Precision timing for the High Luminosity Upgrade of CMS

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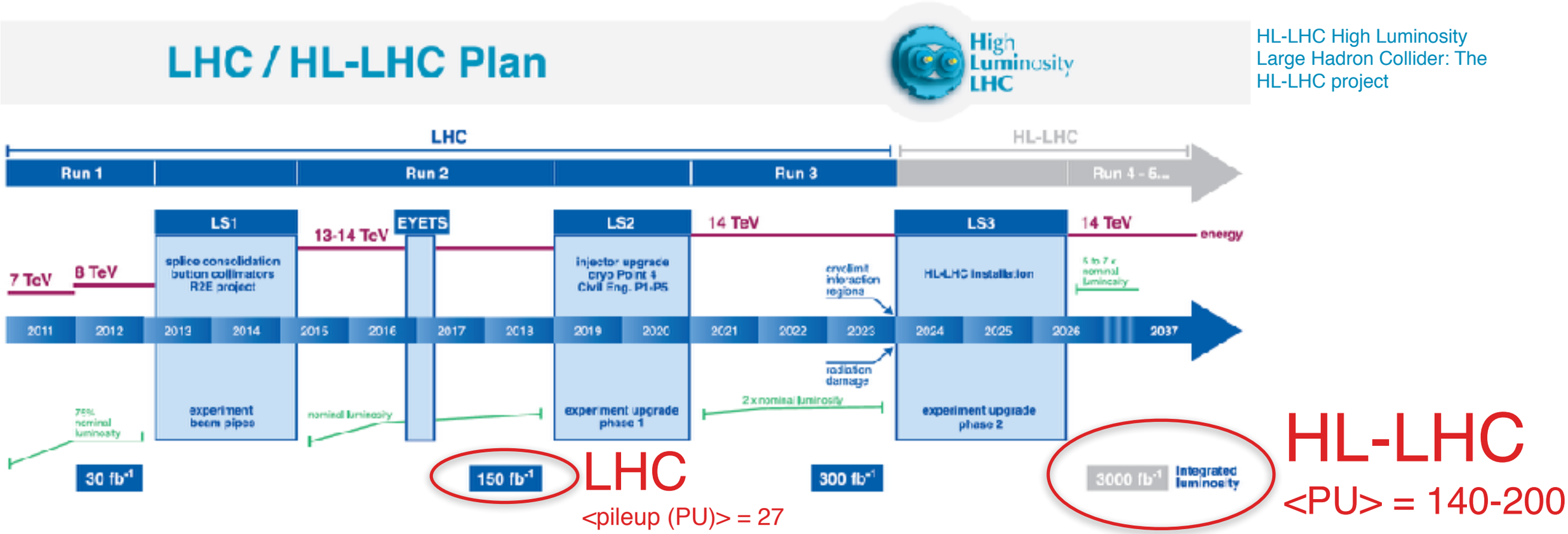
HL-HLC overview



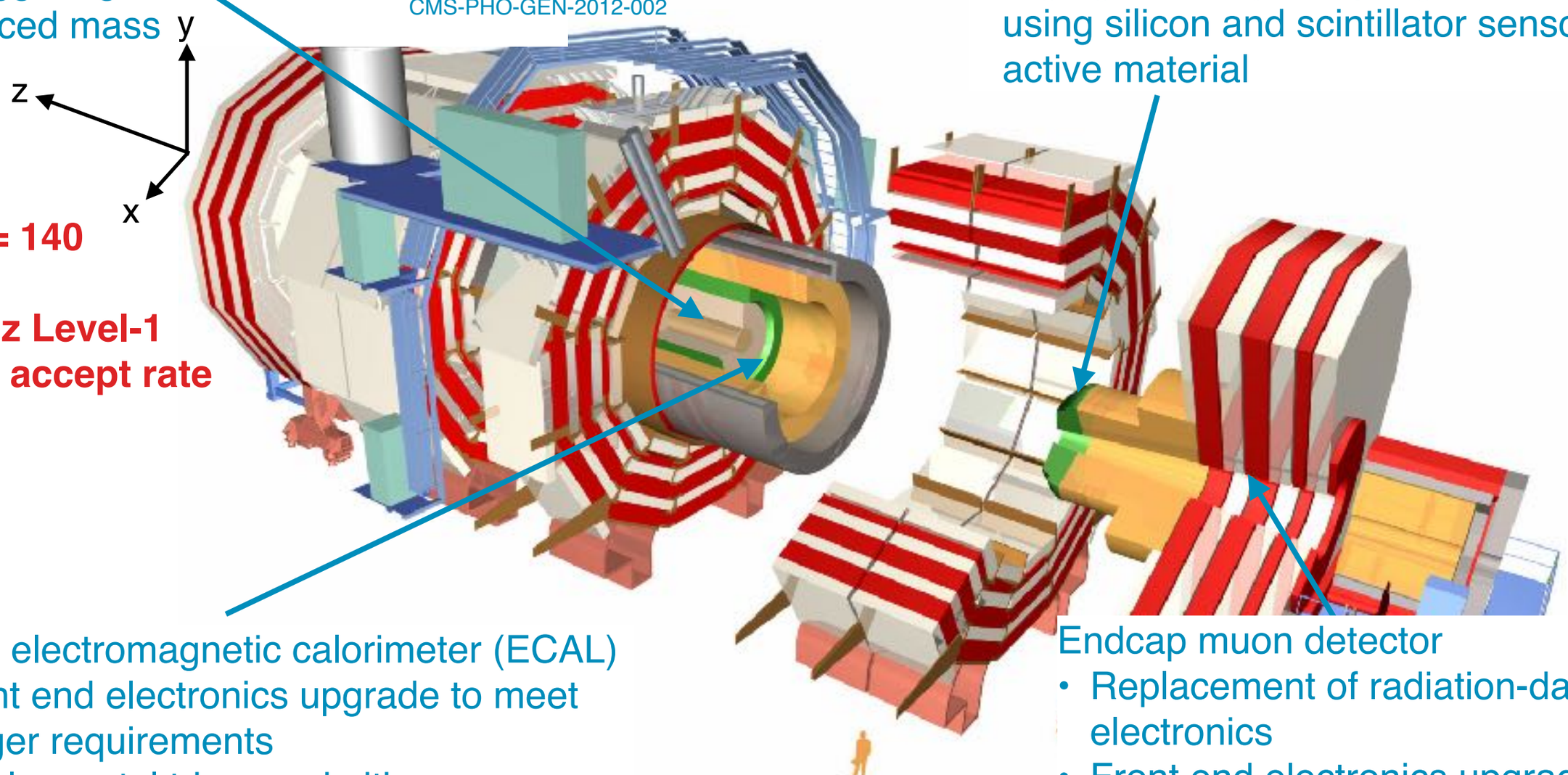
HL-LHC High Luminosity Large Hadron Collider: The HL-LHC project

- Fully exploiting the High Luminosity LHC (HL-LHC) necessitates significant upgrades
  - Higgs studies with better precision, including exotic decay searches
  - Searches for rare heavy particles associated with supersymmetry (SUSY) and other Standard Model (SM) extensions
  - Searches for long-lived or non-interacting particles
- CMS upgrade philosophy: **equal or better performance under HL-LHC conditions**

Current CMS Phase 2 upgrade plan

Silicon tracker
- Full replacement (Si bulk defects)
- 4× increased granularity
- L1 triggering
- Reduced mass

Endcap calorimeter
- Full replacement (light loss)
- High granularity sampling calorimeter using silicon and scintillator sensors as active material



<PU> = 140

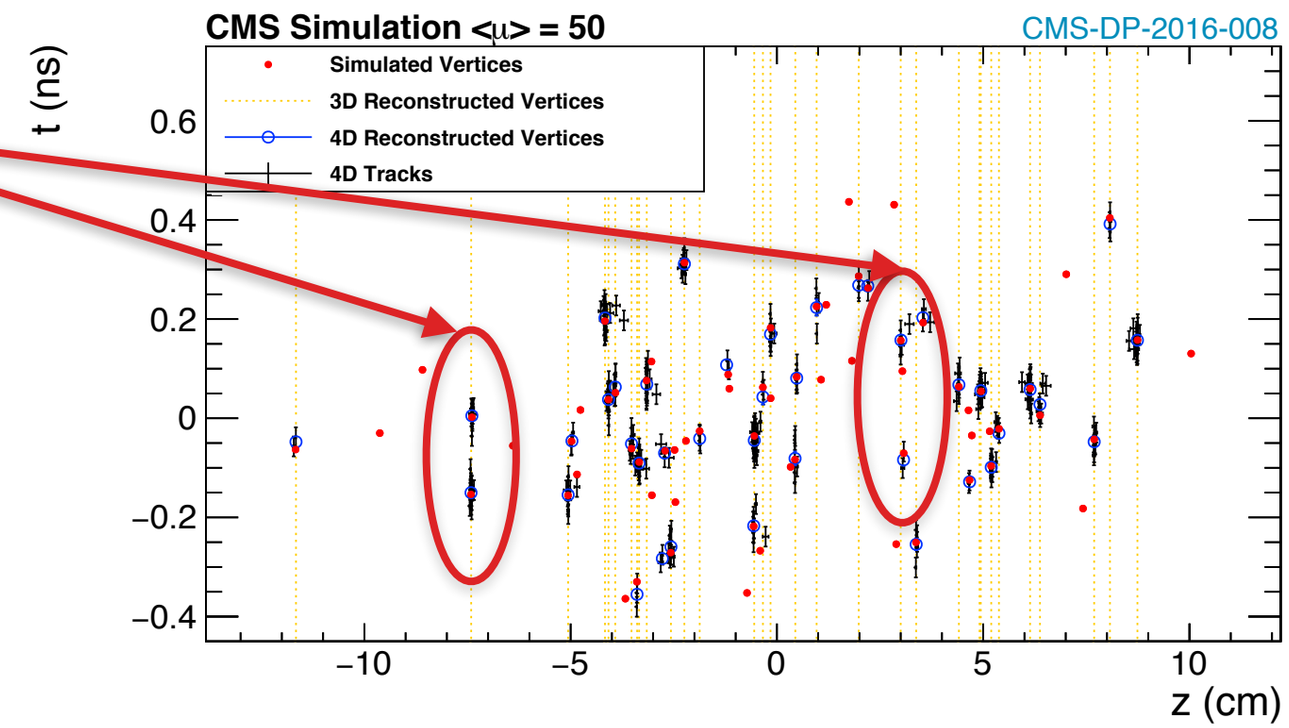
750 kHz Level-1 trigger accept rate

Barrel electromagnetic calorimeter (ECAL)
- Front end electronics upgrade to meet trigger requirements
- Single crystal trigger primitives
- Cooling to 8°C to reduce dark-current-induced noise

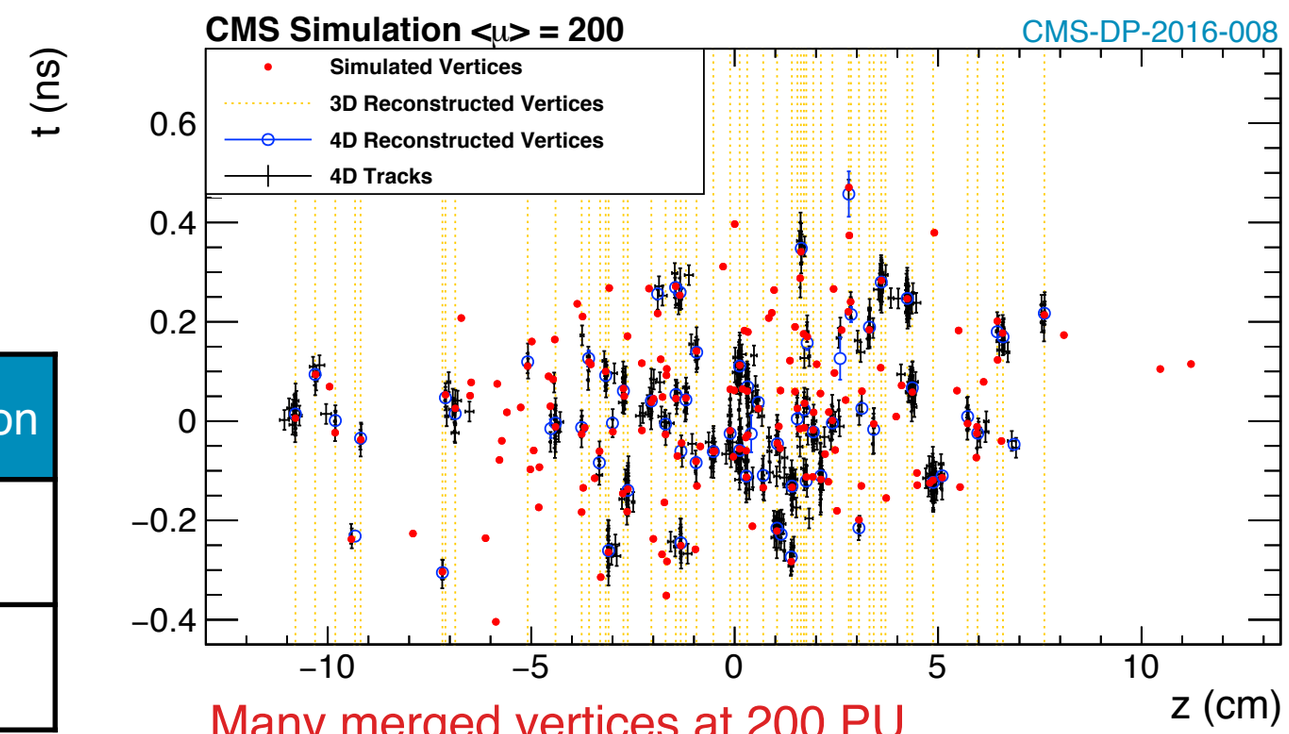
Endcap muon detector
- Replacement of radiation-damaged electronics
- Front end electronics upgrade to meet trigger requirements
- Increased redundancy
- Possible extension to higher η

