# Proposed Timing Detectors for ATLAS and CMS

Lindsey Gray *on behalf of the ATLAS and CMS collaborations*

24 April 2018

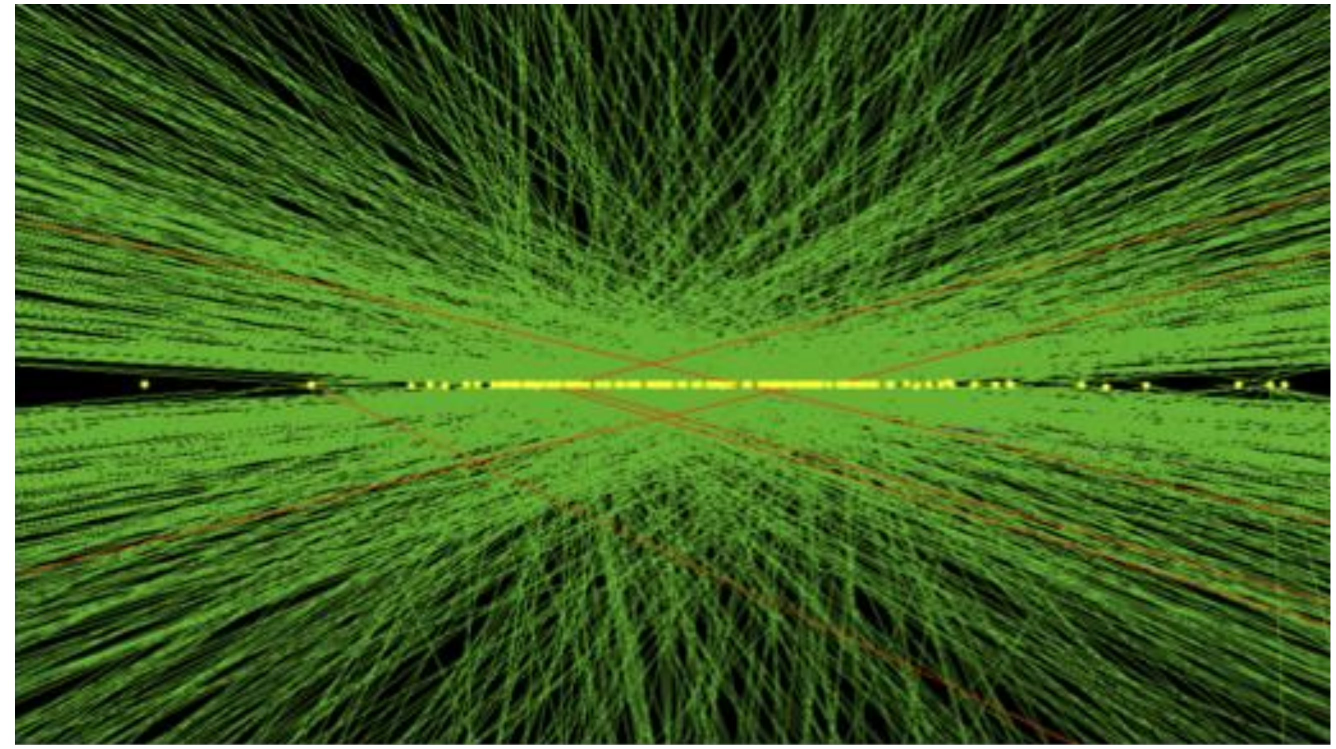
ACES 2018 - Sixth Common ATLAS CMS Electronics Workshop for LHC Upgrades

# Challenges of the HL-LHC

- Phase-2 upgrades originally targeted $5x10^{34}$ Hz/cm$^2$ = 140 pileup (PU)
- LHC performance is *exceptional*
- Ultimate HL-LHC luminosity target is now $7.5x10^{34}$ Hz/cm$^2$ = 200PU
  - 25% increase in int. luminosity/year

Extending performance at high PU is the key!

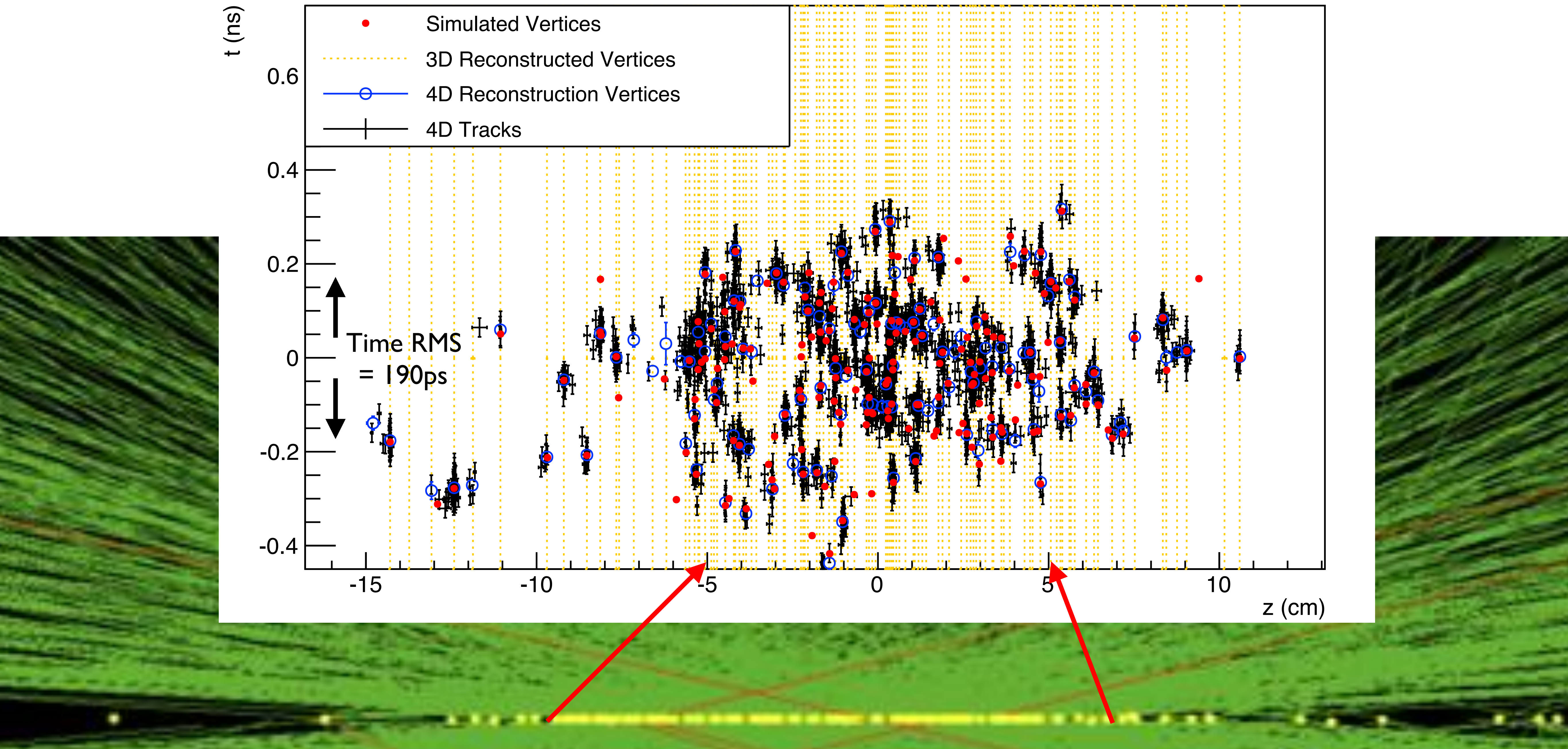
200PU HL-LHC Event:



- CMS and ATLAS considering timing as an option since 2015
  - Since then we have developed innovative analysis techniques and performed extensive studies
  - The key technologies have made significant progress

▸ CMS and ATLAS have now included a precision MIP Timing Detectors in their Phase-2 upgrade scopes

# Timing Provides Four Dimensional 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**

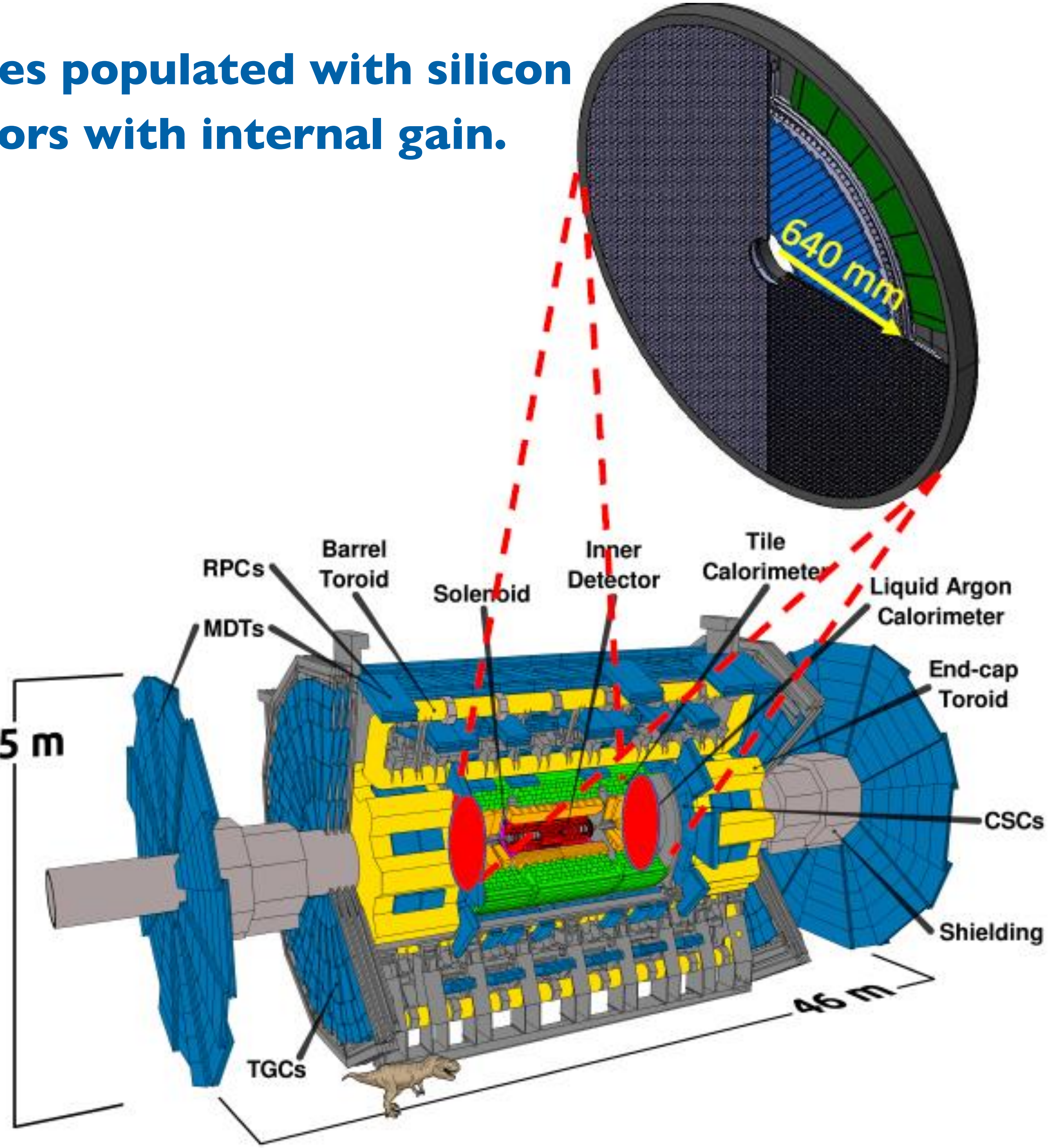
- for reasonable vertexing: 15% vertex merge rate reduced to 1%
- similar to current running conditions

# ATLAS High-Granularity Timing Detector (HGTD)

**Staves populated with silicon sensors with internal gain.**

- **z = 3500mm**
- **2 layers each side**
- **$2.4 < |\eta| < 4.0$**
- **30 ps per track over HL-LHC duration**
- **1.3 mm x 1.3 mm sensor pitch**

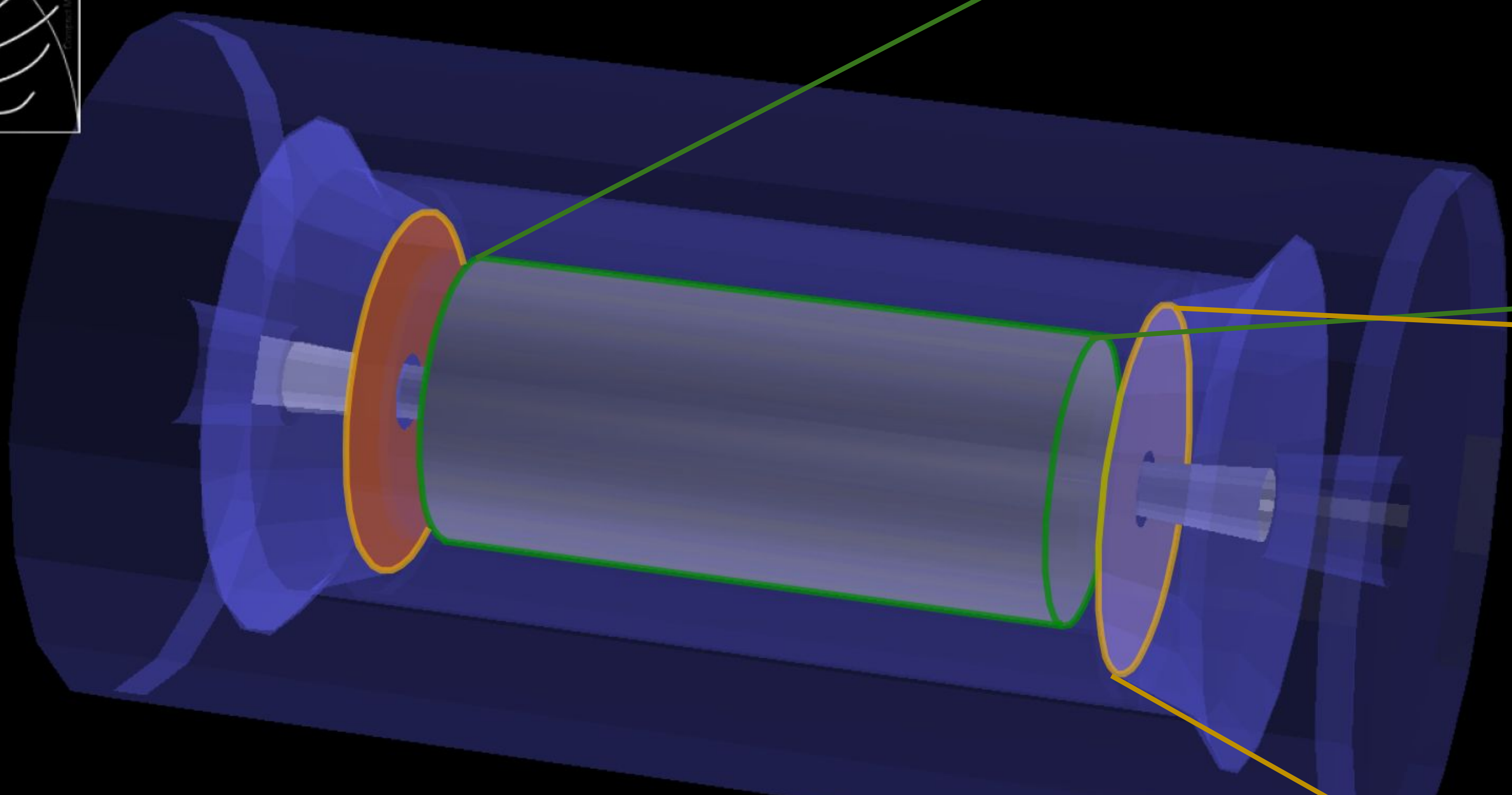
**max. dose ~4.5e15 n.eq/cm²**



# CMS Global Timing Concept

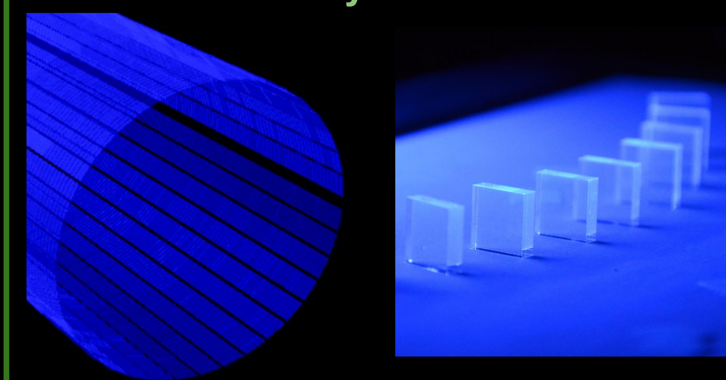
**Calorimeter upgrades:**

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



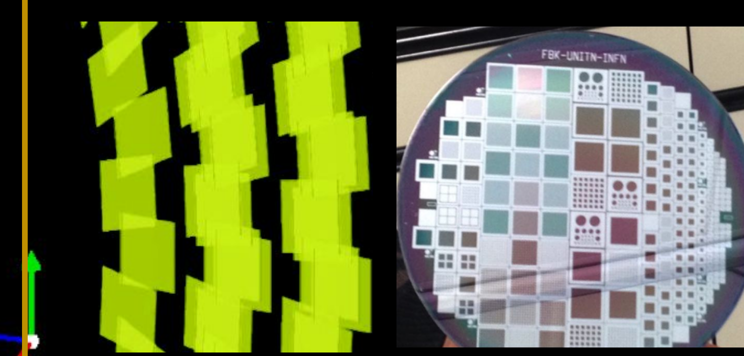
## BARREL

TK/ECAL interface ~ 25 mm thick
Surface ~ **40** m²
Radiation level ~ $2\times10^{14}\ n_{eq}/cm^2$
Sensors: **LYSO crystals + SiPMs**



