Development of MIP Timing Detector for the CMS Phase-2 Upgrade

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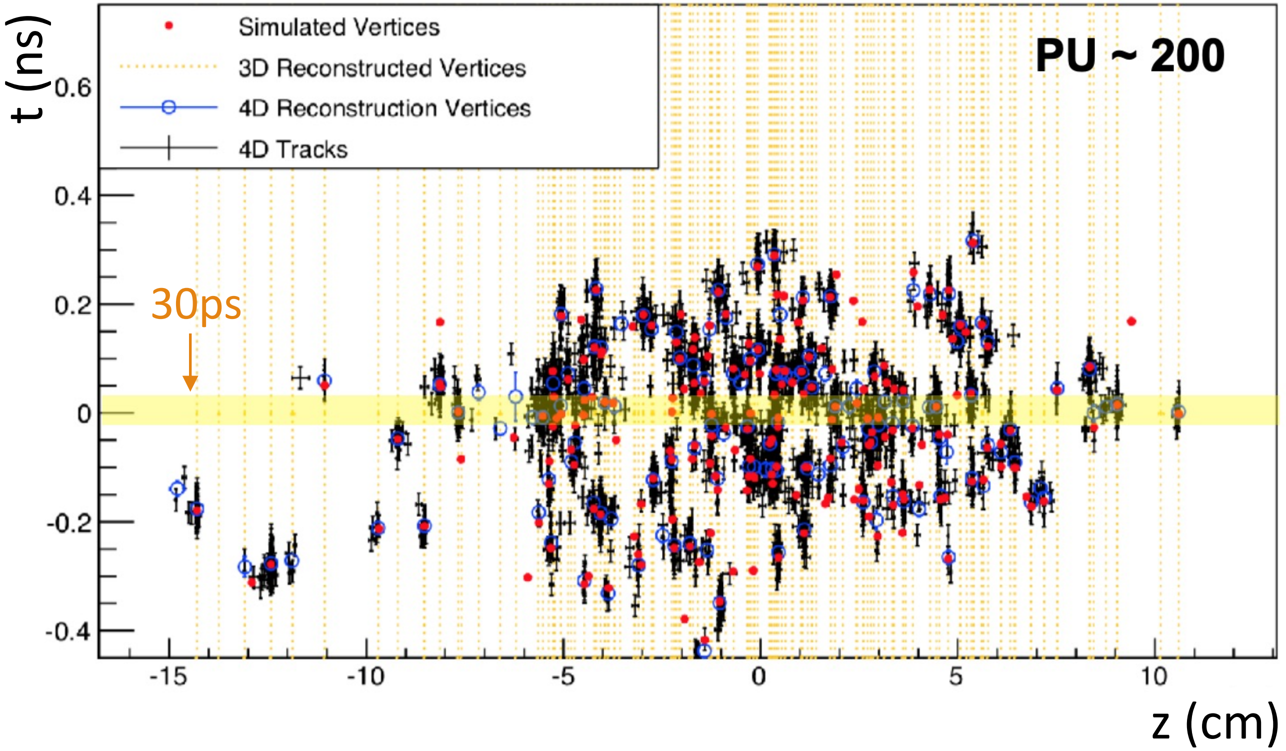
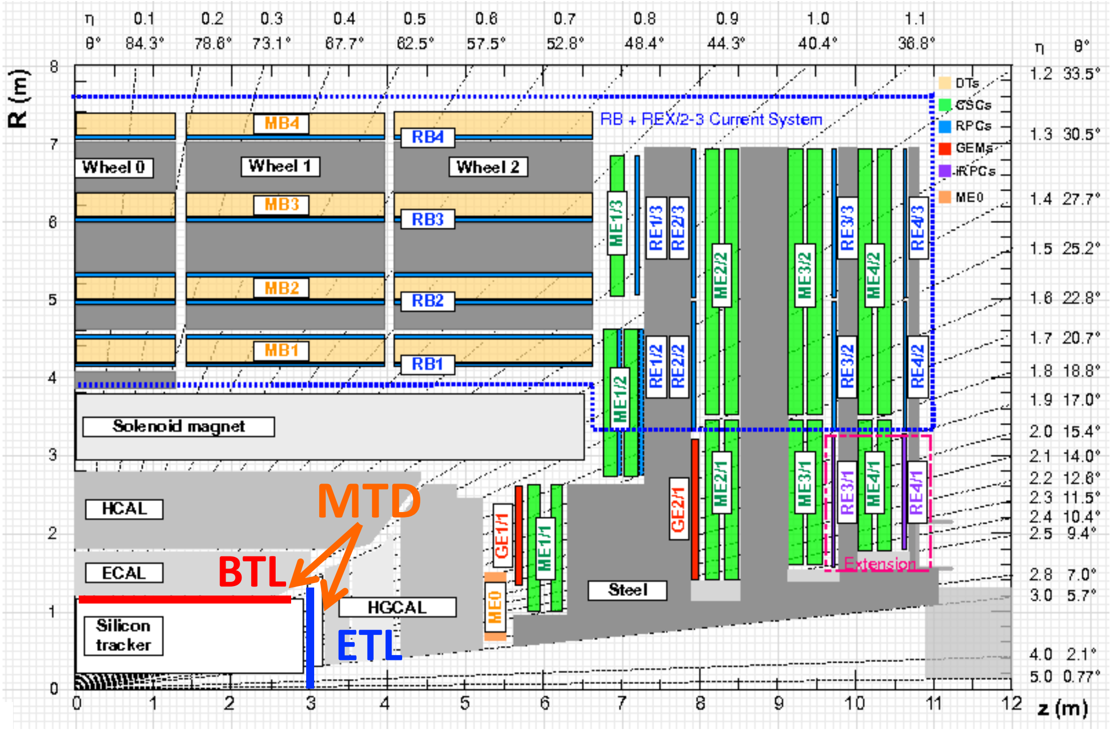
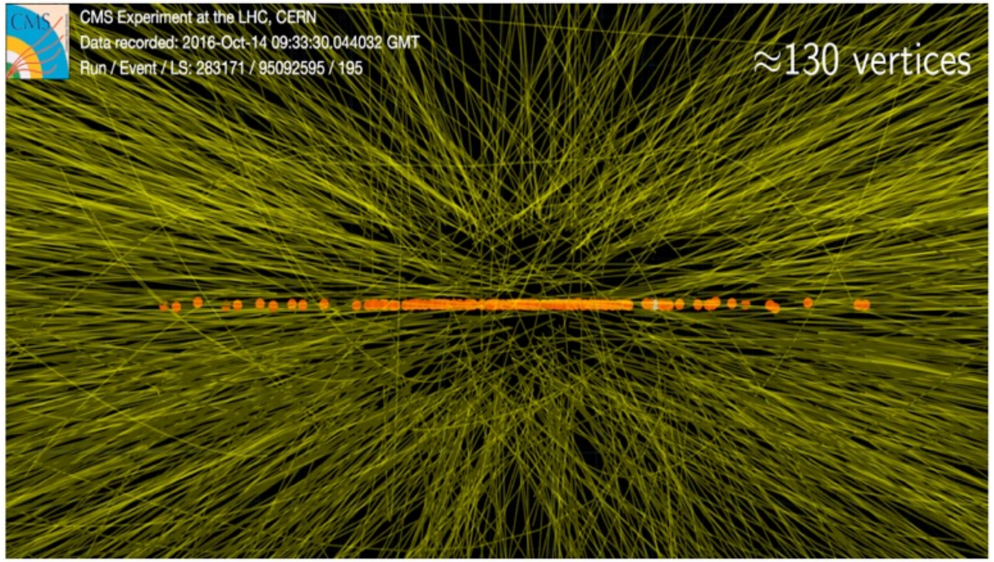
MIP Timing Detector for CMS Phase-2 Upgrade

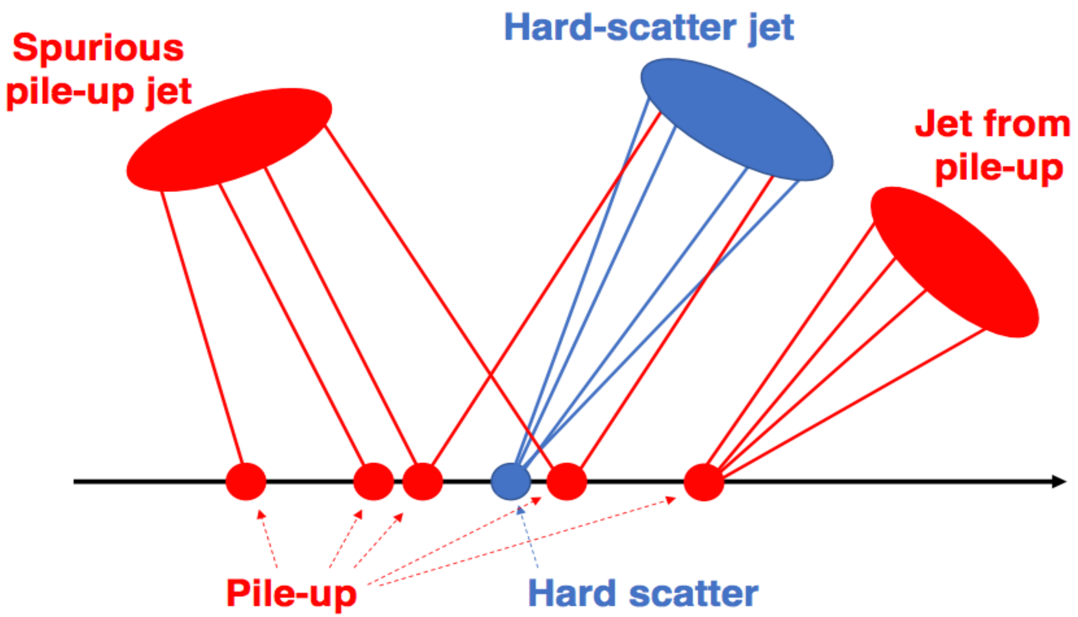




- Important to maintain detector performance during HL-LHC running
  - Time information will help to reduce pileup effects from approximately 200 simultaneous interactions
- MIP timing detector (MTD) consists of barrel timing layer (BTL) and endcap timing layer (ETL), providing 30-50 ps time resolution per track
  - BTL: LYSO crystal scintillator + SiPM readout
  - ETL: Silicon based sensor (LGAD) + ASIC readout

MTD Physics motivation: pile-up mitigation





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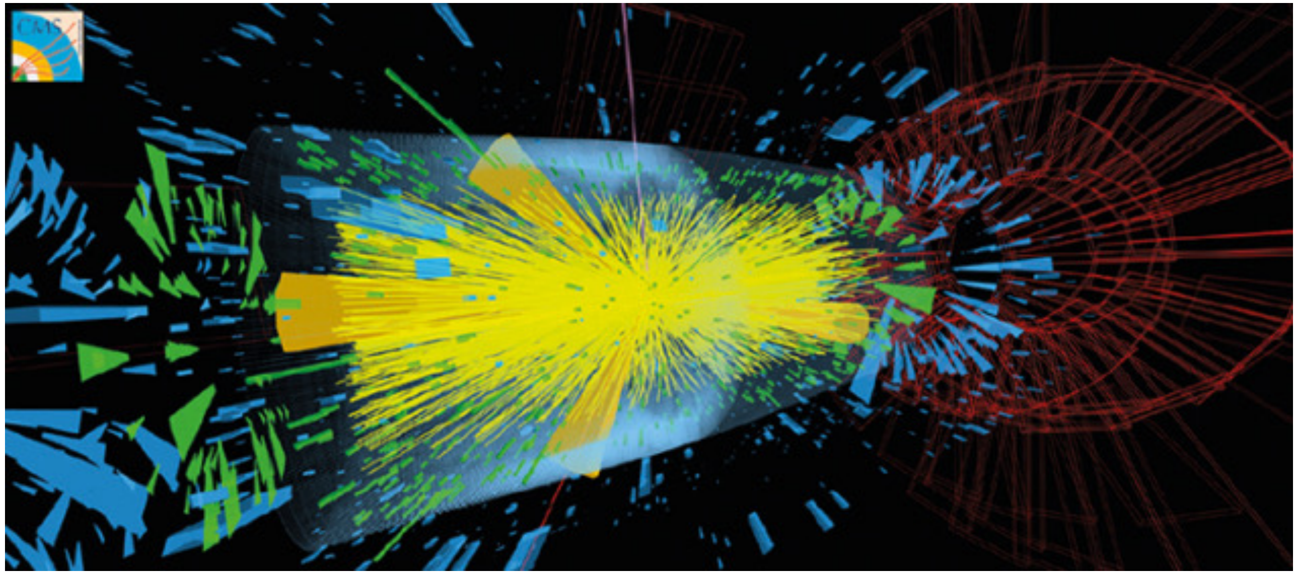
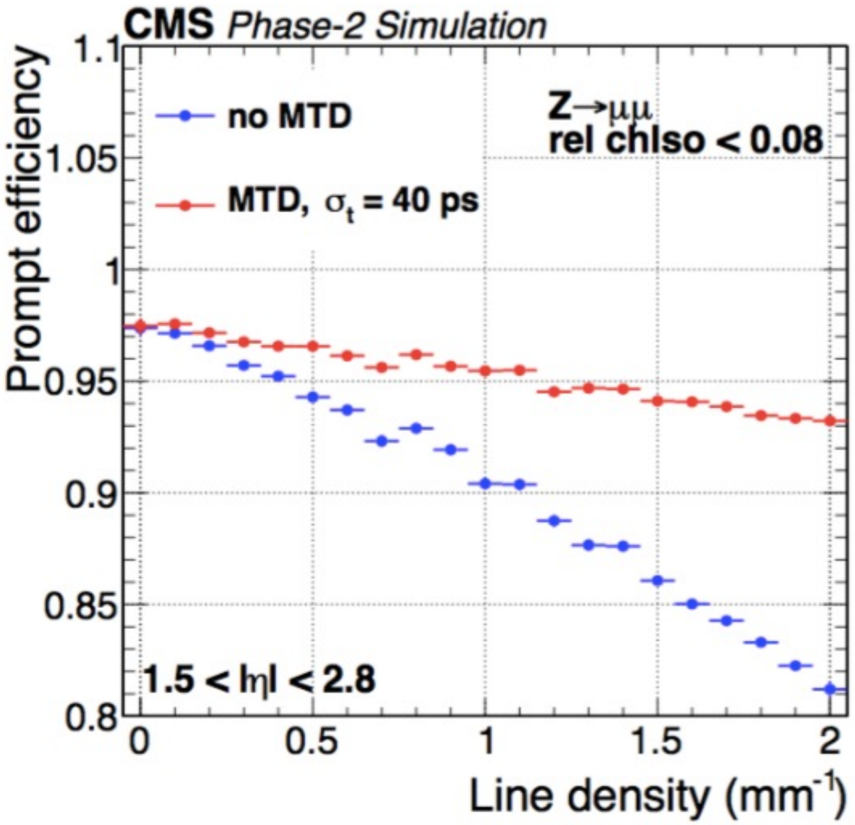
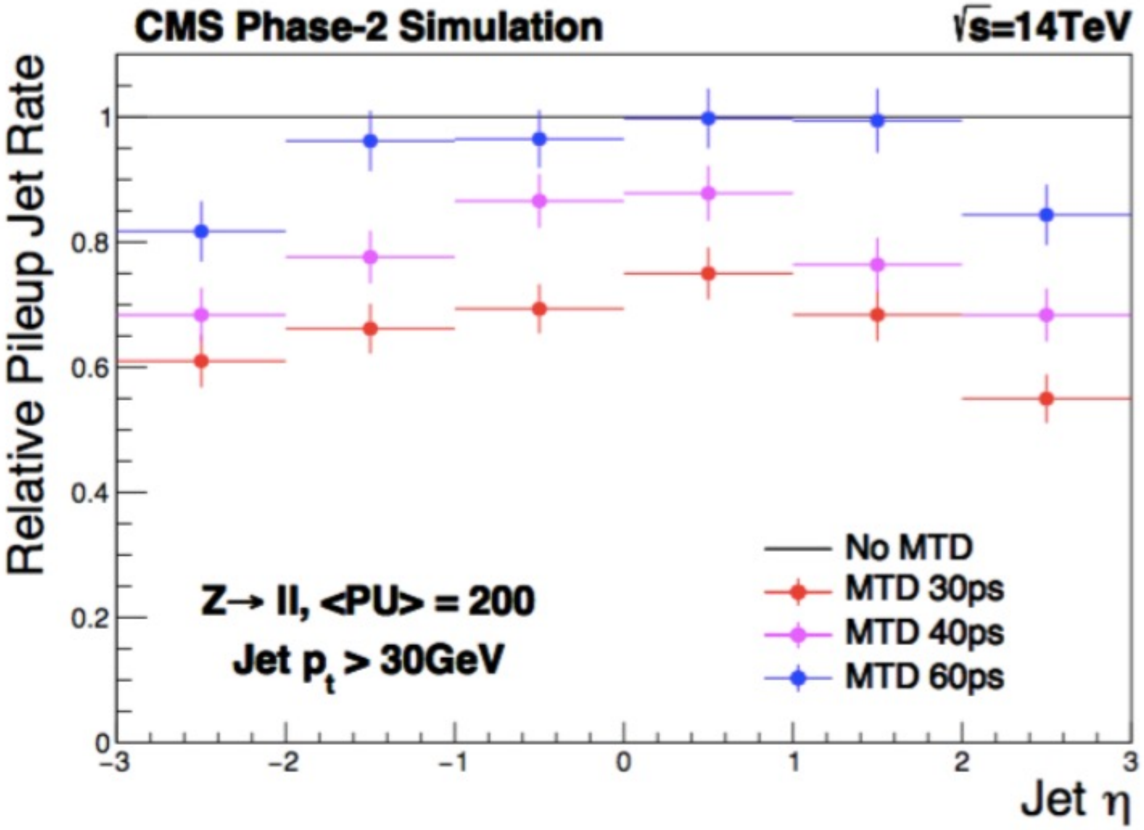


The display of an event with a Higgs boson produced in the VBF process on top of 200 pile-up collisions.

