Istituto Nazionale di Fisica Nucleare

B Physics at the HL-LHC with CMS

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on behalf of the CMS Collaboration

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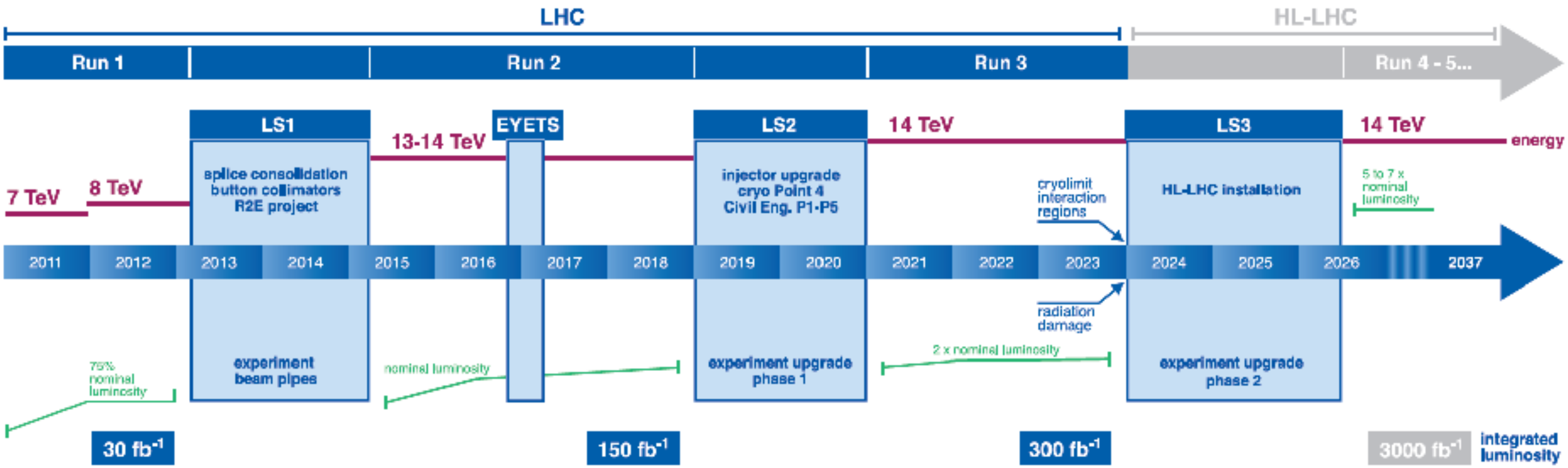
outline

- **LHC Upgrade**: opportunities and challenges
- **CMS Upgrades**
  - Tracker upgrade
  - L1 Track trigger
    - Physics case: $B_s \to \phi\phi$
  - Muon system upgrade
  - MIP timing detector
- **Flavour Physics Perspectives** for two benchmark channels
  - $B_{(s)} \to \mu\mu$
  - $\tau \to 3\mu$
- **Conclusions**

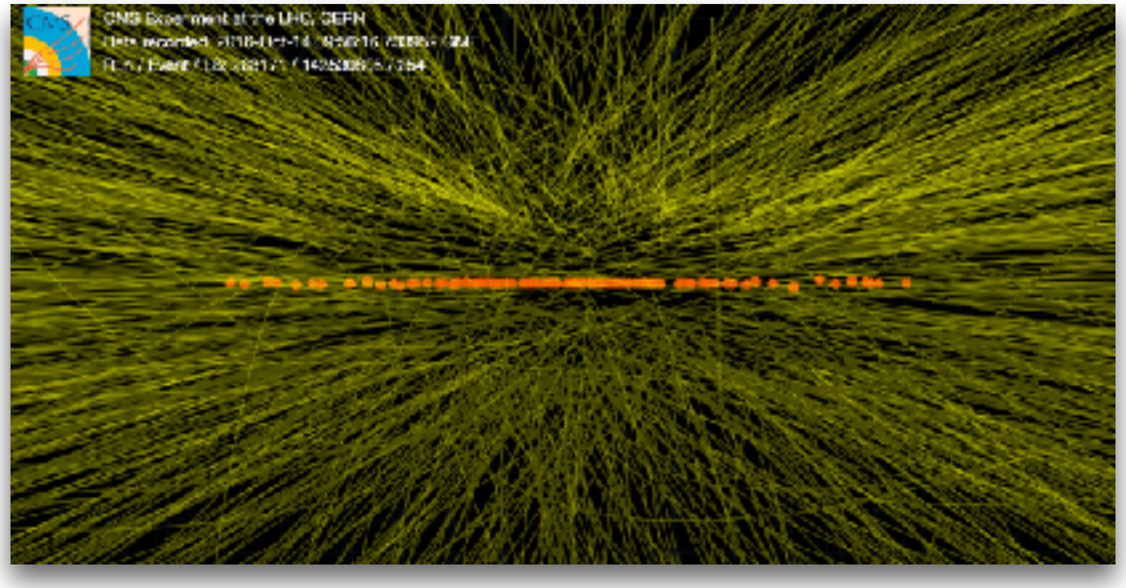
HL-LHC opportunities



- **Physics potential @3000 fb^{-1}**
  - Extend discovery reach in searches for new physics & rare SM processes
  - Higgs boson precision measurements
  - Improved SM measurements
  - **Precision measurements in flavour sector**
    - Rare B decays, CP violation, top FCNC, …

HL-LHC challenges

http://cds.cern.ch/record/2231915



- Harsh operating conditions will make it difficult to exploit this potential:
  - expected **average pileup of 200,** with resulting increase of particle density
  - **radiation damage** to the detector

- B physics is among the physics topics that might suffer more from the HL-LHC conditions
  - relative low momenta of the typical signatures
  - high precision required by the measurements

- On the other hand, the **Phase-II upgrades of the CMS detector promise to recover a good detection ability and even give better performances than those of the current detector**
  - Lifetime of detectors ➔ replace inner tracker & forward calorimeter
  - Increased readout bandwidth ➔ replacing electronics
  - PU mitigation ➔ higher detector granularity to reduce occupancy

    ➔ improved trigger capabilities

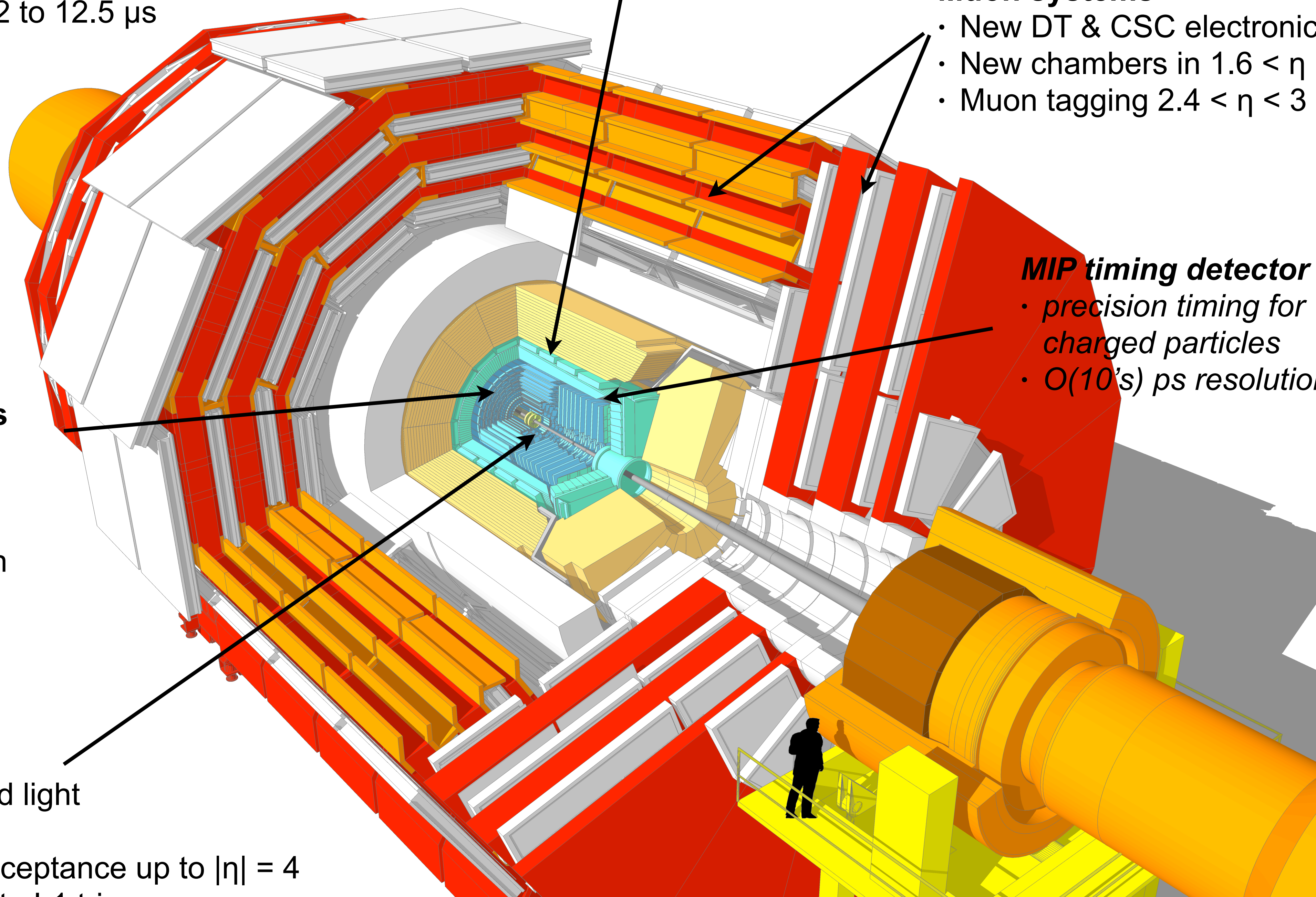
    ➔ precision timing

CMS Phase II upgrades overview

Trigger/HLT/DAQ
- Track information in hardware event selection
- 750 kHz hardware event selection
- 7.5 kHz events registered
- latency increased from 3.2 to 12.5 μs

Barrel EM Calorimeter
- New electronics
- Low operating temperature = 10°

Muon systems
- New DT & CSC electronics
- New chambers in $1.6 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$



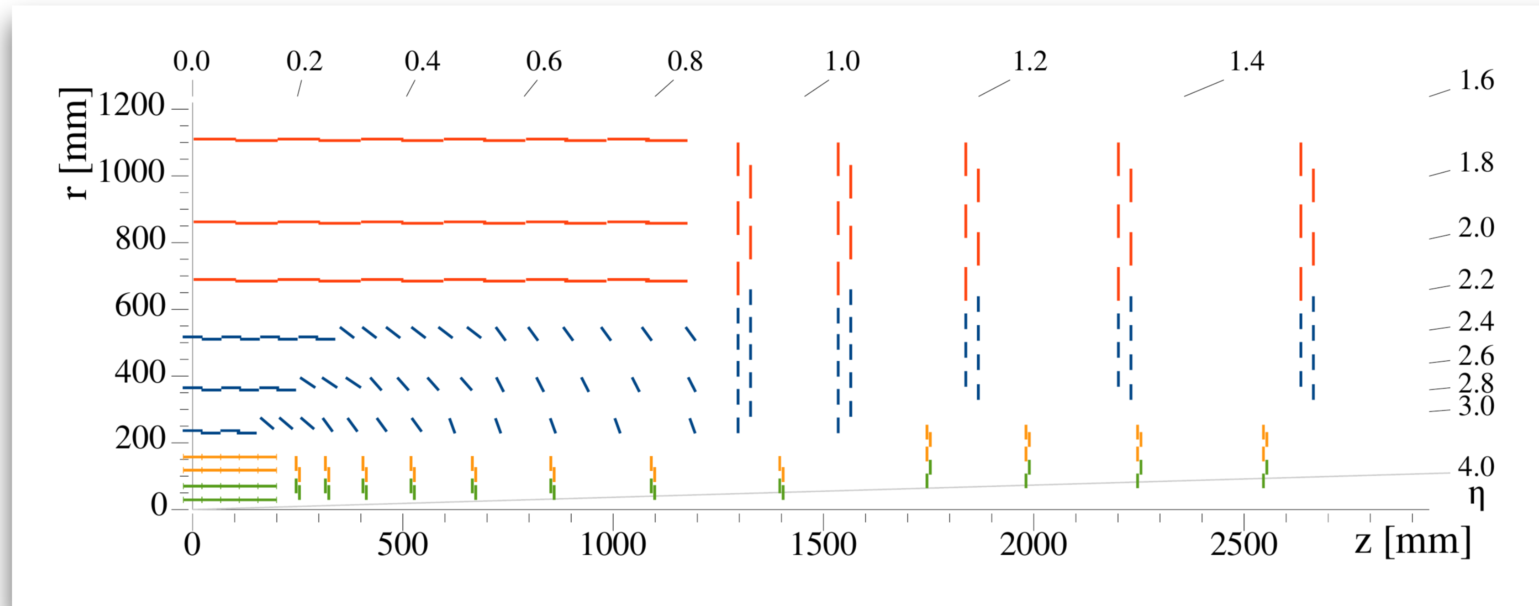
MIP timing detector
- *precision timing for charged particles*
- *O(10's) ps resolution*

