Proposal for a MIP Timing Detector in the CMS Phase 2 Upgrade

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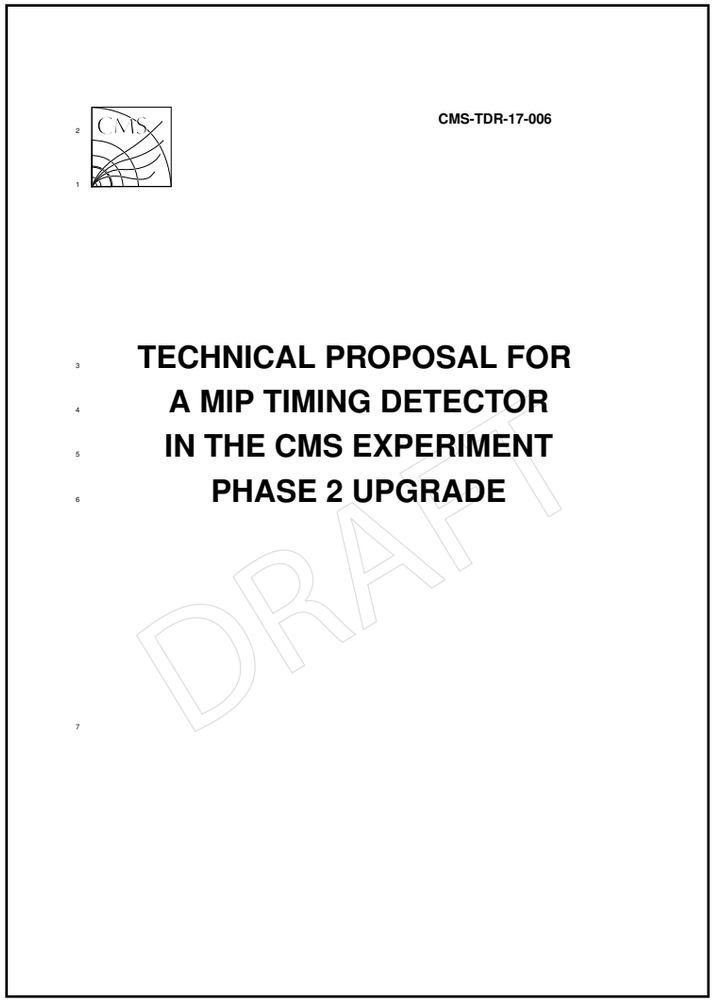
on behalf of the CMS Collaboration

1 December 2017

LHCC Meeting

Outline


CMS-TDR-17-006

TECHNICAL PROPOSAL FOR
A MIP TIMING DETECTOR
IN THE CMS EXPERIMENT
PHASE 2 UPGRADE

DRAFT

detector descriptions, physics performance, schedule, and cost estimates

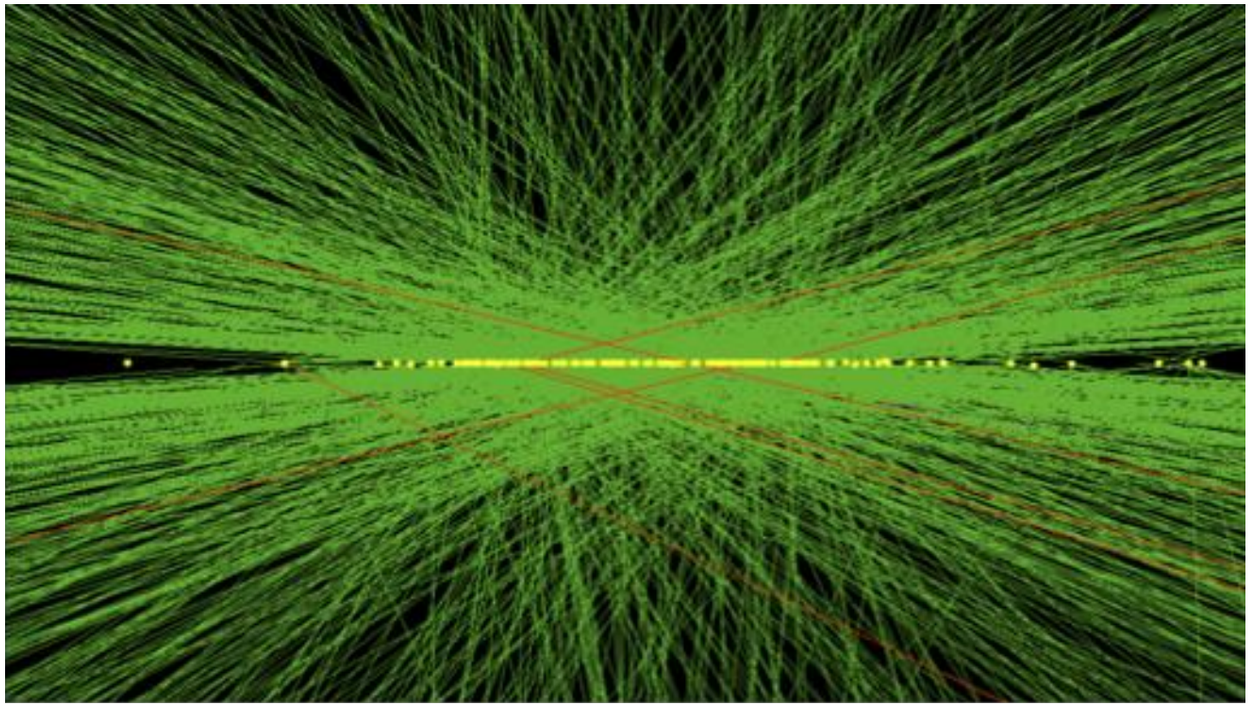
- The benefits of precise timing
- Physics performance
- Overview and performance of the proposed detector

Challenges of the HL-LHC

- CMS Phase-2 originally targeted 5×10^{34} Hz/cm^2 = 140 pileup (PU)
- LHC performance is *exceptional*
- Ultimate HL-LHC luminosity target is now 7.5×10^{34} Hz/cm^2 = 200PU
  - 25% increase in int. luminosity/year

Extending performance at high PU is the key! →

200PU HL-LHC Event:



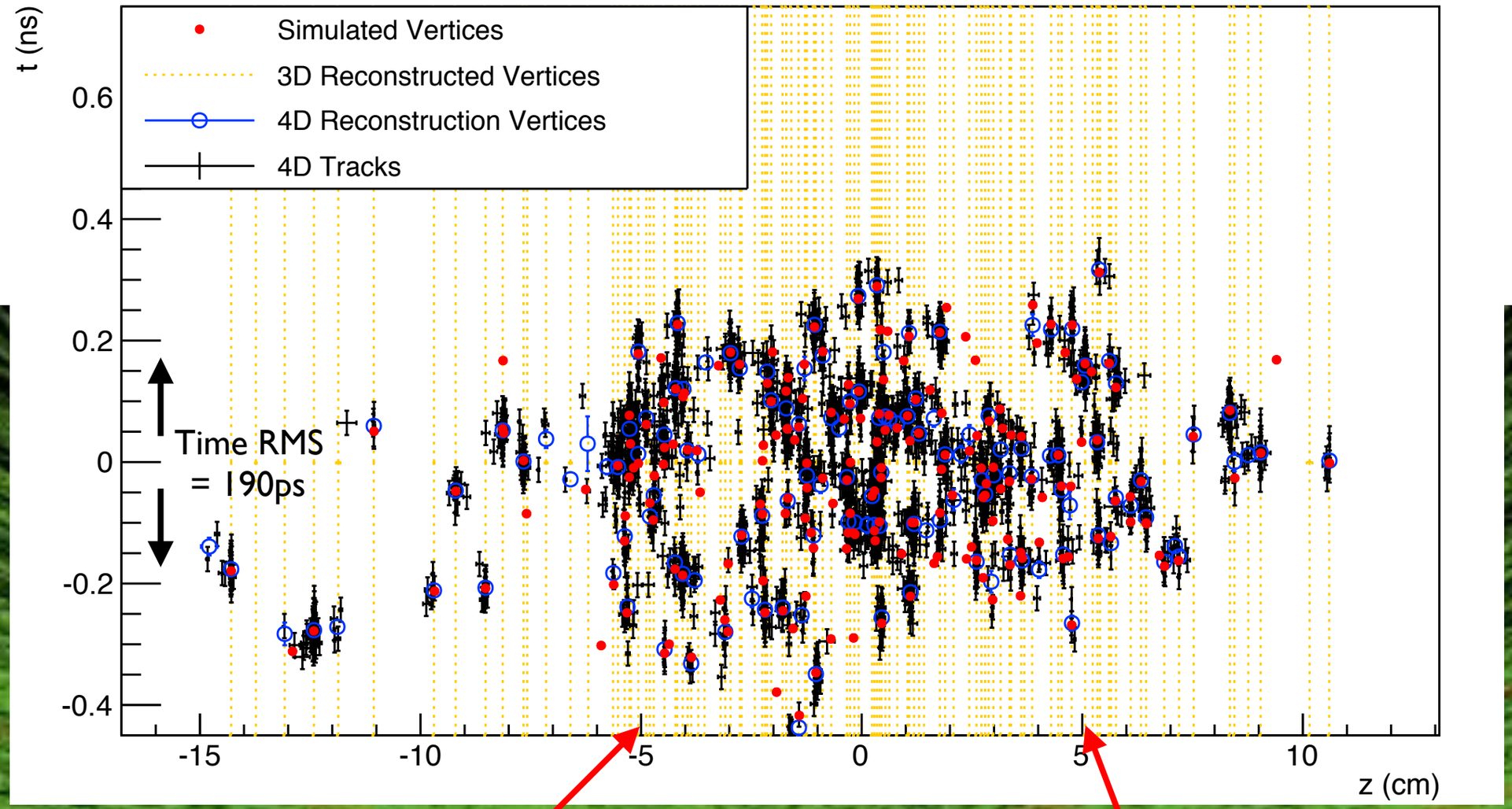
- The CMS Technical Proposal (2015) introduced timing as an option
  - Since then we have developed innovative analysis techniques and performed extensive studies
  - The key technologies have made significant progress

▸ CMS has now included a hermetic precision MIP Timing Detector in the Phase-2 upgrade scope

Motivation

- Physics performance at high pileup will determine where CMS will level luminosity
  - High leveling integrates more luminosity
  - Hence the need for optimizing performance at 200PU
- HL-LHC may well operate with parameters different from current design (fewer bunches / increased pileup density)
  - Solution must be robust
  - Algorithms can only go so far, but always benefit from more information
- Maintaining 50PU performance in 200PU conditions benefits full range of CMS physics output

Hermetic Timing Provides 4D Tracking



With timing resolution of 30 ps, the time separation of interaction vertices is evident.

Reduces the effective number of vertices from 200 to 40-50

- for reasonable vertexing: 15% vertex merge rate reduced to 1%
- similar to current running conditions

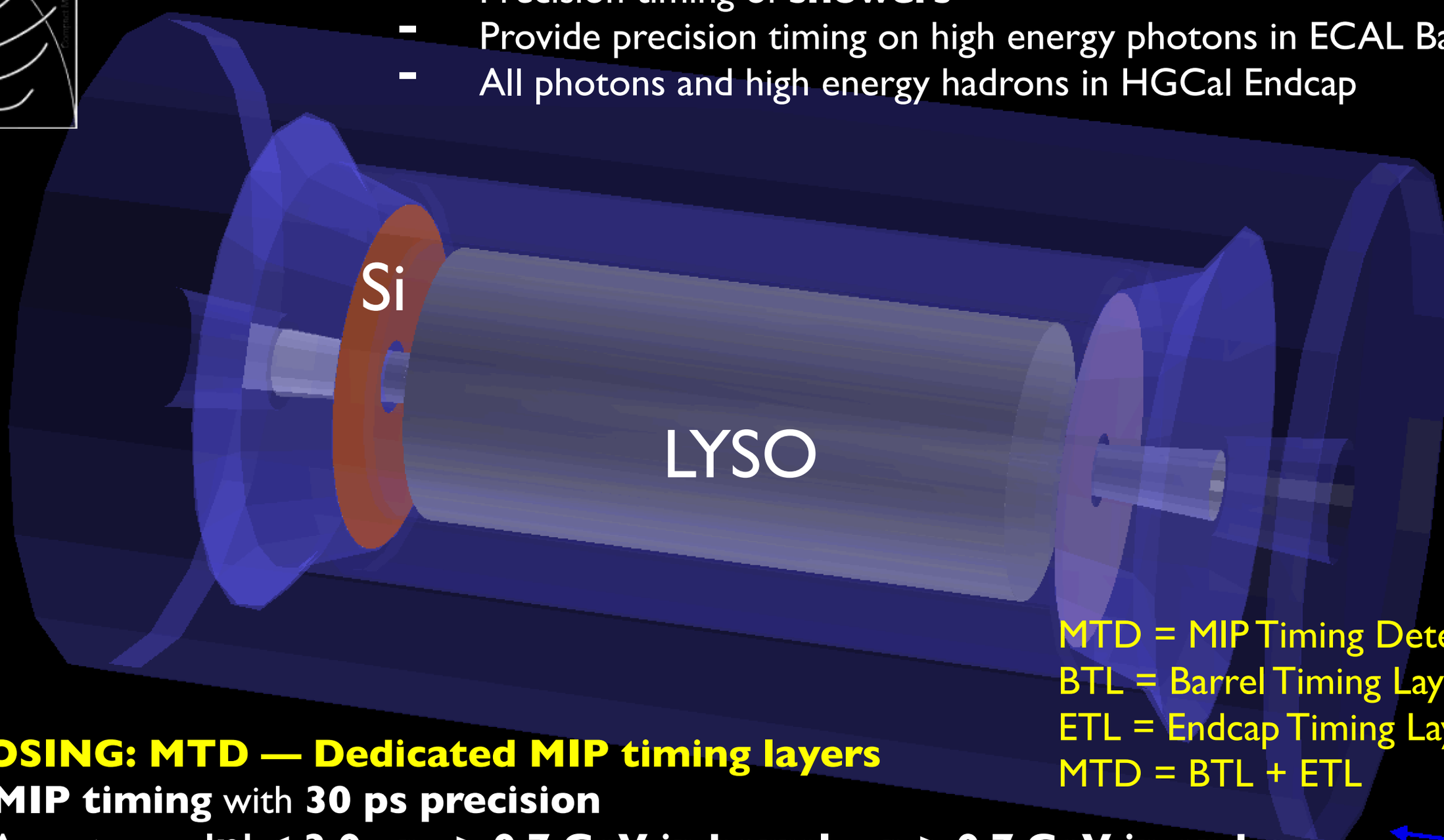
Timing Provides 4D Particle Flow

- In this presentation we show the additional benefit of timing on top of the full Phase-2 CMS detector
- CMS reconstruction relies on **Particle Flow**
  - Provide *most complete* global description of an event
- Charged hadrons make up 60% of hadronic event content
  - CMS is highly dependent on accurate *track assignment*
  - Momentum of low p_T charged hadrons measured through tracking rather than calorimetry
- Tracking is key to the performance of CMS and a timing detector should be tailored to provide maximum benefit

CMS Global Timing Concept

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



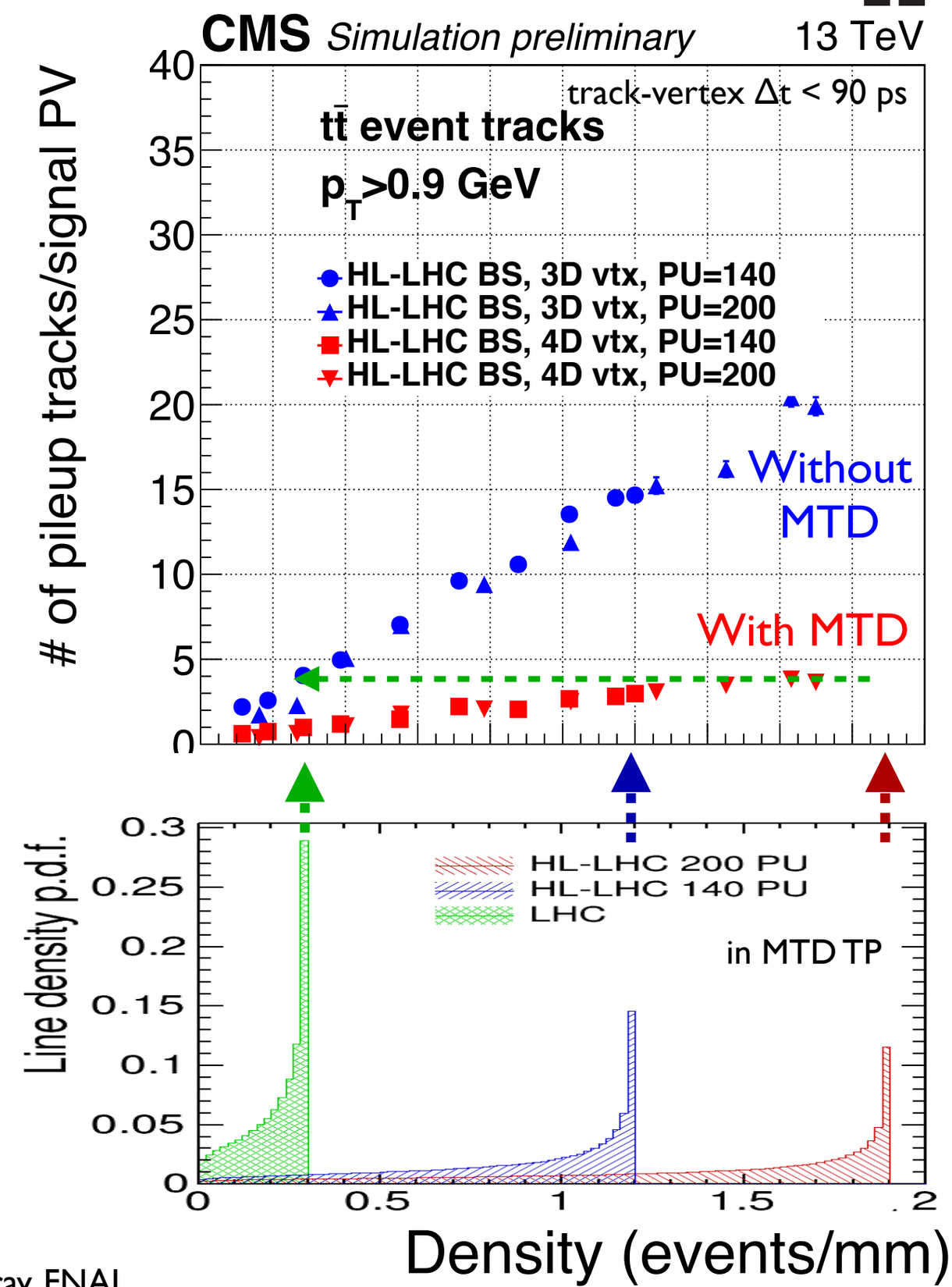
MTD = MIP Timing Detector
BTL = Barrel Timing Layer
ETL = Endcap Timing Layer
MTD = BTL + ETL

PROPOSING: MTD — Dedicated MIP timing layers

- **MIP timing** with **30 ps precision**
- Acceptance: **$|\eta| < 3.0$, $p_T > 0.7$ GeV in barrel, ~p > 0.7 GeV in endcap**
- Location: just outside the tracker

Mitigating Confusion from Pileup

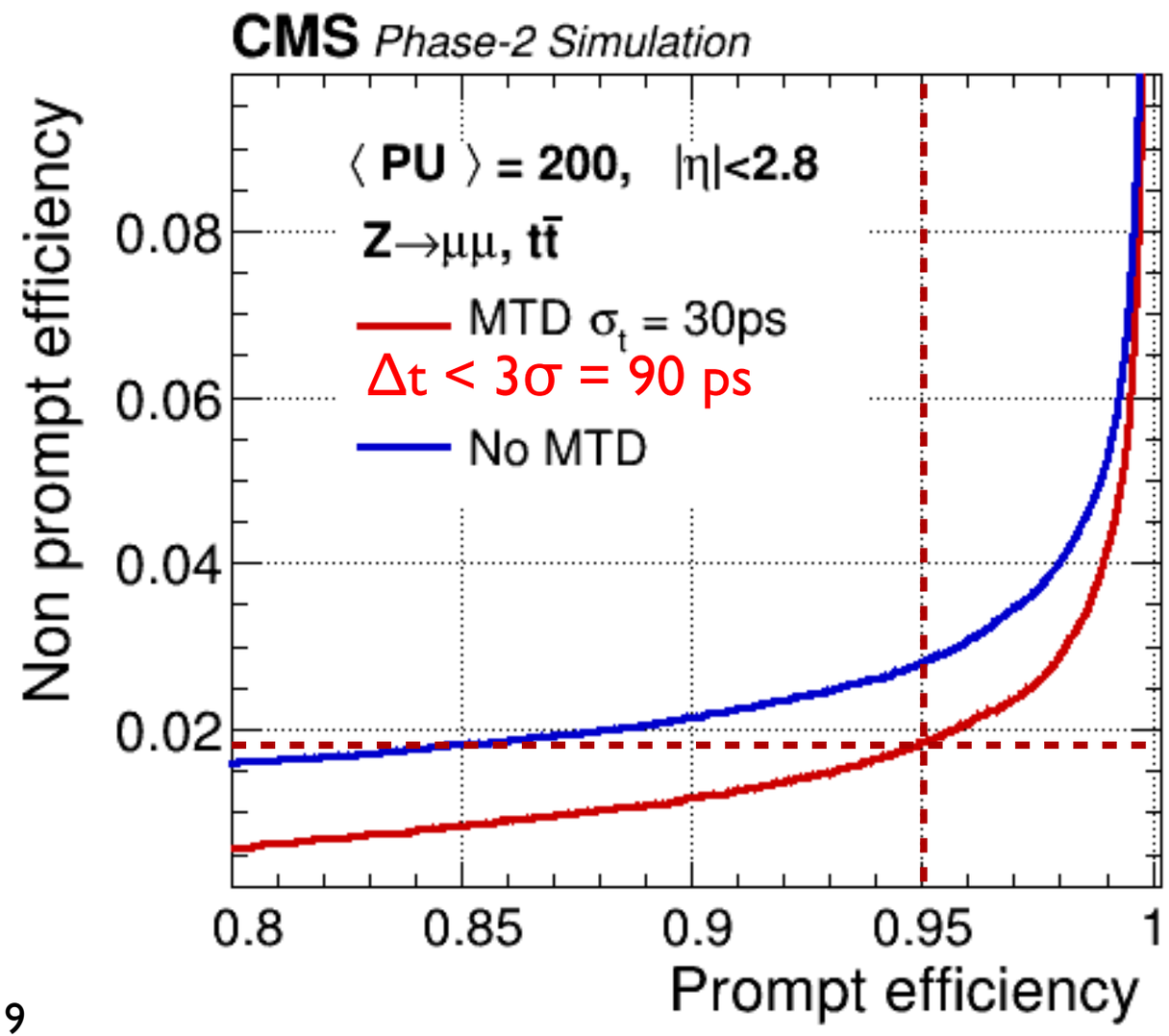
- Pileup tracks are incorrectly associated to primary vertex of interest
  - Timing significantly reduces "*effective*" vertex line density
  - Recover performance in several observables
  - Provide additional robustness against changes in beam configuration