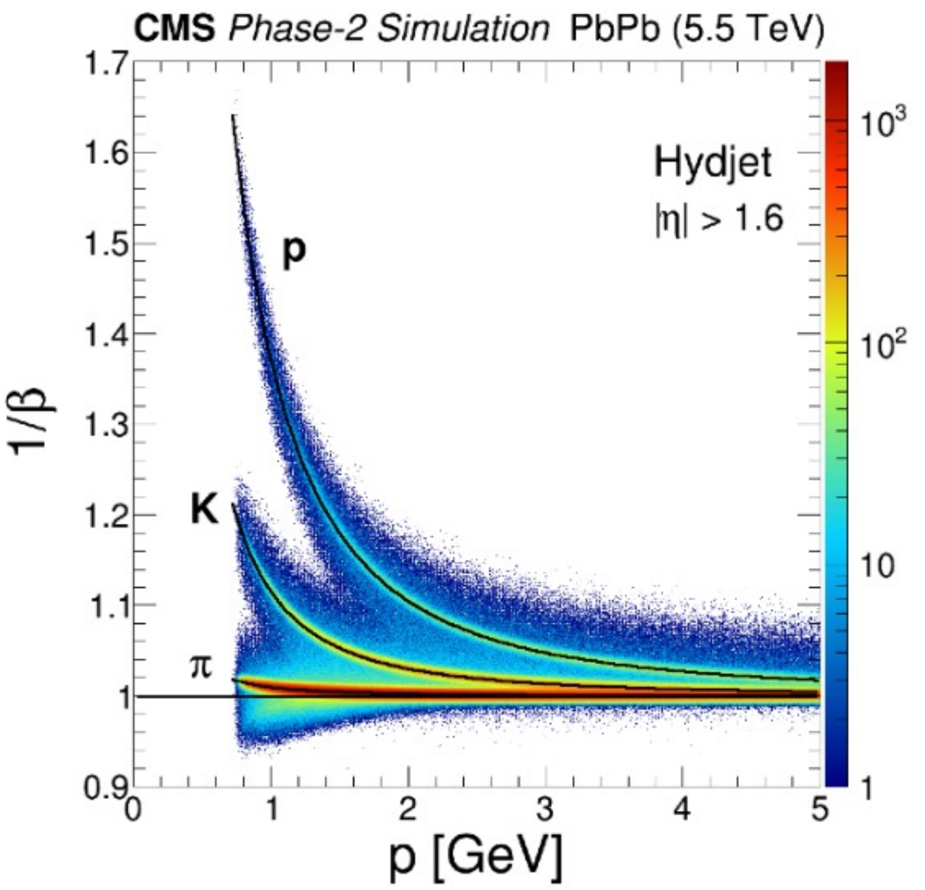
MTD Physics motivation: pile-up mitigation

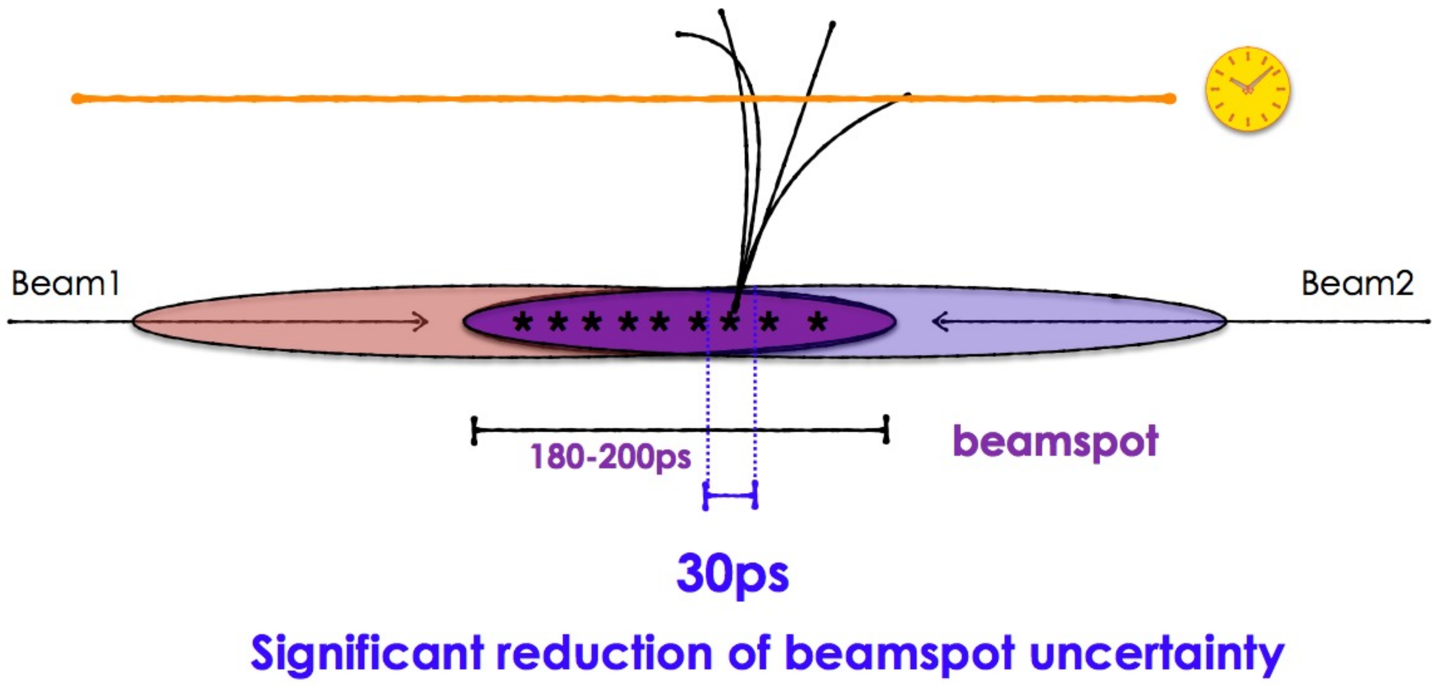




- The mitigation of pile up effect improves all physics objects
- 4D vertexing (position+time) can remove
  - Spurious pileup tracks from "isolation cone" around leptons
  - Rejects spurious jets formed from pileup particles.

MTD Physics motivation: particle ID

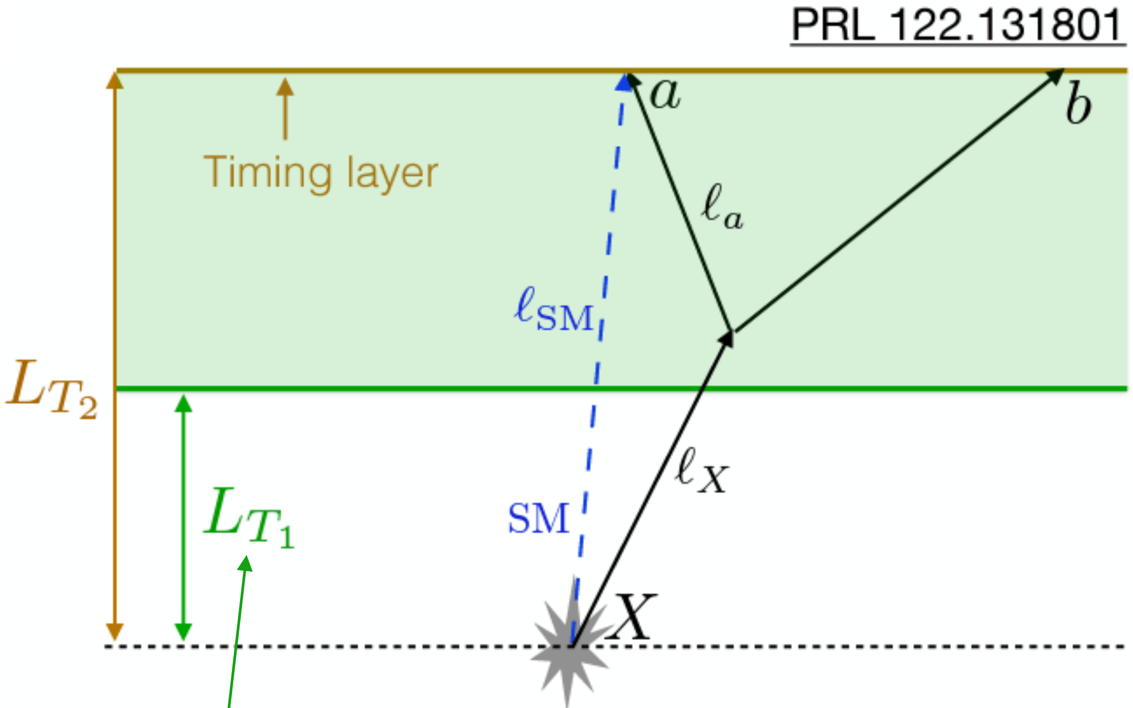




- ❑ MTD can provide significant improvement for particle ID
  - ◦ heavy ion charm tag.
- ❑ Significant gains for searches for long-lived new particles.

4D vertex reconstruction of primary and secondary vertices

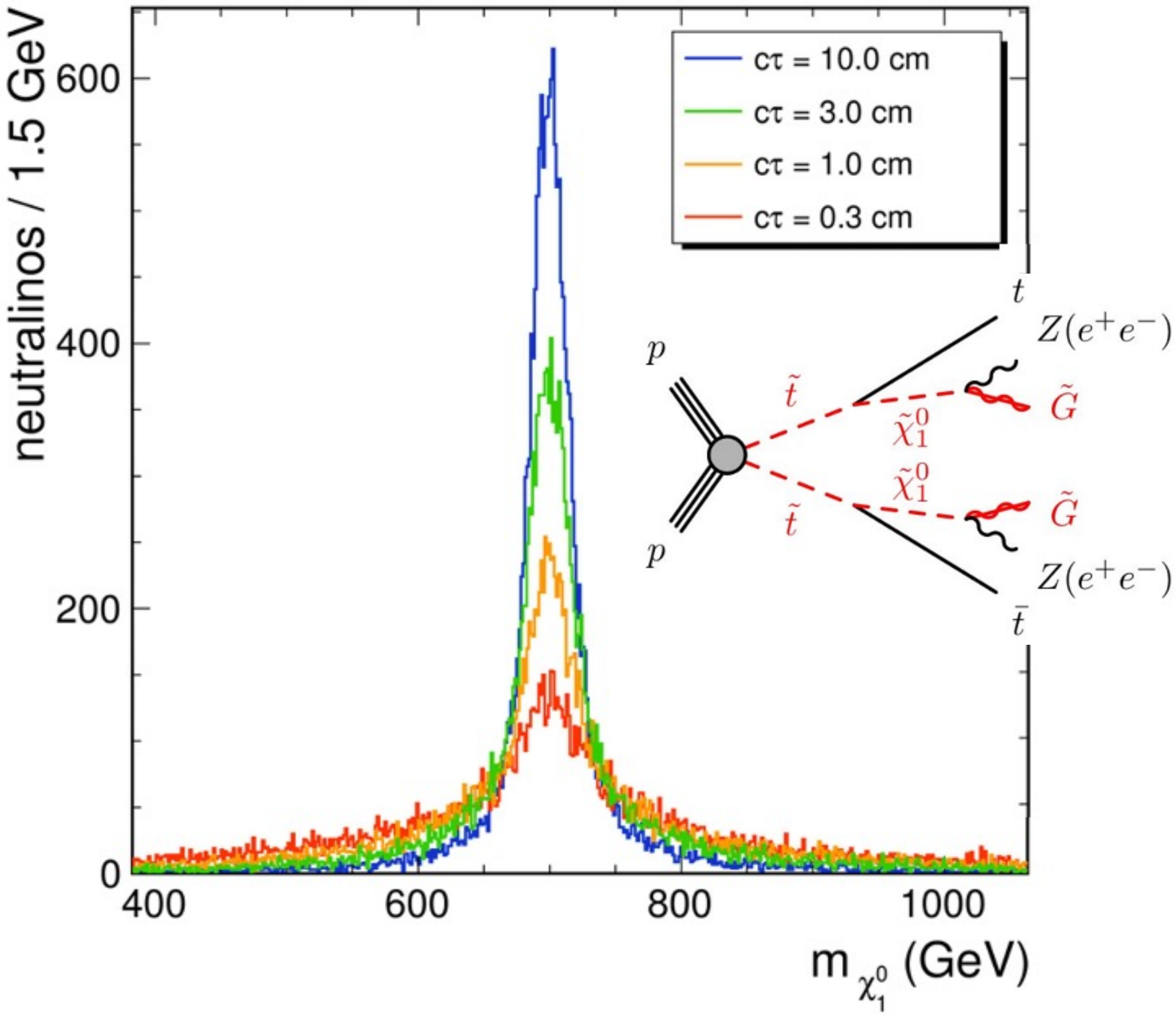
Provides a close kinematic for Long Lived Particles decaying within MTD



$$\Delta t^i_{\rm delay} = \frac{\ell_X}{\beta_X} + \frac{\ell_i}{\beta_i} - \frac{\ell_{\rm SM}}{\beta_{\rm SM}}$$

Minimal displacement requirement

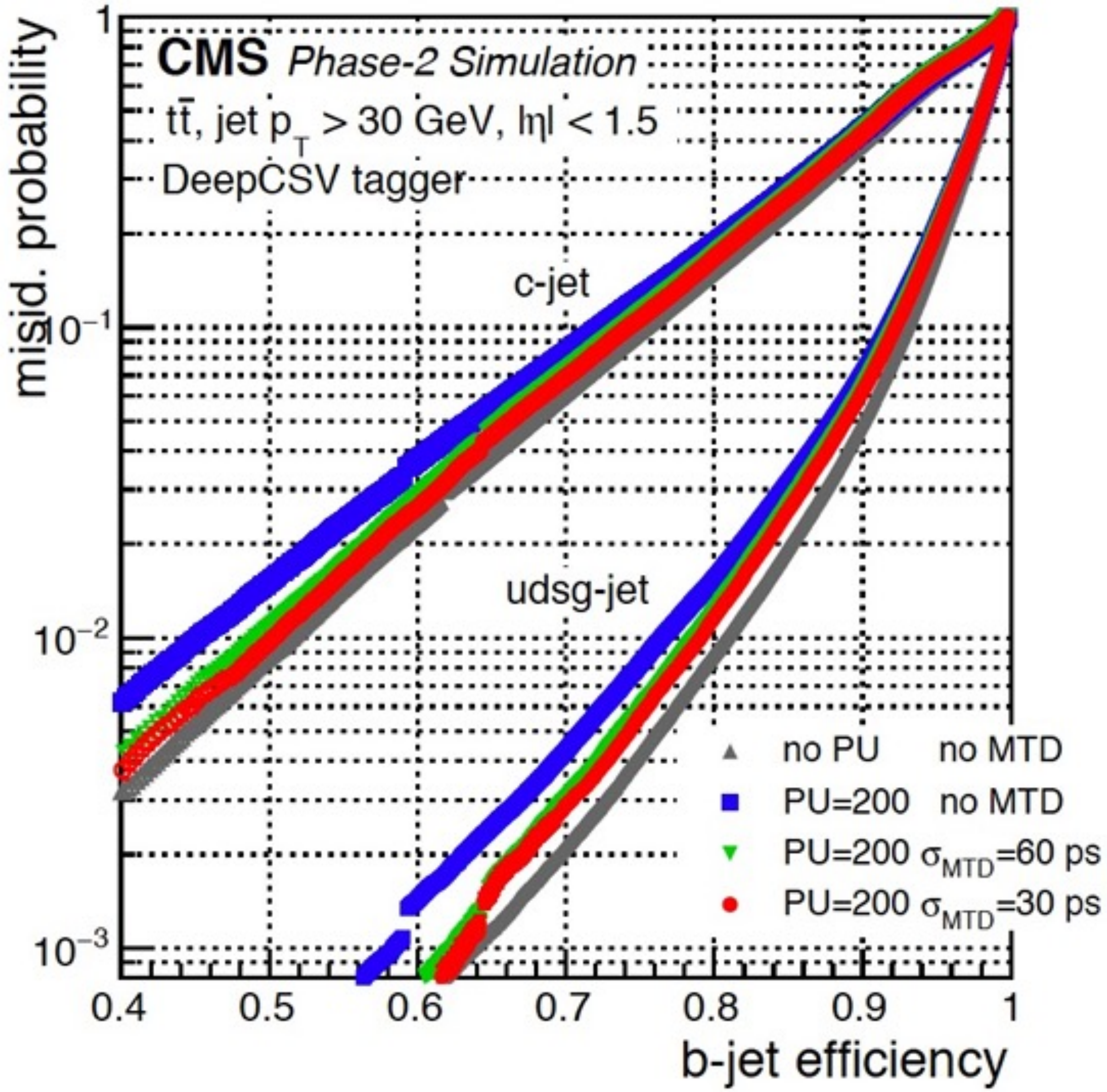
700 GeV neutralino (SUSY)



