technische universität
dortmund

Federal Ministry
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and Research

LHCb

$B^0_{(s)} \rightarrow \mu^+\mu^-$ combination at the LHC

Discovery Physics at the LHC, Kruger 2014

1st – 5th December 2014

Maximilian Schlupp
on behalf of the CMS and LHCb
collaborations

History in a nutshell

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Two-body decays of B mesons

Various exclusive and inclusive decays of B mesons have been studied using data taken with the CLEO detector at the Cornell Electron Storage Ring. The exclusive modes examined are mostly decays into two hadrons. The branching ratio for a B meson to decay into a charmed meson and a charged pion is found to be about 2%. Upper limits are quoted for other final states ψK^-, $\pi^+\pi^-$, $\rho^0\pi^-$, $\mu^+\mu^-$, e^+e^-, and $\mu^\pm e^\mp$. We also give an upper limit on inclusive ψ production and improved charged multiplicity measurements.

B. Search for exclusive $\overline{B}^0$ decays into two charged leptons

Our search for the $\pi^+\pi^-$ final state is not sensitive to the mass of the final-state particles, provided that they are light, since the mass enters only in the energy constraint. Therefore, the upper limit of 0.05% applies for any final-state particles with a pion mass or less. When the final-state particles are leptons the limits are improved by using the lepton identification capabilities of the CLEO detector.[14] For the decay $\overline{B}^0\to\mu^+\mu^-$, we improve our limit by requiring that both muons penetrate the iron and produce signals in drift chambers. We find no such events. After correcting for detection efficiency (33%), we set an upper limit of 0.02% at 90% confidence for this decay. We improve our limit for $\overline{B}^0\to e^+e^-$ by requiring that only one of the electrons be positively identified in the dE/dx and shower-chamber systems. One found candidate, coupled with a detection efficiency of 33%, gives a 90%-confidence-level upper limit of 0.03%. Finally, for the decay $\overline{B}^0\to\mu^\pm e^\mp$, we require the muon to be identified but the electron needs to be positively identified if it is in the fiducial volume of the electron detectors. This procedure gives an efficiency of 42%. The two candidate

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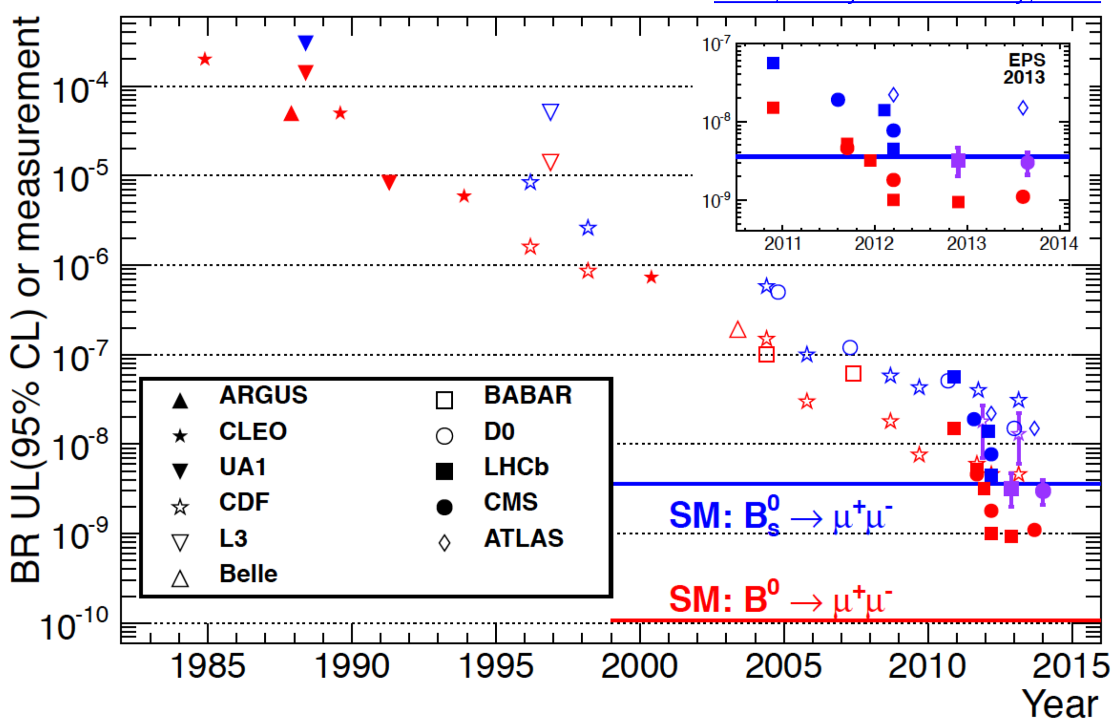
CMS, B-Physics Summary, 2013

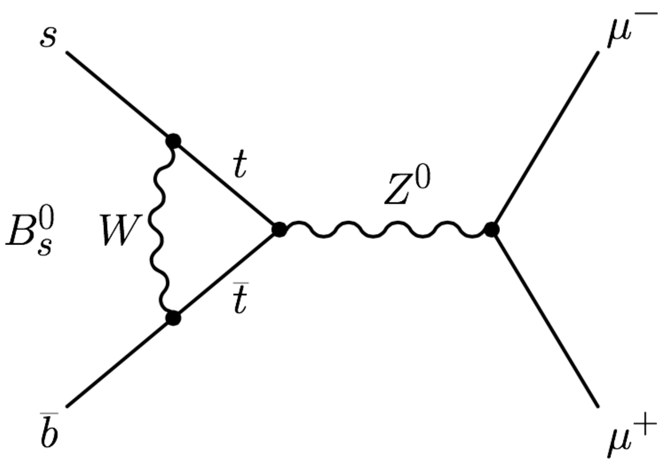


Motivation – Why B→μμ in the first place

- Highly suppressed in the Standard Model (SM)
  - Flavour Changing Neutral Current
  - **Helicity suppressed** in SM weak interaction

  - Low energy effective branching fraction

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\mathrm{SM}} \propto \frac{m_\mu^2}{M_{B_s^0}^2} \times |\mathcal{C}_{10}|^2$$



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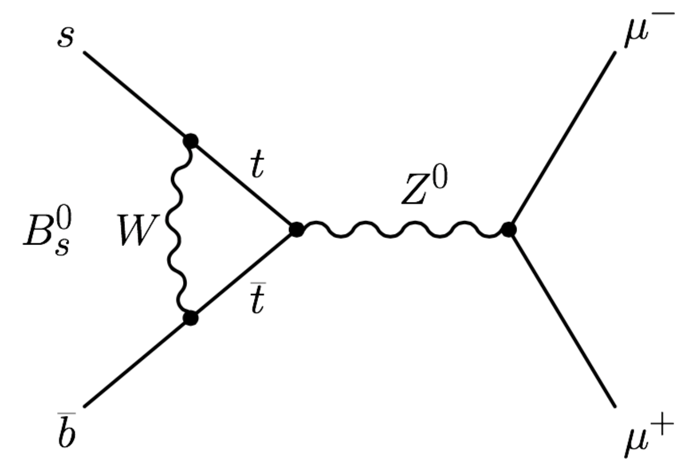
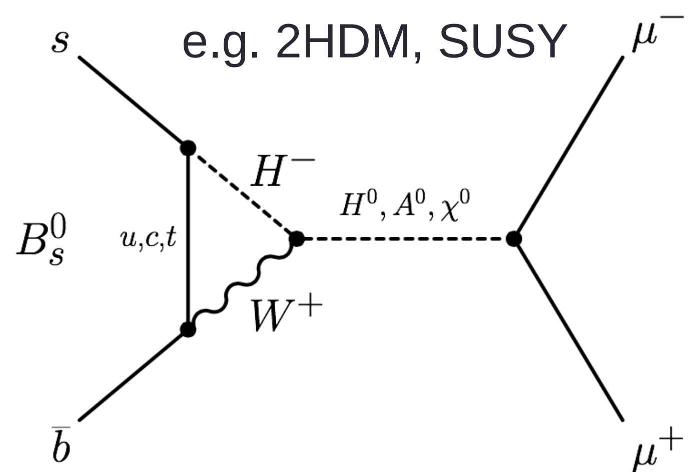


