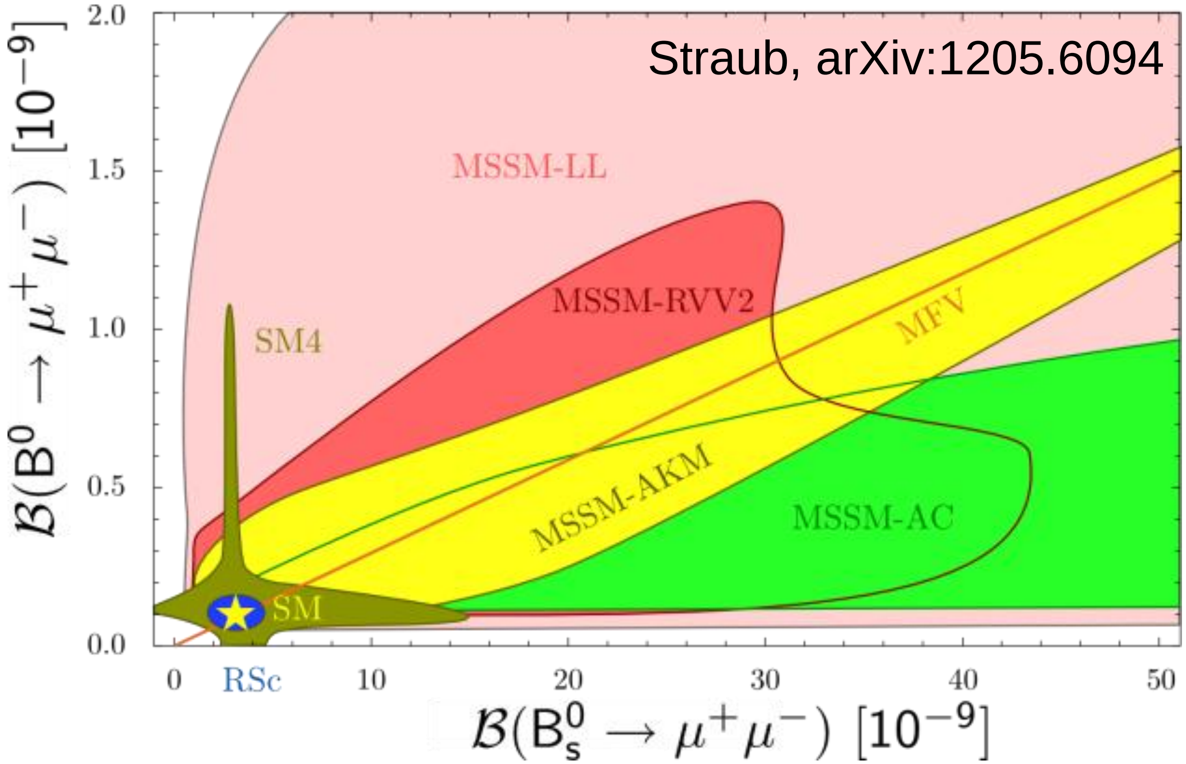
Ex:2HDM



Very good pace to look for physics beyond SM

Lot of NP models can be probed

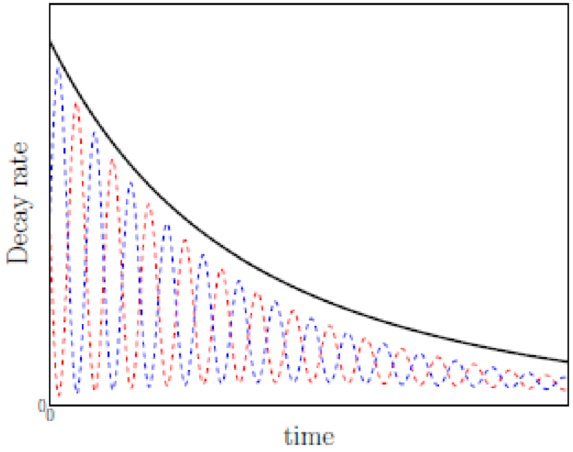
- Models with extended Higgs sector, e.g SuperSymmetry with large $\tan\beta$ as $BR \propto \tan^6\beta$
- Lepto-quarks
- Z' models
- MFV hypothesis
- Fourth generation
- …



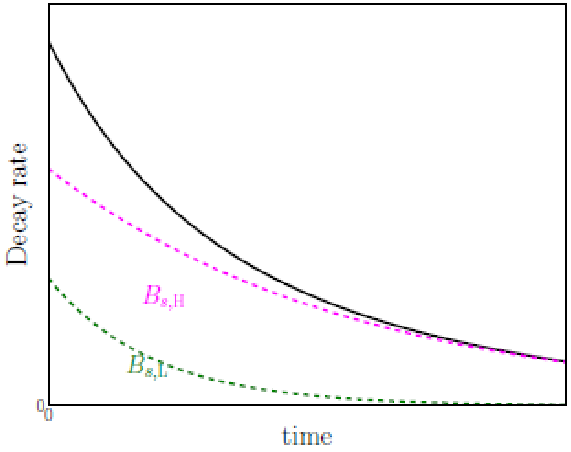
Experimental observables

- Neutral B mesons oscillate in admixture of mass eigenstates

Flavour basis



Mass e-state basis



$$\Gamma(B_s^0(t) \to f) + \Gamma(\bar{B}_s^0(t) \to f)$$

$$\Gamma(B_{s,\mathrm{H}} \to f)\, e^{-\Gamma_{\mathbf{H}} t} + \Gamma(B_{s,\mathrm{L}} \to f)\, e^{-\Gamma_{\mathbf{L}} t}$$

Experimental observable

- Experimental observable is the time integrated B:

$$B(B_s^0 \to f)_{\rm exp} \equiv \frac{1}{2}\int_0^\infty \langle \Gamma(B_s^0(t) \to f)\rangle dt$$

- Theoretical definition for the prediction:

$$B(B_s^0 \to f)_{\rm theo} \equiv \frac{\tau_{B_s^0}}{2}\langle \Gamma(B_s^0(t) \to f)\rangle \Big|_{t=0}$$

- Time integrated prediction:

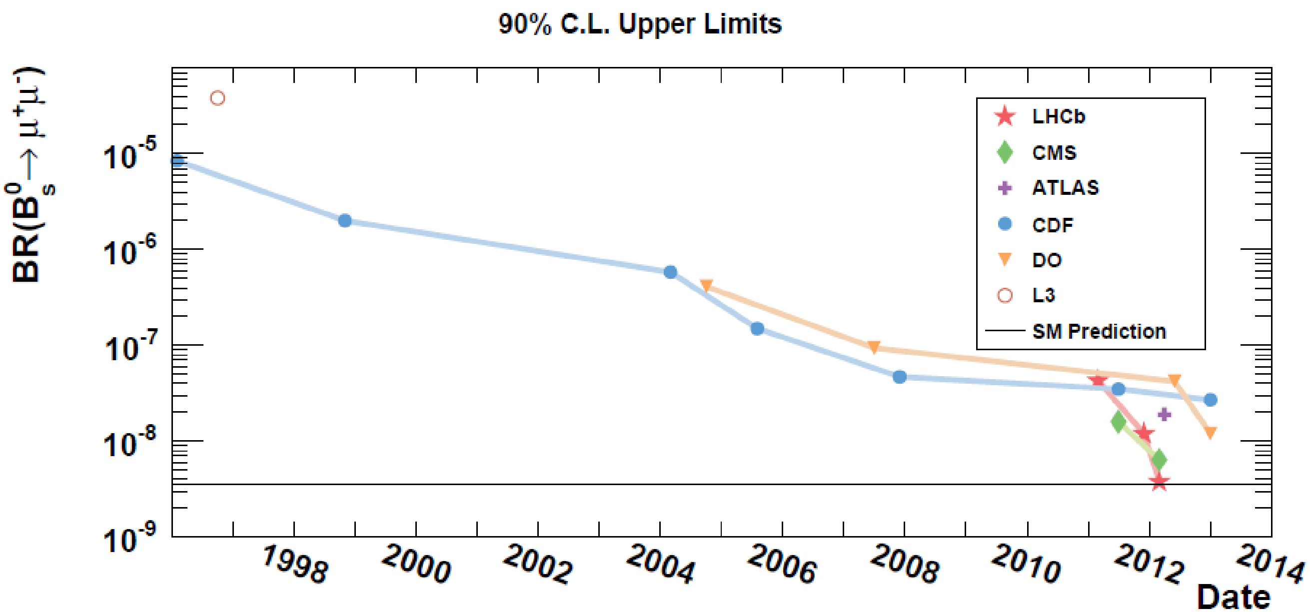
$$BF(B_s^0 \to \mu^+\mu^-)_{exp} = BF(B_s^0(t) \to \mu^+\mu^-)_{t=0} \times \frac{\mathbf{1 + A_{\Delta\Gamma} y_s}}{\mathbf{1 - y_s^2}}$$

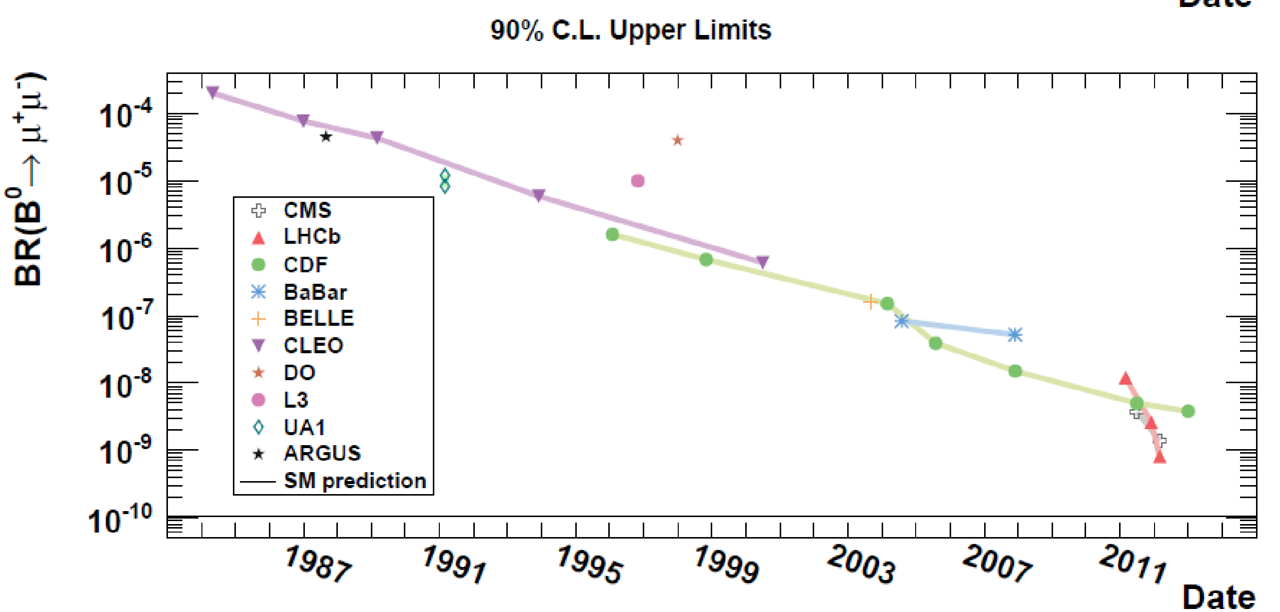
$$\mathcal{A}^f_{\Delta\Gamma} = \frac{\Gamma(B_{s,\rm H} \to f) - \Gamma(B_{s,\rm L} \to f)}{\Gamma(B_{s,\rm H} \to f) + \Gamma(B_{s,\rm L} \to f)} \qquad y_s = \frac{\Gamma_L - \Gamma_H}{\Gamma_L + \Gamma_H} = 0.0615 \pm 0.0085$$

$$in\ the\ SM:\ A_{\Delta\Gamma} = 1 \quad \boldsymbol{B\left(B_s^0 \to \mu^+\mu^-\right)^{SM}_{exp} = (3.56 \pm 0.30) \times 10^{-9}}$$

De Bruyn et al., PRL 109, 041801(2012), uses ys from HFAG

A long hunting…

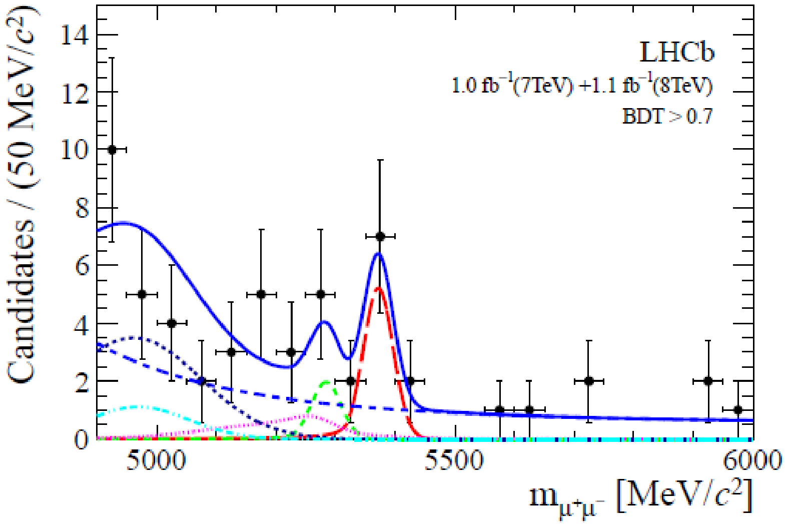




…before the first evidence!

