Fast timing layers: the CMS example

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on behalf of the CMS Collaboration

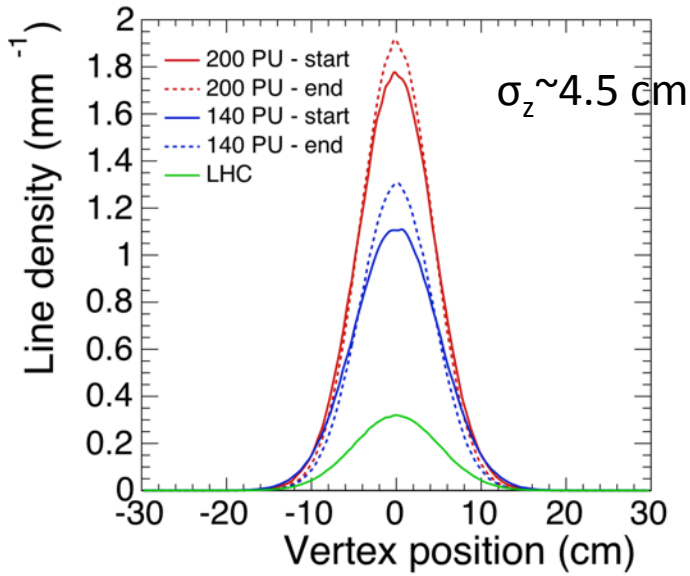
Outline:

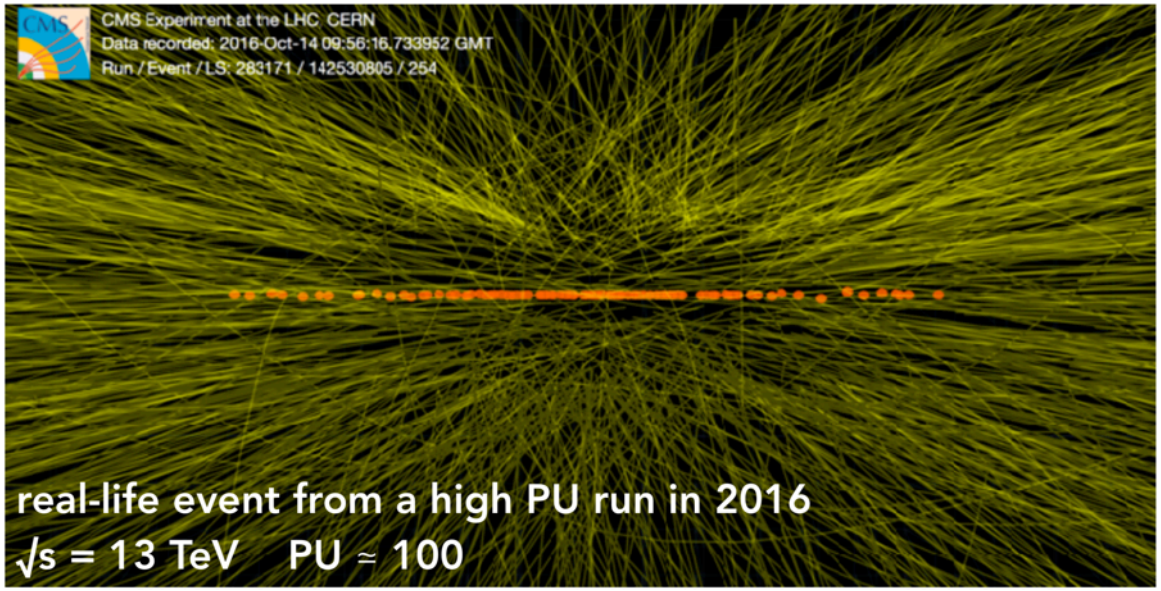
- Introduction and motivation for the CMS MTD
- MTD overview
- Objects level and physics analyses performance benefits

Workshop on new techniques for particle reconstruction in VBS
Krakow, 23.10.2018

Introduction

- **HL-LHC**: significant upgrade of LHC and injectors to increase beam intensity
  - Baseline: peak $L_{inst} = 5.0 \times 10^{34}$ cm^{-1}s^{-1}, 140 pileup events, line density ~1.2 mm^{-1}
  - Ultimate: Peak $L_{inst} = 7.5 \times 10^{34}$ cm^{-1}s^{-1}, 200 pileup events, line density ~1.9 mm^{-1}



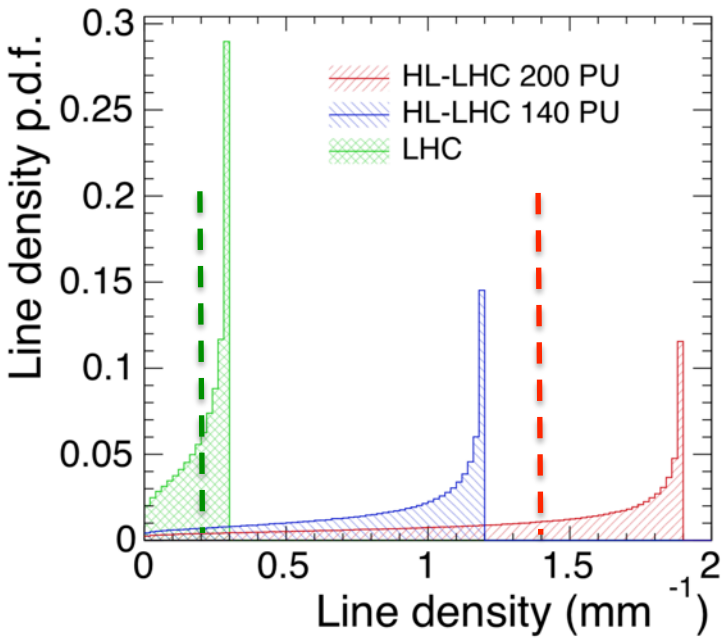


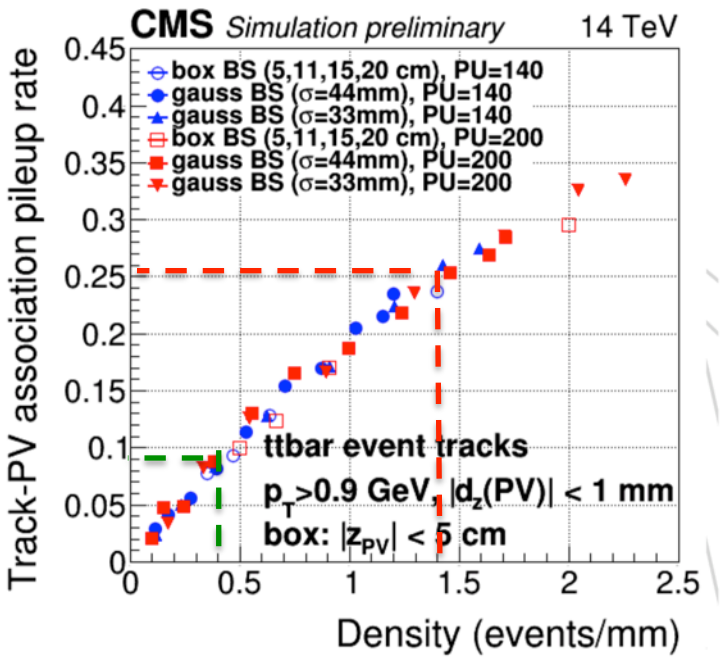
Impact of pileup

- Due to the increased line density (> 1 mm^{-1}), a larger number of spurious (pileup) tracks are associated to the primary vertex (~25% at 200PU)

