# CMS Upgrade and B-physics at the HL-LHC

Subir Sarkar
Saha Institute of Nuclear Physics

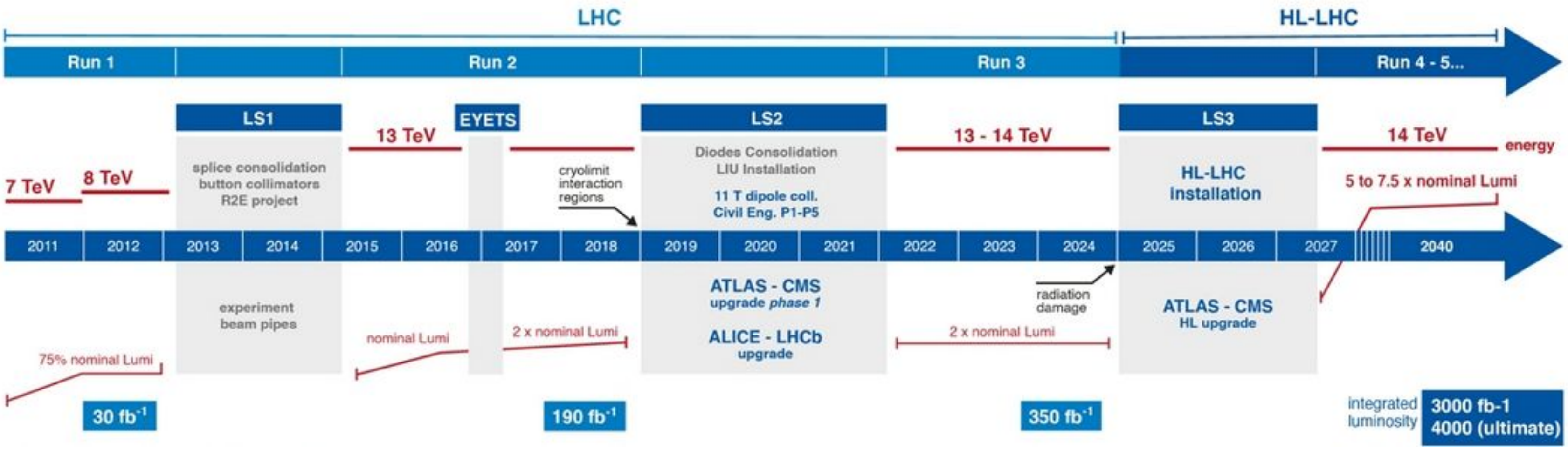
On behalf of the CMS Collaboration

Beauty 2020, 19th International Conference on B-Physics at Frontier Machines
September 21-24, 2020

# Outline

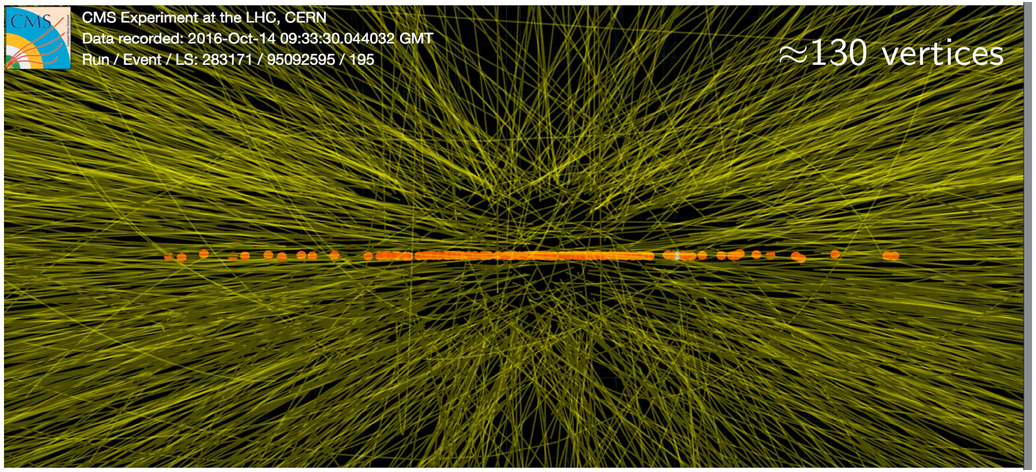
- HL-LHC - prospects and challenges
- CMS Phase-2 Upgrade overview
- Tracking at Level1
- CMS B-physics program for HL-LHC
  - $B_s \to \phi\phi \to K^+K^-K^+K^-$
  - $B_{d/s} \to \mu^+\mu^-$
- Summary

# High Luminosity LHC Scenario




- Physics prospects with 3000-4000 $fb^{-1}$
  - precision measurements of the Higgs boson properties
  - Higgs boson self coupling
  - improved SM measurements and access to rare SM processes
  - extending discovery reach for physics beyond the SM
  - precision measurements in the flavour sector

