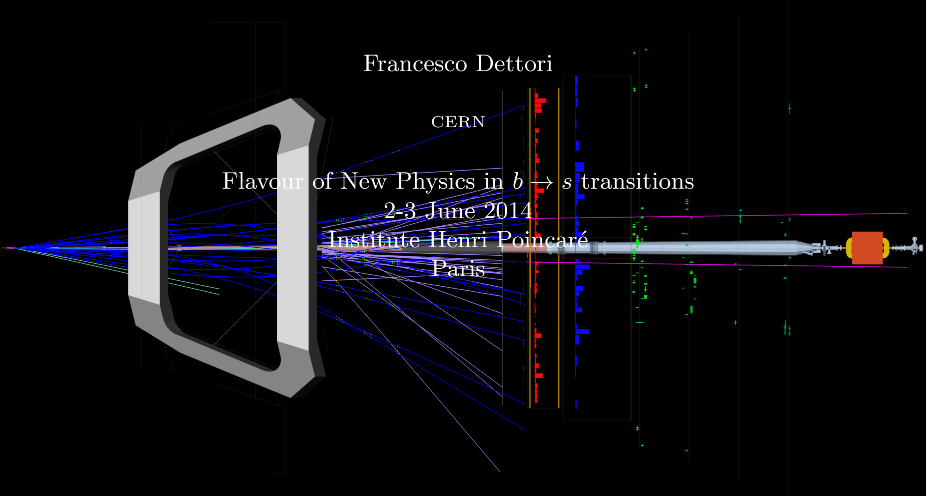
Status of the quest for $B_{d,s} \to \mu^+\mu^-$ decays



Francesco Dettori

CERN

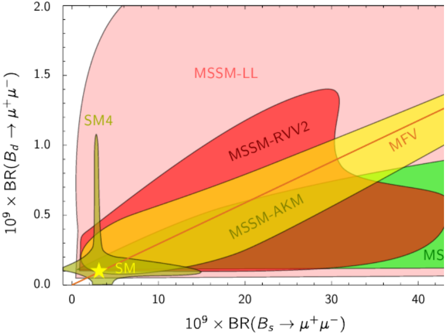
Flavour of New Physics in $b \to s$ transitions
2-3 June 2014
Institute Henri Poincaré
Paris

Outline

- Introduction to $B_{d,s} \to \mu^+\mu^-$ decays
- Search for $B_{d,s} \to \mu^+\mu^-$ at LHCb
- Combination with the CMS experiment
- Conclusions

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

- Flavour changing neutral currents, helicity suppressed
- Probably the cleanest rare decay both experimentally and theoretically
- Sensitive to pseudoscalar and scalar couplings
- Almost any new physics model could predict a contribution to the branching fractions
- Ratio of branching fraction is probe of minimal flavour violation models



Original figure from D. Straub - Nuovo Cim. C035N1 (2012) 249-256

A word on the SM branching fractions

The branching fraction of $B_s \to \mu^+\mu^-$ can be written in the SM as:

$$\mathcal{B}^{t=0}(B_s \to \mu^+\mu^-) = \frac{G_F^4 M_W^4}{\pi^2} \tau_{B_s} f_{B_s}^2 m_{B_s} m_\mu^2 \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}} |V_{tb}V_{ts}^*|^2 |C_{10}|^2$$

To compare with experimental values, which are time integrated, a correction due to the finite $B_s^0 - \bar{B}_s^0$ width difference has to be applied [De Bruyn et al. [PRL 109, 041801]] [Phys.Rev.Lett.108 (2012) 101803]

$$\mathcal{B}^{\langle t \rangle}(B_s \to \mu^+\mu^-) = \left(\frac{1 + \mathcal{A}_{\Delta\Gamma} y_s}{1 - y_s^2} \right) \times \mathcal{B}^{t=0}$$

which also introduces a model dependency.
Most recent predictions (time integrated)

$$\mathcal{B}(B_s \to \mu^+\mu^-)^{\langle t \rangle} = (3.65 \pm 0.23) \cdot 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-)^{\langle t \rangle} = (1.06 \pm 0.09) \cdot 10^{-10}$$

