Rare $B^0_{s,d}$ dileptonic decays at LHCb

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Flavour Changing Neutral Currents

Flavour Physics in Standard Model:

- no flavour transitions in the **leptonic sector**:

e	μ	τ
ν_e	ν_μ	ν_τ

(e.g. $\mu \not\rightarrow e\gamma$)

- **quark sector**:

u	c	t
d	s	b

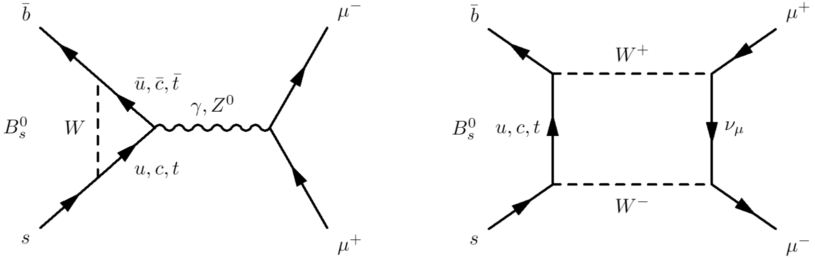
$$\mathcal{L}_{int}^{W-q} \sim g W_\mu^+ \overline{u} V_{CKM} \gamma_\mu d + h.c.$$

- flavour transitions at tree level occur only in the **charged currents**
- **no Flavour Changing Neutral Current** (FCNC) at tree level

$$\begin{array}{cccc} \left(q = \frac{2}{3}\right) & c & & t \\ & & \swarrow V_{ts} & \uparrow V_{bt} \\ \left(q = -\frac{1}{3}\right) & s & \not\leftarrow & b \end{array}$$

Flavour Changing Neutral Currents

Transitions involving Flavour Changing Neutral Current can proceed only through **loop processes** ("*penguin*" or "*box*" topologies):



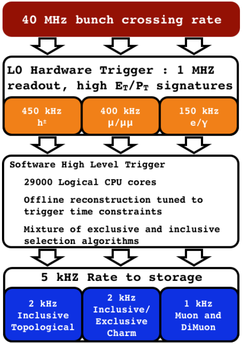
- NP particles, not easy to produce as observable states, could appear as **virtual states inside the loops** modifing the SM predictions concerning the rates (**indirect searches** of New Physics)
- What we need: very **precise theoretical predictions** to be compared with as **precise experimental measurements**
- $B^0_{s,d} \to \ell\bar{\ell}$:
  - Theory: only one hadronic input, additional SM suppression due to helicity
  - Experiment: purely leptonic (μ) final state

The LHCb detector - The L0 trigger

Few numbers:

LHCb bunch crossing frequency	40 MHz
Rate of visible interactions	10 MHz
Rate of $\overline{b}b$ production	100 KHz
Fraction of events with all decay products in detector acceptance	15 %
Interesting BRs ($\lesssim 10^{-3}$)	$\sim 10Hz$

In terms of data's volume we have that **40 MHz $\sim$ 40 Tb/s** ! $\Rightarrow$ we need a **very preliminary selection** to reduce the volume of data & select the potentially interesting events which will be carefully analyzed off-line



The LHCb detector - The L0 trigger

The Level0 Trigger system:

- hardware tool based on **custom made electronics**
- operates synchronously with the 40 MHz bunch crossing frequency
- exploits few characteristic properties of B mesons decay products: **very large transverse momentum p_T & energy E_T**
- reduces the rate of data acquisition from 40 MHz to 1 MHz

Three components

- **Pileup system**: reconstructs PV position along the beam axis & charged tracks multiplicity
- **Calorimeter trigger**: reconstructs the highest E_T hadron, e and γ
- **Muon trigger**: reconstruct the two highest p_T μs

These information are passed to the L0 Decision Unit which derives the final choice if retain or reject the event

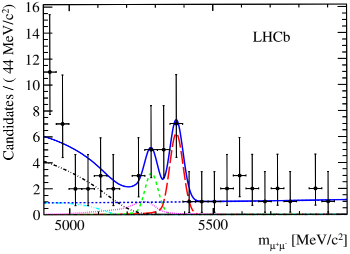
$B_{s,d} \to \mu^+\mu^-$

Theory predictions [Bobeth *et al.*, arXiv:1311.0903v1]:

$$BR_{SM}(B^0_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$
$$BR_{SM}(B^0_d \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

Experimental status:

- November '12: first evidence for $B^0_s \to \mu^+\mu^-$ (@ 3.5 σ - 2.1 fb^{-1}) [LHCb, PhysRevLett.110.021801]
- July '13: update of the analysis (3.1 fb^{-1}) [LHCb,PhysRevLett.110.101805]:
  - $BR(B^0_s \to \mu^+\mu^-) = 2.9^{+1.1}_{-1.0} \times 10^{-9}$ @ 4σ
  - $BR(B^0_d \to \mu^+\mu^-) = 3.7^{+2.4}_{-2.1} \times 10^{-10}$ @ 2σ

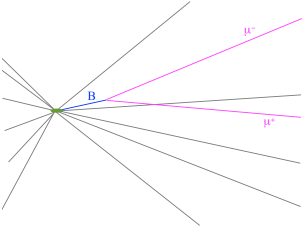


The selection

Counting experiment: we count the number of "signal-like" events in our data sample and then we convert this number into a BR.

Very efficient discrimination between:

Signal

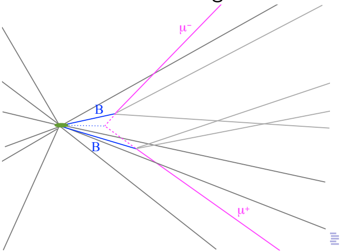


- good tracks with high impact parameter
- displaced secondary vertex with a good pointing
- good PID

Physical bkg: "true" B decays with one or more misidentified or non-reconstructed particles or decays in flight: $B^0_{s,d} \to K\pi$, $B^0 \to \pi\mu\nu$, ...

Can potentially "pollute" the B^0_d mass region but hardly the B^0_s region!

Combinatorial background

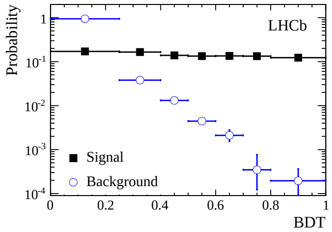


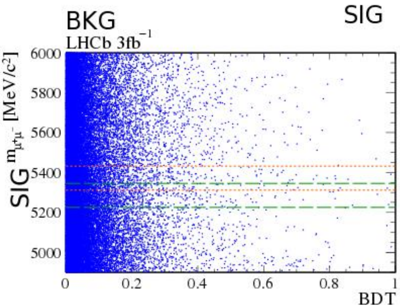
BDT classification

Too many background events ⇒ the invariant mass is not enough to discriminate between signal & background

We need other variables ⇒ a Boosted Decision Tree (BDT) with **12 input variables** encoding the topological & cinematical properties of the candidate

by design constant for MC signal and peaked at zero for background





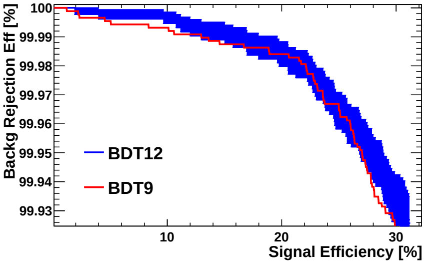
BDT output must be as much as possible **independent** of the invariant mass $m_{\mu^+\mu^-}$ of the dimuon system (especially for the bkg)

The BDT machine

Boosted Decision Tree performs a **chain of sequential cuts** on certain **input variables** in order to select/reject as much as possible signal/background events in a given dataset

BDT is a "*learning algorithm*":

- **trained** on sample of known composition (Monte Carlo generated dataset) to make him learning **how** to perform these cuts for signal/background-like classification of events
- **tested** as well on sample of known composition (MC) to **evaluate** its performances
- **applied** to a sample of unknown composition (*i.e.* our data sample)
- performances depends from **input variables** & **tuning parameters**



Performances evaluation:

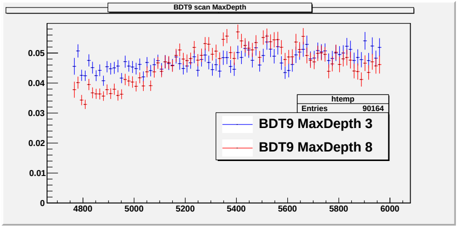
- Receiving Operating Curves (ROC): if we select x% of signal events (by cutting on BDT output) we reject $ROC(x)$ % of background events
- at a **fixed signal efficiency**, the better classifier is the one which gives the **highest background rejection**