Vertex merging at high PU

Few merged vertices at 50 PU



- Current CMS detector upgrades address increased pileup with increased channel granularity
- In 140-200 PU events, granularity may not be enough

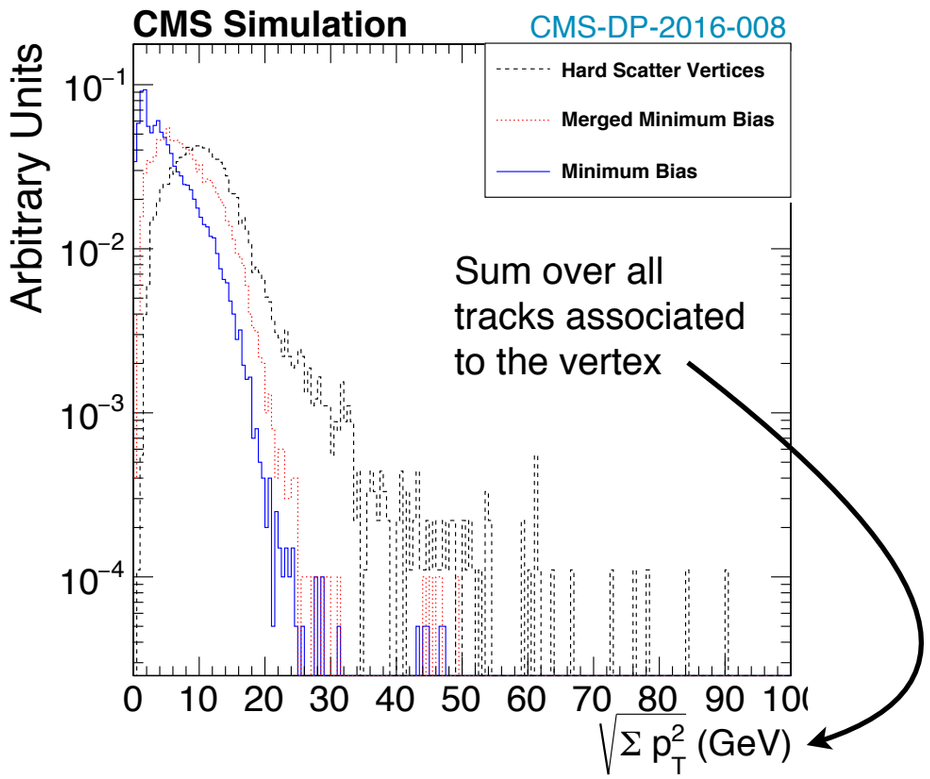


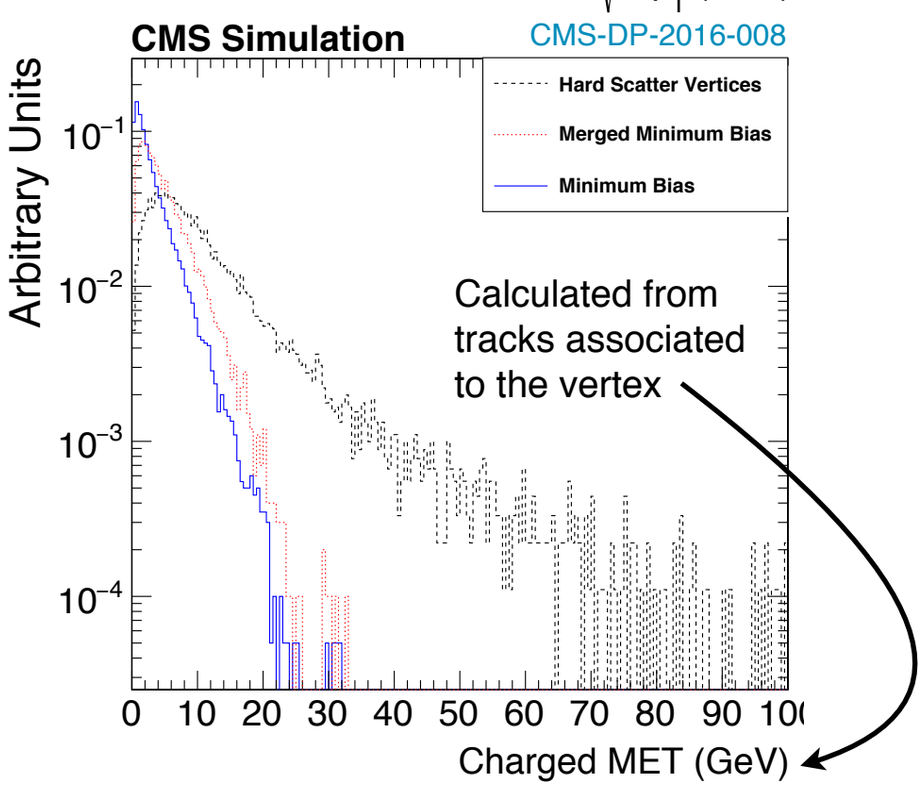
Many merged vertices at 200 PU

<PU>	3D merged vertex fraction
50	3.3%
200	13.4%

CMS-DP-2016-008

Effects of vertex merging





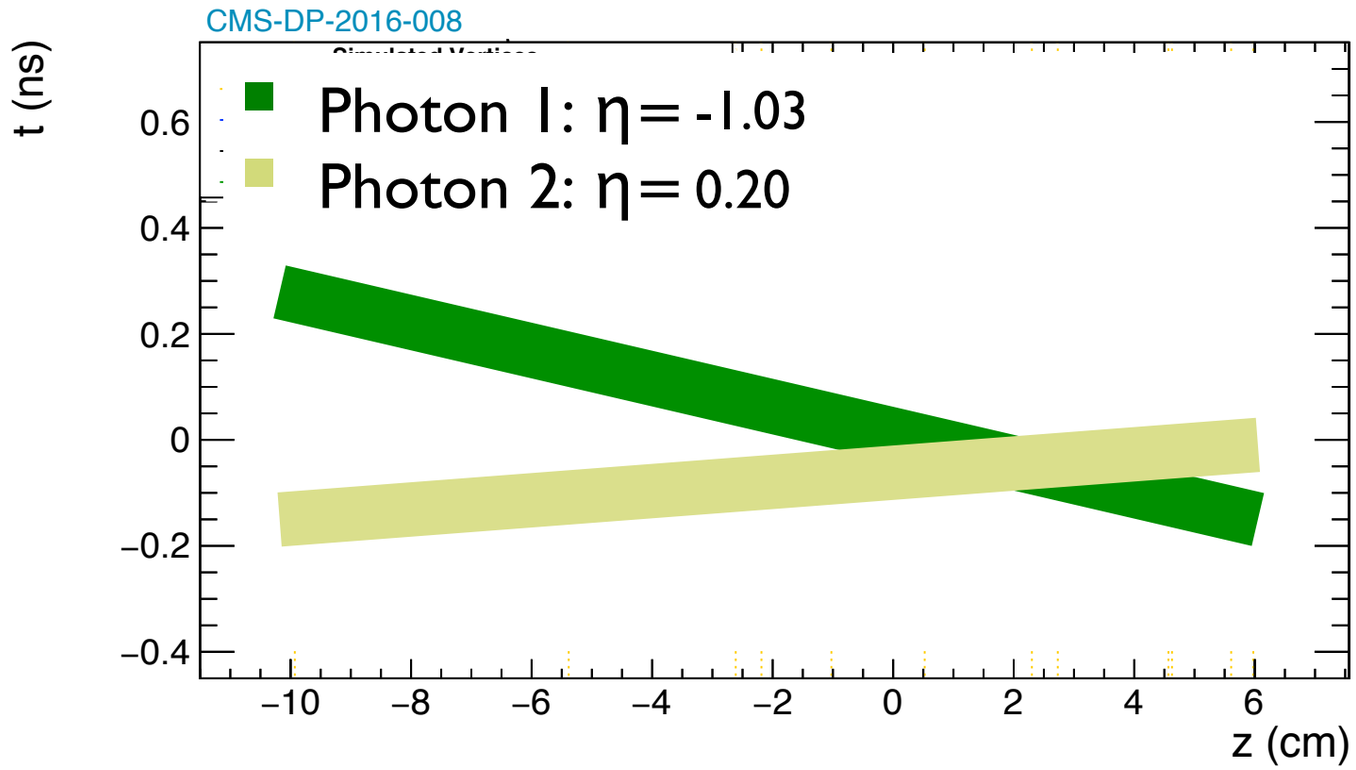
- Track associated to wrong primary or secondary vertex
  - Jet identification suffers
  - Wrong isolation energy sum calculated → photon and lepton identification suffers
- Vertex with highest activity incorrectly identified → diphoton mass resolution suffers
- All effects lead to a degradation of jet and missing transverse energy (ME_T) resolution
- **All effects increase the trigger bandwidth consumed by uninteresting PU interactions**

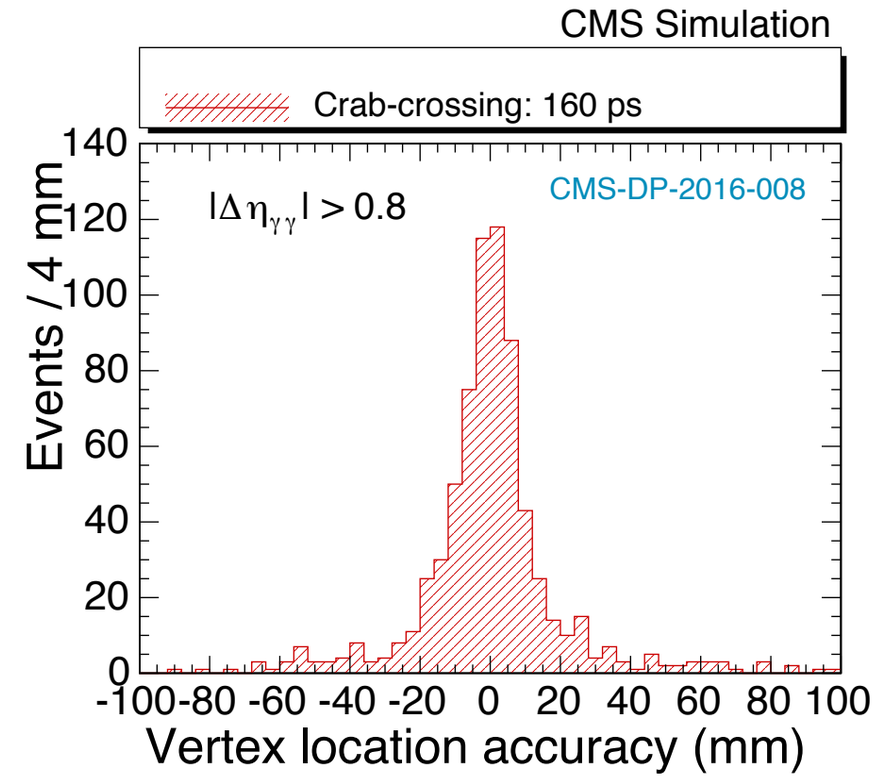
Blue solid: minimum bias
Black dashed: Z→μμ hard scatter
Red dotted: minimum bias with 100% 2→1 vertex merging

