Object performance at the HL-LHC with the CMS Phase2 detector

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On behalf of CMS Collaboration
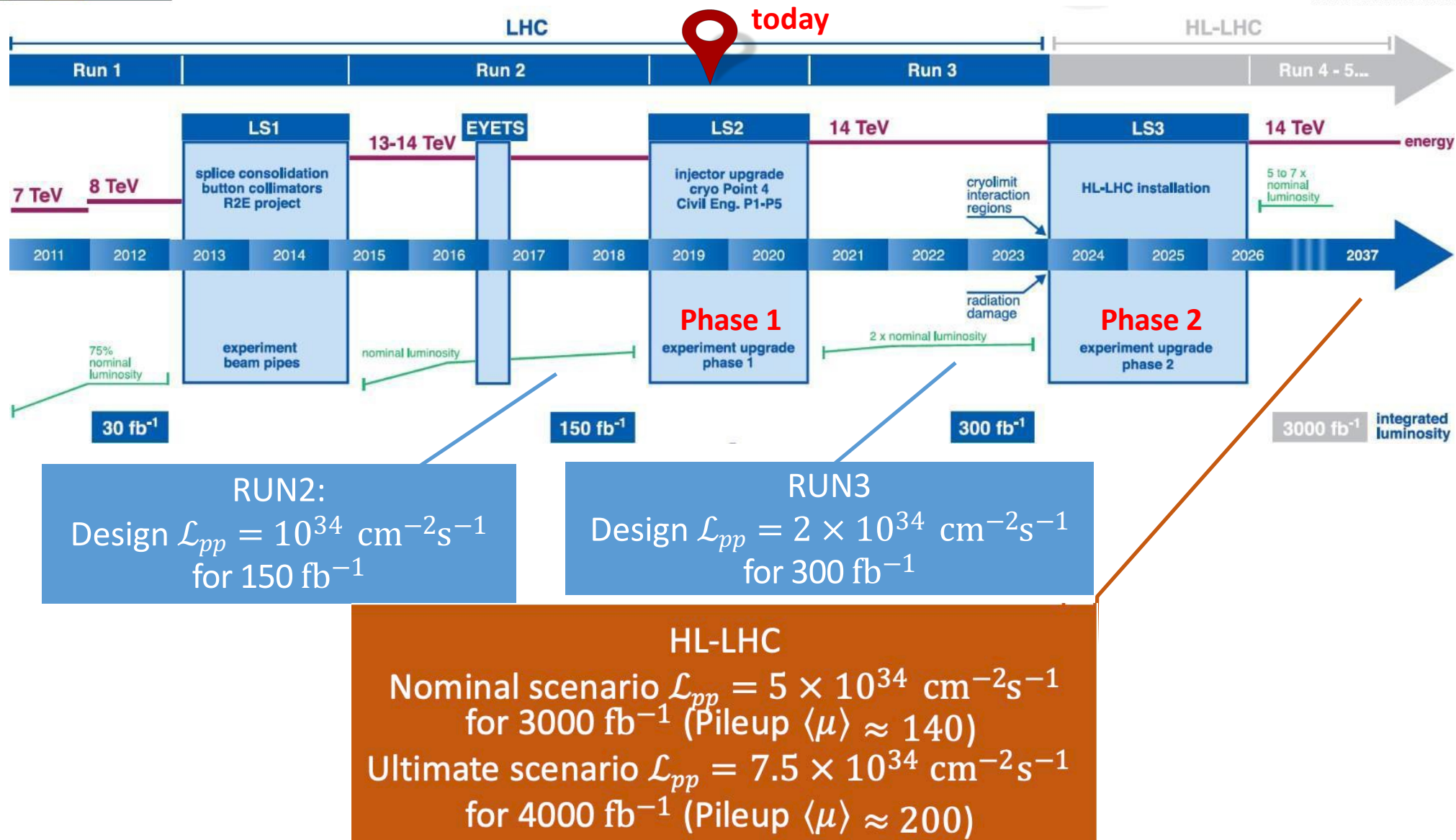
LCWS2019: International Workshop on Future Linear Colliders
-28 Oct-1 Nov 2019, Sendai (Japan)

Path to high-luminosity (HL) LHC

RUN2:
Design $\mathcal{L}_{pp} = 10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$
for 150 fb^{-1}

RUN3
Design $\mathcal{L}_{pp} = 2 \times 10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$
for 300 fb^{-1}

HL-LHC
Nominal scenario $\mathcal{L}_{pp} = 5 \times 10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$
for 3000 fb^{-1} (Pileup $\langle\mu\rangle \approx 140$)
Ultimate scenario $\mathcal{L}_{pp} = 7.5 \times 10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$
for 4000 fb^{-1} (Pileup $\langle\mu\rangle \approx 200$)

Phase 2 detector requirements

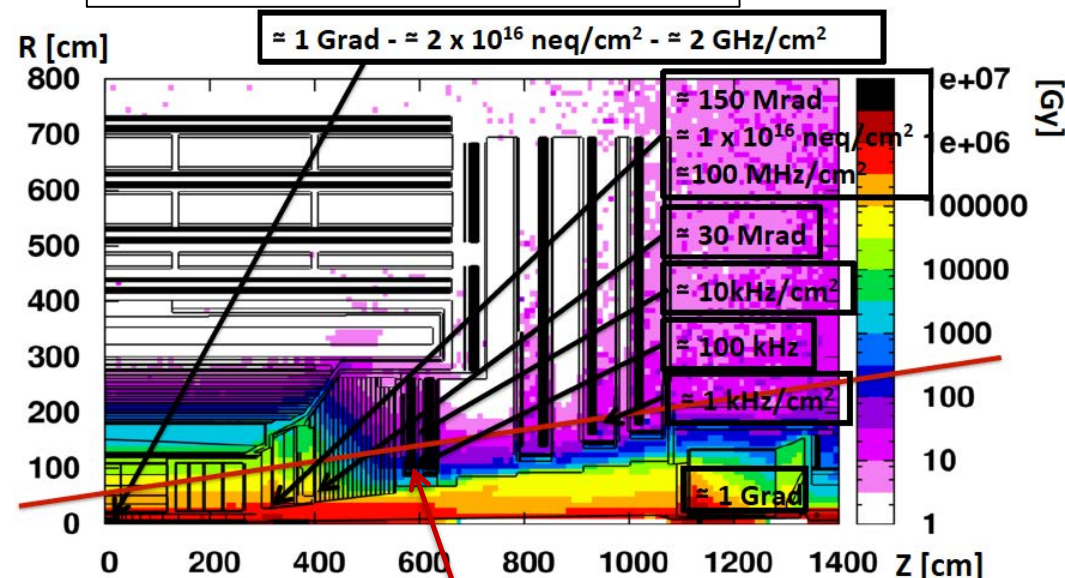**Challenges:**

- high instant. luminosity ($5 - 7.5 \times 10^{34}$ cm^{-2}s^{-1})
  - → high pileup   (140 – 200)
- high integrated luminosity ($3 - 4$ ab^{-1})
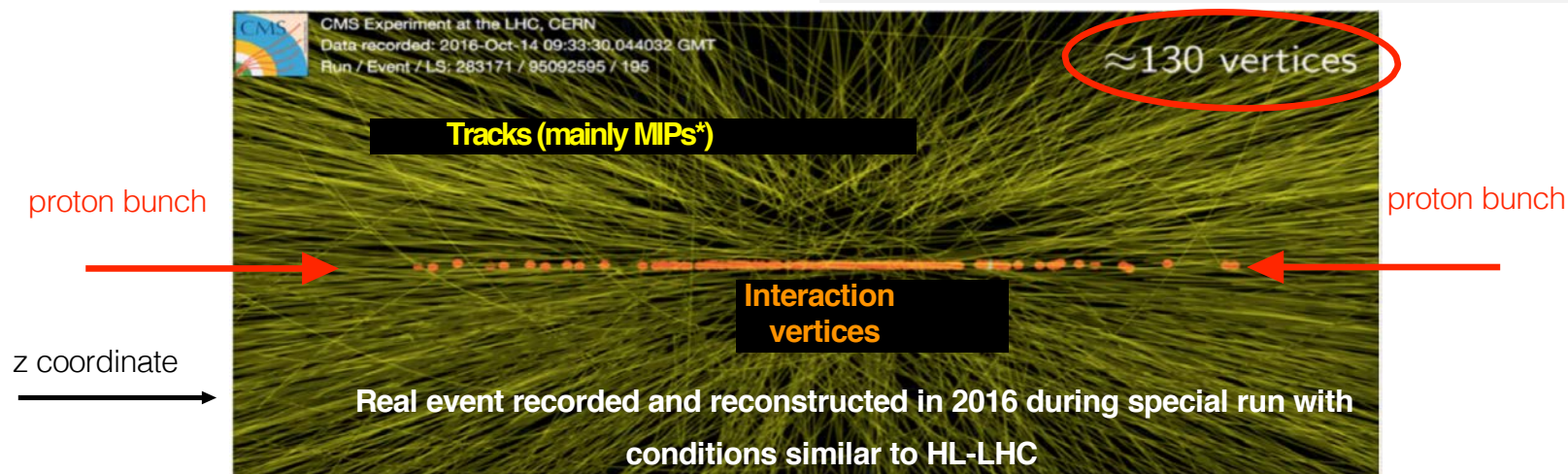 - → high irradiation

Requirement of the CMS Phase 2 upgrade:

- High trigger and readout rate
- high resolution 4D space+time (+ energy) detector
- detectors must resist to the high radiation levels and some have to be replaced in LS3

5×10^{34} Hz/cm^2 and 3000 fb^{-1} luminosities

≃ 1 Grad - ≃ 2×10^{16} neq/cm^2 - ≃ 2 GHz/cm^2

≃ 150 Mrad
≃ 1×10^{16} neq/cm^2
≃100 MHz/cm^2
≃ 30 Mrad
≃ 10kHz/cm^2
≃ 100 kHz
≃ 1 kHz/cm^2
≃ 1 Grad

below the red line: beyond limit of currently used detector technologies in several systems

≈130 vertices

Tracks (mainly MIPs*)

proton bunch   proton bunch

Interaction vertices

z coordinate

Real event recorded and reconstructed in 2016 during special run with conditions similar to HL-LHC

CMS Phase 2 upgrades

L1 Trigger – HLT - DAQ
track information at L1 at 40 MHz
latency 3.2 μs -> 12.5 μs
HLT input 100 kHz -> 750 kHz
output 1 kHz -> 7.5 kHz

Barrel EC Calorimeters
crystal granularity read-out at 40 MHz
30 ps e/γ resolution at 30 GeV

Muon system
DT & CSC FE/BE new read-out
new GEM/RPC $1.6 < |\eta| < 2.4$
GEM coverage up to $|\eta| = 2.8$

new Tracker
track-trigger at 40 MHz
increased granularity
extended acc. to $|\eta| < 4$

new MIP Timing Detector
Barrel layer: crystal + SiPM
Endcap layer: $|\eta| < 3$
Low Gain Avalanche Diodes
30 ps TOF resolution

new Endcap Calorimeters
 Si/W – Scint-SiPM/SS
4D shower topology : 30 ps TOF resolution
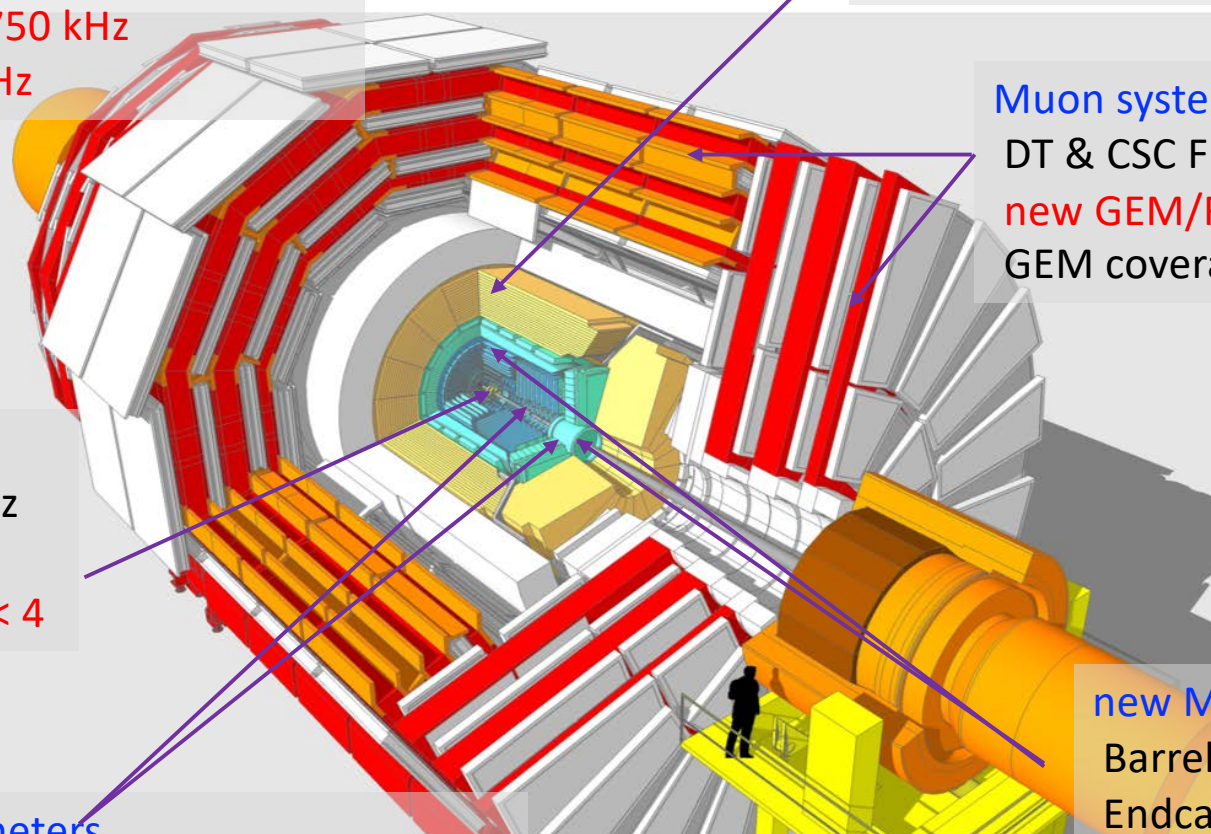
New Tracker

Outer Tracker: design driven to provide tracks (p_T > 2-3 GeV) at 40 MHz to the **L1 trigger** => each module consists of 2 closely spaced sensors (~mm)

- strip-strip (2S) modules: modules with 1016 strips (5 cm x 90 μm)

