CMS B Physics Prospects at the HL-LHC

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On Behalf of the CMS Collaboration

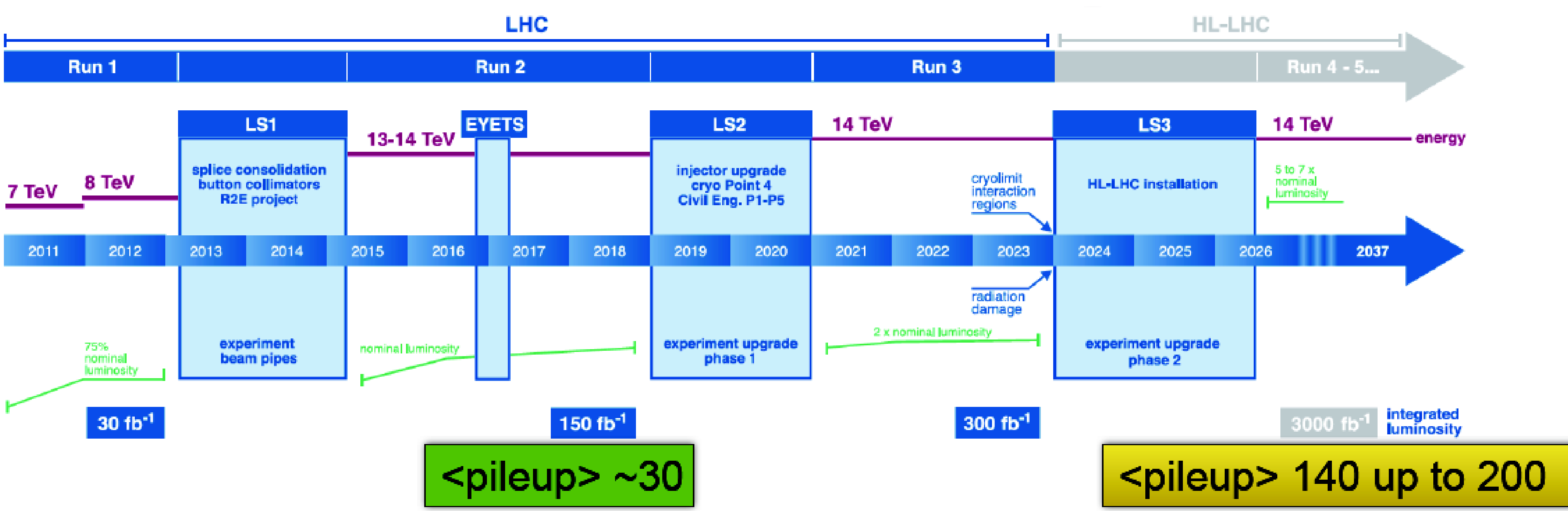
Workshop on the physics of HL-LHC, and perspectives at HE-LHC
CERN, October 30 – November 1, 2017

Outline

- Introduction
- HL-LHC and CMS Phase-2 Upgrade
- B Physics Benchmark Studies
  - $B_{d/s} \to \mu^+\mu^-$
  - $B_s \to \varphi\varphi \to 4K$
- Conclusion

HL-LHC Scenario

- HL-LHC is expected to deliver > 3/ab to both CMS and ATLAS at √s = 14 TeV in 10 years (2026-36)
  - x 10 of LHC Runs 1-3 combined
  - average no of collisions will be ~ 140-200 / bunch crossing as compared to the present value of ~ 40-50



HL-LHC & CMS Phase-2 Upgrade

- HL-LHC luminosity (140-200 pileup) tends to weaken B physics potential
  - low p_T signature
  - requirement of very high precision
- Experiments must ensure that
  - overall physics potential is not affected
- Detector, DAQ, Trigger, computing upgrade inevitable. For CMS
  - L1 trigger rate will be unmanageable at 40 MHz with only calorimeter and muon information
  - Tracking at L1 crucial to retain full physics potential
    - will enable us to measure muons as before
  - sensitivity of several physics analysis may get a boost by the upgrade

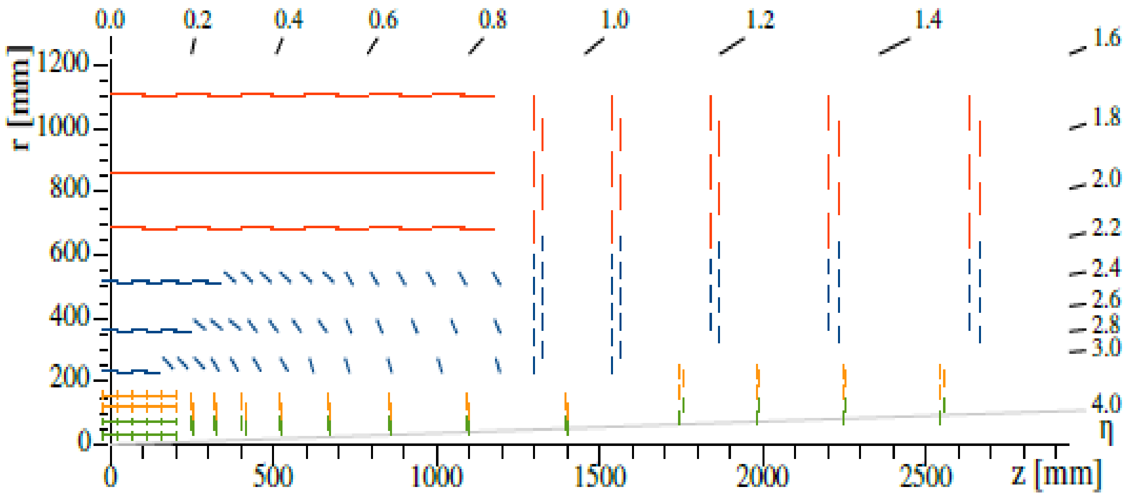
CMS Phase-2 Upgrade

- A new, improved tracker
  - improved radiation resistance, less material budget, finer pixel pitches, real-time tracking capability
  - better track momentum resolution
- Increased muon coverage
  - enhanced muon trigger
- New forward calorimeter with high resolution and granularity
- Increased trigger bandwidth and latencies
- Trigger strategy
  - tracking performed at L1 @ 40 MHz

