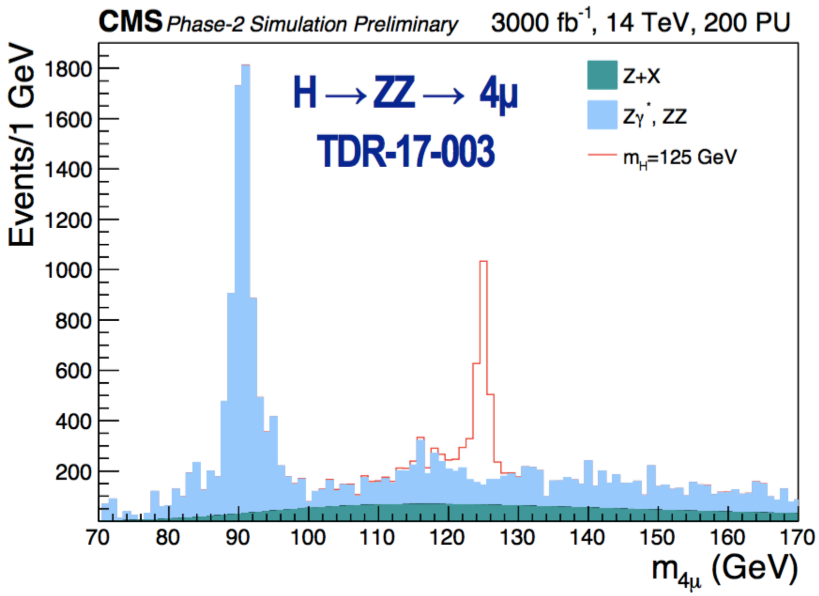
A timing layer in CMS for the High-Luminosity LHC

Tommaso Tabarelli-de-Fatis
Università and INFN di Milano Bicocca (Italia)

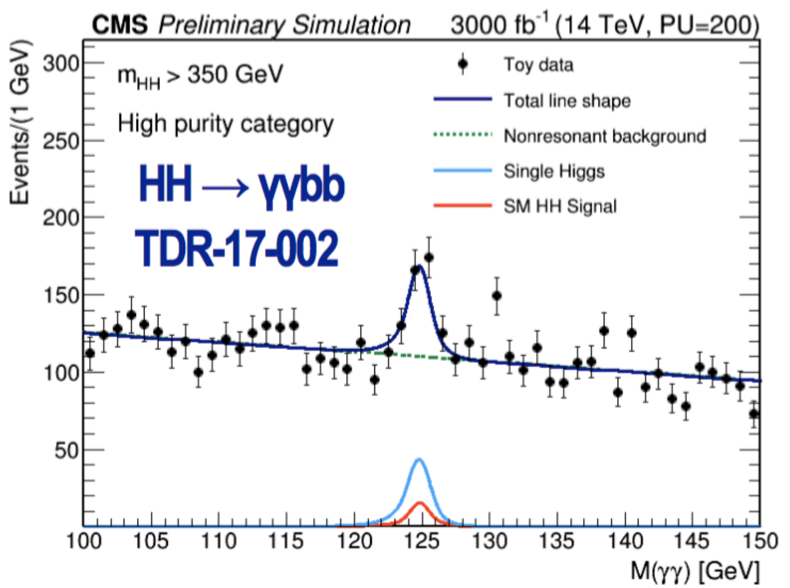
[Padova – 13 Dicembre 2017]

A minimal list of HL-LHC physics goals

- **Higgs boson measurements**
  - Couplings measurements to <10% level
    - H→ZZ→4l, H→γγ
  - Rare (or new) Higgs boson production and decay modes
    - VBF+H→ττ and H→μμ, H→Zγ
    - (VBF) + H → invisible
  - Higgs self-coupling (HH production)
    - Stat. uncertainty on signal yield ~50%

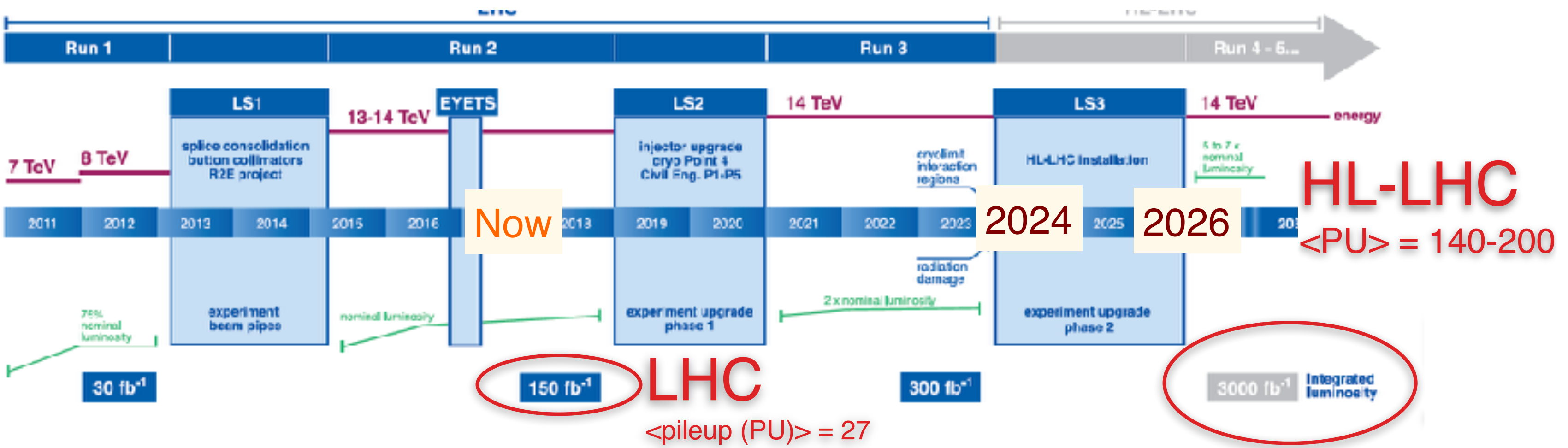


- **Direct search for new particles**
  - **SUSY**: explore difficult parameter regions and "weak production" modes
  - **Exotica**: push the limits, probe small prod. rates



- **Probe standard model also with rare flavour processes**

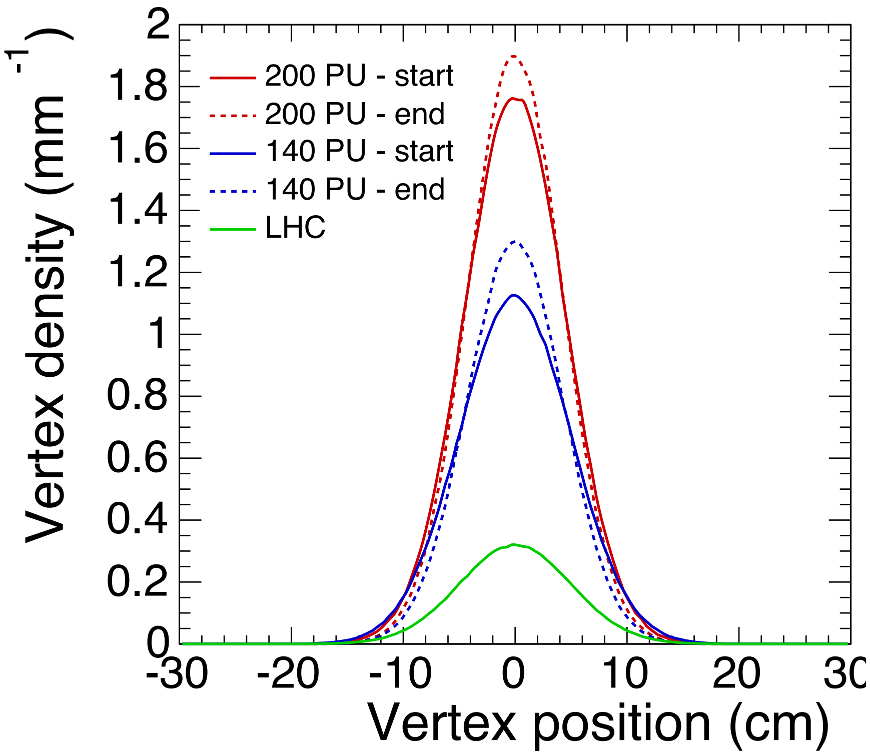
High Luminosity – LHC (Phase-2)

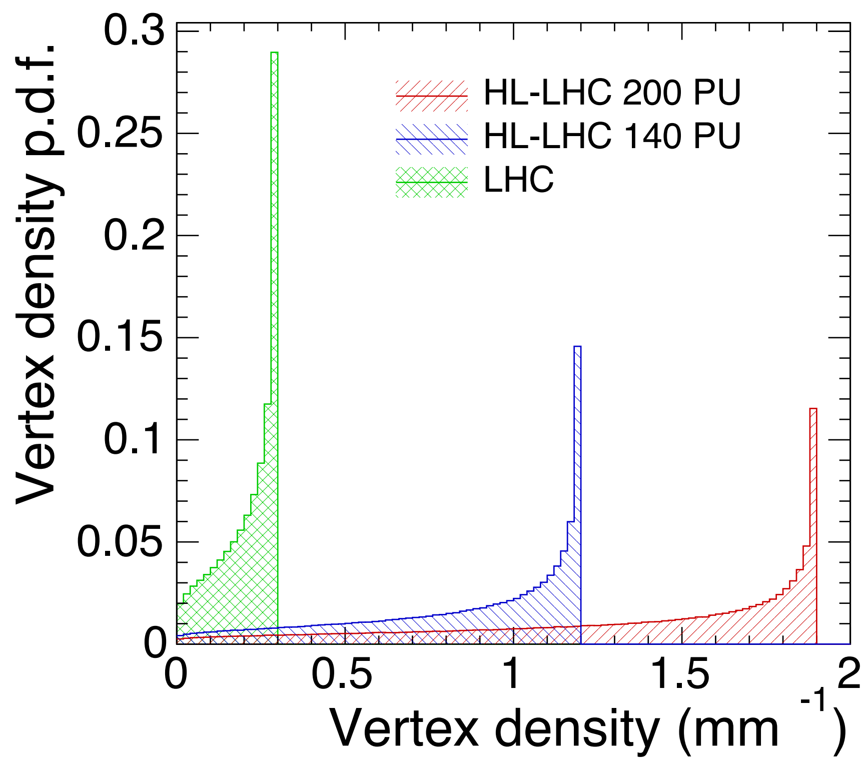


- **HL-LHC:** Upgrade of LHC and injectors to increase beam intensity
  - $L_{inst} > 5 \times 10^{34}\ cm^{-1}\ s^{-1}$, up to 140-200 pileup
  - Ultimate integrated luminosity target of 3000 fb^{-1} (10x LHC) - baseline

- **Experiments:** ATLAS and CMS upgrades for HL-LHC conditions
  - Radiation hardness
  - Mitigate physics impact of high pileup (more than 5x LHC)

Luminous region

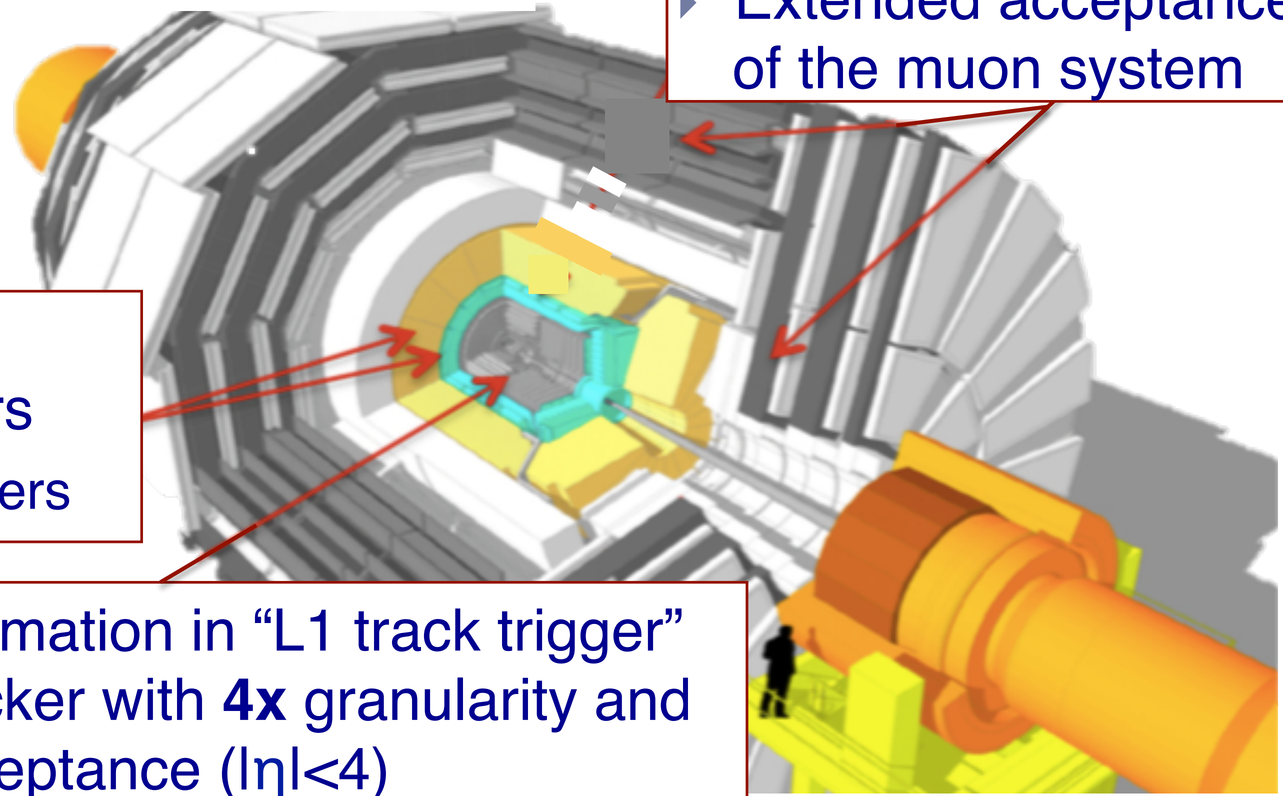




- **Luminosity leveled to "what the experiments can stand"**
  - Adjust the beam transverse size at the interaction point (β* function)
- L_{inst} = 5.3×10^{34} cm^{-2} s^{-1} → 140 pileup
- L_{inst} = 7.6×10^{34} cm^{-2} s^{-1} → **200 pileup → L_{int} = 4000 fb^{-1}**