## ENDCAPS

On the CE nose ~ 42 mm thick
Surface ~ **12** m²
Radiation level ~ $2\times10^{15}\ n_{eq}/cm^2$
Sensors: **Si with internal gain (LGAD)**

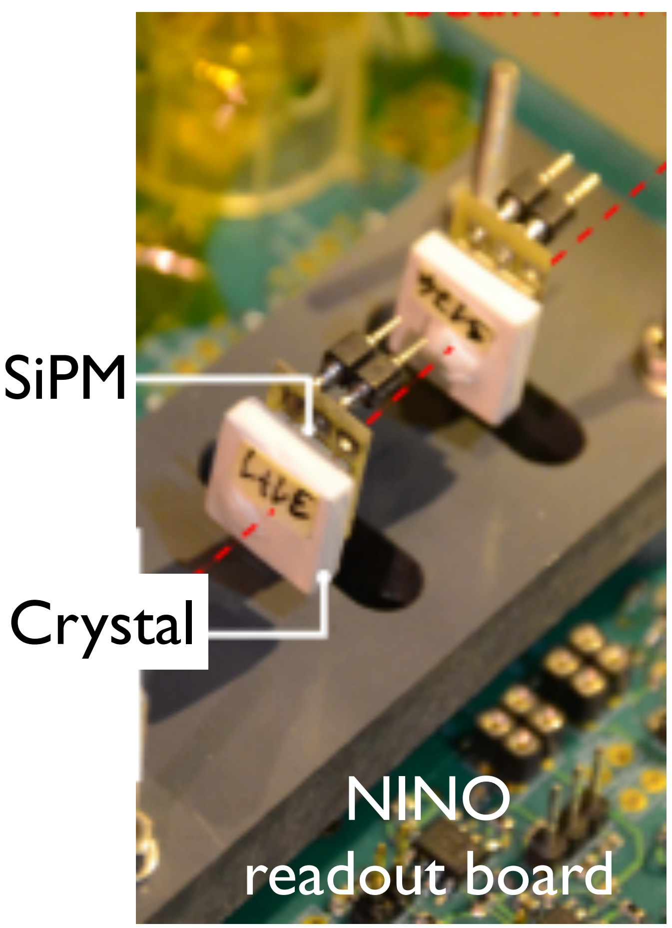


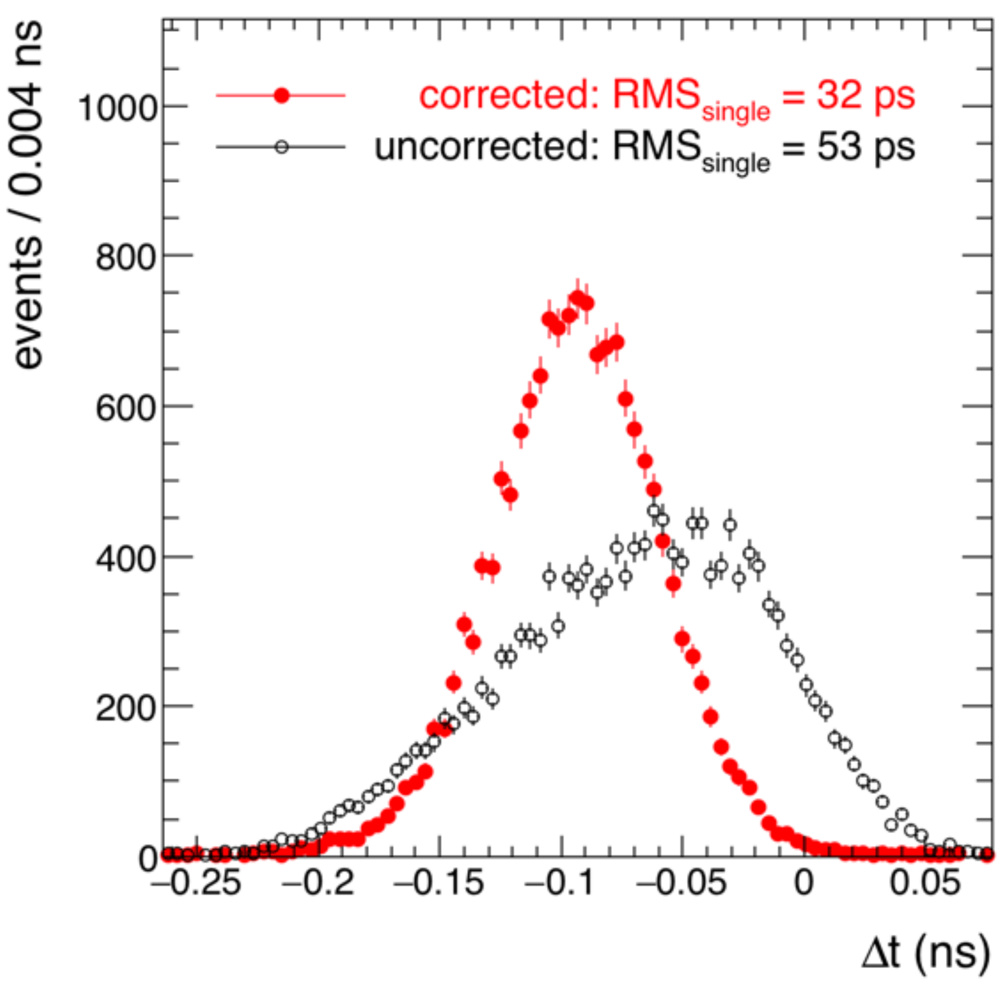
- Thin layer between tracker and calorimeters
- MIP sensitivity with time resolution of ~30 ps (40 ps end of life)
- Hermetic coverage for |η|<3

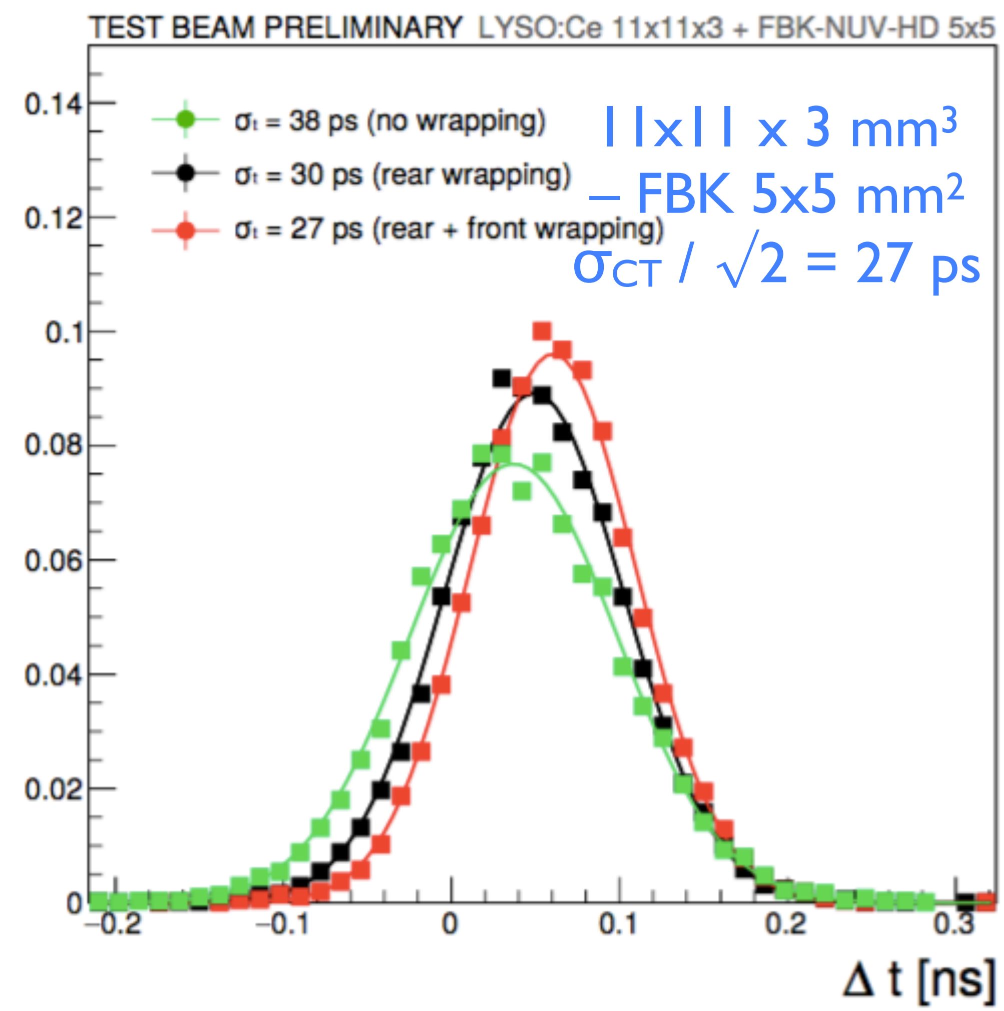
# Precision Timing Fast Scintillating Crystals - Performance

- Nominal geometry: 11x11mm$^2$ + 4x4 mm$^2$ SiPM
  - with semi-constant slant thickness of ~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

‣ Pursuing crystal bar double ended readout or large-area-sparse SiPM to mitigate