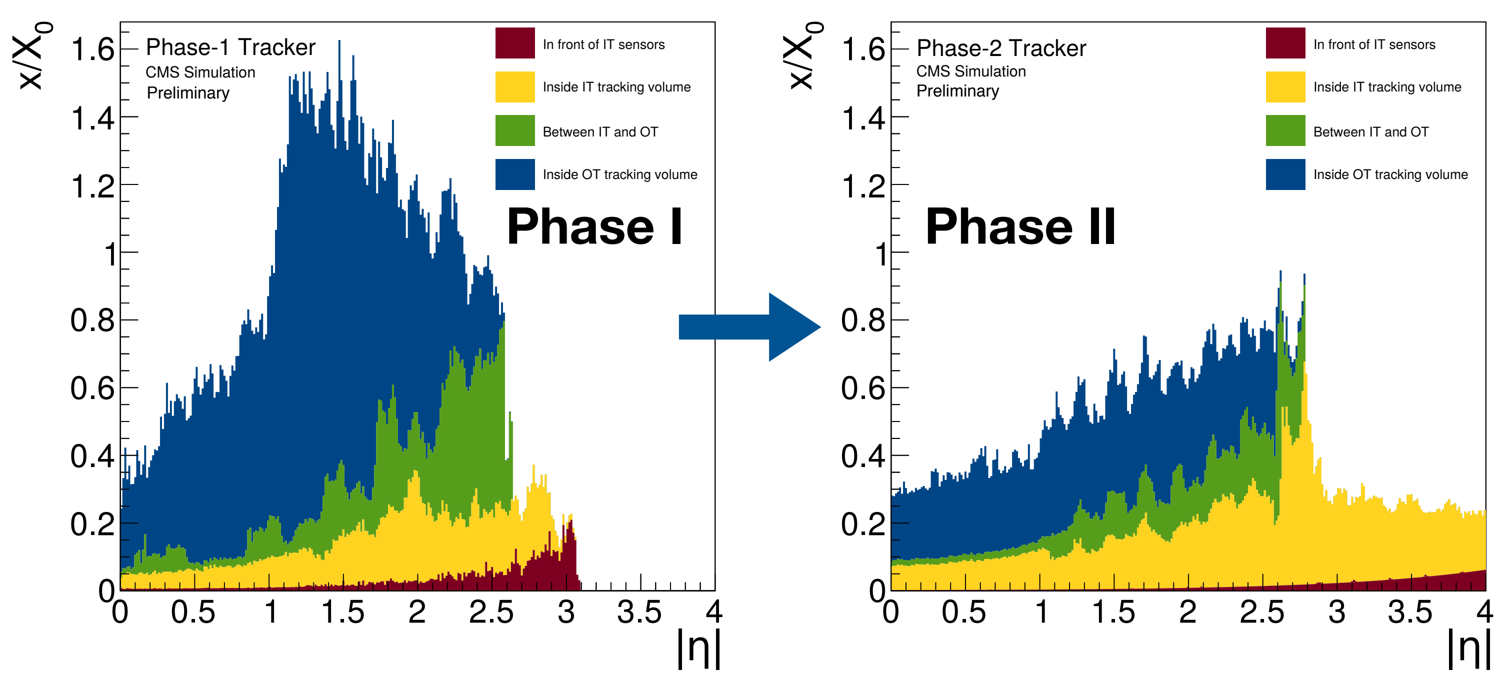
New endcap calorimeters
- Sampling calorimeter
- Radiation tolerant
- High granularity
- 3D shower reconstruction

New tracker
- Radiation tolerant and light
- Higher granularity
- Increased forward acceptance up to $|\eta| = 4$
- Tracking information to L1 trigger

Tracker upgrade

- Needed to deal with radiation damage and cope with higher pileup
- **Inner tracker:**
  - pixel sensors
  - narrower pitch than present pixel detector
  - increased granularity to limit the occupancy
  - coverage up to |η|~4
- **Outer tracker:**
  - design driven by addition of hardware track trigger capabilities
  - pixel-strip & 2-strip sensors
  - progressively tilted modules
- Substantial reduction of the material budget with respect to present detector





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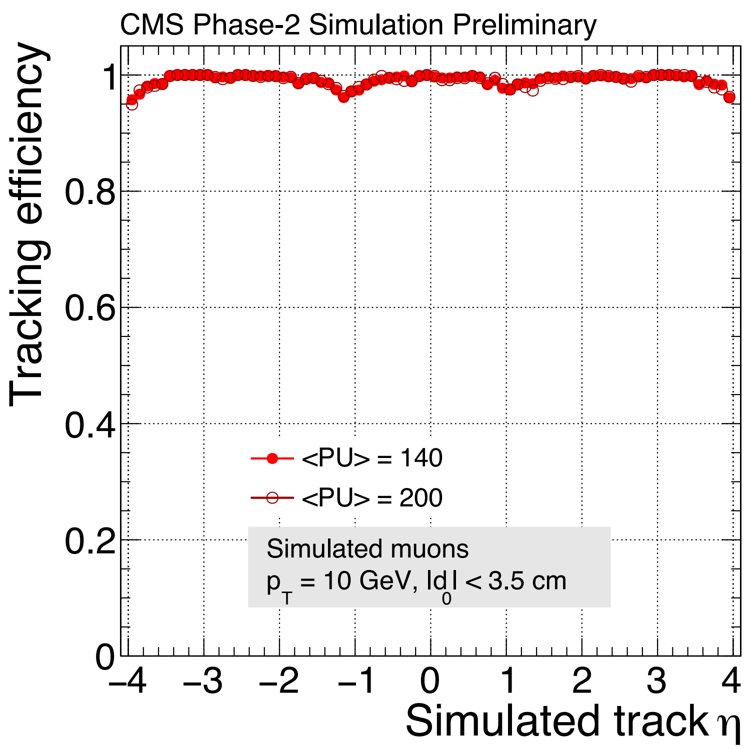
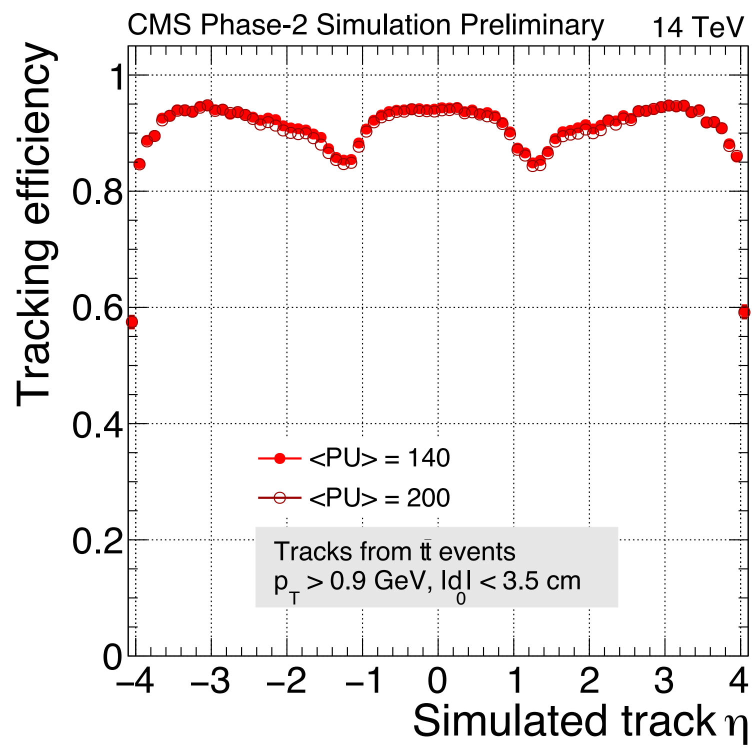
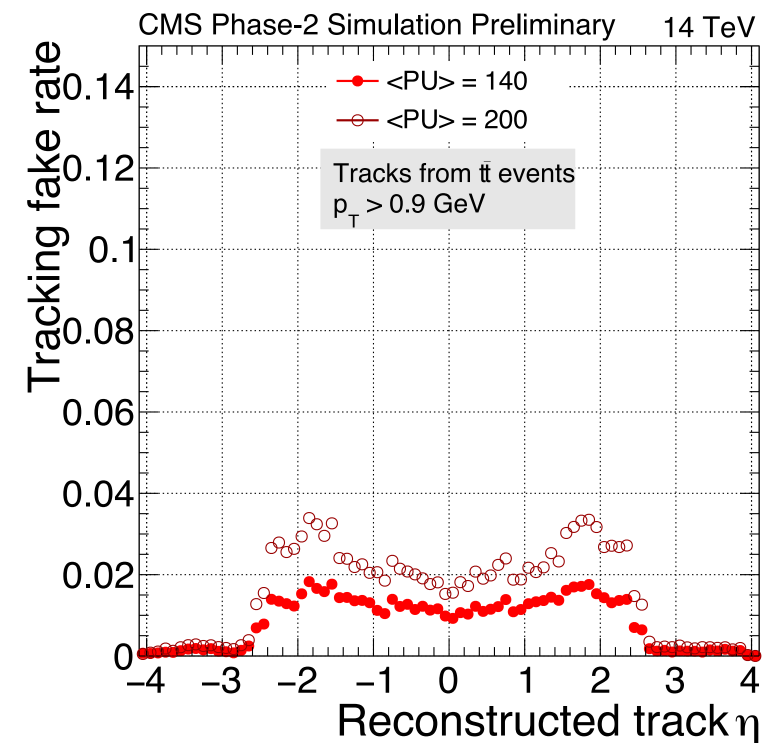
Tracker performance: efficiency/fake

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)

Tracker performance: resolution

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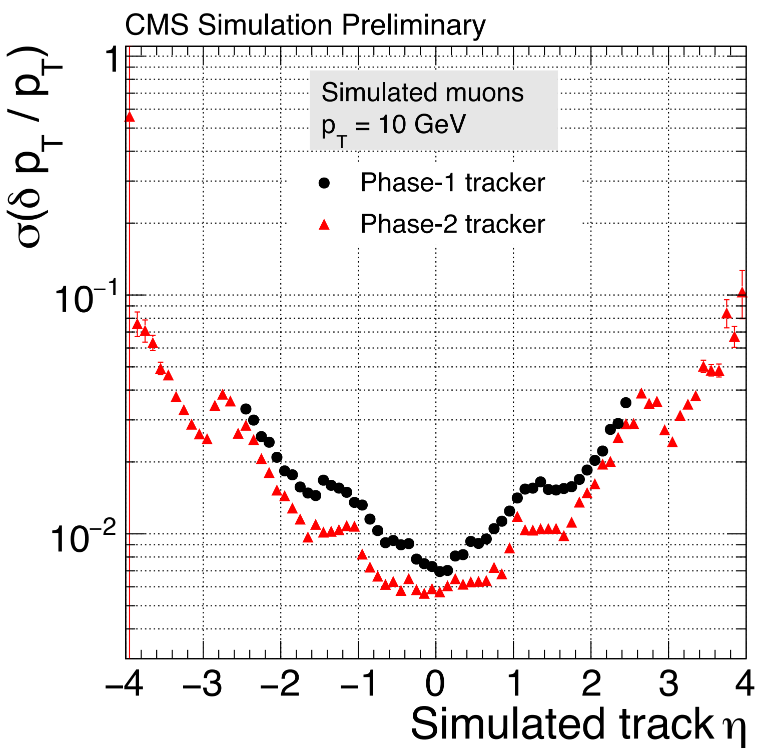
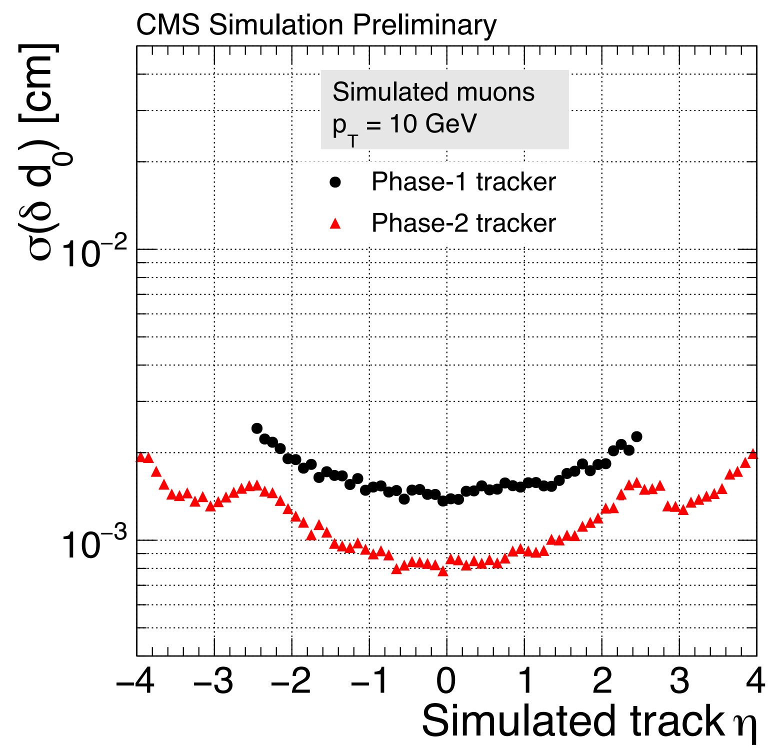
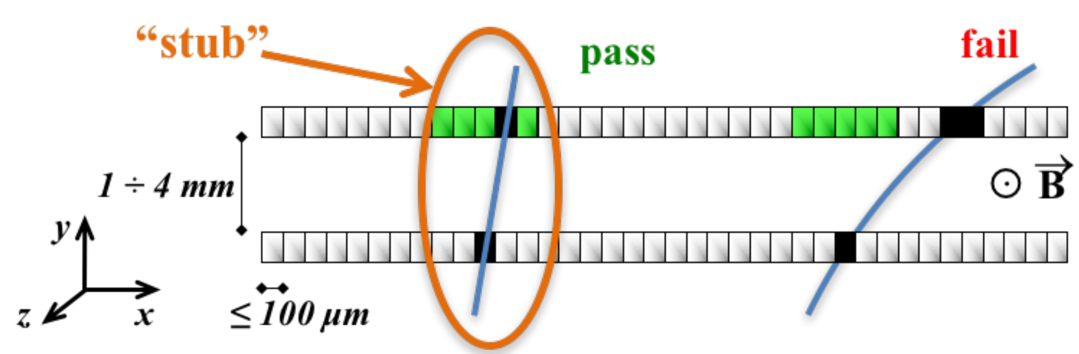




- Significant improvements in transverse momentum and transverse impact parameter resolution with respect to current detector
  - thanks to better hit resolution and lower material budget

