Performance of Precision Timing Sensors for the Compact Muon Solenoid Experiment

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On behalf of the CMS Experiment
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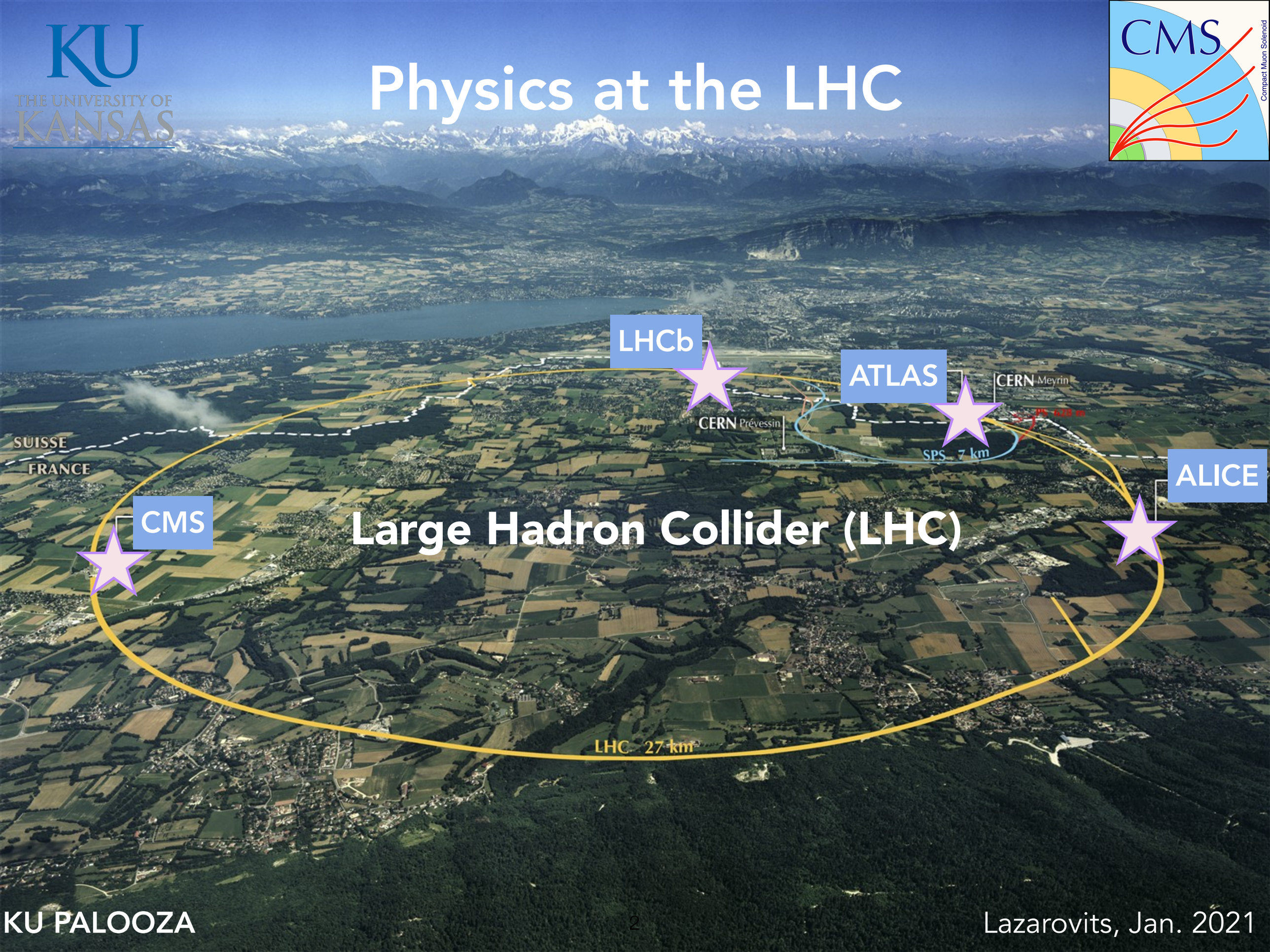
Physics at the LHC

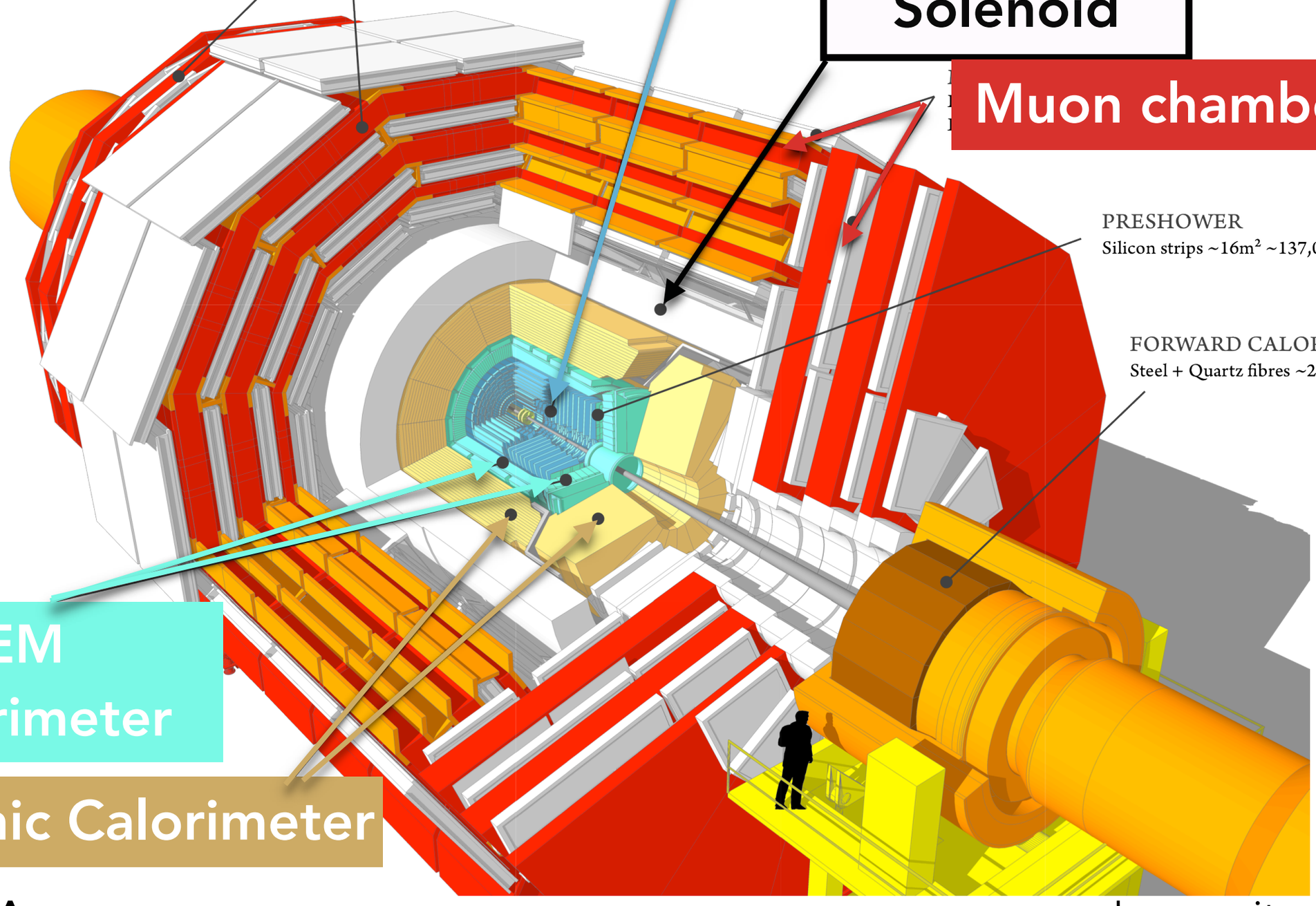


Compact Muon Solenoid (CMS)

CMS DETECTOR

Total weight	: 14,000 tonnes
Overall diameter	: 15.0 m
Overall length	: 28.7 m
Magnetic field	: 3.8 T

