$B \to \mu^+\mu^-$ rare decays at CMS

BEAUTY2018 - La Biodola, Isola d'Elba - Italy

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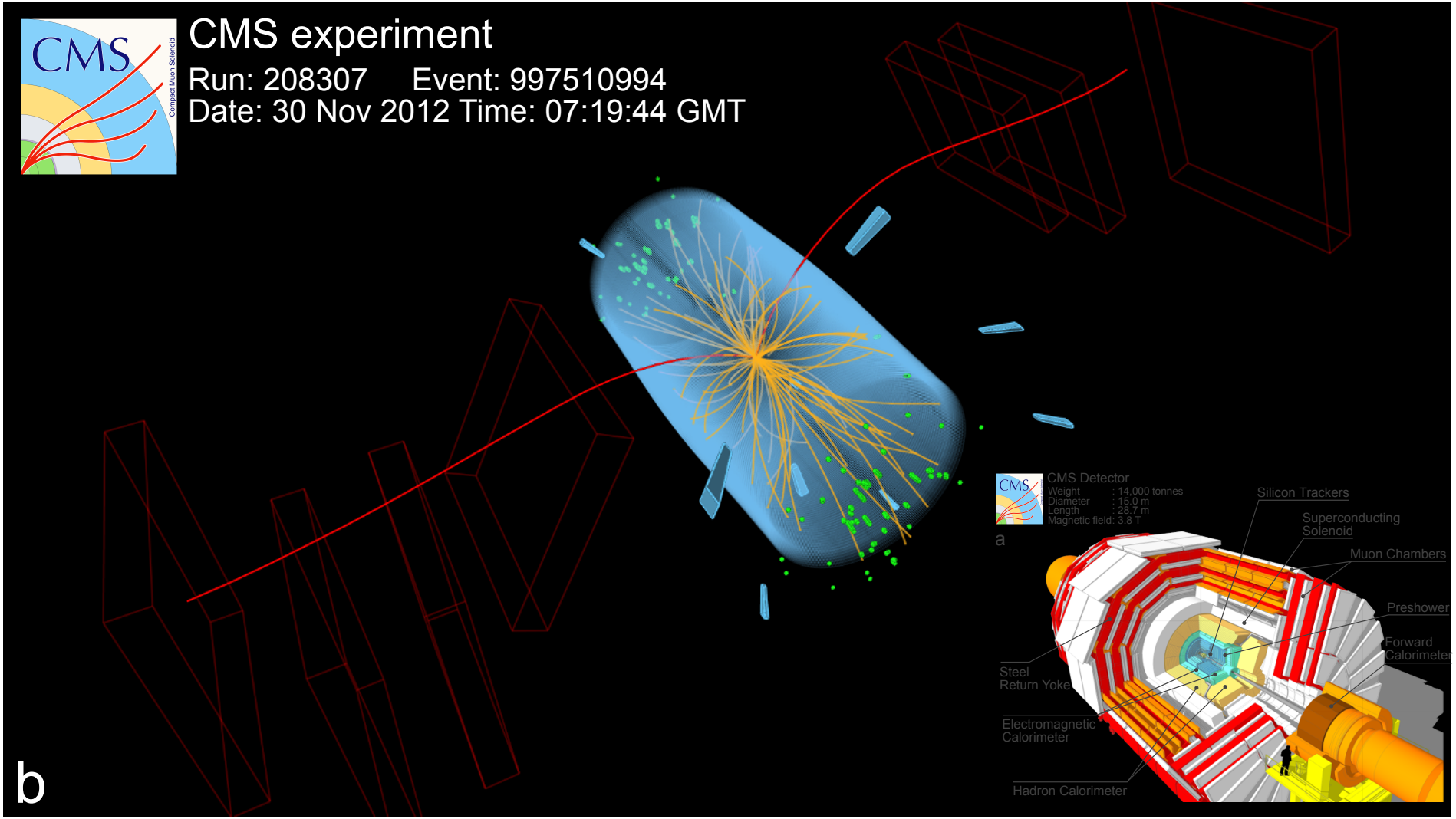
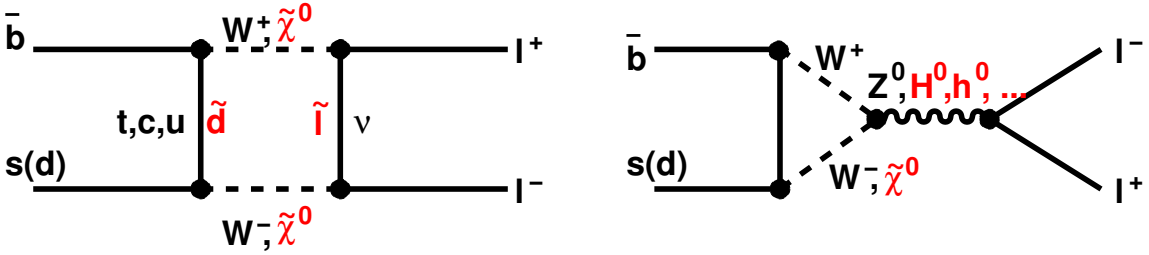
Event display - $B_s^0 \to \mu^+\mu^-$ candidate