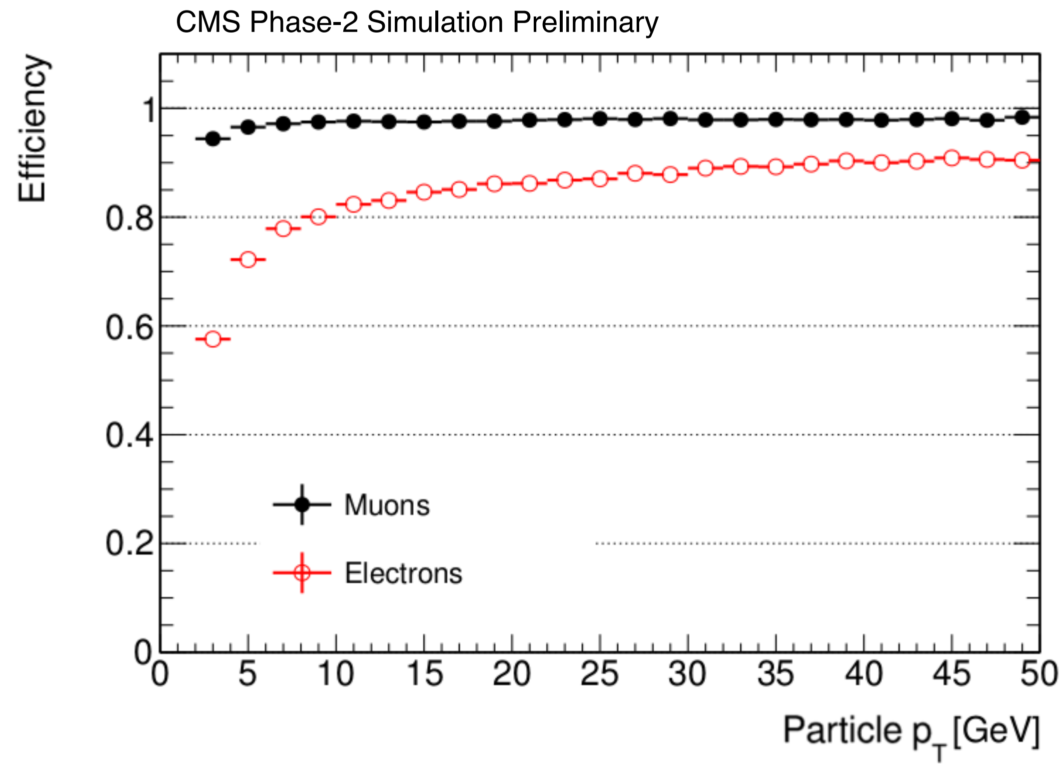
L1 track trigger

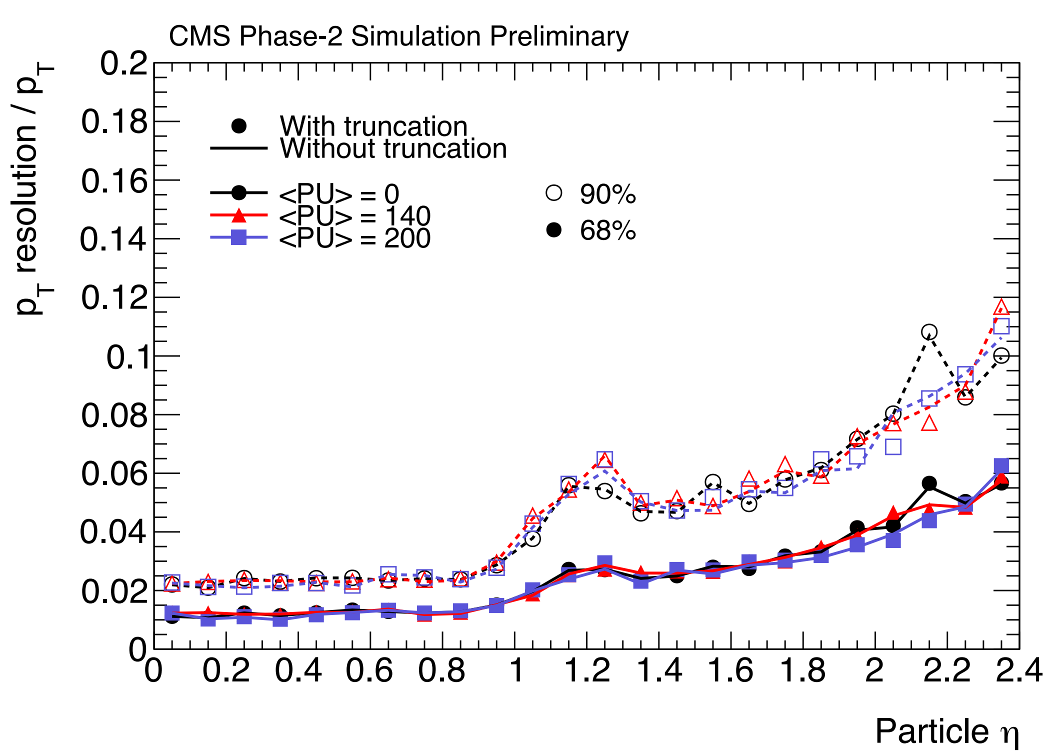
- Efficient event selection for data acquisition is a **key prerequisite to fully benefit from the increased luminosity**
- Introduction of tracking information at L1 is crucial to
  - improve the p_T resolution of various objects at L1 (e.g. muons)
  - contribute to the mitigation of pileup
  - allow the exploitation of information on track isolation
- Hardware trigger capabilities **provided by the "pT modules" of the outer tracker**
  - two single-sided closely-spaced sensors
  - by correlating hits on the two sensors a local p_T measurement is determined, allowing **on-detector filtering** through application of p_T thresholds
  - hardware trigger receives track stubs with $p_T > 2$ GeV → 10-100x reduction in data-volume
  - "stubs" are then sent to the off-detector L1 tracking system, which reconstructs tracks for input to the L1 trigger
  - limited in angular acceptance up to $|\eta| = 2.4$

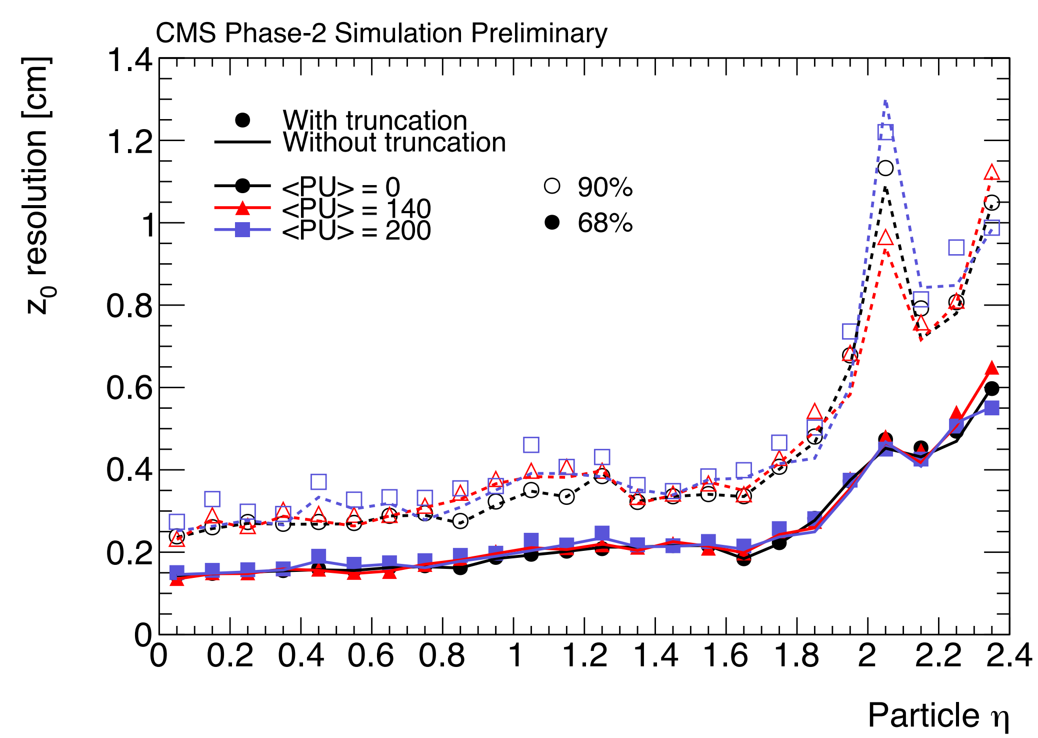


L1 track trigger performance

- Performance studies shown for PU 200 scenario and stub p_T > 3 GeV
- **Excellent efficiency for muons** (around 98%)
- **Slower turn-on** and lower plateau **for electrons**
    - more challenging due to material interactions (further algorithmic improvements ongoing)
- **Excellent resolution on p_T and z_0** for muons with p_T > 10 GeV, negligible degradation with PU



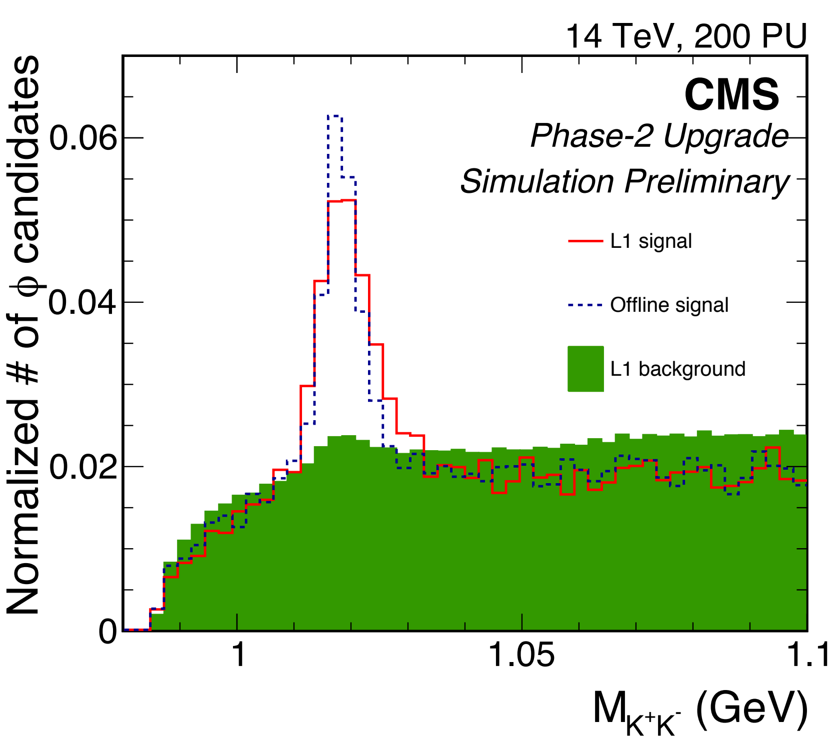


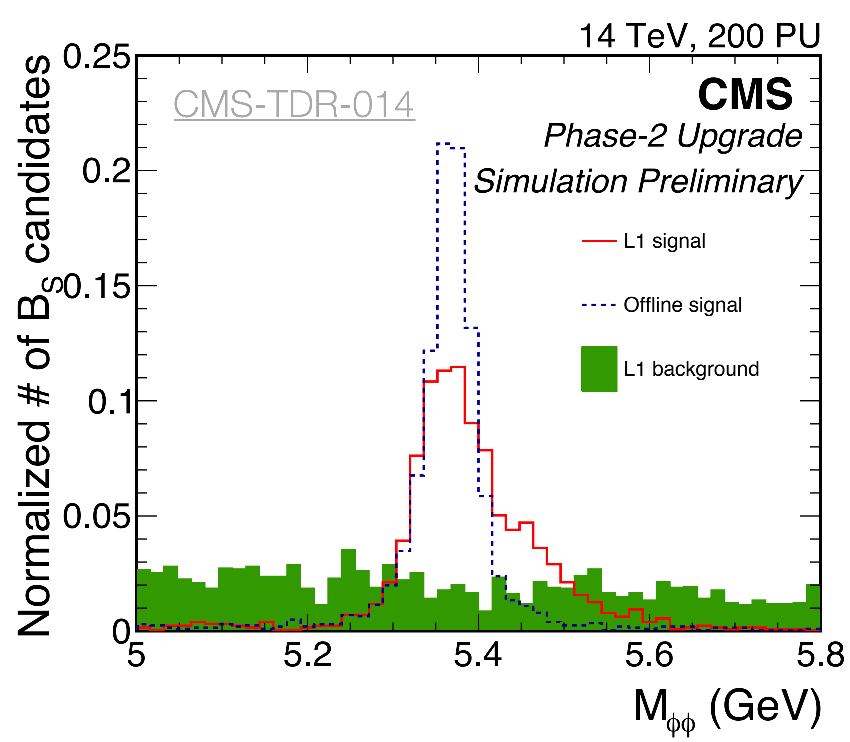


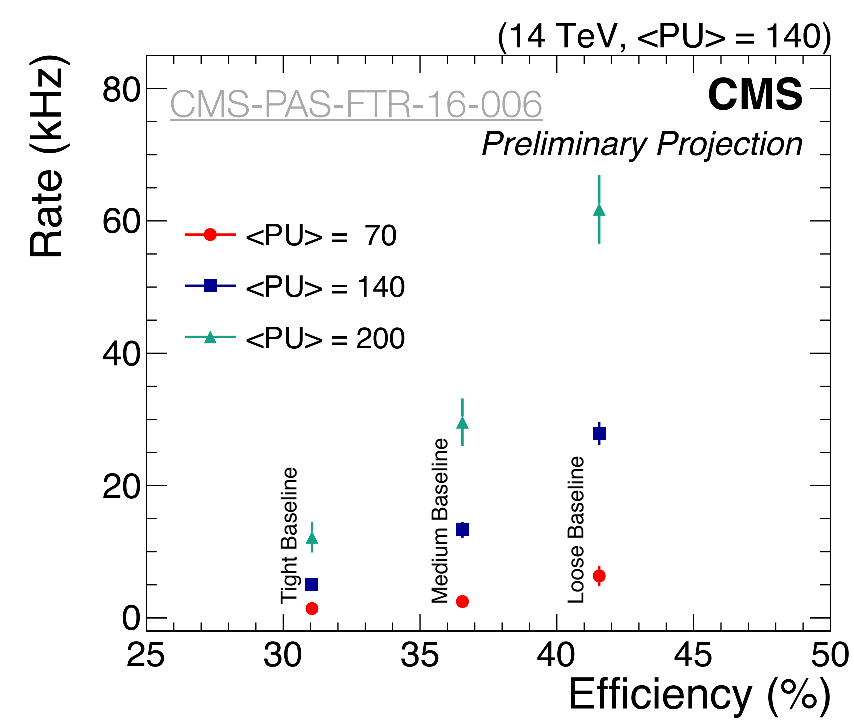
CMS-TDR-014

$B_s \to \phi\phi$: test case for L1 track trigger

- $B_s \to \phi\phi \to 4K$, forbidden at tree level in the SM, is sensitive to BSM contributions
    - also suitable to measure CP violating phase through B_s mixing
- **Not covered by existing triggers → L1 track finder will allow identification of ϕ and B_s candidates already at L1**
    - oppositely charged tracks from the same vertex
    - application of topological cuts at L1 to reduce background
    - very soft p_T of the lowest-p_T kaon (close to the threshold of 2 GeV)
- Studies on simulations estimate trigger efficiency is sufficient, but further improvements are required to keep a low trigger rate (e.g. displaced vertex finding tool)

