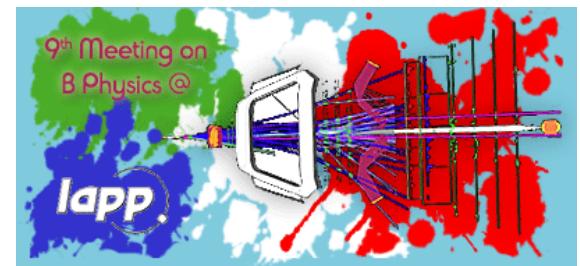


Experimental report on

$$B^0 \rightarrow K^* \mu^+ \mu^- \text{ and}$$
$$B_s^0 \rightarrow \mu^+ \mu^-$$

Mathieu Perrin-Terrin*

9th Franco-Italian B-Physics Workshop
Monday, February 18th 2012,
LAPP, Annecy France



*CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France

Outlines

- Motivations for $B^0 \rightarrow K^* \mu^+ \mu^-$
- The LHCb analysis
- Motivations for $B_s^0 \rightarrow \mu^+ \mu^-$
- Experimental Status
- The LHCb Analysis
- Toward a precision measurement

Motivations for $B^0 \rightarrow K^* \mu^+ \mu^-$

Probing New Physics With $B^0 \rightarrow K^* \mu^+ \mu^-$

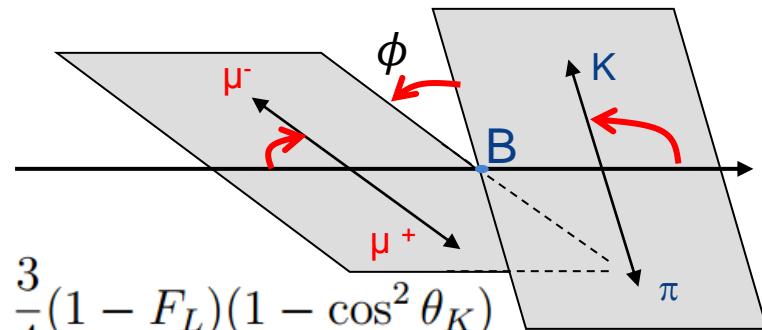
- Flavour Changing Neutral Current
- Access to $C_7^{(\prime)}$, $C_9^{(\prime)}$, $C_{10}^{(\prime)}$ via angular and q^2 differential B measurement
- Decay described by $q^2, \theta_\ell, \theta_K, \phi$

$$\frac{1}{\Gamma} \frac{d^4\Gamma}{d \cos \theta_\ell d \cos \theta_K d\hat{\phi} dq^2} = \frac{9}{16\pi} \left[F_L \cos^2 \theta_K + \frac{3}{4}(1 - F_L)(1 - \cos^2 \theta_K) \right.$$

$$F_L \cos^2 \theta_K (2 \cos^2 \theta_\ell - 1) +$$

$$\frac{1}{4}(1 - F_L)(1 - \cos^2 \theta_K)(2 \cos^2 \theta_\ell - 1) +$$

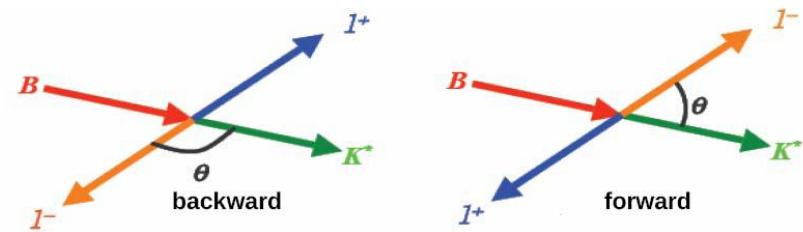
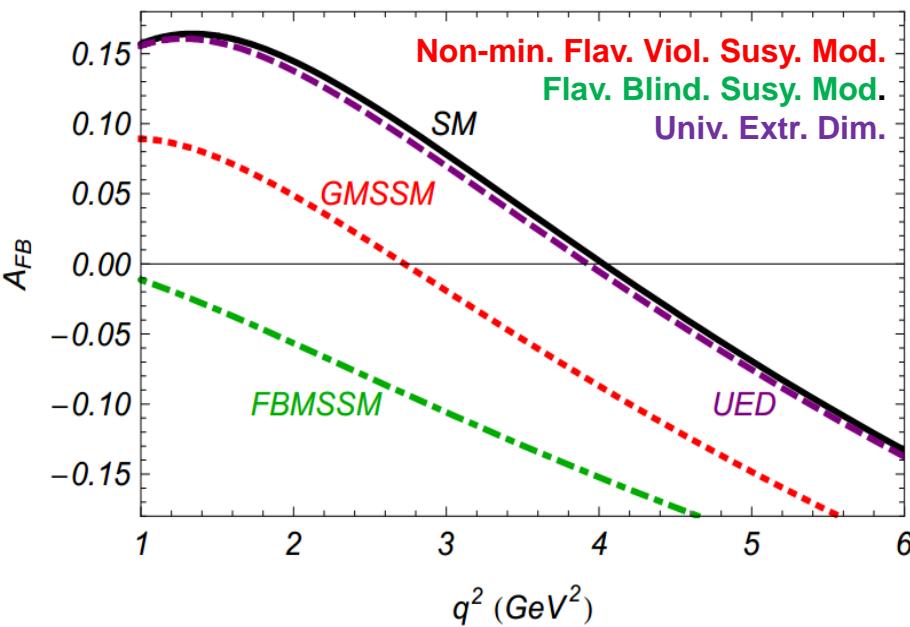
$$\left. \begin{aligned} & S_3 (1 - \cos^2 \theta_K)(1 - \cos^2 \theta_\ell) \cos 2\hat{\phi} + \\ & \frac{4}{3} A_{FB} (1 - \cos^2 \theta_K) \cos \theta_\ell + \\ & A_{Im} (1 - \cos^2 \theta_K)(1 - \cos^2 \theta_\ell) \sin 2\hat{\phi} \end{aligned} \right]$$



Angular Observables sensitive to NP

- Forward Backward Asym. of θ_l distribution:

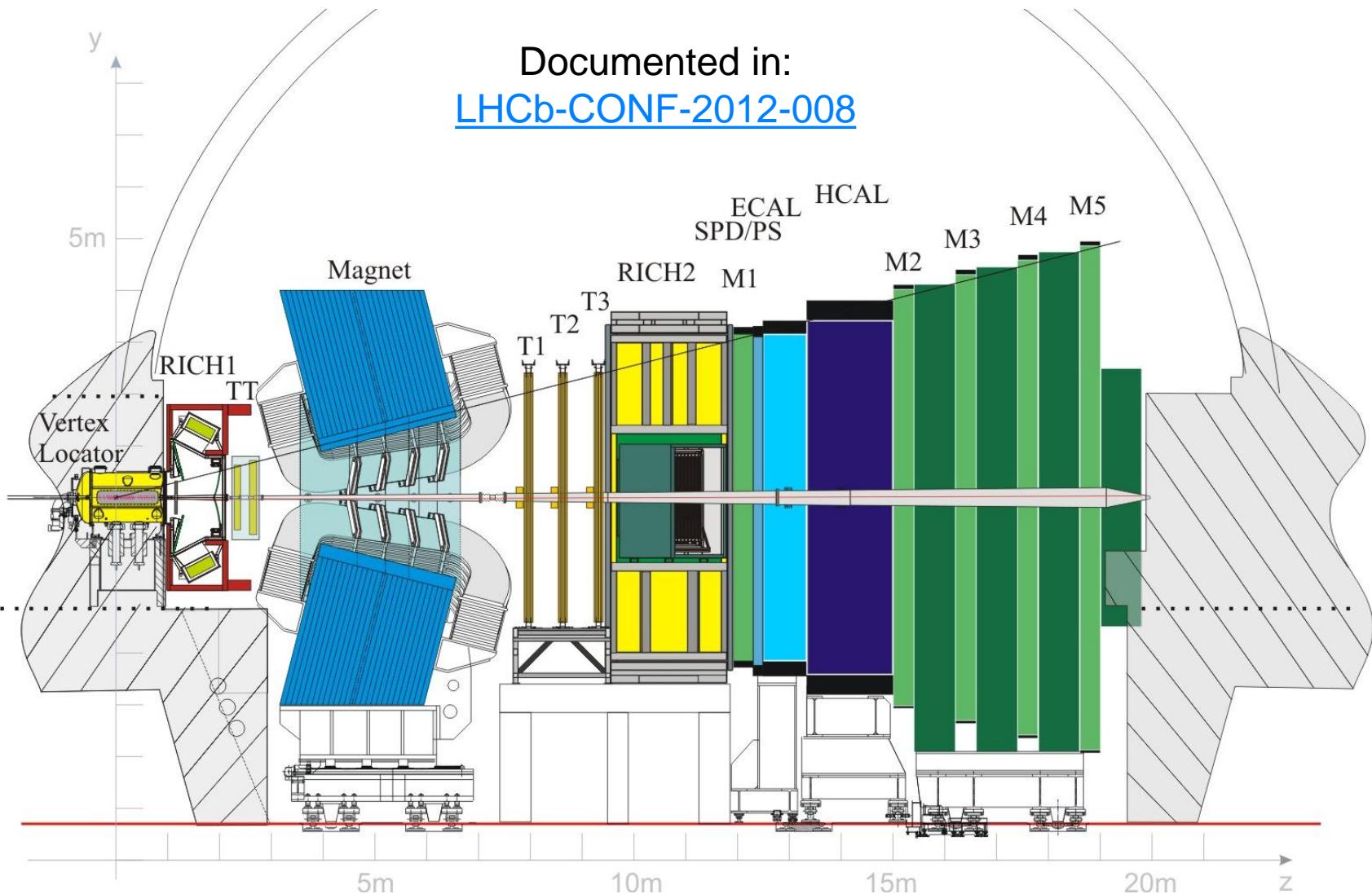
$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$



Zero Crossing Point well predicted

$B^0 \rightarrow K^* \mu^+ \mu^-$ at LHCb

Documented in:
[LHCb-CONF-2012-008](#)