- November 2012: LHCb find the first evidence with 1 (7 TeV) + 1 (8 TeV) fb^{-1}

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



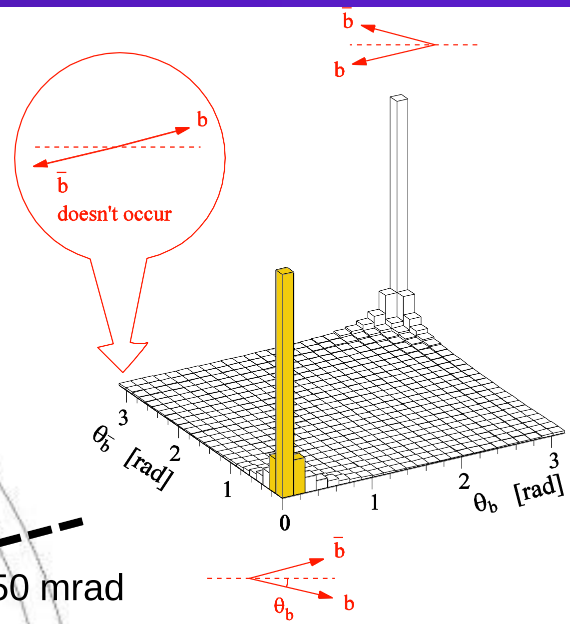
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 9.4 \times 10^{-10} \text{ at } 95\,\% \text{ CL}$$

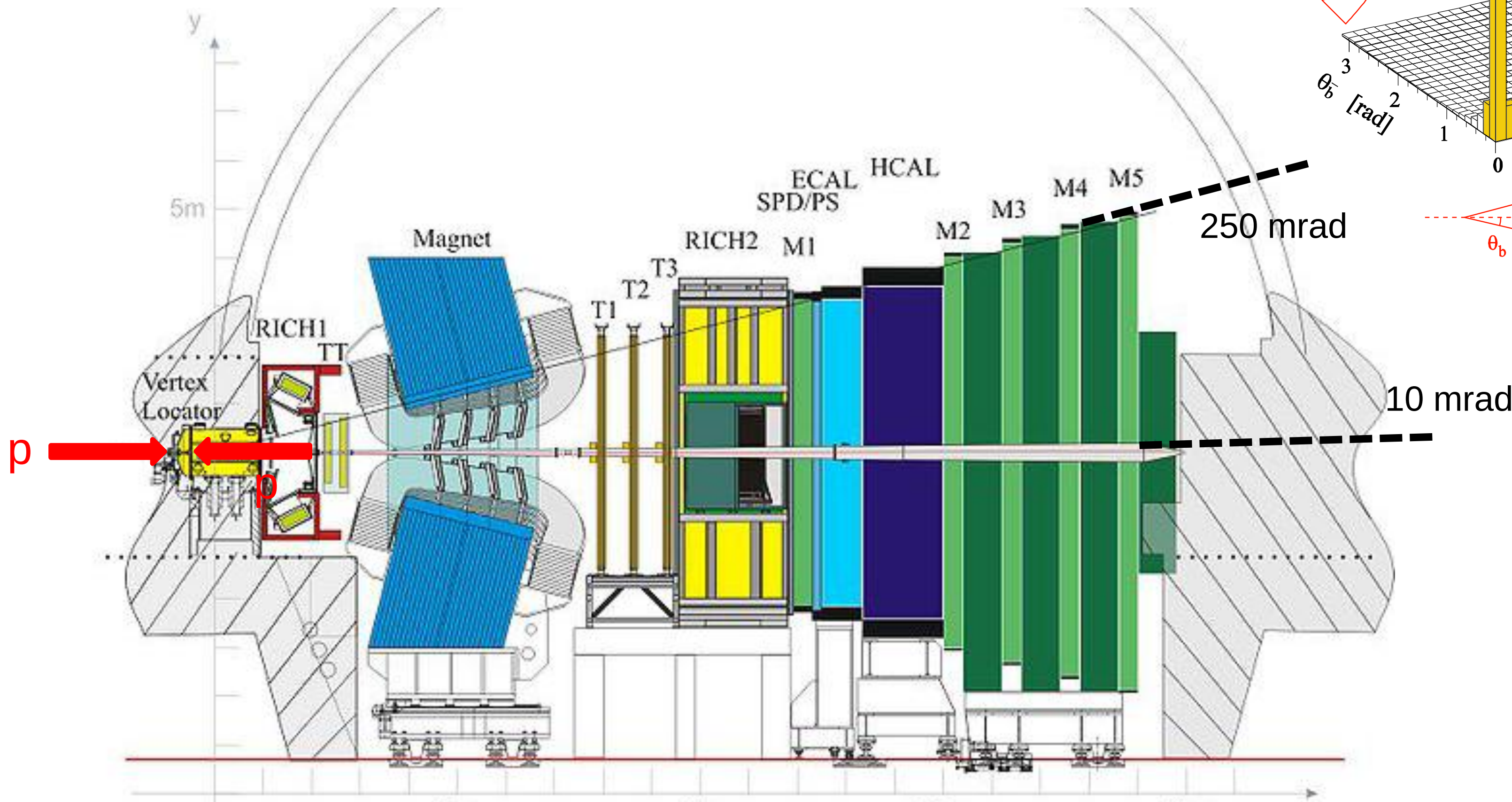
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$$

Significance of 3.5 σ !

- Today we present an update with the full dataset: 1 (7 TeV) + 2 (8 TeV) fb^{-1}
- All data consistently reprocessed
- All data in $m(B^0_{(s)})\pm 60$ MeV/c^2 are blind until analysis completion!

- Forward spectrometer optimised for heavy flavour physics at the LHC
  - Large acceptance 2<η<5
  - Large boost : B mesons flight ~1cm

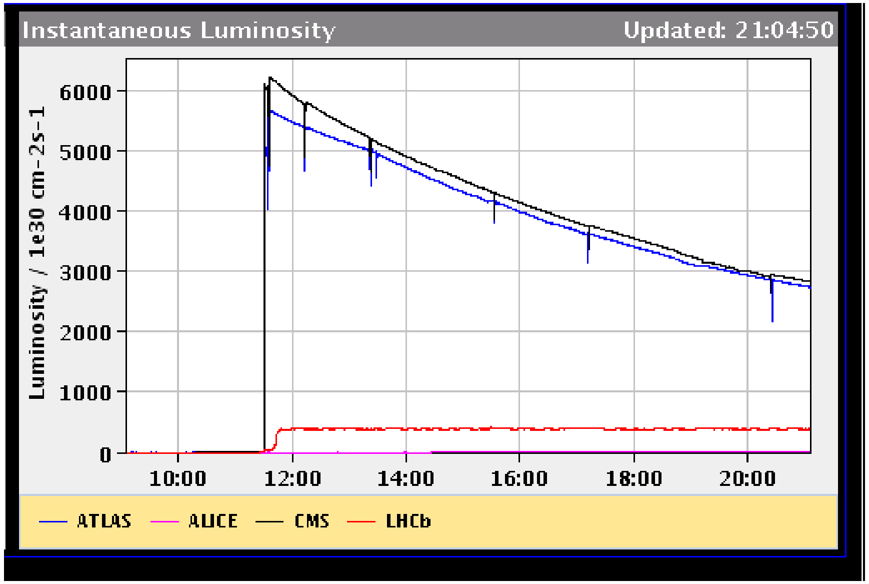




$B_{s/d} \rightarrow \mu^+\mu^-$ at LHCb

- Running at a constant luminosity of 4.10^{32} cm^{-2} s^{-1} thanks to the luminosity leveling

This is twice the design luminosity!



- Interactions per crossing

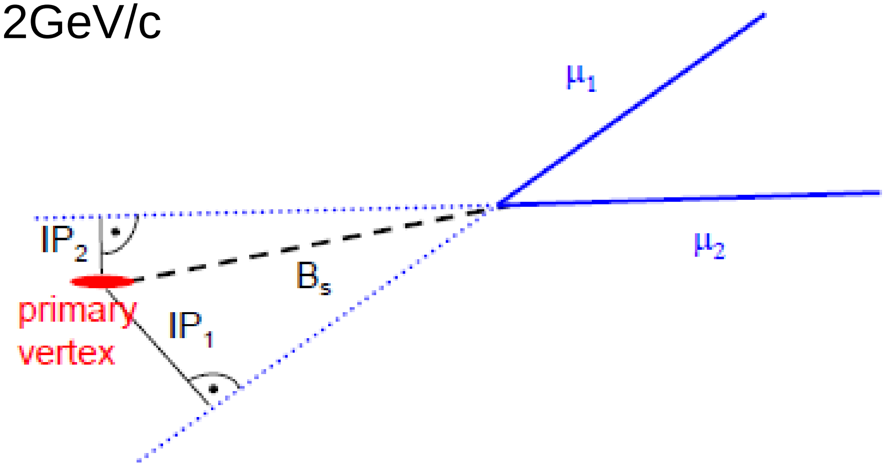
$<\mu>\sim 1.7$

This is four times more than design!

- Large muon trigger efficiency:
  - L0 single muon p_T>1.76 GeV/c, dimuon sqrt(p_T1xp_T2)>1.6GeV/c
  - HLT: IP and invariant mass cut
  - Global efficiency for $B_{s/d} \rightarrow \mu^+\mu^-$: ~90%

$B_{s/d} \to \mu^+\mu^-$ at LHCb

- Excellent momentum and IP resolution:
  - δp/p ~0.4% to 0.6% for p=5-100 GeV/c
  - σ(IP) = 25 μm @ 2GeV/c



- Excellent muon identification:
  - Use muon chambers information + global PID likelihood (RICH, CALO, MUON)
  - $\varepsilon(\mu \to \mu)$~98%, $\varepsilon(\pi \to \mu)$~0.6%, $\varepsilon(K \to \mu)$~0.4%, $\varepsilon(p \to \mu)$~0.3%

Analysis strategy

Analysis strategy

- Selection
  - Oppositely charged muons making a good vertex separated from the PV with $m_{\mu\mu}$ in the range [4.9-6] GeV/c^2
  - Loose cut on a MVA discriminant
  - Similar to control channels ($B_{d/s} \to h^+h^-$, $B^+ \to J/\psi K^+$)

- Signal and background discrimination:
  - Boosted decision tree combining kinematic and geometrical properties
  - Invariant mass
  - Data driven calibration through control channels

- Normalization using $B^+ \to J/\psi K^+$ and $B_d \to K\pi$

- Background estimation
  - Combinatorial from $m_{\mu\mu}$ sidebands
  - Double misidentified $B_{d/s} \to h^+h^-$ (h=K,π)
  - Detailed study on various exclusive background

Analysis strategy

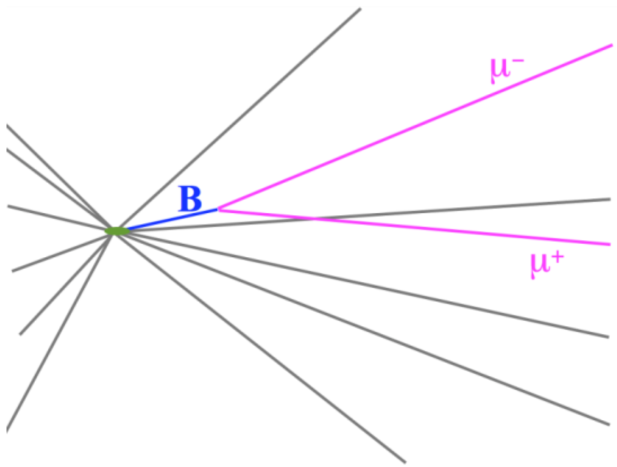
- Results
  - BR measurement using a maximum likelihood fit to the invariant mass in bins of BDT
  - In case no significant signal is found, limit measurement using the modified frequentist CLs method in bins of mass and BDT

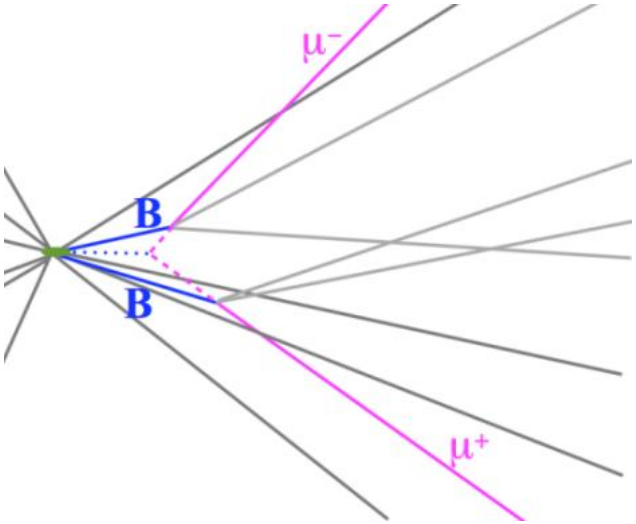
Strategy similar to previous analysis
Main improvements:
- new detector alignment and reconstruction
- Improved BDT classifier
- Refined exclusive background estimate

Signal discrimination

Signal discrimination: BDT

- Goal is to differentiate signal events from combinatorial background bb→μμX





- BDT training, choice of variable and BDT parameters optimization based on MC signal and bb→μμX background (new sample equivalent to 7 fb^{-1})

- 12 variables used (previously 9) based on kinematic and topological information
- chosen to avoid correlation with invariant mass

BDT variables

B candidate:

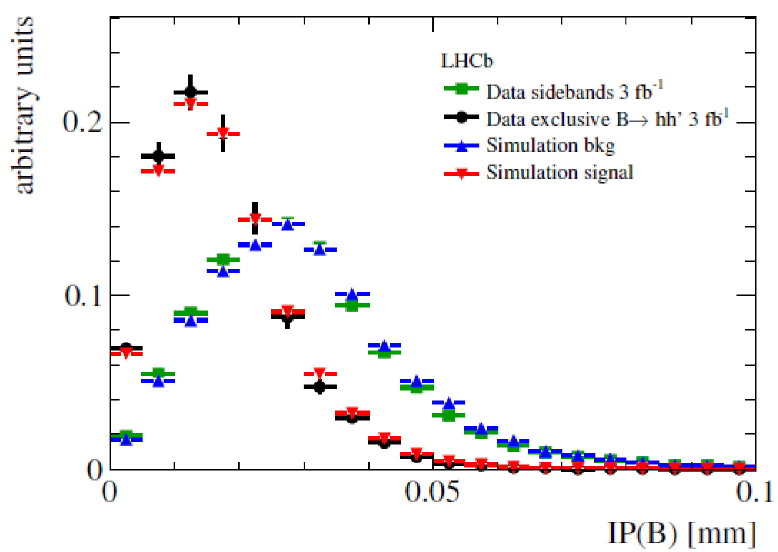
- proper time
- IP
- p_T
- isolation
- Angle between the B momentum and P_{thrust}
- Angle between μ^+ direction in the B rest frame and P_{thrust} in the B rest frame