- pixel-strip (PS) modules: modules with macro-pixel (1.5 mm x 100 μm) on one side and 960 strip (2.4 cm x 100 μm) on the other, tilted in Barrel (hermetic coverage with less modules and material)
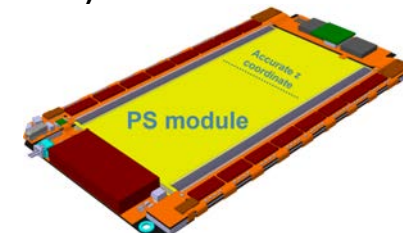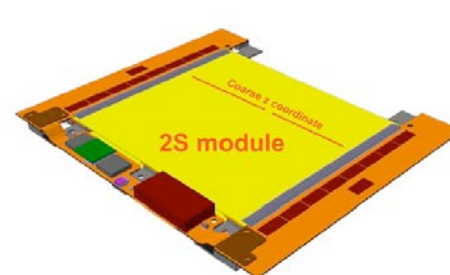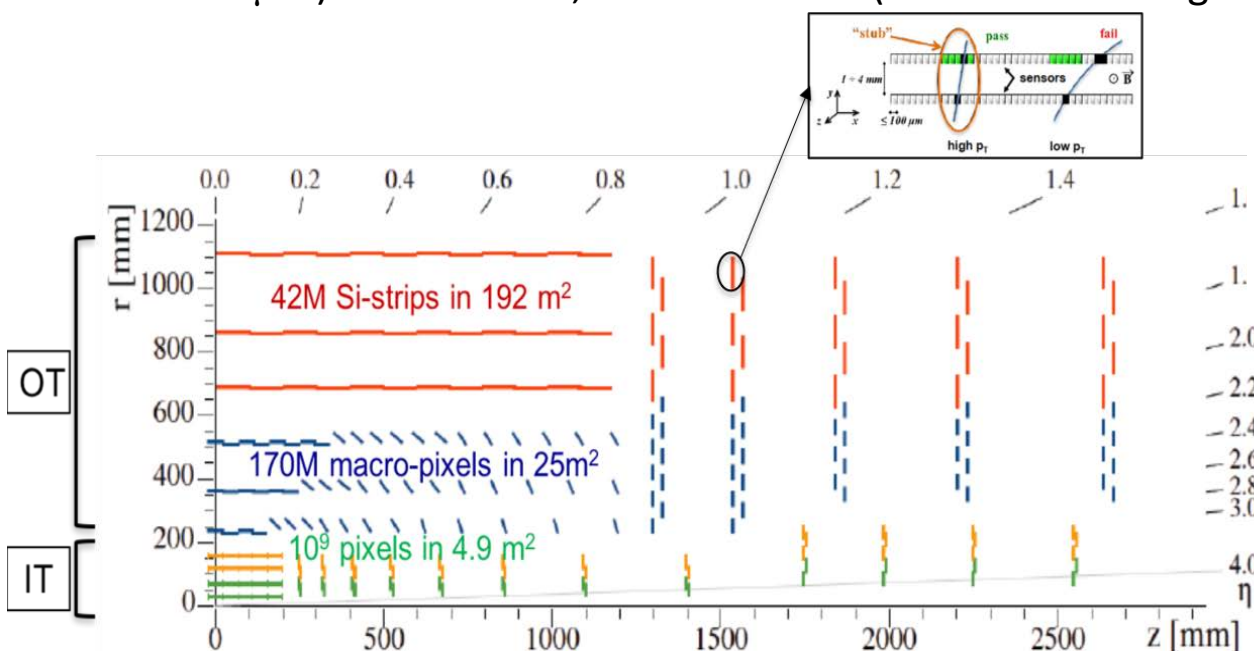
CMS-TDR-014
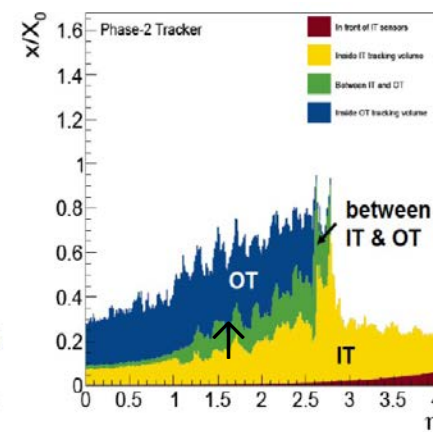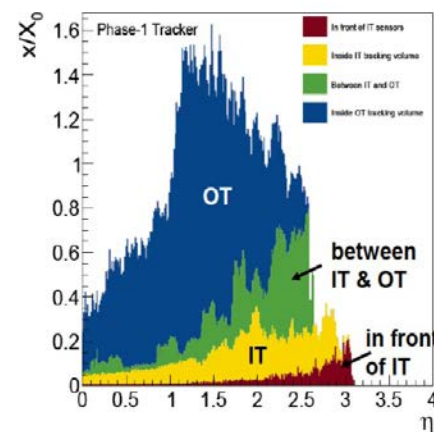
Inner Tracker (Pixel):
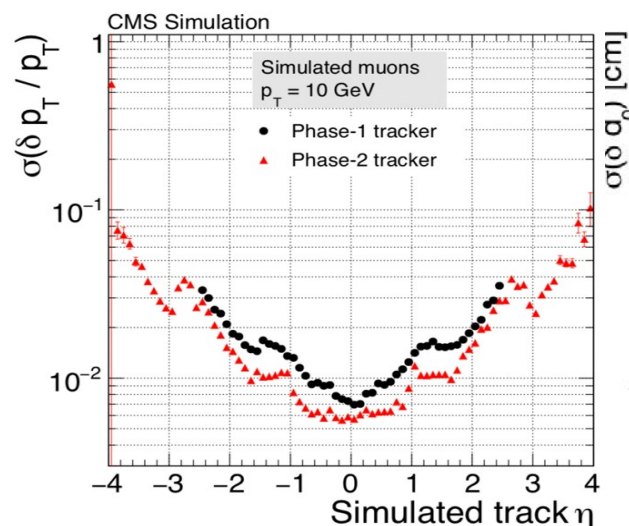
- extended coverage up to |η| < 4.0
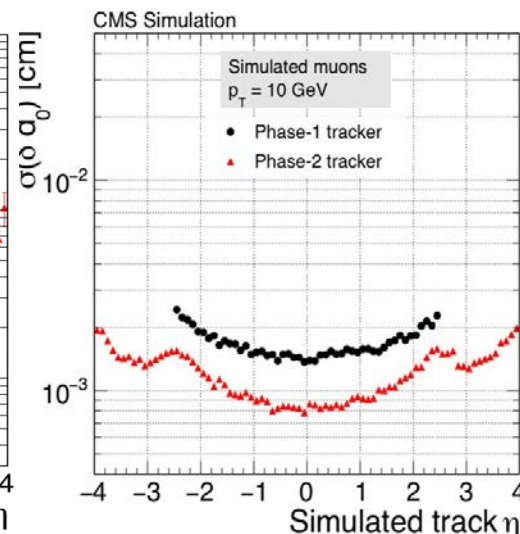
- 6x better granulariry than current Phase 1 pixel:
  Pixel size: 25 x 100 μm² or 50 x 50 μm²,

Substantial reduction of the material budget

Track performance

CMS-TDR-014

CMS-TDR-014

Track resolution vs η

- improved resolution and extended η range

CMS-TDR-014

CMS-TDR-014

CMS-TDR-014
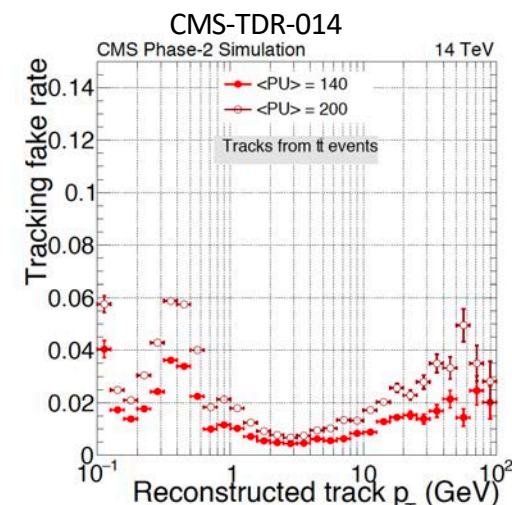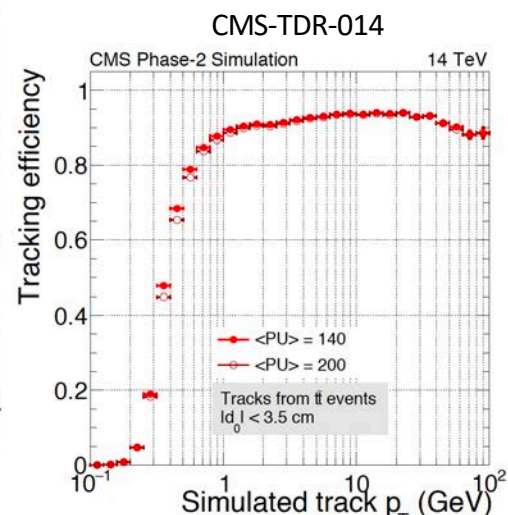
Track and fake efficiency vs p_T

- track reconstruction efficiency > 90% for p_T > 1 GeV

- fake rate < 2% (4%) at 140 (200) PU for p_T within 1-100 GeV

- improved tracking in jet core thanks to better tracker granularity: important for high p_T jets and boosted objects measurements.
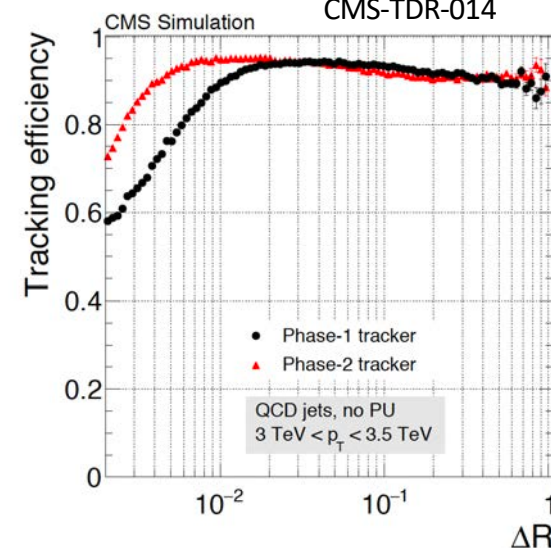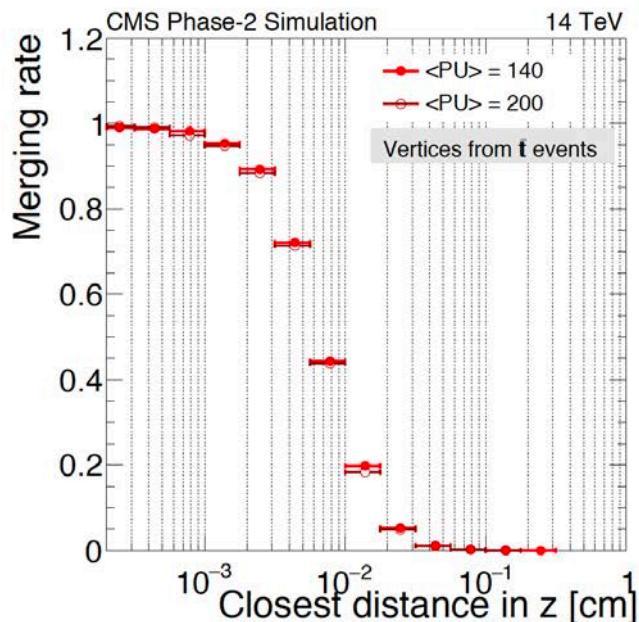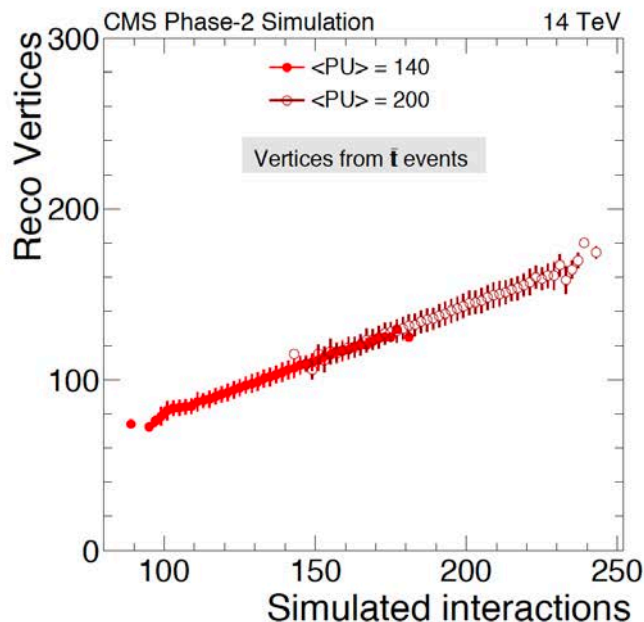
Primary vertex and MET Performance
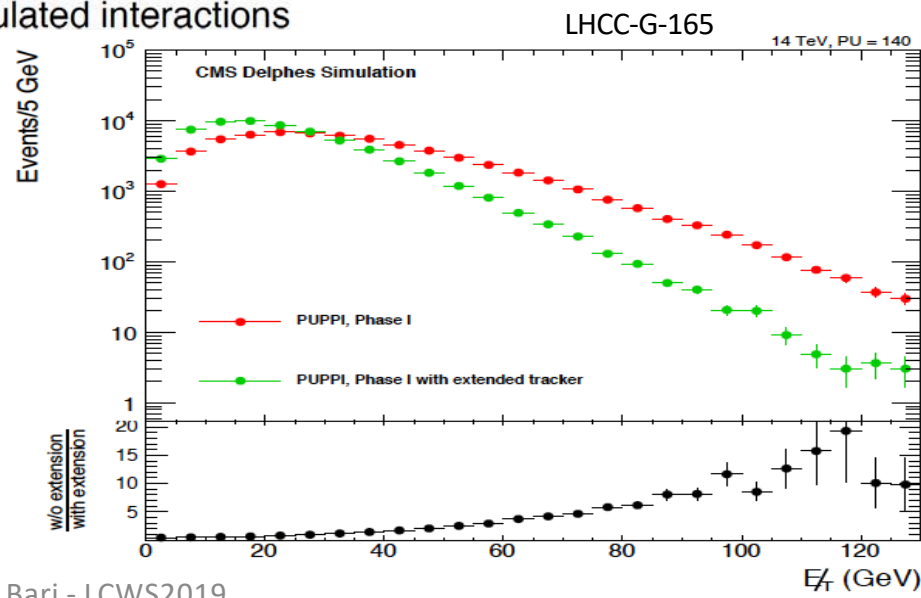
CMS-TDR-014

CMS-TDR-014

Good Primary Vertex (PV) reconstruction efficiency:

- PV merging rate high for |Dz| < 300 µm

- linear dependence as a function of pileup

LHCC-G-165

Improved MET reconstrution

- MET distribution with extended tracker

  → the rate of DY events with mis-reconstructed MET significatly decreases with extended tracker.

Muon Upgrade

- Upgrades of the existing muon detectors
  - current detectors withstand HL-LHC radiation level
  - Upgrade electronics of DT, CSC and RPC to ensure longevity to cope with longevity and new trigger and readout requirements.

