Measurement of rare $B \to \mu^+\mu^-$ decays with the Phase-2 upgraded CMS detector at the HL-LHC

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Ozlem Ozcelik on behalf of the CMS collaboration

Bogazici University

ozlem.ozcelik@cern.ch

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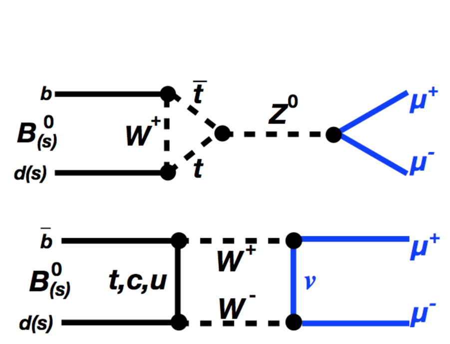
Introduction



The decays are highly suppressed in Standard Model [1] due to

- effective FCNC
- helicity suppressed
- CKM suppressed $|V_{ts}| > |V_{td}|$

$\to \mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.57 \pm 0.17) \times 10^{-9}$

$\to \mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$ (time-integrated measurement)

∘ $\Delta\Gamma_s = \Delta_L - \Delta_H = 0.082 \pm 0.007$ ps^{-1}

∘ effective lifetime : ($y_s \equiv \tau_{B^0_s}\Delta\Gamma_s/2 \equiv 0.062 \pm 0.006$ and $\tau_{B^0_s} = 1.510 \pm 0.005$ ps)

$$\tau_{\mu^+\mu^-} \equiv \frac{\int_0^\infty t\langle(\Gamma(B_s(t)) \to \mu^+\mu^-)\rangle}{\int_0^\infty \langle(\Gamma(B_s(t)) \to \mu^+\mu^-)\rangle} = \frac{\tau_{B_s}}{1-y_s^2}\left(\frac{1+2A_{\Delta\Gamma}y_s+y_s^2}{1+A_{\Delta\Gamma}y_s}\right) \quad (1)$$

In SM, only heavy eigenstates decay to dimuons - $A_{\Delta\Gamma} = 1 \to \tau^{SM}_{\mu^+\mu^-} = 1.615$ ps. The decay could receive contributions beyond the SM as $A_{\Delta\Gamma}$ value within whole range [-1, +1].

Analysis strategy

- **Signal** : Two unlike-sign global muons fit to a common displaced vertex to reconstruct B candidate.
- **Background** :
  - ∘ Combinatorial from two uncorrelated semi-leptonic B decays.
  - ∘ Rare semi-leptonic B decays, e.g. $B^0 \to h\mu + \nu$, where a hadron misidentified as a muon and the neutrino carries away a small amount of energy.
  - ∘ Two-body hadronic decays, "peaking" background, e.g. $B^0 \to K^+\pi^-$, when both hadrons misidentified as muons.

Selection :

1. An advanced muon identification algorithm based on BDT, muon BDT, to separate genuine muons from the hadrons that are misidentified as muons.
2. A second BDT is used to separate signal events from backgrounds.

To extract the signal yield, an unbinned maximum likelihood fit (UML) is performed in bins of the second BDT. For the determination of the BF, a normalization decay channel $B^+ \to J/\psi K^+$ is used. The formula for the BF is :

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \frac{N_{\text{sig}}}{N_{\text{norm}}} \times f_u/f_s \times \frac{\epsilon_{\text{sig}}}{\epsilon_{\text{norm}}} \quad (2)$$

Based on the fit results, projection along the proper decay time distribution for the B^0_s signal events is built with the sPlot technique [2]. 1D binned ML fit to decay time distribution, constrained with resolution and efficiency, is used to extract the effective lifetime.

Study of dimuon mass resolution

The background contribution to the $B^0 \to \mu^+\mu^-$ signal yield from the $B^0_s \to \mu^+\mu^-$ and $B^0 \to \pi^-\mu^+\nu$ decays are studied.