- "New Physics" (NP) with enlarged scalar/pseudoscalar sector

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) \propto |\mathcal{S}|^2 + \left|\mathcal{P} + \frac{m_\mu}{M_{B_s^0}}(\mathcal{C}_{10} + \mathcal{C}_{10}^{\mathrm{NP}})\right|^2$$

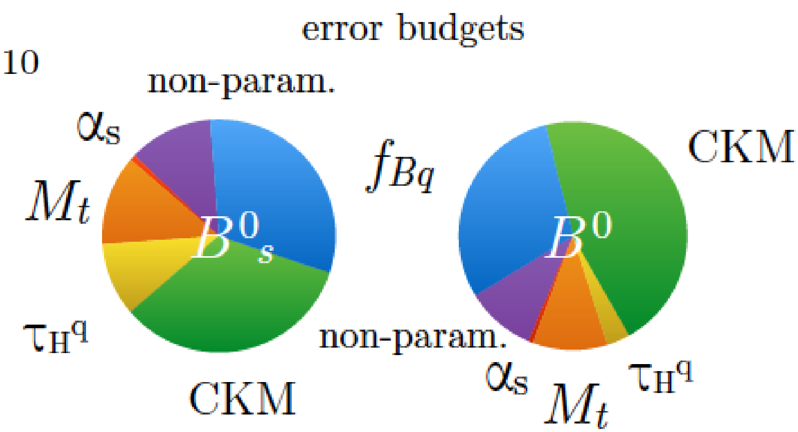
e.g. 2HDM, SUSY



- Time integrated branching fraction predictions

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

Bobeth et al., PRL 112(2014) 101801*

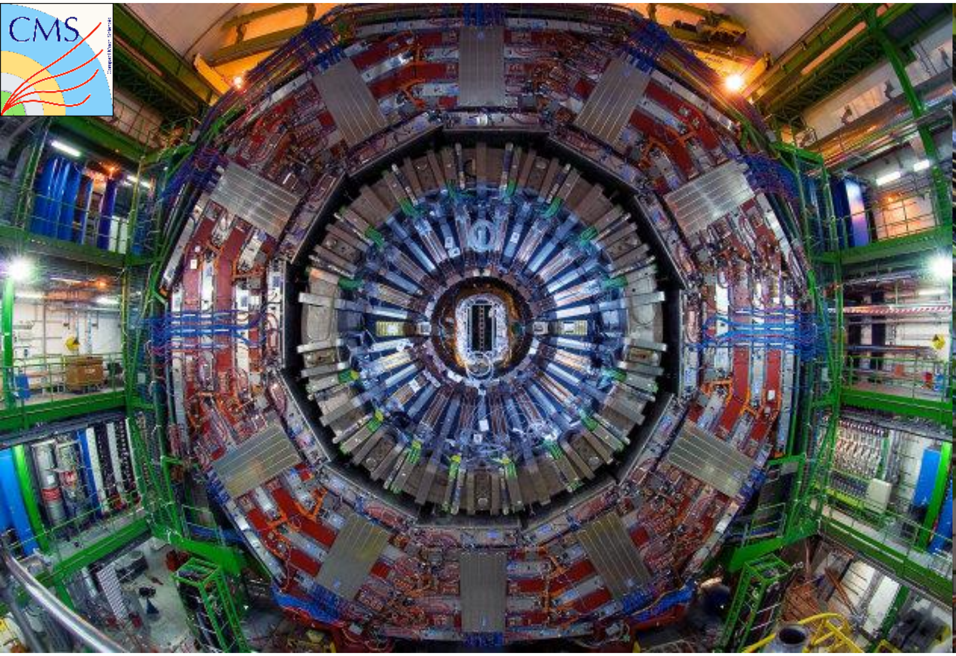


- Ratio of branching fractions powerful to discriminate between NP models (Minimal Flavour Violation) & precisely predicted within the SM

$$\mathcal{R} = \frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)} = 0.0295^{+0.0028}_{-0.0025}$$

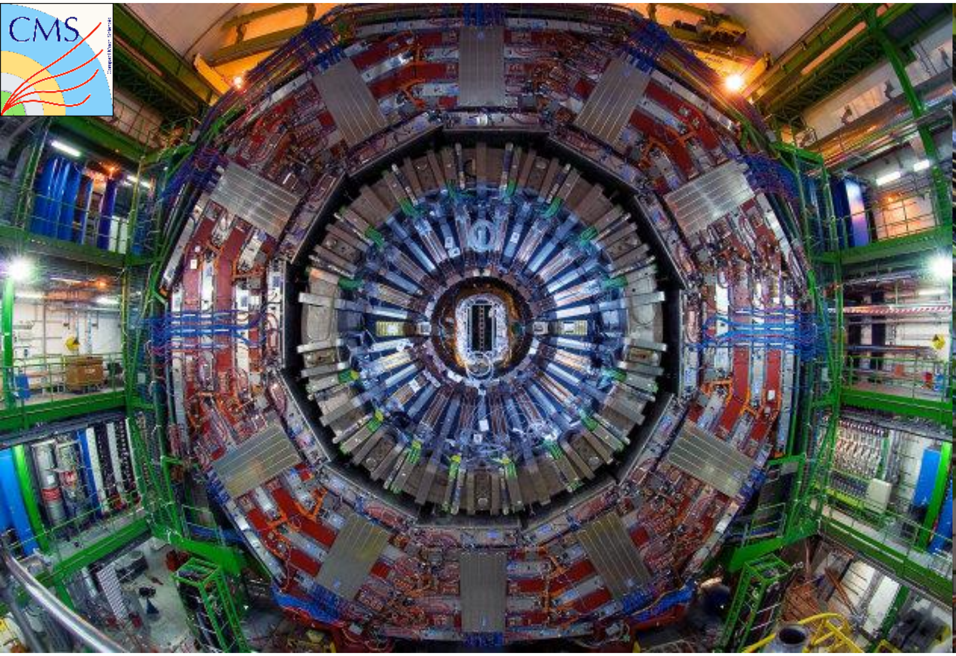
*updated with latest top quark mass measurement (Tevatron & LHC)
arXiv:1403.4427 [hep-ex]

Experiments & Dataset



- Multipurpose 4π-detector ($-2.4<\eta<2.4$)
- Single-arm forward spectrometer ($2<\eta<5$) designed to study b- & c-quarks