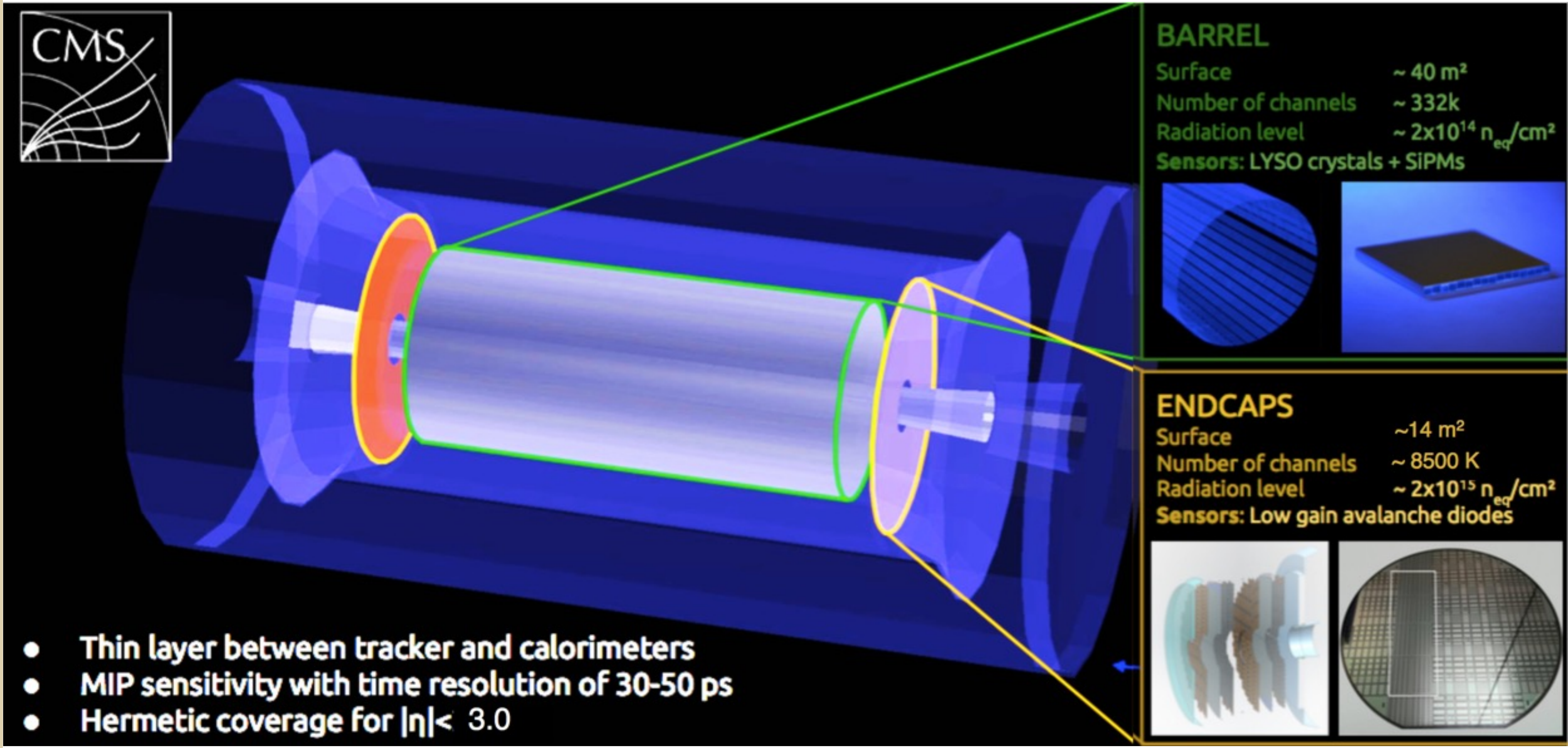
b-tagging performance with MTD

- b-quark jets are important:
  - Primary decay mode of the Higgs, via $H \rightarrow b\bar{b}$
  - Exclusive decay mode of the top quark, via $t \rightarrow Wb$

- Significant improvement with MTD for b-quark identification efficiency while reduced c-jet or light jets mistag rate.

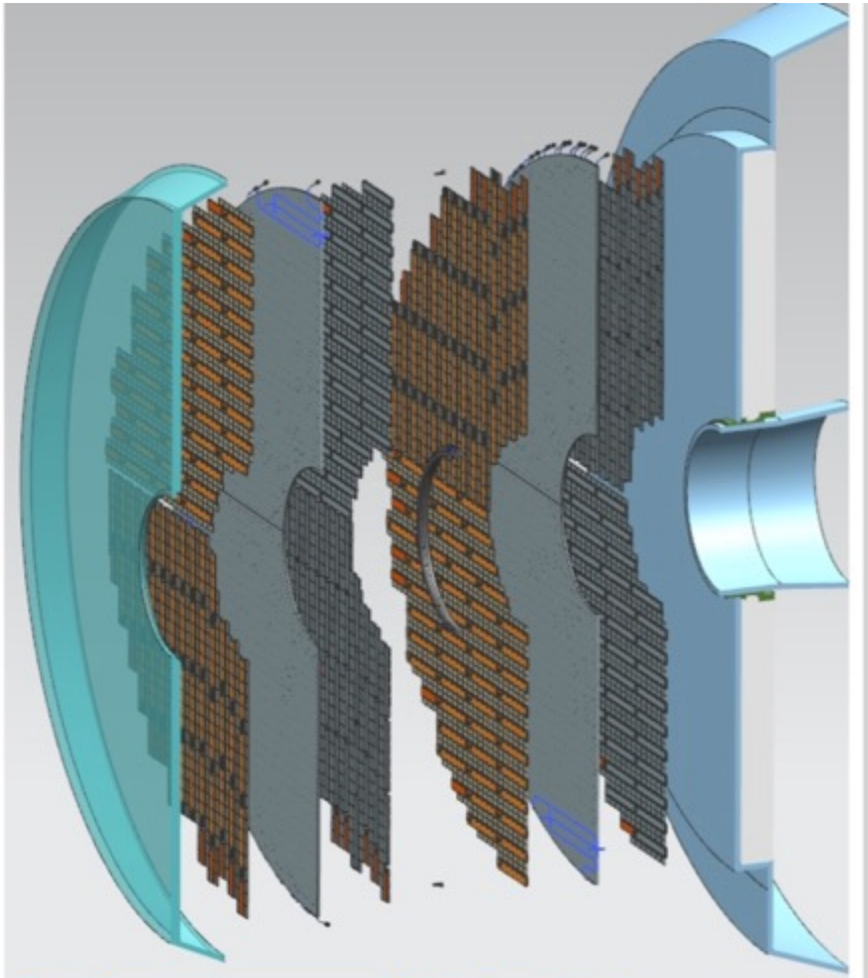


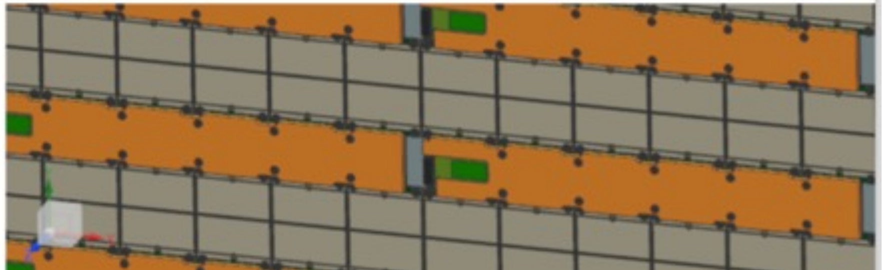
Mip Timing Detector (MTD) Project



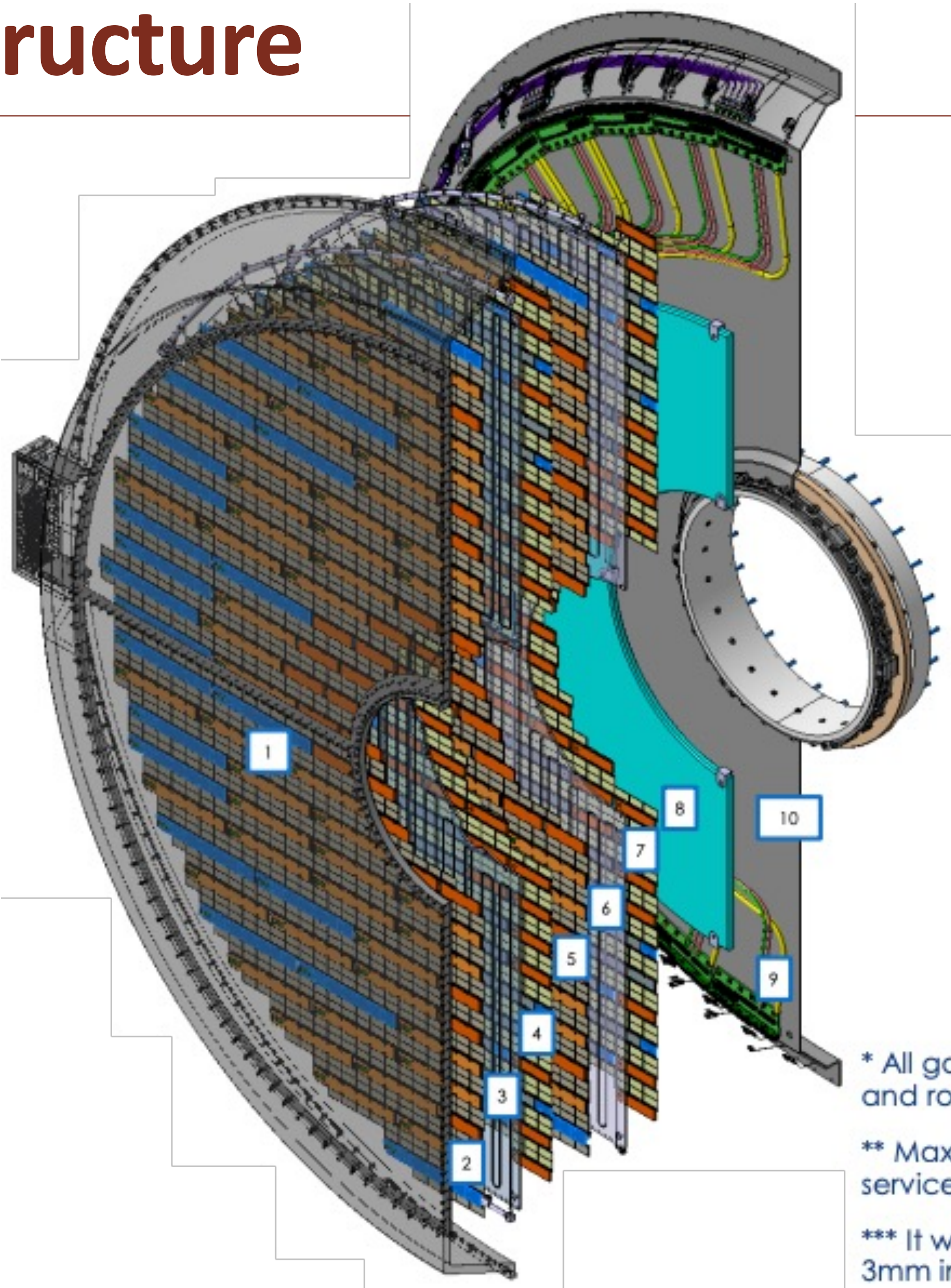
Overview of endcap timing layer (ETL)

- Two layers of silicon sensors covering 1.6 < |η| < 3.0
- Sensors mounted in rows on each face of Al cooling disks
- Readout boards placed between sensor rows, staggered wrt opposite face for full sensor coverage.
- Two such disks to provide average of 1.8 hits per track.
- Mounted on neutron moderator upstream of the CE, in an independently cooled and accessible volume.





ETL structure



ETL z-profile

Element	Elements in Z	Thickness [mm]
1	Thermal screen	20
	Gap between thermal screen and front disc	1
2	Front face of electronics of the front DEE	8**
3	**Front disc**	**7.5**
4	Rear face of electronics of the front DEE	8
	Gap between front and back discs	1
5	Front face of electronics of the back DEE	8
6	**Back disc**	**7.5**
7	Rear face of electronics of the back DEE	8
	Gap between cables and back disc	1
8 + 9	Patch panels 0 + cables [9] + moderator [8] at the innermost section	21
10	**Back support plate**	**5**
	Gap between ETL back support plate and HgCal thermal screen	3***
	Total	99

* All gaps (1mm) are an additional clearance for disc deformation while transporting and rotating. More detailed study whether 1mm is sufficient are needed.

** Maximum thickness of the on-detector electronics should not exceed 8mm, services included.

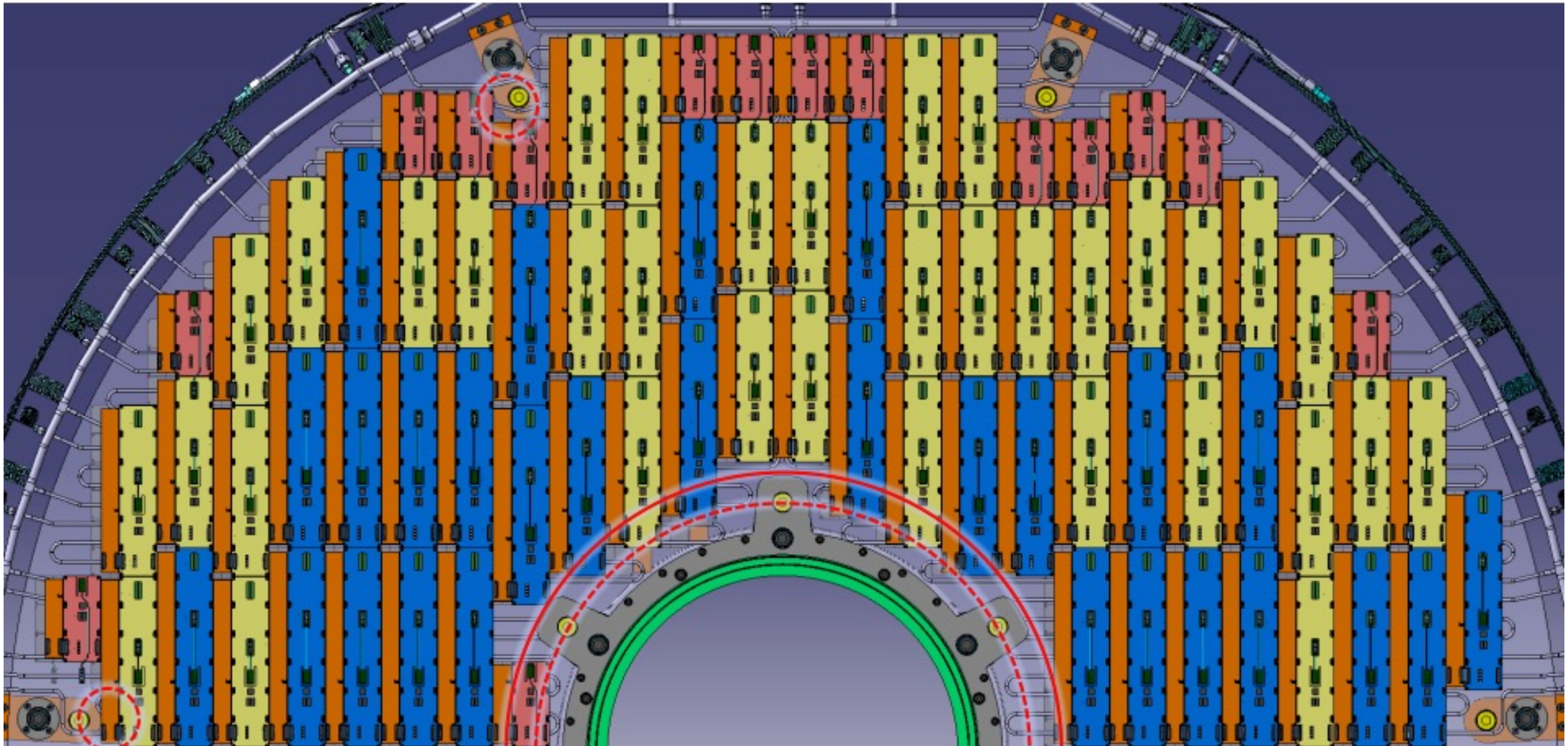
*** It was simulated that a support structure of HgCal at cold operations shrinks by 2-3mm in Z while its thermal screen stays in the same position.

Components that still need prototyping to finalize the z-profile.