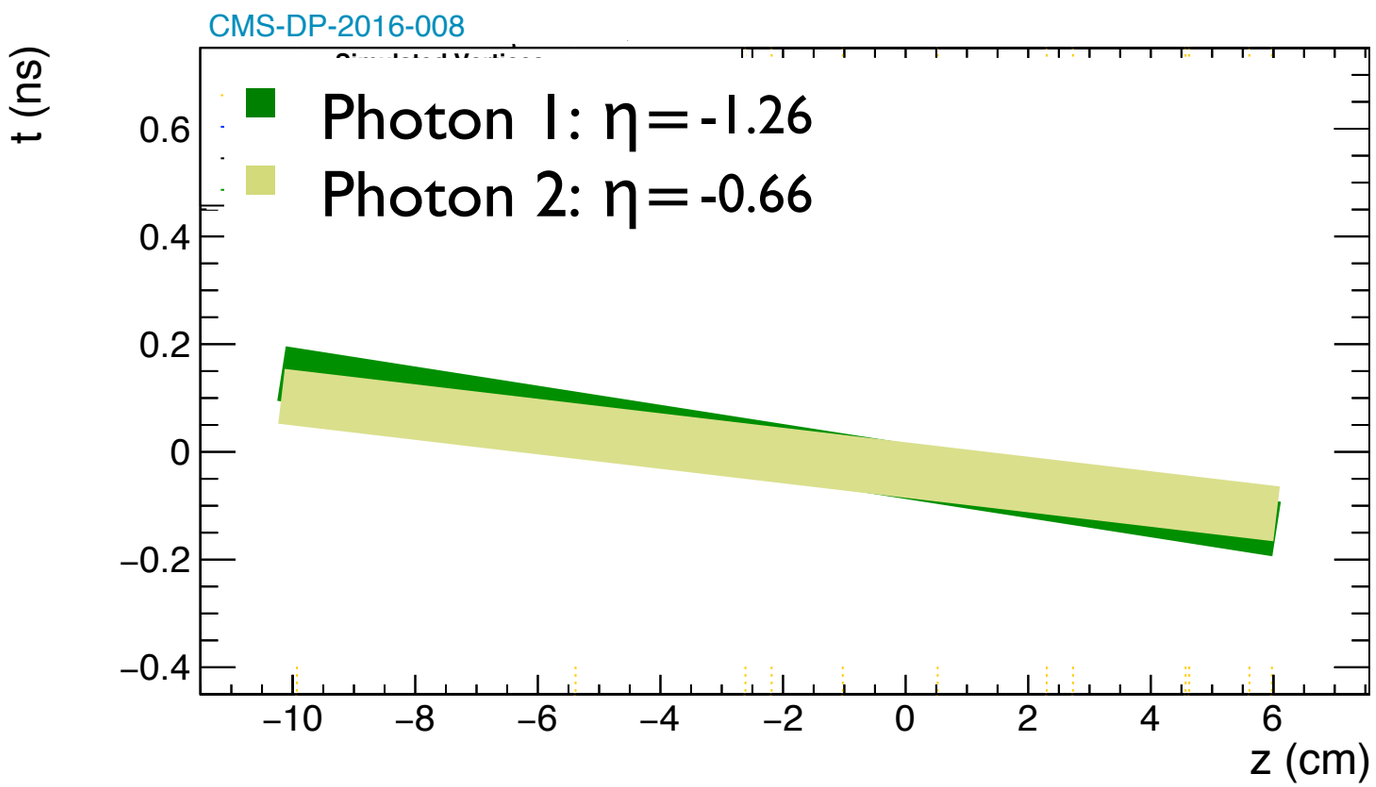
Partial mitigation with upgrade detector

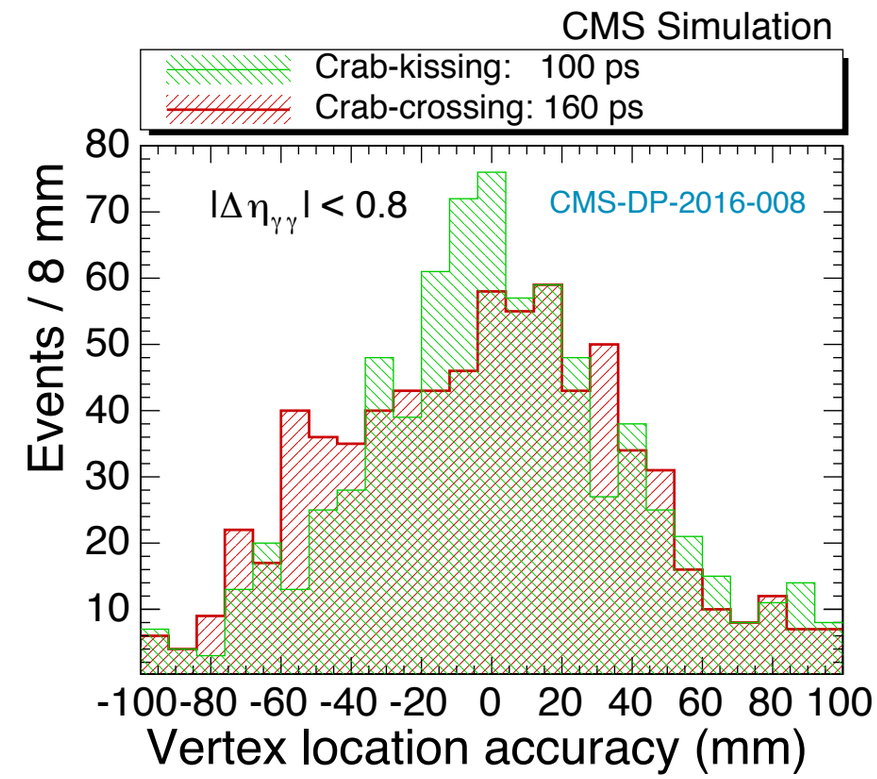
- $H \rightarrow \gamma\gamma$ events
- Assumed 30 ps time resolution on high energy photons from Higgs decay
- Vertex z position estimated from timing of two candidate Higgs decay photons
- Phase 1 performance: 10 mm precision on vertex location *accuracy*, i.e. 10 mm Gaussian spread in |true vertex z - reconstructed vertex z|

Partial mitigation with upgrade detector

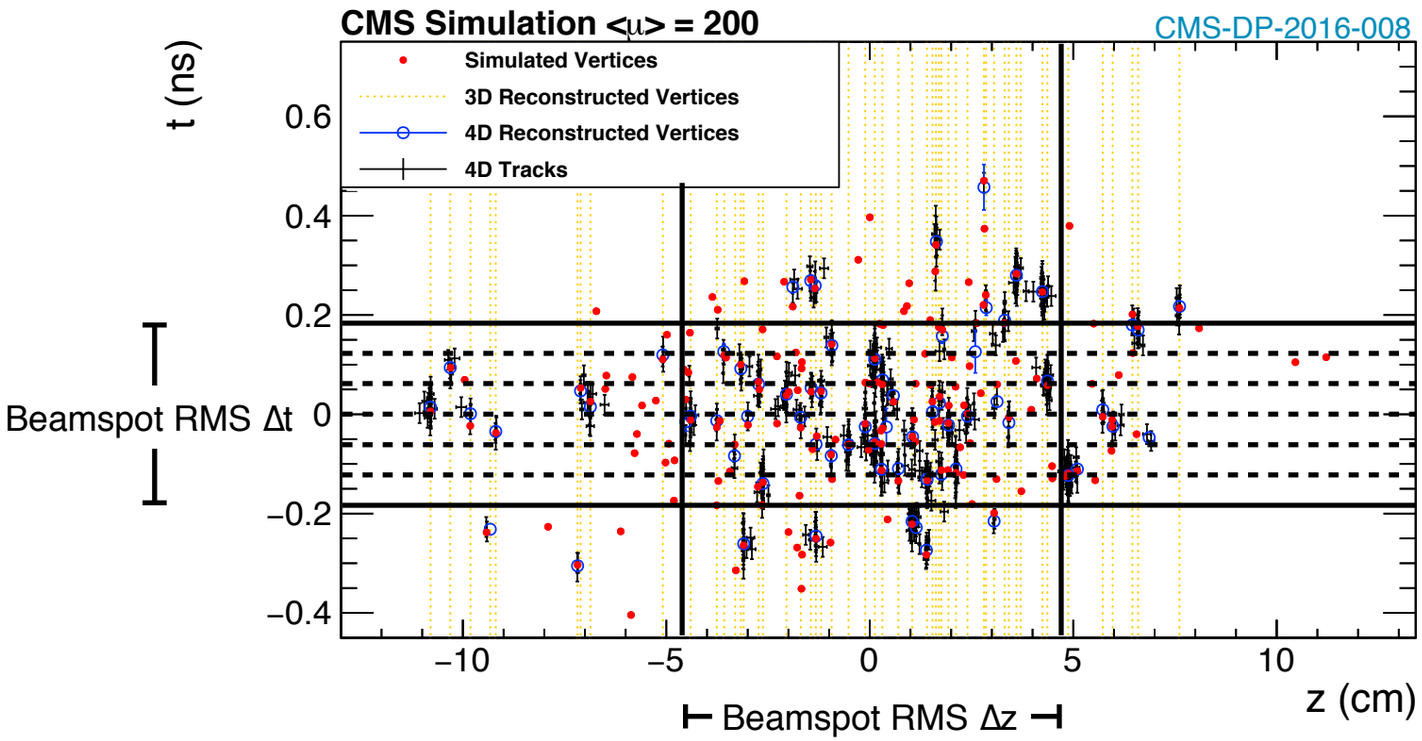








Need for additional timing information

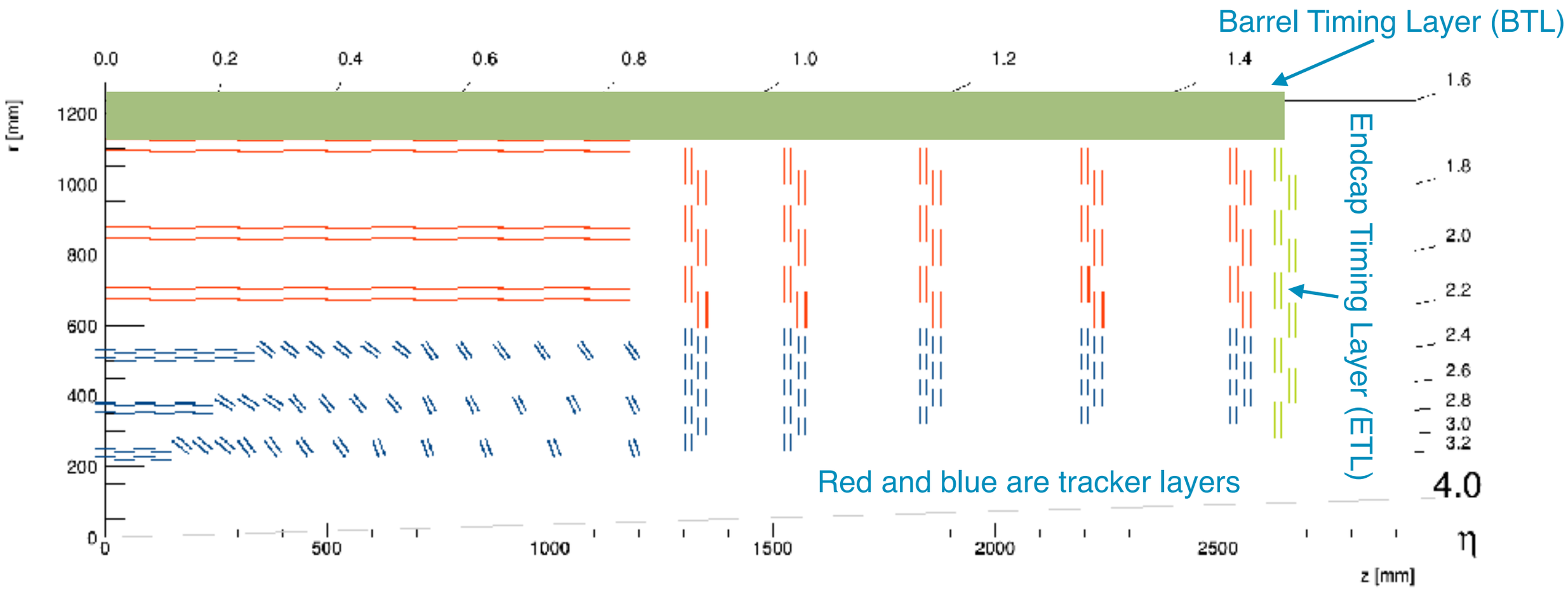


CMS-DP-2016-008

<PU>	3D merged vertex fraction	4D merged vertex fraction
50	3.3%	0.5%
200	13.4%	1.5%