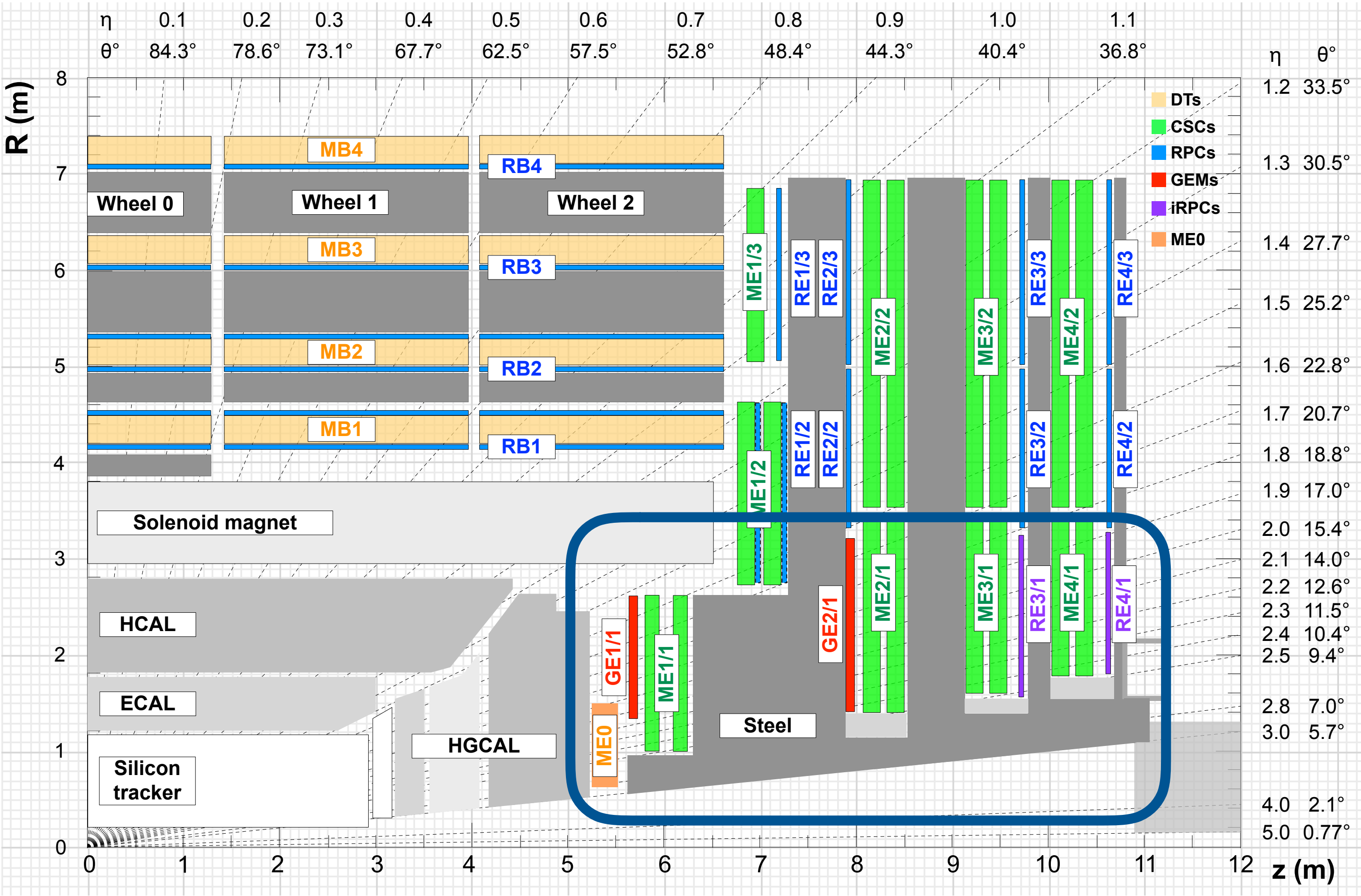




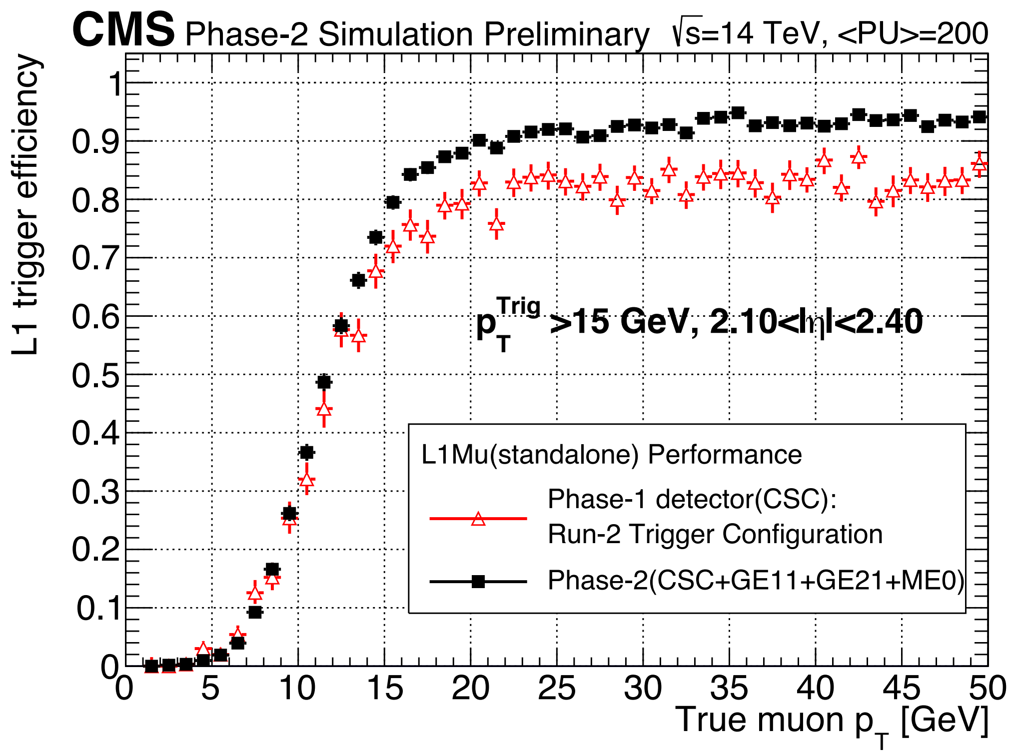


Muon detectors upgrade

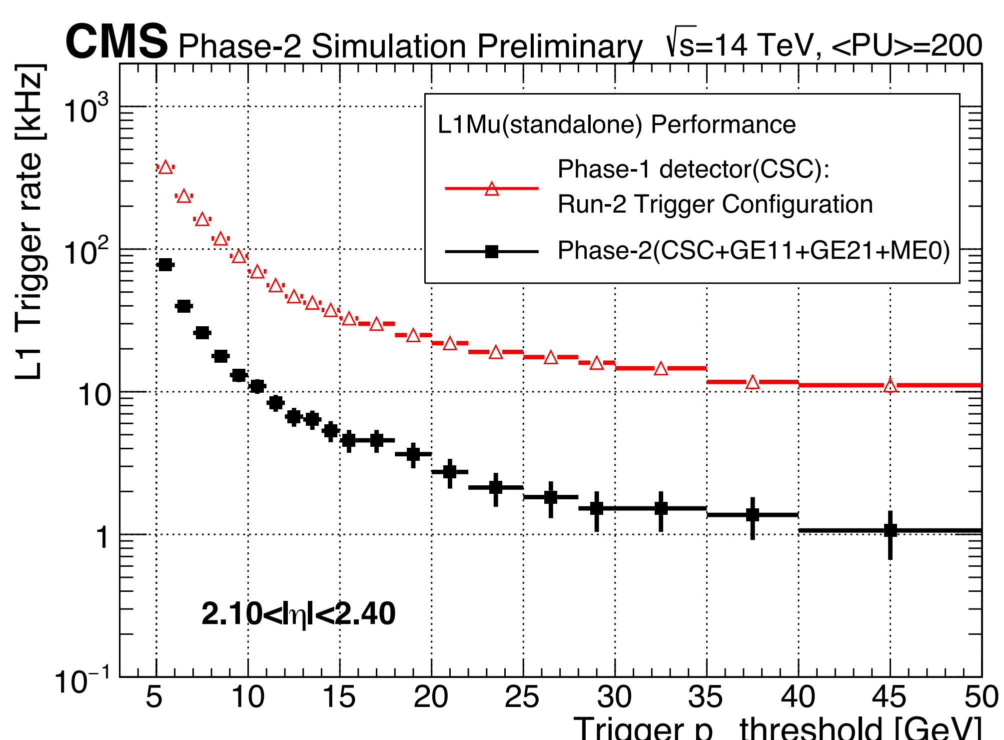
- Upgrade electronics to cope with radiation hardness and meet the trigger/readout latency requirements
- Enhance muon performance in the forward region
  - addition of RPC (iRPC) and GEM (GE1/1, GE2/1) chambers in the forward region to improve the efficiency, fake rejection and resolution in the region 1.6 < |η| < 2.4
  - extend the forward coverage up to |η| = 2.8 with new GEM chambers (ME0)



