Very rare $B$ decays

Barbara Sciascia, LNF-INFN
on behalf of LHCb collaboration
including results from ATLAS and CMS
SM couldn’t be in better shape…

…still suffers of a series of theoretical and cosmological problems.

- “hierarchy problem”: how to get from Planck scale $O(10^{19} \text{ GeV})$ to EW scale $O(100 \text{ GeV})$ without “fine tuning” quantum corrections?

- “flavor puzzle”: unexplained hierarchical structure of the Yukawa coupling

- non coherent inclusion of the gravity at the quantum level

- “matter-antimatter symmetry”: from current measurements baryogenesis can only generate $10^{-20}$, but $O(10^{-10})$ is needed.

- no good candidate for dark matter

- neutrino oscillations…..
Standard Model couldn’t be in better shape...

Standard Model (SM) is likely to be the low-energy limit of a more fundamental theory, with new degrees of freedom. 

Expect New Physics (NP).

What we observe is the sum of SM+NP

Two complementary ways to look for NP:

**direct searches** [ATLAS and CMS]:
we didn’t yet look in the “right place”

**indirect searches** [ATLAS, CMS, and LHCb]:
we “already observe” NP [but how to set limits on it?]

Assume that tree-level diagrams are dominated by SM and loop (box, penguin) diagrams could contain NP.
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Assume that tree-level diagrams are dominated by SM and loop (box, penguin) diagrams could contain NP.

Find observables where **SM predictions are very accurate**
and **precisely measure** these observables: the difference gives information about the amount and the characteristic of NP.

Very rare B decays: good places to look for NP.
B physics at LHC

ATLAS and CMS largely in central region (|\eta|<2.4), LHCb forward region (2<\eta<5)

Measured \(\sigma(pp\rightarrow bbX)\) cross-section (at 7 TeV):
ATLAS \((32.7 \pm 0.8^{+4.5}_{-5.8}) \ \mu b\) (\(p_T(B)>9\) GeV and |\eta|<2.5)  
CMS \((28.1 \pm 2.4 \pm 2.0 \pm 3.1) \ \mu b\) (\(p_T(B)>5\) GeV and |\eta|<2.4)  
LHCb \((75.3 \pm 5.4 \pm 13.0) \ \mu b\) (2<|\eta|<6)

Each experiment: \(O(10^{10})/fb\) bb pairs on tape
Compare to combined BaBar and Belle data sample of \(\sim 10^9 B^0\bar{B}^0\) pairs. For any channel where the (trigger, reconstruction, stripping, offline) efficiency is not too small, LHC have the world's largest data sample… the right place to look for very rare B decays.

[PLB 694 (2010) 209]  
b fragmentation $f_s/f_d$

- Important to set the normalization for BF

- LHCb used semileptonic decays: ratio of $B_s \to D_s \mu X$ to $B \to D^+ \mu X$
- Combined with hadronic results: ratio of $B_s \to D_s^- \pi^+$ to $B \to D^- K^+$
- Recently updated using new $BF(D_s \to K^+ K^- \pi^+)$ from CLEO, BaBar and Belle
- Updated B lifetime measurements

\[
f_s/f_d = 0.259 \pm 0.015_{\text{STAT+SYST}}
\]

$P_T$ dependence negligible (<1\sigma) for B decays measurements.
For 8 TeV data, check the $\sqrt{s}$ dependence studying the $B_s \to J/\psi \phi/B^+ \to J/\psi K^+$ ratio: stable ~1.5 $\sigma$
Talk topics

$B_{(s)} \rightarrow \mu \mu$

$B_{(s)} \rightarrow 4 \mu$

$B_{(s)} \rightarrow e \mu$

*Search for Majorana neutrinos in $B^- \rightarrow \pi^+ \mu^- \mu^-$*
Standard Model prediction for $B_{(s)} \rightarrow \mu \mu$:

$B(B_s \rightarrow \mu \mu) = (3.65 \pm 0.23) \times 10^{-9}$

$B(B_d \rightarrow \mu \mu) = (1.06 \pm 0.09) \times 10^{-10}$


Entering the precision realm:
- the increased theory accuracy is essential in interpreting the experimental findings in terms of the SM or NP.
- NP models predict various and different enhancements or suppressions.
- even if no deviation from the SM is found, the role of $B_{q} \rightarrow \mu \mu$ in constraining new physics will become significantly stronger.