Bold aspects of CMS Upgrade for HL-LHC

- **CMS Phase-2 originally targeted 5.3×10^{34} cm^{-2} s^{-1} (140 PU)**
  - Level-1 trigger accept rate 750 kHz
  - Events recorded at 7.5 kHz

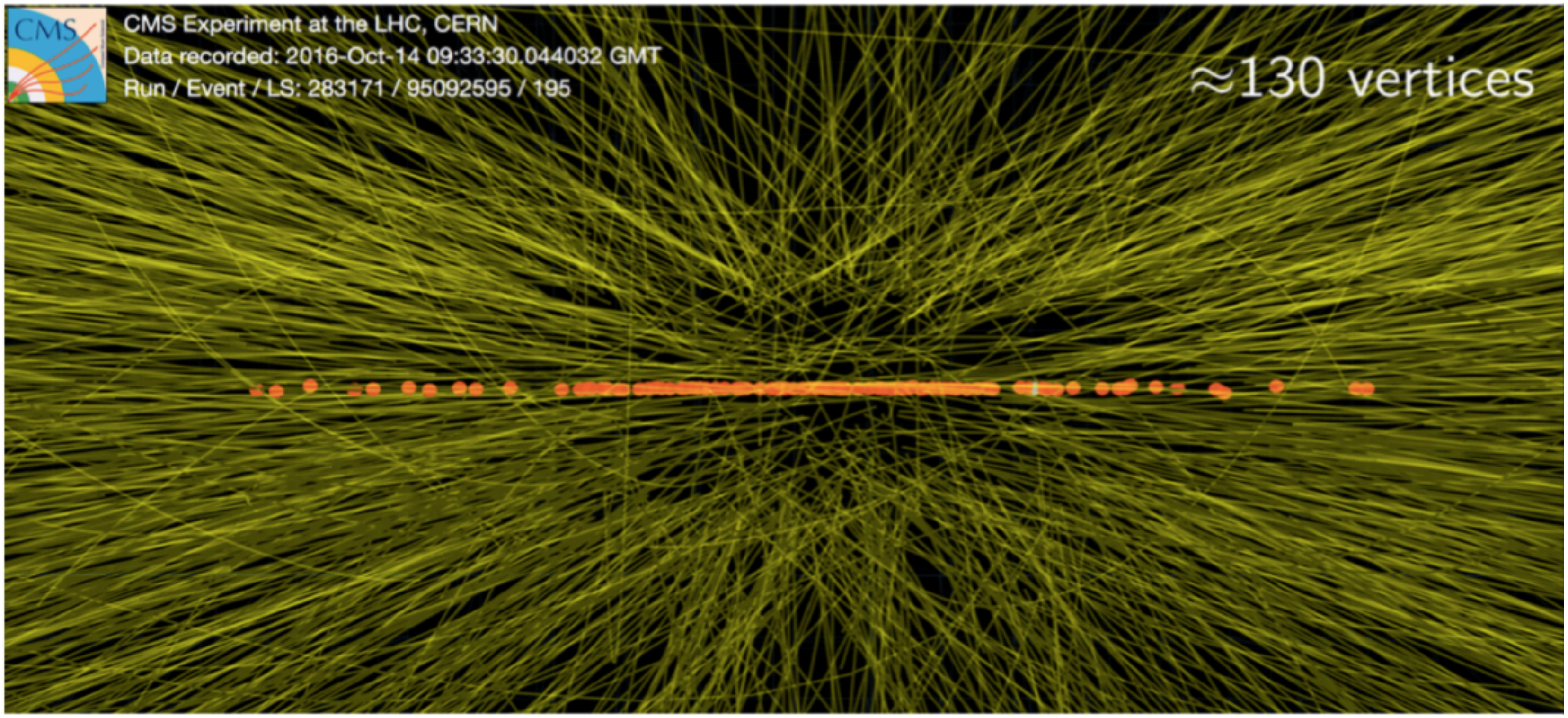


- Extended acceptance of the muon system

- High granularity endcap calorimeters
  - 3D image of showers

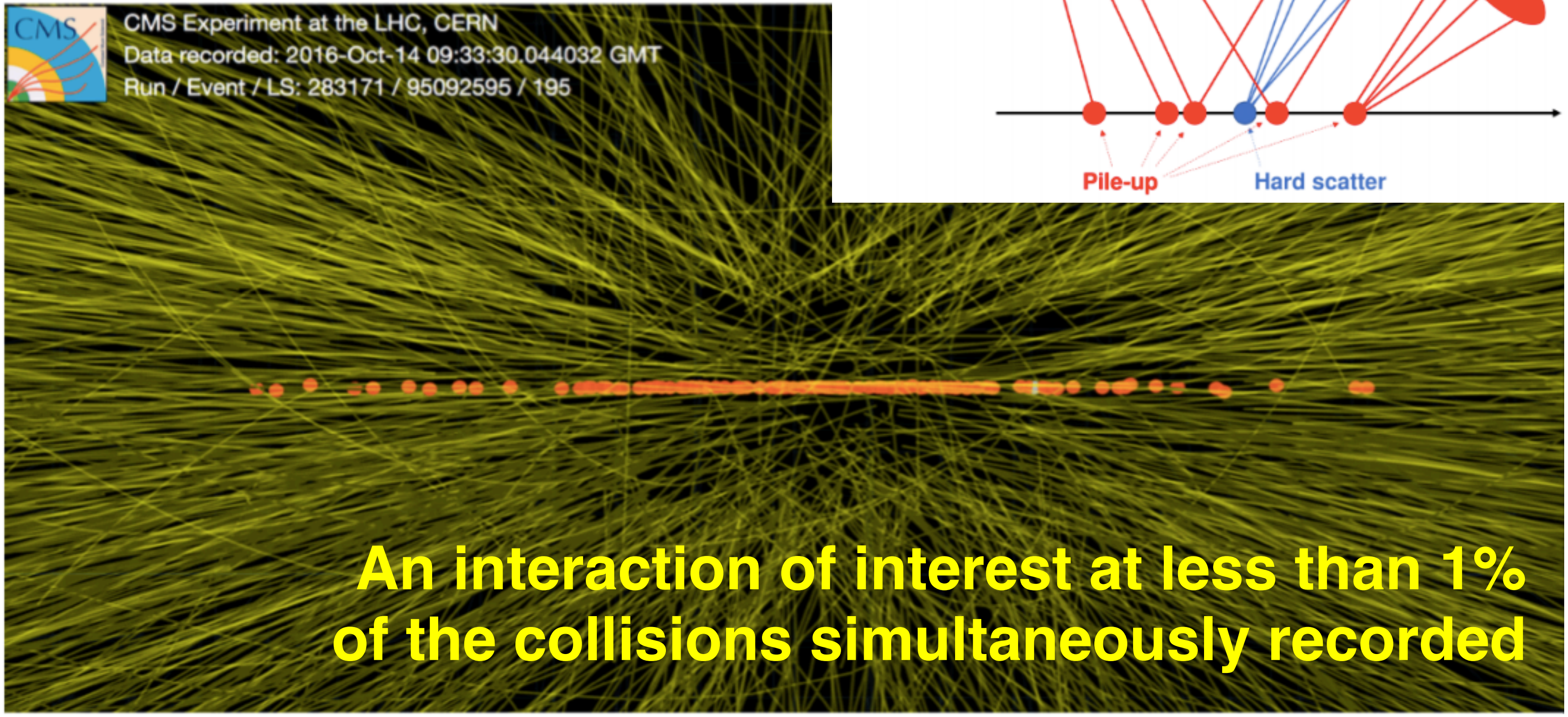
- Tracking information in “L1 track trigger”
- All silicon tracker with **4x** granularity and extended acceptance (|η|<4)

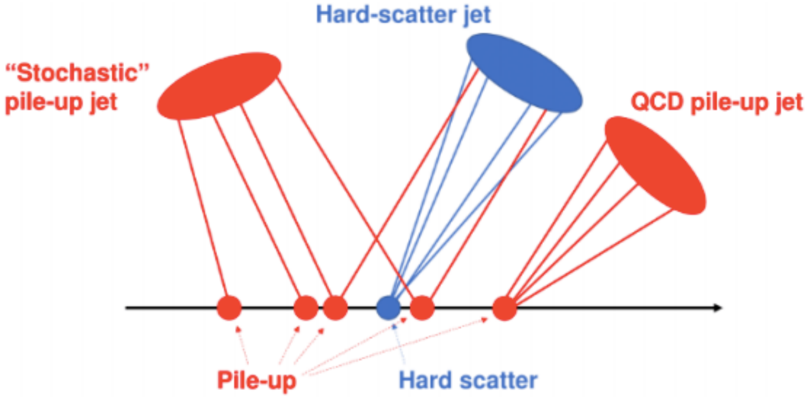
Proof of concept



- **Real life event with HL-LHC-like pileup from special run in 2016 with individual high intensity bunches**
  - One such collision every 25 ns at HL-LHC

Proof of challenge !

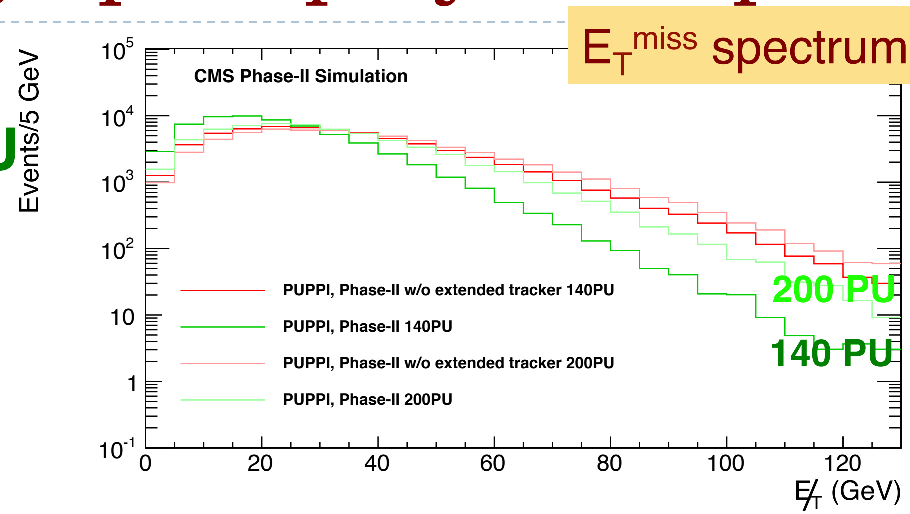


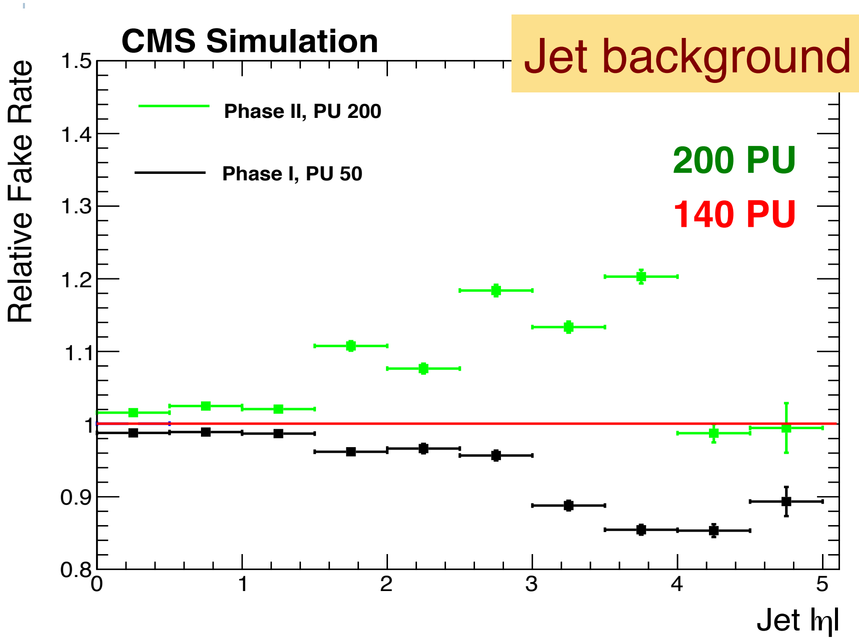


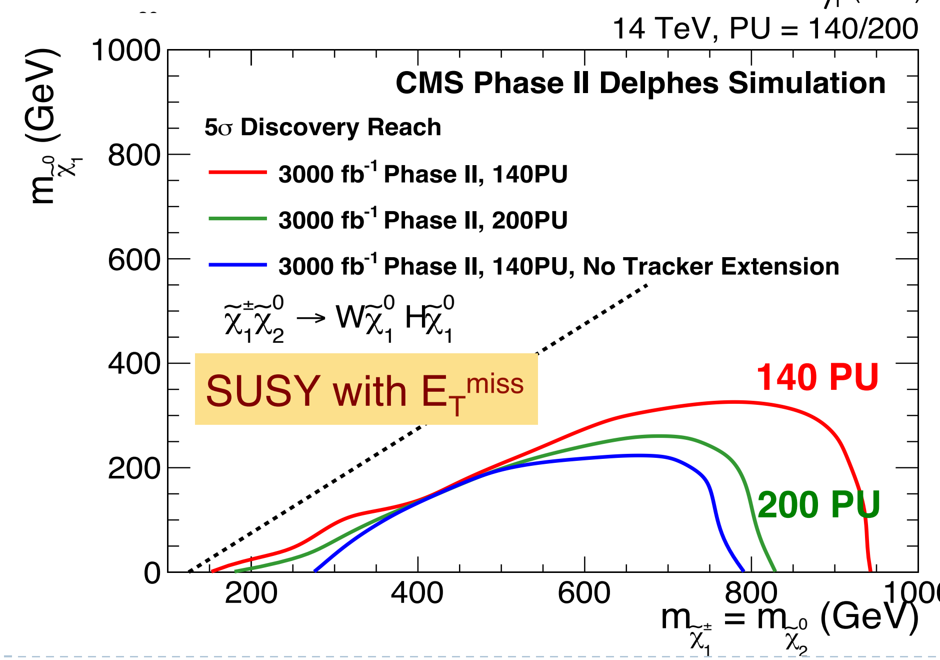
- **Vertex merge rate ~15% at 200 PU (with Phase-2 CMS)**
  - Hardest reconstructed collision not necessarily the most interesting
- **Incorrect association of tracks (and neutrals) with vertices**
  - Contamination of primary and secondary vertices, isolation cones, jets…
  - Incorrect reconstruction of the event kinematics (missing energy)