Muon performance - L1 trigger



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



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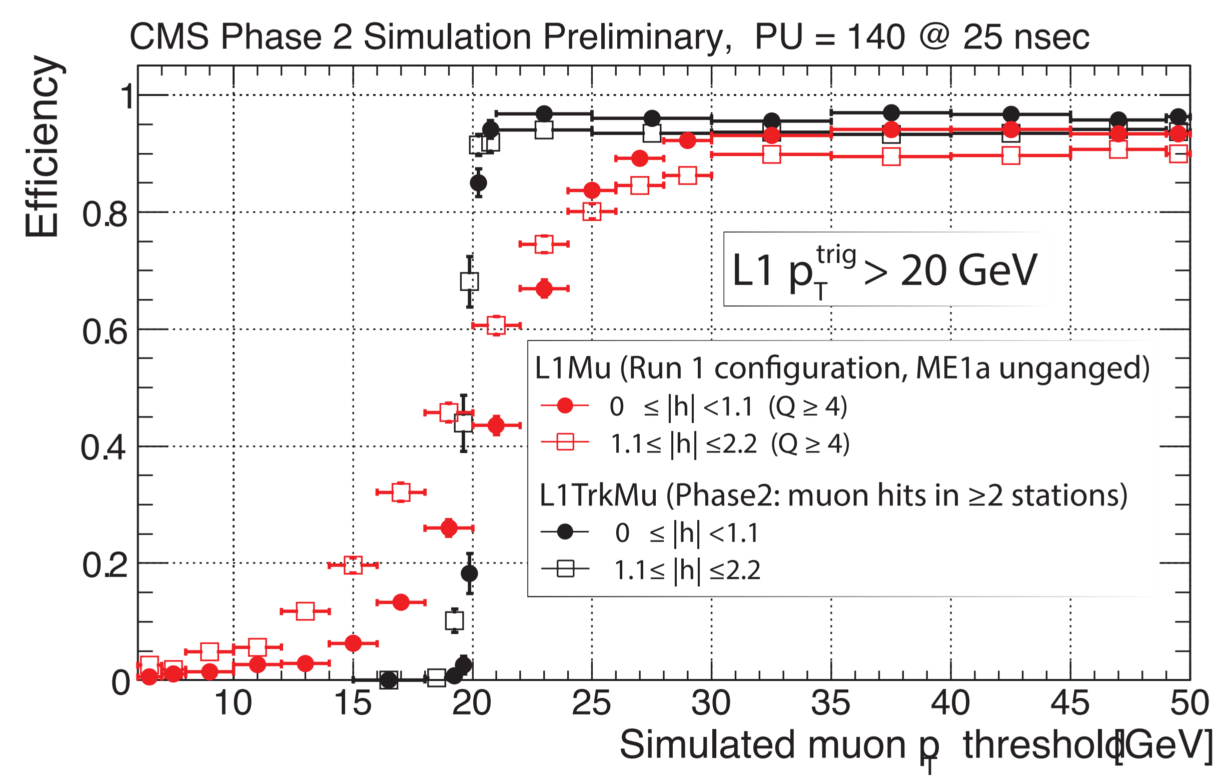
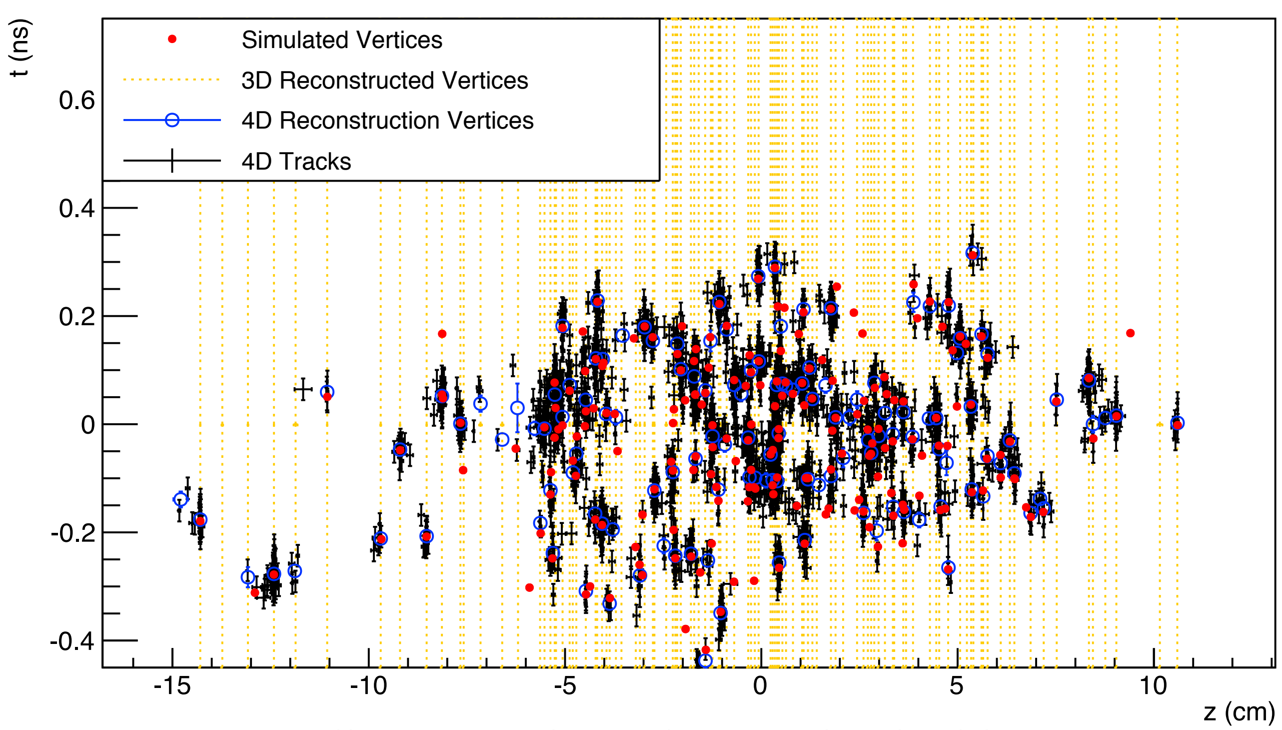
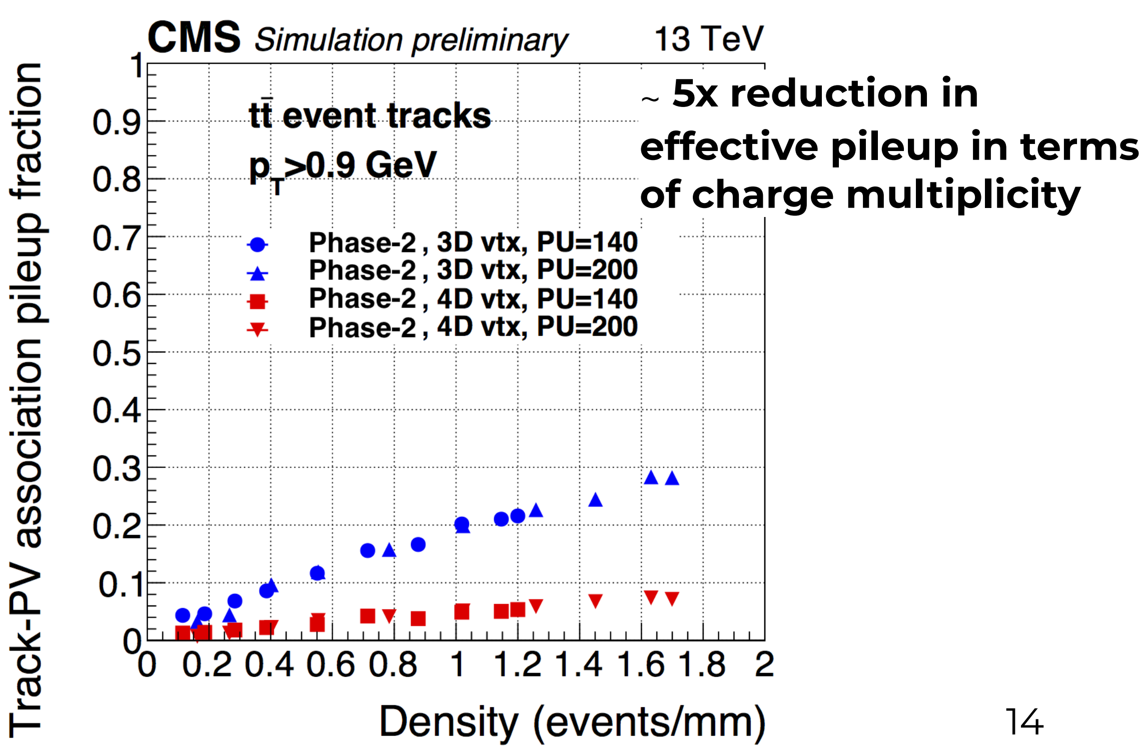


Impact of pileup and its mitigation

- Primary vertex and tracks from hard interaction are efficiently reconstructed, but pileup contamination increases rapidly with pileup density
  - quantities based on charged particles, currently nearly free of pileup, will be affected
- **Performance can be recovered exploiting the time distributions of the interactions**
  - 10’s of ps timing resolution 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 (σ_t ~ 30 ps) for charged hadrons & converted photons down to a few GeV
  - traditional 3D vertex fit can be upgraded to a 4D fit



https://cds.cern.ch/record/2296612/files/LHCC-P-009.pdf



Perspectives for $B_{(s)} \to \mu\mu$

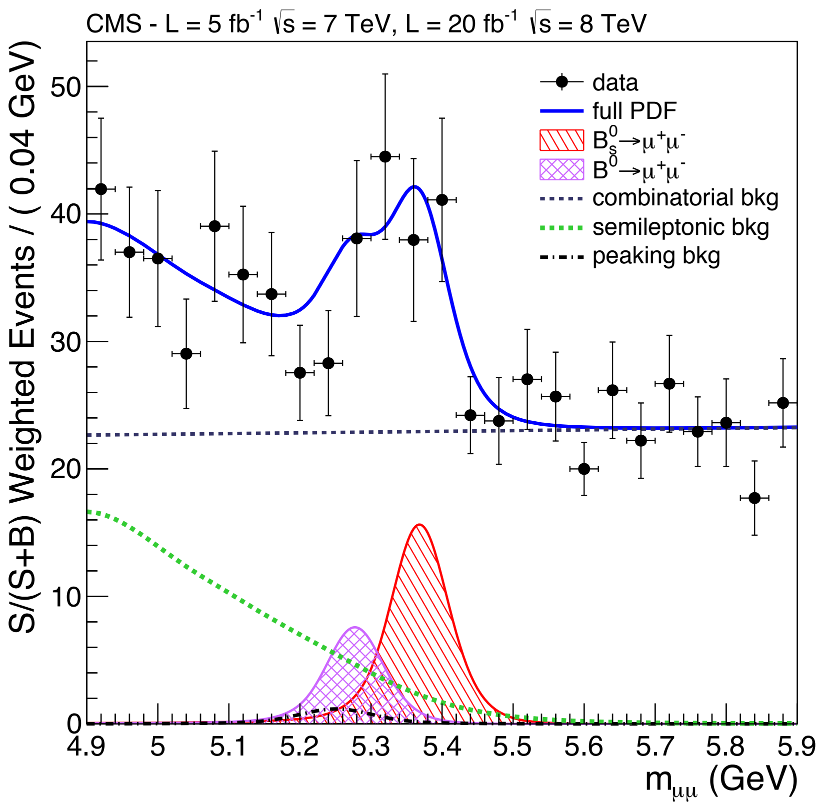
- $B_{(s)} \to \mu\mu$ decays only proceed via FCNC processes forbidden at tree level → highly suppressed in SM but enhancements/further suppressions of the BRs predicted in several SM extensions
- Current experimental results all in agreement with the SM, though statistically limited

	$\mathcal{B}(B_s \to \mu\mu)$	$\mathcal{B}(B^0 \to \mu\mu)$	
SM	$\mathbf{(3.66 \pm 0.23) \times 10^{-9}}$	$\mathbf{(1.06 \pm 0.09) \times 10^{-10}}$	
Run I (CMS)	$(3.0^{+1.0}_{-0.9}) \times 10^{-9}$	1.1×10^{-9} @95% CL	PRL 111 (2013) 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 (2015) 68
Run I (ATLAS)	$(0.9^{+1.1}_{-0.8}) \times 10^{-9}$	4.2×10^{-10} @95% CL	EPJ. C 76 (2016) 513
Run I + Run II (LHCb)	$(3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$	3.4×10^{-10} @95% CL	Phys.Rev.Lett. 118 (2017)

- **It will constitute a precision measurement in the HL-LHC era**
- Projections available for two scenarios:
    - Phase-I scenario: expected performance for Run II and III (300 fb^{-1} @14 TeV)
    - Phase-II upgrade scenario: expected performance after full detector upgrade & 3000 fb^{-1}

Projections strategy

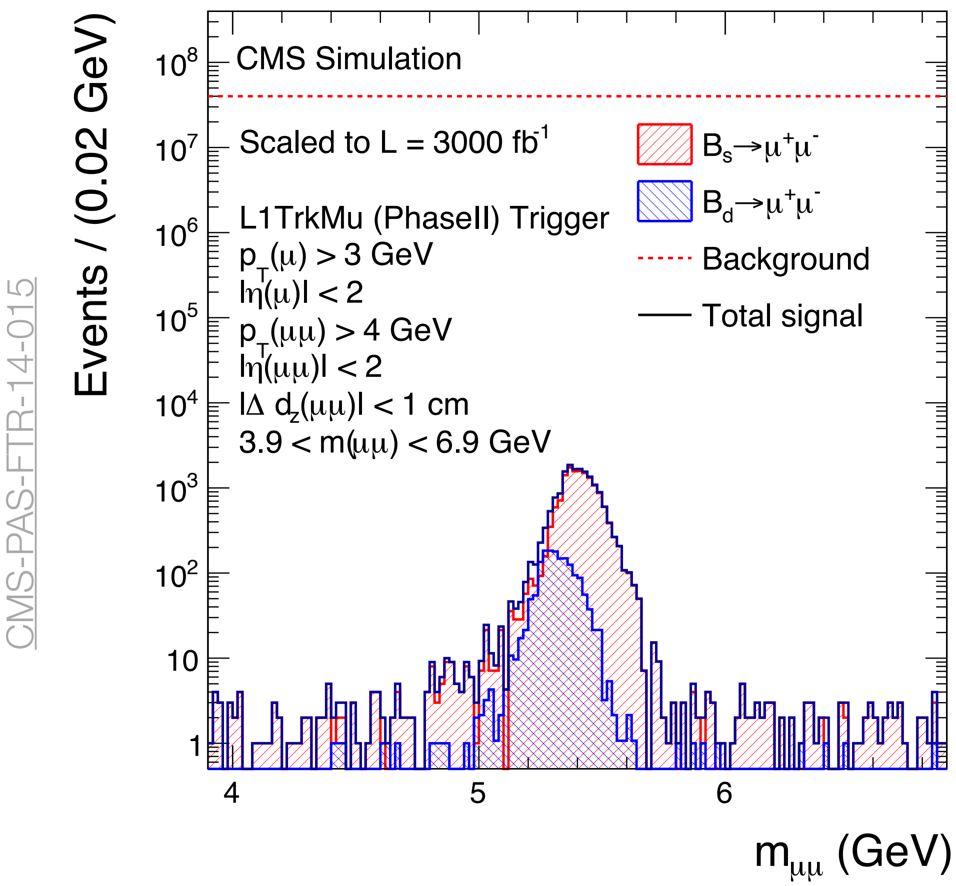
- **Starting point for the projections is CMS Run I analysis**
  - including improvements from the CMS+LHCb combination
  - all the details are in Giacomo's talk, in brief:
    - dimuon trigger at L1, additional mass and displaced vertex requirement at the HLT
    - MVA-based muon offline identification
    - normalized to the reference channel $B^+ \to J/\psi K^+$
    - branching fractions extracted by UML fits in 12 categorized BDT bins



- **Effects of any possible improvements on the analysis strategy have not been considered**

Inputs to the projections

- Evaluation of the analysis performance done using **pseudo-experiments**, starting from the baseline Run-1 PDFs for signals and backgrounds + assumptions/inputs listed below
- **Production cross sections and BRs predicted by the SM** are assumed for B^0 and B^0_s
- **L1 trigger:** two opposite-charge muons (tracker+muon stations) with $p_T > 3$ GeV and $|\eta| < 2$, from the same PV ($\Delta Z < 1$ cm) and with invariant mass between 3.9 and 6.9 GeV



- **invariant mass resolution at L1** is measured to be about **70 MeV** for both resonances
- preliminary rate estimates of few hundred Hz at L1 → very promising

