Prospects of CMS in B Physics in Phase 2

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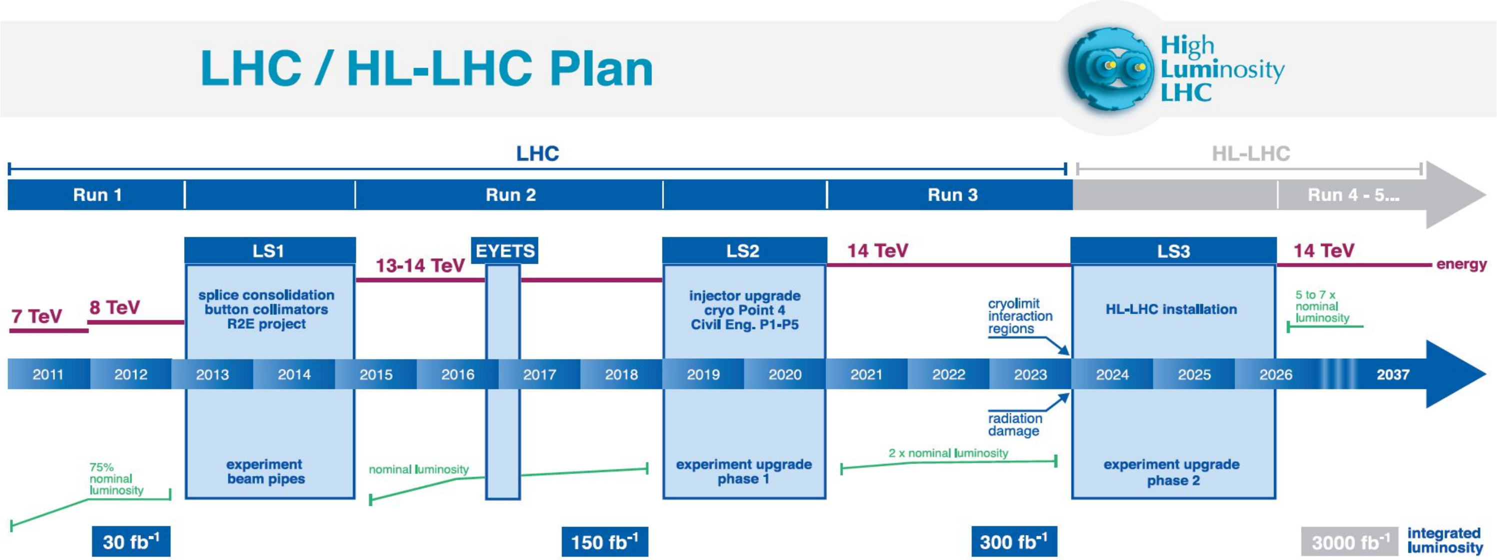
Outline

- Introduction
- CMS Phase-2 Upgrade
- B Physics Benchmark Studies
  - $B_{d/s} \rightarrow \mu^{+}\mu^{-}$
  - $B_{s} \rightarrow \phi\phi \rightarrow$ 4 Kaons
- Conclusions

High Luminosity LHC Scenario



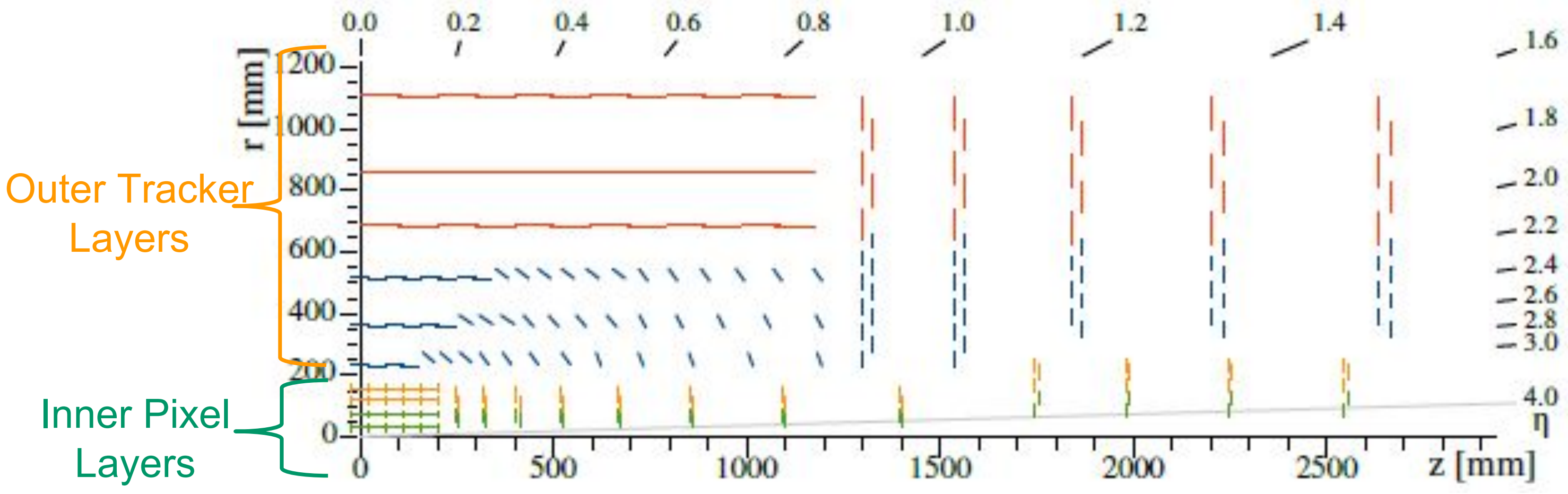
- HL-LHC is expected to deliver > 3 ab^{-1} data to both CMS and ATLAS at $\sqrt{s}$ = 14 TeV in 10 years (2026-36)
  - 10 x LHC Run 1-3 data
  - Average number of collisions will be ~ 140-200 / bunch crossing
    - 5 x current LHC running ~ 40-50
  - Increase in Pileup affects B - physics adversely.