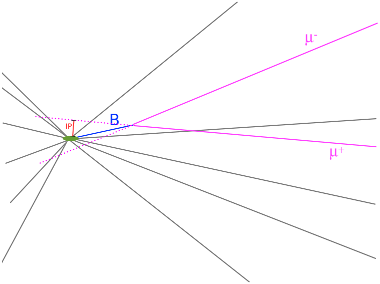
[Bobeth et al. PRL 112 (2014) 101801.] full electroweak two loop corrections and three loop QCD corrections [Bobeth et al. [1311.1348]] [Hermann et al. [1311.1347]]
Main uncertainties:

	f_{B_q}	CKM	τ_H^q	M_t	α_s	Other parameters	Nonparametric	$\sum$
$\overline{\mathcal{B}}_{s\ell}$	4.0%	4.3%	1.3%	1.6%	0.1%	< 0.1%	1.5%	6.4%
$\overline{\mathcal{B}}_{d\ell}$	4.5%	6.9%	0.5%	1.6%	0.1%	< 0.1%	1.5%	8.5%

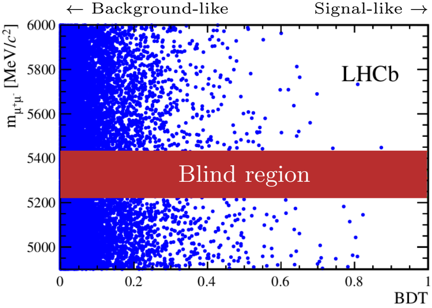
[Phys. Rev. Lett. 111, 101805 (2013)]

Analysis strategy at LHCb

1. Loose selection:
   - ⋆ Pairs of opposite charged muons
   - ⋆ Vertex displaced with respect to interaction point
   - ⋆ $m_{\mu\mu} \in (4900, 6000)$
   - ⋆ $p_{\rm T}$, IP and quality requirements

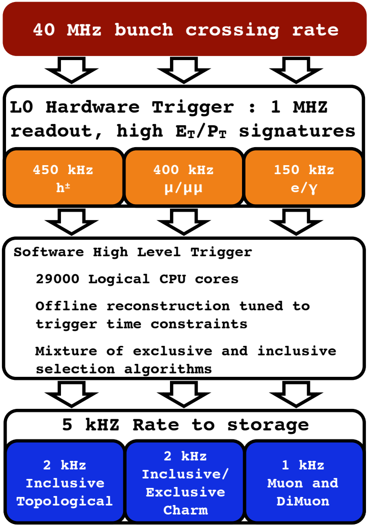


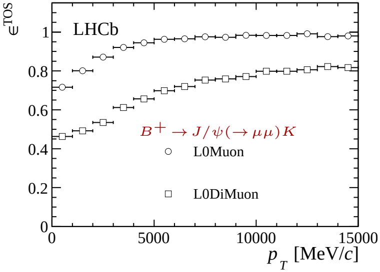
2. Search in a two dimensional plane of invariant mass and BDT



Trigger

[Phys. Rev. Lett. 111, 101805 (2013)]





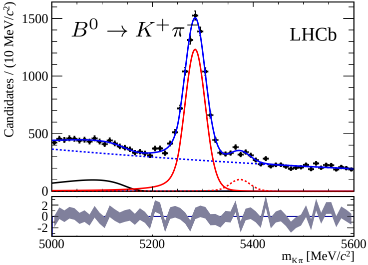
- Single and dimuon triggers
- $(\varepsilon_{B_s \to \mu^+\mu^-} \simeq 90\%)$

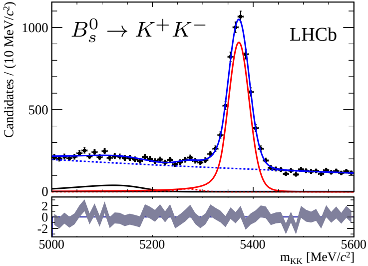
How to know where to look?