- CMS event reconstruction dependent on ***track assignment*** to vertices
  - incorrect assignment of tracks to the interaction deteriorates the performance of the reconstruction of vertices, jets and missing ET and the identification (isolation) of leptons and photons

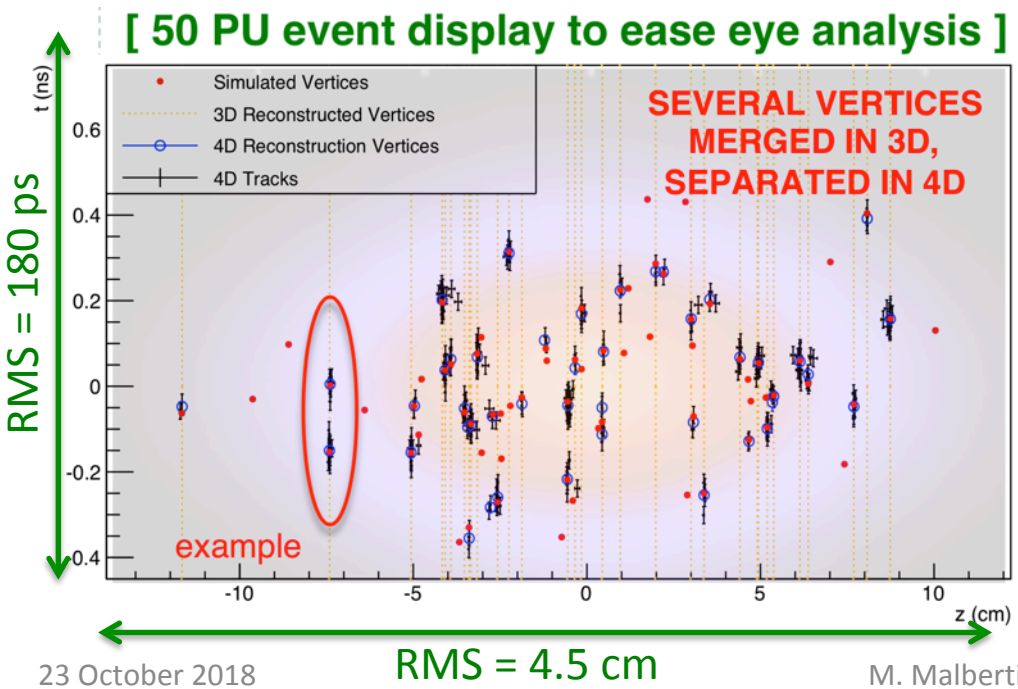
- Maintaining 50PU performance at high pileup benefits the full CMS program at the HL-LHC

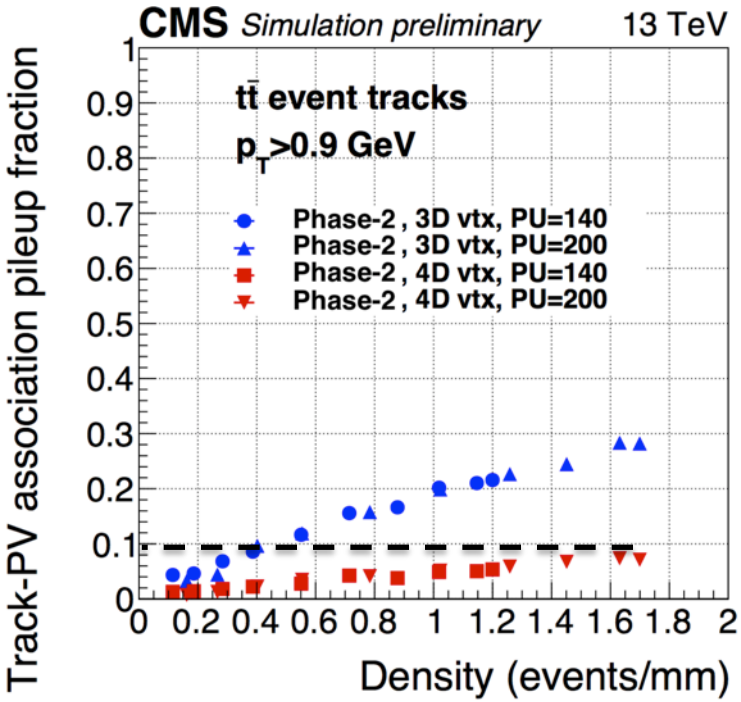




Pileup mitigation with track timing

- Interactions spread in time with RMS ~ 180 ps, uncorrelated with z (σ_z~4.5 cm)
- Precision track timing allows:
  - **4D vertex reconstruction**
    → resolve vertices that are close in space but separated in time
  - additional requirement in track-PV association: **|Δt(track,PV)| < 3·σt**
    → suppress spurious pileup tracks
- With **~30 ps resolution, recover LHC (40PU) track purity of vertices**