CMS Phase-2 Upgrade

- CMS has planned to implement the following upgrades to retain full physics potential during the HL-LHC period
  - Increased Muon coverage
  - New forward calorimeter with high granularity and resolution
  - Increased trigger bandwidth and latencies
  - A new improved Tracker with better radiation hardness and p_T resolution
  - Inclusion of tracking information at Level1 trigger
    - Level1 Trigger with only the calorimeter and muon chamber information will not be able to cope with 40 MHz input rate.

As the proposed Phase-2 tracker plays the most important role in the physics processes discussed in this talk, we shall discuss about the tracker upgrade and tracking at Level1 trigger.

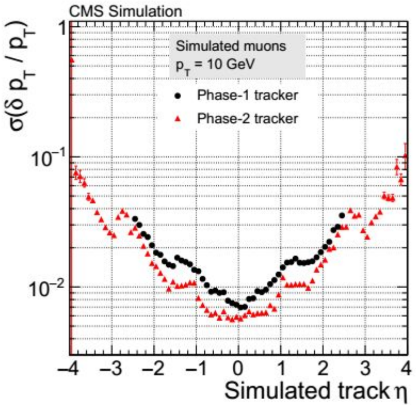
CMS Phase-2 Tracker Layout



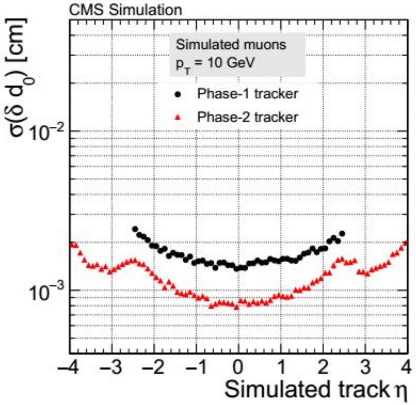
- 4 inner pixel layers
- 6 outer tracker layers
    - 2 closely placed silicon sensors (called pT modules)
        - Inner 3 layers - one macro-pixel and the other strip detectors
        - Outer 3 layers - both strip detectors
- Only outer tracker information will be used in L1.

Tracking Performance & Physics Projections

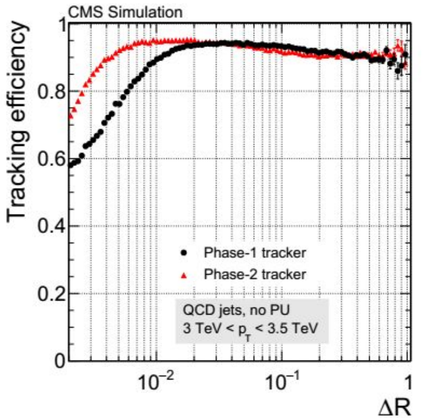
p_T resolution



IP resolution

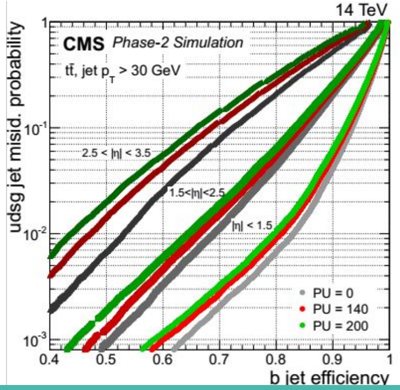


Tracking efficiency

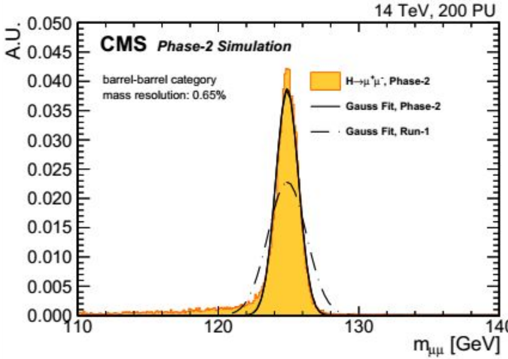


CMS Phase-2 Tracker TDR (CERN-LHCC-2017-009)