- **Equal or better performance under HL-LHC conditions** may not be achievable without more effective PU rejection
- Precision timing of minimum ionizing particles (MIPs) adds a crucial independent handle on PU identification
  - **30 ps MIP timing resolution** effectively reduces PU in the 180 ps beamspot
  - Merged vertex rate reduced to ~current level
  - Isolation and jet ID performance comparable to current detector

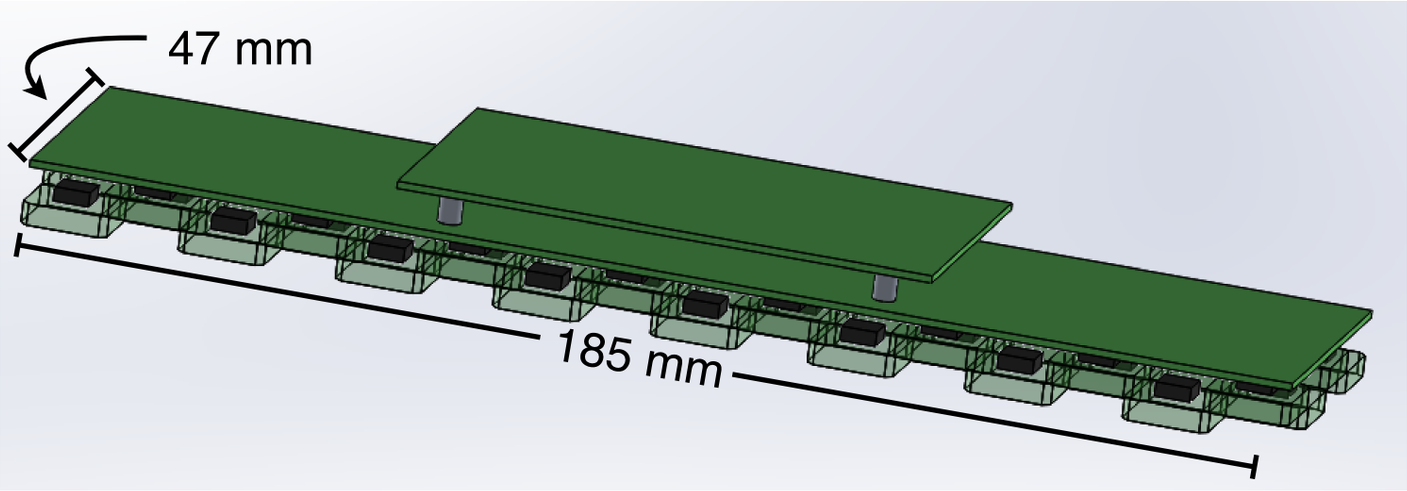
Technologies under consideration

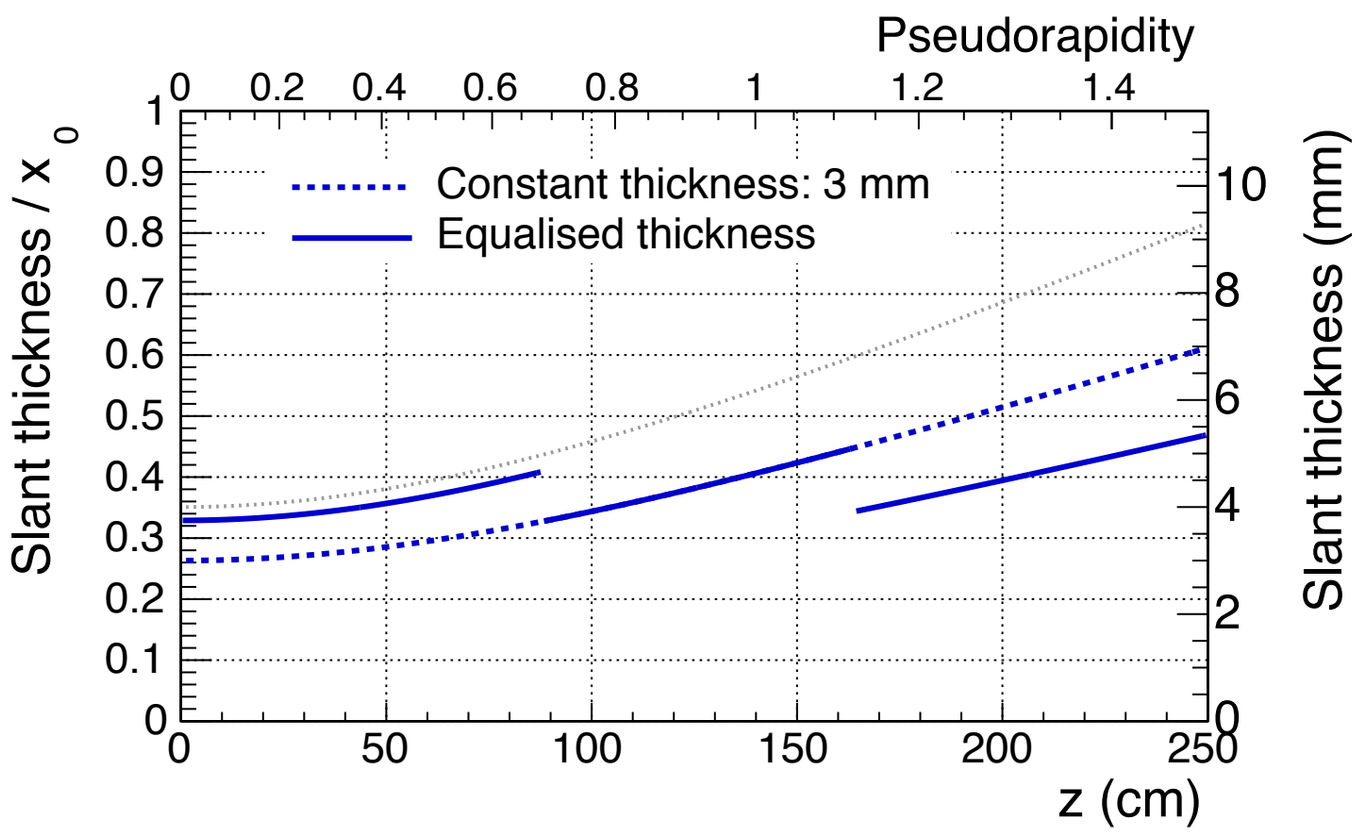


- In front of ECAL barrel (EB)
  - LYSO:Ce scintillating crystal layer
  - Silicon photomultiplier (SiPM) readout
- In front of ECAL endcap (EE)
  - Silicon low gain avalanche detector (LGAD)
  - Readout via bump bonded custom chip

Recall M. M. Obertino's talk on Tuesday

BTL mechanics

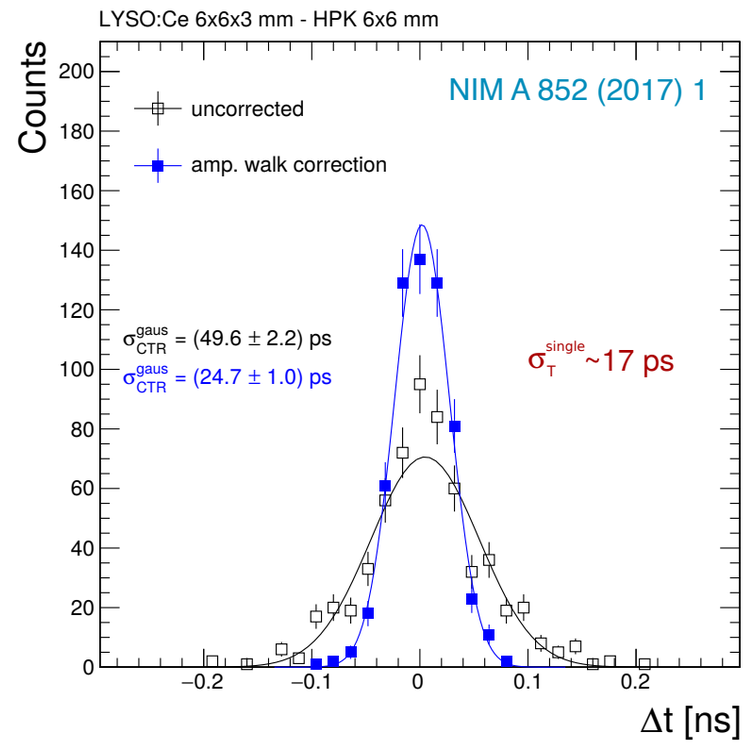


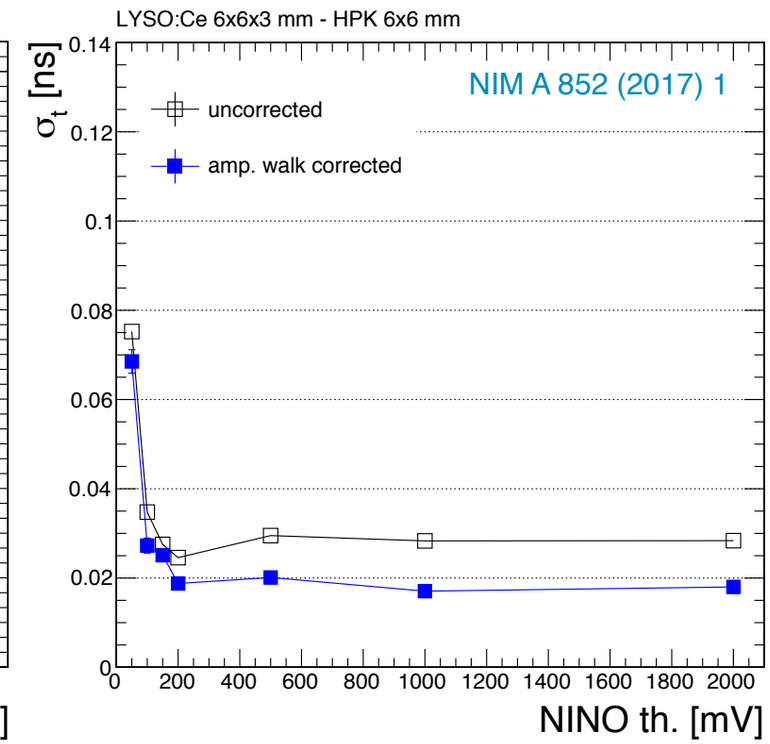


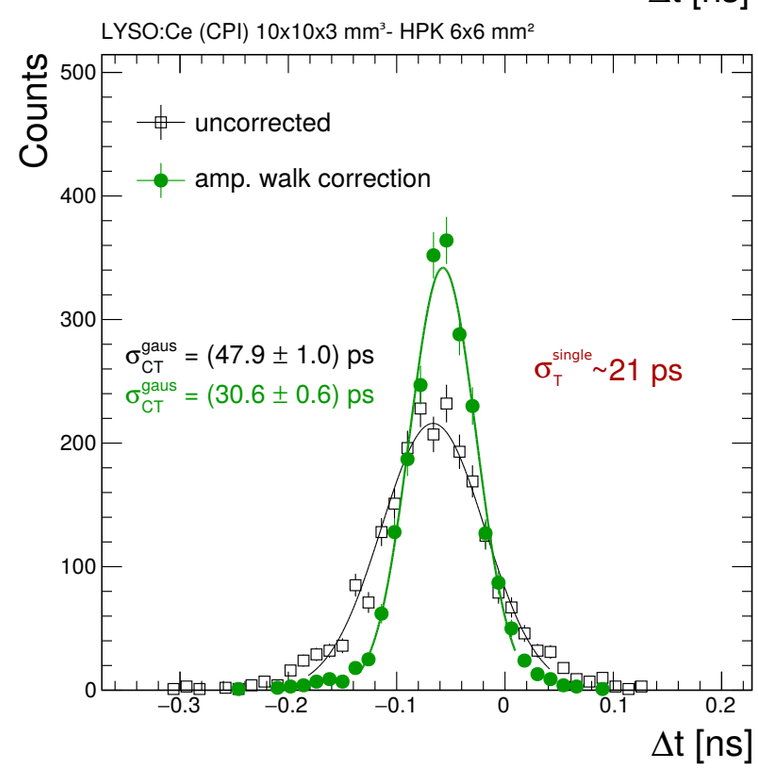
- 2.40-3.75 mm thick LYSO:Ce crystal with 12 × 12 mm^2 cross section glued to 4 × 4 mm^2 SiPM
  - Occupancy < 3% with 0.5 MIP threshold per channel
  - 1 MIP ~ 5k pe
- Tile thickness decreases with increasing |η| to maintain uniform material budget
- Cracks between tiles minimized with 0.5 mm edge overlap
- CO_2 cooling to -30°C to mitigate SiPM dark current