Theory error budget from PRL 112:101801, 2014
$B_s \rightarrow \mu\mu$: first observation (LHCb)

November 2012

1/fb (7 TeV) + 1.1/fb (8 TeV)

$B_s \rightarrow \mu\mu$, compatibility with bkg only hypothesis: p-value = 1-CLb = 5.3×10^{-4} (3.5 \sigma excess)

$B_d \rightarrow \mu\mu$, compatibility with bkg only hypothesis: p-value = 1-CLb = 0.11
Strategy very similar for the LHC experiments.

- **Loose pre-selection:**
  Pairs of opposite charged muons
  Vertex displaced with respect to primary vertex
  Many quality requirements

- **Normalization to** $B^+ \rightarrow J/\psi K^+$
  (also $B_d \rightarrow K \pi^+$ for LHCb)

\[
\mathcal{B}(B_{(s)}^0 \rightarrow \mu^+ \mu^-) = \frac{\mathcal{B}_{\text{norm}} \varepsilon_{\text{norm}} f_{\text{norm}}}{N_{\text{norm}} \varepsilon_{\text{sig}} f_{d(s)}} \times N_{B_{(s)}^0 \rightarrow \mu^+ \mu^-}
\]

- **Blind analysis** (fully defined without looking at the events in the signal region)

- **Multivariate and 2D classification**

- **Results:** unbinned maximum likelihood (UML) fit in case of signal, CLs method for the limits.
**Combinatorial**: good muons, bad pointing, bad isolation, random mass, high yield \((10^9 \times \text{signal})\)

**“Double misID”**: bad muons, good pointing, good isolation, peaking mass \((10^3 \times \text{signal})\)

**Exclusive**: (good) muons, bad isolation, peaking but lower yield, low yield \((20 \times \text{signal})\)

<table>
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<th><strong>Semileptonic</strong></th>
<th>(B \rightarrow \pi^- \mu^+ \nu)</th>
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<td>(B_s \rightarrow K^- \mu^+ \nu)</td>
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<tr>
<td>(\Lambda_b \rightarrow p \mu^+ \nu)</td>
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<tr>
<td>(B^+_c \rightarrow J/\psi \mu^+ \nu)</td>
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<tr>
<td>(B_s \rightarrow D_s^- (\rightarrow \mu^- \nu) \mu^+ \nu)</td>
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<table>
<thead>
<tr>
<th><strong>Rare</strong></th>
<th>(B^{+(0)} \rightarrow \pi^{+(0)} \mu^- \mu^-)</th>
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<tbody>
<tr>
<td>(B_{(s)} \rightarrow \mu^+ \mu^- \gamma)</td>
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</table>
Analysis of 2011+2012 dataset: 5/fb (7 TeV) + 20/fb (8 TeV)

Selection:
- improved muon identification (BDT)
- new and improved variables
- MVA analysis (BDT, discriminating and isolation variables)

Selection cuts differentiated for barrel (both $|\eta(\mu)|<1.4$) and endcap region (all other pairs).

Two approaches for interpretation:
- optimized cut on BDT output (1D-BDT)
- equalized expected signal yields BDT bins (categorized-BDT)

Strategy (decided before unblinding):
- $B_d \rightarrow \mu\mu$: 1D-BDT, UL with CLs
- $B_s \rightarrow \mu\mu$: categorized-BDT, UML fit
Analysis of 2011+2012 dataset: 1/\text{fb} (7 \text{ TeV}) + 2/\text{fb} (8 \text{ TeV})
2/\text{fb} of previous analysis included [re-constructed and re-analyzed]

Signal discrimination with BDT:
- **output**: defined to be flat for signal and peaked at zero for background (analysis in BDT bins)
- **signal shape**: from Bhh data events
- **bkg shape**: from dimuon mass sidebands