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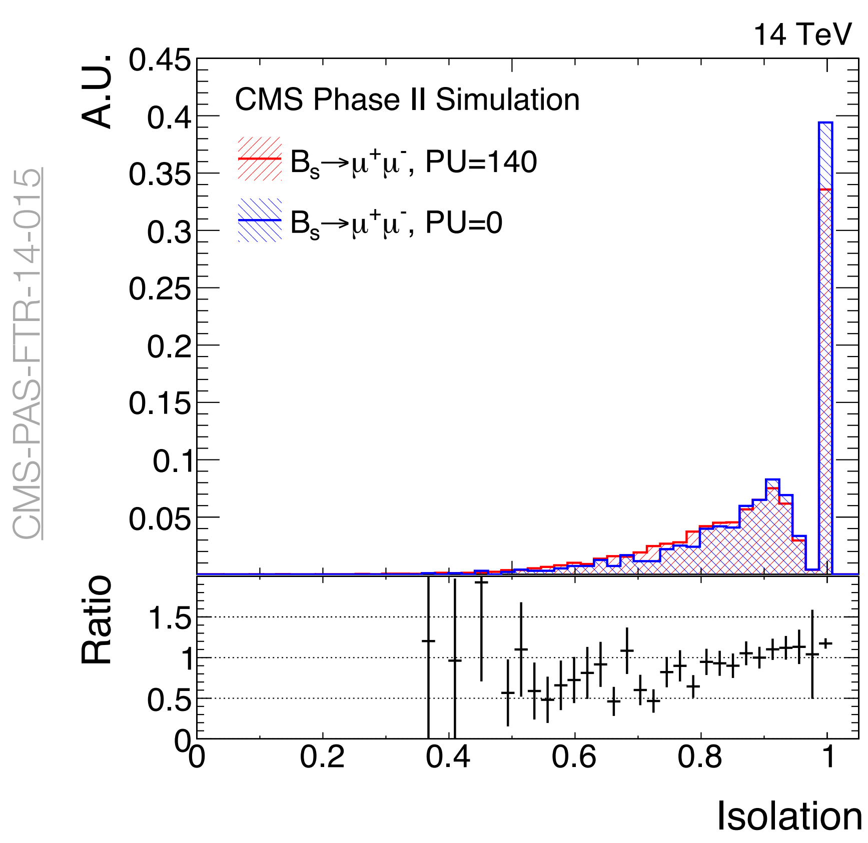
- **Pileup effects:** large number of PVs will impact discriminating variables (e.g. isolation) and involve tighter cuts on muon reconstruction to maintain same level of fakes



- -2.5% on single muon tracking efficiency
- -16% on isolation efficiency
- **-30% efficiency loss overall**

however, not accounting for mitigation that will be possible thanks to the MTD

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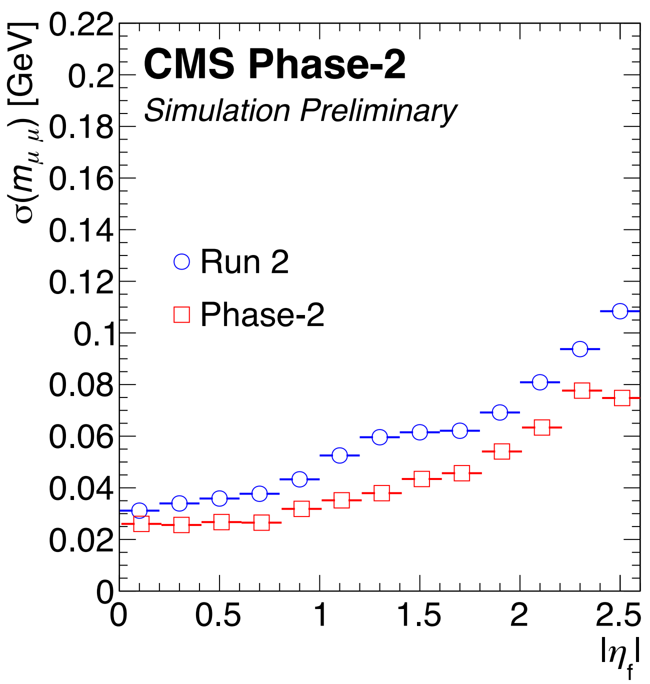
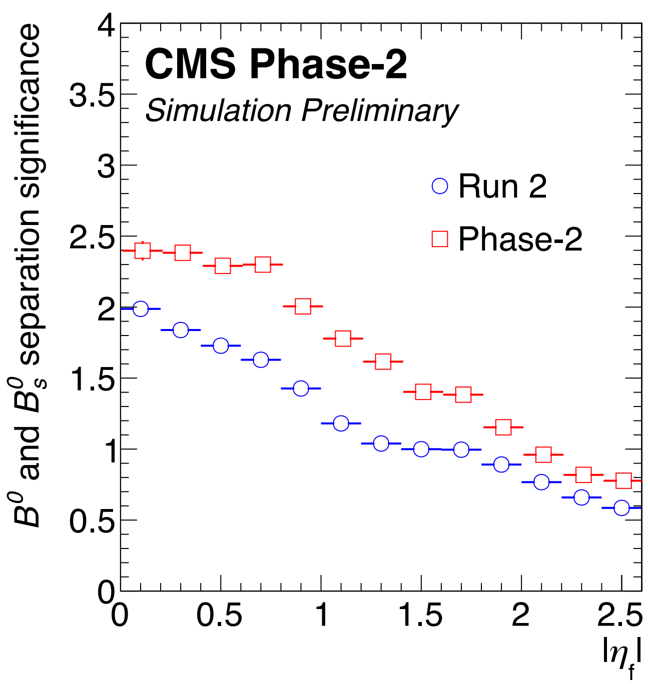
- **Dimuon mass resolution:** improved momentum resolution of the tracks is beneficial, especially in the barrel region

CMS-TDR-014





- +40% improvement in the dimuon mass resolution for $|\eta| < 1.0$
- +25% gain in the significance of the separation between the mass peaks of B^0_s and B^0
- improved background rejection and reduced cross-feed from B^0_s into B^0 signal region

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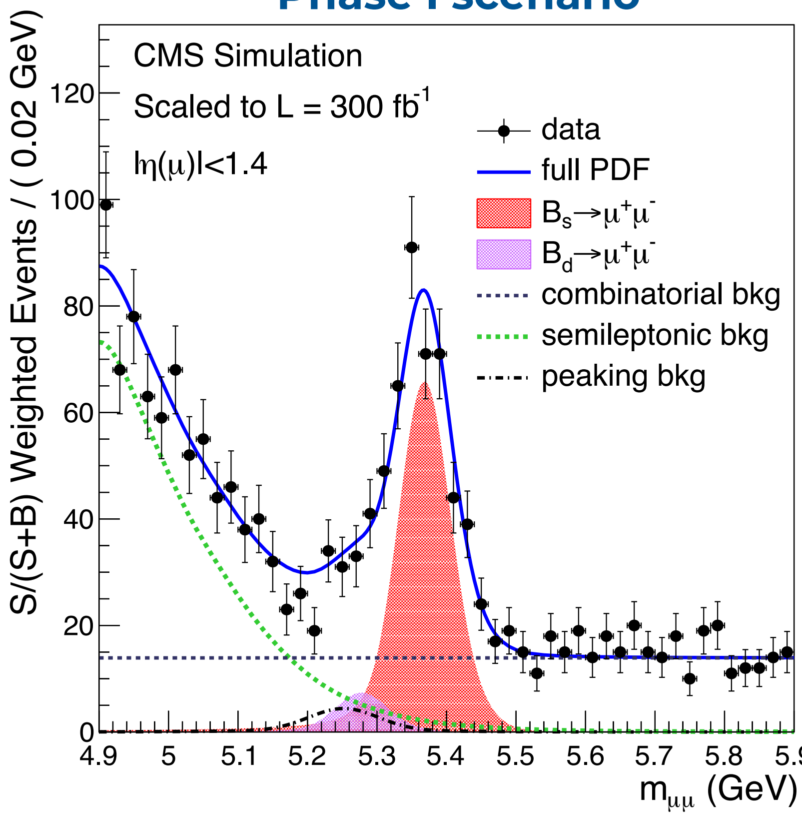
- **Dimuon mass resolution:** improved momentum resolution of the tracks is beneficial, especially in the barrel region
- **Scaling of systematic uncertainties:**

CMS-PAS-FTR-14-015

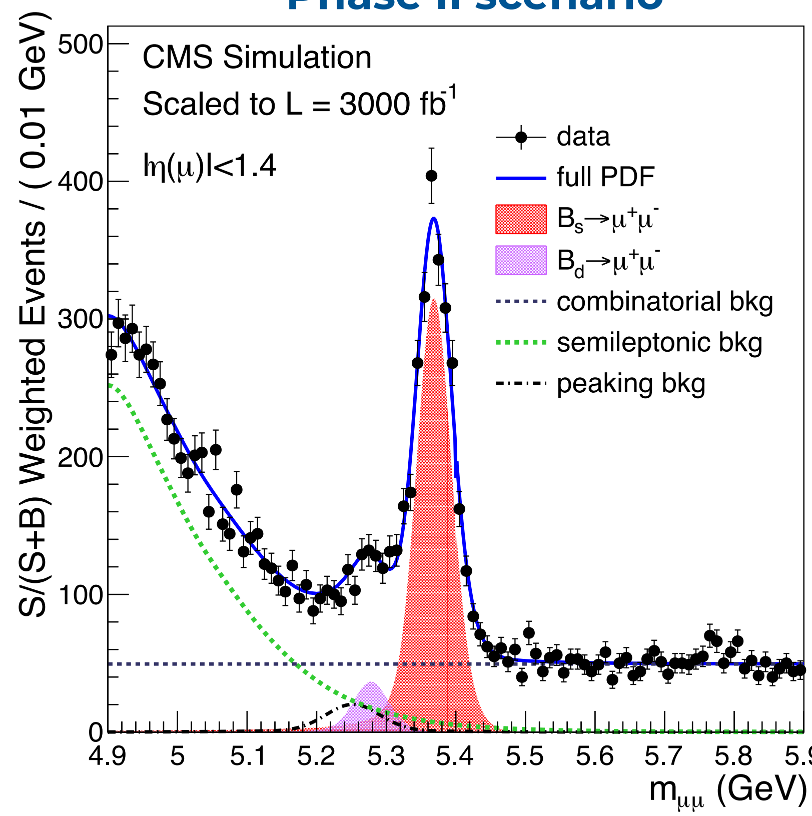
	Run I	Phase I	Phase II
f_s/f_u	9%	5%	5%
norm yield	5%	5%	3%
peaking background	60%	20%	10%
semileptonic decays	50%	25%	20%

$B_{(s)} \to \mu\mu$ projections: results

Phase I scenario



Phase II scenario



L (fb^{-1})	$\delta\mathscr{B}(B_s \to \mu\mu)$	$\delta\mathscr{B}(B^0 \to \mu\mu)$	B^0 sign.	$\delta[\mathscr{B}(B^0 \to \mu\mu)/\mathscr{B}(B_s \to \mu\mu)]$
100	14%	63%	0.6−2.5σ	66%
300	12%	41%	1.5−3.5σ	43%
300 (barrel)	13%	48%	1.2-3.3σ	50%
3000 (barrel)	11%	18%	**5.6-8.0σ**	**21%**

CMS-PAS-FTR-14-015

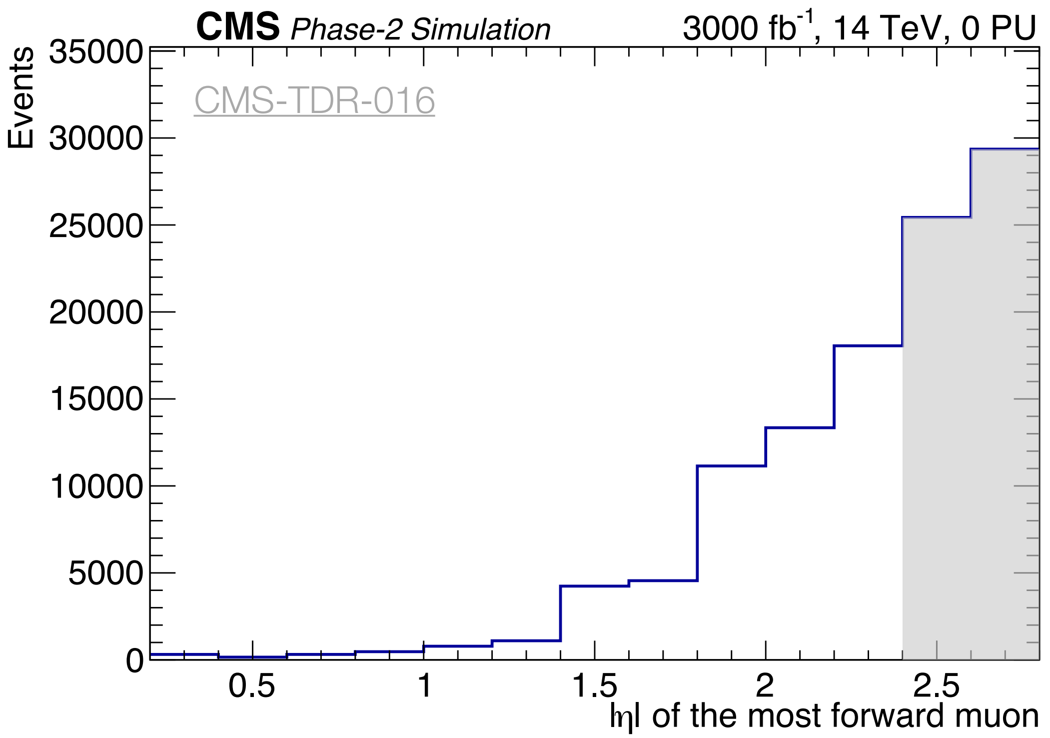
Analysis performance @CMS in HL-LHC era will greatly benefit from tracker upgrades

Search for the LFV $\tau \to 3\mu$ decay

- Lepton flavour violating process, predicted BR from SM is < 10^{-14}
- Possible enhancements by many order of magnitudes foreseen in BSMs
- Best experimental limit so far given by Belle $B(\tau \to 3\mu) < 2.1 \times 10^{-8}$ @90% CL