Analysis Overview

- **Data Sample**

1fb^{-1} of pp collisions at 7TeV

900 ± 34 signal events*

- **Selection**

increase **signal purity**

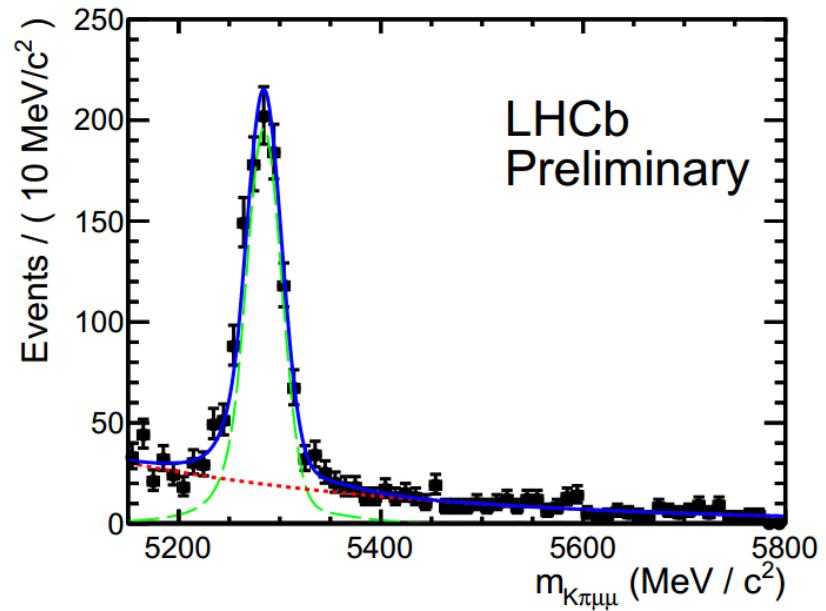
avoid **biasing** angular distribution

- **Angular Acceptance** correction: from MC checked on data

- Extract q^2 - differential B in each q^2 bin

- Extract A_{FB}, F_L, S_3, A_{Im} with an angular fit in each q^2 bin

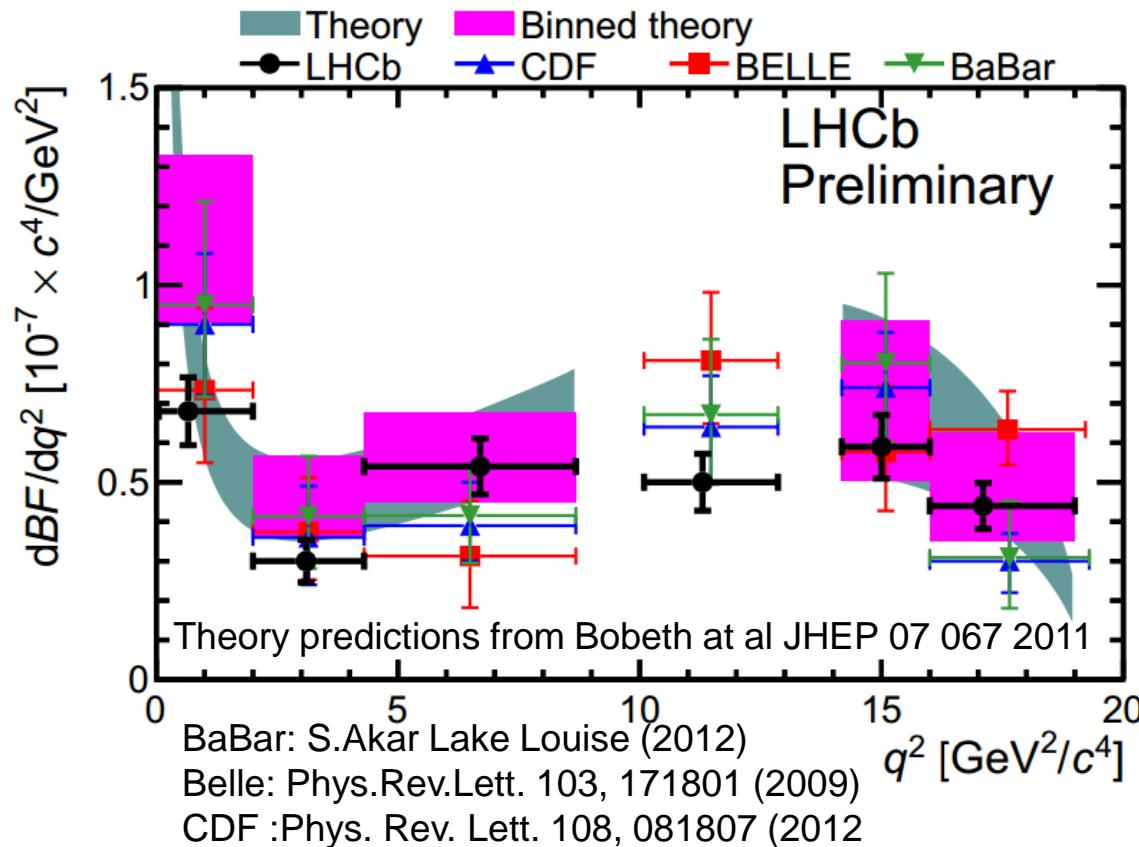
- Extract A_{FB} zero-crossing point



*BABAR+BELLE+CDF ~ 600 events

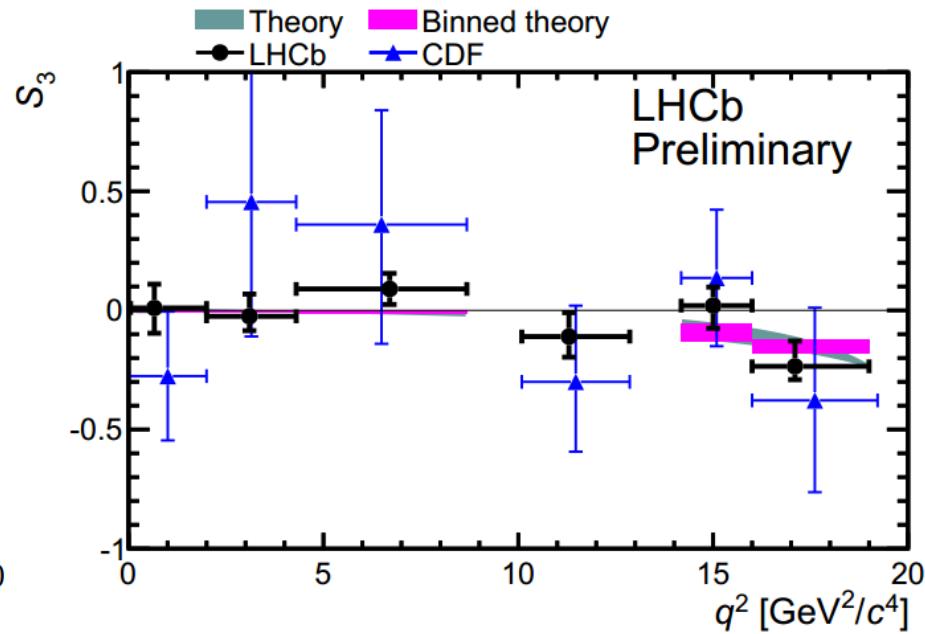
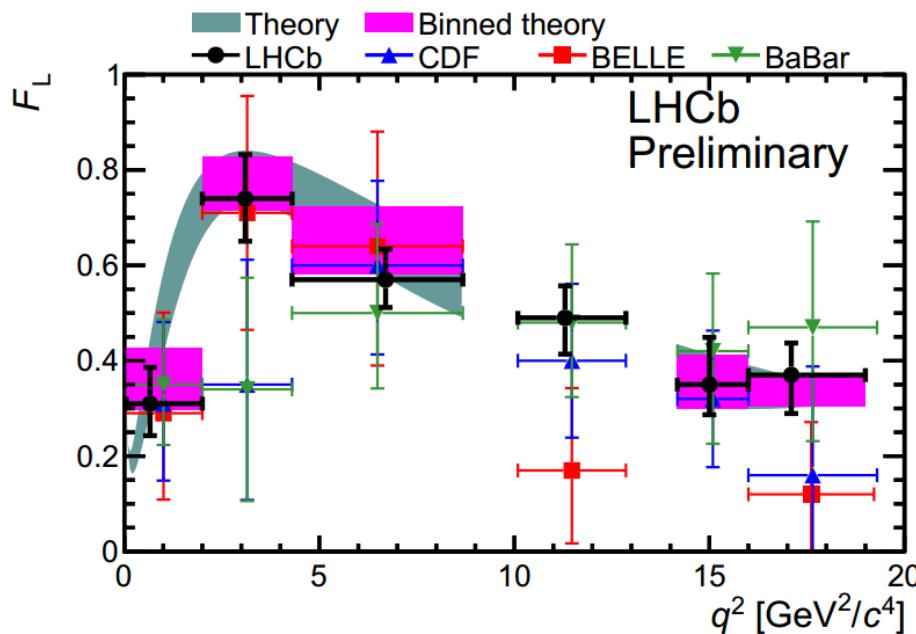
q^2 –differential cross section

- Normalisation to $B^0 \rightarrow K^{*0} J/\psi$



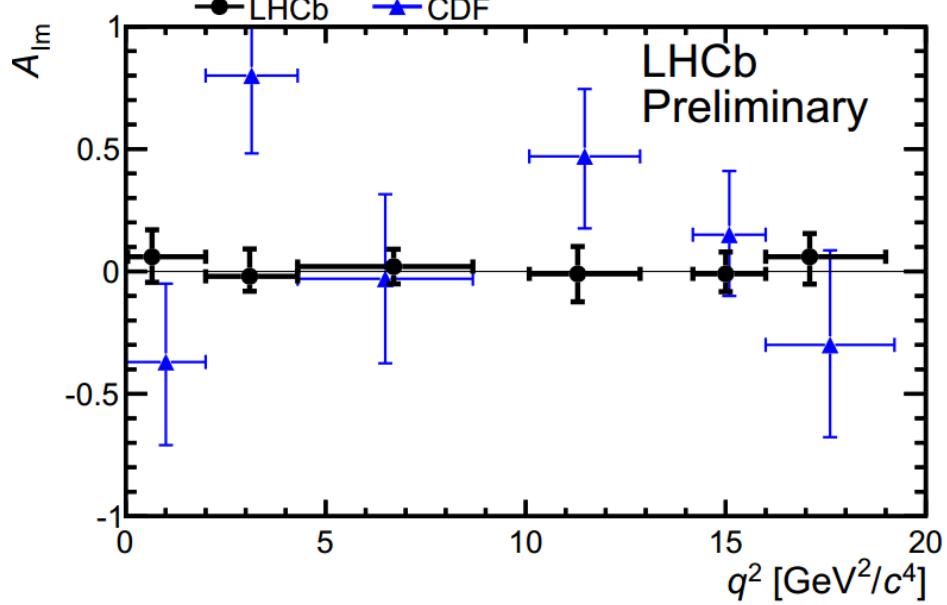
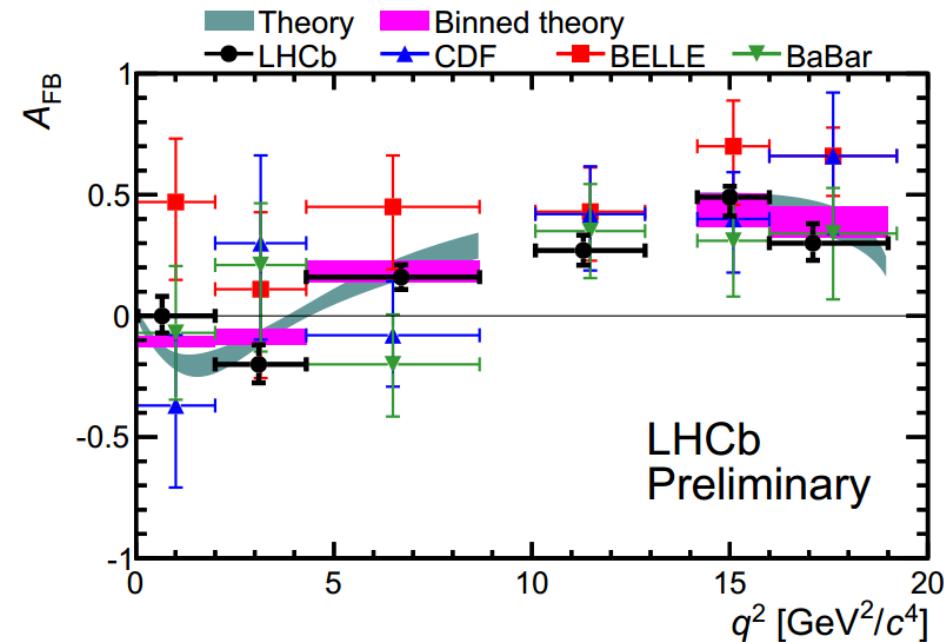
Consistent with SM

Angular Observables: F_L and S_3



Consistent with SM

Angular Observables: A_{FB} and A_{Im}

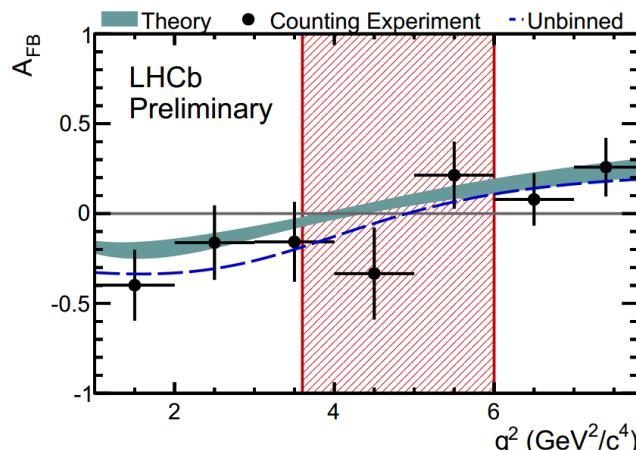
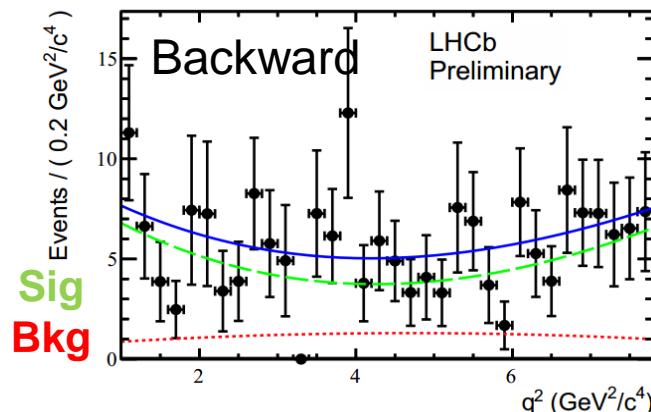
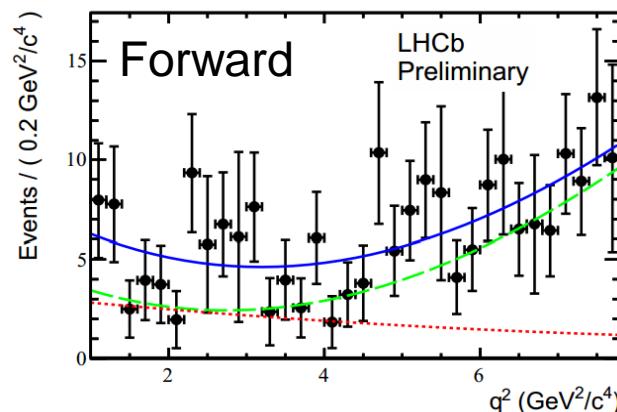


$$A_{Im}^{SM} = \sigma(10^{-3})$$

Consistent with SM

A_{FB} zero crossing point

- Unbinned fit of the q^2 and $m_{K\pi\mu\mu}$ distributions in each of the forward and backward going events samples



World First Measurement of q_0^2 :

$$q_0^2 = (4.9^{+1.1}_{-1.3}) \text{ GeV}^2/\text{c}^4$$

$$q_{0,SM}^2 = (4 - 4.3) \text{ GeV}^2/\text{c}^4$$

Consistent with SM

Conclusions

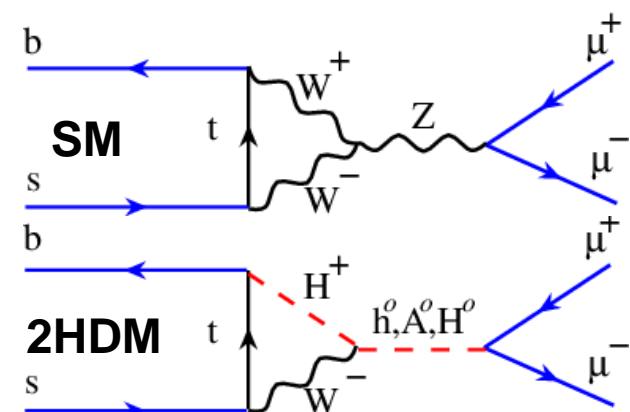
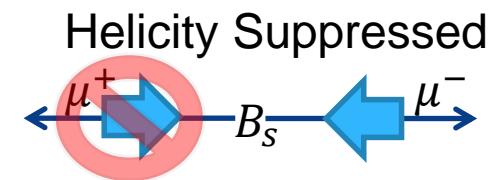
- $B^0 \rightarrow K^* \mu^+ \mu^-$ a probe for NP
- LHCb has the largest sample
- Precisions measurements have started
- First measurement of the zero crossing point
- All measurements compatible with SM
- Updates soon, with new features:
 - More statistics
 - Paper in preparation
 - S-wave
 - Additional observable measurements

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 predictions at $t=0$:



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

Buras et al., Eur.Phys.J. C72 (2012) 2172

- Time integrated B measured experimentally, 9% larger:

$$\langle B(B_s^0 \rightarrow \mu^+ \mu^-)_{SM} \rangle = (3.54 \pm 0.30) \times 10^{-9}$$

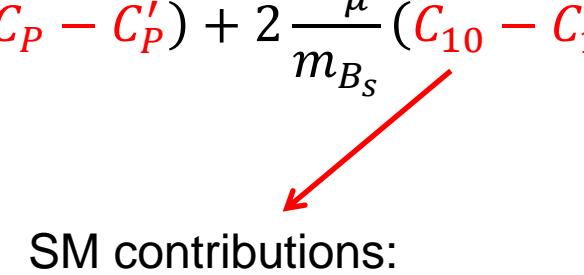
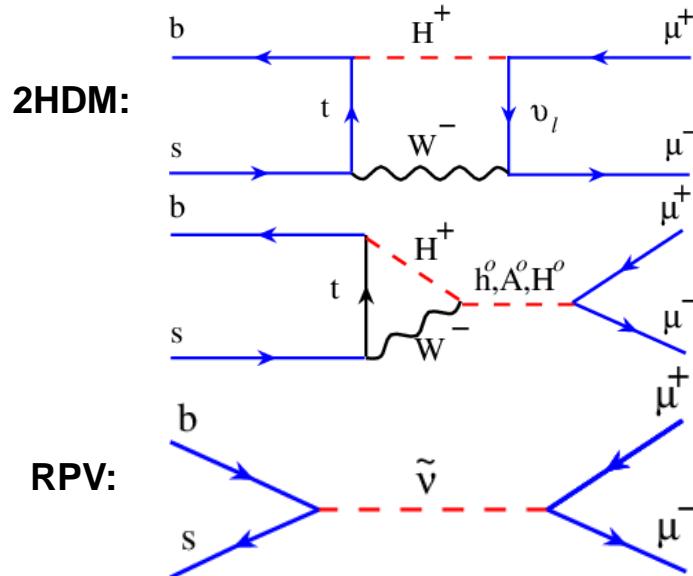
De Bruyn et al., PRD86, 014027 (2012)

$B_{(s)}^0 \rightarrow \mu^+ \mu^-$ phenomenology

Model independent expression of the Branching Ratio:

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

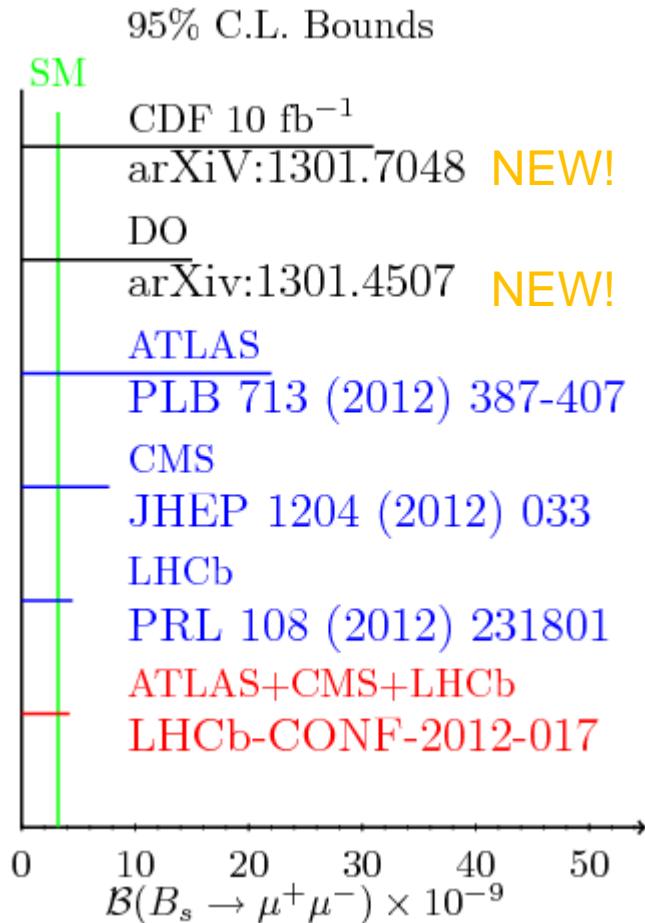
In MSSM: $c_{S,P}^{MSSM} \propto \frac{m_b^2 m_\mu^2 \tan^6 \beta}{M_A^4}$



Experimental Picture

Experimental Status

Drastic improvement of the upper limits since last year:



- LHCb last summer 2012 Results:
 $B(B^0 \rightarrow \mu^+ \mu^-) < 1.0 \times 10^{-9}$
 $B(B_s^0 \rightarrow \mu^+ \mu^-) < 4.5 \times 10^{-9}$
- Significant NP enhancements ruled out for $B(B_s^0 \rightarrow \mu^+ \mu^-)$
- Road map now:
 - Constrain $B(B^0 \rightarrow \mu^+ \mu^-)$
 - **Measure $B(B_s^0 \rightarrow \mu^+ \mu^-)$**

D0 – CDF – ATLAS – CMS – Analyses

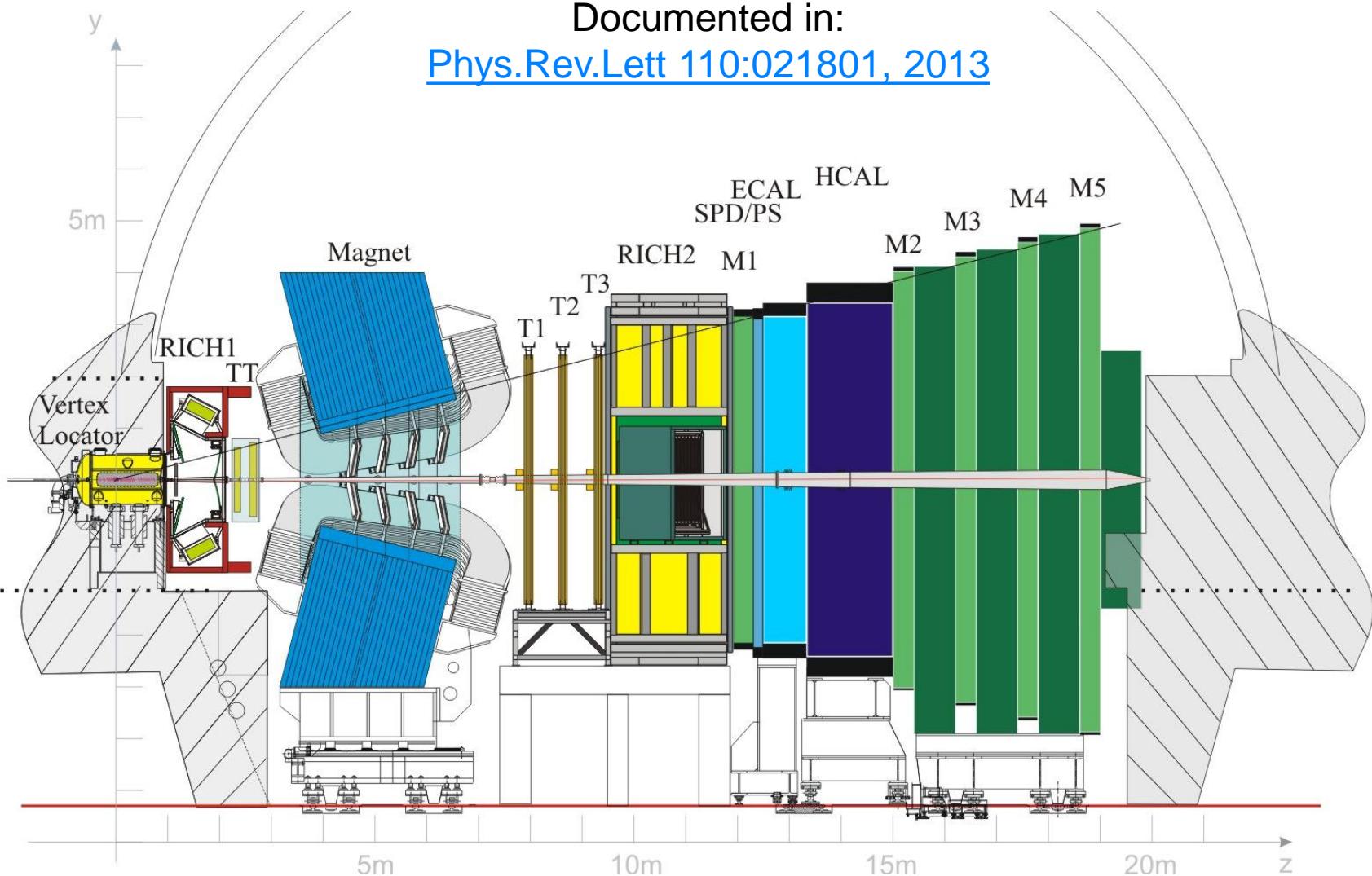
	D0	CDF	ATLAS	CMS	LHCb
$\int \mathcal{L}$ [fb $^{-1}$]	10.4	10	3.4	5	1+1.1
\sqrt{s} [TeV]	1.96	1.96	7	7	7+8
$N(B^+ \rightarrow J\psi K^+)$	87.4K	30.2K	6.8K	106.5K	340.1K+424.2K
$\sigma_{B_s^0}$ [MeV/c 2]	125	24	60 – 110	37 – 77	25
$N(B_s^0 \rightarrow \mu^+ \mu^-)_{SM}$	1.23	2.4	0.88	2.7	11+13
$B(B_s^0 \rightarrow \mu^+ \mu^-) \times 10^9 <^{95\%}_{CL}$	15	31	22	7.7	4.2 + Evidence
Analysis Type	MVA	MVA	MVA	NO MVA	MVA

- No more updates expected by Tevatron experiments ☹
- New results by CMS, eagerly waited:
 - More statistics
 - MVA analysis?

LHCb Analysis

$B_s^0 \rightarrow \mu^+ \mu^-$ at LHCb

Documented in:
[Phys.Rev.Lett 110:021801, 2013](https://doi.org/10.1103/PhysRevLett.110.021801)



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

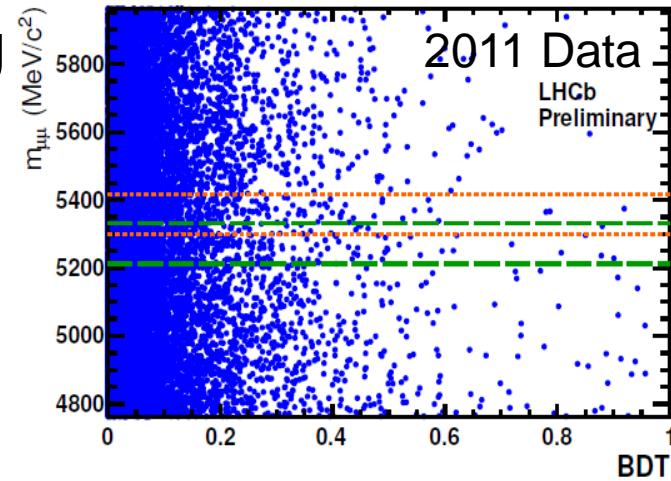
$B \rightarrow hh'$ and $B^+ \rightarrow J/\psi K^+$

3. Extract Limit and BR

Data Set:

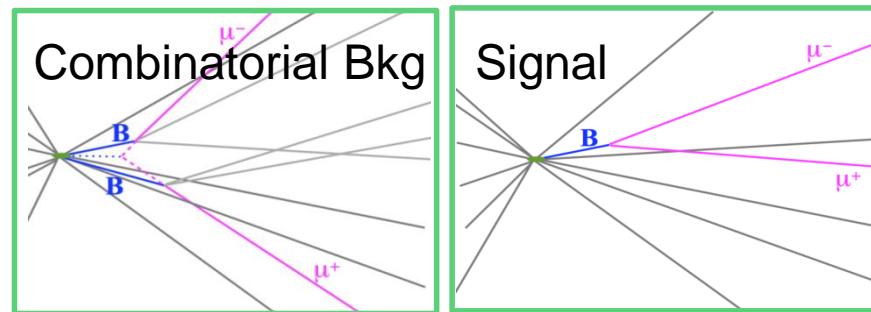
1.0 fb^{-1} + 1.1 fb^{-1} collected in 2011 and 2012 at 7 and 8 TeV

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

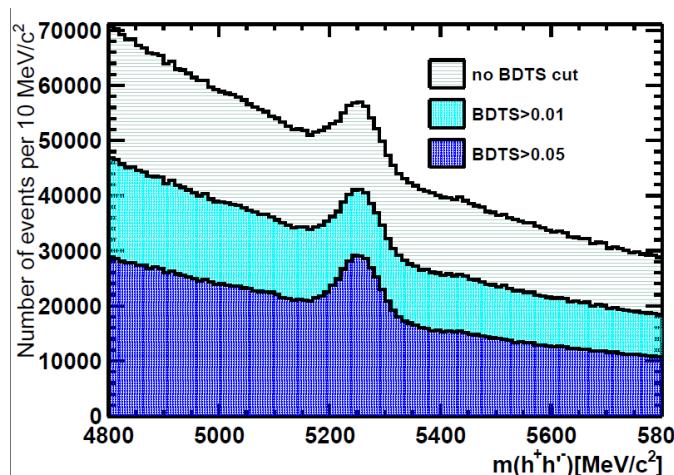


Selection

- 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 the output of a MVA combining information about the candidate topology



Min. Trigger Bias $B \rightarrow h'h'$ evt
invariant mass spectrum
with different tight selection



70% bkg rejection
95% sig efficiency

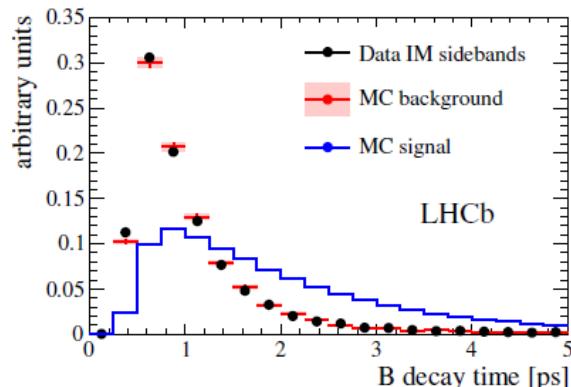
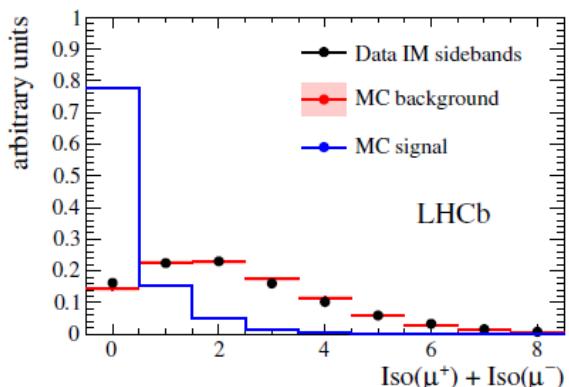
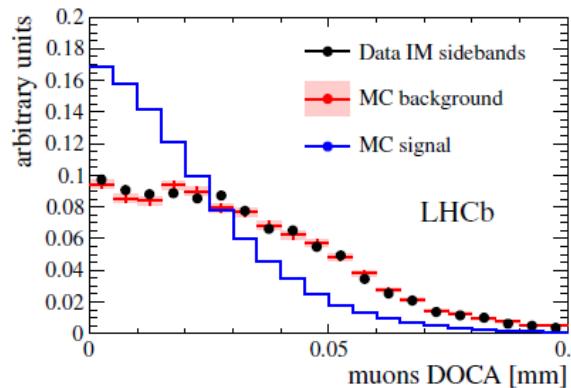
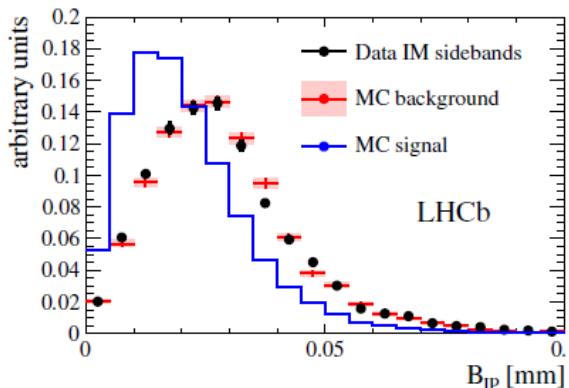
MVA Selection Variables

- B Candidate
 - impact parameter*
 - impact parameter χ^2
 - χ^2 of the vertex
 - pointing angle
 - distance of closest approach*
- Muons
 - minimum impact parameter
- Nota for the following:
Selection biases the life time distribution

*common with BDT

Classification – BDT Definition

- 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:

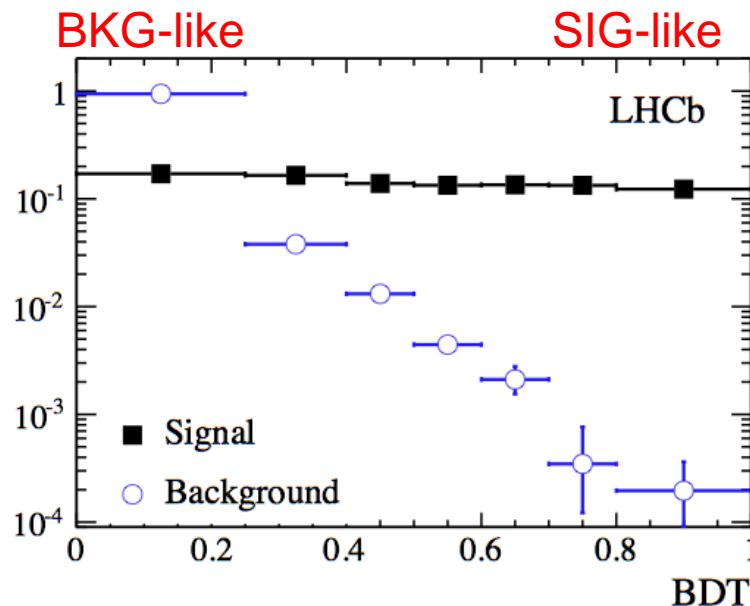
- **proper time**
- impact parameter
- transverse momentum
- B isolation

muons:

- min p_T
- **min IP significance**
- dist. of closest approach
- muon isolation,
- polarisation angle

Signal BDT PDF

- Flat for signal by design
- Sig line shape calibrated on data using an unbiased $B^0 \rightarrow hh'$ sample (same topology as signal)



Combinatorial Background

- 2011 strategy**

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

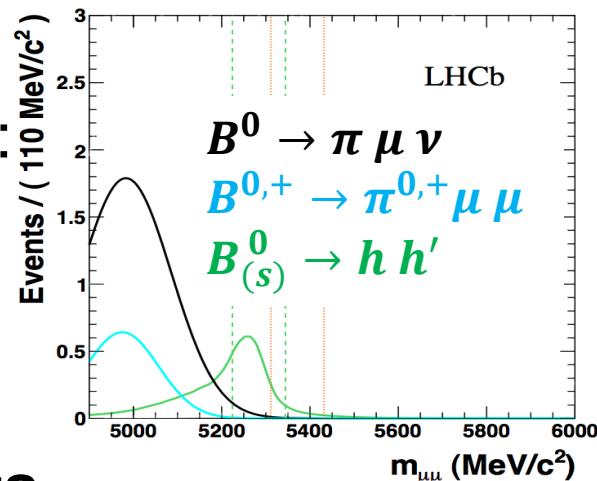
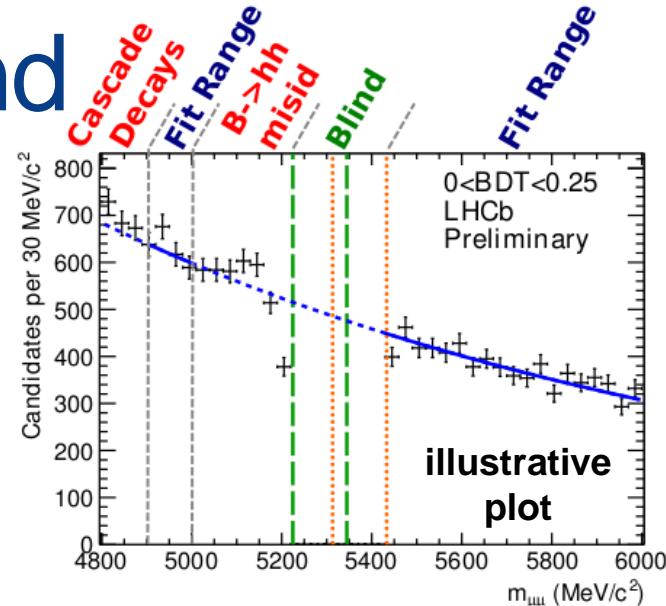
- 2012 refinement**

Study additional background sources:

$$B^0 \rightarrow \pi \mu \nu \quad \text{and} \quad B^{0,+} \rightarrow \pi^{0,+} \mu \mu$$

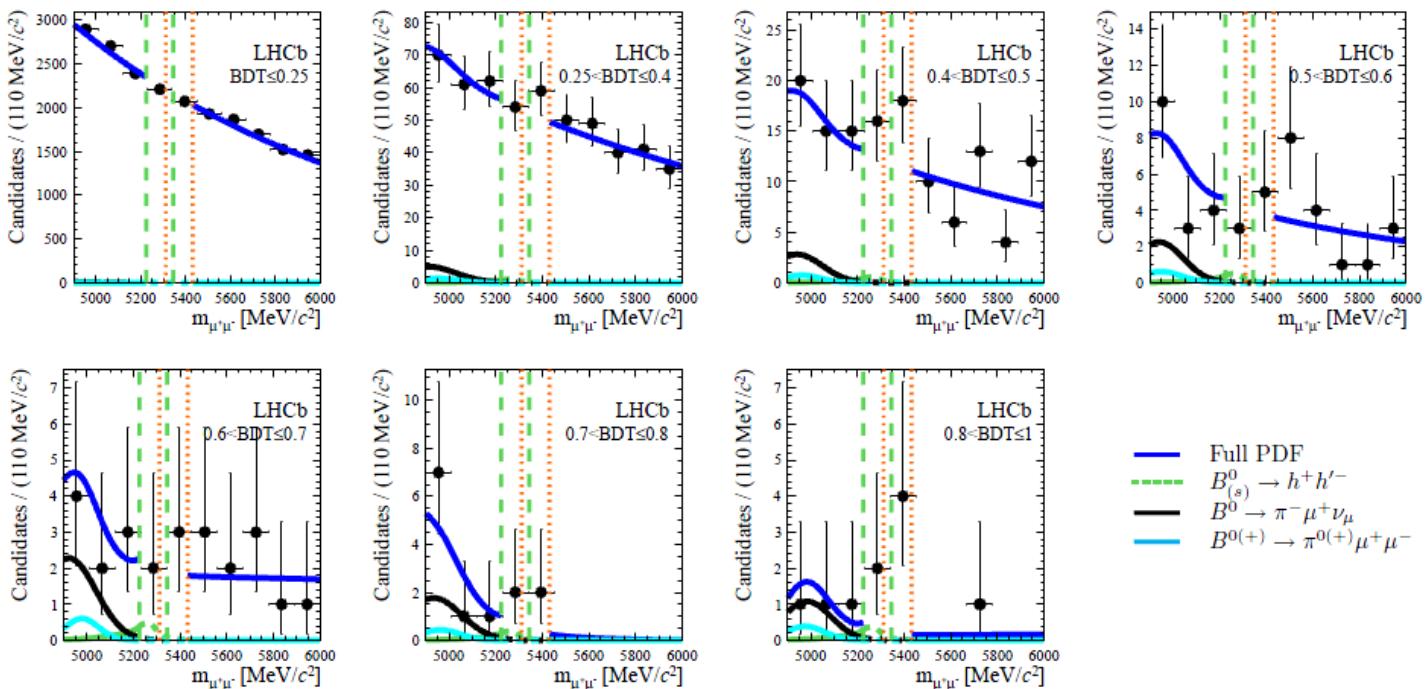
➤ Yields for $[4900 - 6000] \text{ MeV}/c^2$, $\text{BDT} > 0.8$:

$B^0 \rightarrow \pi \mu \nu$	4.04 ± 0.28
$B^{0,+} \rightarrow \pi^{0,+} \mu \mu$	1.32 ± 0.39
$B_{(S)}^0 \rightarrow h h'$	1.37 ± 0.11

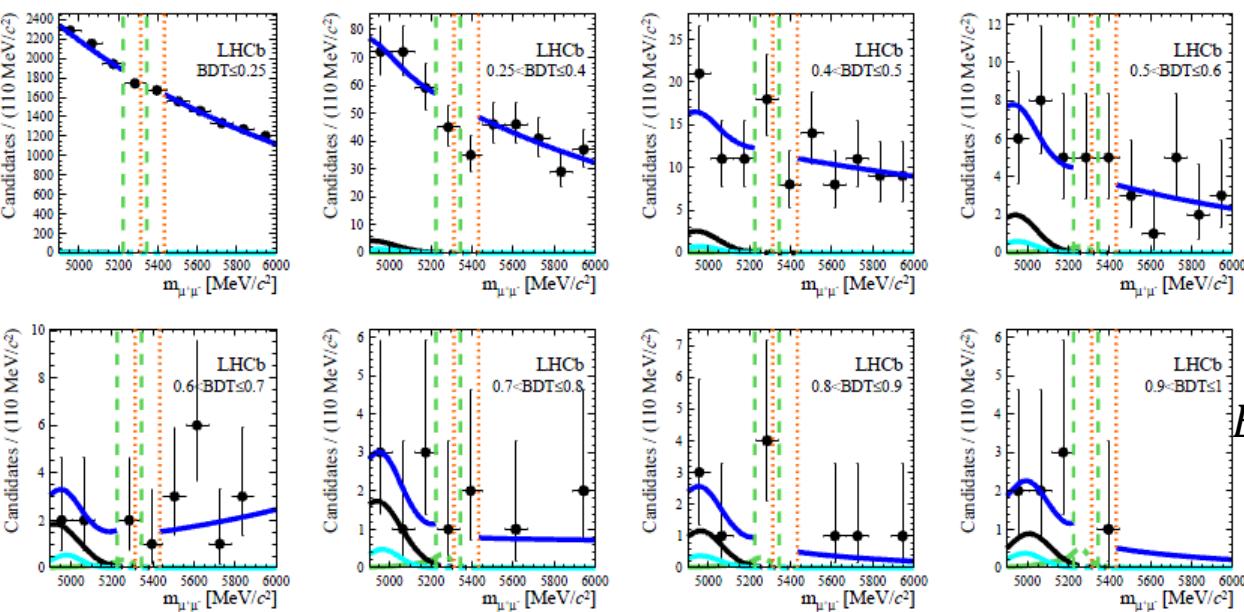


- Re-evaluate 2011 Bkg and update limits**
 interpolation: exponential + exclusive PDF

2012



2011

**Upper Limits: new (old)**

$$B(B_s^0 \rightarrow \mu\mu) < 5.1 \text{ (4.5)} \times 10^{-9}$$

$$B(B^0 \rightarrow \mu\mu) < 13 \text{ (10.3)} \times 10^{-10}$$

at 95%CL

Normalisation

- Number of signal events corresponding to a B :

$$N_{B_{(s)}^0 \rightarrow \mu^+ \mu^-} \propto B(B_{(s)}^0 \rightarrow \mu^+ \mu^-) \times N_{B_s}$$

- N_{B_s} obtained with a channel of known Br:

$$N_{B_s} \propto \frac{N_{B^+ \rightarrow J/\psi K^+}}{B(B^+ \rightarrow J/\psi K^+)} \times \frac{f_s}{f_u}$$

$$N_{B_s} \propto \frac{N_{B^0 \rightarrow K\pi}}{B(B^0 \rightarrow K\pi)} \times \frac{f_s}{f_d}$$

- Correcting for efficiencies:

$$N(B_s^0 \rightarrow \mu^+ \mu^-) = B(B_{(s)}^0 \rightarrow \mu^+ \mu^-) \times \frac{N_{norm}}{B_{norm}} \frac{\epsilon_{sig}^{REC} \epsilon_{sig}^{SEL,REC}}{\epsilon_{norm}^{REC} \epsilon_{norm}^{SEL,REC}} \frac{\epsilon_{sig}^{TRIG,SEL}}{\epsilon_{norm}^{TRIG,SEL}} \frac{f_{B_{(s)}^0}}{f_{norm}}$$

Extracted
from Data

Evaluated from MC,
x-checked with data

Measured on
data

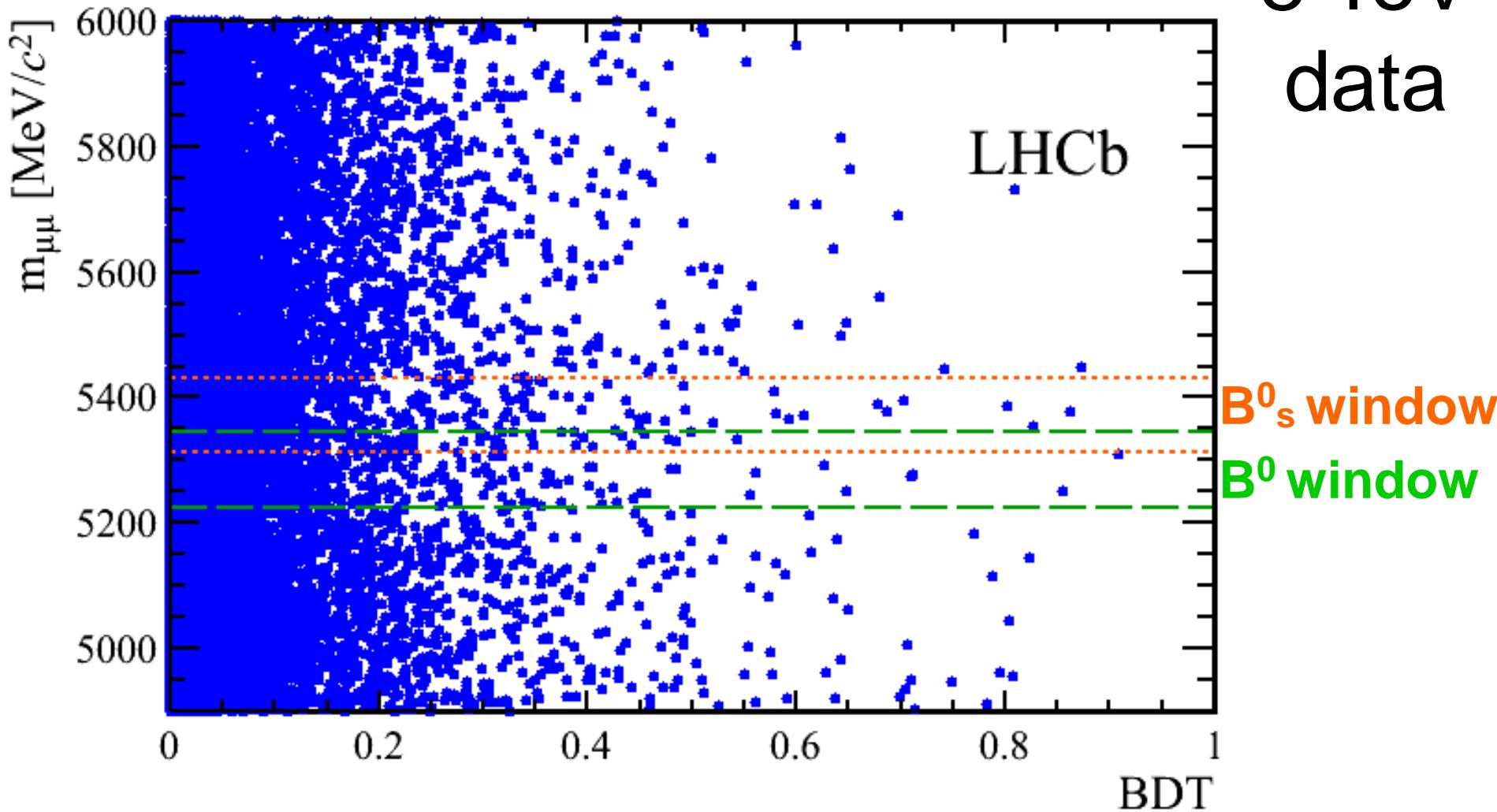
Ratio of prob for a b quark
to hadronise into a $B_{(s)}^0$ or
into the norm. init. state