Motivational aspects



- $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ decays are highly suppressed in the SM
  - involve flavour-changing neutral current (FNCN) transitions
  - can happen via box and penguing topologies
  - helicity suppressed
- SM expectations (ref):

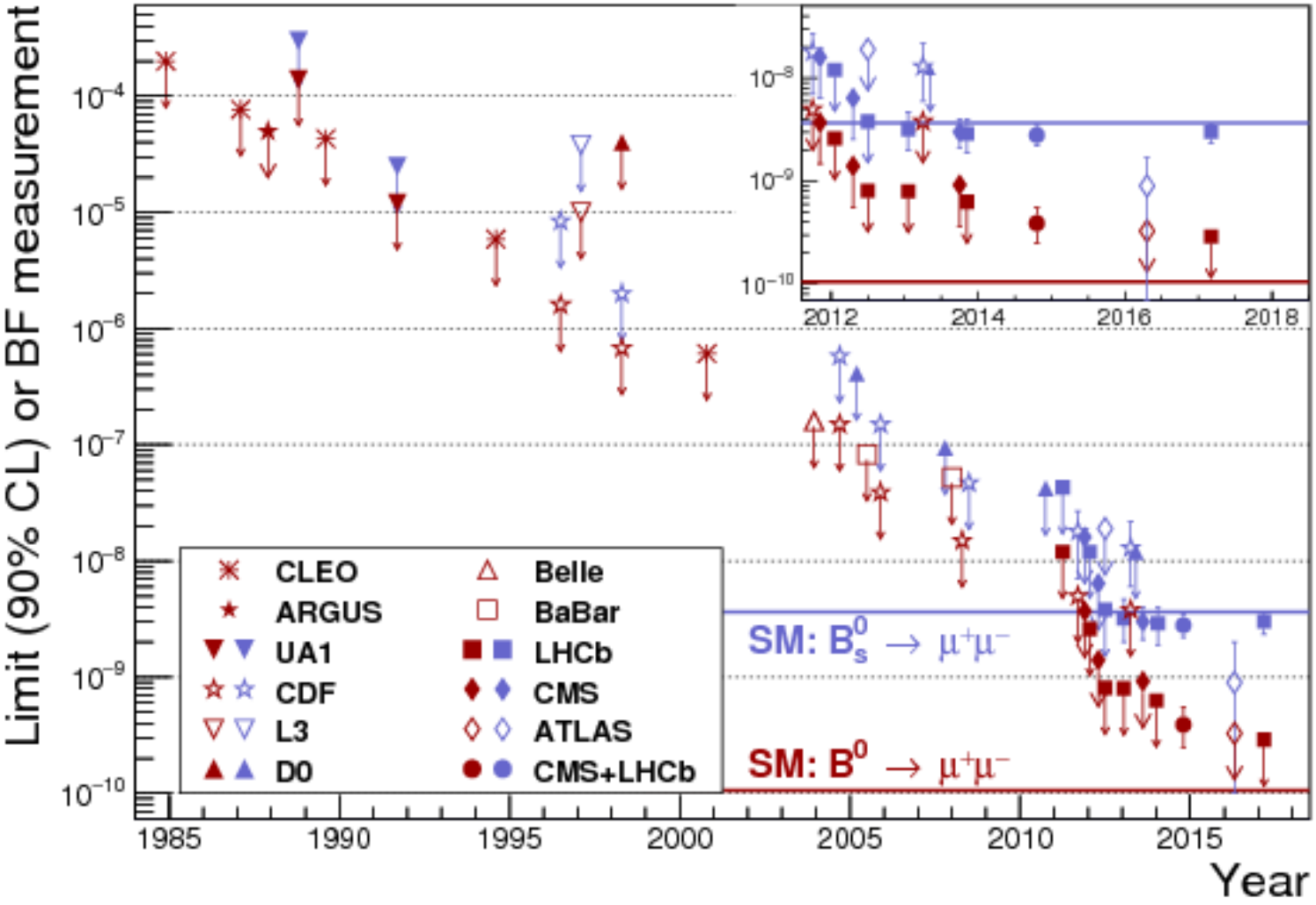
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9} \blacksquare \mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