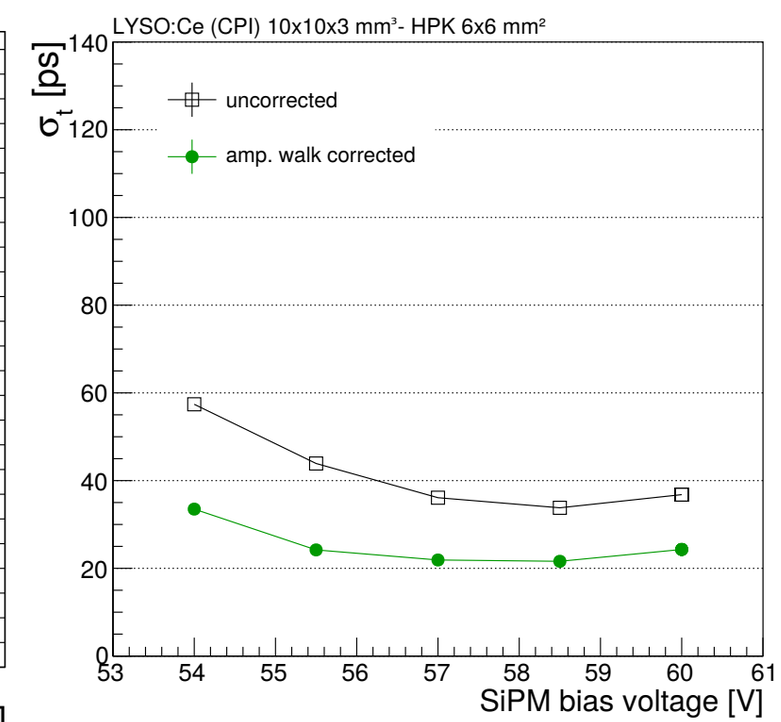
BTL tile time resolution

- Coincidence time resolution (CTR) measured in 150 GeV muon beam at CERN
- Δt measured between 2 LYSO/SiPM tiles ⇒ single-tile time resolution = CTR/√2
- Timewalk corrected **single-tile resolution better than 25 ps** in 2 different geometries

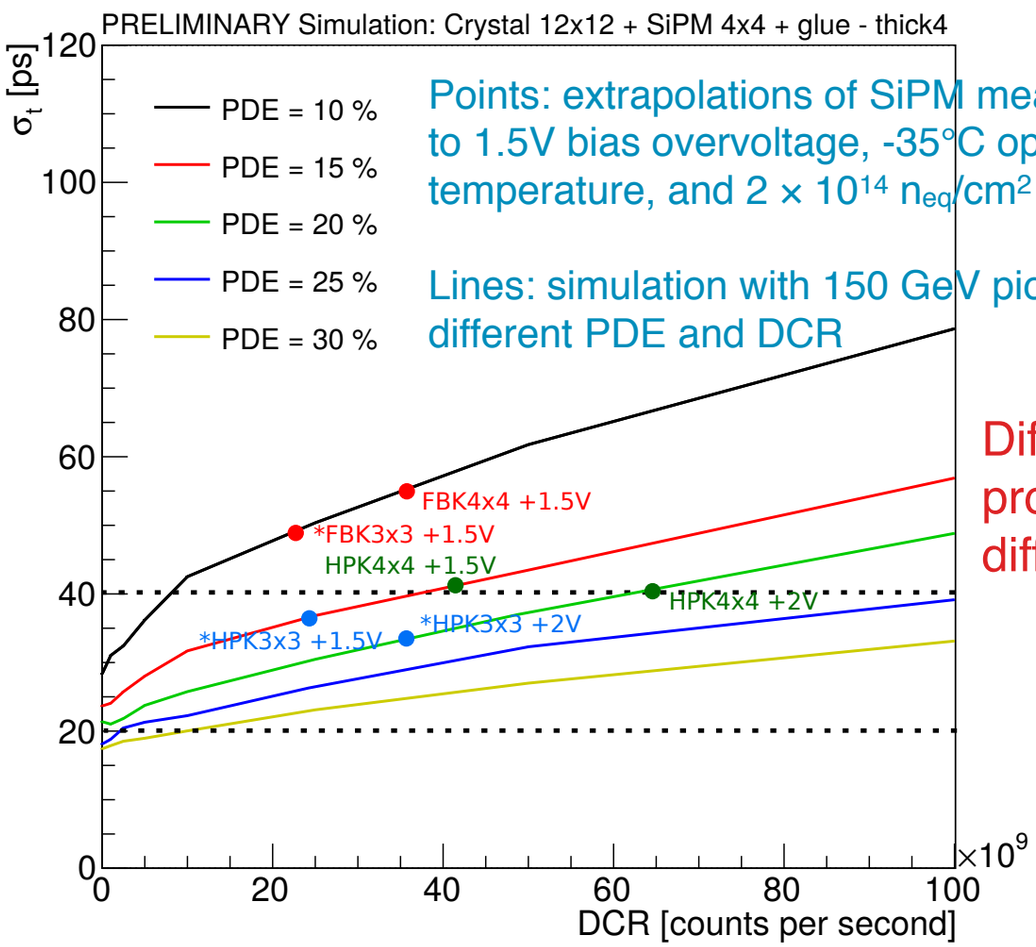








BTL tile radiation hardness



Points: extrapolations of SiPM measurements to 1.5V bias overvoltage, -35°C operating temperature, and 2×10^{14} n_{eq}/cm^2

Lines: simulation with 150 GeV pions for different PDE and DCR

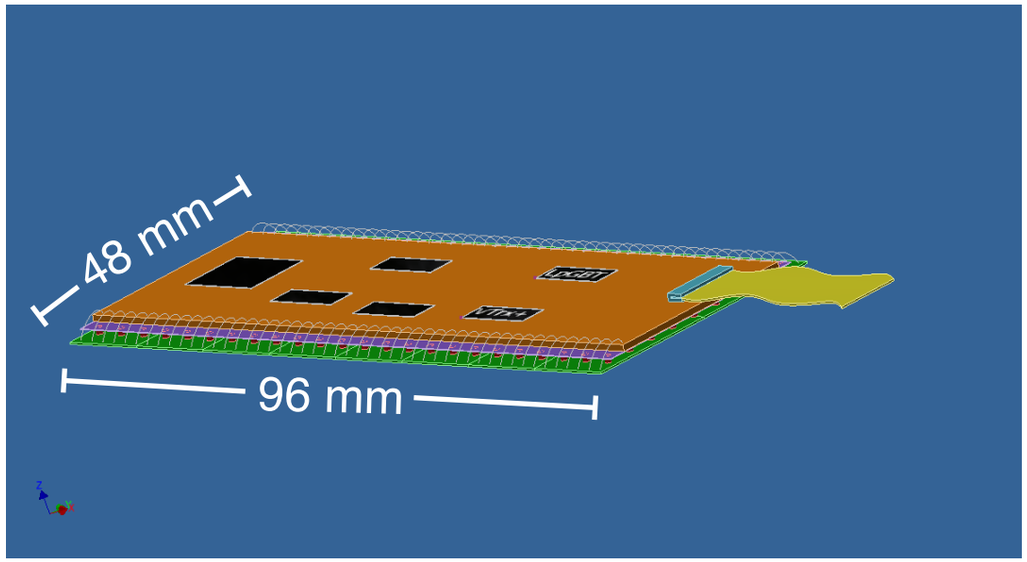
Different "end-of-life" properties for different SiPMs

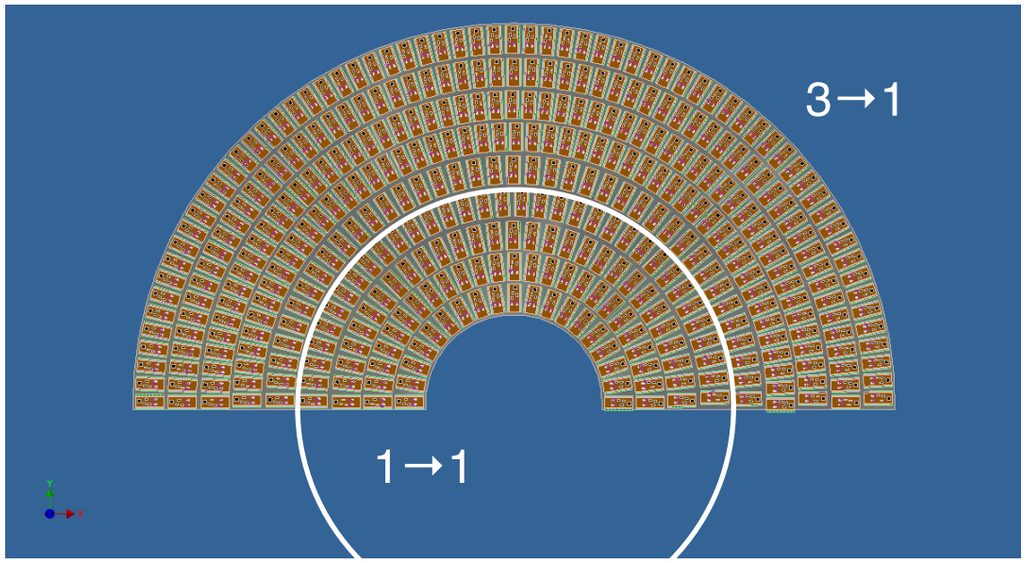
Parameter	Spec	FBK	FBK	HPK	HPK
Area	> 9 mm^2	16 mm^2	9 mm^2	16 mm^2	9 mm^2
Cell pitch	-	12.5μm	12.5μm	15μm	15μm
Number of cells	> 30k	> 100k	> 56k	> 71k	> 39k
PDE	$> 10\%$	10%	10%	15%	15%
Operating voltage	-	34V	34V	40V	40V
Current/device	-	0.7 mA	0.4 mA	1.3 mA	0.7 mA
Power consumption	< 57 mW	25 mW	14 mW	52 mW	29 mW
Gain	$> 10^5$	0.8×10^5	0.8×10^5	1.8×10^5	1.8×10^5
DCR/device	< 70 GHz	41 GHz	23 GHz	43 GHz	24 GHz

PDE = photon detection efficiency

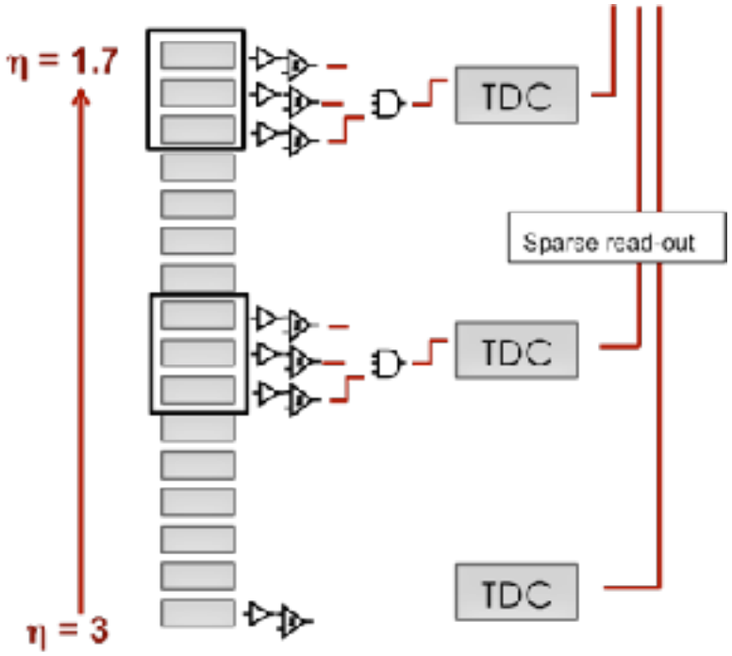
- $1.3\text{-}1.6 \times 10^{14}$ n_{eq}/cm^2 and 20 kGy expected after 10 years of HL-LHC operation
- Radiation-induced absorption coefficient (RIAC) at 2×10^{14} p/cm^2 ~ 3 m^{-1} ⇒ not a problem for 3 mm tiles
- Relative light loss ~10% at 100 kGy exposure
- Time resolution degradation from increased SiPM dark count rate (DCR): ~20 ps → ~40 ps
- Room for optimization: reflective wrappings, smaller SiPMs, thicker tiles