B tagging efficiency



H → μμ

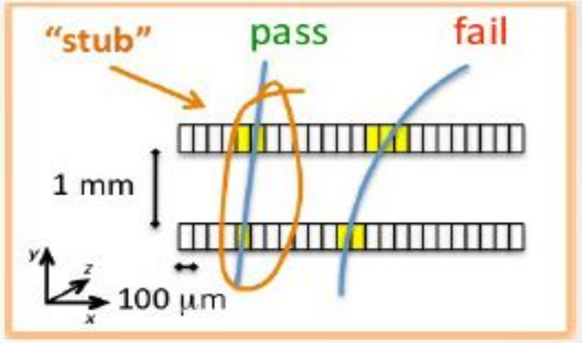


- Better η coverage
- Even in the same η region, the performance of Phase-2 tracker is better.
- b-Tagging can be extended to high η region
- Results of physics processes will also improve
  - Due to improved p_T resolution

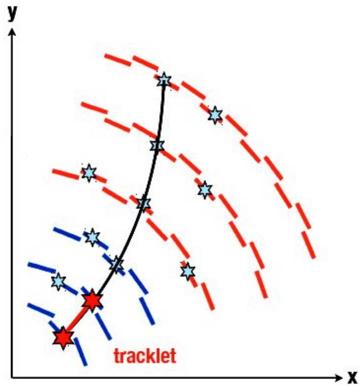
L1 Tracking

- pT Modules are designed to reject low-p_T tracks at the front-end of the detector
  - 2 closely placed silicon sensor
  - Can correlate hits in its two layers and create a “Stub”.
  - Can discriminate low-p_T and high-p_T “Stubs”
    - Low-p_T tracks bends more in magnetic field.
  - Can accept “Stubs” with p_T as low as 2 GeV.
- Only “Stub” informations will be used at Level1
  - A Level1 track is formed by connecting the “Stubs” in different layers.
  - Tracking information can be matched with Calorimeter or Muon Chamber information.
- If an event gets selected at Level1 all the hits in pipeline are passed to HLT.

pT modules and Stub



L1 Tracking



B Physics Projection Studies

Search for very rare FCNC leptonic B decays

- $B_{d/s} \rightarrow \mu^+\mu^-$
  - di-muon trigger
  - L1 track trigger to ensure high efficiency for low p_T muons
  - Offline study

Search for rare FCNC fully hadronic B decays

- $B_s \rightarrow \phi\phi \rightarrow$ 4 Kaons
  - No object based trigger
  - Inaccessible without the L1 tracks
  - p_T threshold as low as 2 GeV
  - L1 study

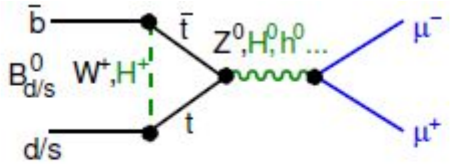
Both the searches give a handle for indirect search of new physics beyond SM.

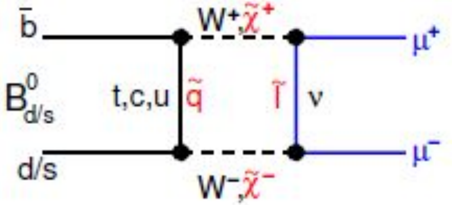
Both the studies are part of the CMS Phase-2 Tracker Technical Design Report (CERN-LHCC-2017-009). Unless stated otherwise, all plots are from the Tracker TDR. A few pre-TDR public results will also be shown.

$B_{d/s} \to \mu^+\mu^-$

$B_{d/s} \to \mu^+\mu^-$

- Proceed though FCNC and thus highly suppressed in the SM
  - EW-Penguin and box diagrams, but no tree level
  - Helicity suppressed
- SM expected branching fractions
  - $Br(B_s \to \mu^+\mu^-) \approx (3.57 \pm 0.16) \times 10^{-9}$
  - $Br(B_d \to \mu^+\mu^-) \approx (1.02 \pm 0.06) \times 10^{-10}$
- Measurements





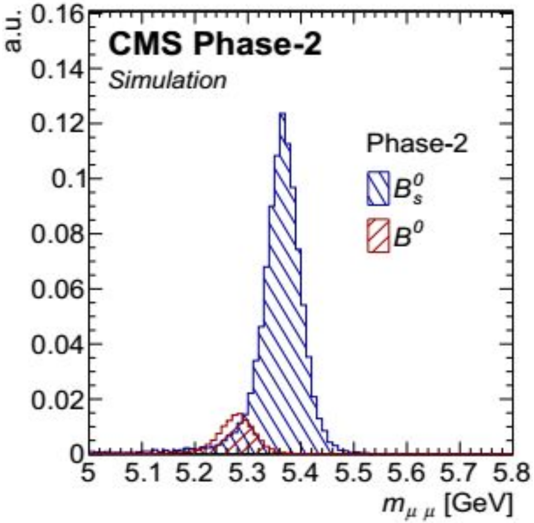
Experiment	$Br(B_s \to \mu^+\mu^-)$	$Br(B_d \to \mu^+\mu^-)$
CMS (2013)	$(3.0 \pm^{1.0}_{0.9})\,10^{-9}$	$< 1.1 \times 10^{-9}$ (95% CL)
LHCb + CMS (2015)	$(2.8 \pm^{0.7}_{0.6})\,10^{-9}$	$(3.9 \pm^{1.6}_{1.4})\,10^{-10}$
ATLAS (2016)	$(0.9 \pm^{1.1}_{0.8})\,10^{-9}$	$< 4.2 \times 10^{-10}$ (95% CL)
LHCb (2017)	$(3.0 \pm 0.6 \pm^{0.3}_{0.2})\,10^{-9}$	$< 3.4 \times 10^{-10}$ (95% CL)

Presence of new physics, e.g 2HDM, Lepto-quarks, SUSY may enhance the branching fractions.