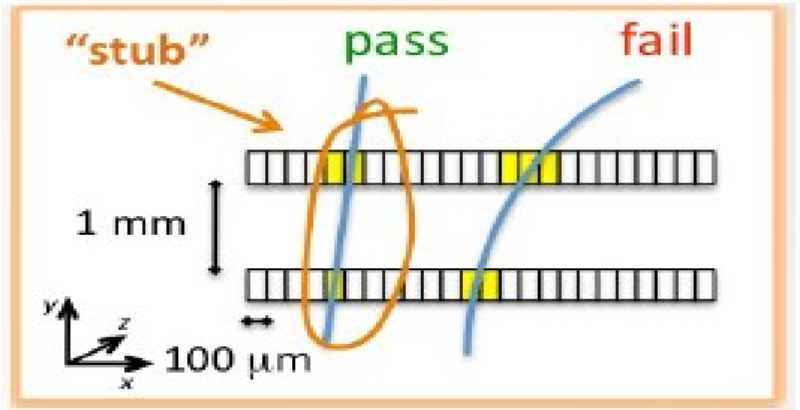
More information

- CMS Detector performance at high pp pile-up – Josh Bendavid
- Tracking in CMS at the HL-LHC (Poster) – Erica Brondolin
- CMS track trigger + tracker impact (Favour WG: Session 4) – Louise Skinnari

CMS Phase-2 Tracker & L1 Tracking

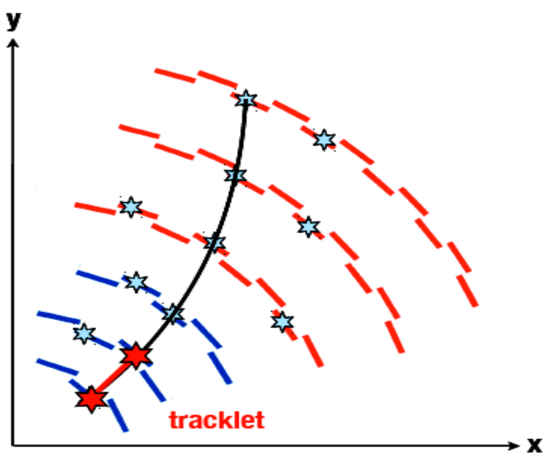


pT Module and stub



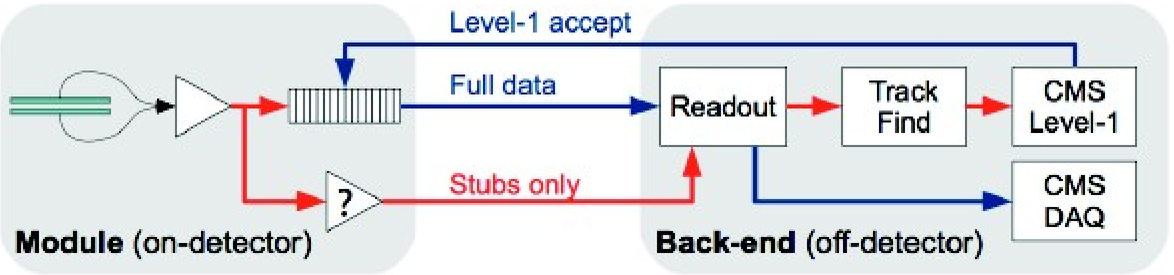
- two silicon sensors separated by a small gap (a few mm)
- hits in two sensors correlated
- tracks bend in strong magnetic field
- stubs with $p_T < 2$ GeV rejected in real-time

➢ Several track finding algorithms having similar performances (see Tracker TDR). The "tracklet" approach used for $B_s \to \varphi\varphi \to 4K$



➢ Form a tracklet with two stubs from neighbouring layers and propagate the tracklet to construct the track

L1 Trigger functionality down to track $p_T \sim 2$ GeV



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

Search for rare FCNC fully hadronic B decay final states

- $B_s \rightarrow \varphi\varphi \rightarrow 4K$
  - Feasibility study
  - Inaccessible w/o L1 track trigger
  - p_T threshold as low as 2 GeV

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.

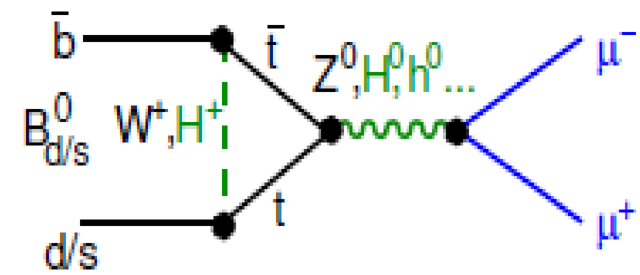
- Flavour physics with b from top decays – see SM WG: session 4, Wednesday morning
- $\tau \rightarrow 3\mu$, Exotic Quarkonia etc. are under study, but no public projection results available yet

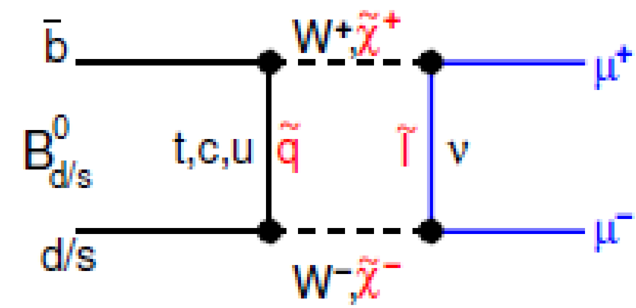
See Plenary "Flavour physics probes of new physics" by Vincenzo Vagnioni