SM expectations 2012+2011 in the mass windows:
13 + 11 $B_s^0 \rightarrow \mu^+ \mu^-$ and **1.5 + 1.3 $B^0 \rightarrow \mu^+ \mu^-$**

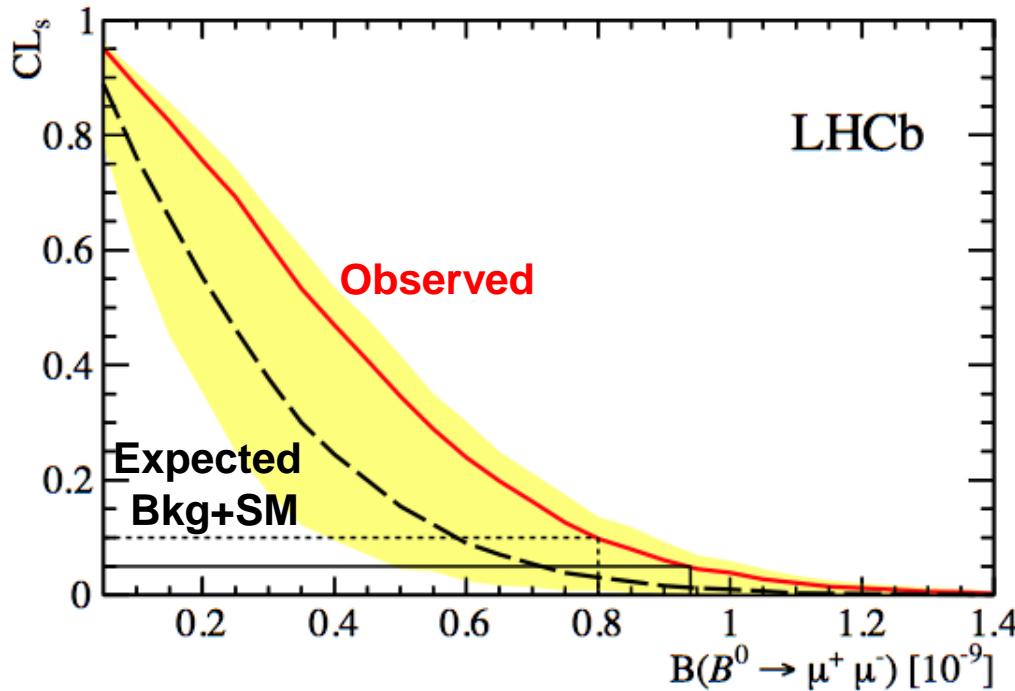
Results

2012
8 TeV
data

Mass-BDT plane



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



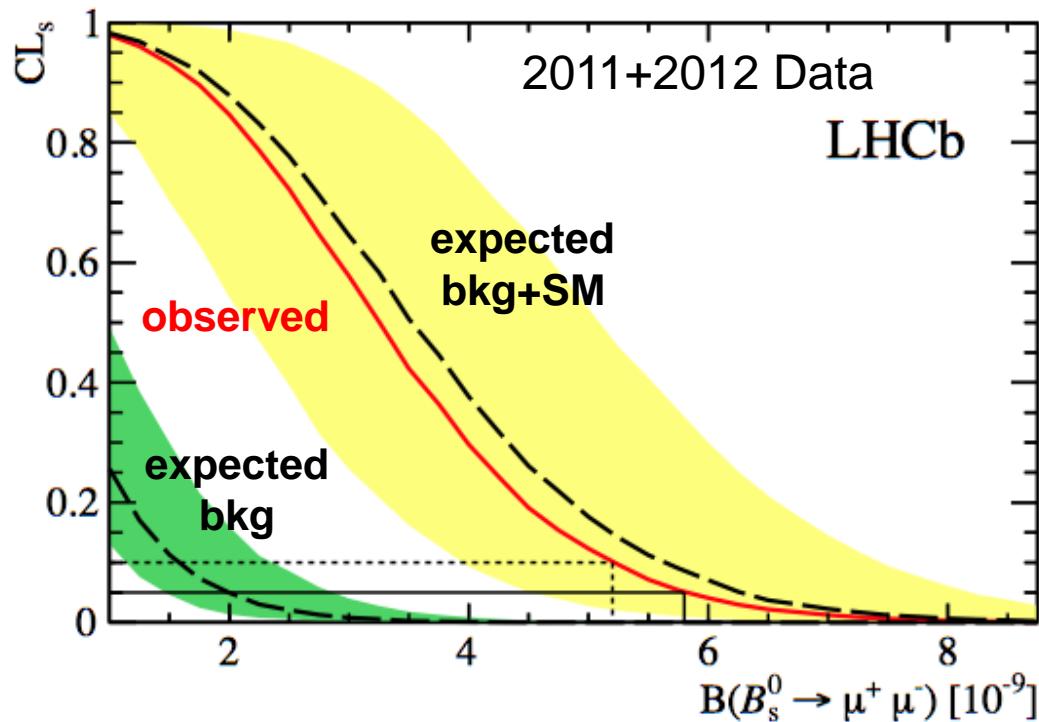
Compatibility with bkg
only hypothesis:
p-value = $1-CL_b = 11\%$

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

$B_s^0 \rightarrow \mu^+ \mu^-$ sensitivity 2011-2012

Good separation between the 2 expectations



Bkg only p-value:
 5.3×10^{-4}
 3.5σ excess

FIRST EVIDENCE

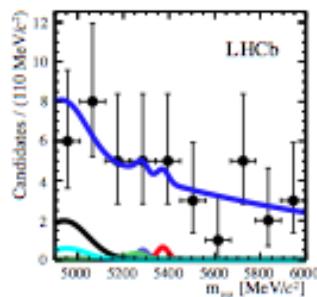
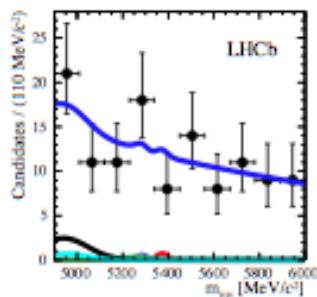
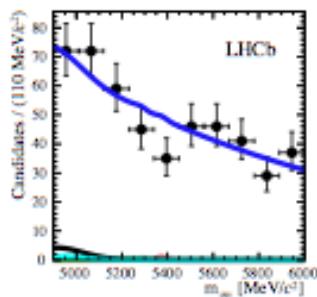
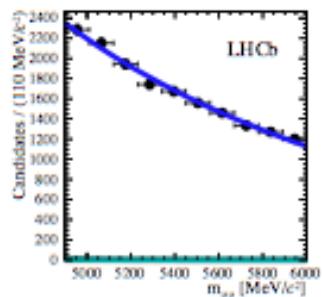
Double-sided limit at 95% CL :

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

where the lower and upper limits are evaluated at:

$$CL_{s+b} = 0.975 \text{ and } CL_{s+b} = 0.025$$

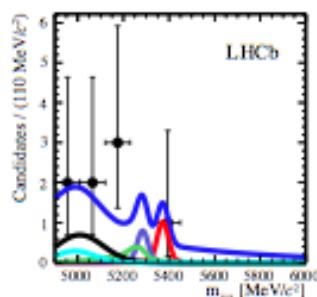
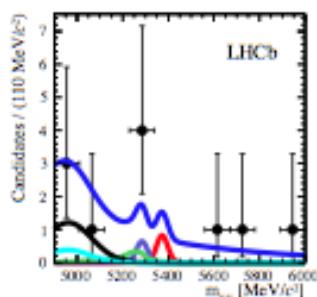
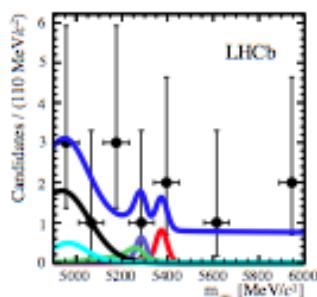
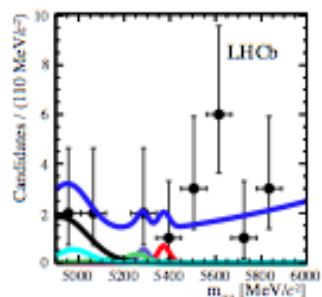
Unbinned maximum likelihood fit



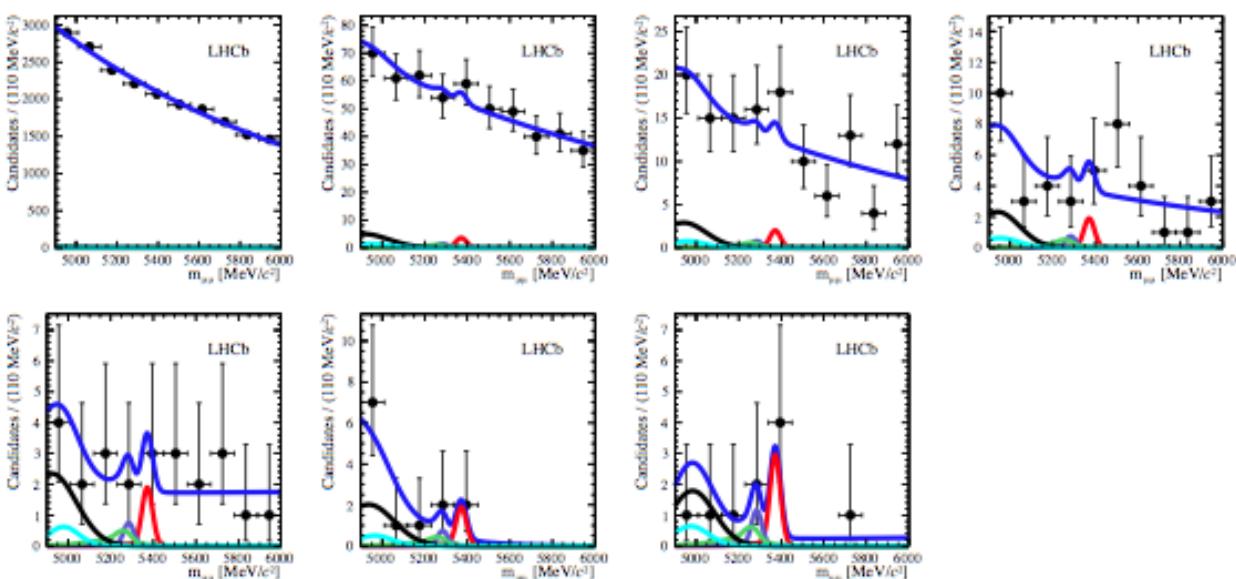
2011

7 TeV data, 1.0 fb⁻¹
8 BDT bins

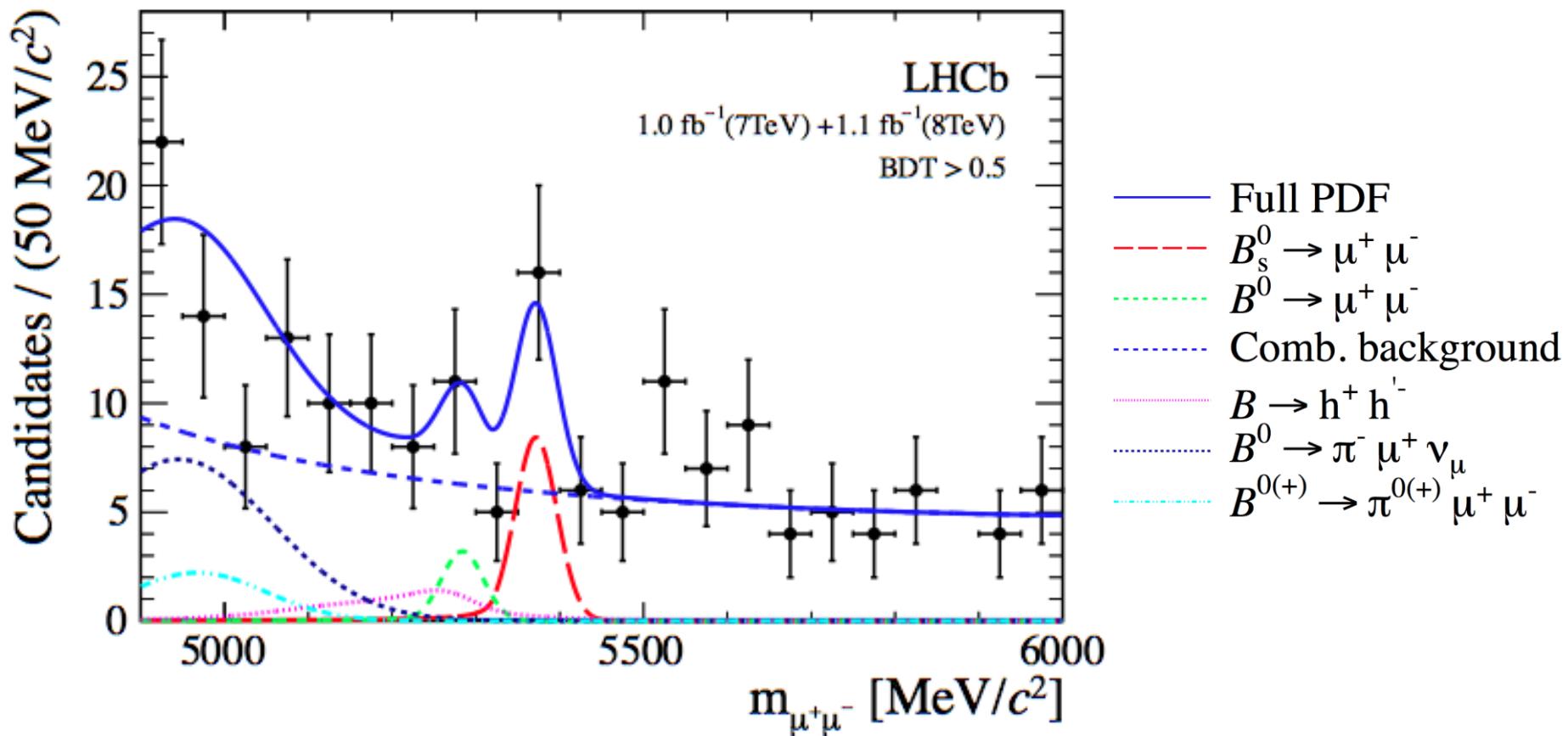
$B_s^0 \rightarrow \mu^+ \mu^-$
 $B^0 \rightarrow \mu^+ \mu^-$
 $B_s^0 \rightarrow h^+ h'^-$
 $B^0 \rightarrow \pi^- \mu^+ \nu_\mu$
 $B^{\pm,0} \rightarrow \pi^{\pm,0} \mu^+ \mu^-$
total