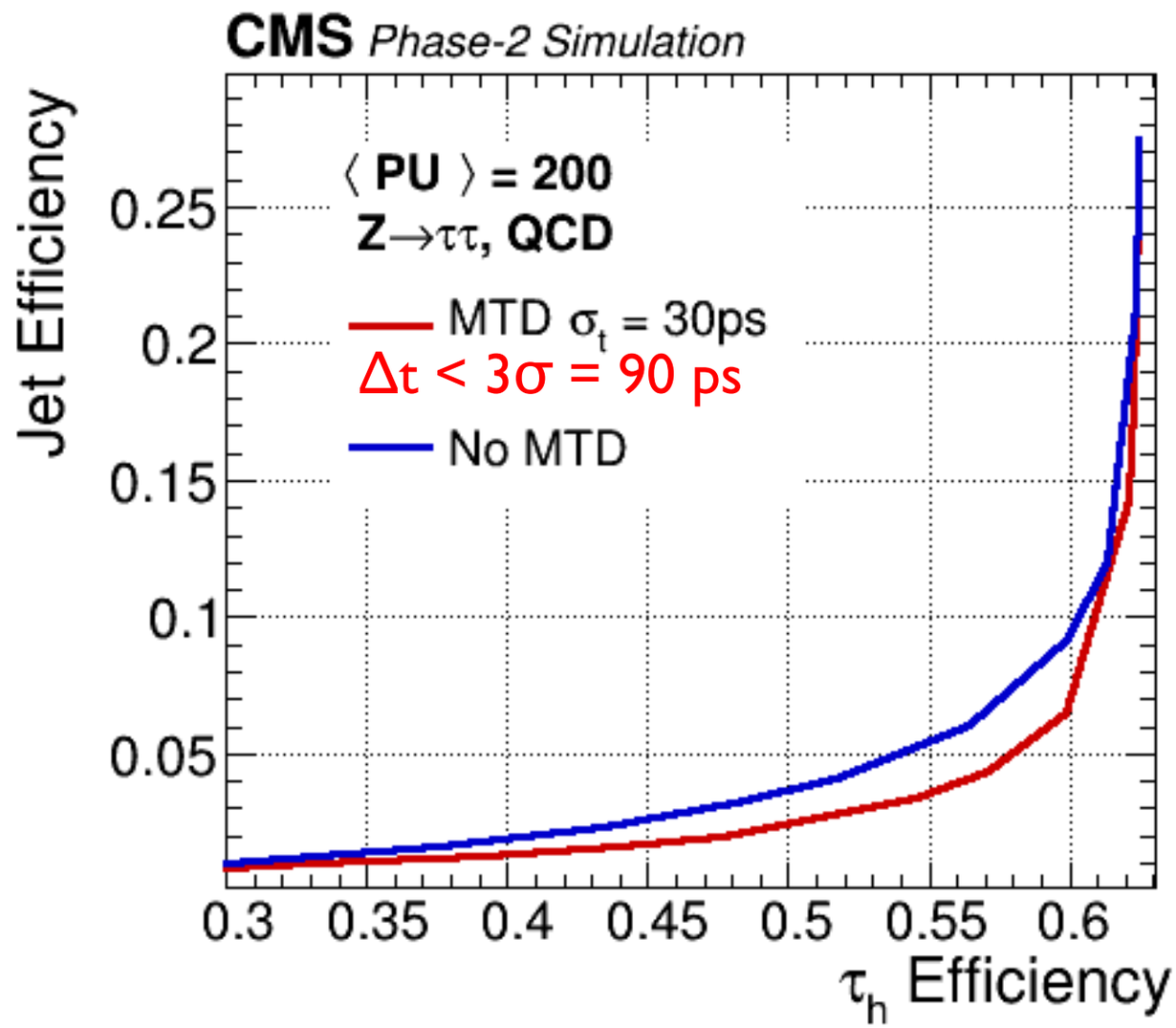


Lepton Isolation With Timing

- Timing cuts remove pileup tracks from lepton isolation cones
- Reduces dependence on pileup density (see backup)

▶ 60% improvement in background rejection for constant signal efficiency using pertinent working points



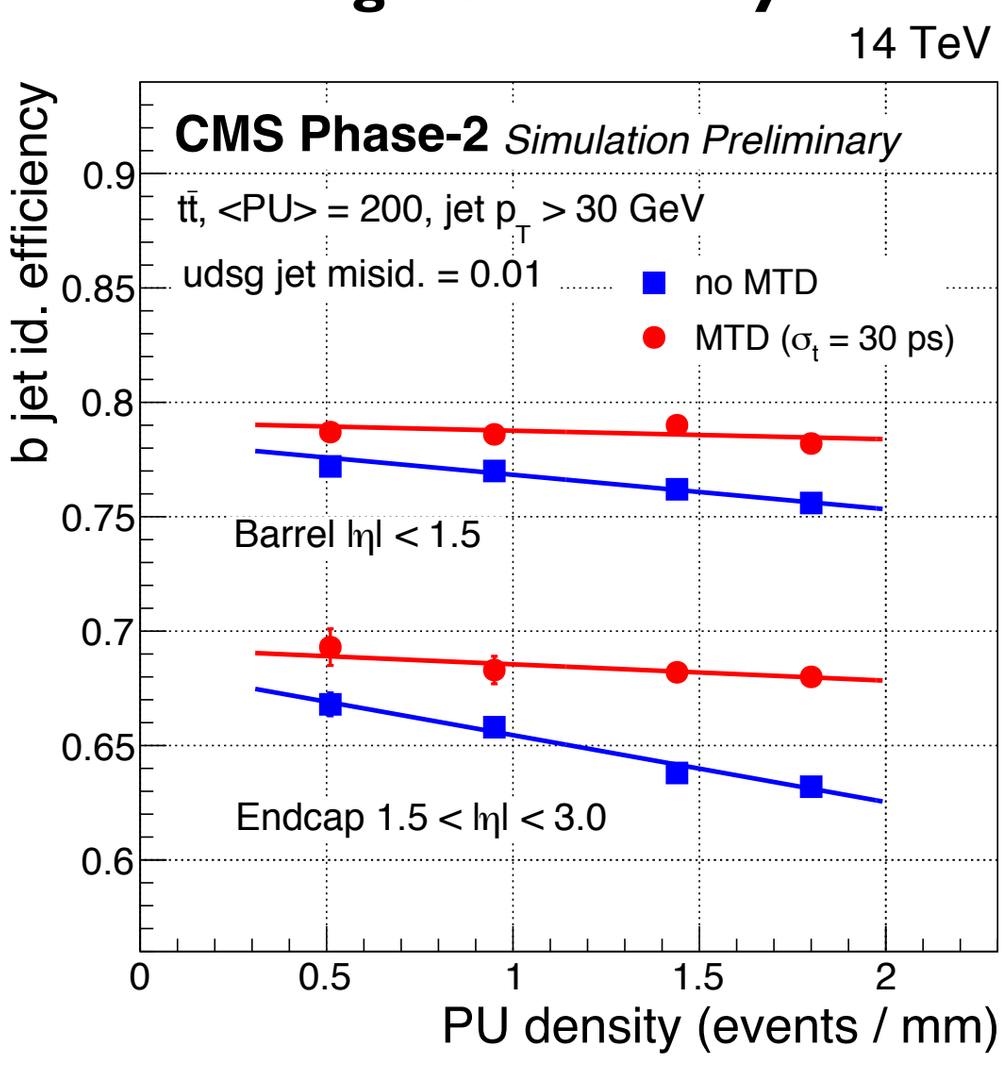


B-Tagging With Timing

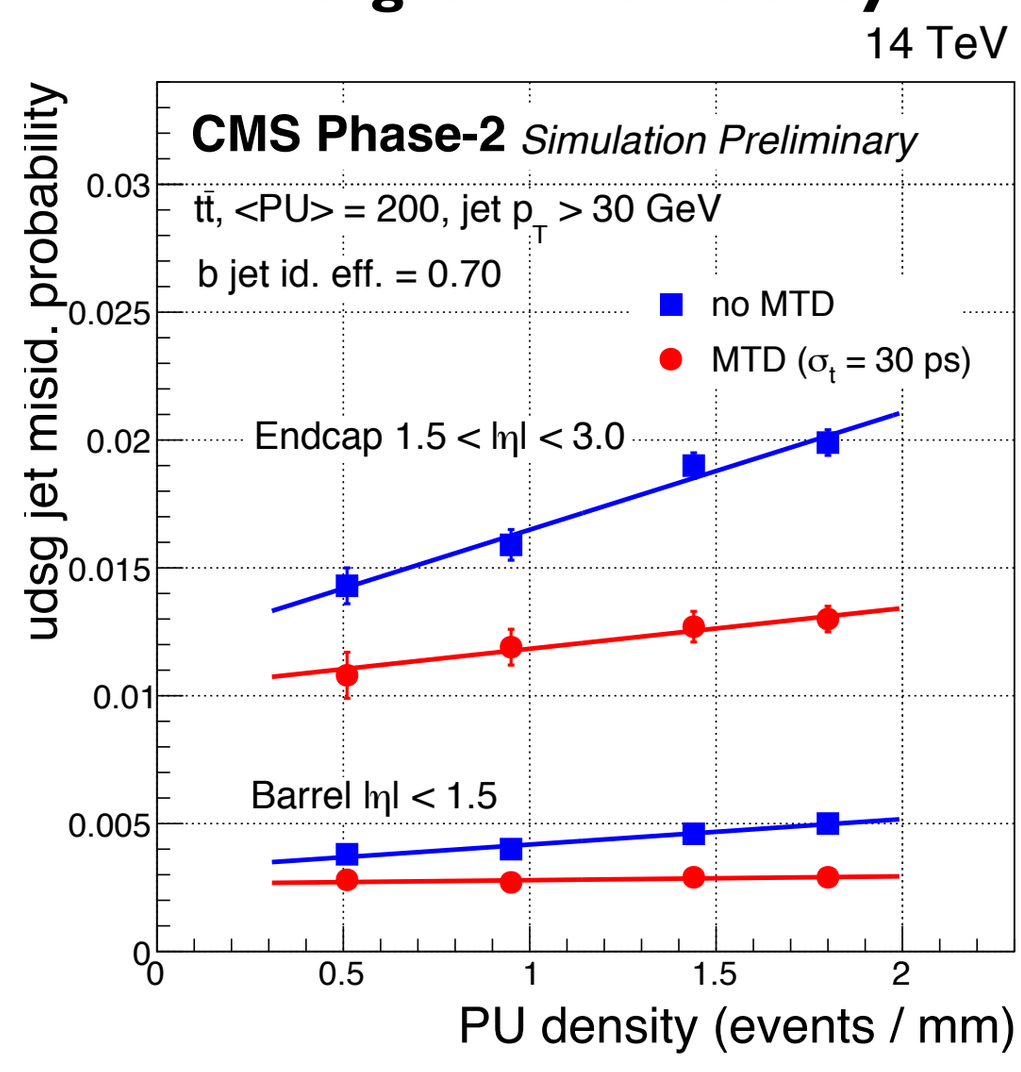
- Precision timing rejects spurious secondary vertices
- Significant improvements for working points at constant signal efficiency or background rejection
  - Gain in efficiency amplified in multi-particle final states (ε^N)

- Removes pileup-density dependence in b-tagging

Signal Efficiency



Background efficiency

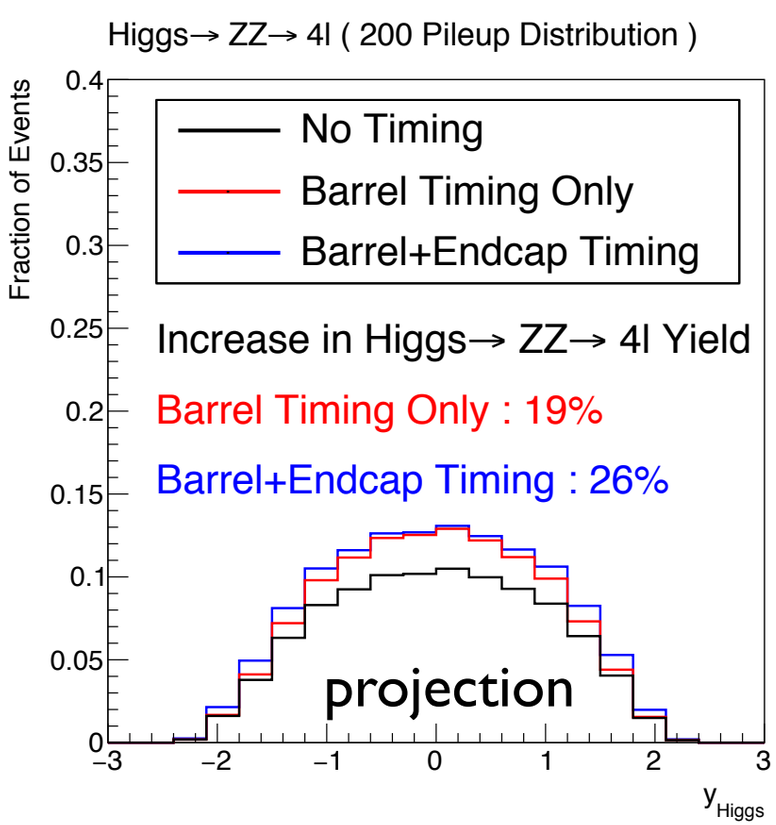


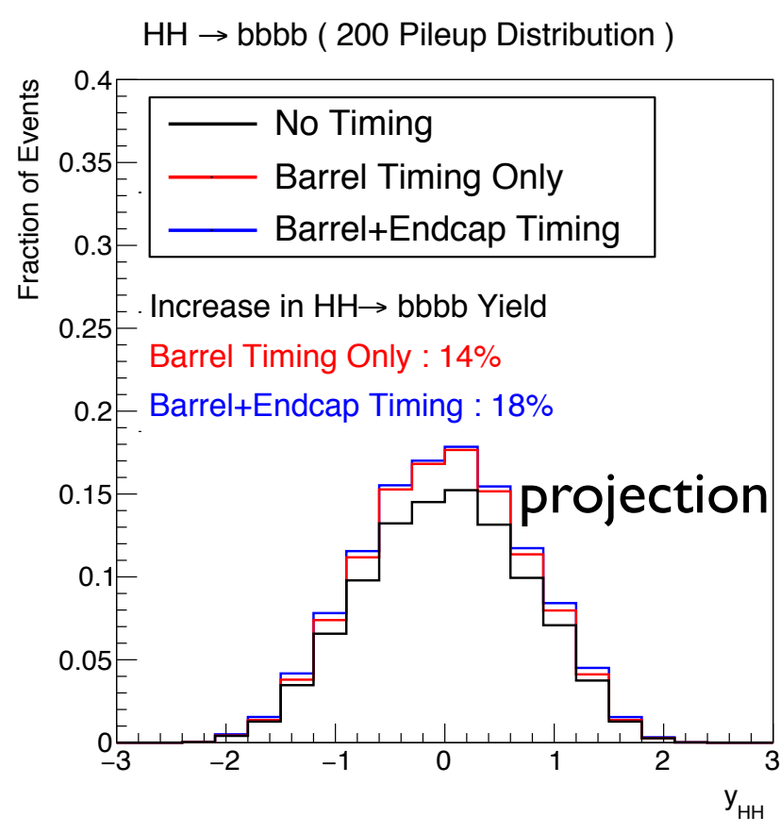
(di-)Higgs Acceptance Improved

- Object-level acceptance improvements compound in multi-object final states

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

- Corresponds to 18-26% increase in effective integrated luminosity

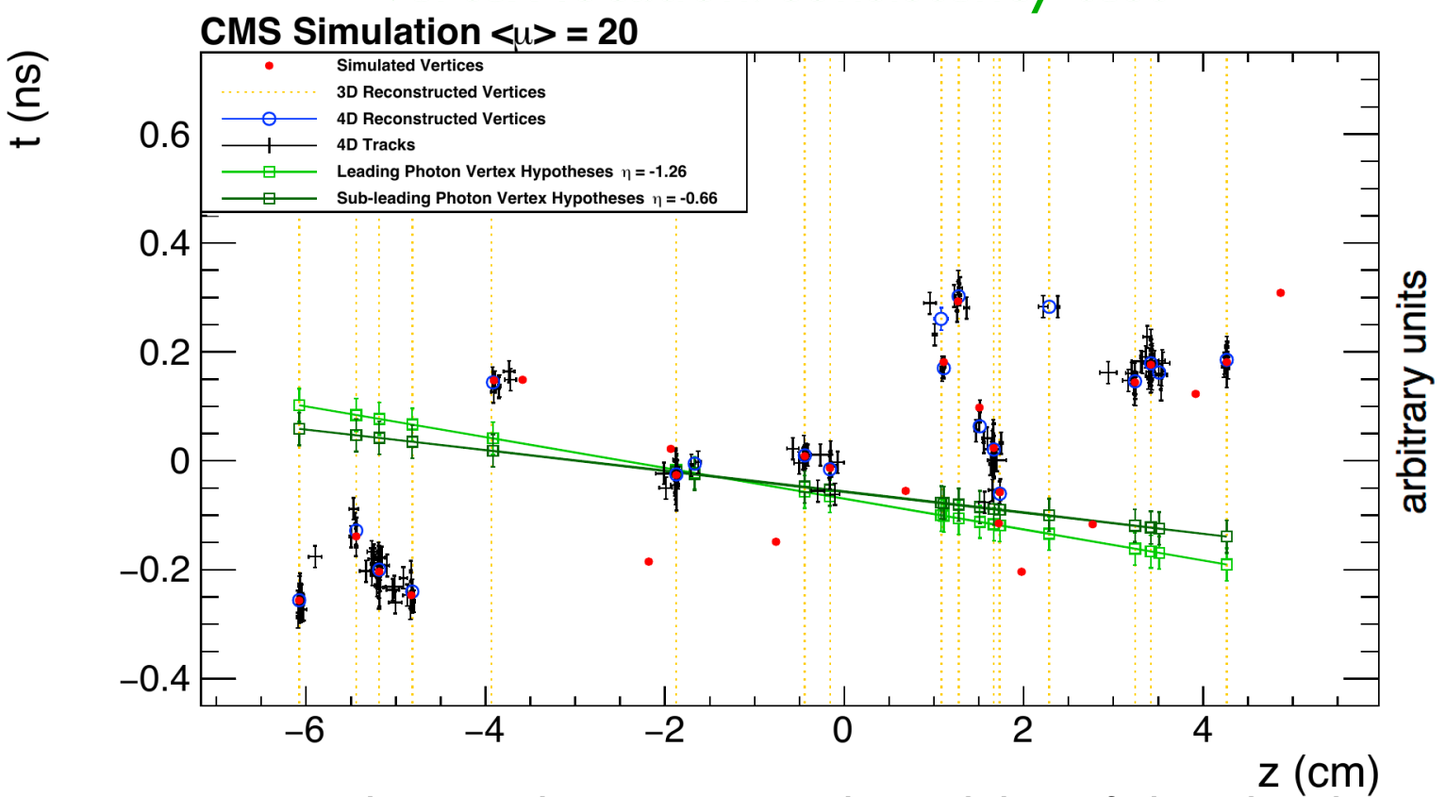


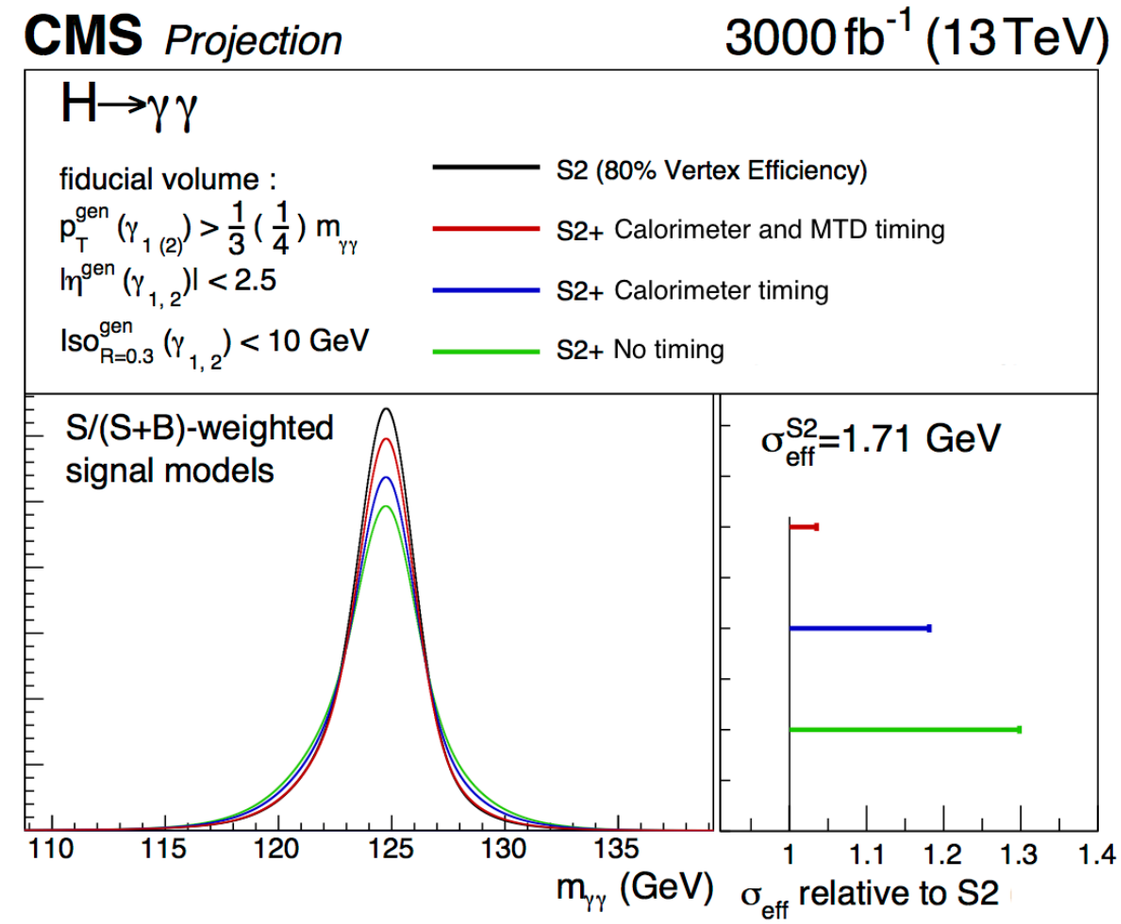


- Large impact on barrel region since physics signature is *central*

Higgs to Di-photon Vertex Tagging

Calculate photon time at each vertex location: consistency test





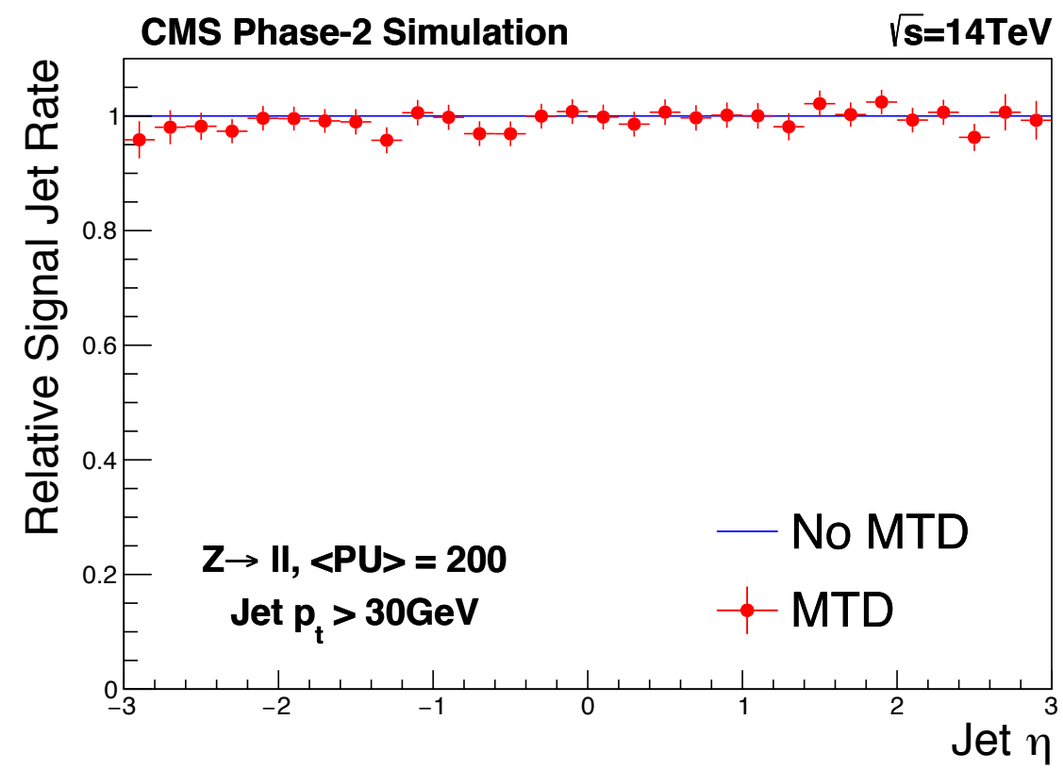
- Unique capability to match photon time to vertex time + position
  - CMS ECAL is non-pointing, but has photon timing capability
  - 50% of events additionally require MIP timing to find correct vertex