Calibration of signal PDFs: mass

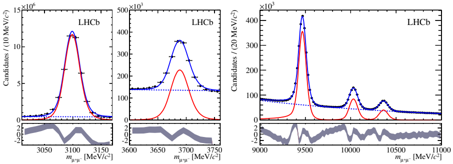
[Phys. Rev. Lett. 111, 101805 (2013)]

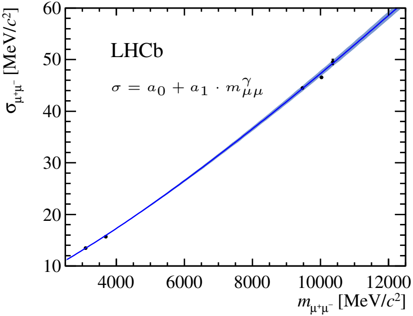
Mass central value





Mass resolution

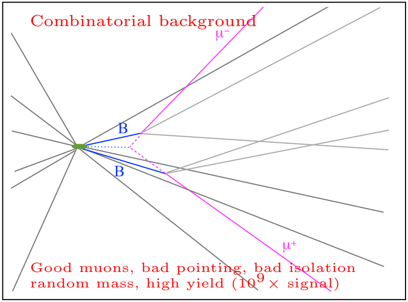




$$\sigma_{B^0} = (24.6 \pm 0.4)\ \mathrm{MeV}/c^2$$

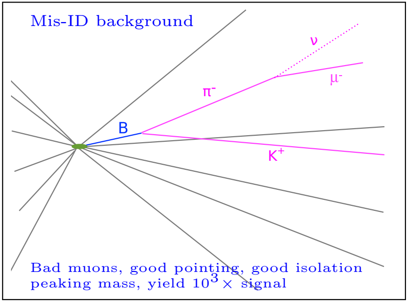
$$\sigma_{B_s^0} = (25.0 \pm 0.4)\ \mathrm{MeV}/c^2$$

Backgrounds



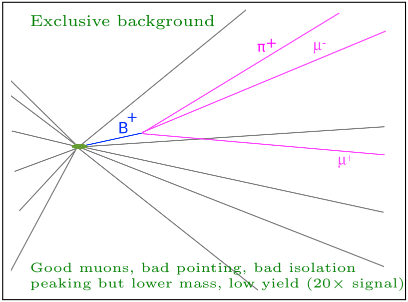
Combinatorial background

Good muons, bad pointing, bad isolation
random mass, high yield ($10^9 \times$ signal)



Mis-ID background

Bad muons, good pointing, good isolation
peaking mass, yield $10^3 \times$ signal



Exclusive background

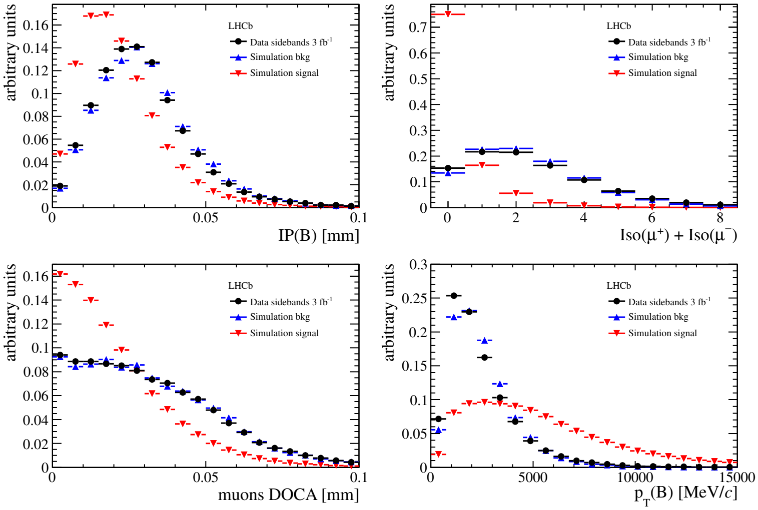
Good muons, bad pointing, bad isolation
peaking but lower mass, low yield (20× signal)