Experiments & Dataset

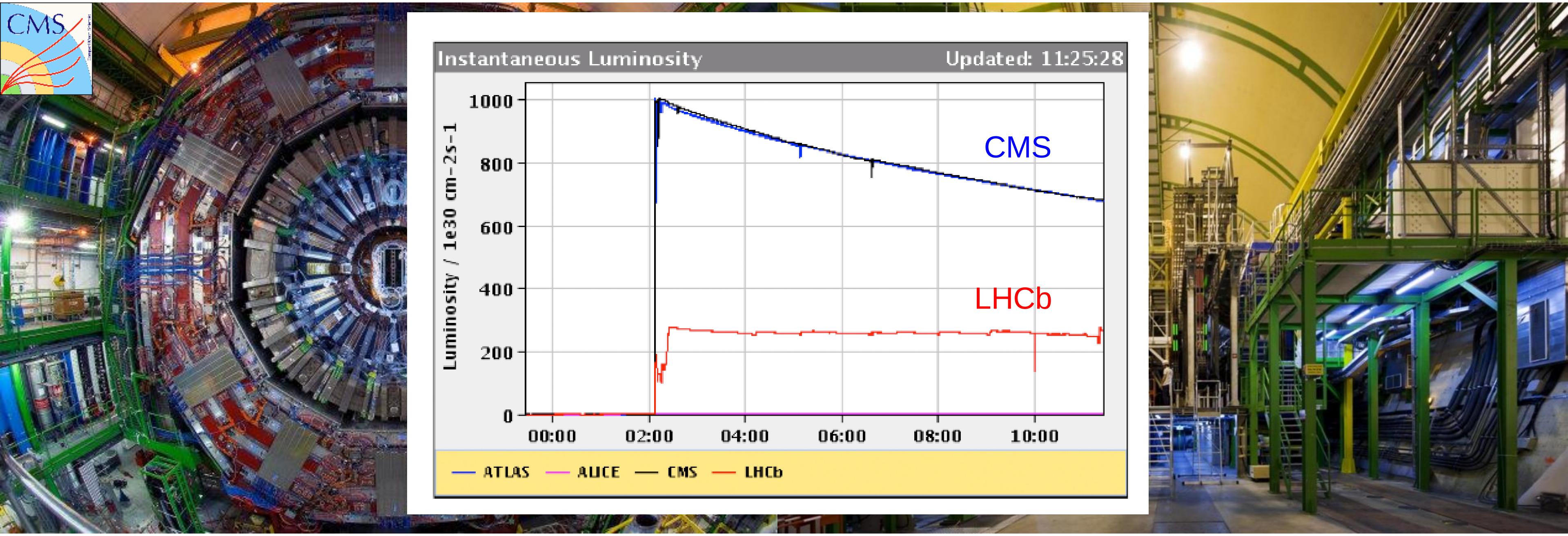


- Multipurpose 4π-detector ($-2.4<\eta<2.4$)
- Single-arm forward spectrometer ($2<\eta<5$) designed to study b- & c-quarks

- Good B / muon trigger (39-85%)
- Good muon PID
  (90% $\mu \rightarrow \mu$ and 0.04-0.2% $h \rightarrow \mu$)
- No hadron PID
- Di-muon mass resolution 32-75 MeV/c^2
- Excellent (primary) vertex resolution

- Excellent B / muon trigger (92%)
- Good muon PID
  (97% $\mu \rightarrow \mu$ and 0.03-0.8% $h \rightarrow \mu$)
- Good hadron PID
- Di-muon mass resolution 25 MeV/c^2
- Excellent (primary) vertex resolution

Experiments & Dataset



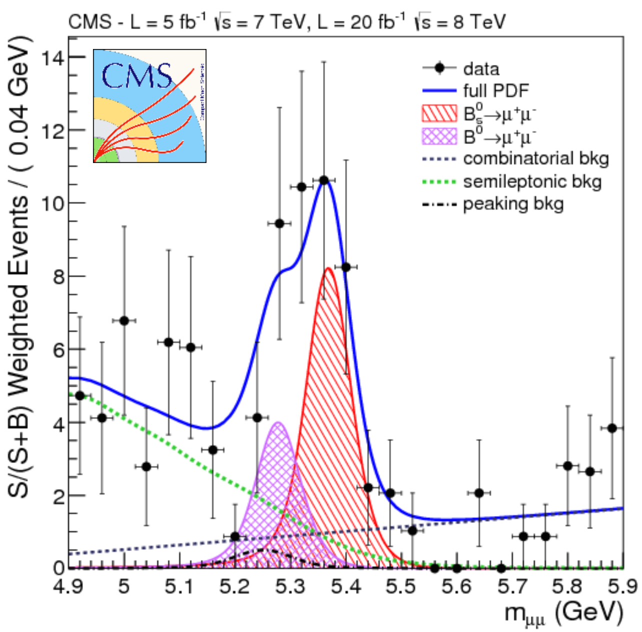
- CMS runs at highest possible instantaneous luminosity
  - Much higher multiple pp interactions
    <μ> = 21
  - Much higher integrated luminosity
    5 fb^{-1} @ 7 TeV
    20 fb^{-1} @ 8 TeV

- LHCb "levels" luminosity to have stable conditions throughout a fill
  - Less multiple pp interactions
    <μ> = 1.79
  - Less integrated luminosity
    1 fb^{-1} @ 7 TeV
    2.1 fb^{-1} @ 8 TeV

➔ Results in roughly equal sensitivity for $B^0_{(s)} \rightarrow \mu^+\mu^-$ in Run I

- Single experiment's results were presented at EPS 2013

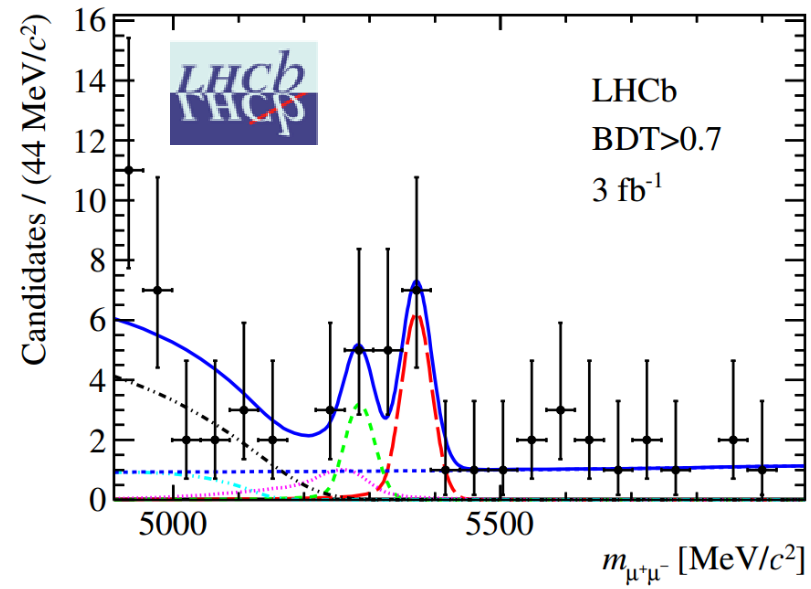
PRL 11 (2013) 101804



$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = 3.0^{+1.0}_{-0.9} \times 10^{-9} \quad (4.3\sigma)$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.5^{+2.1}_{-1.8} \times 10^{-10} \quad (2.0\sigma)$$

PRL 11 (2013) 101805



$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = 2.9^{+1.1}_{-1.0} \times 10^{-9} \quad (4.0\sigma)$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.7^{+2.4}_{-2.1} \times 10^{-10} \quad (2.0\sigma)$$

- Prelim. Combination

"[…], it is clear that the $B^0_s \to \mu^+\mu^-$ decay is observed (i.e. >5σ), while the yield of $B^0 \to \mu^+\mu^-$ decays is not statistically significant (i.e. <3σ)"

LHCb-CONF-2013-012
CMS-PAS-BPH-13-007

Full combination

- Perform full likelihood combination

- Results extracted from the combined dataset
  - Branching fractions for $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$
  - Ratio of branching fractions
  - Signal strength relative to the SM

  } directly from fit

- Crucial: calculate combined significances
  → Have one/two dimensional confidence regions for each result evaluated using Wilks' Theorem
  → Feldman-Cousins based method
    - Cross-check confidence intervals and significance for $B^0 \to \mu^+\mu^-$
    - Validate assumption that Wilks' Theorem holds