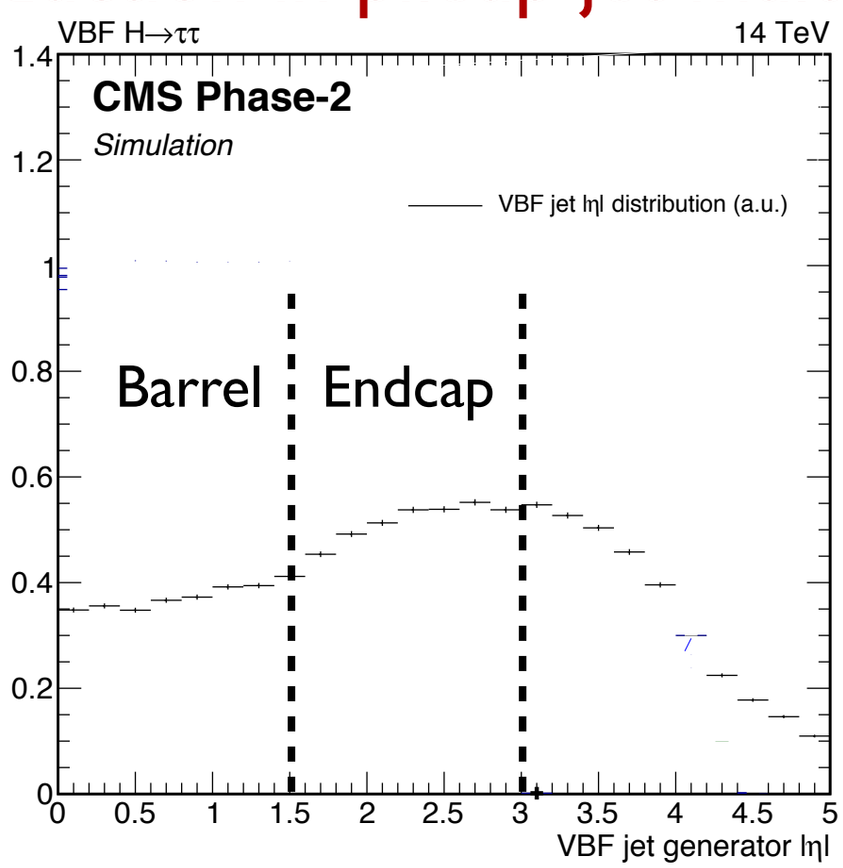
- Identifies photon vertex: improves di-photon mass resolution by 25% and also H(γγ) signal significance

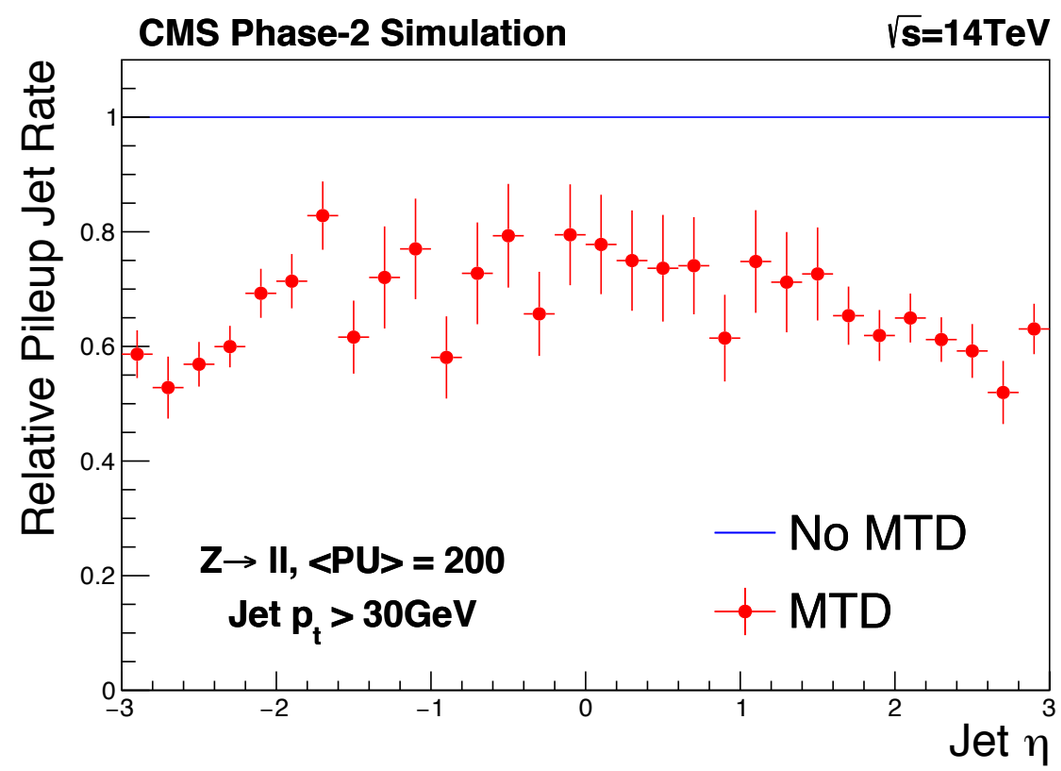
Pileup Jet Performance

- Timing cleans tracking information provided to PUPPI* so it can better identify neutrals from pileup
  - No impact on signal jet efficiency
  - Largest impact in the endcaps

▶ 20% (barrel), 40% (endcap) reduction in pileup jet multiplicity

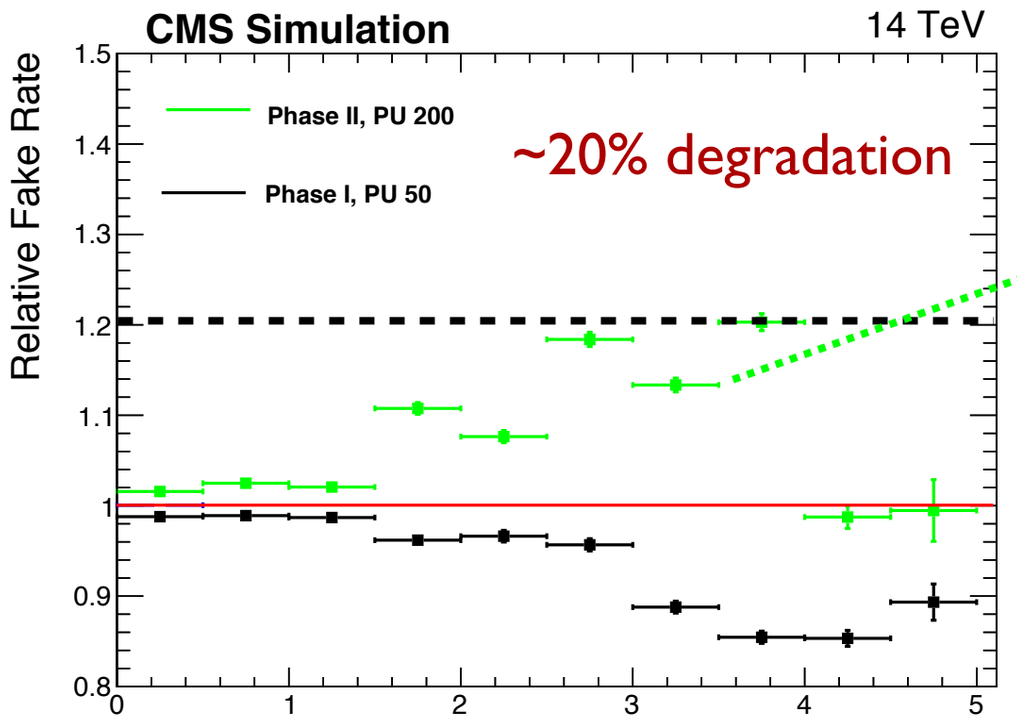




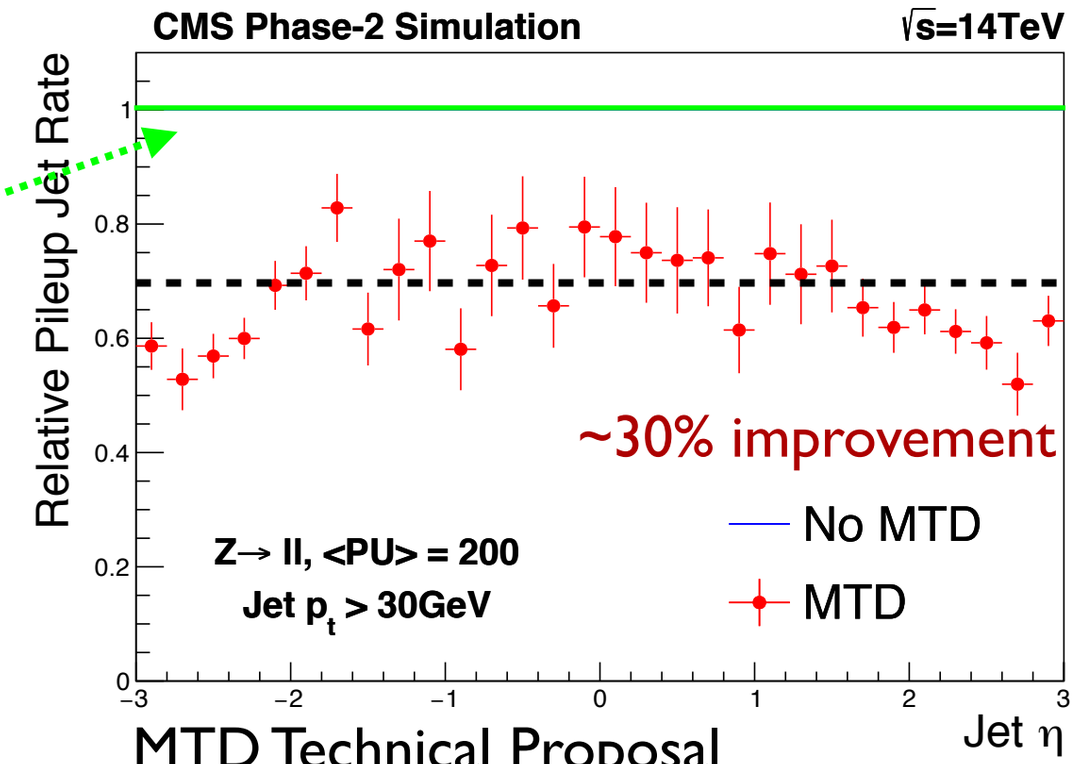


 * https://arxiv.org/abs/1407.6013

VBF Higgs to Tau Tau



Scope Document (no MTD)



MTD Technical Proposal

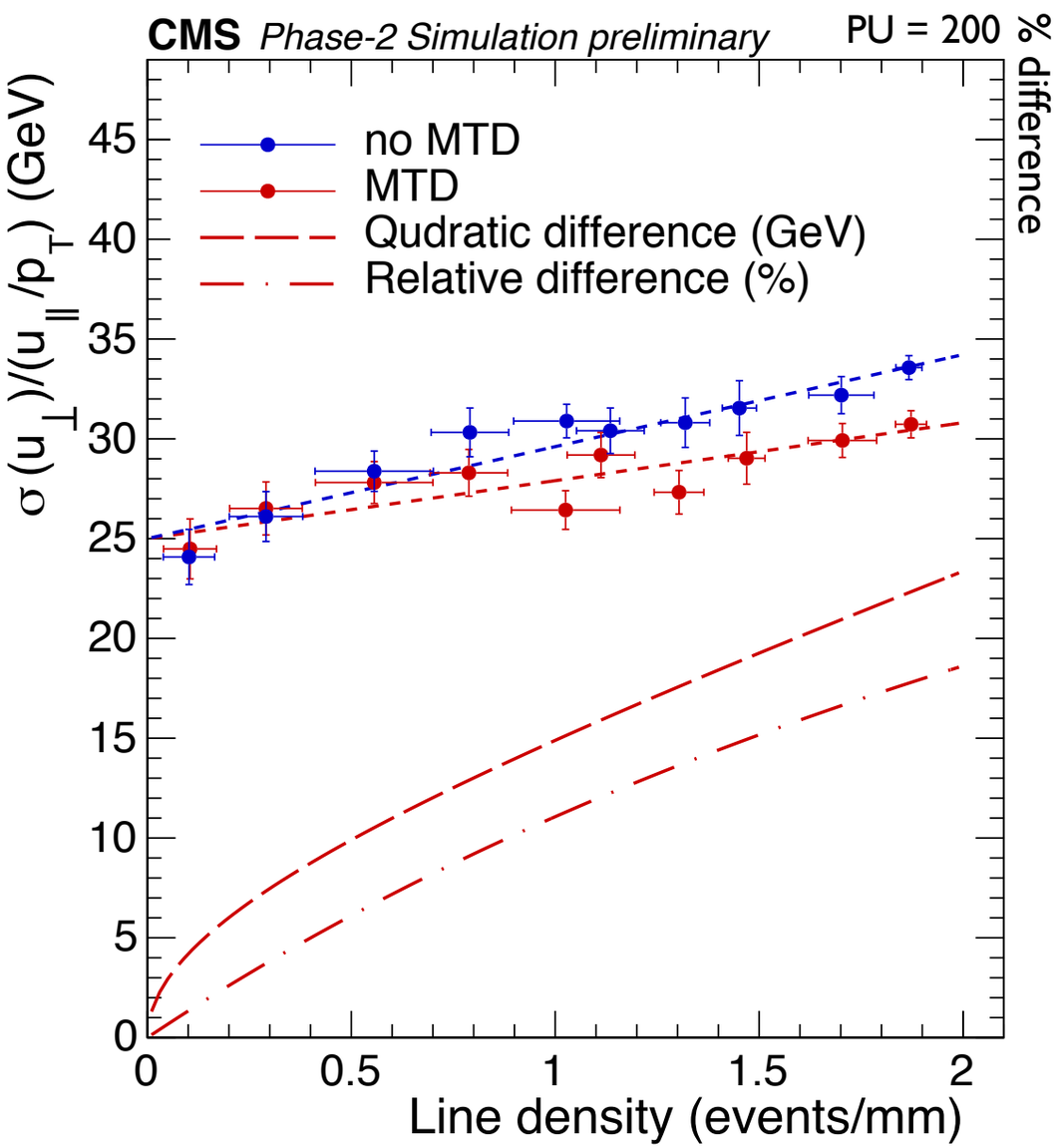
- Performance gain from timing ($S/\sqrt{B}$) 80% :
  - +30% from isolation
  - +30% from VBF tagging (pileup jet rejection)
  - +10% from di-tau mass resolution (p_T^{miss} resolution)
- Large impact from ETL

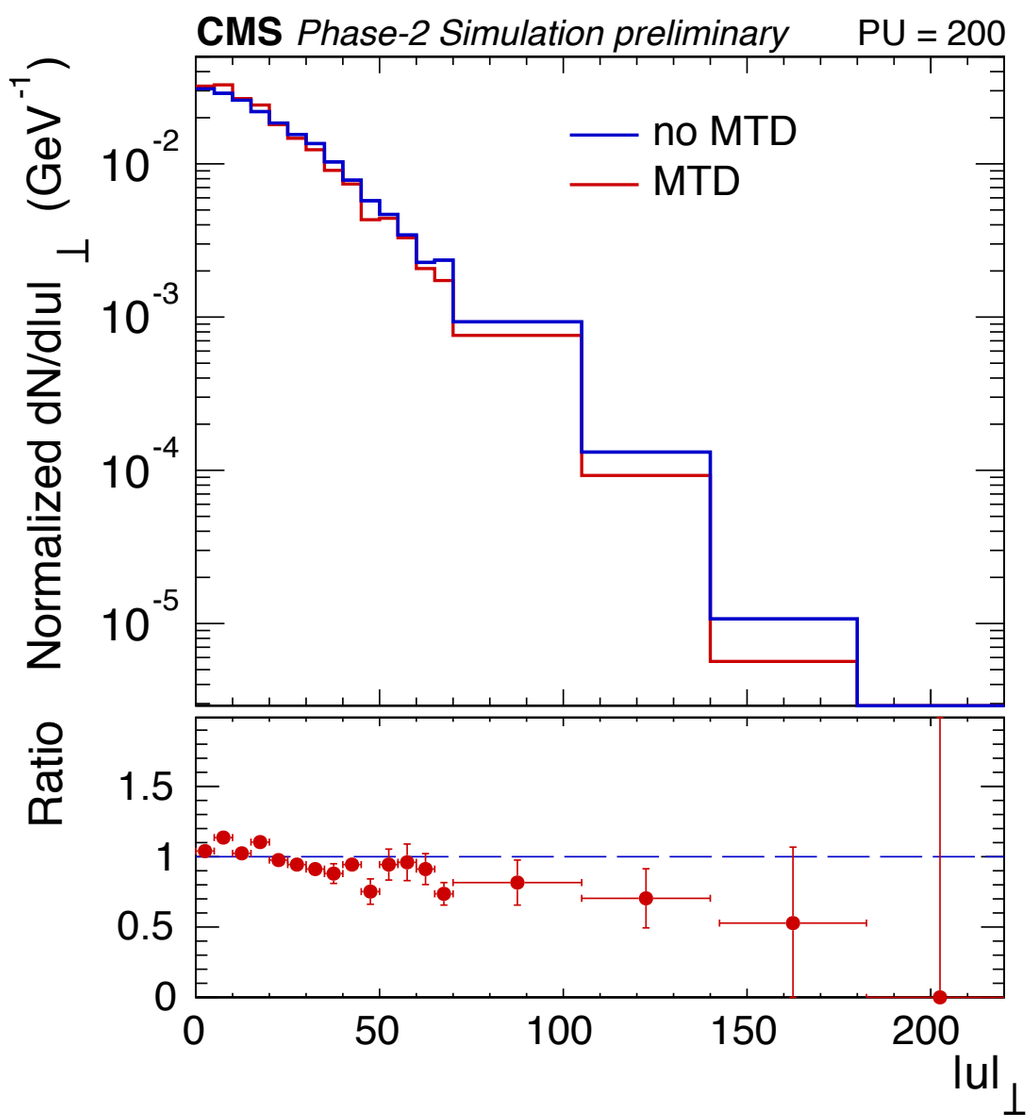
▸ Timing offsets performance degradations from 140 to 200 PU

MET Performance

- PUPPI MET resolution improves 15% at 200PU
  - Recovers 140 pileup performance
- MET tails reduced 40% for MET > 150 GeV