Goal: precise measurement of branching fractions and other observables

Analysis

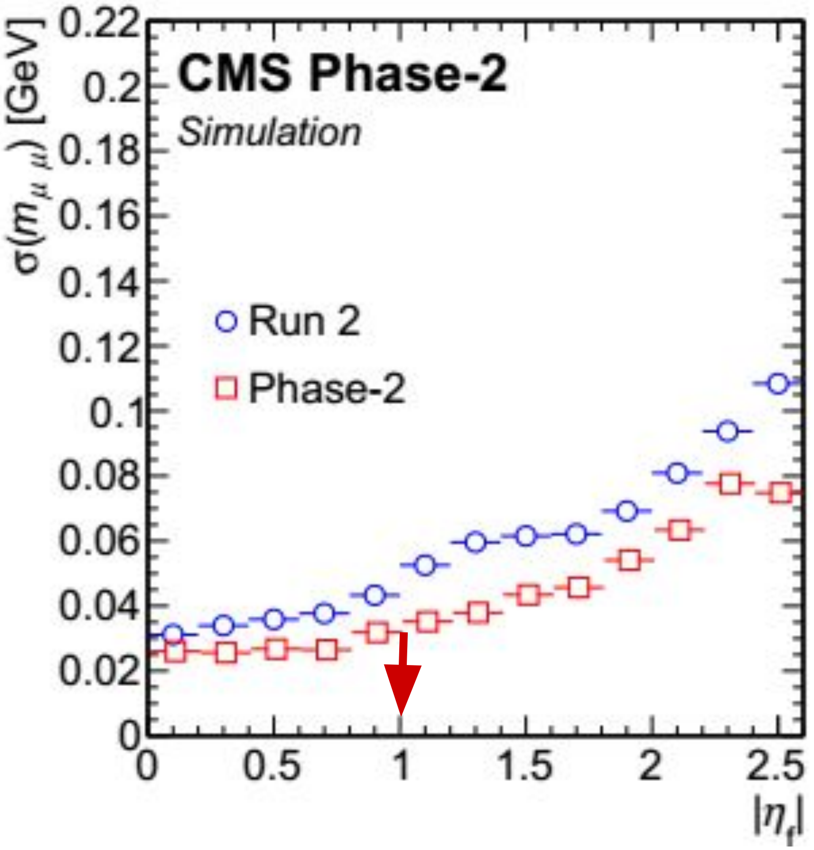
- B candidates are formed from two oppositely charged muon candidates with
  - $p_T > 4$ GeV for $|\eta| < 1.4$
  - $p_T > 2$ GeV for $|\eta| > 1.4$
- A simple Gaussian fit is performed on the mass distribution to find the peak position and the resolution



Pseudorapidity of the most forward muon $|\eta_f| < 1.4$

$B_s \rightarrow \mu^+\mu^-$ mass distribution is normalized to unit area, whereas the $B_d \rightarrow \mu^+\mu^-$ mass distribution is normalized to the SM predicted value. Improvement in mass resolution leads to better separation of mass peak (not possible in Run 2)