Detector layout
Front layer

- Short (3 modules) SHs 15
- Standard (6 modules) SHs 35
- Large (7 modules) SHs 28

- Small SHs possibly to be placed as well at the inner radius in order to maximize the coverage
- More detailed model of the power board is required in order to verify possible clashes with the detector mechanics

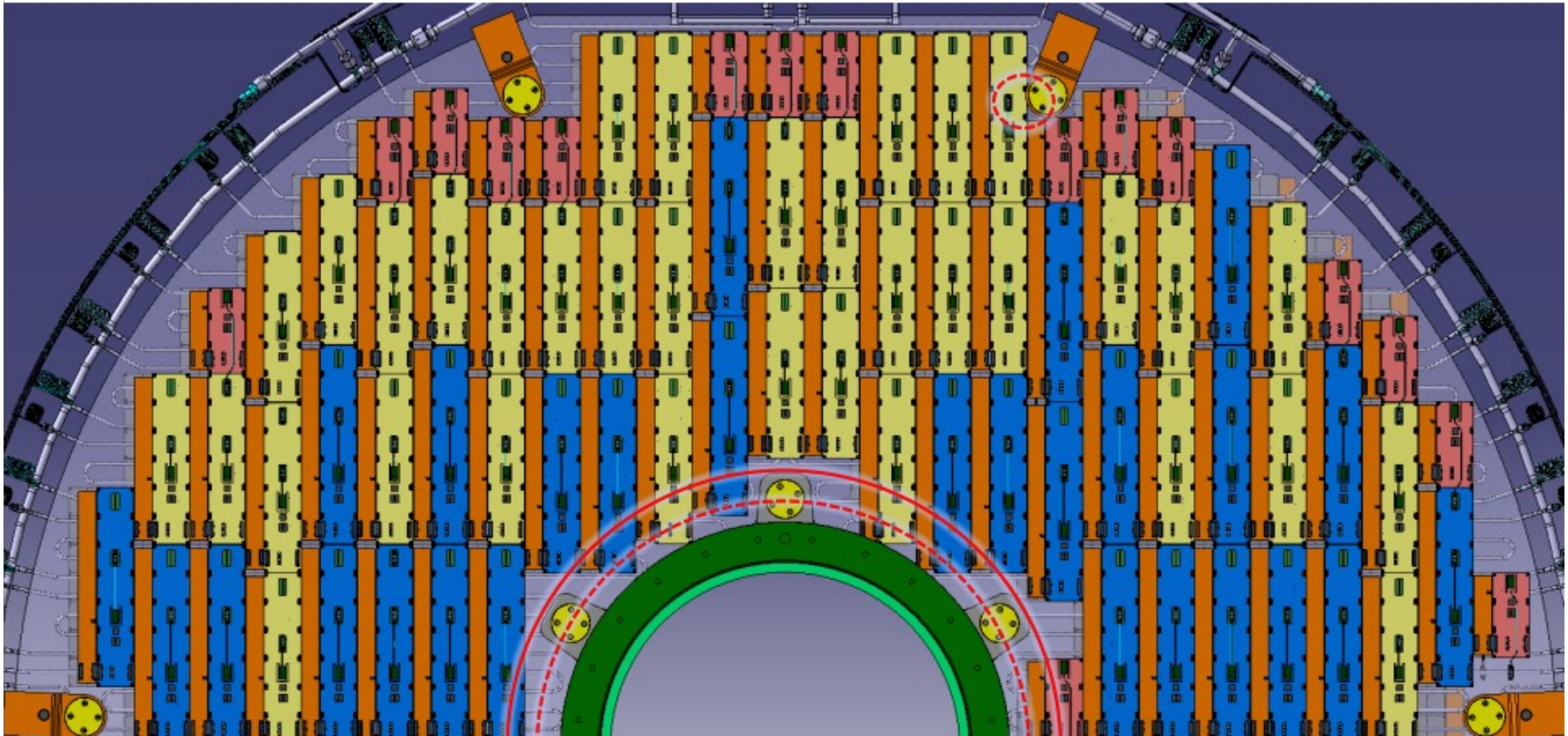


Detector layout

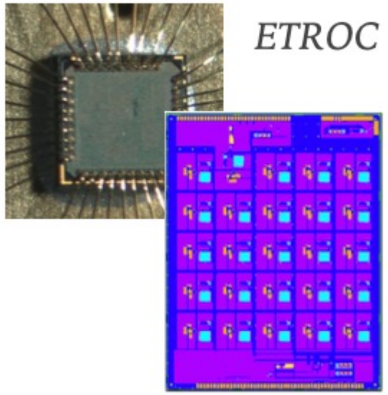
Rear layer

- Short (3 modules) SHs 16
- Standard (6 modules) SHs 35
- Large (7 modules) SHs 27

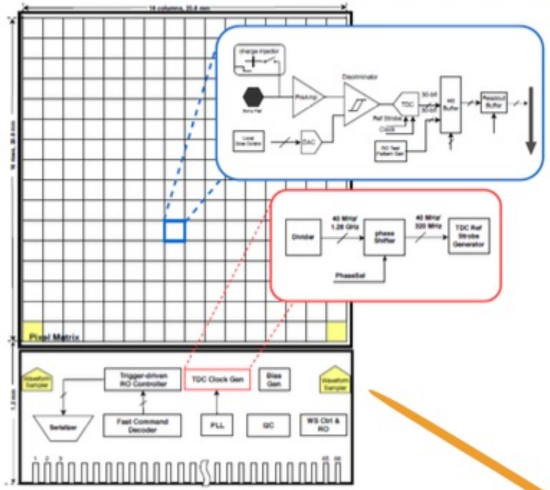
- More detailed design of the service hybrid attachment to the discs shall be developed (amount and location of bolts/pins) to verify whether rows can be shifted up or down in order to maximize the coverage at the inner radius



MTD ETL module with LGAD and ETROC



ETROC

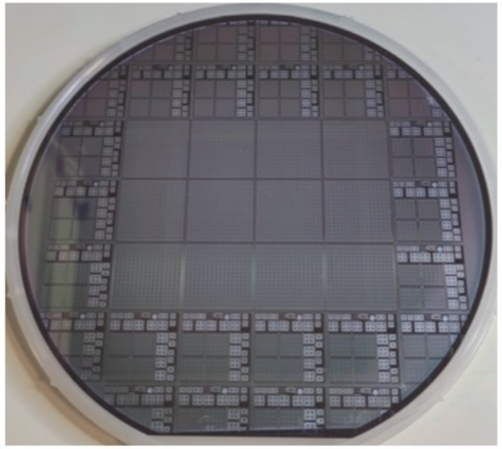


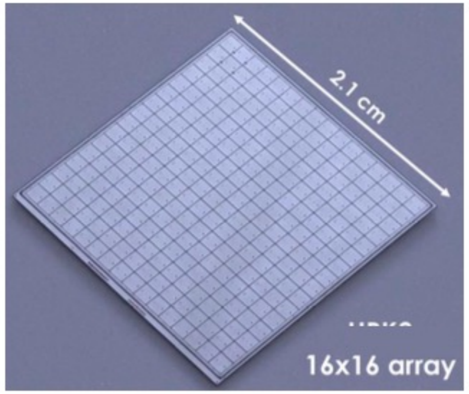
R&D productions

Strong effort to combine inputs from studies into a complete detector design and layout: **~8000 modules** (4 sensors each) on 2 endcaps

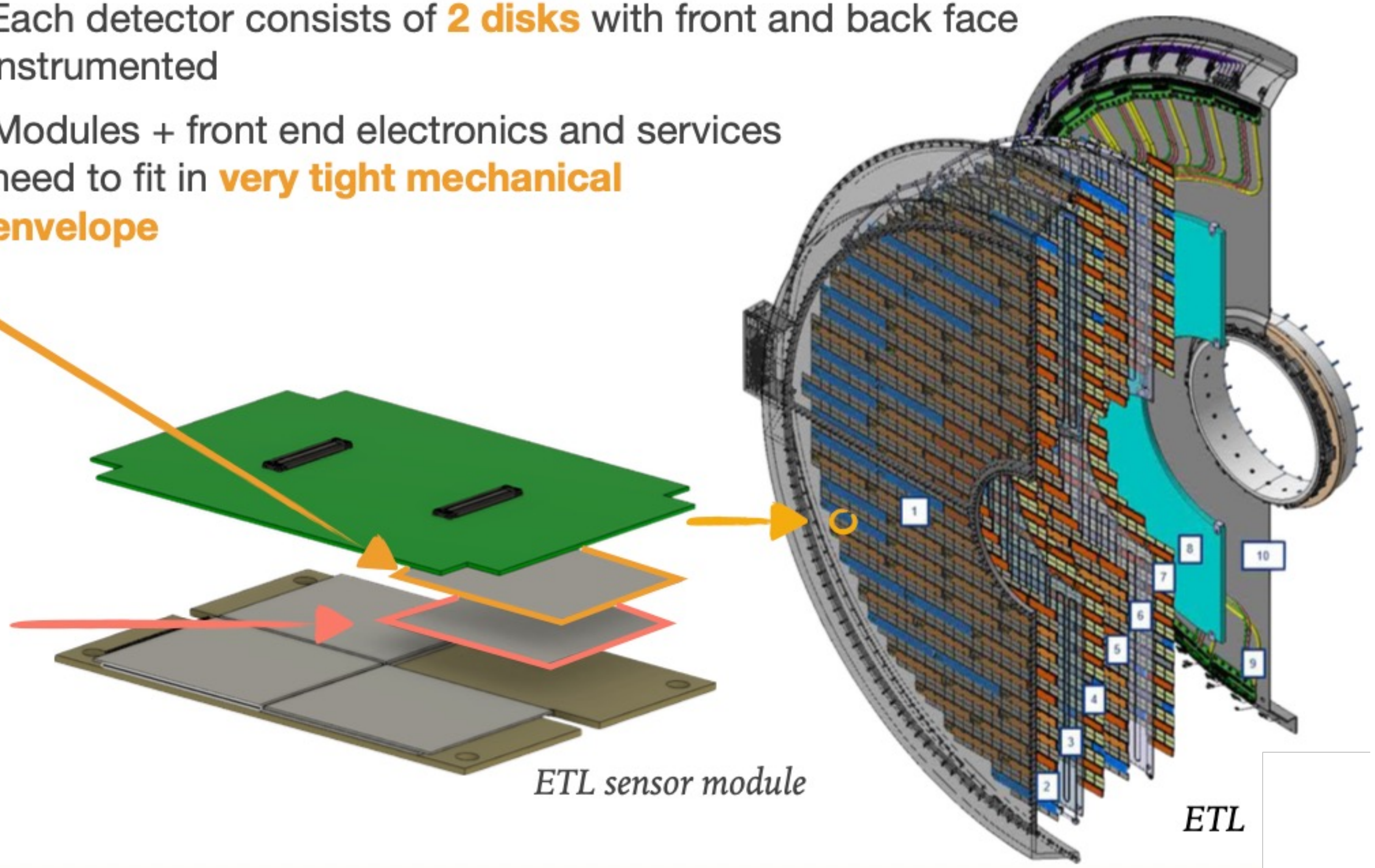
Each detector consists of **2 disks** with front and back face instrumented

Modules + front end electronics and services need to fit in **very tight mechanical envelope**





ETL sensors



ETL sensor module

ETL

CMS requirements for ETL

- BTL and ETL shall be maintained as close as possible to −30◦C
  - To control the noise or dark current rate and leakage currents.

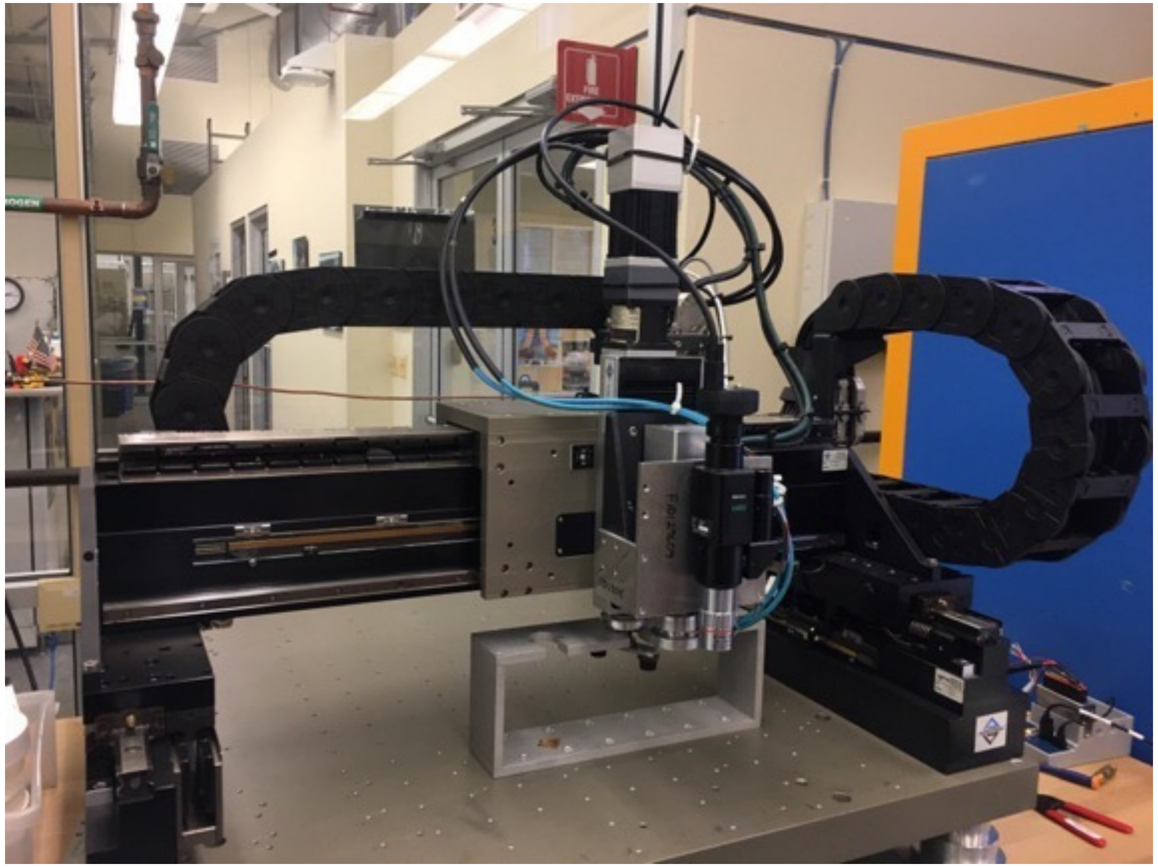
- Occupancy less than a few percent, ensuring a large probability for single hits
  - detector must also produce a manageable data volume.
  - < 0.1% low η, 1% highest η

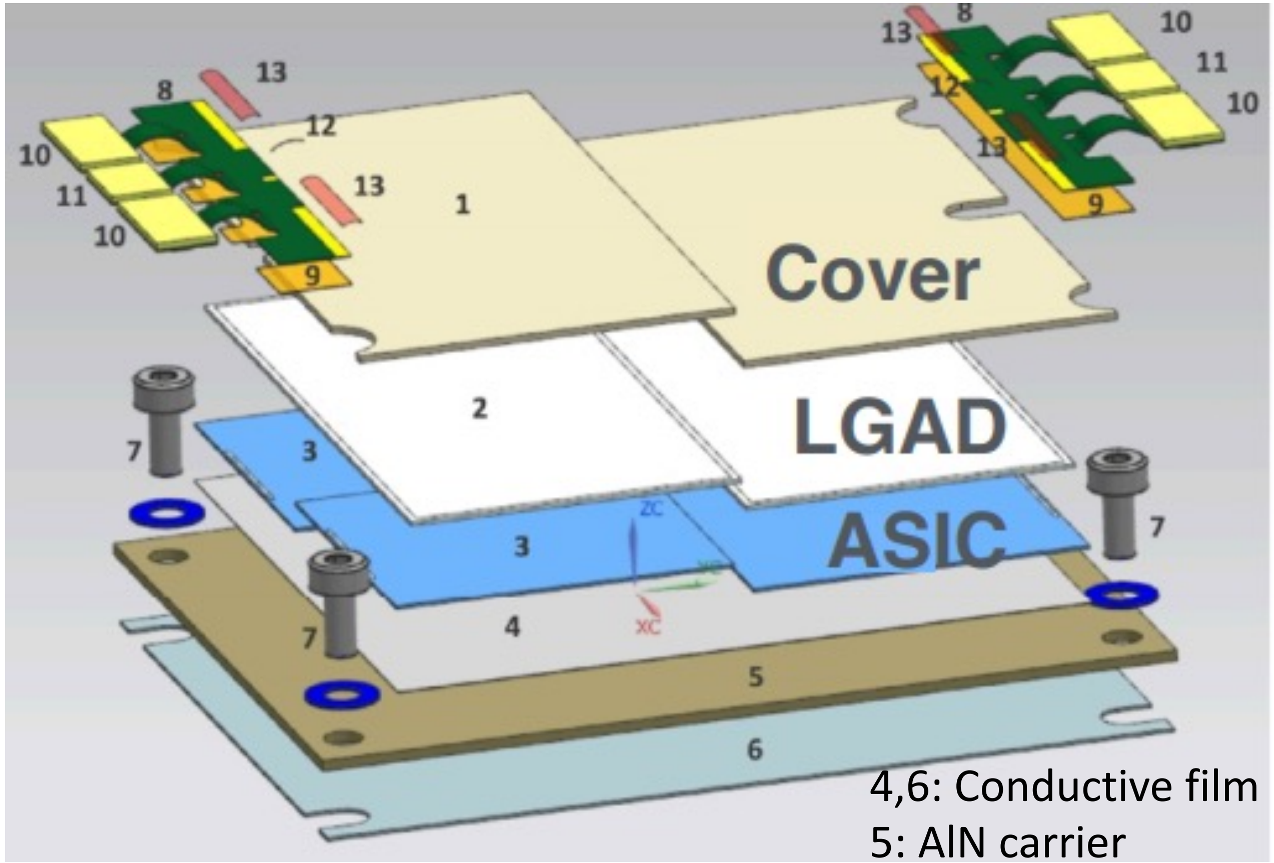
- Compatibility with CMS Trigger and Data Acquisition systems

- Radiation tolerance
  - 1.6×10^{15} n_{eq}/cm^2 in the highest η (3.0) part of the endcap
  - 1.5×10^{14} n_{eq}/cm^2 in the lowest η (1.6) part of the endcap