Hadronic	$B \to h^+ h'^-$ with $h = \pi, K$
Semileptonic	$B^0 \to \pi^- \mu^+ \nu$ $B^0_s \to K^- \mu^+ \nu$ $\Lambda^0_b \to \bar{p} \mu^+ \nu$ $B^+_c \to J/\psi \mu^+ \nu_\mu$ $B^0_s \to D^-_s (\to \mu^- \nu) \mu^+ \nu$
Rare decays	$B^{+(0)} \to \pi^{+(0)} \mu^+ \mu^-$ $B^0_s \to \mu^+ \mu^- \gamma$

In red the ones added as separate component
Various others considered but found to be negligible.

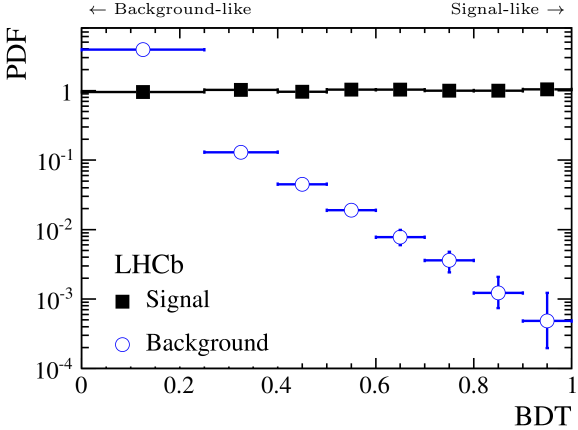
BDT

- Multivariate discriminant with 12 variables
- Trained on MC and calibrated with Data



BDT: calibration of the PDF

- Signal calibrated with exclusive $B \to h^+h^-$ decays separated with PID (same method as for the mass PDF calibration but in bins of BDT)
- Background calibrated with full fit to the sidebands (see next slides)
- Exclusive backgrounds relying on MC



Exclusive backgrounds: $B \to h^+h^-$ and semileptonics

$B \to h^+h^-$:

- Yield fitted on data (with hadronic reconstruction)
- MisID probability measured with control channels in data
- Convoluted with MC spectrum
- Corrected for trigger bias

Semileptonic and rare decays

- Normalised to $B^+ \to J/\psi K^+$
- MisID again from data
- Largest errors from theoretical input for some of them (e.g. $\Lambda_b^0 \to p\mu^-\nu$)

Normalisation

$$\mathcal{B}(B_q^0 \to \mu^+\mu^-) = \frac{\epsilon_{\rm cc}}{\epsilon_{\rm sig}} \cdot \frac{f_{\rm cc}}{f_q} \cdot \frac{N_{B_q^0 \to \mu^+\mu^-}}{N_{\rm cc}} \cdot \mathcal{B}_{cc} = \alpha_q \cdot N_{B_q^0 \to \mu^+\mu^-}$$

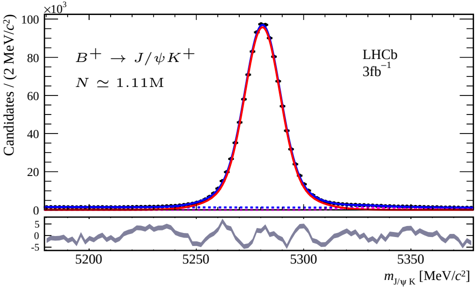
- Two control channels: $B^+ \to J/\psi K^+$ and $B^0 \to K^+\pi^-$
  Results compatible with each other and averaged for final result
- Reconstruction and selection efficiencies from MC but cross-checked with data
- Trigger efficiency from data ($\varepsilon_{B_s \to \mu^+\mu^-} \simeq 90\%$)
- Hadronisation fractions from updated LHCb measurement
  $f_s/f_d = 0.259 \pm 0.015$ [LHCb-CONF-2013-011]
- Correction on efficiencies due to lifetime bias: SM assumed