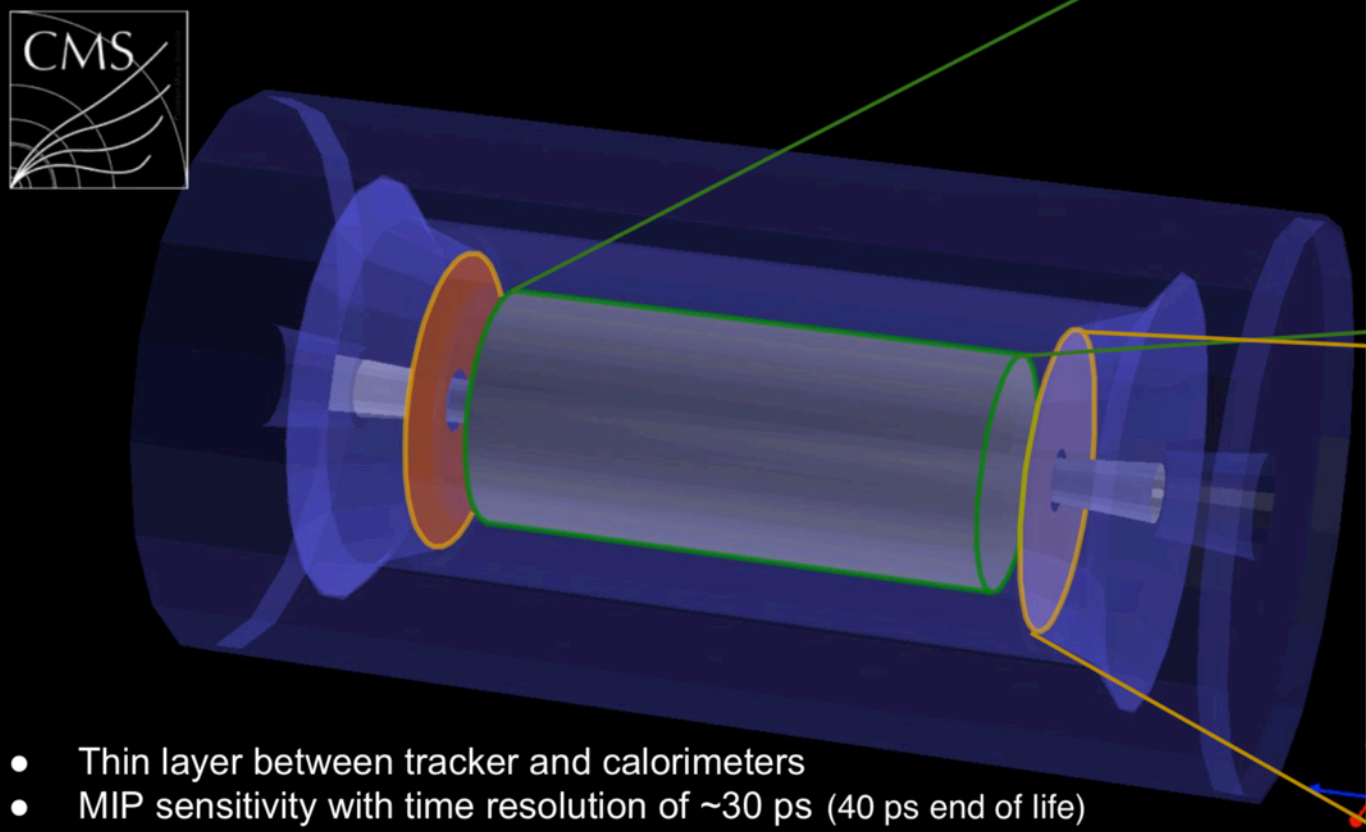




CMS MIP Timing Detector overview

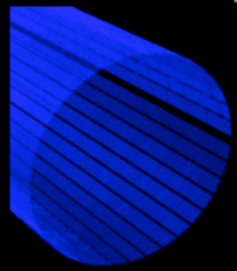
Calorimeter upgrades:

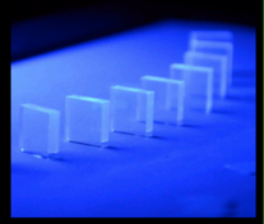
- Precision timing of **showers**
- Provide precision timing on high energy photons in ECAL Barrel
- All photons and high energy hadrons in HGCal Endcap



BARREL

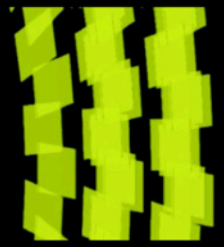
TK/ECAL interface ~ 25 mm thick
Surface ~ **40** m²
Radiation level ~ 2×10^{14} n_{eq}/cm^2
Sensors: **LYSO crystals + SiPMs**

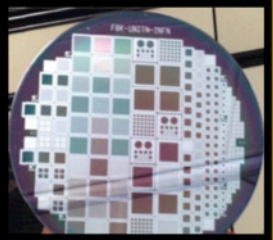




ENDCAPS

On the CE nose ~ 42 mm thick
Surface ~ **12** m²
Radiation level ~ 2×10^{15} n_{eq}/cm^2
Sensors: **Si with internal gain (LGAD)**



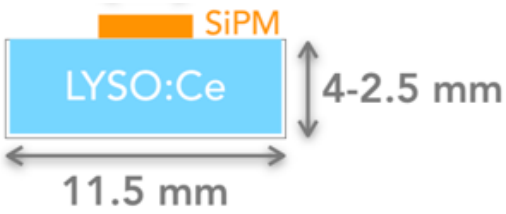


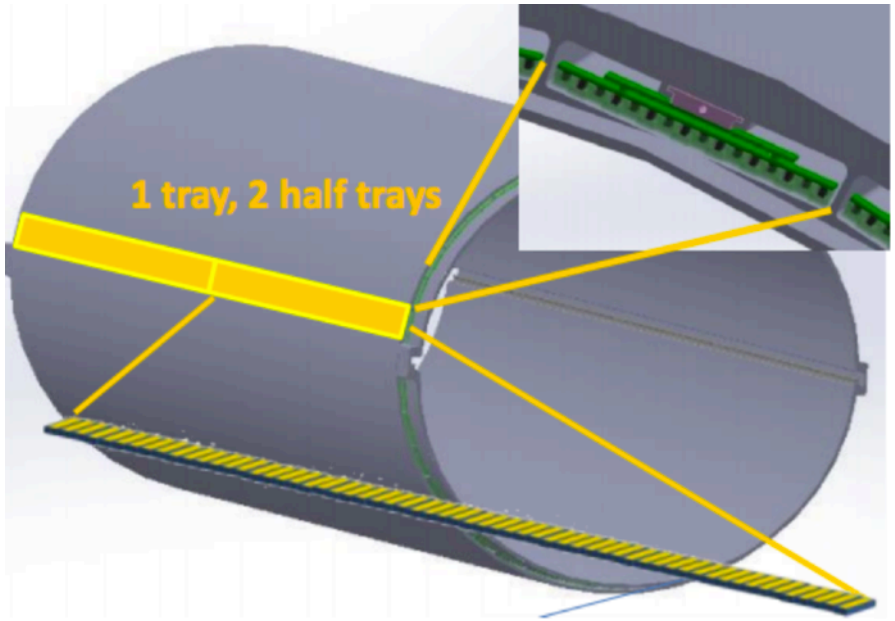
- Thin layer between tracker and calorimeters
- MIP sensitivity with time resolution of ~30 ps (40 ps end of life)
- Hermetic coverage for |η|<3

MTD Technical Proposal: CERN-LHCC-2017-027; LHCC-P-009: http://cds.cern.ch/record/2296612/

BTL layout

- **LYSO:Ce+SiPMs** embedded in the tracker support tube
  - operated at ~ −30°C (limit SiPMs self-heating and dark rate)
  - SiPM active area limited to < 16 mm^2

