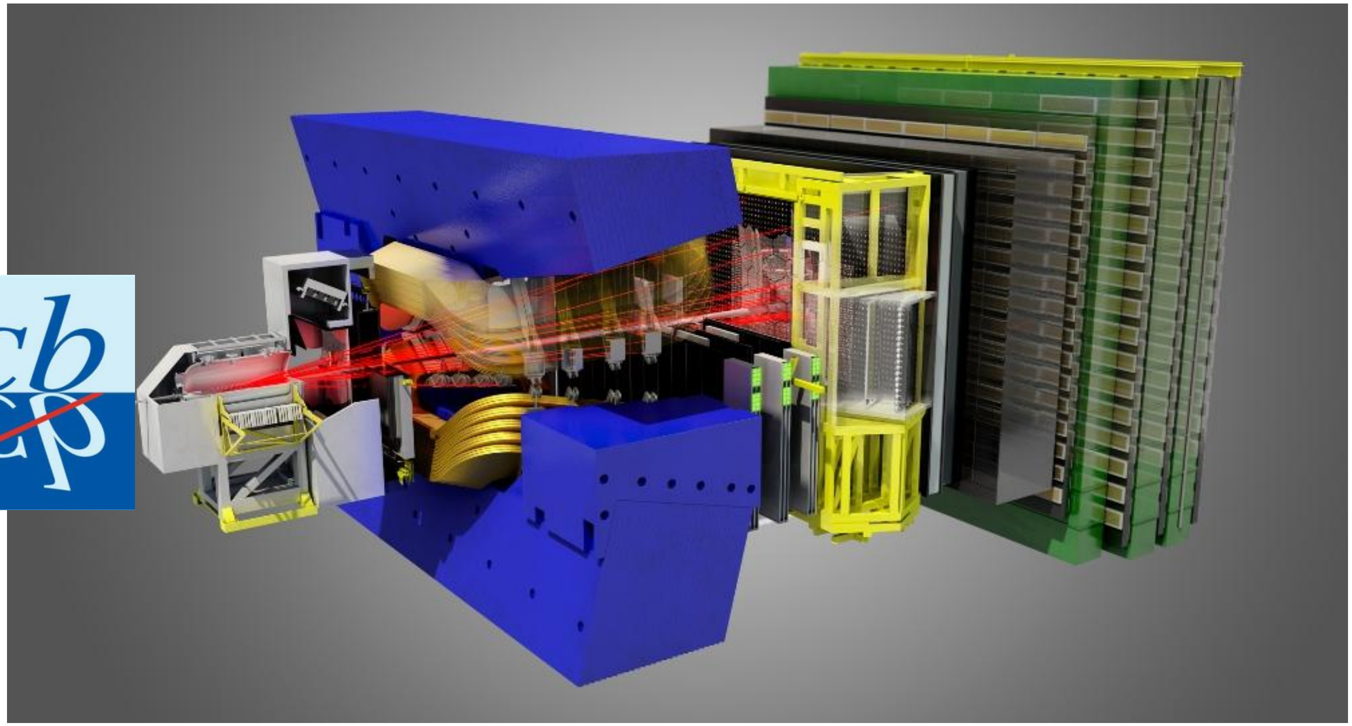
Поиск редких распадов $B_{s,d} \to \mu^+\mu^-$ в эксперименте LHCb



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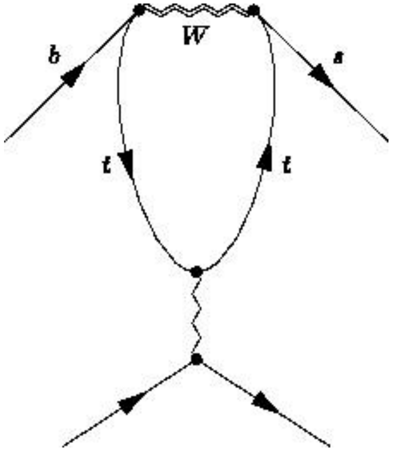
Новогодняя сессия ОФВЭ, 25 декабря, 2012

OUTLOOK

- Introduction. Recent $B_{s,d} \to \mu^+\mu^-$ results
- Physics motivation
- LHCb detector. Fast facts
- Main backgrounds for $B_{s,d} \to \mu^+\mu^-$
- Strategy of the analysis
- Last results
- Future plans. Conclusions

Introduction. B mesons penguin diagram decays

- Standard Model forbids flavor-changing neutral currents (FCNC) diagrams
- FCNC can be introduced by penguin one loop diagrams
- If B-meson decay can be realized only via penquin diagram decay, these decays can be sensitive to the new physics



Decay examples: $B_s \rightarrow \mu^+\mu^-$, $B_d \rightarrow K^*\mu^+\mu^-$, $B_d \rightarrow K^*\gamma$, $B_s \rightarrow \varphi\gamma$, etc.

..and many of them now can be studied at LHCb detector

Introduction. $B_s \to \mu^+\mu^-$ decay. Existing upper limits

- We are looking for some evidence of possible enhancements for the Standard Model.
  SM diagrams branching ratios:
  $Br(B_s \to \mu^+\mu^-) = (3.54 \pm 0.3) \times 10^{-9}$,
  $Br(B_d \to \mu^+\mu^-) = (1.1 \pm 0.1) \times 10^{-10}$

- **Observed upper limits at the Tevatron :**

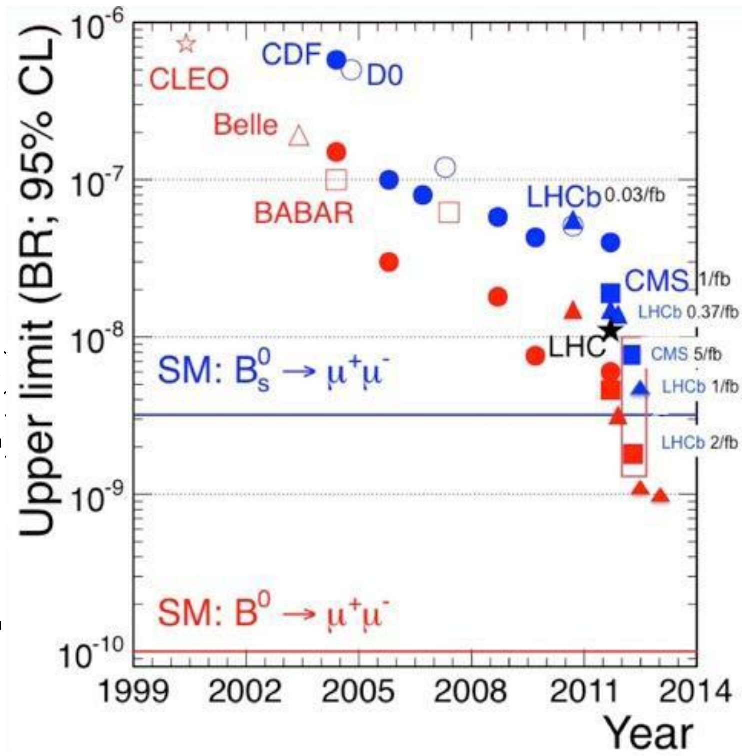
✓ **D0** ($L = 6.1$ fb^{-1}): $Br(B_s \to \mu^+\mu^-) < 5.1 \times 10^{-8}$ @95% CL