Physics impact of high-pileup by examples

- **VBF H→ττ requires >40% more luminosity at 200 than at 140 PU**
  - Jet fake rate and E_T^{miss} resolution and tau isolation
- **Searches with E_t^{miss} less sensitive at 200 than at 140 PU**





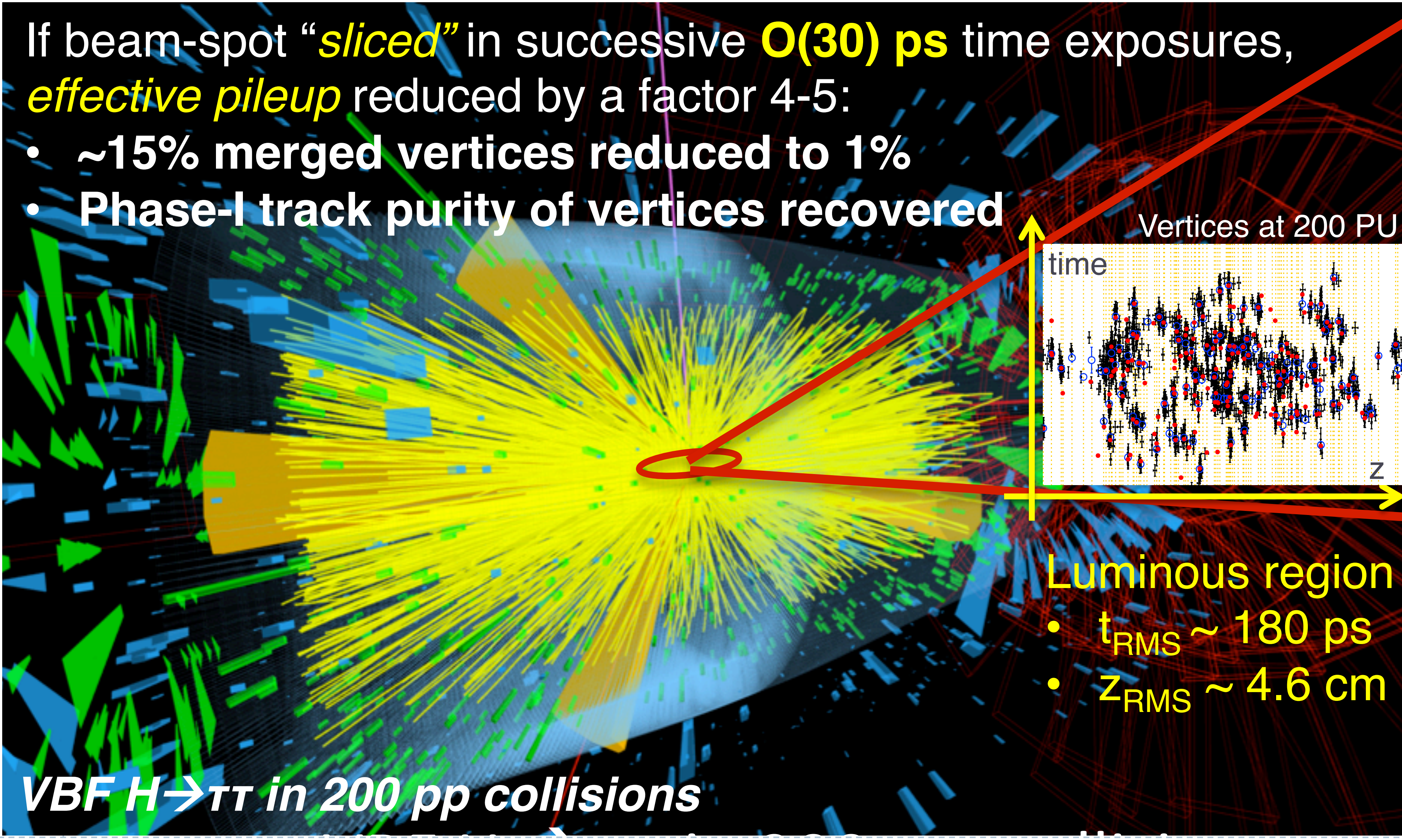


Reference: CMS Upgrade Scope document: [CERN-LHCC-2015-19, LHCC-G-165]

Mitigation of pileup with precision timing

If beam-spot "*sliced*" in successive **O(30) ps** time exposures, *effective pileup* reduced by a factor 4-5:

- **~15% merged vertices reduced to 1%**
- **Phase-I track purity of vertices recovered**



Vertices at 200 PU

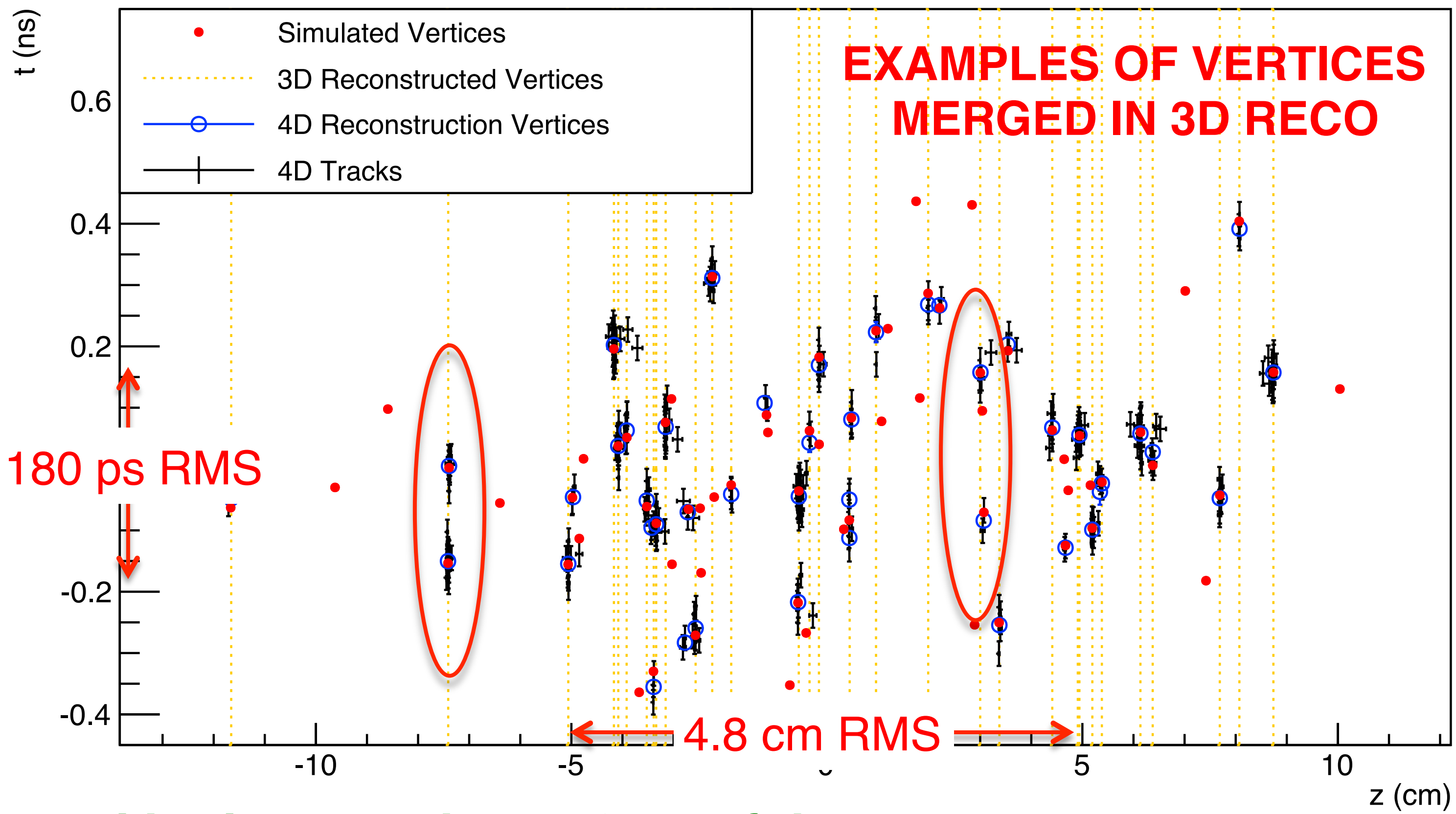
Luminous region

- t_{RMS} ~ 180 ps
- z_{RMS} ~ 4.6 cm

VBF H→ττ in 200 pp collisions

4D particle-flow with timing information

[50 PU event display to ease eye analysis]

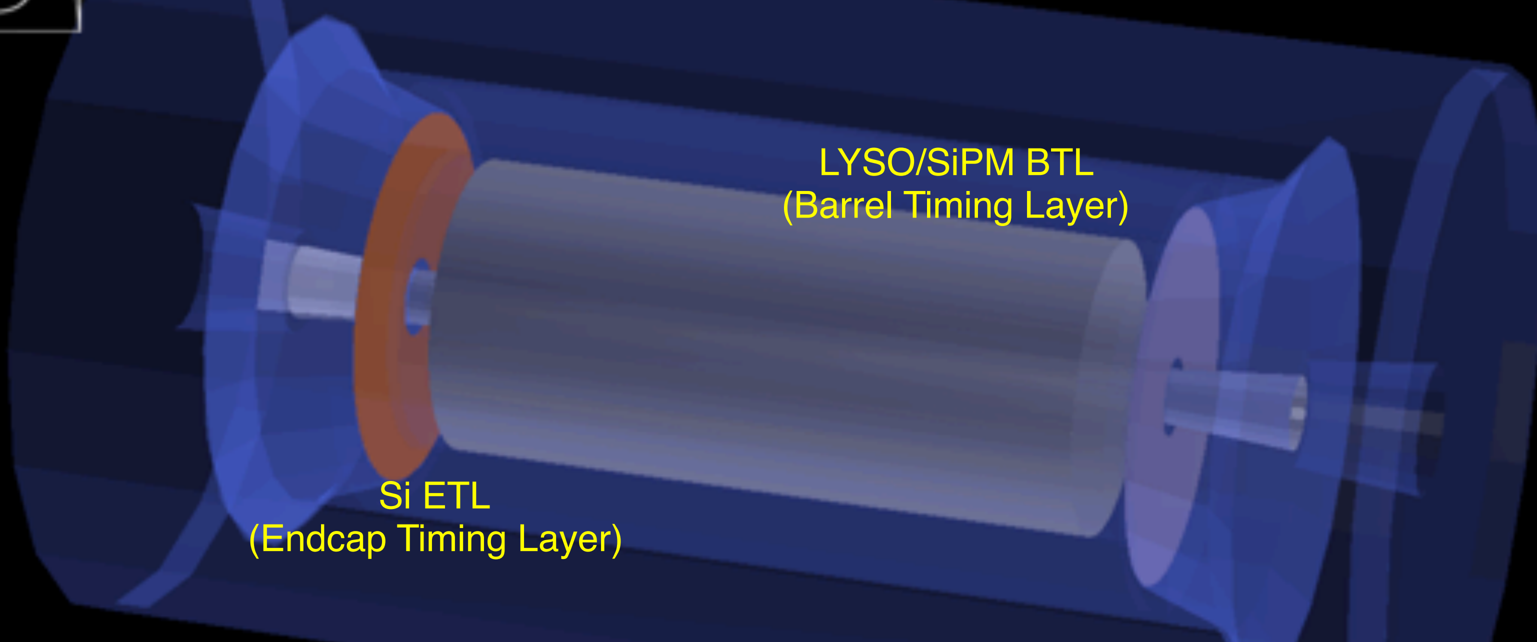


- **Charged hadrons make up 60% of the event content**
  - CMS event reconstruction relies on accurate track assignment
- **Timing detector tailored to provide maximum benefit to particle flow**