- Extension of the muon system coverage to benefit from the extension of the tracker, HGCAL & new L1 trigger features

  Allow to maintain low threshold for physics and extend acceptance

  - New GEM stations (GE1/1, GE2/1) and iRPC (RE3/1,RE4/1) : improve reconstruction and triggering in the current acceptance up to 2.4
  - Six layers triple GEM (ME0): extension to η= 2.8

- Including all muon detector into the trigger
  - Better p_T resolution allows lower rate
  - Kalman filter approach in trigger hardware, to take into account the energy loss and multiple scattering
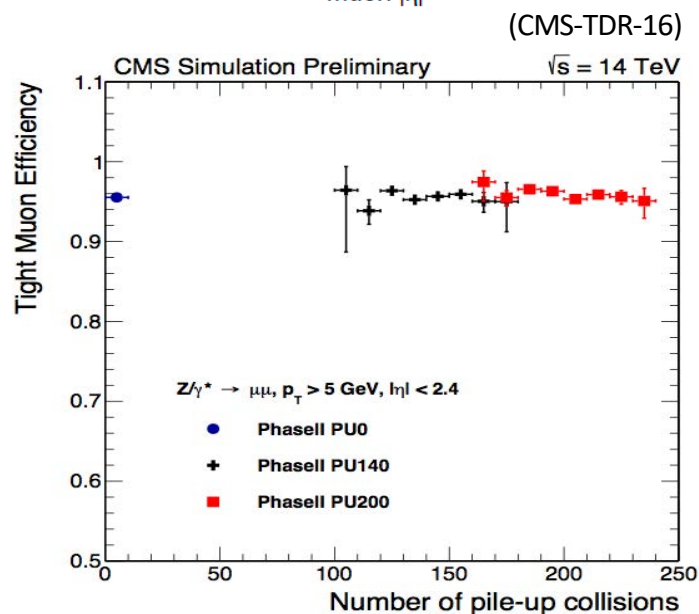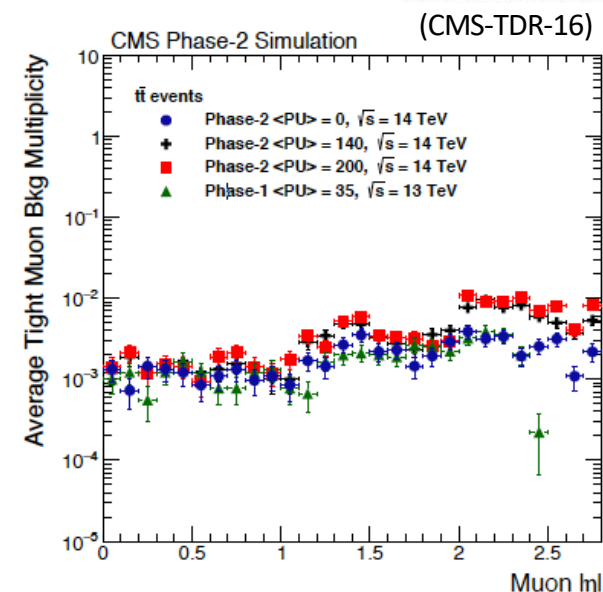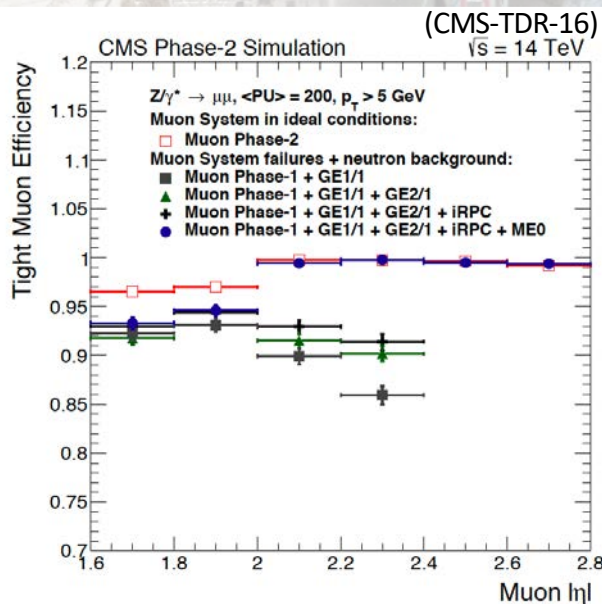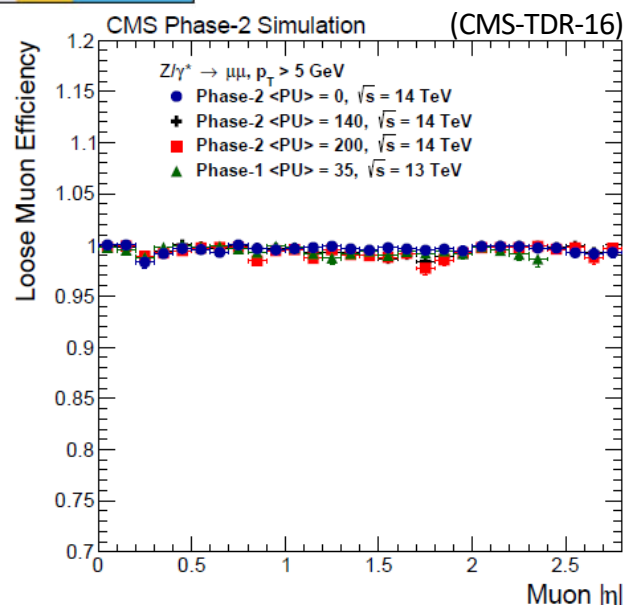 - Capability to trigger on displaced Muons
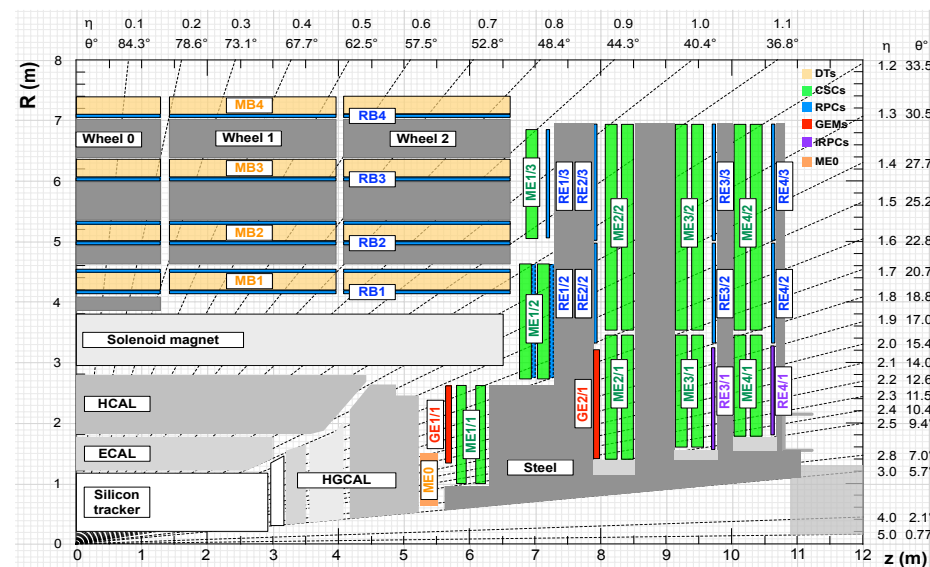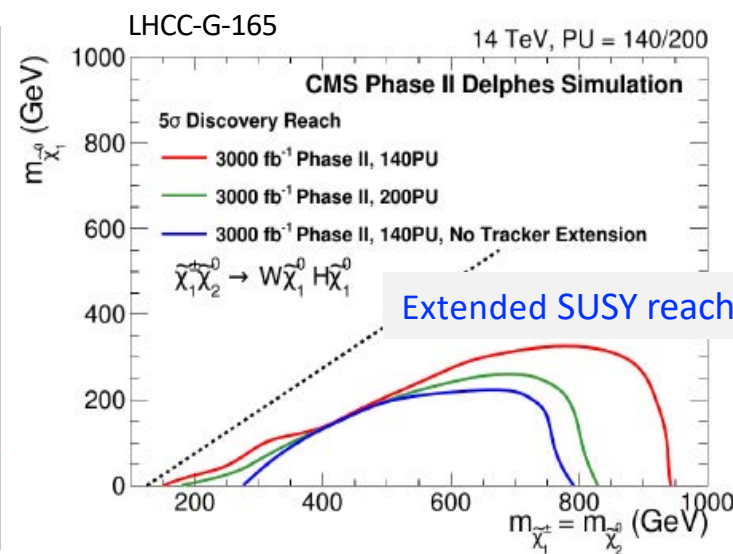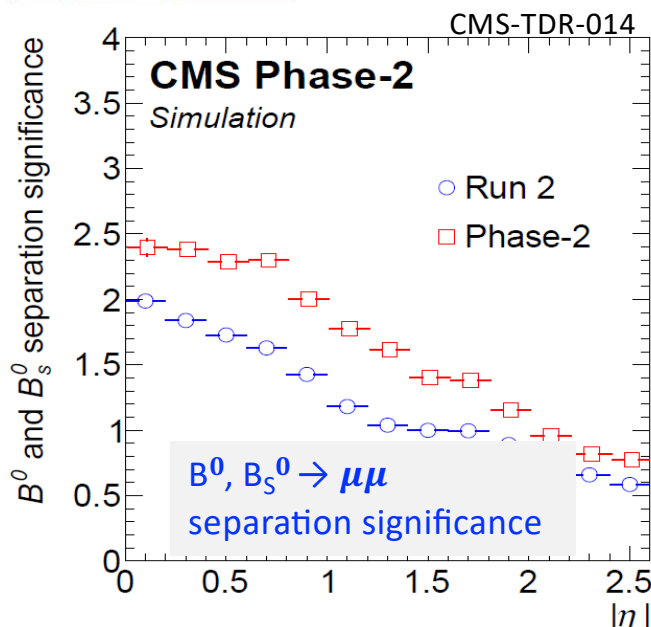
Muon object performance

- Muon reconstruction/identification in general **robust against Pileup**

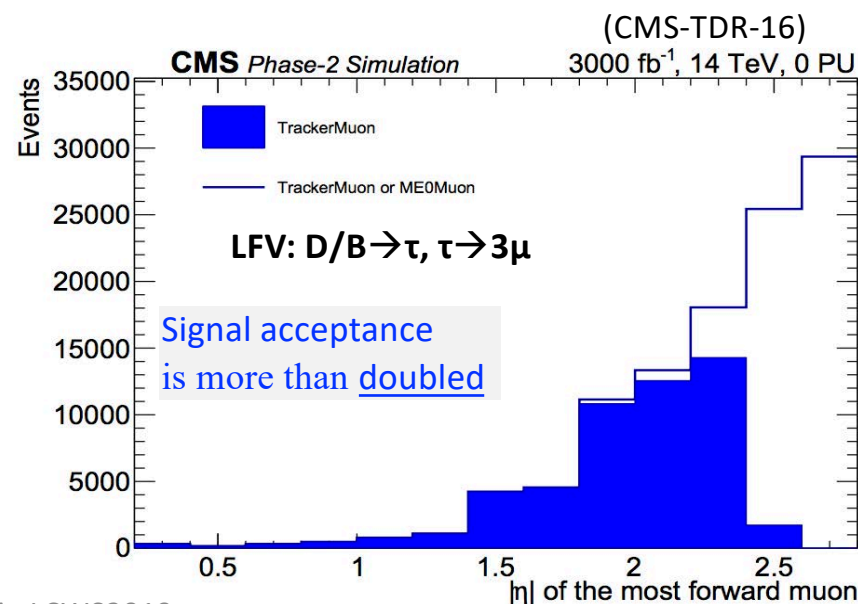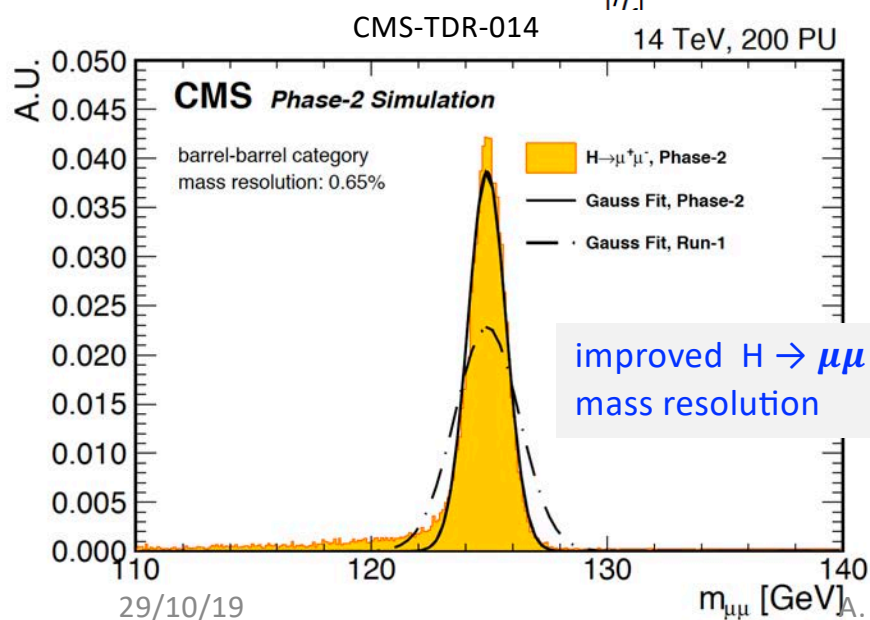- **Excellent muon reconstruction/identification** efficiency and background rejection **up to |η| < 2.9**

Performance and physics impact

CMS-TDR-014

CMS Phase-2 Simulation

○ Run 2
□ Phase-2

B^0, $B_s^0 \rightarrow \mu\mu$ separation significance

LHCC-G-165

14 TeV, PU = 140/200

CMS Phase II Delphes Simulation

5σ Discovery Reach

3000 fb⁻¹ Phase II, 140PU
3000 fb⁻¹ Phase II, 200PU
3000 fb⁻¹ Phase II, 140PU, No Tracker Extension

$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0 H\tilde{\chi}_1^0$

Extended SUSY reach

Many BSM searches and SM measurements benefit from extended tracker and muon acceptance

CMS-TDR-014

14 TeV, 200 PU

CMS Phase-2 Simulation

barrel-barrel category
mass resolution: 0.65%

$H \rightarrow \mu^+\mu^-$, Phase-2
Gauss Fit, Phase-2
Gauss Fit, Run-1

improved $H \rightarrow \mu\mu$ mass resolution

(CMS-TDR-16)

CMS Phase-2 Simulation   3000 fb⁻¹, 14 TeV, 0 PU

TrackerMuon
TrackerMuon or ME0Muon

LFV: D/B→τ, τ→3μ

Signal acceptance is more than doubled

Standard tools to fight against pileup

- **Timing of calorimeter** @ hardware level, effective to remove out-of-time pileup.

- **PFCHS jets - Charged Hadron Subtracted (CHS)** - : charged particles from non-primary vertices (pileup) are removed before performing **Particle Flow jet (PF)** clustering.

  - **relies on track-vertex association <u>in space</u>:**
    optimal z-cut at ~1mm for track-vertex compatibility

