First Evidence of \( B_s^0 \rightarrow \mu^+ \mu^- \)

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Motivations to search for

\[ B_{(s)}^0 \rightarrow \mu^+ \mu^- \]
Why $B_{(s)}^0 \rightarrow \mu^+ \mu^-$?

- Testing SM in the loops:
  - Flavour Changing Neutral Current
  - No tree diagram, only higher orders

- Possible new particles in the loops

- Precise SM prediction:

$$B(B_s^0 \rightarrow \mu^+ \mu^-)_{SM} = (3.23 \pm 0.27) \times 10^{-9}$$
$$B(B^0 \rightarrow \mu^+ \mu^-)_{SM} = (1.07 \pm 0.10) \times 10^{-10}$$

Buras et al., arXiv:1208.0934

A good place to look for Physics Beyond SM
\[ B_{(s)}^0 \rightarrow \mu^+ \mu^- \text{ phenomenology} \]

Model independent expression of the Branching Ratio:

\[ B(B_s^0 \rightarrow \mu^+ \mu^-) \propto 1 - \frac{4m_{\mu}^2}{m_{B_s}^2} |C_s - C'_s|^2 + \left| (C_P - C'_P) + 2 \frac{m_{\mu}}{m_{B_s}} (C_{10} - C'_{10}) \right|^2 \]

In MSSM:

\[ c_{S,P}^{MSSM} \propto \frac{m_b^2 m_{\mu}^2 \tan^6 \beta}{M_A^4} \]

SM contributions:

2HDM:

- 75% contribution

RPV:

- 24% contribution
Constrains from $B_s^0 \rightarrow \mu^+ \mu^-$

(NUHM1 similar)

CMS Direct Searches
4.4 fb$^{-1}$ (1.1 fb$^{-1}$)

LHCb 1 fb$^{-1}$

F. Mahmoudi, [1205.3099]

May 2012
Experimental Picture
Experimental Observable

• Neutral $B_s^0$ mesons oscillate:

$$\langle \Gamma(B_s^0(t) \to f) \rangle \equiv R_H^f e^{-\Gamma_H^s t} + R_L^f e^{-\Gamma_L^s t}$$

• Experimental observable is the time integrated BR:

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

• Theoretical definition for the prediction:

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

• Time integrated prediction:

$$B(B_s^0 \to \mu^+\mu^-)_{\text{SM exp}} = (3.54 \pm 0.30) \times 10^{-9}$$

De Bruyn et al., PRL 109, 041801 (2012), uses $\Delta \Gamma_s$ from LHCb-CONF-2012-002
Historical Picture

• The story begins in 1984 at CLEO:

Two-body decays of $B$ mesons

Our search for the $\pi^+\pi^-$ final state is not sensitive to the mass of the final-state particles, provided that they are light, since the mass enters only in the energy constraint. Therefore, the upper limit of 0.05% applies for any final-state particles with a pion mass or less. When the final-state particles are leptons the limits are improved by using the lepton identification capabilities of the CLEO detector.\textsuperscript{14} For the decay $B^0 \to \mu^+\mu^-$, we improve our limit by requiring that both muons penetrate the iron and produce signals in drift chambers. We find no such events. After correcting for detection efficiency (33%), we set an upper limit of 0.02% at 90% confidence for this decay. We im-

• Since then:
CLEO, ARGUS, UA1, Belle, BaBar, D0, CDF, ATLAS, CMS, LHCb
Experimental Status

95% C.L. Bounds

<table>
<thead>
<tr>
<th>SM</th>
<th>95% C.L. Bounds</th>
</tr>
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</table>
| DO | \begin{align*}
B(B^0 \rightarrow \mu^+ \mu^-) &< 1.0 \times 10^{-9} \\
B(B_s^0 \rightarrow \mu^+ \mu^-) &< 4.5 \times 10^{-9}
\end{align*} |
| ATLAS | arXiv:1204.0735 |
| CMS | J. HEP 1204 (2012) 033 |
| LHCb | PRL 108 (2012) 231801 |
| LHCb-CONF-2012-017 | |