✓ **CDF** ($L = 7$ fb^{-1}) **:** $0.46 \times 10^{-8} < BR < 3.9 \times 10^{-8}$ @90% CL
(BR=1.8+ 1.1 -0.9) x 10^{-8} Not confirmed

LHC before October 2012

✓ **ATLAS** (2.4 fb^{-1}): $BR(B_s \to \mu^+\mu^-) < 22 \times 10^{-9}$@ 95% CL

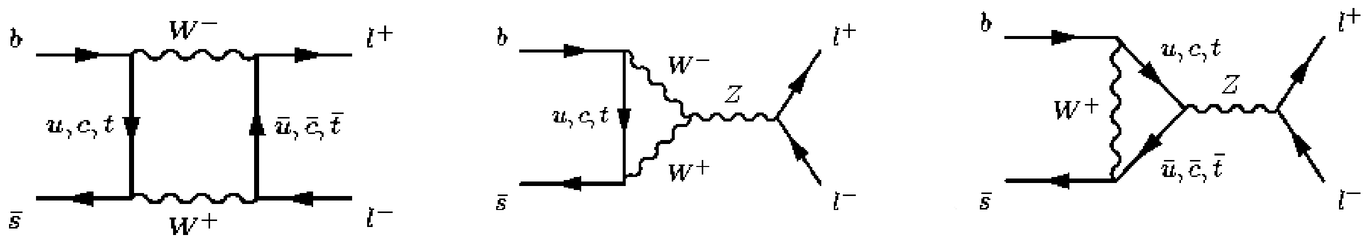
✓ **CMS** (5 fb^{-1}): $BR(B_s \to \mu^+\mu^-) < 7.7 \times 10^{-9}$ @ 95% CL



✓ **LHCb** limits at $L = 1$ fb^{-1} (2011 data) :
$Br(B_s \to \mu^+\mu^-) < 4.5 \times 10^{-9}$, $Br(B_d \to \mu^+\mu^-) < 1.0 \times 10^{-9}$ @ 95% CL, **PRL 108, 231801 (2012)**

$B_s \to \mu^+\mu^-$ Standard Model diagrams

- $B_s \to \mu^+\mu^-$ is double suppressed decay: FCNC process and helicity suppressed

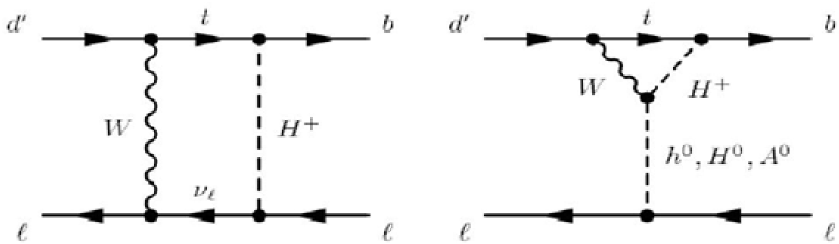


$$BR(B_q \to l^+l^-) \approx \frac{G_F^2 \alpha^2 M_{B_q}^3 f_{B_q}^2 \tau_{B_q}}{64\pi^3 \sin^4\theta_W} |V_{tb}V_{tq}^*|^2 \sqrt{1 - \frac{4m_l^2}{M_{B_q}^2}}$$
$$\left\{ M_{B_q}^2 \left(1 - \frac{4m_l^2}{M_{B_q}^2}\right) c_S^2 + \left[M_{B_q} c_P + \frac{2m_l}{M_{B_q}} (c_A - c_A') \right]^2 \right\}.$$

Main uncertainty come from decay constant f_{Bs}. Can be improved with better lattice calculations

Physics motivation: MSSM models

- $B_s \to \mu^+\mu^-$ branching ratio can be very sensitive to the SUSY diagrams contributions. Two Higgs-Dublet (2HDM) model provides a big contribution in the region of large tan β

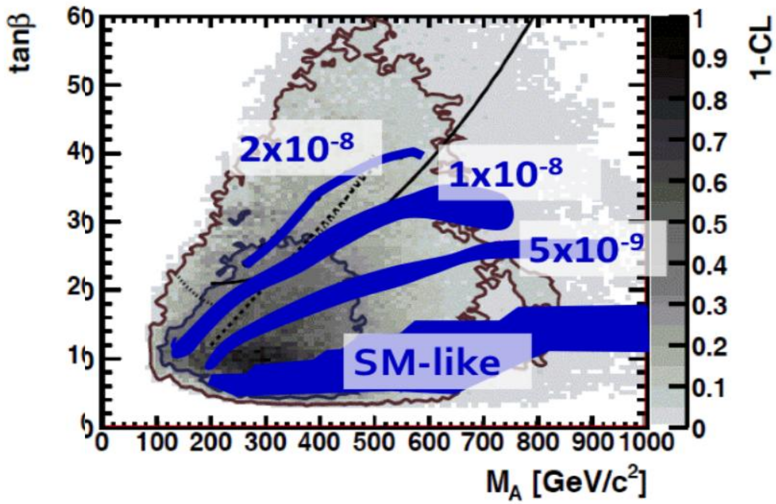


$$BR(SUSY) \propto BR(SM) \cdot \frac{m_b^4 \cdot (\tan\beta)^6}{m_{H^0}^4}$$

- The indirect $B_s \to \mu^+\mu^-$ search restriction power for SUSY parameters (blue regions) can be comparable with the results of direct SUSY searches (gray region):