Full Combination

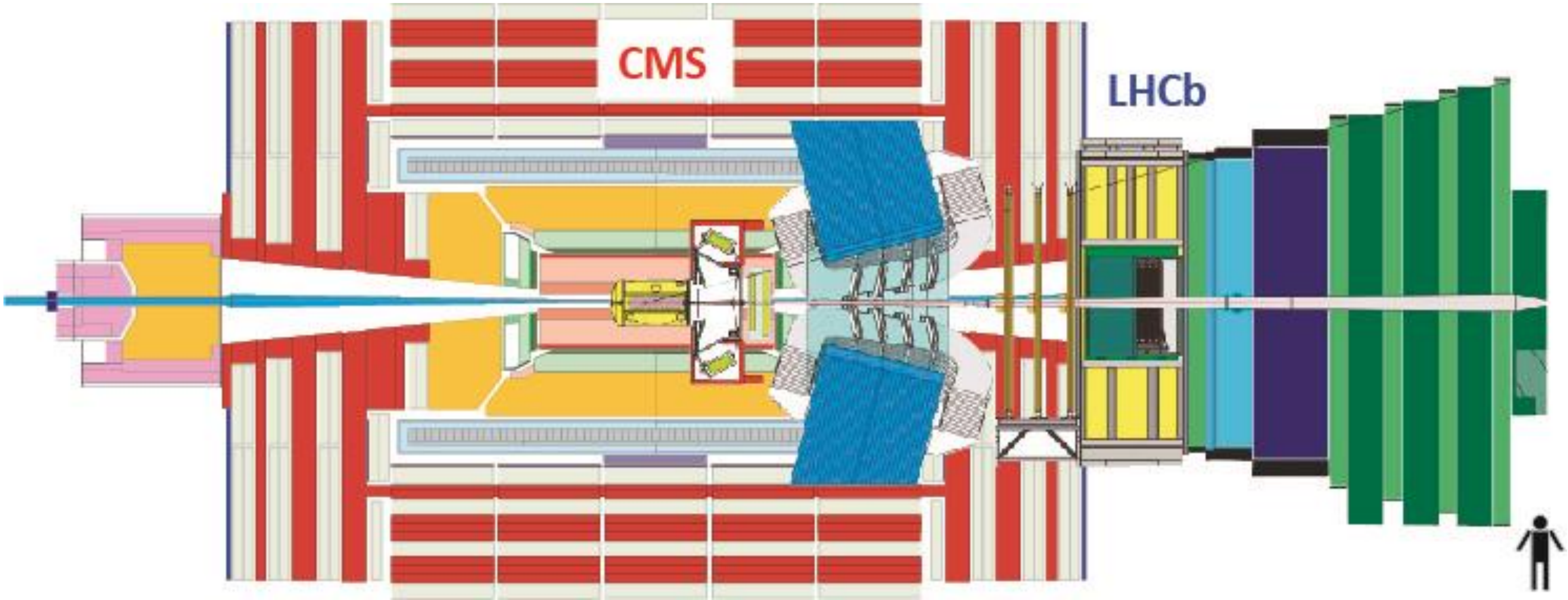
- Both collaborations used very similar analysis strategies
  - Soft preselection
  - Multivariate classifier (BDT) for signal/background separation
    - Fit invariant mass distribution ($m_{\mu\mu}$) in bins of the BDT
  - Normalize with $B^+ \to J/\psi K^+$ with $J/\psi \to \mu^+\mu^-$ (also $B^0 \to K^+\pi^-$ for LHCb)

- Necessary changes to harmonize the analyses
  - Align $\Lambda^0_b \to p\mu^-\nu$ background component
    - Include in both fit models
    - Update branching fractions and Monte Carlo simulated events to have more realistic decay properties
  - Calculate and apply lifetime bias correction
  - Update to latest ratio of hadronization fractions $f_s/f_d = 0.259 \pm 0.015$