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

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

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





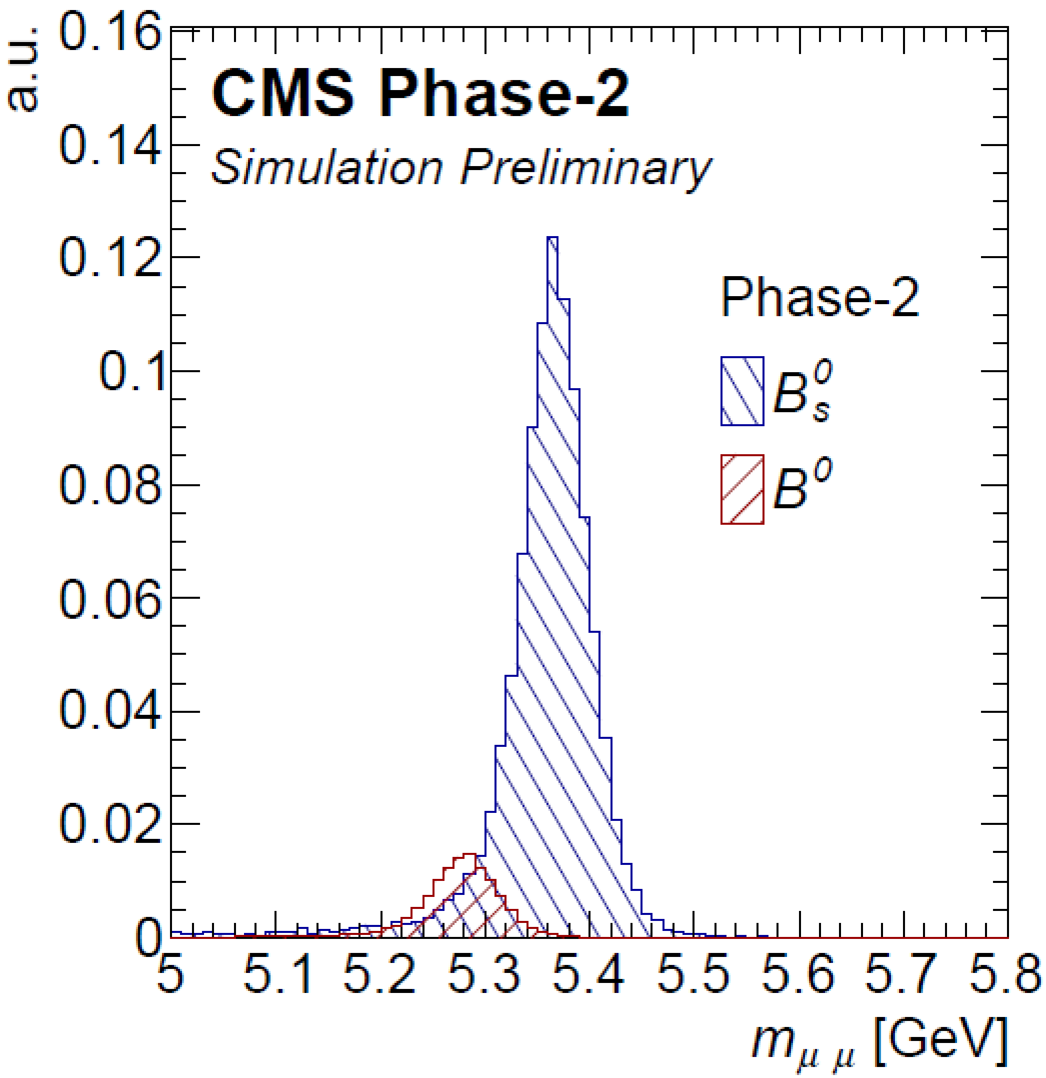
Experiment	**Br ($B_s \rightarrow \mu^+\mu^-$)**	**Br ($B_d \rightarrow \mu^+\mu^-$)**
CMS (2013)	$(3.0 \pm^{1.0}_{0.9})\,10^{-9}$	$< 1.1 \times 10^{-9}$ (95% CL)
LHCb+CMS (2015)	$(2.8 \pm^{0.7}_{0.6})\,10^{-9}$	$(3.9 \pm^{1.6}_{1.4})\,10^{-10}$
ATLAS (2016)	$(0.9 \pm^{1.1}_{0.8})\,10^{-9}$	$< 4.2 \times 10^{-10}$ (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 cause modification to branching fractions
- Goal: precise measurement of branching fractions and other observables

Analysis Framework

- B candidates are formed from two oppositely charged muon candidates with
  - $p_T > 4$ GeV for $|\eta| < 1.4$ and $p_T > 2$ GeV for $|\eta| > 1.4$
- Important variables for background rejection
  - flight length significance of the B candidate
  - significance of the 3D impact parameter of the B candidate with respect to the selected primary vertex
  - distance of closest approach (d_{CA}) between the two muon trajectories
  - isolation variables for muons and B candidates
- No noticeable pileup effect observed upto <PU> = 45
- A simple Gaussian fit to the mass distributions performed in a restricted range to find the peak position and standard deviation

Mass Distribution

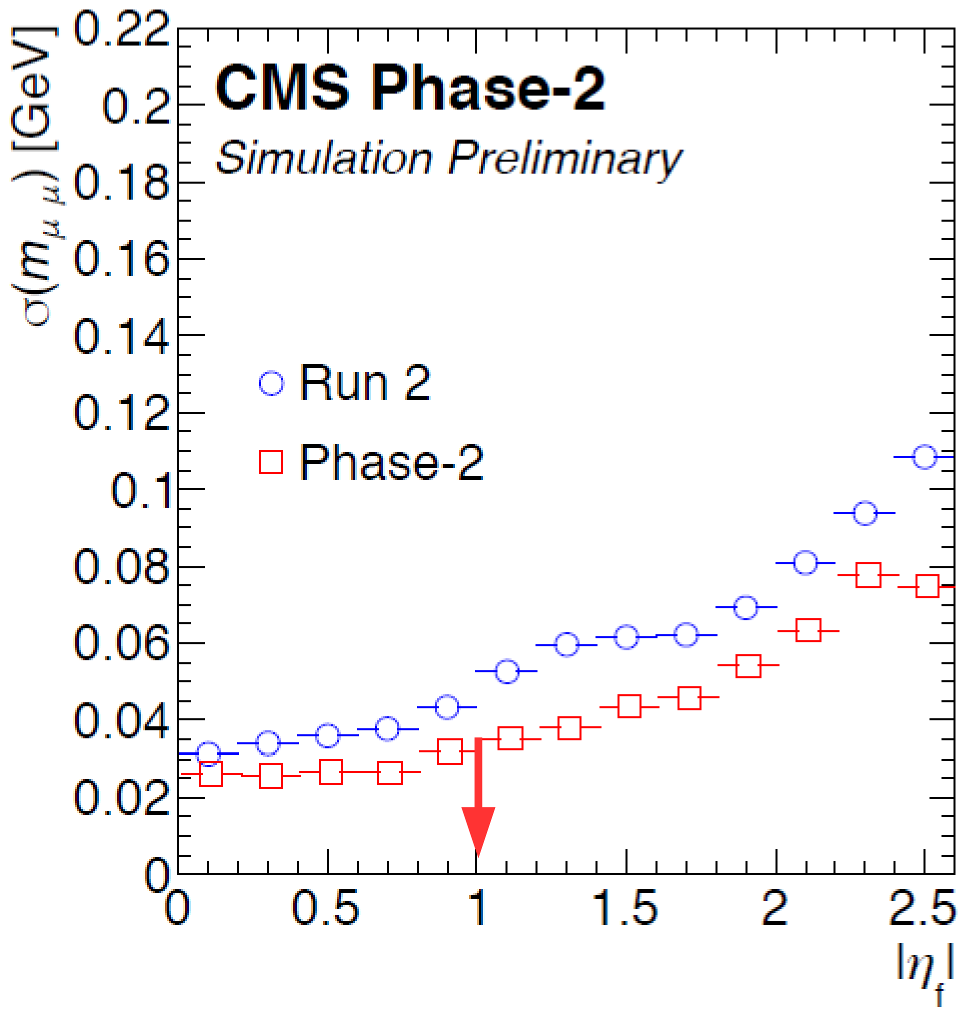


- pseudo-rapidity of the most forward muon candidate, $|\eta_f| < 1.4$

Distribution of $B_s \rightarrow \mu^+\mu^-$ is normalized to unity, while $B_d \rightarrow \mu^+\mu^-$ distribution is normalized according to SM expectation. Improvement in mass resolution leads to better separation of mass peak (not possible in Run-2)