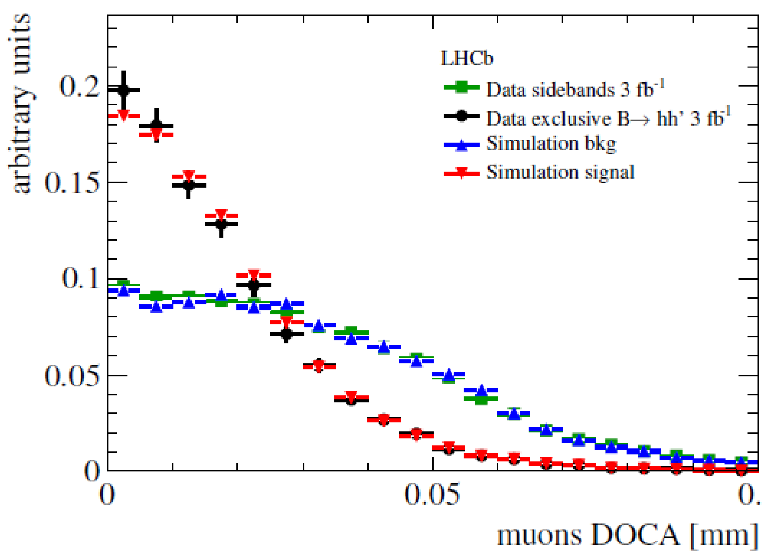
Muons:

- min IP significance
- distance of closest approach
- isolation
- polarization angle
- $|\eta(\mu_1)-\eta(\mu_2)|$
- $|\varphi(\mu_1)- \varphi(\mu_2)|$

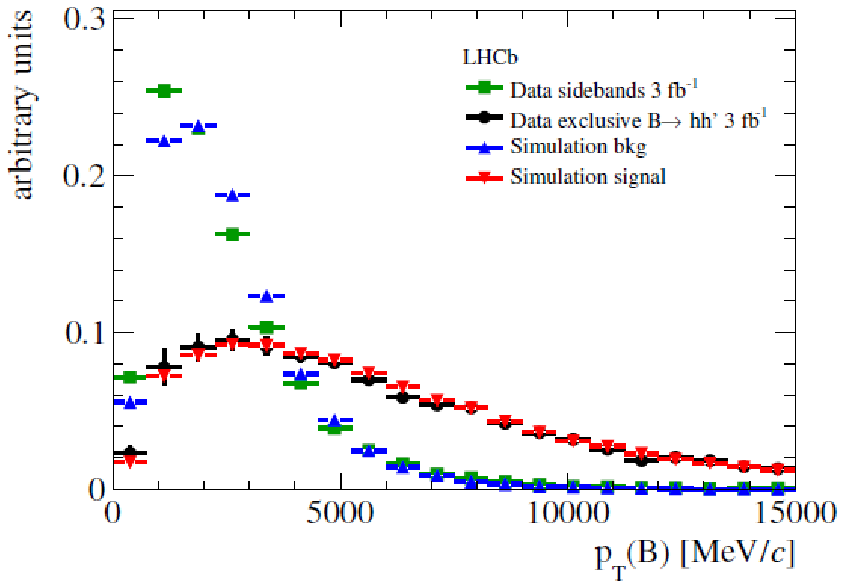
NEW

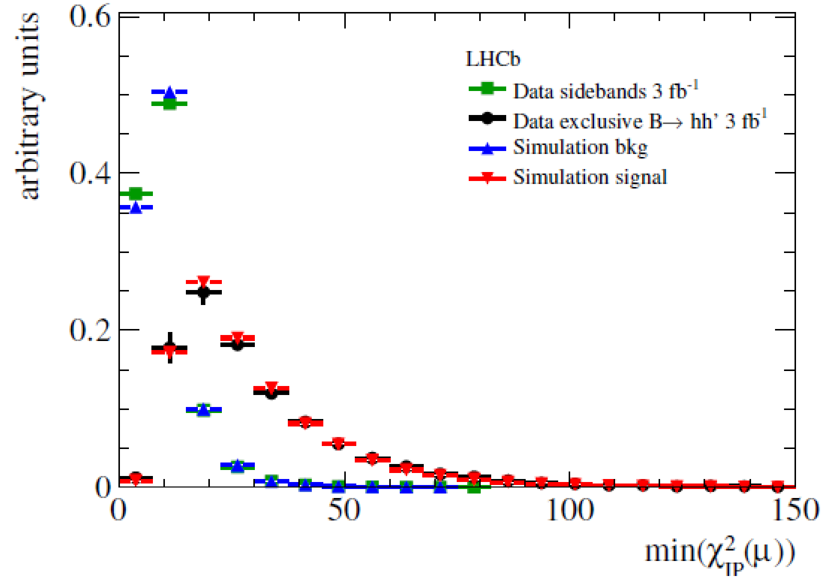
P_{thrust} is the sum of momenta of all tracks consistent with originating from the decay of the other b hadron

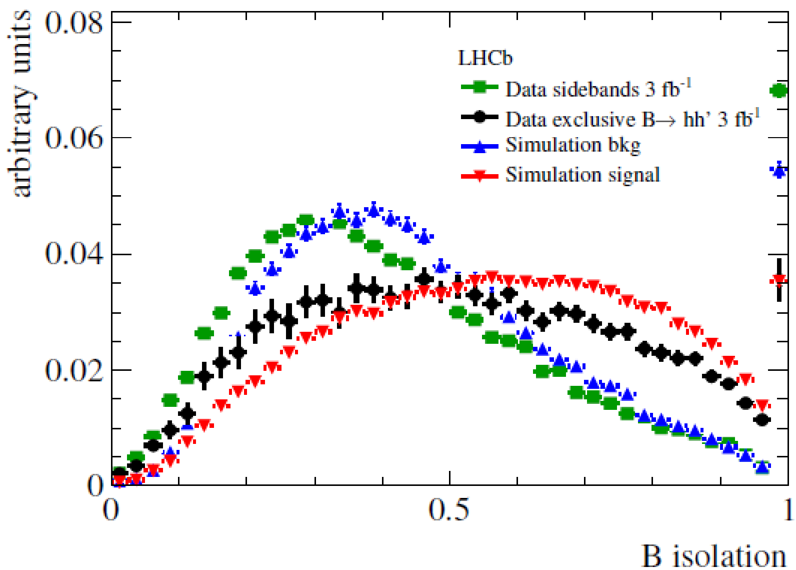


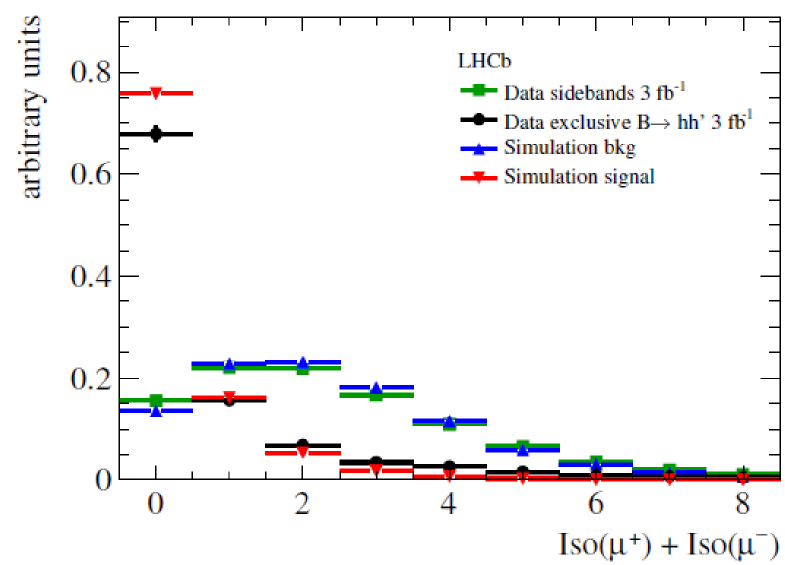


BDT variables



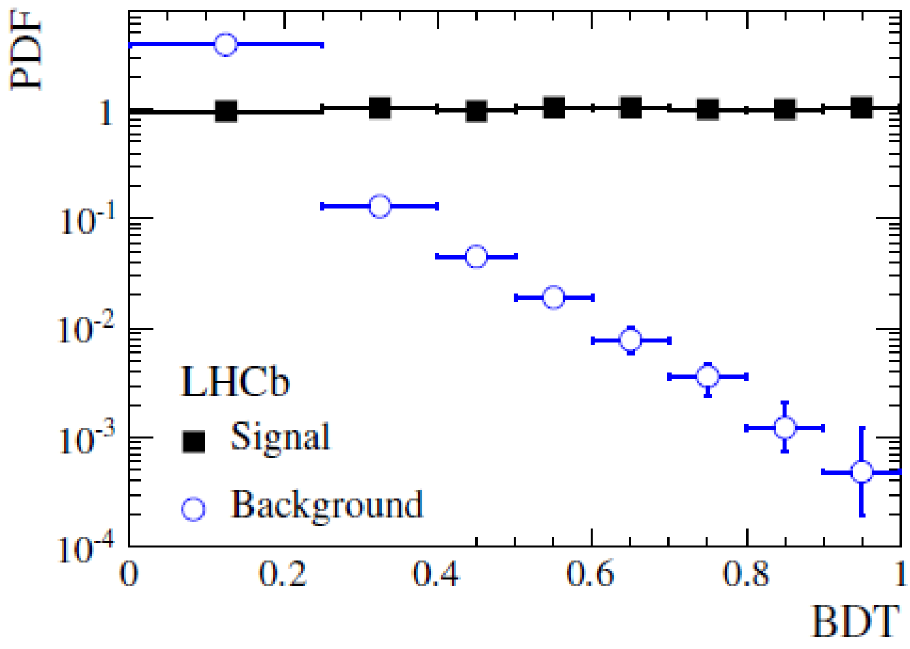






BDT output

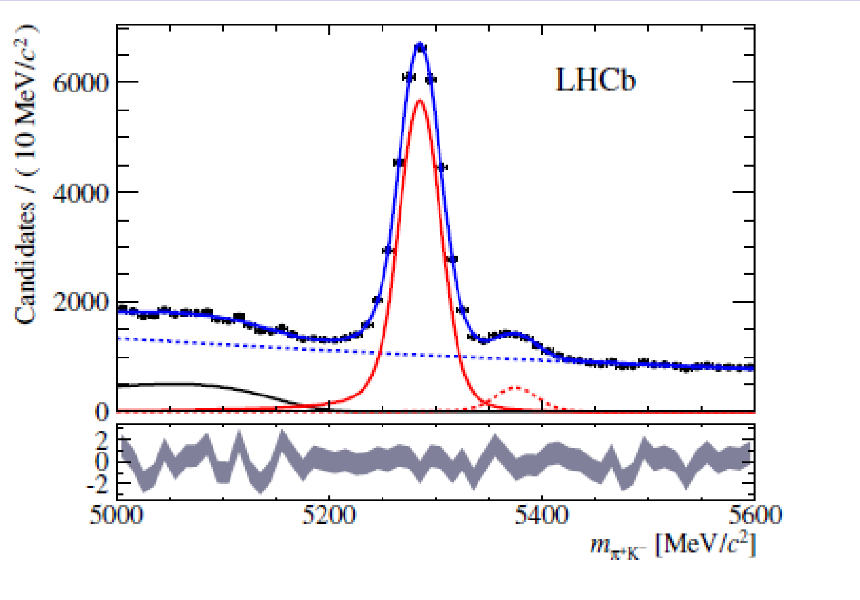
- BDT output defined to be flat for signal and peaked at 0 for background
- Signal shape derived from $B_{d/s} \rightarrow h^+h'^-$ (h=K,π) data (same topology as signal)
- Background from dimuon mass sidebands



- Analysis performed in 8 BDT bins

Signal discrimination: invariant mass

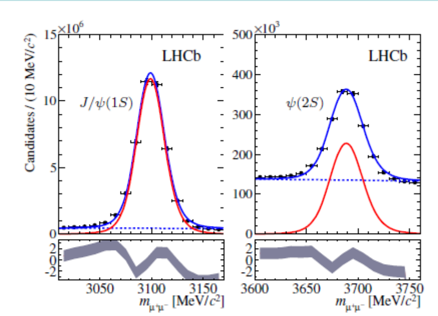
- Central value taken from exclusive $B_{d/s} \to h^+h'^-$

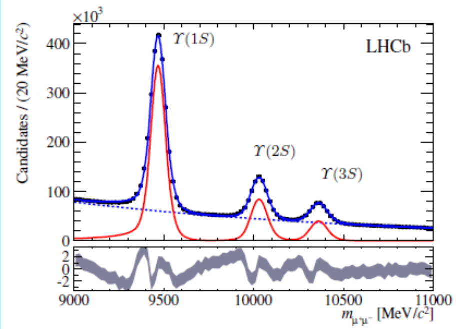


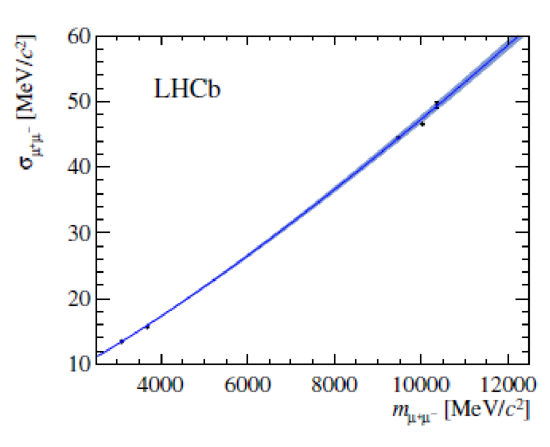
$$\mu_{B^o} = (5284.90 \pm 0.10 \pm 0.20)\ \text{MeV/c}^2$$

$$\mu_{B_S} = (5371.85 \pm 0.17 \pm 0.19)\ \text{MeV/c}^2$$

- Resolution from $B_{d/s} \to h^+h'^-$ exclusive and di-muon resonances.
- The 2 methods are in agreement







$$\sigma_{B^o} = (22.83 \pm 0.07 \pm 0.42)\ \text{MeV/c}^2$$

$$\sigma_{B_S} = (23.24 \pm 0.08 \pm 0.44)\ \text{MeV/c}^2$$

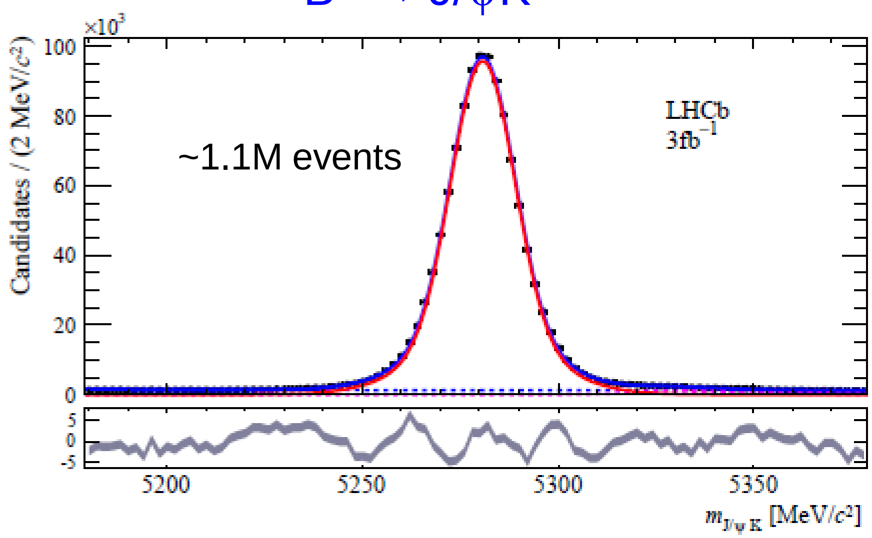
Normalization

$$\mathrm{BR} = \mathrm{BR}_{\mathrm{cal}} \times \frac{\epsilon_{\mathrm{cal}}^{\mathrm{GEN}}\,\epsilon_{\mathrm{cal}}^{\mathrm{SEL\&REC|GEN}}\,\epsilon_{\mathrm{cal}}^{\mathrm{TRIG|SEL}}}{\epsilon_{\mathrm{sig}}^{\mathrm{GEN}}\,\epsilon_{\mathrm{sig}}^{\mathrm{SEL\&REC|GEN}}\,\epsilon_{\mathrm{sig}}^{\mathrm{TRIG|SEL}}} \times \frac{f_{\mathrm{cal}}}{f_{B_q^0}} \times \frac{N_{B_q^0\to\mu^+\mu^-}}{N_{\mathrm{cal}}} = \alpha_{\mathrm{cal}} \times N_{B_q^0\to\mu^+\mu^-}$$