BDT performances

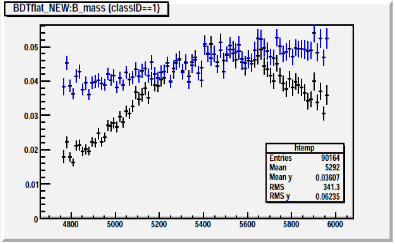
While optimizing the set of input variables & BDT tuning parameters we must take care of possible correlation with the di-muon system invariant mass **expecially** for background events

These two factors are correlated with each other

Effects of BDT tuning parameters



Effects of BDT input variables



(In figures: bias induced by BDT tuning parameter (MaxDepth) and the minimum transverse momentum of the two μ in a BDT with 13 input variables)

This kind of correlation could create a "false peak" under the signal region

$B_s^0 \to \tau^+\tau^-$

- In SM we have [Bobeth *et al.*, arXiv:1311.0903v1] :

$$BR_{SM}(B_s^0 \to \tau^+\tau^-) = (7.73 \pm 0.49) \times 10^{-7}$$
$$BR_{SM}(B_d^0 \to \tau^+\tau^-) = (2.22 \pm 0.04) \times 10^{-8}$$

- $B_s^0 \to \tau^+\tau^-$ a good candidate where do look for NP effects even if these are absents in other $B_{(s)}^0$ decays [Dighe *et al*, arXiv:1207.1324v2]:
  - respecting all the constraints on other B_s^0 decays it could be as large as 15%
  - in models with a flavour depending Z' coupling it could be up to 5%
  - in models with scalar Leptoquark it could be up to 0.3%

- Current status:
  - $BR(B_d^0 \to \tau^+\tau^-) < 4 \cdot 10^{-4}$ @ 90% CL by BaBar
  - $BR(B_s^0 \to \tau^+\tau^-)$ has **not yet been constrained**

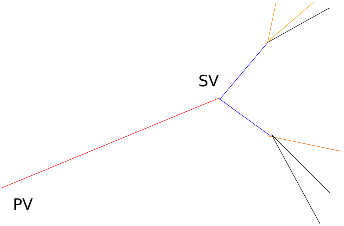
Challenging issues

τ particles have a very short lifetime $\Longrightarrow$ we must reconstruct them from their daughter particles

But...

- at least a neutrino for each τ decay (1 for semileptonic or 2 for leptonic channels) $\Rightarrow$ at least **2 unreconstructable neutrinos** (due to the detector geometry) and so...
- we cannot completely reconstruct the two τ momenta & invariant mass (not easy τ identification)
- we can rely only on a **partial mass reconstruction**

B_s
τ
ν
visible tracks (μ or π)



The "best" τ decays to look for this channel are

- $\tau \to 3\pi + \nu(+\pi^0)$
- $\tau \to \mu + \nu + \nu$ which has a higher trigger efficiency, but no reconstructable vertex

The $\tau \to 3\pi\ \nu$ channel

We have $BR(\tau \to 3\pi + \nu) \sim 10\%$

What we gain?

- we can reconstruct the 2 τ decays vertexes and, together with the Primary Vertex (PV), the **decay plane** $\Rightarrow$ **partially reconstruct the undetected neutrino's momenta**
- thanks to the decay chain $\tau^\pm \to a_1^\pm \nu \to \rho^0 \pi^\pm \nu \to \pi^+\pi^-\pi^\pm \nu$ we can improve the τ selection

The most "dangerous" background sources for this channels are

- $B_s \to D_s^{(\star)} D_s^{(\star)}$, $B_s \to D_s^{(\star)} \tau \nu_\tau$
- $B_d \to D^{(\star)} \tau \nu_\tau$, $B_d \to D^{(\star)} 3\pi$

where

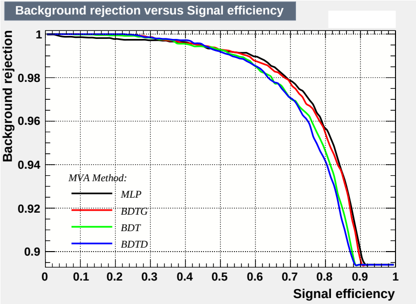
- $D_{(s)}^{(\star)}$ goes into 3 charged π & neutral particles
- $D_{(s)}^{(\star)}$ goes into $\tau\nu$

Work going on

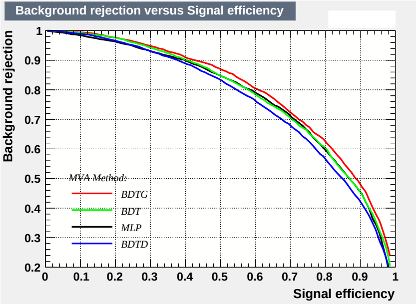
An analysis at its first stages: many possible strategies under study

- **BDT selection**
  - use of a first MVA classifier to discriminate against combinatorial background
  - refine the selection against physical background using a second BDT operator

BDT for $B_s^0 \to \tau^+\tau^-$ -like events selection



BDT for refined $B_s^0 \to \tau^+\tau^-$ selection



- A parallel approach, based on a topological reconstruction of the events (ZVTOP), is being explored

- A big effort is going on in order to try to (approximatively) solve the decay triangle and find out some good discriminating variable to fit: **analitical & numerical calculations**

Summary & Prospects

- Rare $B^0_{(s)}$ decays are very powerful tools to confirm the SM flavour structure & to look for hints of NP
- The measured value for $BR(B^0_s \rightarrow \mu^+\mu^-)$ is in agreement with its Standard Model prediction
- A complete re-analysis of the all 3.1 fb^{-1} dataset is going on to improve the $B^0_{(s)} \rightarrow \mu^+\mu^-$ analysis
- The study of the $B^0_{(s)} \rightarrow \tau^+\tau^-$ channel has only recently started and we aim to set a (non trivial) upper limit by summer 2014

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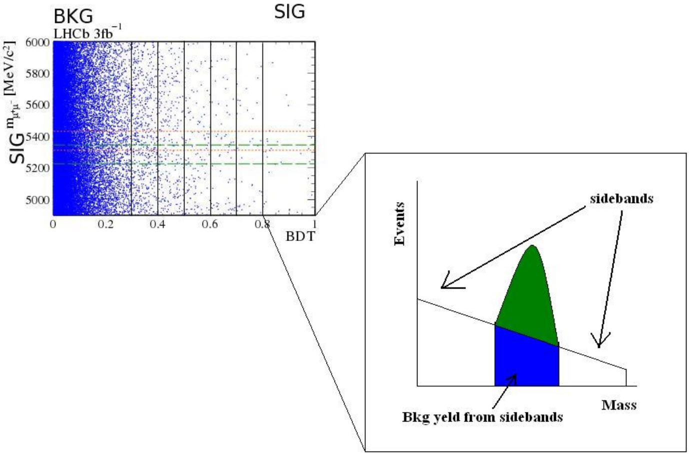
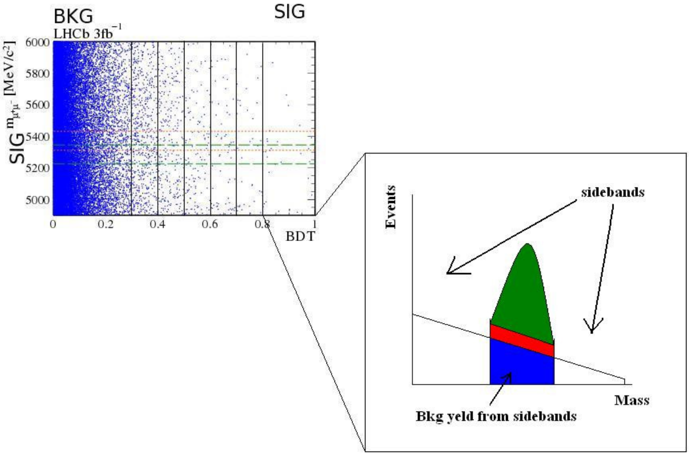
Thanks for your attention !

Backup

Effects of correlation between BDT and the 2μ invariant mass



Effects of correlation between BDT and the 2μ invariant mass



Theoretical introduction

Flavour structure of the Standard Model

The dynamics of the 12 elementary matter (fermionic) fields

$$\Psi_i = \{\underbrace{(\ell_i, \nu_i)_L, (\ell_i)_R}_{SU(3)_C\ singlets}\}_{(i=e,\mu,\tau)} \oplus \{\underbrace{(u_i, d_i)_L, (u_i)_R, (d_i)_R}_{SU(3)_C\ triplets}\}_{(i=u,c,t)}$$

is described by the $SU(2)_L \otimes U(1)_Y \otimes SU(3)_c$ gauge invariant lagrangian

$$\mathcal{L}_{SM} = \underbrace{-\frac{1}{4}F^A_{\mu\nu}F^{\mu\nu}_A + i\overline{\Psi}_i D_\mu \gamma^\mu \Psi_i}_{gauge} + \underbrace{\frac{1}{2}|D_\mu \phi|^2 - V(\phi)}_{Higgs} + \underbrace{Y_{ij}\overline{\Psi}^L_i \phi \Psi^R_j}_{Yukawa} + h.c.$$

where "$F^A_{\mu\nu}$" are the *field strengths* of the gauge connections "$\mathcal{A}_i = \gamma, Z^0, W^\pm, (g_i)_{i=1,2,\ldots,8}$", "$\phi$" is the Higgs field and $V(\phi) = -m\phi^2 + \lambda\phi^4$ is the Higgs field's potential.