increase purity from 77% to 98%
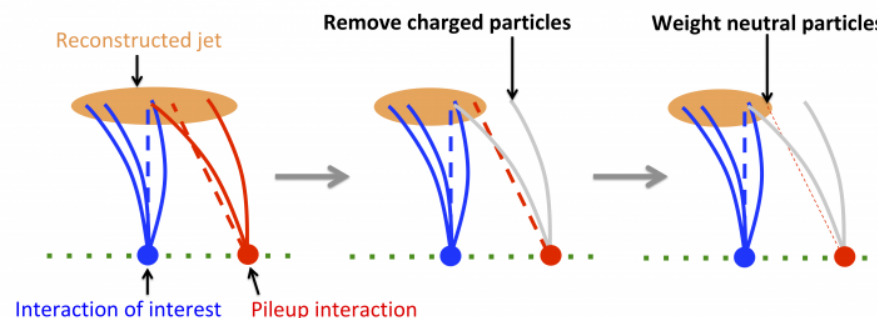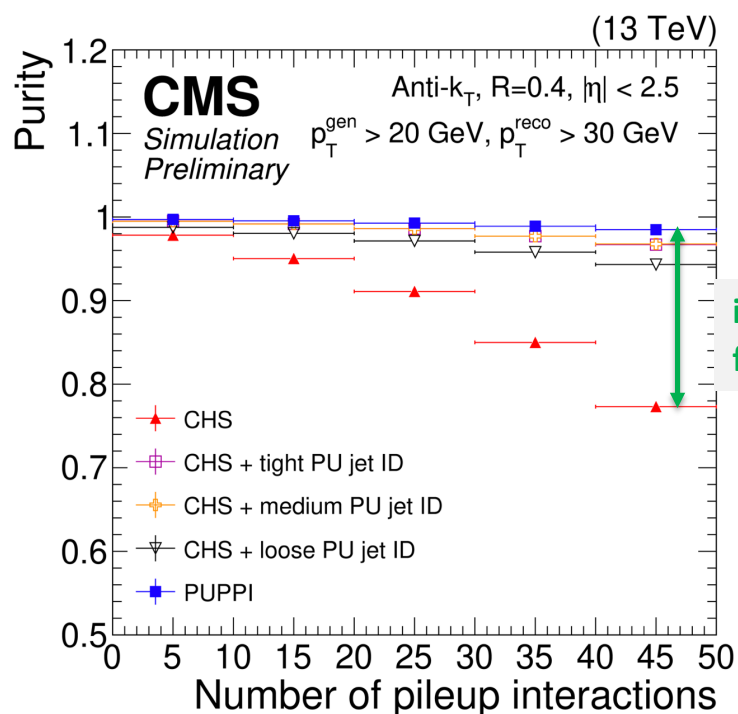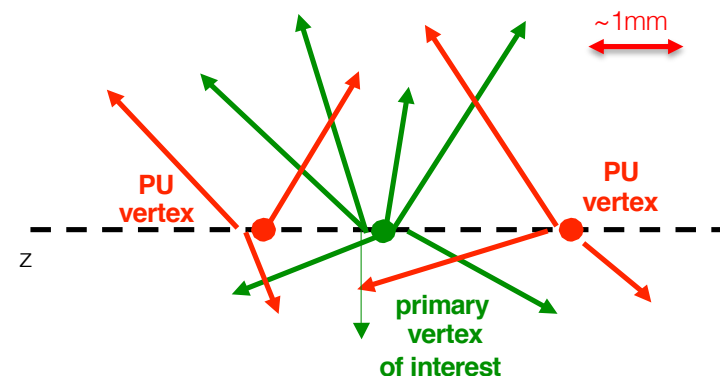
- **PUPPI jet (PileUp Per Particle Identification jets):**
  each individual PF particle is weighted to account for the probability of coming from the leading vertex (LV) or pileup (PU) interactions
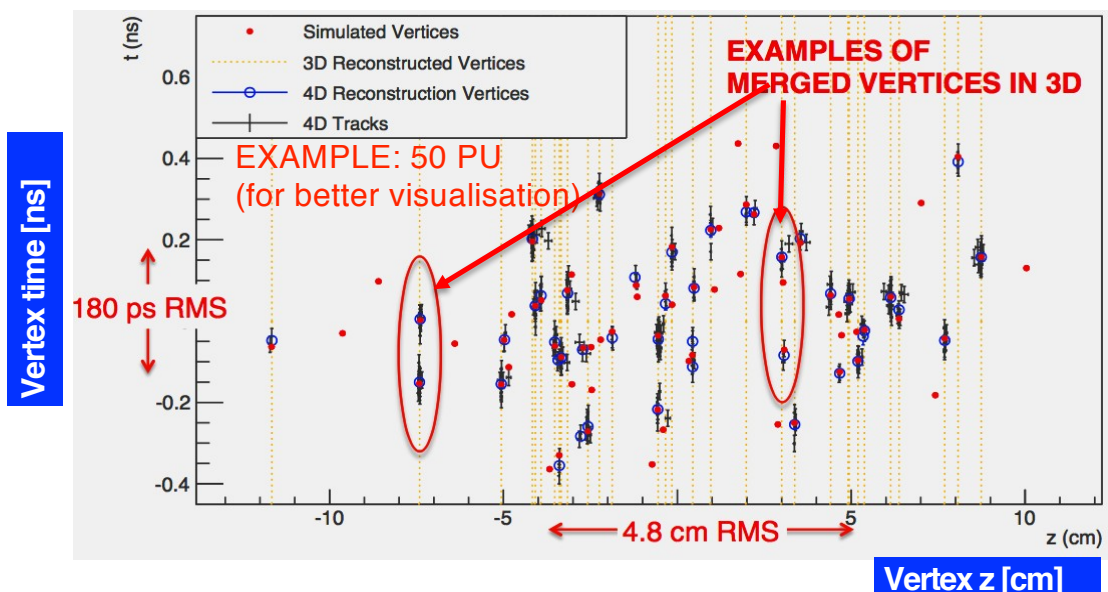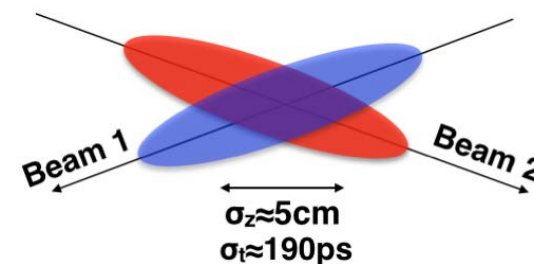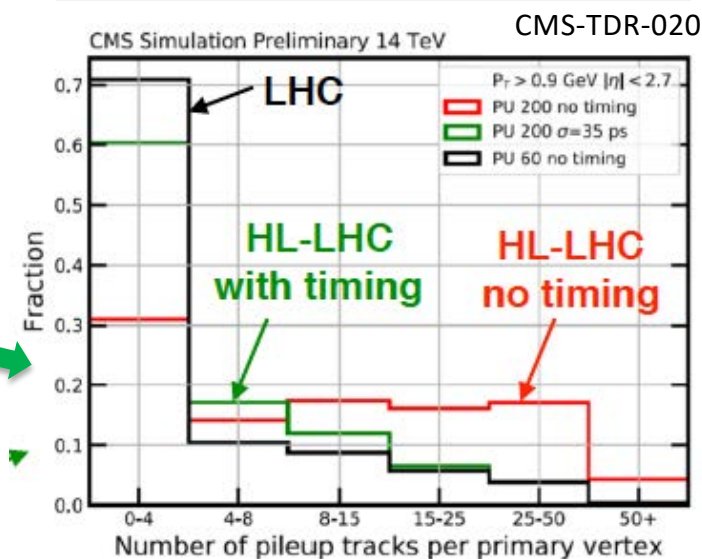
Pileup mitigation: precise timing

Collision vertices within a bunch crossing

EXAMPLES OF MERGED VERTICES IN 3D

EXAMPLE: 50 PU (for better visualisation)

180 ps RMS

4.8 cm RMS

- Simulated Vertices
- 3D Reconstructed Vertices
- 4D Reconstruction Vertices
- 4D Tracks

Vertex time [ns]

Vertex z [cm]

Crossing scheme

$\sigma_z \approx 5$cm
$\sigma_t \approx 190$ps

PU tracks incorrectly associated to primary vertex of interest

CMS-TDR-020

CMS Simulation Preliminary 14 TeV

$P_T > 0.9$ GeV $|\eta| < 2.7$
- PU 200 no timing
- PU 200 $\sigma=35$ ps
- PU 60 no timing

LHC

HL-LHC with timing

HL-LHC no timing

reduce pileup at HL-LHC ~ to current LHC levels

Basic Idea: vertices merged in z might be <u>separated in time</u>

- better time resolution σ_t → better vertex separation

- Calorimeter Precision timing of showers
  - high-energy photons in ECAL Barrel
  - photons and high-energy hadrons in Endcap Calorimeter

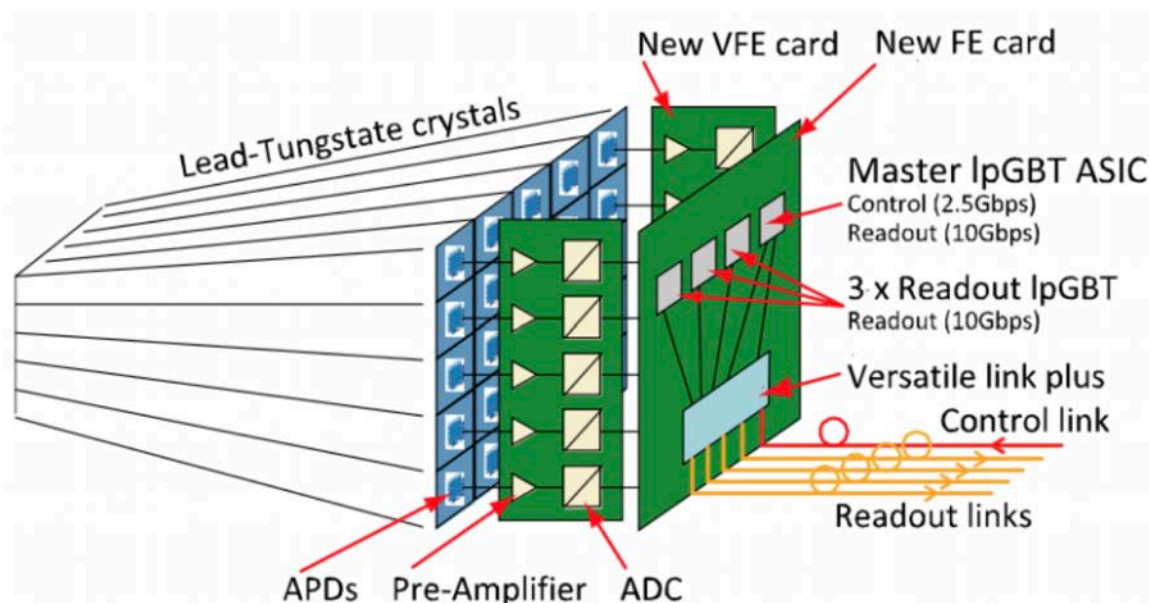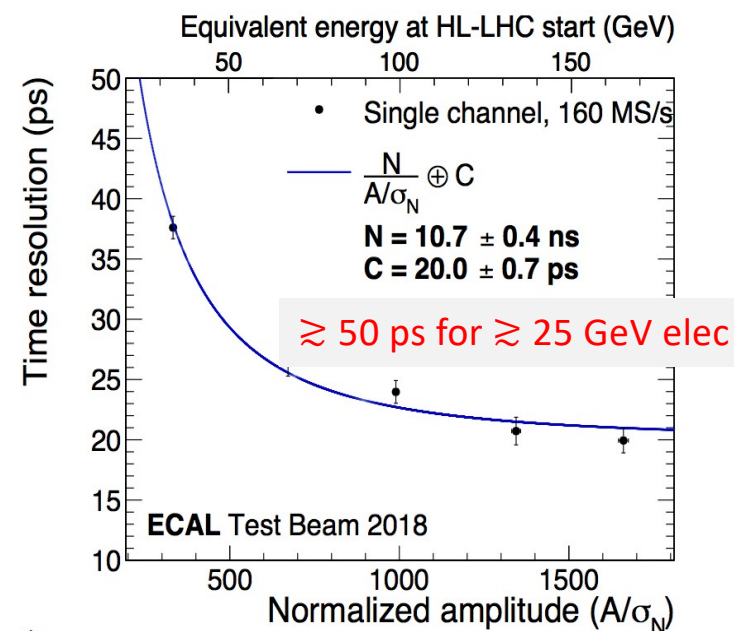- MTD: MIP Timing Detector: Precision timing of tracks

Barrel calorimeter

ECAL Barrel has to accomodate the Level-1 trigger requirements on latency and rate, provide more precise timing resolution, and mitigate the increasing noise from the photodetectors.

- $PbWO_4$ crystal granularity readout (Avalanche PhotoDiodes) at 40 MHz in high pileup conditions
- replace front-end electronics:
  - 160 MHz sampling against spikes (due to hadron interactions within APD volume),
  - 30 ps resolution for 30 GeV e/γ
  - all cells available at Level 1 trigger
- operate from 18° to 9°C to mitigate APD aging

New VFE card   New FE card

Lead-Tungstate crystals

Master lpGBT ASIC
Control (2.5Gbps)
Readout (10Gbps)

3 x Readout lpGBT
Readout (10Gbps)

Versatile link plus
Control link

Readout links

APDs   Pre-Amplifier   ADC

CMS $PbWO_2$ Crystals+ APDs + new FE

Equivalent energy at HL-LHC start (GeV)

- Single channel, 160 MS/s

$$\frac{N}{A/\sigma_N} \oplus C$$

N = 10.7 ± 0.4 ns
C = 20.0 ± 0.7 ps

≳ 50 ps for ≳ 25 GeV elec

ECAL Test Beam 2018

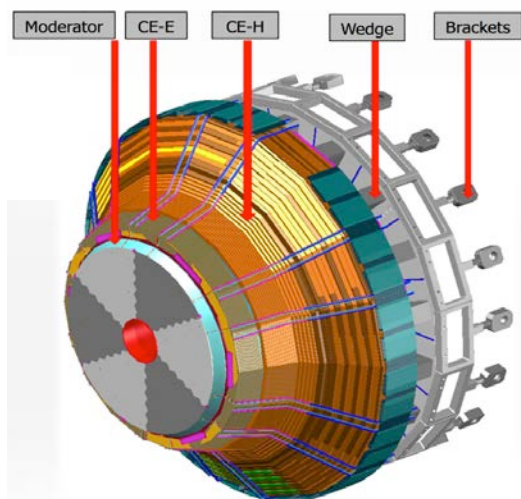Time resolution (ps)

Normalized amplitude (A/σ_N)
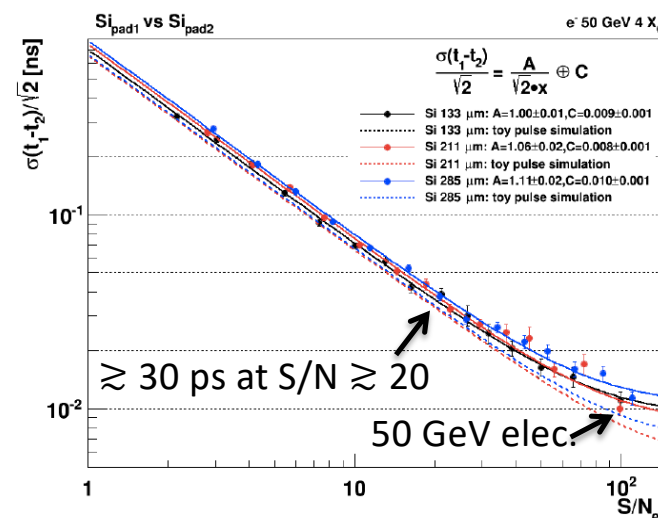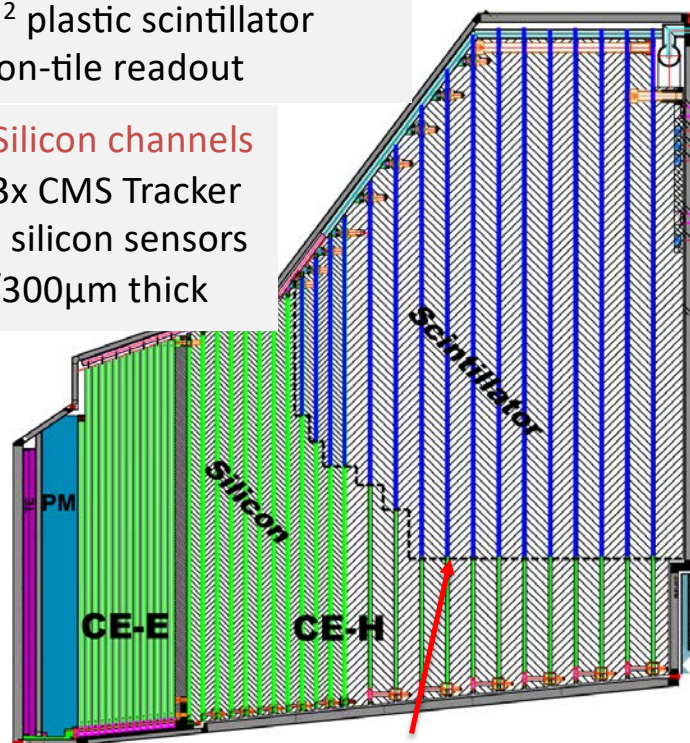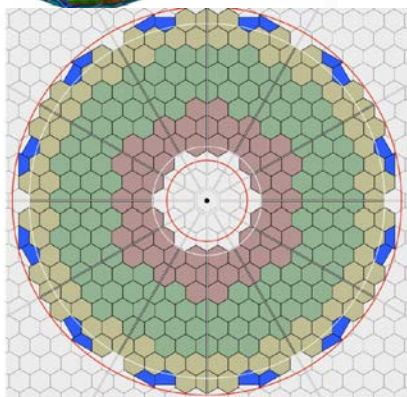
High Granularity endcap Calorimeter

- 4D shower topology with timing resolution ~30 ps for few GeV γ and hadrons above 2 GeV Pt
  - electromagnetic calo: 28 layers Silicon/W-Pb (26 X_0 - 1.7 λ)
  - hadronic calo: 8 layers Si + 16 mixed Si-Scintillators tiles within stainless steel absorber (9 λ)

mixed layers in hadronic part
500 m^2 plastic scintillator
SiPM-on-tile readout

6 million Silicon channels
600 m^2 ≈ 3x CMS Tracker
hexagonal silicon sensors
(100/200/300μm thick

Si_{pad1} vs Si_{pad2} e^- 50 GeV 4 X_0

$$\frac{\sigma(t_1-t_2)}{\sqrt{2}} = \frac{A}{\sqrt{2 \cdot x}} \oplus C$$

Si 133 μm: A=1.00±0.01,C=0.009±0.001
Si 133 μm: toy pulse simulation
Si 211 μm: A=1.06±0.02,C=0.008±0.001
Si 211 μm: toy pulse simulation
Si 285 μm: A=1.11±0.02,C=0.010±0.001
Si 285 μm: toy pulse simulation

≳ 30 ps at S/N ≳ 20

50 GeV elec.

350 krad, maintains S/N ≥ 5 for MIP calibration (consistently with SiPM rad. tol.)