LHCb-CONF-2013-011

After harmonization you can start combining…

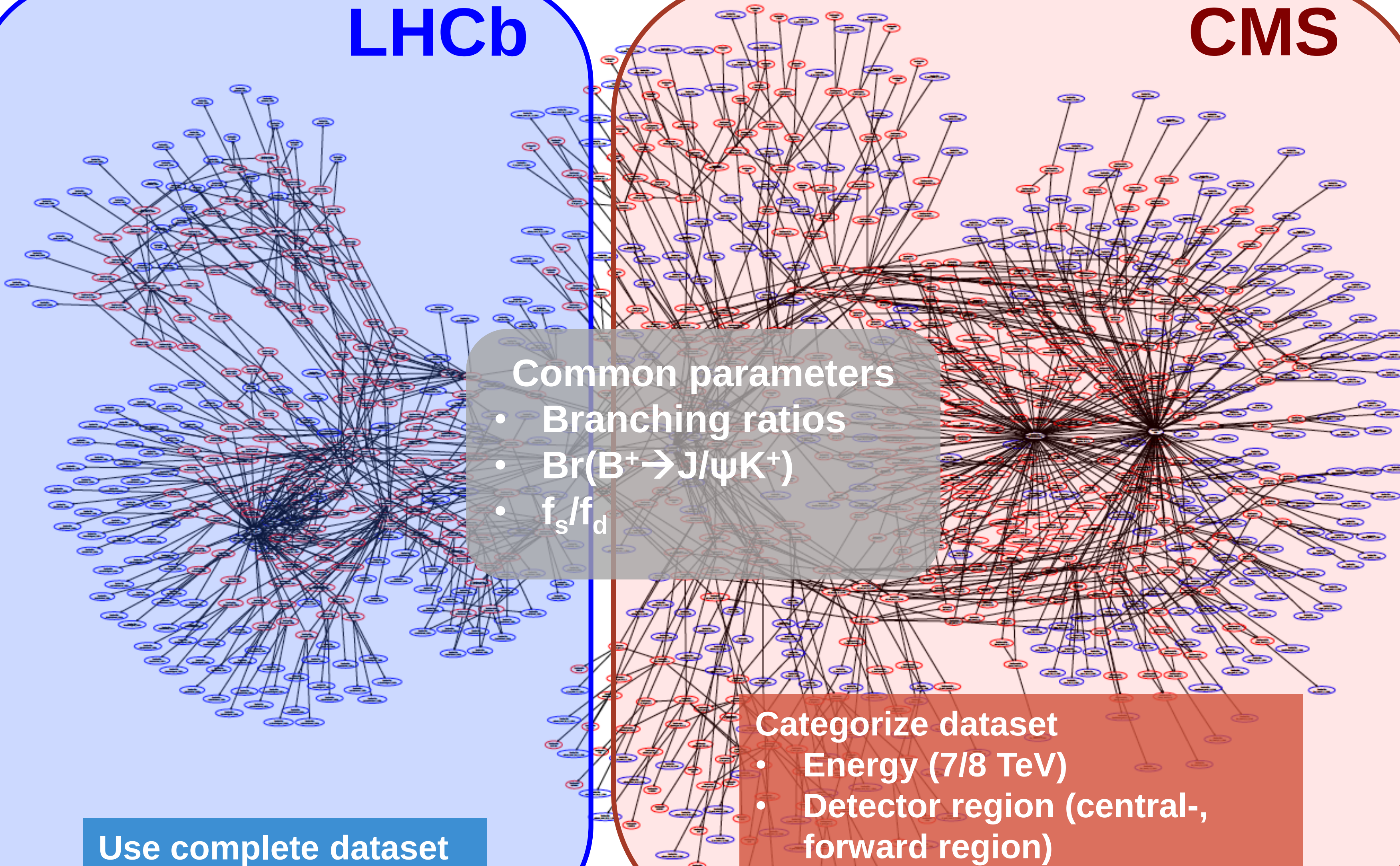
Combine the dataset



Combine the fit models

LHCb

CMS



Common parameters

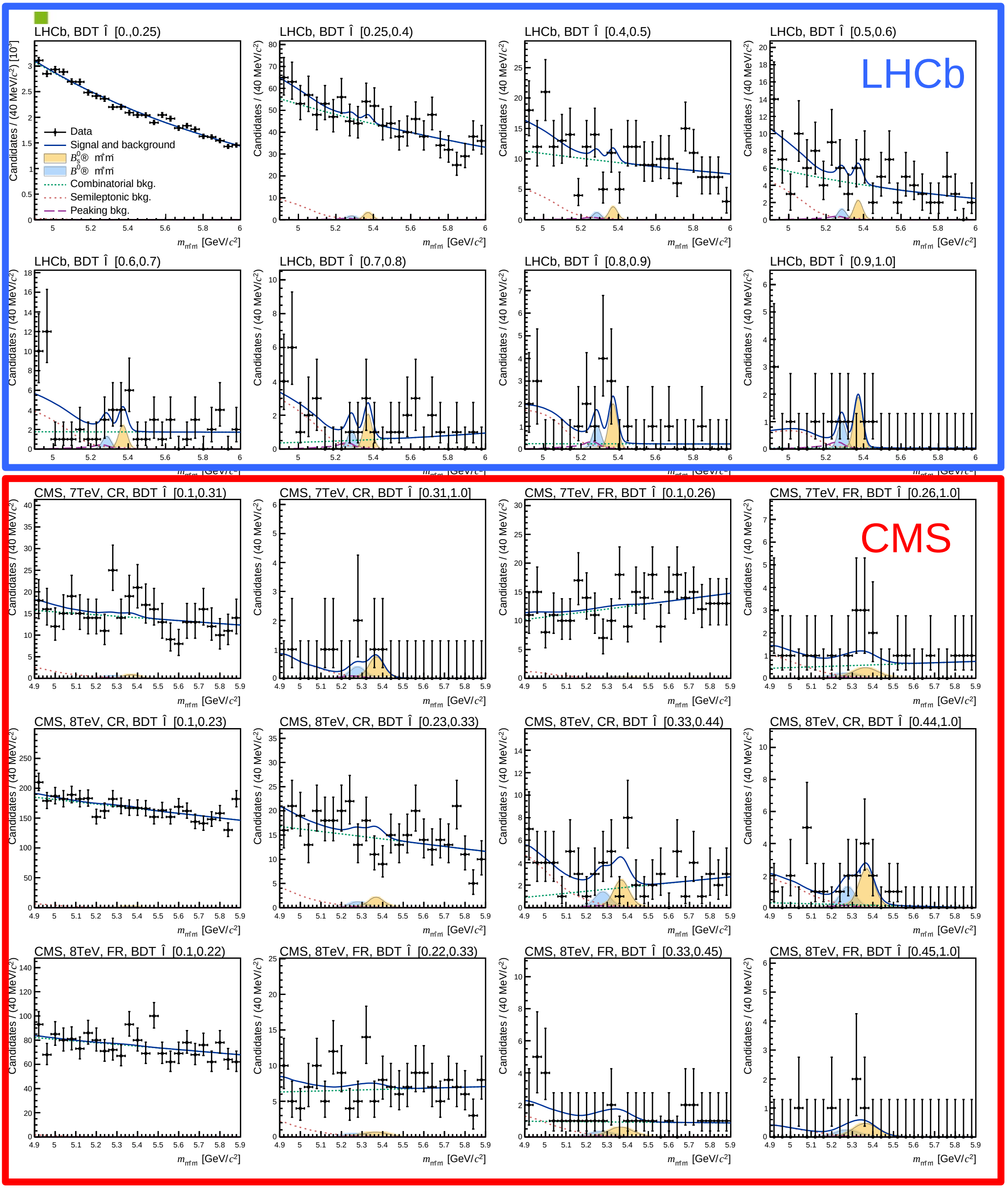
- Branching ratios
- $Br(B^+ \to J/\psi K^+)$
- f_s/f_d

Use complete dataset
Fit in 8 bins of BDT

Categorize dataset

- Energy (7/8 TeV)
- Detector region (central-, forward region)

Fit in 2/4 bins of BDT (12 in total)



Full mass fit

- Simultaneous unbinned maximum likelihood fit
  - 20 bins of BDT

CMS & LHCb, arXiv:1411.4413 [hep-ex]

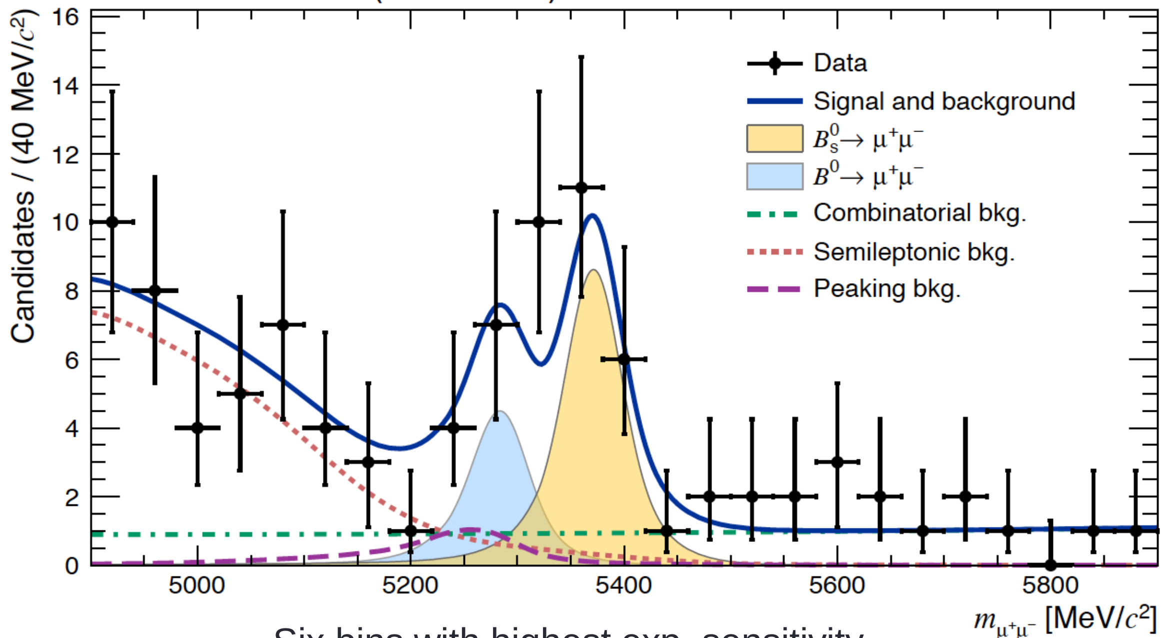
Simultaneous fit result

- Branching fractions

$$\mathcal{B}\left(B_s^0 \to \mu^+\mu^-\right) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

$$\mathcal{B}\left(B_d^0 \to \mu^+\mu^-\right) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$$

CMS and LHCb (LHC run I) [CMS & LHCb, arXiv:1411.4413 [hep-ex]]