The Electro-Weak $SU(2)_L \otimes U(1)_Y$ gauge symmetry is spontaneously broken by

$$\overline{\phi}_0 = \mathcal{V}$$

The "*Yukawa*'s coupling" generates the masses of the fermions and is responsable of the particular flavour structure of the SM.

Flavour Changing Neutral Currents
Two main features:

- no flavour transitions in the **leptonic sector**

- **quark sector**:
  - flavour transitions at tree level occur only in the **charged currents**:

$$\mathcal{L}_{int}^{W-q} \sim g W_{\mu}^{+} \overline{u} V_{CKM} \gamma_{\mu} d + h.c.$$

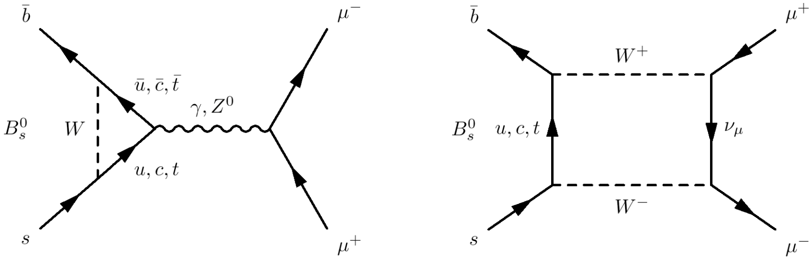
  - **no Flavour Changing Neutral Current** (FCNC) at tree level

e.g.

$$\begin{array}{cccc} \left(q = \frac{2}{3}\right) & c & & t \\ & & \swarrow V_{ts} & \uparrow V_{bt} \\ \left(q = -\frac{1}{3}\right) & s & \not\leftarrow & b \end{array}$$

Flavour Changing Neutral Currents

Transitions involving Flavour Changing Neutral Current can proceed only through **loop processes** ("*penguin*" or "*box*" topologies):



- Due to the presence of the loop, all processes involving such transitions are suppressed and thus **very rare**.
- Powerful tools to test SM predictions and to perform **indirect searches** of New Physics (NP)
- NP particles, not easy to produce as observable states, could appear as **virtual states inside the loops** modifing the SM predictions concerning the rates
- What we need: very **precise theoretical predictions** to be compared with as **precise experimental measurements**

$B^0_{s,d} \to \ell\bar{\ell}$

One of the "golden" channels is $B^0_{s,d} \to \ell\bar{\ell}$

"*Operator Product Expansion*" (OPE) approach:
we write down an effective hamiltonian $\mathcal{H}_{eff}$ separating the contributions coming from

- **low energy (long distance)** physics: local operator $\mathcal{O}_i$
- **high energy (short distance)** physics: Wilson coefficients C_i which are computed perturbatively

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V^{\star}_{ts} \sum_i C_i \cdot \mathcal{O}_i$$

For $B^0_s \to \ell\bar{\ell}$, the relevant operators are $\left(P_{L,R} = \frac{1 \pm \gamma^5}{2}\right)$:

$\mathcal{O}^{(\prime)}_{10}$	$(\bar{b}\gamma^{\mu} P_{L,(R)} s)(\bar{\ell}\gamma_{\mu}\gamma^5 \ell)$
$\mathcal{O}^{(\prime)}_{S}$	$(\bar{b} P_{L,(R)} s)(\bar{\ell}\ell)$
$\mathcal{O}^{(\prime)}_{P}$	$(\bar{b} P_{L,(R)} s)(\bar{\ell}\gamma^5 \ell)$

$$BR(B^0_s \to \bar{\ell}\ell) = \left(\frac{G_F^2 \alpha^2}{64\pi^3}\right) \cdot |V^{\star}_{tb} V_{ts}|^2 \cdot \tau_{B_s} \cdot f^2_{B_s} \cdot M^3_{B_s} \cdot \sqrt{1 - 4\frac{m^2_{\ell}}{M^2_{B_s}}}$$
$$\times \left\{ \left(1 - 4\frac{m^2_{\ell}}{M^2_{B_s}}\right) |C_S - C'_S|^2 + \left|(C_P - C'_P) + 2(C_{10} - C'_{10})\frac{m_{\ell}}{M_{B_s}}\right|^2 \right\}$$

$B^0_{s,d} \to \ell\bar{\ell}$ in SM

- In the SM $C^{(\prime)}_{S,P}, C'_{10} \simeq 0$ and the relevant operator is $\mathcal{O}_{10}$.

For the amplitude we have the following expression (**CP averaged at $t = 0$**)

$$BR_{SM}(B^0_q \to \bar{\ell}\ell) = \left(\frac{G_F^2\alpha_{em}^2}{16\pi^3 sin^4(\theta_W)}\right) \cdot |V^\star_{tb}V_{ts}|^2 \cdot f^2_{B_q} \cdot \tau_{B_q} \cdot M_{B_q} \cdot m^2_\ell \cdot \sqrt{1 - 4\frac{m^2_\ell}{M^2_{B_q}}} \cdot \mathcal{Y}^2\left(\frac{m_t^2}{M_W^2}\right)$$

Some comments:

- only one hadronic input
- loop suppression
- additional helicity suppression: $BR(B^0_q \to \bar{\ell}\ell) \to 0$ for $m_\ell \to 0$
- contribution from physics in the loop: dependence from the *top* quark mass

- In BSM scenarios we can have
  - $C^{(\prime)}_{S,P}, C'_{10} \neq 0$
  - a shift in the value of $C^{SM}_{10} \to C^{SM}_{10} + \delta C^{NP}_{10}$
  - **still** only one hadronic input

The "extra" contributions due to $C^{(\prime)}_{S,P} \neq 0$ are not helicity suppressed.

$B^0_{s,d} \to \ell\bar{\ell}$ SM predictions

- $B^0_{s,d} \to \mu^+\mu^-$:

$$BR_{SM}(B^0_s \to \mu^+\mu^-) = (3.23 \pm 0.27) \times 10^{-9}$$

[Eur.Phys.J. C72, 2172 (2012) - PhysRevLett.110.222003]

What we measure is the **time integrated BR** [PhysRevD.86.014027] :

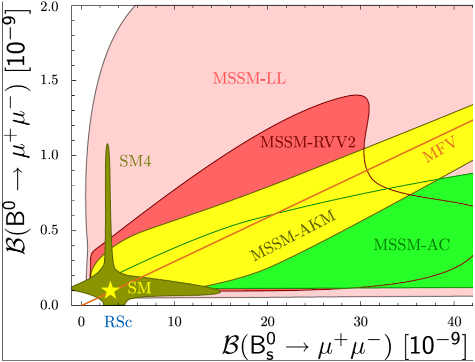
$$\langle BR_{SM}(B^0_s \to \mu^+\mu^-)\rangle = (3.56 \pm 0.29) \times 10^{-9}$$

$$BR_{SM}(B^0_d \to \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10}$$

- $B^0_s \to \tau^+\tau^-$: we have an enhancement due to the helicity suppression of a factor

$$\left(\frac{m_\tau}{m_\mu}\right)^2 \cdot \sqrt{\frac{M^2_{B_s} - 4m^2_\tau}{M^2_{B_s} - 4m^2_\mu}} \sim 210$$

Some possible scenarios before LHCb results

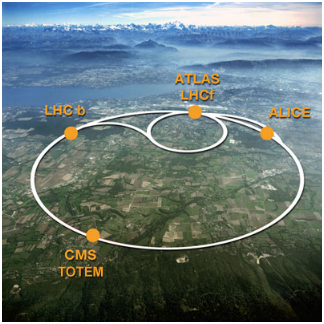


[Straub '12]

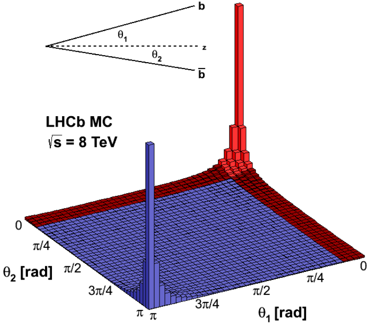
Experimental overview

B mesons production
B mesons are produced in $p-p$ collisions at the LHC.