- LHCb Results:
  \begin{align*}
B(B^0 \rightarrow \mu^+ \mu^-) &< 1.0 \times 10^{-9} \\
B(B_s^0 \rightarrow \mu^+ \mu^-) &< 4.5 \times 10^{-9}
\end{align*}

- Significant NP enhancements ruled out for \( B(B_s^0 \rightarrow \mu^+ \mu^-) \)

- Road map now:
  - Constrain \( B(B^0 \rightarrow \mu^+ \mu^-) \)
  - Measure \( B(B_s^0 \rightarrow \mu^+ \mu^-) \)
Two key points to look for $B_{(s)}^0 \rightarrow \mu^+ \mu^-$:

1. **Production** of $B$ mesons: (x-section and trigger)
2. **Separation** **Signal/Background** (detector performance)
   - Combinatorial background: $b\bar{b} \rightarrow \mu\mu X$
   - **Physical Backgrounds:**
     e.g. $B \rightarrow K\pi, KK, \pi\pi$ where $K, \pi$ decay in flight to $\mu$
Searching for $B_{(s)}^0 \rightarrow \mu^+ \mu^-$ at LHCb
• The LHCb detector:
  • Single arm forward spectrometer
  • Acceptance: \( 2 < \eta < 6 \)

• Key Point 1: Production of \( B \) mesons: \( b \) quarks are produced forward

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Accept.</th>
<th>X-section</th>
<th>( b\bar{b} ) pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF</td>
<td>(</td>
<td>\eta</td>
<td>&lt; 1 )</td>
</tr>
<tr>
<td>ATLAS</td>
<td>(</td>
<td>\eta</td>
<td>&lt; 2.2 )</td>
</tr>
<tr>
<td>CMS</td>
<td>(</td>
<td>\eta</td>
<td>&lt; 2.2 )</td>
</tr>
<tr>
<td>LHCb</td>
<td>( 2 &lt; \eta &lt; 6 )</td>
<td>( 94 \pm 8 \mu b )</td>
<td>( \sim 9 \times 10^{10} )</td>
</tr>
</tbody>
</table>

arXiv: 1207.4287v2
**LHCb Trigger for** $B_{(s)}^0 \rightarrow \mu^+ \mu^-$

**Sig. candidates triggered by the $\mu$-lines:**

- **Single muon**
  
  L0 requires 1 muon with $p_T > 1.76$ GeV/$c^2$
  
  HLT require IP and mass cut

- **Di-muons**
  
  L0 requires di-muons with $\sqrt{p_{T,1}p_{T,2}} > 1.6$ GeV/$c^2$
  
  HLT require IP and mass cut

**Overall:** 90% of the sig. candidates pass the trigger

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Key Point 2: Separation Sig/Bkg

Sig Separated form Combinatorial Bkg thanks to:

- excellent mass and momentum resolution (magnet, tracking)
  \[ \frac{\delta p}{p} \sim 0.4 \rightarrow 0.6\% \text{ for } p = 5 \rightarrow 500 \text{ GeV/c} \]
  \[ \Delta m_{\mu\mu} \sim 25 \text{ MeV/c}^2 \] (2 [3-4] times better than CMS [ATLAS])

- excellent secondary vertex resolution: (high boost and tracking)
  \[ B \] average flight distance 10 mm
  \[ \sigma_{IP} = 25 \mu m \text{ at } p_t = 2 \text{ GeV/c} \]

Sig Separated form Physical Bkg thanks to:

- particle identification information (RICH – muons chambers)
  \[ \epsilon(\mu \rightarrow \mu) \sim 98\% \]
  \[ \epsilon(\pi \rightarrow \mu) \sim 0.6\% \]
  \[ \epsilon(K \rightarrow \mu) \sim 0.3\% \]
  \[ \epsilon(p \rightarrow \mu) \sim 0.3\% \]
LHCb Analysis
Overview of the Analysis