Non-Universal Higgs Mass model

NUHM1



SM- like Br ratio

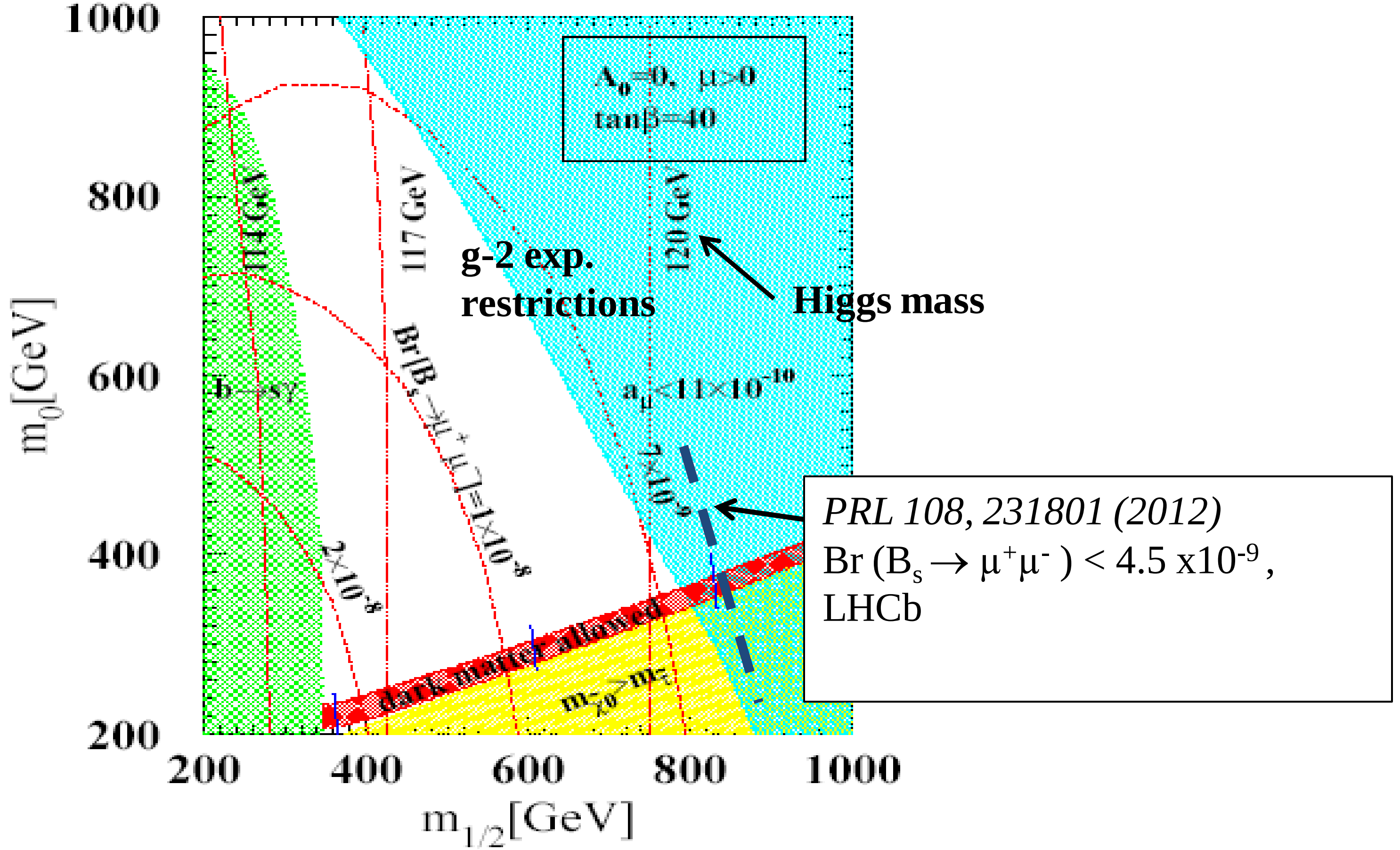
SM- like Br ratio

Point	M_h (GeV)	M_A (GeV)	$\tan\beta$	μ (GeV)	M_{SUSY} (GeV)
1	124.6	402.8	17.4	-961	1898
2	125.8	705.8	28.4	1334	1928
3	124.2	846.9	35.9	1869	1547
4	125.5	773.3	13.0	-2022	940
5	125.3	585.3	31.0	2666	1703
6	125.8	519.0	16.2	-166	1714
7	125.9	728.9	11.7	114	2096
8	125.9	440.5	44.9	758	2385
9	125.6	336.2	10.1	197	1030
10	125.7	432.5	21.2	-249	1140
11	124.6	877.5	45.2	102	1402
12	124.4	255.7	5.6	-1125	1804

Phenomenological MSSM

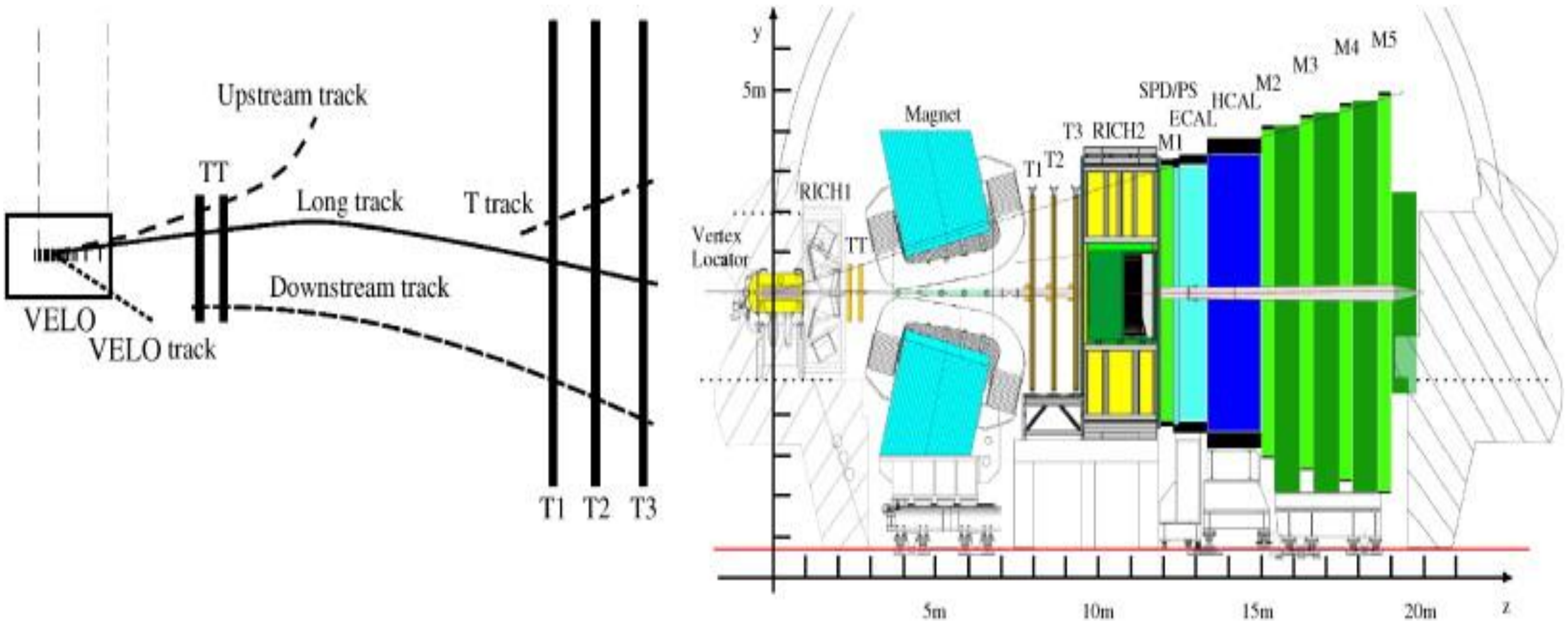
Physics motivation: mSUGRA model

- $Br(B_s \to \mu^+\mu^-)$ restricts the possible region for the mSUGRA model parameters



- The last LHCb published $Br(B_s \to \mu^+\mu^-)$ upper limit provides restrictions better than **g-2** (light blue color) experiment
- Higgs mass allows to restrict mSUGRA parameters too

LHCb detector



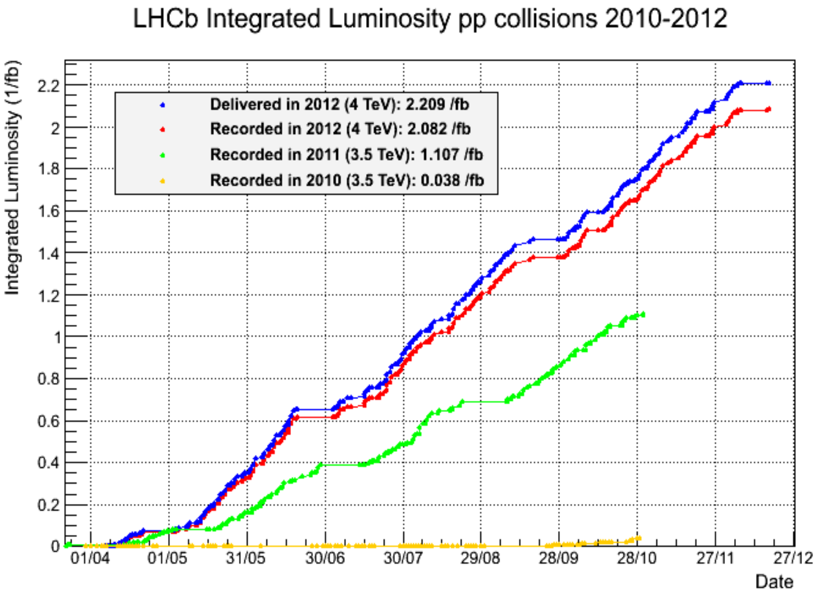
LHCb detectors are used for $B_s \to \mu^+\mu^-$ analysis:

- M1, M2, M3, M4, M5 – muon stations
- VELO (Vertex Locator) – vertex detector (B meson decay vertex)
- TT, T1,T2,T3 – tracking stations (momentum measuring)
- RICH1, RICH2 – Cherenkov detectors (pion, kaon identification)
- Calorimeters (muon identification)

Fast facts

❑ 2011 year $L = 1\ fb^{-1}$ at $\sqrt{s} = 7$ TeV

❑ 2012 year, integrated luminosity around 2000 pb^{-1}. pp – collision, $\sqrt{s} = 8$ TeV. data taking efficiency >90%



❑Parameters are relevant to the $B_{s,d} \to \mu^+\mu^-$ analysis:

- ✓muon identification efficiency : $\varepsilon(\mu) \sim 97\%$
- ✓dimuon trigger efficiency : ~ 90%
- ✓misidentification rate $\varepsilon(h \to \mu) < 1\%$ for p>10 GeV/c
- ✓momentum resolution: $\Delta p / p = 0.4\%$ at 5 GeV/c to 0.6 % at 100 GeV/c
- ✓ $\sigma(M\_B_{s,d} \to \mu^+\mu^-) = 25\ MeV/c^2$
- ✓ impact parameter resolution: σ(IP) =25 μm at pT=2 GeV/c and σ(IP) =20 μm for high pT tracks

Main backgrounds

- bb$\rightarrow \mu^+\mu^- X$ events, dimuon combinatoric background
  - ✓ can be suppressed using different geometric and kinematic criteria

- misidentified muons from $B^0 \rightarrow \pi^-\mu^+\nu$ - 41.1±0.4 , $B^{0(+)} \rightarrow \mu^+\mu^- \pi^{0(+)}$ - 11.9±3.5 events in full BDT response and mass range
  - ✓ it has a negligible influence to the background contributions under the peak;
  - ✓ allow to define better the shape of the combinatoric background

- misidentified muons from $B_{d/s} \rightarrow h^+h^-$ decays

✓ contribution from $B_{d/s} \rightarrow h^+h^-$ can be calculated from $B_{d/s} \rightarrow h^+h^-$ MC with a known misidentification probablity was measured in data

✓The peaking background is $0.76^{+0.26}_{-0.18}$ in ±60 MeV/c² around the B_s mass and $4.1^{+1.7}_{-0.8}$ in ±60 MeV/c² region of the B_d mass

Strategy of analysis

- **Selection conditions**
  - ✓ Muon trigger
  - ✓ Preliminary selections to reduce datasets size
  - ✓ Blind signal region $5306 < M_{Bs} < 5426$ MeV
- **Signal and background training**

✓ Use $B_s \to \mu^+\mu^-$ and $bb \to \mu\mu X$ Monte–Carlo to train the Boosted Decision Tree method

- **$B_s \to \mu^+\mu^-$ signal calibration**

✓ Use the control channel **B→hh** decays with the similar geometry

- **Upper limit calculation**

✓ Use the signal channel and normalization channel efficiency to calculate the normalization factor

✓ Use the predicted background and number of observed events with the modified frequentist CLs method to estimate the upper limit for the given confidence level

List of input parameters for the Boosted Decision Tree method

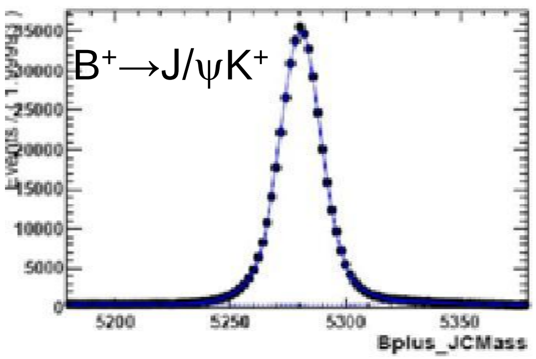
❑ A decision tree is able to split the phase space into a large number of hypercubes , where each can be identified as “signal-like” or “background-like”

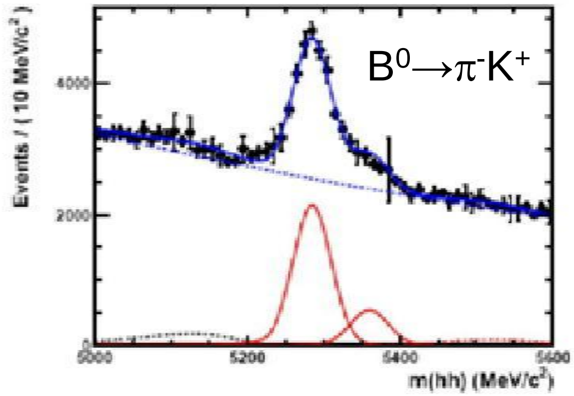
❑Output of Boosted Decision Tree is combining a decay geometry, B_s meson life time and kinematical information. The phase space in the analysis is defined by input parameters:

- ✓ Transverse momentum of the B_s - *meson*
- ✓ Minimum muon transverse momentum
- ✓ Cosine of the B_s polarization angle
- ✓ B_s meson impact parameter
- ✓ Minimum distance between muon tracks
- ✓ Muon track impact parameter significance
- ✓ Muon isolation
- ✓ B_s meson isolation
- ✓ B_s life time

Normalization channels

- ❑ To calculate the $B_s \to \mu^+\mu^-$ branching ratio we need to know the total number of B_s mesons and next to use this number for the normalization
- ❑ 2 normalization channels used





Normalization channel branching | **Fragmentation ratio** | **fs/fd = 0.256±0.02**

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

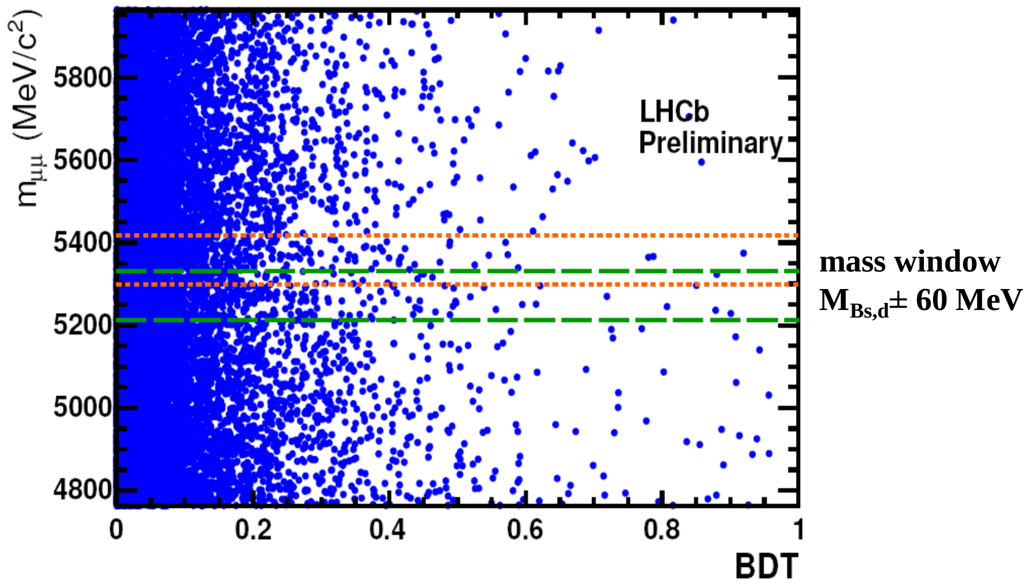
Calculated from MC | **Measured from data** | **Number of events in normalization channel**