Photons performance
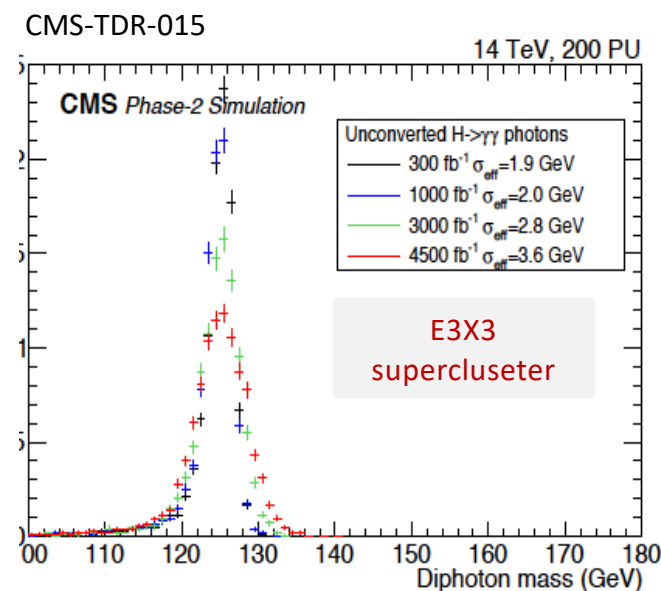
HL-LHC will provide x10 larger dataset for Higgs physics
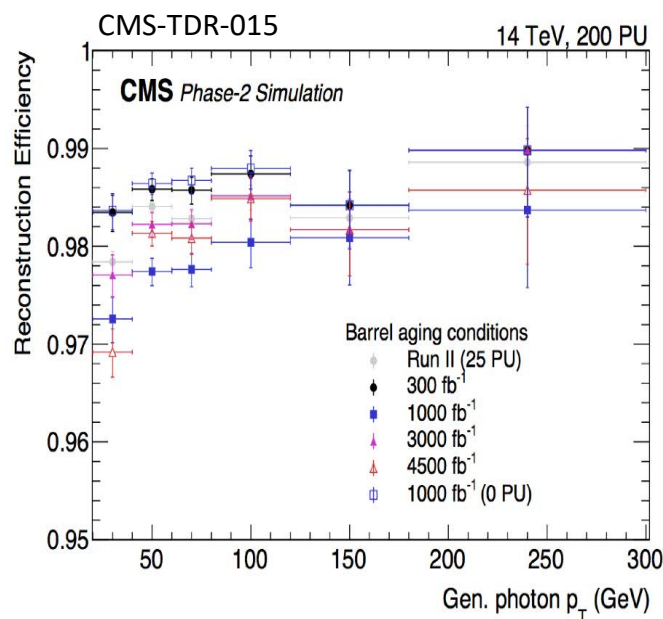
Photon reconstruction

small impact of ageing
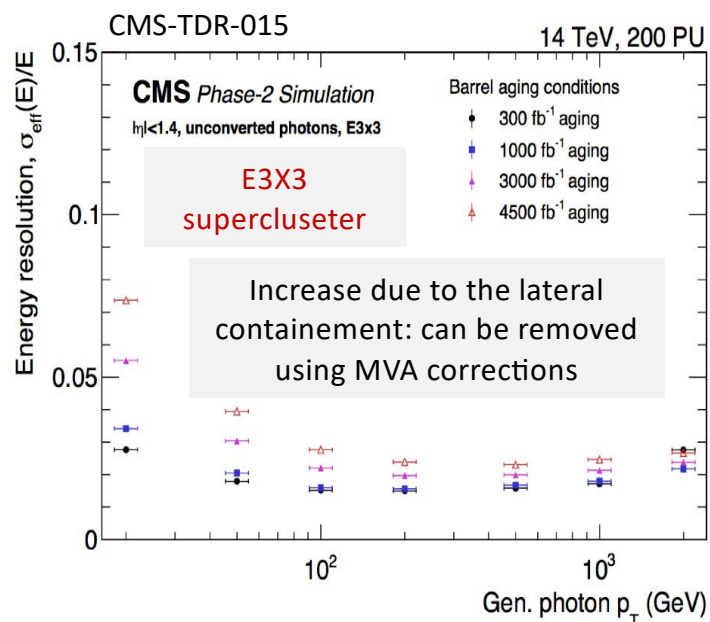
Photon energy resolution

2.5 to 4% resolution for E_T=50 GeV

H→γγ resolution

Slow degradation with ageing

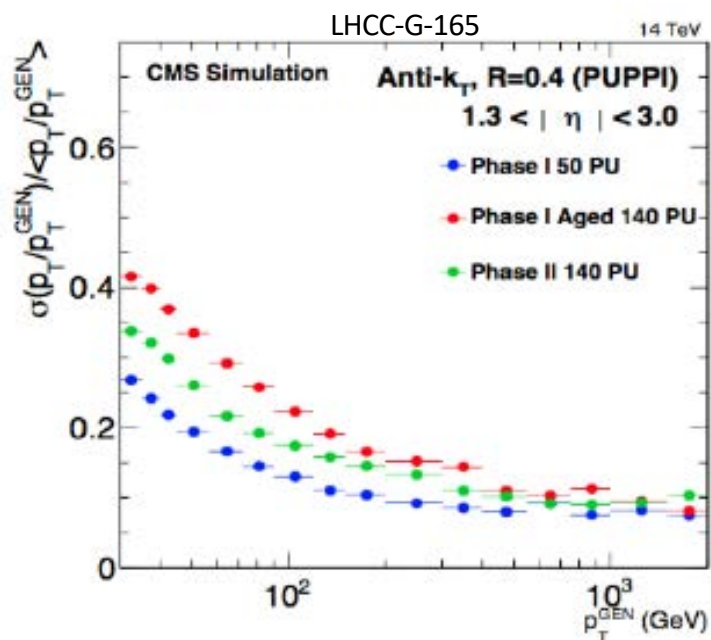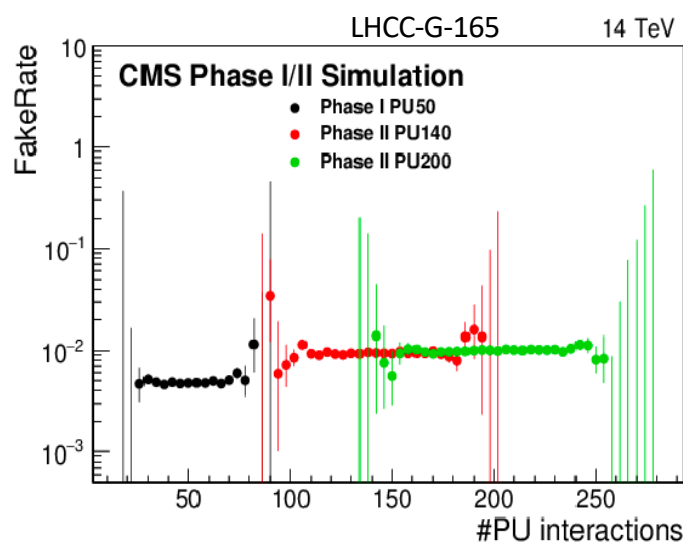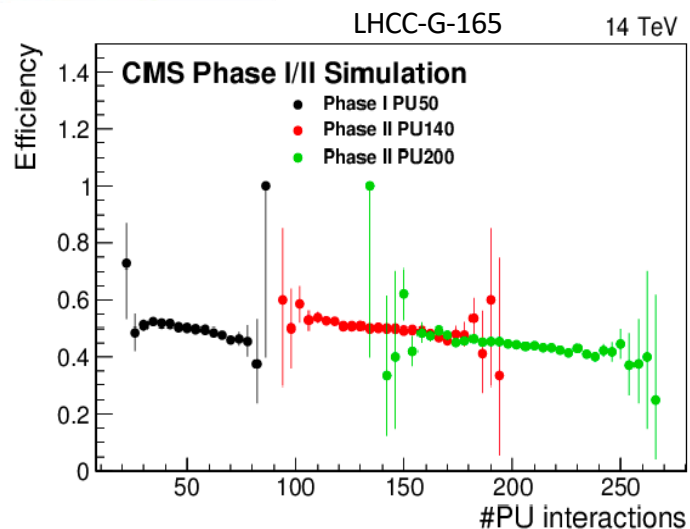With full optimisation (MVA corrections), we expect to achieve similar H→γγ resolutions for Phase-2 and 1000fb^{-1} as was obtained in Run 2

Tau and Jet performance
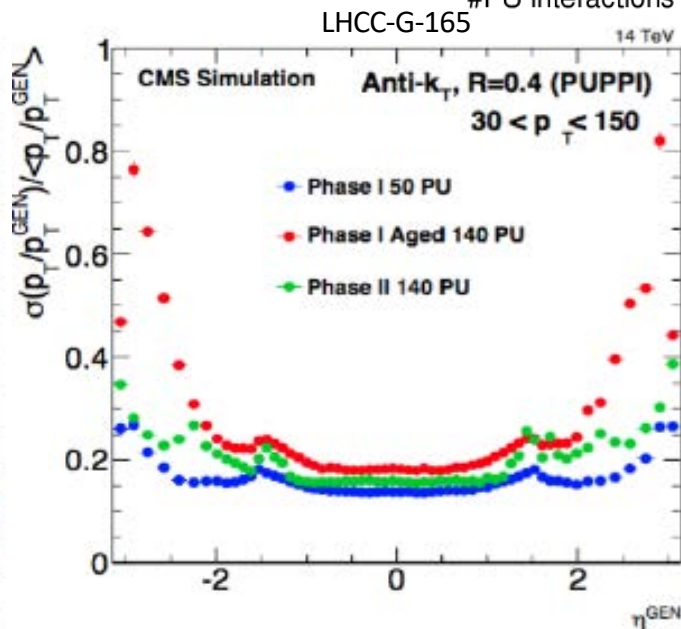
- **Comparable τ misidentification rates for the 140 and 200 pileup** environments, with only a moderate relative drop of about 10% in efficiency

- **Jet p_T resolution <30%** for jet with p_T> 20 GeV (PU140)

- **Jet p_T resolution uniform in η** compared to the Phase-I endcap calorimeter projection (aged+PU140)
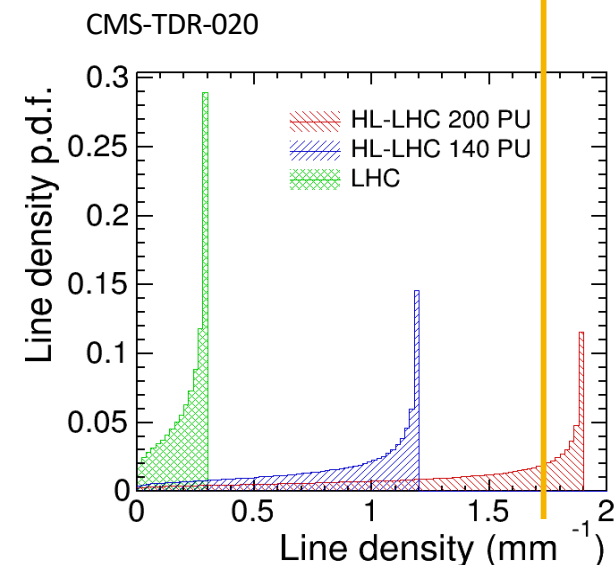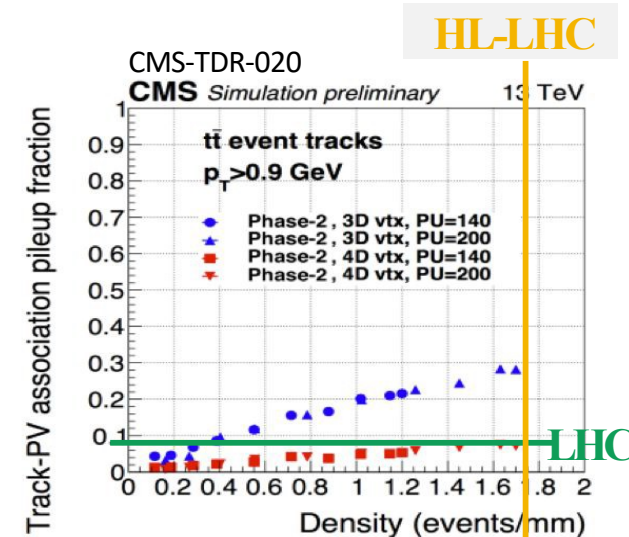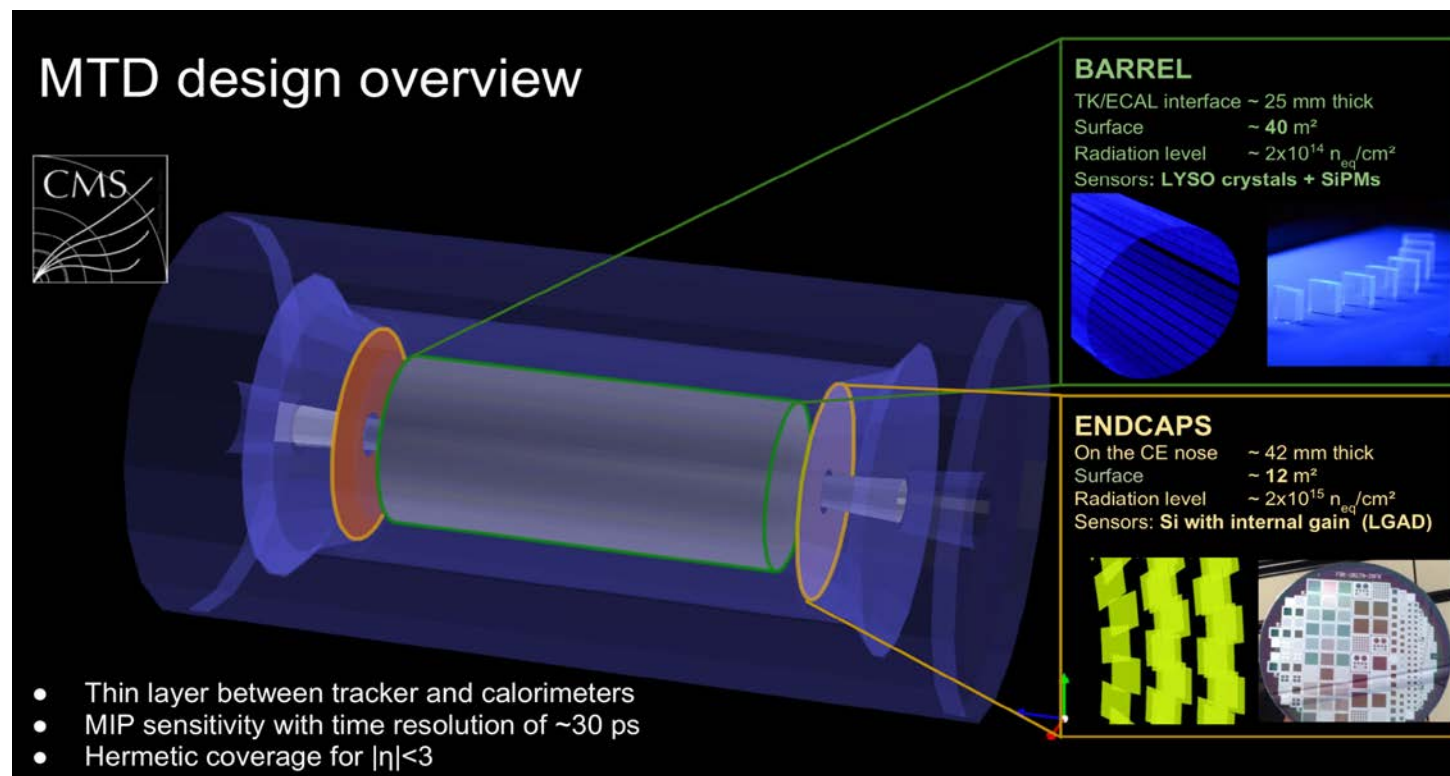
MIP Timing Detector