# Challenges at the HL-LHC

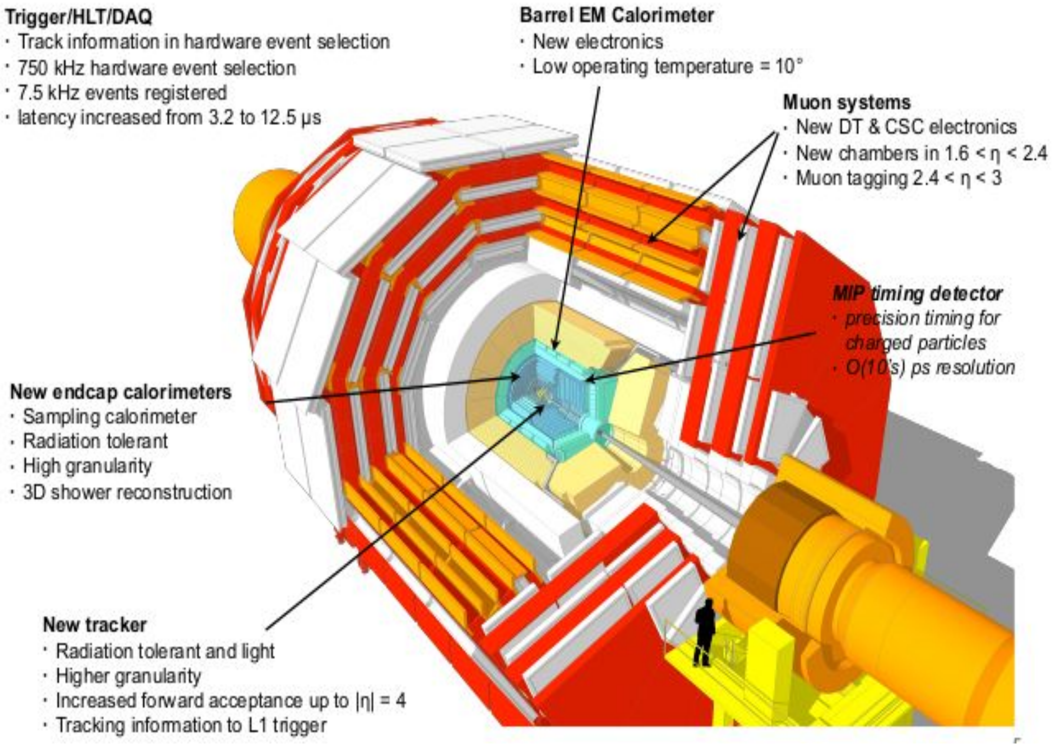



A CMS event from a special run in 2016 with HL-LHC like pileup interactions

- B physics potential, in particular, will suffer significantly from the HL-LHC pileup conditions
  - low $p_T$ signature
  - requirement of very high precision measurements

- Extremely harsh environment
  - expected average pileup interactions of 140-200
  - increase of particle density
  - radiation damage to the detector
- L1 trigger rate will be unmanageable at 40 MHz with only calorimeter and muon information
  - availability of tracking information at L1 crucial to retain full physics potential

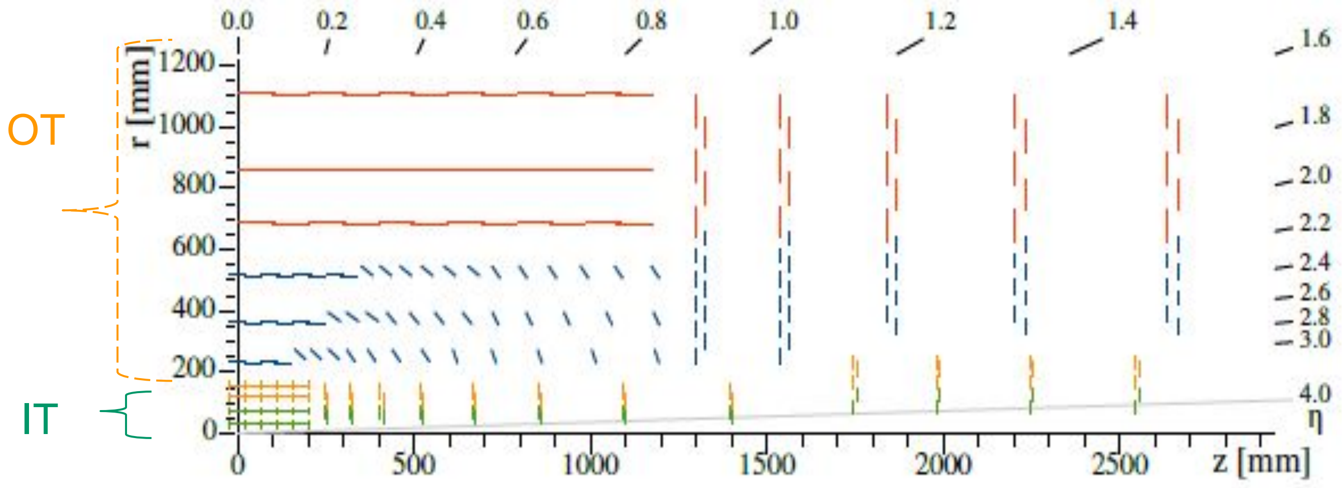
# CMS Phase-2 Upgrade Overview




- CMS upgrades include
  - a new tracker with improved radiation hardness and $p_T$ resolution
  - increased Muon coverage
  - a new forward calorimeter with high granularity and resolution
  - addition of the MIP timing detector (MTD)
  - replacement of electronics
  - increased trigger bandwidth and latencies
  - inclusion of tracking information at Level1 trigger

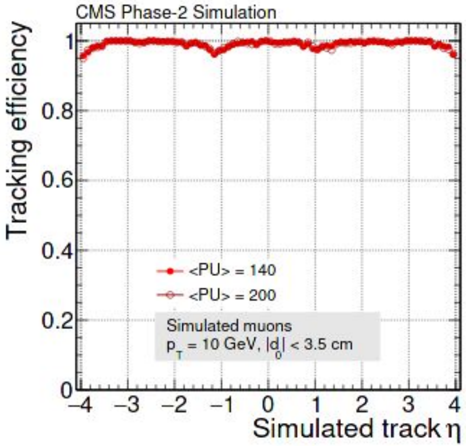
# Phase-2 Tracker Upgrade

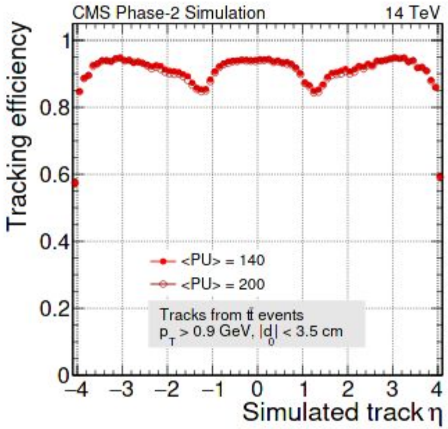
CMS-TDR-014

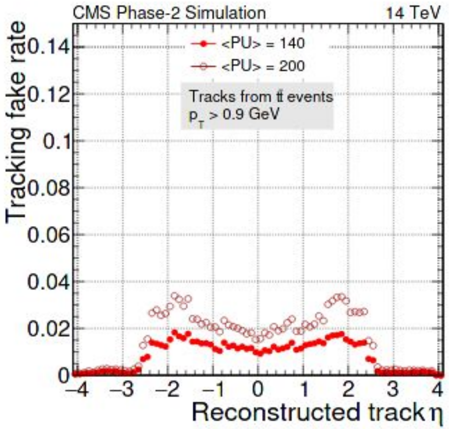



- Inner tracker (IT)
  - pixel sensors
  - narrower pitch than present pixel detector
  - increased granularity to limit the occupancy
  - coverage up to |η|~4
- Outer tracker (OT)
  - design driven by addition of hardware track trigger capabilities
  - pixel-strip & 2-strip sensors
  - progressively tilted modules