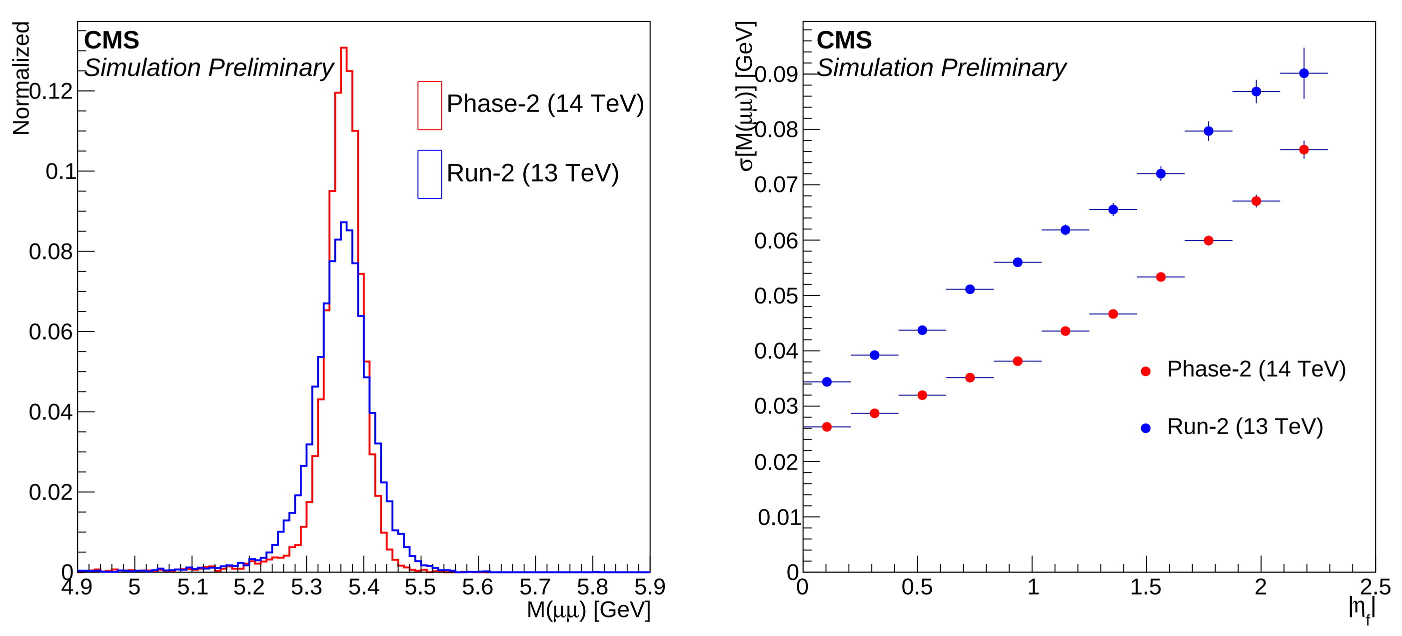


Figure 1: (left)Mass distributions for $B^0 \to \mu^+\mu^-$ in the Run-2 and Phase-2 scenarios for $|\eta_f| < 1.4$. A single Gaussian is fit to the core of the mass distribution. (right) Mass resolution as a function of $|\eta_f|$.

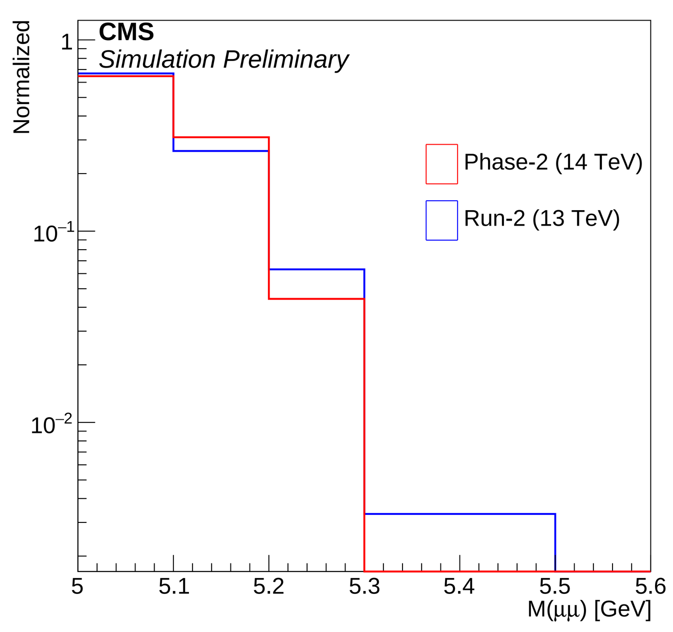
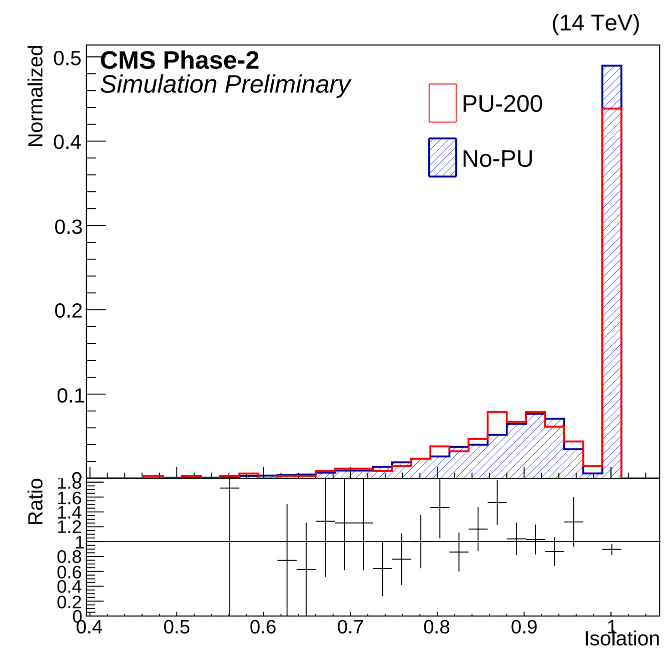