Ratio of probability for a b-quark to hadronize into a given meson, $f_u = f_d$

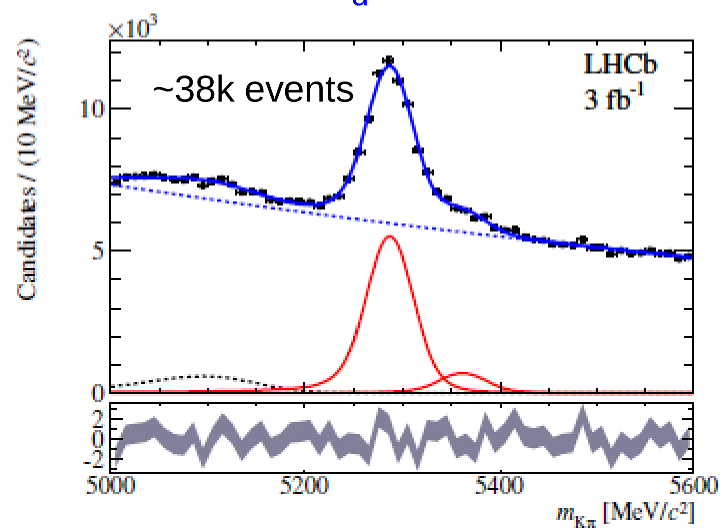
- 2 normalization channels used:

$B^+ \to J/\psi K^+$



Similar trigger than signal, one more track

$B_d \to K\pi$



Same topology as signal, different trigger

B fragmentation f_s/f_d

- f_s/f_d is measured at LHCb with 2 independent methods
  - Ratio of $B^0 \to D^- K^+/\pi^+$ and $B_s \to D_s^- \pi^+$ (JHEP 04 (2013) 1)
  - $B_s \to D_s X\mu$ and $B \to D^+ X\mu$ (PRD 85 (2012), 032008)

- Recently updated using new BR($D_s \to KK\pi$) from CLEO, Babar and Belle and new B lifetime measurements

- Average :

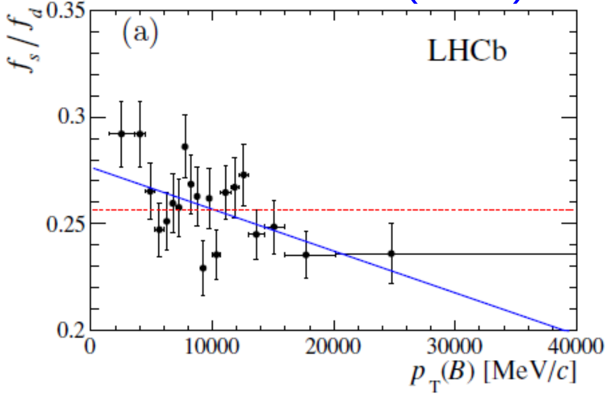
$$f_s / f_d = 0.259 \pm 0.015$$

LHCb-CONF-2013-011

(Error decreased from 7.8% to 5.8%)

JHEP 04 (2013) 1

LHCb also found a small dependence with the pT(B). Effect neglible for this analysis.



Normalization: results

$$\mathrm{BR} = \mathrm{BR}_{\mathrm{cal}} \times \frac{\epsilon^{\mathrm{GEN}}_{\mathrm{cal}}\,\epsilon^{\mathrm{SEL\&REC|GEN}}_{\mathrm{cal}}\,\epsilon^{\mathrm{TRIG|SEL}}_{\mathrm{cal}}}{\epsilon^{\mathrm{GEN}}_{\mathrm{sig}}\,\epsilon^{\mathrm{SEL\&REC|GEN}}_{\mathrm{sig}}\,\epsilon^{\mathrm{TRIG|SEL}}_{\mathrm{sig}}} \times \frac{f_{\mathrm{cal}}}{f_{B^0_q}} \times \frac{N_{B^0_q\to\mu^+\mu^-}}{N_{\mathrm{cal}}} = \alpha_{\mathrm{cal}} \times N_{B^0_q\to\mu^+\mu^-}$$

Evaluated from MC, cross checked with data. Corrected for time acceptance effect

Measured in data using $J/\psi \to \mu^+\mu^-$

Ratio of probability for a b-quark to hadronize into a given meson

- The 2 normalization channels give compatible results

  Average:

$$\alpha_{B^0_s \to \mu^+\mu^-} = (9.01 \pm 0.62)\ 10^{-11}$$
$$\alpha_{B^0_d \to \mu^+\mu^-} = (2.40 \pm 0.09)\ 10^{-11}$$

SM expectations in the signal mass windows:
40 ± 4 $B^0_s \to \mu^+\mu^-$ and 4.5 ± 0.4 $B^0 \to \mu^+\mu^-$

Time acceptance

- Time dependent decay rate:

$$\begin{aligned}\Gamma\left(\mathrm{B_s}\to\mu^+\mu^-\right) &= \Gamma\left(\mathrm{B_s^0(t)}\to\mu^+\mu^-\right)+\Gamma\left(\overline{\mathrm{B}}_\mathrm{s}^0\mathrm{(t)}\to\mu^+\mu^-\right)\\ &= R_H e^{-\Gamma_H t}+R_L e^{-\Gamma_L t}\\ &= \left(R_H+R_L\right)e^{-\Gamma_s t}\left[\cosh\frac{y_s t}{\tau_{\mathrm{B_s^0}}}+\mathcal{A}_{\Delta\Gamma}\sinh\frac{y_s t}{\tau_{\mathrm{B_s^0}}}\right]\end{aligned}$$

$$y_s = \frac{\Gamma_L-\Gamma_H}{\Gamma_L+\Gamma_H}$$

From HFAG: $y_s = 0.0615 \pm 0.0085$

$$\mathcal{A}_{\Delta\Gamma} = \frac{\Gamma_{B^0_{s,H}\to\mu^+\mu^-}-\Gamma_{B^0_{s,L}\to\mu^+\mu^-}}{\Gamma_{B^0_{s,H}\to\mu^+\mu^-}+\Gamma_{B^0_{s,L}\to\mu^+\mu^-}}.$$

Channel and model dependent, =1 in the SM (De Bryun et al, arXiv:1204.1737)

- Since the selection biases the decay time, the time integrated efficiency is also model dependent

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

Time acceptance

- The efficiency determined from MC should be corrected using latest PDG value $\tau_{B_{s,H}} = 1.615 \pm 0.021$ ps

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

Correction for B_s : 4.57±0.02%

We also need to correct for the B^0 as we assume the same efficiency as for B_s

Correction for B^0 : 1.50±0.01%

- As the BDT distribution is obtained from $B_{d/s} \to h^+h'^-$ control sample, dominated by $B_d \to K\pi$, it should also be corrected due to the different decay time of B_d and B_s. This correction goes from 0.3 to 4.7% depending on the bin.

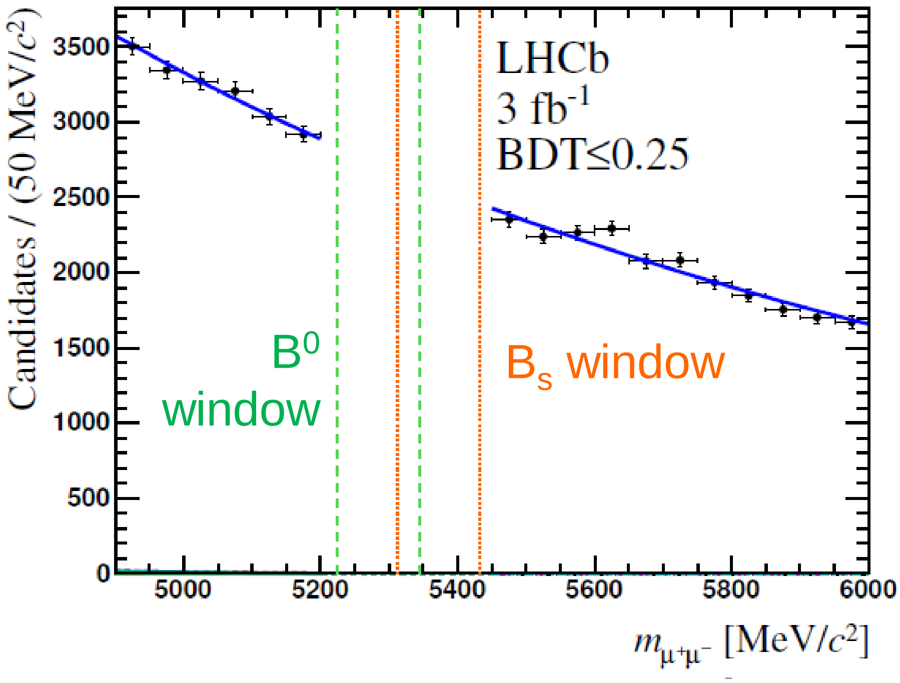
Background estimation

Combinatorial background

- The main background source in the signal window is combinatorial from bb→μμX

- For the limit computation, the expected number of background events is obtained by a exponential fit to the invariant mass sideband in each BDT bin

In higher BDT region, other sources of background become dominant

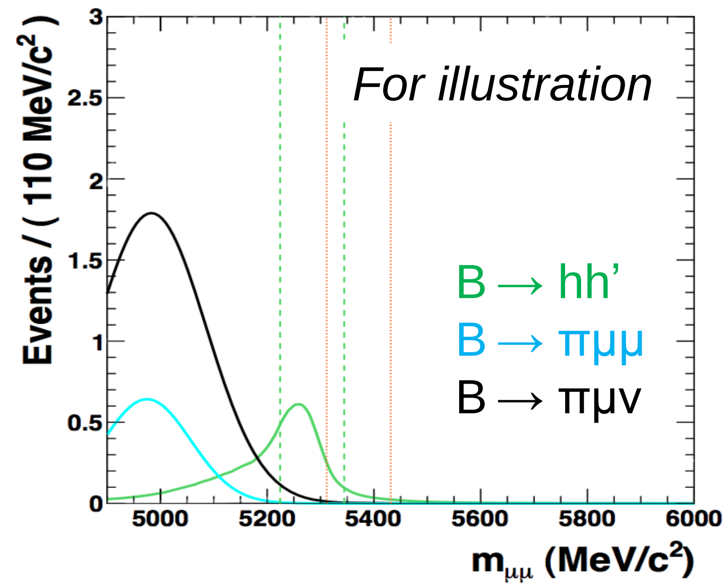


Exclusive background sources

- Exclusive background can both enter in the signal search windows and/or spoil the evaluation of the combinatorial background from sidebands

- In the signal region: only the $B_{d/s} \to h^+h'^-$ double misID matters

- In the sidebands, decays with one hadron misidentified as muon or 2 muons coming from the same vertex can fake the signal:



$B^0 \to \pi^- \mu^+ \nu$
$B_s \to K^- \mu^+ \nu$
$\Lambda_b \to p \mu \nu$

$B^{0/+} \to \pi^{0/+} \mu\mu$
$B_c \to J/\psi(\mu\mu)\, \mu\nu$

Other channels, as $B_{(s)} \to D_{(s)}\mu X$ with $D \to \mu X$, found to be negligible

$B_{d/s} \to h^+h'^-$ double misID

1. MisID probabilities are measured on data as function of P and P_T
   - $\pi \to \mu$ and $K \to \mu$ measured in $D^* \to D^0\pi$, $D^0 \to K\pi$
   - $p \to \mu$ measured in $\Lambda \to p\pi$

2. These probabilities are then convoluted with the MC spectra of $B_{d/s} \to h^+h'^-$ to get the average double misID efficiency $\boldsymbol{\varepsilon}_{\mu\mu \to hh}$ (~10^{-5})

3. The rate is obtained applying $\varepsilon_{\mu\mu \to hh}$ to the measured $B_{d/s} \to h^+h'^-$ yield

4. The mass shape is evaluated from MC

5. $B_{d/s} \to h^+h'^-$ is included as a fit component with rate constrained to the expected yield

Other exclusive backgrounds

- Number of expected events normalized to the yield of $B^+ \to J/\psi K^+$
- For backgrounds components that should be included in the fit:
  - The mass PDF in each BDT bin is determined from MC
  - The normalization is fixed to the number of expected events.
- $B^0 \to \pi^- \mu^+ \nu$, $B_s \to K^- \mu^+ \nu$, $B^{0/+} \to \pi^{0/+} \mu\mu$ are included as fit component
- $\Lambda_b \to p\mu\nu$: evaluated as a systematic
- $B_c \to J/\psi\mu\nu$: peak at low BDT, taken into account by the exponential fit