STEEL RETURN YOKE
12,500 tonnes



Trackers

Solenoid

Muon chambers

PRESHOWER
Silicon strips ~16m^2 ~137,000 channels

FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

EM Calorimeter

Hadronic Calorimeter

Pileup Increase with LHC Upgrade

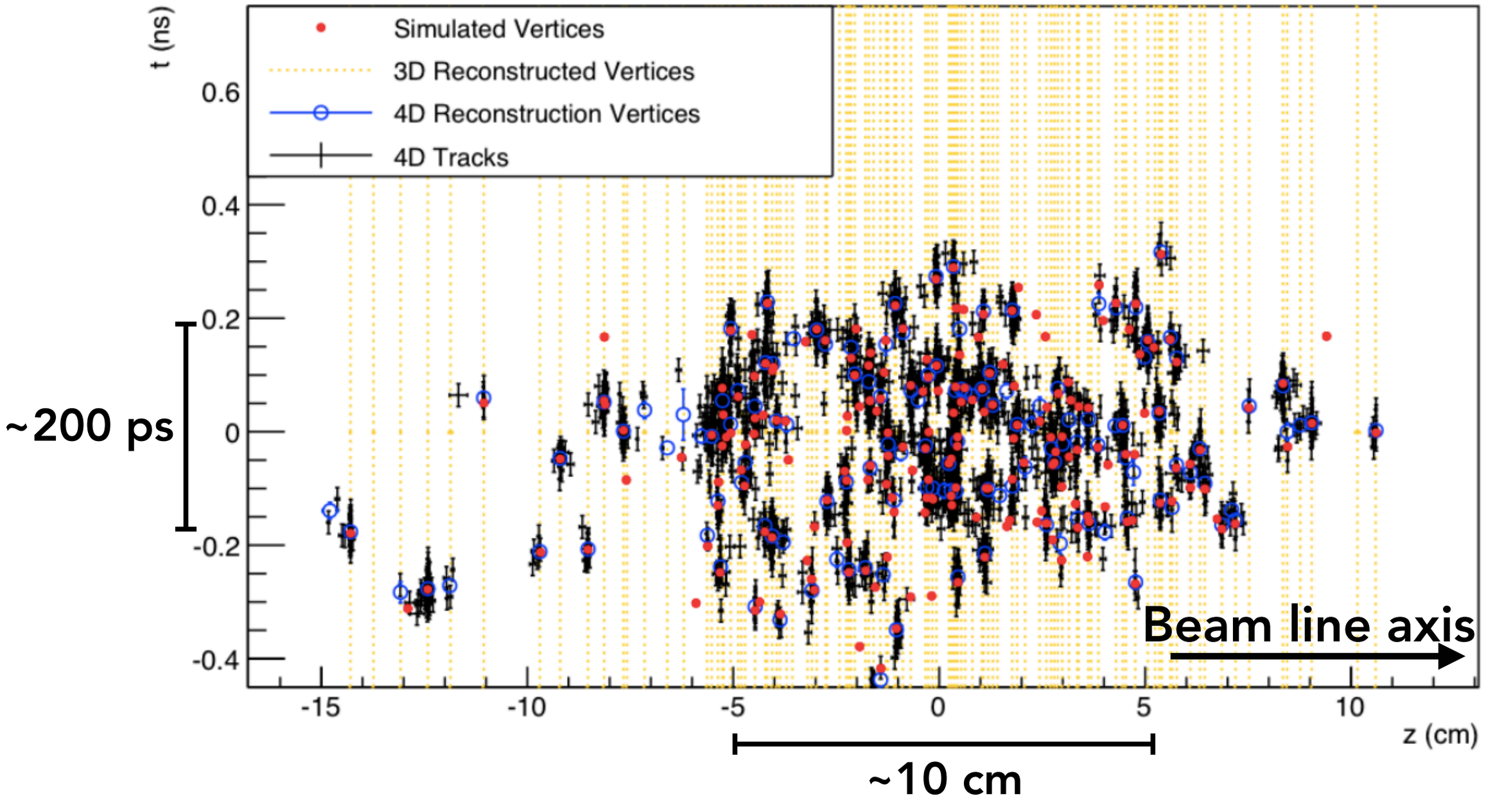
Beam line axis

~10 cm

40 million bunch crossings/sec
with 100-200 interactions/crossing

Resolving Pileup With Precision Timing

Vertices that overlap in 3D are clearly separated in 4D

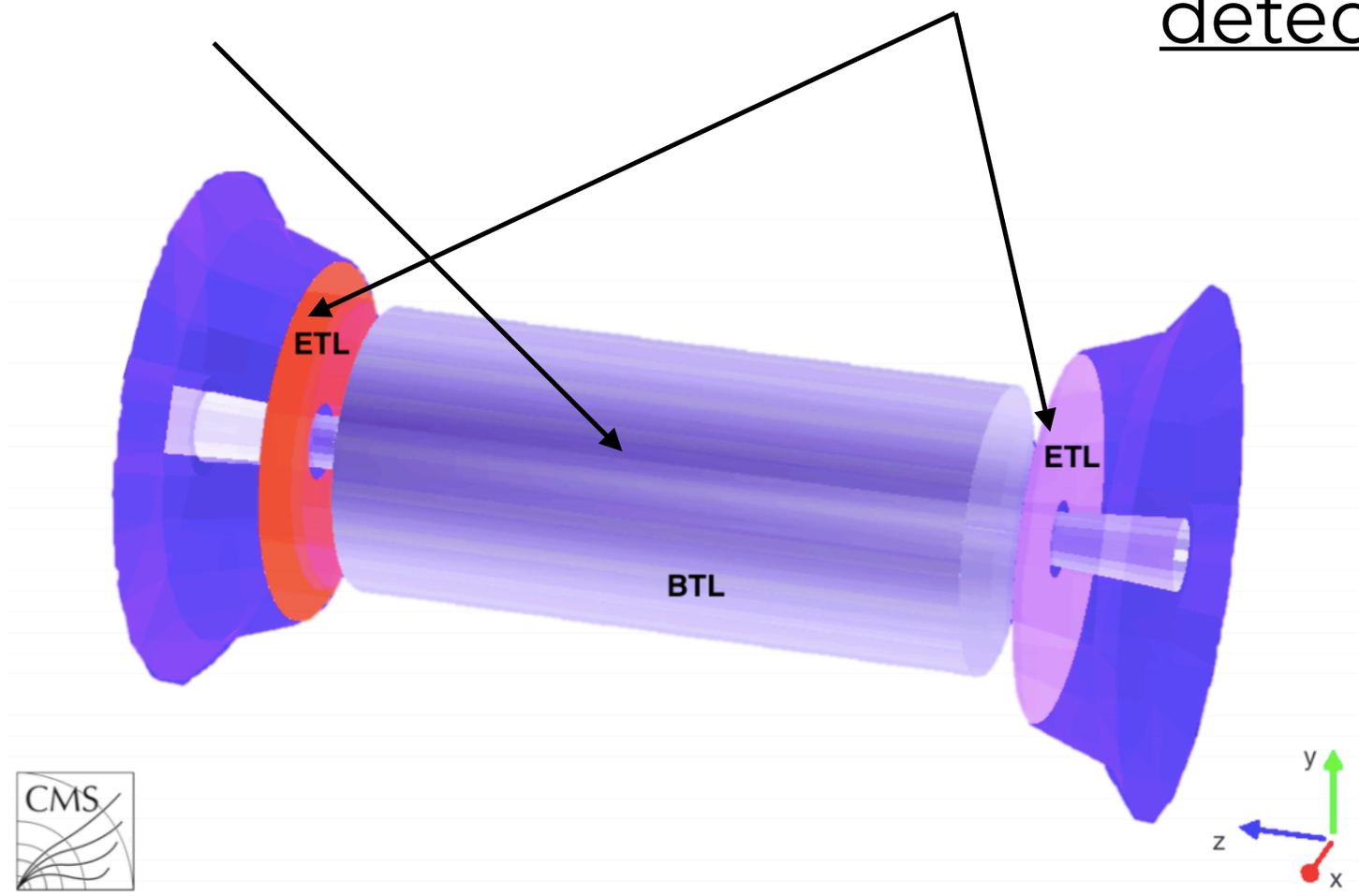


MTD Structural Overview (within CMS)

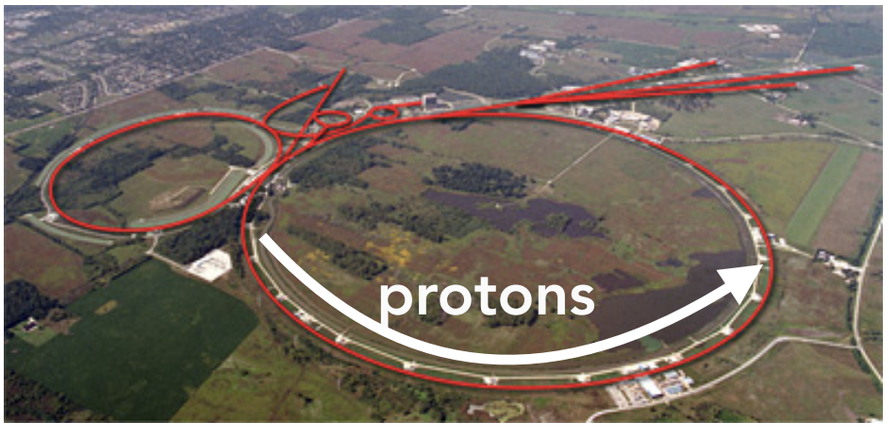
Barrel Timing Layer (BTL)

Endcap Timing Layer (ETL):

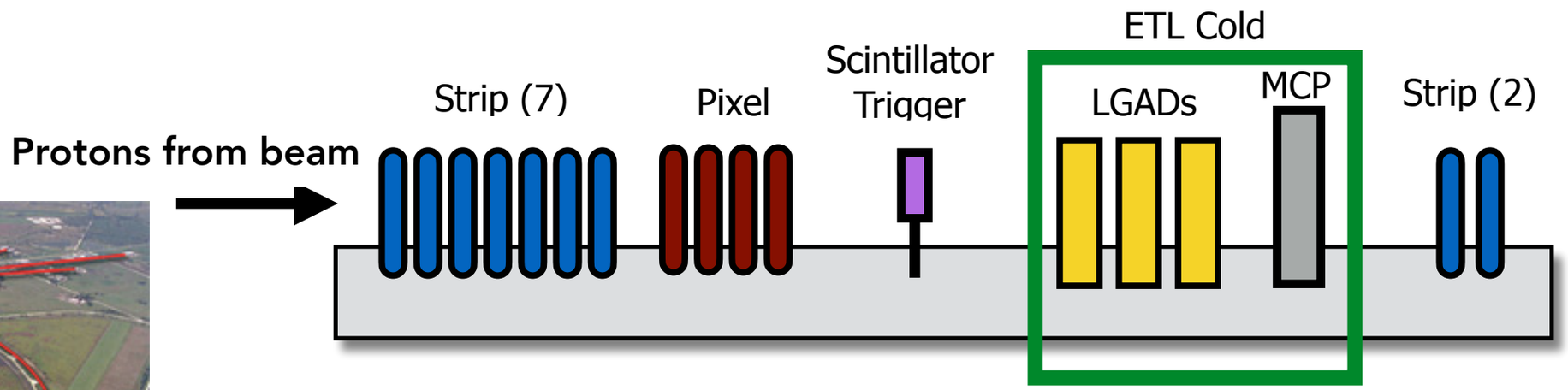
Silicon low gain avalanche detectors (LGADs)

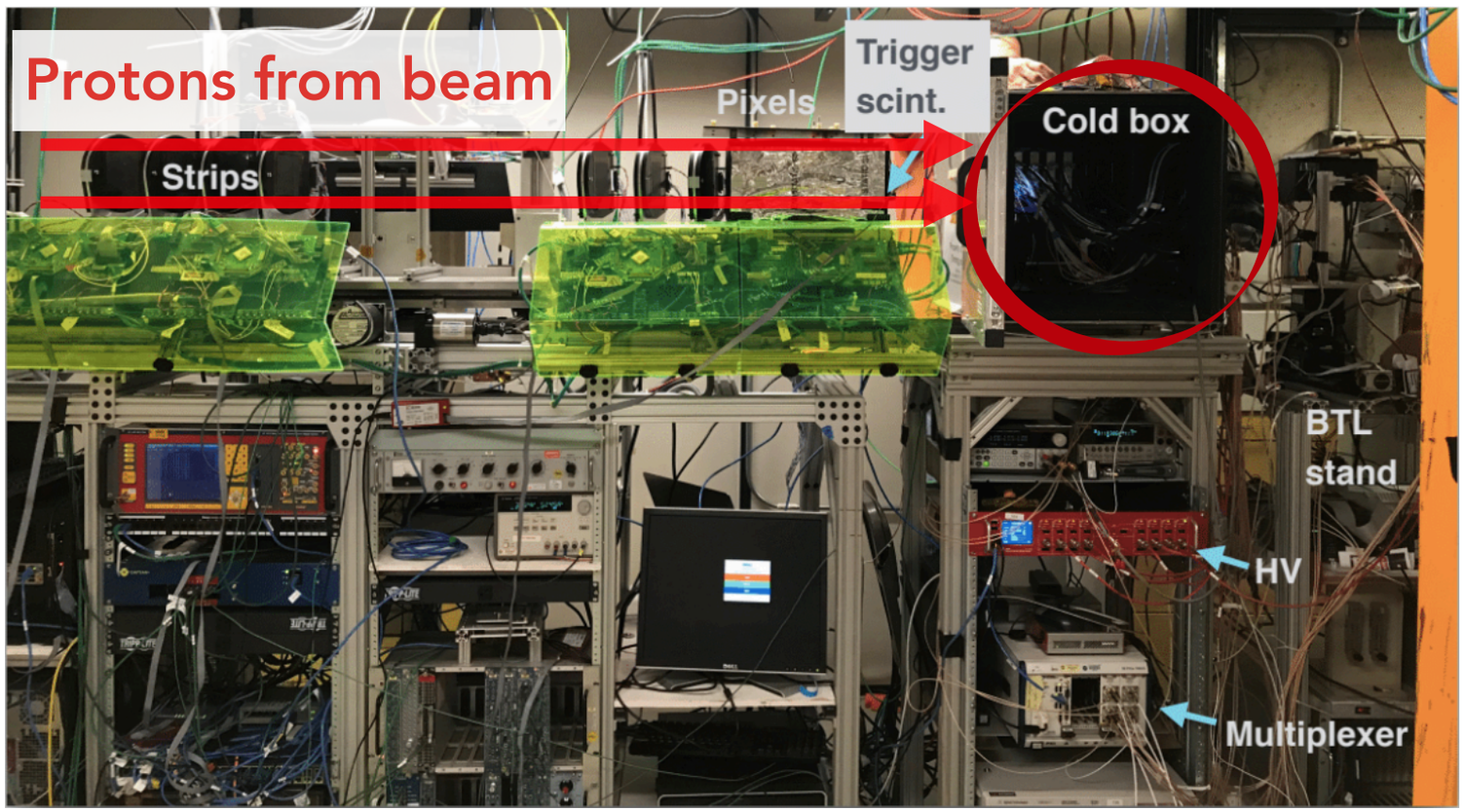


Test Beam Setup @ Fermilab



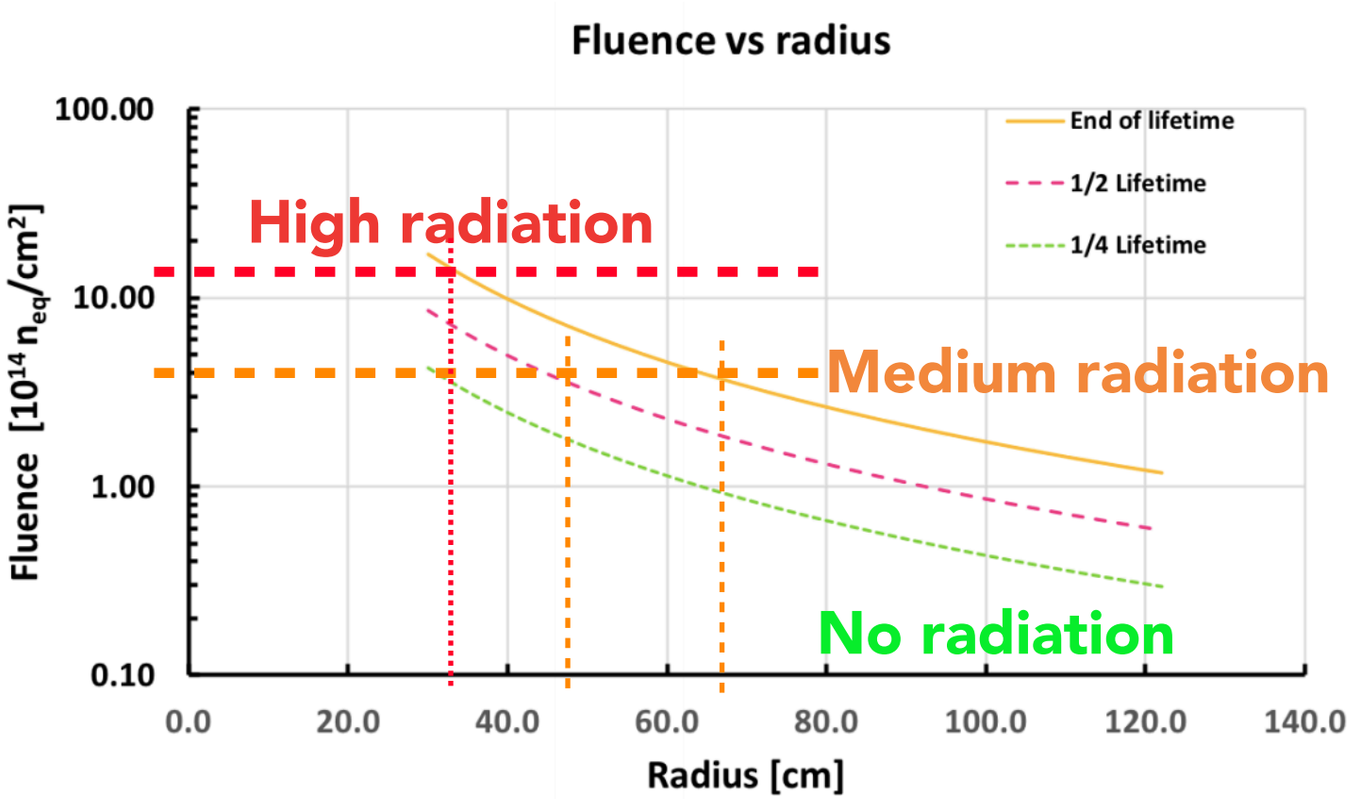
Fermilab particle accelerator, Batavia, IL