ETL Module assembly

- Fermilab, SiDet, Detector test Area

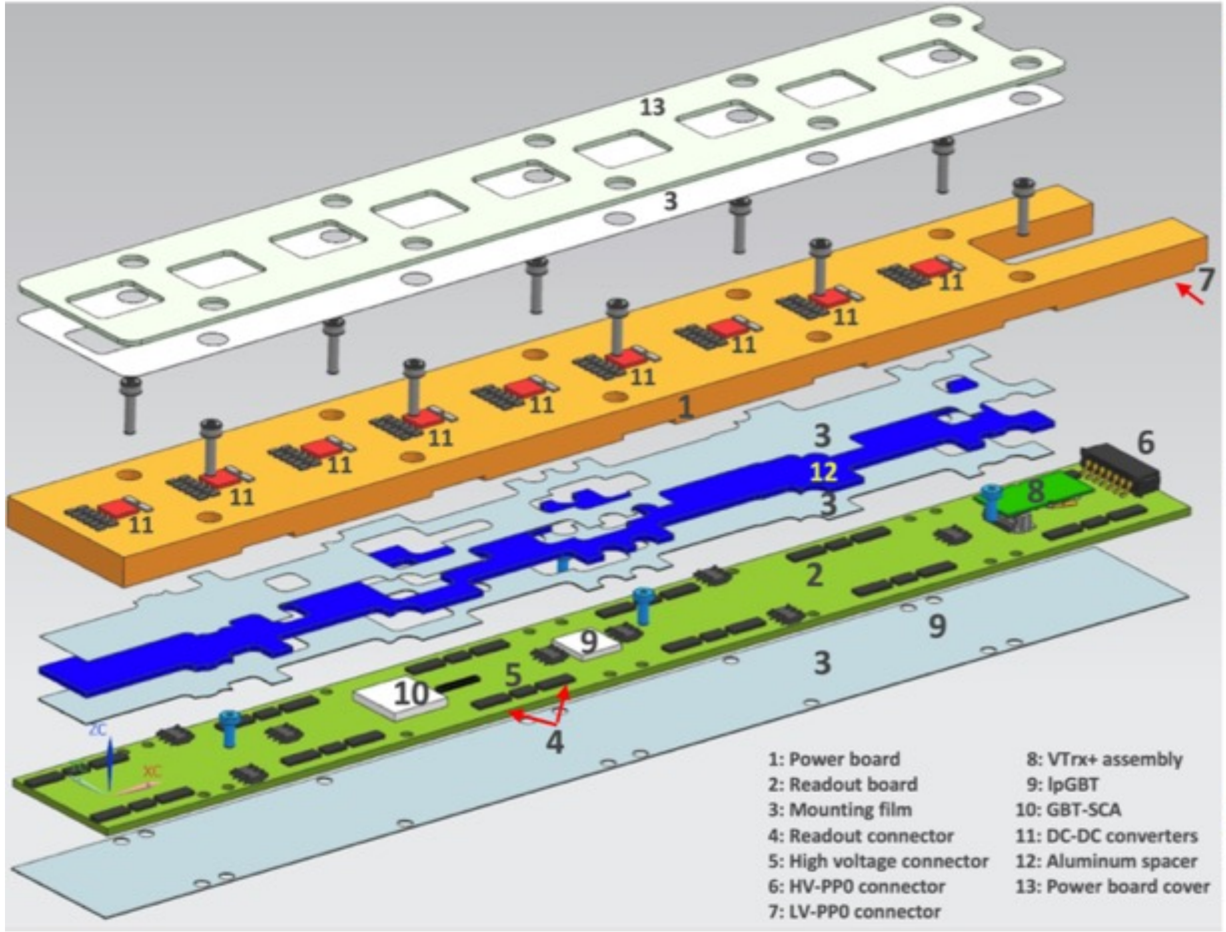


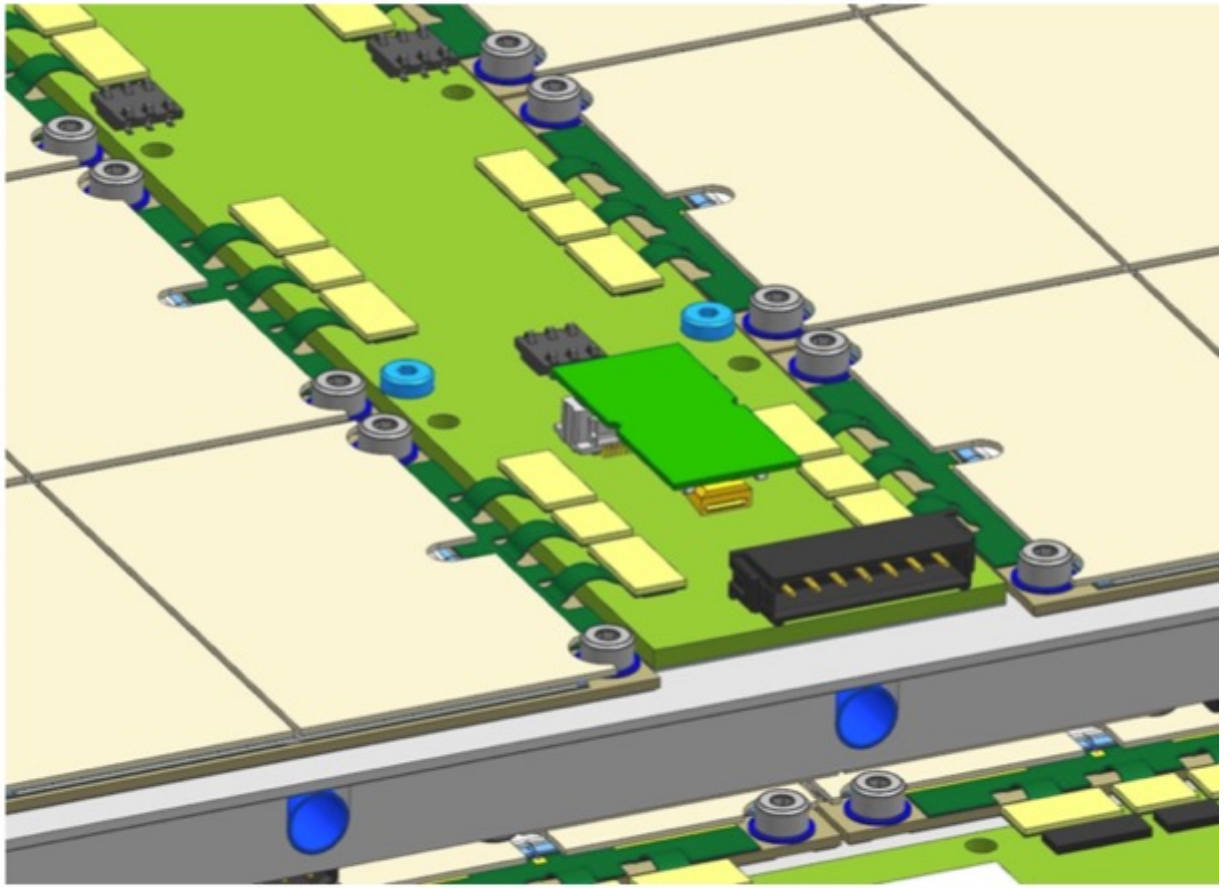


- LGAD+ASIC assemblies mounted on AlN (Aluminum Nitride) carrier plates
- Aerotech 3+1 axis gantries were used for ETL module assembly
- Labview program for the set-up and motion of gantry required for module assembly

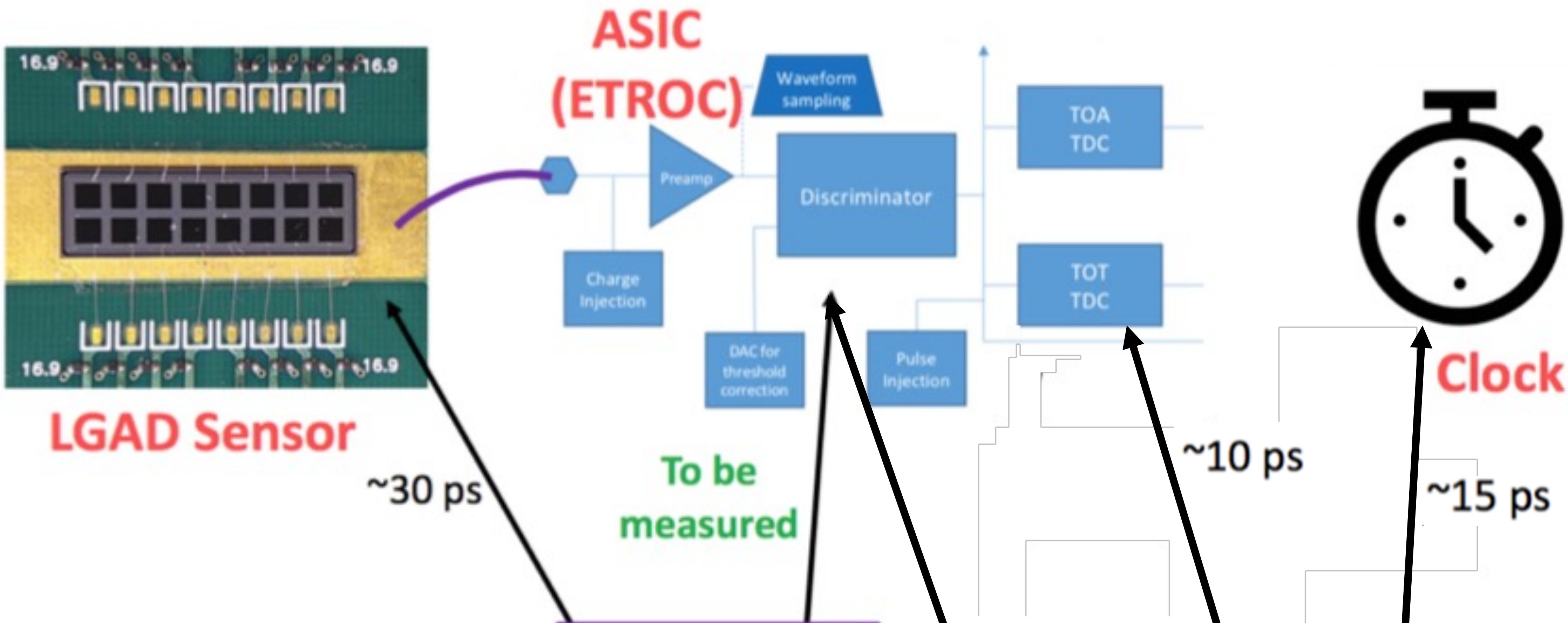
Service hybrids

- Service hybrids providing control, readout, and power, are mounted between rows of modules.





Parameters for time resolution determination

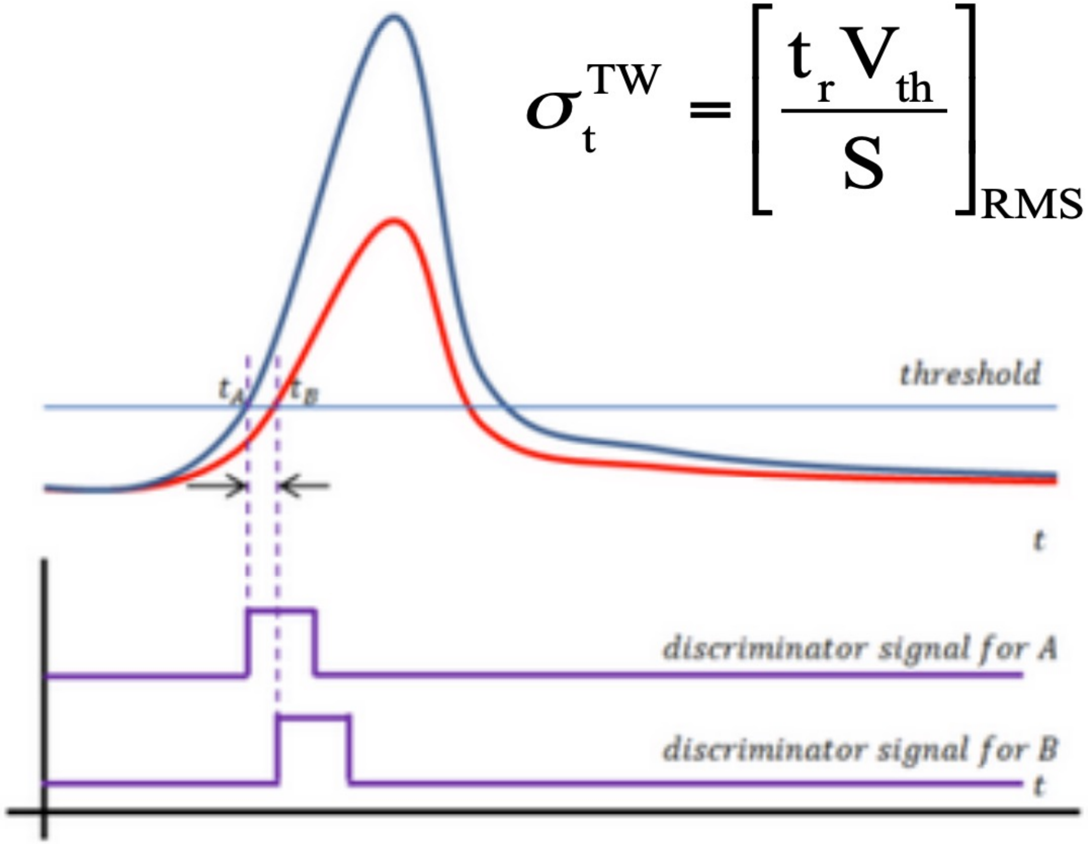


- Total time resolution: $\sigma_t^2 = \sigma_{\text{Ioniz.}}^2 + \sigma_{\text{Jitter}}^2 + \sigma_{\text{Time walk}}^2 + \sigma_{\text{TDC}}^2 + \sigma_{\text{Clock}}^2$
- Expecting $\sigma_t < 40$ ps
- Jitter in ASIC is measured from **preamplifier** and discriminator

Noise source

Time walk: the voltage value V_{th} is reached at different times by signals of different amplitude

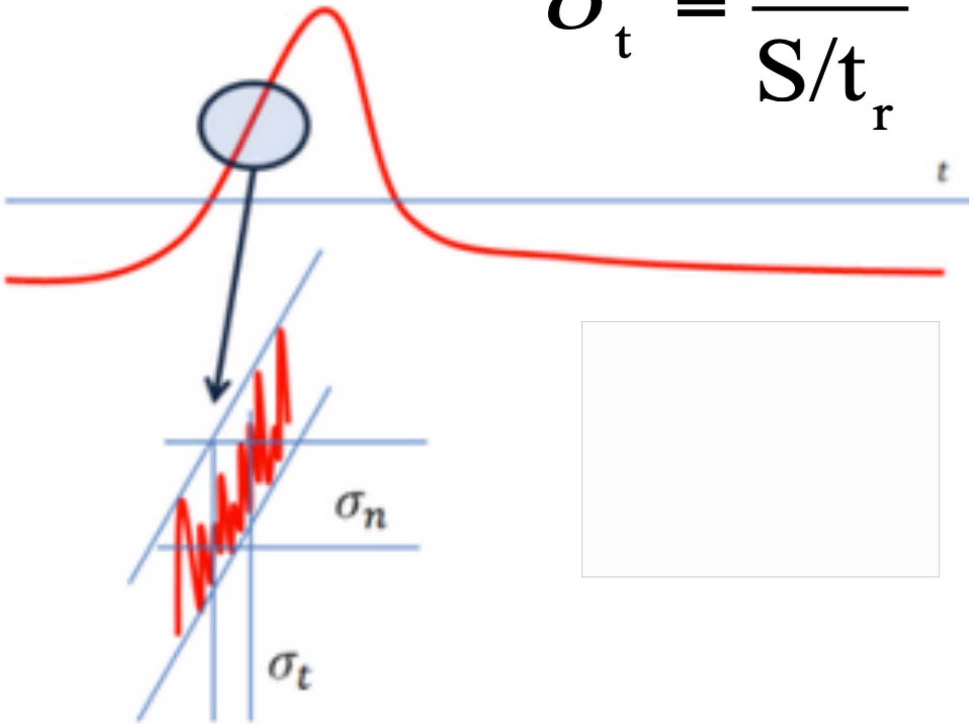
$$\sigma_t^{TW} = \left[\frac{t_r V_{th}}{S}\right]_{RMS}$$



Due to the physics of signal formation

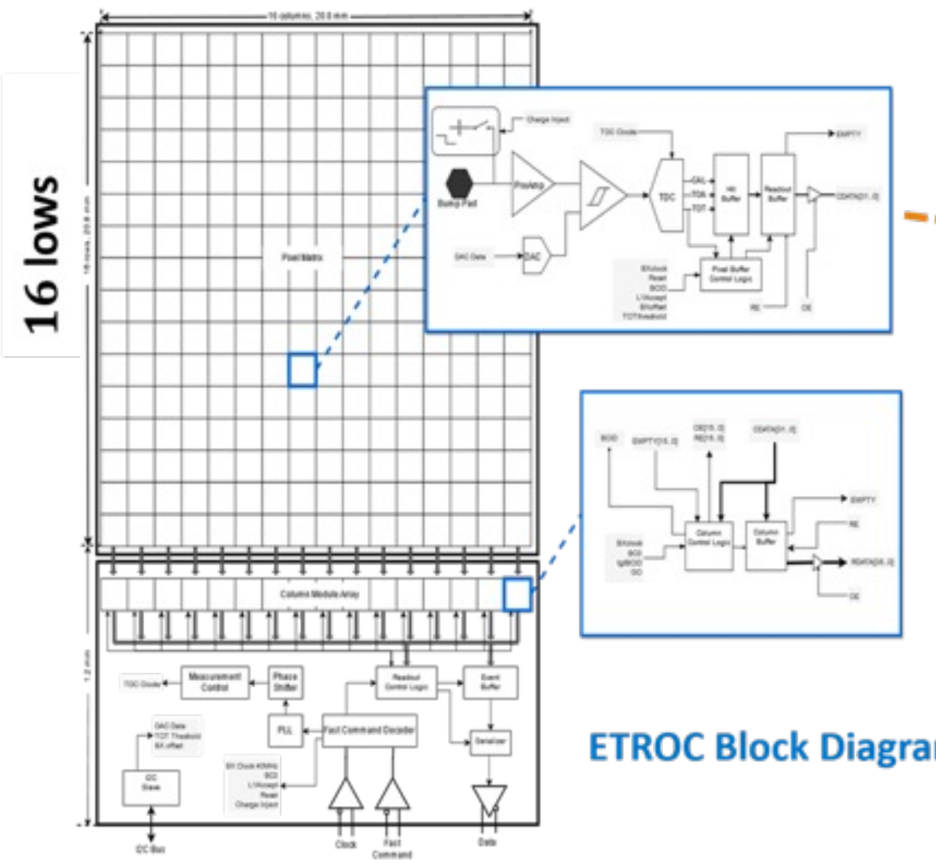
Jitter: the noise is summed to the signal, causing amplitude variations