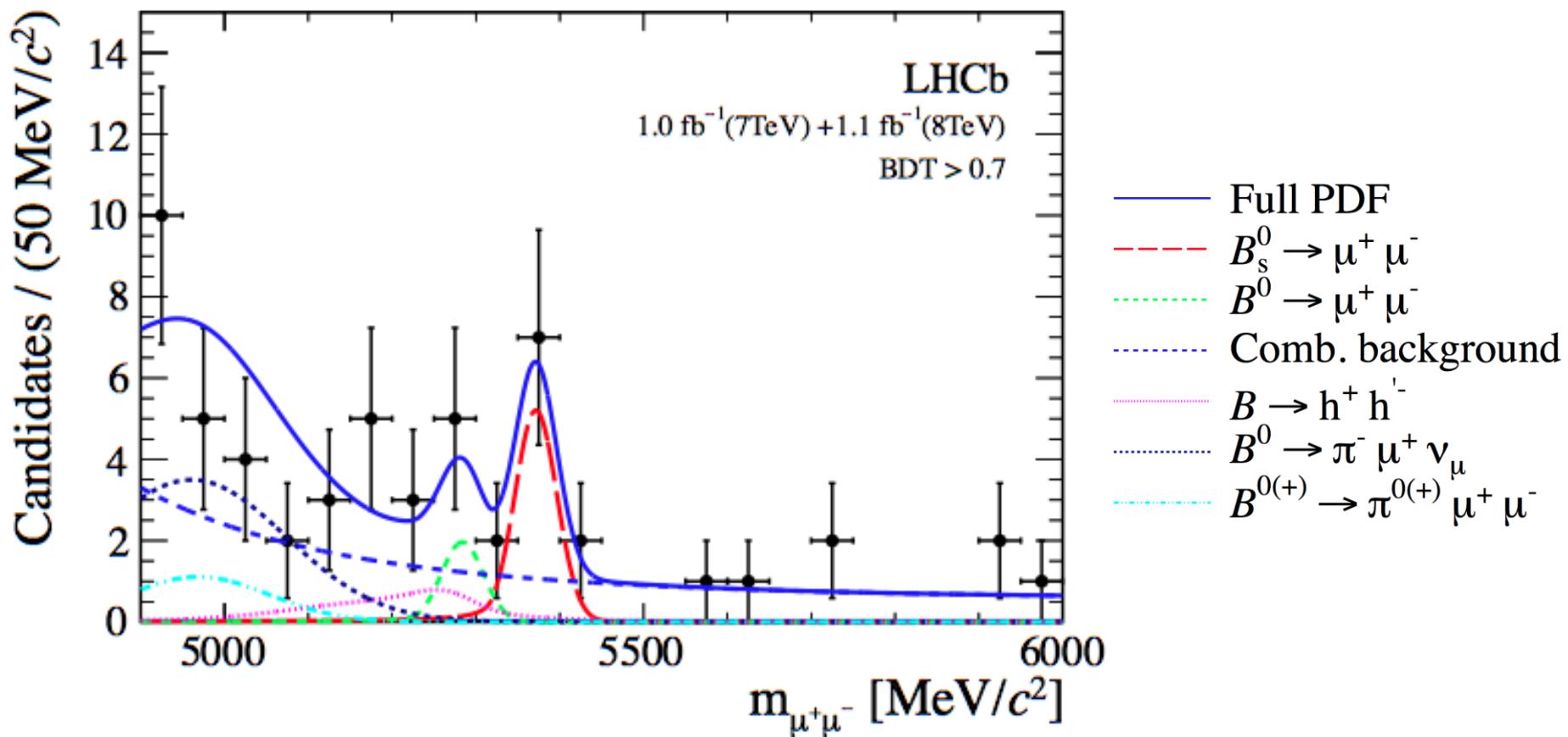
2012

8 TeV data, 1.1 fb⁻¹
7 BDT bins

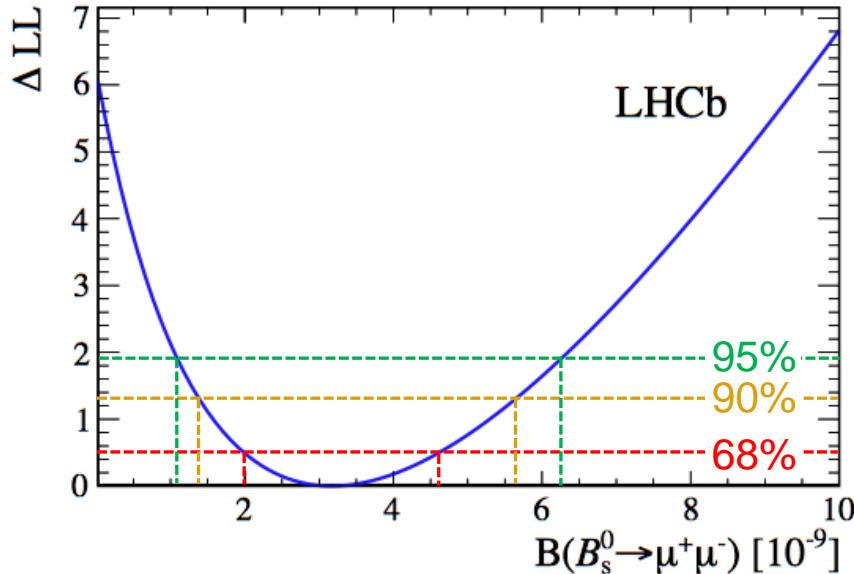
In the Signal Region BDT>0.5



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 time integrated 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

Comparing Measurements with Predictions

- B_s^0 mesons time-evolve in the mass eigenstates:

$$\langle \Gamma(B_s^0(t) \rightarrow \mu^+ \mu^-) \rangle \equiv R_H e^{-\Gamma_H^S t} + R_L e^{-\Gamma_L^S t}$$

- In NP, R_L and R_H are unknown and parametrised by:

$$A_{\Delta\Gamma} = \frac{R_H - R_L}{R_H + R_L} \underset{SM}{\Rightarrow} 1.0$$

- Theoretical definition used for the predictions:

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

- What is really experimentally measured?

De Bruyn et al., PRD86, 014027: time integrated $B = \frac{1}{1-y_s} B_{\text{theo}}$

More complicated in the analysis in fact...

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

- Experimental quantity actually measured is:

$$N(B_s^0 \rightarrow \mu^+ \mu^-) \equiv \frac{N_{Bs}}{2} \int_0^\infty \langle \Gamma(B_s^0(t) \rightarrow \mu^+ \mu^-) \rangle \epsilon(t) dt$$

depends on $A_{\Delta\Gamma}, y_s$ time dep. eff.

- Convert N to B_{meas} with the normalisation factor α : $B_{meas} \equiv N \times \alpha$

if $\epsilon(t)$ flat, and $A_{\Delta\Gamma}$ is SM: $B_{meas} = \frac{1}{1-y_s} \times B_{theo}$

else: $B_{meas} = f(y_s, A_{\Delta\Gamma}) \times B_{theo}$

Proposal: Give results to be compare with B_{theo}^{SM} at t=0 (i.e with $A_{\Delta\Gamma}^{SM}$)

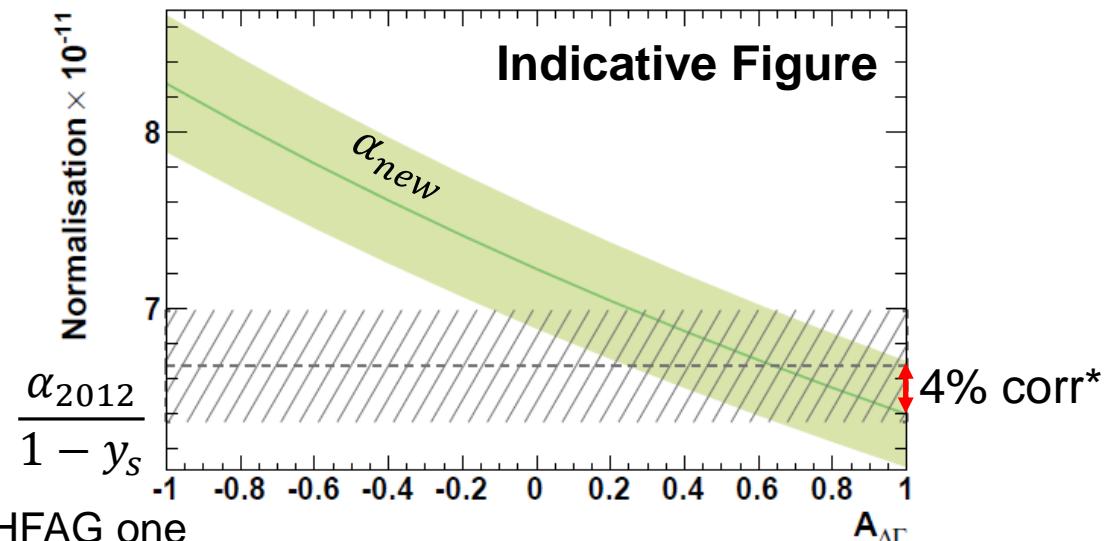
Give a curve to translate to any other $A_{\Delta\Gamma}$

$y_s = 0.069$ from HFAG

- Redefine the normalisation:

$$B_{meas}^{new} \equiv N \times \alpha_{new} = B_{theo}$$

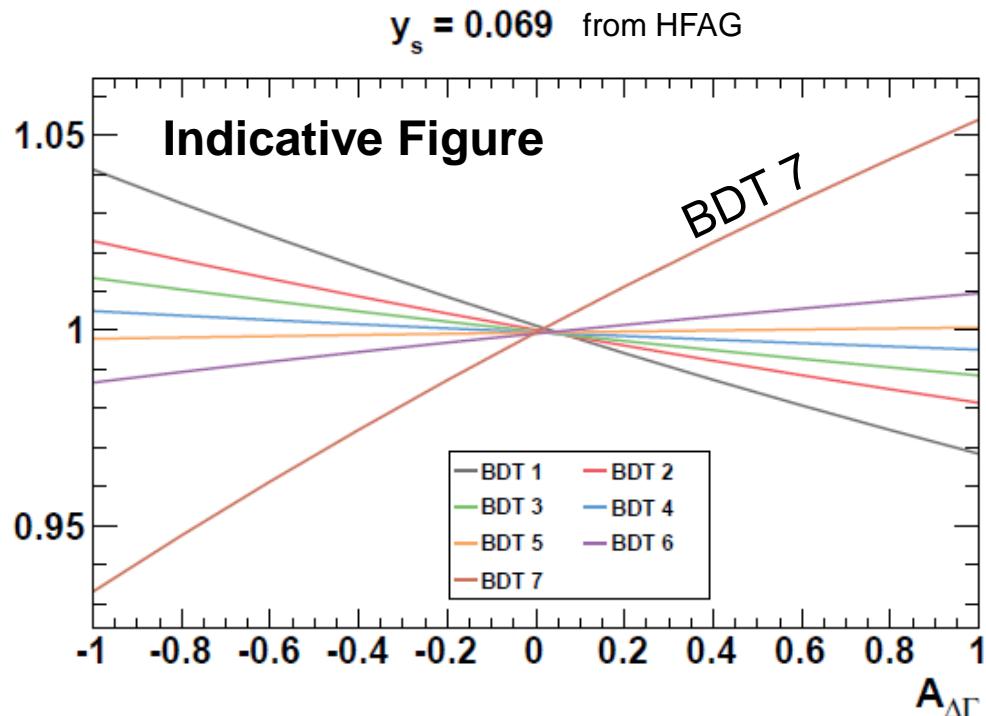
$$\alpha_{new} = \frac{\alpha_{old}}{f(y_s, A_{\Delta\Gamma})}$$



*Nota:

The MC y_s value begin different from the HFAG one
and the sig. Γ from the norm. channels one (differences till now neglected) affect this correction

- BDT PDF obtained from $B^0 \rightarrow hh'$
- Need to correct to match $B_s^0 \rightarrow \mu^+ \mu^-$ life-time distribution
- Correction will depend also on $A_{\Delta\Gamma}$



- Corr. on the number of evts
- BDT 7: most sensitive bins
- Norm.+Calib. Corr: 10% i.e. $B(B_s^0 \rightarrow \mu\mu)^7_{meas}$ 10% smaller
(current uncertainties are larger but upgrade ones will be smaller)

- How to correct a-posteriori?

Discussion

- Effects clearly **exist**
- Numbers are still **unofficial**
- Study crucial for:
 - a **precision measurement**
 - a **meaningful comparison between experiment and theory**
- Documentation in preparation...
- **Question to Theorists:**

Which is the range of interest for $A_{\Delta\Gamma}$?