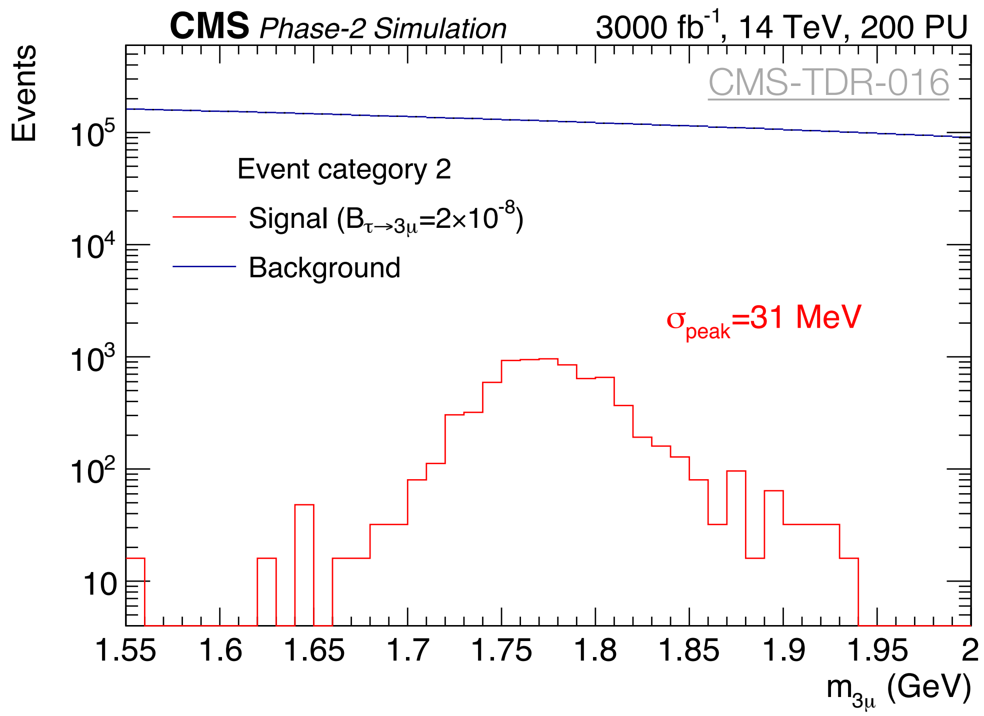
- Main sources of τ leptons in pp collisions are D_s decays into $\tau\nu$
    - final state muons have **very low momenta** and are **mainly produced in the forward direction**
    - only ~1.3% of signal events have all three muons within $|\eta| < 2.4$ and $p > 2.5$ GeV (current CMS acceptance)
    - **will benefit from the extended η coverage of the muon system and the improved trigger resolution at low p_T**

The available projections do take advantage of the new ME0 chambers, but do not exploit the full potential of the improved muon reconstruction coming from correlation of muon hits in the GEM and CSC detectors



$\tau \to 3\mu$ analysis and projections

- Events are split into 2 categories based on the pseudorapidity of the most forward muon
- **Dedicated L1 trigger**, specialized for the 2 categories (in both cases, $m_{3\mu} < 3$ GeV)
  - Cat. 1: 2 muons ($p_T > 2$ GeV) and one GEM-CSC segment in the first muon endcap station
  - Cat. 2: 1 muon and 2 segments in the first muon endcap station, allowing for ME0 segments in η = 2.4–2.8 range
- **Dedicated muon identification** targeting low momentum muons
- Analysis based on a discriminant built on the product of ratios of 1D signal and background probability density functions for ~ a dozen of observables



	Cat. 1	Cat. 2
|η| most forward muon	< 2.4	> 2.4
average 3μ mass resolution	18 MeV	31 MeV
L1 trigger efficiency	80%	50%
***B*(τ → 3*μ*) limit per category**	4.3×10^{-9}	7.0×10^{-9}
combined limit	**3.7×10^{-9}**	

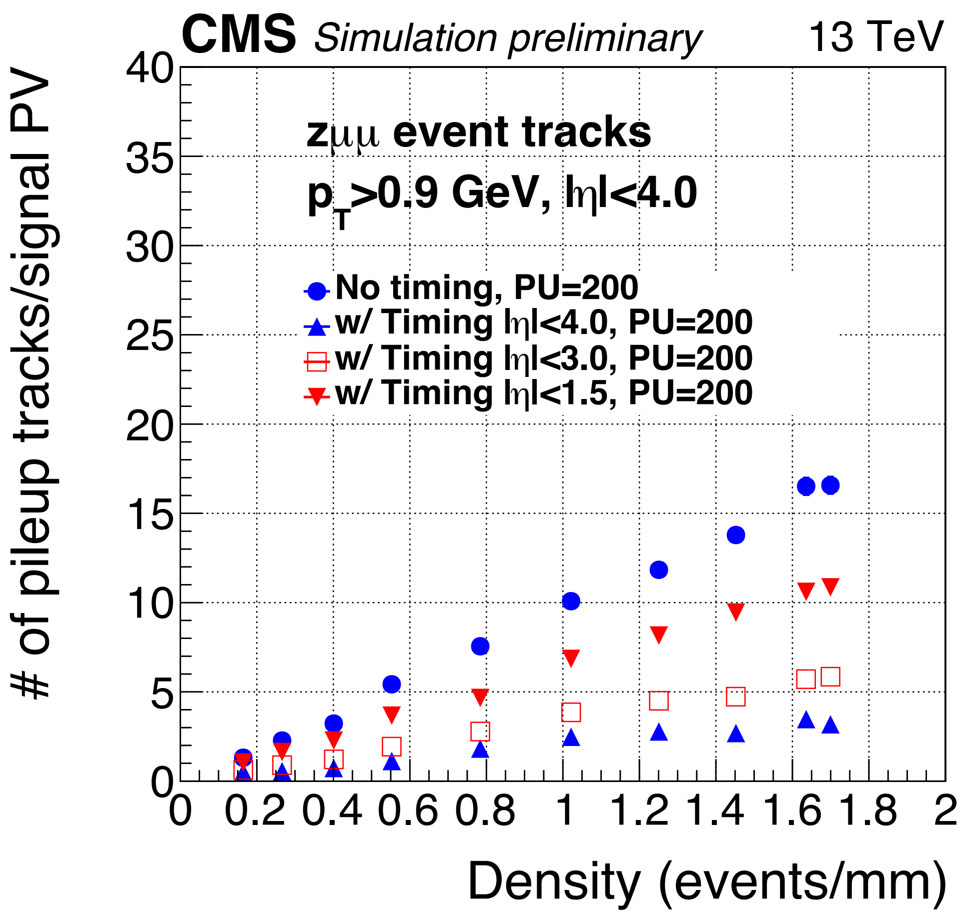
Summary

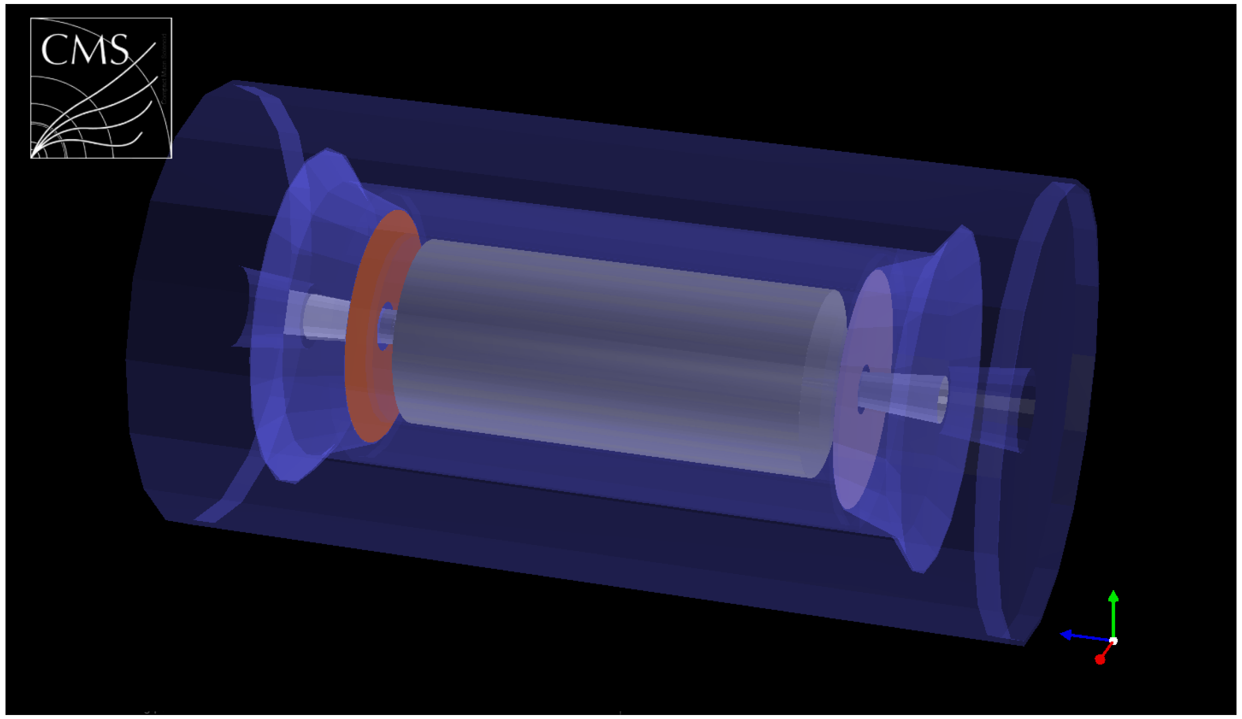
- The HL-LHC will extend the physics reach of the CMS detector and allow to **access very rare decays**
- **Detector upgrades are necessary to maintain excellent performances on all objects used in the analyses and achieve the physics goals**
    - the tracker and muon system upgrades enlarge their coverage and improve resolution
    - the L1 track trigger is essential to keep the event rate manageable while retaining reasonable efficiency for low pT signals
    - the additional timing layer helps mitigating the pileup effects

- Perspectives on the analysis side:
    - **observation of $B^0 \to \mu^+\mu^-$ in excess of 5σ is possible in 3000 fb^{-1}**
    - the Phase-II detector performance will allow to measure $B(B^0 \to \mu^+\mu^-)$ and the BR ratio with precisions of 18% and 21% respectively
    - **very forward muon coverage** improves limit on $\tau \to 3\mu$ decay as an effective integrated luminosity gain of +35%
    - studies ongoing to access **new low p_T final states thanks to the L1 track trigger**

extra

MTD and pileup mitigation

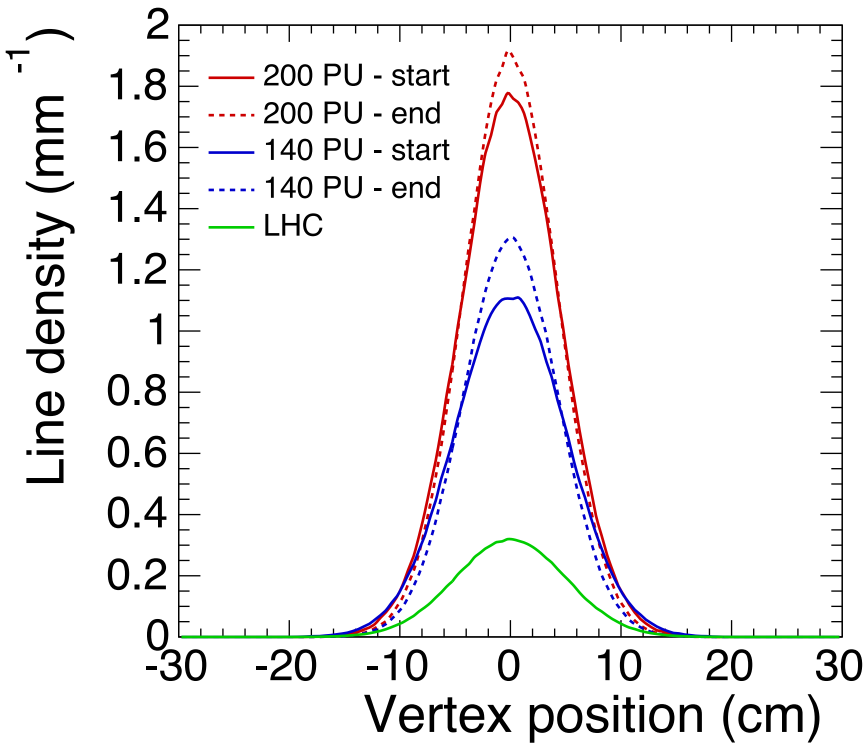


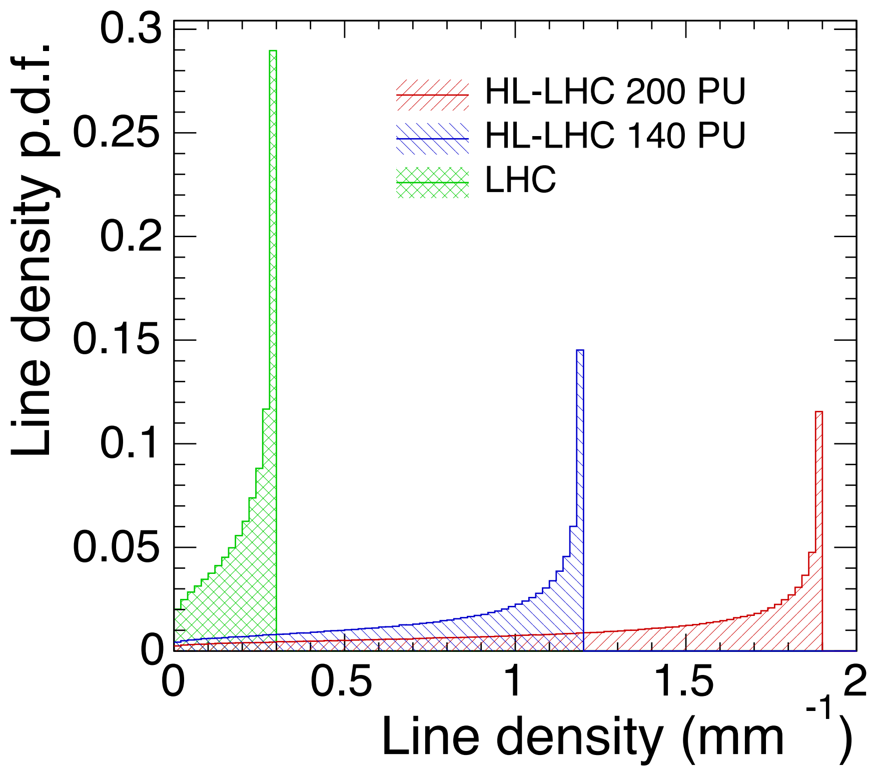


LYSO barrel (grey cylinder), at the interface between the Tracker and the ECAL, and two silicon endcap (orange discs) timing layers in front of the CE calorimeter.