Strategy:
1. Loose selection
2. Classify events in a 2D binned plane
   \( m_{\mu\mu} \times \text{BDT} \) combining topological information and derive expectations for sig and bkg
   - need control channels
     \( B \rightarrow hh' \) and \( B^+ \rightarrow J/\psi K^+ \)
3. Extract Limit and BR

Data Set:
1.0 fb\(^{-1}\) + 1.1 fb\(^{-1}\) collected in 2011 and 2012 at 7 and 8 TeV

Blind analysis: all choices are made without looking at the signal region
Selection

• Selection should be:
  • very efficient for the signal
  • similar for signal and control channels

• Initial Selection requires:
  • good tracks with a large impact parameter
  • good and displaced secondary vertex pointing to the primary vertex

• Tighten initial selection to reduce combinatorial Bkg:
  • cut on a output of a MVA combining information about the candidate topology

80% background rejection for 92% signal efficiency.
Classification - BDT

- Boosted Decision Tree
- Inputs: 9 inputs variables uncorrelated with $m_{\mu\mu}$
- Trained and tested on MC signal and $b\bar{b} \rightarrow \mu\mu X$

B candidate:
- proper time
- impact parameter
- transverse momentum
- B isolation

muons:
- $\text{min } p_T$
- $\text{min IP significance}$
- dist. of closest approach
- muon isolation, polarisation angle
Classification - BDT

- Flat for signal by design

- Sig line shape calibrated on data using an unbiased $B \rightarrow hh'$ sample (same topology as sig)

- Combinatorial Bkg derived from data by interpolating from the mass side-bands
Sig Mass PDF - Mean

- Signal Crystal Ball Shape
- Mean taken form $B^0 \rightarrow \pi\pi, K\pi$ and $B_s \rightarrow KK$

\[
m_{B^0} = (5284.36 \pm 0.26_{\text{stat}} \pm 0.13_{\text{syst}}) \text{ MeV}/c^2
\]
\[
m_{B^0_s} = (5371.55 \pm 0.41_{\text{stat}} \pm 0.16_{\text{syst}}) \text{ MeV}/c^2
\]

- The two modes are resolved: $m_{B_s} - m_{B_d} \sim 87 \text{ MeV} \sim 3.5\sigma_{B^0}$
Sig Mass PDF - Resolution

- $m_{\mu\mu}$ resolution depends on the invariant mass central value:

Interpolate the resolution of the resonances: $J/\psi$, $\psi(2S)$, $\Upsilon(1S, 2S, 3S)$

- Averaging with the resolution obtained form the $B \to hh'$ fits:

$$\sigma_{B^0} = (24.63 \pm 0.13_{\text{stat}} \pm 0.36_{\text{syst}}) \text{ MeV}/c^2$$

$$\sigma_{B^0_s} = (25.04 \pm 0.18_{\text{stat}} \pm 0.36_{\text{syst}}) \text{ MeV}/c^2$$
Normalisation

• Number of signal events corresponding to a $B$:
  \[ N_{B_{(s)}^0 \rightarrow \mu^+ \mu^-} \propto B(B_{(s)}^0 \rightarrow \mu^+ \mu^-) \times N_{Bs} \]

• $N_{Bs}$ cannot be obtained directly and precisely at hadron collider

• Need to normalise to a channel of known Br:
  \[ N_{Bs} \propto \frac{N_{B^+ \rightarrow J/\psi K^+}}{B(B^+ \rightarrow J/\psi K^+)} \times \frac{f_s}{f_d} \]
  \[ N_{Bs} \propto \frac{N_{B^0 \rightarrow K\pi}}{B(B^0 \rightarrow K\pi)} \times \frac{f_s}{f_d} \]