ETL mechanics





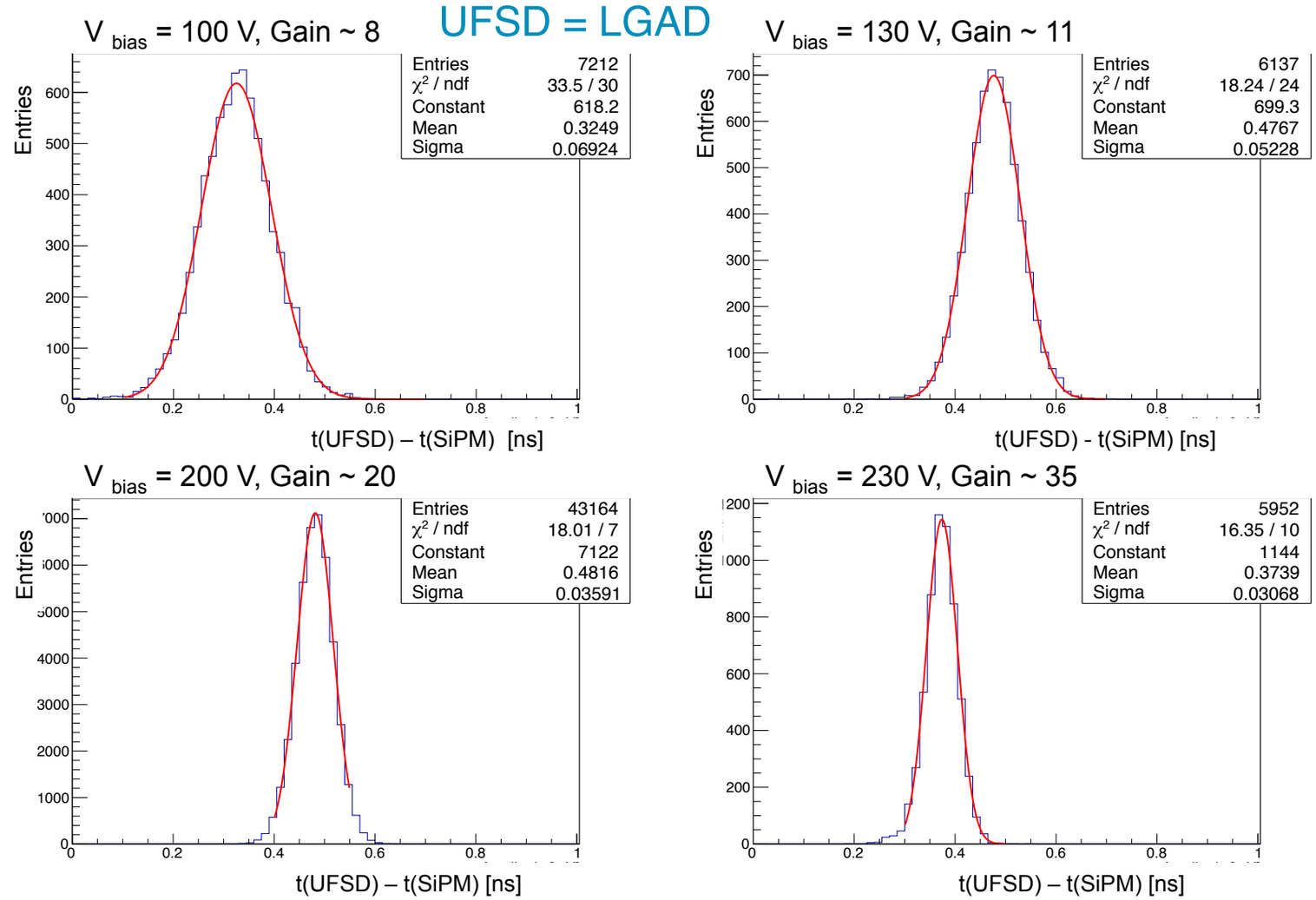
- LGAD concept
  - Extra p^+ doping layer locally generates high electric fields for charge multiplication (gain ~ 20)
  - Thin sensor (50 µm) insures fast rise time
  - Both effects increase slew rate and time resolution
- 1 × 3 mm^2 LGAD pixels on 48 × 96 mm sensors
  - Occupancy <5%
  - Capacitance 7 pF
- 3→1 pixel ganging at low |η| after comparator stage
- CO_2 cooling to -30°C to mitigate dark current



ETL time resolution

- CTR measured in 180 GeV pion beam at CERN
- Δt measured between pairs of LGADs and between LGAD and SiPM
- For V_{bias} > 200 V, **single LGAD time resolution better than 35 ps**

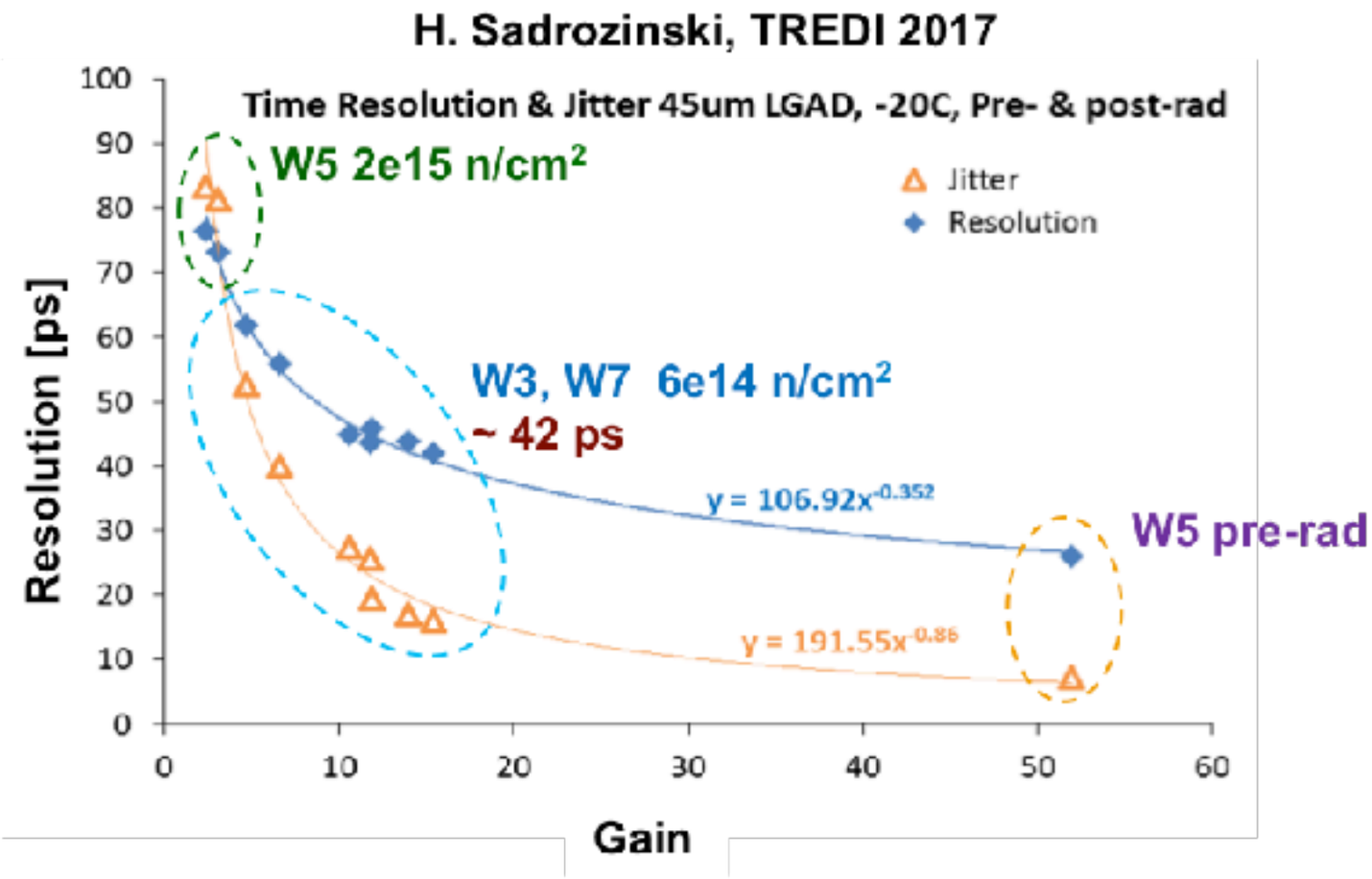
UFSD = LGAD

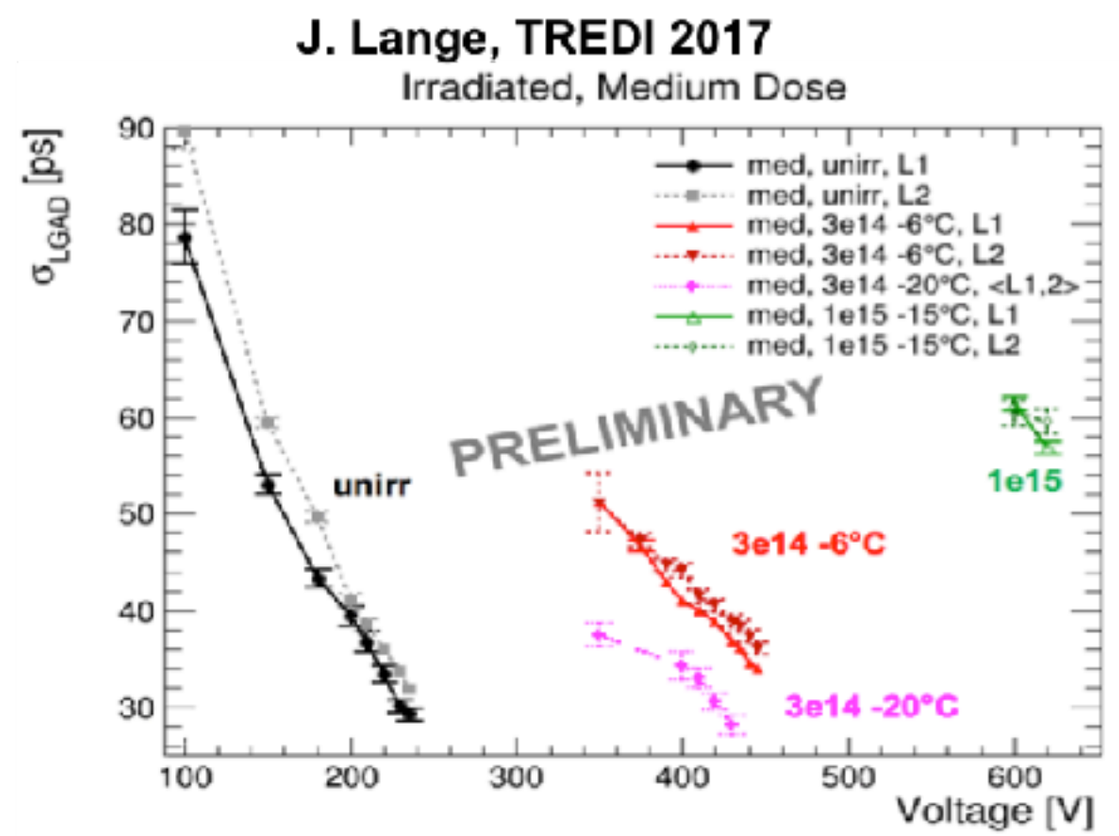


NIM A 850 (2017) 83 NIM A 850 (2017) 83

V bias [V]	200V	230V
$\sigma_t(N=1)$	34.1 ps	27.4 ps
$\sigma_t(N=2)$	24.2 ps	19.8 ps
$\sigma_t(N=3)$	19.9 ps	16.4 ps