**$B_{(s)} \rightarrow \mu \mu$ at LHCb**

**PDF**

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<th>LHCb</th>
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<td>0.8</td>
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**$B_{(s)}$ mass peak position from Bhh events**

**Mass resolution, 2 independent methods:**
- from **interpolation** of dimuon resonances
- from Bhh events

\[
\sigma_{B^0} = 22.8 \pm 0.4 \text{ MeV}/c^2
\]
\[
\sigma_{B^0} = 23.2 \pm 0.4 \text{ MeV}/c^2
\]
Analysis of 2011 dataset: 4.9/fb [supersedes 2.4/fb 2011 result]

Selection:
- improved event reconstruction
- final selection based on MVA (BDT)

Normalization from a multi-dimensional UML fit

Systematic uncertainty dominated by:
- normalization
- acceptance and efficiency evaluation

\[ \mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) < 1.5 (1.2) \times 10^{-8} \text{ at 95\% (90\%)} \]
Result of the UML fit in the categorized-BDT approach

\[ \mathcal{B}(B_s^0 \to \mu^+ \mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9} \]
\[ \mathcal{B}(B^0 \to \mu^+ \mu^-) = (3.5^{+2.1}_{-1.8}) \times 10^{-10} \]

Significances:

UML fit in the categorized-BDT

\( B_s \mu \mu \, 4.3 \, \sigma \)

[expected 4.8 \( \sigma \) (median)]

\( B_d \mu \mu \, 2.0 \, \sigma \).

UML fit in the 1D-BDT

\( B_s \mu \mu \, 4.8 \, \sigma \)

[expected 4.7 \( \sigma \) (median)]
$B_{(s)} \rightarrow \mu \mu$: evidence at LHCb

Simultaneous UML fit to mass spectra on 8 BDT bins.
Combinatorial bkg, $B_s$ and $B_d$: yields free
Exclusive bkg: yields and PDFs constrained to their expectations.

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

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

Significances:
- $B_s \mu \mu$: $4.0 \sigma$
- $B_d \mu \mu$: $2.0 \sigma$

[expected $5 \sigma$ (median)]

Full PDF
- $B_s \rightarrow \mu \mu$
- $B_d \rightarrow \mu \mu$
- Combinatorial
- $B_{(s)} \rightarrow \pi(K) \mu \nu$
- $B_{(s)}^{0(+)} \rightarrow \pi^{0(+)} \mu \mu$

LHCb
- BDT > 0.7
- 3 fb$^{-1}$

Candidates / (44 MeV/c$^2$)
For $B_d$:
- No significant evidence of signal over background
- Quote an upper limit evaluated using CLs method.

$LHCb$:

$\mathcal{B}(B^0 \to \mu^+ \mu^-) < 7.4 \times 10^{-10}$

(at 95% CL)

$CMS$:

$\mathcal{B}(B^0 \to \mu^+ \mu^-) < 1.1 \times 10^{-9}$

(at 95% CL)
Naive combination (central values, no significance assessment)

\[ \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (2.9 \pm 0.7) \cdot 10^{-9} \]
\[ \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = 3.6^{+1.6}_{-1.4} \cdot 10^{-10} \]

Work is ongoing to do a full combination of LHCb and CMS measurements: combined fit to the two datasets, sharing of all PDFs and correlated parameters \((f_s/f_d, BR(B^+ \rightarrow J/\psi K^+), \ldots)\).

Output: combined BF and 2D scans, significances. Results expected end of summer.
B_{(s)} \rightarrow \mu\mu: the long quest

A long quest over more than 4 orders of magnitude and more than 25 years. Crucial role of hadronic colliders, Tevatron first, and now LHC.

Symbols: experiments
Red: B_{d}\rightarrow \mu\mu search
Blue: B_{s}\rightarrow \mu\mu search

\diamond full Run1 ATLAS update on the way
$B_{(s)} \rightarrow \mu\mu$: what about NP models?

[D.Straub arXiv:1107.0266]
$B_{(s)} \rightarrow \mu \mu$: what about NP models?