A dedicated layer for precision timing of tracks

Calorimeter upgrades

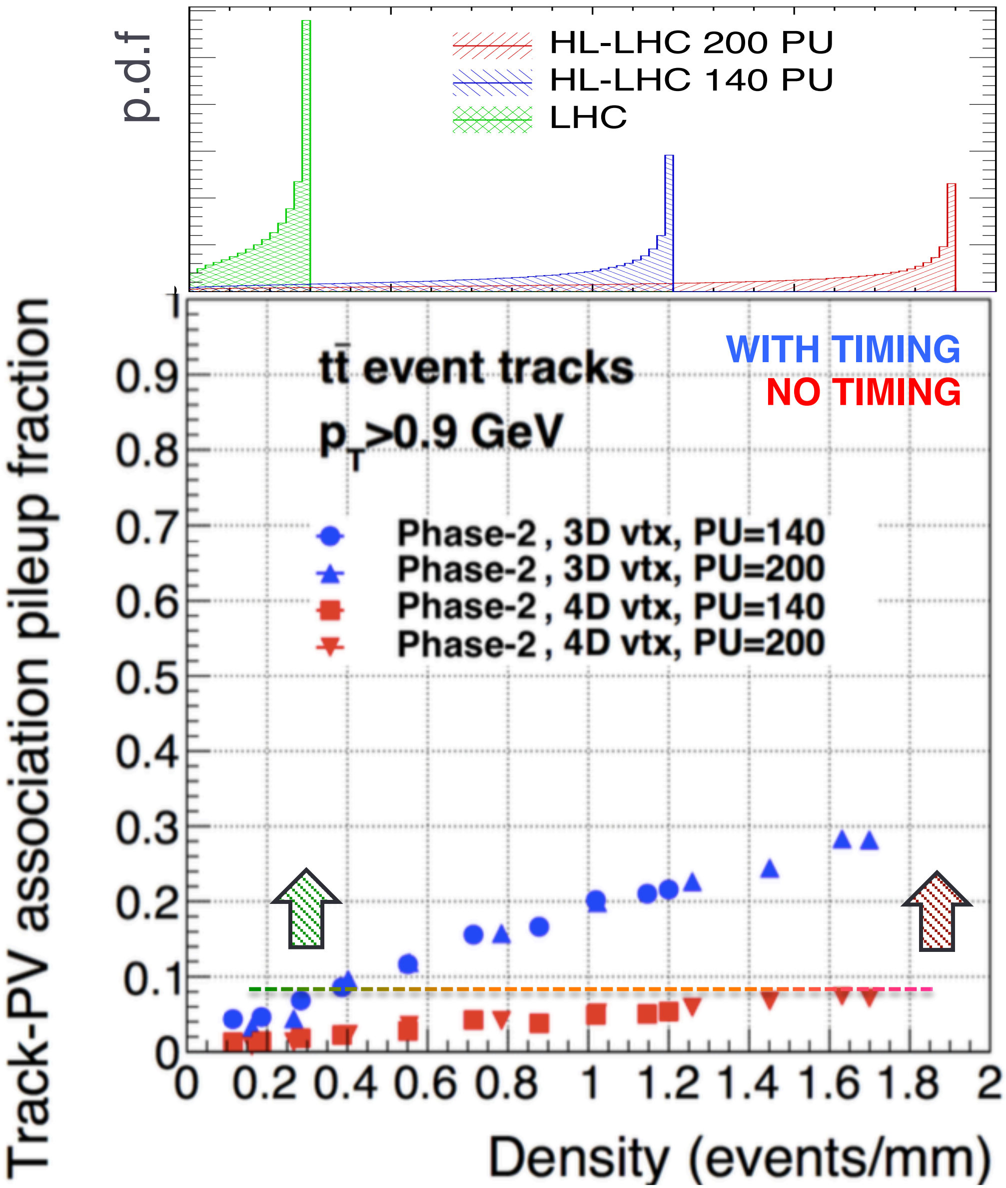
- Precision timing on high energy photons in ECAL Barrel
- All photons and high energy hadrons in HGCal Endcap



- **New MIP Timing Detector (MTD) just outside the tracker**
  - MIP timing with **30 ps precision**
  - **Acceptance: $|\eta|<3.0$ and $p_T>0.7$ GeV in the barrel,**
    $\sim p > 0.7$ GeV in the endcap

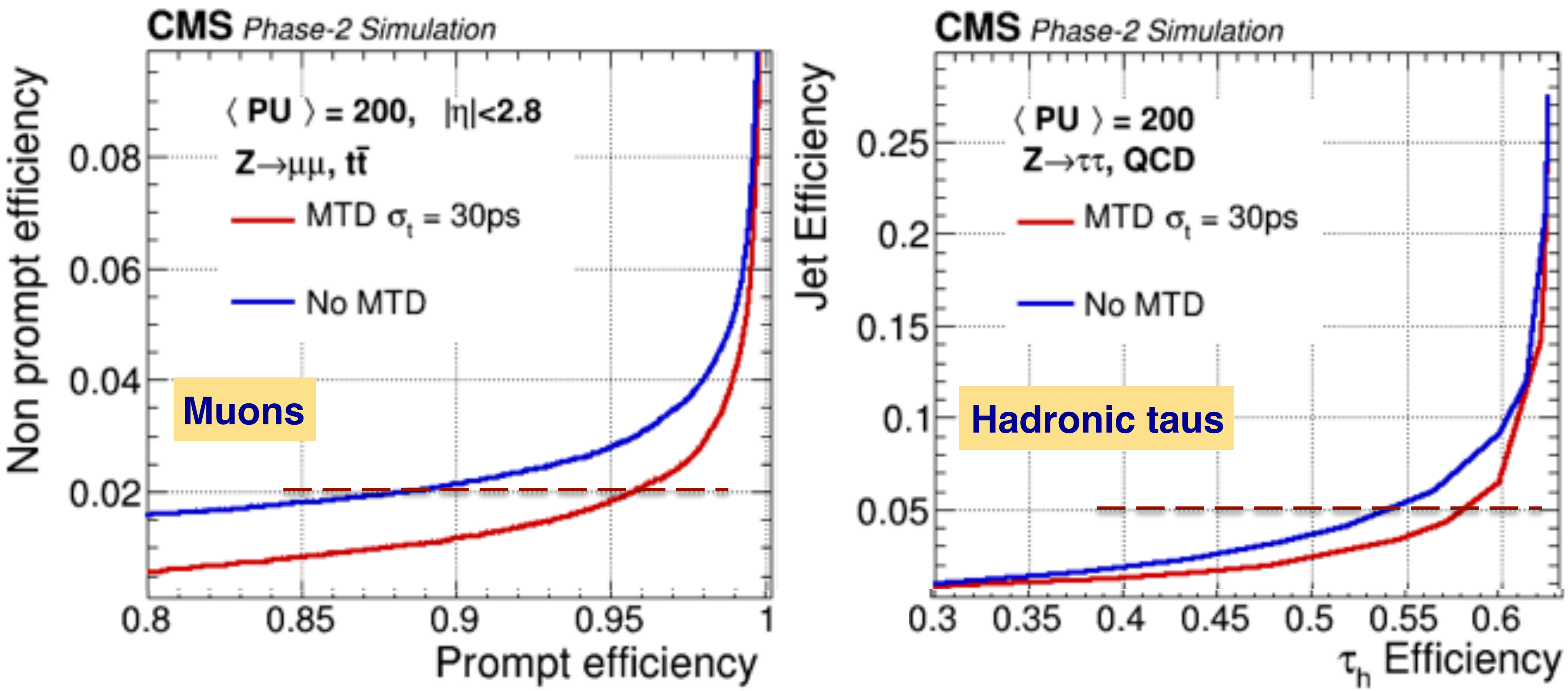
Track-vertex association with track timing

- **Timing significantly reduces the "effective" vertex line density**
  - 200 PU equivalent to current LHC PU
- **Provide robustness against adjustment of luminosity scenarios**
- **Recover performance in several observables**



Particle isolation: ROC curves

Track association with vertex: Δt < 90 ps

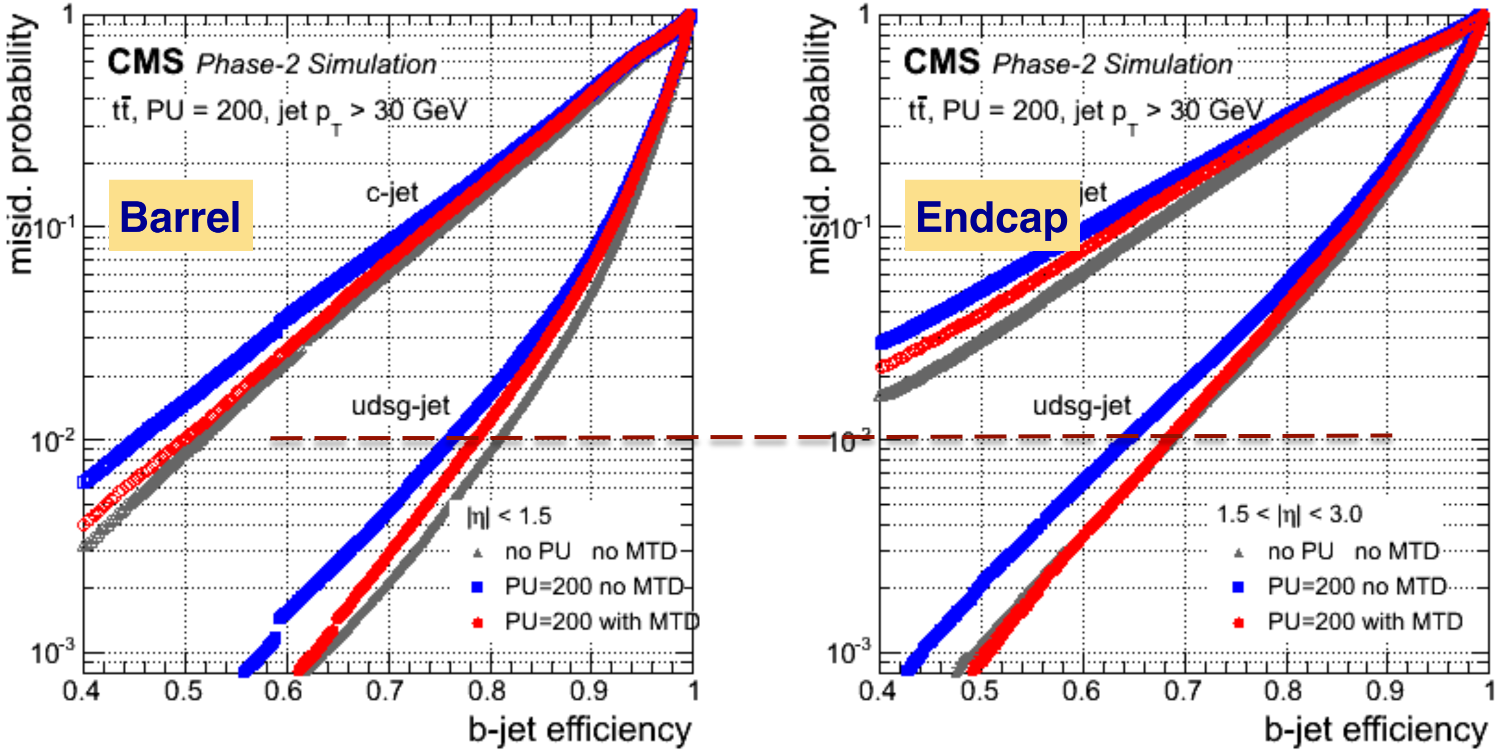


- **Isolation efficiency up by 7 ÷ 10% per lepton (*)**
  - Acceptance gain in searches and precision measurements
  - *[Gain amplified in multi-particle final states]*

(*) at constant background rejection power]

b tagging with timing

- **Efficiency up 4-6% at constant background rejection of 1% for light jets from removal of spurious secondary vertices**
  - inclusion of timing in the b-jet algorithm ongoing
- *[Gain amplified in multi-particle final states]*

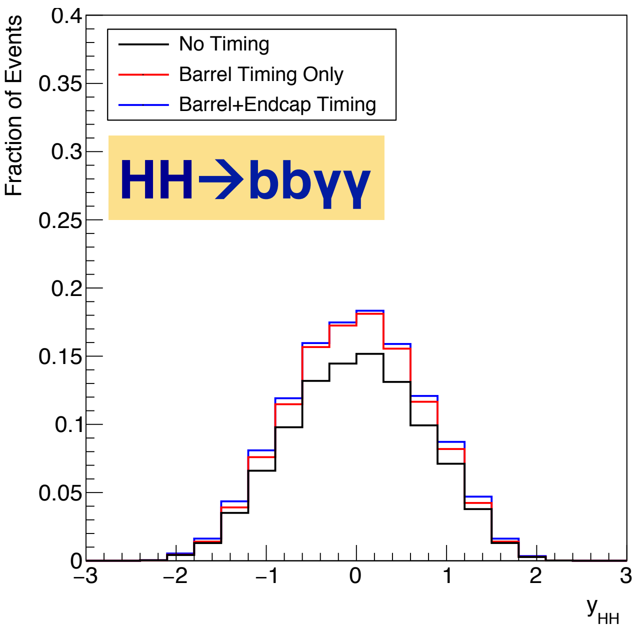


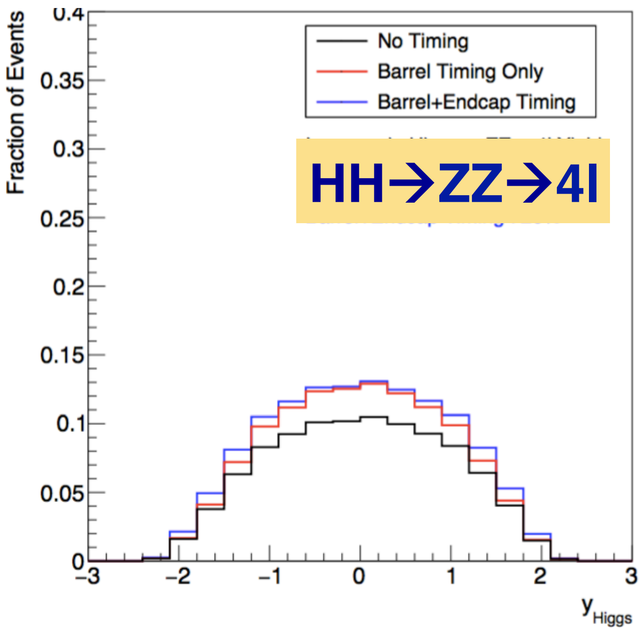
Δt < 90 ps

(di-)Higgs boson acceptance projections

- **Gain in signal yield ~20-25% in multi-object final states**
  - *[at constant rejection power for reducible background]*