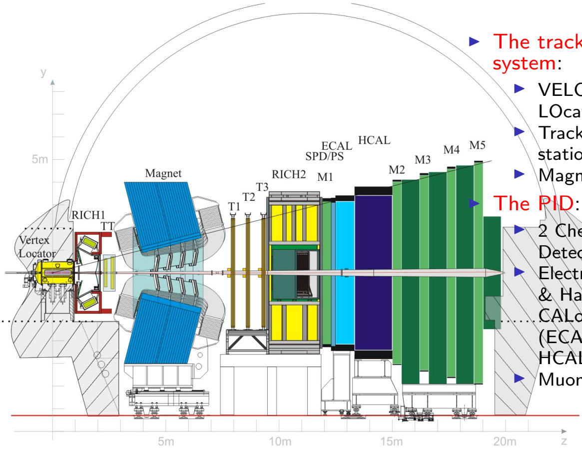
LHC ring



Angular distribution of $b-\overline{b}$ pair



LHCb detector A dedicated detector for the study of B decays is the LHCb detector
It is a **one arm spectrometer with a forward geometry**:
mainly a **track detector** together with a very good **Particle IDentification (PID)** system



- The tracking system:
  - VELO: VErtex LOcator
  - Tracking stations
  - Magnet
- The PID:
  - 2 Cherenkov Detector
  - Electromagnetic & Hadronic CALorimeter (ECAL & HCAL)
  - Muon chambers

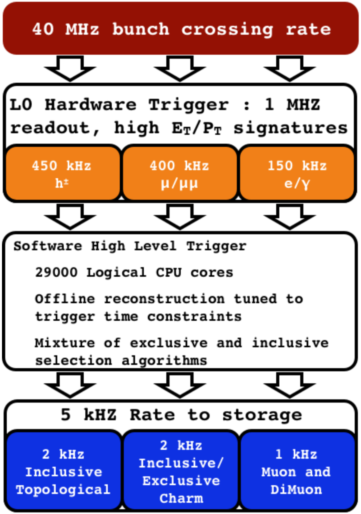
The LHCb trigger system

Inside the detector the two beams collide at a rate of 1 bunch crossing every 50 *ns* (25*ns* design).

The trigger selects relevant events through a chain of sequential decisions

- based on few properties of the tracks recorded by the detector
- obtained using hardware (Level-0) & software (High Level Trigger) information

Total efficiency on the $B_s \to \mu^+\mu^-$ signal $\sim$ 90%



$B_{s,d} \rightarrow \mu^+\mu^-$

The BR measurement To measure the BR we perform a "counting" experiment.

$$BR(B_q^0 \to \mu^+\mu^-) = \frac{N_{B_q^0 \to \mu^+\mu^-}}{N_{B_q}^{tot}}$$

We get the $N_{B_q}^{tot}$ using other normalization channels of known BR:

$$BR(B_q^0 \to \mu^+\mu^-) = \frac{BR_{norm}}{N_{norm}} \cdot \frac{\epsilon_{norm}}{\epsilon_{sig}} \cdot \frac{f_{norm}}{f_q} \cdot N_{B_q^0 \to \mu^+\mu^-}$$

"f_i": hadronization probability

Normalization channels chosen in order to have

- same trigger efficiency: $B^+ \to J/\psi K^+$
- same topology: $B^0 \to K\pi$

of our signal.

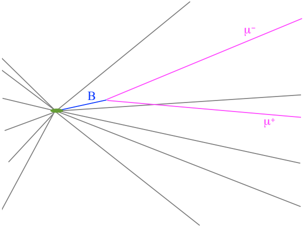
Expected number of signal events:

Data Set	2011 (7 TeV - 1.0 fb^{-1})	2012 (8 TeV - 1.1 fb^{-1})
$B_s^0 \to \mu^+\mu^-$	11	13
$B_d^0 \to \mu^+\mu^-$	1.3	1.5

The selection

In order to perform our measurement we need to discriminate in a very efficient way between

Signal

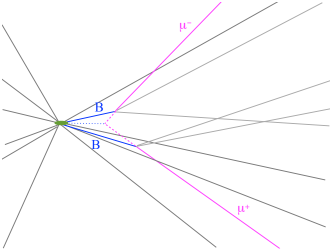


- good tracks with high impact parameter
- displaced secondary vertex with a good pointing
- good PID

Physical bkg: "true" B decays with one or more misidentified or non-reconstructed particles or decays in flight: $B^0_{s,d} \to K\pi$, $B^0 \to \pi\mu\nu$, ...

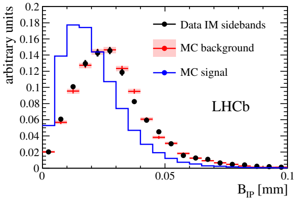
Can potentially "pollute" the B^0_d mass region but hardly the B^0_s region!

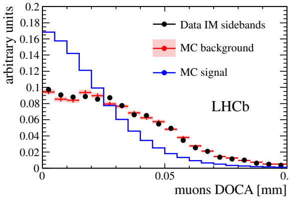
Background

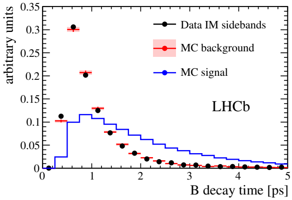


BDT classification

A Boosted Decision Tree (BDT) refines the selection. **9 input variables**

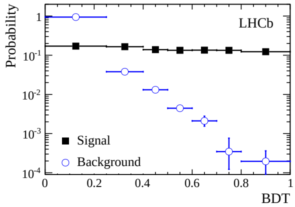






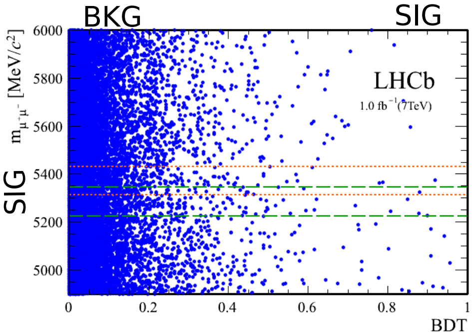
BDT combines in a unique variable the **topology & kinematics** information concerning the event.

- The BDT output is by design constant for MC signal and peaked at zero for background



- BDT output must be as much as possible **independent** of the invariant mass $m_{\mu^+\mu^-}$ of the dimuon system (especially for the bkg)

The Fit strategy We classify our events in a 2-dimensional plane in BDT & $m_{\mu^+\mu^-}$



We perform a blind analysis (all choices are done without looking at the signal region $[M_{B_d^0} - 60$ MeV , $M_{B_s^0} + 60$ MeV$])$

Number of signal events obtained performing an "Extended Maximum Likelihood" fit: the probability distribution is not constrained to 1 so it describes both the shape and the dimension of the sample

Results: the first evidence! [PhysRevLett.110.021801]

- No significative excess in $B_d^0 \to \mu^+\mu^-$ has been observed $\Rightarrow$ we set bounds on its value:

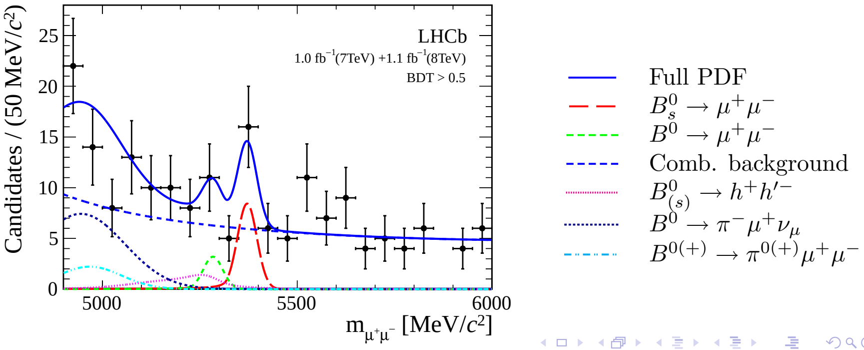
$$BR(B^0 \to \mu^+\mu^-) < 9.4 \cdot 10^{-10} \text{ @ } 95\%\ CL$$

- An excess wrt the bkg only expectation with a significance of 3.5σ is seen in the $B_s^0 \to \mu^+\mu^-$ channel:

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

while the bounds are:

$$1.1 \cdot 10^{-9} < BR(B_s^0 \to \mu^+\mu^-) < 6.4 \cdot 10^{-9} \text{ @ } 95\%\ CL$$