[D.Straub arXiv:1205.6094]

March 2012
After July 2013

"The value of a negative result [...] Arguably, this year’s most significant result from CERN was a negative one. [...] This kind of result doesn’t generate the same media attention that comes with a discovery, but by focusing theoretical attention in the right place it can be very positive for the evolution of the field."
Search for $B_{(s)} \rightarrow \mu^+ \mu^- \mu^+ \mu^-$

$B_{(s)} \rightarrow \mu^+ \mu^- \mu^+ \mu^-$: strongly suppressed in SM.

[PRL 110 (2013) 211801]

NP: significant enhancement can occur, e.g. in MSSM it is mediated via the new scalar $S$, and pseudoscalar $P$ sgoldstino particles [PRD 85 (2012) 077701].

HyperCP (E871) evidence of $\Sigma^+ \rightarrow p \mu^+ \mu^-$.  

[PRL 94 (2005) 021801]

The narrow range of dimuon masses may indicate that the decay proceeds via a neutral intermediate state, $\Sigma^+ \rightarrow p P^0, P^0 \rightarrow \mu^+ \mu^-$ with $m_P=214.3(5)$ MeV and

$$B(\Sigma^+ \rightarrow p P^0, P^0 \rightarrow \mu^+ \mu^-) = \left[3.1^{+2.4}_{-1.9}(\text{stat}) \pm 1.5(\text{syst})\right] \times 10^{-8}.$$
Candidates / (20 MeV/$c^2$)

Candidates / (4.5 MeV/$c^2$)

Search for $B_{(s)} \rightarrow \mu^+ \mu^- \mu^+ \mu^-$

[PRl 110 (2013) 211801]

Searching for $B_{(s)} \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ searched at LHCb (1/fb)

BF normalized to $B \rightarrow J/\psi K^*$. 

In the near future LHCb will:
- update the $B_{(s)} \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ search with the full Run1 data set
- measure $BF(\Sigma^+ \rightarrow p \mu^+ \mu^-)$

No signal evidence, set 95%(90%) CL:

$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-) < 1.6(1.2) \times 10^{-8}$

$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-) < 6.6(5.3) \times 10^{-9}$

Following the model in PRD 85 (2012) 077701 these correspond to limit on $B_{(s)} \rightarrow SP$:

$\mathcal{B}(B_s^0 \rightarrow SP) < 1.6(1.2) \times 10^{-8}$

$\mathcal{B}(B^0 \rightarrow SP) < 6.3(5.1) \times 10^{-9}$

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B.Sciascia INFN - Very rare B decays - FPCP, Marseille 27 May 2014
The decays $B_{(s)} \rightarrow e \mu$ are **forbidden within the SM** (LFV) but are allowed in models with a local gauge symmetry between quarks and leptons.

Pati-Salam model predicts a new interaction to mediate transitions between leptons and quarks via exchange of spin-1 gauge bosons [Pati-Salam lepto-quarks, LQ] that carry both color and lepton quantum numbers.

**Direct searches** by CMS and ATLAS put limits in the range 0.5-1 TeV to LQ linking quark and leptons of the **same** generation.

$B \rightarrow e \mu$ decays can be **mediated** by other LQ that couple leptons and quarks that are **not necessarily from the same generation**.

**Previous limit from CDF:**

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

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

[CDF 2/fb, PRL 102 201901]
**Search for $B_{(s)} \rightarrow e\mu$ (LHCb)**

[LHCb, PRL 111(2013) 141801]

**Strategy** identical to that of the $B_{(s)} \rightarrow \mu\mu$

**Dataset:** $1/fb$ (2011, 7 TeV)

Events are classified in the (mass,BDT) plane and normalized to $B_d \rightarrow K\pi$ control sample.

**Blind analysis.**

No excess over background is seen; upper limit on $\text{BR}(B_{(s)} \rightarrow e\mu)$ obtained with CLs method
Implications of $B_{(s)} \rightarrow e\mu$ result

From limits on $BR(B_{(s)} \rightarrow e\mu)$ lower bounds on Pati-Salam LeptoQuark masses are inferred

\[
m_{LQ_s}(B_s^0 \rightarrow e\mu) > 107(101) \text{ TeV/} c^2 \text{ @ 90(95)% CL}
\]

\[
m_{LQ_d}(B^0 \rightarrow e\mu) > 135(126) \text{ TeV/} c^2 \text{ @ 90(95)% CL}
\]

With 1/fb LHCb has put limits 20x more stringent than the world best limits.