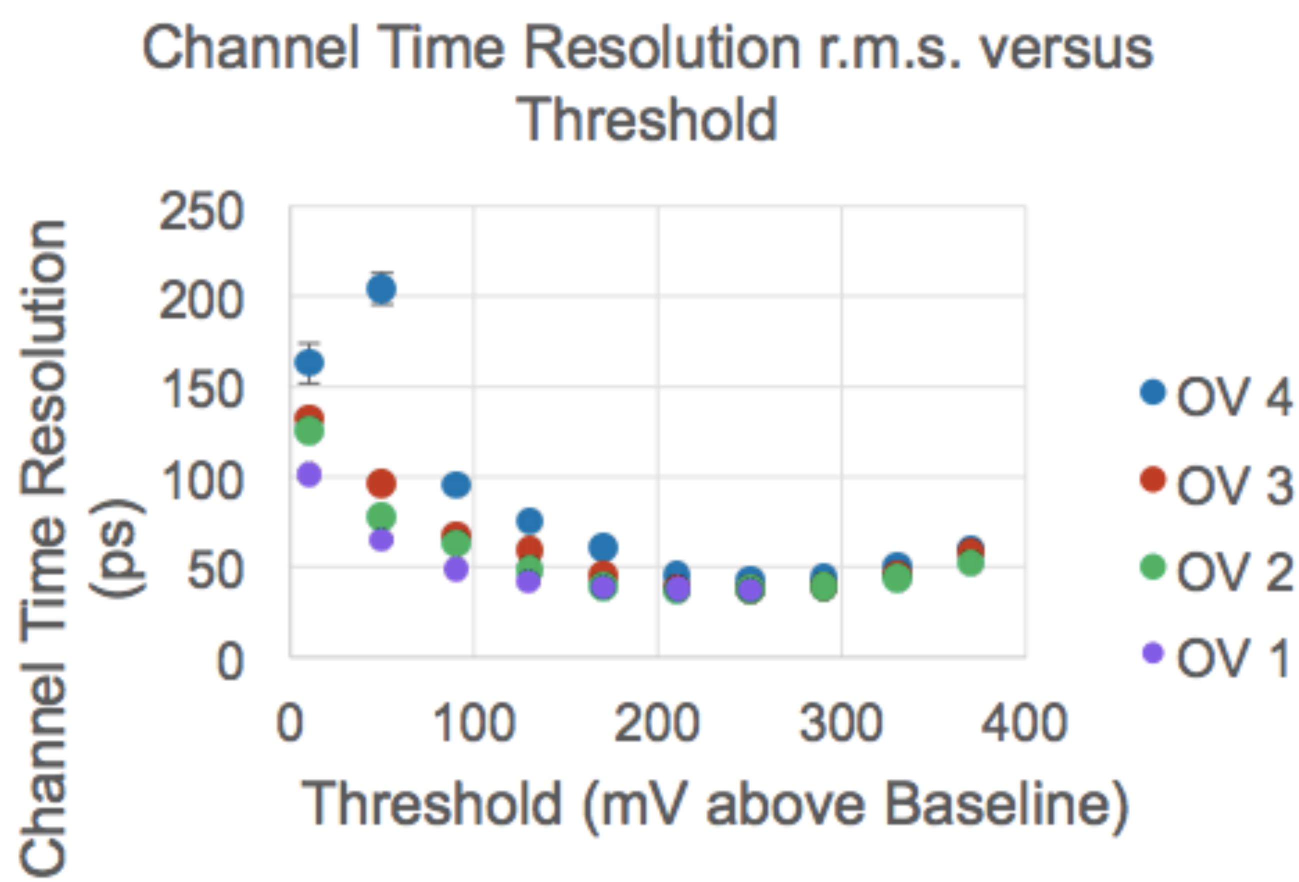



# BTL ASIC - TOFHiR

- 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

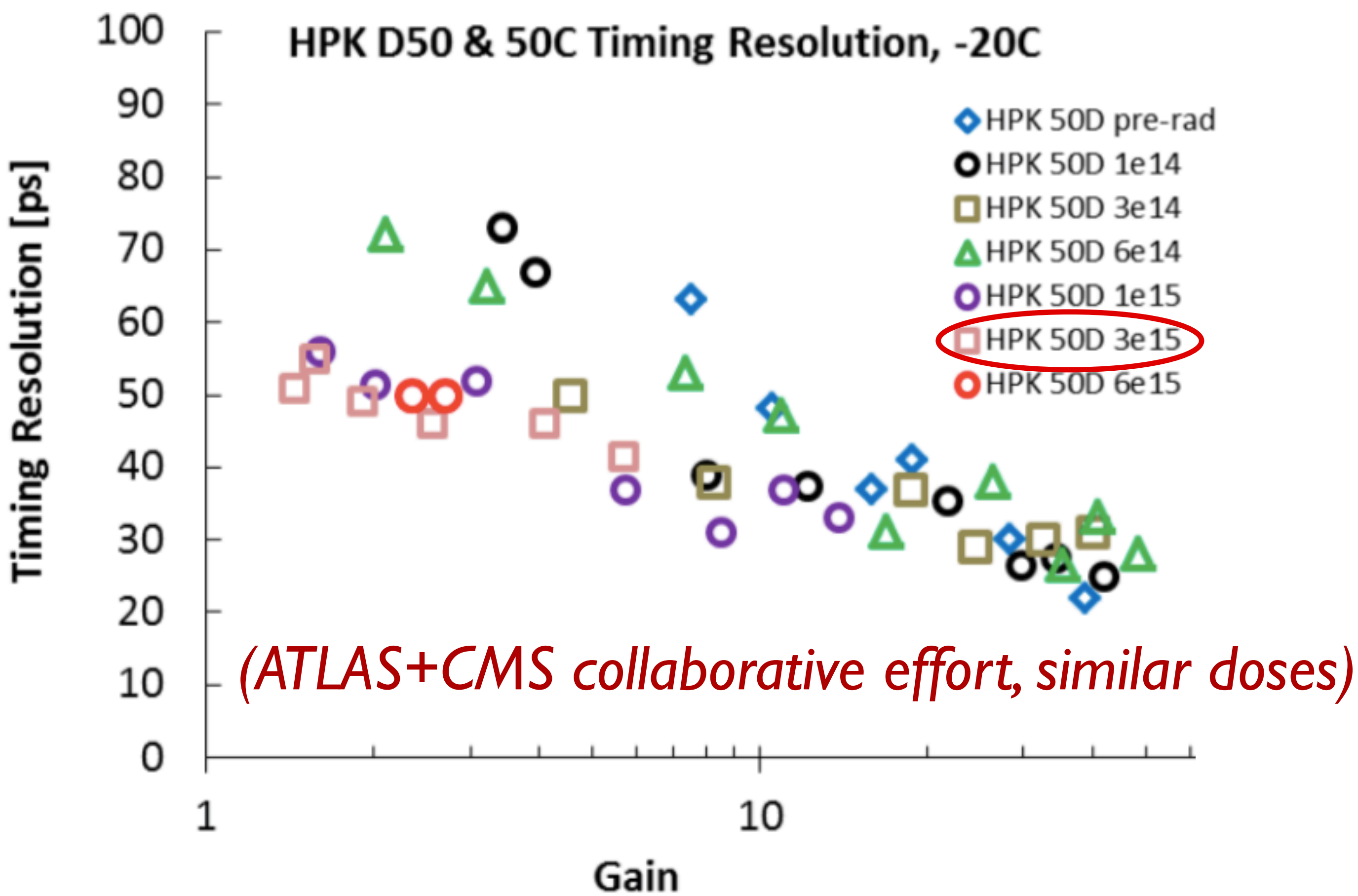



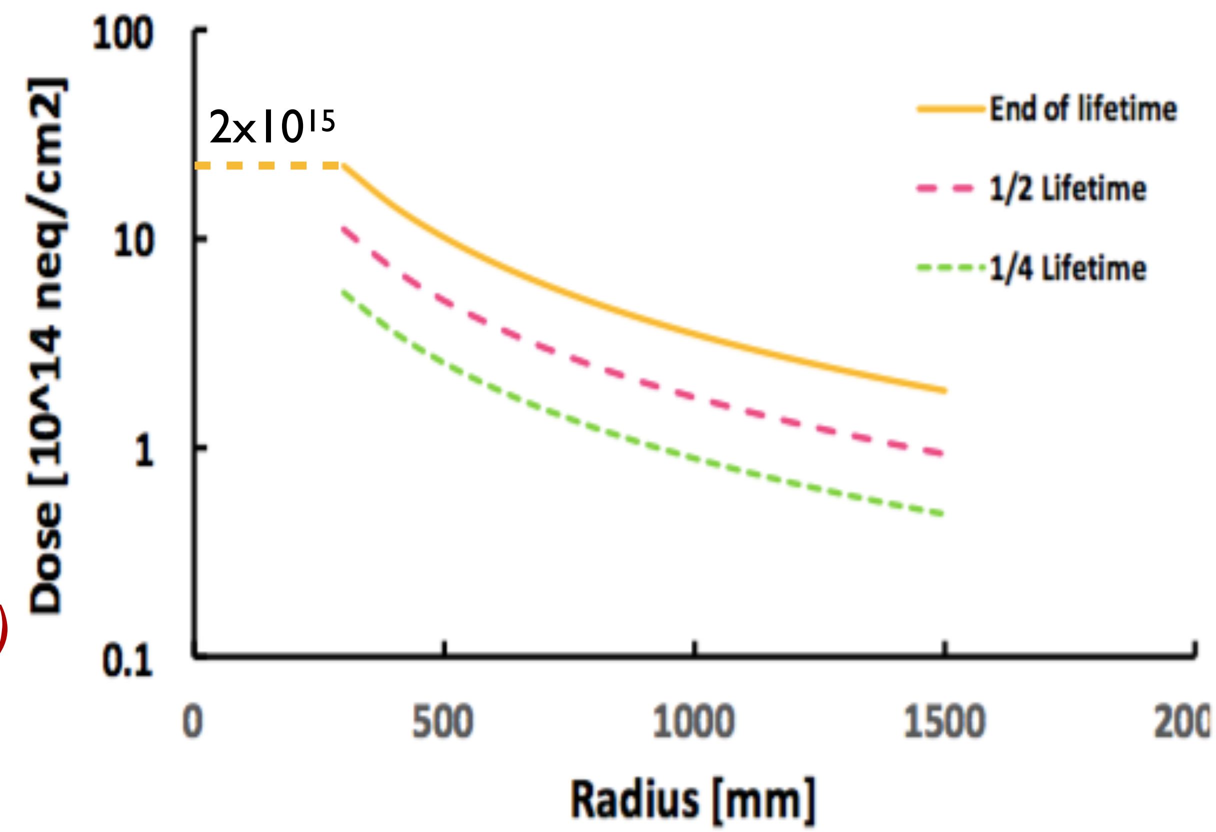


Fermilab

# Low Gain Avalanche Detectors - Irradiated Performance

- 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)

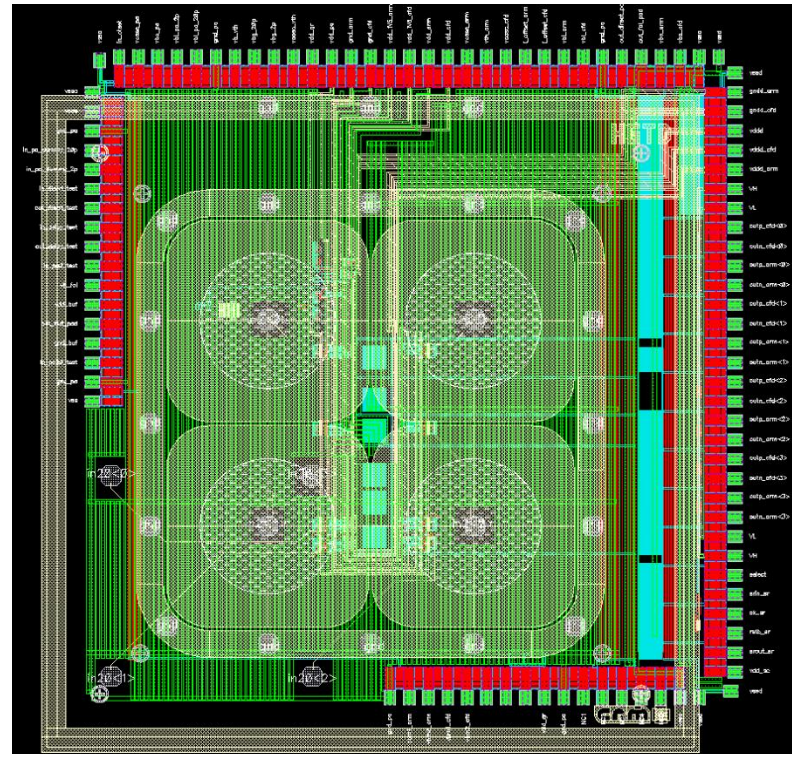


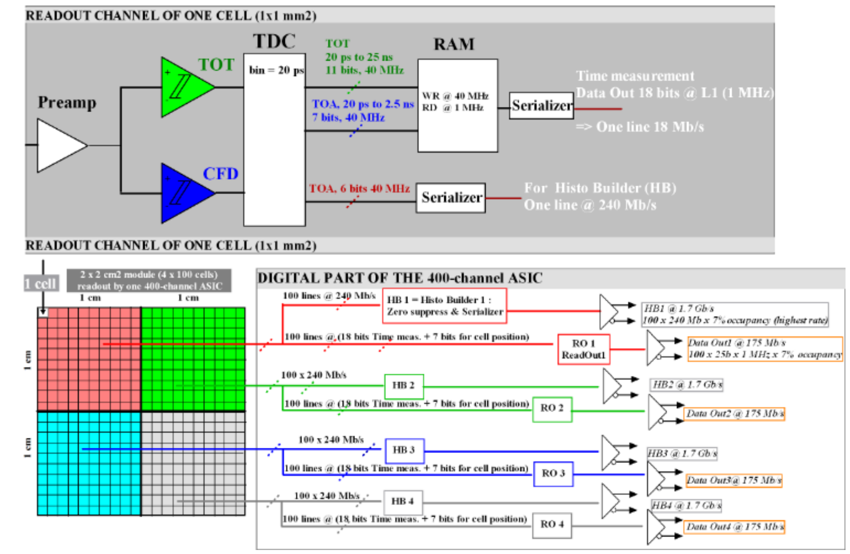




▶ LGAD can deliver < 40 ps timing resolution for entirety of HL-LHC

- New optimization studies with latest LGADs indicate further improvements

# ASICs for LGADs






- ALTIROC = ATLAS LGAD Timing ROC
  - Submission of a chip (TSMC130 nm) in December 2016 (MPW CERN/IMEC), received at the end of March 2017
  - 20 ps timing measurement with LGAD sensors for ATLAS HGTD
  - Test chip bondable to sensors of 1x1 mm² and 2x2 mm²
  - High speed preamp (1 GHz) + TOT + constant fraction discriminator (20 ps)