Six bins with highest exp. sensitivity

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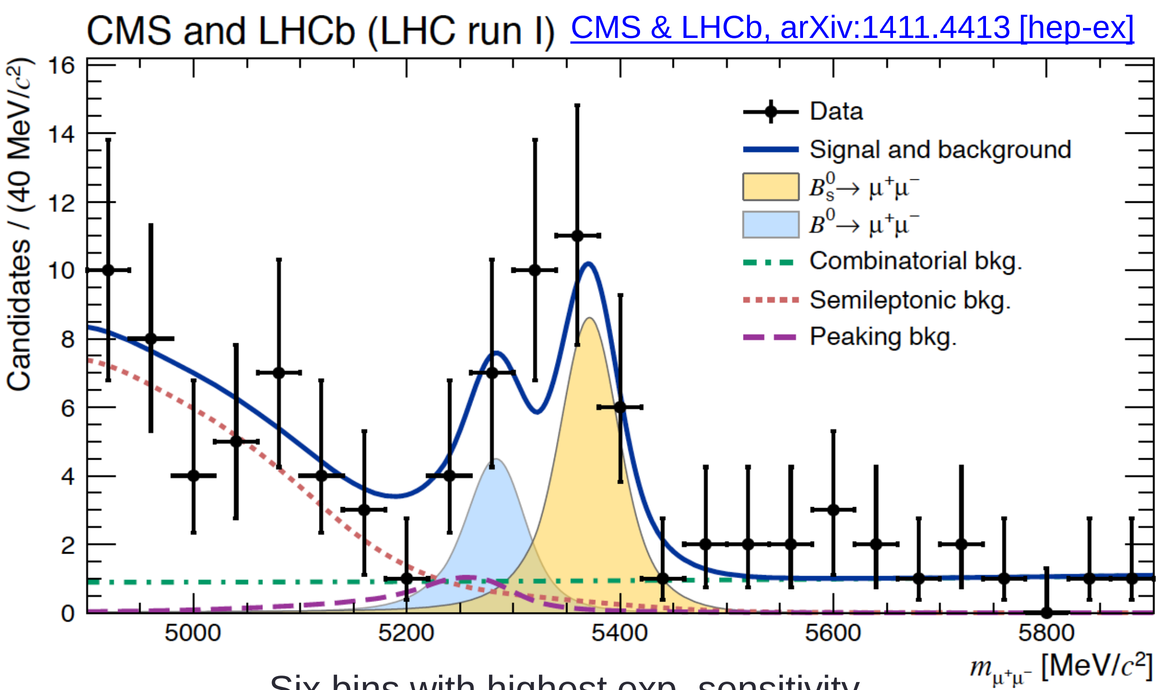

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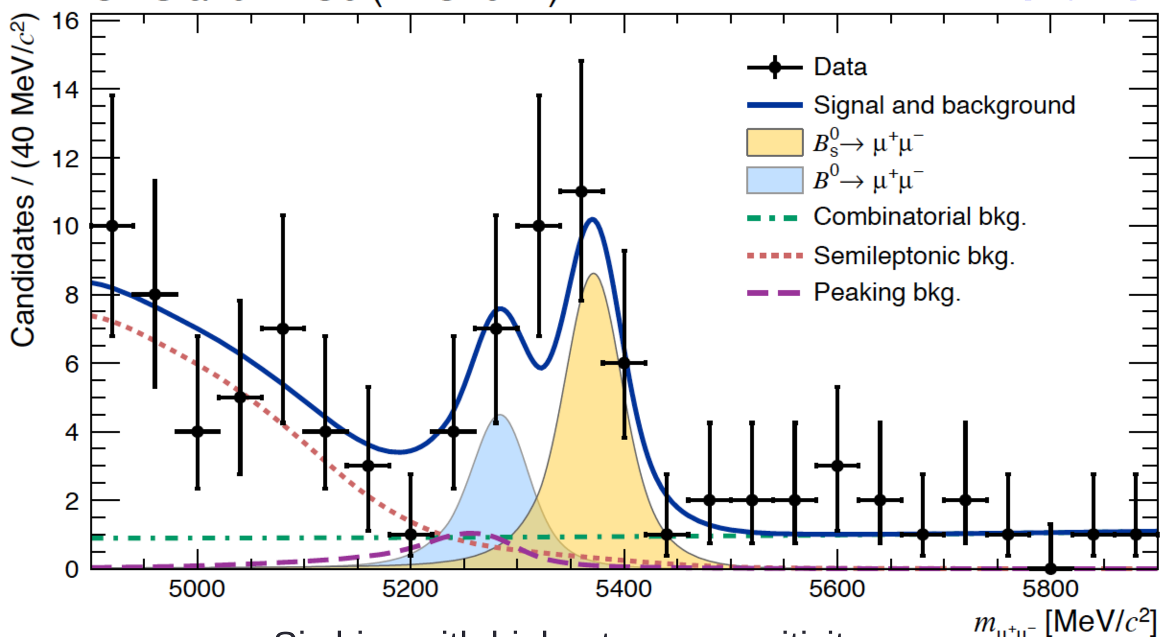
- Using Wilks' theorem

6.2σ for $B^0_s \to \mu^+\mu^-$
First observation
(exp. SM 7.6σ)

3.2σ for $B^0 \to \mu^+\mu^-$
First evidence
(exp. SM 0.8σ)

CMS and LHCb (LHC run I) [CMS & LHCb, arXiv:1411.4413 [hep-ex]]

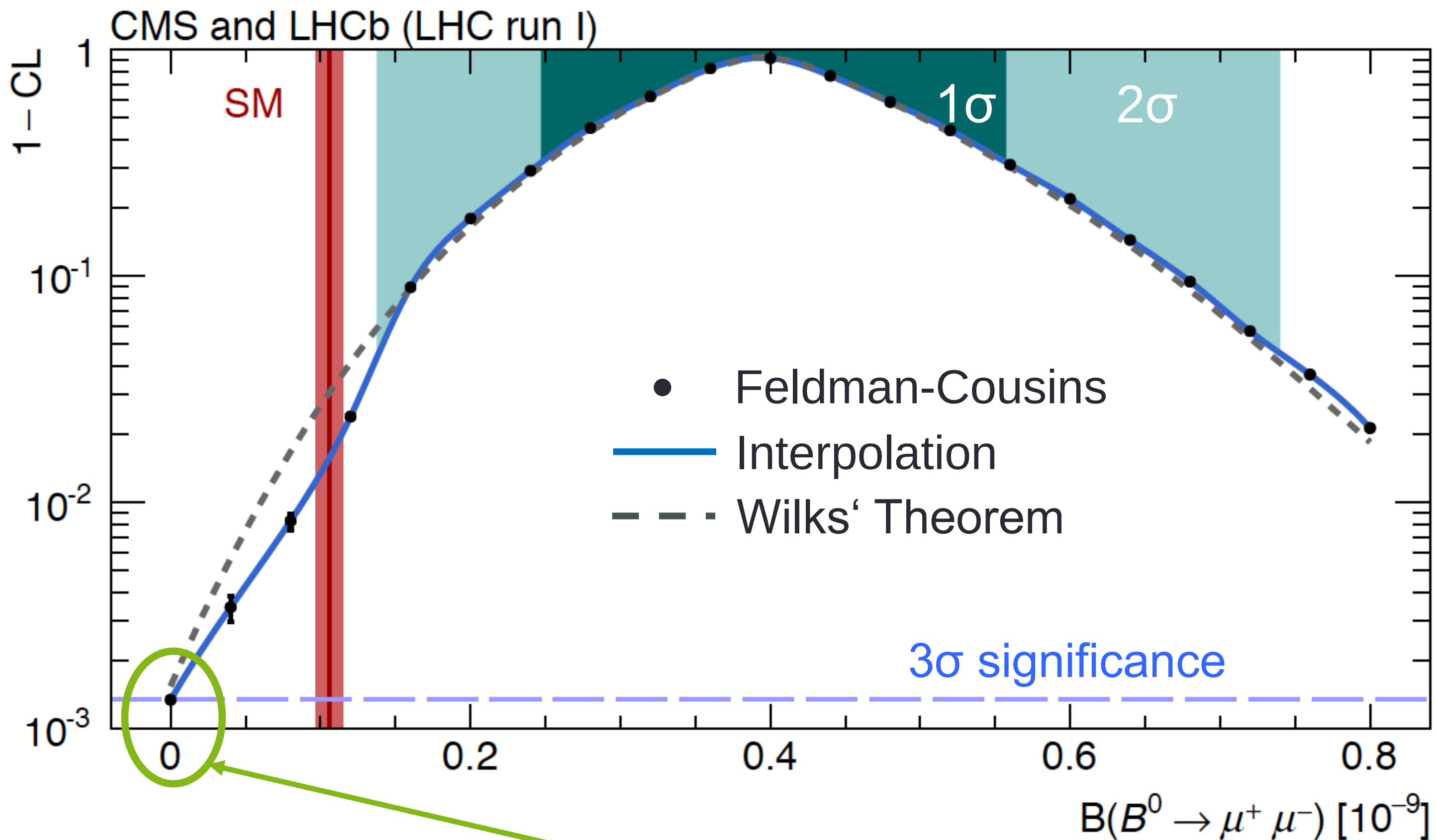


Six bins with highest exp. sensitivity

- B^0 signal close to 3σ
- Possible effect of physical boundary of non-negative branching fractions