• Correcting for efficiencies:
  \[ B(B_{(s)}^0 \rightarrow \mu^+ \mu^-) \times \frac{N_{\text{norm}}}{B_{\text{norm}}} \times \frac{\epsilon_{\text{REC}} \epsilon_{\text{SEL,REC}}}{\epsilon_{\text{norm}} \epsilon_{\text{REC,REC}}} \times \frac{\epsilon_{\text{TRIG,SEL}}}{\epsilon_{\text{norm}}} \times \frac{f_{B_{(s)}^0}}{f_{\text{norm}}} = \frac{B(B_{(s)}^0 \rightarrow \mu^+ \mu^-)}{\alpha_{\text{norm}}} \]

Extracted from Data  Evaluated from MC, x-checked with data  Measured on data  Ratio of prob for a $b$ quark to hadronise into a $B_{(s)}^0$ or into the norm. init. state
\( B^+ \rightarrow J/\psi K^+ \)

\( B^0 \rightarrow K\pi \)

- Use \( f_s/f_d \) measured at LHCb \( \text{PRD85 (2012) 032008 and LHCb-PAPER-2012-037} \)
- Weighted average of the 2 channels:
  \[
  \alpha_{B^0_s \rightarrow \mu^+\mu^-} = (2.80 \pm 0.25) \times 10^{-10} \\
  \alpha_{B^0 \rightarrow \mu^+\mu^-} = (7.16 \pm 0.34) \times 10^{-11}
  \]

SM expectations 2012+2011 in the mass windows:
\[ 13 + 11 \quad B^0_s \rightarrow \mu^+\mu^- \quad \text{and} \quad 1.5 + 1.3 \quad B^0 \rightarrow \mu^+\mu^- \]
Combinatorial Background

- **2011 strategy**
  Exponential interpolation from the mass side-bands:
  \[ [4900 – 5000] \cup [5432 – 6000] \text{ MeV/c}^2 \]

- **2012 refinement**
  Study additional background sources:
  \( B^0 \rightarrow \pi \mu \nu \) and \( B^{0,+} \rightarrow \pi^{0,+} \mu \mu \)

  Yields for \([4900 – 6000]\text{ MeV/c}^2\), BDT>0.8:

<table>
<thead>
<tr>
<th>Decay</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B^0 \rightarrow \pi \mu \nu )</td>
<td>4.04 ± 0.28</td>
</tr>
<tr>
<td>( B^{0,+} \rightarrow \pi^{0,+} \mu \mu )</td>
<td>1.32 ± 0.39</td>
</tr>
<tr>
<td>( B_{(s)}^0 \rightarrow h h' )</td>
<td>1.37 ± 0.11</td>
</tr>
</tbody>
</table>
Combinatorial Background Interpolation

- Fit the mass side-bands with an exponential and separate PDFs for $B_{(s)}^0 \rightarrow h h'$, $B^0 \rightarrow \pi \mu \nu$ and $B^{0,+} \rightarrow \pi^{0,+} \mu \mu$

- PDF determination of Exclusive Bkg:
  - Derive misId probability $\pi, K \rightarrow \mu$ on data in $p$ and $p_T$ bins
  - Apply these probabilities to large MC samples
  - Mass and BDT PDF extracted from the weighted MC sample
  - Normalisation to $B^+ \rightarrow J/\psi K^+$

- Other backgrounds studied; all negligible:
  $B^0_s \rightarrow K \mu \nu$, $\Lambda_b \rightarrow p \mu \nu$, $B_c \rightarrow J\psi(\mu\mu) \mu \nu$
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Results
Mass-BDT plane

2012 8 TeV data

B_{s} window

B_{0} window
$B_s^0 \rightarrow \mu^+ \mu^-$ Candidate

B candidate: $m_{\mu\mu} = 5353.4$ MeV/c$^2$  
$\mathcal{P}_T = 4077.4$ MeV/c  
$\tau = 2.84$ ps

muons: $p_{T\mu^+} = 2329.5$ MeV/c  
$p_{T\mu^-} = 4179.4$ MeV/c
$\tau = 2.84 \text{ ps}$