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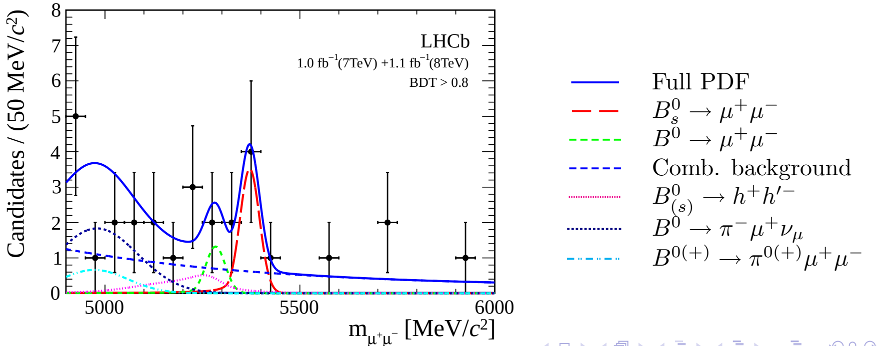
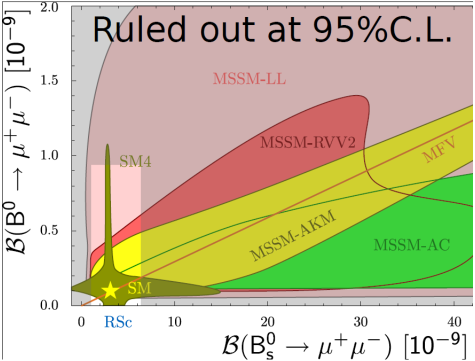


Results interpretation

The value found for $B_s \to \mu^+\mu^-$ is consistent with the time integrated BR in the SM hypothesis.

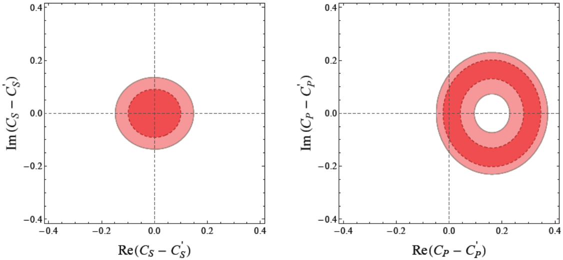


[Straub '12, update]

Results interpretation $B^0_{s,d} \to \ell\bar{\ell}$ constraints only $C_{S,P} - C'_{S,P}$ [arXiv:1306.0022v1]:

$$BR(B^0_s \to \bar{\ell}\ell) = \left(\frac{G_F^2\alpha^2}{64\pi^3}\right) \cdot |V^\star_{tb}V_{ts}|^2 \cdot \tau_{B_s} \cdot f^2_{B_s} \cdot M^3_{B_s} \cdot \sqrt{1 - 4\frac{m^2_\ell}{M^2_{B_s}}}$$
$$\times \left\{ \left(1 - 4\frac{m^2_\ell}{M^2_{B_s}}\right) |C_S - C'_S|^2 + \left| (C_P - C'_P) + 2(C_{10} - C'_{10})\frac{m_\ell}{M_{B_s}} \right|^2 \right\}$$

Allowed regions for $C_{S,P} - C'_{S,P}$ at 1σ & 2σ

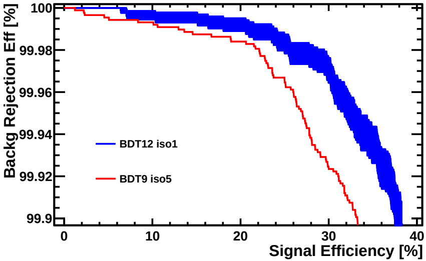


Other channels are needed to have **complementary information**, *e.g.* on $C_{S,P} + C'_{S,P}$: $B \to K^{(\star)}\mu^+\mu^-$ channel [PhysRevD.86.034034]

Work going on The update of the analysis with the all 2011+2012 ($3.1 fb^{-1}$) dataset is going on.

A big effort devoted to the improvement of the performances of the MVA classifier, studying:

- BDT input variables (looking also at the matching MC-Data)



- correlation of the BDT classifier's output with the dimuon invariant mass
  - effects of variables
  - classifier's parameters
- new algorithm (Neural Network)

$B_s^0 \to \tau^+\tau^-$

$B_s^0 \to \tau^+\tau^-$: motivations

No evidence of huge NP effects in $B_s \to \mu^+\mu^-$

Observable	Discrepancy wrt SM
$BR(B \to D(D^\star)\tau\nu)$	3.4σ
A_{SL}^b like-sign dimuon asymmetry	3.9σ

Presence of τ particles & constraints on many B^0 decay modes make $B_s^0 \to \tau^+\tau^-$ a good candidate where do look for NP effects [arXiv:1207.1324v2]:

- respecting all the constraints on other B_s^0 decays it could be as large as 15%
- in models with a flavour depending Z' coupling it could be up to 5%
- in models with scalar Leptoquark it could be up to 0.3%

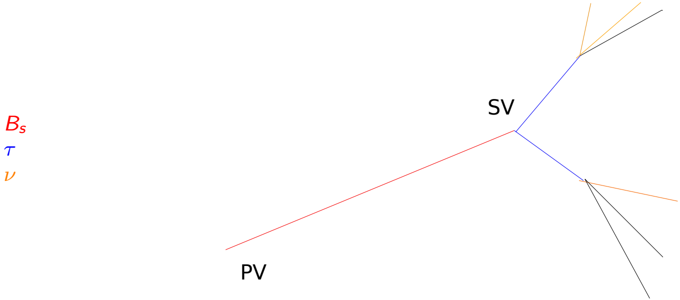
Current status:

- $BR(B_d^0 \to \tau^+\tau^-) < 4 \cdot 10^{-4}$ @ 90% CL by BaBar
- $BR(B_s^0 \to \tau^+\tau^-)$ has **not yet been constrained**

Challenging issues τ particles have a very short lifetime $\Longrightarrow$ we must reconstruct them from their daughter particles

But...

- at least a neutrino for each τ decay (1 for semileptonic or 2 for leptonic channels) $\Rightarrow$ at least **2 unreconstructable neutrinos** (due to the detector geometry) and so...
- we cannot completely reconstruct the two τ momenta, hence the $\tau^{\pm}$ invariant mass
- we can rely only on a **partial mass reconstruction**



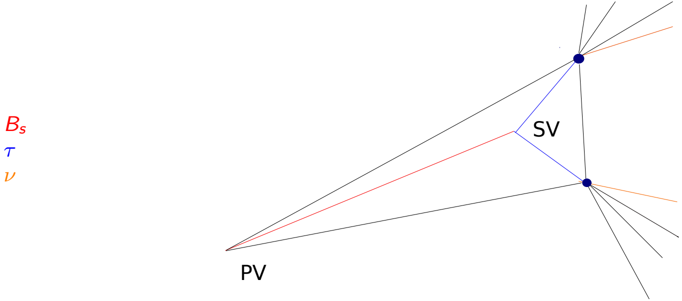
The "best" τ decays to look for this channel are

- $\tau \rightarrow 3\pi + \nu(+\pi^0)$
- $\tau \rightarrow \mu + \nu + \nu$ which has a higher trigger efficiency, but no reconstructable vertex

The $\tau \to 3\pi\ \nu$ channel
With this channel we can reconstruct the 2 τ decays vertexes and, together with the Primary Vertex (PV), the **decay plane**.

We have $BR(\tau \to 3\pi + \nu) \sim 10\%$

Knowing the decay plane we could manage to **partially reconstruct the undetected neutrino's momenta** $\Longrightarrow$ we can improve the partial mass reconstruction.



The most "dangerous" background sources for this channels are

- $B_s \to D_s^{(\star)} D_s^{(\star)}$: $BR_{eff} \sim 10^{-4}$
- $B_s \to D_s^{(\star)} \tau \nu_\tau$: $BR_{eff} \sim 10^{-5}$

Work going on

• We tried a **statistical reconstruction** of the B_s invariant mass but it's very sensitive to detection errors

• Other techniques are being explored, using other possible kinematics variables: software analyses & analitical calculations

• Ultimately we shall interpret LHCb data in terms of phenomenological constraints on SM & BSM models

Integrated BR [PhysRevD.86.014027]