30 ps time of flight resolution for charged particles within $|\eta| < 3.0$

- Barrel Timing Layer (~1 m radius) within Tracker Support Tube:
  - thin crystals (Lyso) 57x3x2.4-3.75 mm^3 + SiPM 4x4 mm^2, ~250k channel
- Endcap Timing Layer in front of High Granularity Calorimeter
  - Si sensors with low gain (LGAD) 1.3x1.3 mm^2 pads, ~250k channels

MTD design overview

BARREL
TK/ECAL interface ~ 25 mm thick
Surface ~ 40 m^2
Radiation level ~ 2×10^{14} n$_{eq}$/cm^2
Sensors: LYSO crystals + SiPMs

ENDCAPS
On the CE nose ~ 42 mm thick
Surface ~ 12 m^2
Radiation level ~ 2×10^{15} n$_{eq}$/cm^2
Sensors: Si with internal gain (LGAD)

- Thin layer between tracker and calorimeters
- MIP sensitivity with time resolution of ~30 ps
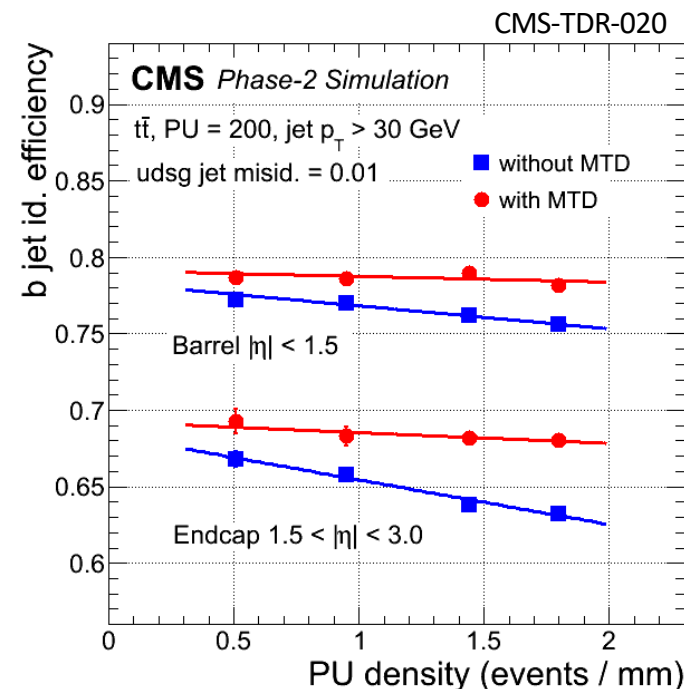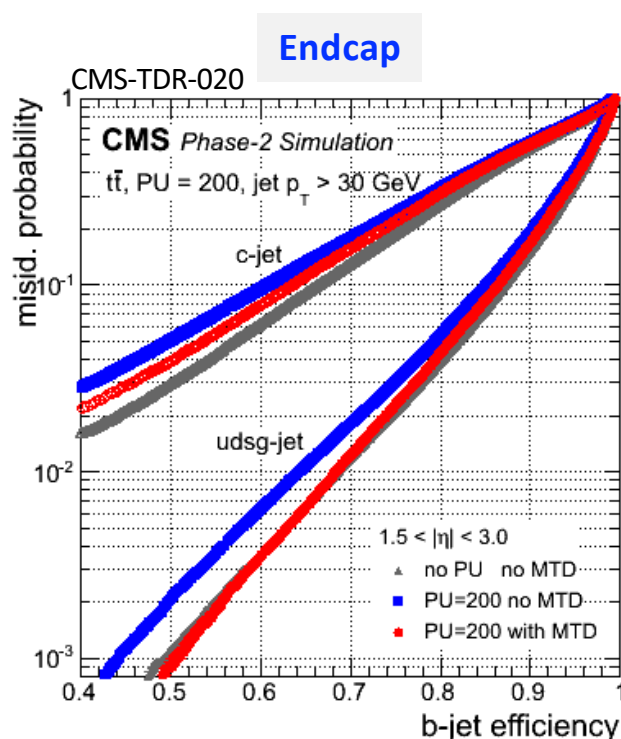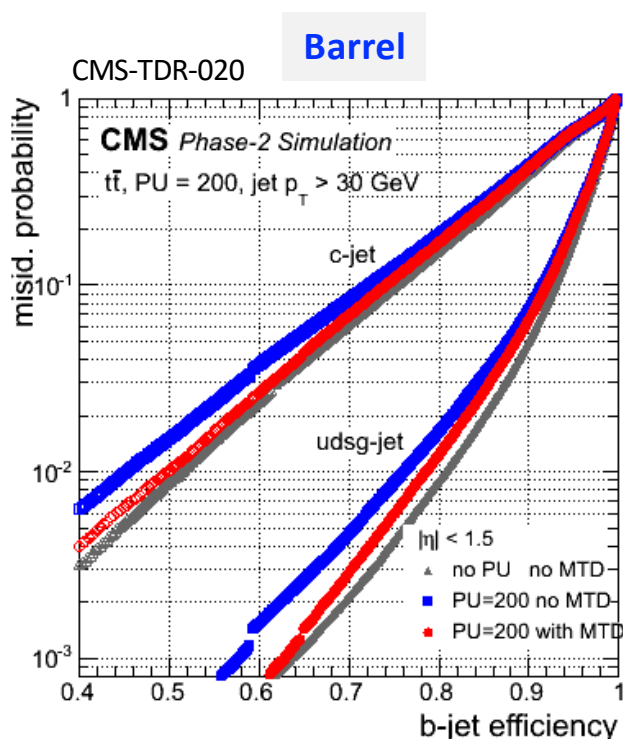- Hermetic coverage for $|\eta|<3$

B-Tagging with timing

Precision timing rejects spurious secondary vertices

- Significant improvements for working points at constant signal efficiency or background rejection
- Removes pileup-density dependence in b-tagging and 3-5% efficiency improvement

Lepton Isolation with Timing

- **Precision timing significantly improves charged lepton isolation in both barrel and endcap**
  - Prompt muon vs misidentified muons or non-prompt muon candidates, originating mostly from semileptonic decays of heavy-flavour hadrons in simulated tt events.
- **Reduces dependence on pileup density:**
  - improvement in background rejection for constant signal efficiency both for muons and taus.
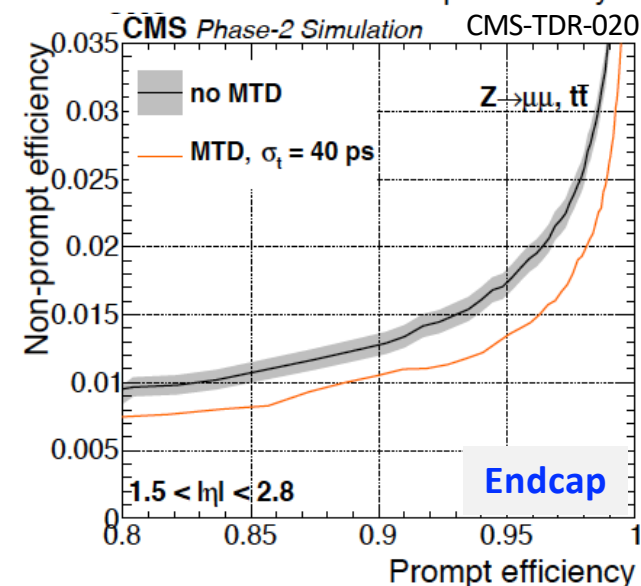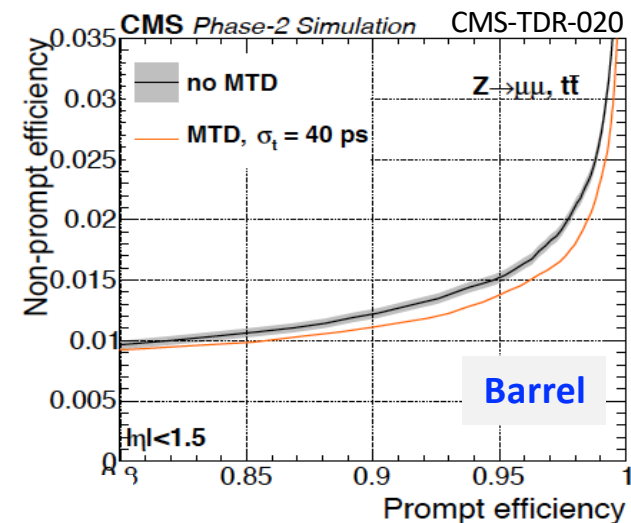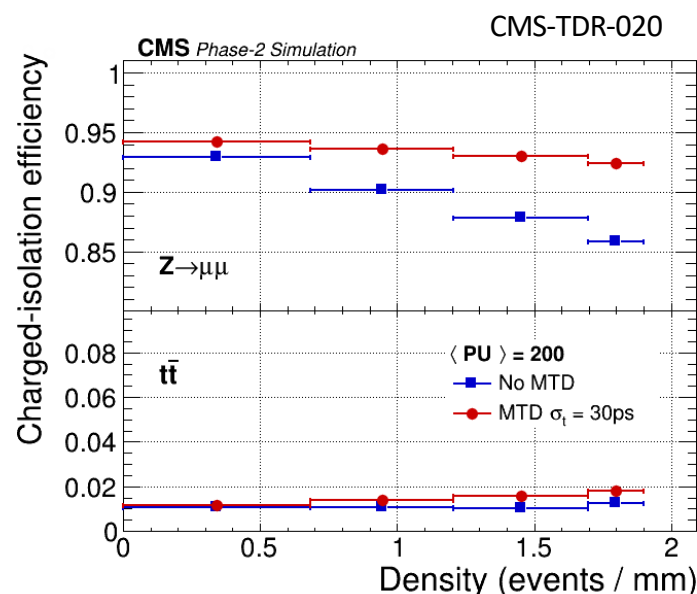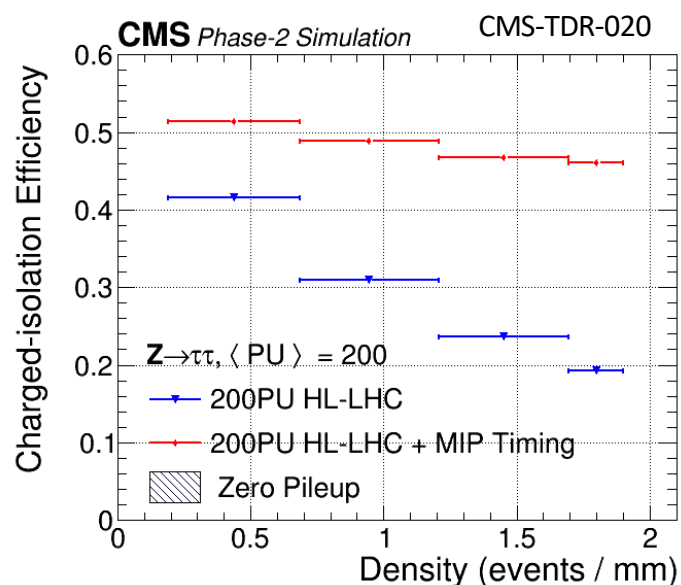
Conclusion

- In coming years LHC will increase its luminosity. For proton proton
  - Goal is to accumulate the integrated luminosity of $\geq 3,000$ fb^{-1}
  - Expect 140~200 pileup interactions per beam bunch crossing

- Main challenge in the detector upgrade is mitigation of large number of pileup interactions and keep the current performance:
  - Increased detector granularity and acceptance in η
  - Precise timing measurement
  - Trigger: more bandwidht, new functions and algorithms

- Several Technical Proposals and Technical Design Reports already accepted by LHCC
  - 2015: Phase 2 CMS TP and scope documents
  - 2018: TDRs for Tracker, Muon, Barrel Calorimeters and Endcap calorimeters approved
    + interim TDRs for L1 triggers and DAQ
  - 2019 TDR for MIP Timing Detectors
  - CERN yellows report released

- R&D is advanced phase, the schedule is tight, the construction phase is started: we proceed full steam to get ready for this new challenge
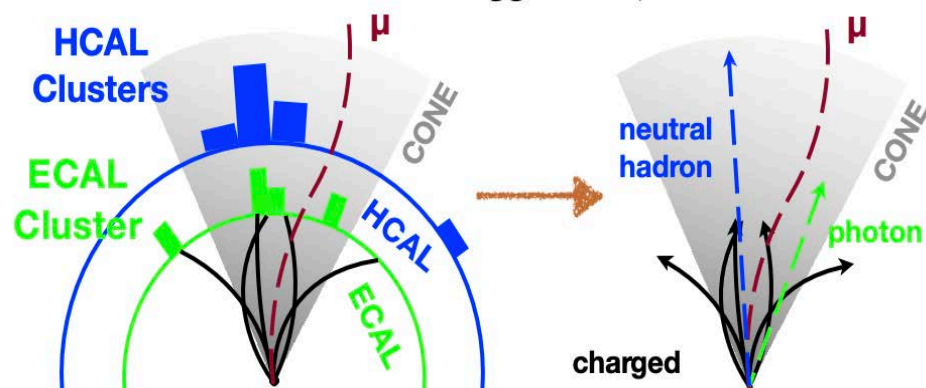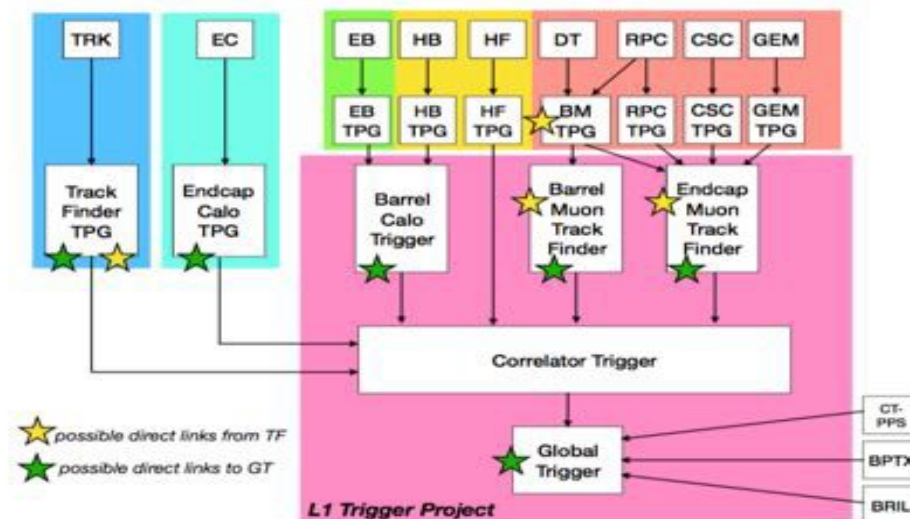
Backup

A new realm for triggering: full detector view@L1

Improved triggering with full detector view:

- Trigger decision include calorimeter & tracker information.
  Tracking requires larger latency

  L1Rate 750 kHz & 12.5 us latency

- Sophisticated clustering algorithms deployed in
  the detector back-end electronics.