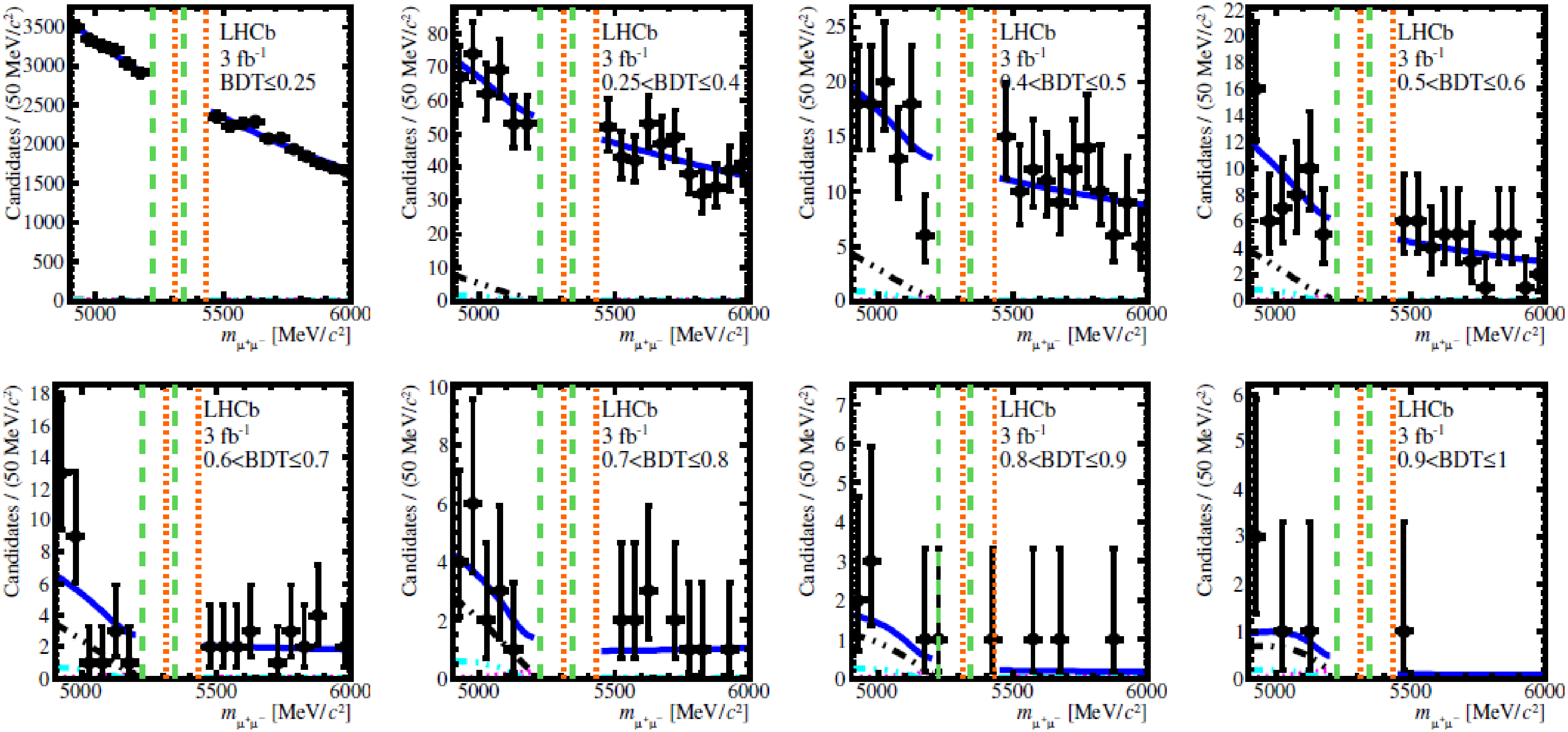
Expected background yield in [4.9-6] GeV/c^2

	Yield in full BDT range	Fraction with BDT > 0.7 [%]
$B^0_{(s)} \to h^+ h'^-$	15±1	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
$\Lambda^0_b \to p \mu^- \bar{\nu}_\mu$	70±30	11

Background fit

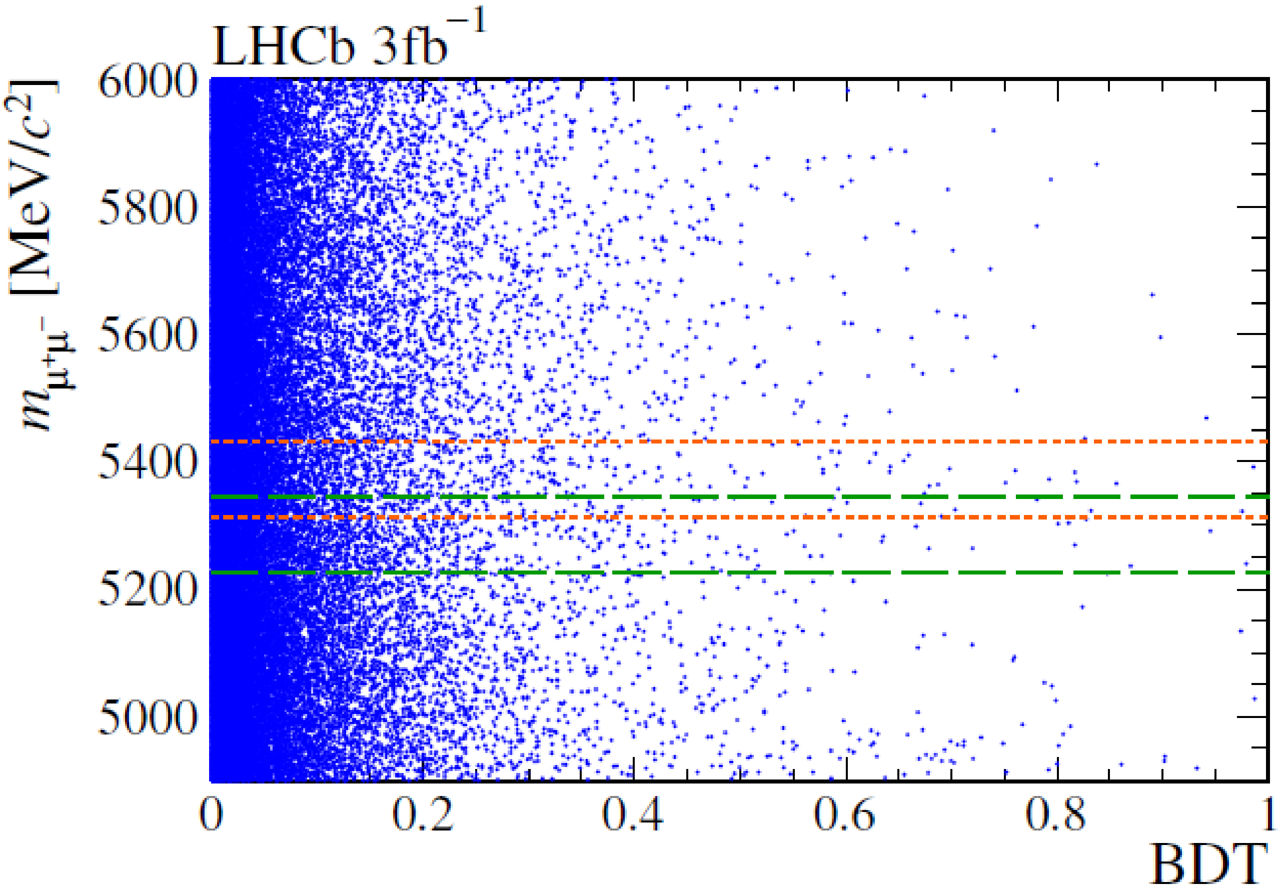
$B^0 \rightarrow \pi^- \mu^+ \nu$,
$B_s \rightarrow K^- \mu^+ \nu$,
$B^{0/+} \rightarrow \pi^{0/+} \mu\mu$

$B_{d/s} \rightarrow h^+ h'^-$
total



Results

Open the box



B_s window

B^0 window

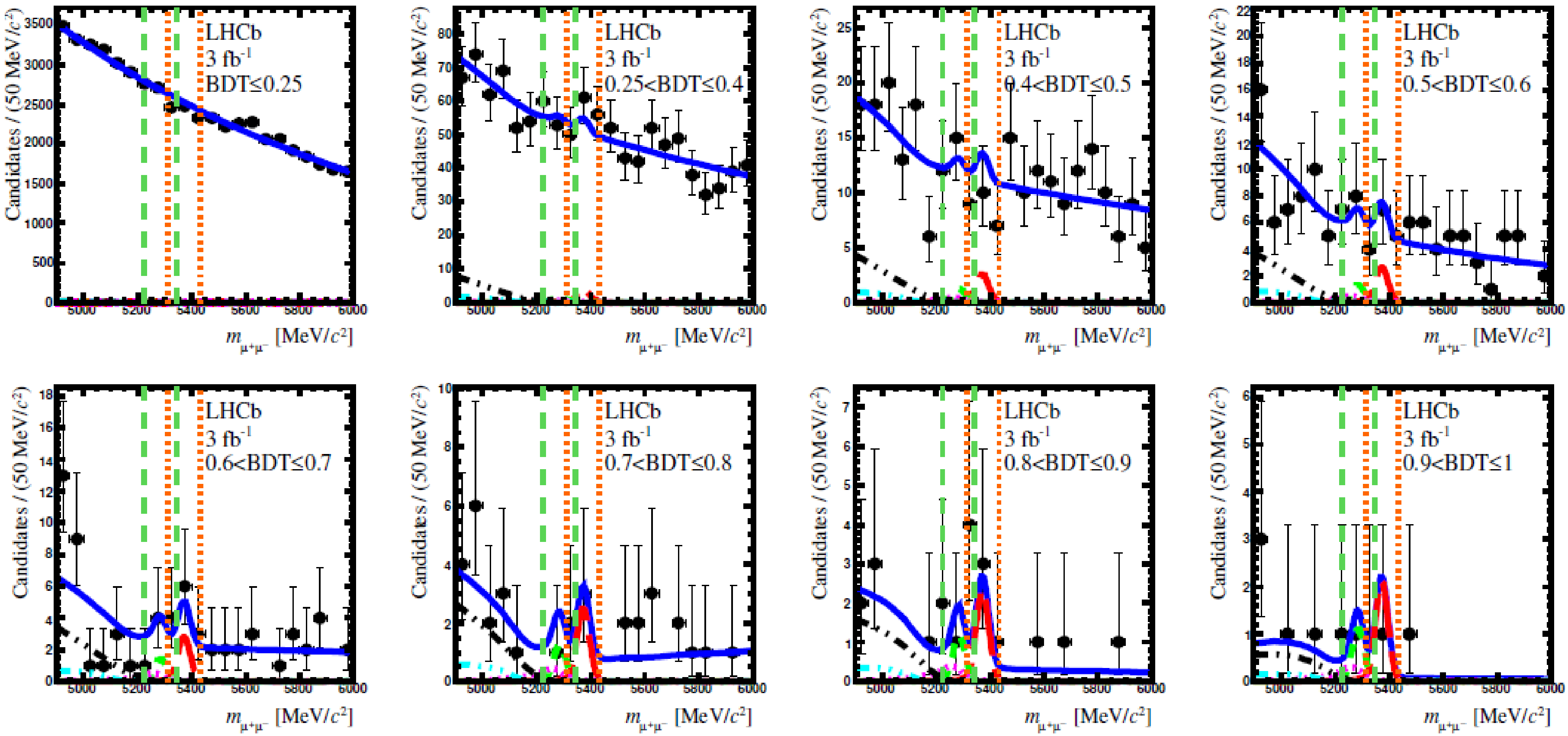
$B_s \to \mu^+\mu^-$ branching fraction fit

- Simultaneous unbinned maximum likelihood fit to the mass spectra
- Free parameters: $BR(B^0 \to \mu^+\mu^-)$, $BR(B_s \to \mu^+\mu^-)$ and combinatorial background
- Signal yield fraction in each BDT bin is constrained to expectation from $B_{d/s} \to h^+h'^-$ calibration
- Yields of exclusive backgrounds are constrained to their expectations
- Additional systematic :
  - $\Lambda_b \to p\mu\nu$ component
  - Variation of the exclusive background mass shape