- ❑ Averaging of the 2 normalization channels gives us for the 1.1 fb^{-1}:

$\alpha(\mathbf{B_s \to \mu^+\mu^-}) = 2.52 \pm 0.28 \times 10^{-10}$, $\alpha(\mathbf{B_d \to \mu^+\mu^-}) = (6.45 \pm 0.30) \times 10^{-11}$

Extraction of the limit and branching ratio

μμ mass – BDT response plane

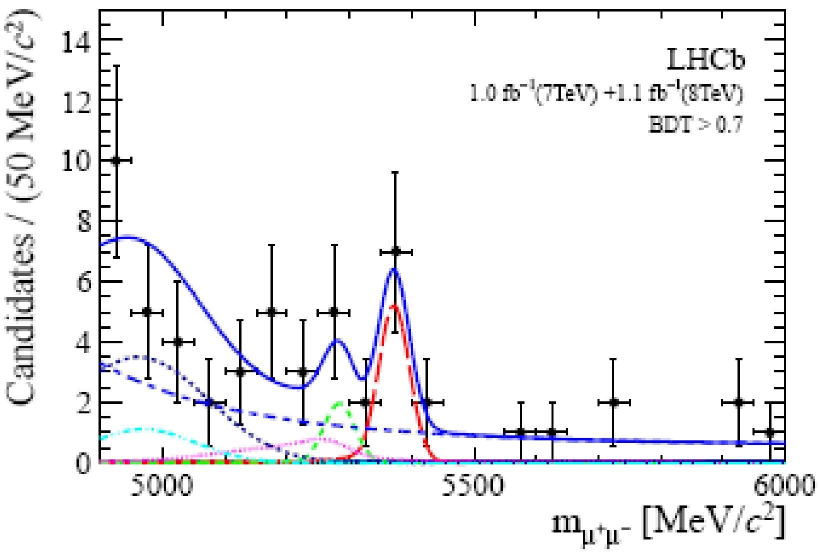


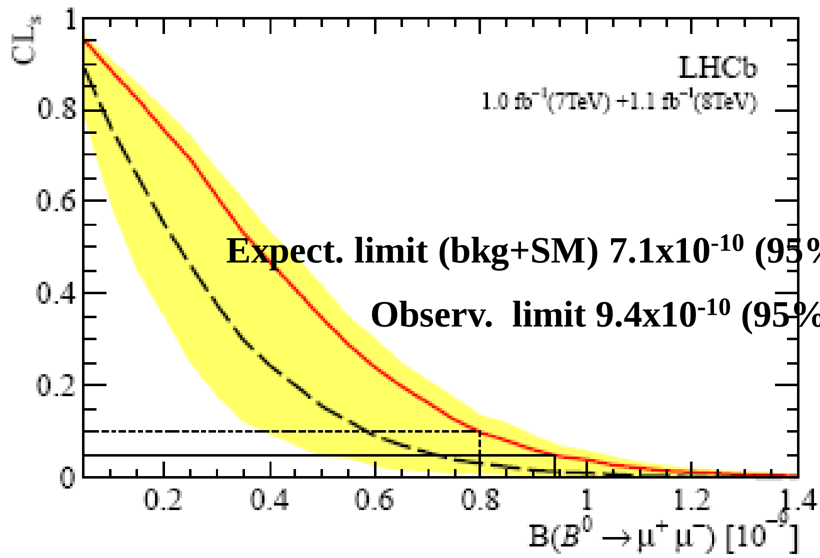
- ❑ The CLs analysis was performed in 2D space for the BDT response and dimuon invariant mass. The BDT response for the combinatorial background is extracted from a fit of the dimuon mass sidebands in each BDT bin
- ❑ To calculate upper limit for each observed event we calculated a probability to be compatible with the Signal + Background hypothesis or only Background hypothesis as a function of the branching ratio. To set a limit we excluded the assumed branching ratio value at a given confidence level
- ❑The comparison of observed events distributions in the $\mathbf{B_s \to \mu^+\mu^-}$ signal region and expected background for the 2012 dataset gives p-value (1-CLb) of 9 x10^{-4} . We have observed an excess of $\mathbf{B_s \to \mu^+\mu^-}$ candidates with respect to the background expectation with a significance of 3.3 standard deviations.

LHCb result with 2.1 fb^{-1} 2011+2012 data

"First evidence for the decay $B_s \rightarrow \mu^+\mu^-$ "
Accept. by PRL December, 6, 2012
hep-ex > arXiv:1211.2674

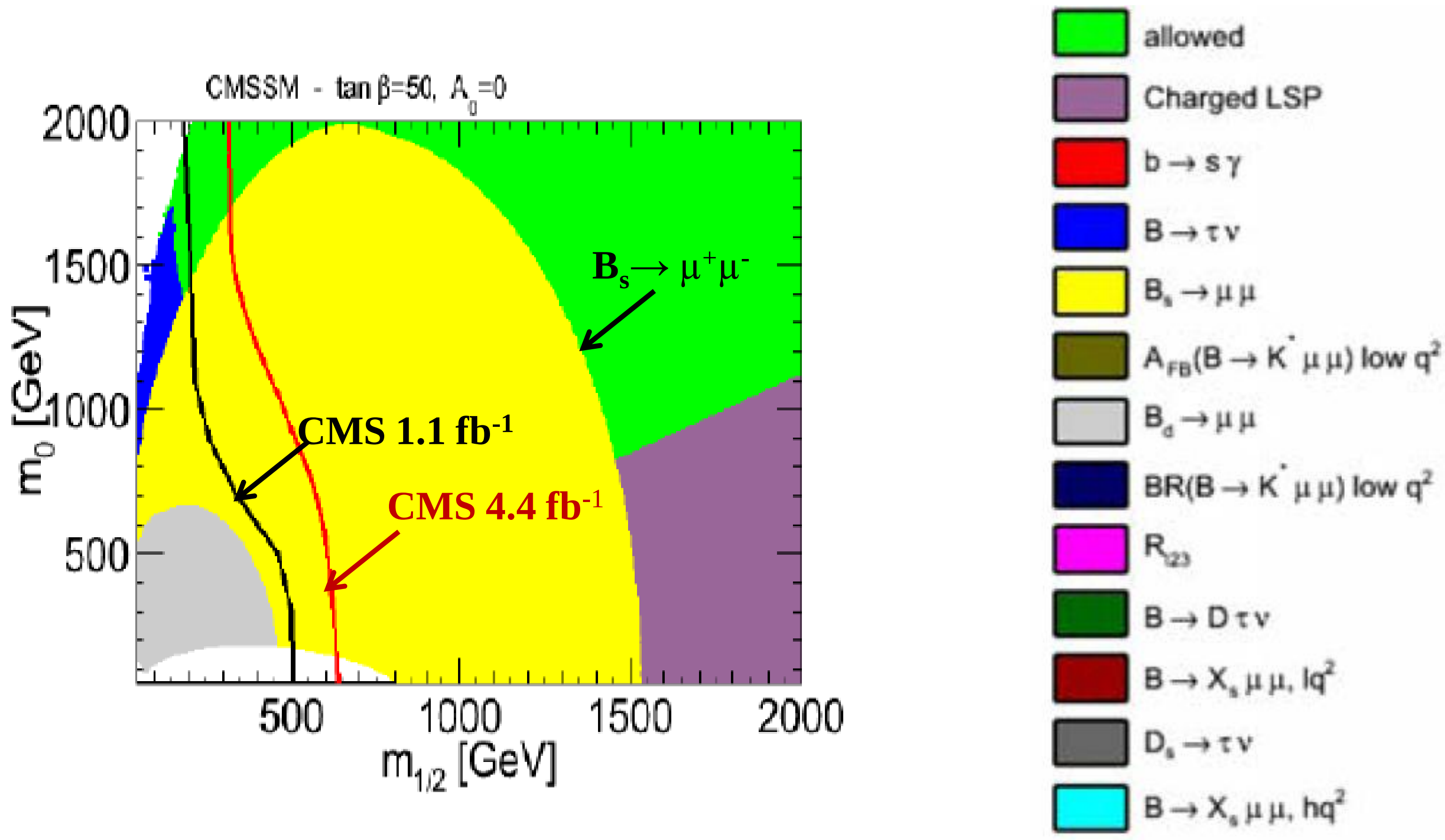
Dataset	Limit at	90 % CL	95 % CL
2012	Exp. bkg+SM	8.5×10^{-10}	10.5×10^{-10}
	Exp. bkg	7.6×10^{-10}	9.6×10^{-10}
	Observed	10.5×10^{-10}	12.5×10^{-10}
2011+2012	Exp. bkg+SM	5.8×10^{-10}	7.1×10^{-10}
	Exp. bkg	5.0×10^{-10}	6.0×10^{-10}
	Observed	8.0×10^{-10}	9.4×10^{-10}