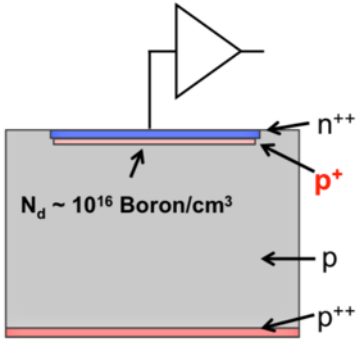




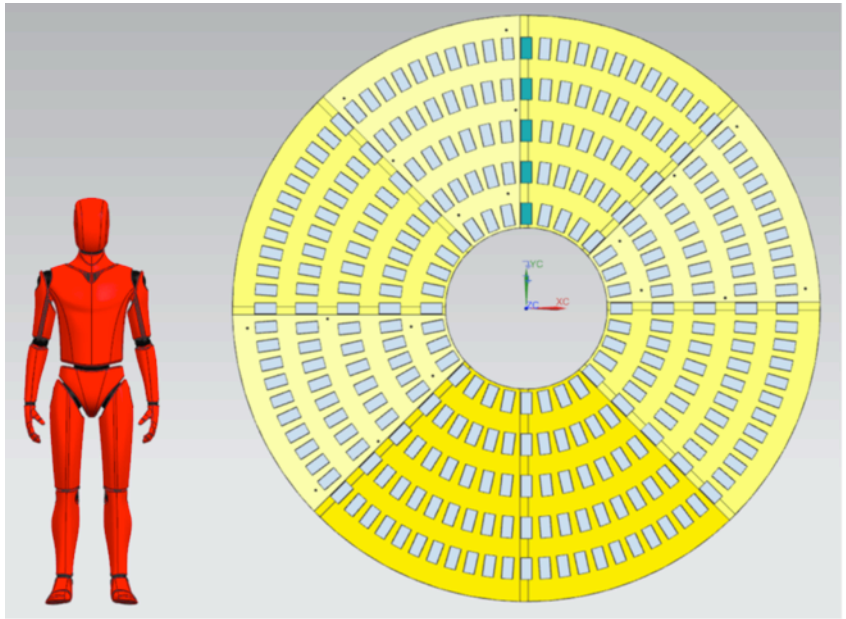
- ASIC: **TOFHiR** (adapted from commercially- available TOFPET)
  - leading edge discrimination + amplitude measurement for time-walk corrections
- **Challenge: SiPM Dark Count Rate and sensor design**

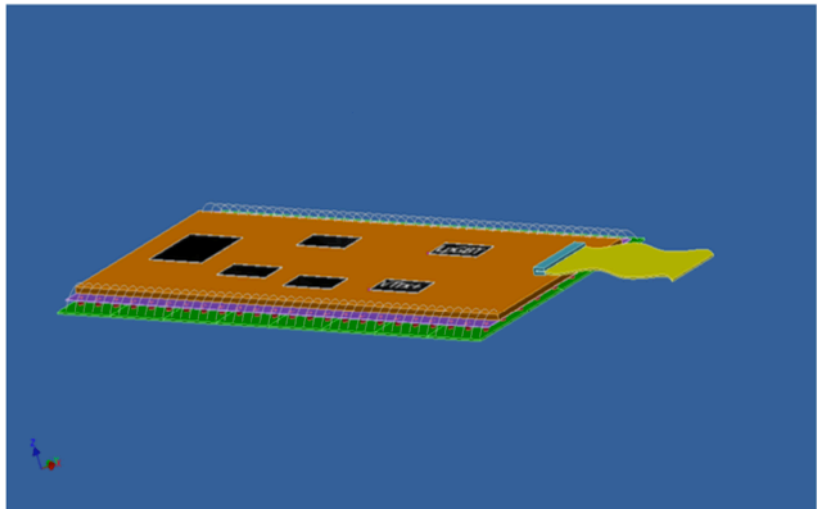
ETL layout

- **Low gain avalanche diodes (LGADs)**
  - Typical gain 10-30
  - LGAD qualified in beams at irradiation levels needed for HL-LHC
  - 1x3 mm^2 pads
  - Overlapping 2-disks structure
  - Total 1.8 M channels
  - **Challenge: scale to large area and readout chip with <30 ps resolution**