# Phase-2 Tracker Upgrade: Efficiency, Fake rate, material budget

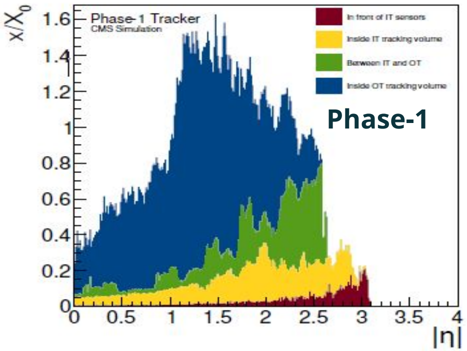


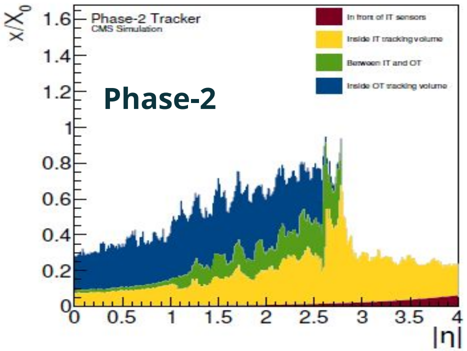




CMS-TDR-014

- High efficiency maintained over the full pseudorapidity coverage both for muons (p T > 10 GeV) and tracks from ttbar events (p T > 0.9 GeV)
- Level of fake tracks increases with pileup, but still under control (always < 4% even at 200 PU)



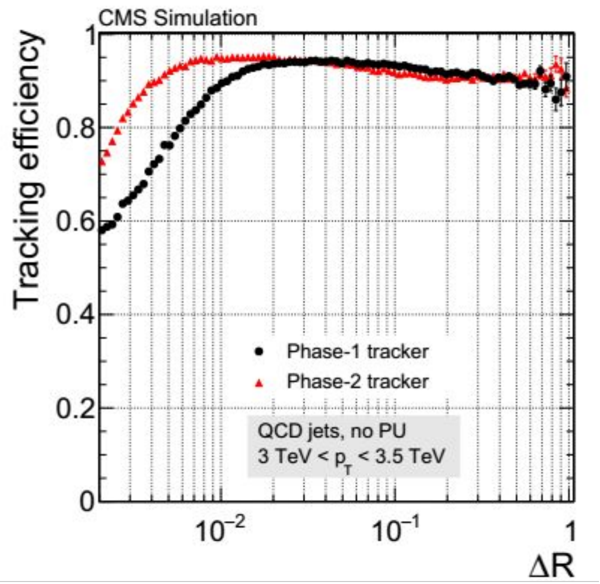




Substantial reduction of the material budget with respect to present detector

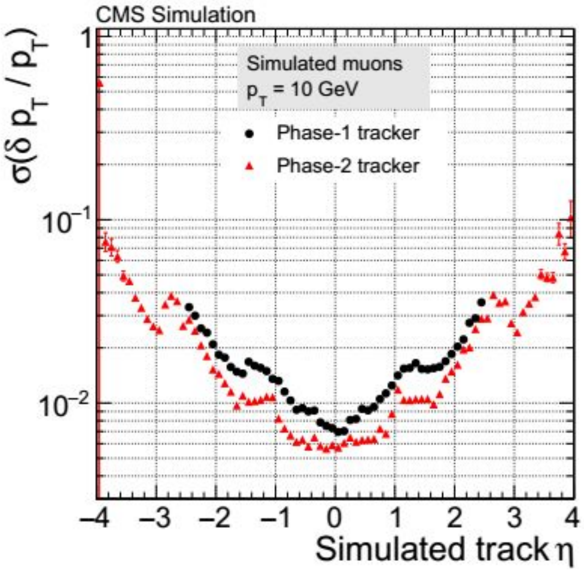
# Tracking Performance - Phase-2 vs Phase-1

CMS-TDR-014

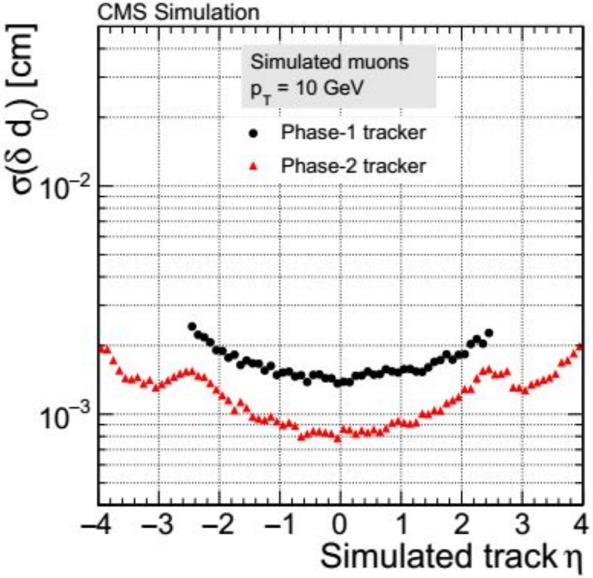
Tracking efficiency




$p_T$ resolution




IP resolution

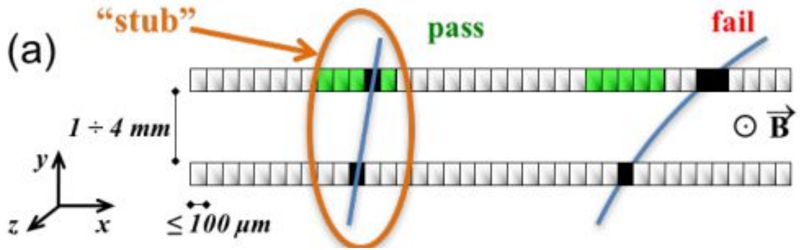



- Larger η coverage
- In the same η region, Phase-2 tracker performs better
- b-Tagging can be extended to high η region
- Improved $p_T$ and IP resolution will improve overall physics performance

# L1 Tracking

- Availability of tracking information at L1 enables CMS to
  - improve $p_T$ resolution of various objects (e.g. muons)
  - mitigate impact of pileup interactions
  - exploit track isolation
  - perform particle-flow reconstruction of physics objects at the trigger level

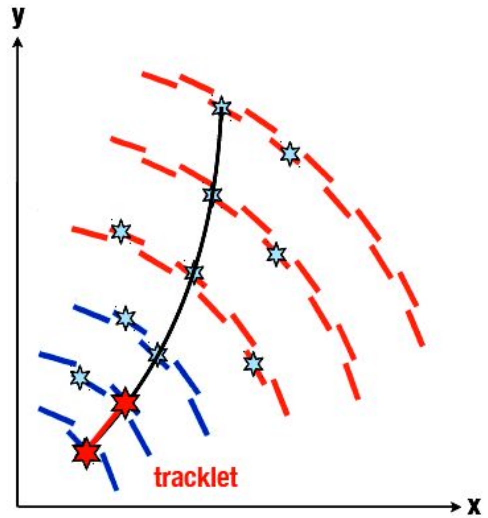
- OT modules are designed to select high-$p_T$ tracks at the detector front-end
  - two closely-spaced single-sided sensors
  - correlate hits on the two sensors
    - a local $p_T$ measurement is possible to allow on-detector filtering using $p_T$ thresholds
    - a "stub" formed
  - limited in angular acceptance up to $|\eta|$ = 2.4