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

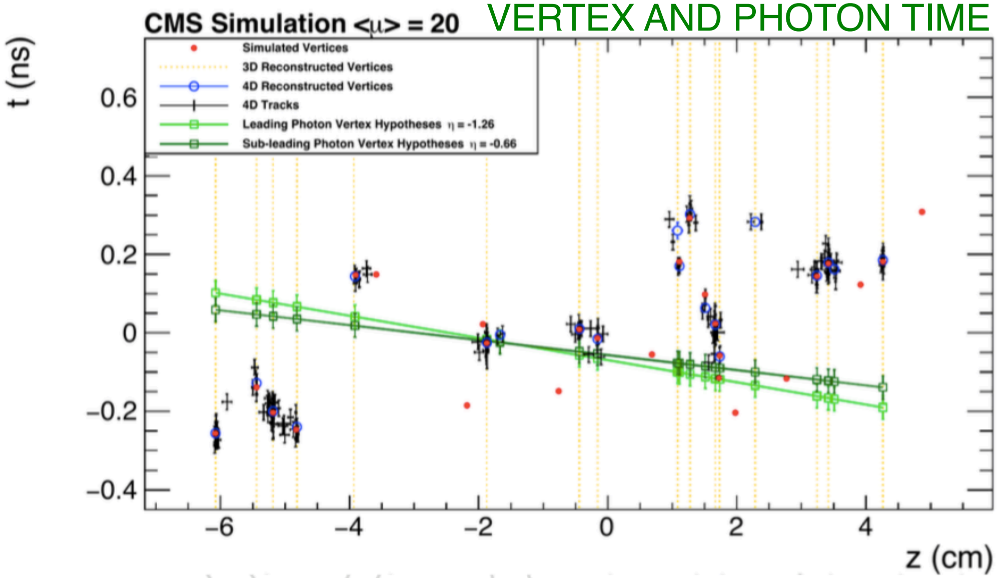


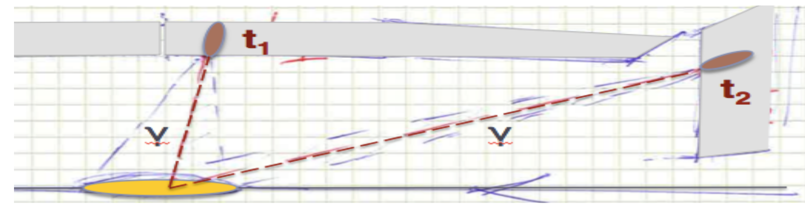


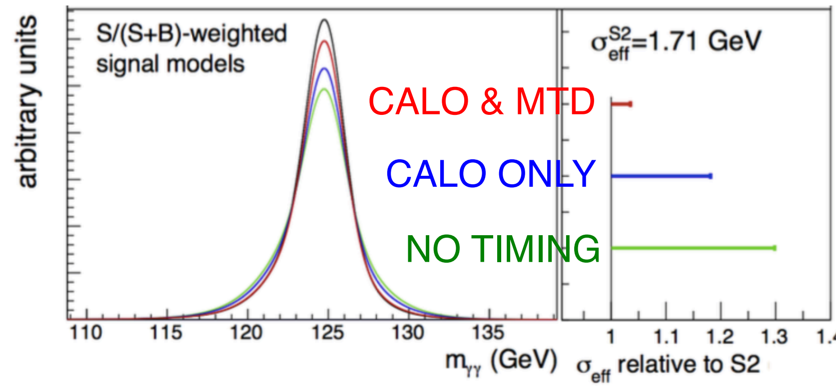
- Proportionate increase in the effective integrated luminosity
- Large impact from barrel MTD (central signatures)

H→γγ vertex tagging

TRIPLE COINCIDENCE:
VERTEX AND PHOTON TIME



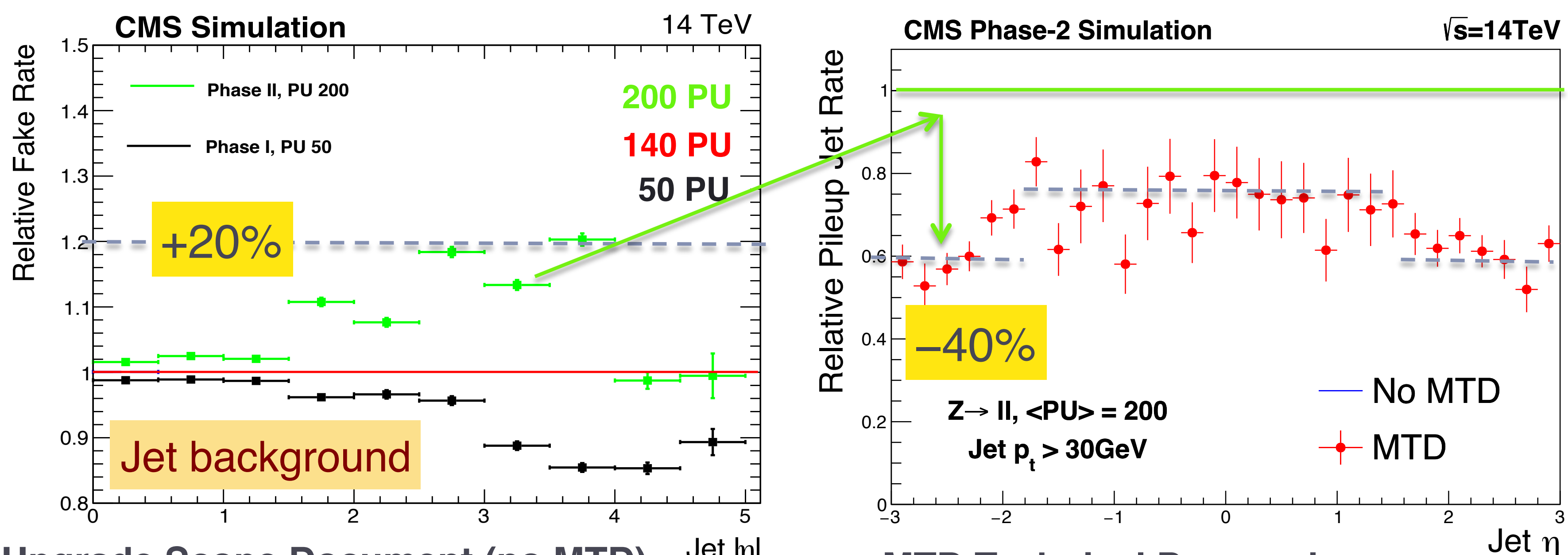




- **Unique capability to match photon time to vertex time + position**
  - CMS ECAL is non-pointing, but will have photon timing capability
  - 50% of events require MIP timing to find correct vertex
- **Identifies photon vertex: improves di-photon mass resolution by 25% and also H→γγ signal significance**

Projections for VBF + H → ττ

- **Performance gain from timing (S/√B) ~80% :**
  - **+30%** from isolation
  - **+30% from VBF tagging [pileup jet rejection]**
  - **+10%** from di-tau mass resolution [p_T^{miss} resolution]
- Timing offsets performance degradations from 140 to 200 PU
- Large impact from endcap MTD

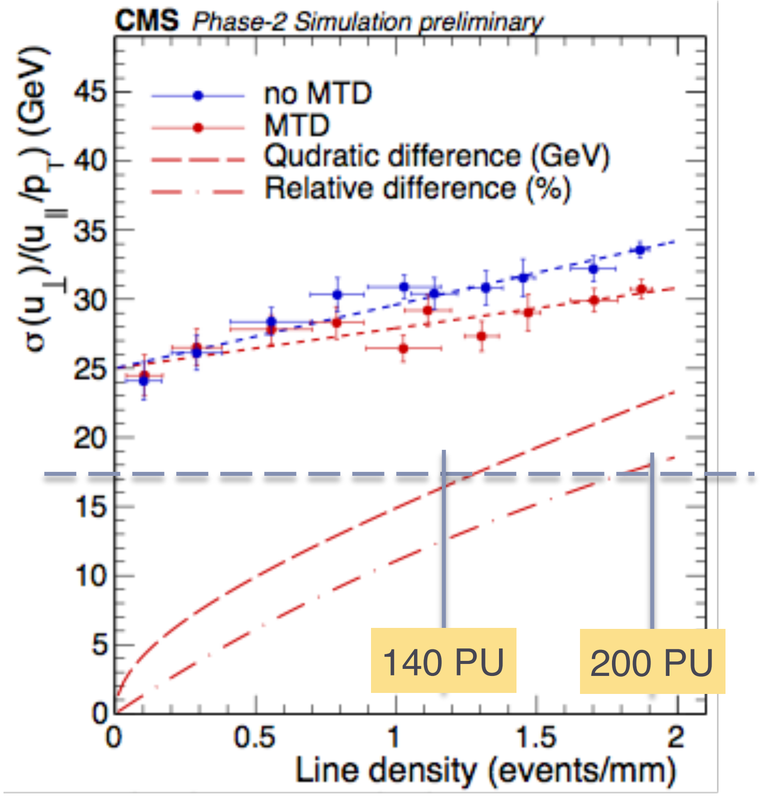


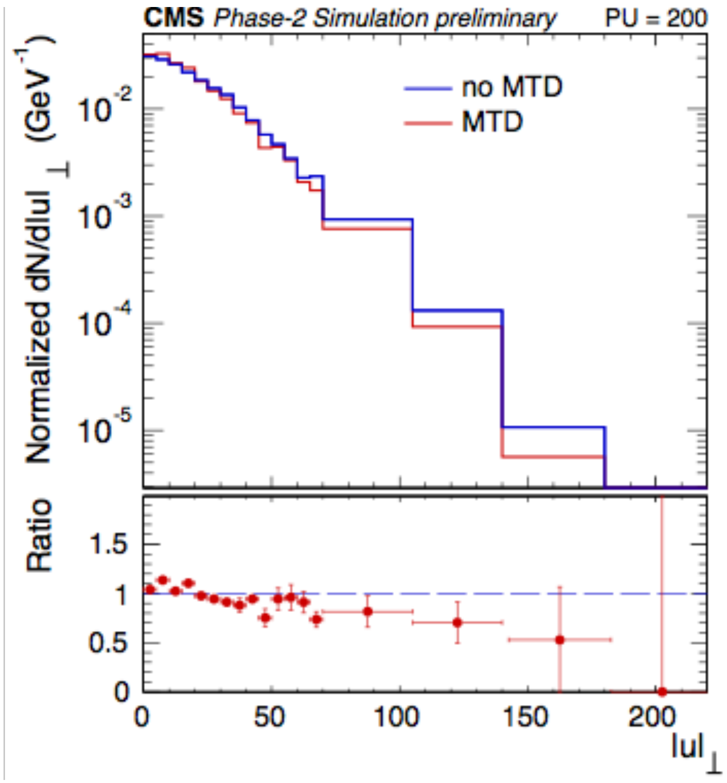
Upgrade Scope Document (no MTD)

MTD Technical Proposal

Missing p_T performance with MTD

- **Puppi MET resolution improves by 15% at 200 PU**
  - Recovers performance at 140 PU
- **Missing p_T tails reduced 40% for p_T^{miss} > 150 GeV**
  - Game changer for searches in high pileup

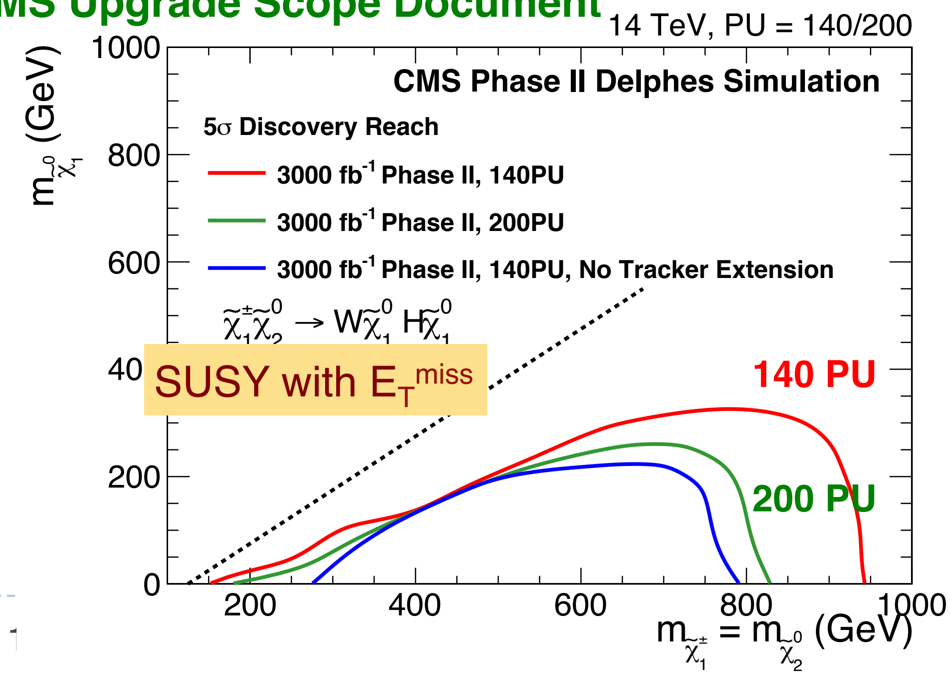


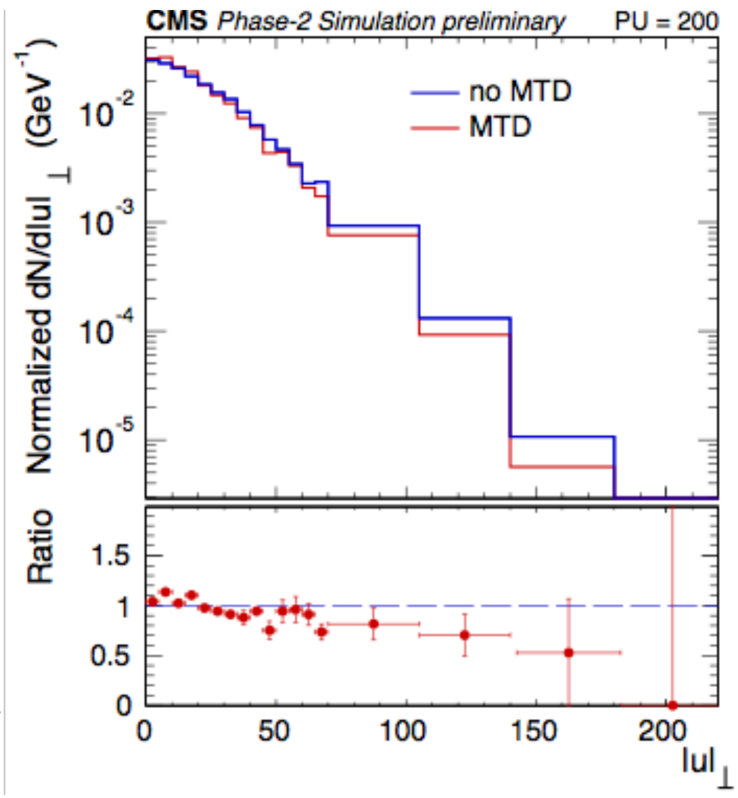


Searches in missing p_T tails

- **Extend the reach of searches for massive invisible particles**
  - Without MTD: searches at 200 PU less sensitive than at 140 PU
  - Sensitivity spoiled by MET tails from pileup
- **With MTD: MET tail reduction offsets the performance loss**
  - Search at 200 PU same sensitivity as at 140 PU (for the same luminosity)
  - 200 PU running provides +25% luminosity
    → +150 GeV sensitivity