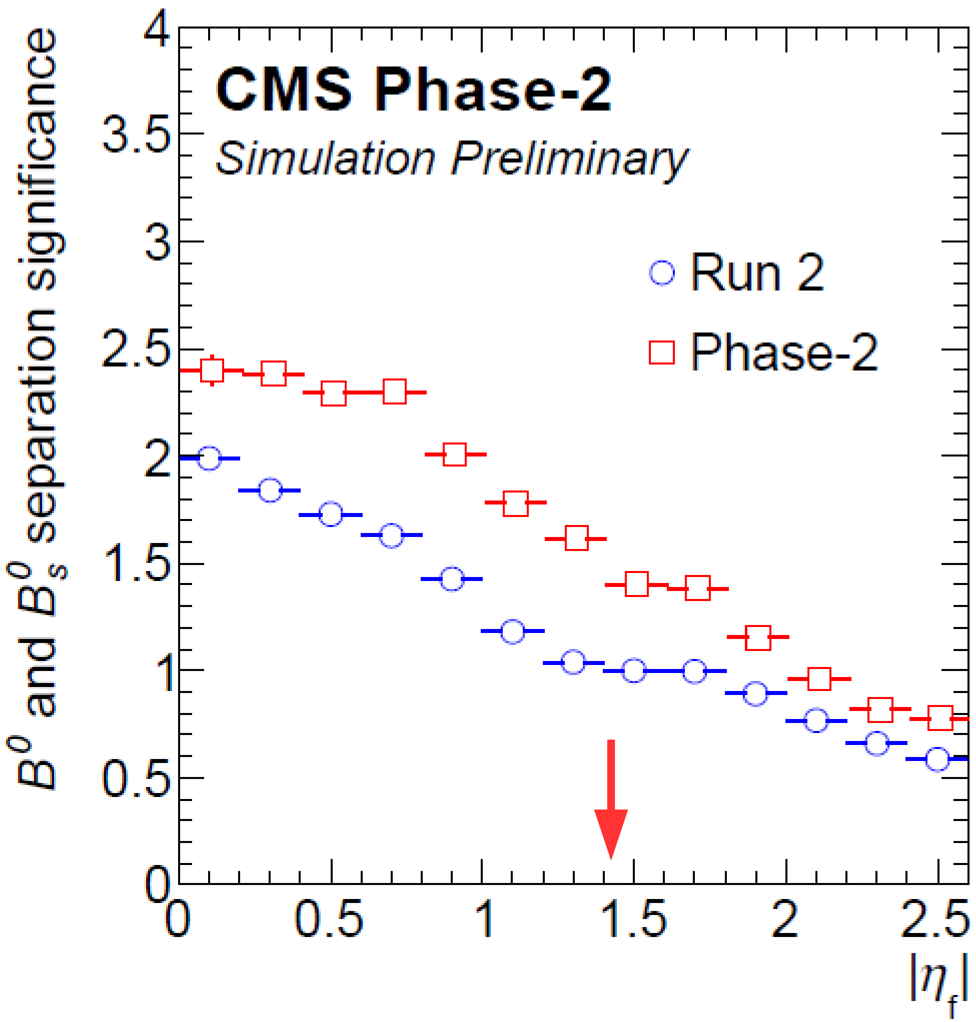
Mass Resolution

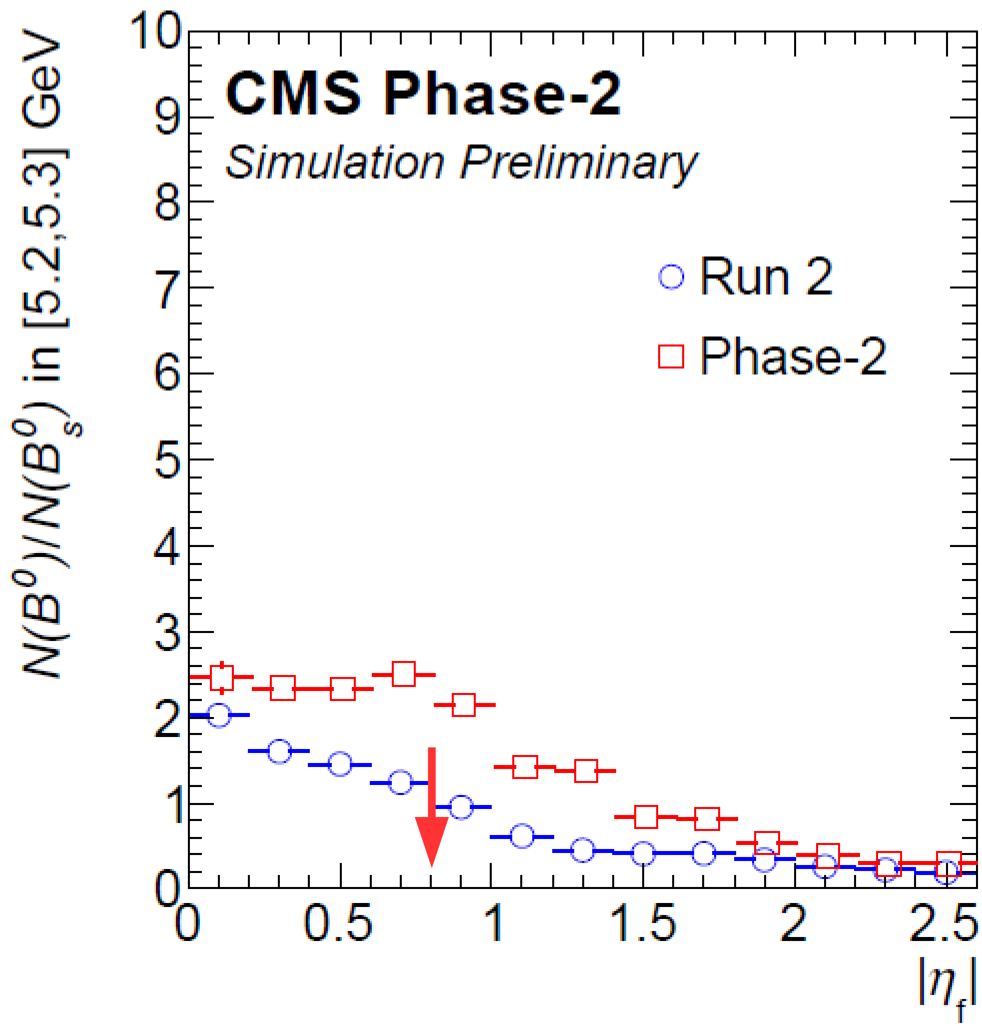
- Comparison of Phase-2 against Run-2 in terms of $|\eta_f|$