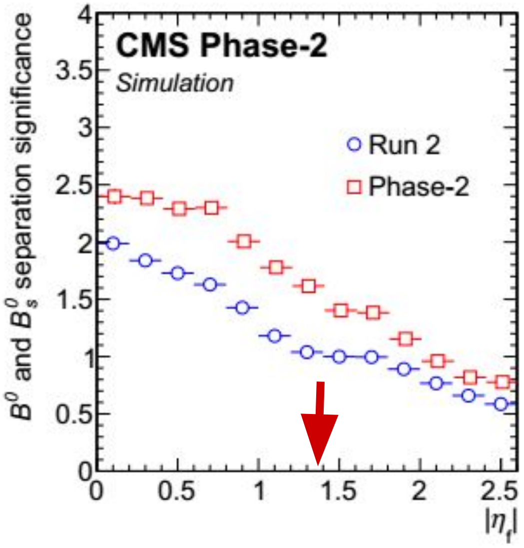
B_s Mass Resolution

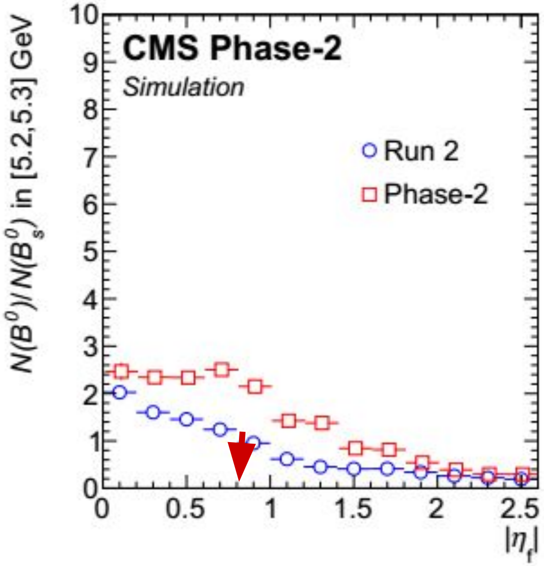


- B_s mass resolution vs pseudorapidity of the most forward muon candidate $|\eta_f|$
- Comparison of Run 2 and Phase-2

Improvement in the momentum resolution leads to ~ 40% gain in mass resolution for $|\eta_f| < 1.0$.

Mass Peak Separation and Leakage

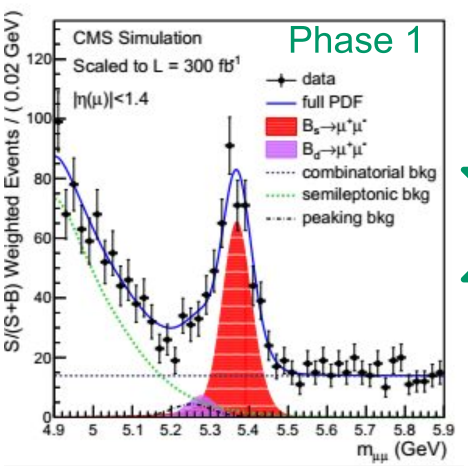


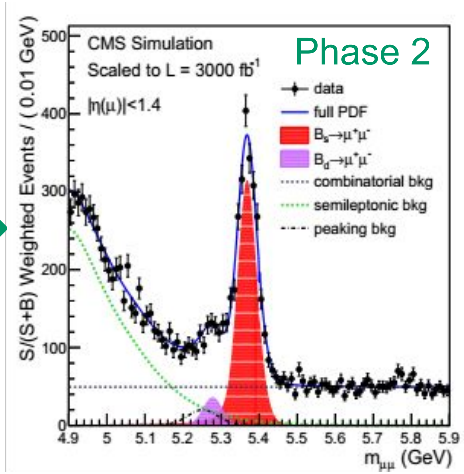


- Mass Peak Separation
  - ~ 25 % improvement in mass peak separation for $|\eta_f| < 1.4$
    - Reduces cross-feed
    - Helps rejecting backgrounds, rare semi-leptonic decay.

- Leakage
  - Ratio of number B_d events over number of B_s events in the B_d invariant mass range
  - Phase-2 visibly better and robust for $|\eta_f| < 0.8$. High leakage in the region $|\eta_f| > 1.4$, which makes the measurement difficult in that region.

Projection of Analysis Sensitivity





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- Observation of $B_d \to \mu^+\mu^-$ at 5σ or more.
- More precise measurement
  - $Br(B_s \to \mu^+\mu^-)$
  - $Br(B_d \to \mu^+\mu^-)$
  - And their ratio

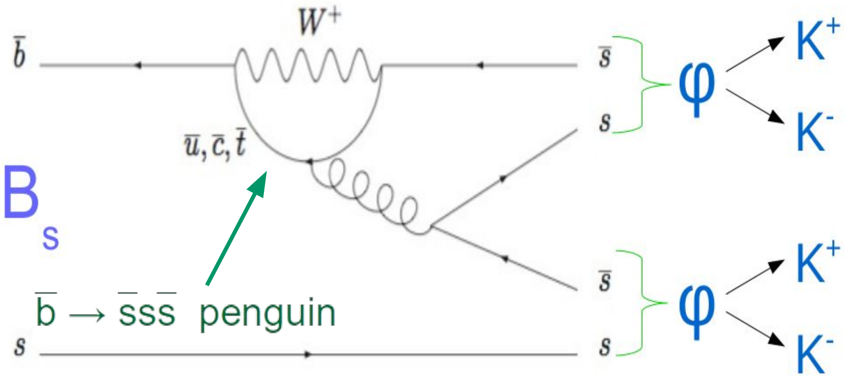
FTR-14-015

Estimate of analysis sensitivity

$\mathcal{L}$ (fb^{-1})	$N(B^0_s)$	$N(B^0)$	$\delta\mathcal{B}(B^0_s \to \mu^+\mu^-)$	$\delta\mathcal{B}(B^0 \to \mu^+\mu^-)$	B^0 sign.	$\delta\frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B^0_s \to \mu^+\mu^-)}$
20	18.2	2.2	35%	> 100%	$0.0 - 1.5\,\sigma$	> 100%
100	159	19	14%	63%	$0.6 - 2.5\,\sigma$	66%
300	478	57	12%	41%	$1.5 - 3.5\,\sigma$	43%
300 (barrel)	346	42	13%	48%	$1.2 - 3.3\,\sigma$	50%
3000 (barrel)	2250	271	11%	18%	$5.6 - 8.0\,\sigma$	21%