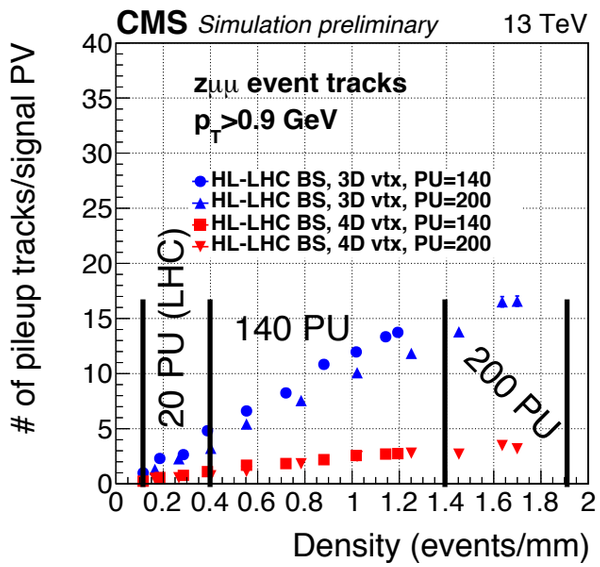
ETL sensor radiation hardness

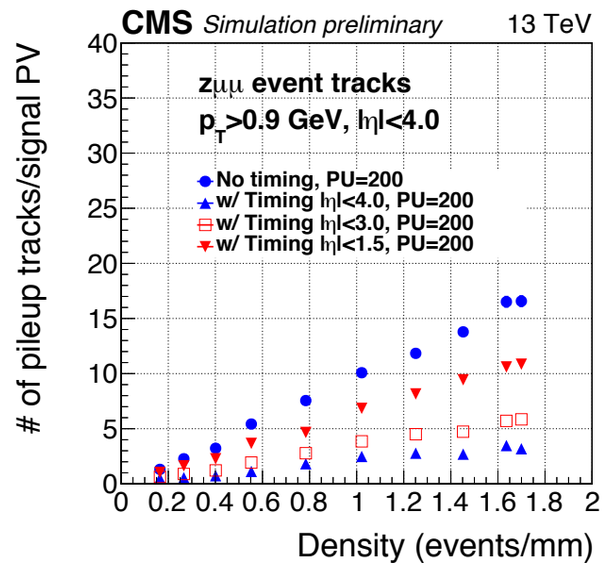


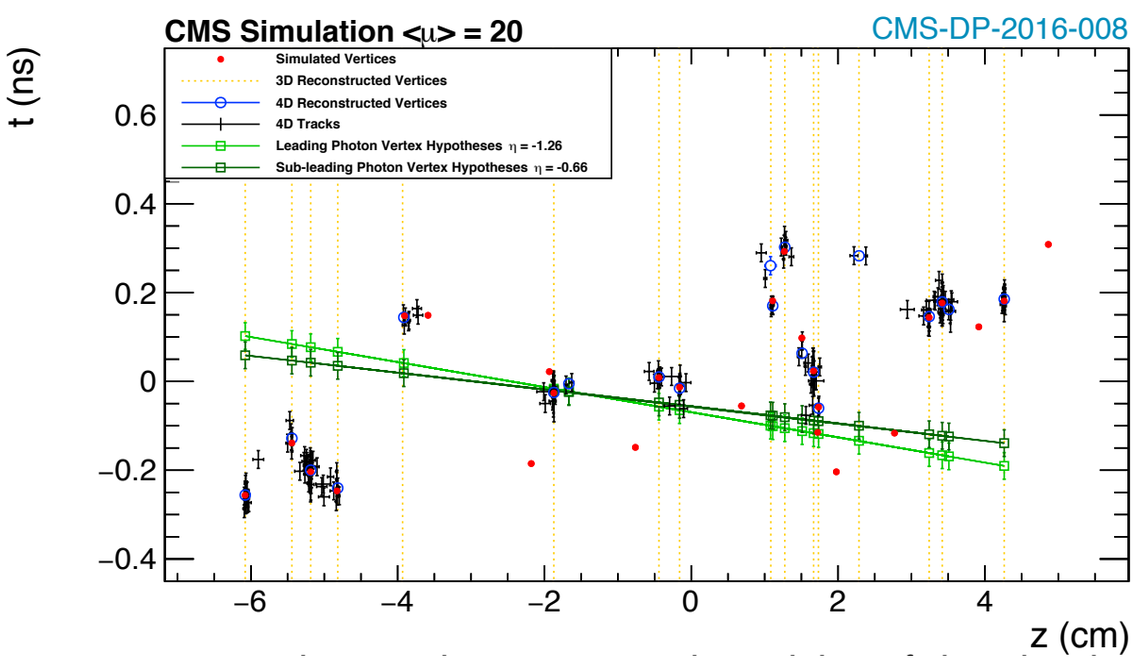


- Maximum expected HL-LHC fluence: 1×10^{15} n_{eq}/cm^2
- Gain decreases with irradiation, worsening time resolution as expected (slower slew rate)
- Timing performance can be recovered with higher bias voltage

4D vertexing

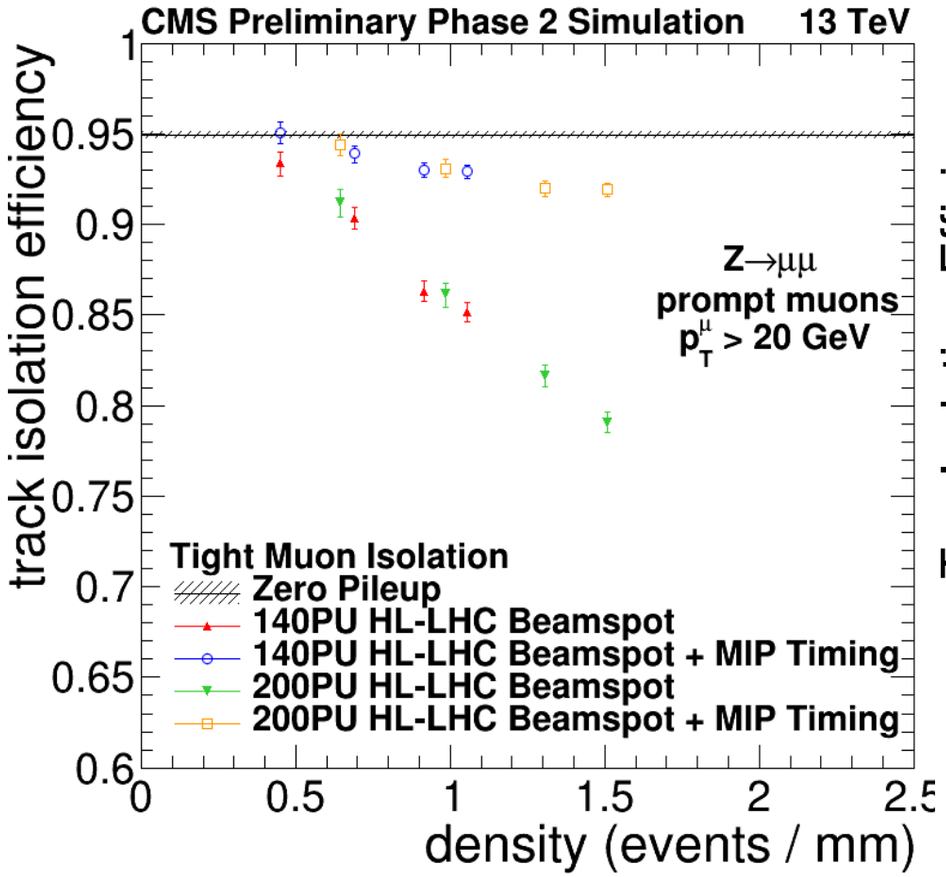


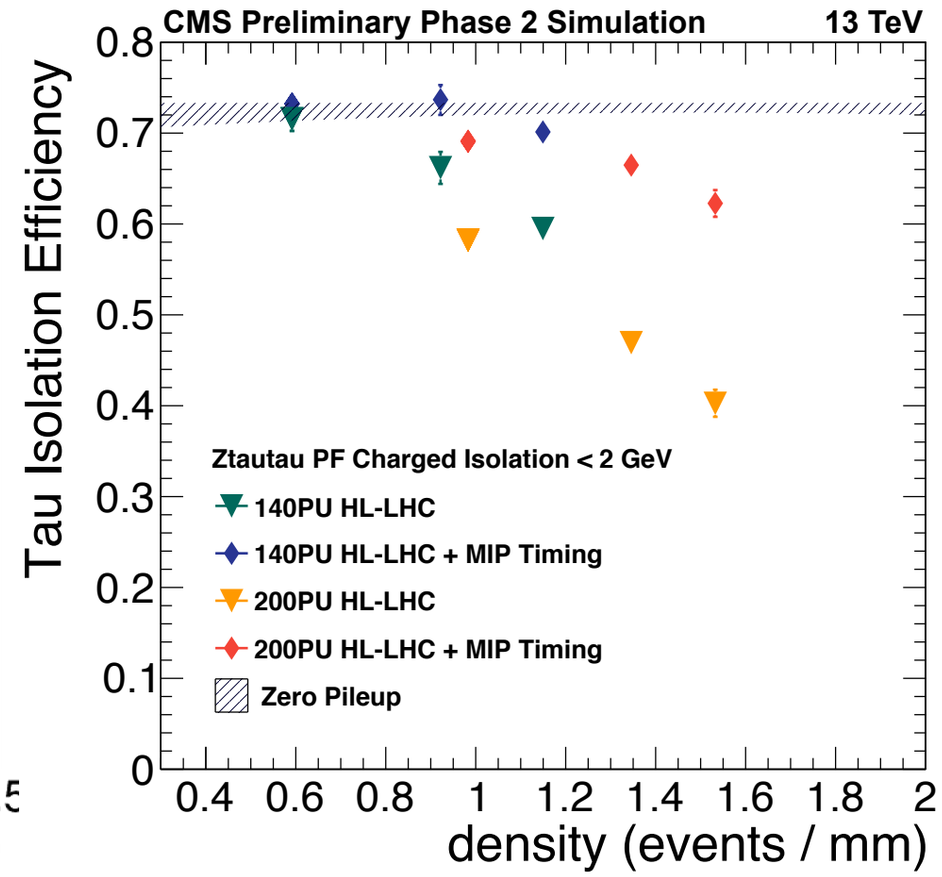




- Assuming 25 ps vertex timing resolution, **mis-assignment of pileup tracks** to hard interaction in HL-LHC conditions **reduced to ~LHC levels**
- Significant improvement even with timing layer $|\eta| < 3$
- **Ambiguities in H→γγ vertex location** by triangulation much **reduced by correlation** with vertex timing