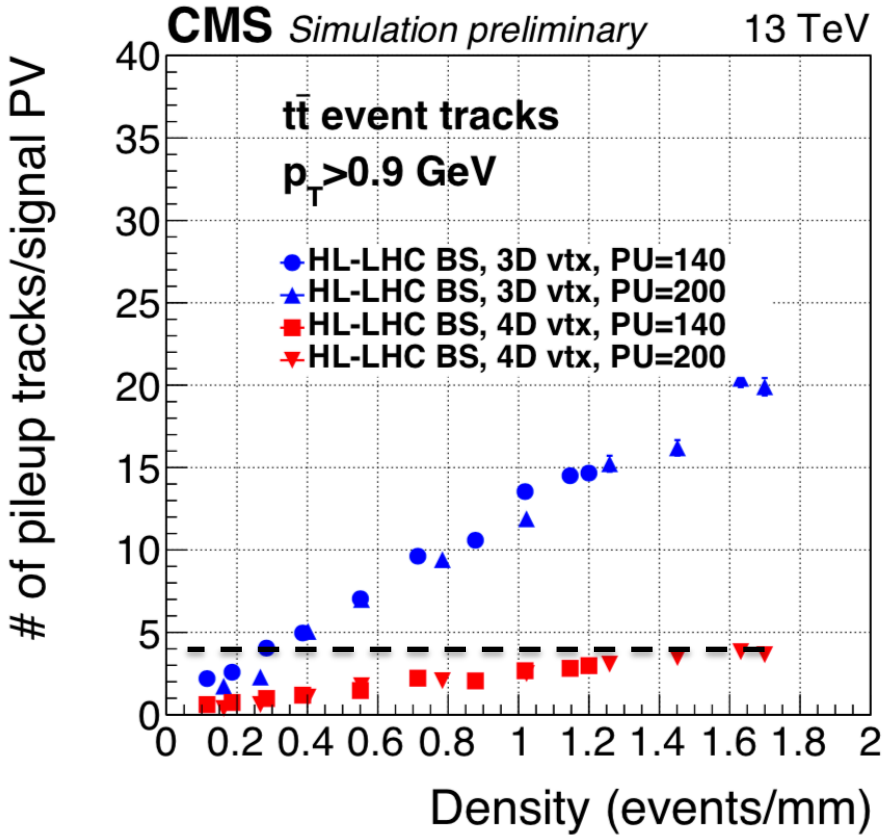
Low gain avalanche detectors

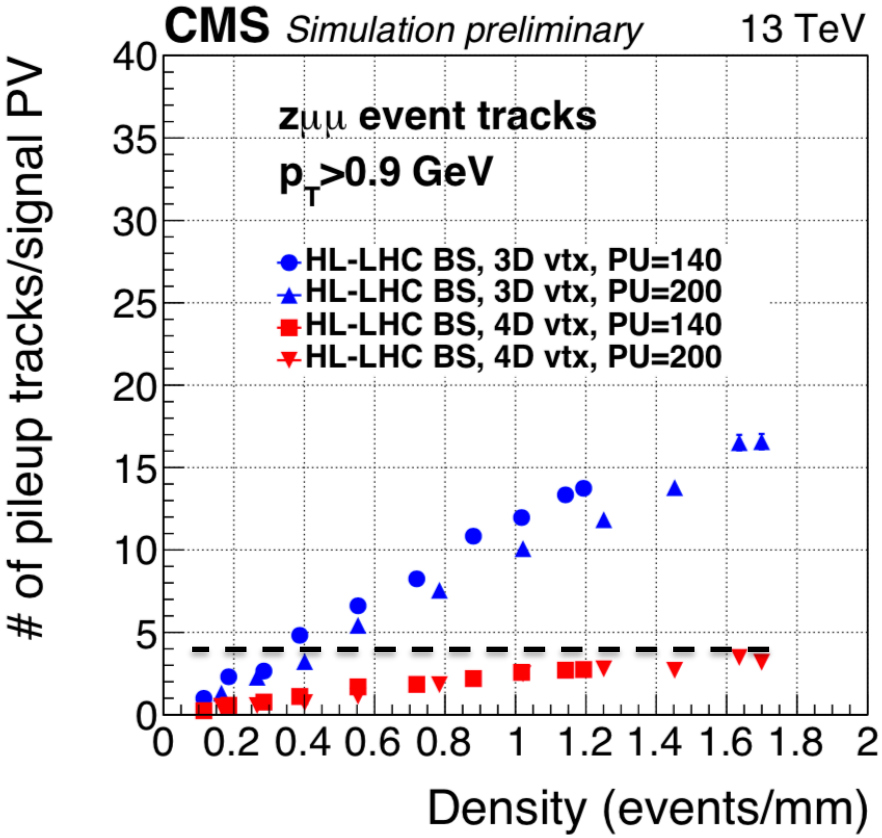




Performance benefits

Track-Vertex Association



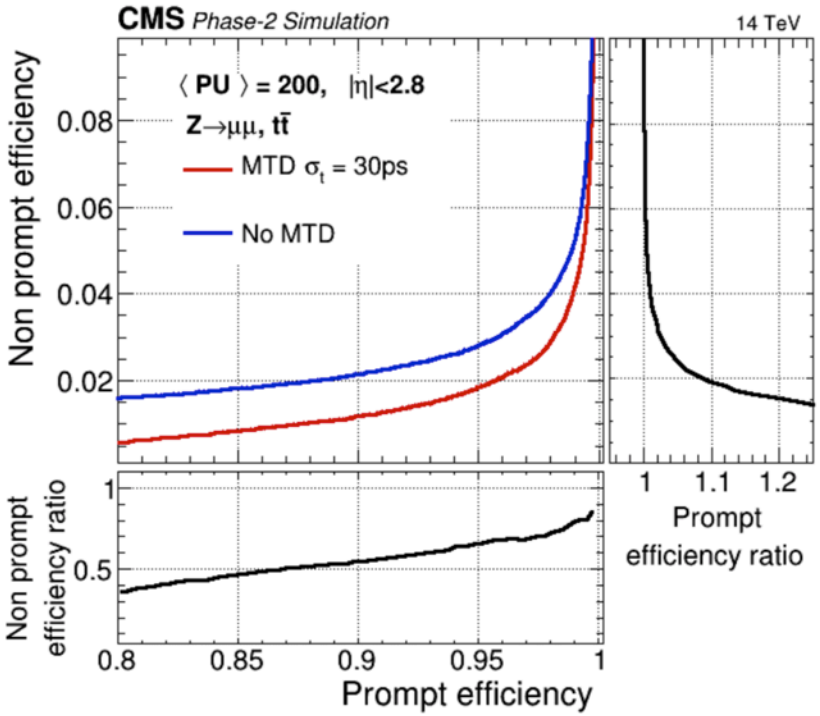


- **4-5x reduction in effective pileup** in terms of charged multiplicity across full pseudorapidity range with 3σ (90 ps) cut on timing
- Reduces pileup contamination for charged particles at 200 PU back to LHC Run 2 levels

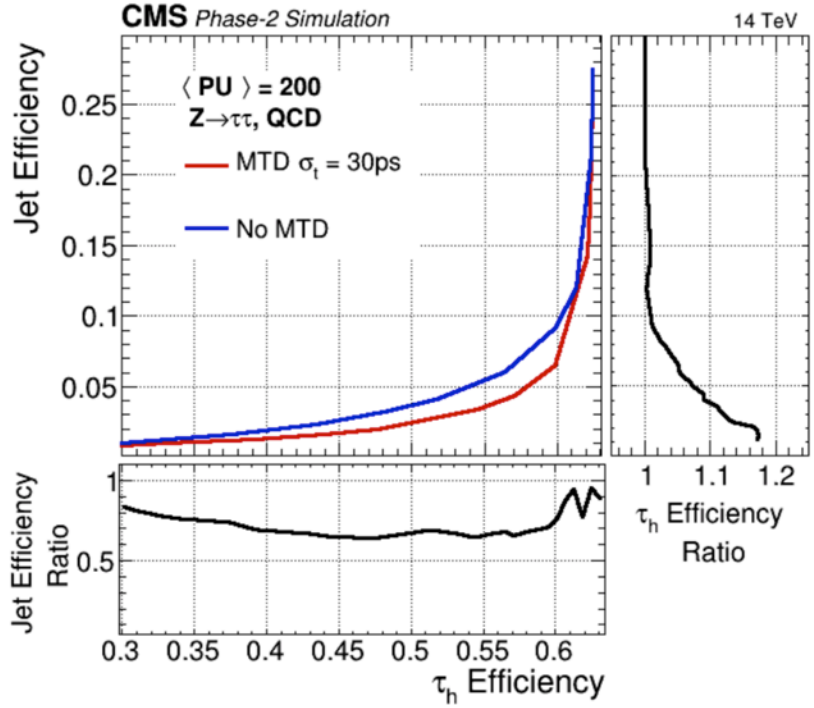
Lepton isolation

- Timing selections ($|\Delta t(\text{track,PV})| < 3\cdot\sigma_t$) remove pileup tracks from lepton isolation cones
- Background rejection improvement (~30-60%) wrt "no timing" for same signal efficiency