→ Cross-check B^0 signal with more sophisticated statistical method

Cross-check I: Significance



CMS & LHCb, arXiv:1411.4413 [hep-ex]

- Feldman-Cousins: perform many hypothesis tests based on pseudo experiments
  - Avoids boundary problem
  - Better coverage

- p-Value wrt. the no B^0 signal hypothesis
  $p = (1.34 \pm 0.05) \times 10^{-3}$

  Corresponds to 3.0σ
  → Confirms significance from Wilks' Theorem

Cross-check II: Confidence Intervals

- Confidence intervals from Feldman-Cousins procedure

$$\mathcal{B}\left(B^0 \to \mu^+\mu^-\right) \in [2.5, 5.6] \times 10^{-10} \text{ @ } 68.3\% \text{ CL}$$

Wilks' $[2.5, 5.6] \times 10^{-10}$ @ 68.3% CL

$$\mathcal{B}\left(B^0 \to \mu^+\mu^-\right) \in [1.4, 7.4] \times 10^{-10} \text{ @ } 95.5\% \text{ CL}$$

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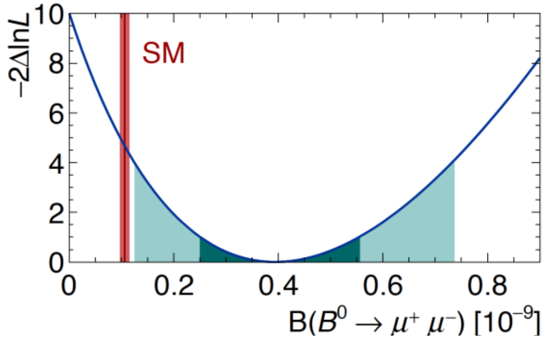

CMS & LHCb, arXiv:1411.4413 [hep-ex]

→ Excellent agreement between FC and Wilks' theorem

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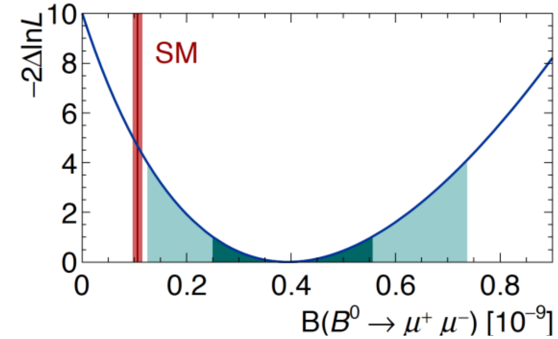

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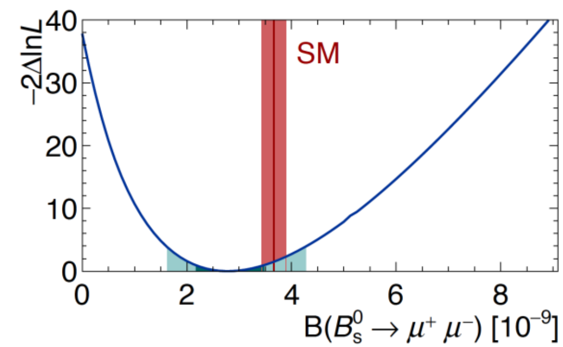
Wilks‘	$[1.3, 7.4] \times 10^{-10}$ @ 95.5% CL

→ Excellent agreement between FC and Wilks' theorem

- Confidence intervals for B^0_s (Wilks‘)

$$\mathcal{B}\left(B^0_s \to \mu^+\mu^-\right) \in [2.2, 3.5] \times 10^{-9} \text{ @ } 68.3\% \text{ CL}$$

$$\mathcal{B}\left(B^0_s \to \mu^+\mu^-\right) \in [1.6, 4.3] \times 10^{-9} \text{ @ } 95.5\% \text{ CL}$$



CMS & LHCb, arXiv:1411.4413 [hep-ex]

Signal strength

- Signal strength

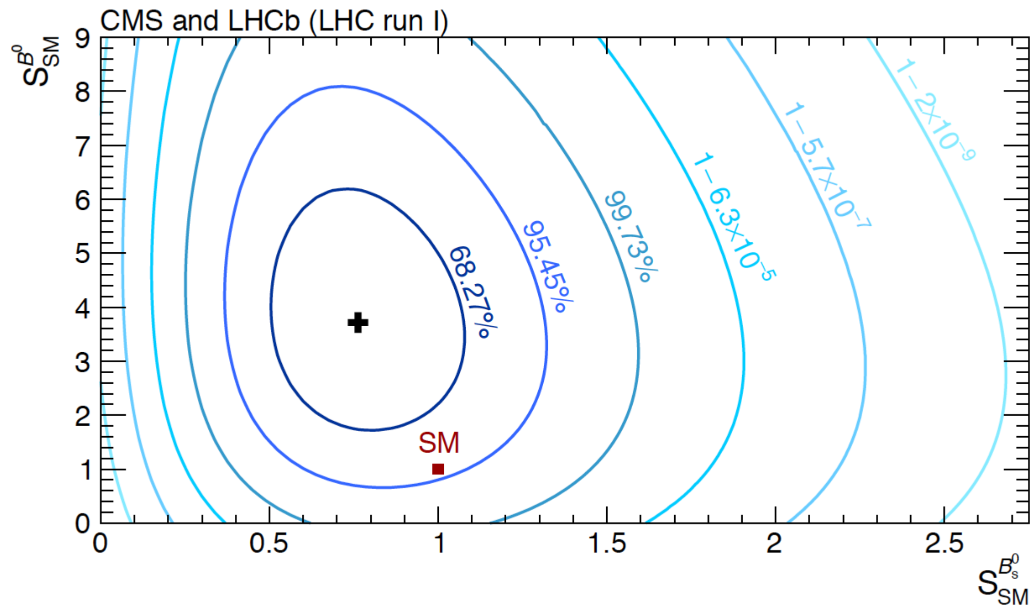
$$\mathcal{S}_{\rm SM}^{B^0_{(s)}} = \frac{\mathcal{B}(B^0_{(s)}\to\mu^+\mu^-)}{\mathcal{B}(B^0_{(s)}\to\mu^+\mu^-)^{\rm SM}}$$

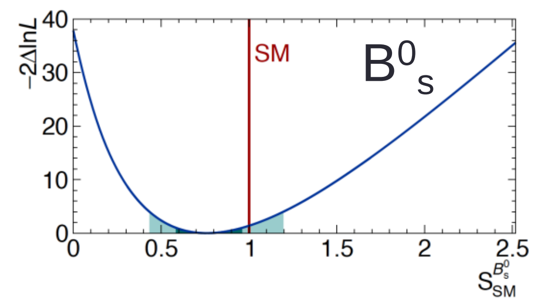
- Theoretical uncertainties included in the fits