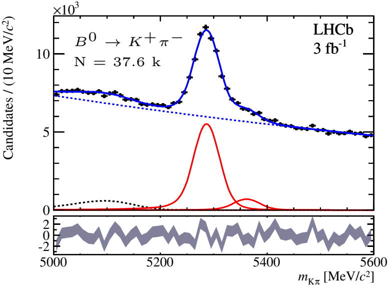
Normalisation

Normalisation for the full dataset (3fb^{-1})

$$\alpha_{B_s \to \mu^+\mu^-} = (9.01 \pm 0.62) \times 10^{-11} \qquad \alpha_{B^0 \to \mu^+\mu^-} = (2.40 \pm 0.09) \times 10^{-11}$$

i.e. 40 ± 4 (4.5 ± 0.4) expected $B_s \to \mu^+\mu^-$ ($B^0 \to \mu^+\mu^-$) events in the full BDT range





Correction of lifetime bias

Integrated efficiency is $\epsilon = \frac{\int_0^\infty \Gamma(t)\epsilon(t)dt}{\int_0^\infty \Gamma(t)dt}$

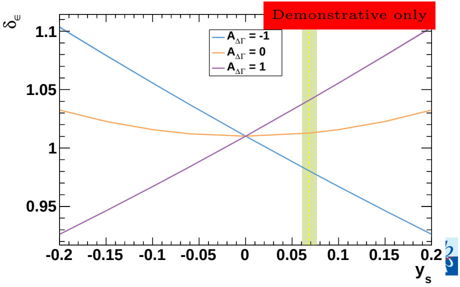
However the real width is a function of NP parameters

$$\begin{aligned}\Gamma\left(B_s \to \mu^+\mu^-\right) &= \Gamma\left(B_s \to \mu^+\mu^-\right) + \Gamma\left(\bar{B}_s^0 \to \mu^+\mu^-\right) \\ &= R_H e^{-\Gamma_H t} + R_L e^{-\Gamma_L t} = \left(R_H + R_L\right) e^{-\Gamma_s t}\left[\cosh \frac{y_s t}{\tau_{B_s}} + \mathcal{A}_{\Delta\Gamma} \sinh \frac{y_s t}{\tau_{B_s}}\right]\end{aligned}$$

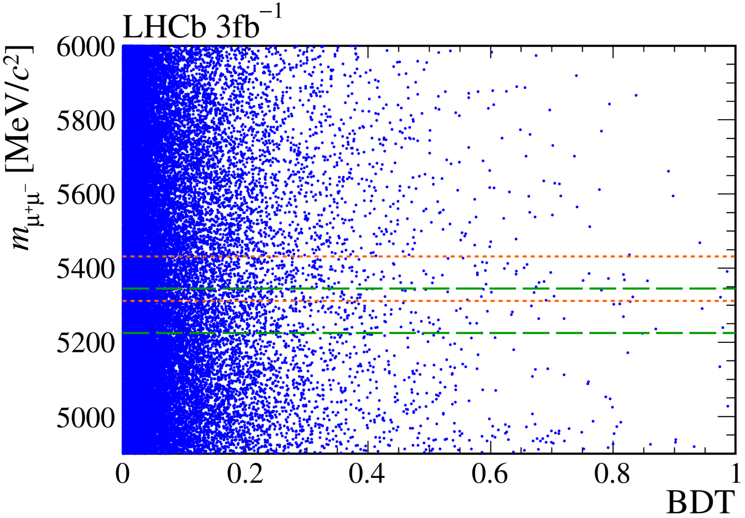
Therefore we have a bias that depends on the MC model used to calculate the efficiency