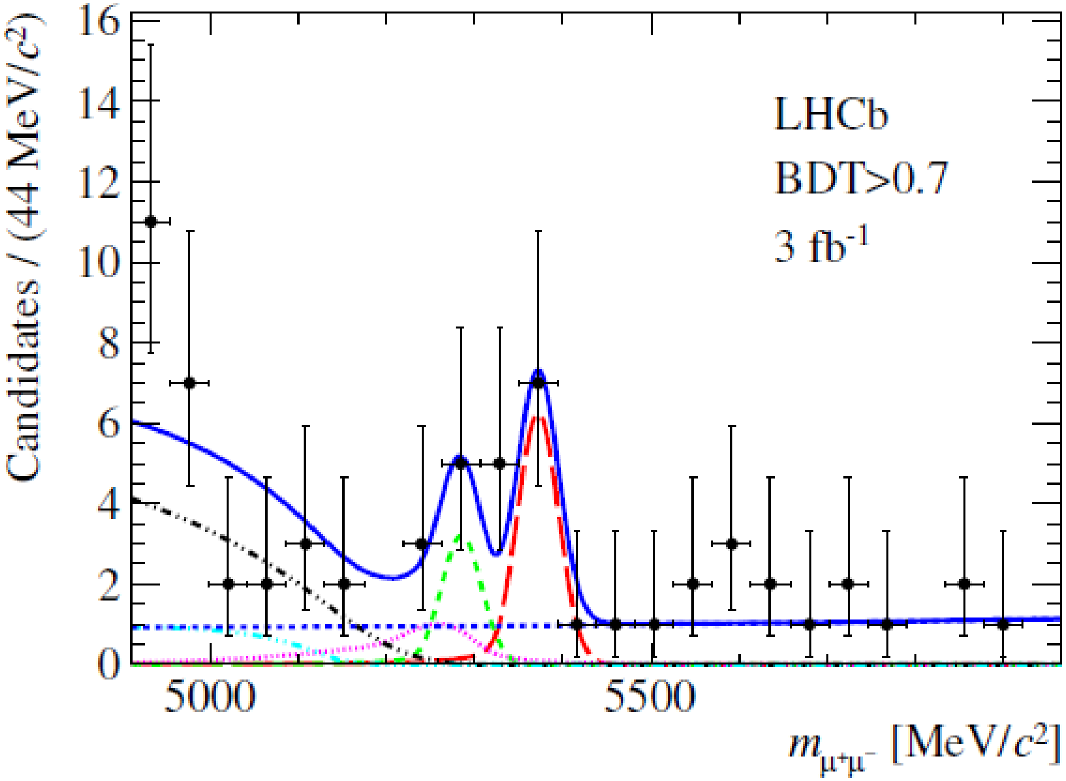
Fit projections

$B^0 \to \pi^- \mu^+ \nu$
$B_s \to K^- \mu^+ \nu$
$B^{0/+} \to \pi^{0/+} \mu\mu$

$B_{d/s} \to h^+ h'^-$
$B_s \to \mu^+ \mu^-$
$B^0 \to \mu^+ \mu^-$
Total



BDT>0.7



$B^0 \to \pi^-\mu^+\nu$

$B_s \to K^-\mu^+\nu$

$B^{0/+} \to \pi^{0/+}\mu\mu$

$B_{d/s} \to h^+h'^-$

$B_s \to \mu^+\mu^-$

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

Total

Fit result

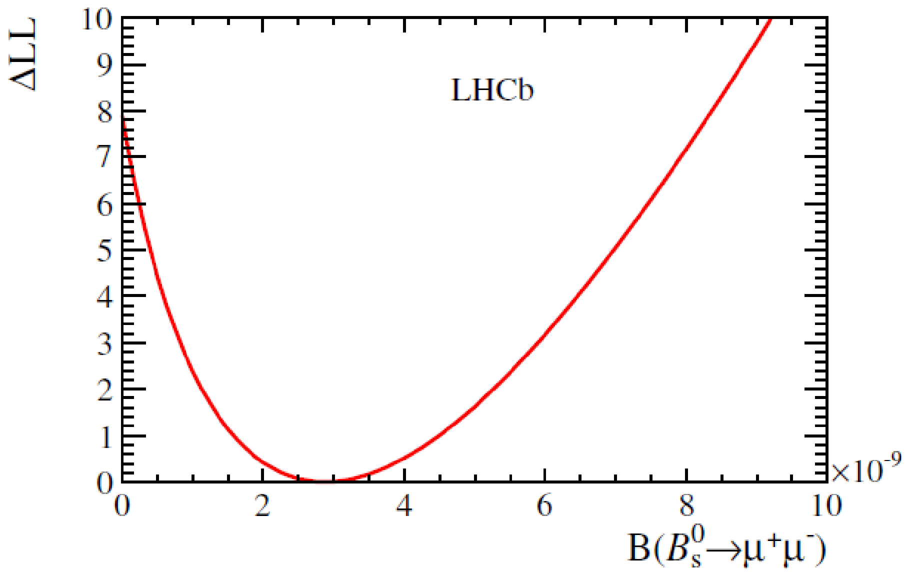
arXiv:1307.5024, Phys.Rev. Lett.111(2013) 101805

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

Significance: 4.0 σ
expected 5.0 σ(median)

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

Significance: 2.0 σ

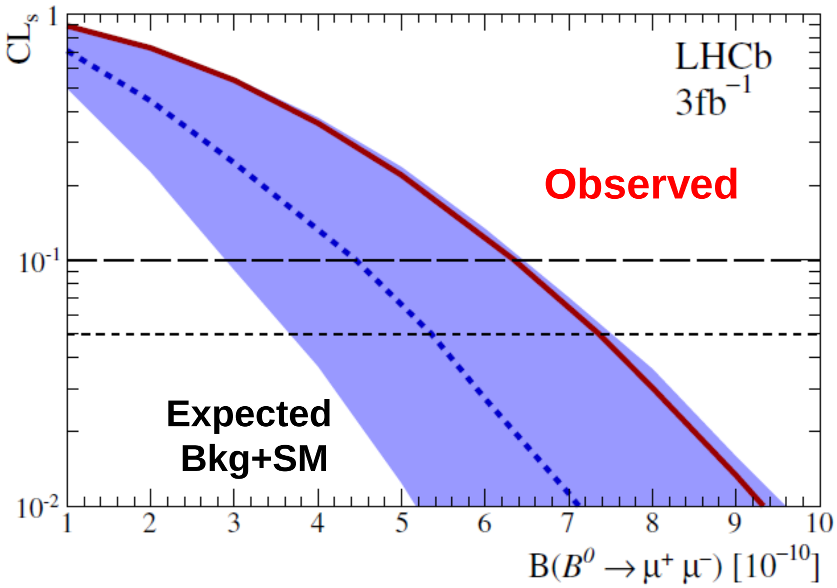


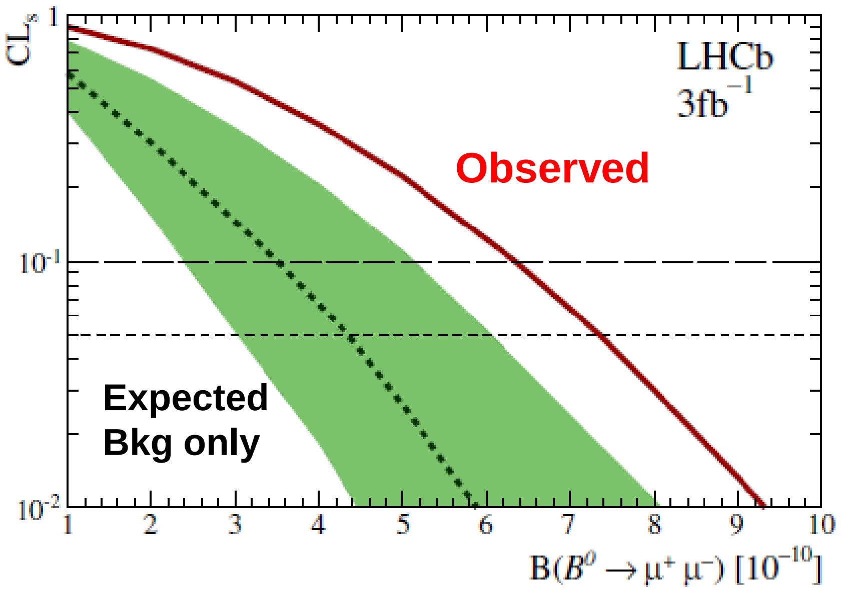
Correlation between BR($B^0 \to \mu^+\mu^-$) and BR($B_s \to \mu^+\mu^-$) : 3.3%

Profile Likelihood:
All parameters except $B(B_s^0 \to \mu^+\mu^-)$ are floated within their errors.

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

- Use CLs method: evaluate compatibility with bkg only (CL_b) and signal+bkg (CL_{s+b}) hypothesis
- The 95%CL upper limit is defined at $CL_s = CL_{s+b}/CL_b = 0.05$





	Limit at 95%CL
Expected bkg only	4.4×10^{-10}
Expected bkg + SM	5.4×10^{-10}
observed	7.4×10^{-10}

CMS result

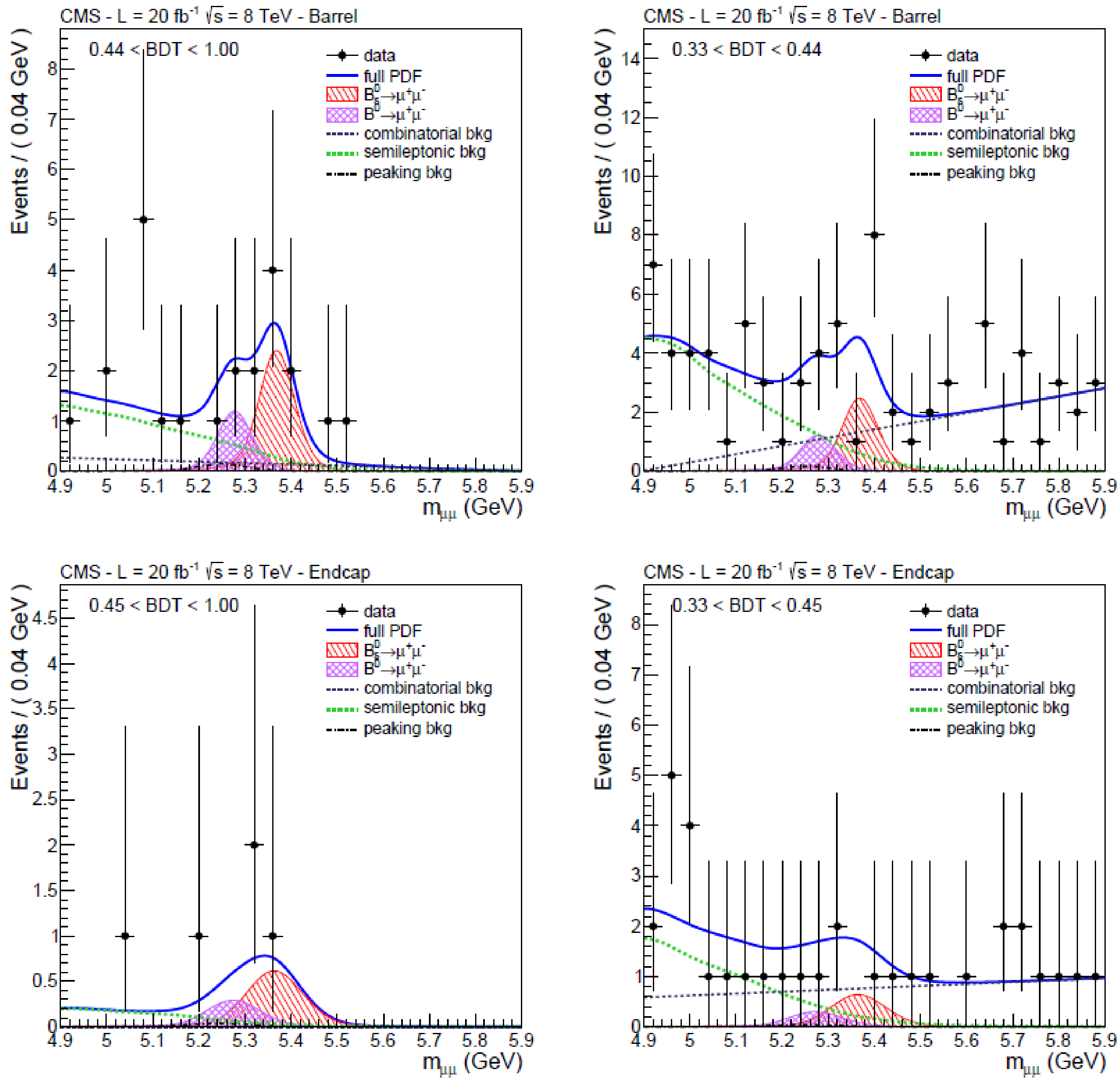
Analysis overview

- Dataset: 5 (7 TeV) + 20 (8 TeV) fb^{-1}
- Trigger requirement :
  - leading (subleading) muon pT> 3 (4)GeV, dimuon pT>4.9 GeV for $|\eta_{\mu\mu}|<1.8$
  - leading (subleading) muon pT> 4 (4)GeV, dimuon pT>7 GeV for $|\eta_{\mu\mu}|>1.8$
  - $4.8<m_{\mu\mu}<6$ GeV
  - Vertex fit $p(\chi^2) > 0.5\%$
- Use 2 discriminant variables: dimuon mass and BDT
- Normalization channel: $B^+ \to J/\psi K^+$
- Control sample: $B_s \to J/\psi\phi$
- Divide dataset in 2 categories, keeping 2011 and 2012 data separated:
  - Both muons in the barrel : $|\eta_{\mu\mu}|<1.4$, better sensitivity, mass resolution ~40MeV
  - At least one muon in the endcap, more events but mass resolution ~60MeV

BDT

- Training on MC signal and data sidebands:
  - To avoid biases, use 3 separate samples: train on 1st, test on 2nd and apply on 3rd $\Rightarrow$ 3 BDT per categories
- 12 variables used, independent of pile-up conditions
- Signal BDT distribution taken from MC, systematics evaluated using control sample
- Then, 2 possible methods:
  - Simple cut on BDT output, optimized for each sample: limit computation
  - Analysis in 3 bins of BDT vs mass (higher expected sensitivity) : simultaneous maximum likelihood fit

Example of fit projections in the most sensitive bins for 8 TeV data



Results

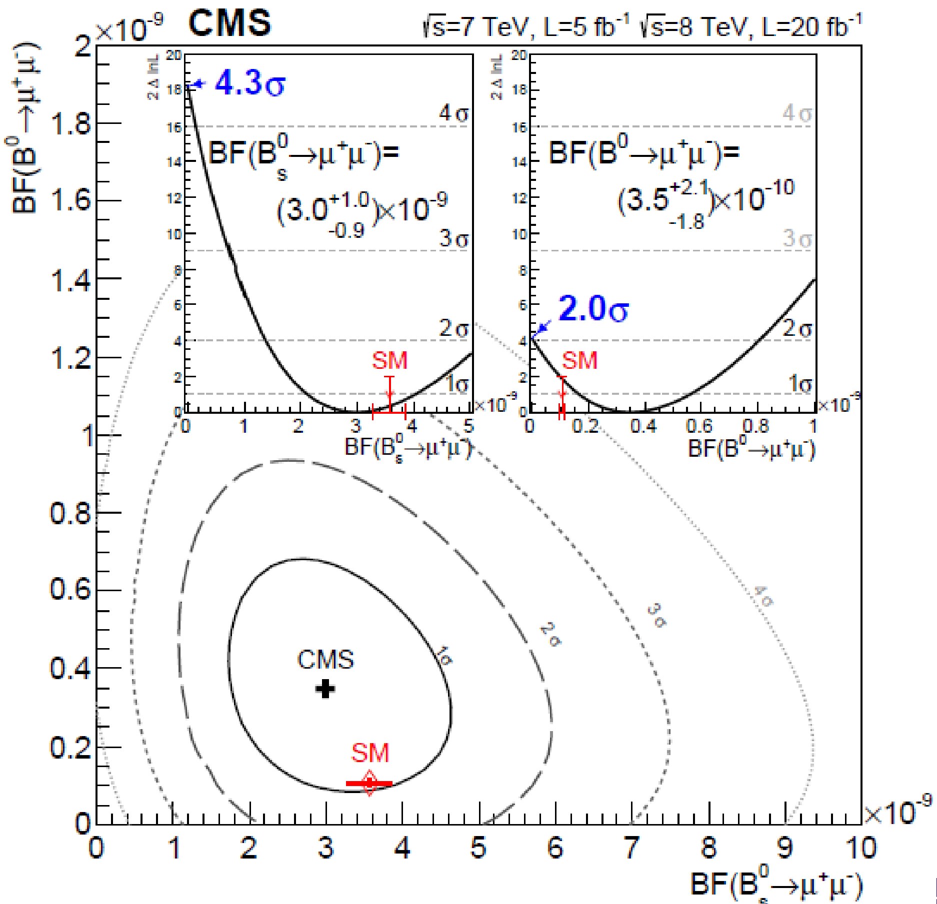
arXiv:1307.5025, Phys.Rev. Lett.111(2013) 101804

$$BR(B_S^0 \to \mu^+\mu^-) = (3.0^{+0.9}_{-0.8}(stat)^{+0.6}_{-0.4}(syst)) \times 10^{-9}$$