- B_s^0 mesons are "affected" by the $B_s^0 - \overline{B}_s^0 \Longrightarrow$ sizable difference between decay widths of heavier lightest mass eigenstate, parametrized by

$$y_s \equiv \frac{\Gamma_H - \Gamma_L}{\Gamma_H + \Gamma_L} = 0.061 \pm 0.006$$

HFAG average measured experimentally looking at $B_s^0 \to J/\psi\phi$

- untagged BR

$$\langle \Gamma(B_s(t) \to f) \rangle \equiv \Gamma(B_s(t) \to f) + \Gamma(\overline{B}_s(t) \to f) = R_H^f e^{-\Gamma_H t} + R_H^f e^{-\Gamma_H t}$$

$$= (R_H + R_L)\, e^{-\Gamma t} \times [\cosh(y_s \Gamma t) + \mathcal{A}_{\Delta\Gamma} \cdot \sinh(y_s \Gamma t)]$$

with $\mathcal{A}_{\Delta\Gamma} \equiv \frac{R_H - R_L}{R_H + R_L}$

- the "experimental" BR

$$BR(B_s \to f)_{exp} \equiv \frac{1}{2} \int_0^\infty \langle \Gamma(B_s(t) \to f) \rangle dt = \frac{(R_H + R_L)}{2\Gamma} \times \left[\frac{1 + \mathcal{A}_{\Delta\Gamma} \cdot y_s}{1 - y_s^2} \right]$$

- the relation is

$$BR(B_s \to f)_{theo} = \left[\frac{1 - y_s^2}{1 + \mathcal{A}_{\Delta\Gamma} \cdot y_s} \right] \cdot BR(B_s \to f)_{exp}$$

Particles properties

	M (MeV)	τ (s)
B_s^0	5366	1.518×10^{-12}
B_d^0	5279	1.525×10^{-12}
$\tau^{\pm}$	1776	290×10^{-15}
$\mu^{\pm}$	105	2.19×10^{-6}
f_{B_s}	227 MeV	
y_s	0.0613	$\pm$ 0.0059

$\tau \longrightarrow 3\pi + \nu$ decay chain

$$\tau \longrightarrow a_1 \ + \ \nu$$

$$a_1 \longrightarrow \rho \ + \ \pi$$

$$\rho \longrightarrow 2\pi$$

μ trigger line

- one μ:
  - L0: $P_T(\mu) > 1.76\ GeV$
  - HLT: cut on Impact Parameter (IP)
- two μ:
  - L0: $\sqrt{P_{T,1} \cdot P_{T,2}} > 1.6\ GeV$
  - HLT: IP & mass cut

Hadronization fraction $\frac{f_s}{f_d}$ is measured experimentally comparing the abundances of

- $B_s^0 \to D_s^- \pi^+$ wrt $B^0 \to D^- K^+$ & $B^0 \to D^- \pi^+$ [PRD85 032008 (2012)]
- $B_s^0 \to D_s^- \mu^+ X$ wrt $B_s^0 \to D_s^- \mu^+ X$ [LHCb-paper-2012-037 in preparation]

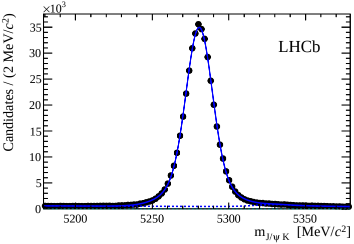
At 7 TeV we have $\frac{f_s}{f_d} = 0.256 \pm 0.020$

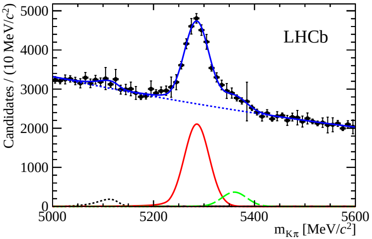
Normalisation channels

$$BR(B_q^0 \to \mu^+\mu^-) = \underbrace{\frac{BR_{norm}}{N_{norm}} \cdot \frac{\epsilon_{norm}^{SEL}\epsilon_{norm}^{SEL,REC}}{\epsilon_{sig}^{SEL}\epsilon_{sig}^{SEL,REC}} \cdot \frac{\epsilon_{norm}^{TRIG}}{\epsilon_{sig}^{TRIG}} \cdot \frac{f_{norm}}{f_q}}_{\alpha_{norm}} \cdot N_{B_q^0 \to \mu^+\mu^-}$$

- extracted from data
- evaluated on MC & cross-checked on data
- measured from data
- ratio of probabilities that a b quark hadronizes with a q and a u & d quark

Normalisation channels





Using the measured value of $\frac{f_s}{f_d}$ & the averaged value of the two channels we get

$$\alpha_{B_s^0 \to \mu\mu} = (2.80 \pm 0.25) \times 10^{-10}$$

$$\alpha_{B_s^0 \to \mu\mu} = (7.16 \pm 0.34) \times 10^{-11}$$

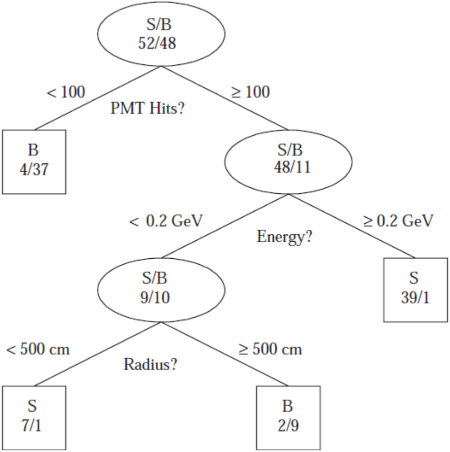
Exclusive bkg

Channels & yelds in the [4900-6000] MeV, in $BDT > 0.8$ bins

channel	2011	2012
$B^0 \to \pi\mu\nu$	3.51 ± 0.25	4.04 ± 0.28
$B^0_{s,d} \to hh'$ misID	0.91 ± 0.12	1.37 ± 0.11
$B^{0,+} \to \pi^{0,+}\mu\mu$	1.12 ± 0.35	1.32 ± 0.39
$\Lambda^0_b \to p\mu^-\nu$	0.29 ± 0.17	0.50 ± 0.29
$B^0_s \to K^-\mu^+\nu_\mu$	0.33 ± 0.13	0.46 ± 0.19
$B^+_c \to J/\psi(\mu\mu)\mu^+\nu_\mu$	0.29 ± 0.33	0.34 ± 0.39

- negligible
- accounted in the analysis

BDT


S/B
52/48
< 100
≥ 100
PMT Hits?
B
4/37
S/B
48/11
< 0.2 GeV
≥ 0.2 GeV
Energy?
S/B
9/10
S
39/1
< 500 cm
≥ 500 cm
Radius?
S
7/1
B
2/9

BDT Standard variables

For the B:

- Proper times
- Impact parameter
- Transverse momentumn
- B isolation

For the 2 μ

- Distance Of Closest Approach (DOCA)
- Minimum IP significance
- Min$(P_T(\mu^+), P_T(\mu^-))$
- Isolation of the 2 μ
- Polarization angle

BDT variables

- "B isolation": CDF definition [arXiv:0508036]

$$I_{CDF} = \frac{p_T(B)}{p_T(B) + \sum_{tracks} p_T(tracks)}$$

where the sum run over the *long* tracks, excluding the muon candidates, which satify $\sqrt{\delta\eta^2 + \delta\phi^2} < 1$, where $\delta\eta$ & $\delta\phi$ are the differences in pseudorapidity & polar angle between the track and the B candidate.

- "polarization angle": is the cos of the angle between the direction of the muon in the B_s^0 rest frame and the normal to the plane containing the B_s^0 momentum and the beam axis

BDT variables

- "other B angle": angle between the B candidate's momentum and the trust momentum of the B, defined as the sum of momenta of all the long tracks coming from the B PV and excluding those coming from long lived particles. If no such tracks is set to 0
- "angle wrt p_T": angle between the direction of the positive muon candidate in the rest frame of the B and the trust momentum in the B rest frame
- "$|\Delta\eta|$": absolute value of the difference between the pseudorapidity of the two muon candidates
- "$|\Delta\phi|$": absolute value of the difference between the sferical ϕ coordinate of the two muon candidates

Fit procedure

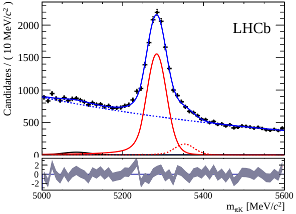
$$
\begin{aligned}
\mathcal{F}(BDT, M) =& N_{tot} \cdot p(BDT, M) = N_s \cdot f_s(BDT, M) + N_d \cdot f_d(BDT, M) + \\
& N_{ex} \cdot f_{ex}(BDT, M) + N_{comb} \cdot f_{comb}(BDT, M)
\end{aligned}
$$

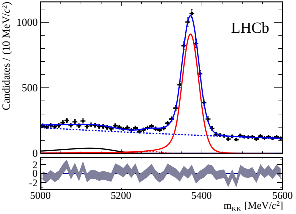
where N_i & $f_i(BDT, M)$ are respectively the number of events & the pdf for the various categories of events:

- s: $B_s^0 \to \mu^+\mu^-$
- d: $B_d^0 \to \mu^+\mu^-$
- ex: exclusive bkg
- comb: combinatorial bkg