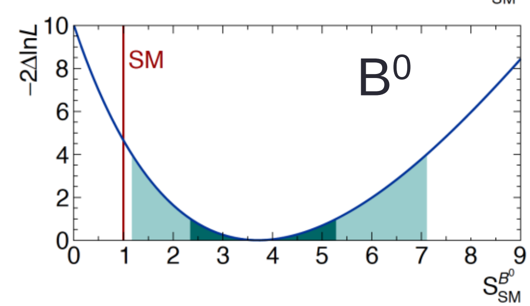
$$\mathcal{S}_{\rm SM}^{B^0_s} = 0.76^{+0.20}_{-0.18}$$

$$\mathcal{S}_{\rm SM}^{B^0} = 3.7^{+1.6}_{-1.4}$$

→ Compatible with the SM within 1.2σ for B^0_s and 2.2σ for B^0

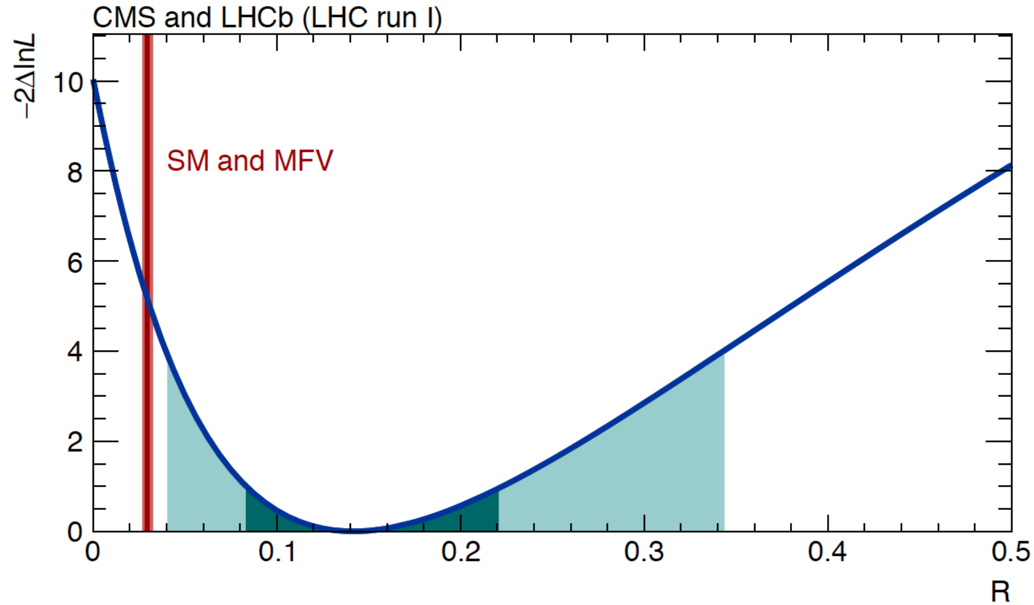






CMS & LHCb, arXiv:1411.4413 [hep-ex]

Ratio of branching fractions



- Ratio of branching fractions as test for MVF models

$$\mathcal{R} = \frac{\mathcal{B}\left(B^0 \to \mu^+\mu^-\right)}{\mathcal{B}\left(B_s^0 \to \mu^+\mu^-\right)}$$

- RunI CMS+LHCb result

$$\mathcal{R} = 0.14^{+0.08}_{-0.06}$$

$$\mathcal{R}_{\mathrm{SM}} = 0.0295^{+0.0028}_{-0.0025}$$

Compatible with the SM within 2.3σ (including theoretical uncertainties)

CMS & LHCb, arXiv:1411.4413 [hep-ex]

Summary

- Combined CMS+LHCb analysis of $B^0_s \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ decays with the full Run I dataset
- The decay $B^0_s \rightarrow \mu^+\mu^-$ is observed with a significance of 6.2σ
  - Compatible with the SM within 1.2σ
- First evidence for the decay $B^0 \rightarrow \mu^+\mu^-$ with an excess of 3.2σ over the background-only hypothesis
  - Compatible with the SM within 2.2σ
- The ratio of the branching fractions is measured to be consistent with the SM within 2.3σ

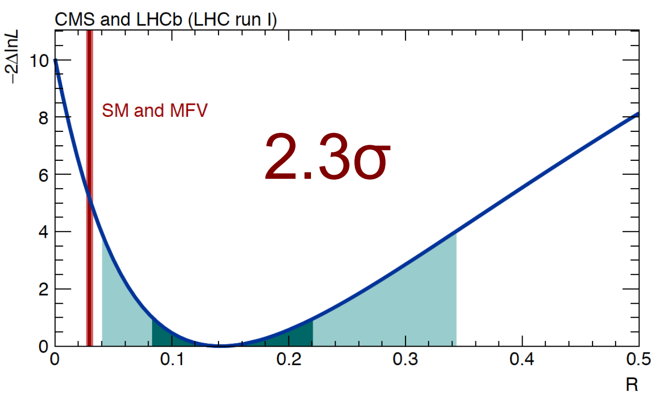
Outlook

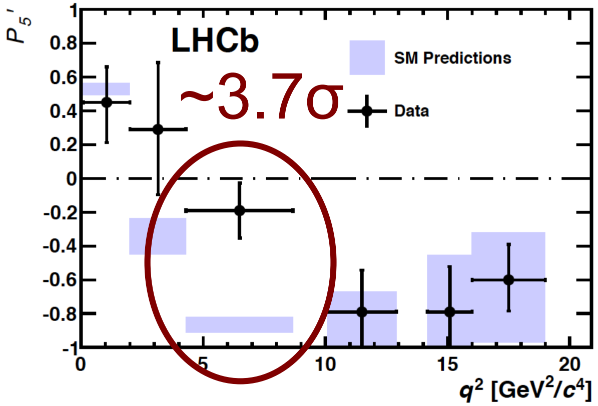
- This is just the beginning
- Precision of 25% for B^0_s and 38% for B^0 leaves room for surprises
- Is the excess in B^0 a lucky/unlucky fluctuation?

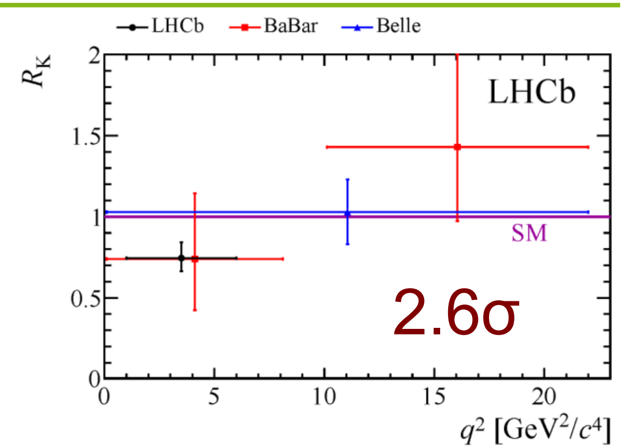
$$\mathcal{S}_{\mathrm{SM}}^{B^0} = 3.7^{+1.6}_{-1.4}$$

- $B^0 \rightarrow \mu^+\mu^-$ plays crucial role in future studies
- **If** central values are correct, ratio of branching fractions provides inside of the flavour structure of “new physics”
- First measurements of the effective lifetime of $B^0_s \rightarrow \mu\mu$ as orthorgonal observable in Run II

Reading the tea leaves







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

$B^0 \to K^{*0}\mu^+\mu^-$ (P_5' anomaly)

$R_K = \dfrac{B^+ \to K^+\mu^+\mu^-}{B^+ \to K^+e^+e^-}$

- Standard Model overwhelmingly successful in LHC Run I
- But interesting anomalies started to show up(?)
  - $B^0 \to K^{*0}\mu^+\mu^-$ depends on parametrization
  - In very clean decays
- LHC Run II is eagerly awaited

Spares

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2D condifence contours