Muons

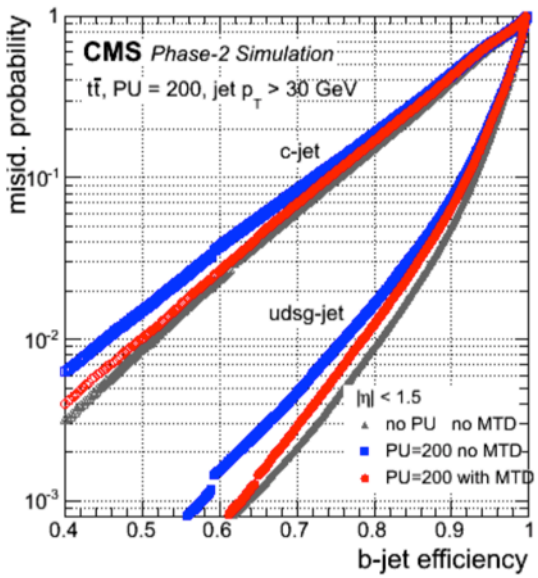


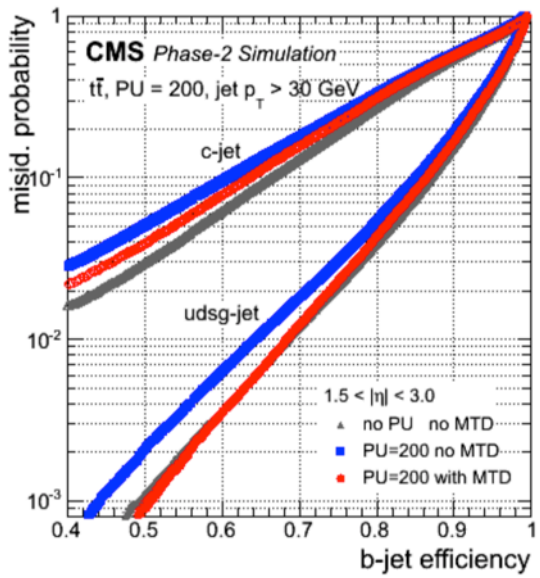
Taus

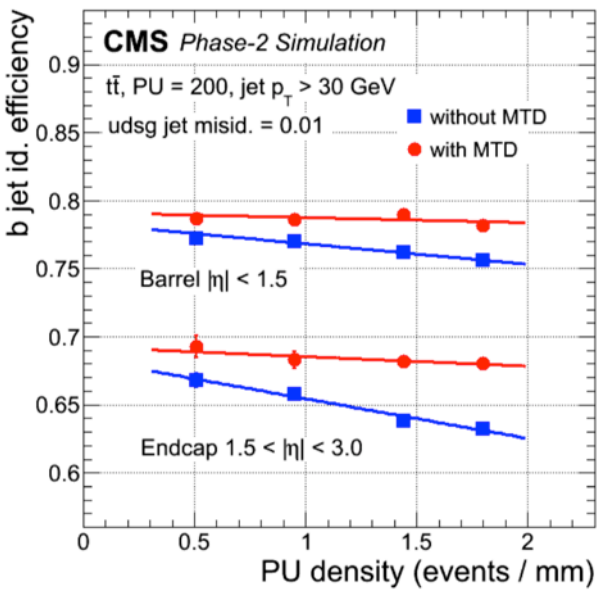


B-tagging

- b-tagging also improved in both barrel and endcap with additional cleaning of pileup tracks for secondary vertex reconstruction and discriminators
  - PU dependence improved
  - gain 5-9% in efficiency

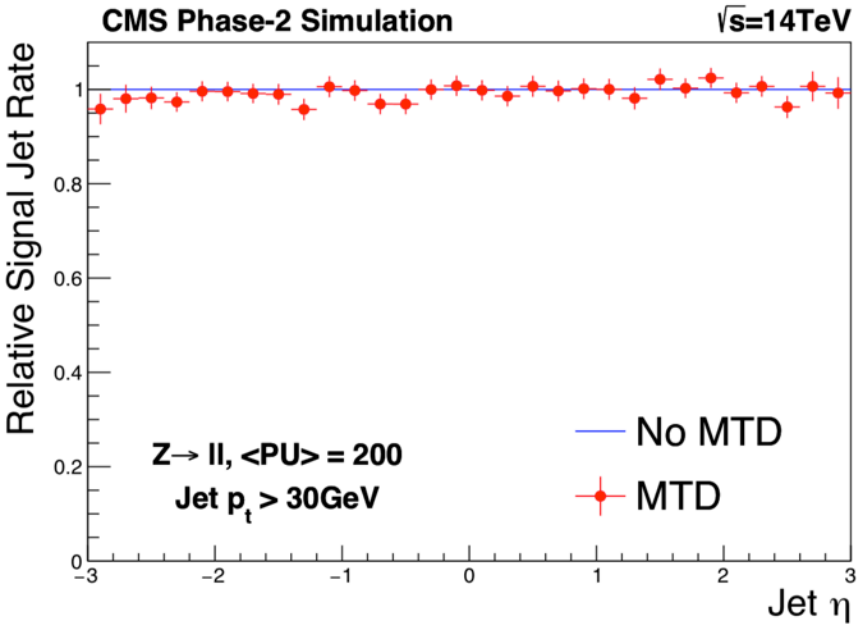


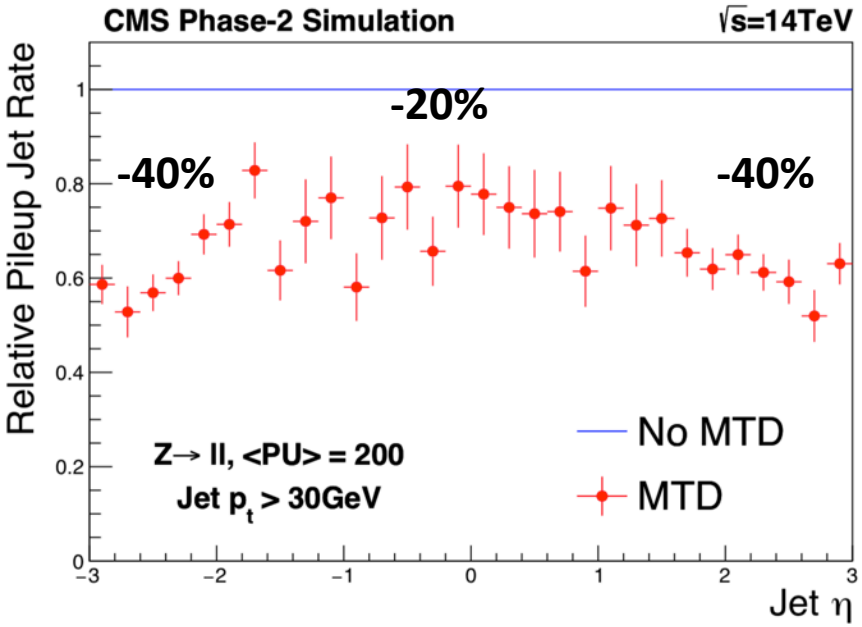




Pileup Jet Suppression

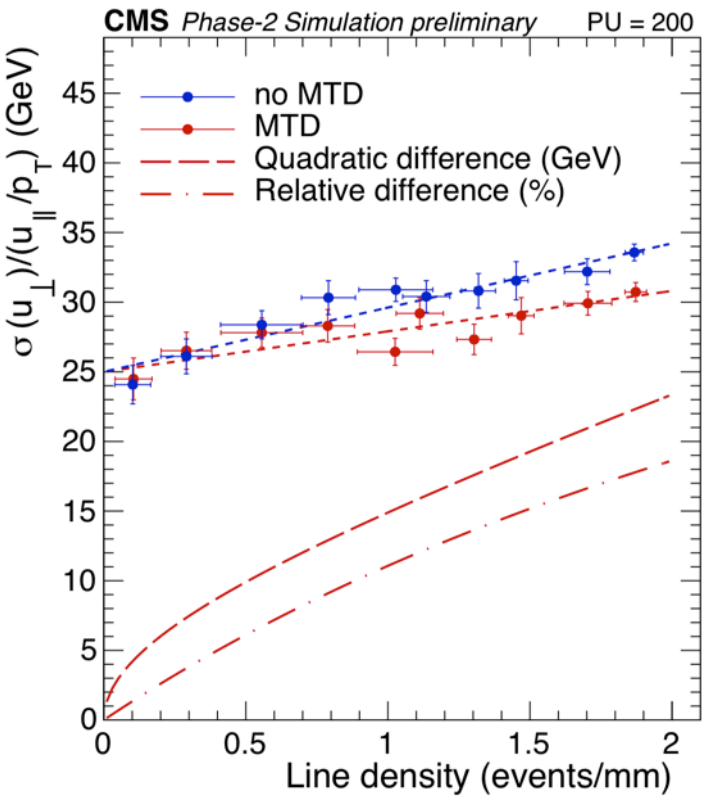
- The addition of precision timing reduces the rate of pileup jets
  - 20% (barrel) and 40% (forward)
  - minimal effect on the signal jet rate
- Impact for central jet vetoes or forward jet tagging