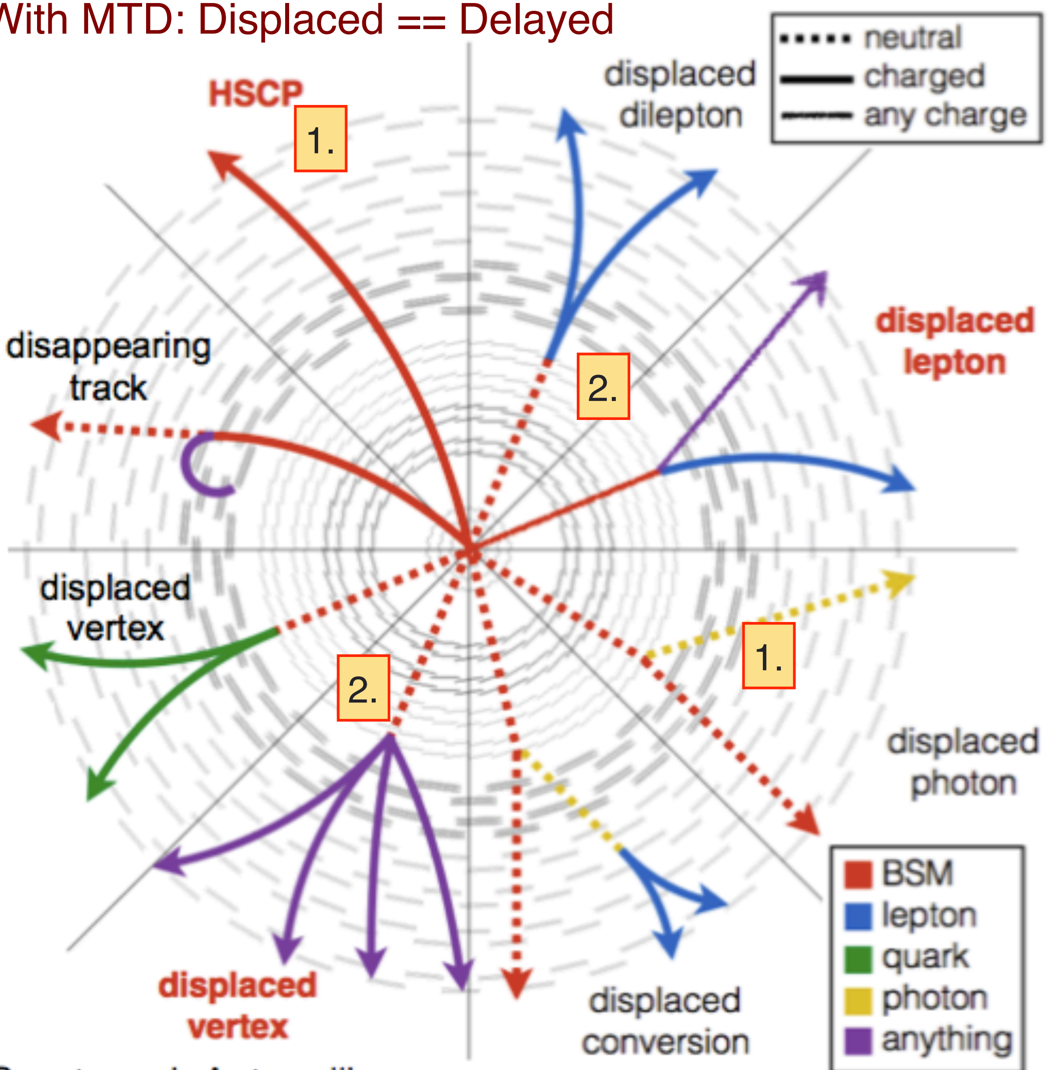
CMS Upgrade Scope Document





Searches for long-lived particles (LLP)

With MTD: Displaced == Delayed



Courtesy J. Antonelli

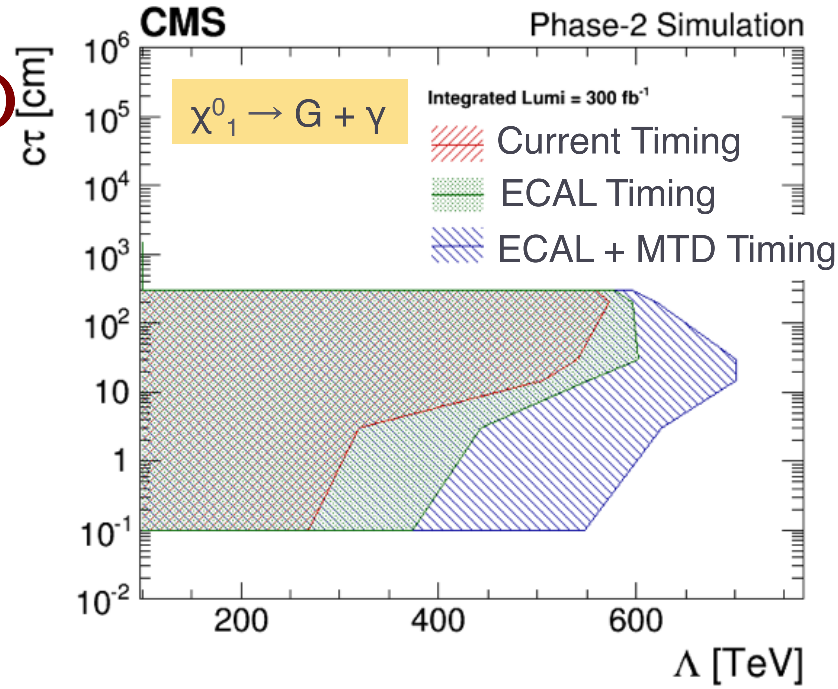
- **Postulated in many BSM:**
  - split-SUSY, GMSB, RPV SUSY, SUSY with degenerate states
  - cτ ~ O(1 cm)
- **New capabilities afforded by the MTD (examples):**
  1. Improved TOF resolution for charged and neutral particles
  2. Ability to reconstruct LLP velocity from the decay *length* and *time:*
     - Peaking observable from decay kinematics

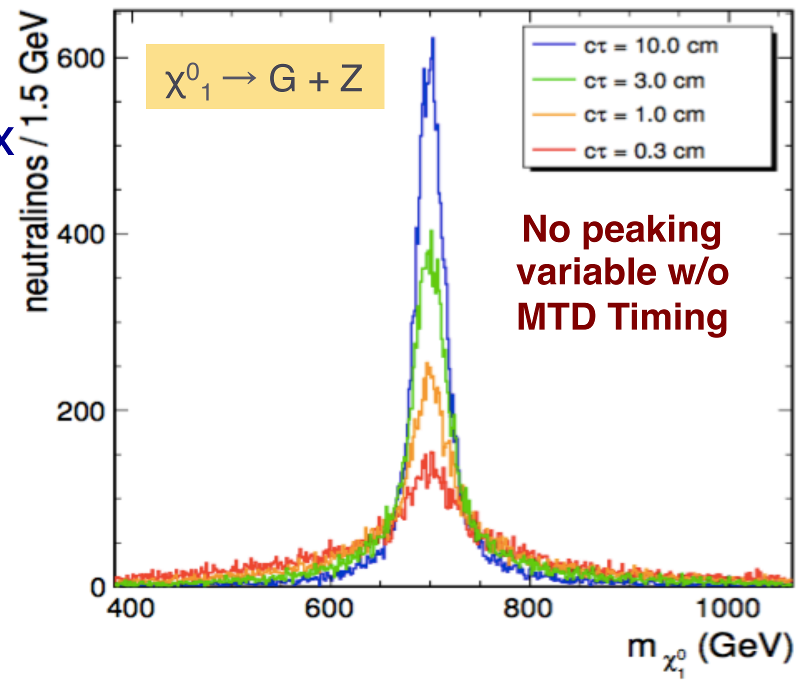
LLP searches with MTD

1. **Vast acceptance extension for massive LLP**
   - Example: photon + vertex timing [neutralino to photon + gravitino]

2. **LLP mass (or mass splitting) reconstruction**
   - **Model-independent peaking observable** (depend on how velocity relates to the model structure)
   - Example: primary and secondary vertex timing [neutralino to gravitino + Z]

- **MTD *fundamentally* changes how we execute these searches**
   - Massive particles yield central signatures → barrel coverage





Summary on performance

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

Higgs boson physics

Searches

- **MTD: improves the full range of Phase-2 physics**
  - ~20-30% improvements across all measurements
  - Recovery of performance for MET-tail based searches
- Enhanced capability for reconstructing the secondary vertices of long-lived particles (LLPs)
  - Resonance reconstruction for LLPs (novel method)

MTD: design and technologies

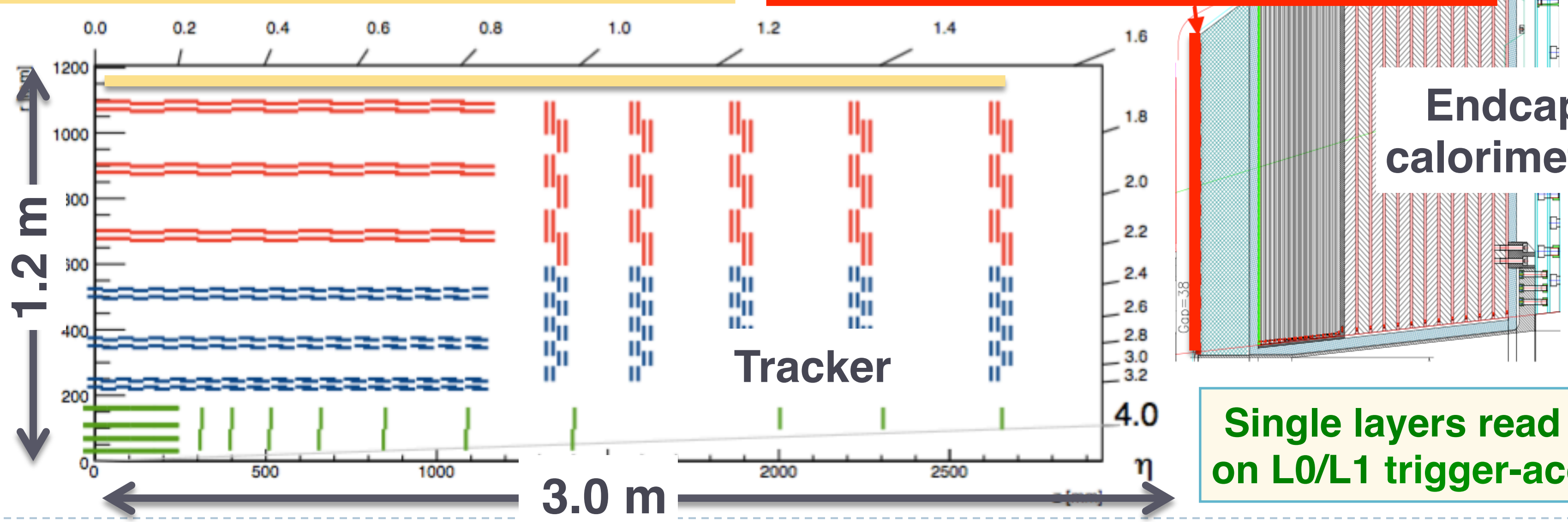
- Hermeticity: barrel (|η|<1.48) and endcap (1.6<|η|<2.95)
- Radiation: **$2x10^{14}$ (barrel)** and **up to $2x10^{15}$ neq/cm^2 (endcap)**
- Minimal impact on calorimeter performance
- Mechanics and services compatible with existing upgrades

LYSO/LSO tiles with SiPM readout:

- TK/ ECAL interface **~ 25 mm thick**
- Surface ~40 m^2 ; 250k channels
- Integrate with tracker

Si with internal gain (LGAD):