[LHCb, PRL 111(2013) 141801]
Neutrinos can either be their own antiparticles, in which case they are called “Majorana” particles, or Dirac fermions.

Heavy Majorana neutrinos can be sought in heavy flavor decays and couplings to a single fourth neutrino generation can be determined, or limits imposed.

The lepton number violating process $B^- \rightarrow \pi^+ \mu^- \mu^-$ is forbidden in the SM, but can proceed via the production of on-shell Majorana neutrinos.

Experimentally $B^- \rightarrow \pi^+ \mu^- \mu^-$ is the most sensitive channel [Atre et al.]:
- allows the widest range of mass $(m_\pi + m_\mu < m_N < 5 \text{ GeV})$
- higher rate (comes with a factor $V_{ud}$ while e.g. $B^- \rightarrow K^+ \mu^- \mu^-$ comes with $V_{us}$).

The lifetime of $N$ is unknown.

[JHEP 05 (2009) 030]
Search for Majorana neutrino in $B^+ \rightarrow \pi^+ \mu^- \mu^-$

Experimental status:

- CLEO: $\text{BR}(B^+ \rightarrow \pi^+ \mu^- \mu^-) < 1.4 \times 10^{-6}$ at 90%
- Babar: $\text{BR}(B^+ \rightarrow \pi^+ \mu^- \mu^-) < 10.7 \times 10^{-8}$ at 90%
- LHCb (0.4/fb): $\text{BR}(B^+ \rightarrow \pi^+ \mu^- \mu^-) < 1.3 \times 10^{-8}$ at 95%

Recent update by LHCb based on the 3/fb recorded

Two selections: (unknown $\tau_N$, search for $N$ with a lifetime up to 1000 ps)
- assuming $N$ has short lifetime, $B$ vertex formed by $\pi^+ \mu^- \mu^-$
- detached neutrino: first vertex for $\pi^+ \mu^-$, attached to the second $\mu^-$ to form the $B$ candidate

Normalization to $B^+ \rightarrow J/\psi K^+$.

Efficiencies taken from MC or data driven methods.

Extended maximum likelihood fit to the $\pi^+ \mu^- \mu^-$ sidebands to determine the combinatorial background. Peaking background shape taken from MC, yields constrained to $B^+ \rightarrow J/\psi K^+$

Limits obtained with the CLs method
Short neutrino lifetime search

Peaking background:
\( B^+ \rightarrow J/\Psi K^+ (\pi^+) \), \( B^+ \rightarrow \Psi(2S) K^+ \)

No signal observed:
\( BR(B^{-} \rightarrow \pi^+ \mu^- \bar{\mu}^-) < 4.0 \times 10^{-9} \) at 95% CL

Limit as function of neutrino mass:
- scan over neutrino mass with 5 MeV step up to 5000 MeV
- at each point, fit \( m(\pi^+ \mu^-) \) in a \( 3\sigma \) window (\( \sigma \) neutrino mass resolution evaluated from MC)

[in the \( \pi^+\mu^-\bar{\mu}^- \) signal region (5239-5320 MeV)]
Search for Majorana neutrino in $B^- \rightarrow \pi^+ \mu^- \mu^-$

Long neutrino lifetime search

No signal observed, limit as function of neutrino mass and lifetime

[no signal observed, limit as function of neutrino mass and lifetime]

[background]

[LHCb, PRL 112 (2014) 131802]
Limit on $V_{\mu 4}$

**Model-dependent** upper limits on the coupling of a single fourth-generation Majorana neutrino to muons $V_{\mu 4}$ for each value of $m_N$ are extracted using the formula from Atre et al. [JHEP 05 (2009) 030]

$$\mathcal{B}(B^- \rightarrow \pi^+ \mu^- \mu^-) = \frac{G_F^4 f_B^2 f^2 \pi m_B^5}{128 \pi^2 \hbar} |V_{ub}V_{ud}|^2 \tau_B \left(1 - \frac{m^2_N}{m^2_B}\right) \frac{m_N}{\Gamma_N} |V_{\mu 4}|^4$$

The total width of the neutrino depend on its mass; we parameterize it by:

$$\Gamma_N = [3.95 m_N^3 + 2.00 m_N^5(1.44 m_N^3 + 1.14)] \times 10^{-13} |V_{\mu 4}|^2$$
**Conclusions**

Very rare B decays, a powerful tool for NP searches. So far overall good agreement with SM.