$\rho_{T\mu^-} = 4.2 \text{ GeV/c}$

$\rho_{T\mu^+} = 2.3 \text{ GeV/c}$

$\rho_{T(B)} = 4.1 \text{ GeV/c}$
CLs method

- **Idea:** compare observed data with expectations
- **Define a test statistic** for this comparison:
  
  - Calibrate this test statistic with pseudo-experiment

  *if Br was such then \( Bkg \) Only* would give \( -2\ln Q \) of *such*

- **Compute the** \(-2\ln Q\) **of the observed data**

\[
CL_s = \frac{CL_{sb}}{CL_b}
\]

Illustrative plot
$B^0 \rightarrow \mu^+ \mu^-$ upper limits 2011-2012

Obs. limit: $B(B^0 \rightarrow \mu^+ \mu^-) < 9.4 \times 10^{-10}$ at 95% CL

Exp. limit: $B(B^0 \rightarrow \mu^+ \mu^-) < 7.1 \times 10^{-10}$ at 95% CL

Compatibility with bkg only hypothesis: p-value = 1-CLb = 11%
$B_S^0 \rightarrow \mu^+ \mu^-$ sensitivity 2011-2012

Good separation between the 2 expectations

Bkg only p-value: $5.3 \times 10^{-4}$
3.5 $\sigma$ excess

FIRST EVIDENCE

Double-sided limit at 95% CL:

$1.1 \times 10^{-9} < B(B_S^0 \rightarrow \mu^+ \mu^-) < 6.4 \times 10^{-9}$

where the lower and upper limits are evaluated at:

$CL_{s+b} = 0.975$ and $CL_{s+b} = 0.025$
Branching Ratio Fit

- Unbinned maximum likelihood fit of the $m_{\mu\mu}$ distribution in the 2012 and 2011 BDT bins.
- $B(B_s^0 \rightarrow \mu^+\mu^-)$ and $B(B^0 \rightarrow \mu^+\mu^-)$ are free and fit simultaneously.
- Combinatorial bkg is free.
- All other parameters (e.g. $m_{B_s}$, $\sigma_{B_s}$, exclusive bkg…) are gaussian constrained to their expectations.

- An additional systematics is added to account for the hypotheses made on the combinatorial bkg shape (exponential vs double-exponential).
Fit projections

2011
7 TeV data, 1.0 fb$^{-1}$
8 BDT bins

$B^0_s \rightarrow \mu^+ \mu^-$
$B^0 \rightarrow \mu^+ \mu^-$
$B^0_{(s)} \rightarrow h^+ h^-'$
$B^0 \rightarrow \pi^- \mu^+ \nu_\mu$
$B^{\pm,0} \rightarrow \pi^{\pm,0} \mu^+ \mu^-$

total

2012
8 TeV data, 1.1 fb$^{-1}$
7 BDT bins
In the Signal Region BDT > 0.5
In the Signal Region BDT > 0.7
**Fit Results 2011+2012**

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

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

Value in agreement with SM prediction:
$B(B_s^0 \rightarrow \mu^+ \mu^-)_{SM} = (3.54 \pm 0.30) \times 10^{-9}$

Nota: 95% interval in perfect agreement with the one provided by the CL$_S$ method
Conclusions

• $B_{(s)}^0 \rightarrow \mu^+\mu^-$ are very powerful tests of the SM

Harvest of the LHCb analysis of the data collected in 2012 and 2011:

• Constrains on $B^0 \rightarrow \mu^+\mu^-$:

  $$B(B^0 \rightarrow \mu^+\mu^-) < 9.4 \times 10^{-10}$$

• First evidence of $B_s^0 \rightarrow \mu^+\mu^-$:

  \[ p\text{-value: } 5.3 \times 10^{-4} \]
  \[ 3.5\sigma \]

• BR measurement:

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

Paper submitted at PRL, arXiv: 1211.2674
Impact of the results

- Hard time for SuperSymmetry…

But SUSY never dies ;-) 

The observation is "quite consistent with supersymmetry. In fact, it was actually expected in (some) supersymmetric models. I certainly won't lose any sleep over the result."