Significance: 4.3 σ (exp. 4.8)

$$BR(B^0 \to \mu^+\mu^-) = (3.5^{+2.1}_{-1.8}(stat+syst)) \times 10^{-10}$$

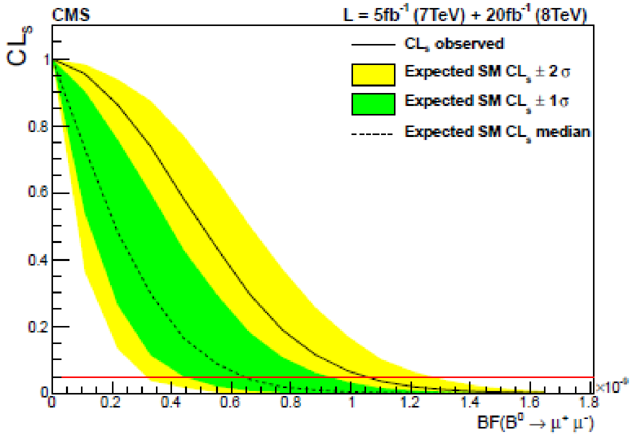
Significance: 2.0 σ



Limit using CLs method:

$$BR(B^0 \to \mu^+\mu^-) < 1.1 \times 10^{-9} \ @ 95\% CL$$

$(0.63 \times 10^{-9}$ expected)



CMS+LHCb combination

Combination input

- One common systematic uncertainty is taken into account, f_s/f_d (as both experiments normalize to $B^+ \to J/\psi K^+$)

- CMS result rescaled to use the latest determination of f_s/f_d

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0\,^{+1.0}_{-0.9}) \times 10^{-9}$$

⇓

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.96\,^{+0.97}_{-0.85} \pm 0.17) \times 10^{-9}$$

Uncertainty due to f_s/f_d

- LHCb: $$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.87\,^{+1.09}_{-0.95} \pm 0.17) \times 10^{-9}$$

Result

LHCb-CONF-2013-012
CMS PAS BPH-13-007

- Several methods used, giving compatible results
- Method based on pseudo experiments, modelling distribution with variable-width Gaussian function (suggested by R. Barlow arXiv:physics/0406120):

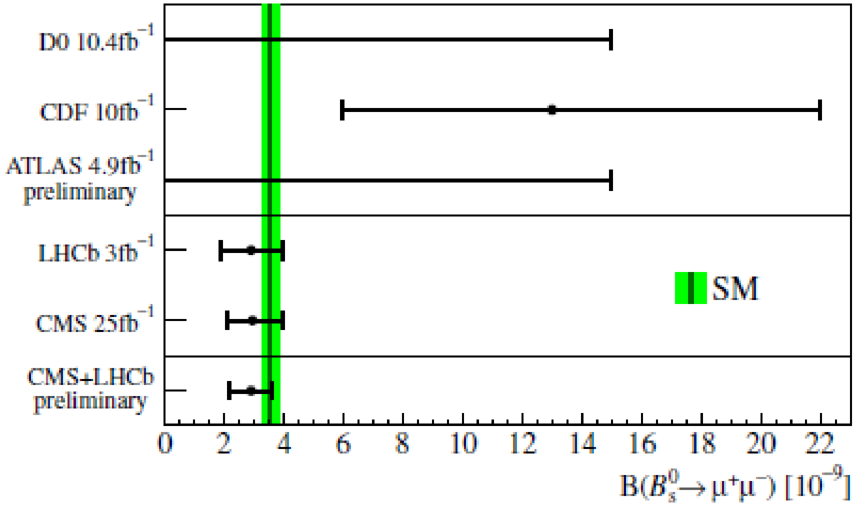
preliminary

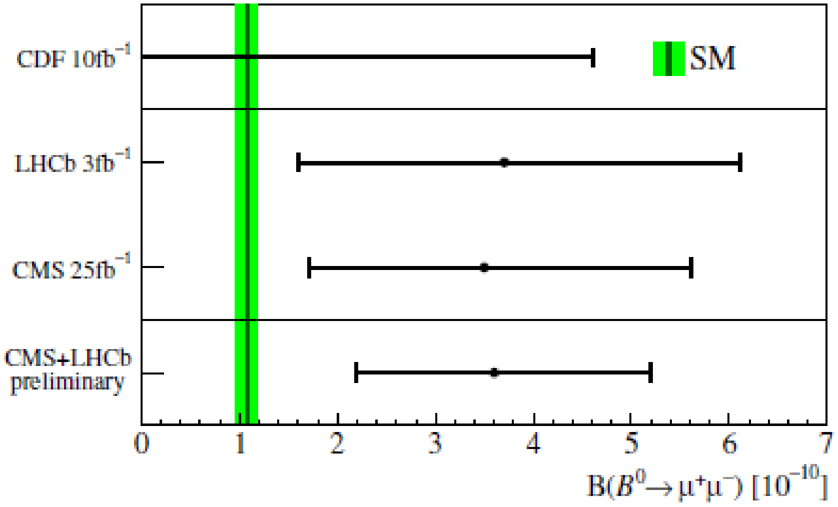
$$BR(B_S^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

Observation!!

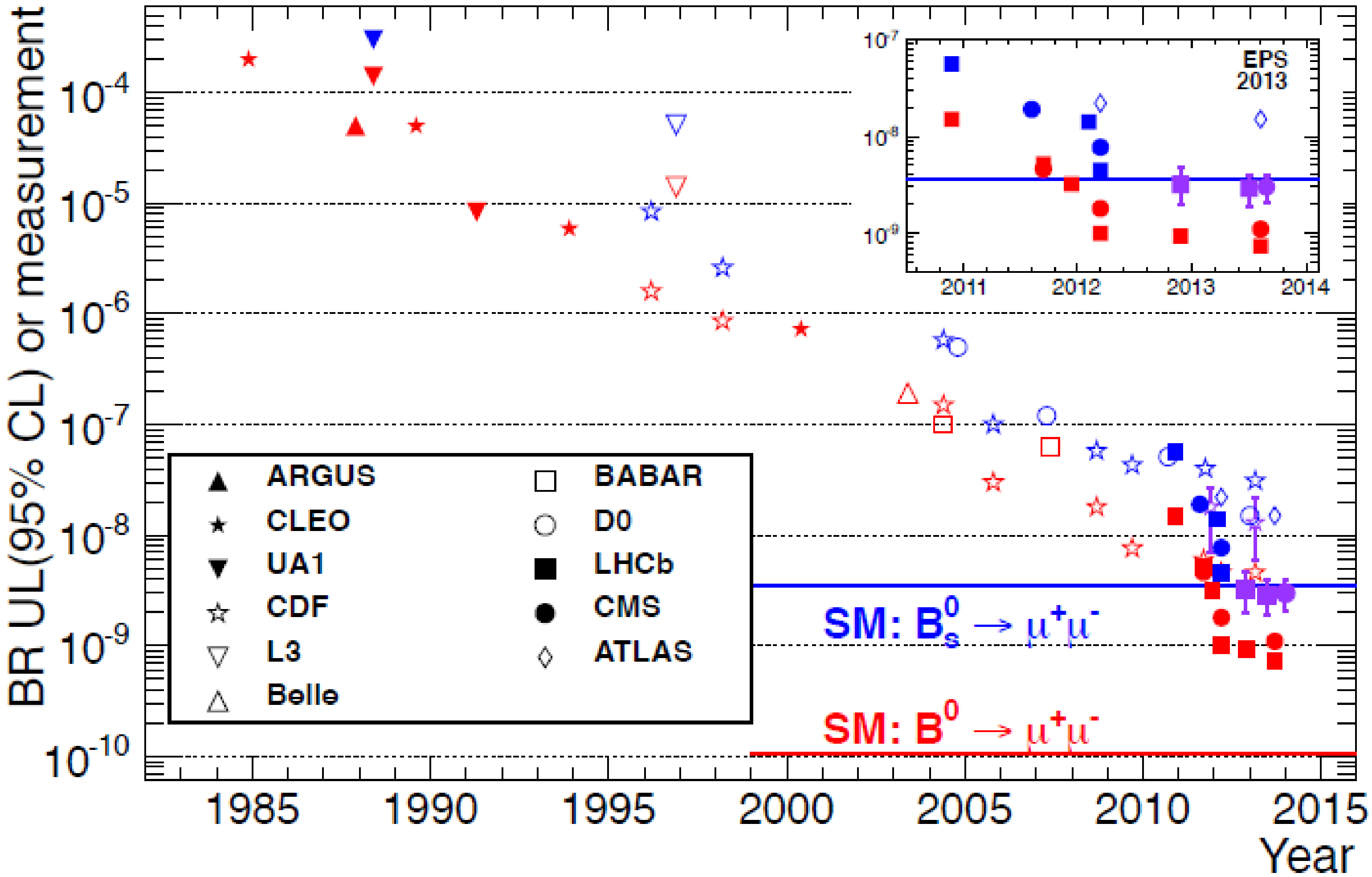
$$BR(B^0 \to \mu^+\mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$$

Not statistically significant





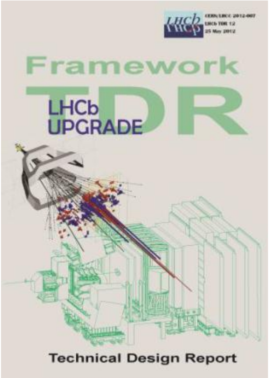
From 1984 to now…



.. And tomorrow

- ~300 fb^{-1} for CMS in 2020, ~8 fb^{-1} for LHCb in 2018
- LHCb upgrade: Expect 5 fb^{-1} per year after 2018 and 50 fb^{-1} in 2028

Type	Observable	Current precision	LHCb 2018	Upgrade ($50\,\text{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\rm fs}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\rm eff}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\rm eff}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)$	–	0.13 %	0.03 %	0.02 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\ A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	8 %	2.5 %	7 %
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ *	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	$\sim 20°$ [19]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\ K_S^0)$	0.8° [18]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–



* Assuming SM BR

Prospects

- Short term:
  - 2018: LHCb+CMS can probably obtain a 10% measurement on $BR(B_s \to \mu^+\mu^-)$
  - The current SM $BR(B_s \to \mu^+\mu^-)$ has a 10% uncertainty $\Rightarrow$ crucial to improve theoretical errors !

    Already a lot of improvement from the Lattice QCD computations ☺
  - Update of B^0 will be interesting!

- Mid term:
  - 2021: each experiment could reach 10% measurement on $BR(B_s \to \mu^+\mu^-)$
  - Sensitivity to $BR(B^0 \to \mu^+\mu^-)$ down to the SM branching fraction by 2021

- Long term:
  - Precision era for $B_s \to \mu^+\mu^-$: effective lifetime measurement,…
  - Precision era for $BR(B^0 \to \mu^+\mu^-)$ / $BR(B_s \to \mu^+\mu^-)$

Summary

CMS 25 fb^{-1}

$$BR(B_S^0 \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9})\times 10^{-9}$$ 4.3 σ

$$BR(B^0 \to \mu^+\mu^-) = 3.5^{+2.1}_{-1.8}\times 10^{-10}$$ 2.0 σ

$$BR(B^0 \to \mu^+\mu^-) < 1.1\times 10^{-9} @95\%CL$$

LHCb 3 fb^{-1}

$$BR(B_S^0 \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0})\times 10^{-9}$$ 4.0 σ

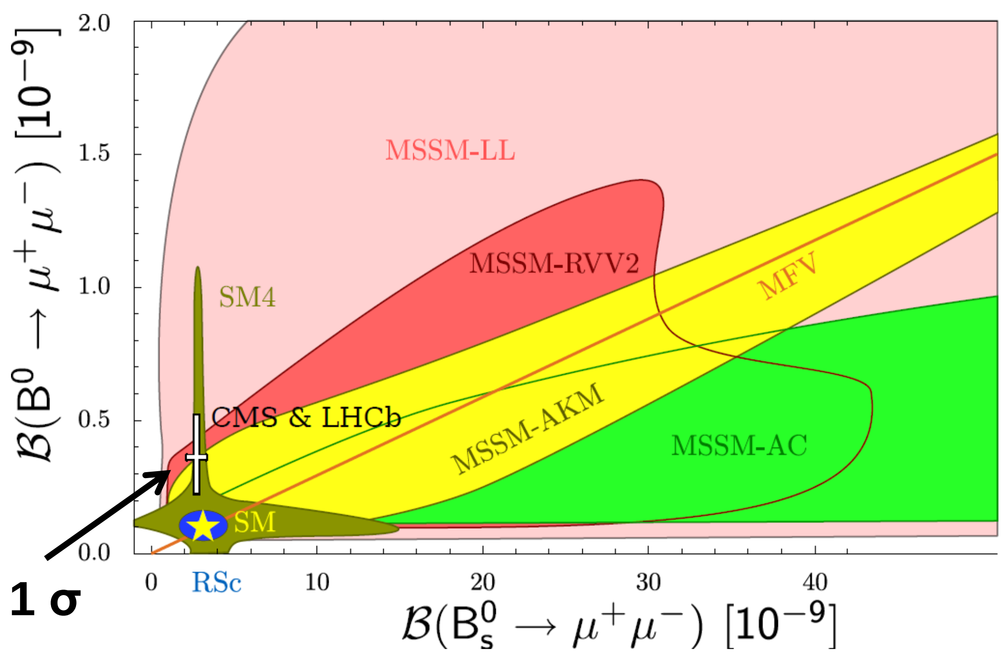
$$BR(B^0 \to \mu^+\mu^-) = 3.7^{+2.4}_{-2.1}\times 10^{-10}$$ 2.0 σ