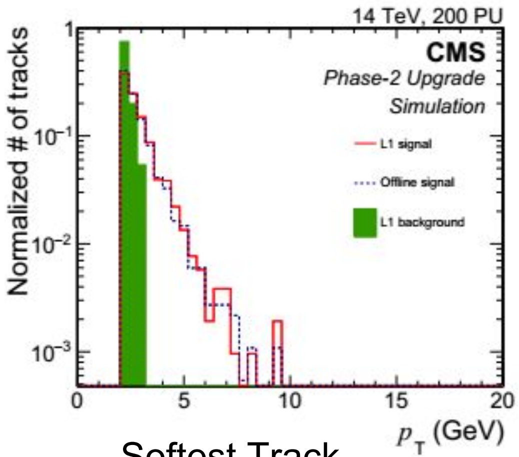
$B_s \rightarrow \phi\phi \rightarrow$ 4 Kaons

$B_s \rightarrow \phi\phi \rightarrow$ 4 Kaons



- FCNC process forbidden at tree level
- b quark decaying through a penguin diagram
  - May receive contribution from heavy particles, beyond the direct reach of LHC
  - Provide new insight to the CP violating phase in the B_s system.

- Rare process
  - $Br(B_s \rightarrow \phi\phi) \approx (1.84 \pm 0.18) \times 10^{-5}$ (PDG)
- Final state Kaons are low p_T tracks
  - Close to the L1 tracking threshold
- A track only analysis
  - An important benchmark analysis with Level-1 Tracking



Softest Track

Analysis Strategy

- Simple cut based analysis, as the goal is to implement in Level-1
- ϕ candidates are reconstructed from pairs of tracks, having opposite charges
  - Originating from same primary vertex
  - Assigning kaon mass to tracks by hand
- B_s candidates are reconstructed from ϕ candidate pairs constrained from the same vertex
  - Events with at least one B_s candidate are selected.
- Signal samples generated with PYTHIA8 and EvtGen, with 140 and 200 Pileup scenario
  - L1 Tracking - To check signal efficiency
  - Offline Tracking - To check if offline is fully efficient over L1.
- Minimum bias events with 70, 140 and 200 Pileup is used to check the event rate at L1.

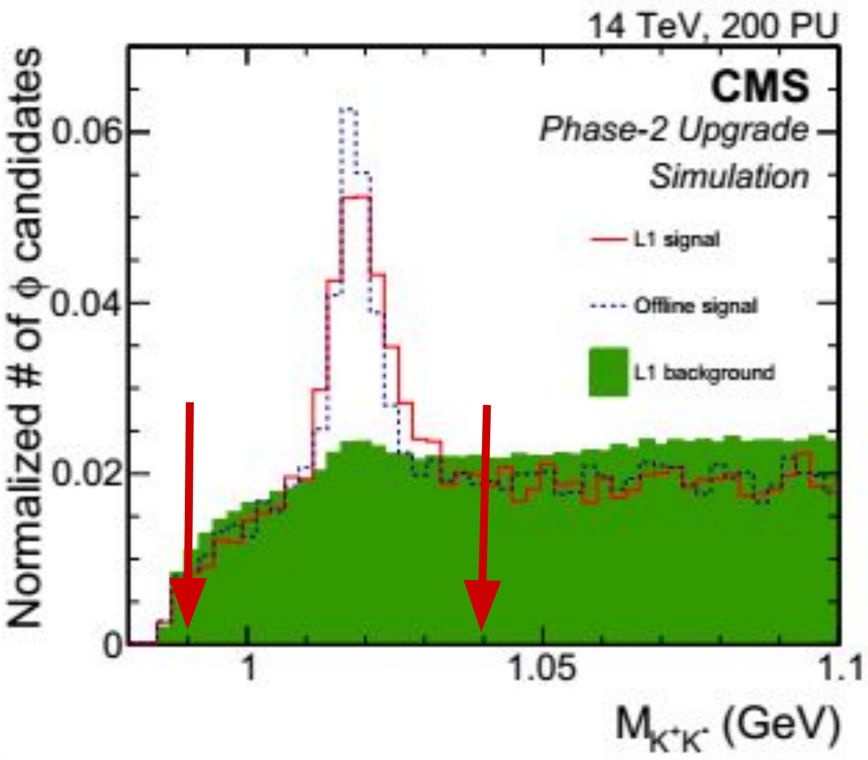
Baseline Selection

- To optimize signal efficiency and trigger rate, three different working points for event selection used
  - Loose, medium and tight