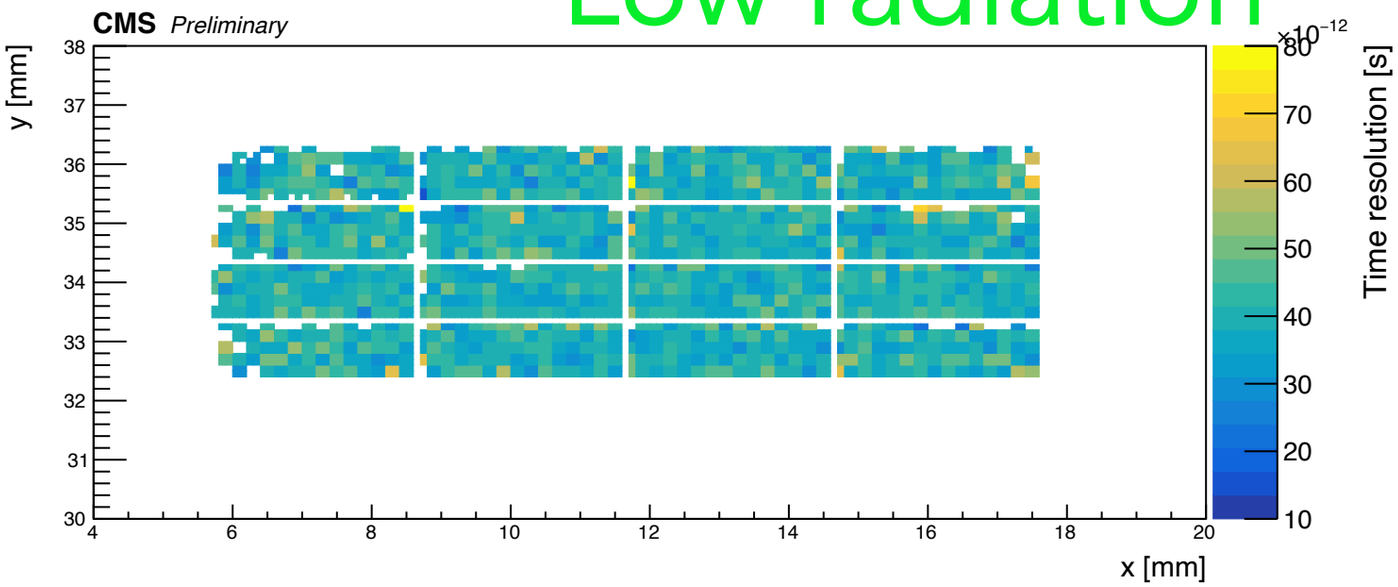
Silicon LGAD Sensor Requirements

- Time resolution requirement: 30-40 picoseconds
- Efficiency requirement: ~100% uniformly throughout the sensor
- Radiation tolerance



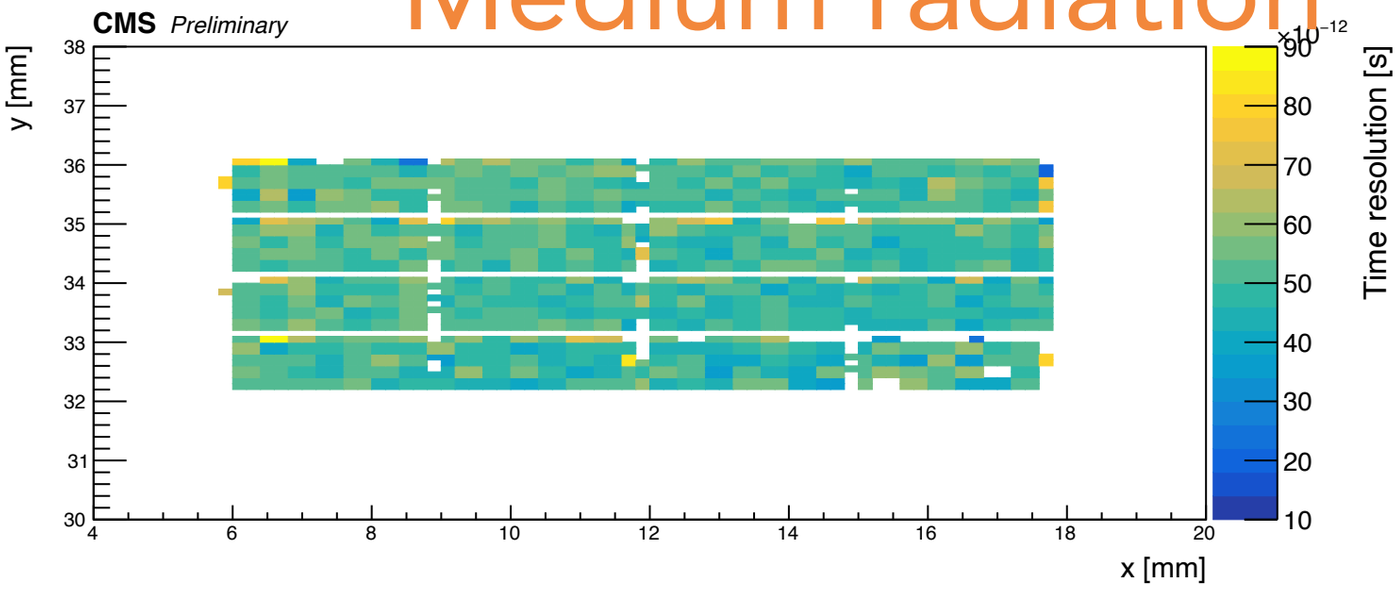
Sensor Requirement: Timing Resolution

Low radiation



☑ **Uniform timing resolution ~ 30 ps**

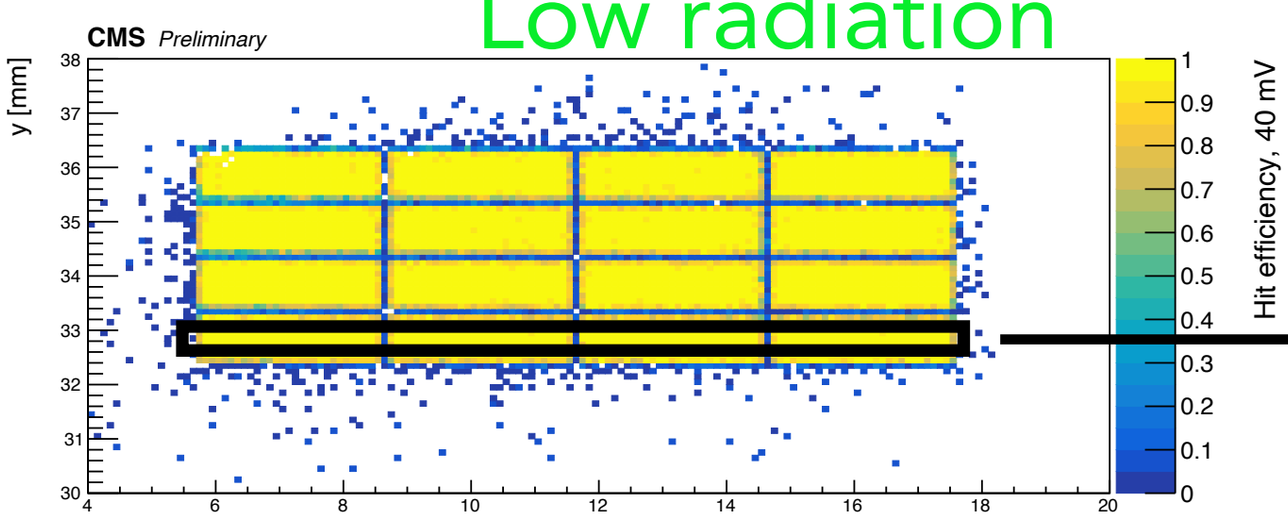
Medium radiation

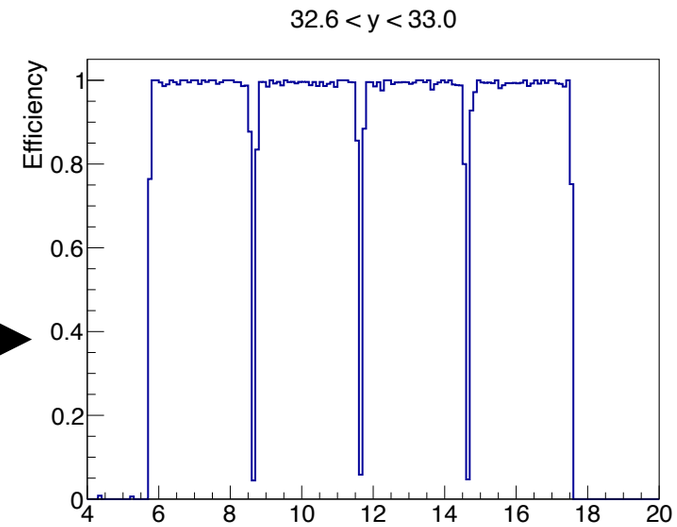


☑ **Uniform timing resolution ~ 30-40 ps**

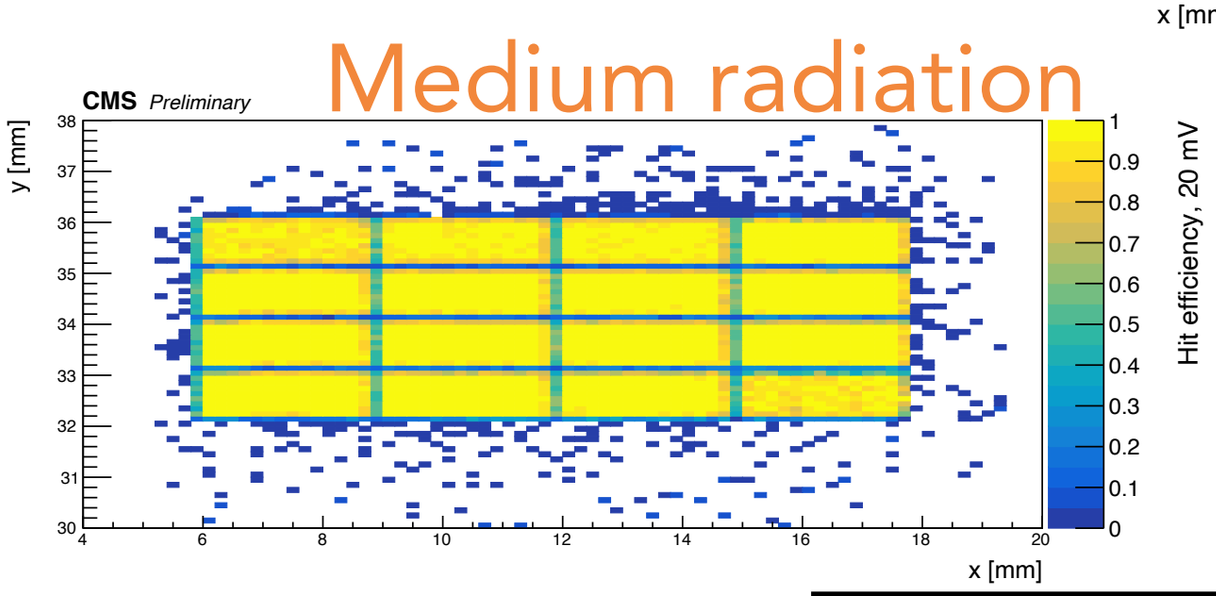
Sensor Requirement: Efficiency + Radiation Tolerance