$$\sigma_t^{J} = \frac{N}{S/t_r}$$

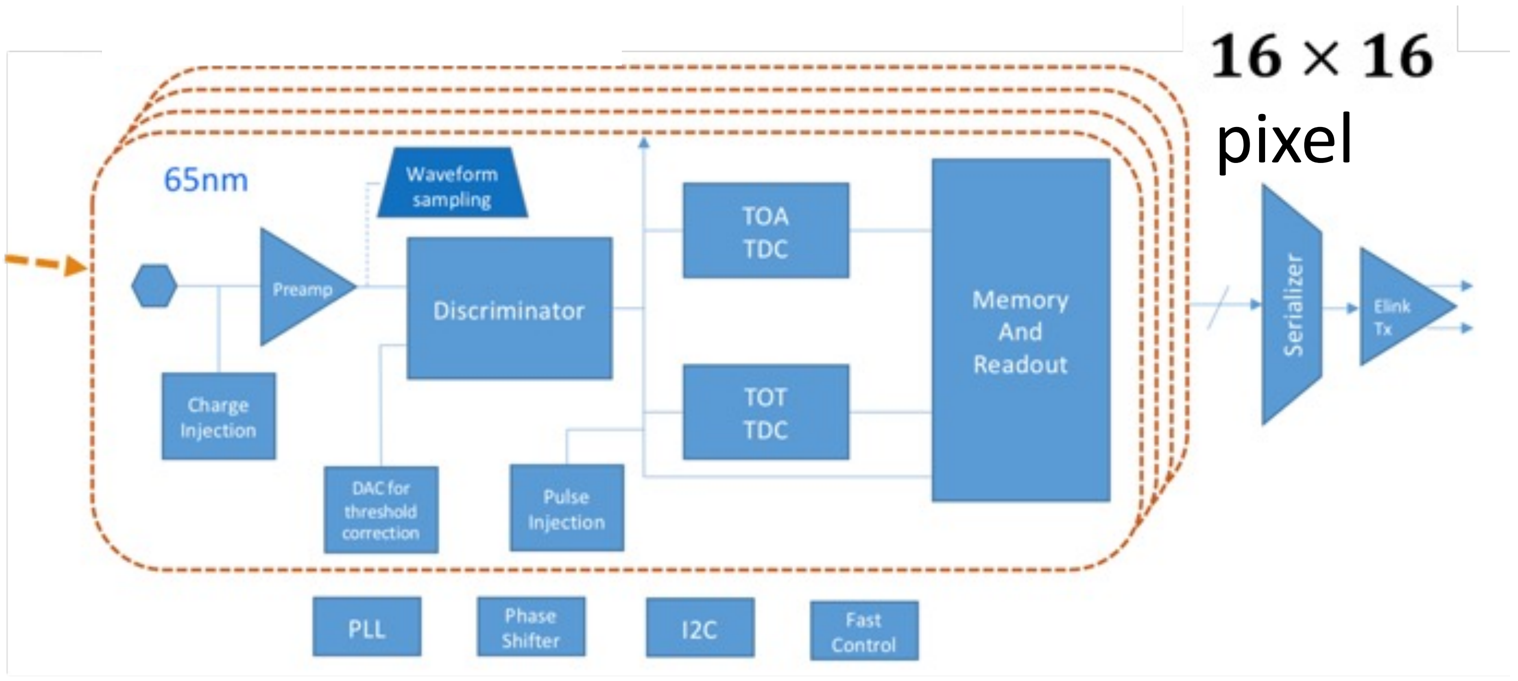


Mostly due to electronic noise

Endcap Timing Layer ReadOut Chip (ETROC)

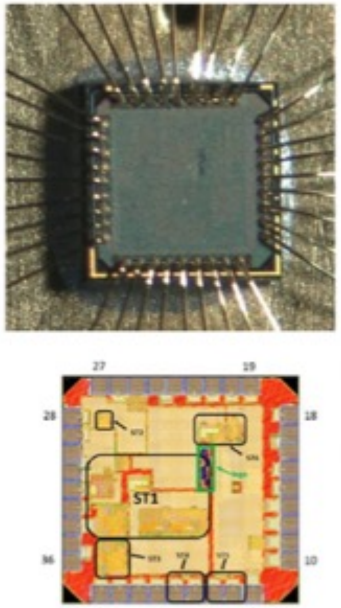


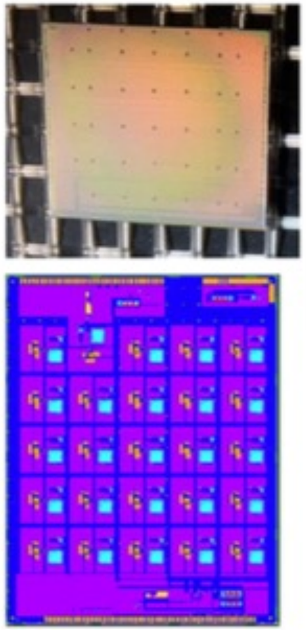
ETROC Block Diagram

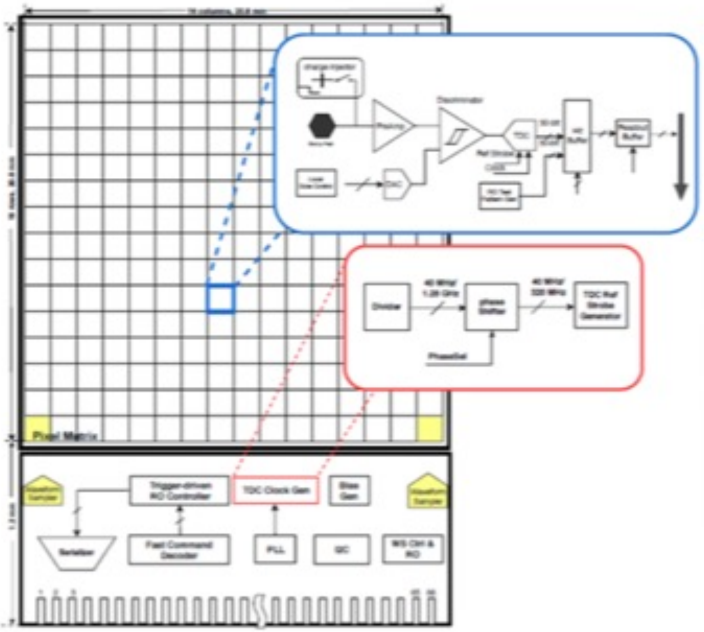


- Total ETROC size: 16 X 16 pixel cell
  - One pixel cell size: 1.3mm X 1.3mm to match the LGAD sensor pixel size
- Targeting signal charge (1MIP): ~6 fC
- TDC (time-to-digital converter) range
  - ~5 ns TOA (time of arrival)
  - ~10 ns TOT (time over threshold)

ETROC Development Plan





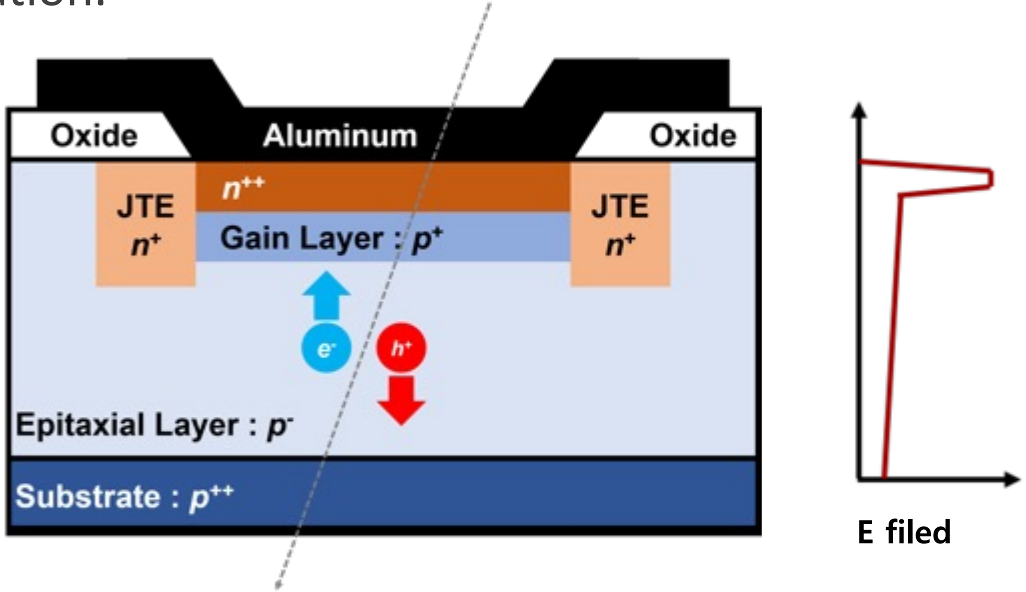


- ETROC0
  - Submitted in Dec. 2018
  - Analog Front-end
  - Tests by far confirmed functionality
  - First round beam test early 2020
- ETROC1
  - Submitted in Aug. 2019
  - 4 X 4 pixel array with full front-end including TDC
  - Chips received middle Dec 2019
  - TDC block works well
  - Single pixel full chain testing on going, and followed by 4x4 array testing
- ETROC2
  - Aim to submit in Q1 2021
  - Designed to be compatible with 16 X 16 pixel array with
  - full functionalities
- ETROC3
  - Aim to submit in Q1 2022
  - Pre-production version

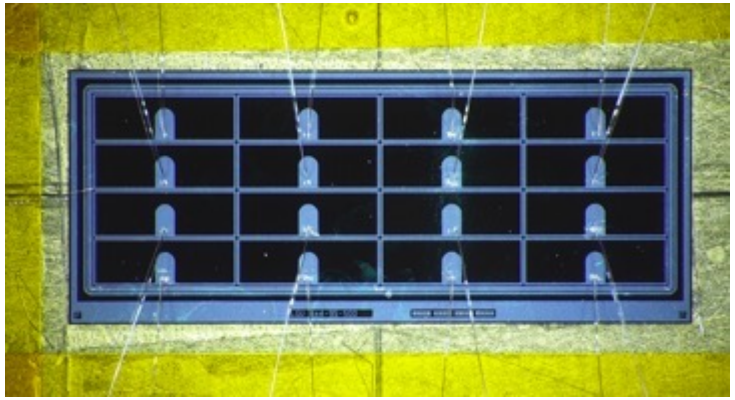
- **KNU group** contributes on studies of the **ETROC0/1** since June, 2019

Low Gain Avalanche Diode (LGAD) Sensors

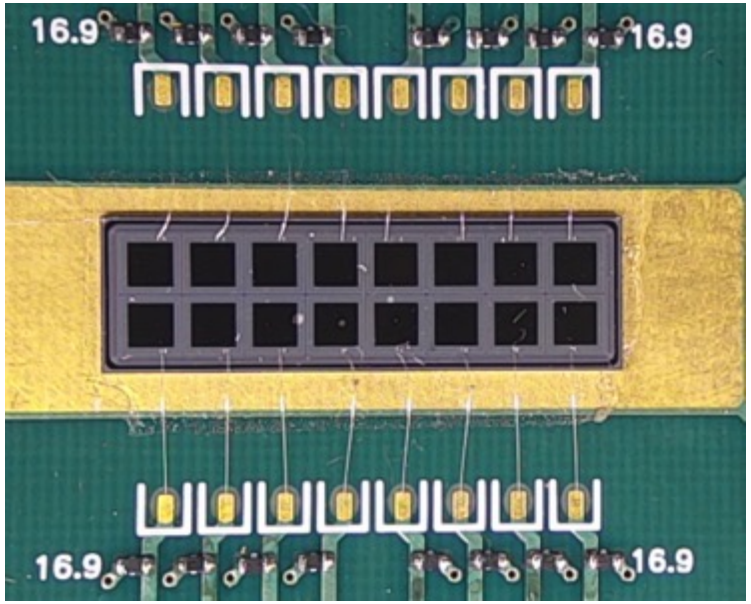
- Sensor producer
  - HPK (Hamamatsu, Japan), FBK (Italy), CNM (Spain), NDL (China)
- LGAD characteristics
  - Precision position reconstruction and timing resolution
  - Gain uniformity
  - Highly improved radiation tolerance
  - Large signals with low noise
  - Thin implanted gain layer of overall thickness of 35–50 µm
- The additional doping layer present at the n-p junction
  - Generates the high field necessary to achieve charge multiplication.



HPK 4x4 sensor array($1\times3\ mm^2$ pads)

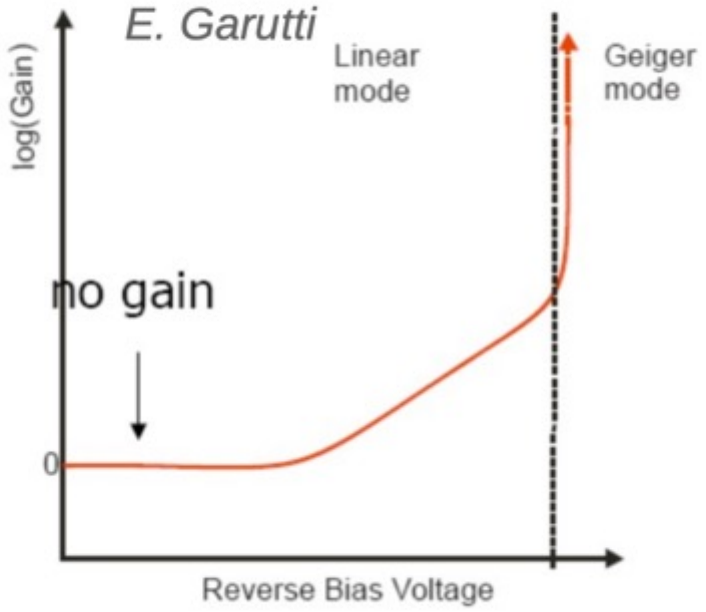


FBK 2x8 sensor array($2\times2\ mm^2$ pads)



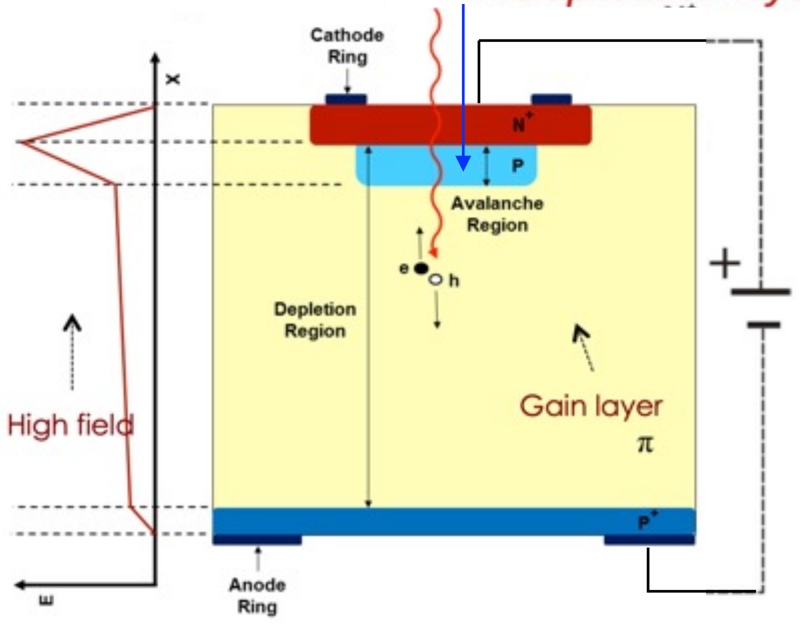
Charge Multiplication

- But devices with charge multiplication were already there:
  - Avalanche Photodiodes (APDs)
    - Photodiodes *Gain=1*
    - APD *Gain=100-1000*
    - Geiger mode (SPAD/SiPM) *Gain~1E7*



APD design

Key feature: multiplication layer



High field obtained by adding an extra doping layer

E ~ 300 kV/cm, closed to breakdown voltage

For HEP (particle detection, not photons)

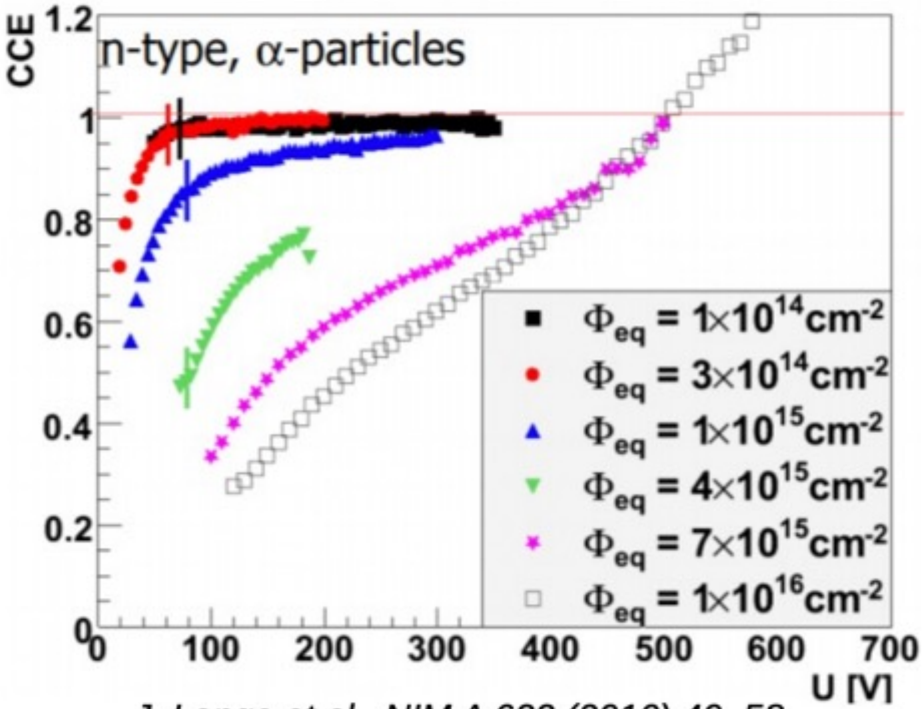
- Keep charge information (linearity, not Geiger mode)
- But APDs are too noisy due to gain

Initial idea was APD with "low Gain" (~10-20) to compensate charge loss after irradiation

Silicon Detectors after Irradiation

- Irradiation degrades the signal of silicon detectors
- Recover it by increasing bias voltage
  - Hit limit of PS or device breaks
- But while investigating thin devices (epitaxial) for the HL-LHC, *Lange et al.*, found that highly irradiated samples, could achieve CCE>1 at high bias voltages (>1E5 V/cm)
  - **Charge multiplication by impact ionization** → Due to very strong electric field

Charge collection efficiency (CCE)