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

Mass Peak Separation and Leakage

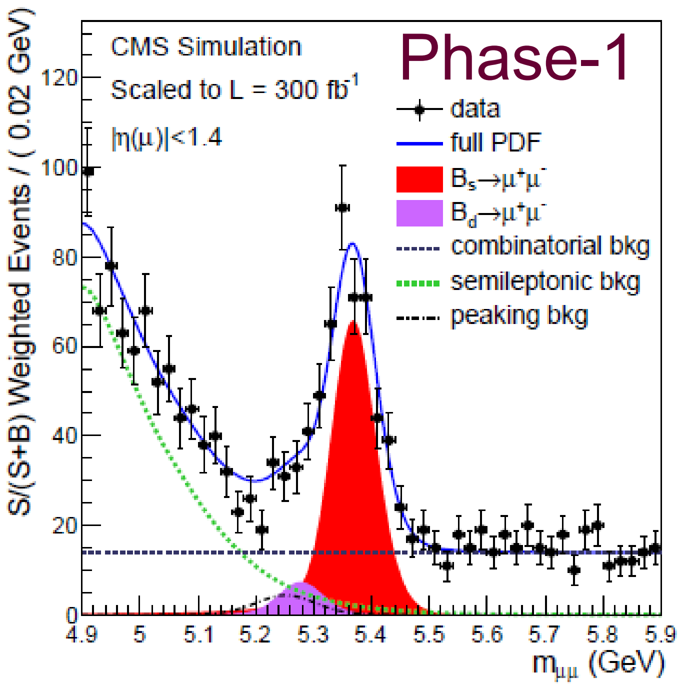




- ~ 25% improvement in mass peak separation for $|\eta_f| < 1.4$, reduces cross-feed
- Aids in rejecting background. e.g. rare semi-leptonic decay

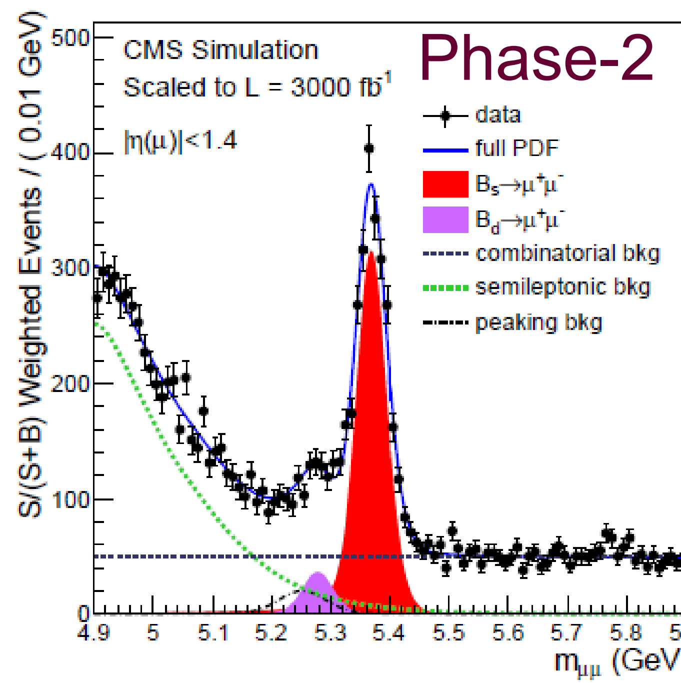
Phase-2 visibly better and robust for $|\eta_f| < 0.8$. Difficult to do the measurement beyond $|\eta_f| > 1.4$

Projection of Analysis Sensitivity



FTR-14-015 (2014)

Improved Tracker

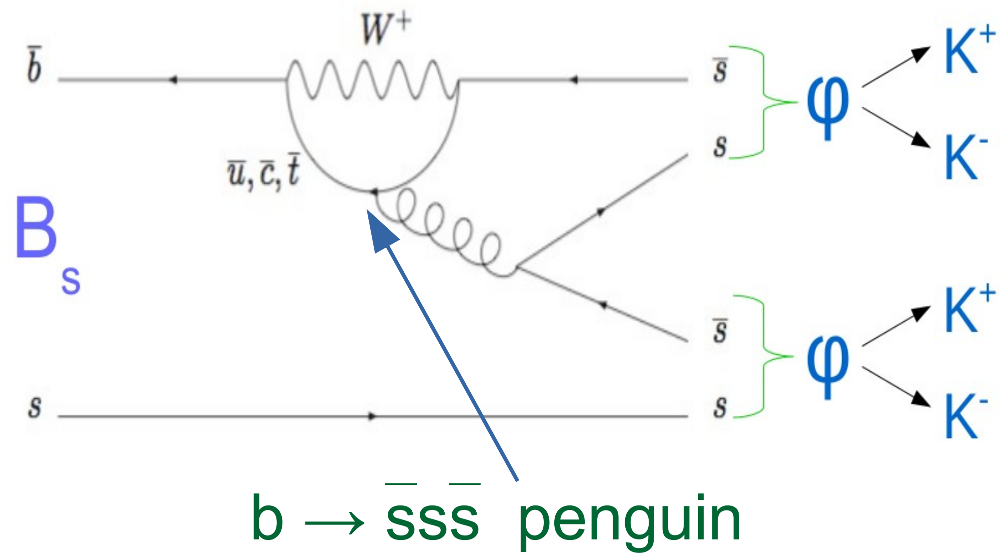


$\mathcal{L}$ (fb^{-1})	$N(B_s^0)$	$N(B^0)$	$\delta\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	$\delta\mathcal{B}(B^0 \to \mu^+\mu^-)$	B^0 sign.	$\delta\frac{\mathcal{B}(B^0\to\mu^+\mu^-)}{\mathcal{B}(B_s^0\to\mu^+\mu^-)}$
20	18.2	2.2	35%	> 100%	$0.0 - 1.5\,\sigma$	> 100%
100	159	19	14%	63%	$0.6 - 2.5\,\sigma$	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%

- Observation of $B_d \to \mu^+\mu^-$ at 5σ or more
- Measurement of Br($B_d \to \mu^+\mu^-$), ratio of Br($B_d \to \mu^+\mu^-$) and Br($B_s \to \mu^+\mu^-$) and other observables (e.g effective lifetime, ...)