Low radiation

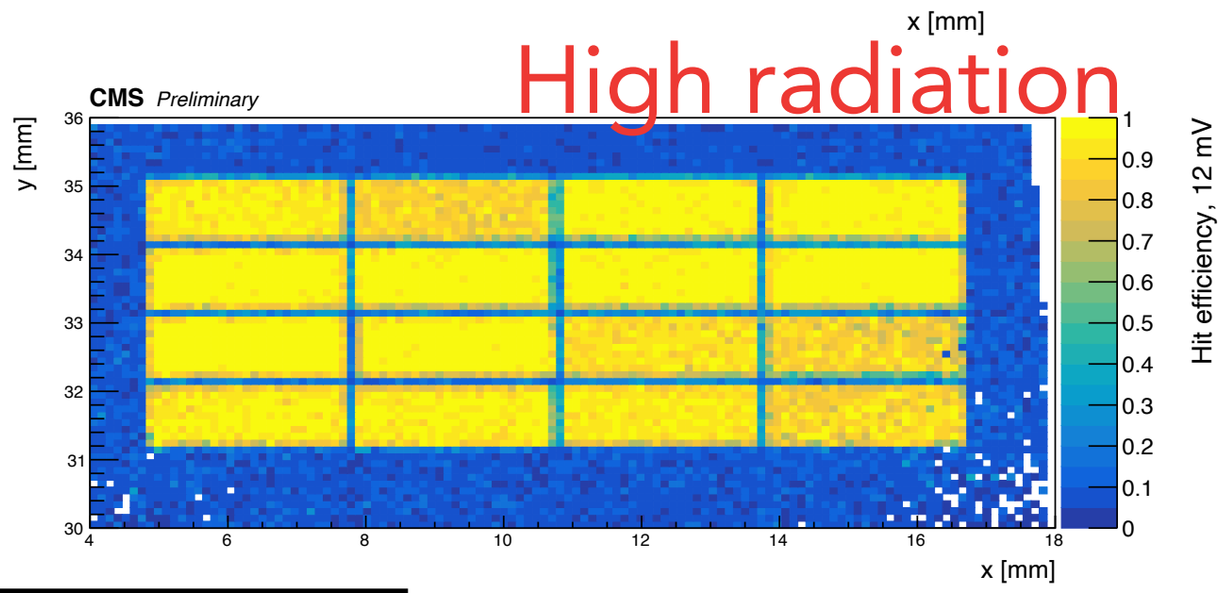




Medium radiation



High radiation



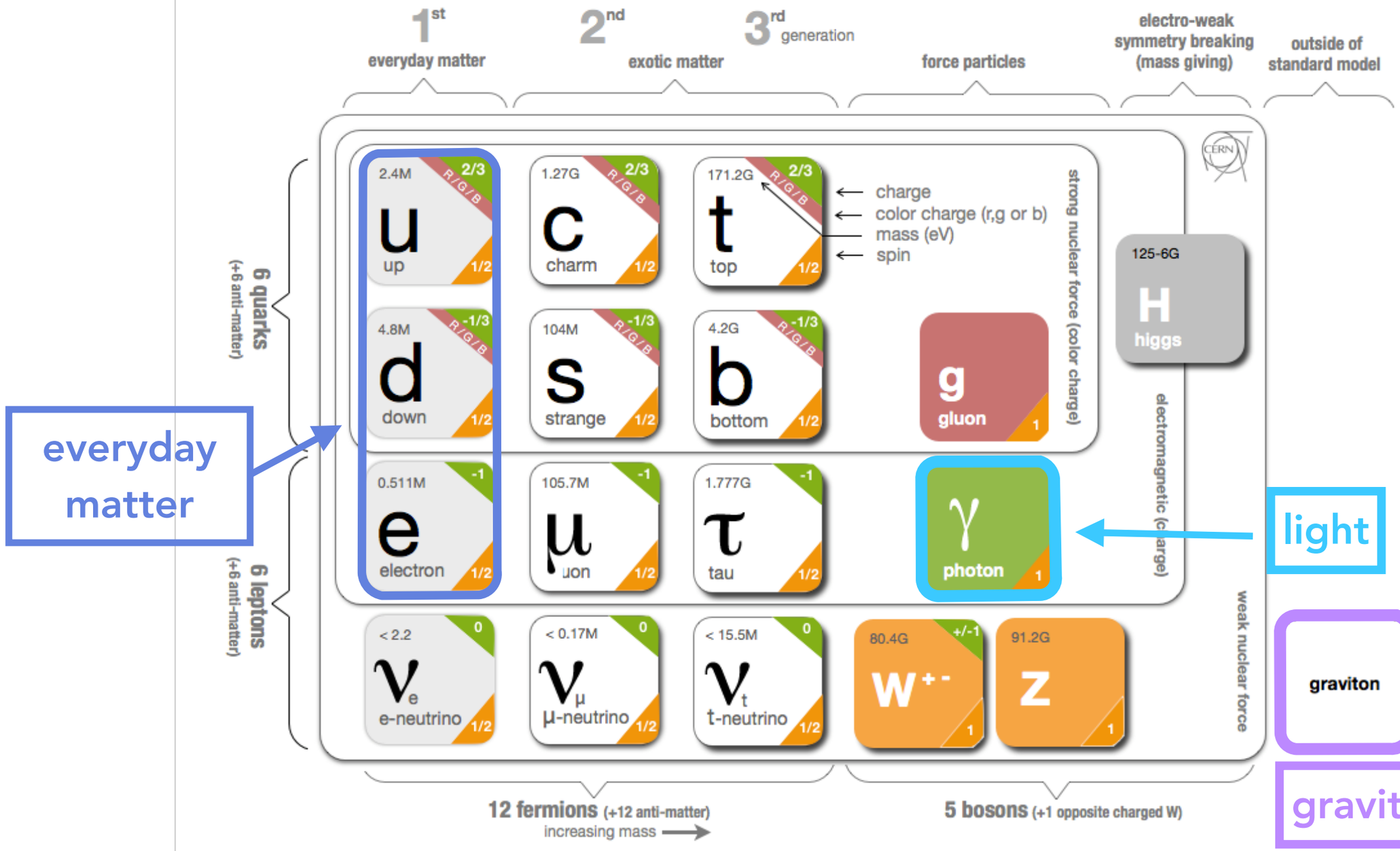
- ☑ ~100% Efficiency
- ☑ Uniform Performance
- ☑ Radiation Tolerant

Summary

- CMS detector at the Large Hadron Collider entering upgrade phase in the near future
  - Comes with increase in pileup
- Precision Timing @ CMS helps to reduce effects of pileup
  - Implemented with MIP Timing Detector
- MTD concluding R&D phase
  - Fermilab test beam: ETL sensors performance meet expectations
  - More tests @ KU will begin soon!

Backup

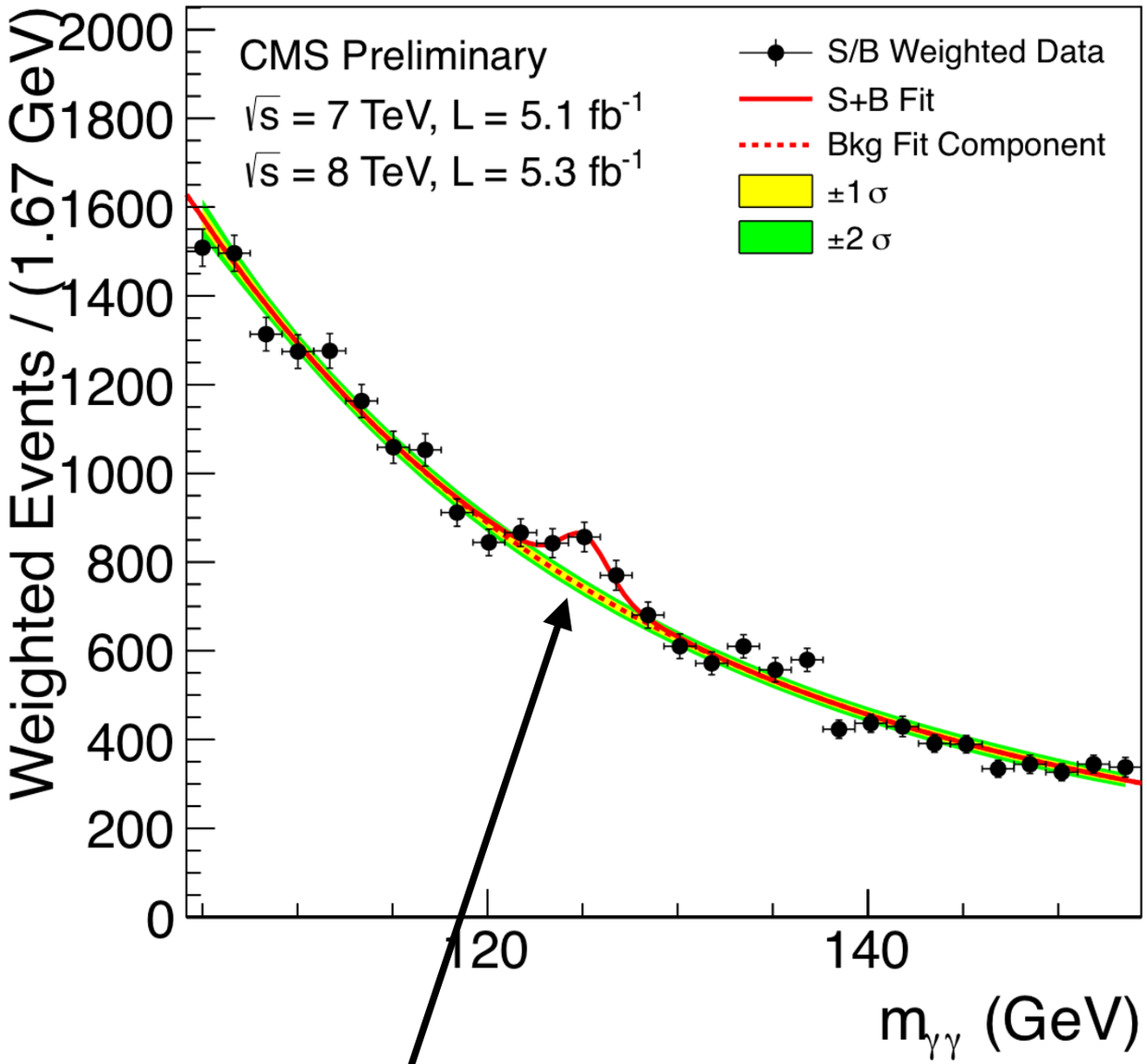
Standard Model: building blocks of the universe