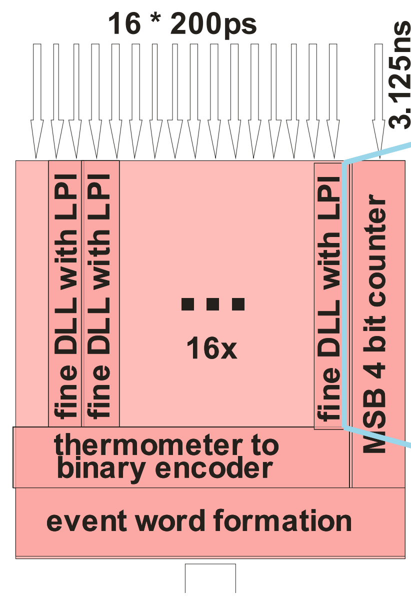
Will evolve to 400 ch chip

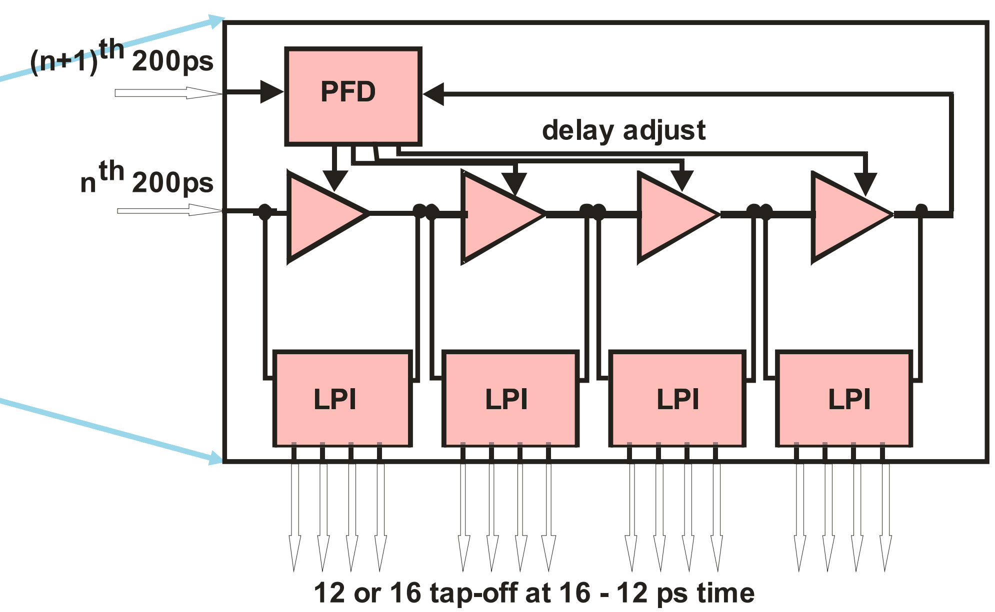
## CMS Endcap Timing ASIC

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

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

96 channel bump-bonded chip, currently targeting larger capacitance

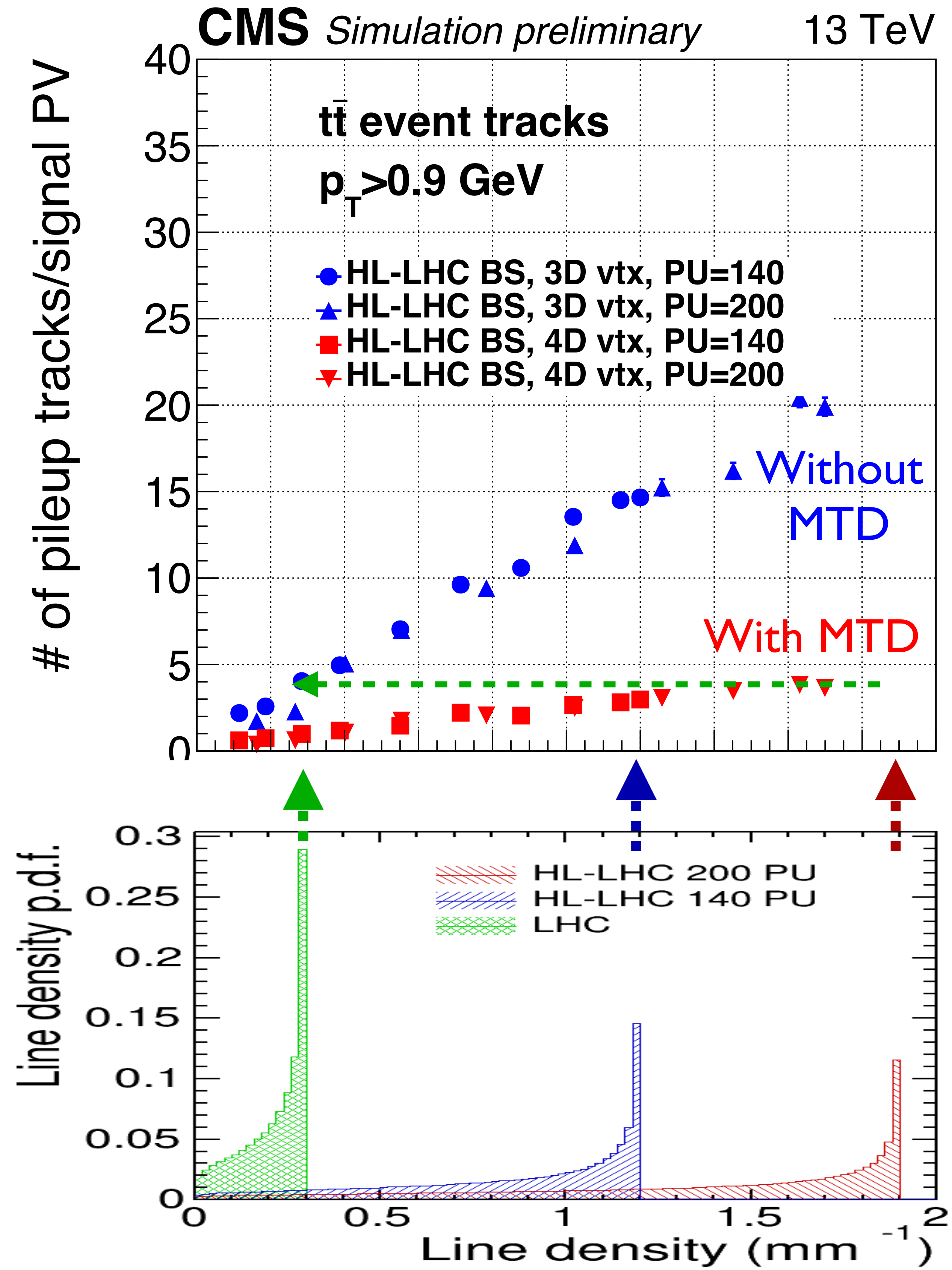



Two-stage fine DLL

# 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
  - Similar arguments apply in the case of forward-only coverage

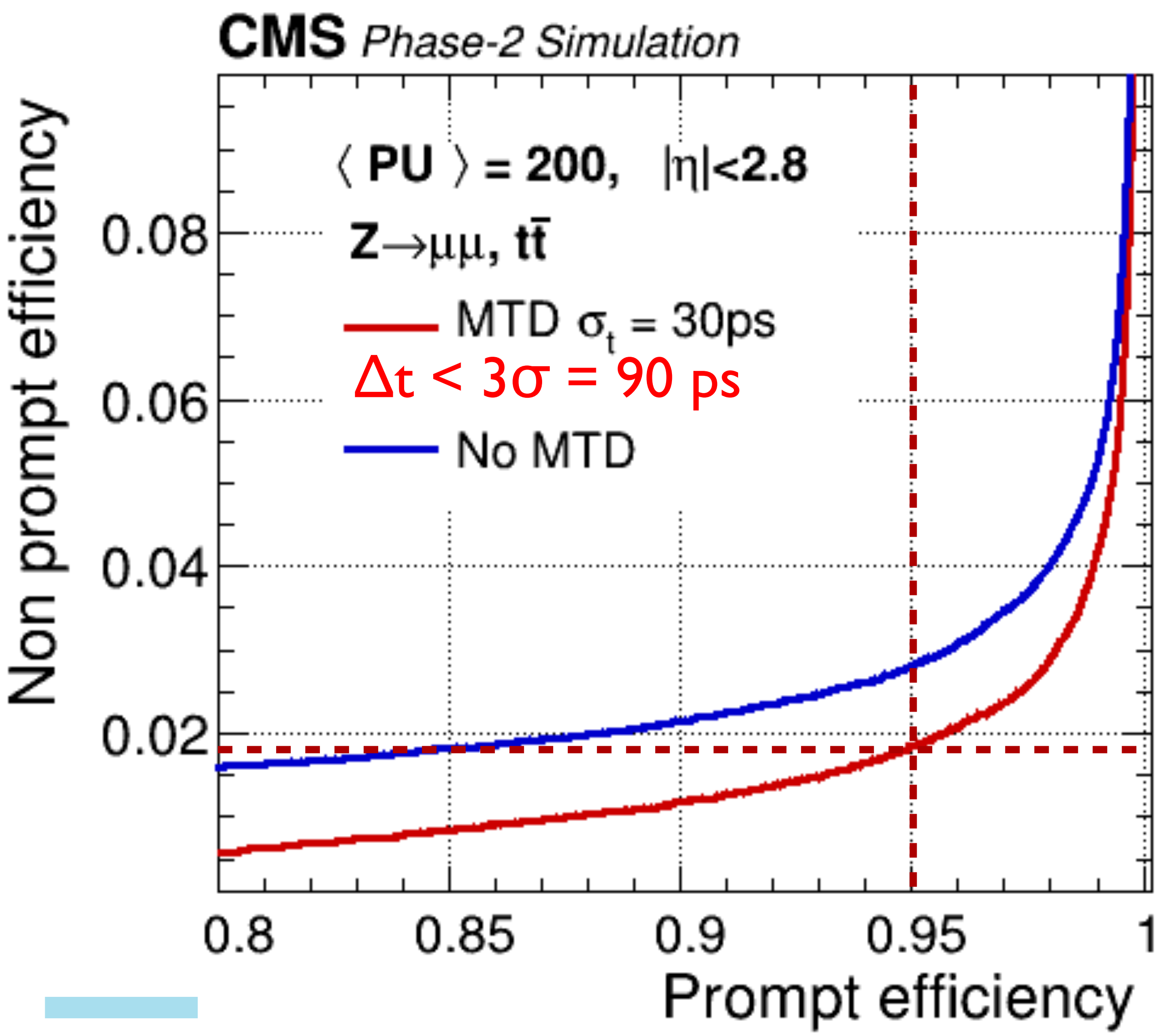


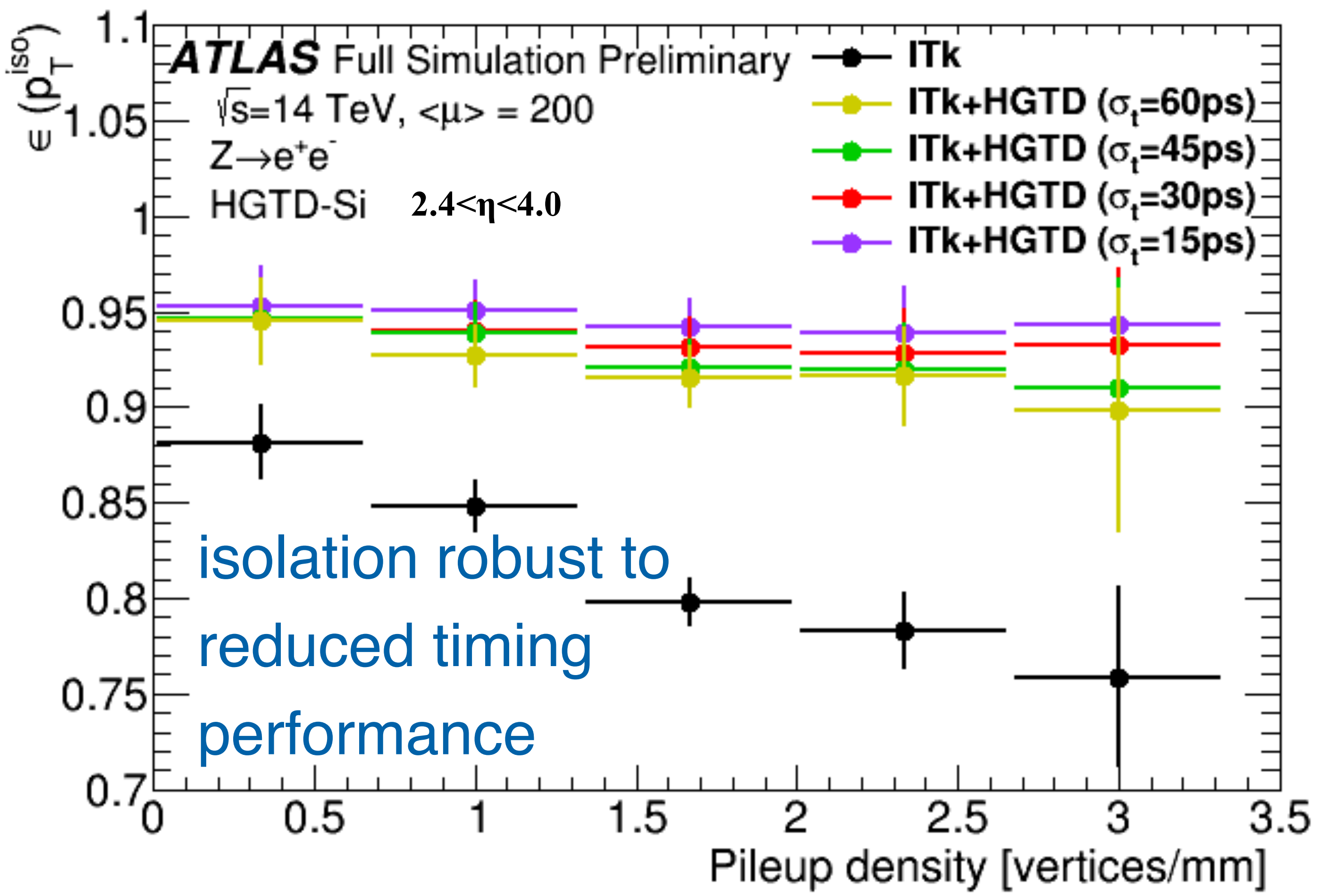


Fermilab

# Lepton Isolation with Timing

- Timing cuts remove pileup tracks from lepton isolation cones
- Reduces dependence on pileup density (also centrally, see backup)
- 60% improvement in background rejection for constant signal efficiency using pertinent working points




more results: see backup

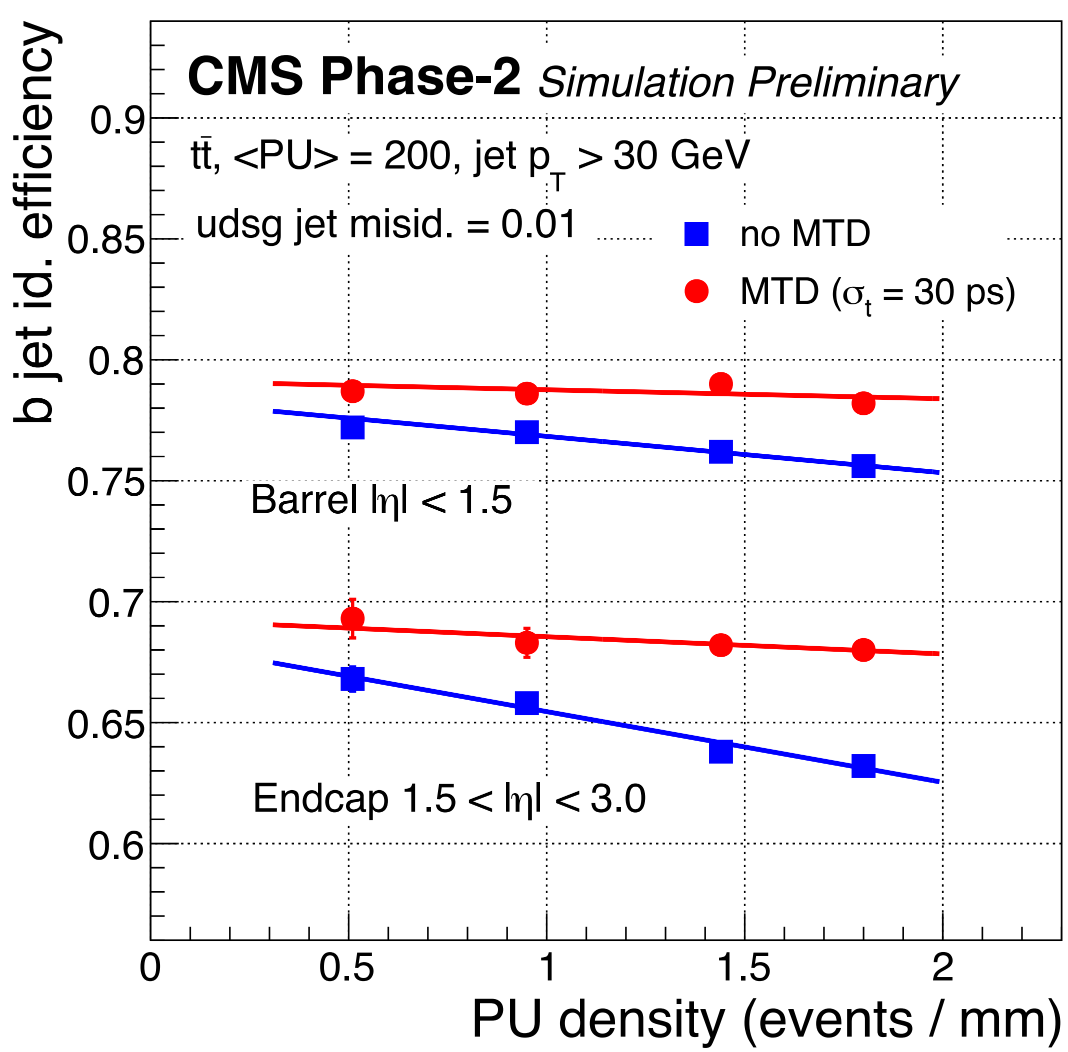
Fermilab

# B-Tagging with Timing

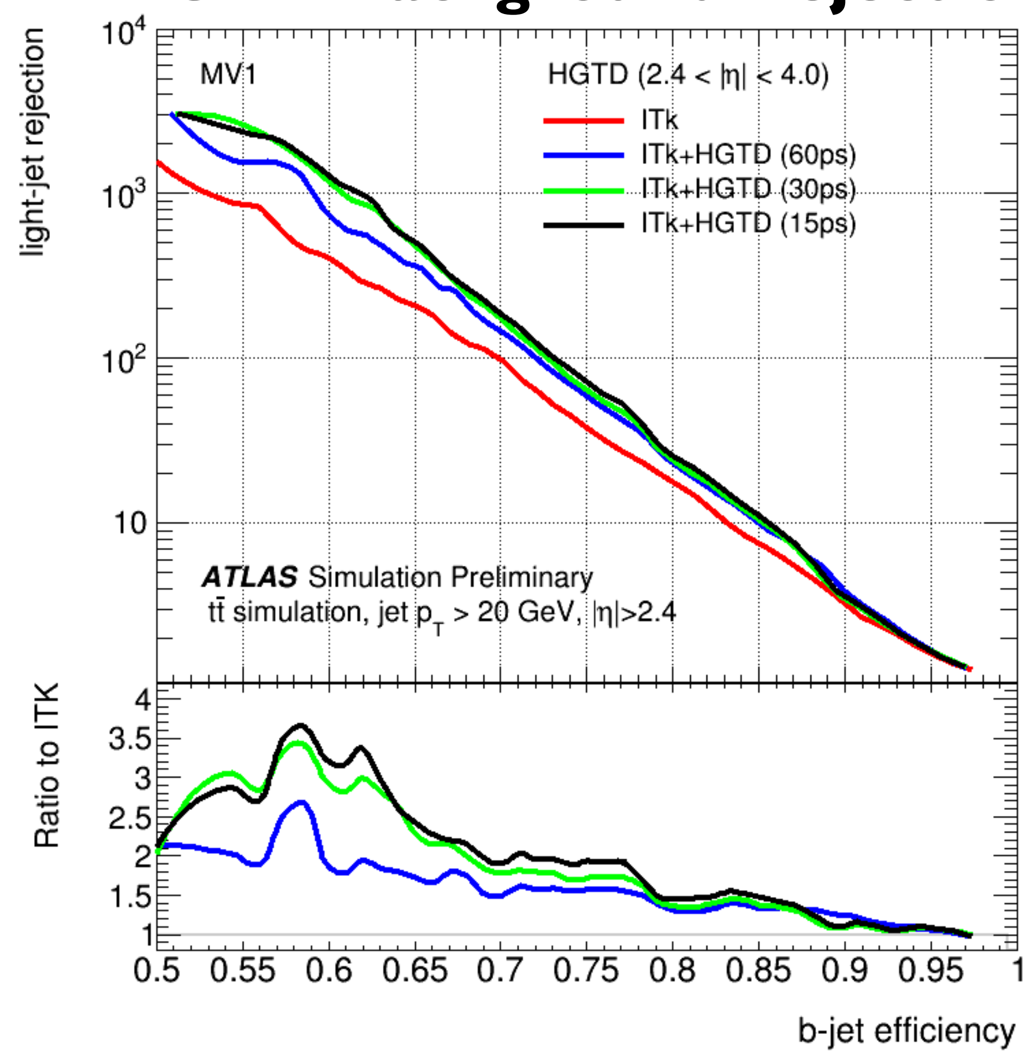
- Precision timing rejects spurious secondary vertices
- Significant improvements for working points at constant signal efficiency or background rejection (see backup)
  - Gain in efficiency amplified in multi-particle final states (ε^N)