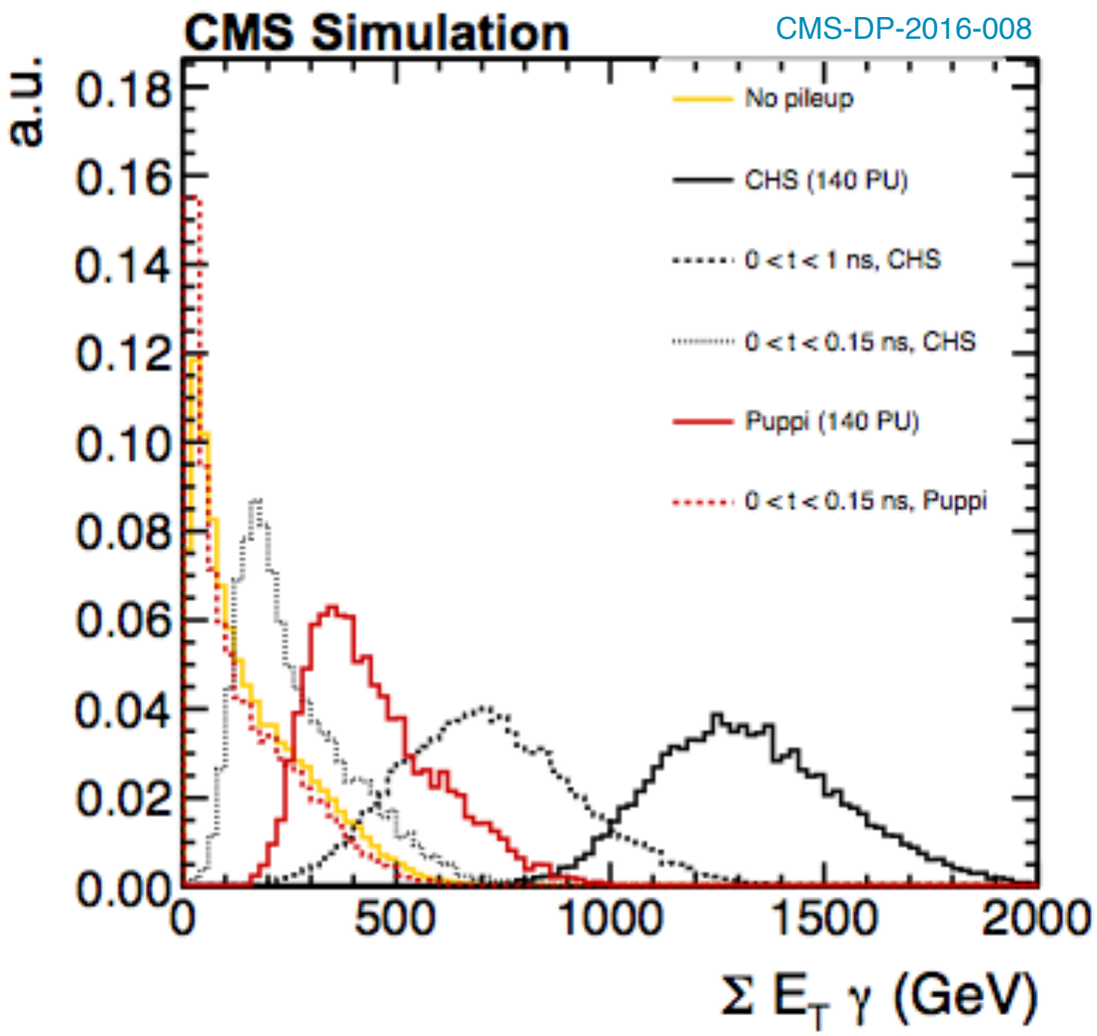
Isolation with precision timing

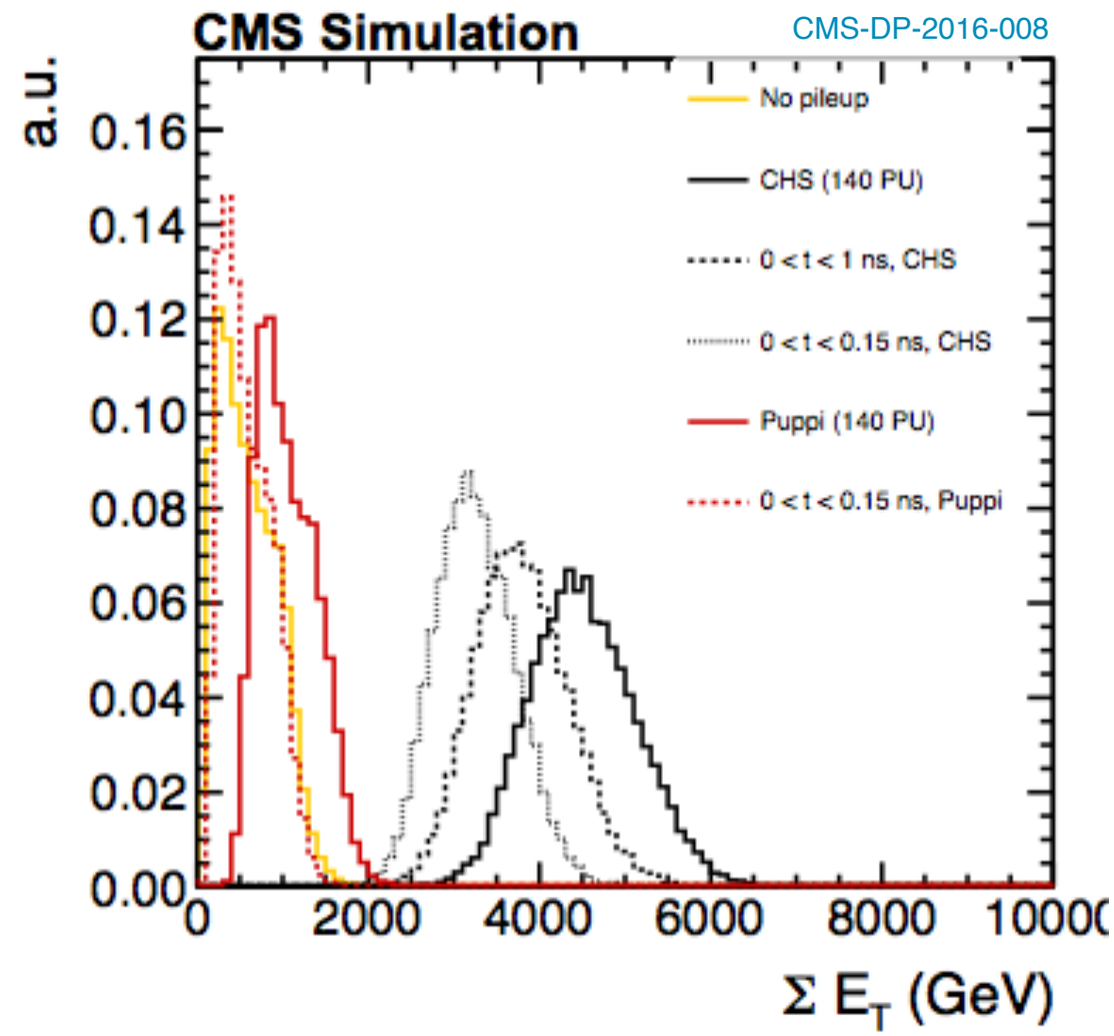




- $|t_{track} - t_{vertex}| < 4\sigma_{time}$
- Isolation efficiency nearly recovered to LHC levels

ME_T with precision timing

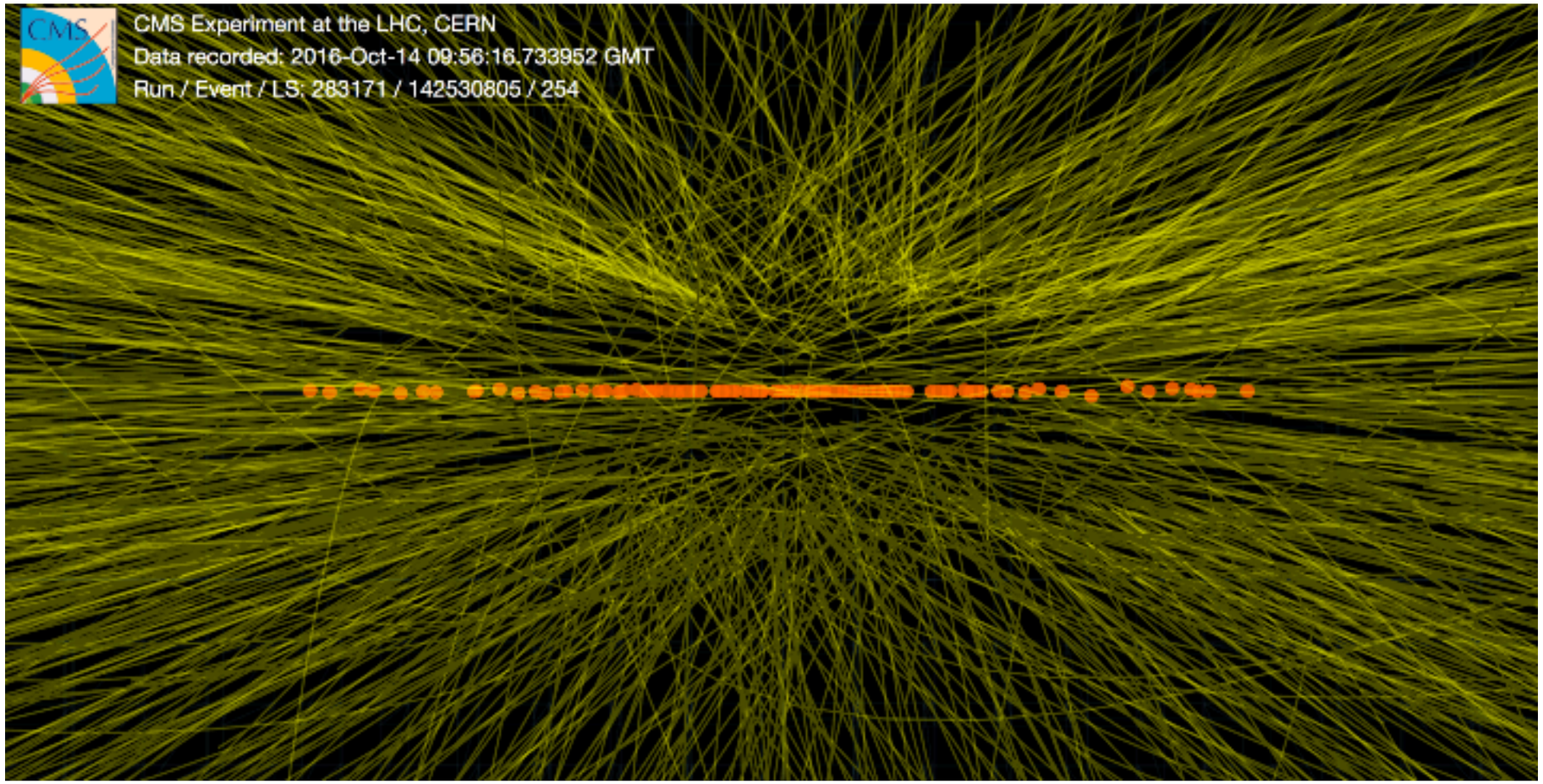




- Black and red: 2 different PU subtraction techniques
- Dashed (dotted): loose(tight) cuts on timing
- PU subtraction markedly improved with timing information

Conclusion

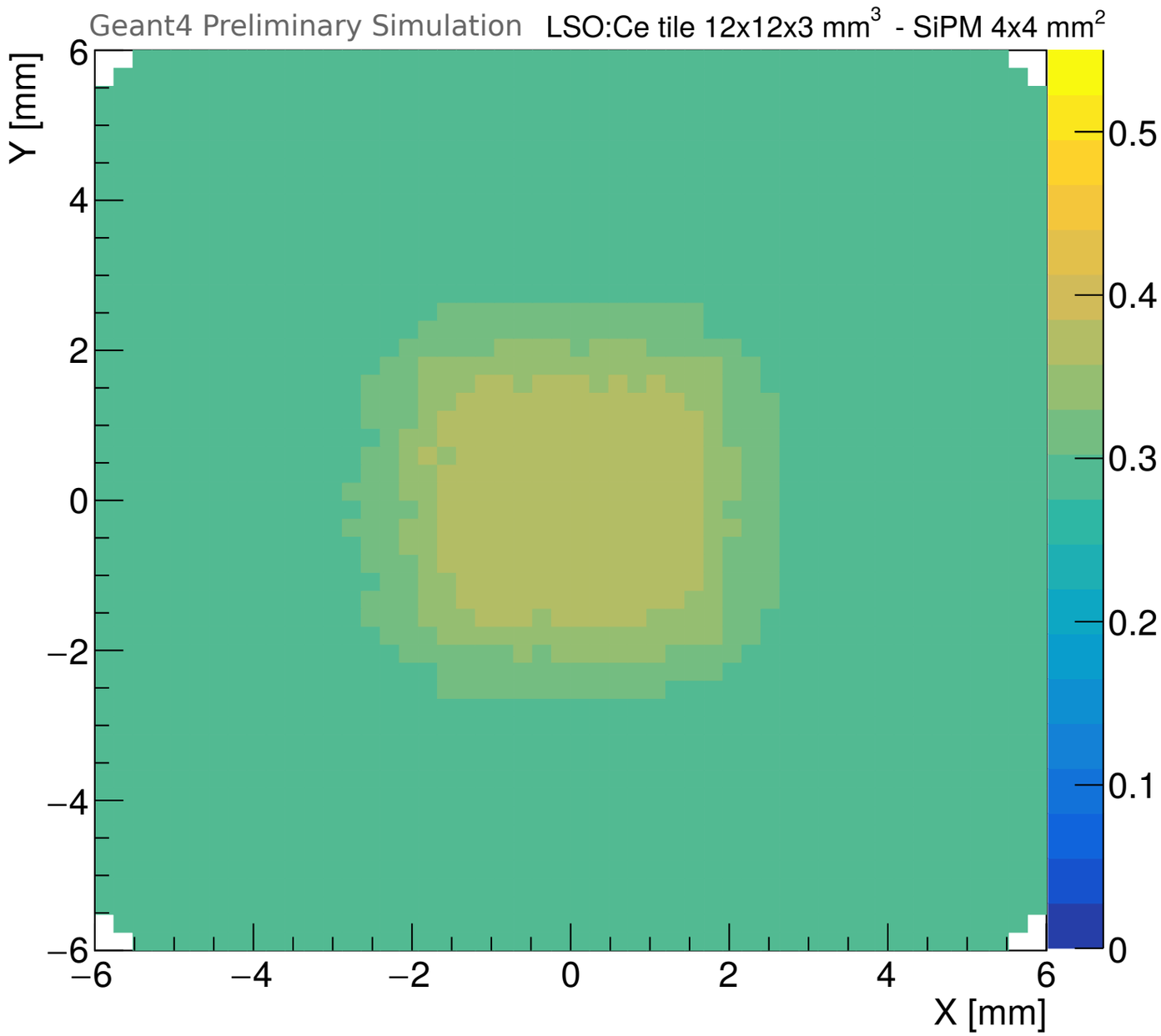
CMS-PHO-EVENTS-2016-008



- To exploit the HL-LHC physics potential, significant upgrades to CMS are required
- 30 ps MIP timing provides crucial discriminating information for resolving 140-200 PU vertices
- Technology is within reach

Backup

LYSO-SiPM light collection efficiency



LYSO radiation tolerance