Goals of Particle Physics

Standard Model (SM) measurements

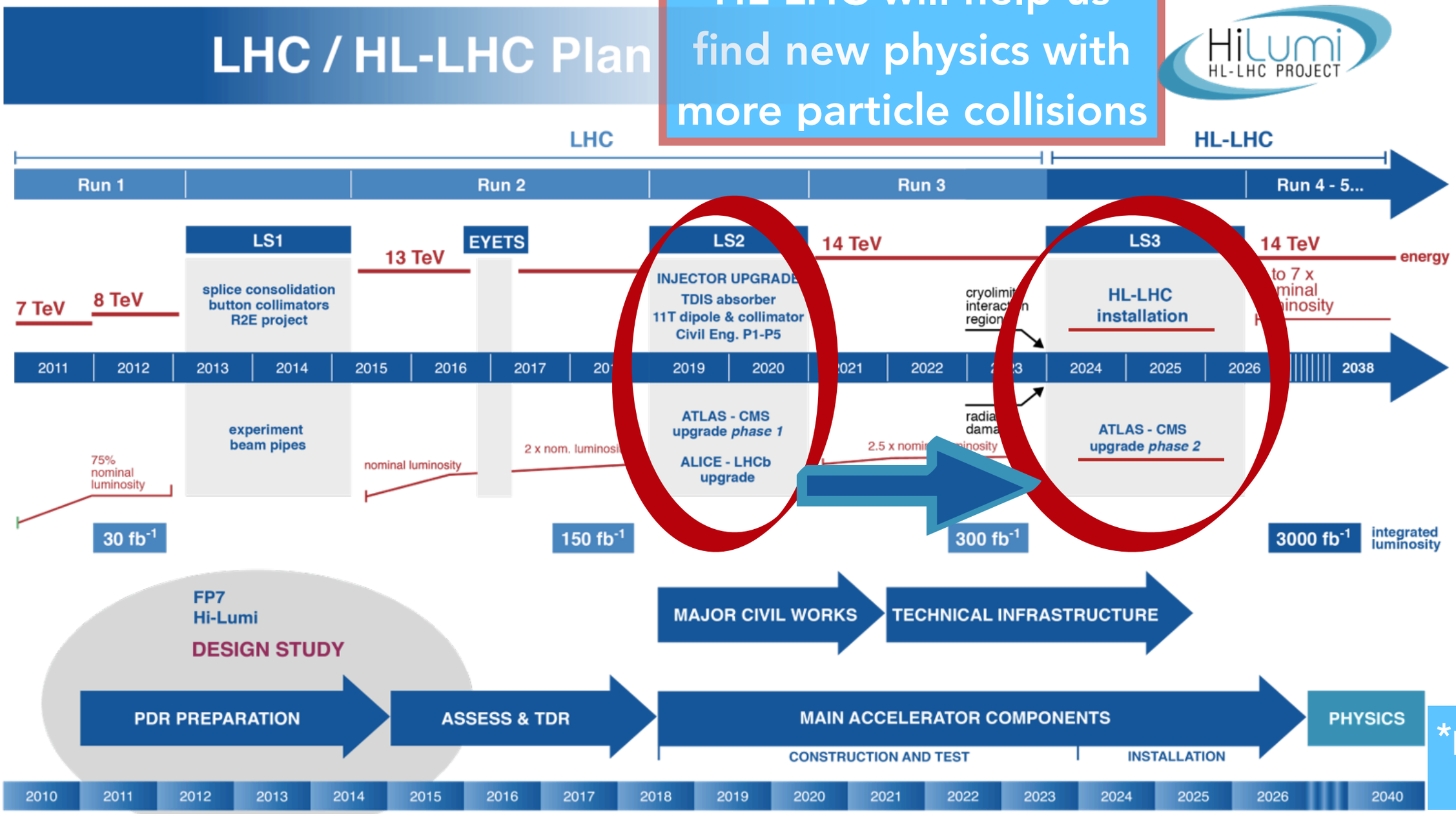
Beyond Standard Model (BSM) aka new physics searches



Higgs boson discovery by CMS (2012)

High Luminosity LHC

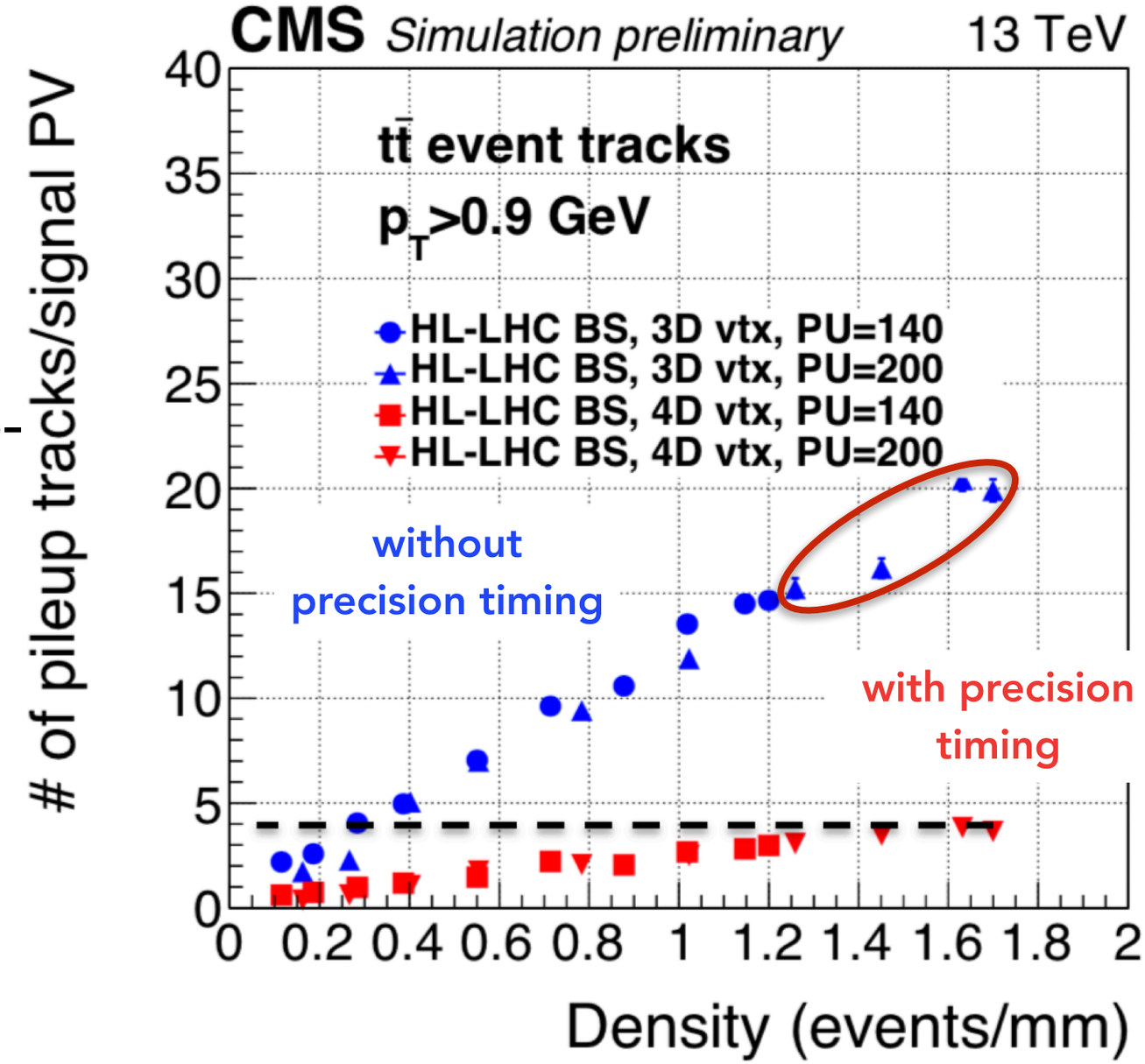
HL-LHC will help us find new physics with more particle collisions



*preliminary schedule

What does improved pileup resolution mean?

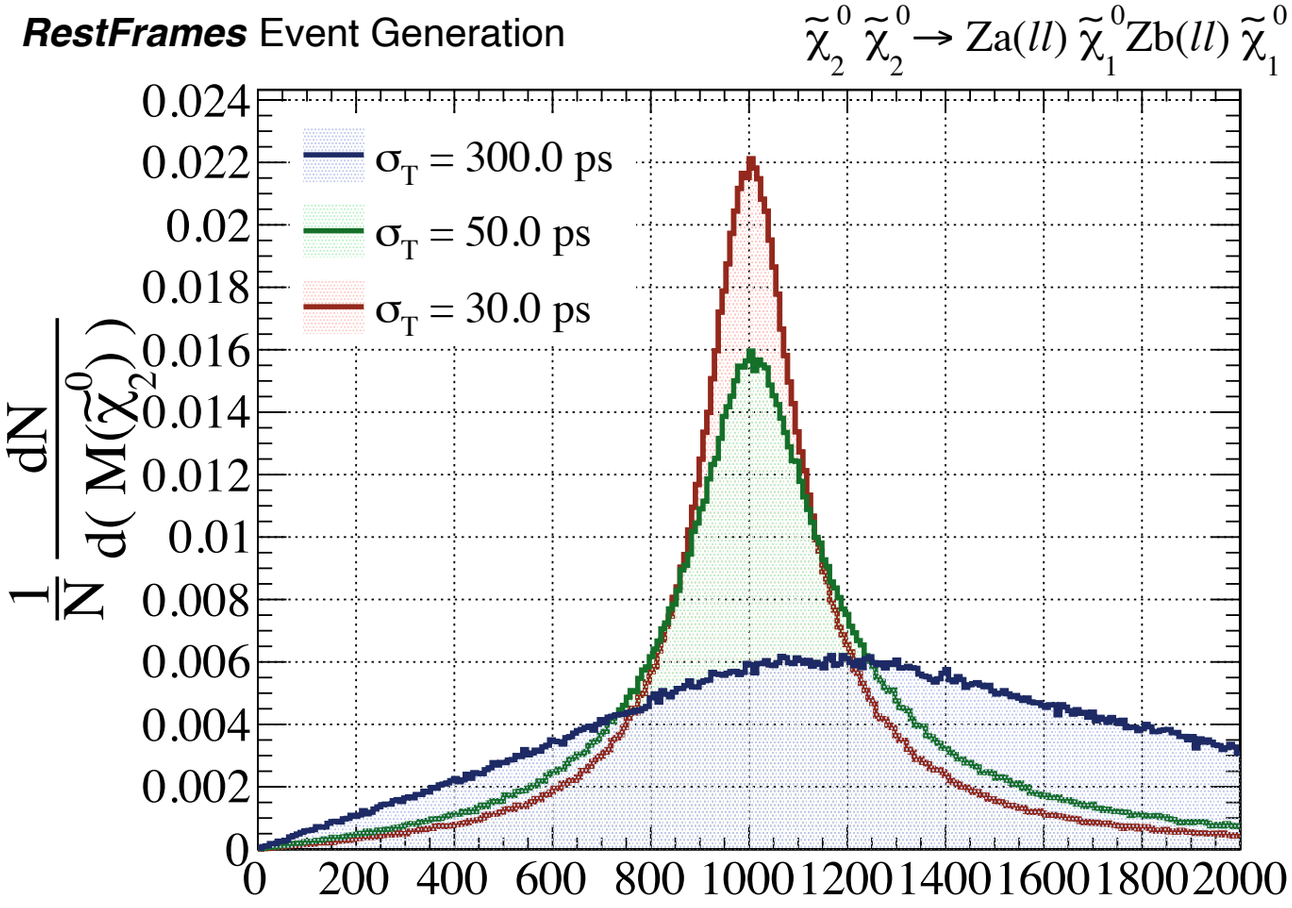
- Improved pileup resolution (CMS LHCC-2019-003)
  - Better tagging capabilities for b-jets
  - Improvement for lepton isolation
  - Increased effective luminosity for rarer signals/Higgs Program



Improvement on resolution of tracks/ PV with increased time resolution

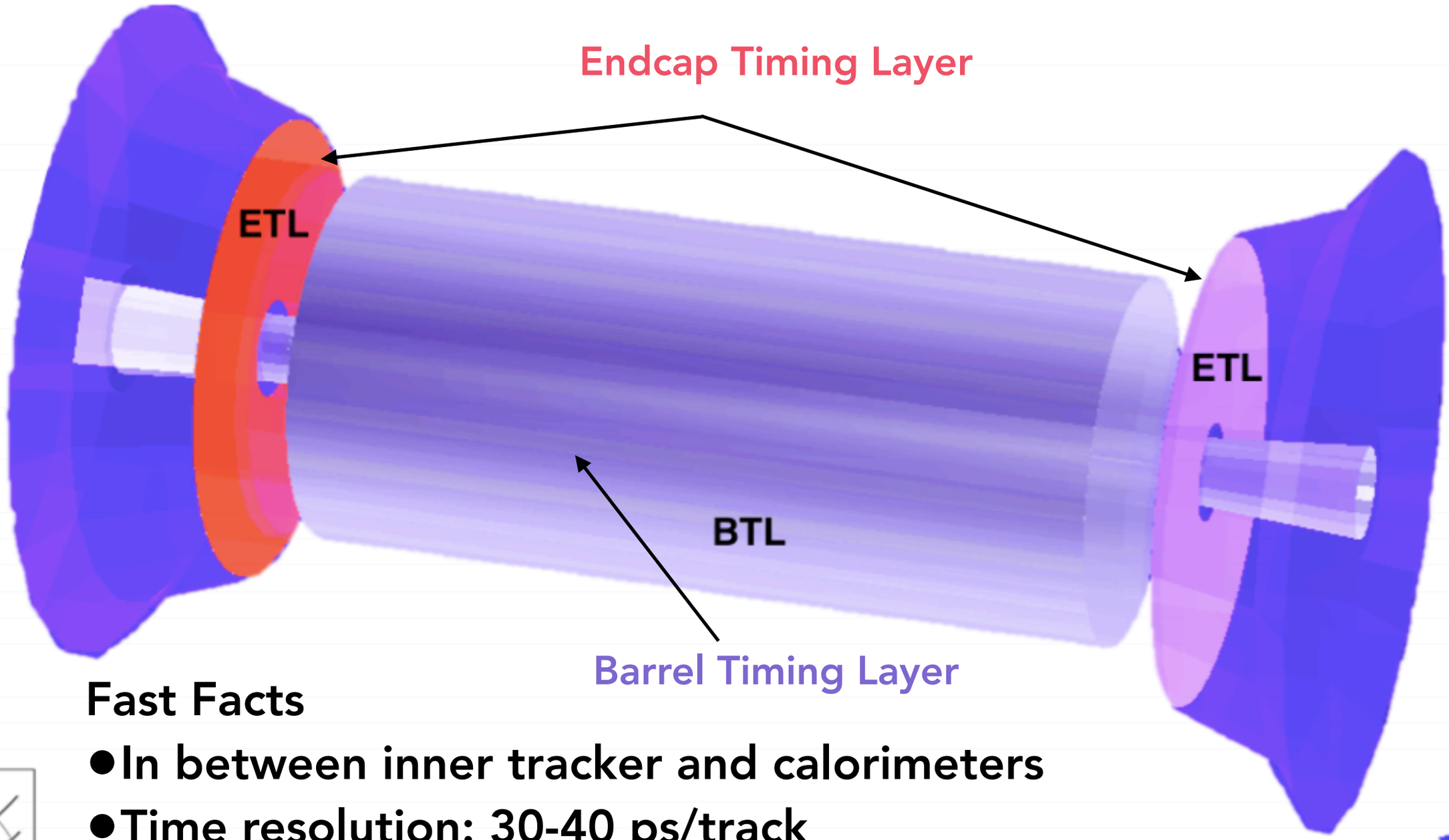
What else can we see with the MTD?