Combination for 2011 and 2012 years data gives the result ,
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2\,^{+1.4}_{-1.2}(\text{stat})\,^{+0.5}_{-0.3}(\text{syst})) \times 10^{-9}$$

Impact to CMSSM parameters



- $B_s \to \mu^+\mu^-$ branching upper limit and experimental branching ratio restricted the big enough region of possible parameters magnitudes at the large tan(β) for the constraint MSSM (CMSSM) model

Conclusions

- LHCb has published first evidence for decay $B_s \to \mu^+\mu^-$ with the significance **3.5 sigma** and branching fraction ***Br(*** $B_s \to \mu^+\mu^-$)=(**3.2 +1.5 -1.2**)x$\mathbf{10^{-9}}$ and double sided limit $1.1 \times 10^{-9} < Br\ (B_s \to \mu^+\mu^-) < 6.4 \times 10^{-9}$ at 95 % CL. Total integrated luminosity L = 2.1 fb^{-1} (2011+2012 years data)

- Word best upper limit **Br**($B_d \to \mu^+\mu^-$)< $\mathbf{9.4 \times 10^{-9}}$ at 95 % CL

- Comparison with the theory prediction ***Br(*** $B_s \to \mu^+\mu^-$) = (**3.54±0.30) x** $\mathbf{10^{-9}}$ - **no** significant enhancement was found by comparison with the Standard Model

- With the SM branching fraction and additional 2012 year integrated luminosity L = 1.1 fb^{-1}, LHCb has good chances to get the significance **4.5** sigma for $B_s \to \mu^+\mu^-$ signal
- LHCb $B_s \to \mu^+\mu^-$ result **not** killed SUSY, but just restricted possible magnitudes for the SUSY parameters

С Новым годом!

Backup slides

mSUGRA model

- mSUGRA or constrained MSSM model, where the MSSM soft breaking parameters obey a set of universal boundary conditions at the has several special aspects that make its predictions clearer and hence more directly accessible to experimental study. mSUGRA is also low energy approximation of Superstring Theory.

- mSUGRA depends on only four additional parameters and one sign beyond those of the Standard Model (SM).

These are:

m_0 - the universal soft breaking mass at the GUT scale M_G;

$m_{1/2}$ - the universal gaugino soft breaking mass at M_G ;

A_0 - the universal cubic soft breaking mass at M_G;

$\tan\beta = \langle H_2 \rangle / \langle H_1 \rangle$ at the electroweak scale, where H_2 gives rise to u quark masses and H_1 to d quark and lepton masses ;

μ - the Higgs mixing parameter in the superpotential ($W\mu = \mu H_1 H_2$);

- Lightest neutralino ν_{01} and the gluino g are approximately related to $m_{1/2}$ by $m_{\nu 01} = 0.4 \cdot m_{1/2}$ and $m_g = 2.8 \cdot m_{1/2}$.

Restrictions to SUSY parameters

http://theor.jinr.ru/~diastp/summer11/lectures/Kazakov-4.pdf

Comparison of the experimental restriction to the $Br(B_s \to \mu^+\mu^-)$ and SM prediction

- To compare the experiment and theory we need to take into account the B_s mixing : De Bruyn et al (arXiv:1204.1735)

✓Theoretical $Br(B_s \to \mu^+\mu^-)$ prediction: CP-average at time , t=0

✓Experimental limit : need to integrate CP-average over t

$$\mathrm{BR}\left(B_s \to f\right)_{\mathrm{theo}} = \left[2 - \left(1 - y_s^2\right)\frac{\tau_f}{\tau_{B_s}}\right]\mathrm{BR}\left(B_s \to f\right)_{\mathrm{exp}} \quad y_s \equiv \frac{\Delta\Gamma_s}{2\,\Gamma_s} \equiv \frac{\Gamma_{\mathrm{L}}^{(s)} - \Gamma_{\mathrm{H}}^{(s)}}{2\,\Gamma_s}$$

✓ as a result using $\mathbf{y_s}$ from *LHCb-CONF-2012-002* we need to compare with theory the *corrected experimental limit :*

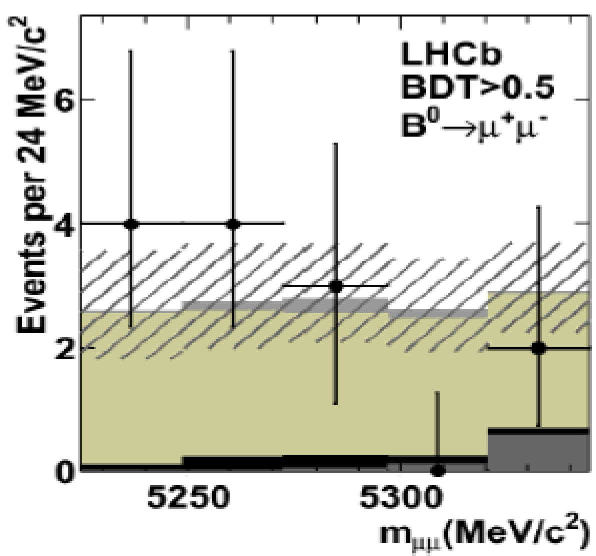
$BR_{t=0}$ $(B_s \to \mu^+\mu^-) < 0.91 \times 4.5 \times 10^{-9} = 4.1 \times 10^{-9}$ @ 95% CL ,