First observation of $B_s \rightarrow \mu^+\mu^-$
- Eagerly anticipate the ATLAS Run 1 update
- Run 2 needed for $B_d \rightarrow \mu^+\mu^-$
- no significant deviation from SM
- rule out a large part of the NP parameters

SM is still rock solid but there is room for the unexpected…
...and perhaps it will really be the careful study of a very rare B decay the key to access the new physics world.
Additional information
**B_{(s)}\mu\mu: decay in theory [details]**

BF(B_{d,s} \rightarrow \mu^+\mu^-) is tiny
- only loop contributions (GIM mechanism)
- proportional to m_\mu^2 (helicity suppression)

Cleanest rare decays: very simple hadronic part, only B decay constant F_B enters

Numerical inputs:

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<th>Parameter</th>
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<th>Unit</th>
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Time dependent acceptance (LHCb)

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

$$\Gamma(B_s^0(t) \rightarrow \mu^+\mu^-) = (R_H + R_L)e^{-\Gamma_st} \left[ \cosh \frac{y_st}{\tau_{B_s}} + A_{\Delta \Gamma} \sinh \frac{y_st}{\tau_{B_s}} \right]$$

where:

$$y_s = \frac{\Gamma_L - \Gamma_H}{\Gamma_L + \Gamma_H} = 0.01615 \pm 0.0085$$

$$A_{\Delta \Gamma} = \frac{\Gamma_{B_s,H}^{0} \rightarrow \mu\mu - \Gamma_{B_s,L}^{0} \rightarrow \mu\mu}{\Gamma_{B_s,H}^{0} \rightarrow \mu\mu + \Gamma_{B_s,L}^{0} \rightarrow \mu\mu}_{SM} = 1$$

- So the time integrated efficiency is model dependent:

$$\varepsilon = \frac{\int \varepsilon(t) \Gamma_{A,y_s}(t) dt}{\int \Gamma_{A,y_s}(t) dt}$$

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

$$\delta_{\varepsilon} = \frac{\varepsilon_{MC}}{\varepsilon_{MC}} = \frac{\int_0^\infty \Gamma(B_s^0(t) \rightarrow \mu^+\mu^-, A_{\Delta \Gamma}, y_s) \varepsilon(t) dt}{\int_0^\infty \Gamma(B_s^0(t) \rightarrow \mu^+\mu^-, A_{\Delta \Gamma}, y_s) dt} \cdot \frac{\int_0^\infty e^{-\Gamma MC t} \varepsilon(t) dt}{\int_0^\infty e^{-\Gamma MC t} \varepsilon(t) dt}$$

Correction for $B_s$: $4.50\pm0.03\%$

Correction for $B_d$: $1.48\pm0.01\%$

- BDT PDF also corrected because time dependent
$B_{(s)} \rightarrow \mu \mu$: UML fit (LHCb, 3/fb, blind)

![Graphs showing the results of the UML fit for different mass windows.]