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

CMS + LHCb :

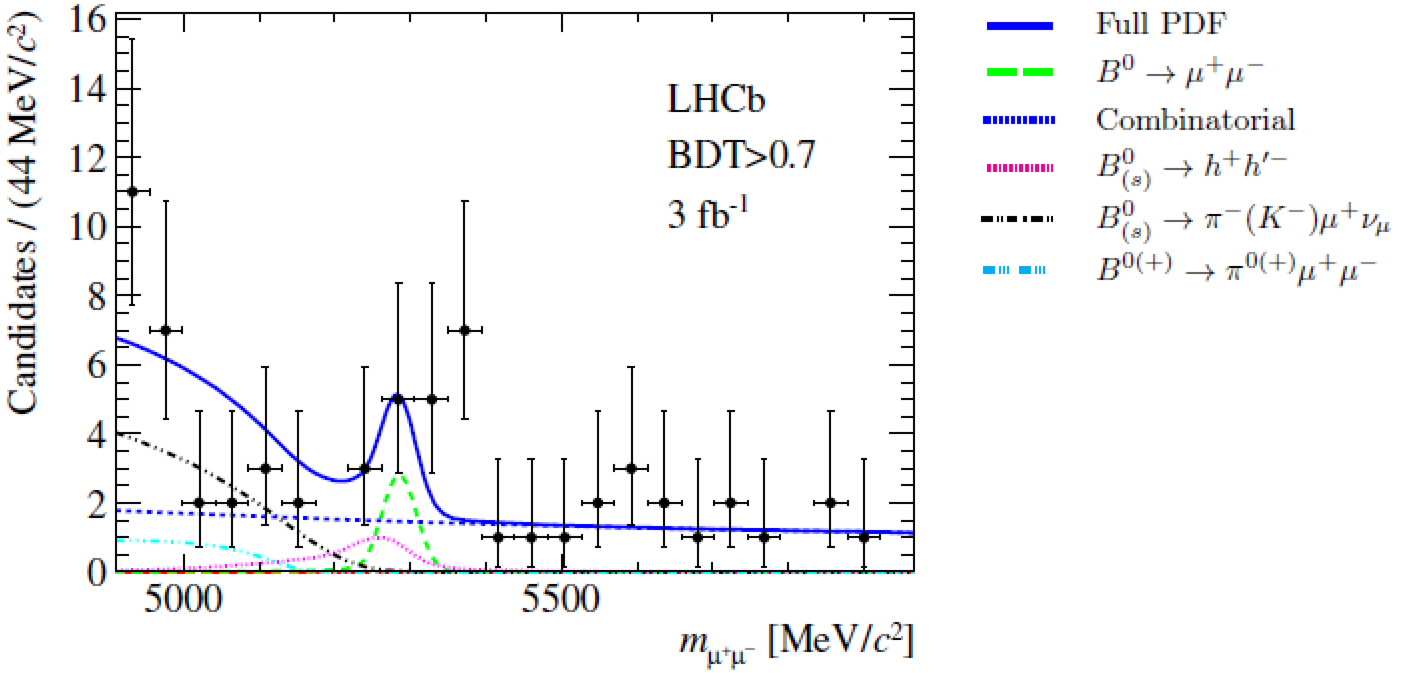
First observation of $BR(B_s \to \mu^+\mu^-)$!!

$$BR(B_S^0 \to \mu^+\mu^-) = (2.9 \pm 0.7)\times 10^{-9}$$



backup

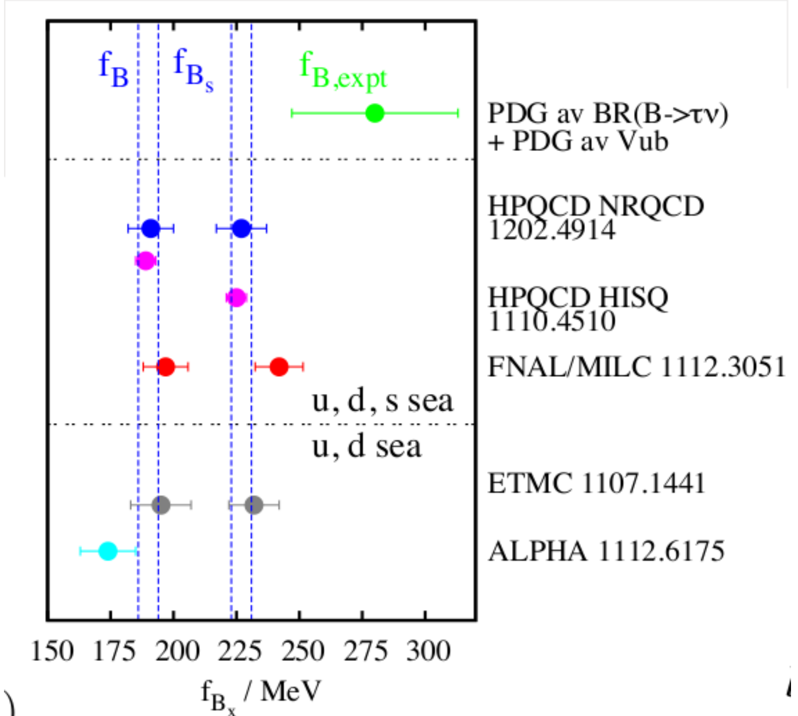
- Fit without Bs signal



Uncertainty with new lattice F_B

- Recent works in Lattice QCD claims uncertainties at 1.3%
- Results still discussed
- 'Conservative' approach:

Central value from weighted average + uncertainty of 8 MeV



- If results confirmed:

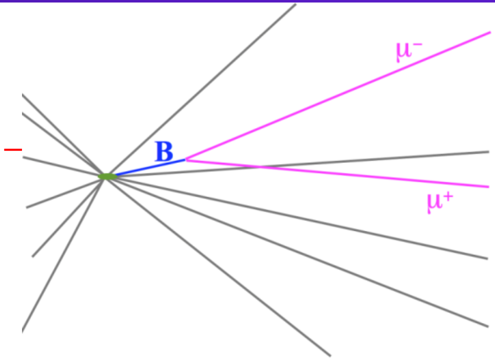
$$BF(B_s^0 \to \mu^+\mu^-) = 3.57 \pm 0.18 \times 10^{-9}$$

- Dominant uncertainty $|V_{tb}^* V_{ts}|$

Uncertainty Budget		
$\mathbf{F_{Bs}}$	**72.5%**	27.0%
$\lvert V_{tb}^* V_{ts}\rvert$	22.8%	**60.0%**
m_t	3.7%	9.8%
τ_{Bs} and y_s	1.1%	2.8%

Selection

- Tighten initial selection to reduce combinatorial Bkg:
  cut on a output of a MVA combining information topology – background rejection for 92% signal efficiency.



B Candidate

impact parameter*

impact parameter χ^2

χ^2 of the vertex

pointing angle

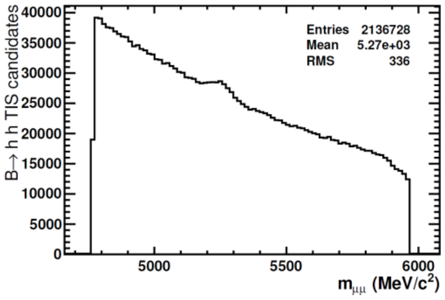
distance of closest approach*

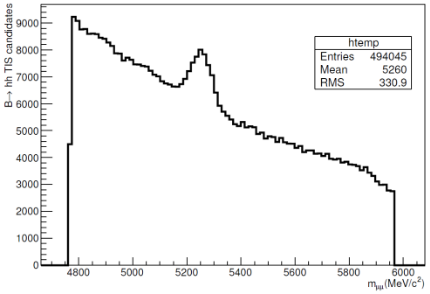
Muons

min IP

*common with BDT

$B_{d/s} \rightarrow h^+h^-$
data





BDT Variables

Polarisation Angle:

angle between the muon momentum in the B rest frame and the vector perpendicular to the B momentum and the beam axis

B Isolation:

$$I = \frac{p_{T,B}}{p_{T,B} + \sum_{tracks} p_{T,track}}$$

sum running on the tracks such that $\delta\eta^2 + \delta\phi^2 < 1.0$

Exclusive background

$$B^0 \to \pi^- \mu^+ \nu_\mu, \qquad (1.44 \pm 0.05) \cdot 10^{-4}$$

Particle Data Group, J. Beringer *et al.*, *Review of particle physics*, Phys. Rev. **D86** (2012) 010001.

$$B_s^0 \to K^- \mu^+ \nu_\mu \qquad (1.27 \pm 0.49) \cdot 10^{-4} \;|\; \mathcal{B}(\Lambda_b^0 \to p \mu^- \nu) = (4.75 \pm 2.11) \cdot 10^{-4}$$

[40] W.-F. Wang and Z.-J. Xiao, *The semileptonic decays $B/B_s \to (\pi, K)(l^+l^-, l\nu, \nu\bar{\nu})$ in the perturbative QCD approach beyond the leading-order*, arXiv:1207.0265.

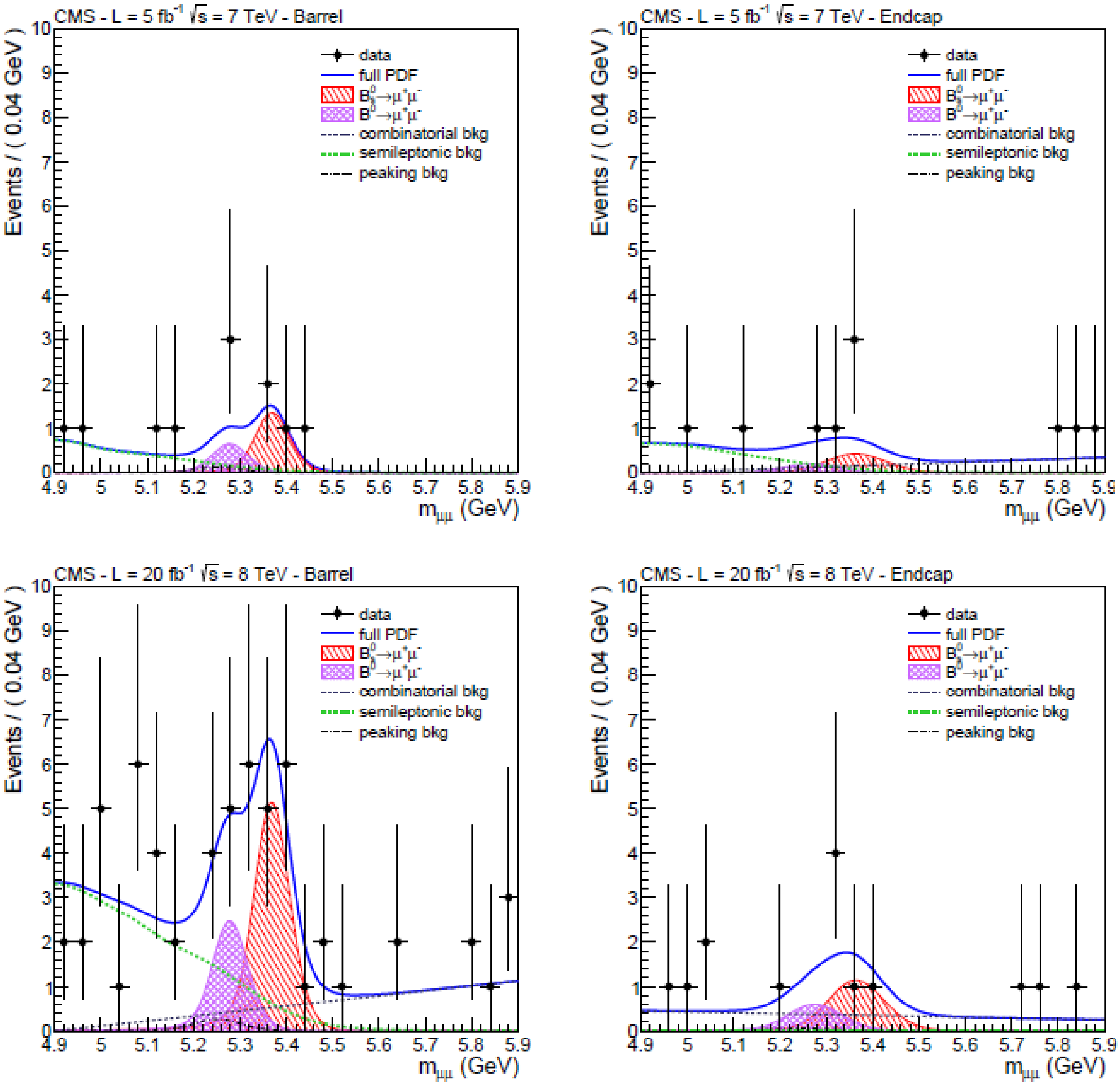
$$\mathcal{B}(B^+ \to \pi^+ \mu^+ \mu^-) = (2.3 \pm 0.6(\text{stat.}) \pm 0.1(\text{syst.})) \cdot 10^{-8},$$

LHCb Collaboration, R. Aaij *et al.*, *First observation of the decay $B^+ \to \pi^+ \mu^+ \mu^-$*, JHEP **1212** (2012) 125, arXiv:1210.2645.

$$\begin{aligned}\mathcal{R} &= \frac{\sigma(B_c^+)\mathcal{B}(B_c^+ \to J/\psi \ell \nu X)}{\sigma(B^+)\mathcal{B}(B^+ \to J/\psi K^+)} \\ &= 0.132^{+0.041}_{-0.037}(\text{stat}) \pm 0.031(\text{sys})^{+0.032}_{-0.020}(\text{lifetime}) \\ &= 0.132^{+0.051}_{-0.052}\end{aligned}$$

CDF Collaboration, F. Abe *et al.*, *Observation of the B_c meson in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV*, Phys. Rev. Lett. **81** (1998) 2432, arXiv:hep-ex/9805034.

CMS cross check with 1D BDT method



Significance

$B_s \to \mu\mu$ 4.8 σ (expected 4.7 σ median)