J. Ellis interviewed by BBC
Fix all the nuisance parameters to their expectations, subtract the error in quadrature with the errors obtained when all parameters are floating:

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

fully dominated by stat error
Comparison 2012-2011

• 2011, 7 TeV (1 fb\(^{-1}\))

\[
B(B_s^0 \rightarrow \mu^+\mu^-) = 1.4^{+1.7}_{-1.3} \times 10^{-9}
\]

p-value 0.11

• 2012, 8 TeV (1.1 fb\(^{-1}\)):

\[
B(B_s^0 \rightarrow \mu^+\mu^-) = 5.1^{+2.4}_{-1.9} \times 10^{-9}
\]

p-value 9 \times 10^{-4}

results from 7 TeV and 8 TeV are compatible at \sim 1.5\sigma
Exclusive Background Effect on 2011

New Analysis:
• $B_s^0 \rightarrow \mu^+ \mu^-$
  • bkg only p-value: 0.11
  • UL = $5.1 \times 10^{-9}$, 95% CL

• $B^0 \rightarrow \mu^+ \mu^-$
  • bkg only p-value: 0.19
  • UL = $13 \times 10^{-10}$, 95% CL

Published Analysis
• $B_s^0 \rightarrow \mu^+ \mu^-$
  • bkg only p-value: 0.18
  • UL = $4.5 \times 10^{-9}$, 95% CL

• $B^0 \rightarrow \mu^+ \mu^-$
  • bkg only p-value: 0.60
  • UL = $10.3 \times 10^{-10}$, 95% CL
$B^0 \rightarrow \mu^+ \mu^-$: limits and sensitivity

7 TeV (1 fb$^{-1}$) + 8 TeV (1.1 fb$^{-1}$):

$B(B^0 \rightarrow \mu^+ \mu^-) < 9.4 \times 10^{-10}$

bkg only p-value (1-CL$_b$): 0.11
(corresponds to $\sim$1.5$\sigma$ excess)

UL are quoted at 95%CL

<table>
<thead>
<tr>
<th></th>
<th>Expected UL (SM+bkg)</th>
<th>Observed UL</th>
<th>Observed 1-CL$_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td>$6.0 \times 10^{-10}$</td>
<td>$13.0 \times 10^{-10}$ *</td>
<td>0.19 *</td>
</tr>
<tr>
<td>8 TeV</td>
<td>$10.5 \times 10^{-10}$</td>
<td>$12.5 \times 10^{-10}$</td>
<td>0.16</td>
</tr>
<tr>
<td>7 TeV + 8TeV</td>
<td>$7.1 \times 10^{-10}$</td>
<td>$9.4 \times 10^{-10}$</td>
<td>0.11</td>
</tr>
</tbody>
</table>

*published results:
UL = $10.3 \times 10^{-10}$
1-CL$_b$ = 0.60
Some projections

- From LHCB-TDR-012:

<table>
<thead>
<tr>
<th>Obs.</th>
<th>End 2018</th>
<th>LHCb upgrade 50 fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B(B^0_s \rightarrow \mu^+ \mu^-) )</td>
<td>( 0.5 \times 10^{-9} )</td>
<td>( 0.15 \times 10^{-9} )</td>
</tr>
<tr>
<td>( B(B^0_s \rightarrow \mu^+ \mu^-) ) / ( B(B^0 \rightarrow \mu^+ \mu^-) )</td>
<td>100%</td>
<td>35%</td>
</tr>
</tbody>
</table>
Hadronisation Probability $f_s/f_d$