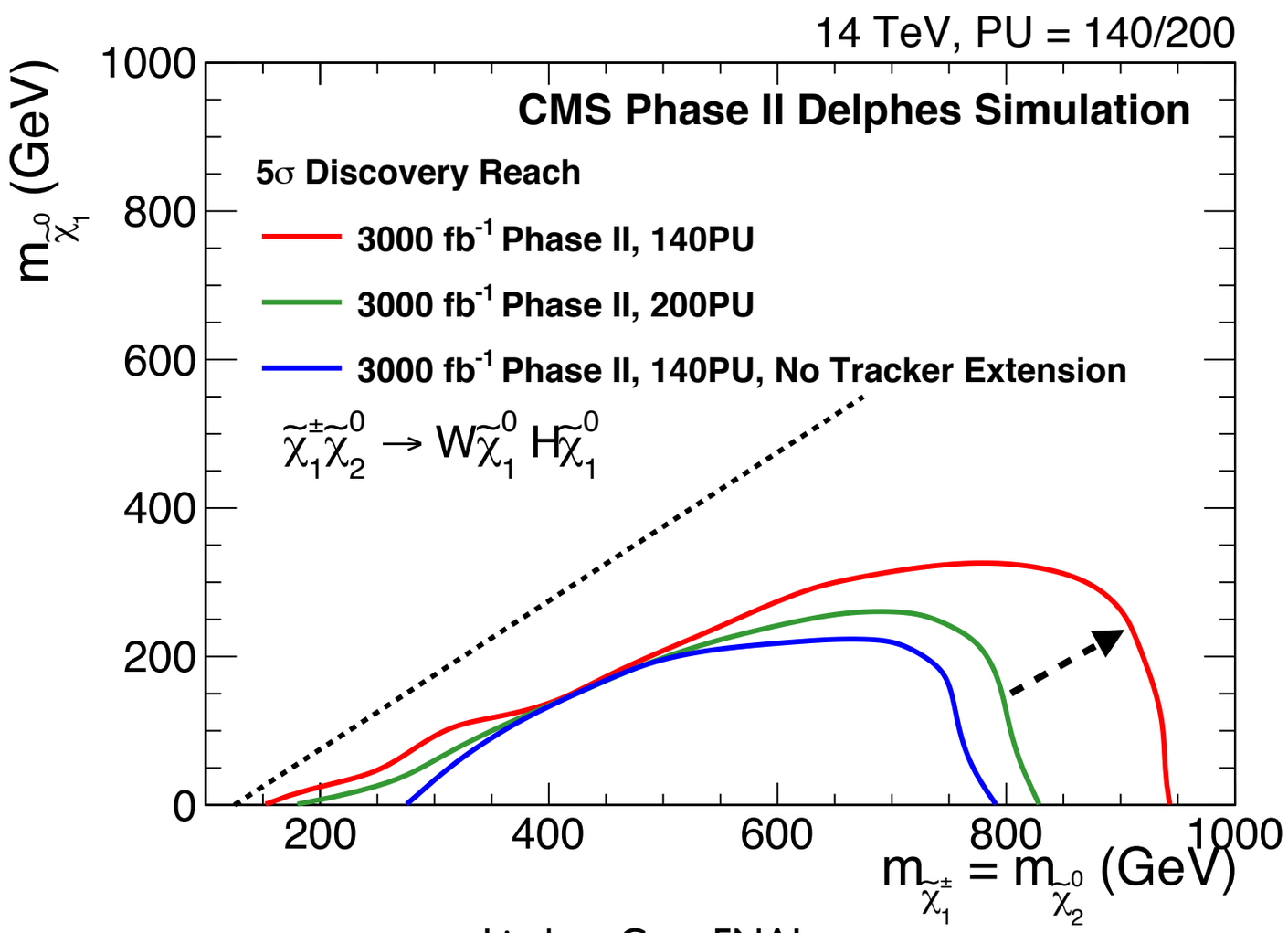
▸ Game-changer for searches in high pileup





Searches in MET Tails

- Extend the physics reach in searches for massive invisible particles
- Without timing, the search is less sensitive at 200 PU than at 140 PU
  - With timing, search at 200 PU recovers sensitivity as at 140 PU (3000 fb^{-1})
- 200 PU running provides 4000 fb^{-1}, timing further improves sensitivity



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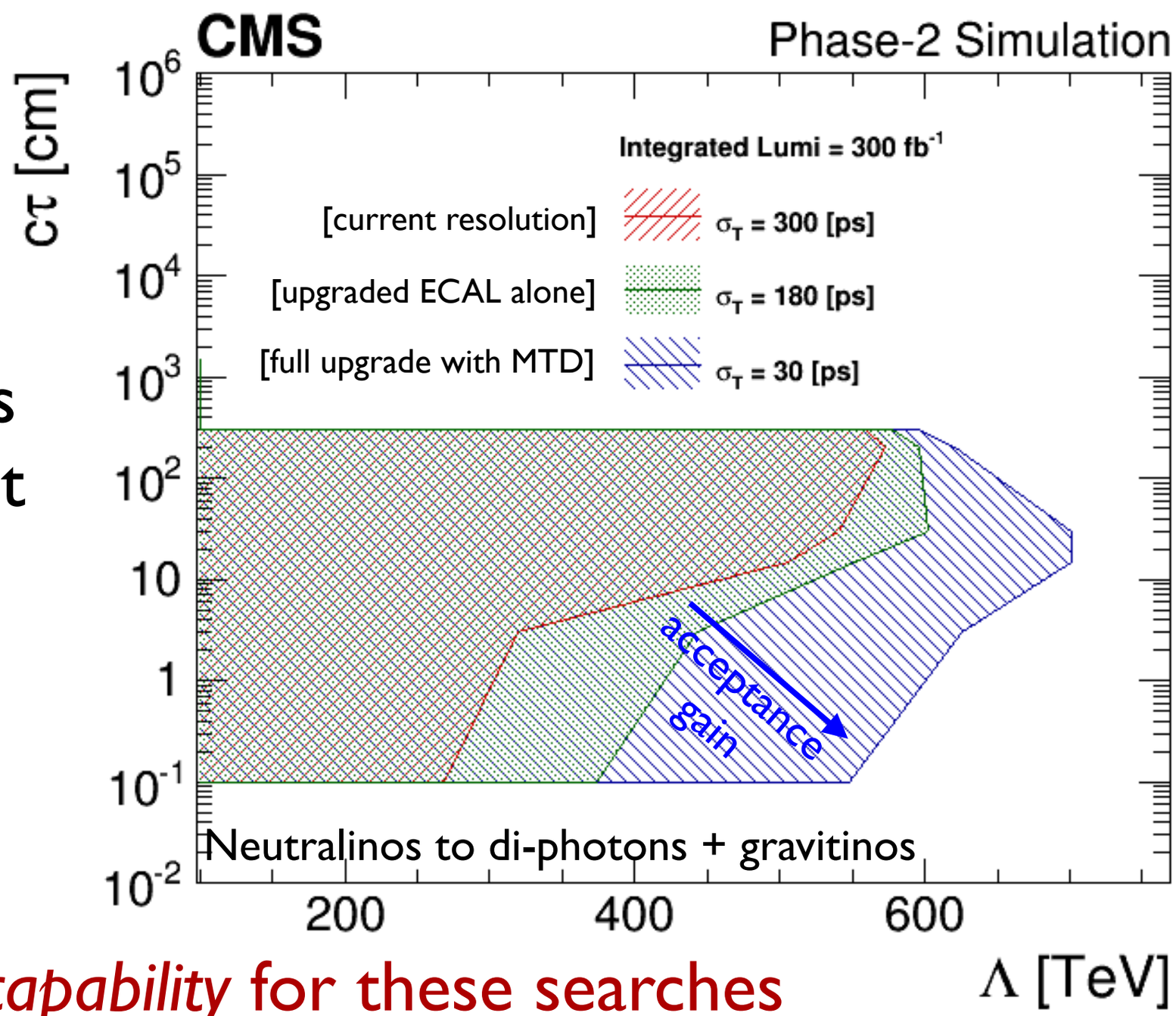
Searches for Long-Lived Particles

- MTD vastly improves acceptance for massive long-lived particles (LLP)

- Ability to measure decay *time* improves search reach by orders of magnitude at highest masses

- Massive particles yield central signatures

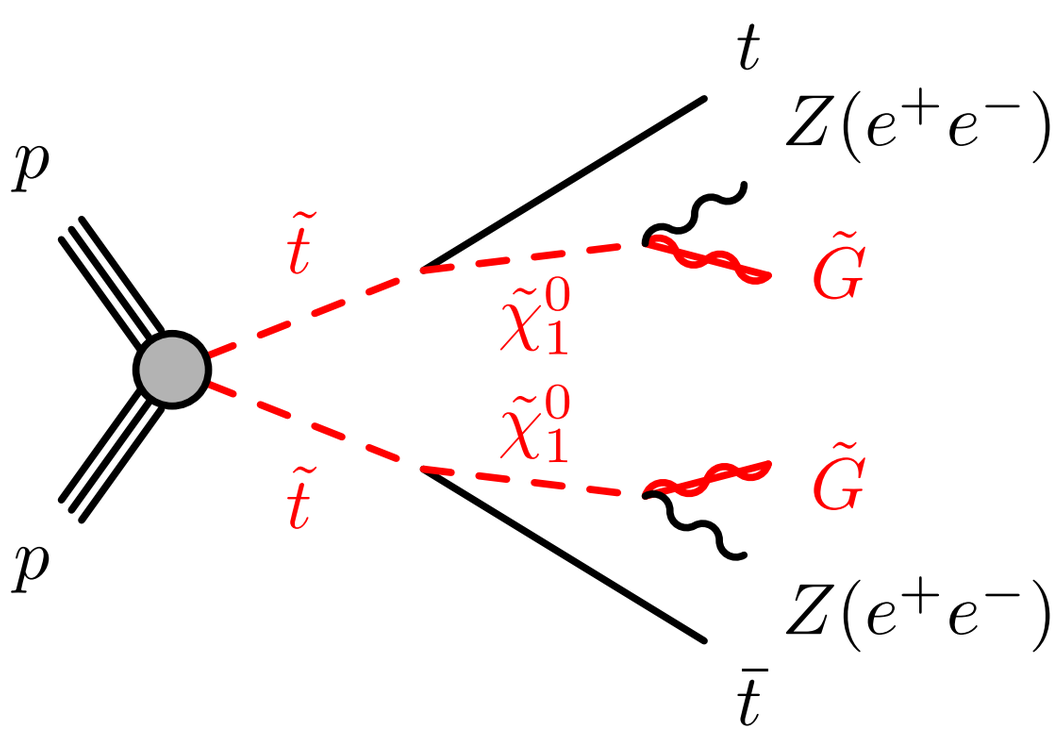


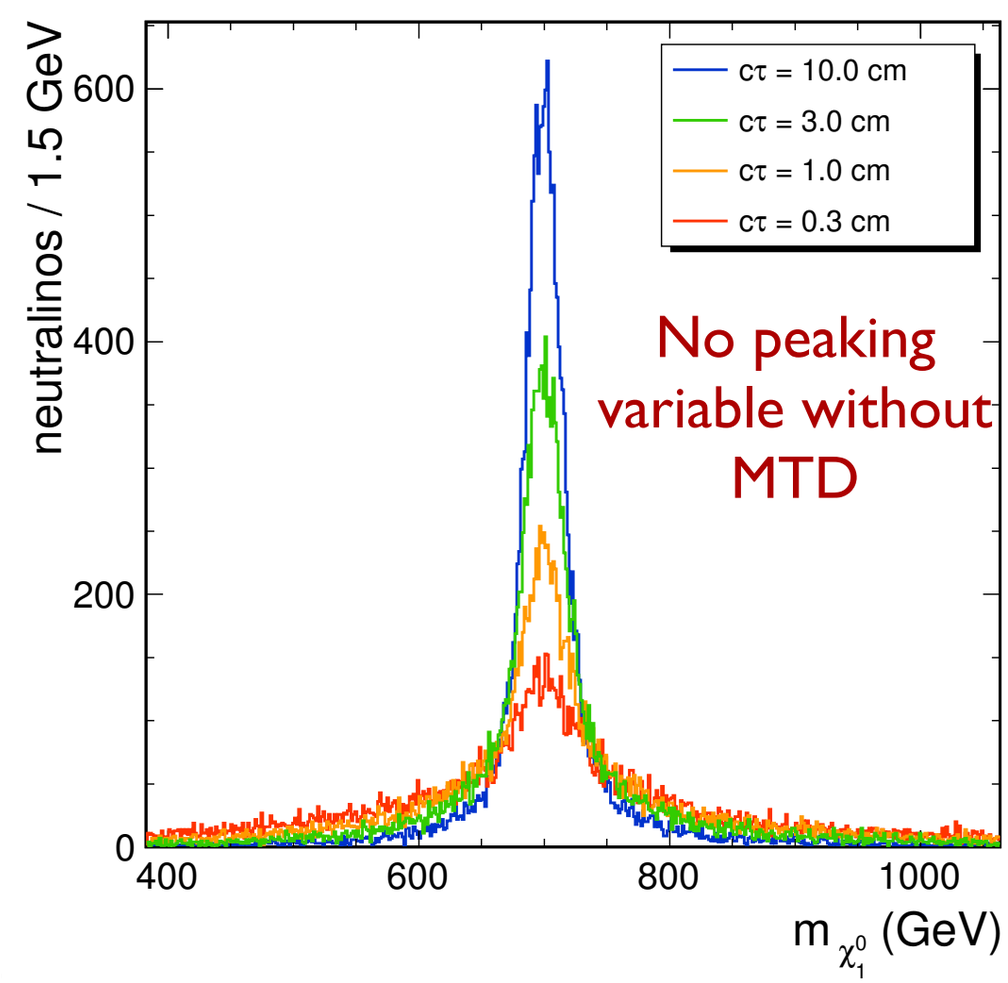
- MTD provides a *new capability* for these searches

Reconstruction of Neutral LLP Masses

- By measuring particle velocity from primary and secondary vertices, we can reconstruct a peaking variable for LLP searches
  - Model independent: can either reconstruct mass or mass splitting depending on how velocity related to model structure

- The MTD *fundamentally* changes how we execute these searches





Performance Summary

- The MTD is a key addition that improves the full range of HL-LHC era physics

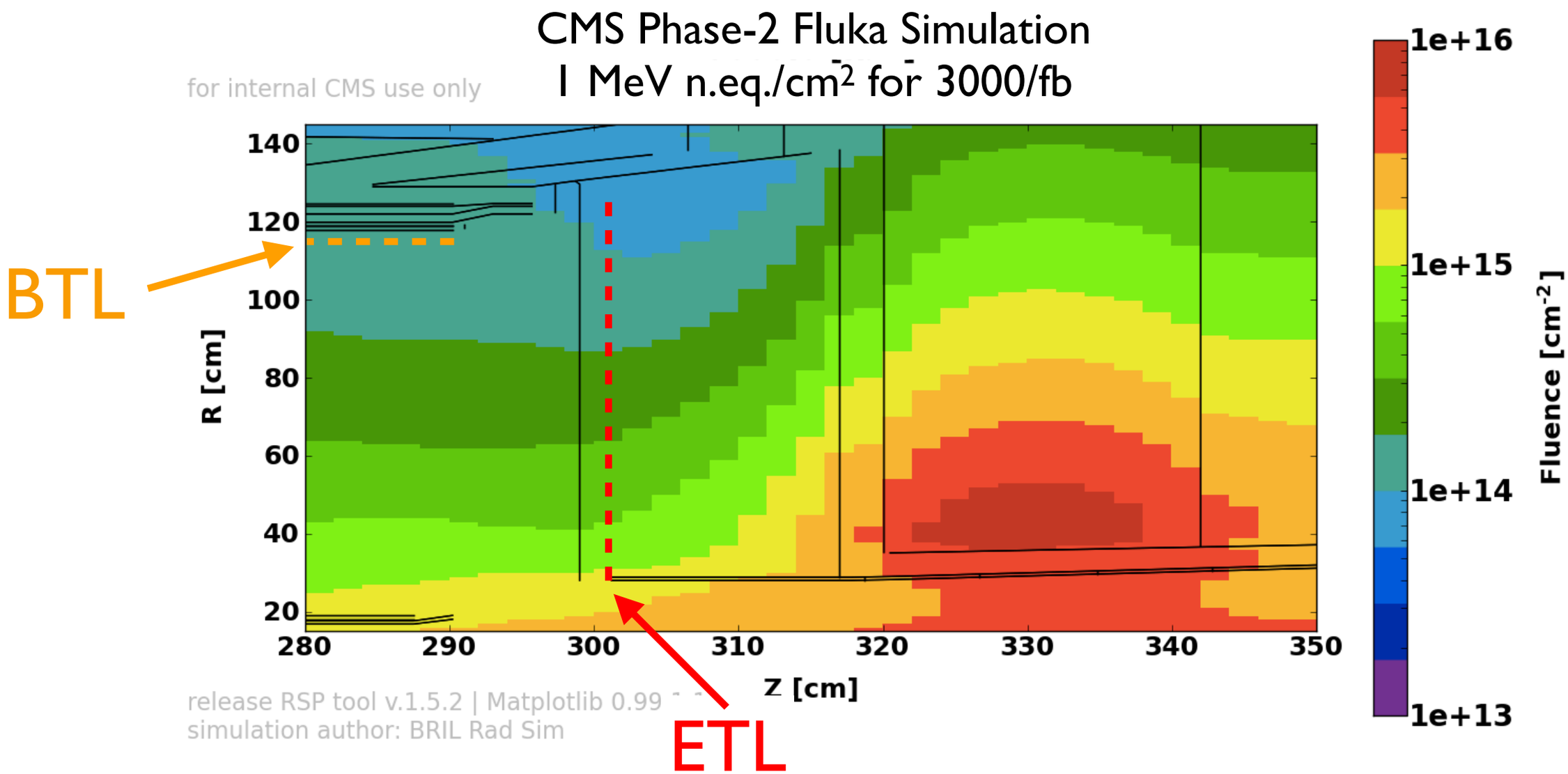
Examples Shown

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

- ~20-30% acceptance improvements across all measurements
- Recovery of performance for large-MET based searches
- Novel capabilities derived from LLP secondary vertex timing

What does such a detector actually look like?

- Technology choices are driven by radiation and cost
  - BTL: LYSO + Silicon Photomultipliers (SiPM)
  - ETL: Low Gain Avalanche Detectors (LGAD)



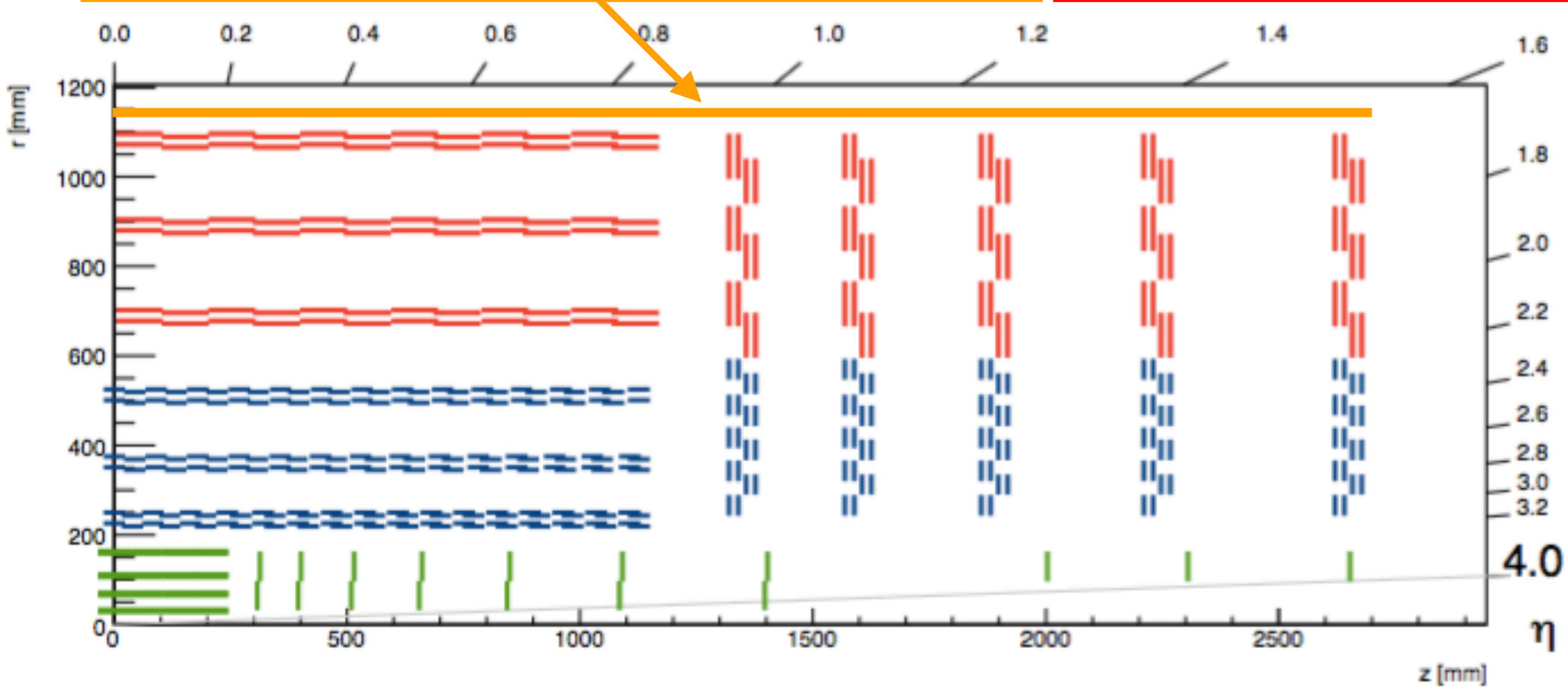
Hermetic MIP Timing: Barrel & Endcap

Requirements:

- Hermeticity: barrel ($|\eta| < 1.48$) and endcap ($1.6 < |\eta| < 2.95$)
- Radiation: 2×10^{14} n_{eq}/cm^2 (barrel) and up to 2×10^{15} n_{eq}/cm^2 (endcap)
- Minimal impact on calorimeter performance
- Mechanics and services compatible with existing upgrades

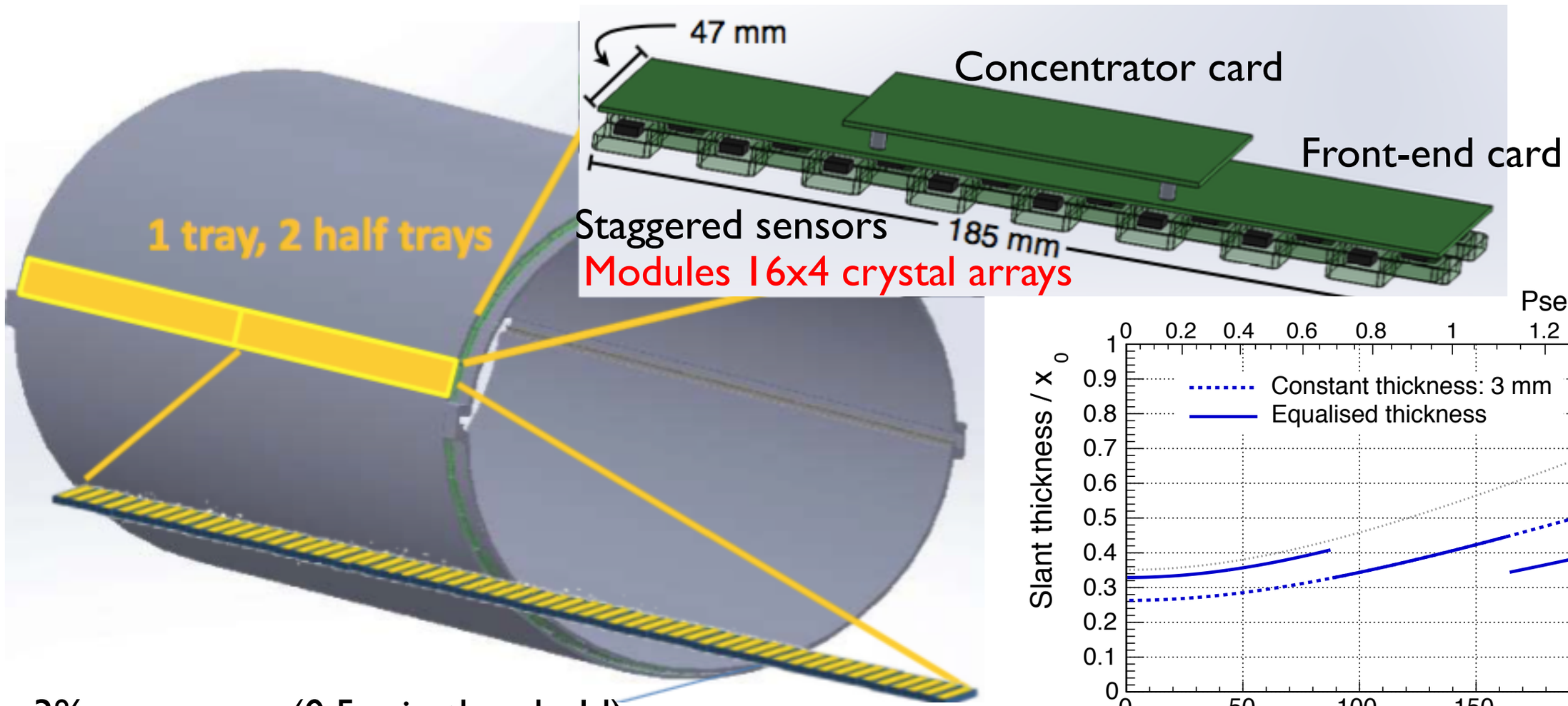
LYSO:Ce tiles with SiPM readout:
- embedded in TK support ~ **25 mm thick**
- Area ~40 m², ~250k channels
- Integrate with tracker