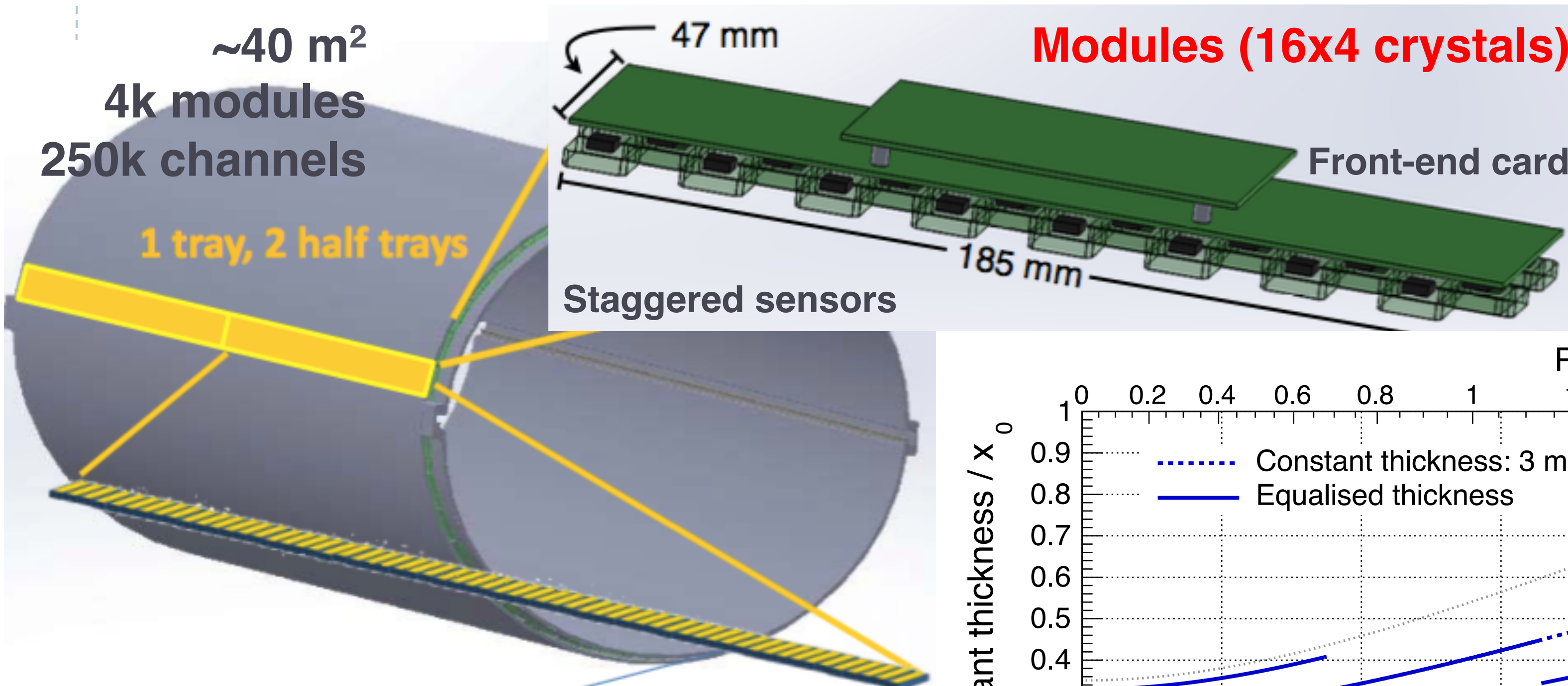
- On the CE nose **~ 42 mm thick**
- Surface ~12 m^2; ~4M channels
- Integration with endcap



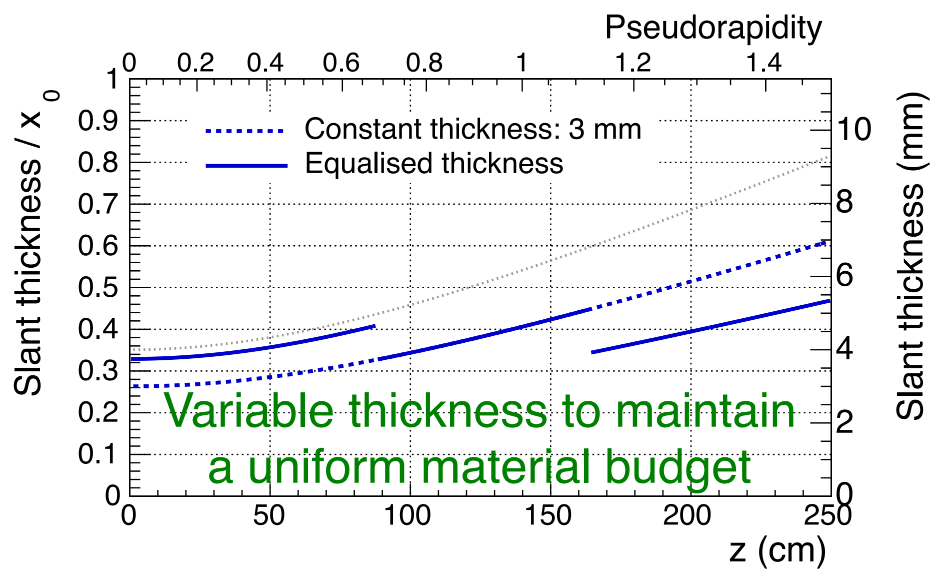
Single layers read out on L0/L1 trigger-accept

Barrel timing layer (BTL) layout

- **LYSO:Ce + SiPMs embedded in the tracker support tube**
  - CO_2 cooling at ~ –30 ^{0}C (limit SiPMs self-heating and dark rate)
- **Production-ready and scalable technology**



- 3% occupancy (0.5 mip threshold)
- **Adapt TOFPET2 ASIC**
  Leading edge timing + amplitude meas.

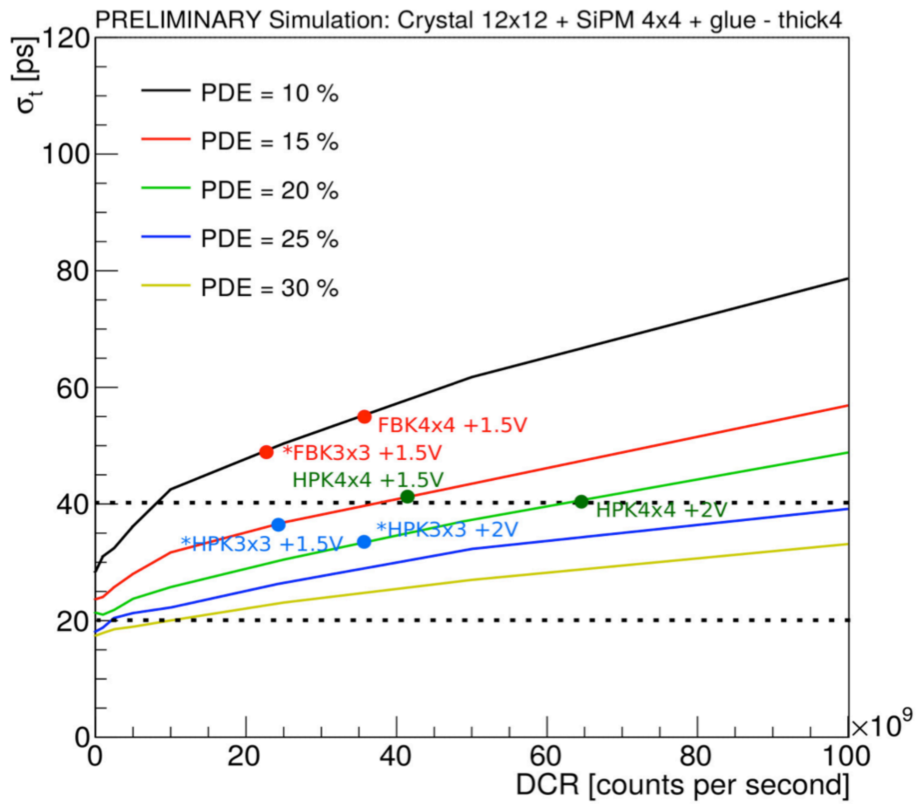


Radiation tolerance of the BTL sensors

- **Radiation at the end of HL-LHC**
  - Fluence: 1.7-2.0×10^{14} n_{eq}/cm^2; Dose: ~18-25 kGy

- **LYSO:** fast, bright scintillator
  - Sufficiently radiation hard

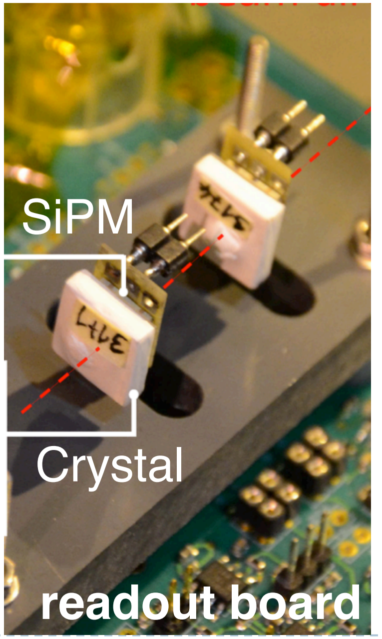
- **SiPM:** existing devices close to 30 ps at end of HL-LHC
  - **Lines**: resolution from simulation varying photon detection efficiency (PDE) and dark count rate (DCR)
  - **Points**: extrapolation to 2.0×10^{14} n_{eq}/cm^2 of SiPMs irradiation studies

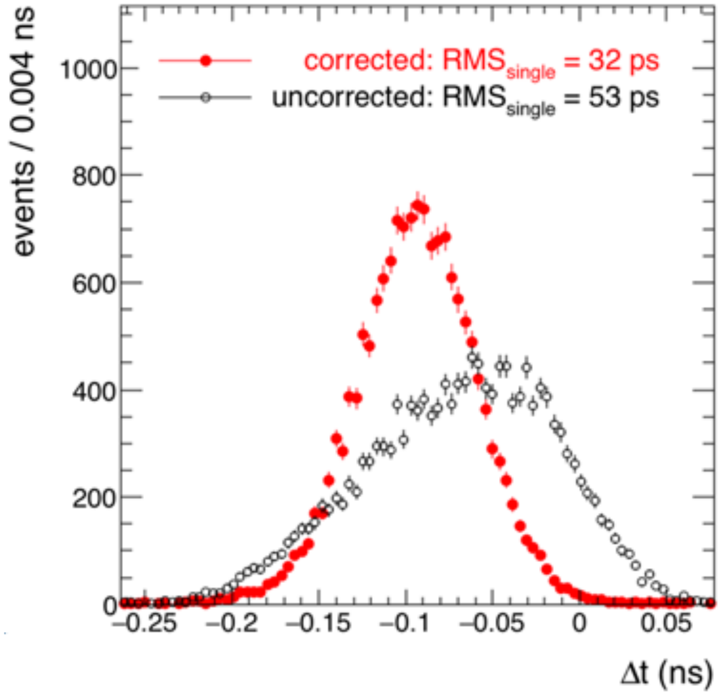


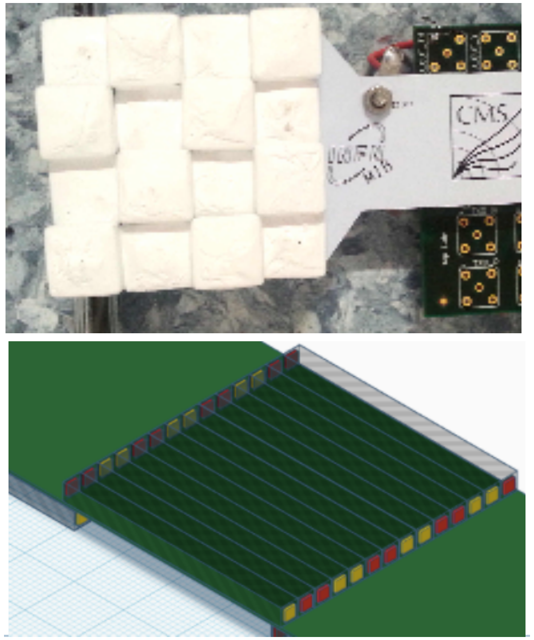
- To optimize: reflective wrappings, SiPMs size / layout, thicker tiles, …

BTL sensor package: time resolution

- **Sensor package qualified in test beams**
  - Nominal geometry: 11x11x4 mm^3 + SiPM 4x4 mm^2
  - Timing dependence on hit position for SiPM small compared to crystal
  - Tracker z resolution sufficient at p_T > 2.0 GeV
- **Options to mitigate position dependence being pursued**
  - Custom SiPM (uniform surface coverage at constant active area)
  - Crystal slabs with double-end read out