- Search for New Physics (NP):
  - complementary to direct searches
  - clear signature
  - loop topologies are sensitive to NP contributions

$\mathrm{B_s^0} \to \mu^+\mu^-$ lifetime

- Complementary to the branching fraction search, the $\mathrm{B_s^0} \to \mu^+\mu^-$ channel offers another handle to test NP
- The effective $\mathrm{B_s^0} \to \mu^+\mu^-$ lifetime $\tau_{\mu^+\mu^-}$ is a theoretically clean probe (ref)
  - $\mathrm{B_s^0}$ mixes between $\mathrm{B_s^0}$ and $\bar{\mathrm{B}}_\mathrm{s}^0$ flavour eigenstates: non-negligible $\Delta\mathrm{m_s}$ and $\Delta\Gamma_\mathrm{s}$
  - Effective lifetime $\tau_{\mu^+\mu^-} = \frac{\int_0^\infty t\langle|\Gamma(\mathrm{B_s^0}(t)\to\mu^+\mu^-)|\rangle dt}{\int_0^\infty \langle|\Gamma(\mathrm{B_s^0}(t)\to\mu^+\mu^-)|\rangle dt}$
- Needs relatively large statistics: enough statistics will be collected in HL-LHC
- Measurement not included in the results showed in these slides

Current BF measurements



(ref)

Data samples and triggers

- Used pp collisions from 2011 and 2012 LHC data taking:
  - 5 fb^{-1} at $\sqrt{s} = 7$ TeV, average PileUp (PU)=9
  - 20 fb^{-1} at $\sqrt{s} = 8$ TeV, average PU=21
- Triggers
  - L1 hardware trigger: generic dimuon trigger
  - HLT for signal: opposite charge dimuon trigger, minimum μ p_{T} [4.0 - 3.0 GeV], vertex probability >0.5%, invariant mass requirement [4.8-6.0] GeV
  - HLT for normalization channels: opposite charge dimuon trigger,minimum μ p_{T} 4.0 GeV, >15% vertex probability, invariant mass requirement [2.9-3.3] GeV, displacement requirement (significance of decay length > 3)

Methods

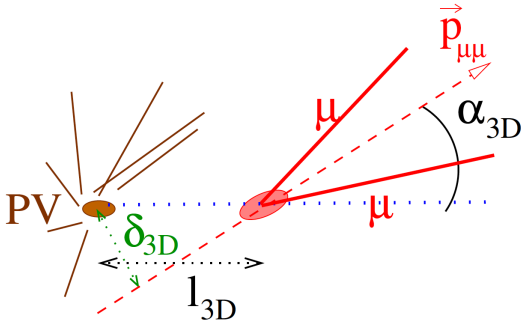
- Signal reconstruction searching for two isolated muons, compatible with a secondary vertex, and with a mass compatible with $\mathrm{B_s^0}$ and $\mathrm{B^0}$ mesons
- Blind analysis, data in the [5.20-5.45] GeV $\mu\mu$ invariant mass region was hidden up to the end of the analysis
- $\mathcal{B}(\mathrm{B_s^0} \to \mu^+\mu^-)$ measured relative to $\mathrm{B^+} \to \mathrm{J/\psi K^+}$ channel:

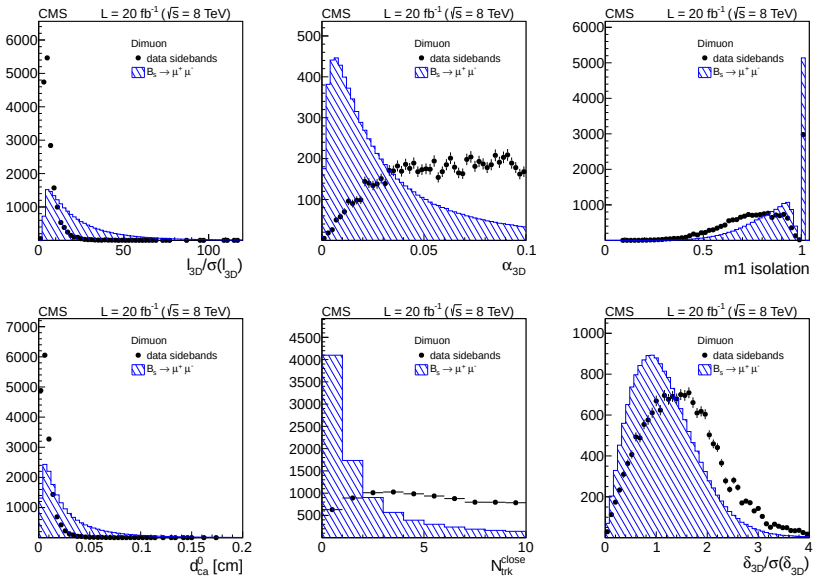
$$\mathcal{B}(\mathrm{B_s^0} \to \mu^+\mu^-) = \frac{n^{obs}_{\mathrm{B_s^0}}}{\epsilon\mathcal{L}\sigma(pp \to \mathrm{B_s^0})} = \frac{n^{obs}_{\mathrm{B_s^0}}}{n^{obs}_{\mathrm{B^+}}} \frac{A_{\mathrm{B^+}}}{A_{\mathrm{B_s^0}}} \frac{\epsilon^{ana}_{\mathrm{B^+}}}{\epsilon^{ana}_{\mathrm{B_s^0}}} \frac{\epsilon^{\mu}_{\mathrm{B^+}}}{\epsilon^{\mu}_{\mathrm{B_s^0}}} \frac{\epsilon^{trig}_{\mathrm{B^+}}}{\epsilon^{trig}_{\mathrm{B_s^0}}} \frac{f_u}{f_s} \mathcal{B}(\mathrm{B^+} \to \mathrm{J/\psi K^+})$$

- External inputs: $\mathcal{B}(\mathrm{B^+} \to \mathrm{J/\psi K^+})$ (includes $\mathrm{J/\psi} \to \mu^+\mu^-$ BF) from PDG and f_s/f_u from LHCb
- $\mathrm{B_s^0} \to \mathrm{J/\psi}\phi(1020)$ decay used as a control channel (MC validation and fragmentation studies)

Selections (MVA)

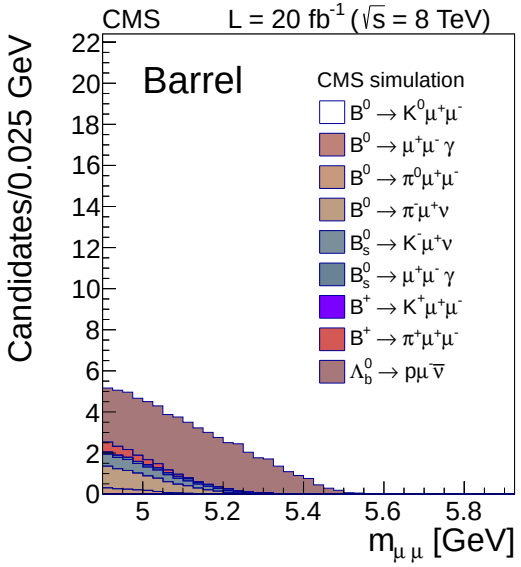
- Analysis-driven muon selections (using MC samples): 50% reduction of hadron-to-muon mis-id probability wrt the standard selections with 90% muon efficiency
- BDT candidate selections:
  - Signal: MC simulations, BG: data dimuon sidebands
  - Samples divided into 3 subsamples to avoid biases, 4 different BDTs (7,8 TeV and Barral-Endcap regions) for a total of 12 trained BDTs
  - 12 pile-up indipendent variables used (some of them shown on the left-hand-side plots)
  - normalization channel selected using the same BDTs (few input variables changed)

