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On behalf of CMS Collaboration

B PHYSICS AT CMS WITH LHC RUN-II AND BEYOND
FROM LHC TO HL-LHC

LHC operation up to LS3 (2023)
25 ns bunch spacing, instantaneous luminosities up to $2 \times 10^{34}$ (2x design!). Accumulate ~300 fb$^{-1}$ by 2023

HL-LHC operation beyond LS3 (2025+)
New low-$\beta$ triplets and crab-cavities to optimize the bunch overlap at the interaction region.
Level the instantaneous luminosity at $5 \times 10^{34}$ from a potential peak value of $2 \times 10^{35}$.
Deliver ~250 fb$^{-1}$ per year for 10 years of operation, accumulate up to 3000 fb$^{-1}$.
FLAVOUR PHYSICS @ FUTURE CMS

High luminosity × Large production cross section =
ONE OF THE BIGGEST B HADRON DATA SETS ON EARTH

- A unique test bench for flavour physics predictions.
- Measurements which require huge statistics will have a significant boost, such as CP phase in $B_s \rightarrow J/\psi \phi$, $B \rightarrow K^* \mu \mu$.
- Will allow to study (ultra) rare processes at a sensitivity level never attained, such as $B \rightarrow \mu \mu$, or lepton-flavor violating decays such as $B \rightarrow \mu \tau$, $\tau \rightarrow \mu \mu \mu$.

$B_{(s,d)} \rightarrow \mu^+ \mu^-$
as a benchmark analysis today!
THE CHALLENGE TOWARD HL-LHC

- Capability of operating at a very high pile-up of 140 interactions.
- The detector has to survive up to 3000 fb\(^{-1}\), and to year 2035.
- Need to preserve a similar performance even at 140 PU, 3000 fb\(^{-1}\) as the current detector as in Run-I.
- Maintain current trigger acceptance for HL-LHC conditions, and preserve lowest possible trigger and analysis thresholds.

An event with 78 reconstructed vertices — expected to exceed doubled pile-up events at the running condition of HL-LHC.
New tracker system:
- Feature 4 pixel barrel layers and 5 disks on the endcaps with half of the material budget in the central region.
- Combined with a smaller silicon sensors pitch, the momentum resolution will be improved, and help to separate $B^0$ and $B_s$ signals.

Enhanced L1 trigger:
- Hardware track trigger at level-1 and maintaining low thresholds at HL-LHC luminosities.
- Higher L1 trigger and software high-level trigger (HLT) accept rates [5-10 times to the phase-I].
- Extended trigger capabilities for the muon system with improved coverage in the forward direction.
THE PHYSICS TARGET

- $B_{s,d}\rightarrow\mu^+\mu^-$ decays are only proceed through FCNC processes and are highly suppressed in SM:
- Loop diagram + Suppressed SM + Theoretically clean = An excellent place to look for new physics.
- Some of the new physics scenarios may boost the $B\rightarrow\mu\mu$ decay rates by 10~20 times easily, for example:
  - 2HDM: $\mathcal{B} \propto \tan^4\beta \& m(H^+)$
  - MSSM: $\mathcal{B} \propto \tan^6\beta$
- $B_s/B_d$ ratio – a stringent test of minimal flavor violation hypothesis.

Ref: D. M. Straub, arXiv: 1012.3893

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

Ref: Bobeth et al, PRL 112, 101801 (2014)
Event classification is carried out by Boosted Decision Tree (BDT).

Branching fractions were extracted by unbinned maximum likelihood fits in 12 categorized BDT bins.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Branching fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s \rightarrow \mu^+ \mu^-$</td>
<td>$(3.0^{+1.0}_{-0.9}) \times 10^{-9}$</td>
</tr>
<tr>
<td>$B_d \rightarrow \mu^+ \mu^-$</td>
<td>$&lt;1.1 \times 10^{-9}$ @ 95% CL</td>
</tr>
</tbody>
</table>

4.3σ observation!
Events are triggered by dimuon events at L1, and with mass/displaced vertex requirement at the HLT.

MVA-based muon identification is introduced.

Normalized to the reference channel $B^+ \rightarrow J/\psi(\rightarrow \mu^+\mu^-) K^+$.

Updates on background decay model and physics parameters presented in the CMS+LHCb combination Nature are incorporated.

We do not introduce possible improvements on the analysis strategy itself.

An optimized analysis for $B^0 \rightarrow \mu\mu$ will provide better results.

Then scale the analysis to LHC Run-2 and beyond!
Pseudo experiments are used to estimate the expected CMS performance in two different scenarios:

- **The Phase-1 scenario**: corresponding to the expected performance of the CMS detector including LHC Run-II and Run-III, to an integrated luminosity of $300 \text{ fb}^{-1}$ at 14 TeV.

- **The Phase-2 upgrade scenario**: corresponding to the expected performance of the CMS detector after the full Phase-2 upgrades and to a luminosity of $3000 \text{ fb}^{-1}$ at 14 TeV.