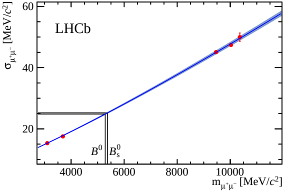
Signal pdf • BDT pdf calibrated on data $B \rightarrow hh$

- Mass pdf: Cristal ball
  - Mean is extracted from
    - $B^0 \rightarrow \pi\pi, K\pi \Longrightarrow m_{B^0} = 5284.36 \pm 0.29\ MeV$
    - $B_s^0 \rightarrow KK \Longrightarrow m_{B_s^0} = 5371.55 \pm 0.44\ MeV$





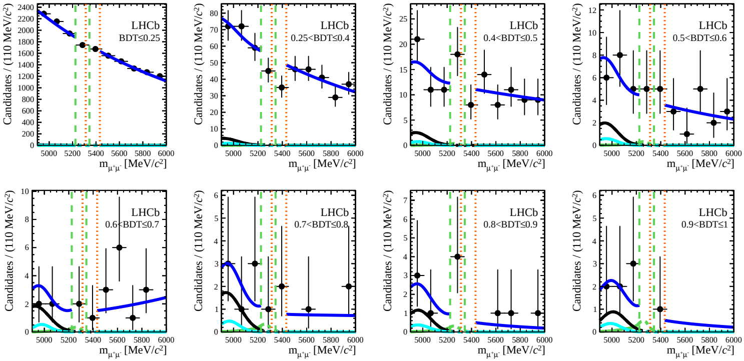
  - Resolution
    - $B^0 \rightarrow \pi\pi, K\pi \Longrightarrow$ $\sigma_{B^0} = 24.63 \pm 0.38\ MeV$
    - $B_s^0 \rightarrow KK \Longrightarrow$ $\sigma_{B_s^0} = 25.05 \pm 0.40\ MeV$



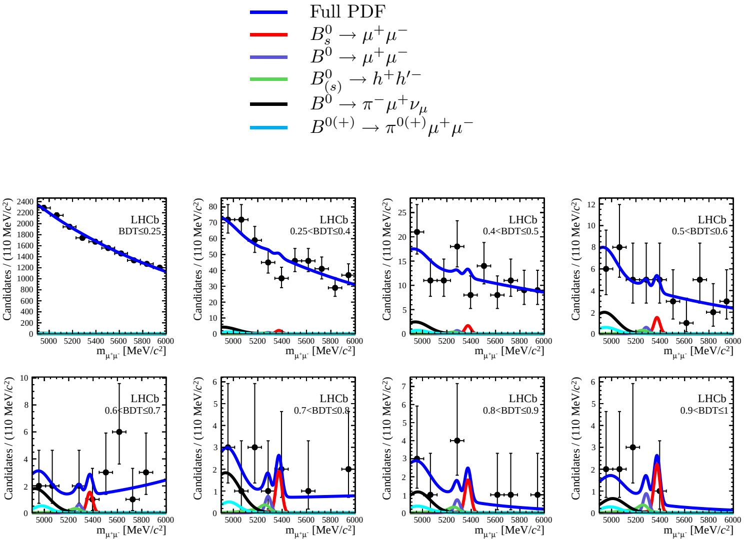
  - The two modes are resolved

Bkg pdf

- Combinatorial: extrapolation from the data sidebands with an exponential
- Exclusive:
  - derive the misID probability $\pi, K \to \mu$ from data in bins of p & p_T
  - apply these probabilities to large MC samples
  - extract the mass & BDT probabilities from this weighted MC sample
  - normalize to $B^+ \to J/\psi K^+$

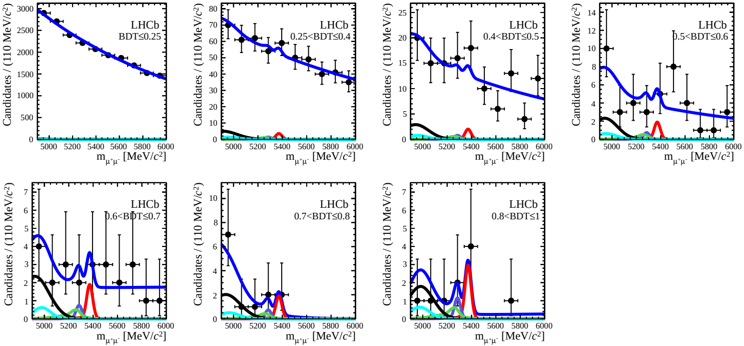


Fit results - 2011



Fit results - 2012

- Full PDF
- $B_s^0 \to \mu^+\mu^-$
- $B^0 \to \mu^+\mu^-$
- $B_{(s)}^0 \to h^+h'^-$
- $B^0 \to \pi^-\mu^+\nu_\mu$
- $B^{0(+)} \to \pi^{0(+)}\mu^+\mu^-$

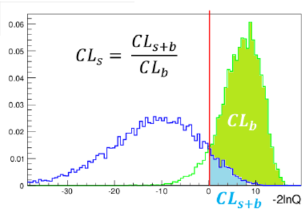


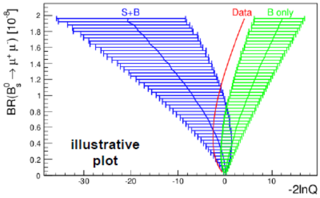
The CL_s method

- bin the signal region in both BDT & M variables (after optimizzation of the binning [LHCb-INT-2012-003])
- define a scale where we can classify experiments from the most bkg-like one to the most sig-plus-bkg like one:

$$\mathcal{Q} = \prod \frac{\mathcal{P}(d_i, s_i + b_i)}{\mathcal{P}(d_i, b_i)}$$

  $\mathcal{P}(d_i, s_i + b_i)$: probability that the expected number of sig+bkg has fluctuated to d_i according to a poissonian distribution
- the scale is calibrated for a range of $BR(B_s^0 \to \mu^+\mu^-)$: two sets of ∼10k pseudo experiments
  - data are only bkg
  - data are sig+bkg in the particular BR hypothesis
- for each BR hypothesis we have a distribution in $\mathcal{Q}$ for the generated experiments
- for each BR hypothesis compute the $\mathcal{Q}$ of our data and the distance between the bkg only hyp & bkg-plus-sig hyp with CL_b & CL_{s+b}

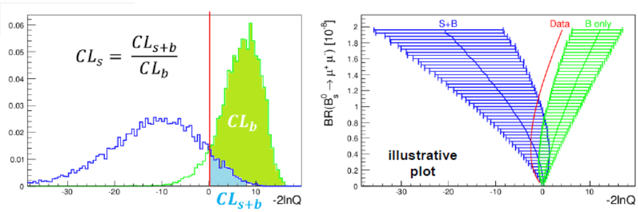




The CL_s method

- compute the compatibility of our data with the bkg-plus-sig hyp with

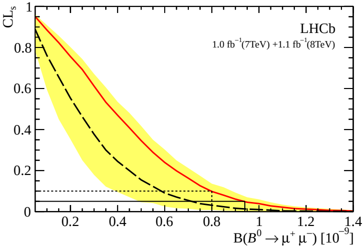
$$CL_s = \frac{CL_{s+b}}{CL_b}$$



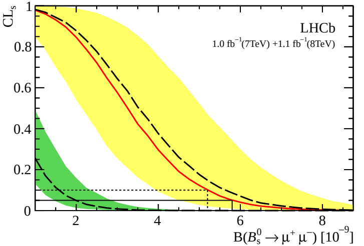
- exclude at the 90% (95%) all the value of BR for which the CL_s is greater than 0.05 (0.1) (upper limit)
- the upper limit is the value for which the data test statistic is getting too close to the sig-plus-bkg test statistic distribution

The CL_s method

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



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



Loop function $\mathcal{Y}$

$$Y(x_t) = Y_0(x_t) + \frac{\alpha_s}{4\pi} Y_1(x_t)$$

with the one-loop function given by [45]