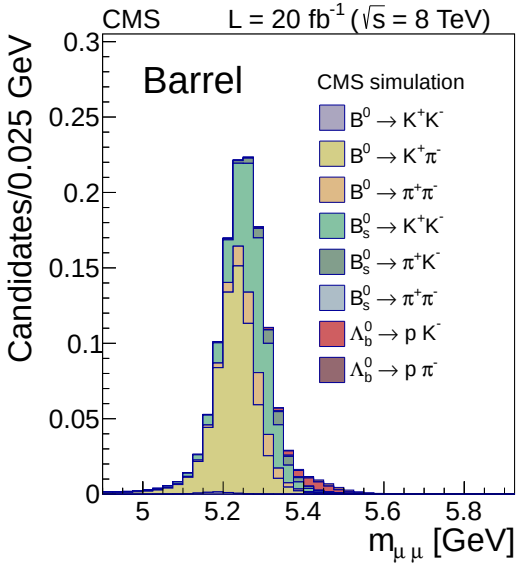




Background

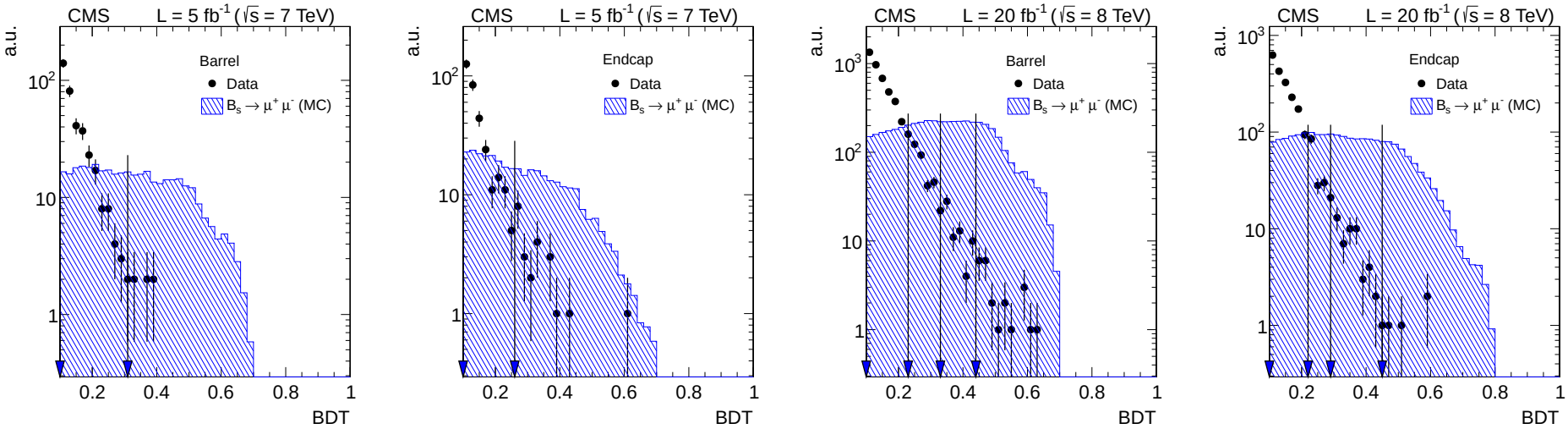
- Three main kinds of background: combinatorial, semileptonic, and fully reconstructed B hadron decays
- Studies using MC samples
- Peaking BG comes from mis-identified hadron-to-muon form B hadron decays which would fall into the signal region