- $B^0 \rightarrow h^+ h^-$
- $B^0_{(s)} \rightarrow \pi^- (K^-) \mu^+ \nu\mu$
- $B^{0(+)} \rightarrow \pi^{0(+)} \mu^+ \mu^-$

Full PDF

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$B_{(s)} \to \mu \mu$: UML fit (LHCb, 3/fb)

Full PDF
$B^0 \to \mu^+ \mu^-$
$B^0 \to \mu^+ \mu^-$
$B^0_{(s)} \to h^+ h^-$
$B^0_{(s)} \to \pi^- (K^-) \mu^+ \nu_\mu$
$B^0_{(s)} \to \pi^0 (\pi^-) \mu^+ \mu^-$

Candidates / (50 MeV/c²)

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

Candidates / (50 MeV/c²)

Candidates / (50 MeV/c²)

Candidates / (50 MeV/c²)
$B_{(s)} \rightarrow \mu\mu$ at CMS: discriminating variables

- Vertexing
  - primary vertex w/o the two muons
  - secondary vertex of the two muons
$B_{(S)} \rightarrow \mu\mu$ at CMS: isolation variables

- **Relative isolation of dimuon**
  
  \[ I = \frac{p_\perp(\mu^+\mu^-)}{p_\perp(\mu^+\mu^-) + \sum_{\Delta R < 1} p_\perp} \]

  - in cone around dimuon momentum
  - for tracks in cone with $\Delta R < 0.7$
    - with $p_\perp > 0.9$ GeV
    - either associated to same PV as candidate
    - or with $d_{ca} < 500$ $\mu$m
      ($d_{ca}$ = distance of closest approach)

- **Muon isolation**
  
  - $\Delta R < 0.5$, $p_\perp > 0.5$ GeV and $d_{ca} < 1$ mm

- **Number of tracks close to SV**
  
  - $p_\perp > 0.5$ GeV and $d_{ca} < 300$ $\mu$m

- **Closest track to SV**
  
  - $d_{ca}^0$
$B_{(s)} \rightarrow \mu\mu$ at CMS: MC vs data

- Comparison of sideband-subtracted distributions
  - in general good agreement

$B^0_s \rightarrow J/\psi \phi$

$B^\pm \rightarrow J/\psi K^\pm$

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$B_{(s)} \to \mu\mu$ at CMS: systematics

- Hadronization probability ratio $f_s/f_u$ from LHCb [JHEP 04, 001 (2013)]
  - additional 5% systematics for possible $p_\perp$ or $\eta$ dependence
  - in-situ studies show no $p_\perp$ dependence
  - ratio of $B^\pm \to J/\psi K^\mp$ vs $B_s^0 \to J/\psi \phi$

- Rare decays
  - hadron to muon misidentification probability
    $K_S^0 \to \pi^+\pi^-$, $\Lambda \to p\pi$, and $D^{*+} \to D^0(K^-\pi^+)^+\pi^+$
    50% uncertainty, treating pions/kaons/protons as uncorrelated
  - branching fraction uncertainties
  - $\Lambda_b \to p\mu\bar{\nu}$:
    large range of predictions in literature
    take average ($6.5 \times 10^{-4}$) and assign 100% uncertainty
    (note that invariant mass covers $B_s^0$ signal region)

- Normalization
  - 5% from yield fits
$B_{(s)} \rightarrow \mu \mu$: UML fit (CMS, 7 TeV and 8 TeV)
$B_{(s)} \rightarrow \mu \mu$: CMS result

[CMS, PRL 111(2013)101804]
**$B_{(s)} \to \mu \mu$: ATLAS analysis strategy**


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**BRANCHING RATIO**

- 2011 data used - 4.9 fb\(^{-1}\)
- signal region (± 300 MeV around $B_s$) blinded
- sideband events – 1/2 background interpolation, 1/2 selection optimization
- high statistics reference signal $B^\pm \to J/\psi (\to \mu^+ \mu^-) K^\pm$ minimizes syst. uncertainty

\[
BR (B_s \to \mu^+ \mu^-) = \frac{N_{B_s \to \mu^+ \mu^-}}{N_{ref}} \times \left( \frac{1}{N_{ref}} \right) \times BR(\text{ref}) \times \left( \frac{f_u/f_s}{f_{\text{PDG, LHC}}_B} \right) \times \left( \frac{\epsilon_{\text{tot}} A_{\text{tot}}}{\epsilon_{\text{tot}} A_{\text{tot, ref}}} \right)_{\text{Monte Carlo}}
\]

\[
\epsilon_{\text{tot}} A_{\text{tot}} = \frac{N_{\text{reconstructed and selected}}}{N_{\text{generated}}}
\]