- Bandwidth: Phase II ~ 50 Tb/s (1.8 in Phase I)

Match the performance of HLT/ Offline algorithms in the correlator:

- Particle Flow @ Level-1 trigger hardware

  - tracking information and global detector
    description to provide the prompt physics object
    at Level-1

- Pile-Up-Per-Particle-Identification (PUPPI) on PF
  candidates @ Level-1

  - To greatly mitigate PU effects at Level-1
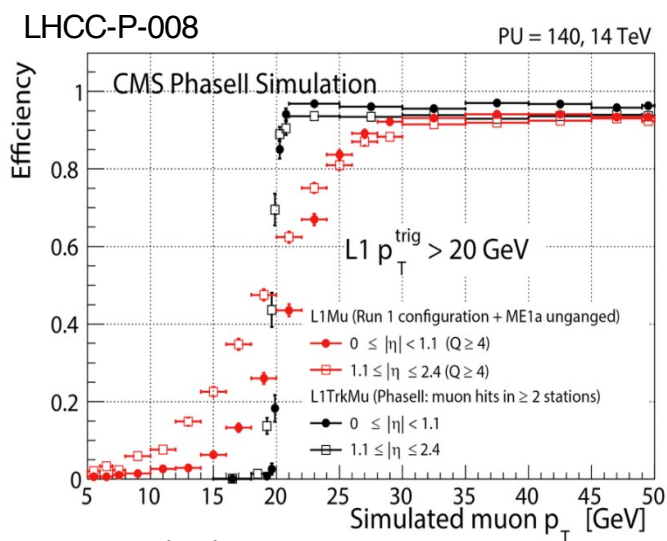
Muons trigger

Stand-alone

- Exploitation of full timing resolution thanks to new DT/RPC electronic

- Improvements in ε and rate in endcap thanks to new chambers

- Development of Kalman filter approach in trigger hardware, to account for the energy loss and multiple scattering

Track-trigger

- L1 Muon trigger provided candidates with high purity, but too high rate due to the poor p_T accuracy

- Matching with L1 Tracks provides a major improvements
  - Resolution 10% → 1% with Efficiency > 95%
  - Factor 6 to 10 of rate reduction for SingleMu p_T > 20 GeV
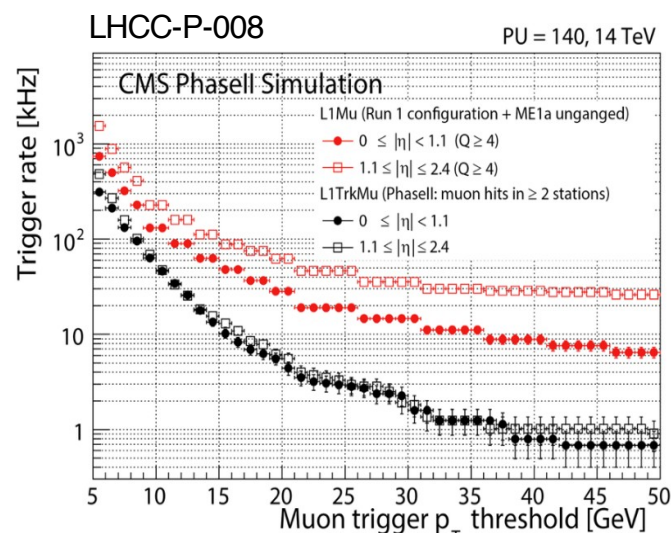
(CMS-TDR-16)

Trigger on highly displaced muons

(CMS-TDR-16)
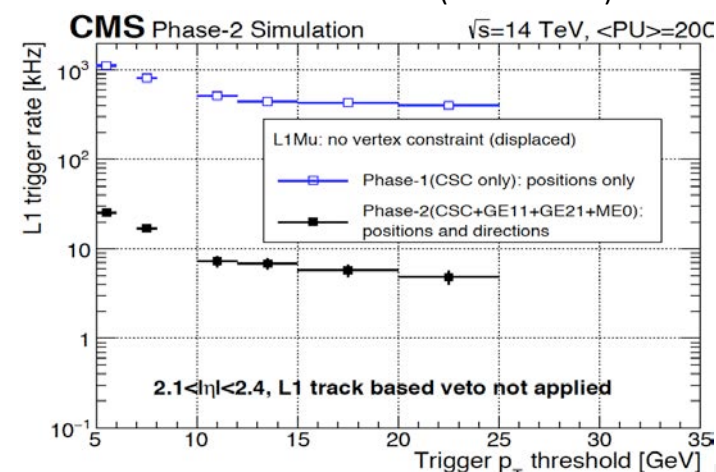
### Trigger on heavy stable charged particle

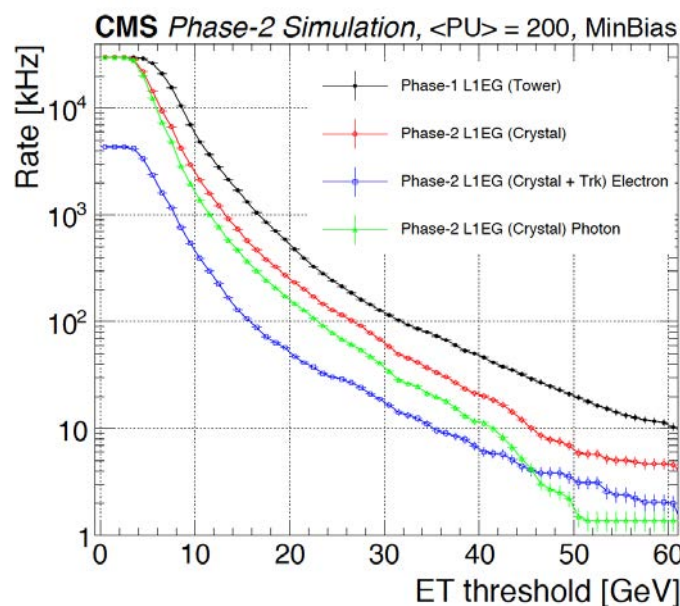(CMS-TDR-16)
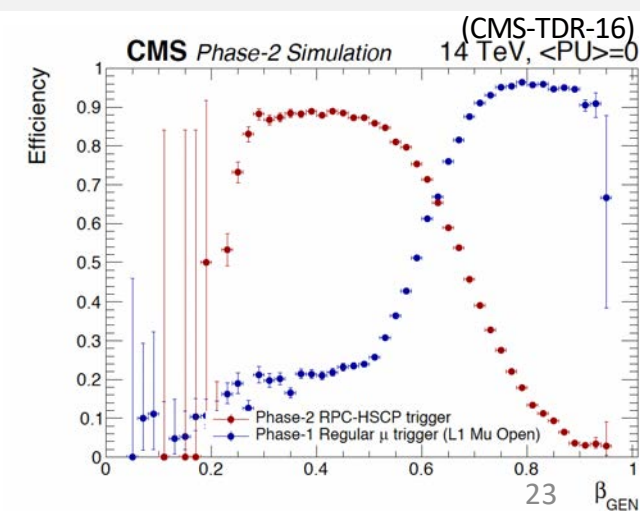
Electrons, Photons, taus trigger

Electron and photons stand alone trigger must provide high efficiency, especially for high-p_t object:

- the digitised response of every crystal of the ECAL barrel will provide crystal level energy measurement
  - Improved position resolution of the EM clustering algorithm (similar to offline)
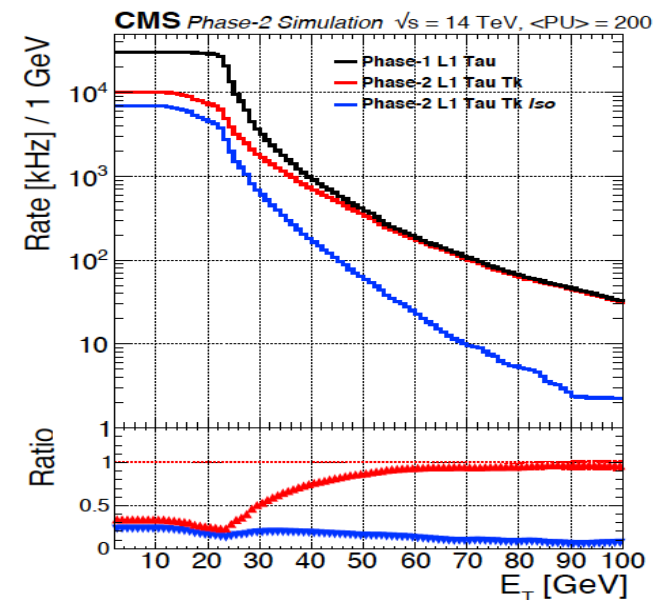- New trigger design improve rates, efficiency for EGM clusters is kept up to ~99% at plateau
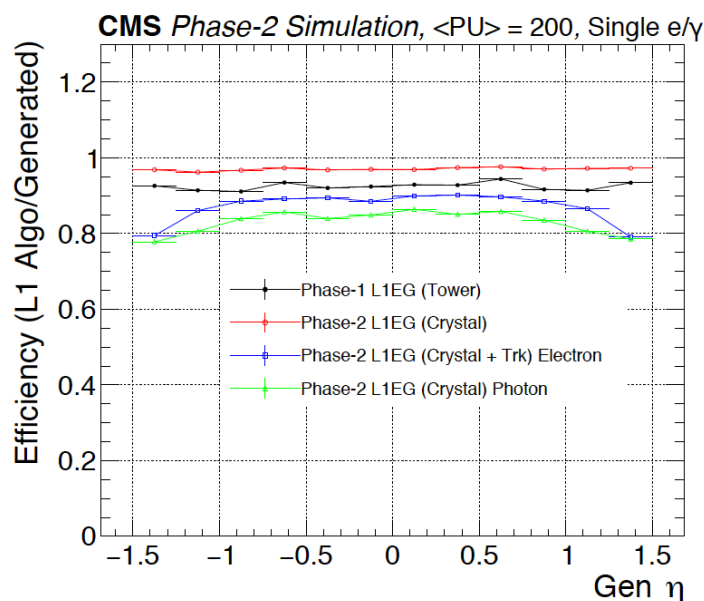
CMS-TDR-017   CMS-TDR-017   CMS-TDR-017


Identification of τ_h is challenging and usage of tracking becomes crucial to reduce the trigger rate:

- The Phase-1 algorithms depoyed at L1 to select τ_h candidates from isolated Calo Clusters
- High p_T L1 tracks matched to Phase-1 L1 Taus (Phase-2 L1 TauTk)
- L1 track-based isolation requirement is applied (Phase--2 L1 TauTkIso) to reduce the rate

Jets, H_T, MH_T, E_t^{miss} trigger

Multi-object triggers very sensitive to PU

- reduce the PU dependency requiring jets from same vertex
- Tracking based ETmiss: vectorial sum of all the tracks pT that come from the PV (z0 consistent with PV within ~1 cm)

$E_T^{miss} \sim 300$ GeV
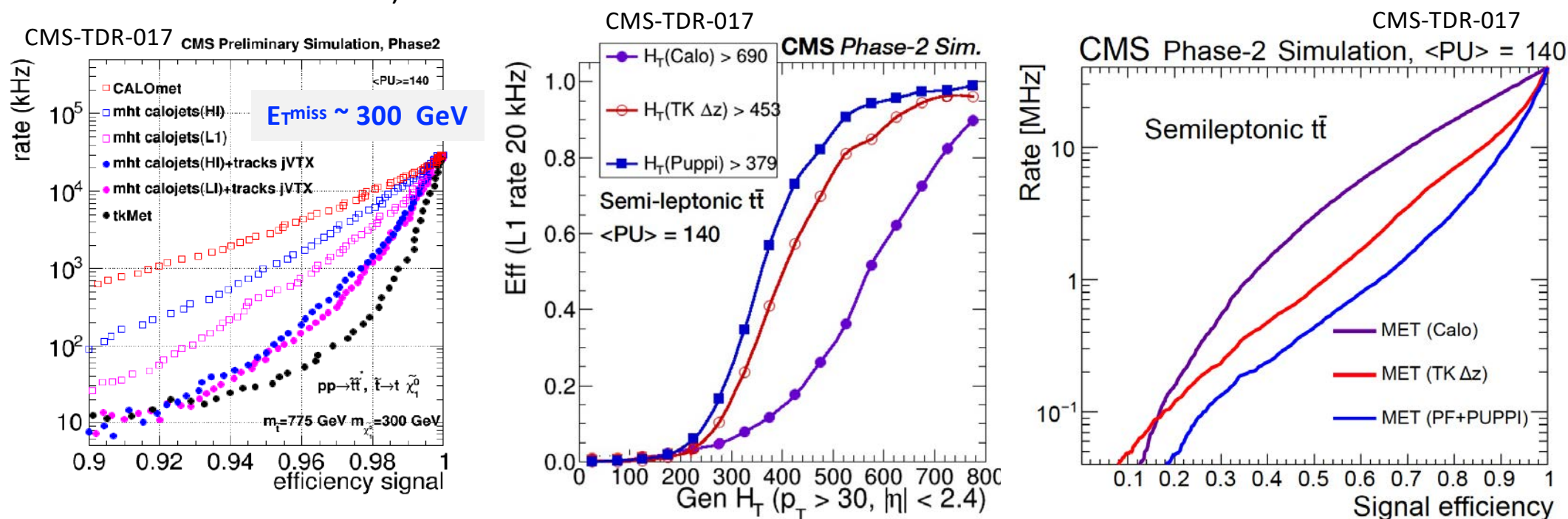
Comparing HT trigger performance from PF-jets and Track--based jets:

- PF+PUPPI more robust against fakes than track--only observables
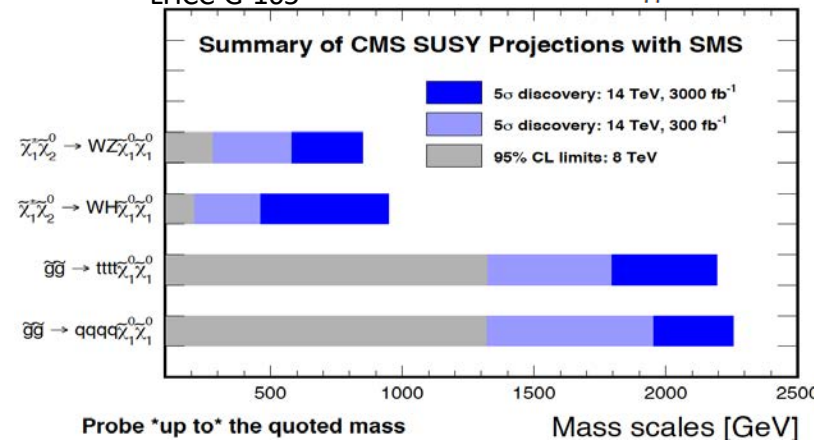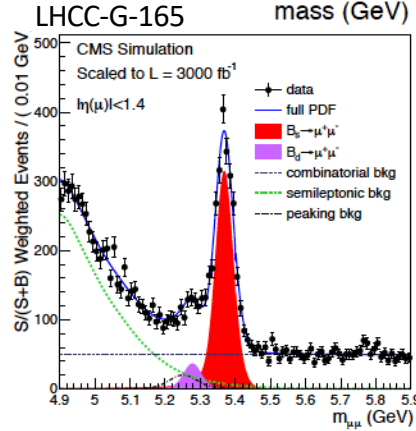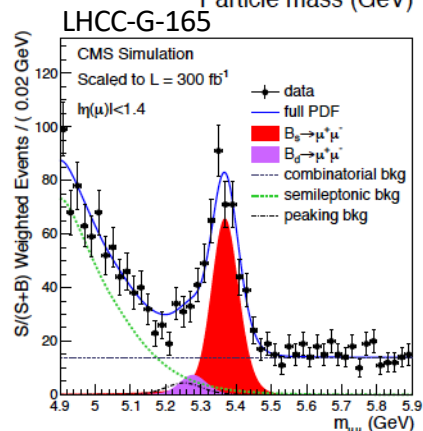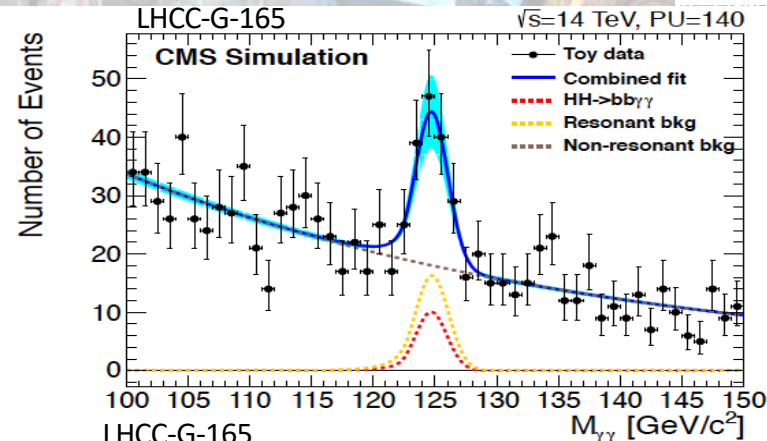- higher signal efficiency, lower rates, lower thresholds