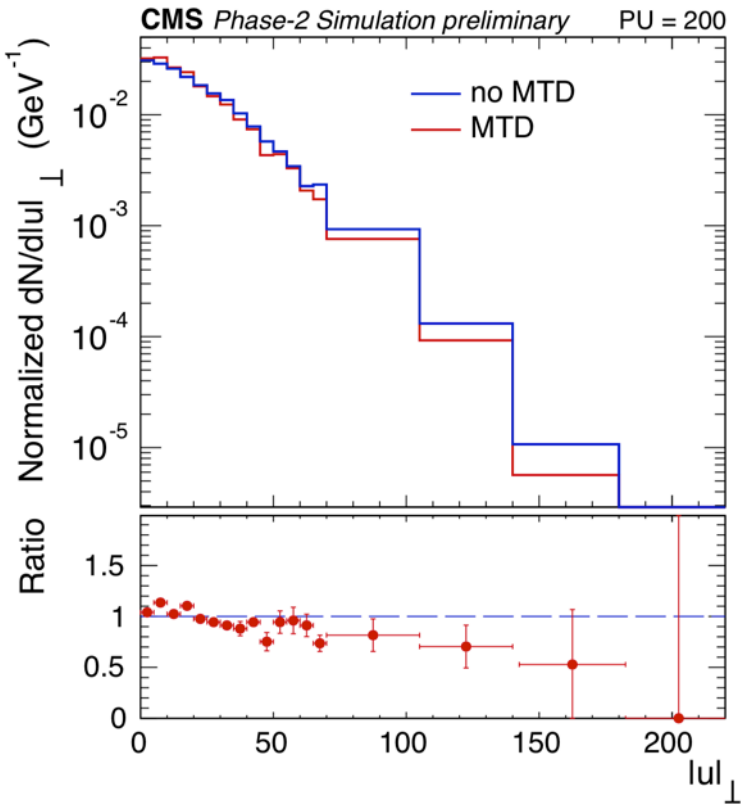




MET performance

- 15% improvement in MET resolution,
- > 30% reduction in tails (reducible background for BSM searches)





Impact on selected physics analyses

Signal	Physics measurement	MTD Impact
$H \rightarrow \gamma\gamma$ $H \rightarrow 4$leptons	**+25%** statistical precision on xsecs → Couplings	Isolation Vertex identification
VBF+$H \rightarrow \tau\tau$	**+30%** statistical precision on xsecs → Couplings	Isolation VBF tagging, MET
HH	**+20%** gain in signal yield → Consolidate searches	Isolation, b-tagging
EWK SUSY	**40%** reducible background reduction → +150 GeV mass reach	MET
Long Lived Particles (LLP)	Peaking Mass Reconstruction → Unique discovery potential	β_{LLP} from timing of displaced vertices

- Substantial benefits across a wide range of objects and across the HL-LHC physics program leveraging gains across the full pseudo-rapidity coverage
- **20-30% increase in effective integrated luminosity**

Summary and conclusions

- HL-LHC conditions pose significant challenges for the experiments
- The capability of time tagging charged tracks with ~30 ps precision is a powerful tool for pileup mitigation at the HL-LHC
- The CMS collaborations has proposed a MIP timing detector, with maximal coverage in eta, pt of charged particles
- The MTD can provide substantial performance gain at HL-LHC for a wide range of physics channels
- VBS studies may benefit from performance improvements on objects reconstruction (leptons, jets, MET)
  - no dedicated studies exist so far