- Improved pileup resolution (CMS LHCC-2019-003)
  - B-tagging + lepton isolation improvement
  - Increased effective luminosity for rarer signals/Higgs Program
- Additional physics capabilities
  - Heavy ion studies/low pT hadron studies
  - LLP studies with timing (arXiv:1903.05825v2)



Improvement on resolution of mass measurement for neutralino with increased timing resolution

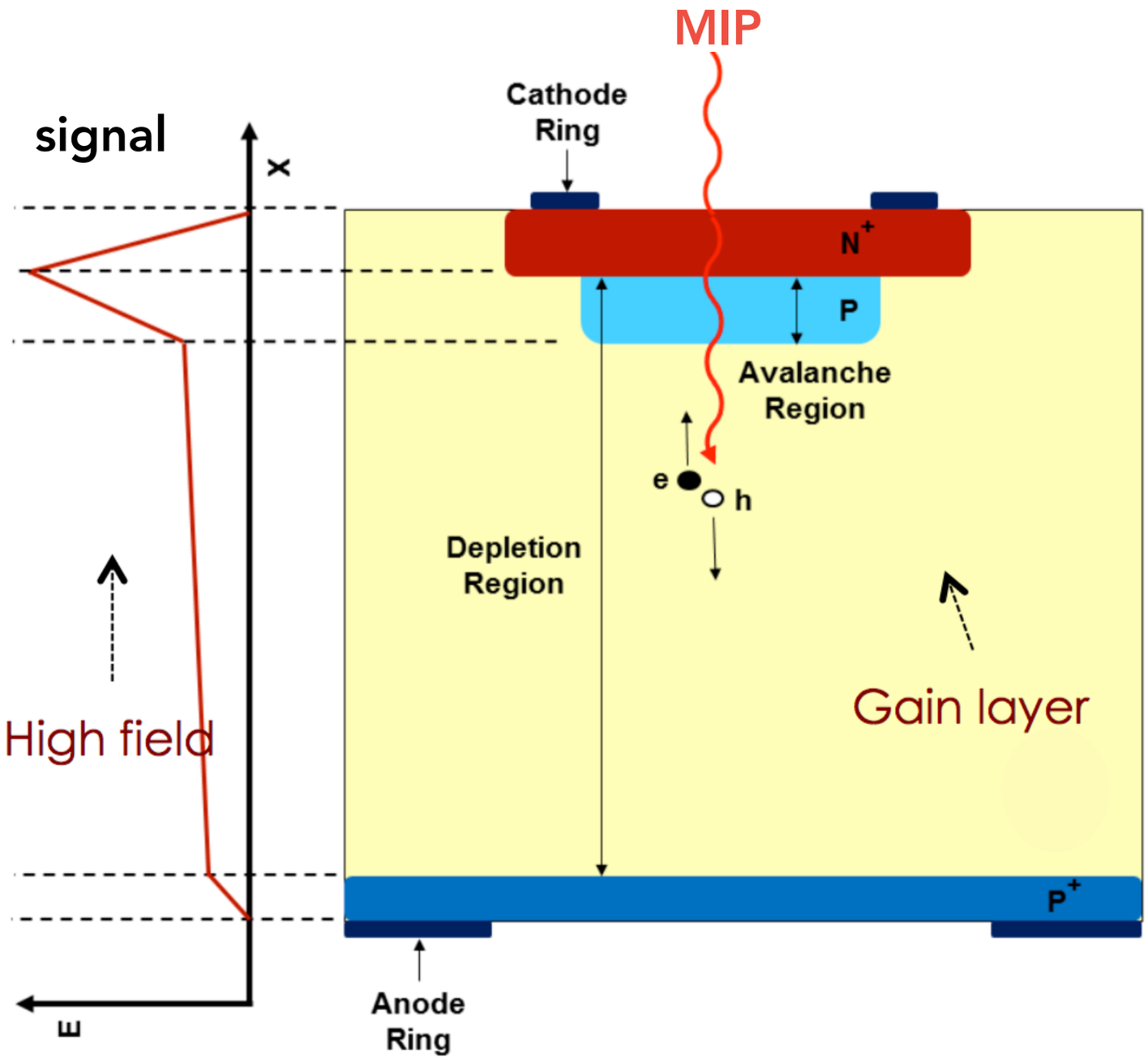
CMS Precision Timing with the MIP Timing Detector (MTD)



Fast Facts

- In between inner tracker and calorimeters
- Time resolution: 30-40 ps/track
- Installation date: 2023 (HL-LHC)

Low Gain Avalanche Detectors

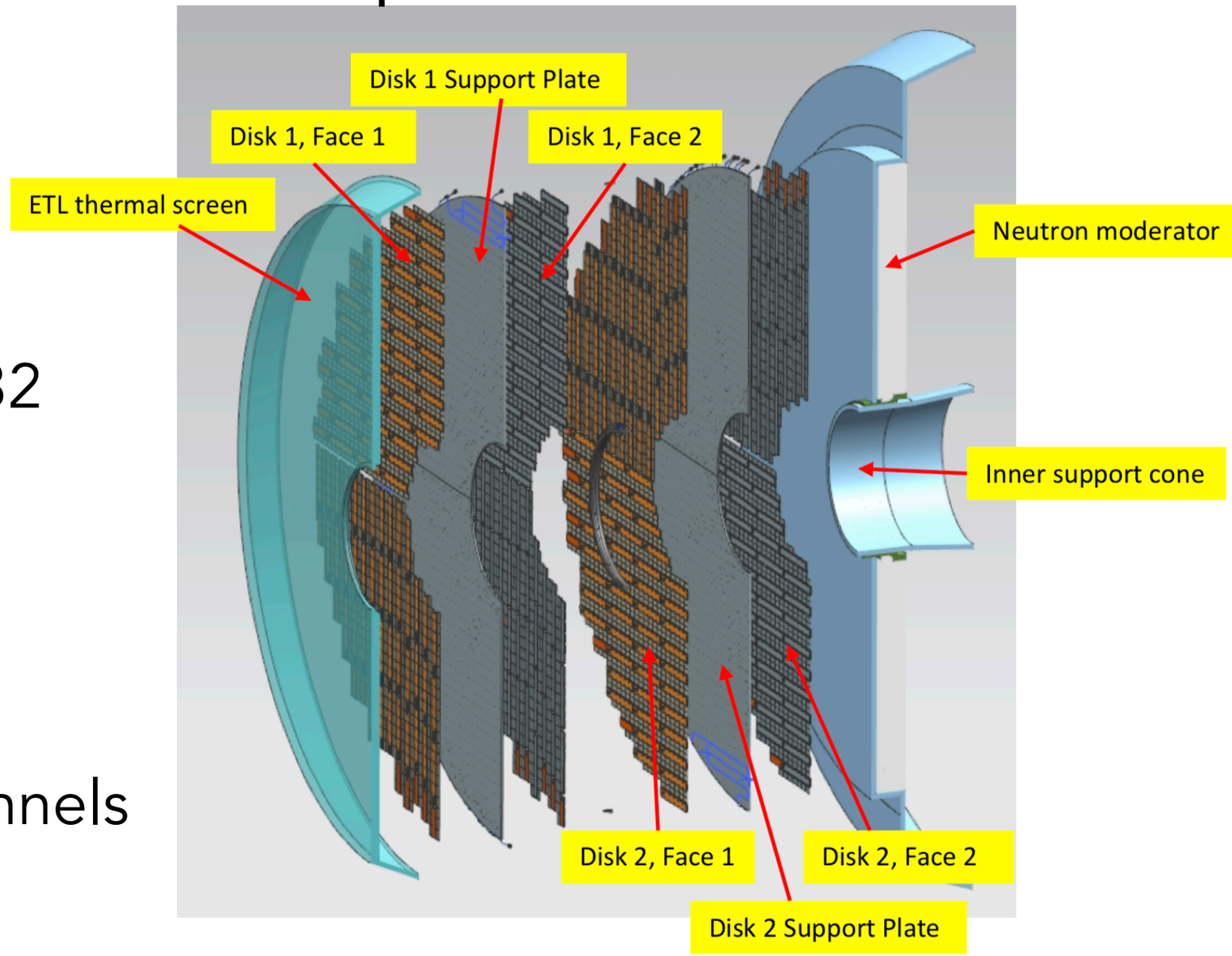


- Silicon doped with boron/ gallium (gain layer)
- Gain layer creates high electric field
- Minimum ionizing particles (MIPs) are able to leave a readable signal

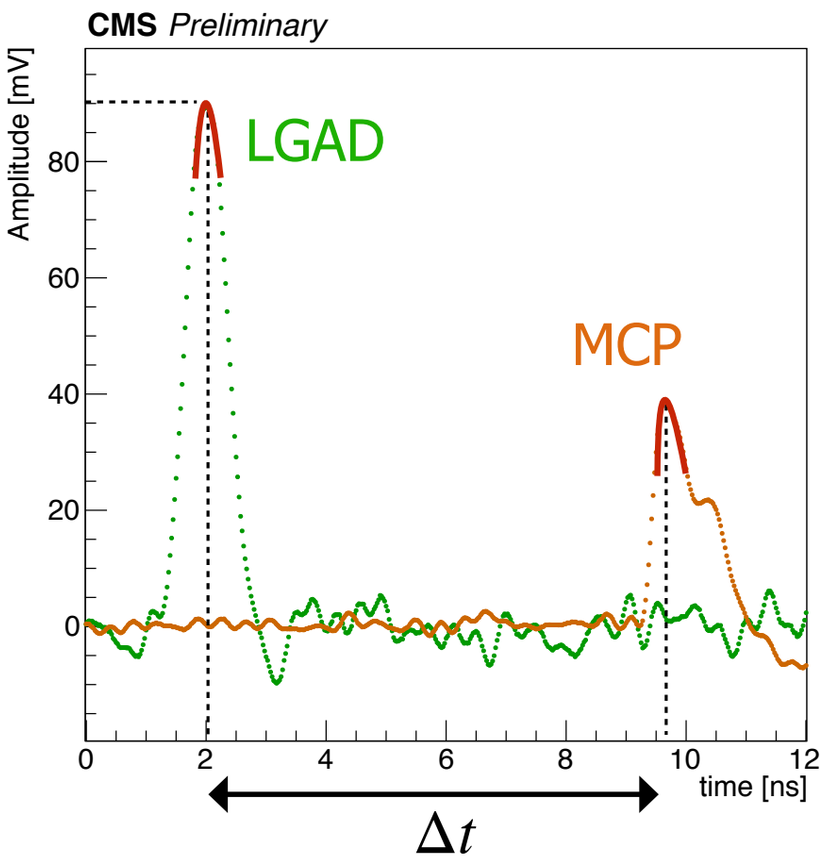
MTD Structural Overview: Endcap Timing Layer (ETL)