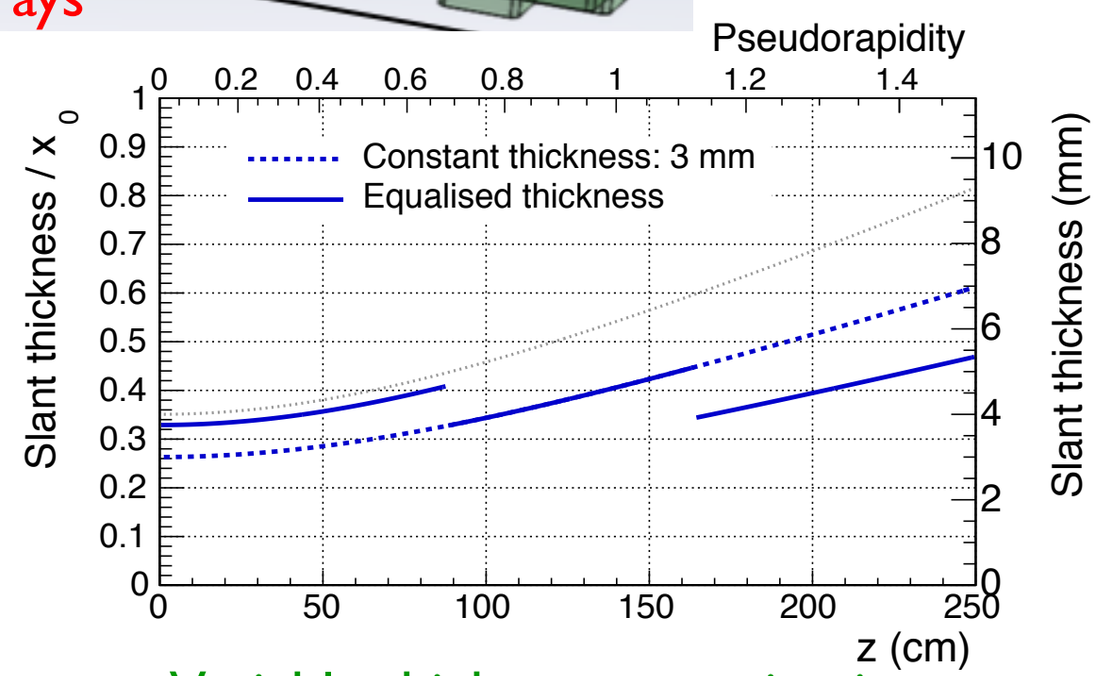
Si with internal gain (LGAD):
- On the endcap nose ~ **42 mm thick**
- Area ~12 m² (total), ~4M channels
- Integrate with endcap



Barrel Timing Layer (BTL) Layout

- LYSO:Ce + SiPM tiles embedded in the tracker support tube
  - CO2 cooling for SiPMs at ~ −30 C
- LYSO:Ce + SiPM is a production-ready and scalable technology



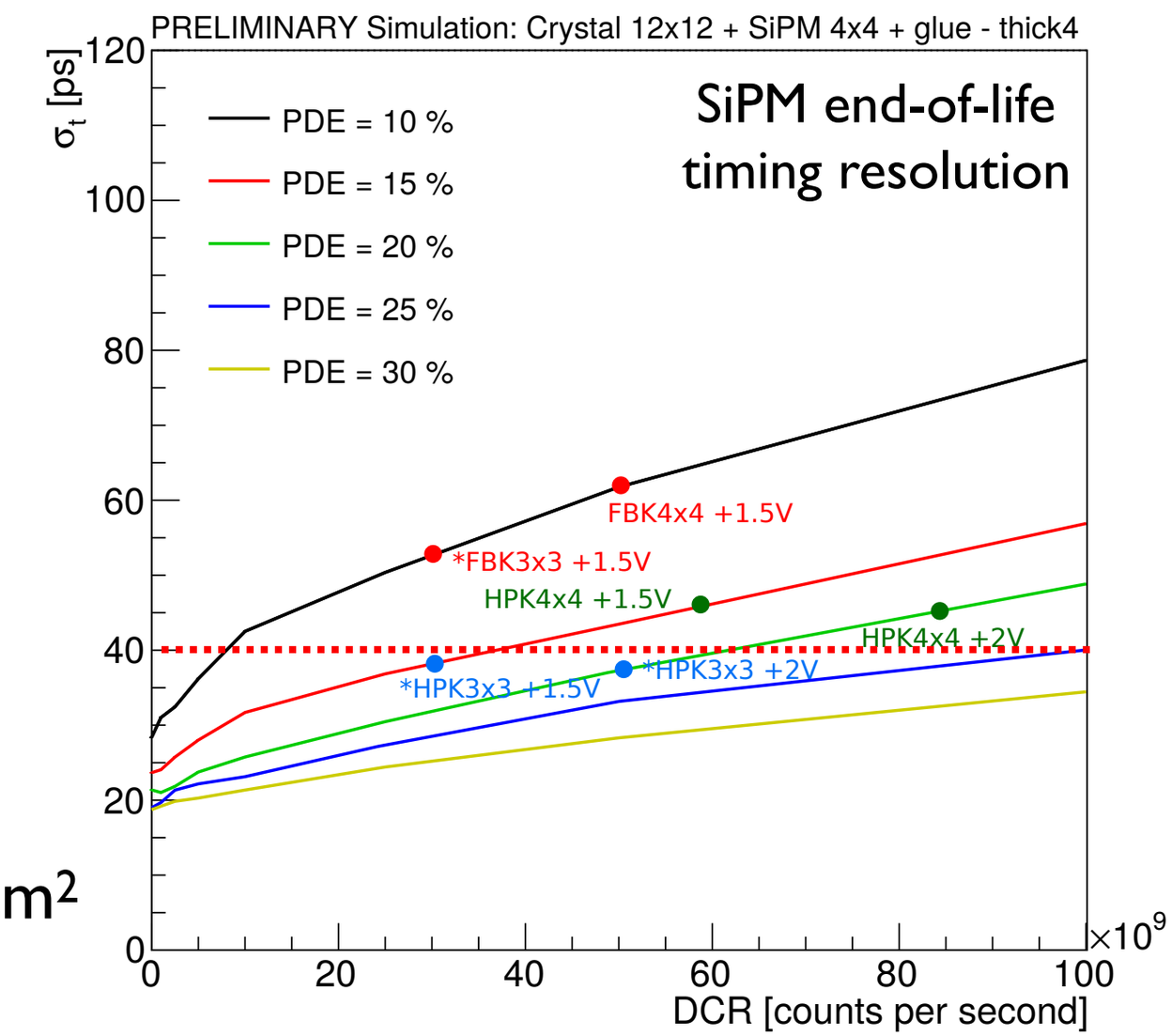


- 3% occupancy (0.5 mip threshold)
- Adapt TOFPET2 ASIC
  - Leading edge timing + amplitude meas.

Variable thickness to maintain a uniform material budget

Radiation Hardness of BTL Sensor Package

- Radiation at the end of HL-LHC
  - Fluence: 1.7-2×10^{14} n_{eq}/cm^2 , Dose: 16-25 kGy
- LYSO: fast, bright scintillator
  - Sufficiently radiation hard
- SiPM: existing devices close to 30ps at end of HL-LHC
  - Lines: resolution from simulation varying photon detection efficiency (PDE) and dark count rate
  - Points: extrapolation to 2x10^{14} n_{eq}/cm^2 of SiPMs irradiation studies

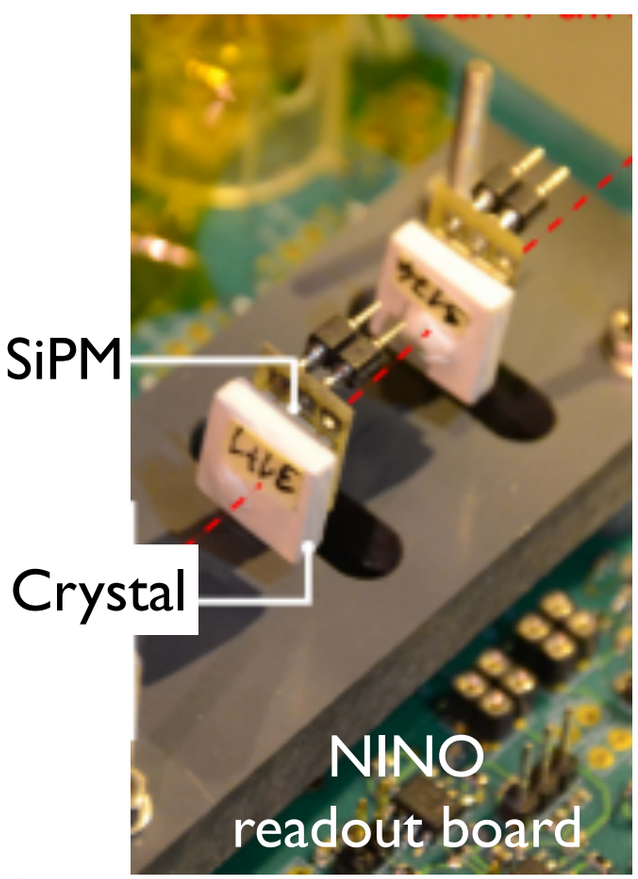


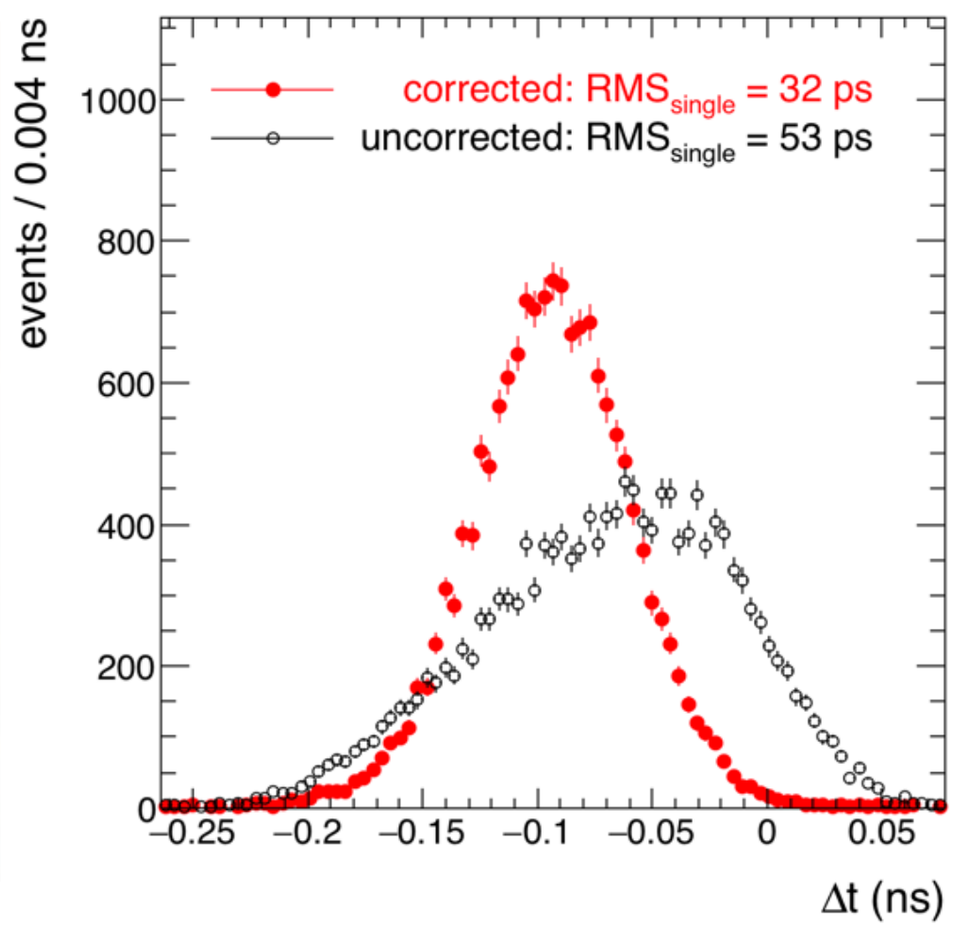
To be optimized: reflective wrappings, SiPMs size / layout, thicker tiles, …

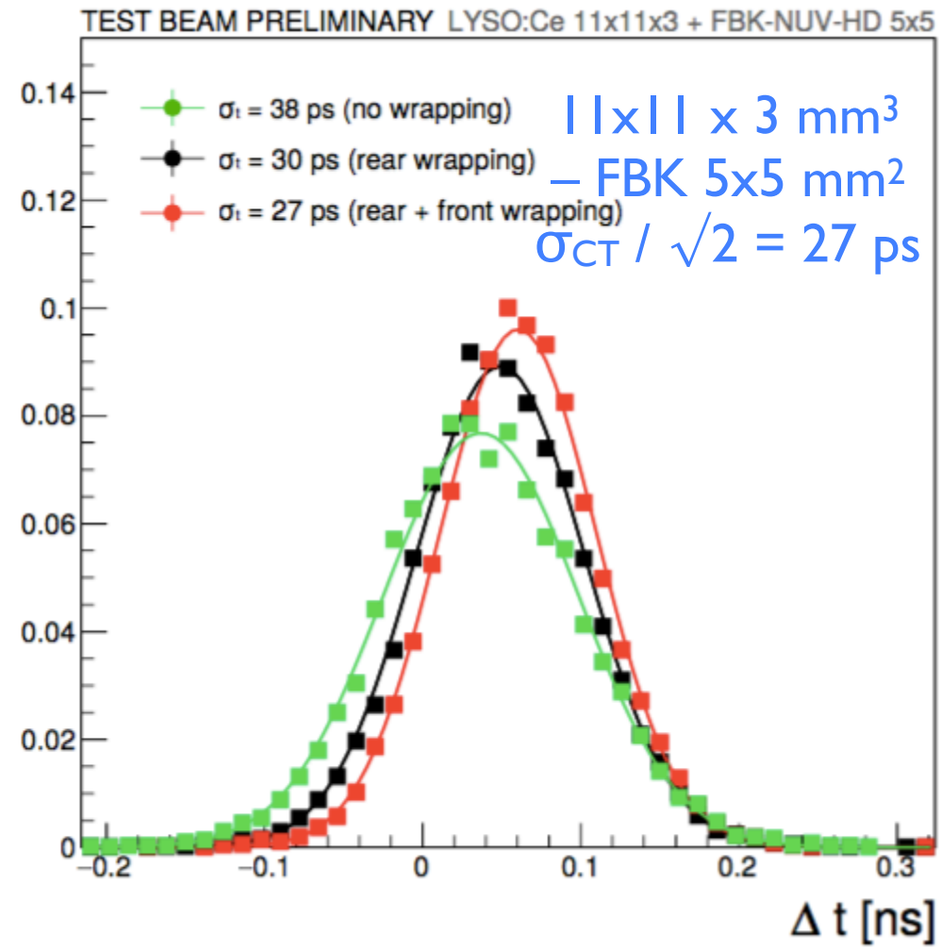
BTL Sensor Package: Time Resolution

- Nominal geometry: 11x11mm^2 + 4x4 mm^2 SiPM
  - Slant thickness is ~4 mm
- Timing correction for hit position necessary if SiPM small compared to Crystal
  - Left plot: over whole tile with and without impact point correction
  - Right plot: test beam through SiPM fiducial

▸ Identified options to mitigate position dependence that are being pursued



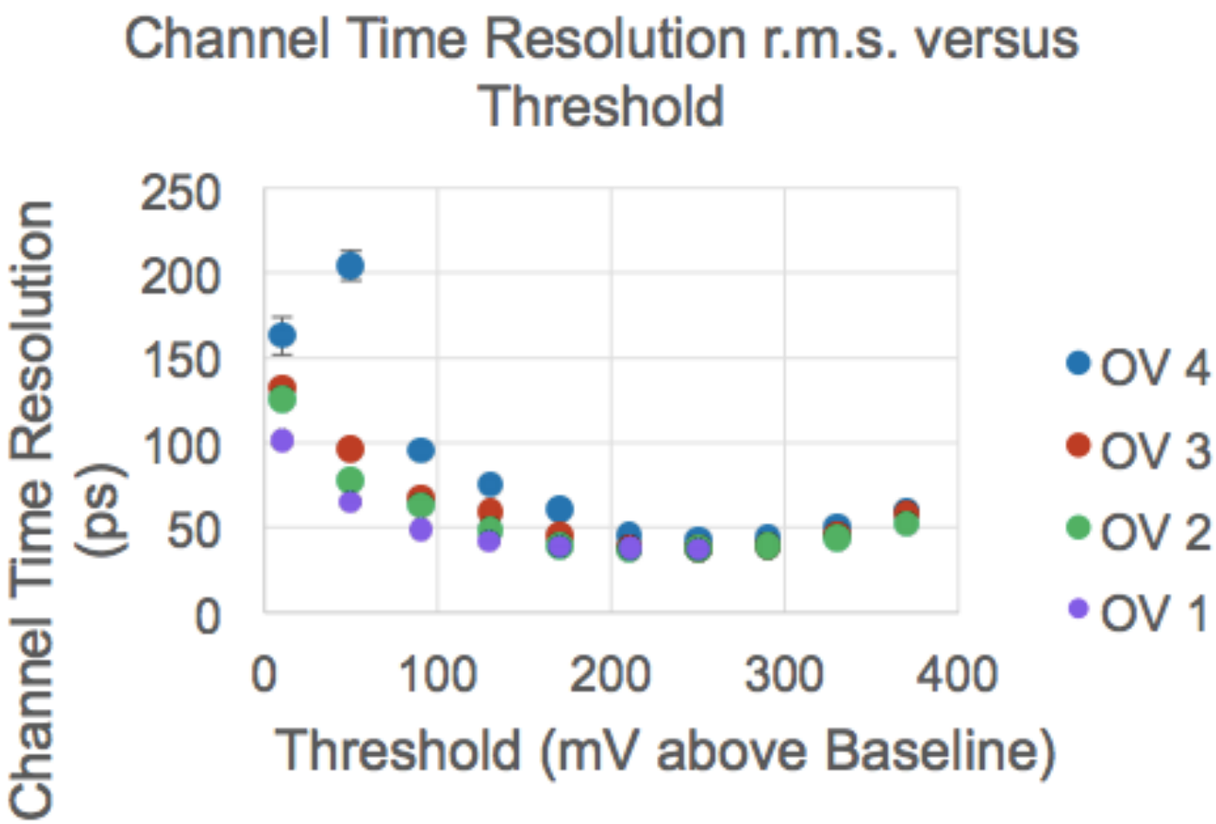




BTL ASIC

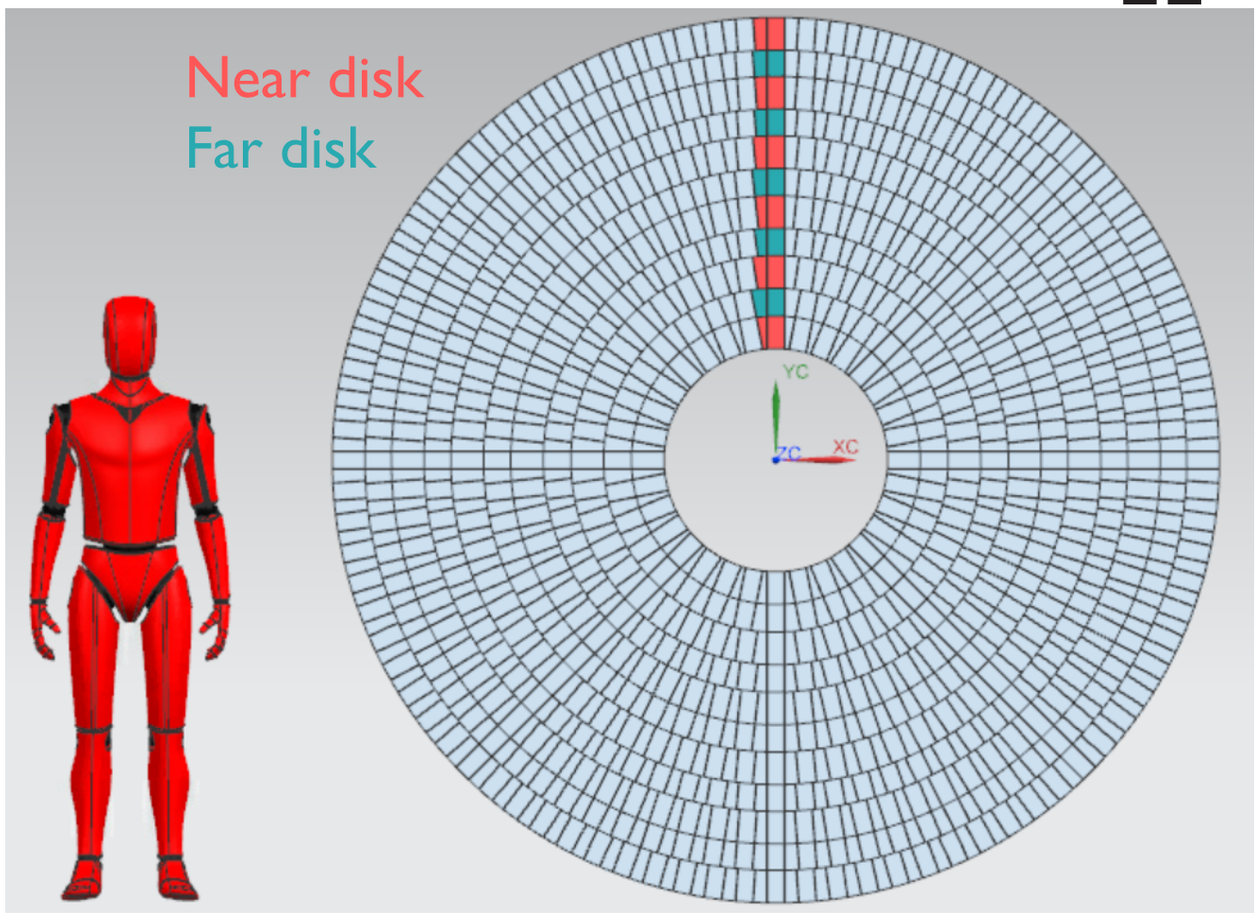
- BTL ASIC will be tailored version of commercial TOFPET2 chip
  - TOFPET2 with sensor package RMS already 37 ps
  - goal is 25 ps for sensor package (achieved at testbeam with NINO)