Backup slides

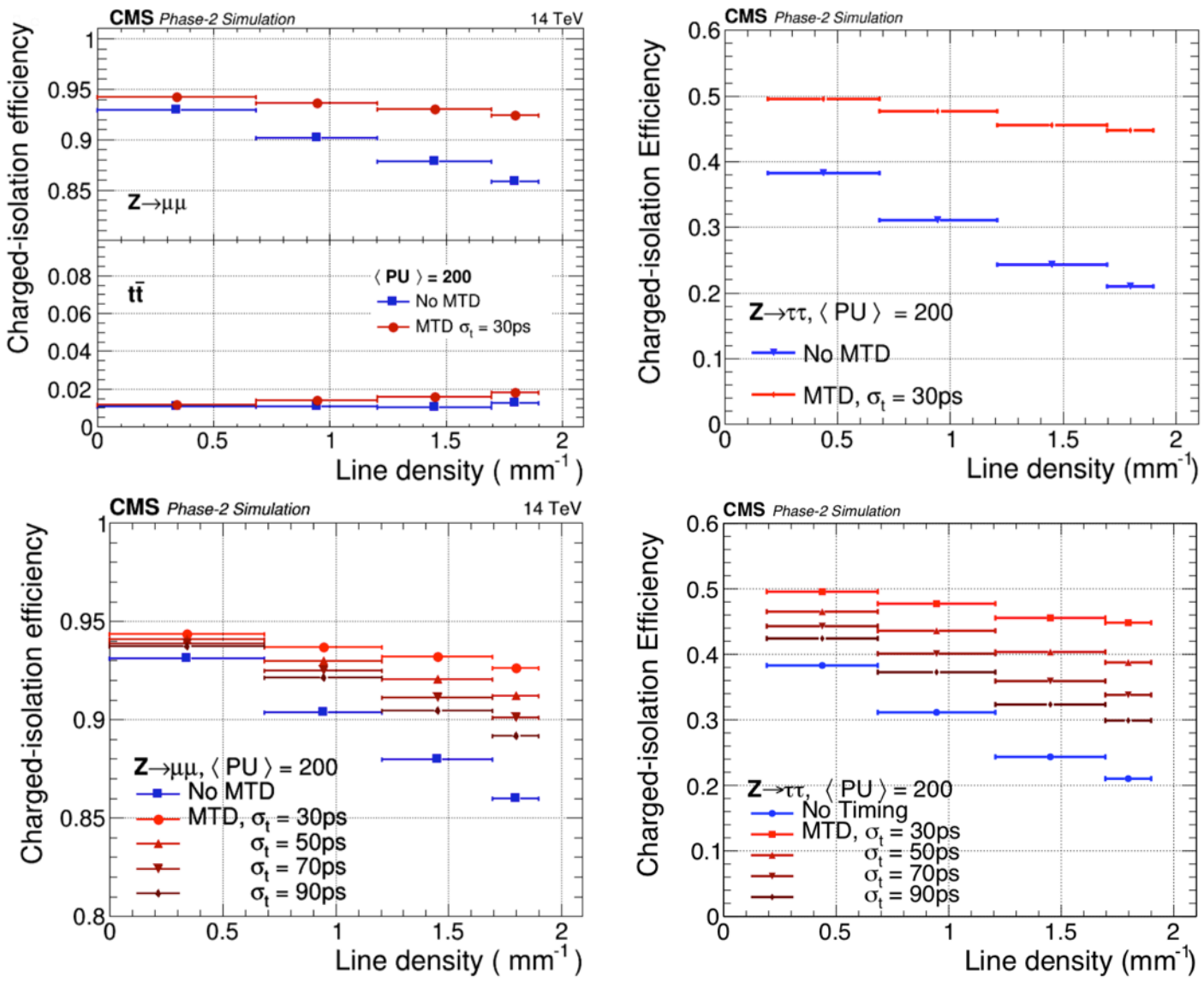
Summary analysis impact

Table 1.1: Representative signals for Higgs boson measurements and SUSY searches used to map each specific detector requirement into the relative performance gain at the analysis level (analysis impact) and in the measured physical quantity (physics impact).

Signal	Detector requirement	Analysis impact	Physics impact
$H \to \gamma\gamma$	30 ps photon and track timing • barrel: central signal • endcap: improved time-zero and acceptance	$S/\sqrt{B}$: +20% - isolation efficiency +30% - diphoton vertex	+25% (statistical) precision on cross section
VBF+ $H \to \tau\tau$	30 ps track timing • barrel: central signature • endcap: forward jet tagging • hermetic coverage: optimal p_T^{miss} reconstruction	$S/\sqrt{B}$: +30% - isolation efficiency +30% - VBF tagging +10% - mass (p_T^{miss}) resolution	+20% (statistical) precision on cross section (upper limit or significance)
HH	30 ps track timing • hermetic coverage	signal acceptance : +20% b-jets and isolation efficiency	Consolidate HH searches
$\chi^{\pm}\chi^{0} \to W^{\pm}H+p_T^{miss}$	30 ps track timing • hermetic coverage: p_T^{miss}	$S/\sqrt{B}$: +40% - reduction of p_T^{miss} tails	+150 GeV mass reach
Long-lived particles	30 ps track timing • barrel: central signature	mass reconstruction of the decay particle	unique sensitivity to split-SUSY and SUSY with compressed spectra

MTD Technical Proposal: CERN-LHCC-2017-027; LHCC-P-009: http://cds.cern.ch/record/2296612/

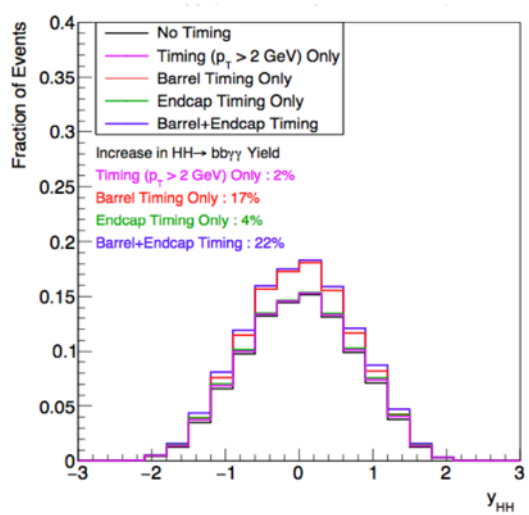
Lepton isolation performance

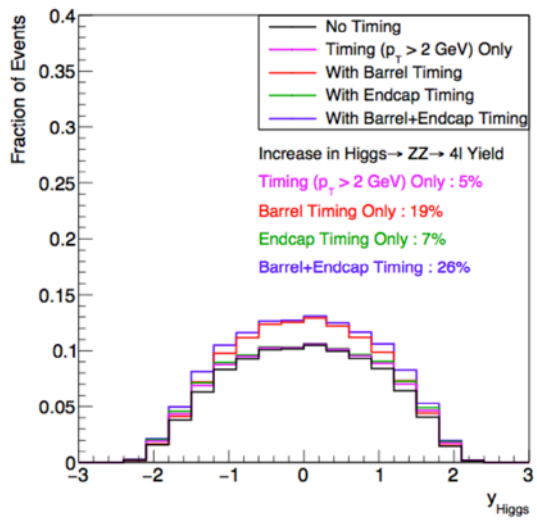


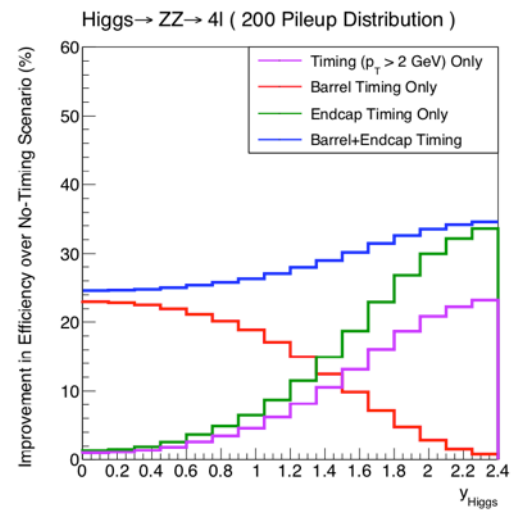
Impact on Higgs measurements

- Using Object-level gains for lepton (photon) isolation and b-tagging to project gains in Higgs/Di-Higgs selection efficiency at fixed background rejection
- Driven mainly by BTL given central nature of this signature
- Corresponds to an 18-26% increase in effective integrated luminosity

Channel	Signal increase (%) BTL	BTL+ETL	Relevance
$HH \to b\bar{b}\gamma\gamma$	17	22	Higgs self-coupling
$HH \to b\bar{b}b\bar{b}$	14	18	Higgs self-coupling
$H \to ZZ \to 4l$	19	26	Mass, width, spin+parity, differential cross sections, EFTs







Technology choice drivers

	Barrel LYSO+SiPM	Endcap LGAD
Coverage	$\|\eta\| < 1.5$	$1.5 < \|\eta\| < 3.0$
Surface Area	~ 40 m^2	~ 12 m^2
Power Budget	$\sim$0.5 kW/m^2	$\sim$1.8 kW/m^2
Radiation Dose	$\leq$ 2e14 neq/cm^2	$\leq$ 2e15 neq/cm^2
Installation Date	2022	2024

- Barrel (LYSO+SiPM):
  - Larger surface area
  - Lower radiation dose
  - Earlier installation date (driven by tracker integration constraints)
  - Mature technology (commercial availability for TOF-PET applications)
- Endcap (LGAD):
  - Smaller surface area
  - Higher radiation dose
  - Later installation date (some additional time for R&D)