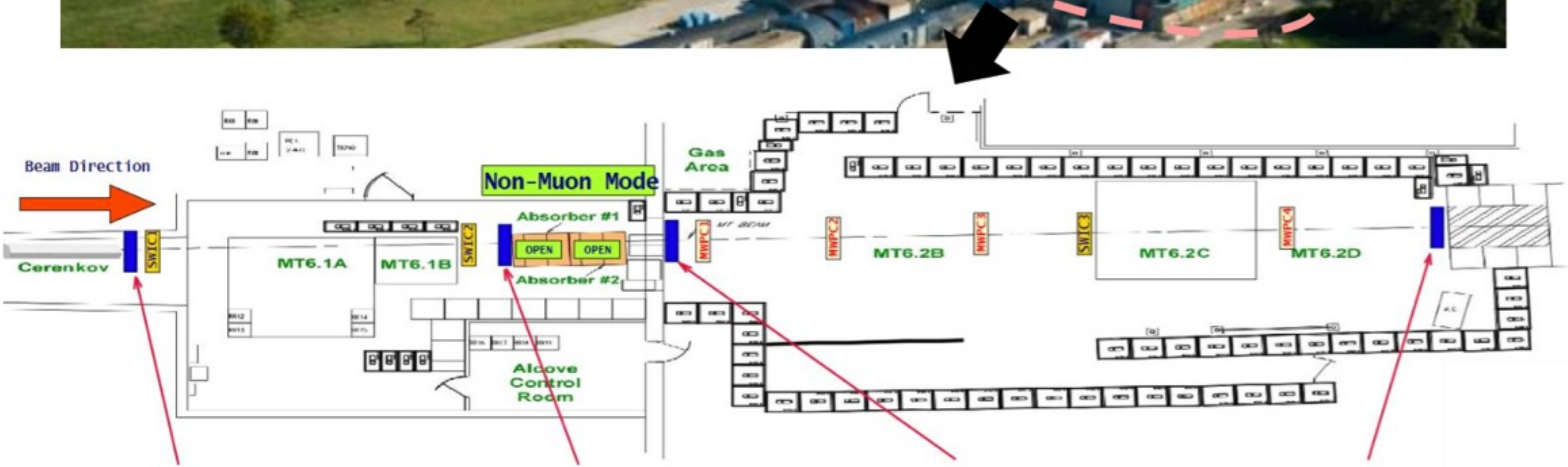


J. Lange et al., NIM A 622 (2010) 49–58

bias voltage

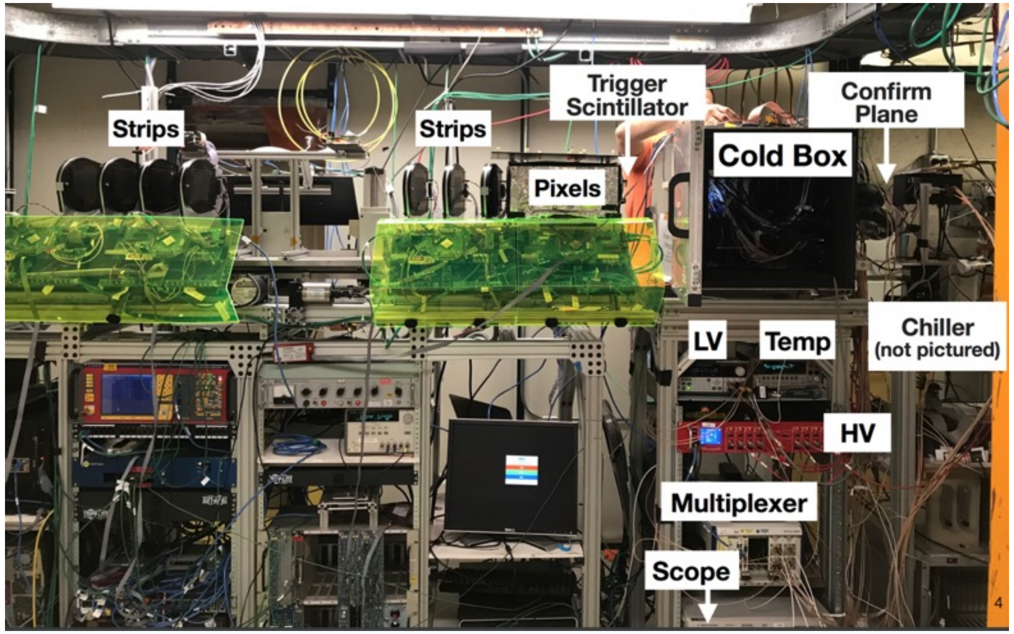
People quickly started thinking if the "charge multiplication" effect could be exploited to create more radiation hard silicon detectors….

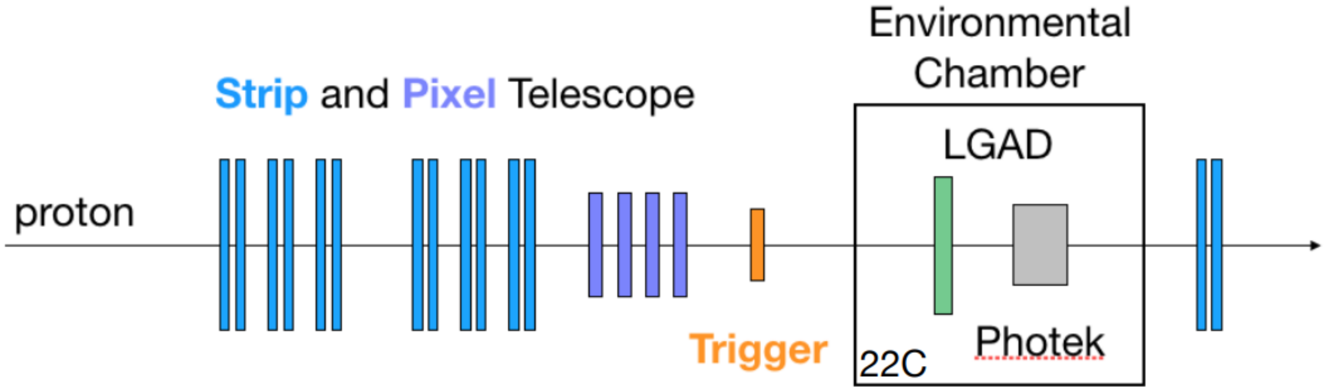
Test beam with 120 GeV proton at Fermilab



LGAD sensor test with 120 GeV proton beam

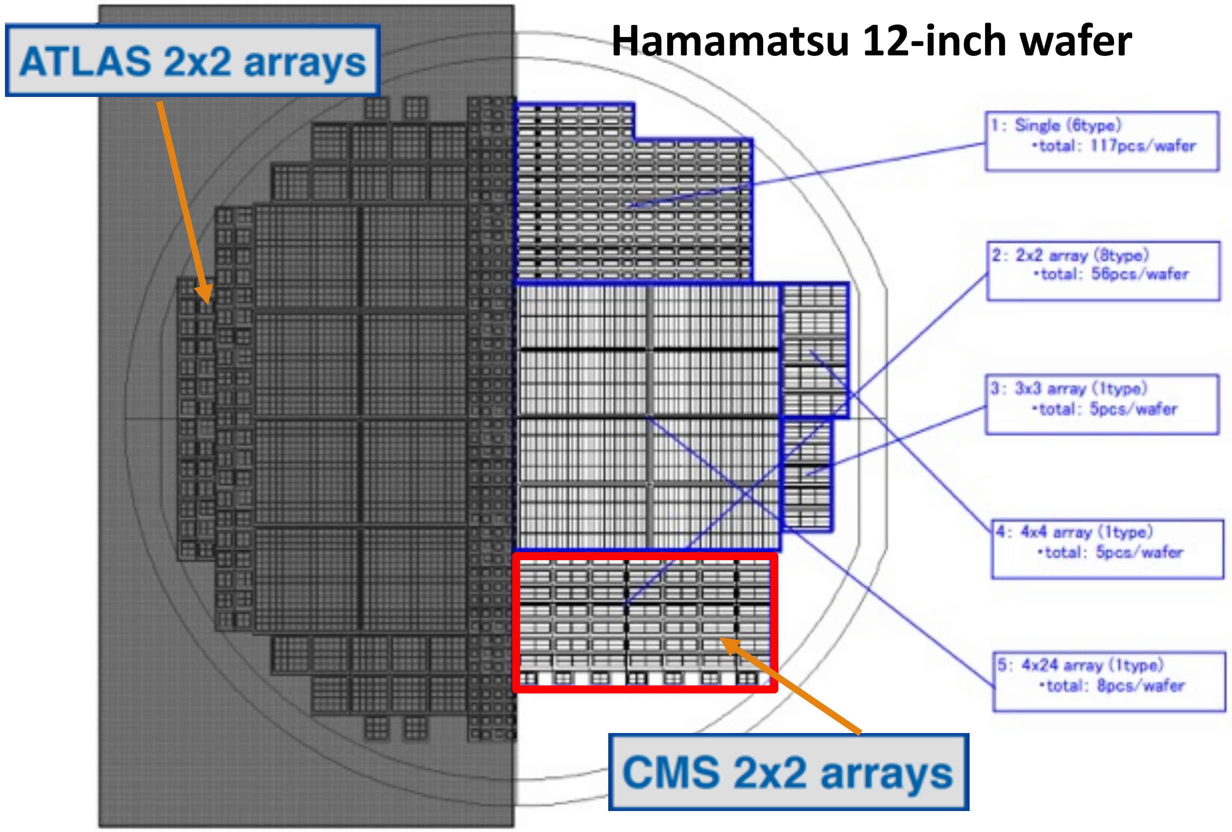
FNAL test beam facility (FTBT)

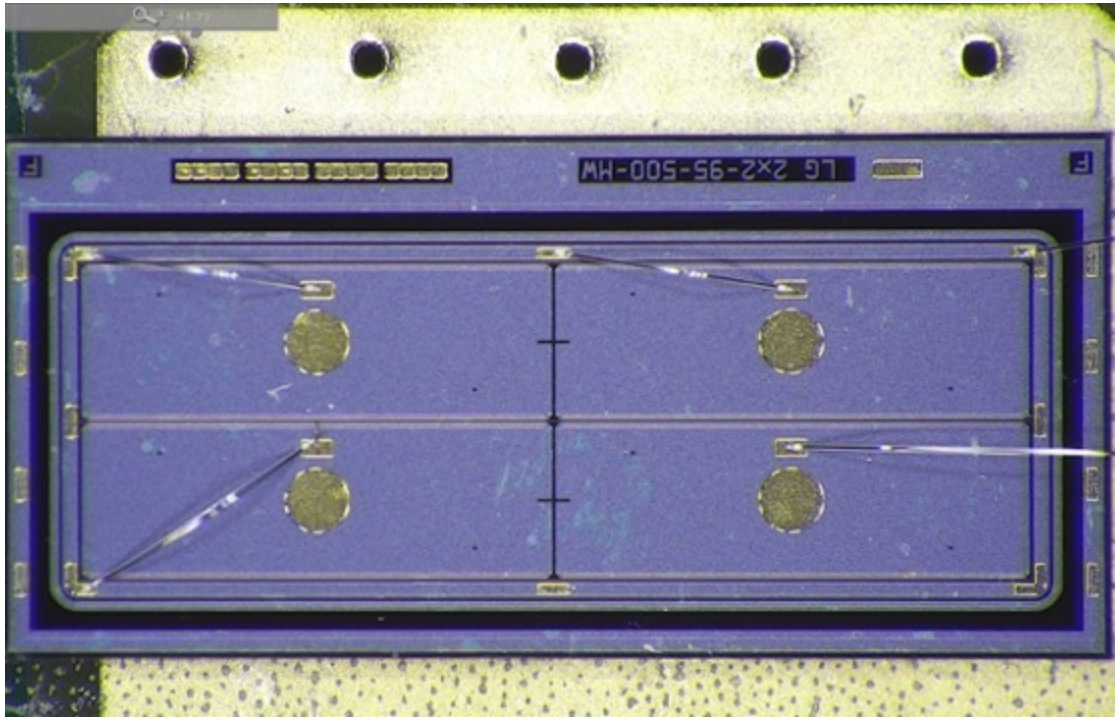




- **Beam properties at FTBT**
  - 120 GeV proton beam
  - Beam width : few mm to few cm
  - 100k protons per 4 second spill per minute
- **Strip and Pixel telescope**
  - Provides proton track position
- **Extra strip layer after cold box**
  - Prevent scattered proton
  - Measure efficiency ~99%
- **Photek Micro-Channel Plate (MCP)**
  - Provided a very precise reference timestamp (~10 ps)
- **Cold box (Environmental Chamber)**
  - LGAD sensor and MCP are mounted

LGAD prototyping campaigns





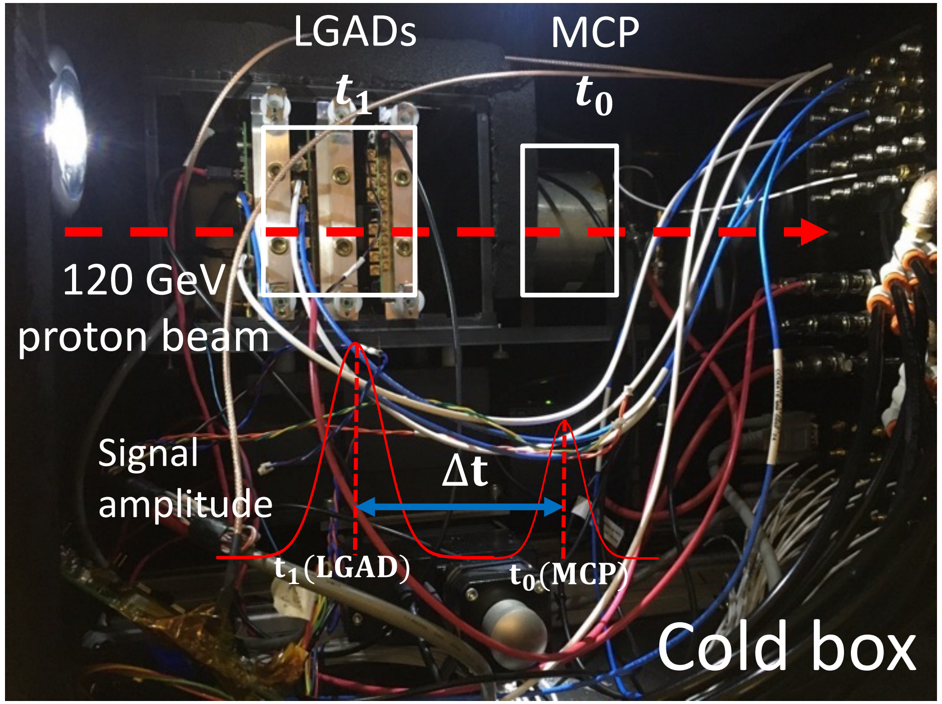
HPK 3.1 sensors (2x2)

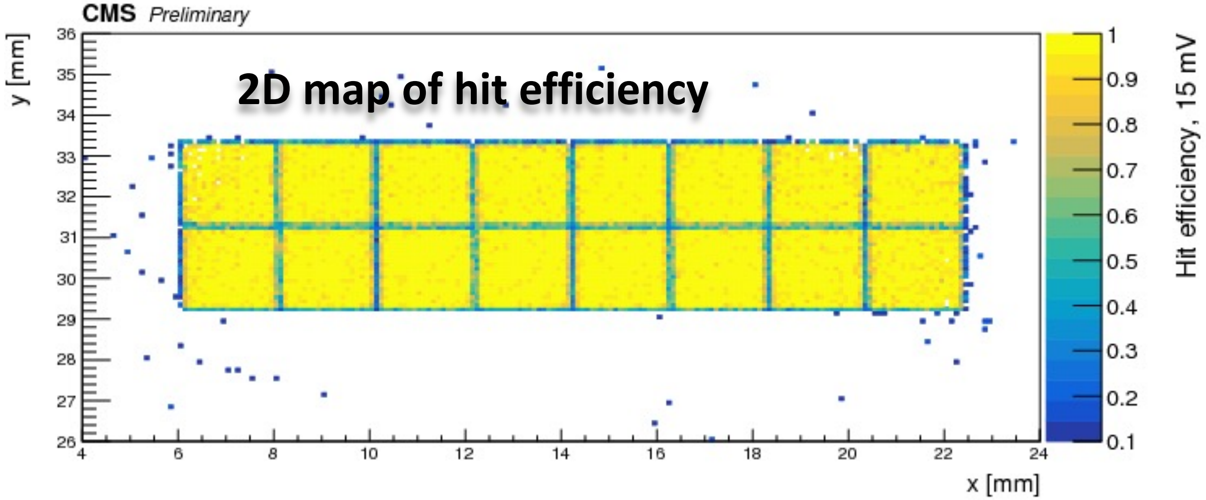
- Optimization of gain layer & thickness for best time resolution
- Improving radiation hardness, Developing large arrays of sensors
- Prototypes satisfy
  - Time performance < 40 ps
  - Uniform performance of all sensor surface

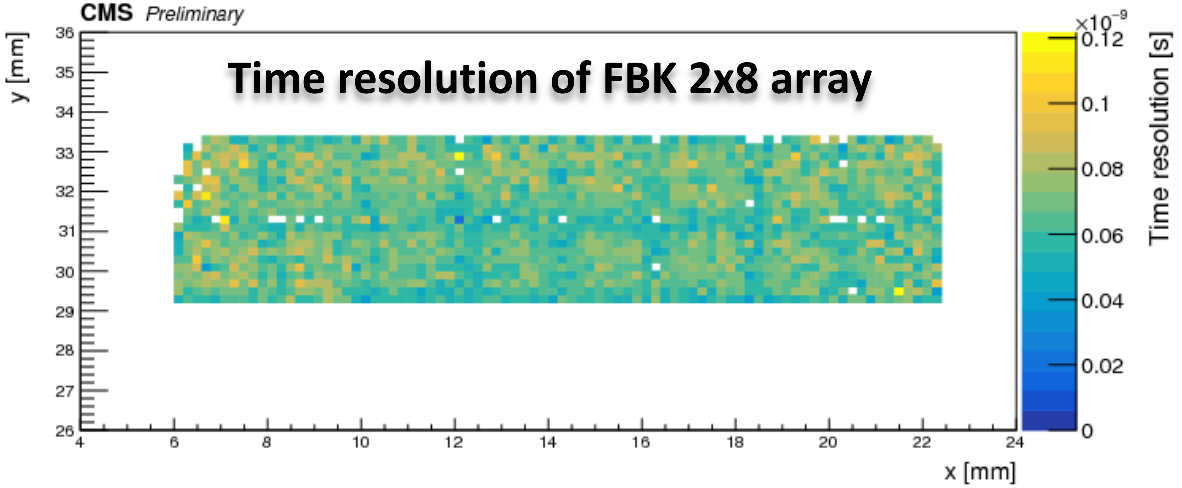
Irradiated FBK 2x8 arrays sensor test

Silicon Detector Facility (SiDet)