Conclusions

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

- Constraints 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-value: 5.3×10^{-4}

3.5σ

- BR measurement:

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

- Work in progress for a **precise comparison** between **theoretical** predictions and **experimental** results

Spares

Fit Statistical Error

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)

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

p-value 0.11

- 2012, 8 TeV (1.1 fb⁻¹):

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

p-value 9×10^{-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
 - $\text{UL} = 5.1 \times 10^{-9}$, 95% CL
- $B^0 \rightarrow \mu^+ \mu^-$
 - bkg only p-value: 0.19
 - $\text{UL} = 13 \times 10^{-10}$, 95% CL

Published Analysis

- $B_s^0 \rightarrow \mu^+ \mu^-$
 - bkg only p-value: 0.18
 - $\text{UL} = 4.5 \times 10^{-9}$, 95% CL
- $B^0 \rightarrow \mu^+ \mu^-$
 - bkg only p-value: 0.60
 - $\text{UL} = 10.3 \times 10^{-10}$, 95% CL

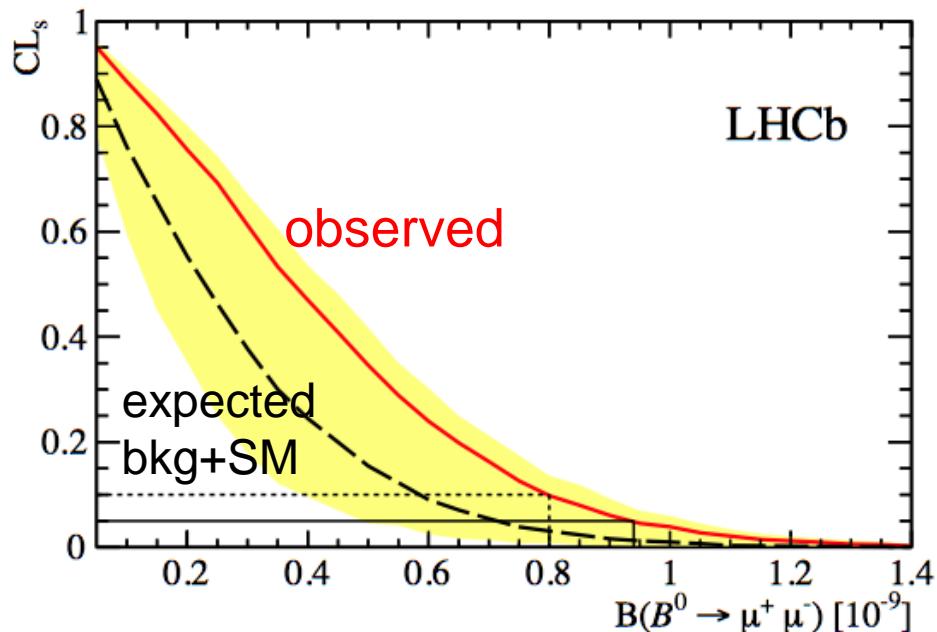
$B^0 \rightarrow \mu^+ \mu^-$: limits and sensitivity

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



	Expected UL (SM+bkg)	Observed UL	Observed 1-CL _b
7 TeV	6.0×10^{-10}	$13.0 \times 10^{-10} *$	0,19 *
8 TeV	10.5×10^{-10}	12.5×10^{-10}	0,16
7TeV + 8TeV	7.1×10^{-10}	9.4×10^{-10}	0,11

*published results:
 $UL = 10.3 \times 10^{-10}$
 $1-CL_b = 0.60$

Some projections

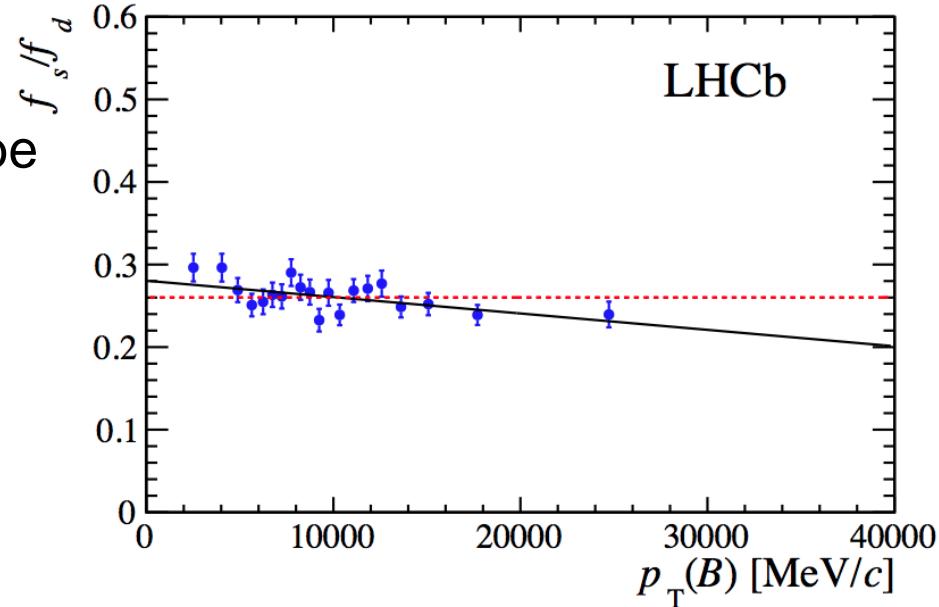
- From LHCb-TDR-012:

Obs.	End 2018	LHCb upgrade $50fb^{-1}$
$B(B_s^0 \rightarrow \mu^+ \mu^-)$	0.5×10^{-9}	0.15×10^{-9}
$\frac{B(B_s^0 \rightarrow \mu^+ \mu^-)}{B(B^0 \rightarrow \mu^+ \mu^-)}$	100%	35%

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 1σ



Exclusive Backgrounds :

$B_s^0 \rightarrow K^+ \mu^- \bar{\nu}_\mu$ and $B^0 \rightarrow \pi^+ \mu^- \bar{\nu}_\mu$

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

	2011	2012
$B^0 \rightarrow \pi^- \mu^+ \nu_\mu$	3.51 ± 0.25	4.04 ± 0.28
$B_{(s)}^0 \rightarrow h^+ h'^- \text{ misID}$	0.91 ± 0.12	1.37 ± 0.11
$B^{+(0)} \rightarrow \pi^{+(0)} \mu^+ \mu^-$	1.12 ± 0.35	1.32 ± 0.39
$\Lambda_b^0 \rightarrow p \mu^- \nu$	0.29 ± 0.17	0.50 ± 0.29
$B_s^0 \rightarrow K^- \mu^+ \nu_\mu$	0.33 ± 0.13	0.46 ± 0.19
$B_c^+ \rightarrow J/\psi \mu^+ \nu$	0.29 ± 0.33	0.34 ± 0.39

Yields for
 $[4900 - 6000] \text{MeV}/c^2$, $\text{BDT} > 0.8$

BDT Variables

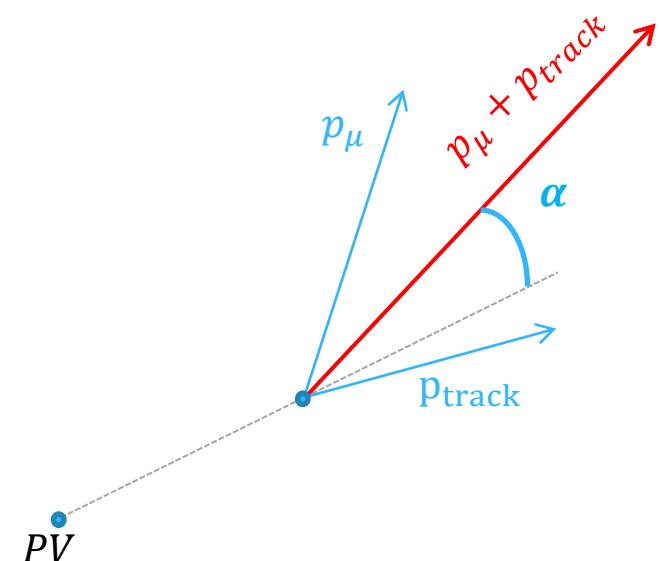
Muon isolation: number of other tracks with which the muon can make a good vertex

Other tracks requirement:

- Long track
- Impact Param Significance with PV > 3

Vertex requirement:

- Angle track-muon<0.27rad
- Distance of Closest Approach < 130 μm
- Distance to PV: 0.5cm<d<4cm
- Distance to SV: -0.15cm<d<30cm
- $$\frac{|\vec{p}_\mu + \vec{p}_{\text{track}}| \sin \alpha}{|\vec{p}_\mu + \vec{p}_{\text{track}}| \sin \alpha + p_{T,\mu} + p_{T,\text{track}}} < 0.6$$



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:

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

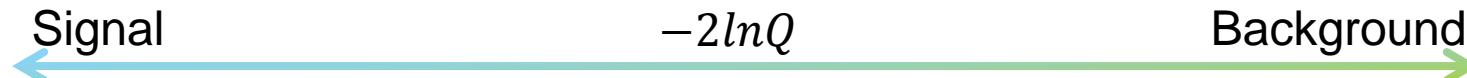
sum running on the tracks such that $\delta\eta^2 + \delta\phi^2 < 1.0$

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:
$$B_s^0 \rightarrow K \mu \nu, \quad \Lambda_b \rightarrow p \mu \nu, \quad B_c \rightarrow J\psi(\mu\mu) \mu \nu$$

CLs method

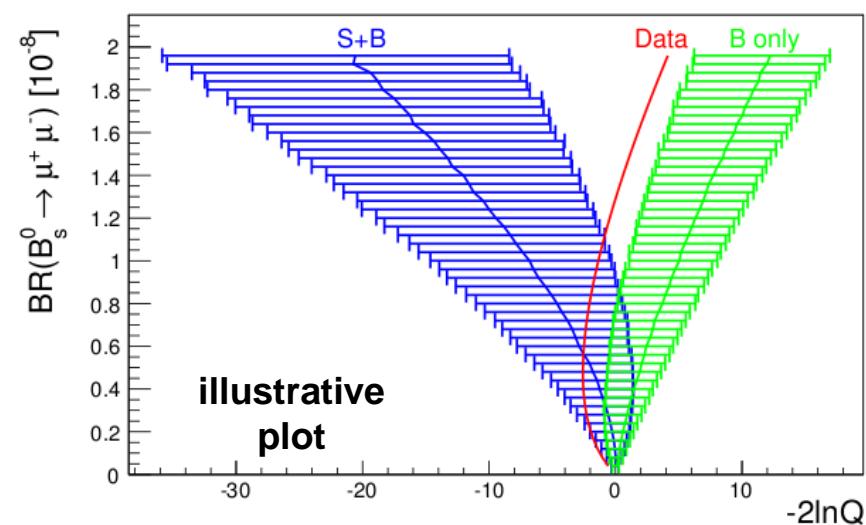
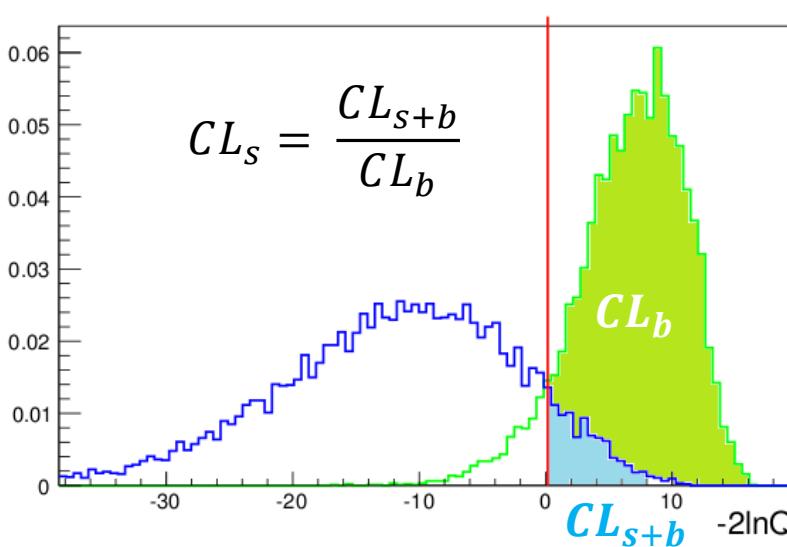
- Idea: compare observed data with expectations
- Define a test statistic for this comparison:

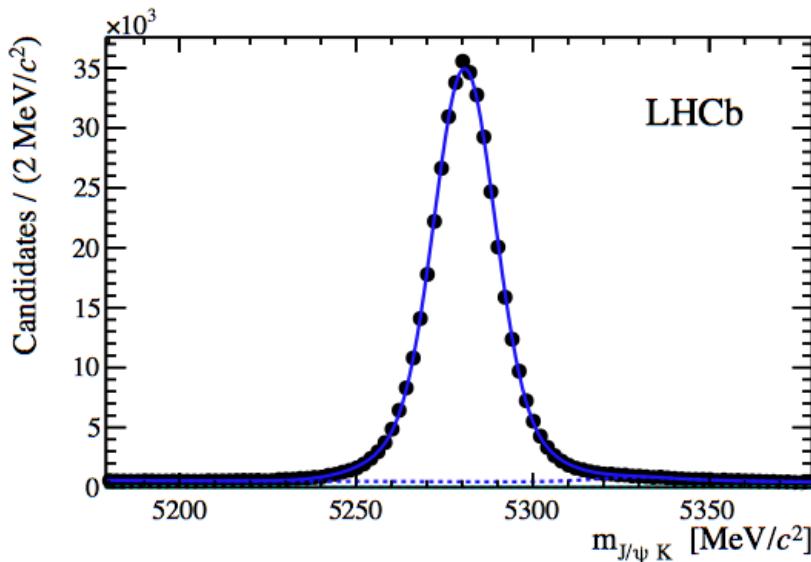
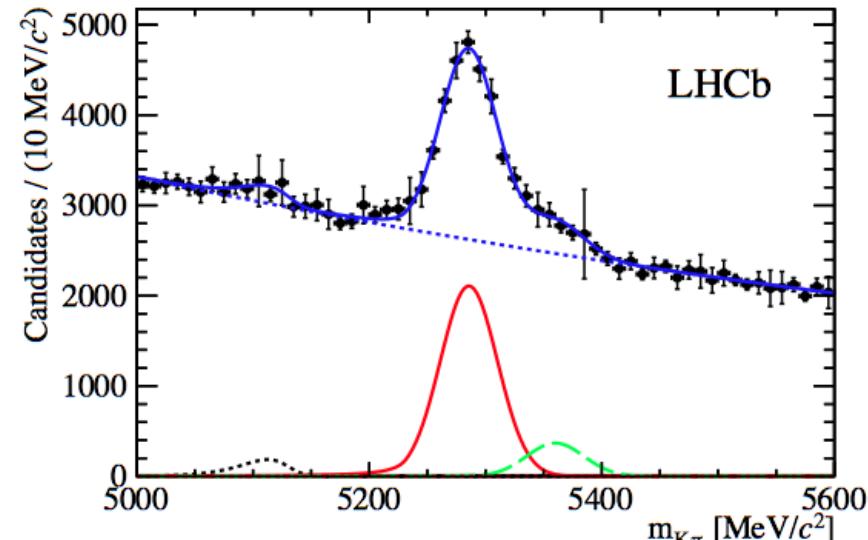


- Calibrate this test statistic with pseudo-experiments

if Br was such then $Bkg\ Only$ would give $-2\ln Q$ of $such$
 $Sig + Bkg$ such

- Compute the $-2\ln Q$ of the observed data



$B^+ \rightarrow J/\psi K^+$  $B^0 \rightarrow K\pi$ 

- Use f_s/f_d measured at LHCb PRD85 (2012) 032008 and LHCb-PAPER-2012-037
- Weighted average of the 2 channels:

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

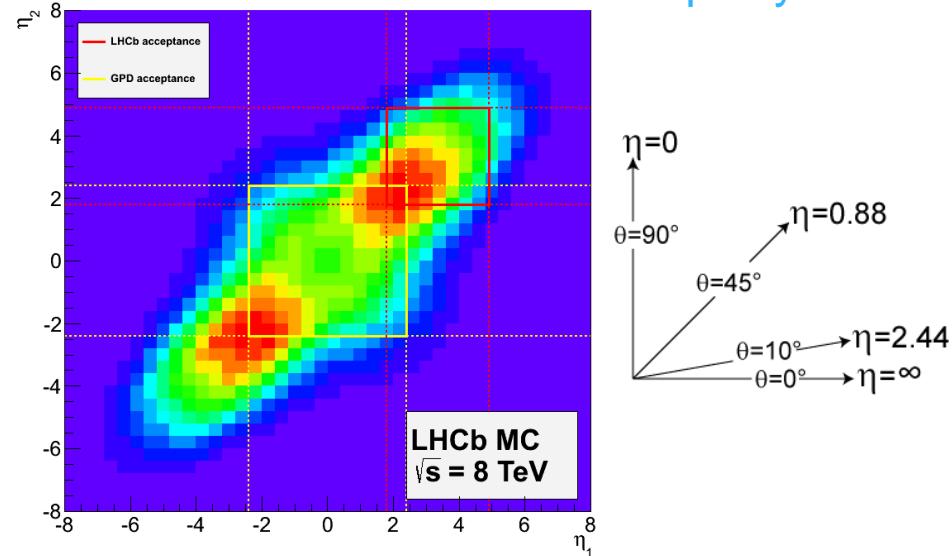
$$\alpha_{B^0 \rightarrow \mu^+ \mu^-} = (7.16 \pm 0.34) \times 10^{-11}$$