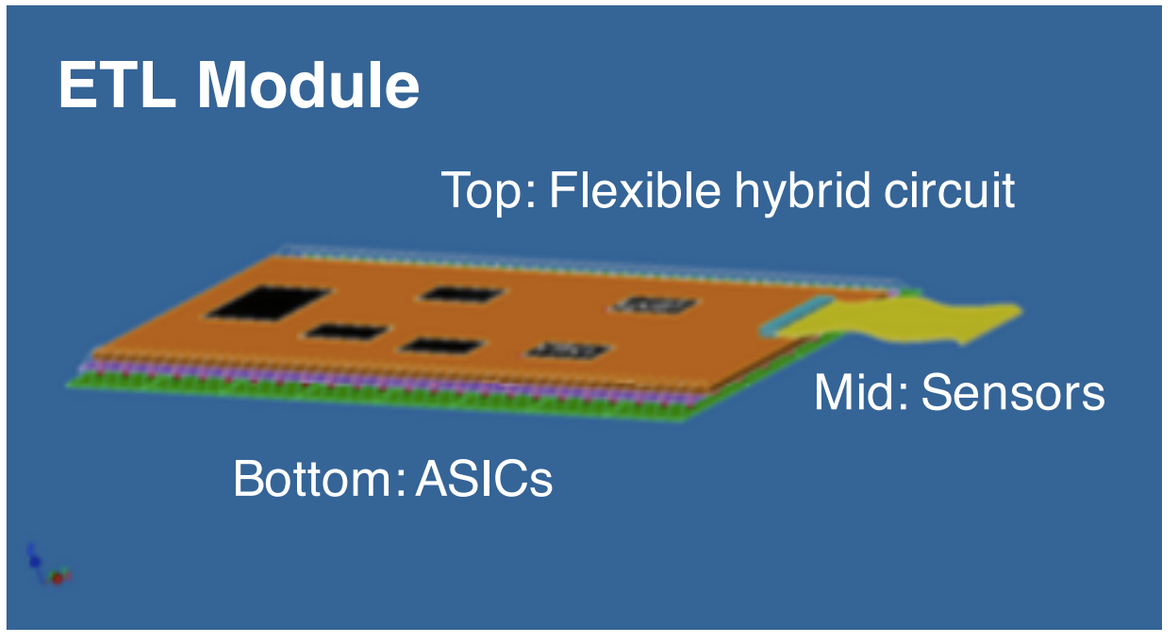
- Reasons for the difference are understood
  - Pulse slew rate (amplifier configuration) and TDC contribution
  - Radiation hard design in parallel – TSMC 130nm



Endcap Timing Layer (ETL) Design

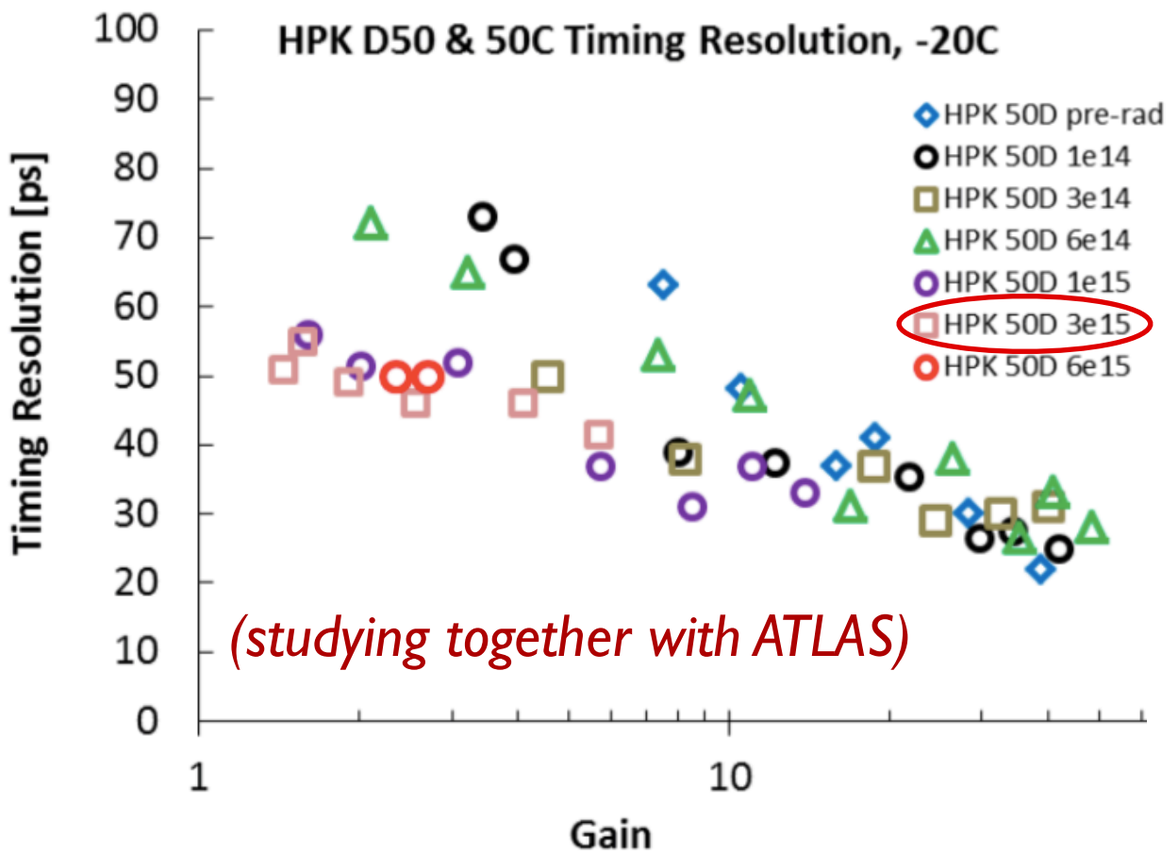
- LGAD Sensors: established technology available from at least three foundries
- Overlapping disk structure
  - Placed in independent cold volume for accessibility
  - Al wedges with embedded cooling pipes (CO2 cooling @ -30 C)
- Sensors on both disk sides
  - Single-hit hermetic coverage
  - Nominal geometry 4.8 x 9.6 cm^2 modules with 1x3 mm^2 pads

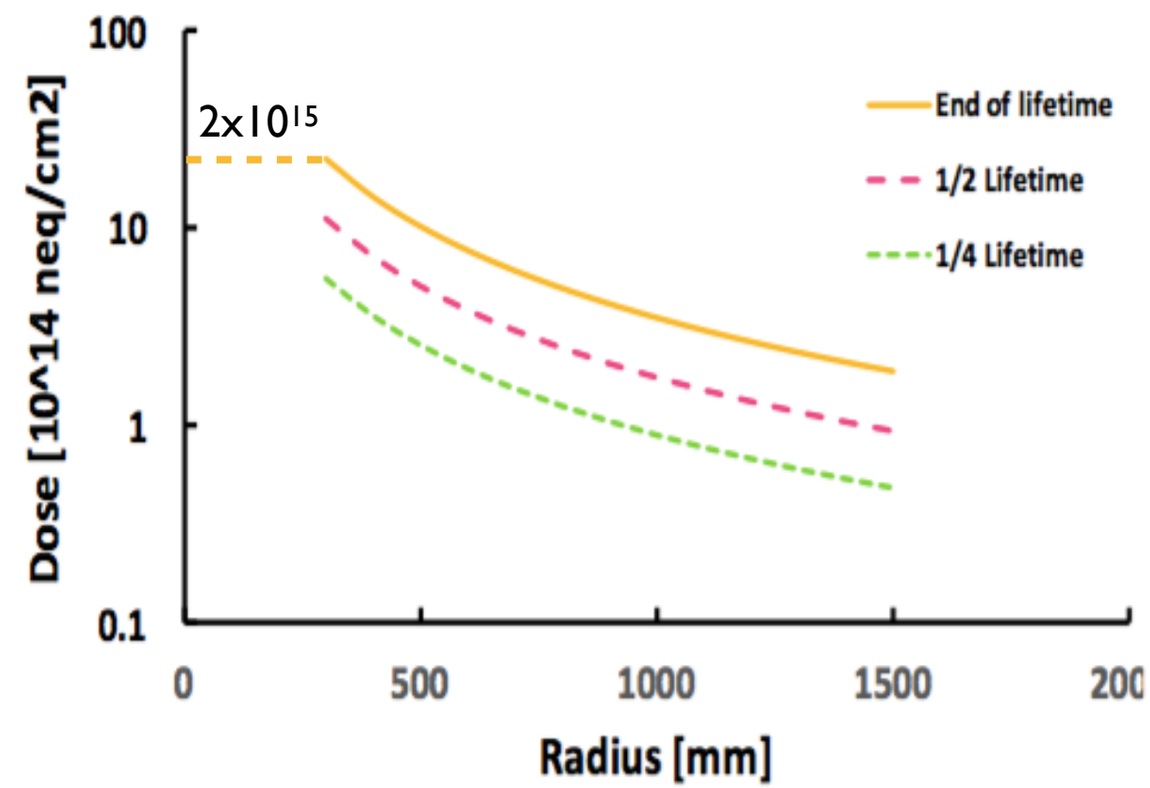




LGAD Performance and Radiation Tolerance

- Over most of ETL area present LGADs achieve 30ps resolution, the issue is only at the highest η
- Measured < 45 ps at 3e15 n_{eq}/cm^2 (1.5x max fluence at highest η)



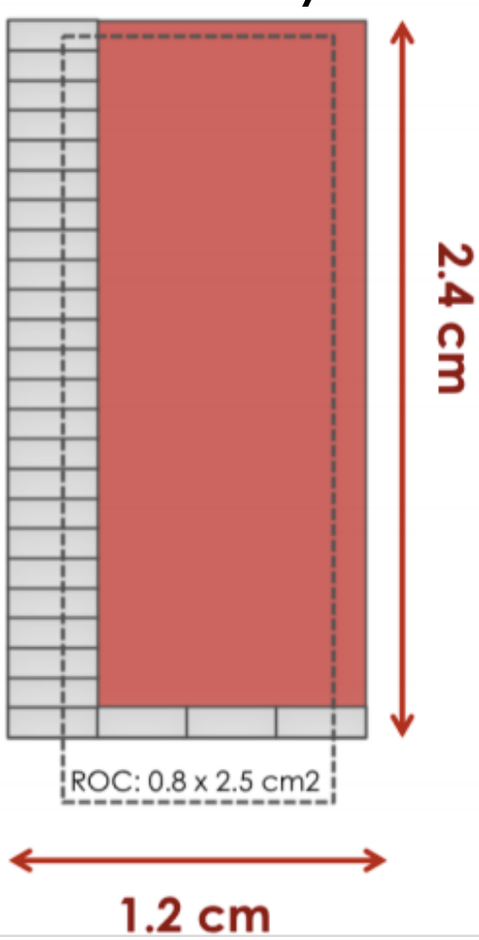


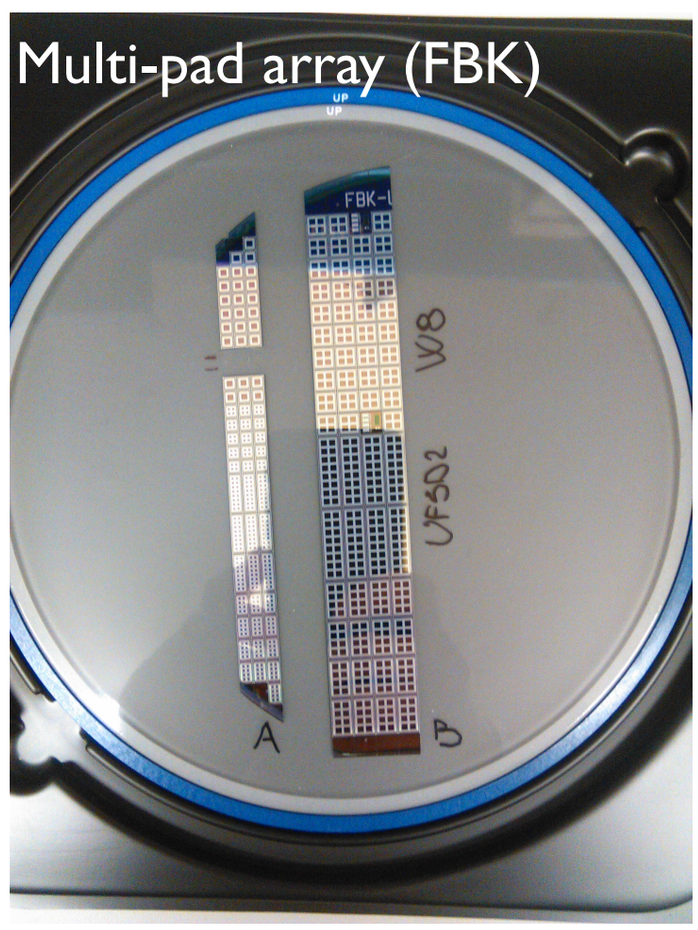
- LGAD can deliver < 40 ps timing resolution for entirety of HL-LHC
- New optimization studies with latest LGADs indicate further improvements

Multi-pad Sensor Development

- Large arrays of LGADs are possible already with small pad sizes
  - Production of pixellated LGAD sensors show large viable pad yields
- Prototypes of multi-pad sensors with CMS pad size now available
  - 2x8 arrays now, 4x24 in early 2018 (1/16 of a full sensor)
  - Will study gain uniformity, viable pad yield, fill factor for large pads

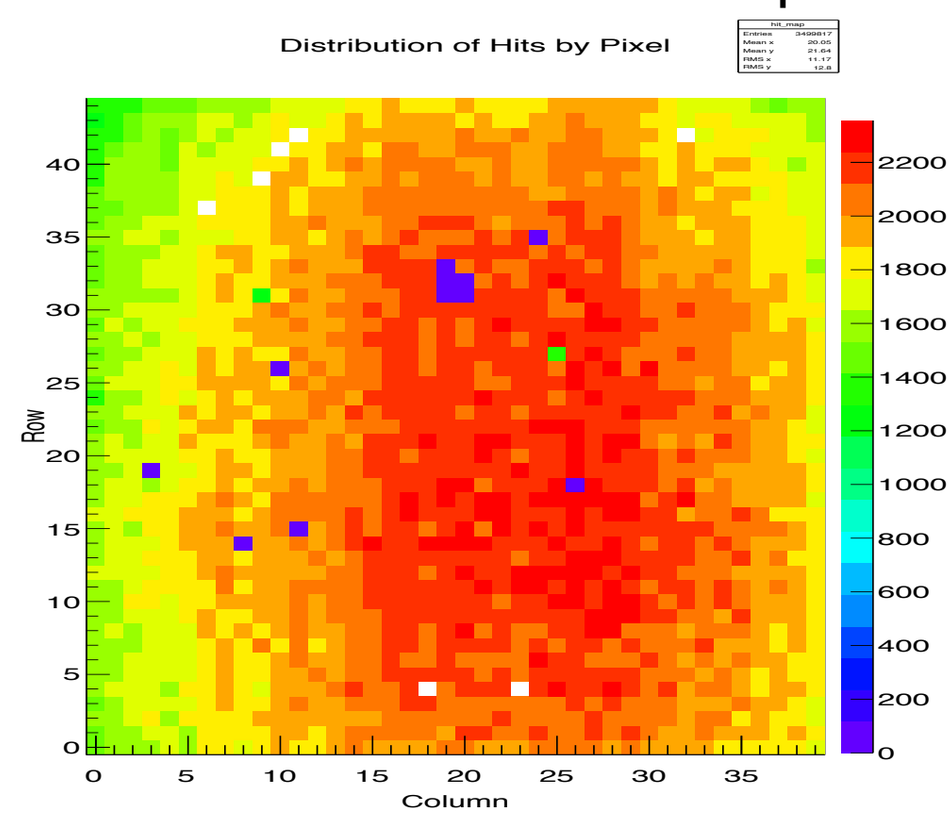
CMS Pad Geometry





Lindsey Gray, FNAL

Pixellated LGAD sensor hit-map



1800 pads!

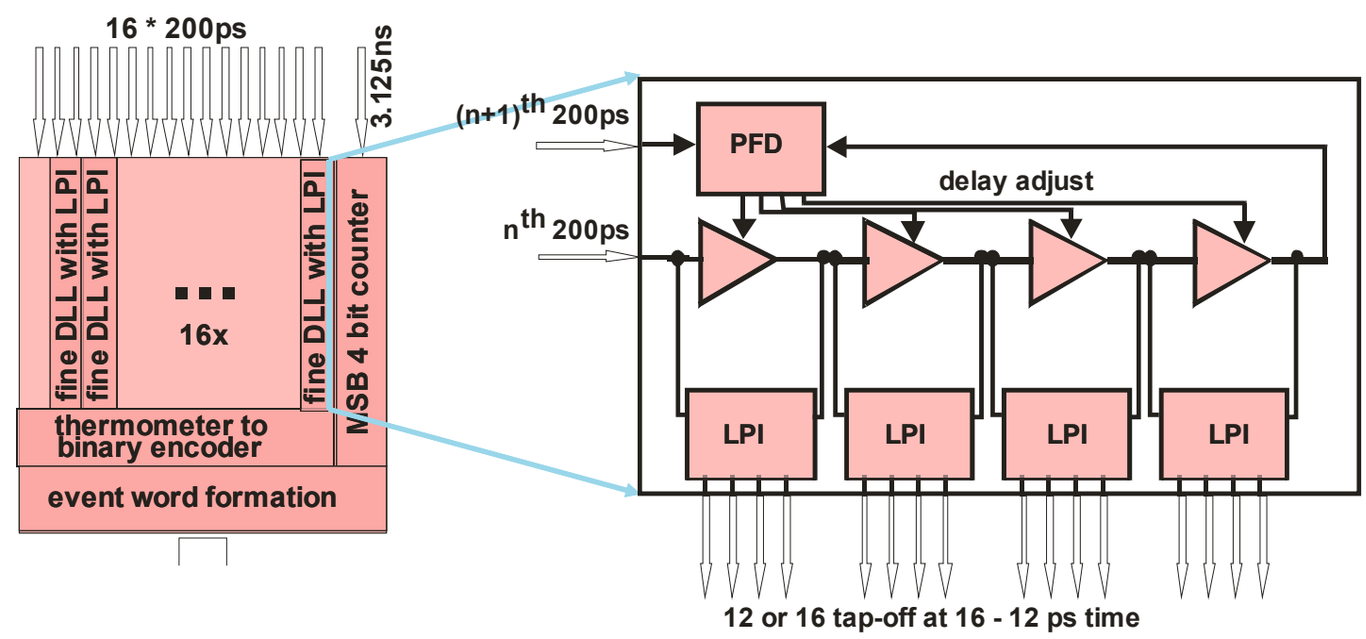
ETL Front-end ASIC

- Chip specs defined: 25 ps without sensor, 110 mW/cm^2
- Use cascade of timing measurements to achieve distributed TDC over large-area ASIC
  - Well 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

Last stage of measurements uses DLL + passive elements to achieve finest binning.

Most precise elements, resistors and capacitors, are radiation tolerant.