- Removes pileup-density dependence in b-tagging

**MTD Signal Efficiency**




**HGTD Background Rejection**

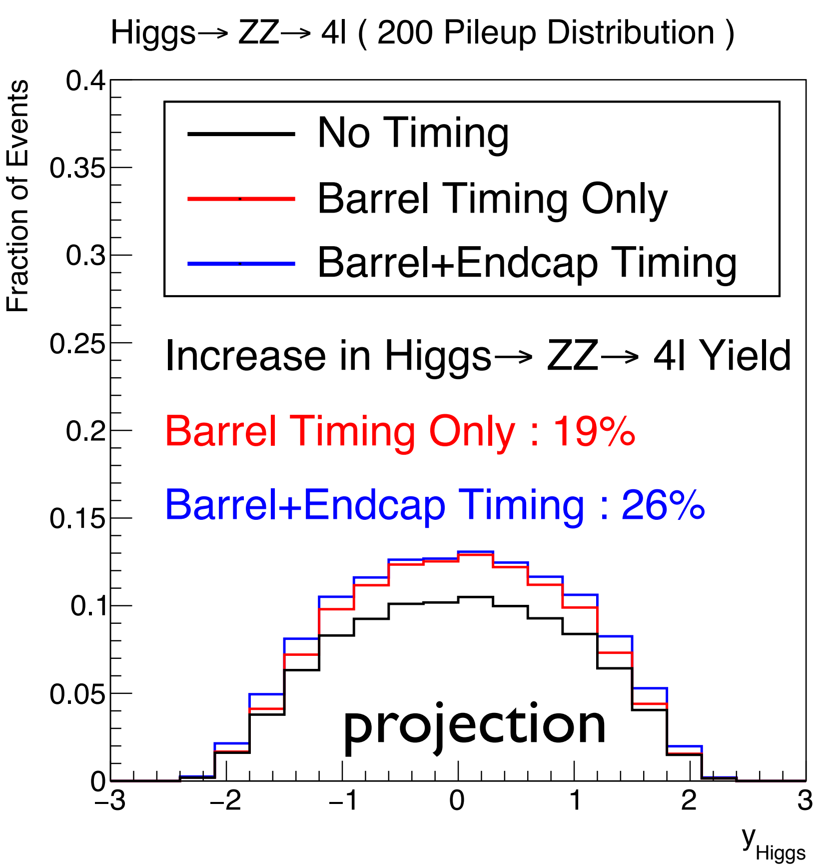


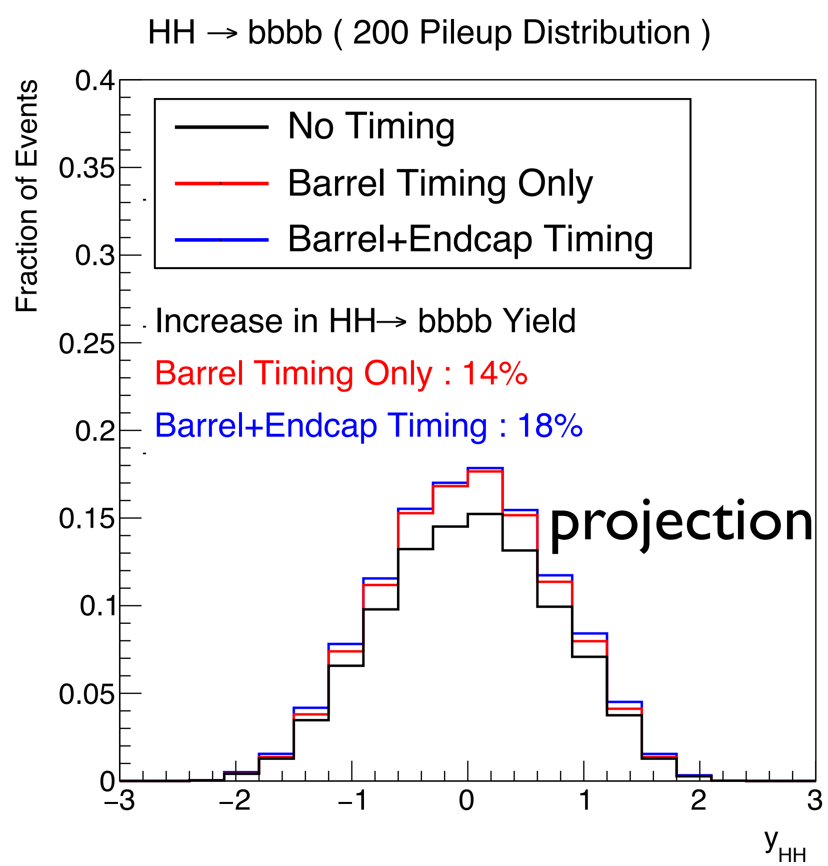
# (di-) Higgs Acceptance Improvement at CMS with MTD

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

| Channel | Signal increase (%) BTL | 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 |

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

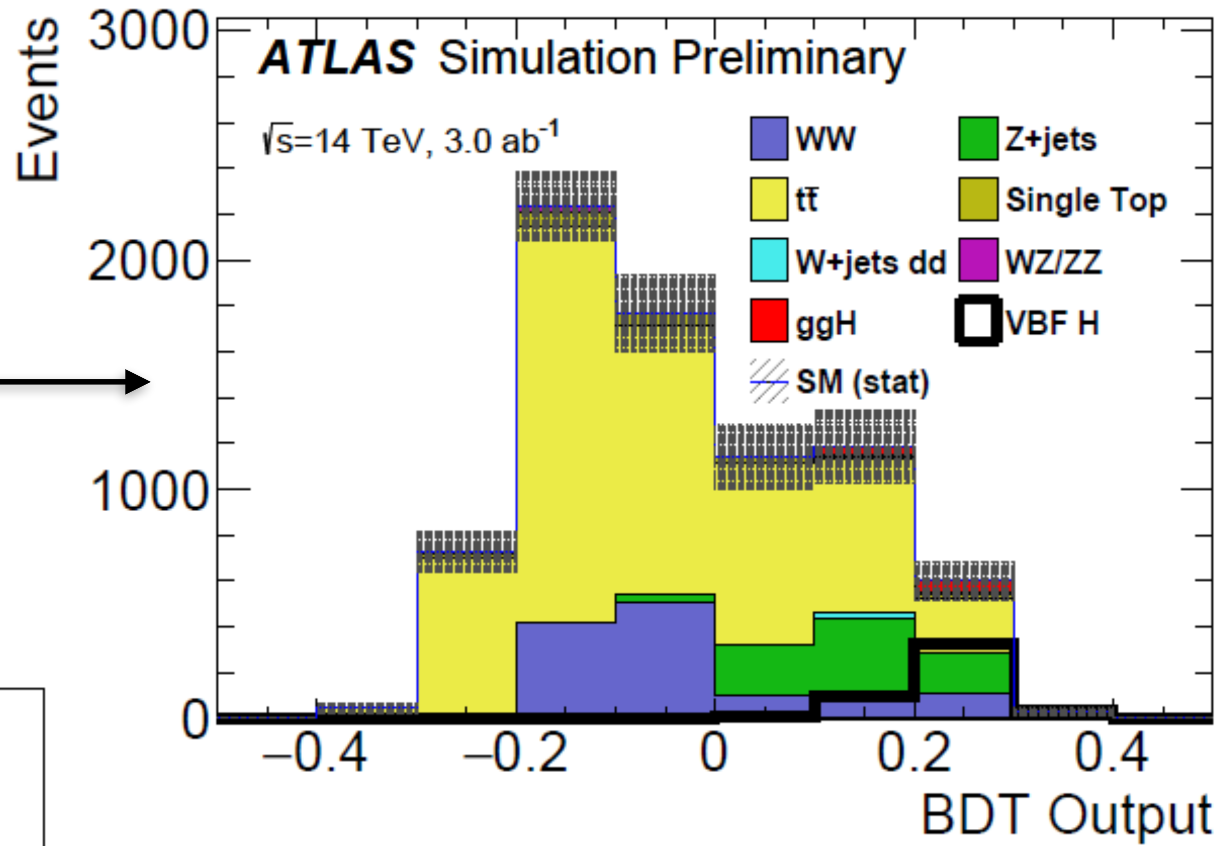


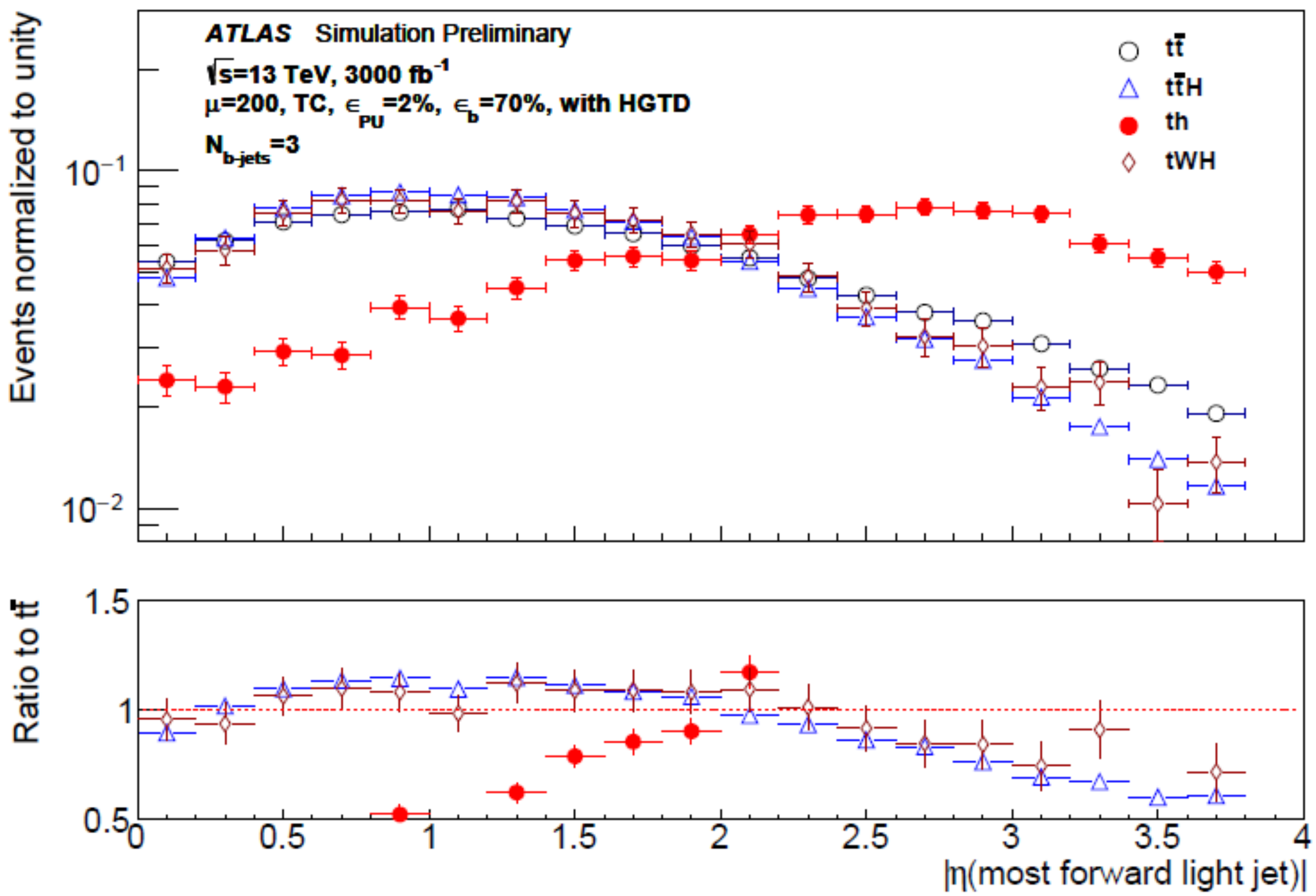




- Large impact on barrel region since physics signature is *central*

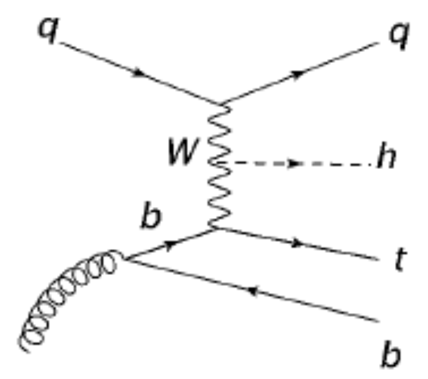
# Forward B-tagging based channels at ATLAS with HGTD

VBF: qqH→qqWW* → qq eνμν:
- BDT
- 43% bg reduction
- dominated by top background rejection (fwd b-tagging)
- 3% pileup rejection
- Relative improvement: 8% (0.088 wrt 0.096)




tH with H to bbar:

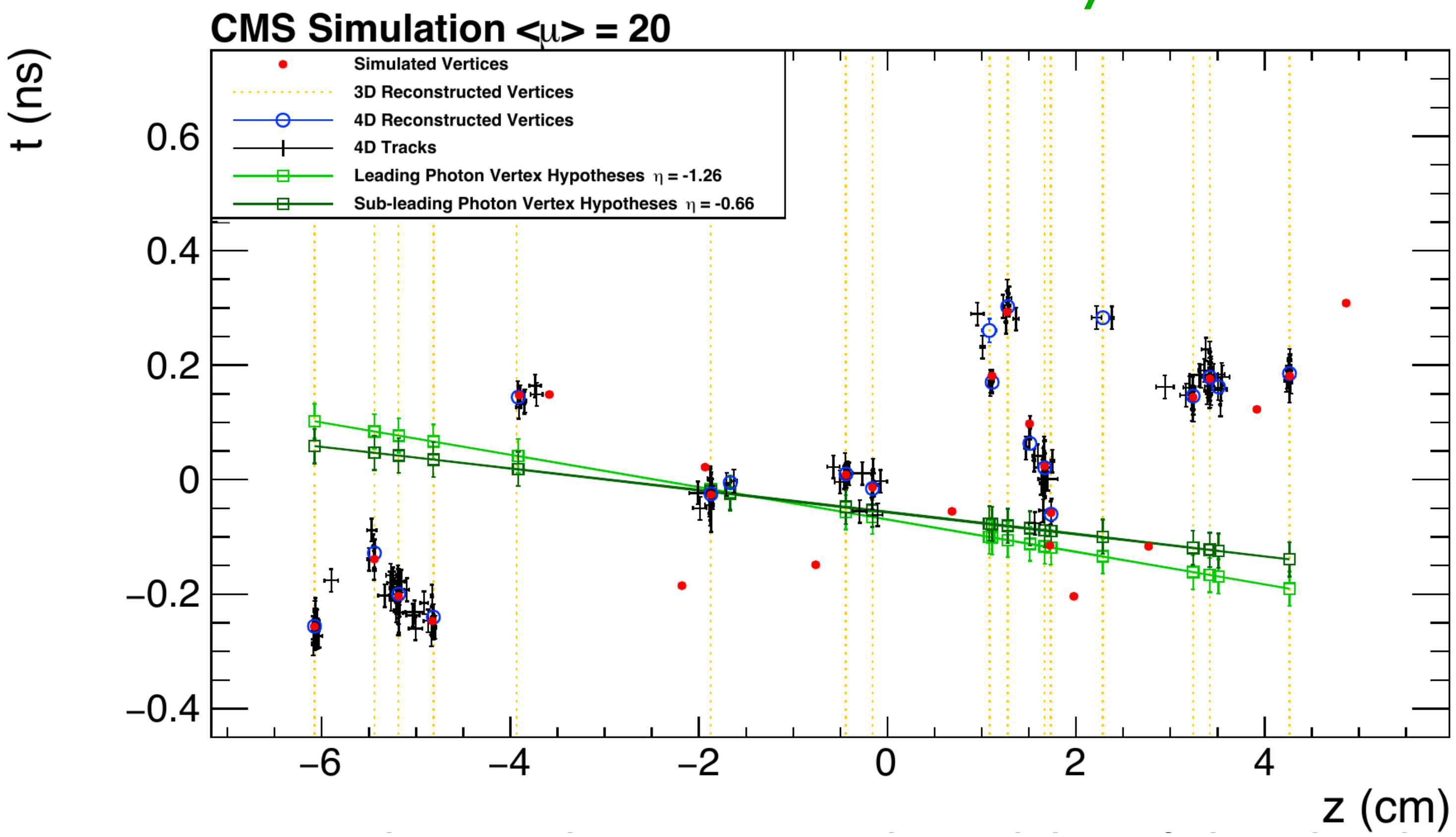


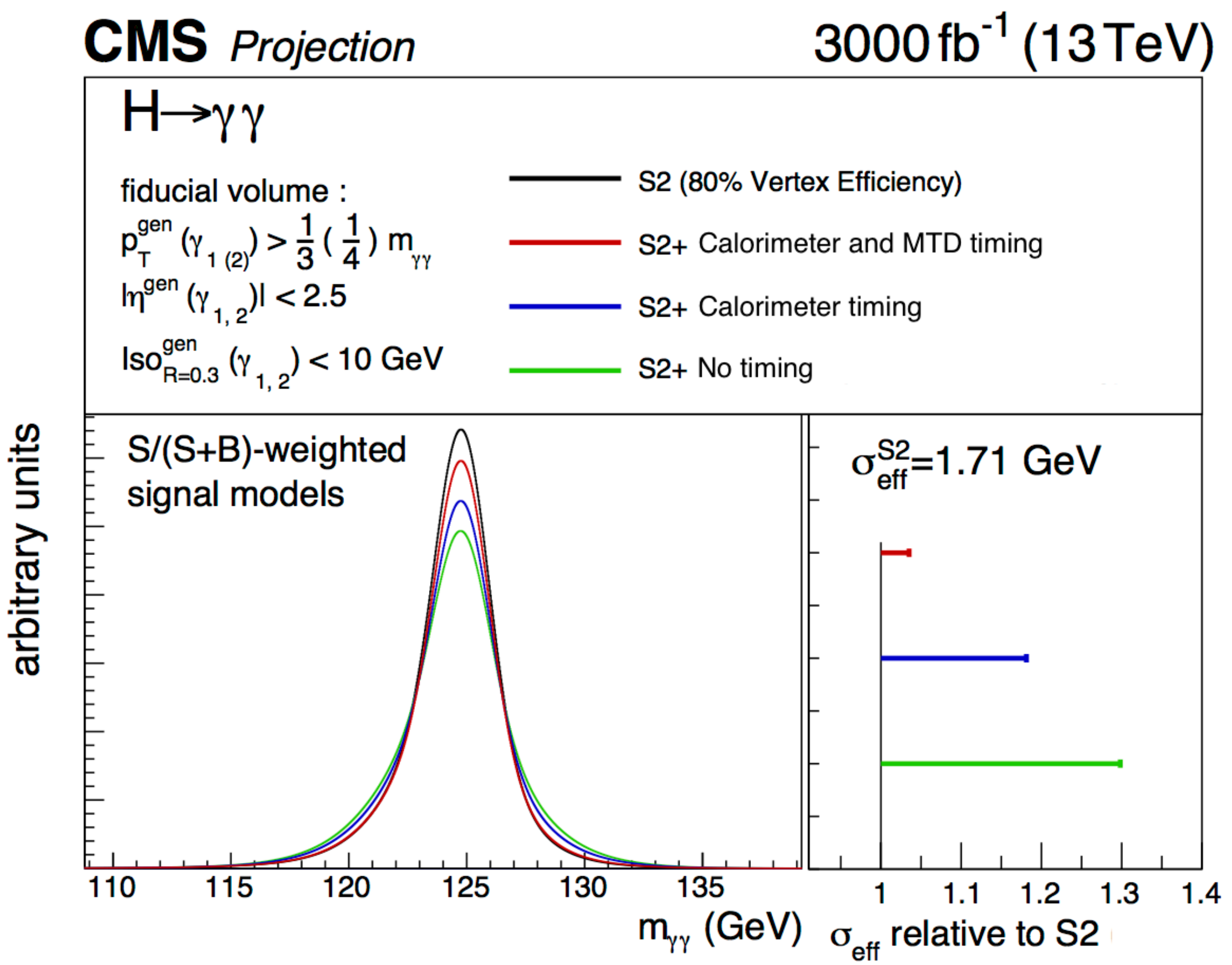

Relative improvement: 11%
(significance: 1.42 wrt 1.28)