Working point	loose	medium	tight
Tracks	$p_T \geq 2\,\text{GeV}, \|\eta\| \leq 2.5$		
Track pair	$d_{xy} \leq 1\,\text{cm}, \|d_z\| \leq 1\,\text{cm}$		$d_{xy} \leq 0.5\,\text{cm}, \|d_z\| \leq 0.3\,\text{cm}$
ϕ-pair	$d_{xy} \leq 1\,\text{cm}, \|d_z\| \leq 1\,\text{cm}$		$d_{xy} \leq 0.5\,\text{cm}, \|d_z\| \leq 1\,\text{cm}$
ϕ-pair	$0.2 \leq \Delta R(\phi_1, \phi_2) \leq 1, \Delta R(K^+, K^-) \leq 0.12$		
ϕ mass	$0.99 \leq M_{K^+K^-} \leq 1.04\,\text{GeV}$	$1.0 \leq M_{K^+K^-} \leq 1.03\,\text{GeV}$	
B_s^0 mass	$5.27 \leq M_{\phi\phi} \leq 5.49\,\text{GeV}$	$5.29 \leq M_{\phi\phi} \leq 5.48\,\text{GeV}$	

d_Z and d_{xy} : distance between a pair of tracks or trajectories of a pair of reconstructed particles along the beam axis (z) and in the plane perpendicular to beam axis (xy), respectively.

ϕ Candidate Mass

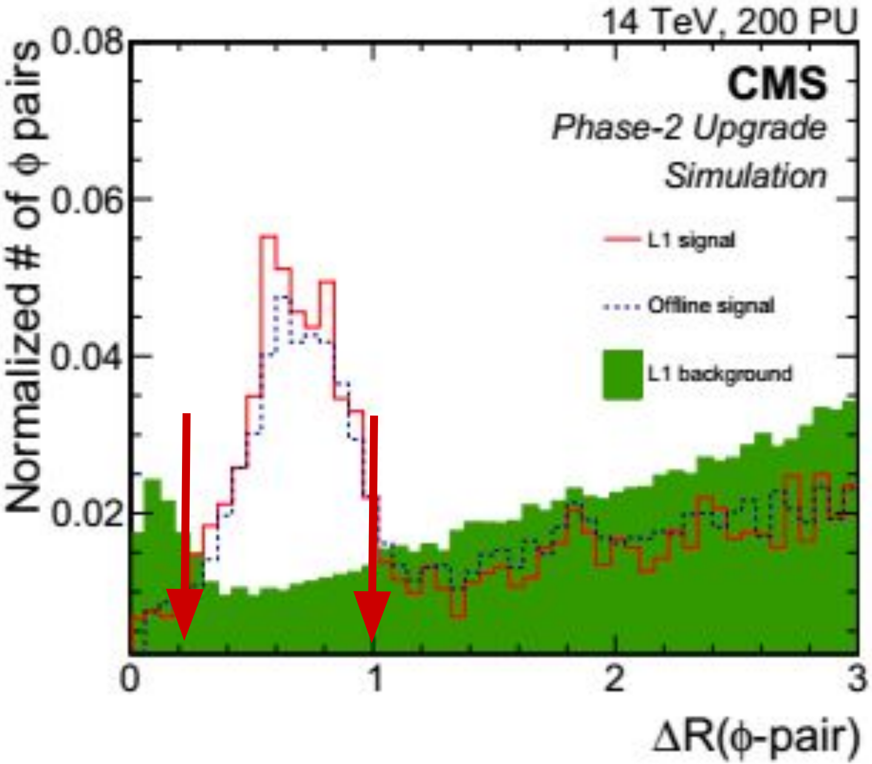


For Loose Baseline

- $0.99 \leq M_{K+K-} \leq 1.04$ GeV

Invariant mass distribution of all track pairs with opposite charges, $|d_Z| < 1$cm, $|d_{xy}| < 1$cm, track $p_T > 2$ GeV. Kaon mass assigned to all the tracks. The event sample does not have any preliminary selection on the B_s mass window. Distributions are normalized to unit area.

ΔR(ϕ-pair)