# L1 Tracking and L1 Trigger

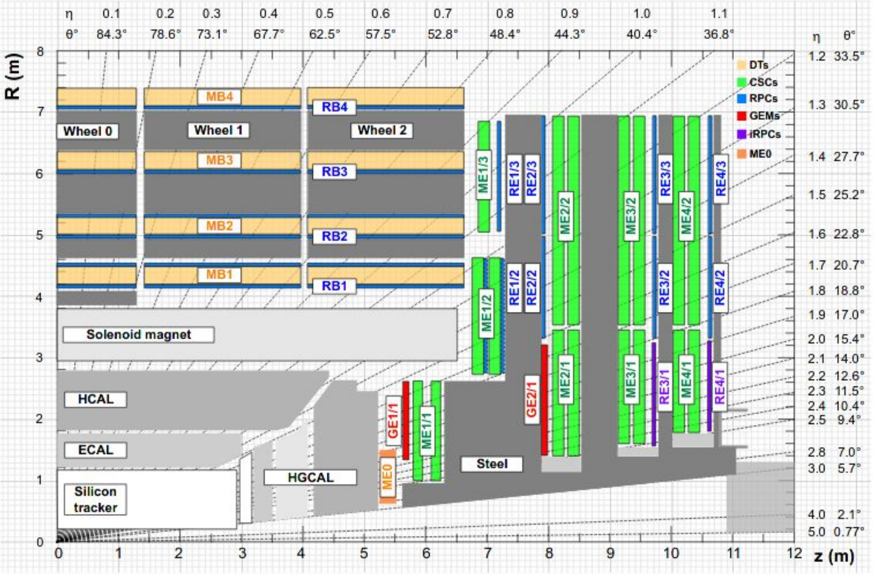
- Hardware trigger receives track "stubs" with $p_T$ > 2 GeV
  - a factor 10-100 reduction in data volume
- "stubs" are then sent to the off-detector L1 tracking system, which reconstructs tracks for input to the L1 trigger
  - a track is formed by connecting the "stubs" in different layers
- Tracking information will be combined with Calorimeter and Muon Chamber information
- Once an event is selected at Level, all the tracker hits in pipeline are passed to HLT

Track reconstruction



# Muon Detector Upgrade

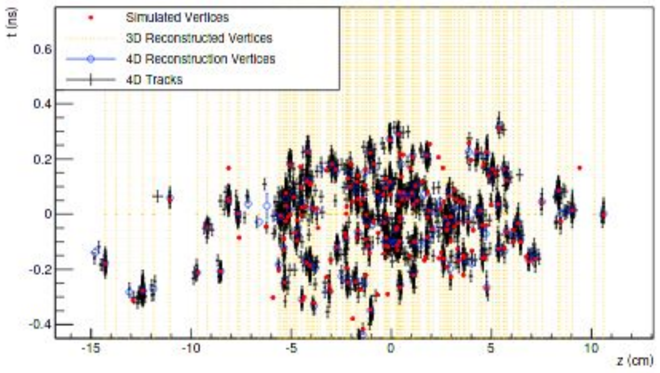
- Additional chambers to enhance muon trigger and reconstruction performance in the forward region
  - RPC (iRPC) in the region 1.6 < |η| < 2.4
  - GEM chambers
    - GE1/1, GE2/1 in front of existing forward muon (CSC) system in the region 1.6 < |η| < 2.4
    - ME0 to extend coverage up to |η| = 2.8
- Upgrade of electronics to cope with radiation hardness, meet trigger/readout latency requirements

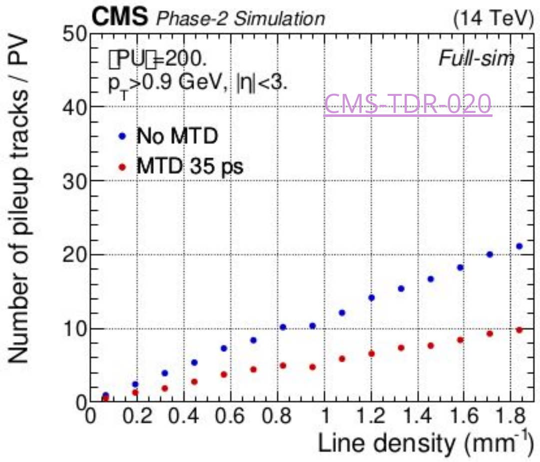



- Higher efficiency
  - more hits along the muon's trajectory in the forward muon system due to the new chambers
  - better interplay detectors ⇔ faster electronics
- Lower rate
  - improved identification and momentum measurement
- Significantly improved turn-on
  - integration with L1 track trigger
- Extended coverage in η for multi-muon triggers

# Mitigation of Impact of Pileup - MIP Timing Detector

- 5-fold increase in pileup will adversely impact quantities based on charged particles
- Performance can be recovered by exploiting the time distributions of different interactions
  - timing resolution of 10-30 ps needed to distinguish between interactions
- Calorimeter upgrades provide precision timing for high/medium energy photons and hadrons
- Additional timing layer (barrel + endcaps outside tracker volume) provides precision timing ($\sigma_t \sim 30$ ps) for charged hadrons & converted photons down to a few GeV
  - traditional 3D vertex fit can be upgraded to a 4D fit
- Particle ID capability for charged particles with $p_T < 2$ GeV (p, K, π)



# CMS B-physics Program

Search for rare FCNC fully hadronic B decays

- $B_s \to \phi\phi \to K^+K^-K^+K^-$
  - no object based trigger
  - inaccessible without the L1 tracks
  - $p_T$ threshold as low as 2 GeV
  - L1 trigger study

**CMS-TDR-021**

Search for very rare FCNC leptonic B decays

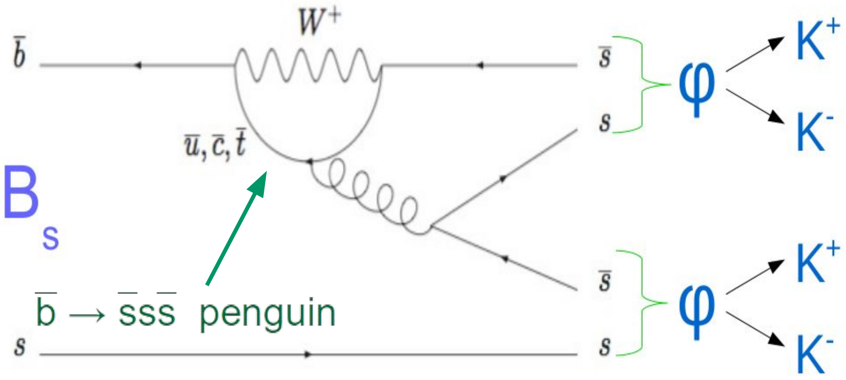
- $B_{d/s} \to \mu^+\mu^-$
  - di-muon trigger
  - L1 track trigger to ensure high efficiency for low $p_T$ muons
  - Full study (L1 + Offline)