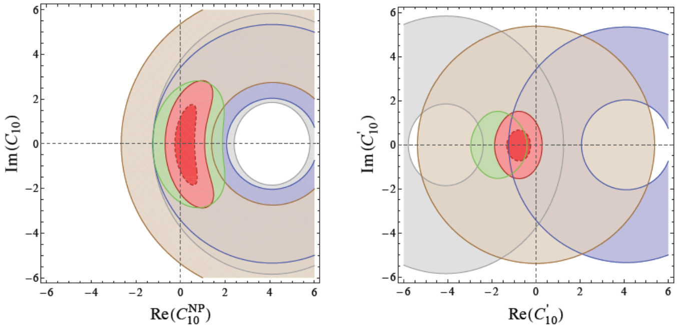
$$Y_0(x_t) = \frac{x_t}{8}\left[\frac{4-x_t}{1-x_t} + \frac{3x_t}{(1-x_t)^2}\ln x_t\right]$$

and

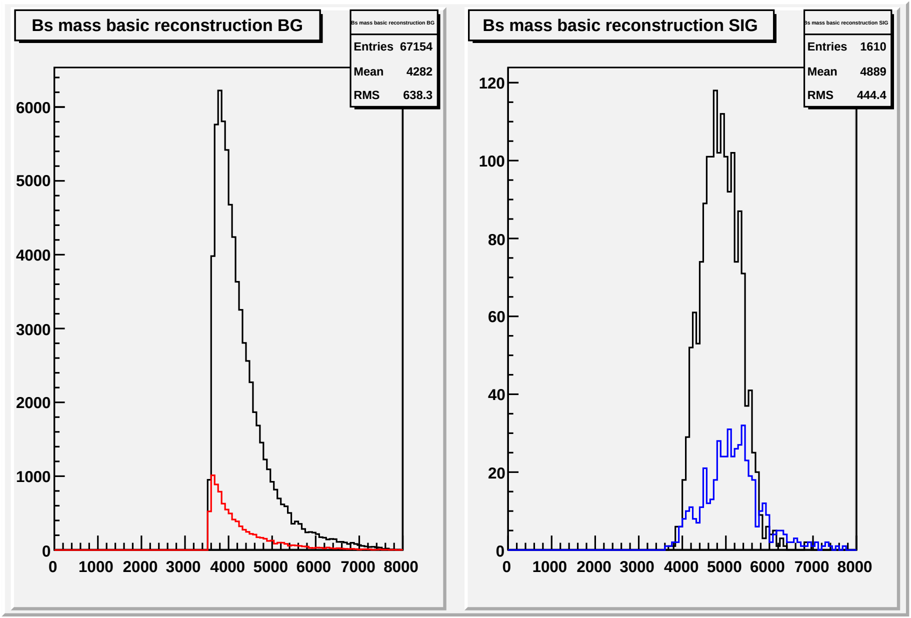
$$\begin{aligned} Y_1(x_t) = \quad & \frac{4x_t + 16x_t^2 + 4x_t^3}{3(1-x_t)^2} - \frac{4x_t - 10x_t^2 - x_t^3 - x_t^4}{(1-x_t)^3}\ln x_t \\ + \quad & \frac{2x_t - 14x_t^2 + x_t^3 - x_t^4}{2(1-x_t)^3}\ln^2 x_t + \frac{2x_t + x_t^3}{(1-x_t)^2} L_2(1-x_t) \\ + \quad & 8x\frac{\partial Y_0(x)}{\partial x}\ln\frac{\mu_t^2}{M_{\mathrm{W}}^2} \end{aligned}$$

Constraints combination [arXiv:1306.0022v1]

$B \to X_s\bar{\ell}\ell$, $B \to K^\star\mu^+\mu^-$, $B \to K\mu^+\mu^-$, $B_s \to \mu^+\mu^-$, combination



Di-τ statistical invariant mass reconstruction



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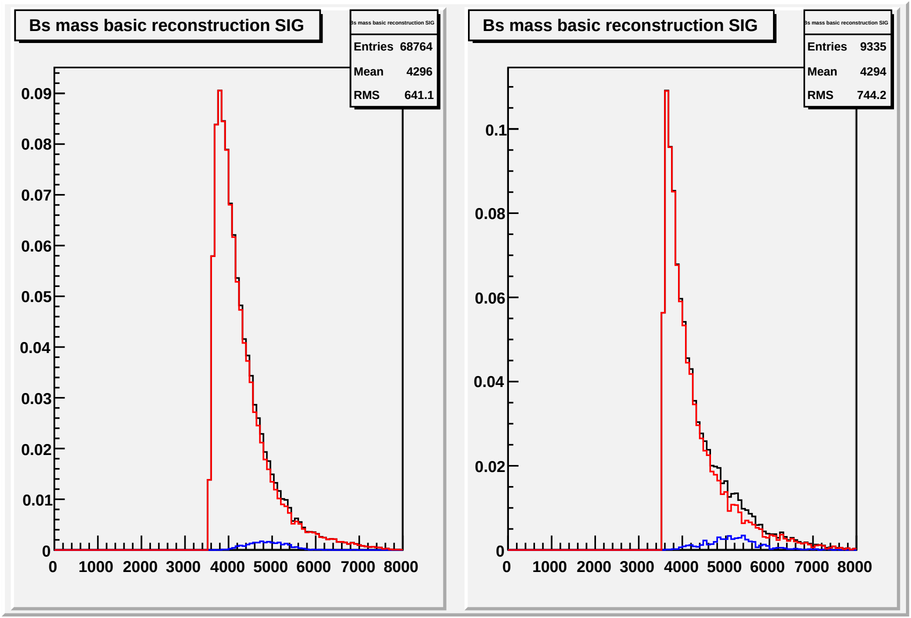

τ's decay products distribution What we know:

- $(3\pi)^+ + (3\pi)^-$ momenta
- τs decay vertexes

What can we reconstruct:

- B_s's PV, and so
- decay plane fixed by (B_s's PV, τ^+'s DV, τ^-'s DV), and so
- orthogonal component with respect the decay plane of the two undetected neutrinos

What kind of constraints can we impose:

- "internal" constraints: m_π, m_τ
- "external constraints": decay triangle
- for this pourpouse also the "internal" constraint m_{B_s} (since we are not using that to reconstruct others quantities related with the decay, *e.g.* the B_s's decay vertex or the neutrinos momentum)

Differential decay rate With the helicity formalism we compute

$$\frac{d\Gamma}{\Gamma d\cos\theta_+ d\cos\theta_- d\phi}$$

where

- $\theta_\pm$ is the polar angle of the $(3\pi)^{(\pm)}$ system in the respective $\tau^\pm$ rest frame
- ϕ is the angle between the two decay plane of τ's daughter particle in the B_s rest frame

This angular distribution is referred to different frames (the B_s, and the τ's rest frames)
We need to boost this distribution in the lab frame

Differential decay rate in the lab frame How to boost: relativistic transformation of the energy:

$$E_{\pm} = \gamma_{\pm} E^{\star}_{\pm}(1 + \beta_{\pm}\beta^{\star}_{a_{1\pm}} \cos\theta_{\pm})$$

where:

- $E_{\pm}$ is the energy of the $a_1^{\pm}$ system in the lab (which is measured)
- $E^{\star}_{\pm}$ is the energy of the $a_1^{\pm}$ system in the $\tau^{\pm}$ rest frames (which is known assuming a 2 body decay)
- $\beta^{\star}_{a_{1\pm}}$ is the β of the $a_1^{\pm}$ system in the $\tau^{\pm}$ rest frame, that is $\beta^{\star}_{a_1^{\pm}} = \frac{p^{\star}_{a_{1\pm}}}{E^{\star}_{\pm}}$
- $\gamma_{\pm}$ is the $\tau_{\pm}$ boost with respect to the lab frame (which is unknown)

The non-trivial angular distribution of τs daughters in τs rest frame translates into a non trivial energy distribution in the lab frame.
Actually, thanks to the conservation laws that constraint $\gamma_{\pm}$, we need to know only one τ's boost, *e.g.* γ_+ *and the* B_s *boost* γ_{B_s}.

So we obtain

$$\frac{d\Gamma}{\Gamma d\cos\theta_+ d\cos\theta_- d\phi} \longrightarrow \frac{d\Gamma}{\Gamma dE_+ dE_- d\phi}(\gamma_+, \gamma_{B_s})$$

Since we don't know γ_+ and γ_{B_s} we have to integrate that differential distribution over all the possible boosts weighting every boost with proper functions $g(\gamma_+)$ and $G(\gamma_{B_s})$ [see *e.g.* arXiv:1209.0772v1]:

$$\frac{d\Gamma}{\Gamma dE_+ dE_- d\phi}|_{tot} = \int d\gamma_{B_s} G(\gamma_{B_s}) \int d\gamma_+ g(\gamma_+) \frac{d\Gamma}{\Gamma dE_+ dE_- d\phi}(\gamma_+, \gamma_{B_s})$$

What about $g(\gamma_+)$ and $G(\gamma_{B_s})$?

- $g(\gamma_+)$: being a function of the energy of the daughter particles of a spin 0 mother particles it's, for fixed mother particle's boost γ_{B_s}, constant in the interval $[\gamma_{B_s} E^\star_\tau (1-\beta^\star_\tau), \gamma_{B_s} E^\star_\tau (1+\beta^\star_\tau)]$
- $G(\gamma_{B_s})$: depends from several factors (*e.g.* how it is produced...) and it could be extracted or from MC simulation, or measured experimentally from others channels (Mathieu's suggestion)

Since we will integrate imposing some constraints we expect to obtain a non trivial distribution, already if we impose only the "internal" constraints