Figure 2: Contribution of $B^0 \to \pi^-\mu^+\nu$ background events (with the pion misidentified as a muon) into the signal regions. The ratio of number of $B^0 \to \pi^-\mu^+\nu$ events for Phase-2 to Run-2 is $5/19$ in the mass interval $5.2 < m < 5.3$ GeV of the B^0 signal region.

Pile-up effects

We study the B^0_s isolation variable with no simulated pile-up (PU) and PU-200 events per bunch crossing.

$$I = \frac{p_T(B)}{\sum_{\text{trk}} + p_T(B)} \quad (3)$$



→ No significant change observed

Figure 3: Normalized isolation variable distributions for the B^0_s signal for the two pile-up scenarios is shown. The blue distribution represents the case with no pile-up while the red one is for average pile-up of 200 interactions per bunch crossing. In the bottom, the ratio between the PU=0 and the PU=200 distributions is also shown.

Sensitivity of branching fraction and decay time measurements

The expected performance of the analysis is estimated with pseudo-experiments based on toy MC. The upgraded mass resolutions are used to construct the PDF models in the UML.

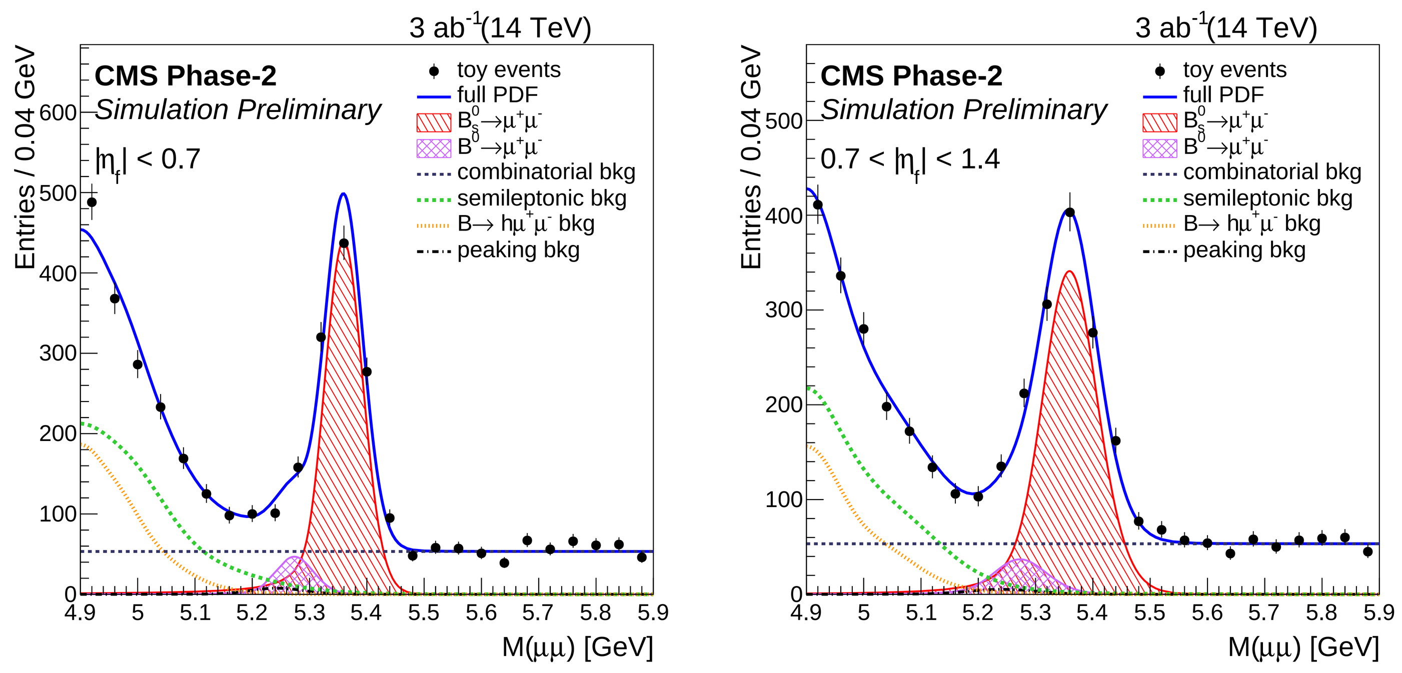


Figure 4: Invariant mass distributions with the fit projection overlayed, corresponding to an integrated luminosity of 3000 fb^{-1}. The left plot shows the central barrel region, $|\eta_f| < 0.7$ and the right plot is for $0.7 < |\eta_f| < 1.4$.

- Background subtracted distribution
- The fit includes
  → efficiency & resolution