**CMS-TDR-014** **CMS-PAS-FTR-18-013**

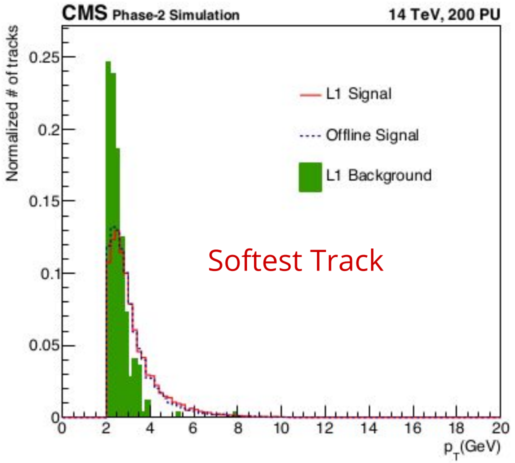
Both the searches offer a handle for indirect search of NP beyond SM

$$B_s \rightarrow \phi\phi \rightarrow K^+K^-K^+K^-$$

# $B_s \to \phi\phi \to$ 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




- A fully hadronic, rare final state
  - $Br(B_s \to \phi\phi) \approx (1.84 \pm 0.18) \times 10^{-5}$ (PDG)
- Final state Kaons are low $p_T$ tracks
  - close to the L1 tracking threshold of 2 GeV

# Analysis Strategy

- $\phi$ candidates are reconstructed from pairs of tracks
  - with opposite charges
  - originating from same primary vertex
  - assuming tracks to be kaons
- $B_s$ candidates are then formed from $\phi$ candidate pairs coming 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 scenarios
  - L1 tracking - to estimate signal efficiency
  - Offline tracking - to check if offline is fully efficient over L1
- Single neutrino-gun events used to estimate event rate at L1

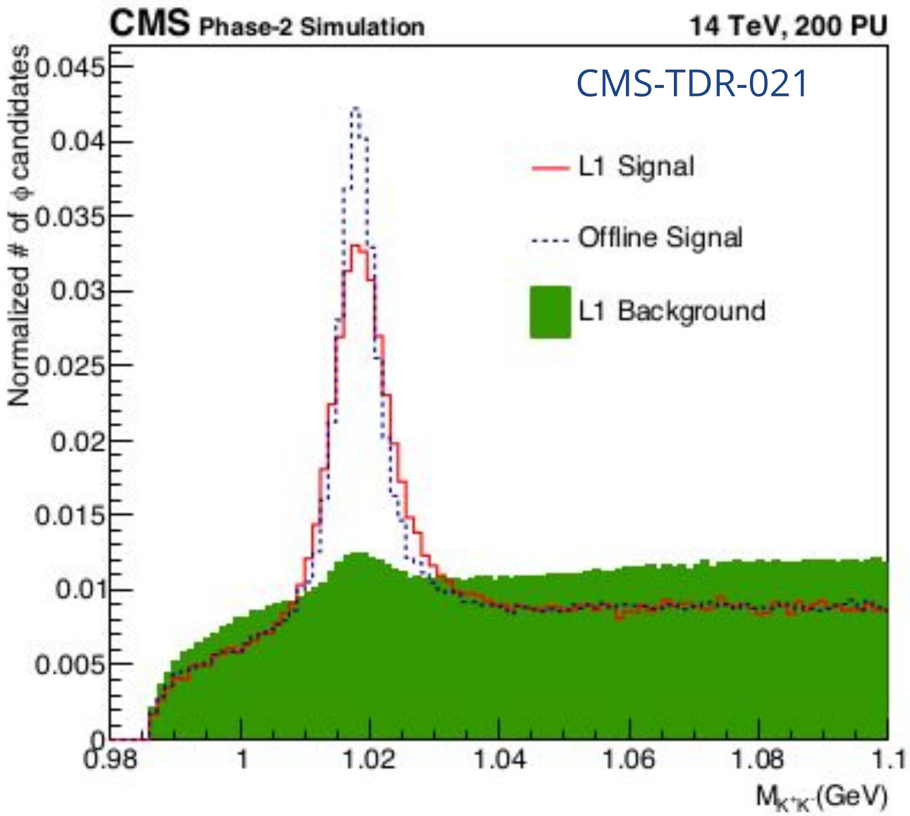
# Baseline Selection

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

| Working point | loose | medium | tight |
|---|---|---|---|
| Tracks | $p_T \geq 2$ GeV, $\lvert\eta\rvert \leq 2.5$, $\chi^2/ndf \leq 20$, $N_{stub} \geq 4$, $N_{stub}^{PS} \geq 2$ | | |
| Track pair | $d_{xy} \leq 0.5$ cm, $\lvert d_z\rvert \leq 0.6$ cm | | |
| $\phi$-pair | $d_{xy} \leq 0.5$ cm, $\lvert d_z\rvert \leq 0.6$ cm | | |
| $\phi$-pair | $0.2 \leq \Delta R(\phi_1, \phi_2) \leq 1$, $\Delta R(K^+, K^-) \leq 0.12$ | | |
| $\phi$ mass | $0.99 \leq M_{K^+K^-} \leq 1.04$ GeV | | |
| $B_s^0$ mass | $5.0 \leq M_{\phi\phi} \leq 5.8$ GeV | | $5.1 \leq M_{\phi\phi} \leq 5.7$ GeV |
| $B_s^0$ $p_T$ | $\geq 10$ GeV | $\geq 12$ GeV | |