Fermilab

# Higgs to Di-photon Vertex Tagging

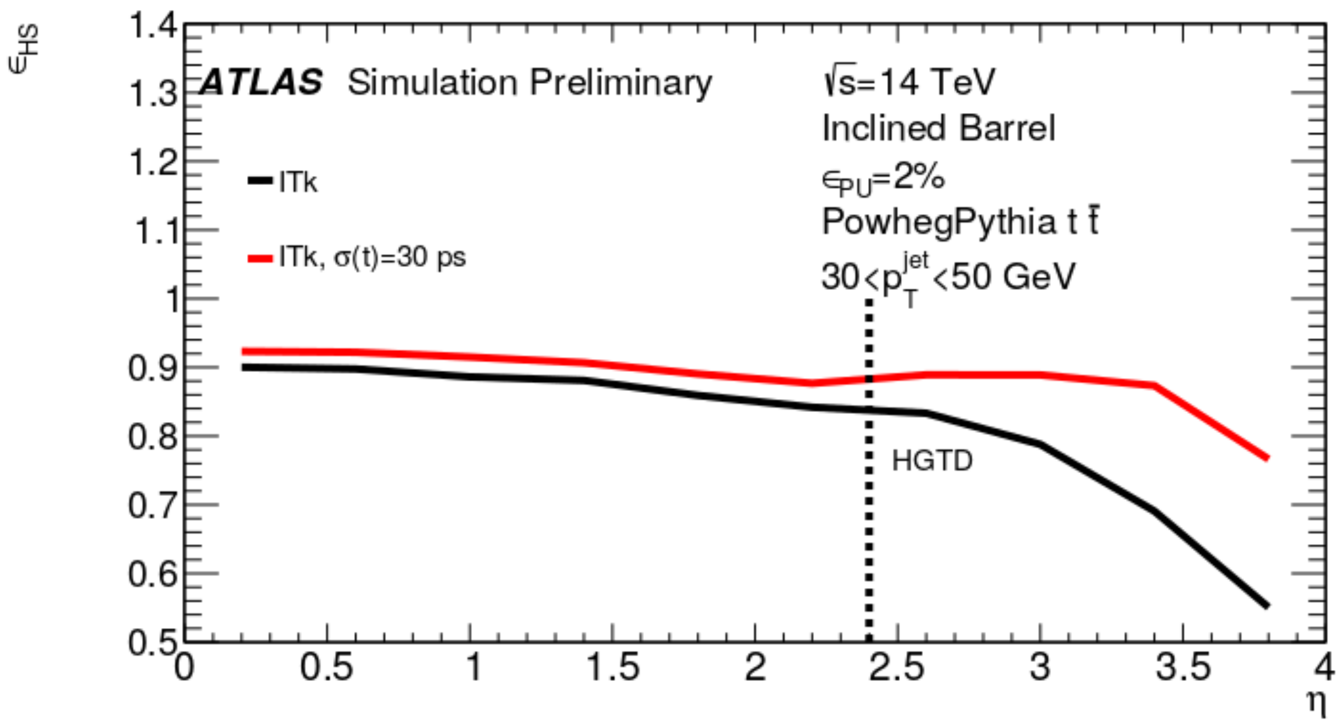
Calculate photon time at each vertex location: consistency test

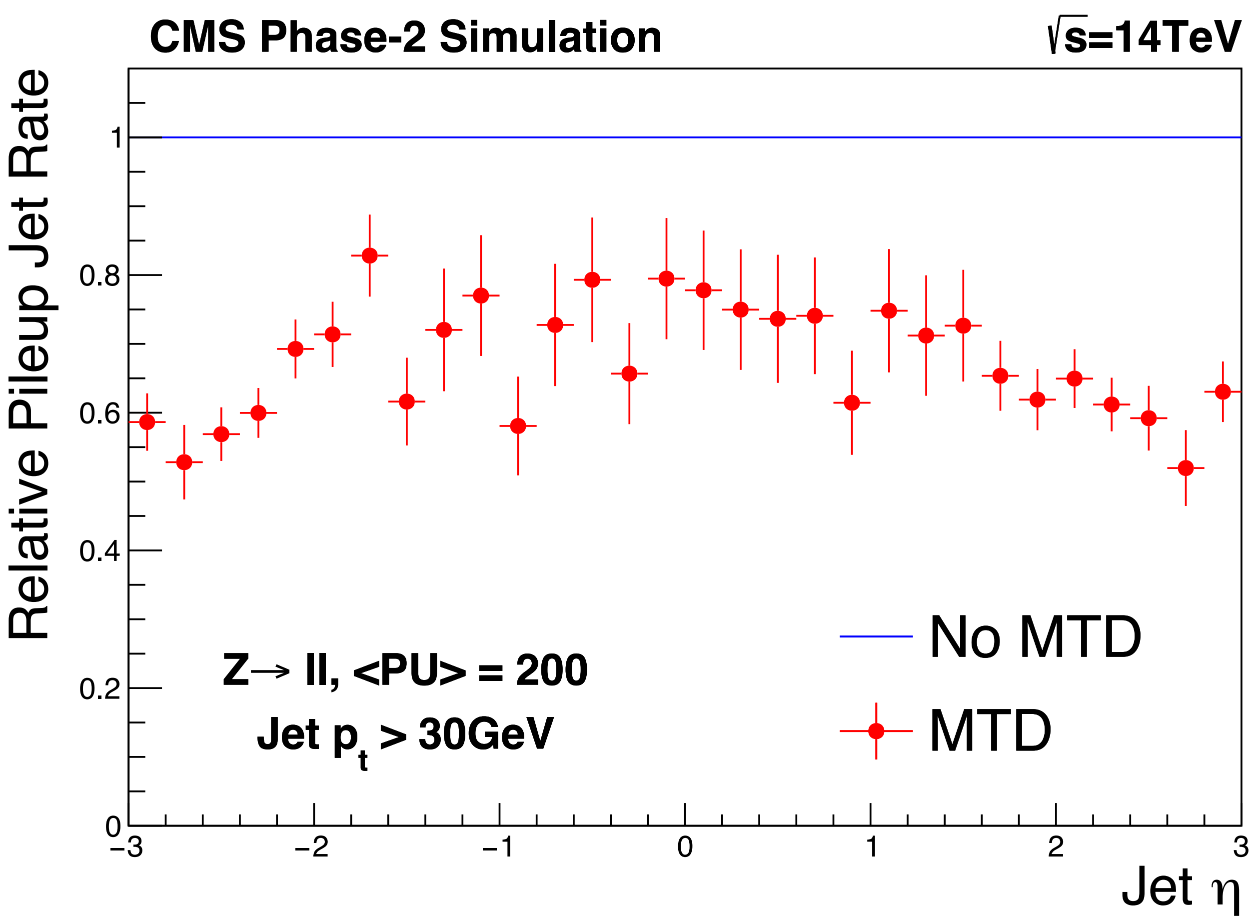



- Unique capability to match photon time to vertex time + position
  - CMS ECAL is non-pointing, but has photon timing capability
  - 50% of events additionally require MIP timing to find correct vertex
- Identifies photon vertex: improves di-photon mass resolution by 25% and also H(γγ) signal significance

# Pileup Jet Rejection with MTD and HGTD




- HGTD timing used to reject outliers when calculating energy-in-vertex

$$R_{p_\mathrm{T}} = \frac{\Sigma p_\mathrm{T}^{\mathrm{trk}}(\mathrm{PV}_0)}{p_\mathrm{T}^{\mathrm{jet}}}$$

▶ 4x improvement in rejection at significantly improved efficiency

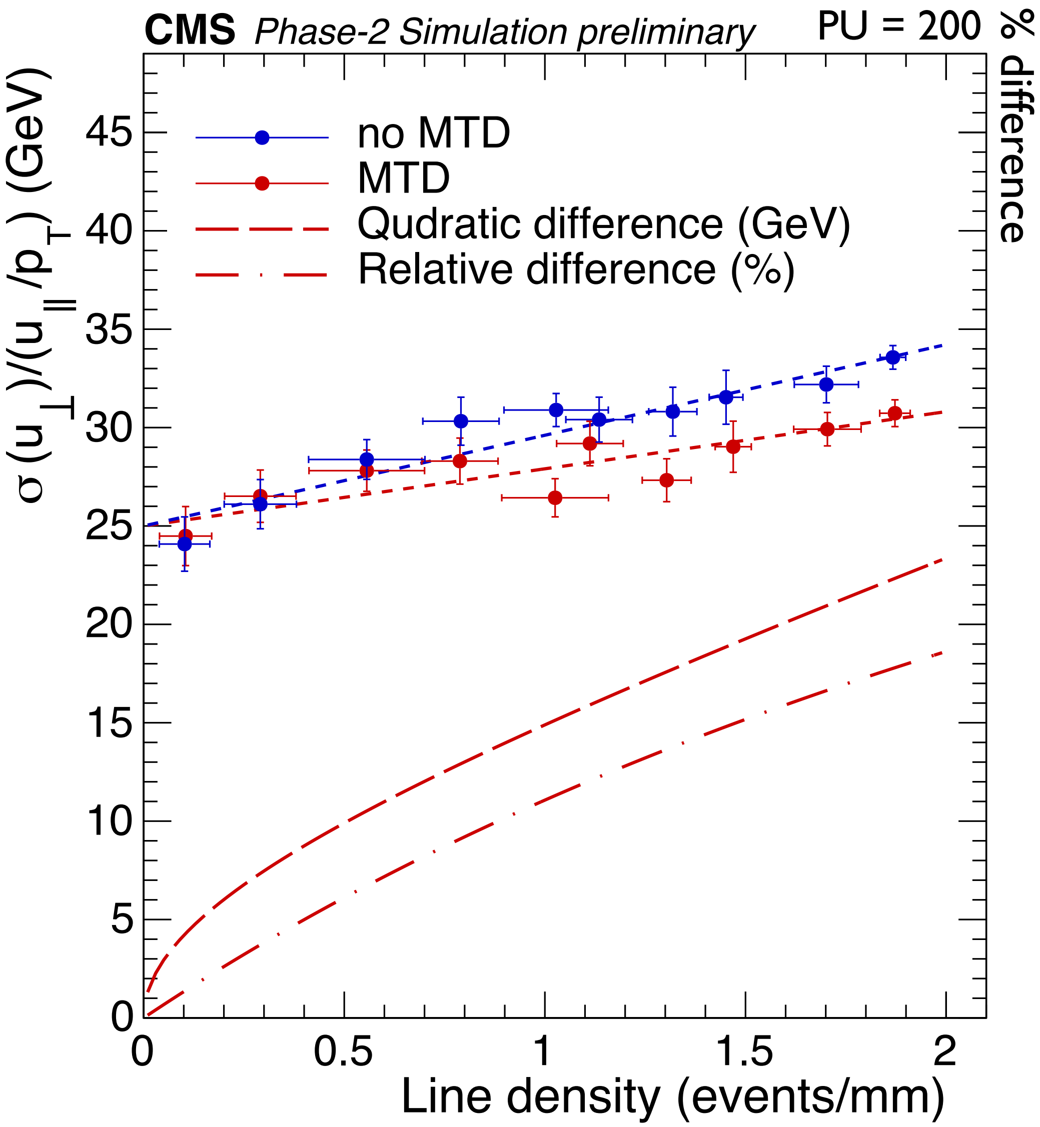
- MTD Timing cleans tracking information provided to PUPPI* to better identify neutrals from pileup
  - No impact on signal jet efficiency
  - Largest impact in the endcaps

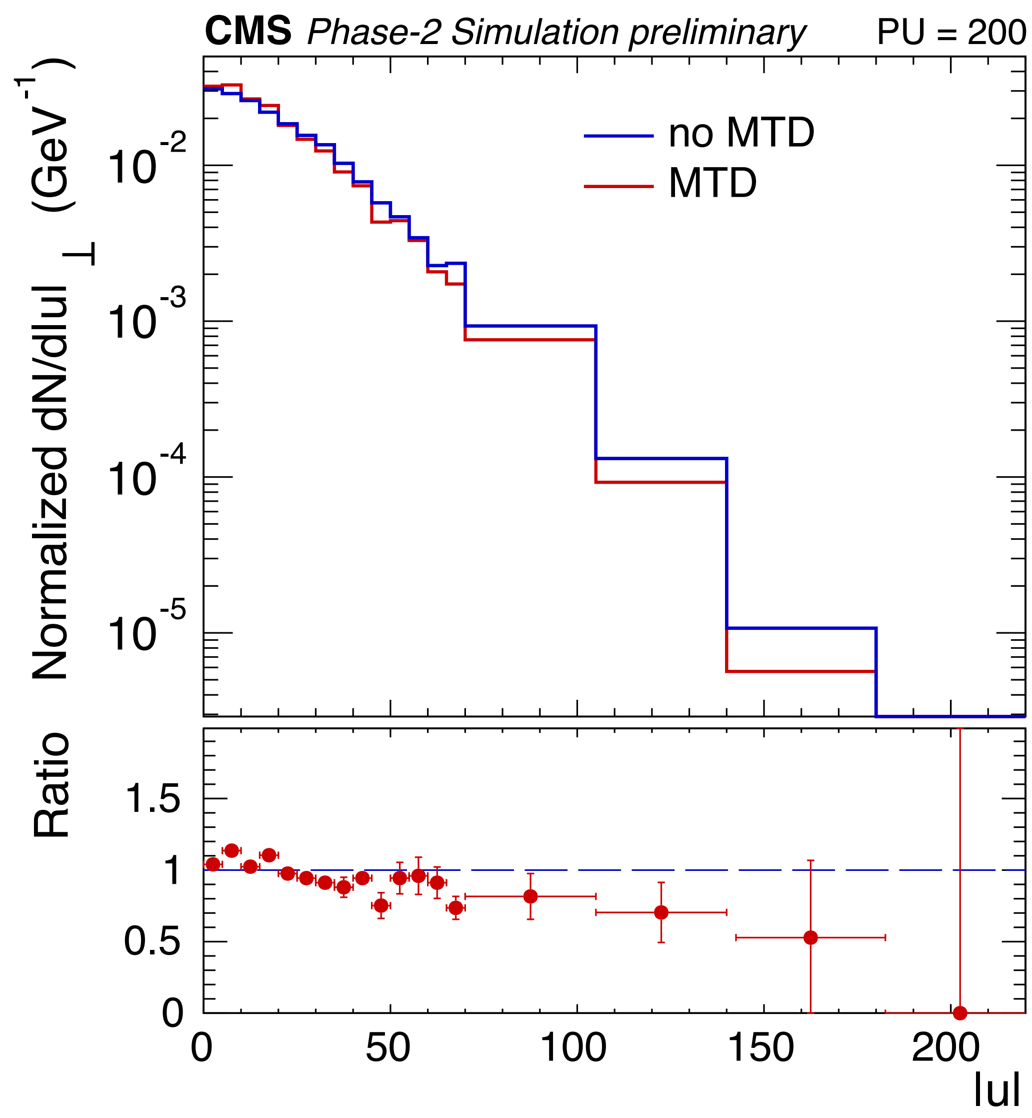
▶ 20% (barrel), 40% (endcap) reduction in pileup jet multiplicity