- derived from simulation ("calibrated" on data)
- systematics taken from data-MC discrepancies in signal distributions
$B_{(s)} \rightarrow \mu \mu$: ATLAS analysis strategy

$\text{BR} (B_s \rightarrow \mu^+ \mu^-) = N_{B_s \rightarrow \mu^+ \mu^-} \times \left( \frac{1}{N_{\text{ref}}} \right)_{\text{DATA}} \times \text{BR} (\text{ref}) \times (f_u/f_s)_{\text{PDG, LHC}} \times \left( \frac{\varepsilon_{\text{tot}} \times A_{\text{tot}}}{\varepsilon_{\text{tot}} \times A_{\text{tot}}}_{\text{ref}} \right)_{\text{MONTE CARLO}} \times B_s \rightarrow \mu^+ \mu^-$

**Signal Extraction**

- $N_{B_s}$ – is a CLs limit derived from:
  - candidate count in the signal region
  - background estimation in the signal region
- $N_{\text{ref}}$ - unbinned maximum likelihood fit (same selection as for the signal)

**Background Composition**

- Resonant: $B \rightarrow hh' (K/\pi)$, fake-muon rates (MC) $\pi^\pm / K^+ / K^- \sim 2.1/4.1/3.3 \%$
- 0.3 $B \rightarrow hh'$ events expected in the signal region
- Continuum: non resonant $\bar{B}b \rightarrow \mu^+ \mu^- X$
- Smooth in dimuon mass
- Sideband interpolation (even-numbered events)
$B_{(s)} \rightarrow \mu\mu$: ATLAS background discrimination

$B_{(s)} \rightarrow \mu \mu$: ATLAS selection optimization


**OPTIMIZATION**

- for selection on:
  - $\Delta m =$ signal mass window width
  - $q =$ BDT output (event classifier)
  - odd-numbered sideband events and signal MC used
  - optimum = maximum of the Punzi estimator:
    \[ P(\Delta m, q) = \frac{\epsilon_{\text{sig}}}{1+N_{\text{bkg}}} \] (@95% CL)
  - $\epsilon_{\text{sig}}$ calculated directly on simulated signal events
  - $N_{\text{bkg}}$ in sig. region estimated by interpolation from sideband data
Search for Majorana neutrino (ATLAS)

A search for a heavy Majorana neutrino decaying into a $W$ boson and a muon has been performed using the ATLAS detector at the LHC. The search is performed using events with two same-sign muons, at least two jets and low missing transverse momentum. The data used in the search were collected in $pp$ collisions at $\sqrt{s} = 7$ TeV in 2011 and correspond to an integrated luminosity of 4.7 fb$^{-1}$. No excess of events above the background prediction is observed and 95% confidence level upper limits are set on the cross section times branching ratio for the production of heavy Majorana neutrinos. The observed limits range from 28 to 3.4 fb for heavy neutrino masses between 100 and 300 GeV.
Search for $B_{(s)} \rightarrow p\bar{p}$ (LHCb)

The results of a search for the rare two-body charmless baryonic decays $B^0 \rightarrow p\bar{p}$ and $B^0_s \rightarrow p\bar{p}$ are reported. The analysis uses a data sample, corresponding to an integrated luminosity of 0.9 fb$^{-1}$, of $pp$ collision data collected by the LHCb experiment at a centre-of-mass energy of 7 TeV. An excess of $B^0 \rightarrow p\bar{p}$ candidates with respect to background expectations is seen with a statistical significance of 3.3 standard deviations. This is the first evidence for a two-body charmless baryonic $B^0$ decay. No significant $B^0_s \rightarrow p\bar{p}$ signal is observed, leading to an improvement of three orders of magnitude over previous bounds. If the excess events are interpreted as signal, the 68.3% confidence level intervals on the branching fractions are

$$B(B^0 \rightarrow p\bar{p}) = (1.47 \pm 0.62 \pm 0.35) \times 10^{-8}$$

$$B(B^0_s \rightarrow p\bar{p}) = (2.84 \pm 2.03 \pm 0.85) \times 10^{-8}$$