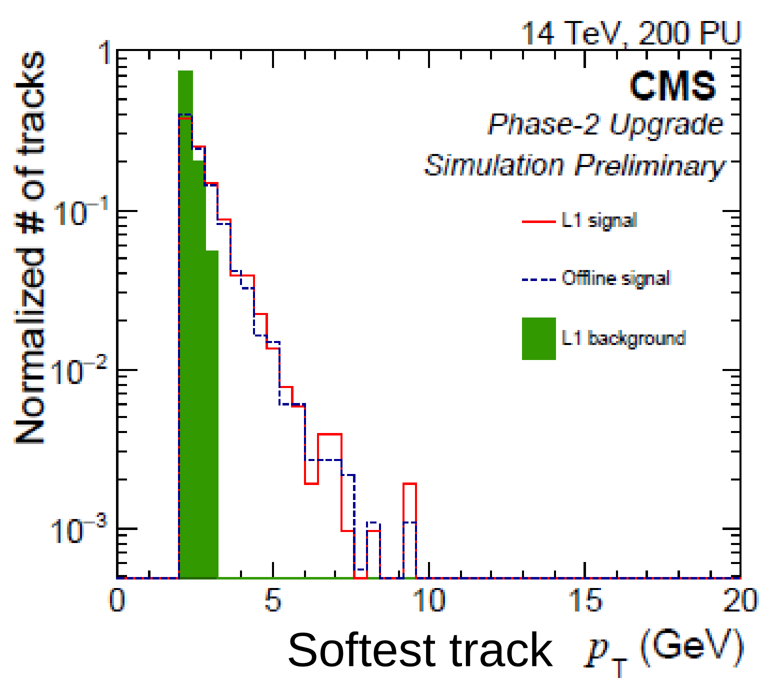
$B_s \to \varphi\varphi \to 4K$

$B_s \to \varphi\varphi \to 4K$



- FCNC process forbidden at the tree level
- b quark decaying through a penguin diagram may receive contribution from massive particles beyond LHC reach and provide new insight to the CP violating phase in the B_s system

- Rare process
  - $Br(B_s \to \varphi\varphi) \approx (1.84 \pm 0.18) * 10^{-5}$ (PDG)
- Final state kaons are low pT tracks
  - close to the L1 tracking threshold and hence difficult to reconstruct
- A track only analysis
  - an important benchmark analysis with Level-1 tracks



Analysis Framework

- $B_s \rightarrow \varphi\varphi \rightarrow 4K$
  - Events generated at $\sqrt{s}$ = 14 TeV with Pythia8 & EvtGen
  - φs decay to $K^+ K^-$ with $p_T(K) > 2$ GeV (to define signal efficiency)
  - 140 pileup events superimposed on each signal event
  - both Level-1 & offline

- Background (MinBias)
  - pileup scenario: 140, 200
  - Level-1 rate only

- Level-1 study
  - tracks using Level-1 tracking algorithm based on outer tracker only
  - calculate efficiency and rate

- Offline study
  - tracks reconstructed using offline algorithm with the full tracker
  - check if offline is fully efficient over L1
  - rate not studied yet

Analysis Strategy

- Reconstruct φ candidates from pairs of oppositely charged L1 tracks
  - assign kaon mass to tracks
  - the track pair must come from the same vertex
  - select all track pairs with invariant mass around the true φ mass, as φ candidates
- Reconstruct B_S candidates from φ candidate pairs constrained to come from the same vertex
  - apply other kinematic selection, e.g space angle between two φ candidates – dR(φ-pair)
  - select φ-pairs with invariant mass inside the B_S mass window
- Select an event if at least one B_S candidate is found