BDT output categorization

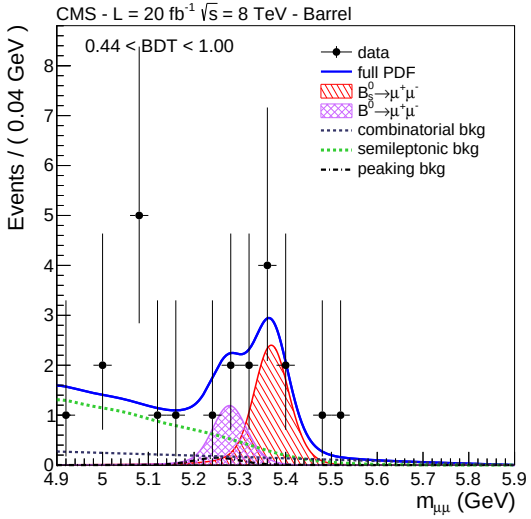
- Two different usages of the BDT ouput:
  - 1D-BDT used for the UL estimation with CL_s for the $B^0 \to \mu^+\mu^-$ channel
  - categorized BDT for the unbinned-ML fit of $B \to \mu^+\mu^-$ channels
- 1D-BDT two categories: barrel and endcap for the two energy eras (7 and 8 TeV), cut on BDT output optimized for best signal significance
- Categorized BDT: 2 bins for 2011 data and 4 bins for 2012 data divided into barrel and endcap regions, cut optimized to balance the signal yield in the bins



Maximum likelihood fit

- The $\mu\mu$ invariant mass was fitted with $\mathrm{B_s^0}$ and $\mathrm{B^0}$ signal and BG pdfs with an unbinned maximum likelihood fit
- $\mathrm{B_s^0}$, $\mathrm{B^0}$ signal, semileptonic, peaking BG pdfs were obtained from simulations

- $\mathrm{B_s^0}$ and $\mathrm{B^0}$ signals: crystall ball pdf
- Peaking BG: gaussian + crystall ball pdf, constrained to expectations
- Semileptonic BG: gaussian kernels, fixed shape, floating normalization
- Combinatorial BG: polynomial 1st deg, no constraints
- Per-event mass uncertainty
- Systematic uncertainties constrained with gaussian PDFs



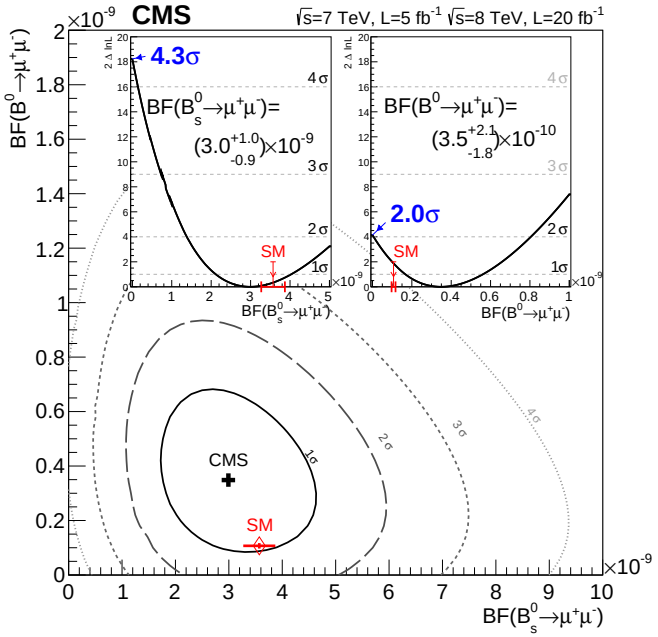
Systematic uncertainties

- Hadron-to-muon misidentification, 50% uncertainty assessed on the measured mis-id probability
- Branching fraction uncertainties, dominated by the 100% uncertainty set for the $\Lambda_b \to p\mu\nu$ channel
- Normalization of the peaking background, 5% measured varying the shapes and the constraints
- Hadronization fraction ratio f_s/f_u from LHCb, 5% uncert. due to possible p_{T} and η dependence (no evidence from internal studies)

Results

(ref)