$$\delta_\epsilon = \frac{\epsilon^{\mathcal{A}_{\Delta\Gamma}, y_s}}{\epsilon^{MC}} = \frac{\int_0^\infty e^{-\Gamma_{\mathcal{A}_{\Delta\Gamma}, y_s}} \epsilon(t)dt}{\int_0^\infty (e^{-\Gamma_{\mathcal{A}_{\Delta\Gamma}, y_s}})dt} \times \frac{\int_0^\infty e^{-\Gamma_{MC} t}dt}{\int_0^\infty e^{-\Gamma_{MC} t}\epsilon(t)dt} \tag{1}$$

This correction is model dependent, we only produce results with SM correction, in the future also model dependent results.

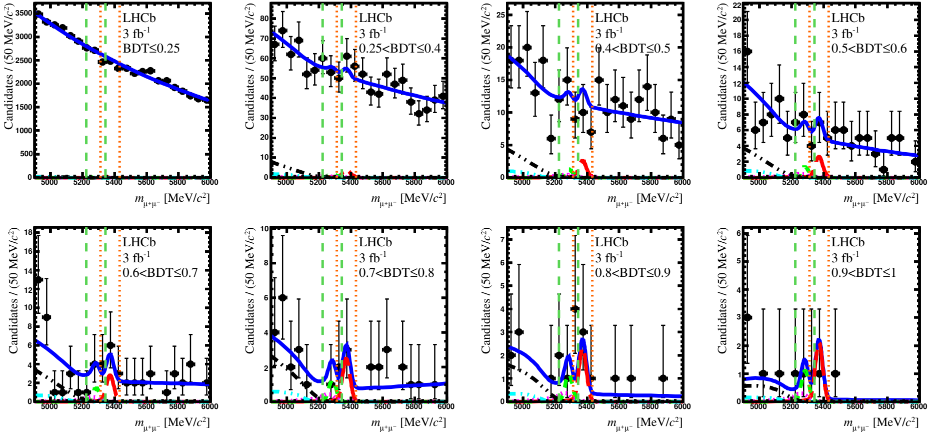


Opening the box

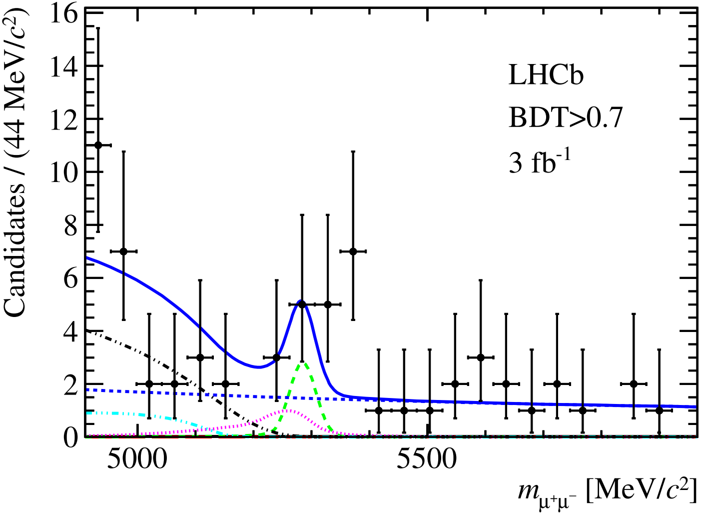


Full fit

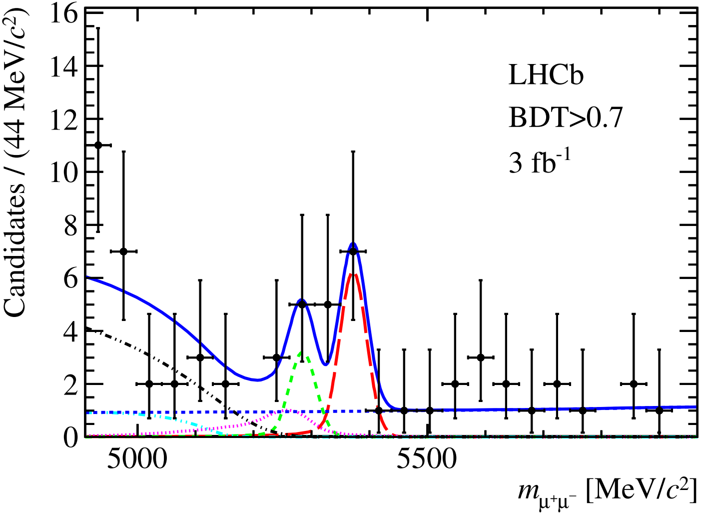
- Unbinned maximum likelihood fit simultaneous in the 8 BDT bins



Opening the box



Opening the box



Results

The full fit gives the following central values

$$\mathcal{B}(B_s \to \mu^+\mu^-) = 2.9^{+1.1}_{-1.0}(stat)^{+0.3}_{-0.1}(syst) \times 10^{-9}$$

with a significance of 4.0σ

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.7^{+2.4}_{-2.1}(stat)^{+0.6}_{-0.4}(syst) \times 10^{-10}$$