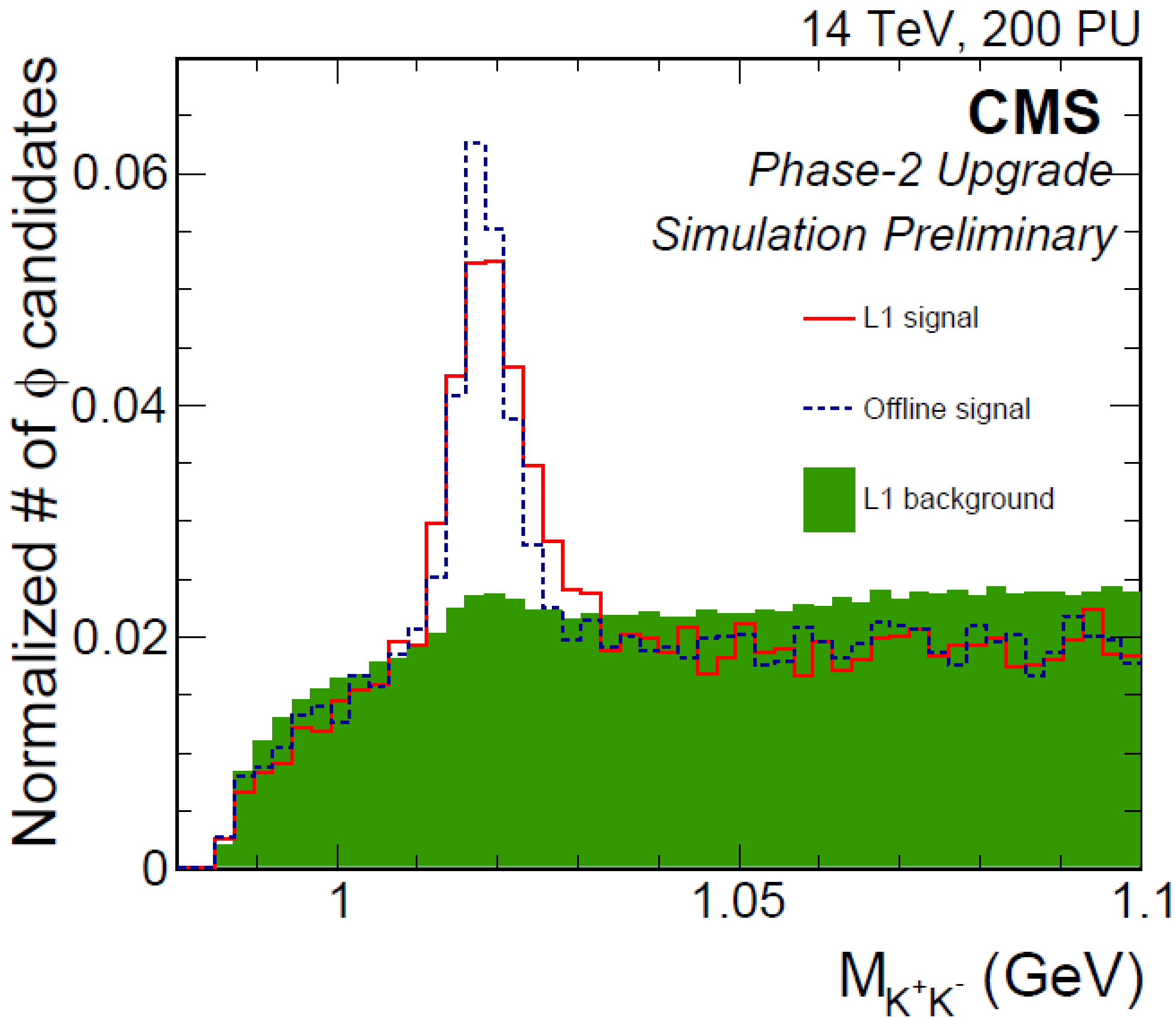
Baseline Selection

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

Working point	loose	medium	tight
Tracks	$p_T \geq 2\,\text{GeV}$, $\lvert\eta\rvert \leq 2.5$		
Track pair	$d_{xy} \leq 1\,\text{cm}$, $\lvert d_z\rvert \leq 1\,\text{cm}$		$d_{xy} \leq 0.5\,\text{cm}$, $\lvert d_z\rvert \leq 0.3\,\text{cm}$
ϕ-pair	$d_{xy} \leq 1\,\text{cm}$, $\lvert d_z\rvert \leq 1\,\text{cm}$		$d_{xy} \leq 0.5\,\text{cm}$, $\lvert d_z\rvert \leq 1\,\text{cm}$
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	$5.27 \leq M_{\phi\phi} \leq 5.49\,\text{GeV}$	$5.29 \leq M_{\phi\phi} \leq 5.48\,\text{GeV}$	

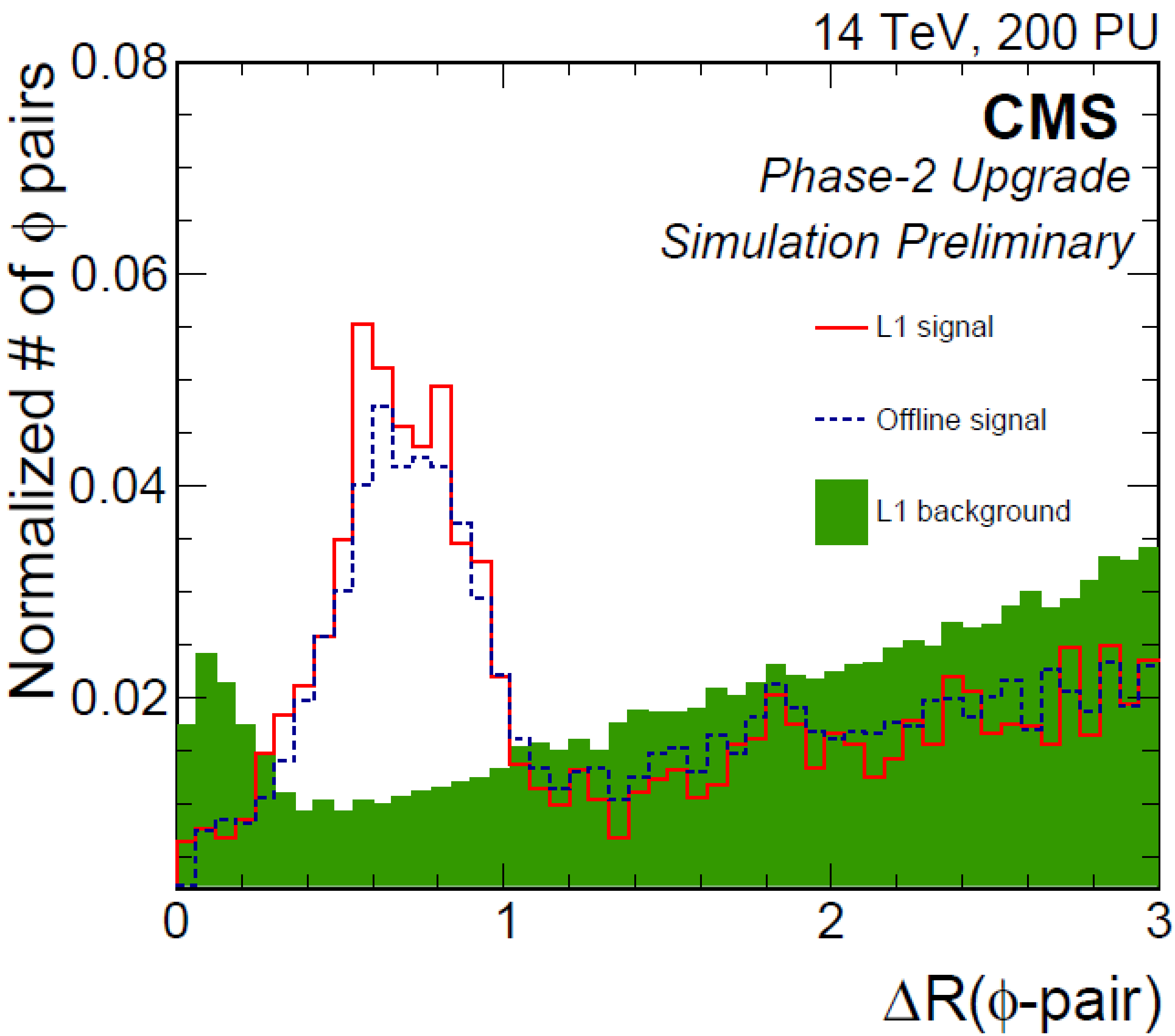
- d_z and d_{xy} : distance between a pair of tracks or trajectories of a pair of reconstructed particles along the beam axis (z) and in the plane perpendicular to the beam axis (xy), respectively