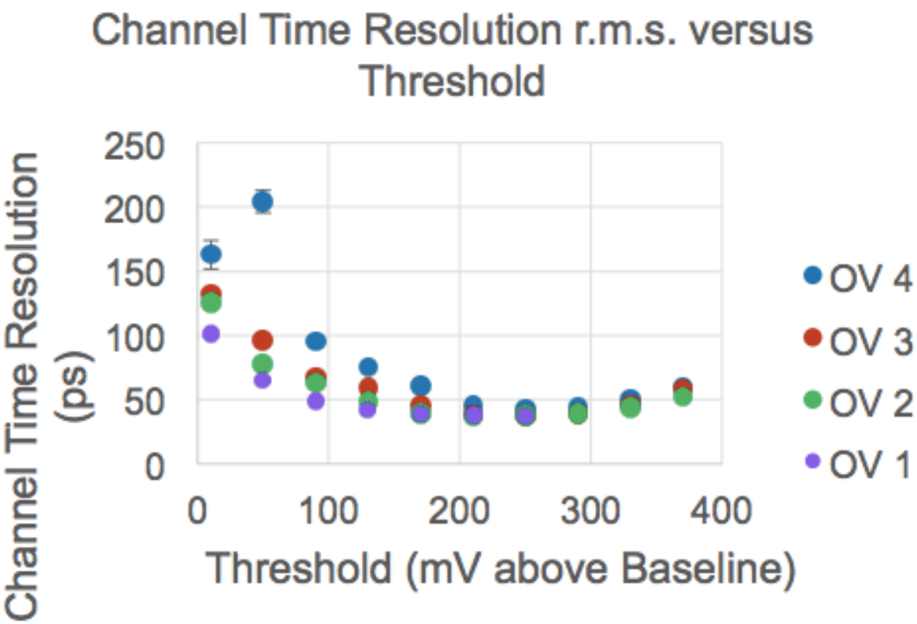






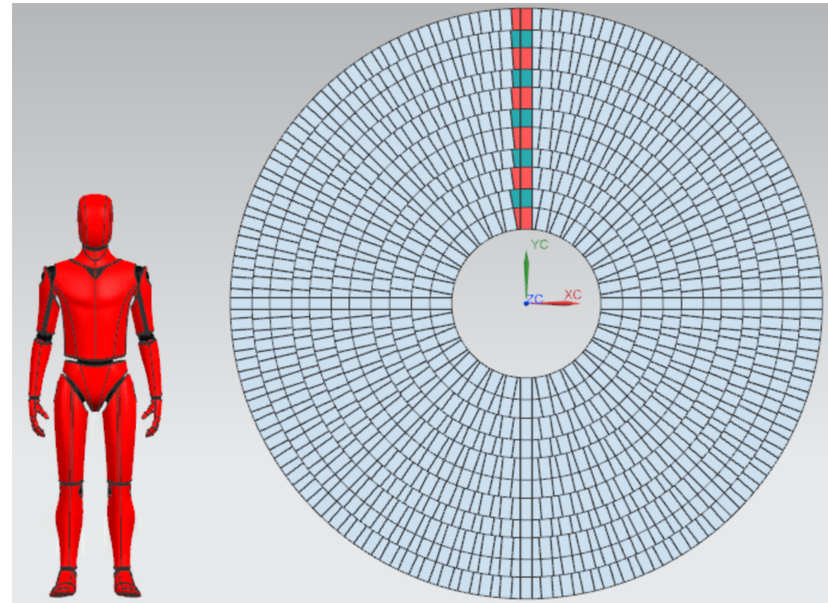
BTL ASIC: TOFHIR

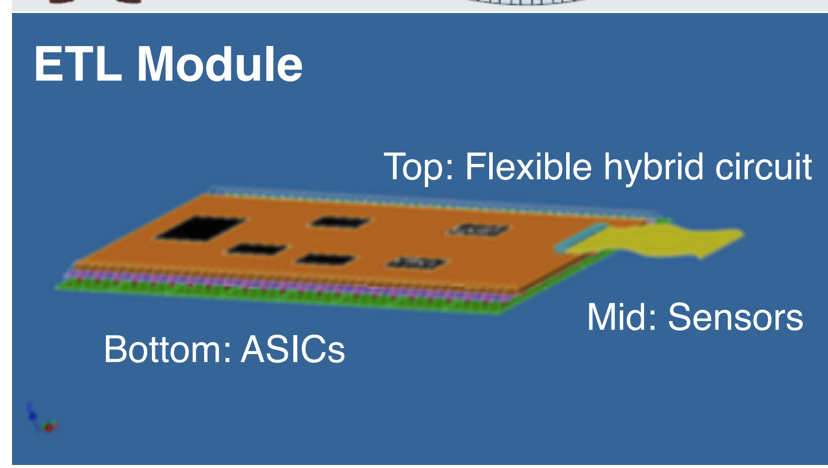
- **TOFHIR: tailored version of commercial TOFPET2 chip**
  - TOFPET2 with sensor package RMS already 37 ps
  - Goal: 25 ps with sensor package (achieved at test beam with NINO)
- **Reasons for the difference understood**
  - Pulse slew rate (amplifier configuration) and TDC contribution
  - Radiation hard design in parallel (TSMC 130 nm)



Endcap timing layer (ETL) layout

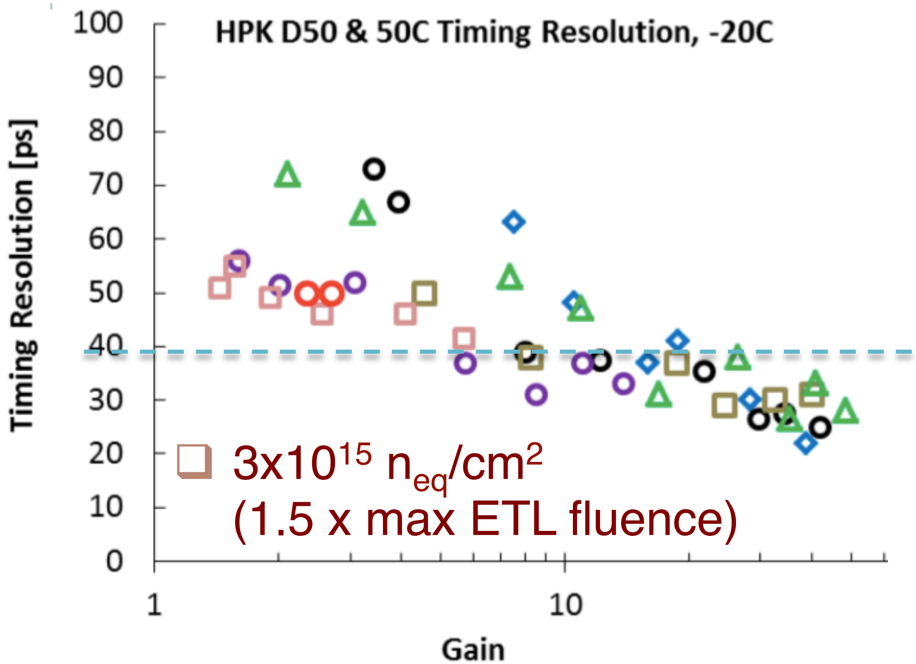
- **Low gain silicon detectors (LGADs):**
  - Established technology available from at least three foundries
- **Overlapping disk structure**
    - Similar to outer tracker
  - Independent cold volume for accessibility
  - Al wedges with embedded cooling pipes (CO_2 cooling at ~ –30 ^{0}C)
- **Sensors on both disk sides**
  - Single layer hermetic coverage
  - Nominal geometry: **4.8 x 9.6 cm^2 modules with 1x3 mm^2 pads**
    - ~3-5% occupancy

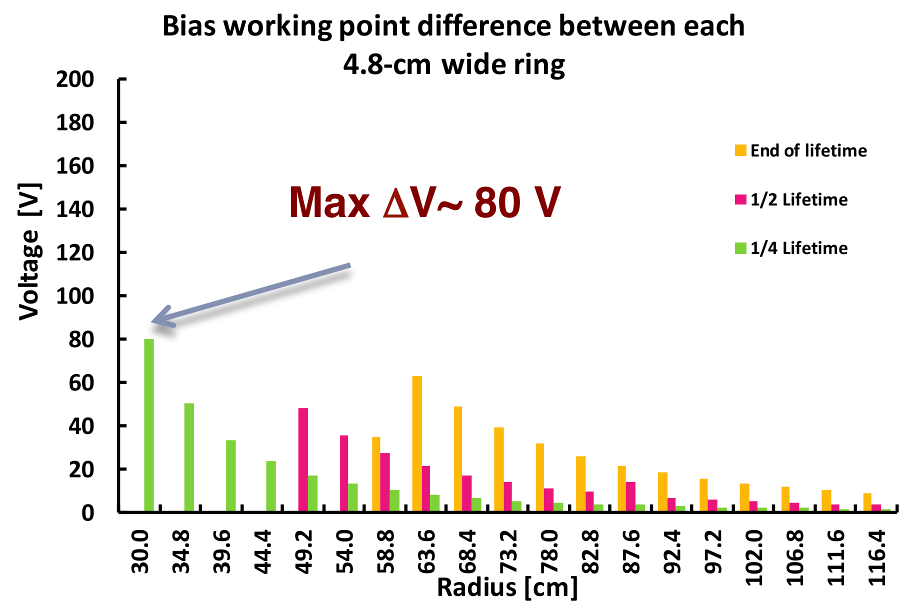




LGAD performance and radiation tolerance

- **Irradiation studies with single pad LGADs:**
  - LGAD can deliver < 40 ps timing resolution for entirety of HL-LHC
  - Compensation of gain loss with increased external bias



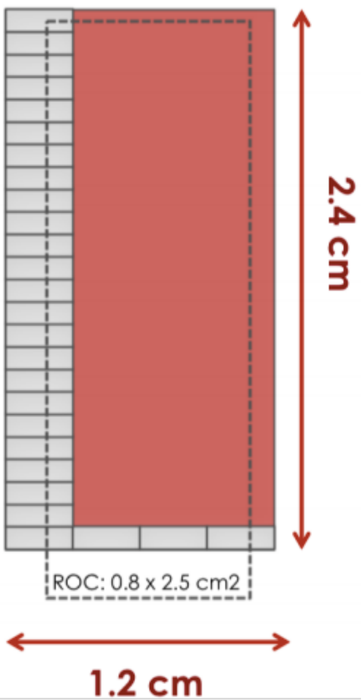


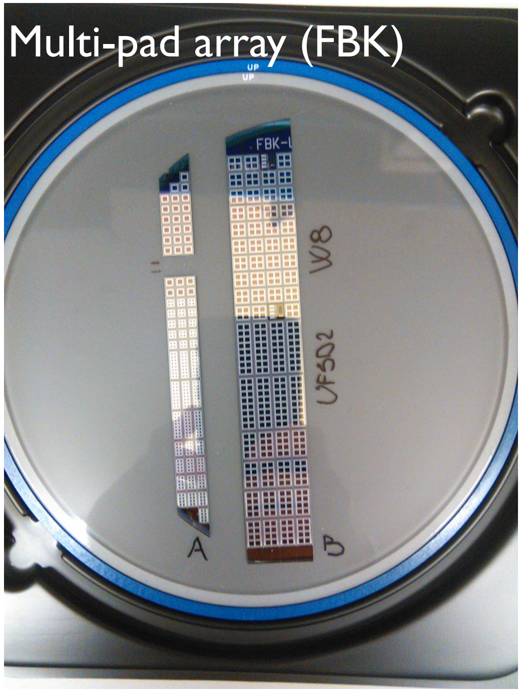
  - R&D: Bias scheme for individual pads
  - R&D: Multi-pad sensors (uniformity, yield, fill factor)

Multi-pad sensor development

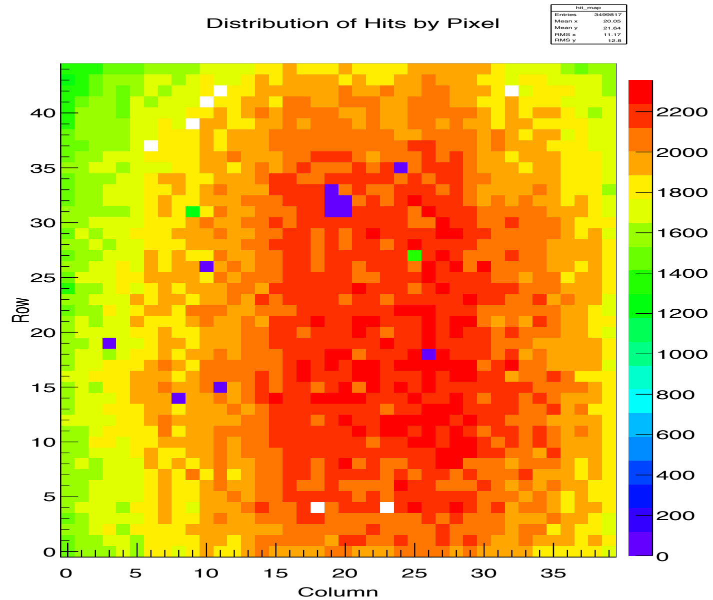
- **Large arrays of LGADs with small pad sizes already possible:**
  - Production of pixelated LGAD sensors show viable pad yields
- **Prototypes of multi-pad sensors with CMS pad size available:**
  - 2x8 arrays now, 4x24 in early 2018 (1/16 of a full sensor)

CMS Pad Geometry





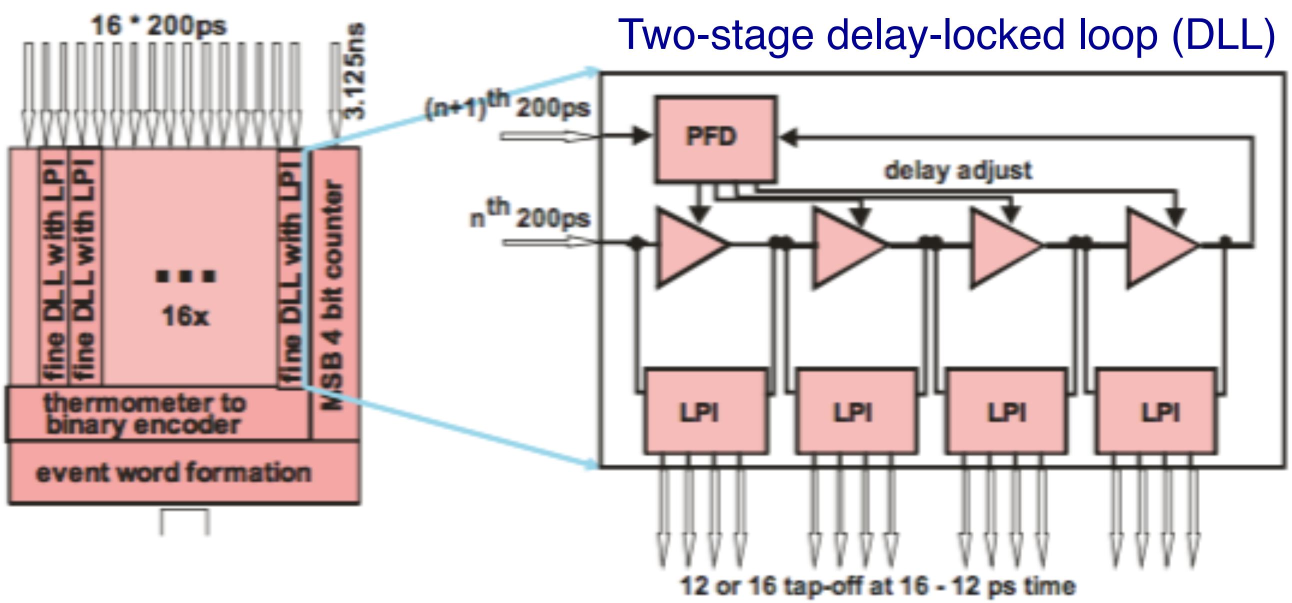
Pixellated LGAD sensor hit-map



1800 pads!

Front-end ETL ASIC

- **Chip specs defined** (25 ps without sensor, 110 mW/cm^2)
  - Cascade of timing measurements to achieve distributed TDC over large-area ASIC
    - Established technology, used already in PicoTDC
    - Layout being designed in 65 nm TSMC benefitting from experience and available common blocks in RD53
- **Simulations ongoing to define layout**



Concluding remarks

- **MTD will benefit the whole physics program**
  - Preserves the performance of Particle Flow and PUPPI
  - Increases effective luminosity: +20% for (di-)Higgs physics
  - Recovers search performance in MET tails
- Benefits equivalent to additional 2-3 years of luminosity
- New capabilities for long-lived particle searches

- **Sensor technologies becoming mature**
- Installation timeline for ETL provides time to complete R&D

- **Further investigations**
- A region-of-interest readout for level one trigger
- Benefit for HLT performance and offline computing
- Ways to extend coverage to $|\eta| < 4.0$