Giacomo Fedi\textsuperscript{a,b} on behalf of the CMS collaboration

\textsuperscript{a}Università di Pisa, \textsuperscript{b}INFN Sezione di Pisa

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

CMS experiment
Run: 208307     Event: 997510994
Date: 30 Nov 2012 Time: 07:19:44 GMT

Muon Chambers
Superconducting Solenoid
Silicon Trackers
Steel Return Yoke
Preshower Forward Calorimeter
Electromagnetic Calorimeter
Hadron Calorimeter

CMS Detector
Weight: 14,000 tonnes
Diameter: 15.0 m
Length: 28.7 m
Magnetic field: 3.8 T

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Motivational aspects

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

- SM expectations (ref):

\[
B(B_s^0 \rightarrow \mu^+ \mu^-) = (3.65 \pm 0.23) \times 10^{-9} \quad \text{and} \quad B(B^0 \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10}
\]

- Search for New Physics (NP):
  - complementary to direct searches
  - clear signature
  - loop topologies are sensitive to NP contributions
Complementary to the branching fraction search, the $B_s^0 \to \mu^+\mu^-$ channel offers another handle to test NP.

The effective $B_s^0 \to \mu^+\mu^-$ lifetime $\tau_{\mu^+\mu^-}$ is a theoretically clean probe (ref):

- $B_s^0$ mixes between $B_s^0$ and $\bar{B}_s^0$ flavour eigenstates: non-negligible $\Delta m_s$ and $\Delta \Gamma_s$.
- Effective lifetime $\tau_{\mu^+\mu^-} = \frac{\int_0^\infty t \langle |\Gamma(B_s^0(t)\to\mu^+\mu^-)| \rangle \, dt}{\int_0^\infty \langle |\Gamma(B_s^0(t)\to\mu^+\mu^-)| \rangle \, dt}$.

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

![Graph showing limit (90% CL) or BF measurement over years for different experiments and B meson decays at CMS.](image)
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 \(\mu\) \(p_T\) [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 \(\mu\) \(p_T\) 4.0 GeV, >15% vertex probability, invariant mass requirement [2.9-3.3] GeV, displacement requirement (significance of decay length > 3)
Signal reconstruction searching for two isolated muons, compatible with a secondary vertex, and with a mass compatible with $B^0_s$ and $B^0$ 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.

$\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-)$ measured relative to $B^+ \rightarrow J/\psi K^+$ channel:

$$\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) = \frac{n_{B^0_s}^{\text{obs}}}{\epsilon L \sigma(pp \rightarrow B^0_s)} = \frac{n_{B^0_s}^{\text{obs}}}{n_{B^+}^{\text{obs}}} \frac{A_{B^+}}{A_{B^0_s}} \frac{\epsilon_{\text{ana}}^{B^+}}{\epsilon_{B^0_s}^{\text{ana}}} \frac{\epsilon_{\mu}^{B^+}}{\epsilon_{B^0_s}^{\mu}} \frac{\epsilon_{\text{trig}}^{B^+}}{\epsilon_{B^0_s}^{\text{trig}}} \frac{f_u}{f_s} \mathcal{B}(B^+ \rightarrow J/\psi K^+)$$

External inputs: $\mathcal{B}(B^+ \rightarrow J/\psi K^+)$ (includes $J/\psi \rightarrow \mu^+\mu^-$ BF) from PDG and $f_s/f_u$ from LHCb.

$B^0_s \rightarrow J/\psi \phi(1020)$ decay used as a control channel (MC validation and fragmentation studies).
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 independent variables used (some of them shown on the left-hand-side plots)
- normalization channel selected using the same BDTs (few input variables changed)
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.
Two different usages of the BDT output:

- 1D-BDT used for the UL estimation with CL$_s$ for the $B^0 \rightarrow \mu^+\mu^-$ channel
- Categorized BDT for the unbinned-ML fit of $B \rightarrow \mu^+\mu^-$ 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
The $\mu\mu$ invariant mass was fitted with $B_s^0$ and $B^0$ signal and BG pdfs with an unbinned maximum likelihood fit.

$B_s^0$, $B^0$ signal, semileptonic, peaking BG pdfs were obtained from simulations.

$B_s^0$ and $B^0$ signals: crystall ball pdf.

Peaking BG: gaussian + crystall ball pdf, constrained to expectations.

Semileptonic BG: gaussian kernels, fixed shape, floating normalization.

Combinatorial BG: polynomial $1^{st}$ 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 $\Lambda_b \rightarrow p\mu\nu$ 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 $\eta$ dependence (no evidence from internal studies)
Results

From the UML fit to the categorized BDT bins

- \( B(B^0_s \rightarrow \mu^+ \mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9} \)
- \( B^0_s \rightarrow \mu^+ \mu^- \) significance: 4.3\( \sigma \) (4.8\( \sigma \) expected)
- \( B(B^0 \rightarrow \mu^+ \mu^-) = (3.5^{+2.1}_{-1.8}) \times 10^{-10} \)
- \( B^0 \rightarrow \mu^+ \mu^- \) significance: 2.0\( \sigma \)

From the UML fit to the 1D-BDT bins

- Upper limit for \( B^0 \rightarrow \mu^+ \mu^- \) decay was set using CL\(_s\)
- \( B(B^0 \rightarrow \mu^+ \mu^-) < 1.1 \times 10^{-9} \) @ 95% CL
CMS-LHCb combined results

- Small modifications to the main analyses, for CMS $B_s^0$ 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:
  - $B(B_s^0 \rightarrow \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$
  - $B_s^0 \rightarrow \mu^+\mu^-$ significance: 6.2$\sigma$ (7.4$\sigma$)
  - $B(B^0 \rightarrow \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$
  - $B_s^0 \rightarrow \mu^+\mu^-$ significance: 3.2$\sigma$ (0.8$\sigma$)

(ref)
Conclusions

- CMS $B_s^0 \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ BF measurement:
  - $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$
  - $B_s^0 \rightarrow \mu^+\mu^-$ significance: $4.3\sigma$ ($4.8\sigma$ expected)
  - $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 1.1 \times 10^{-9}$ @ 95% CL

- All results are consistent with SM expectations and other experiments

- CMS+LHCb measurements showed tension between the measured $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)$ 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 $B_s^0 \rightarrow \mu^+\mu^-$ and 54 $B^0 \rightarrow \mu^+\mu^-$ (1.3-3.3$\sigma$ 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
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

G. Fedi (Università di Pisa)