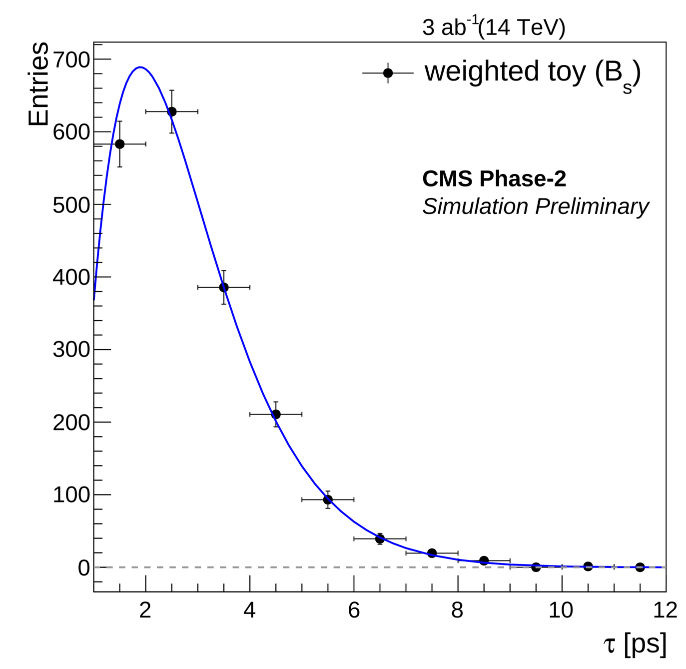


Figure 5: The binned maximum likelihood fit to the background-subtracted decay time distribution for the Phase-2 scenario. The effective lifetime from the fit is 1.61 ±0.05 ps.

Table 1: Estimated analysis sensitivity for different integrated luminosities.

$\mathcal{L}$ (fb^{-1})	$N(B_s)$	$N(B^0)$	$\delta\mathcal{B}(B_s \to \mu\mu)$	$\delta\mathcal{B}(B^0 \to \mu\mu)$	$\sigma(B^0 \to \mu\mu)$	$\delta[\tau(B_s)]$(stat-only)
300	205	21	12%	46%	$1.4 - 3.5\sigma$	0.15 ps
3000	2048	215	7%	16%	$6.3 - 8.3\sigma$	0.05 ps

Conclusions

- The inner tracker of the Phase-2 detector provides an order of 40-50% improvement on the mass resolutions which will allow precise measurements.
- The semi-leptonic background contribution into the signal regions will be reduced substantially.
- The improved separation of the B^0_s and B^0 yields will lower the signal cross feed contamination.
- CMS will have the capability
  - to measure the $B^0_s \to \mu^+\mu^-$ effective lifetime with an uncertainty of 0.05 ps.
  - to observe the $B^0_s \to \mu^+\mu^-$ decay with more than 5 σ.

References

[1] A. Ali. Flavour Changing Neutral Current Processes in B Decays. In *Proceedings of the Fourth KEK Topical Conference on Flavor Physics*. Nuclear Physics B, 1997.

[2] Muriel Pivk and Francois R. Le Diberder. SPlot: A Statistical tool to unfold data distributions. *Nucl. Instrum. Meth.*, A555:356–369, 2005.