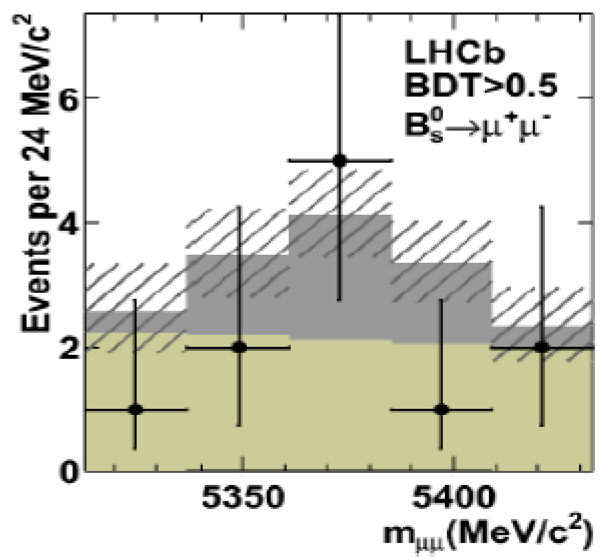
which is close enough to the recent theoretical prediction

Unblind spectra

PRL 108, 231801 (2012)

An example of unblind spectra at BDT >0.5

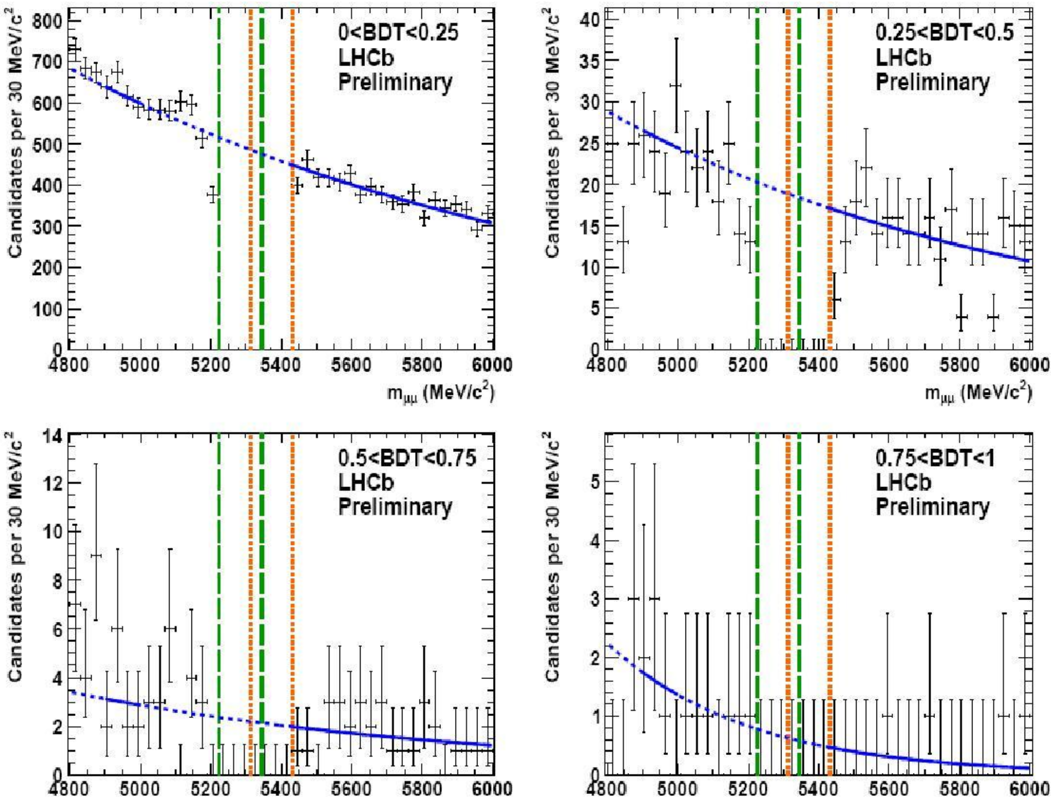




- *Black points* - selected candidates (data)
- *Light gray* – combinatorial background
- *Black* – B→hh background
- D*ark gray* – cross-feed of the two modes $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$
- *Hatched area* – uncertainty on the sum of the expected contributions

Background estimate

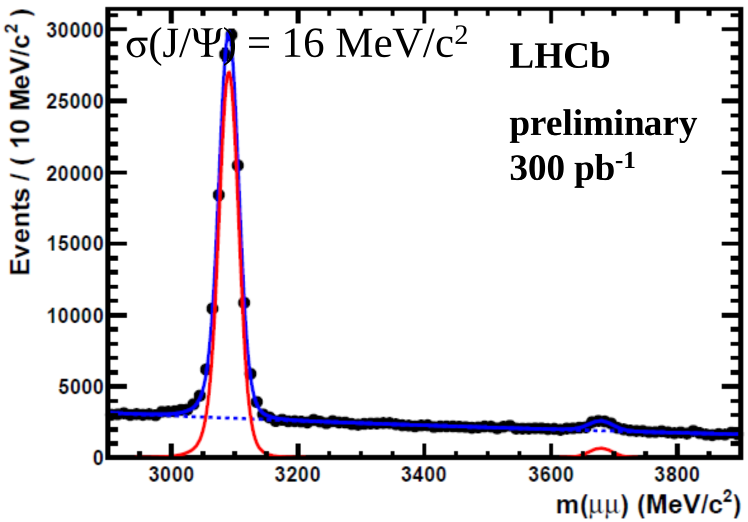
- The combinatorial background estimate was derived from a fit of the mass sidebands for BDT bins with the blind signal region
- The systematics of the backround prediction was studied using the exponential, double exponential and linear fitting functions . 8 BDT bins were used for the analysis.

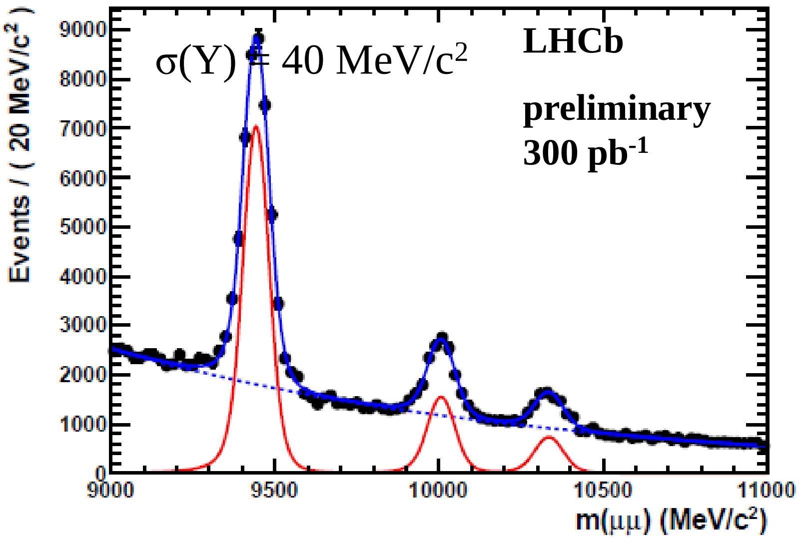


An example of the inv. mass distributions for the case of 4 BDT response bins

Invariant mass calibration

- Invariant mass shape modeled by a Crystal Ball function (Gaussian core portion + low end tail)
- To calculate the resolution we interpolate dimuon resonances (J/ψ, ψ(2s), Upsilons) masses





✓ The power-law interpolation used:

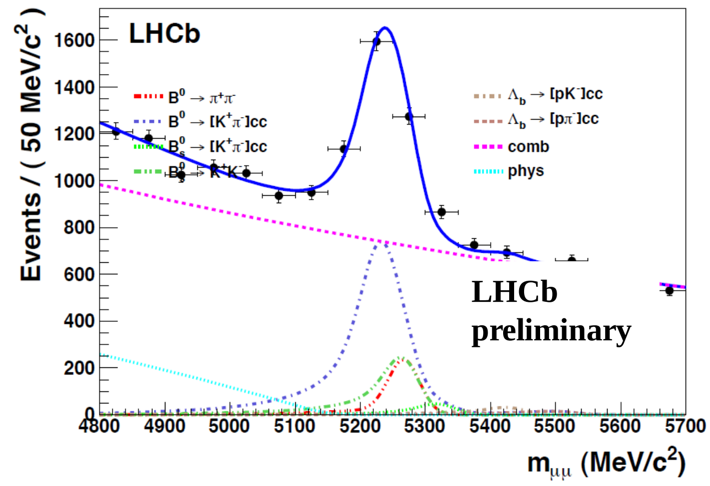
$$\sigma_{\mu\mu}(m_{\mu\mu}) = a_0 + a_1 \cdot m_{\mu\mu}^{\gamma} \quad \gamma = 1.37 \pm 0.08$$

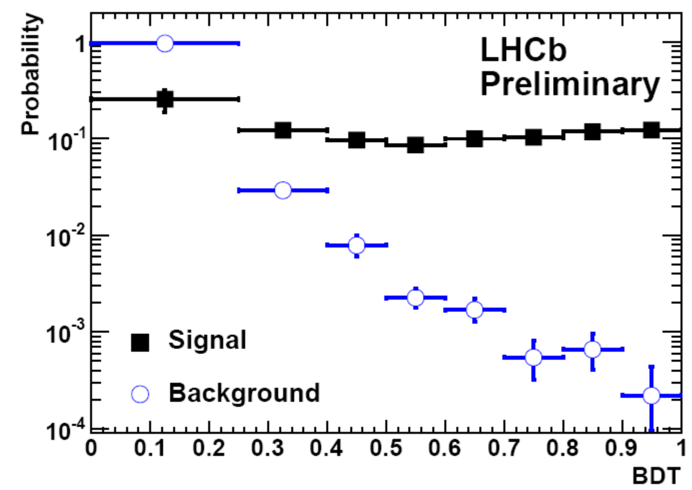
- As a result we have : $\sigma(B_s) = (24.8 \pm 0.3\text{stat} \pm 0.7\text{syst})\ \text{MeV}/c^2$

  $\sigma(B_d) = (24.3 \pm 0.3\text{stat} \pm 0.6\text{syst})\ \text{MeV}/c^2$

BDT response calibration

- ❑ For the calibration of the signal BDT response we have used the data from B mesons hadronic decays - $B_{d/s} \to h^+h^-$
- ✓ The main advantage is same topology as $B_s \to \mu^+\mu^-$
- ✓ The problem is a difference between muon and hadronic trigger. As a result only events triggered independently of the signal (TIS) were used
- ❑ To calibrate the BDT response for the background we have used dimuon data from signal sidebands





Fragmentation ratio calculation

- Fragmentation ratio f_s / f_d is measured at LHCb with hadronic decays $B_0 \rightarrow D^- K^+$ and $B_s \rightarrow D_s^- \pi^+$ *and* $B_0 \rightarrow D^- \pi^+$ and $B_s \rightarrow D^-_s \pi^+$

  Phys. Rev. Lett. 107 21(2011)

  and semileptonic decays: $B_s \rightarrow D_s X\mu$ and $B \rightarrow D^+ X\mu$

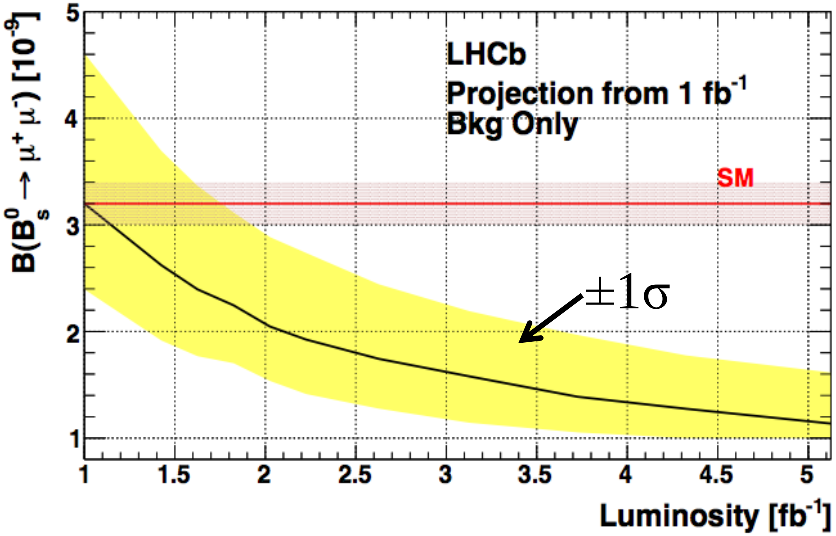
  Phys. Rev. D 85, 032008 (2011)

- Computed average $$f_s / f_d = 0.267^{+0.021}_{-0.020}$$ *lhcb-conf-2011-034*

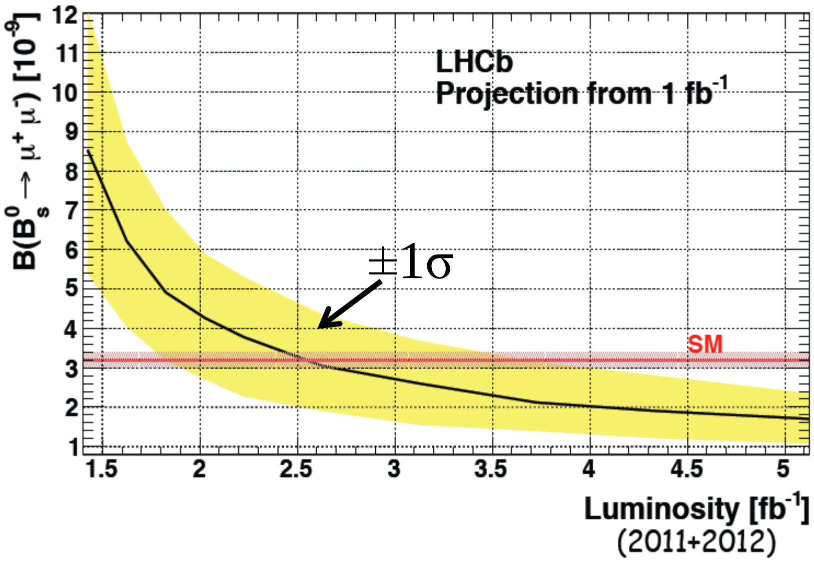
- Dominant systematic error from form factors ratio. Need more precise lattice computation

Prospects with 2012 year data

Exclusion curve for the $B_s \to \mu^+ \mu^-$ branching



3 sigma evidence curve



- We have a chance to have a 3 sigma evidence for the SM level branching fraction with the additional integrated luminosity L=1 .5 fb^{-1} in 2012 year
- or to provide more powerful restriction for the branching fraction in case of destructive interference SM diagrams with some unexpected contribution ..