pileup @HL-LHC

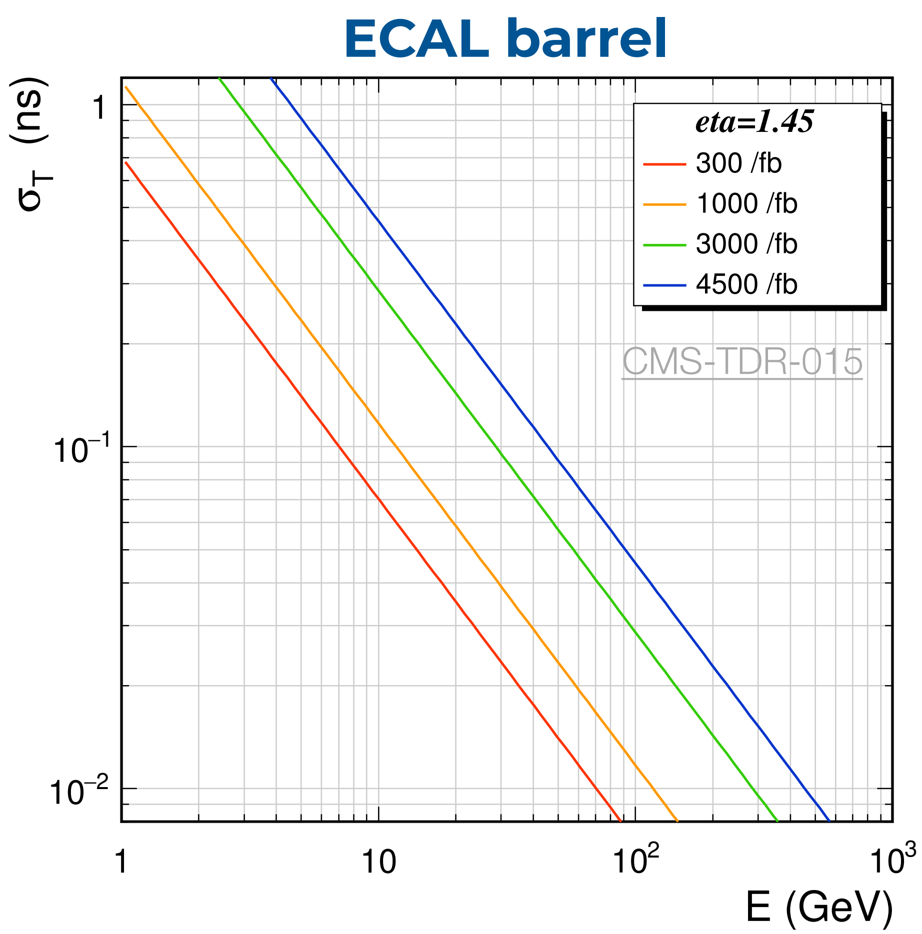
- Spread of the vertices along the beam direction at LHC and HL-LHC with 140 and 200 pileup events
- Probability density function of the vertex density along the beam axis





https://cds.cern.ch/record/2296612/files/LHCC-P-009.pdf

Timing from the upgraded ECAL barrel

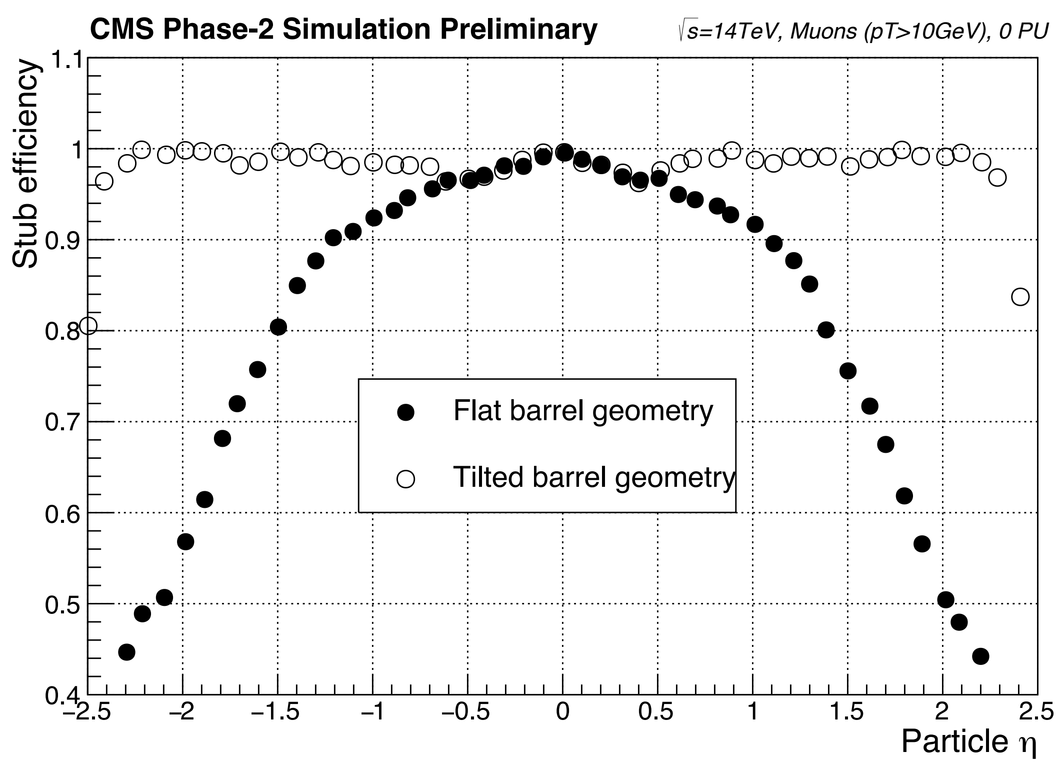


With proper attention to clock distribution, reduced shaping time, and high ADC sampling rates (160 MHz), can achieve ~ 30 ps time resolution for 30 GeV photons at high integrated luminosity (limited by S/N of existing APD photo-detectors)

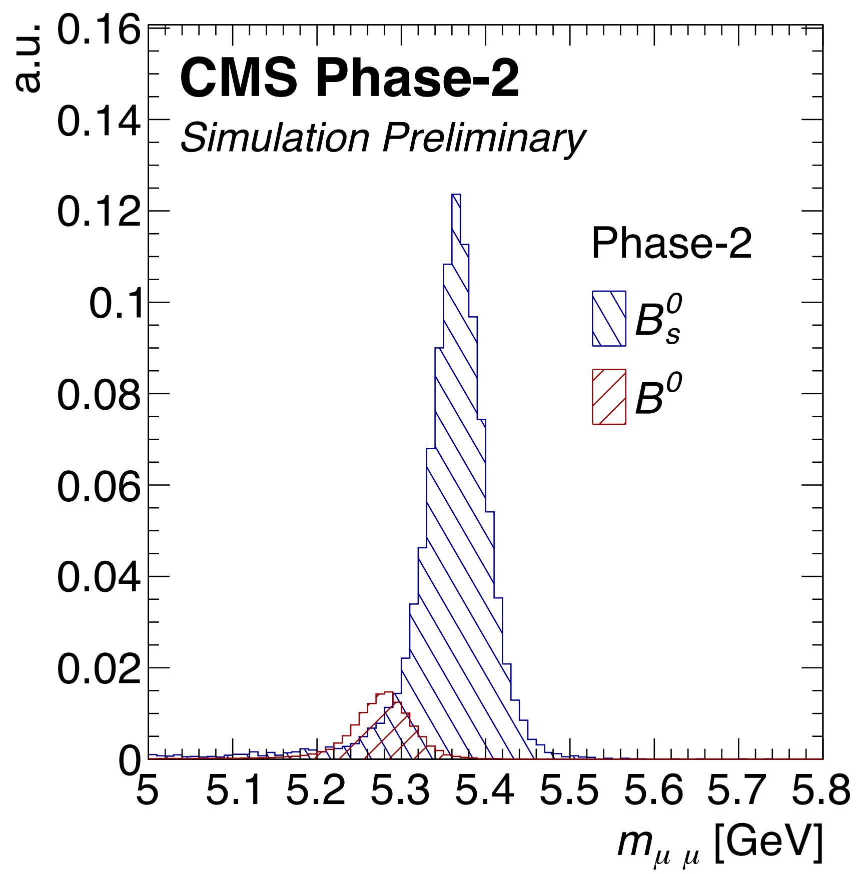
L1 tracker performance

Stub reconstruction efficiency for stubs with pT > 10 GeV in TBPS layer 1, using a Gaussian beam spot distribution, as a function of h, comparing the flat (solid points) and tilted (open circles) tracker barrel geometries.

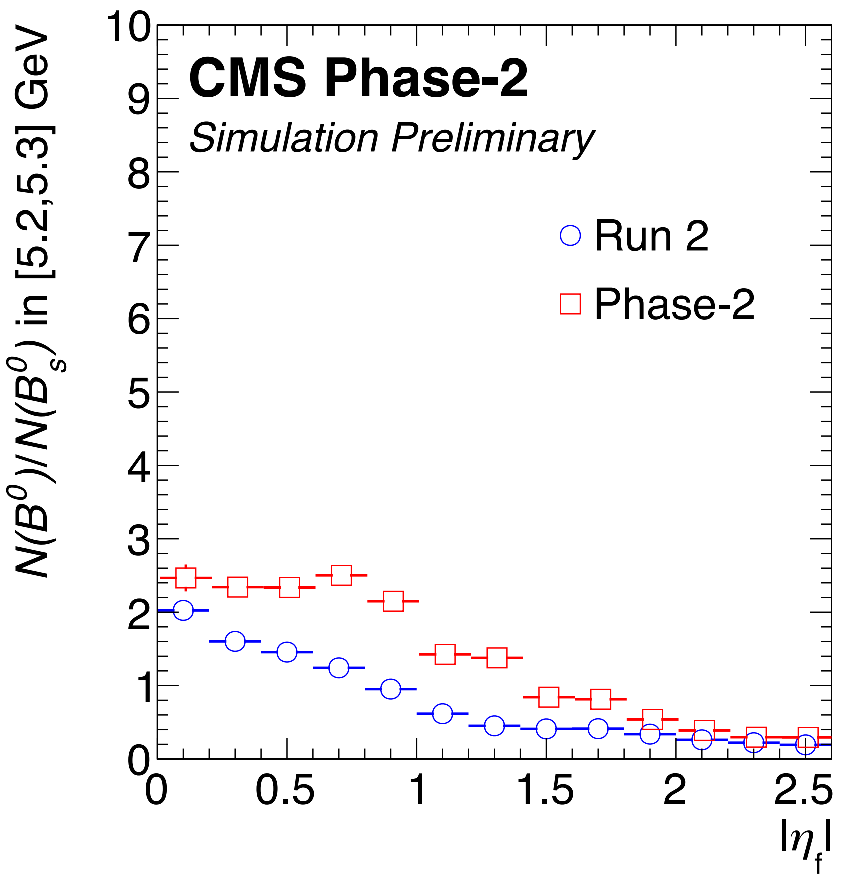
https://twiki.cern.ch/twiki/bin/view/CMSPublic/TDR17001Preliminary



$B_{(s)} \to \mu\mu$



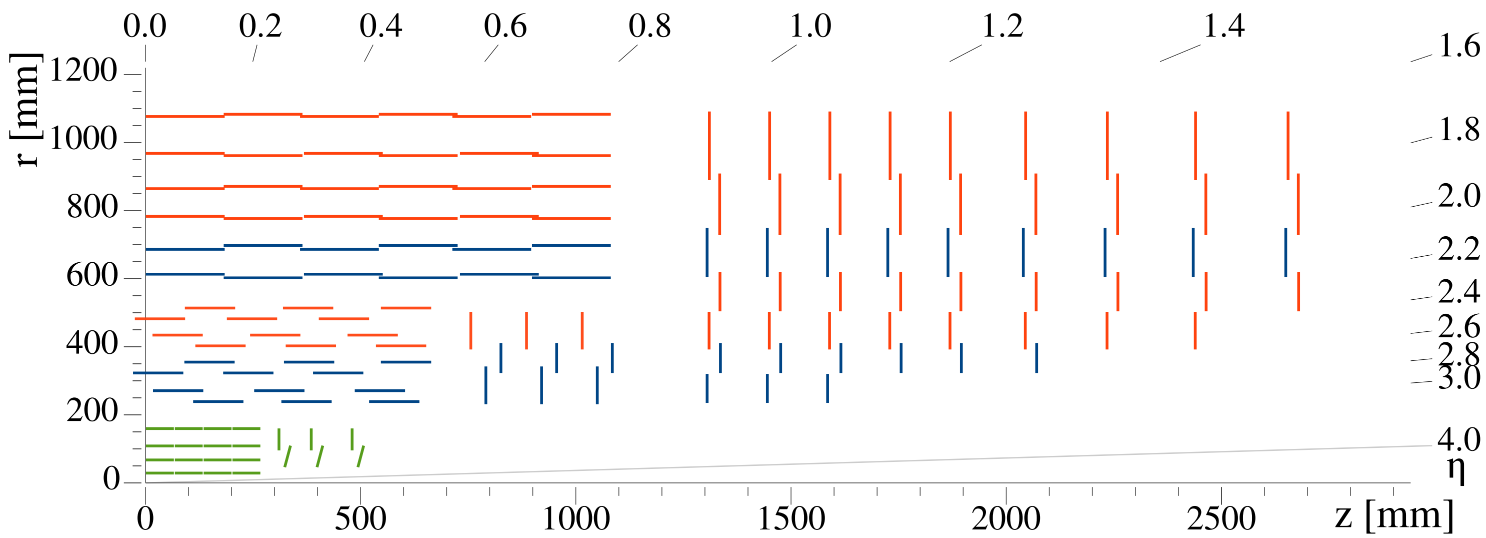
Mass distributions for $B_s \to \mu\mu$ and $B^0 \to \mu\mu$ in Phase-2 for $|\eta| < 1.4$.
The distribution for $B_s \to \mu\mu$ is normalized to unity, and the $B^0 \to \mu\mu$ distribution is normalized correspondingly according to the SM expectation



Leakage of $B_s \to \mu\mu$ into the B0->μμ signal region as a function of pseudorapidity

CMS tracker layout

Phase I CMS tracker



Phase II CMS tracker