with a significance of 2.0σ

- Systematic uncertainty obtained from total minus statistics (in quadrature)
- Plus additional component due to $\Lambda_b^0 \to p\mu^-\nu$ background
- Given no evidence of $B_s \to \mu^+\mu^-$ the following upper limit has been put:

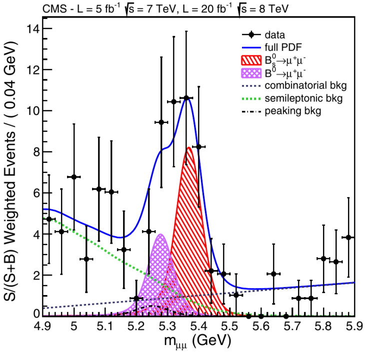
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 6.3(7.4) \times 10^{-10} \text{at } 90\ (95)\% \text{ CL}$$

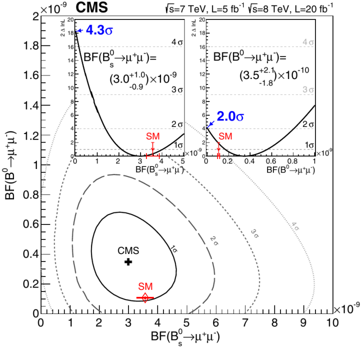
A word on uncertainties

- Statistics, statistics, statistics...
- f_s/f_d error is now down to 6%
- Some backgrounds still with unknown branching fractions, e.g. $\Lambda_b^0 \to p\mu^-\nu$
- Total theoretical error is now 6.4% with some caveats

Our CMS friends

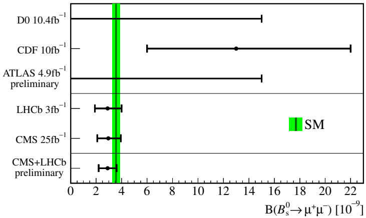
- Analysis of full Run I dataset (25 fb^{-1})
- 4.3 σ evidence of $B_s \to \mu^+\mu^-$ with $\mathcal{B} = 3.0^{+1.0}_{-0.9} \cdot 10^{-9}$
- $B^0 \to \mu^+\mu^-$ significance of 2.0σ with $\mathcal{B} = 3.5^{+2.1}_{-1.8} \cdot 10^{-10}$