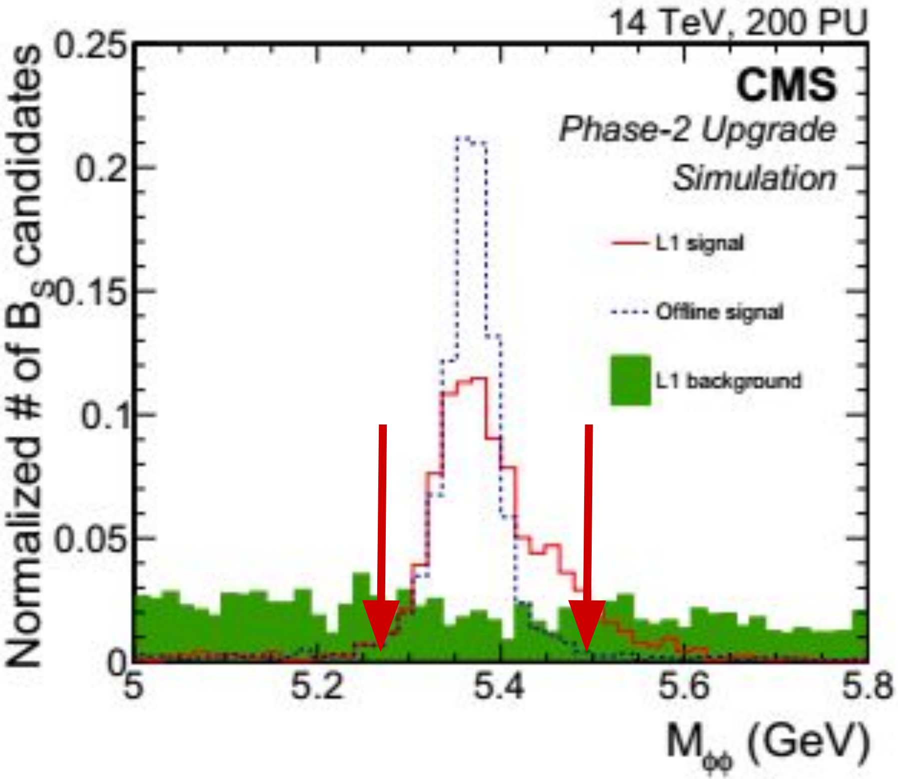


For Loose Baseline

- $0.2 \le \Delta R(\phi\text{-pair}) \le 1$

ΔR(ϕ-pair) distribution for all ϕ pairs with $0.99 \le M_{K+K-} \le 1.04$ GeV, $|d_Z| < 1$ cm and $|d_{xy}| < 1$ cm. The event sample does not have any preliminary selection on the B_s mass window. Distributions are normalized to unit area.

B_s Mass



For Loose Baseline

- $5.27 \leq M_{\phi\phi} \leq 5.49$ GeV

$M_{\phi\phi}$ distribution for all ϕ pairs with $0.99 \leq M_{K+K-} \leq 1.04$ GeV, $|d_Z| < 1$ cm, $|d_{xy}| < 1$ cm and $0.2 \leq \Delta R(\phi\text{-pair}) \leq 1$. The event sample does not have any preliminary selection on the B_s mass window. Distributions are normalized to unit area.

Efficiency and Rate

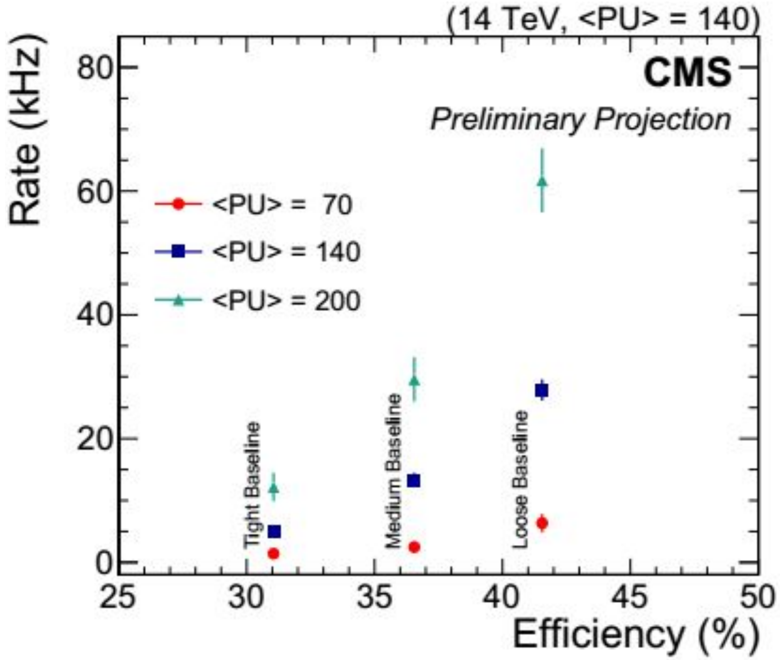
FTR-16-006-PAS

Baseline	Efficiency (%)		Rate (kHz)		
	L1	Offline	<PU> = 70	<PU> = 140	<PU> = 200
Loose	41.6 ± 1.2	61.5 ± 1.3	6.3 ± 1.5	27.9 ± 1.7	61.8 ± 5.2
Medium	36.6 ± 1.1	55.3 ± 1.2	2.5 ± 0.9	13.3 ± 1.2	29.6 ± 3.6
Tight	31.1 ± 1.0	55.1 ± 1.2	1.4 ± 0.7	5.1 ± 0.7	12.2 ± 2.3

- Uncertainties are statistical only.
- Offline efficiency does not include trigger matching for the kaon tracks.

For <Pileup> = 200

- Moderate 30% signal efficiency achievable at a rate ~ 15 kHz



Conclusion

- $B_{d/s} \rightarrow \mu^+\mu^-$
  - Significant improvement in mass resolution leads to better separation of $B_s \rightarrow \mu^+\mu^-$ and $B_d \rightarrow \mu^+\mu^-$ mass peaks
  - Observation of $B_d \rightarrow \mu^+\mu^-$ at 5σ or more
  - More precise measurement of $Br(B_{d/s} \rightarrow \mu^+\mu^-)$, ratio of the branching fractions and other observables
  - Measurements will be difficult in very forward regions
- $B_s \rightarrow \phi\phi \rightarrow$ 4 Kaons
  - Showcases CMS L1 Tracking
  - Signal distinctly visible even at <Pileup> = 200
  - We are working on further reduction in L1 rate
    - Mitigation of pileup effects using timing information

Thank You!