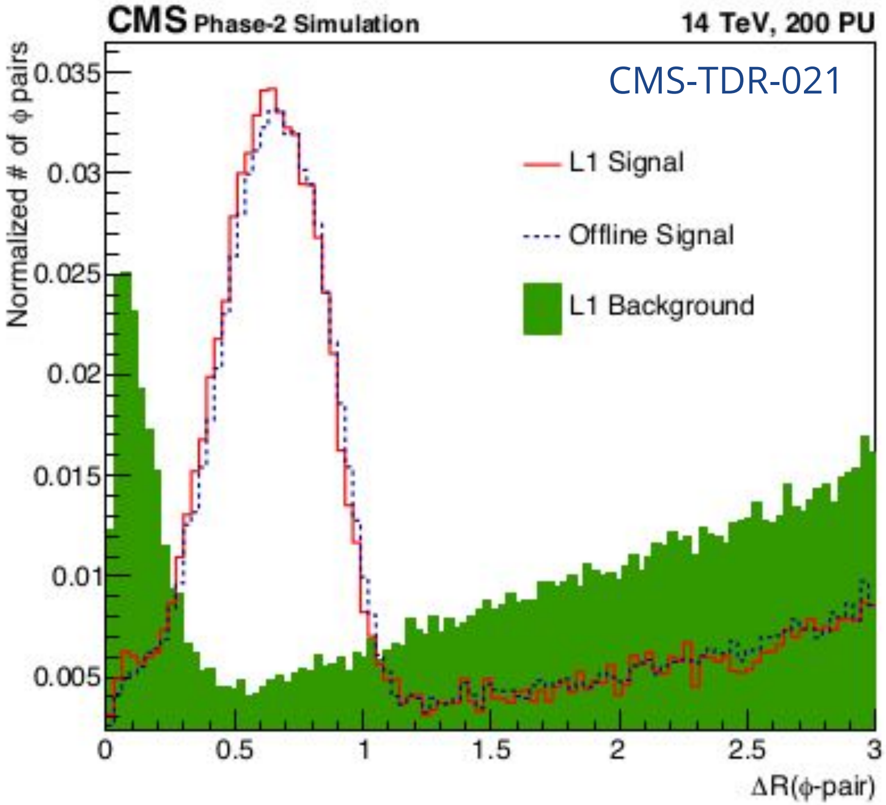
$d_Z$ and $d_{xy}$ : distance between a pair of tracks or trajectories of a pair of reconstructed particles along the beam axis (z) and in the plane perpendicular to beam axis (xy), respectively

# $\phi$ Candidate Mass



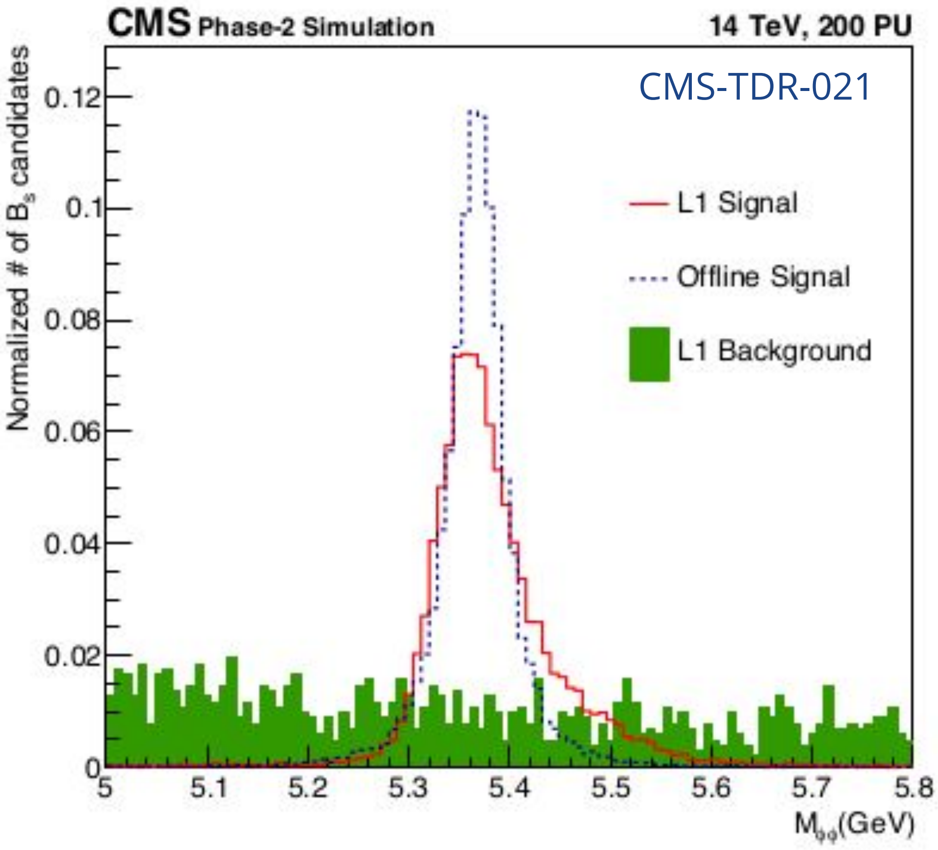

- Invariant mass distribution of all track pairs with
  - opposite charges
  - $|d_Z| < 0.6$ cm, $|d_{xy}| < 0.5$ cm
  - track $p_T > 2$ GeV
  - assuming Kaon
- Distributions normalized to unit area; without any preliminary selection on the $B_s$ mass window

# ΔR($\phi$-pair)




- ΔR($\phi$-pair) distribution for all $\phi$ pairs with
  - $0.99 \le M_{K+K-} \le 1.04$ GeV
  - $|d_z| < 0.6$ cm and $|d_{xy}| < 0.5$ cm
- Distributions normalized to unit area; without any preliminary selection on the $B_s$ mass window

# $B_s$ Mass




- $M_{\phi\phi}$ distribution for all $\phi$ pairs with
  - $0.99 \leq M_{K+K-} \leq 1.04$ GeV
  - $|d_Z| < 0.6$ cm, $|d_{xy}| < 0.5$ cm
  - $0.2 \leq \Delta R(\phi\text{-pair}) \leq 1$
- Distributions normalized to unit area; without any preliminary selection on the $B_s$ mass window

# Efficiencies and Rates

| Baseline | Efficiency (%) | | Rate (kHz) |
|---|---|---|---|
| | L1 | Offline | $< PU > = 200$ |
| Loose | $36.15 \pm 0.37$ | $60.78 \pm 0.50$ | $44.70 \pm 1.65$ |
| Medium | $30.28 \pm 0.33$ | $50.04 \pm 0.44$ | $15.00 \pm 0.95$ |
| Tight | $30.25 \pm 0.33$ | $49.96 \pm 0.43$ | $10.02 \pm 0.78$ |