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

# MET Performance

- (PUPPI) MET resolution improves 15% at 200PU
  - Recovers 140 pileup performance
- MET tails reduced 40% for MET > 150 GeV
  - Improved performance for searches in high pileup



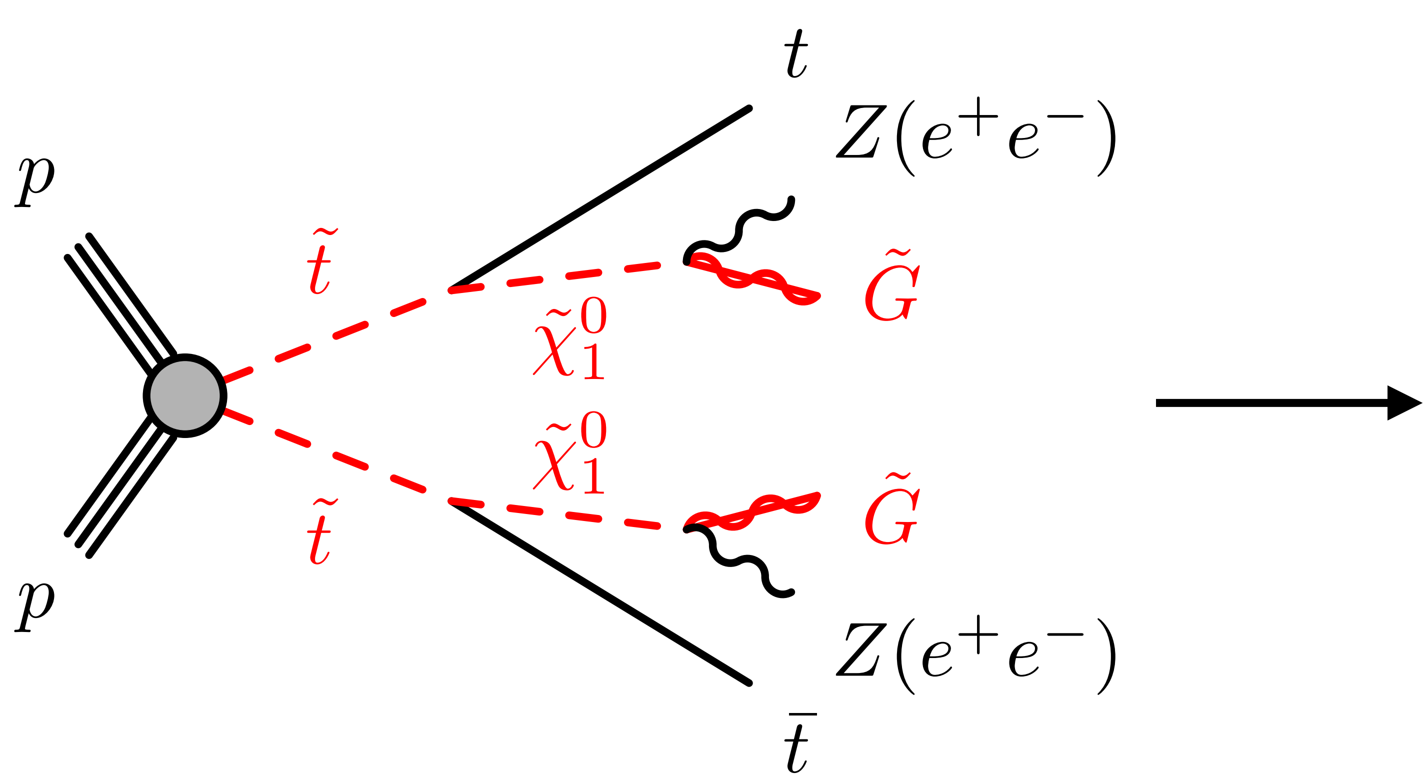


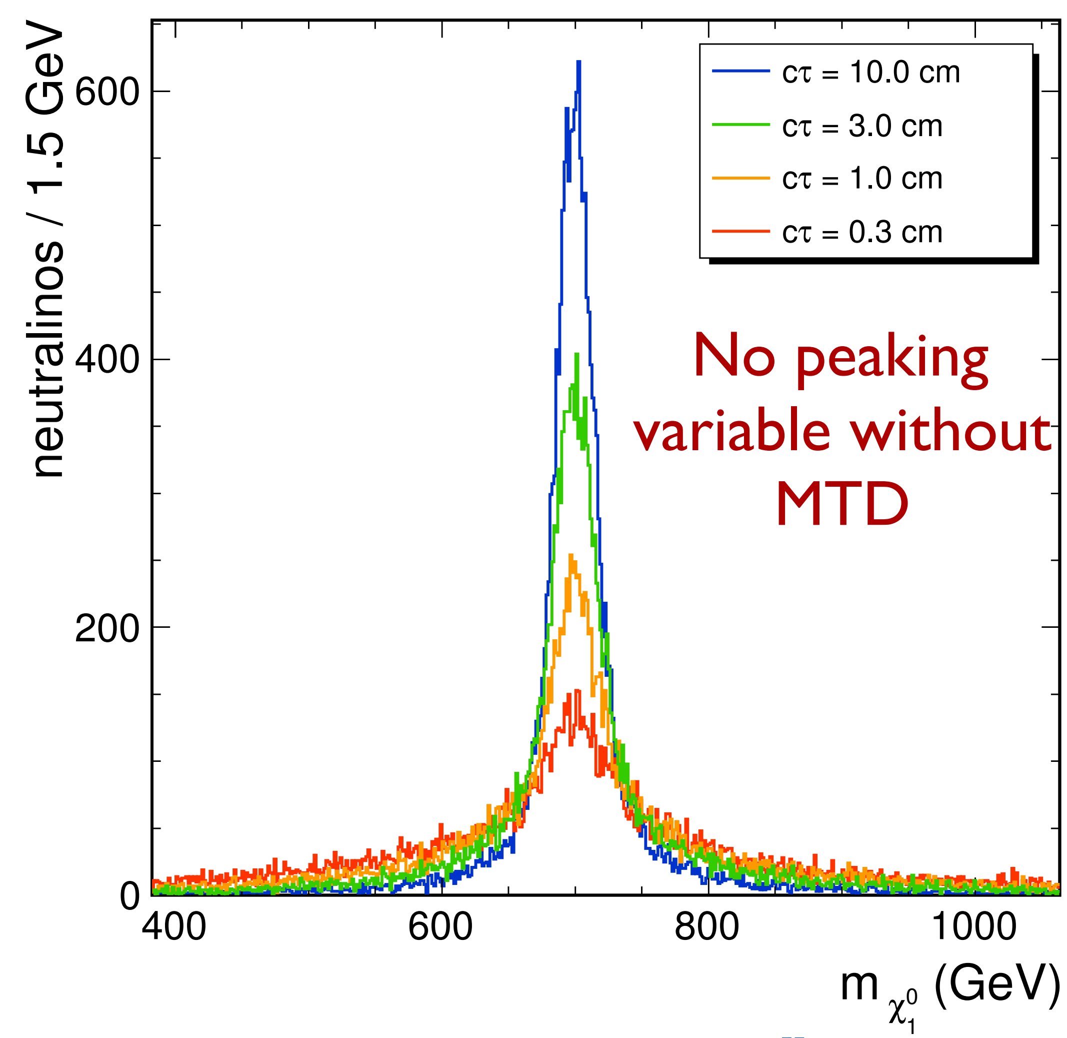
Fermilab

# 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

- Timing layers *allow resonance confirmation* in these searches



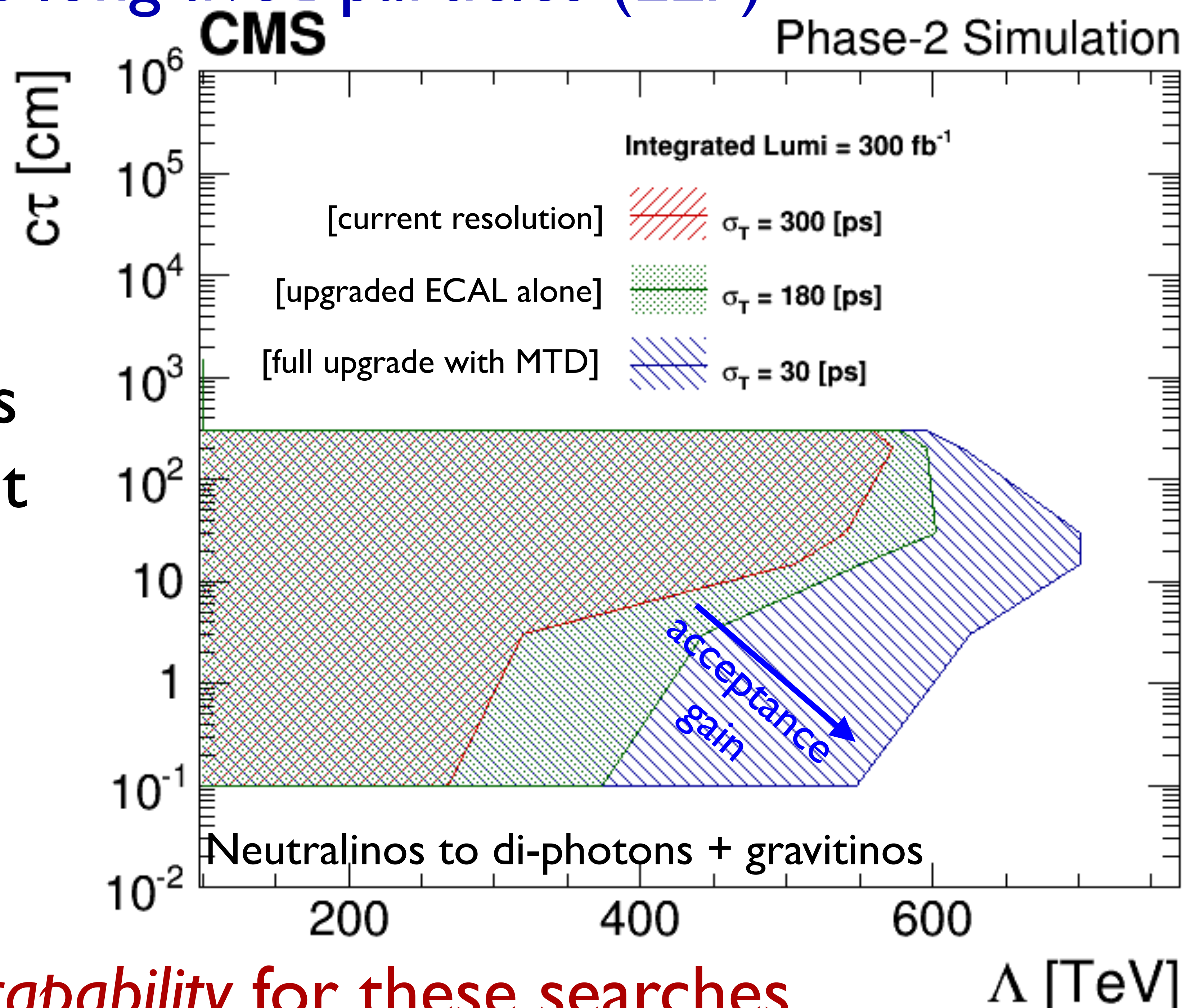



# Searches for Long-Lived Particles

- MTD with central acceptance 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

# Performance Summary

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

https://cds.cern.ch/record/2291131?

Examples in Technical Proposal

| Signal | Projected Physics Impact |
|---|---|
| $H \rightarrow \gamma\gamma$ | 25% improvement in statistical precision on xsecs $\rightarrow$ couplings |
| VBF $H \rightarrow \tau\tau$ | 20% improvement in statistical precision on xsecs $\rightarrow$ couplings |
| $HH$ | 20% increase in signal yield/decrease in running time $\rightarrow$ consolidate searches |
| EWK SUSY | 40% reducible background reduction $\rightarrow$ +150 GeV mass reach |
| Long-Lived Particles | Peaking Mass Reconstruction $\rightarrow$ Unique sensitivity and discovery potential |

- HGTD similarly benefits the forward performance of ATLAS
  - Novel capabilities derived from LLP secondary vertex timing
  - B-tagging improvements significantly improve rare signal acceptance

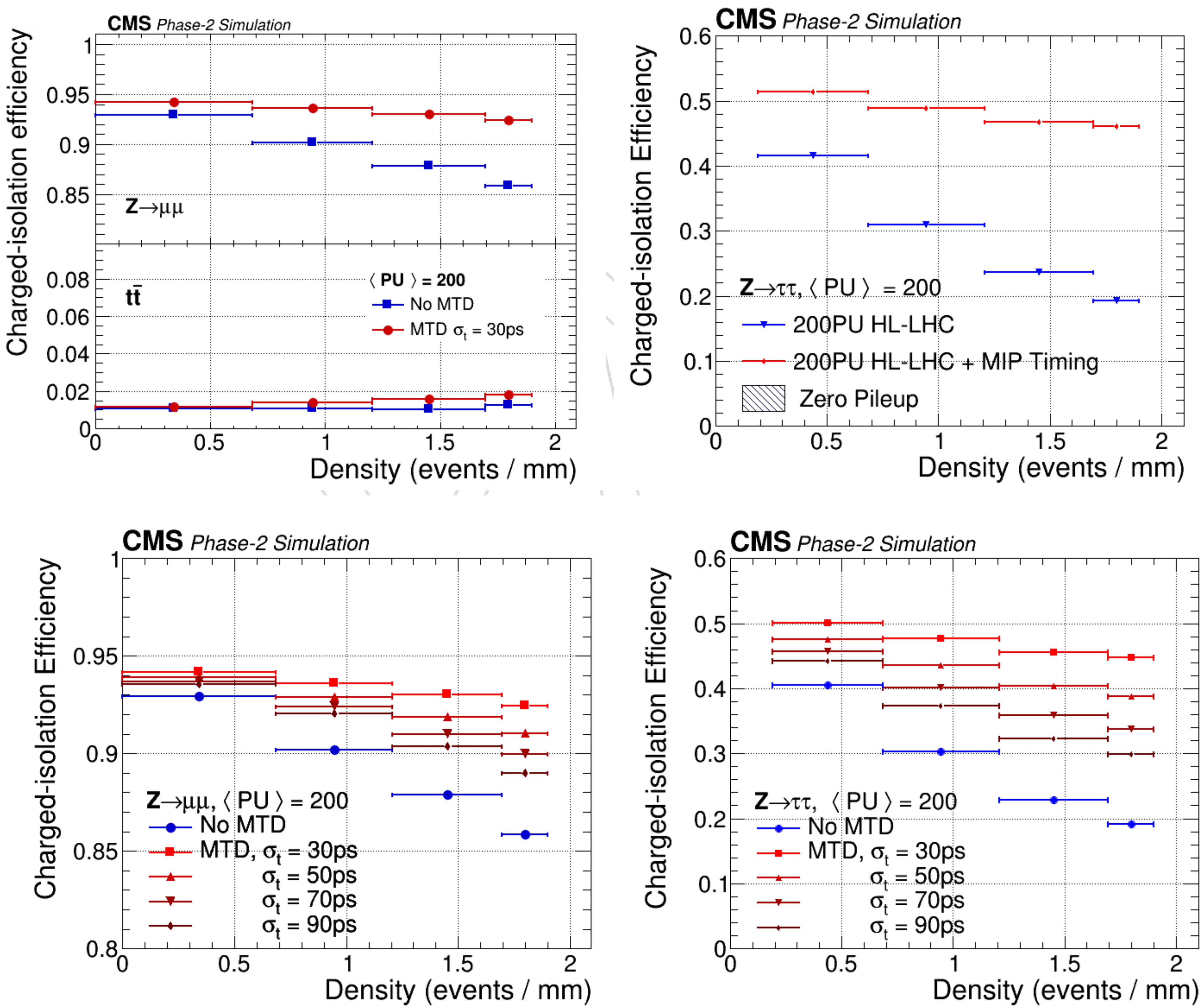
# Concluding Remarks

- MTD and HGTD provide benefits to whole physics program
  - Preserves the performance of Particle Flow and PUPPI in CMS
  - Improved performance of many forward observables in ATLAS
  - Increases effective luminosity: +20% for di-higgs (CMS)
  - Recovers search performance in MET tails
- Benefits equivalent up to additional 2-3 years of luminosity
- New capabilities for long-lived particle searches
- Sensor technologies underlying detectors becoming mature