Two-stage fine DLL

Concluding Remarks

- MTD will benefit the whole physics program
  - Preserves the performance of Particle Flow and PUPPI
  - Increases effective luminosity: +20% for di-higgs
  - Recovers search performance in MET tails
- Benefits equivalent to additional 2-3 years of luminosity
- New capabilities for long-lived particle searches
- Sensor technologies underlying detectors becoming mature
- Many institutions are contributing to the studies and 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 $|\eta| < 4.0$

Backup / Extras

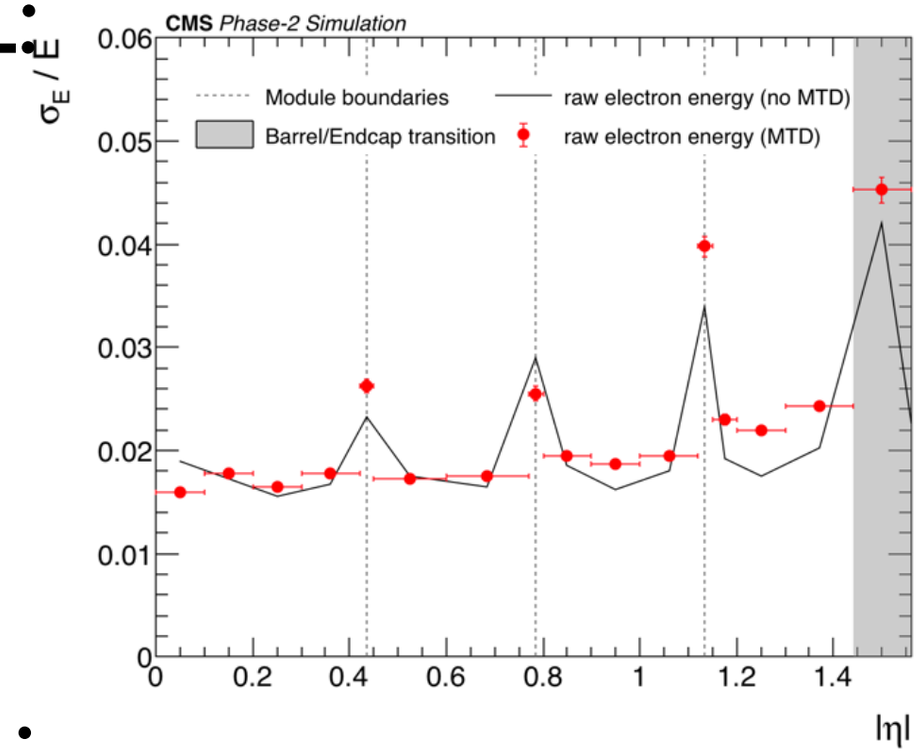
MTD Institutions

Tag	Institution name
INP-BY	Institute for Nuclear Problems of Belarus State University, Minsk, Belarus
HIP-FI	Helsinki Institute of Physics, Helsinki, Finland
IRFU-FR	IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
KIT-DE	Institut für Experimentelle Kernphysik, Karlsruhe, Germany
DEB-HU	Institute of Physics, University of Debrecen, Debrecen, Hungary
Ge-IT	INFN Sezione di Genova [a], Università di Genova [b], Genova, Italy
MiB-IT	INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy
Pd-IT	INFN Sezione di Padova [a], Università di Padova [b], Padova, Italy, Università di Trento [c], Trento, Italy
Rm-IT	INFN Sezione di Roma [a], Sapienza Università di Roma [b], Rome, Italy
To-IT	INFN Sezione di Torino [a], Università di Torino [b], Torino, Italy, Università del Piemonte Orientale [c], Novara, Italy
Ts-IT	INFN Sezione di Trieste [a], Università di Trieste [b], Trieste, Italy
ViU-LT	Vilnius University, Vilnius, Lithuania
LIP-PT	Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
NSU-RU	Novosibirsk State University (NSU), Novosibirsk, Russia
IFCA-SP	Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
USe-SP	University of Sevilla, Sevilla, Spain
CERN	CERN, European Organization for Nuclear Research, Geneva, Switzerland
ETHZ-CH	ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
BU-US	Brown University, Providence, USA
UCSB-US	University of California, Santa Barbara - Department of Physics, Santa Barbara, USA
Caltech-US	California Institute of Technology, Pasadena, USA
FU-US	Fairfield University, Fairfield, USA
FNAL-US	Fermi National Accelerator Laboratory, Batavia, USA
FSU-US	Florida State University, Tallahassee, USA
UIC-US	University of Illinois at Chicago (UIC), Chicago, USA
UI-US	The University of Iowa, Iowa City, USA
KU-US	The University of Kansas, Lawrence, USA
KSU-US	Kansas State University, Manhattan, USA
MIT-US	Massachusetts Institute of Technology, Cambridge, USA
NU-US	Northeastern University, Boston, USA
ND-US	University of Notre Dame, Notre Dame, USA
PU-US	Princeton University, Princeton, USA
UVa-US	University of Virginia, Charlottesville, USA
UW-US	University of Wisconsin - Madison, Madison, WI, USA

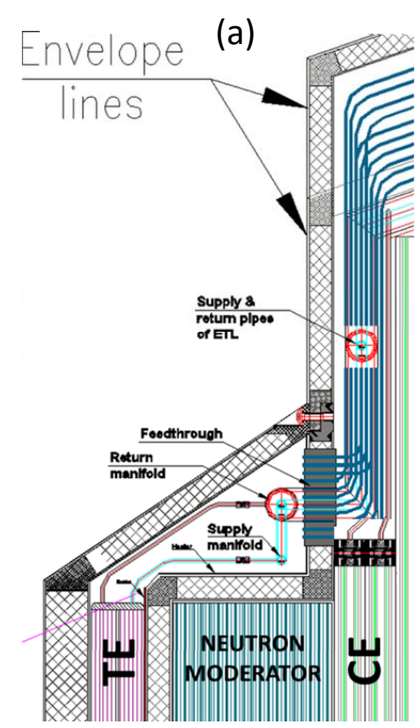
MTD Impact on Other Subdetectors

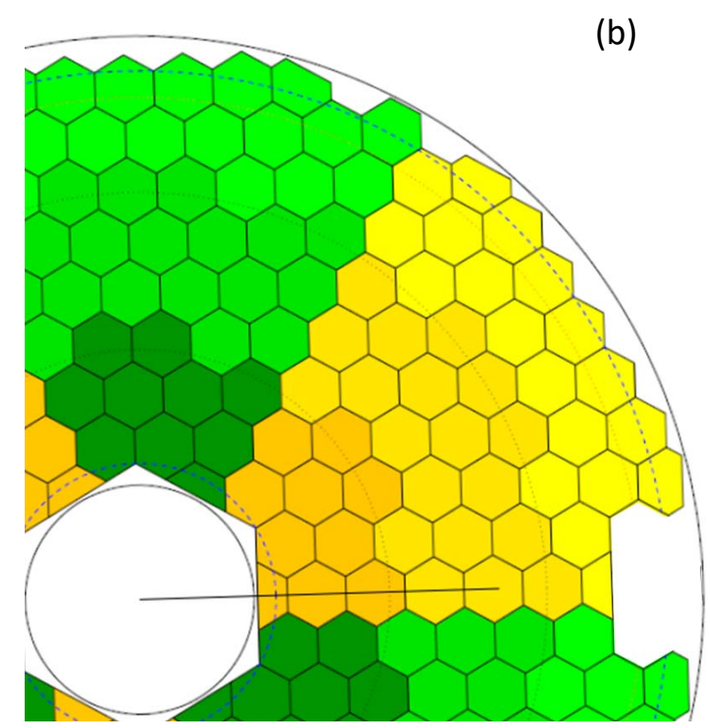
- MTD has a minor impact on upstream sub detectors
- BTL yields minor degradation in energy resolution for photons
  - BTL information not yet included in corrections
  - Small reduction of outer tracker radius by 14mm, negligible impact on tracking performance
- ETL services require modification of first two layers of CE
  - Need to route services to neutron moderator front face
  - Affects two CE trigger towers
  - Possible to minimize impact with services routing optimization

BTL:

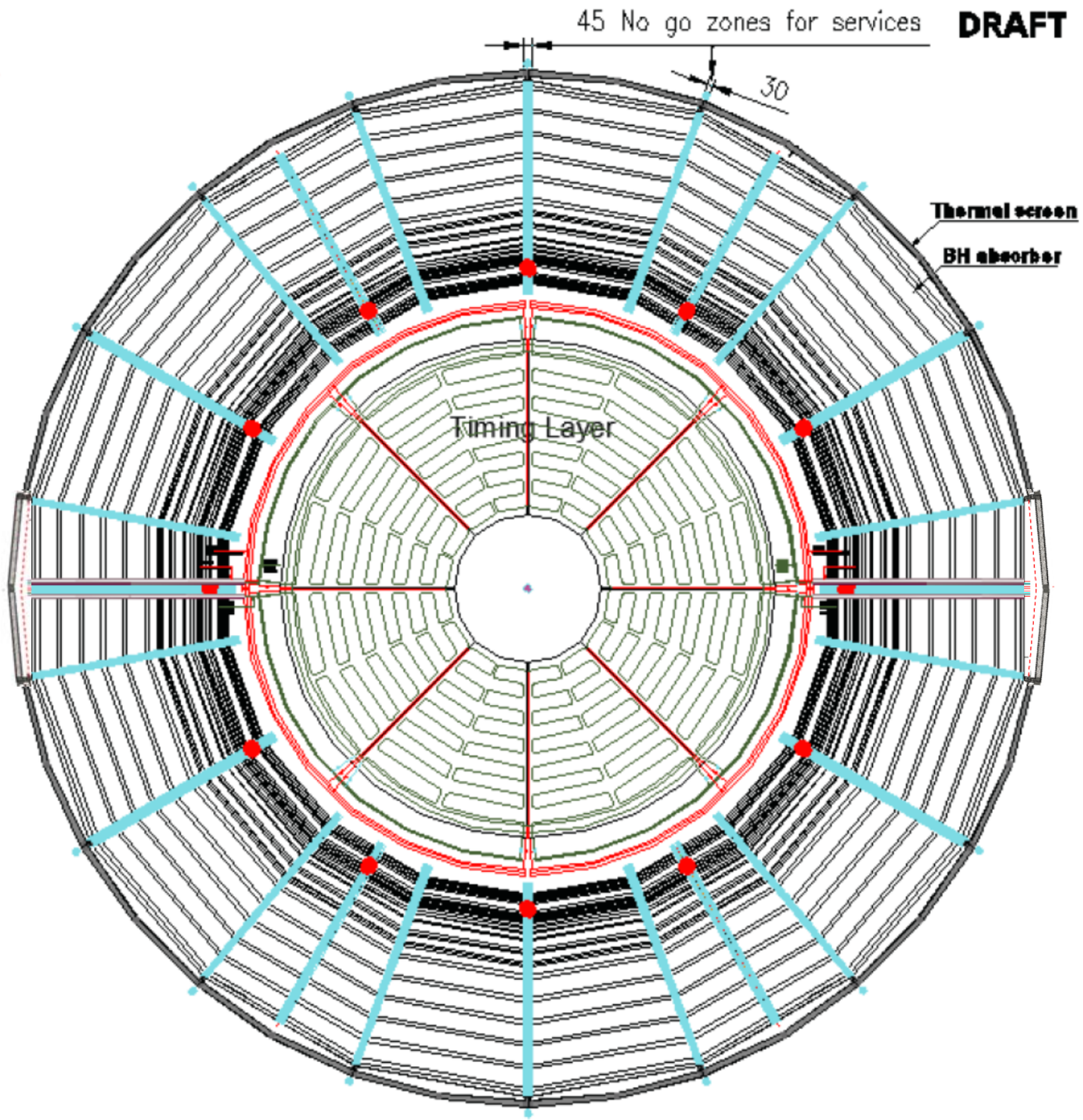


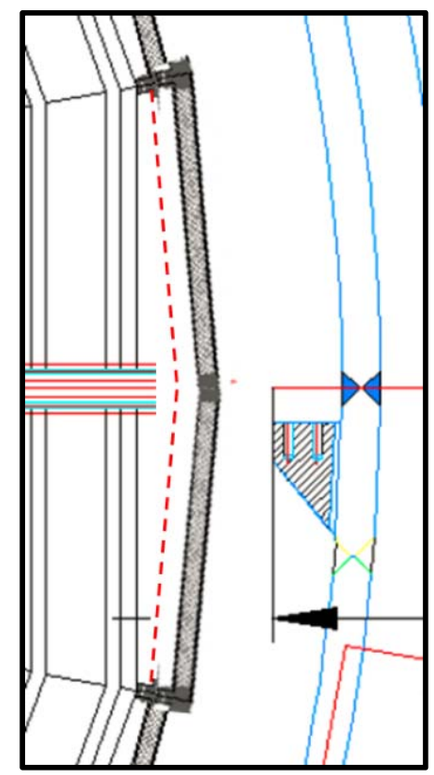
ETL:



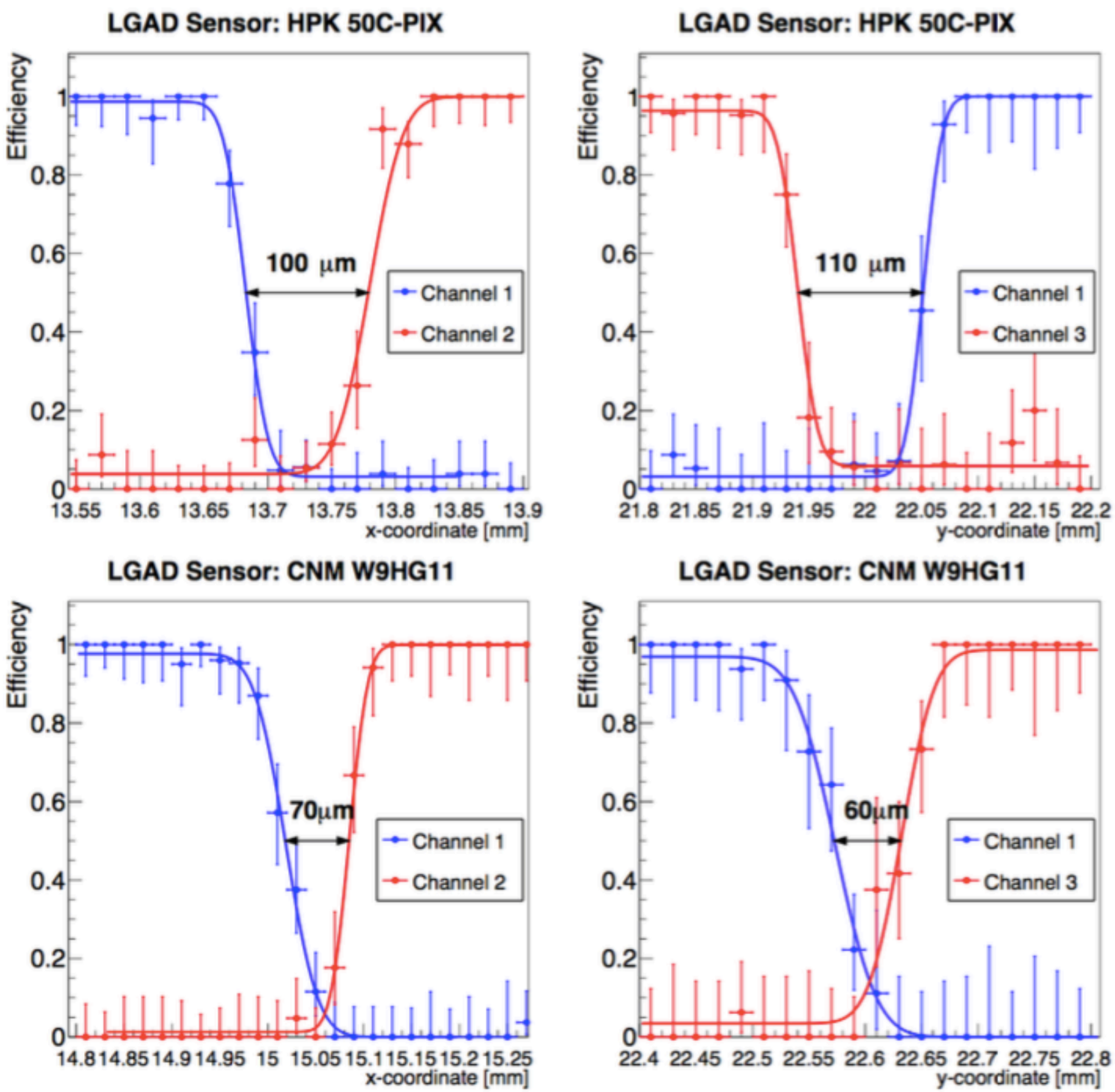


MTD:TE Service Routing





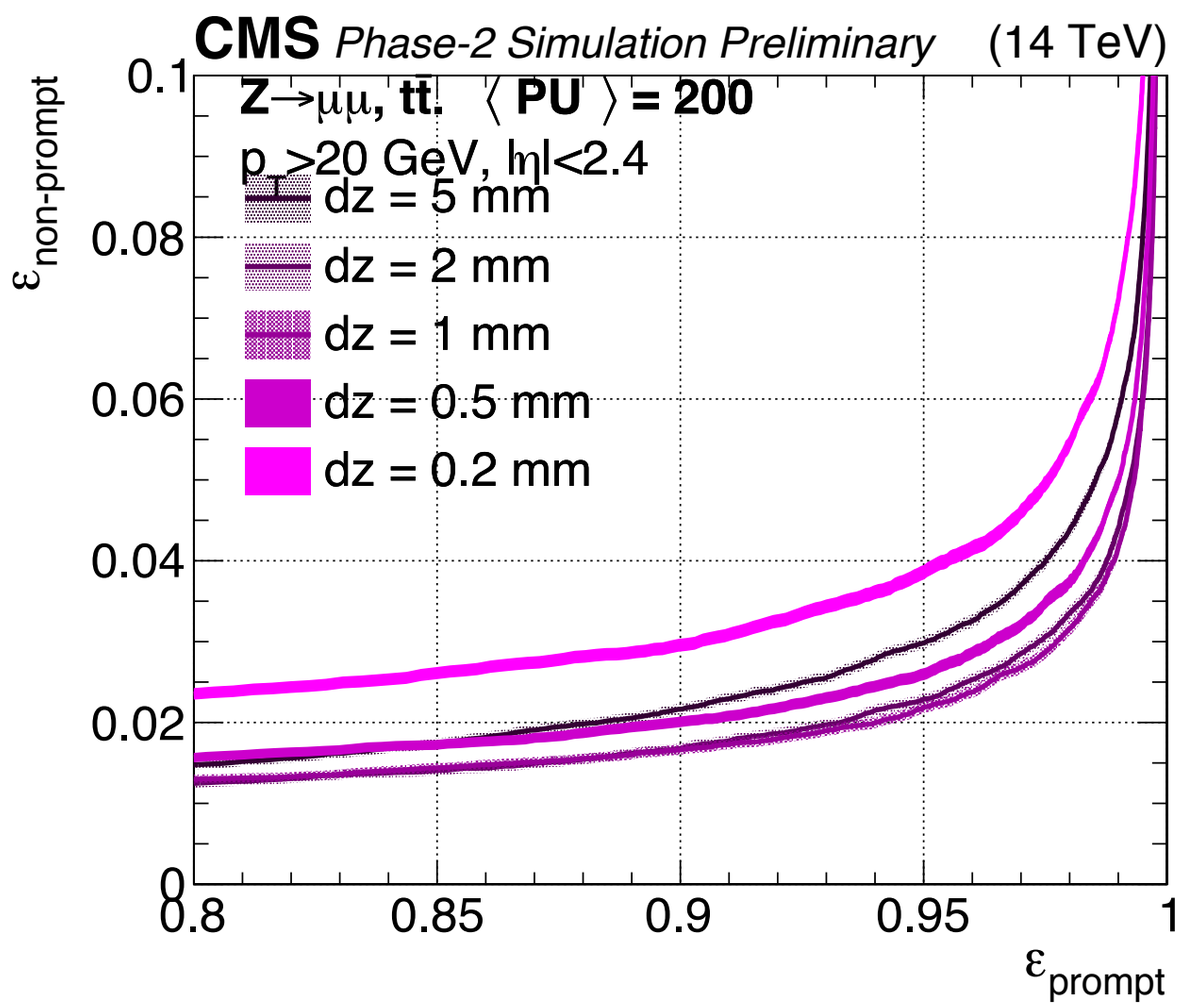
Fill Factor Investigations



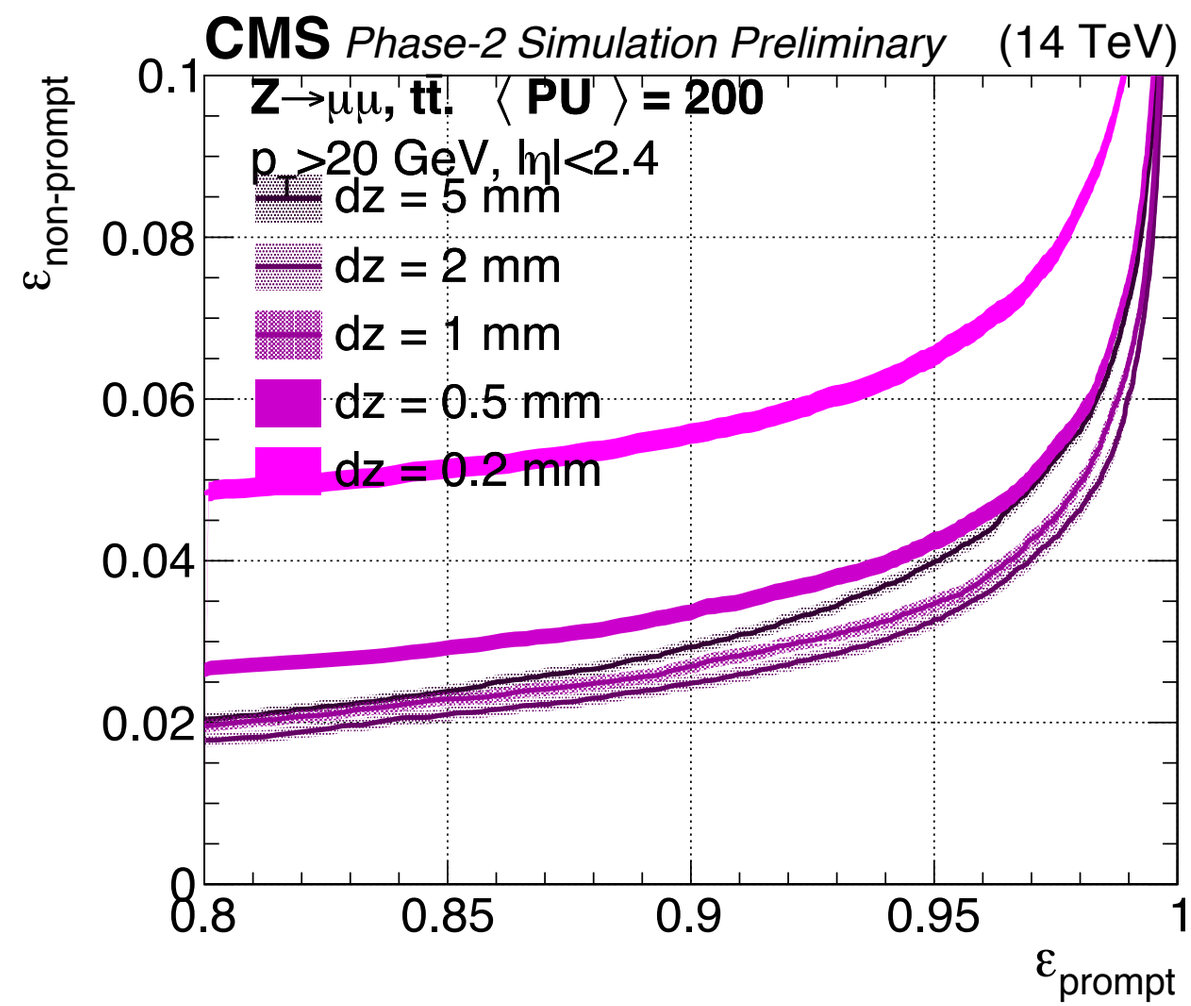
- Mapping of HPK and CNM sensor geometries in test beams
  - Dead regions at pad boundaries:
    - Distance between adjacent gain layers to prevent breakdown
    - Shape of field lines
  - Both under optimization
    - with ATLAS
- Target for CMS
  - Single layer detector
  - Dead regions < 40 μm
    - Inefficiency < 10%
    - Achievable through optimization of p-stop, junction termination extension

Optimal |dz| cut for Isolation (no timing)