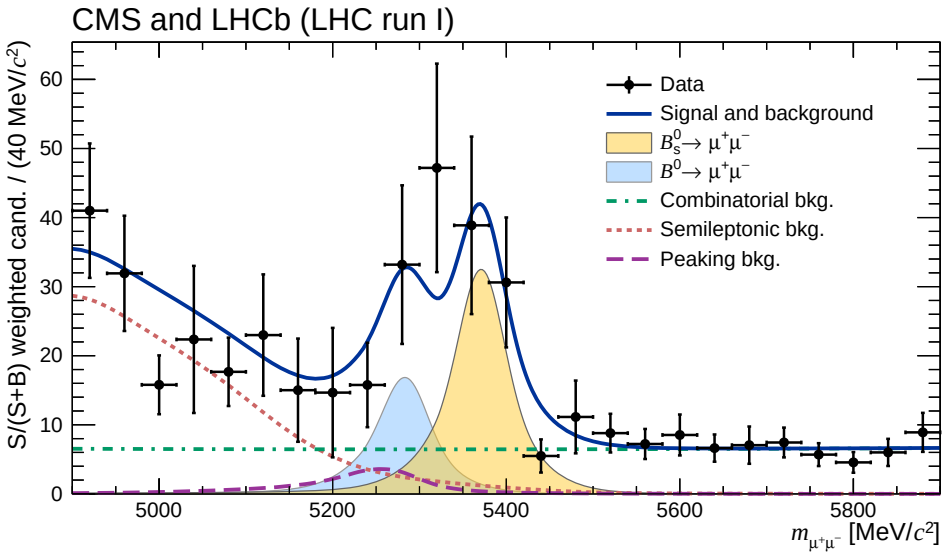
- From the UML fit to the categorized BDT bins
  - $\mathcal{B}(\mathrm{B}_\mathrm{s}^0 \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$
  - $\mathrm{B}_\mathrm{s}^0 \to \mu^+\mu^-$ significance: 4.3σ (4.8σ expected)
  - $\mathcal{B}(\mathrm{B}^0 \to \mu^+\mu^-) = (3.5^{+2.1}_{-1.8}) \times 10^{-10}$
  - $\mathrm{B}^0 \to \mu^+\mu^-$ significance: 2.0σ
- From the UML fit to the 1D-BDT bins
  - Upper limit for $\mathrm{B}^0 \to \mu^+\mu^-$ decay was set using CL_s
  - $\mathcal{B}(\mathrm{B}^0 \to \mu^+\mu^-) < 1.1 \times 10^{-9}$ @ 95% CL

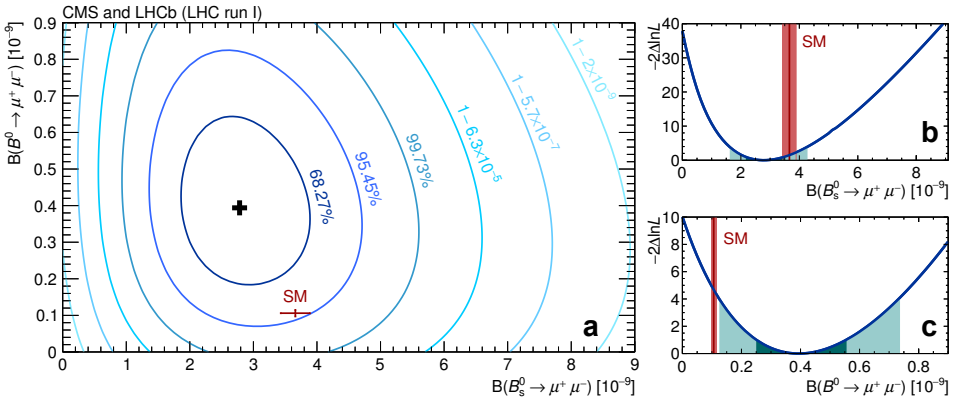


CMS-LHCb combined results

- Small modifications to the main analyses, for CMS $\mathrm{B_s^0}$ neglected decay time bias added as correction to each BDT bin; better evaluation of the semileptonic BG
- Simultaneous fit on CMS+LHCb data samples, categorized in 20 bins
- Common normalization BF and fragmentation ratio
- Results:
  - $\mathcal{B}(\mathrm{B_s^0} \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$
  - $\mathrm{B_s^0} \to \mu^+\mu^-$ significance: 6.2σ (7.4σ)
  - $\mathcal{B}(\mathrm{B^0} \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$
  - $\mathrm{B_s^0} \to \mu^+\mu^-$ significance: 3.2σ (0.8σ)

(ref)