- $f_s/f_d$ is measured at LHCb by comparing abundances of:
  - $B_s^0 \rightarrow D_s^- \pi^+$, $B^0 \rightarrow D^- K^+$ and $B^0 \rightarrow D^- \pi^+$ arXiv:111.2357 aka PRD85 032008 (2012)
  - $B_s^0 \rightarrow D_s^- \mu^+X$ and $B^0 \rightarrow D^- \mu^+X$ LHCb-paper-2012-037 in preparation
- at 7 TeV: $f_s/f_d = 0.256 \pm 0.020$

- $p_T$ dependency small enough to be negligible
- $\sqrt{s}$ dependency checked with $B^+ \rightarrow J/\psi K^+$ and $B_s^0 \rightarrow J/\psi \phi$: stable within $1\sigma$
Exclusive Backgrounds:

\[ B^0_s \rightarrow K^+ \mu^- \bar{\nu}_\mu \text{ and } B^0 \rightarrow \pi^+ \mu^- \bar{\nu}_\mu \]

- \( B^0_s \rightarrow K^+ \mu^- \bar{\nu}_\mu \) contribution is found negligible
- Accounted in the fit as a systematics
- Lower contribution from \( B^0_s \rightarrow K^+ \mu^- \bar{\nu}_\mu \) explained by:
  - \( f_s/f_d = 0.26 \)
  - \( B(B^0_s \rightarrow K^+ \mu^- \bar{\nu}_\mu)/B(B^0 \rightarrow \pi^+ \mu^- \bar{\nu}_\mu) = 0.88 \)
  - \( \epsilon_{K\rightarrow\mu}/\epsilon_{\pi\rightarrow\mu} = 0.28 \) (RICH efficiency and \( B(K^- \rightarrow \mu^- \bar{\nu}_\mu)/B(\pi^- \rightarrow \mu^- \bar{\nu}_\mu) \))

<table>
<thead>
<tr>
<th>2011</th>
<th>2012</th>
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<tbody>
<tr>
<td>( B^0 \rightarrow \pi^- \mu^+ \nu_\mu )</td>
<td>3.51 ± 0.25</td>
</tr>
<tr>
<td>( B^0_{(s)} \rightarrow h^+ h^- ) misID</td>
<td>0.91 ± 0.12</td>
</tr>
<tr>
<td>( B^{+(0)} \rightarrow \pi^{+(0)} \mu^+ \mu^- )</td>
<td>1.12 ± 0.35</td>
</tr>
<tr>
<td>( \Lambda^0_b \rightarrow p \mu^- \nu )</td>
<td>0.29 ± 0.17</td>
</tr>
<tr>
<td>( B^0_s \rightarrow K^- \mu^+ \nu_\mu )</td>
<td>0.33 ± 0.13</td>
</tr>
<tr>
<td>( B^+_c \rightarrow J/\psi \mu^+ \nu )</td>
<td>0.29 ± 0.33</td>
</tr>
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Yields for \([4900 - 6000]\)MeV/c^2, BDT>0.8
BDT Variables

**Muon isolation:** number of other tracks with which the muon can make a good vertex

**Other tracks requirement:**
- Long track
- Impact Param Significance with PV > 3

**Vertex requirement:**
- Angle track-muon < 0.27 rad
- Distance of Closest Approach < 130 µm
- Distance to PV: 0.5 cm < d < 4 cm
- Distance to SV: -0.15 cm < d < 30 cm
- \[
\frac{|p_\mu + p_{track}| \sin \alpha}{|p_\mu + p_{track}| \sin \alpha + p_{T,\mu} + p_{T,track}} < 0.6
\]
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:

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

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

- B Candidate
  - impact parameter*
  - impact parameter $\chi^2$
  - $\chi^2$ of the vertex
  - pointing angle
  - distance of closest approach*

- Muons
  - min IP

*common with BDT