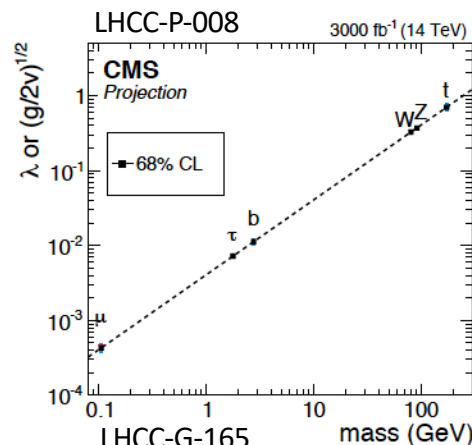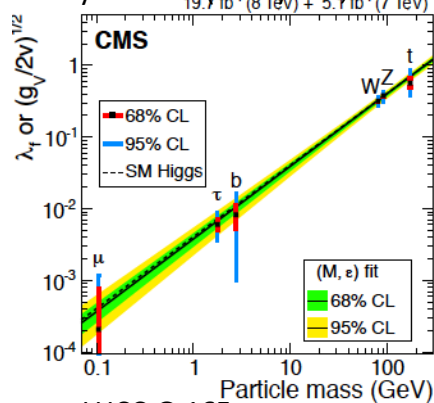# Physics highlights

Investigating the Higgs sector:

- O(%) couplings to fermions & bosons
- Rare decays H—>$\mu\mu$
- Double Higgs
- VBF and HW, HZ production modes
- Triple-gauge coupling, quartic-gauge coupling

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Standard Model Physics:

- Rare $B_{s,d}$ decays
- Vector Boson Scattering (VBS)

SUSY and beyond:

- Scan to level of multi TeV
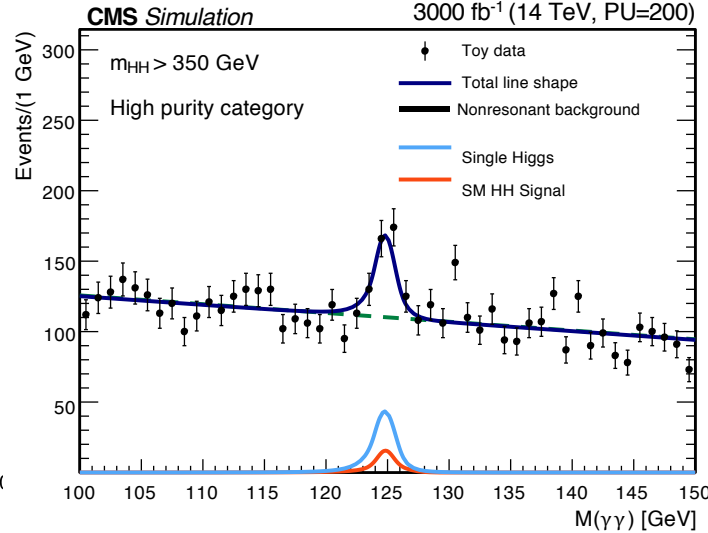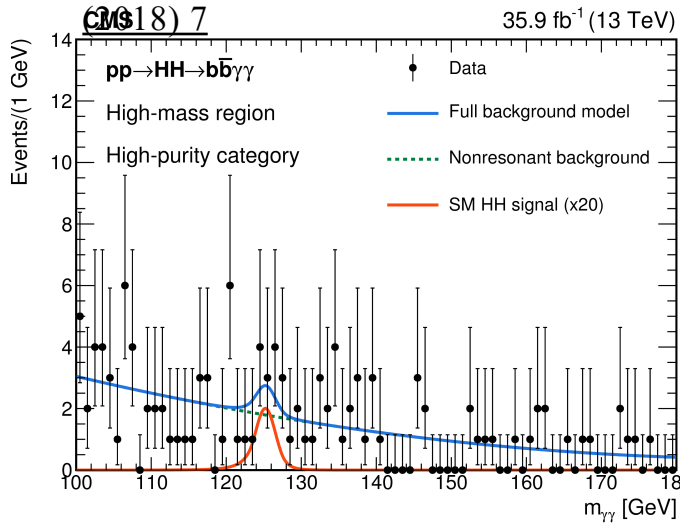- Dark matter: mono-object (jet, vector boson etc)

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Physics impact

HH→bb̄γγ signal

CMS-TDR-015
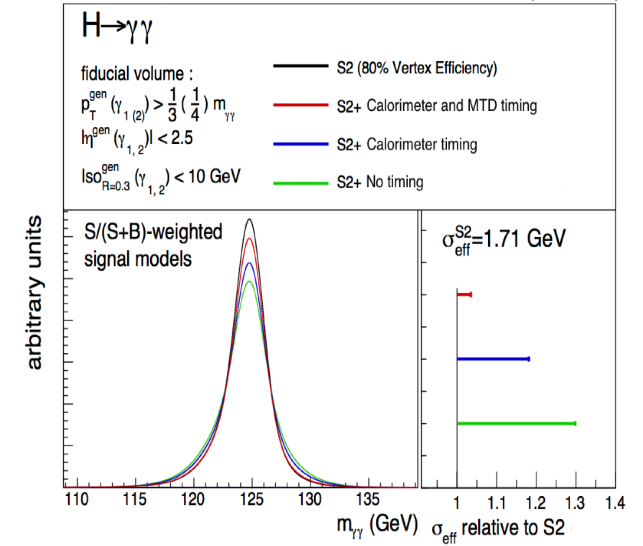
Performance in Run2
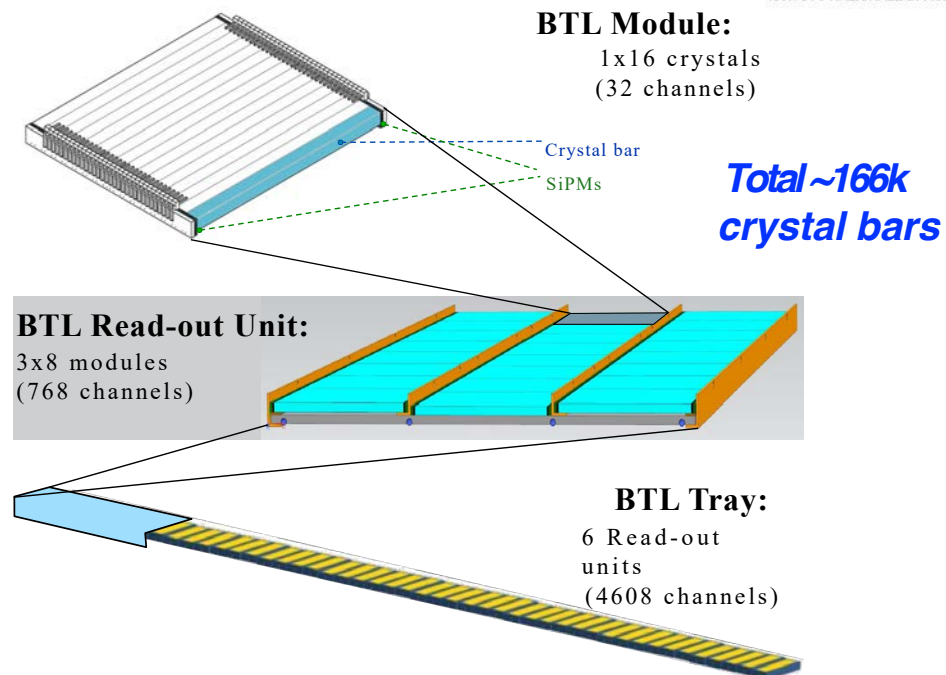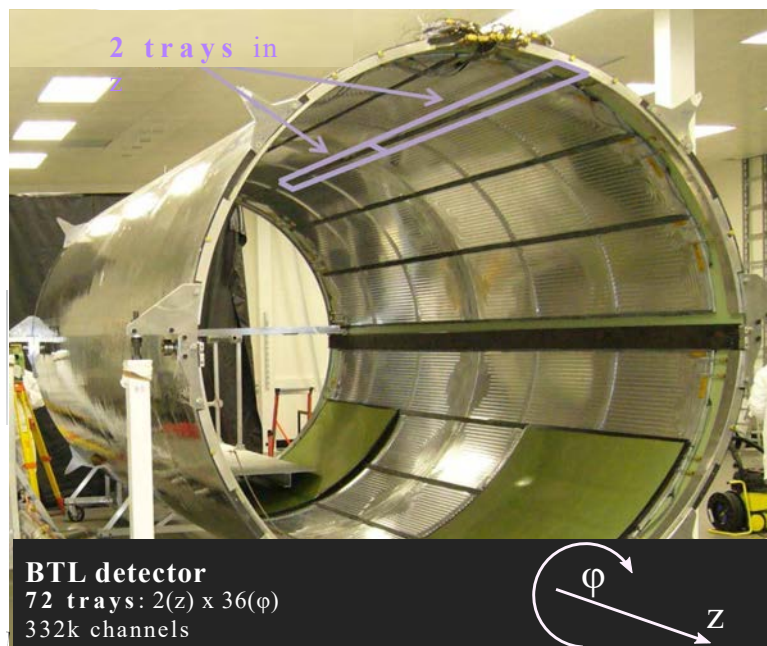
signal with Phase 2 photon resolution

- Combined HH signal significance of 2.6σ (with HH→bb̄γγ as the best sensitivity channel)

- Unique capability to match photon time to vertex time + position

  CMS ECAL is non-pointing, but has photon timing capability

  50% of events additionally require MIP timing to find correct vertex

Identifies photon vertex: improves di-photon mass resolution by 25% and also H(γγ) signal significance

BTL Geometry

2 trays in z

BTL detector
72 trays: 2(z) x 36(φ)
332k channels

φ

z

BTL Module:
1x16 crystals
(32 channels)

Crystal bar
SiPMs

Total ~166k crystal bars

BTL Read-out Unit:
3x8 modules
(768 channels)

BTL Tray:
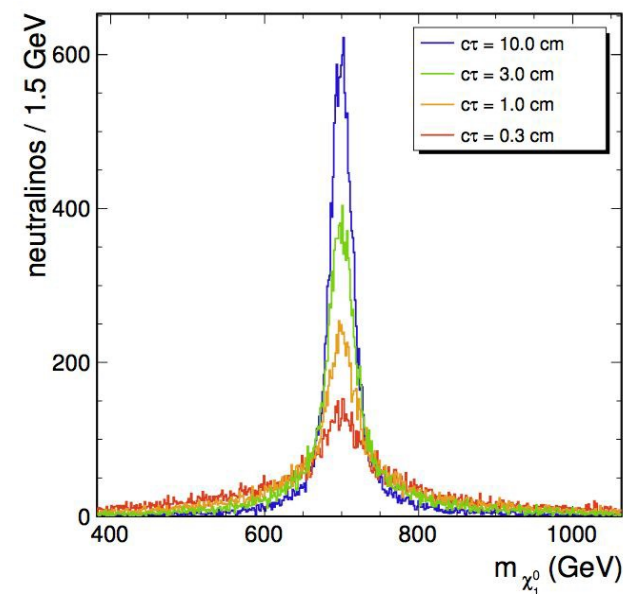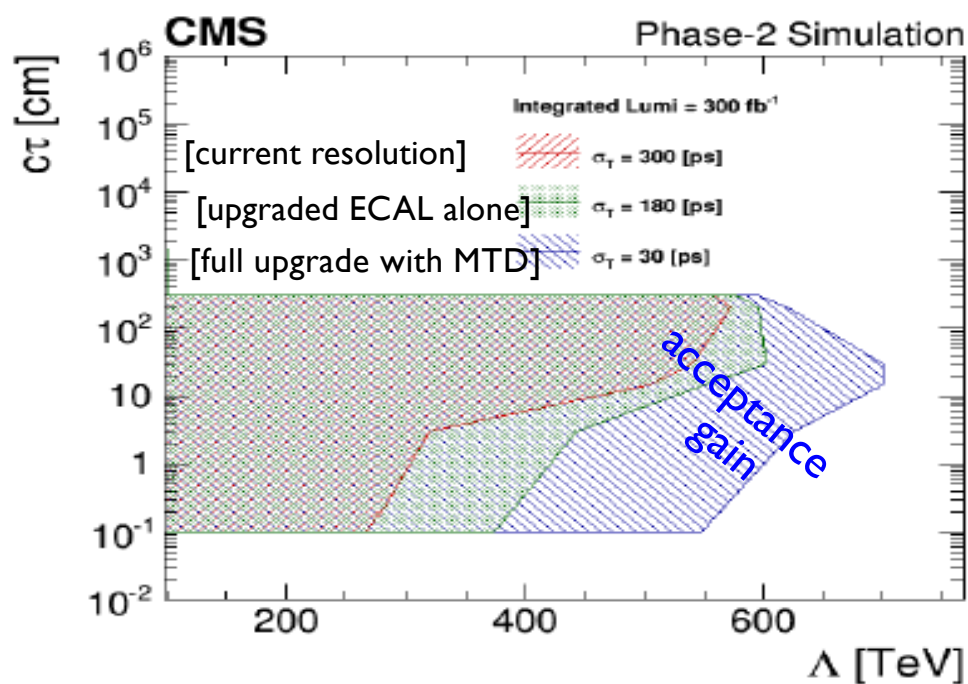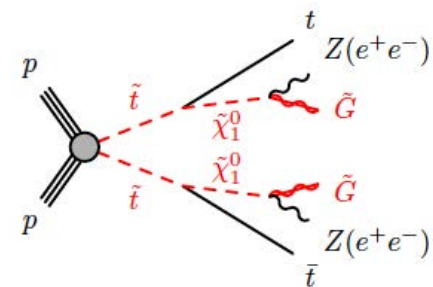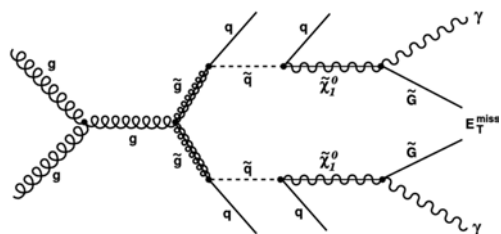6 Read-out units
(4608 channels)

- 40mm-thin cylinder, **integrated in tracker** support tube

  - sharing services and schedule with tracker detector

  - cannot be removed or serviced during entire lifetime of HL-LHC

- To cope with schedule/accessibility/ costs, use sensor technologies well-established and experienced by CMS

  - **array of LYSO:Ce crystal bars** (57 x 3 x 2.4-3.75 mm^3) oriented along φ direction

  - readout by **2 SiPMs** (one per bar side)

- Vertex timing enhances LLP program
- For topologies involving secondary vertices, MTD provides new capability to reconstruct the mass of long-lived NEUTRAL particles

(a) $\chi_1^0 \to G + \gamma$ Limits

(b) $\chi_1^0 \to G + Z$ Peaking Variable