GEANT4-based simulated samples are used to estimated the performance of trigger, resolution, and pile-up effect at the phase-2 running condition.

Muon efficiency and identification are assumed to be the same as Run-I.

Standard Model branching fractions are assumed in the study.
TOWARD THE FUTURE: L1 TRIGGER AT PHASE-2

- Low-$p_T$ di-muon L1 trigger algorithm exploiting the triggering capabilities of the upgraded CMS tracker is studied with full simulation with the Phase-2 scenario.
- Invariant mass resolution for $B \rightarrow \mu \mu$ at L1 is estimated to be $\sim 70$ MeV.
- The rate of the L1 trigger is estimated from the minimum-bias simulation sample, and is equal to a few hundred Hz. This corresponds to a small fraction of the total available L1 bandwidth ($\sim 1$ MHz).

Low-$p_T$ track-trigger-based algorithm as in Run-I is expected to be entirely feasible for Phase-2.
The offline invariant mass resolution is estimated from $B \rightarrow \mu \mu$ simulated samples implementing the full detector simulation of the Phase-I and Phase-II scenarios.

The effects of the high pile-up have studied based on simulated samples as well.

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Phase-1</th>
<th>Phase-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offline barrel mass resolution</td>
<td>42 MeV</td>
<td>28 MeV</td>
</tr>
<tr>
<td>Trigger &amp; muon ID</td>
<td>as Run-I</td>
<td>as Run-I</td>
</tr>
<tr>
<td>Efficiency drop due to PU (sig./bkg.)</td>
<td>as Run-I</td>
<td>–30% / –35%</td>
</tr>
<tr>
<td>Uncertainty: B+ normalization</td>
<td>5%</td>
<td>3%</td>
</tr>
<tr>
<td>Uncertainty: peaking background</td>
<td>20%</td>
<td>10%</td>
</tr>
<tr>
<td>Uncertainty: semi-leptonic B decays</td>
<td>25%</td>
<td>20%</td>
</tr>
<tr>
<td>Uncertainty: fs/fu</td>
<td>5%</td>
<td>5%</td>
</tr>
</tbody>
</table>

A comparison of isolation variable in PU=0 and PU=140 environment.

Inject into pseudo experiments for the sensitivity estimations.
300 fb$^{-1}$, barrel only

3000 fb$^{-1}$ w/ improved tracker

<table>
<thead>
<tr>
<th>L (fb$^{-1}$)</th>
<th>$\delta B(B_s \rightarrow \mu^+\mu^-)$</th>
<th>$\delta B(B_d \rightarrow \mu^+\mu^-)$</th>
<th>$B_d$ sign.</th>
<th>$\delta[B(B_d)]/$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>14%</td>
<td>63%</td>
<td>0.6–2.5σ</td>
<td>66%</td>
</tr>
<tr>
<td>300</td>
<td>12%</td>
<td>41%</td>
<td>1.5–3.5σ</td>
<td>43%</td>
</tr>
<tr>
<td>300 (barrel)</td>
<td>13%</td>
<td>48%</td>
<td>1.2–3.3σ</td>
<td>50%</td>
</tr>
<tr>
<td>3000 (barrel)</td>
<td>11%</td>
<td>18%</td>
<td>5.6–8.0σ</td>
<td>21%</td>
</tr>
</tbody>
</table>

Ref. CMS PAS FTR-14-015
BEFORE MOVING AHEAD...

- The large data from LHC run-II and future operations will provide an excellent probe for the flavor physics.
- As a benchmark study, we estimate the CMS potential to trigger and reconstruct the $B_{s,d} \rightarrow \mu^+\mu^-$ processes at future LHC and HL-LHC runs.
- With the upgraded CMS detector, it will be possible to trigger and reconstruct the signal events even with the high pile-up running conditions at HL-LHC.
- The upcoming large data set will lead to high precision measurements and provide stringent tests of the Standard Model.

*LHC run-II started as planned, CMS is back in business!*
D* events with minimal $p_T$ cuts:
- 300 MeV for K/$\pi$ from D$^0$,
- 250 MeV for $\pi$ from D*.

Inclusive D$^0$ events

D* with tight requirement
A clean $B^+ \rightarrow J/\psi K^+$ candidate w/ visible secondary vertex

$M(J/\psi K^+) = 5.26 \text{ GeV}$

$M(B^\pm): 5.277 \pm 0.001 \text{ GeV}$

$B^\pm \rightarrow J/\psi K^\pm$ events w/ inclusive $J/\psi$ trigger.

$M(B^\pm \rightarrow J/\psi K^\pm) = 5.277 \pm 0.001 \text{ GeV}$

$pt = 2.25 \text{ GeV}$

$pt = 17.09 \text{ GeV}$

$pt = 6.69 \text{ GeV}$

$M(\mu^+ \mu^-) = 3.11 \text{ GeV}$

$txy = 0.41 \text{ cm}$
B hadron events w/ displaced J/ψ+track trigger.

Reconstructed J/ψπ⁺π⁻ events w/ both types of triggers

Stay tuned -
New results are coming soon!