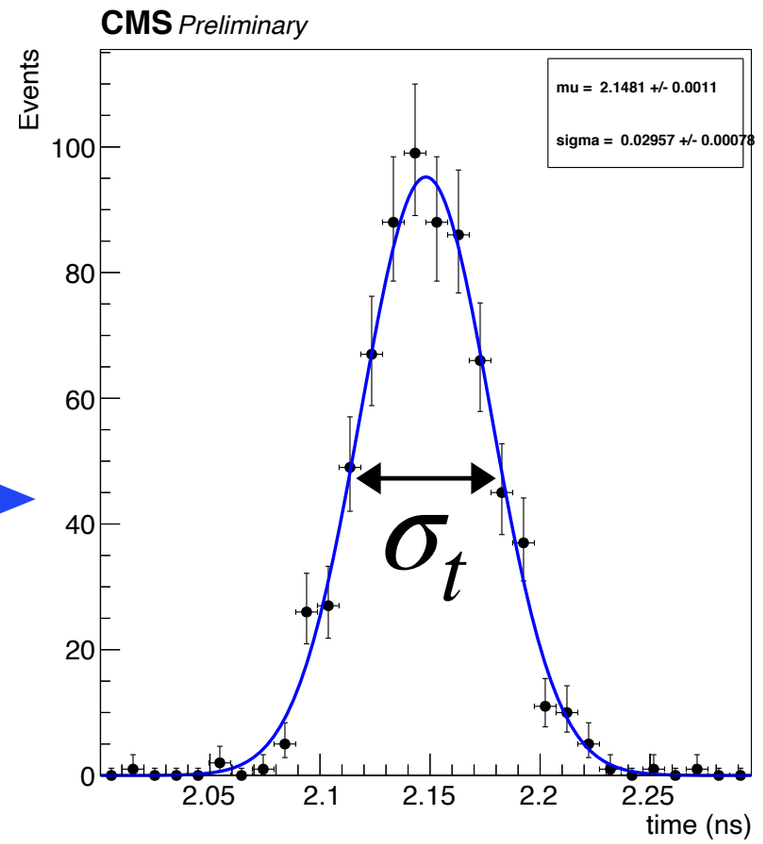
- 15 m^2 of silicon
- 2 disks per endcap
- Each LGAD sensor: 16x32 pads (512)
- Each pad: 1.3x1.3 mm
- ~10 million readout channels

Expanded view of ETL disk half

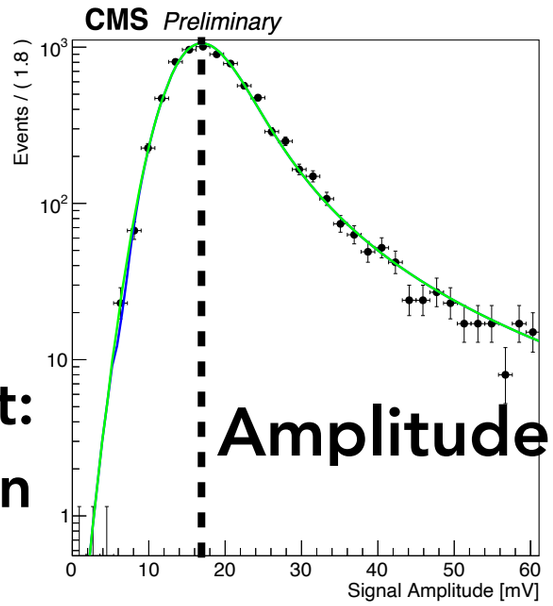


LGAD Event Reconstruction





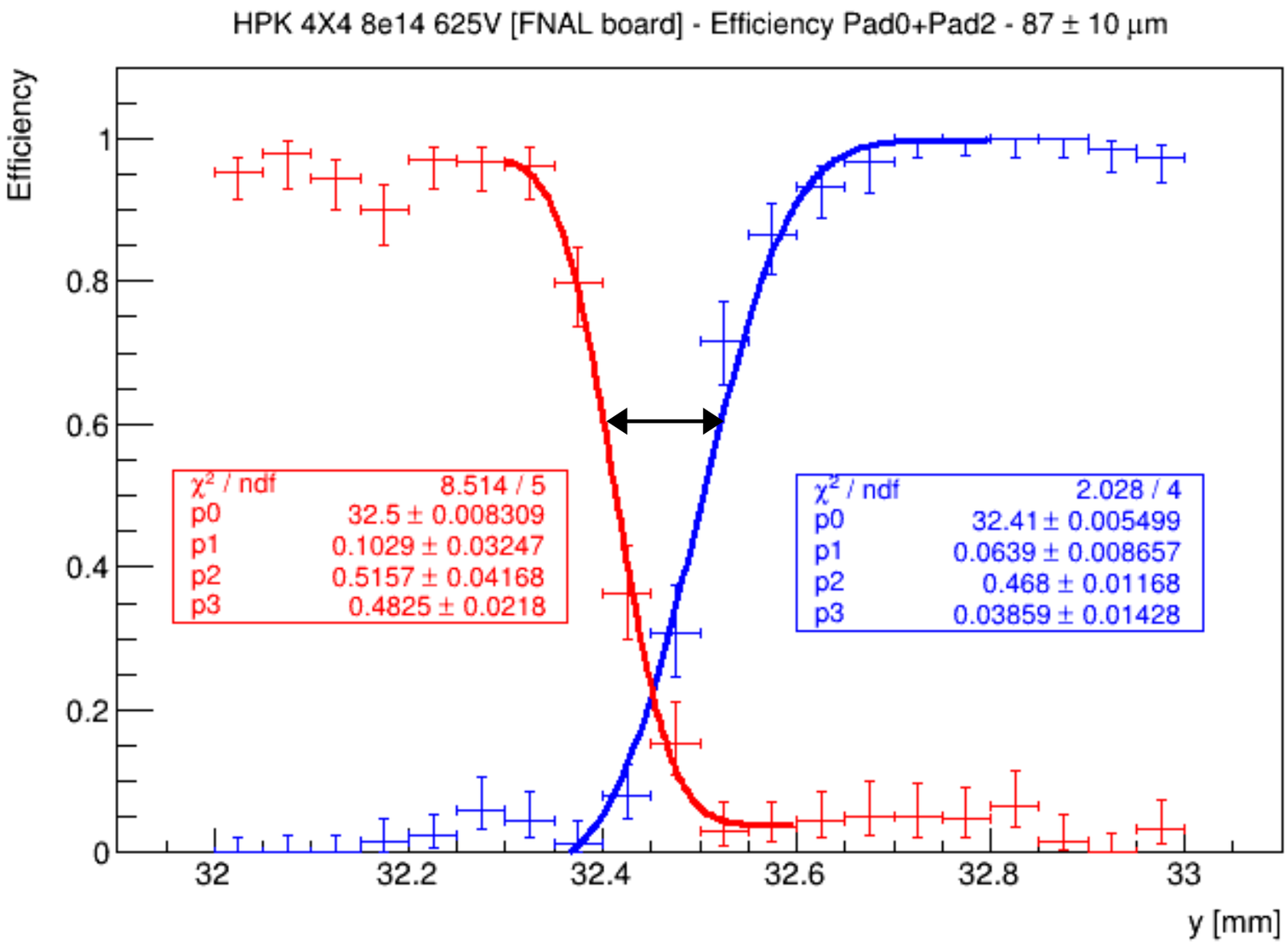
- Take time difference between arrival and LGAD and at MCP
- Make distribution of these time differences (Δt)
- Standard deviation of distribution is time resolution σ_t



Other values of interest:

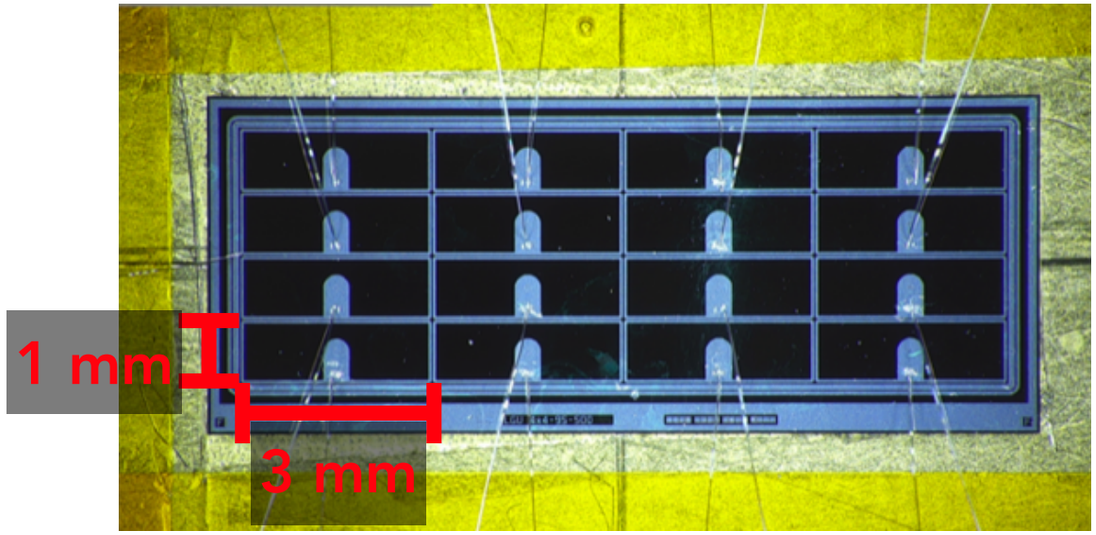
- **Most probable value of amplitude distribution**
- **Efficiency of sensor**