- Timing TDRs for ATLAS and CMS coming in the next year

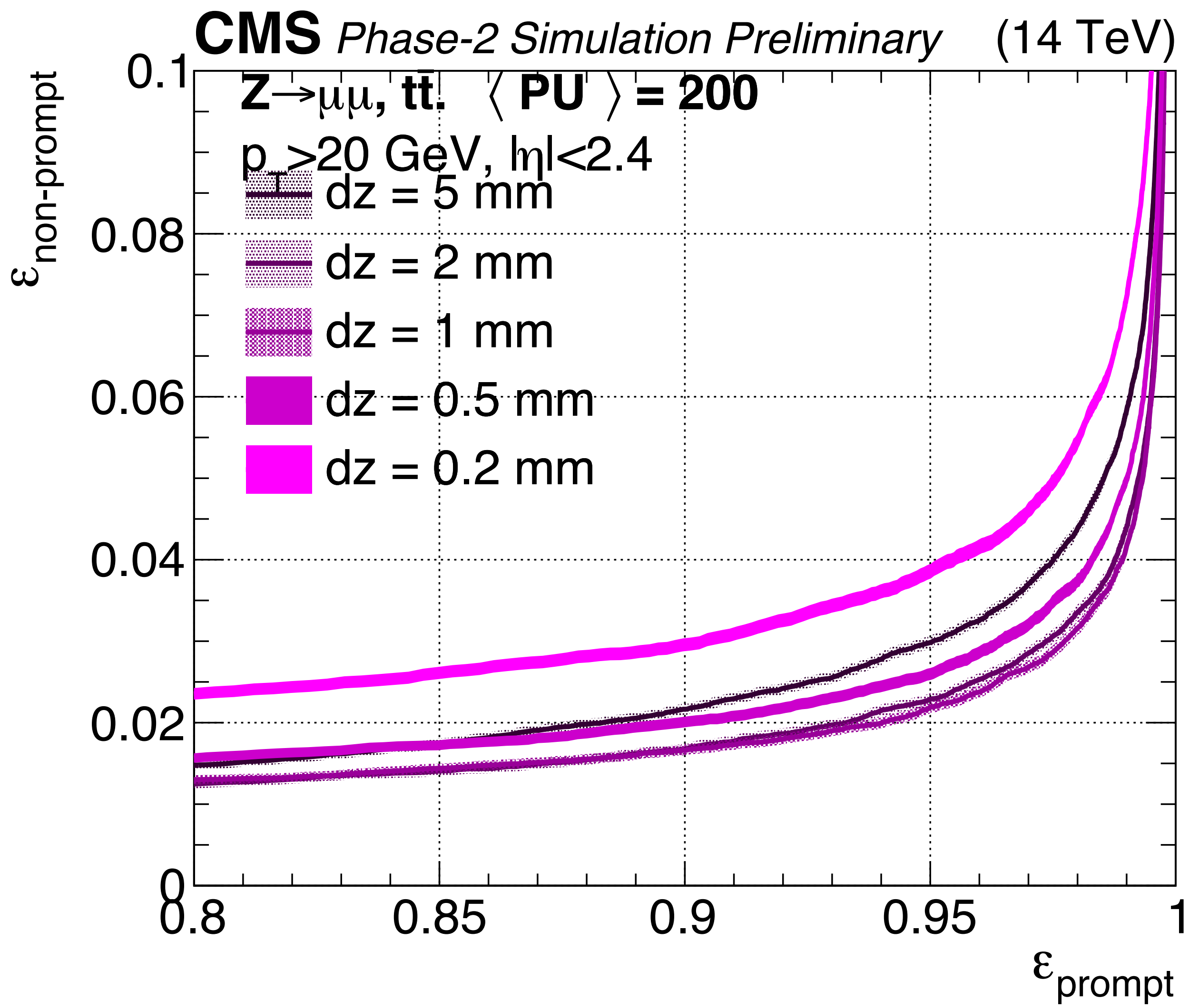
# Backup

# Lepton Isolation Performance

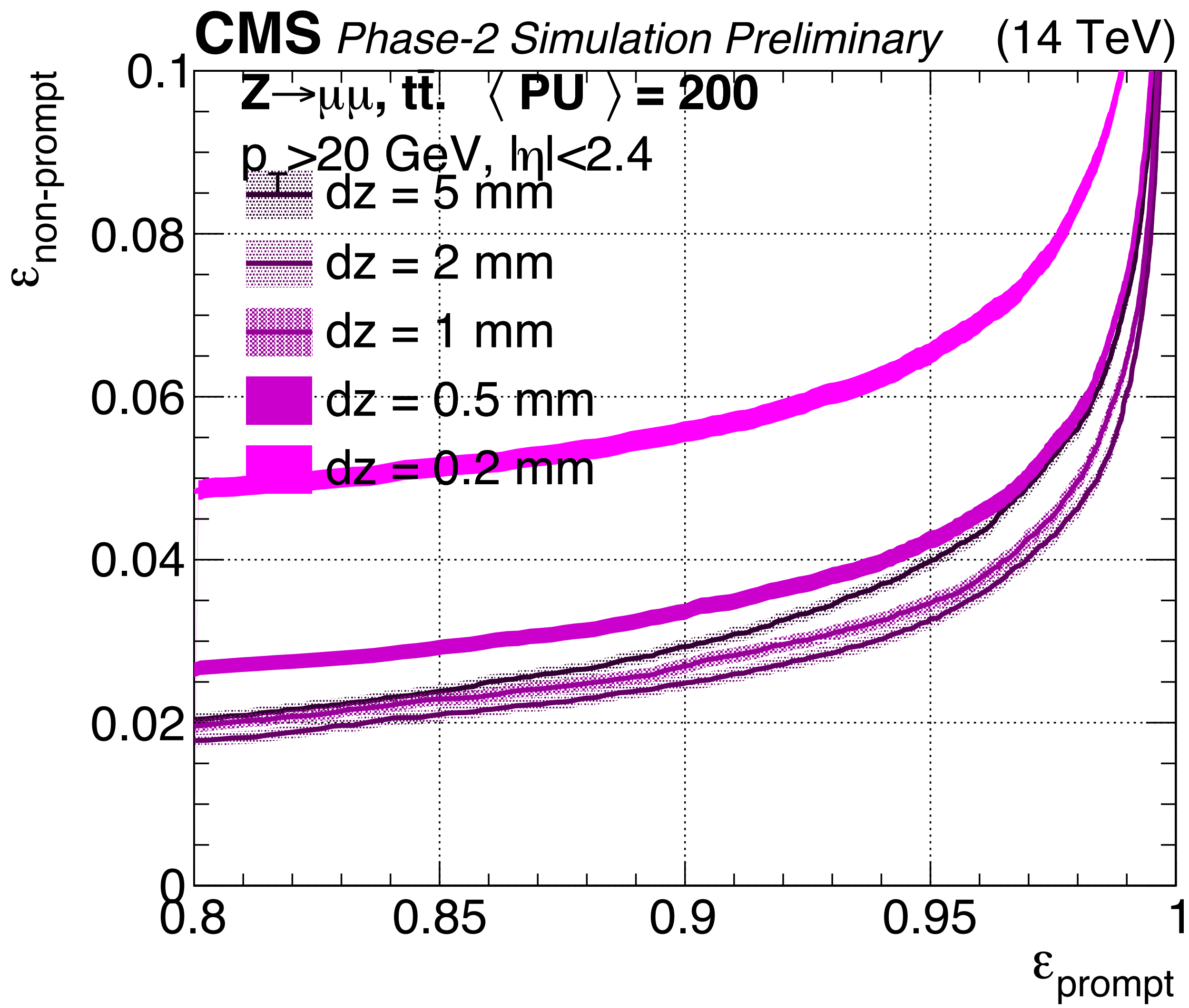


# Optimal |dz| cut for Isolation (no timing)

## Barrel

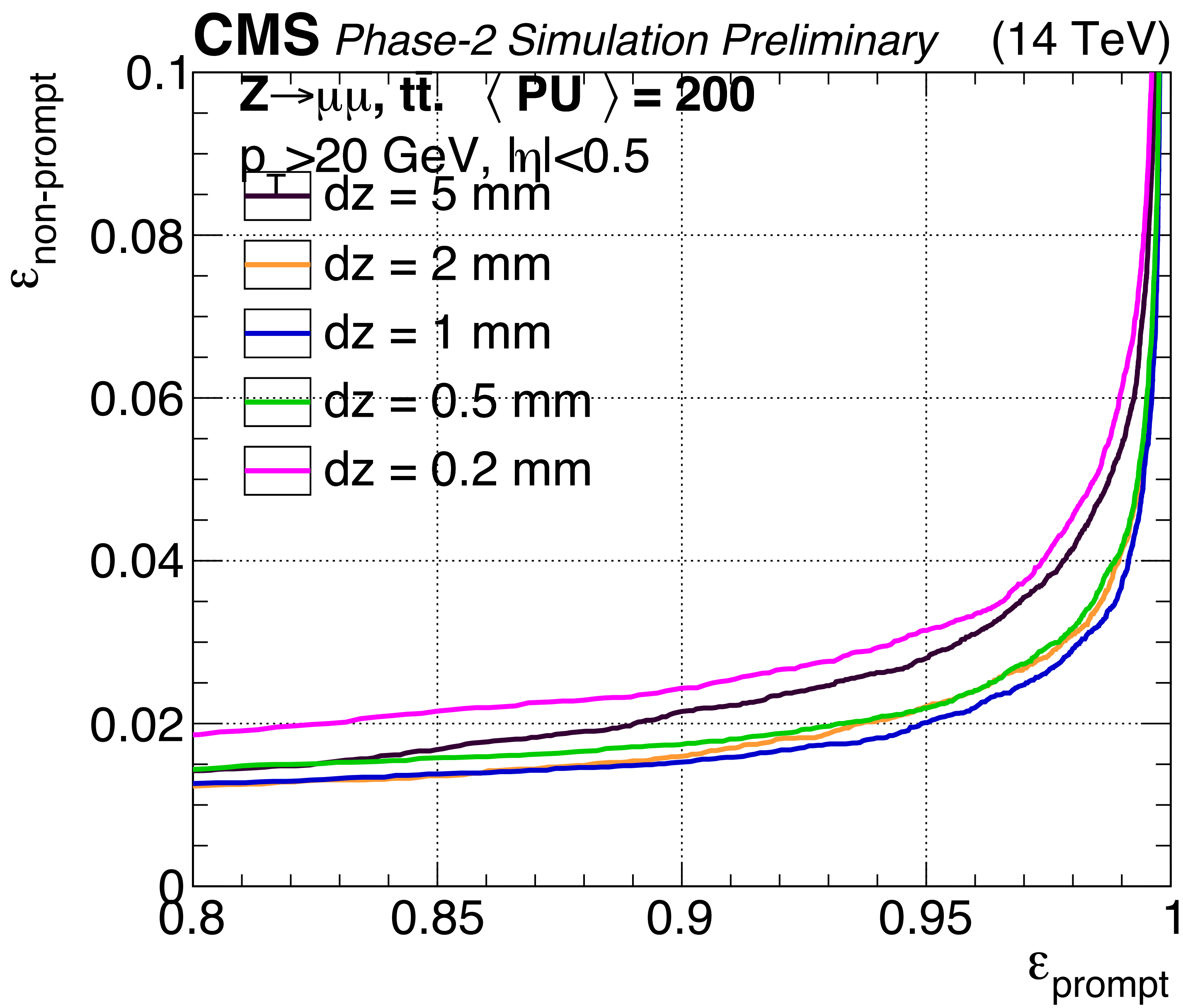



## Endcap



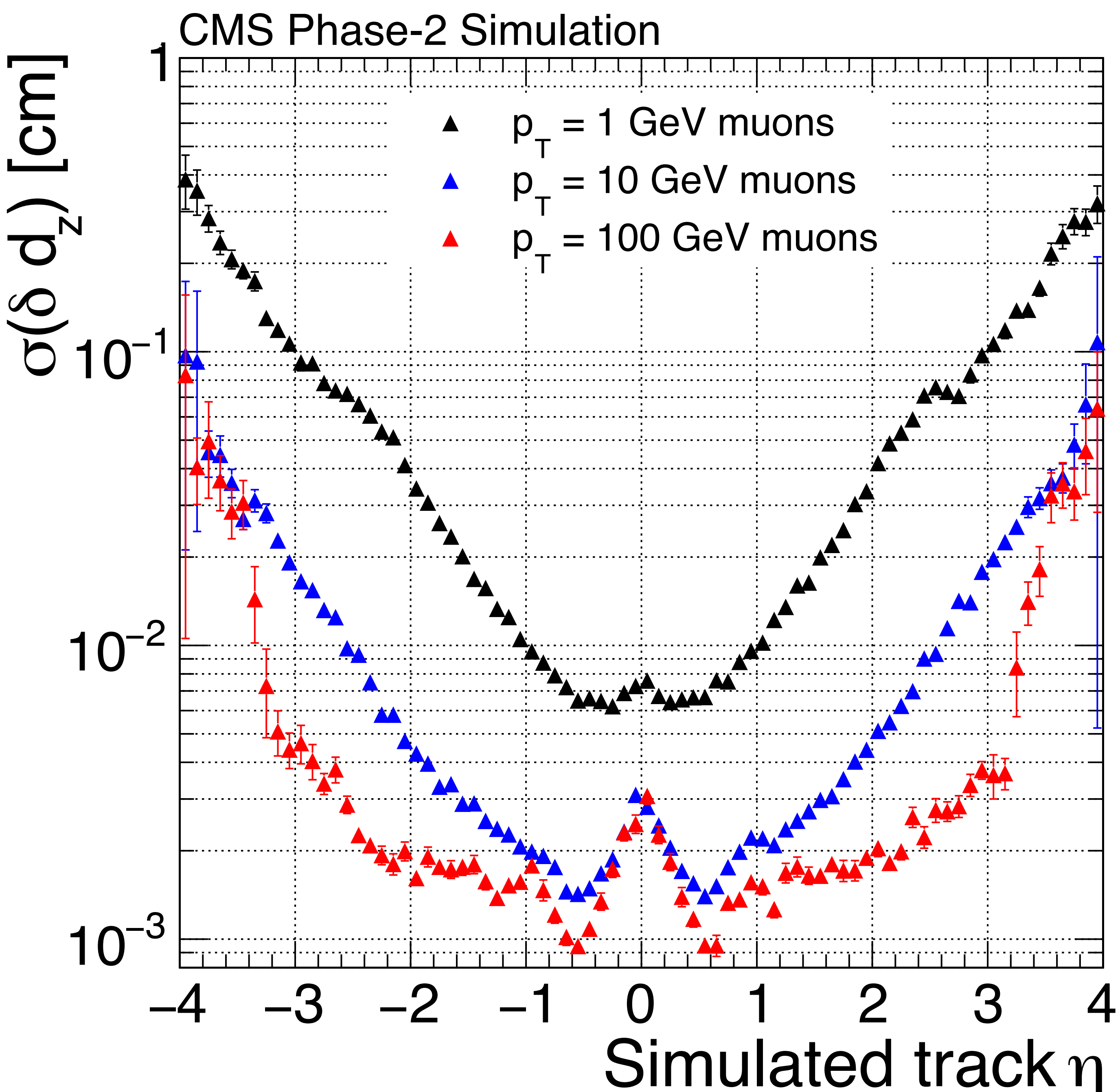

|dz| < 1mm cut outperforms significance-based in both barrel and endcap.

# 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.