SM expectations 2012+2011 in the mass windows:

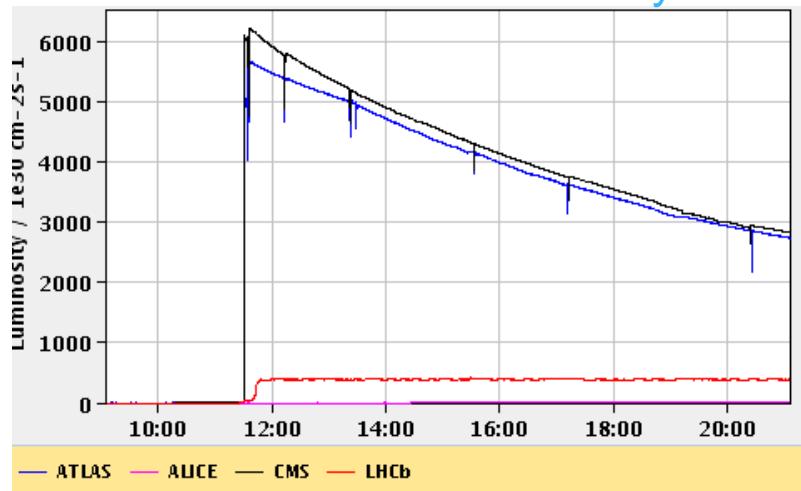
13 + 11 $B_s^0 \rightarrow \mu^+ \mu^-$ and **1.5 + 1.3 $B^0 \rightarrow \mu^+ \mu^-$**

Cross Section Vs Rapidity

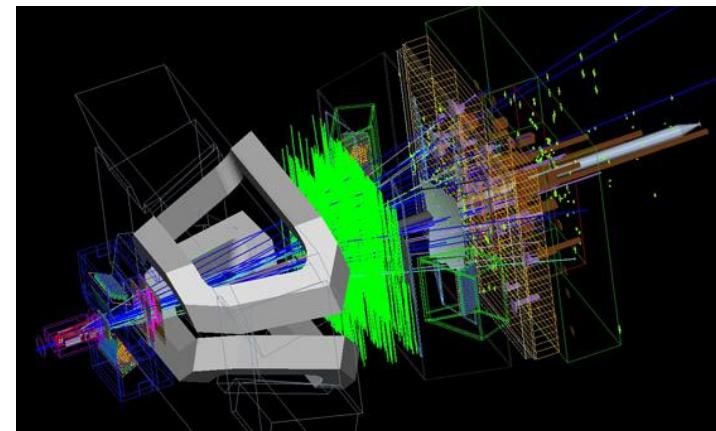
- The LHCb detector:
 - Single arm **forward** spectrometer
 - Acceptance**: $2 < \eta < 6$
 - Low **trigger** thresholds
 - Precise **vertexing**
 - Efficient particle identification
 - Large **boost** (B mesons fly $\sim 1\text{cm}$)



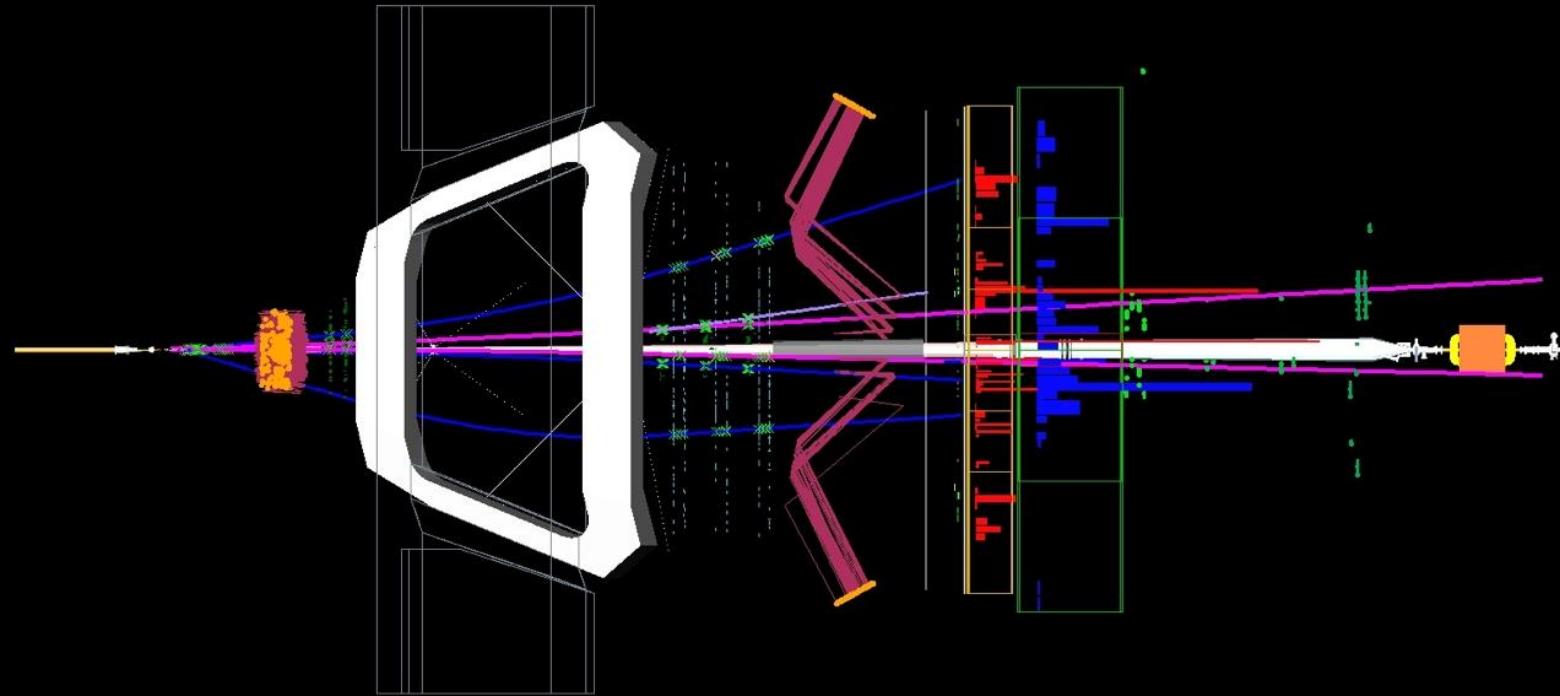
Instantaneous Luminosity



- Constant luminosity $4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ thanks to **luminosity levelling**
- Low pileup** to ease precise physics analysis: 1.7 $p\bar{p}$ interactions/crossing



$B_s^0 \rightarrow \mu^+ \mu^-$ Candidate



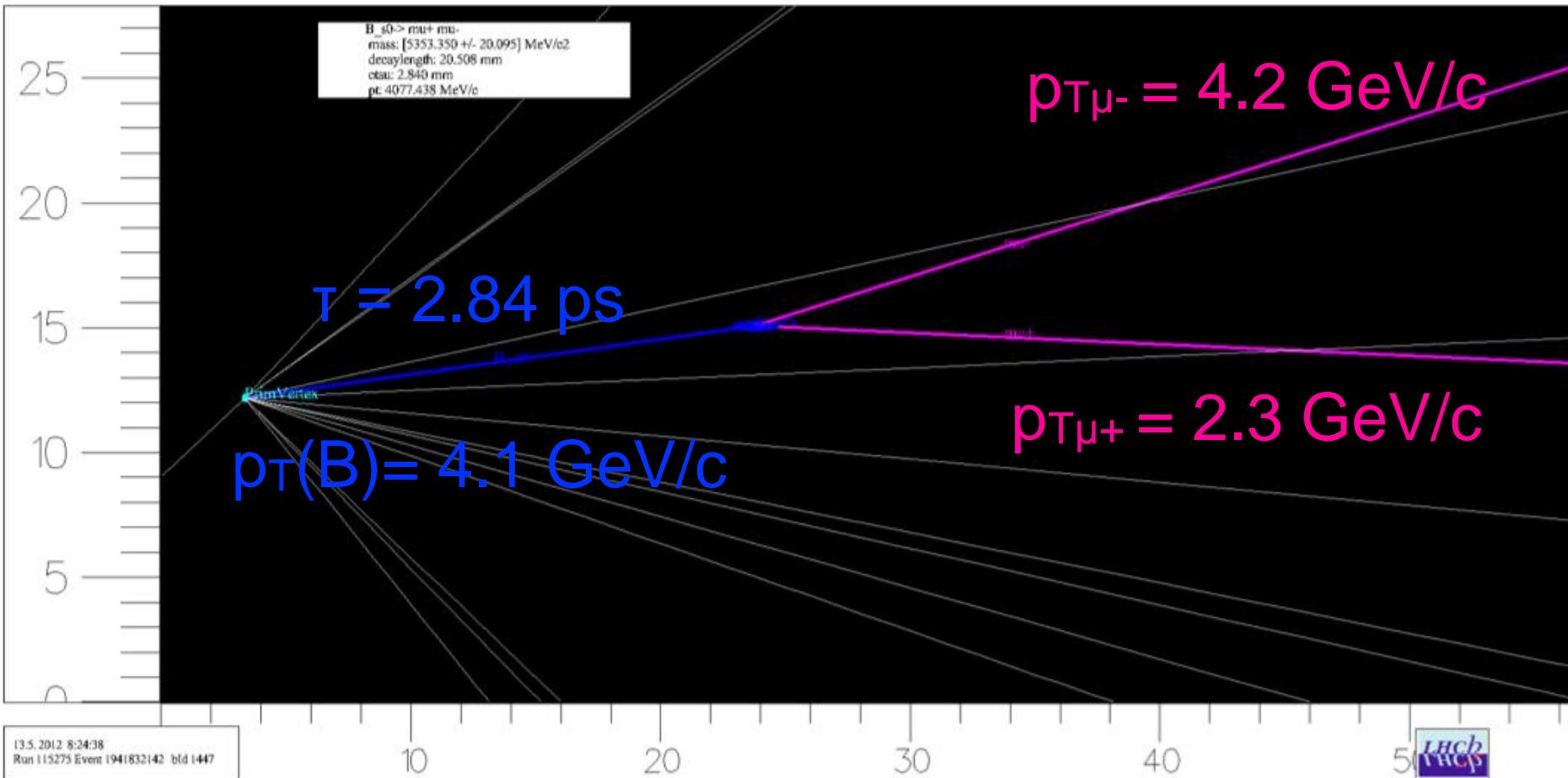
13.5.2012 8:24:38
Run 115275 Event 1941832142 bId 1447



B candidate: $m_{\mu\mu} = 5353.4 \text{ MeV}/c^2$ BDT = 0.826

$p_T = 4077.4 \text{ MeV}/c$ $\tau = 2.84 \text{ ps}$

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

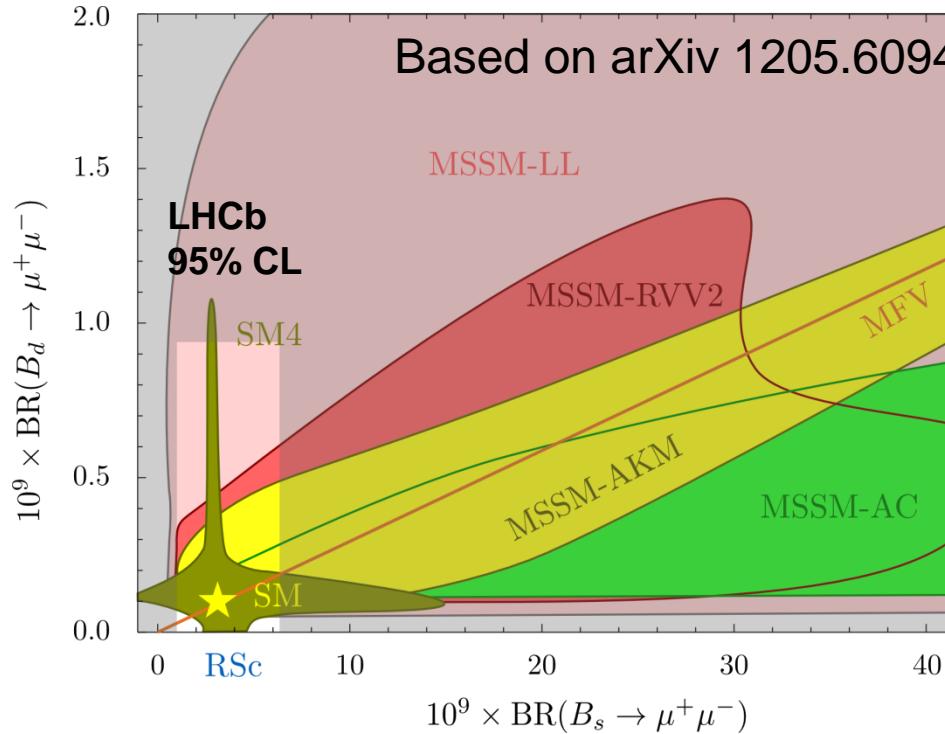


Branching Ratio Fit

- 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} , σ_{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)

Impact of the results

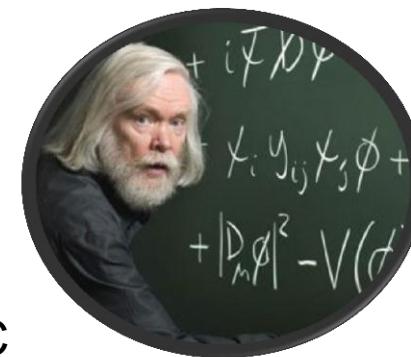
- Hard time for SuperSymmetry...



- 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



Mass PDF - Mean

- **Bkg**: see previous slide
- **Signal Crystal Ball Shape**
- **Mean** form $B^0 \rightarrow \pi\pi, K\pi$ and $B_s \rightarrow KK$

$$m_{B^0} = 5284.36 \pm 0.29 \text{ MeV}/c^2$$

$$m_{B_s^0} = 5371.55 \pm 0.44 \text{ MeV}/c^2$$

- **Resolution** form $B^0 \rightarrow \pi\pi, K\pi$ and $B_s \rightarrow KK$ averaged with $J/\psi, \psi(2S), \Upsilon(1S, 2S, 3S)$

$$\sigma_{B^0} = 24.63 \pm 0.38 \text{ MeV}/c^2$$

$$\sigma_{B_s^0} = 25.05 \pm 0.40 \text{ MeV}/c^2$$

- Two modes are **resolved** :

$$m_{B_s^0} - m_{B^0} \simeq 3.5\sigma_B$$