ETL LGAD Studies: Interpad Distance

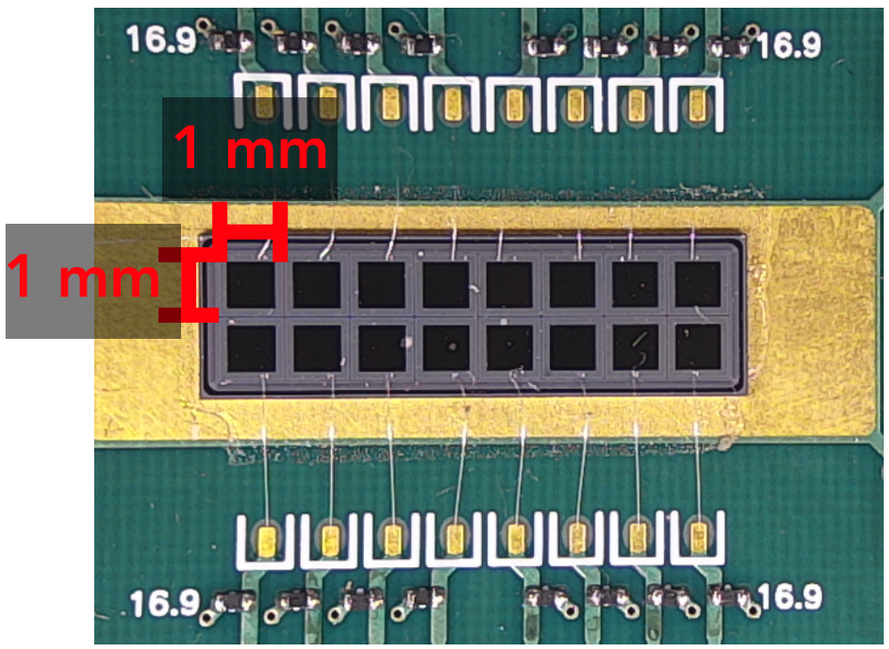


Check "dead area" between pads

LGAD Sensors



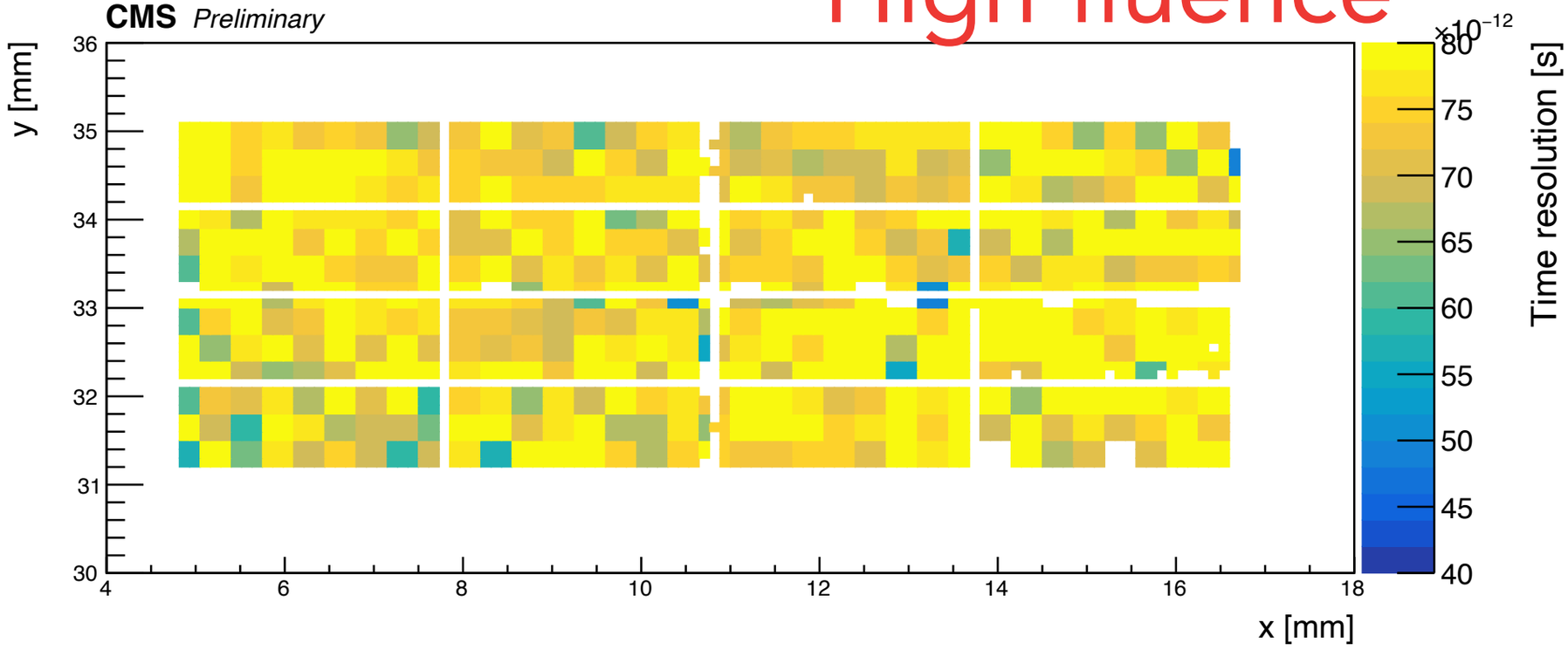
HPK 4x4 LGAD array



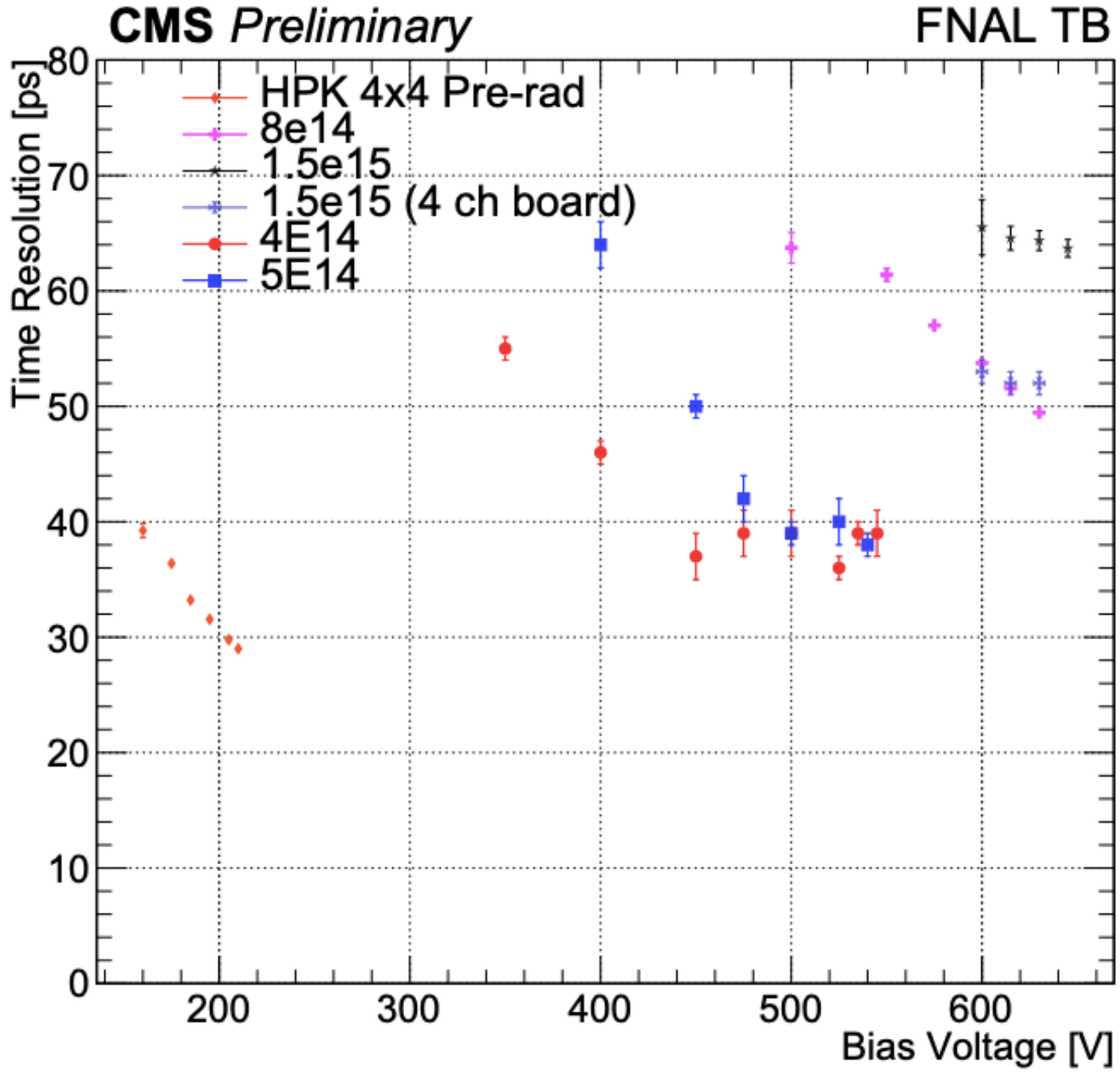
FBK 2x8 LGAD array

ETL LGAD Studies:
Sensor Uniformity - Timing Res.

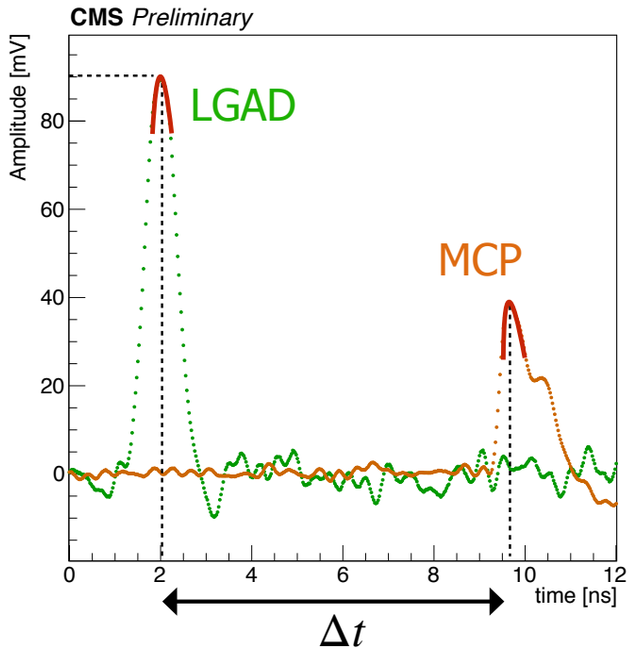
High fluence



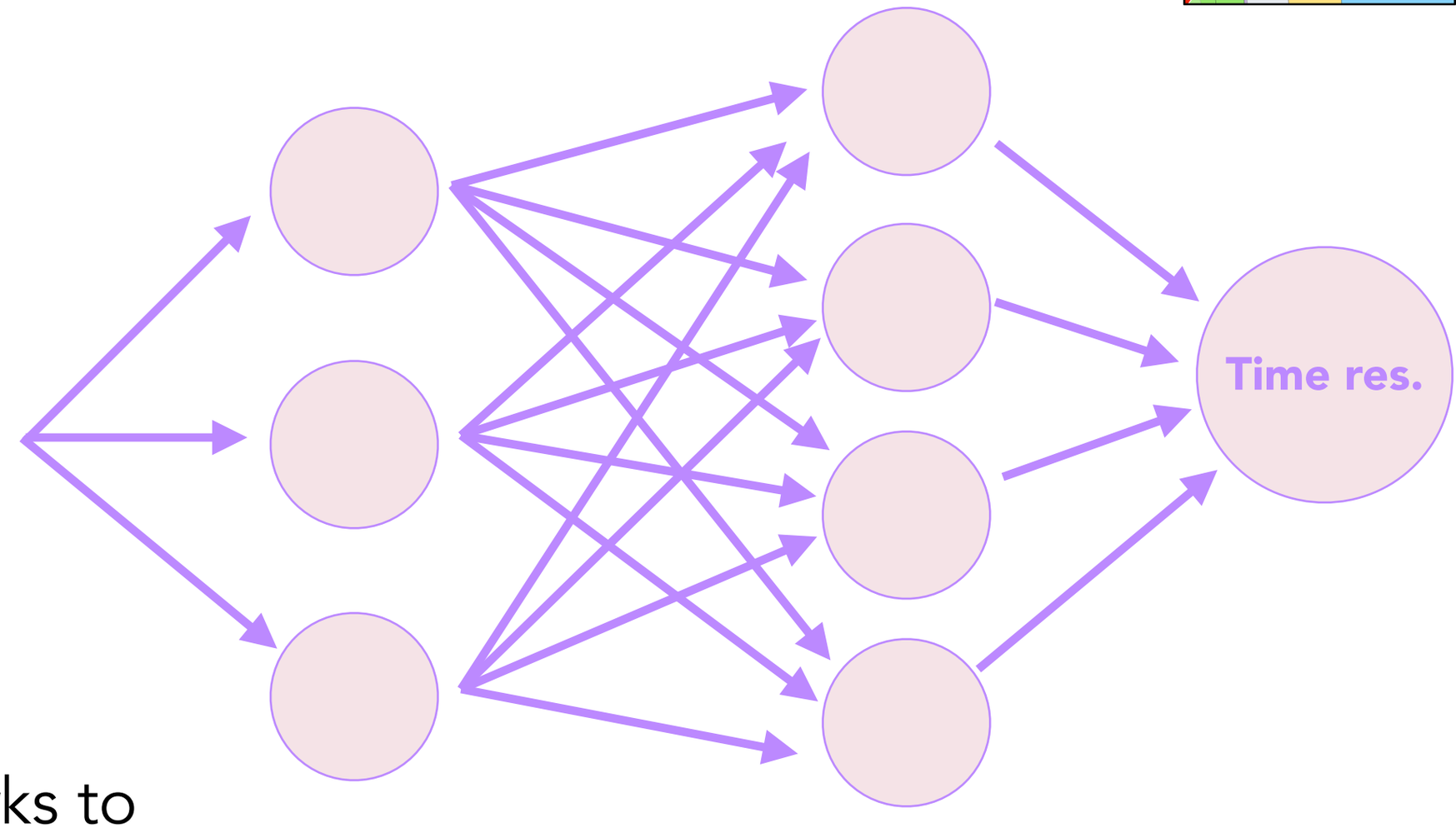
April 2019 Test Beam Results



Machine Learning for Timing



Using neural networks to extract time resolution



Neural network schematic

LLP Mass Calculation

$$\vec{\beta}_{LLP} = \frac{\Delta \vec{x}}{\Delta t}$$

For one LLP

$$m_{LLP} = \frac{\beta_{LLP,T} \cdot (\not{E}_T + p_{Z,T})}{\gamma_{LLP}}$$

Outline

Large Hadron Collider (LHC) and Compact Muon Solenoid (CMS)

Precision Timing Upgrade and the MIP Timing Detector (MTD)

Endcap Timing Layer (ETL) Sensors - Silicon Low Gain Avalanche Detectors

Sensor Performance Requirements and Results

Summary

- Particle Physicists study the building blocks of our universe with
  - particle colliders: Large Hadron Collider, and
  - detectors: Compact Muon Solenoid
- LHC and CMS will undergo an upgrade for more particle collisions to see more physics, comes with more noise (pileup)
- Addition of precision timing hardware (MTD) will reduce effects of pileup
- MTD Endcap Timing Layer sensors meet expectations
  - Fermilab results: time resolution, efficiency, radiation tolerance
  - Upcoming KU studies: mechanical/electrical/thermal robustness