Statistical uncertainty only

For <PU> = 200

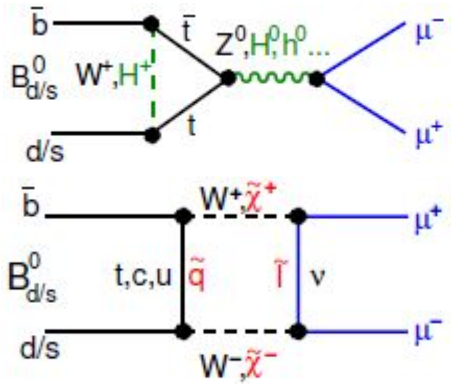
- ~ 30% signal efficiency achievable at a rate ~ 10-15 kHz
- Computation possible on the FPGAs within the given time

FPGAs will be used at the L1 while GPUs will be used at the HLT

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

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

- Proceeds through FCNC, thus highly suppressed in the SM
  - EW-Penguin and box diagrams, but no tree level
  - Helicity suppressed
- Presence of new physics may enhance/suppress the branching fractions
- precise measurement of branching ratio and other observables is the key

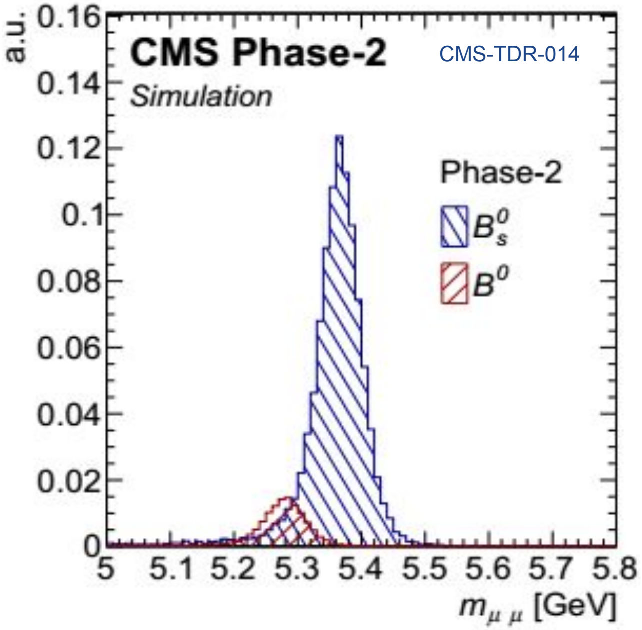



| Results | $Br(B_s \to \mu^+\mu^-)$ | $Br(B_d \to \mu^+\mu^-)$ | |
|---|---|---|---|
| SM | $(3.66 \pm 0.23) \times 10^{-9}$ | $(1.06 \pm 0.09) \times 10^{-9}$ | |
| Run I (CMS) | $(3.0^{+1.0}_{-0.9}) \times 10^{-9}$ | $< 1.1 \times 10^{-9}$ @95% CL | Phys. Rev. Lett. 111, 101804 |
| Run I (CMS + LHCb) | $(2.8^{+0.7}_{-0.6}) \times 10^{-9}$ | $(3.9^{+1.6}_{-1.4}) \times 10^{-10}$ | Nature 522, 68–72 (2015) |
| Run I (ATLAS) | $(0.9^{+1.1}_{-0.8}) \times 10^{-9}$ | $< 4.2 \times 10^{-10}$@95% CL | *Eur.Phys.J.C* 76 (2016) 9, 513 |
| Run I, II (LHCb) | $(3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$ | $< 3.4 \times 10^{-10}$@95% CL | Phys. Rev. Lett. 118, 191801 (2017) |
| ATLAS+CMS+LHCb | $(2.69^{+0.37}_{-0.35}) \times 10^{-9}$ | $< 1.9 \times 10^{-10}$ @95% CL | ATLAS-CONF-2020-049 etc. |

Also see CMS: Search for Rare Decays by Chandiprasad Kar

# Analysis

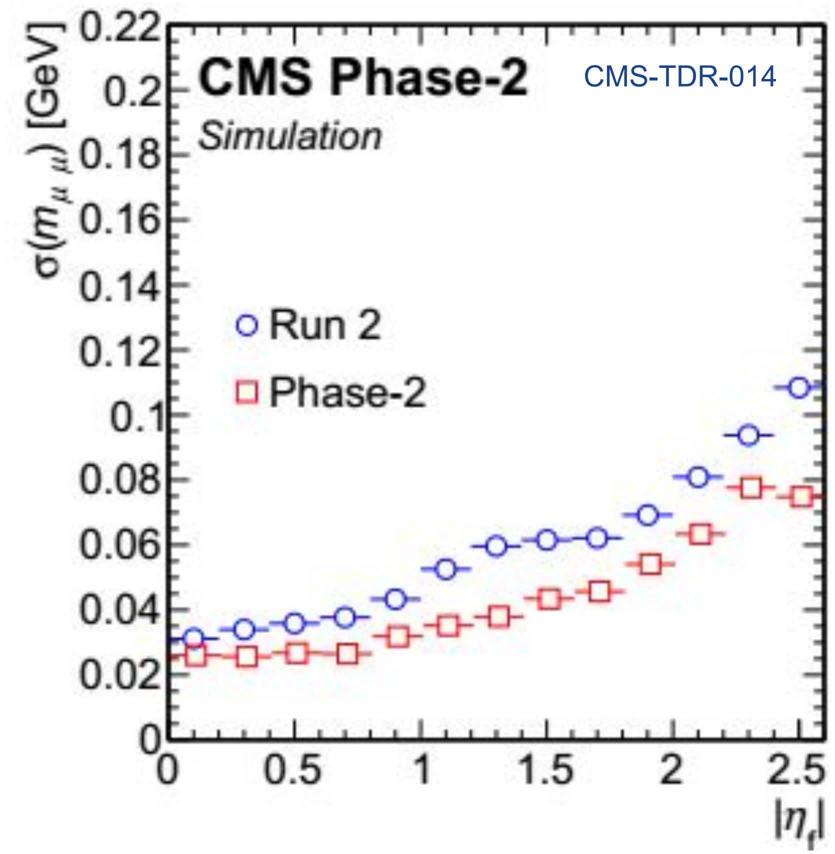
- Input to the projection study
  - CMS Run-2 analysis strategy, updated SM predictions, improvements in L1 trigger, mitigation of impact of Pileup, di-muon mass resolution, scaling of systematic uncertainties
- B candidates are formed from two oppositely charged muon candidates with
  - $p_T > 4$ GeV 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 resolution




- $B_s \to \mu^+\mu^-$ mass distribution is normalized to unit area, whereas the $B_d \to \mu^+\mu^-$ mass distribution is normalized to the SM predicted value
- most forward muon $|\eta_f| < 1.4$