Barrel

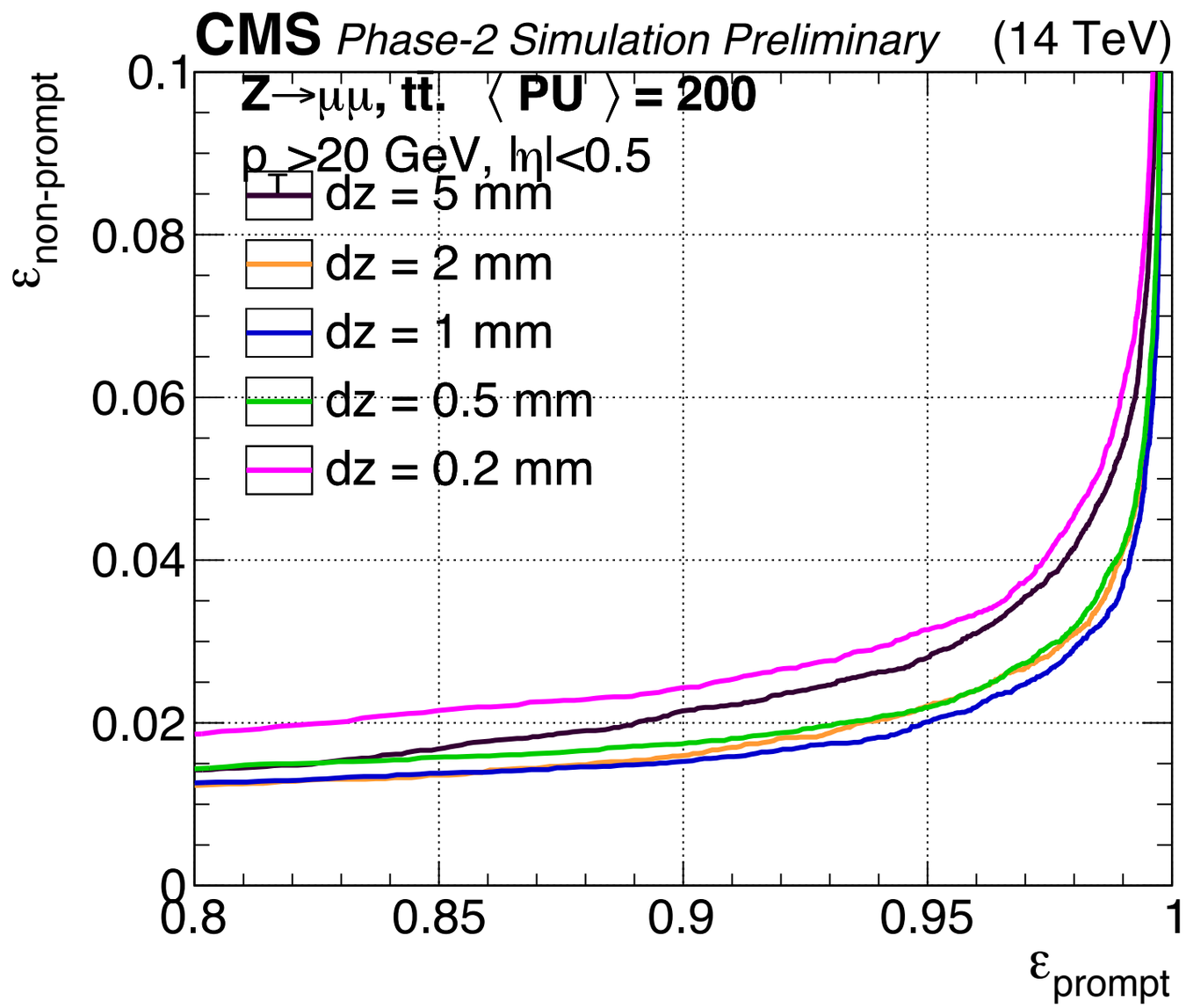


Endcap



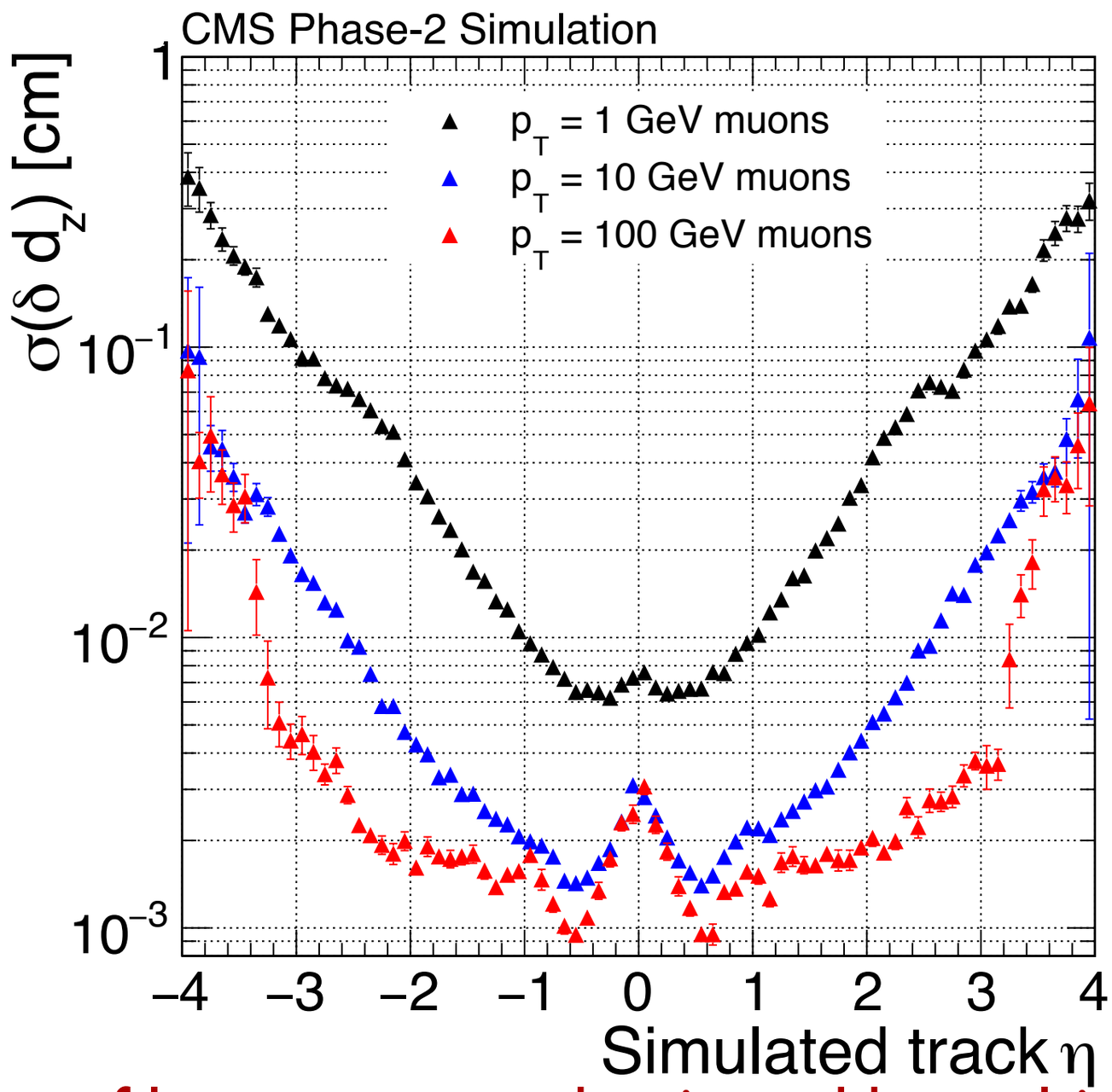
|dz| < 1mm cut outperforms significance-based in both barrel and endcap.

Optimal |dz| cut for Isolation (no timing)



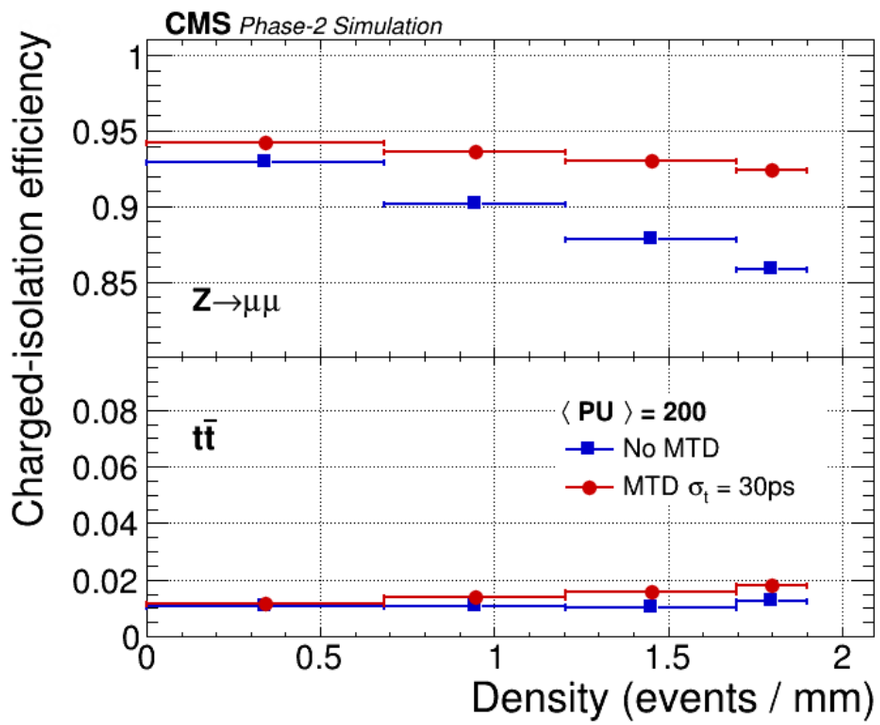
|dz| < 1mm is uniformly the best choice as a function of eta, even in the most central barrel

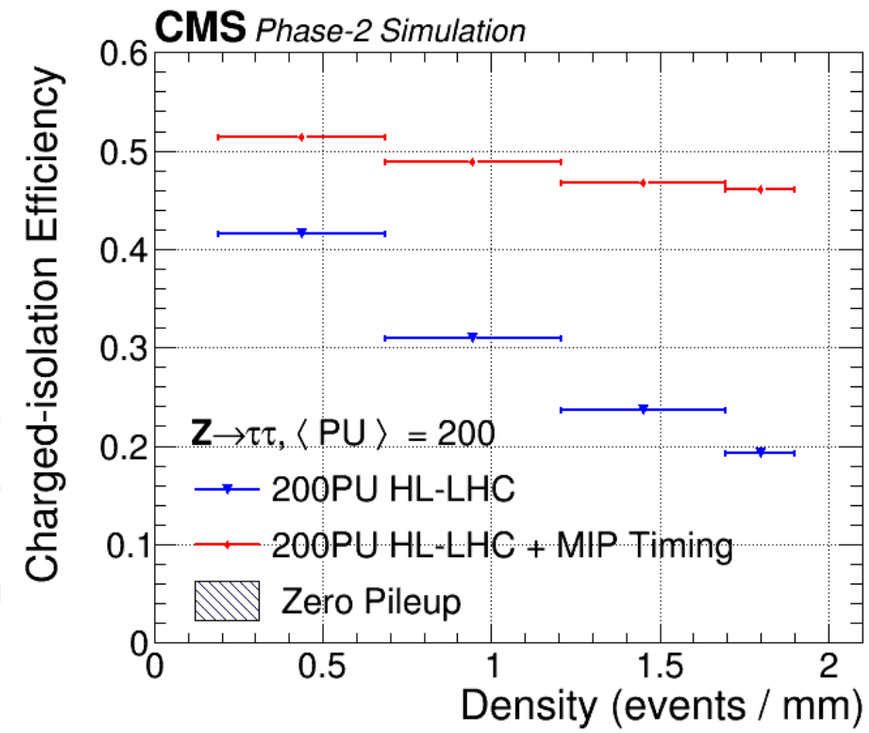
CMS Phase-2 Tracker dz Resolution

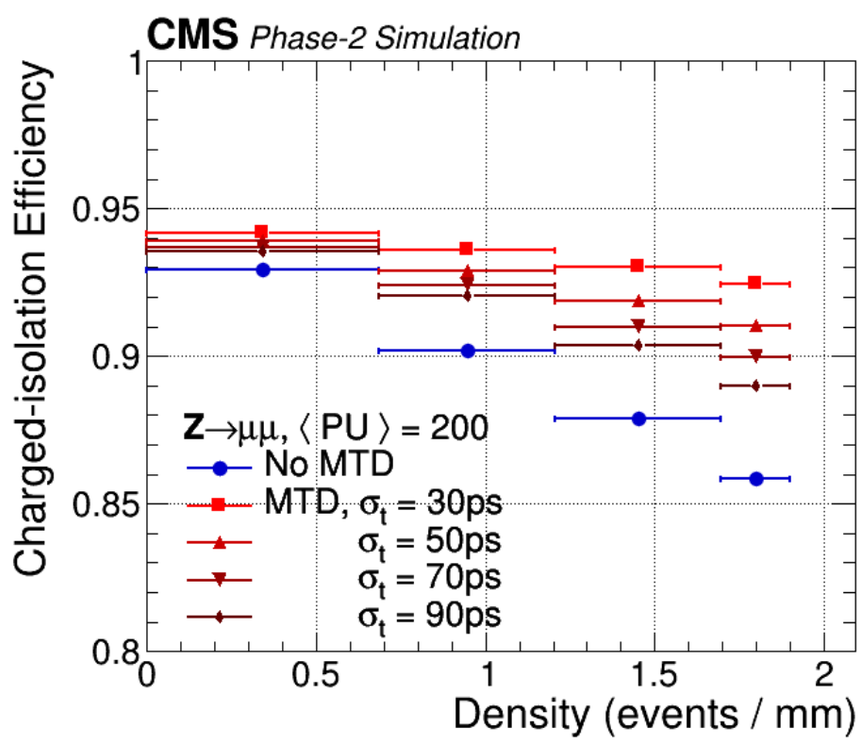


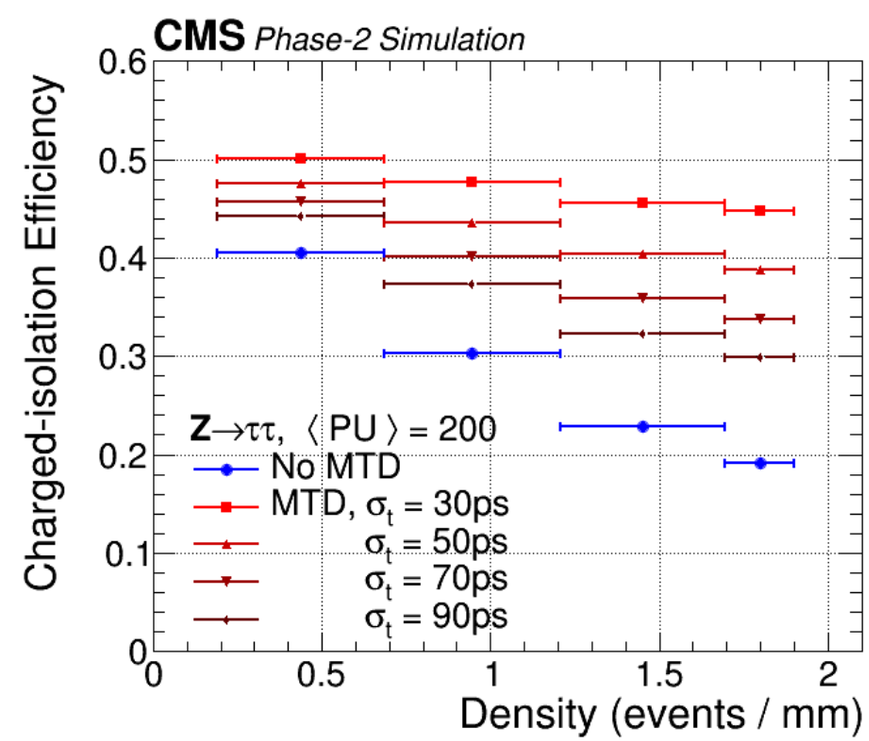
dz resolution of low p_T muons dominated by multiple scattering. 0.7 GeV tracks (most important for isolation) have dz resolutions of 100s of microns in the barrel.

Lepton Isolation Performance

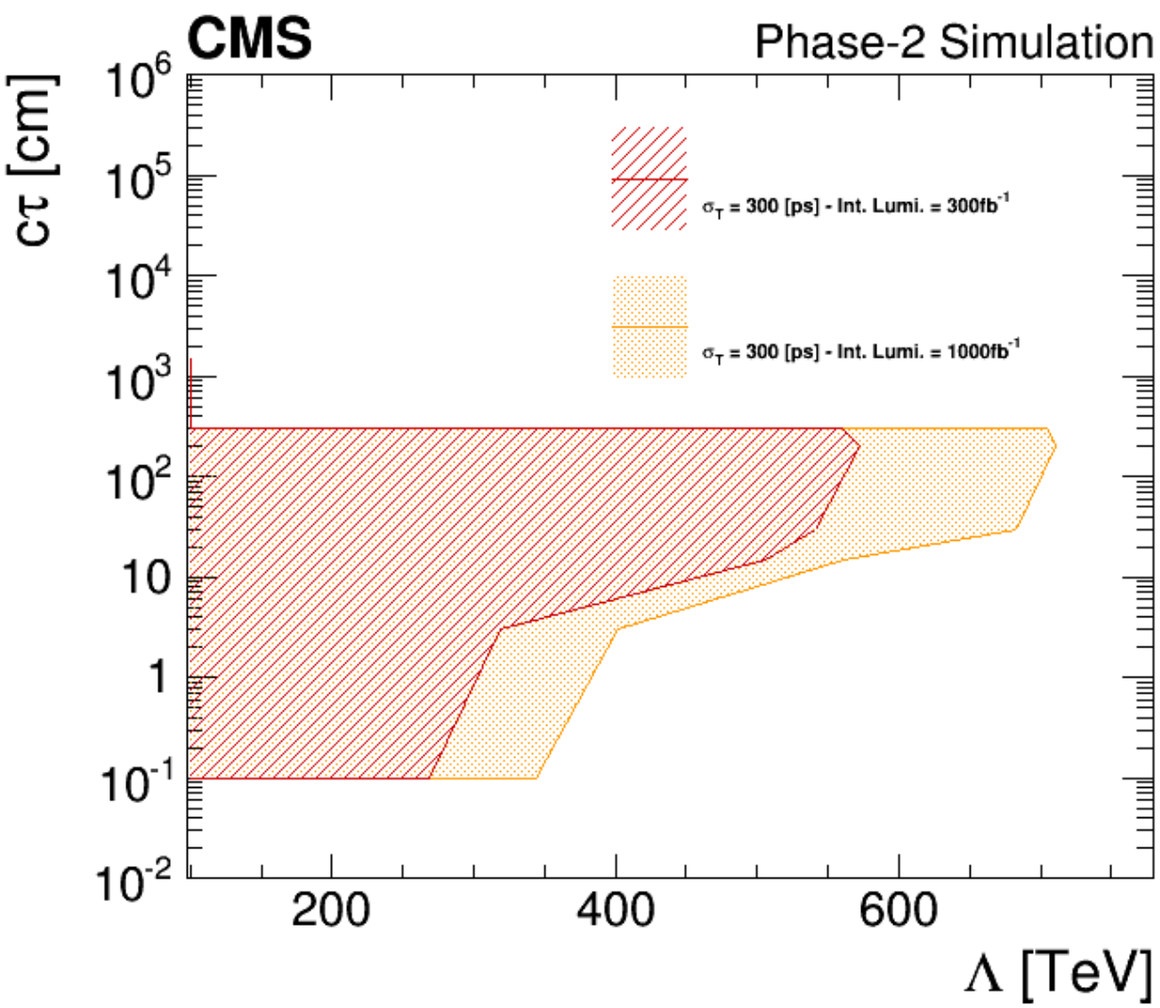


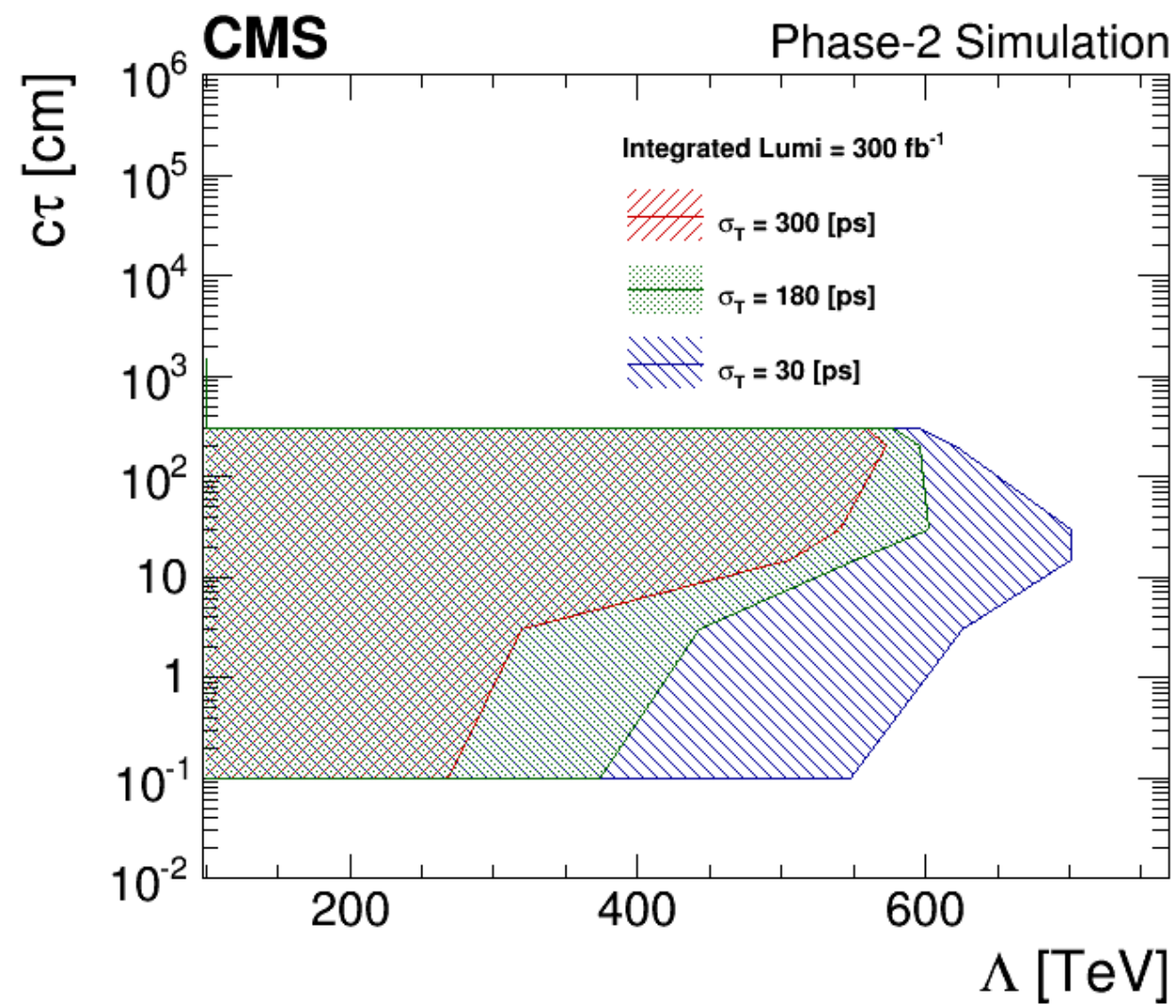






Luminosity Scaling for Neutralino Limits





Chi2 Vertex Sorting For Photons