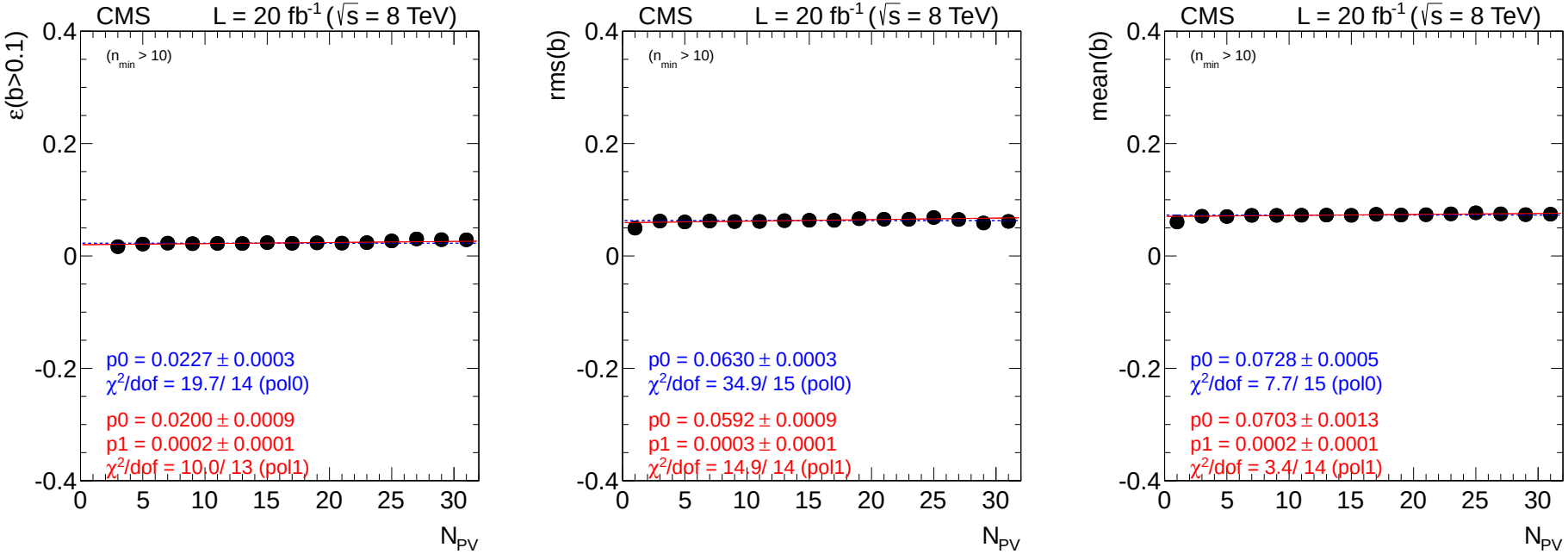
Conclusions

- CMS $\mathrm{B_s^0} \to \mu^+\mu^-$ and $\mathrm{B}^0 \to \mu^+\mu^-$ BF measurement:
  - $\mathcal{B}(\mathrm{B_s^0} \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$
  - $\mathrm{B_s^0} \to \mu^+\mu^-$ significance: 4.3σ (4.8σ expected)
  - $\mathcal{B}(\mathrm{B}^0 \to \mu^+\mu^-) < 1.1 \times 10^{-9}$ @ 95% CL
- All results are consistent with SM expectations and other experiments
- CMS+LHCb measurements showed tension between the measured $\mathcal{B}(\mathrm{B}^0 \to \mu^+\mu^-)$ and the expectations
- Analysis of 2016 and 2017 data set are going on in CMS
  - Dedicated triggers have been developed for signal and normalization channels
  - Better track parameter estimation in 2017 due to the new pixel detector
  - Improved muon ID based on MVA
  - Combined BF+effective lifetime analysis
  - Expected 433 $\mathrm{B_s^0} \to \mu^+\mu^-$ and 54 $\mathrm{B}^0 \to \mu^+\mu^-$ (1.3-3.3σ significance for B^0) at the end of Run2 assuming 300 fb^{-1} of integrated luminosity (CMS-FTR-13-022), for Phase2 projections see Sara Fiorendi's presentation tomorrow

Additional Slides

Pileup dependence studies

- Various pileup dependence studies were carried out
- No dependence in signal MC samples
- BDT output studied against the number of PU vertices



Details on the UML fit on categorized BDT