Improvement in mass resolution leads to better separation of mass peak

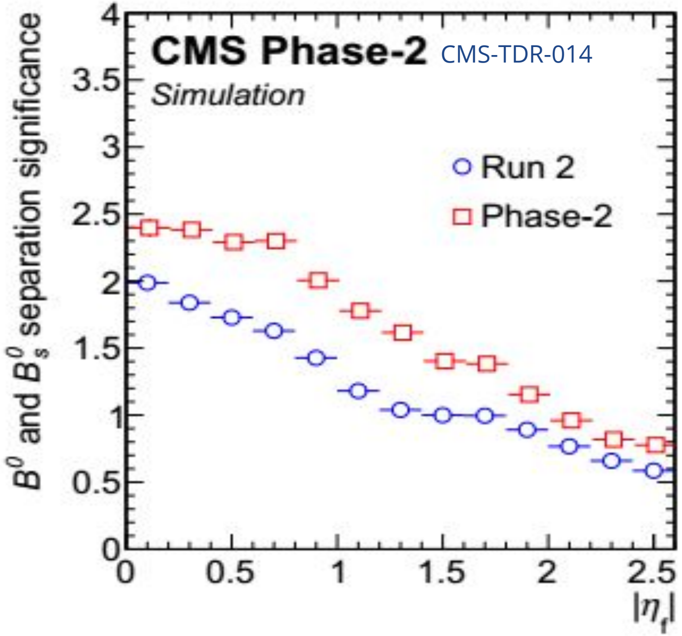
# $B_s$ Mass Resolution

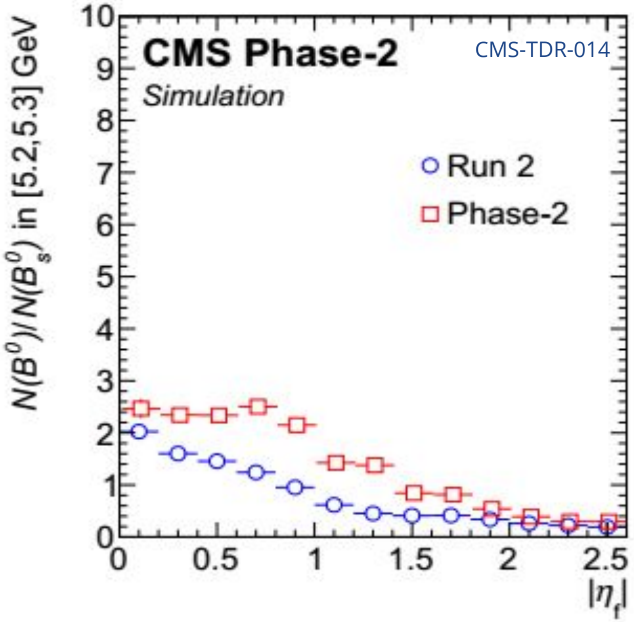



- $B_s$ mass resolution vs pseudorapidity of the most forward muon candidate, $|\eta_f|$
- Comparison of Run 2 and Phase-2

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

# Mass Peak Separation and Leakage



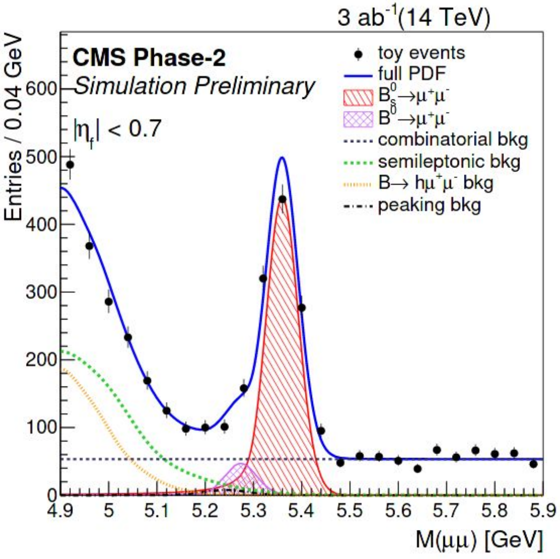



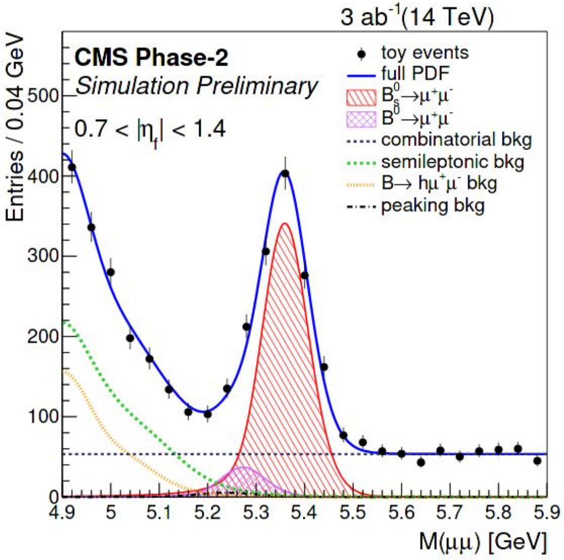

- Mass Peak Separation
  - ~ 25 % improvement in mass peak separation for $|\eta_f| < 1.4$
    - reduces cross-feed
    - helps rejecting backgrounds, rare semi-leptonic decay

- Cross-feed: 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 $|\eta_f| < 0.8$.
  - measurement difficult in the region $|\eta_f| > 1.4$, due to high leakage

# Projection of Analysis Sensitivity

CMS-PAS-FTR-18-013




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

| L (fb$^{-1}$) | N($B_s$) | N($B_d$) | ΔBr($B_s \to \mu^+\mu^-$) | ΔBr($B_d \to \mu^+\mu^-$) | $B_d$ Significance |
|---|---|---|---|---|---|
| 300 | 205 | 21 | 12% | 46% | 1.4 - 3.5σ |
| 3000 | 2048 | 215 | 7% | 16% | 6.3 - 8.3σ |

# Summary

- The HL-LHC and CMS Phase-2 upgrade will extend the physics reach of CMS significantly
- $B_s \rightarrow \phi\phi \rightarrow K^+K^-K^+K^-$
  - showcases the power of CMS L1 Tracking
  - signal distinctly visible even at <PU> = 200 at L1
  - offline analysis is definitely more challenging
- $B_{d/s} \rightarrow \mu^+\mu^-$
  - 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
- $B_s \rightarrow J/\psi\ (\mu^+\mu^-)\ \phi(K^+K^-)$, $H \rightarrow \phi(K^+K^-)\ \gamma$, $H \rightarrow \rho(\pi^+\pi^-)\ \gamma$ will gain from L1 tracking
- $\tau \rightarrow \mu\mu\mu$ will gain from extended muon coverage and L1 tracking

# Thank You!