φ Candidate Mass



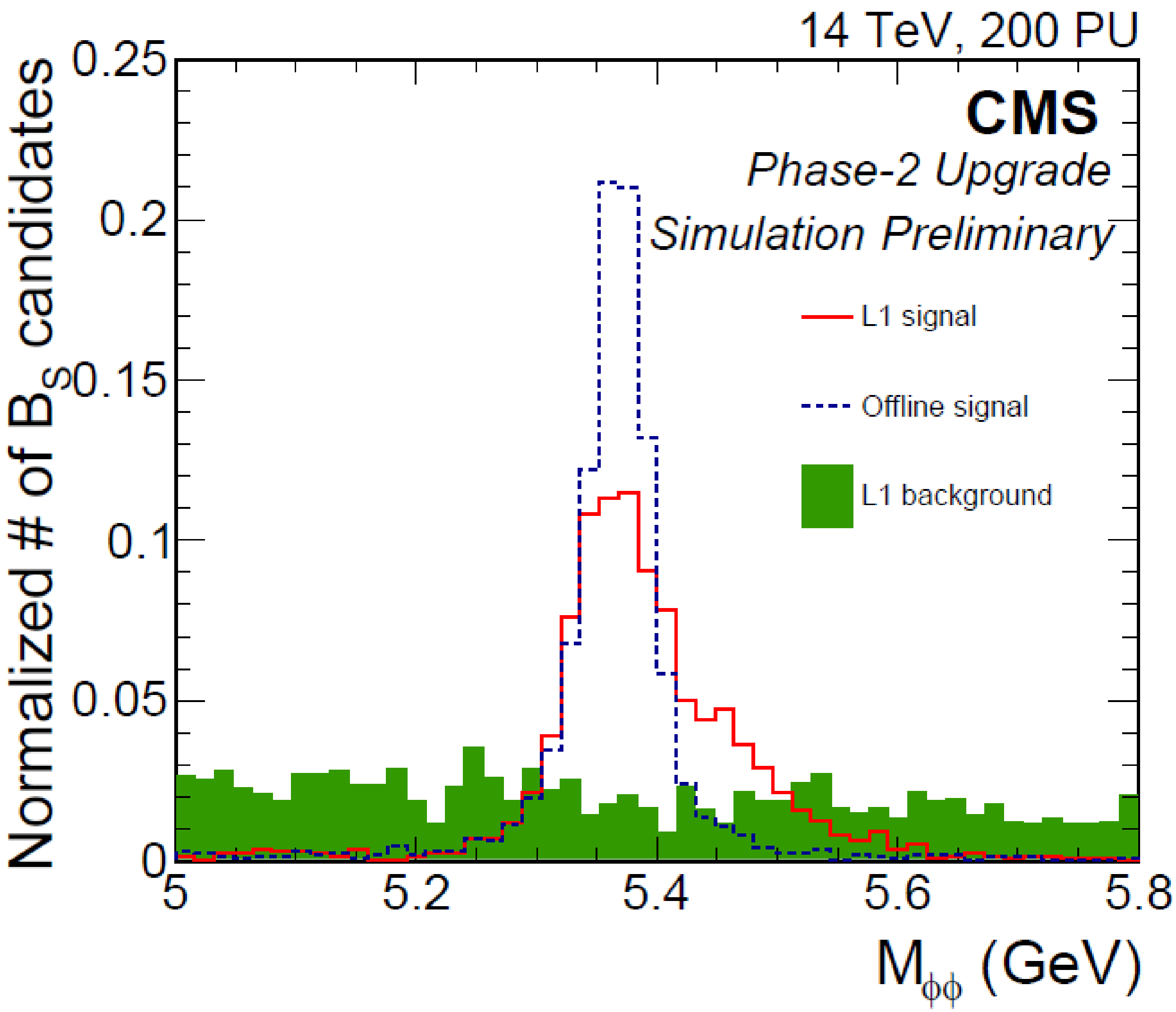
Invariant mass distribution of all track pairs with opposite charges, $|d_z| < 1$cm, $|d_{xy}| < 1$cm, track $p_T > 2$ GeV. Kaon mass assigned to all the tracks. The event sample does not have any preliminary selection on the B_s mass window. Distributions are normalized to unit area

dR(φ-pair)



dR(φ-pair) distribution for all φ-pairs with $0.99 < M_{K^+K^-} < 1.04$ GeV, $|d_z| < 1$cm, $|d_{xy}| < 1$cm

B_s Candidate Mass



Inv mass of φ-pairs with

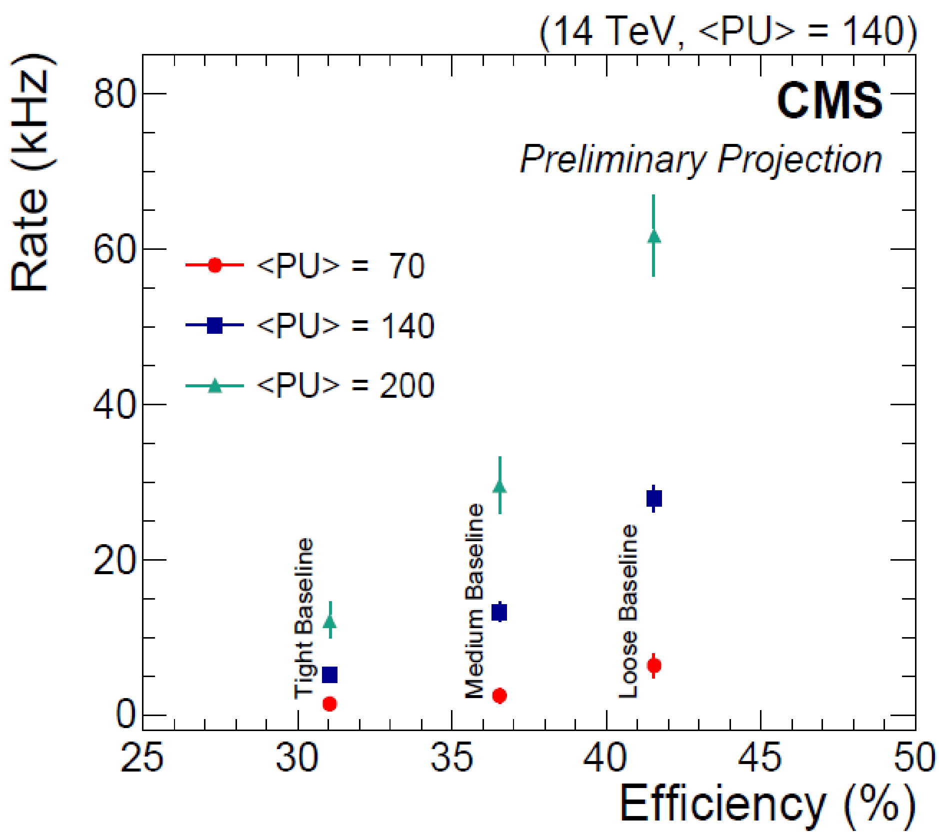
- $|d_z|$(φ-pair) < 1cm
- $|d_{xy}|$(φ-pair) < 1cm
- 0.2 < dR(φ-pair) < 1
- dR(K^+, K^-) < 0.12

For <PU> = 200, 30% signal efficiency achievable at a rate ~ 15 kHz

Efficiency and Rate

CMS PAS FTR-16-006 Technical Proposal Tracker geometry and L1 Tracking

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
- Only <PU> = 140 signal efficiency numbers are used

Conclusion

- $B_{d/s} \to \mu^+\mu^-$
  - significant improvement in mass resolution leads to better separation of $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$ mass peaks
  - observation of $B_d \to \mu^+\mu^-$ at 5σ or more
  - measurement of Br($B_d \to \mu^+\mu^-$), ratio of Branching fractions and other observables
  - measurement of Branching fractions difficult in very forward regions
- $B_s \to \varphi\varphi \to 4K$
  - showcases L1 tracking
  - signal distinctly visible even at <PU> = 200
  - however, L1 event rate may require further improvement
    - mitigation of pileup effects using timing information
    - displaced vertex finding technique at low p_T