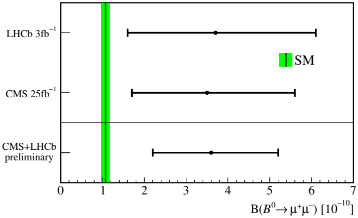


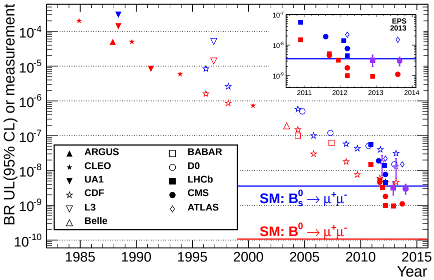


Simple combination of LHCb and CMS results

- Combination of central values
- No significance assessment



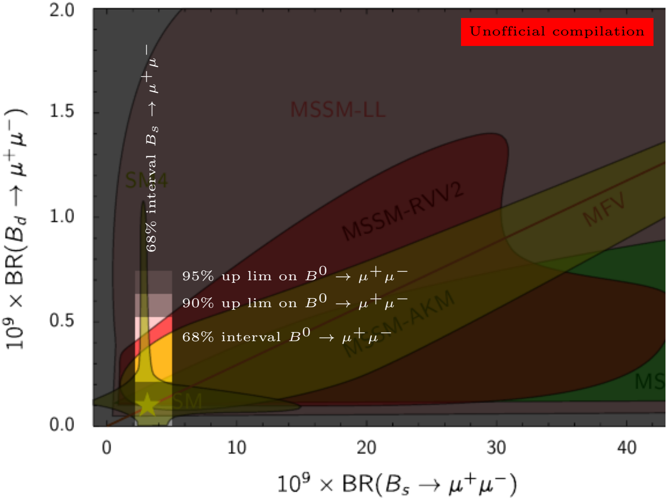




Averages:

- $\mathcal{B}(B_s\to\mu^+\mu^-) = (2.9\pm0.7)\cdot10^{-9}$
- $\mathcal{B}(B^0\to\mu^+\mu^-) = 3.6^{+1.6}_{-1.4}\cdot10^{-10}$

Implications for New Physics models



Full combination of LHCb and CMS results

- Full combination of the two measurements is currently being performed
- Simultaneous fits with shared parameters
- Common inputs like f_d/f_s and $\mathcal{B}$ of control channels also shared
- Outputs: combined branching fractions, combined significances, full 2D contour
- Assessment in terms of $\mathcal{B}/\mathcal{B}_{SM}$ also in place

Future of $B_{d,s} \to \mu^+\mu^-$ at LHCb

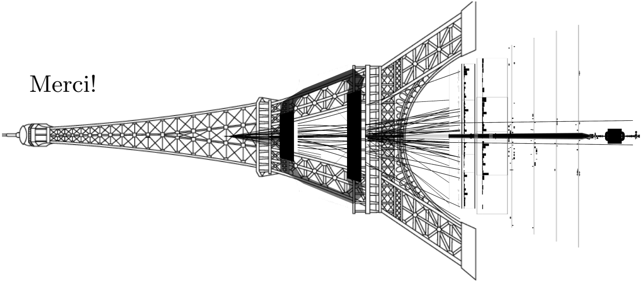
The study of $B_{d,s} \to \mu^+\mu^-$ decays will remain a key point for LHCb

- Full combination with CMS
- Precision measurement of $\mathcal{B}(B_s \to \mu^+\mu^-)$
- Constraints on $\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s \to \mu^+\mu^-)$ and search for $B^0 \to \mu^+\mu^-$ with larger statistics
- Measurement of the effective lifetime

Conclusions

- $B_{d,s} \to \mu^+\mu^-$ decays are tightening the space for NP models
- Presence of $B_s \to \mu^+\mu^-$ is now well established with rate compatible with SM
- $B_s \to \mu^+\mu^-$ will stay a golden channel for LHCb physics program, but also for other LHC experiments
- Uncertainties are still dominated by statistics... waiting for RunII

Merci!



Backup