- Validation of beta source measurement
- Irradiated FBK 2x8 arrays sensor test
  - Signal amplitude
  - Hit efficiency
  - Timing performance
  - Radiation damage
- Prototype LGAD Sensor testing

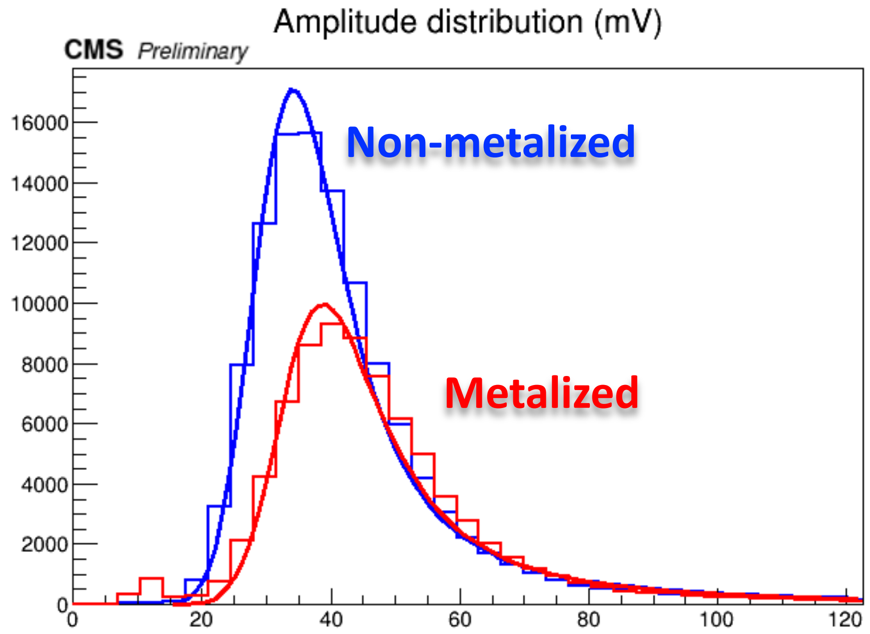




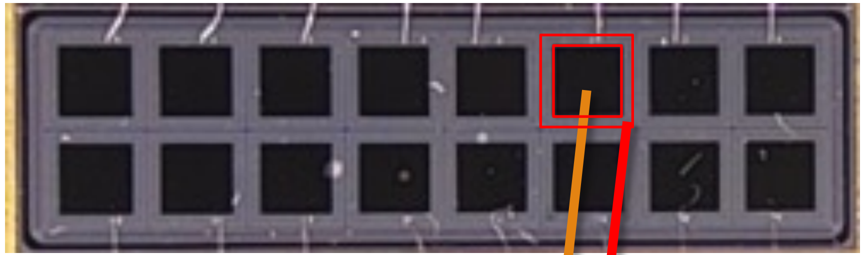


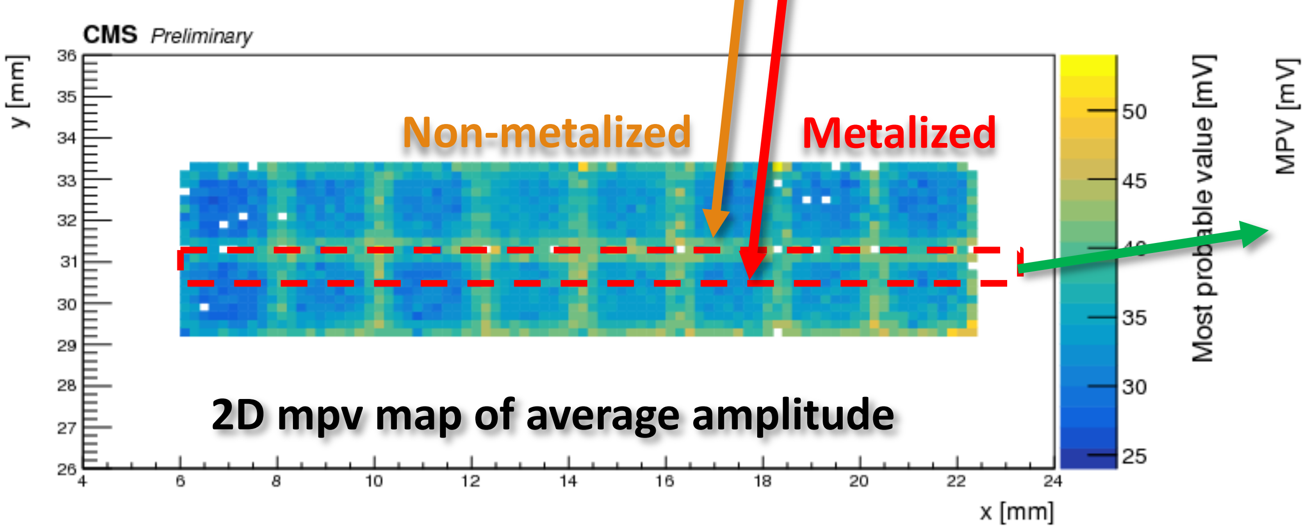
Irradiated FBK 2x8 arrays sensor test – signal amplitude

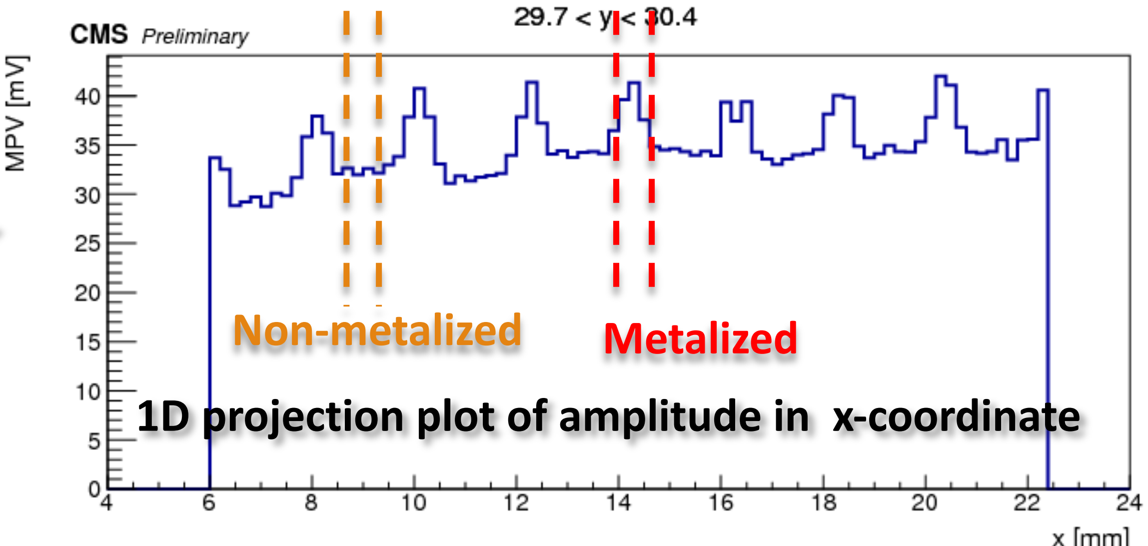
- Hadron fluence - $4 * 10^{14} n_{eq}/cm^2$
- Most of the initial gain gradient is removed
- Better radiation hardness underneath metalization
  - Metalized MPV ~ 40 mV
  - Non-metalized MPV ~35 mV



FBK UFSD2 2x8 arrays ($2\times2\ mm^2$ pads)

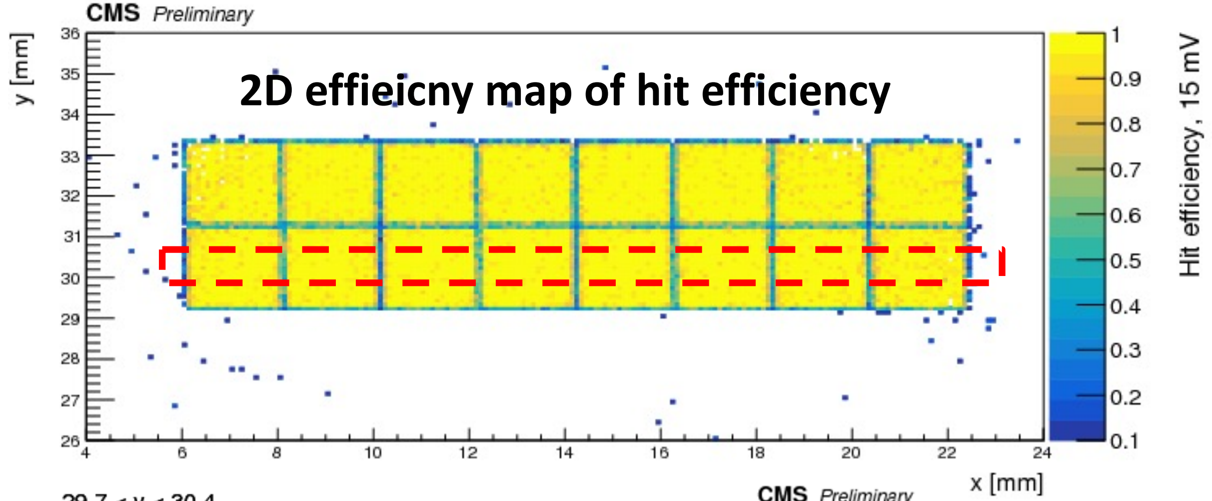


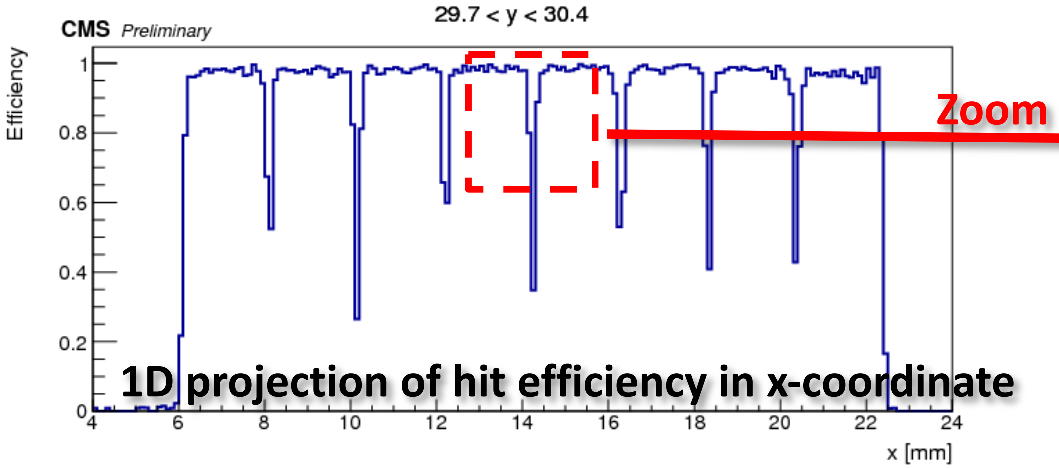


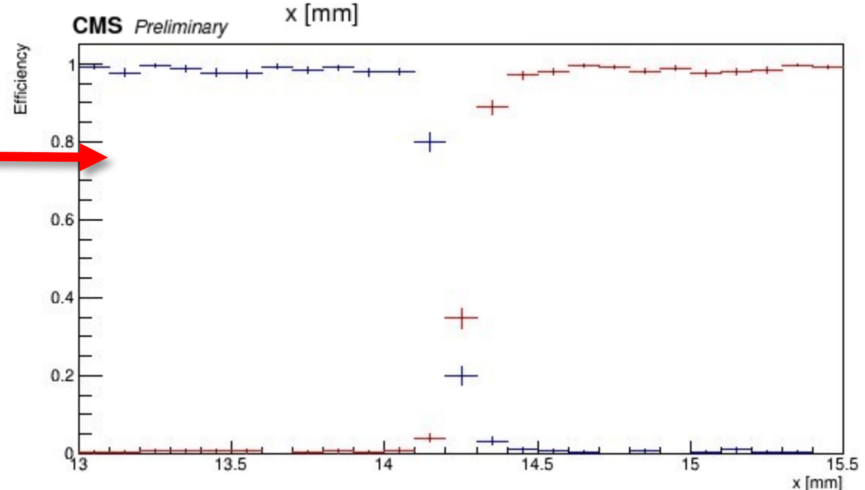


Irradiated FBK 2x8 arrays sensor test - Hit efficiency

- Efficiency measurement
  - $eff = \frac{proton\ track\ \&\&\ signal\ above\ threshold\ in\ LGAD\ pad}{proton\ track\ in\ telescope}$
- Efficiency reaches ~99% in all regions except for gaps
  - LGAD sensor maintains performance despite the radiation damage

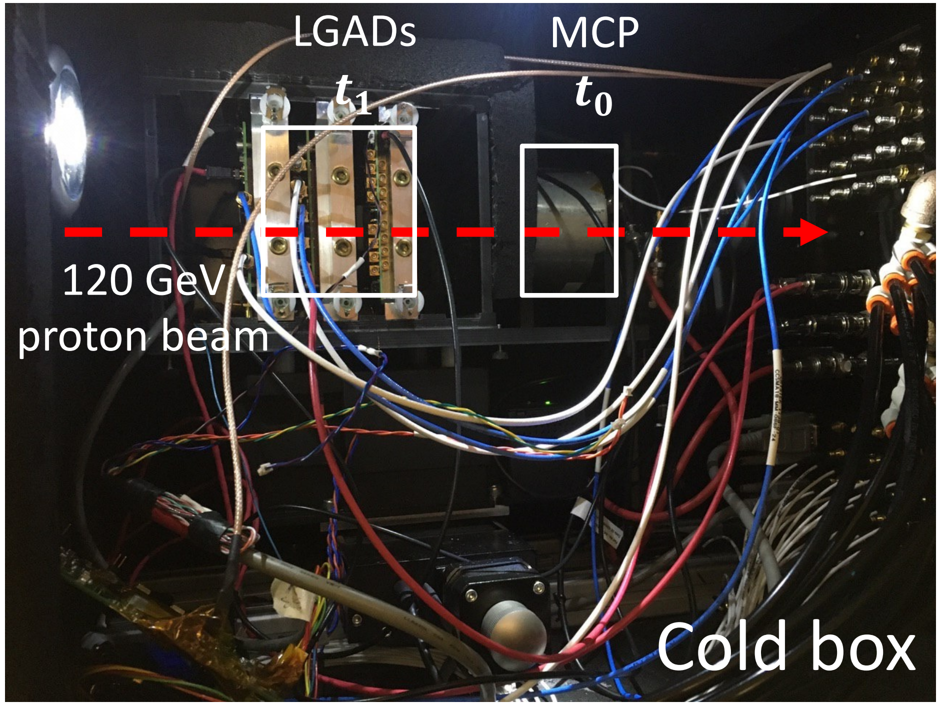




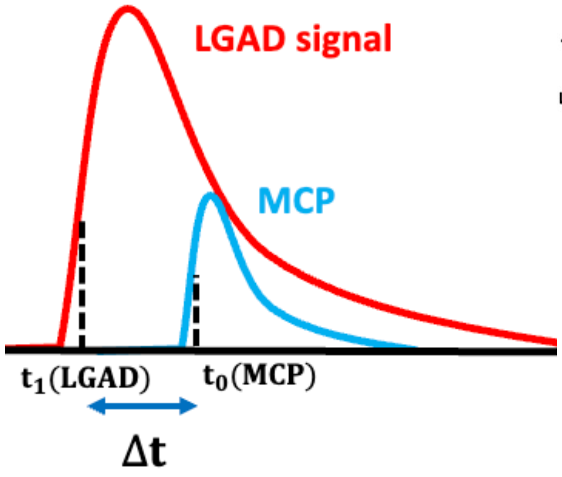


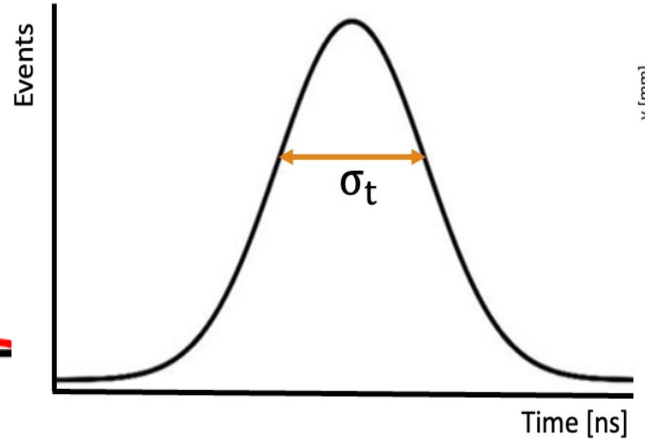
Irradiated FBK 2x8 arrays sensor test – Timing performance

- Timing uniformity with respect to MCP reference
  - Time difference between time stamp of LGAD and MCP
  - $\Delta t = |t_1(LGAD) - t_0(MCP)|$
  - Time resolution : Δt distribution fit with Gaussian to obtain width σ_t

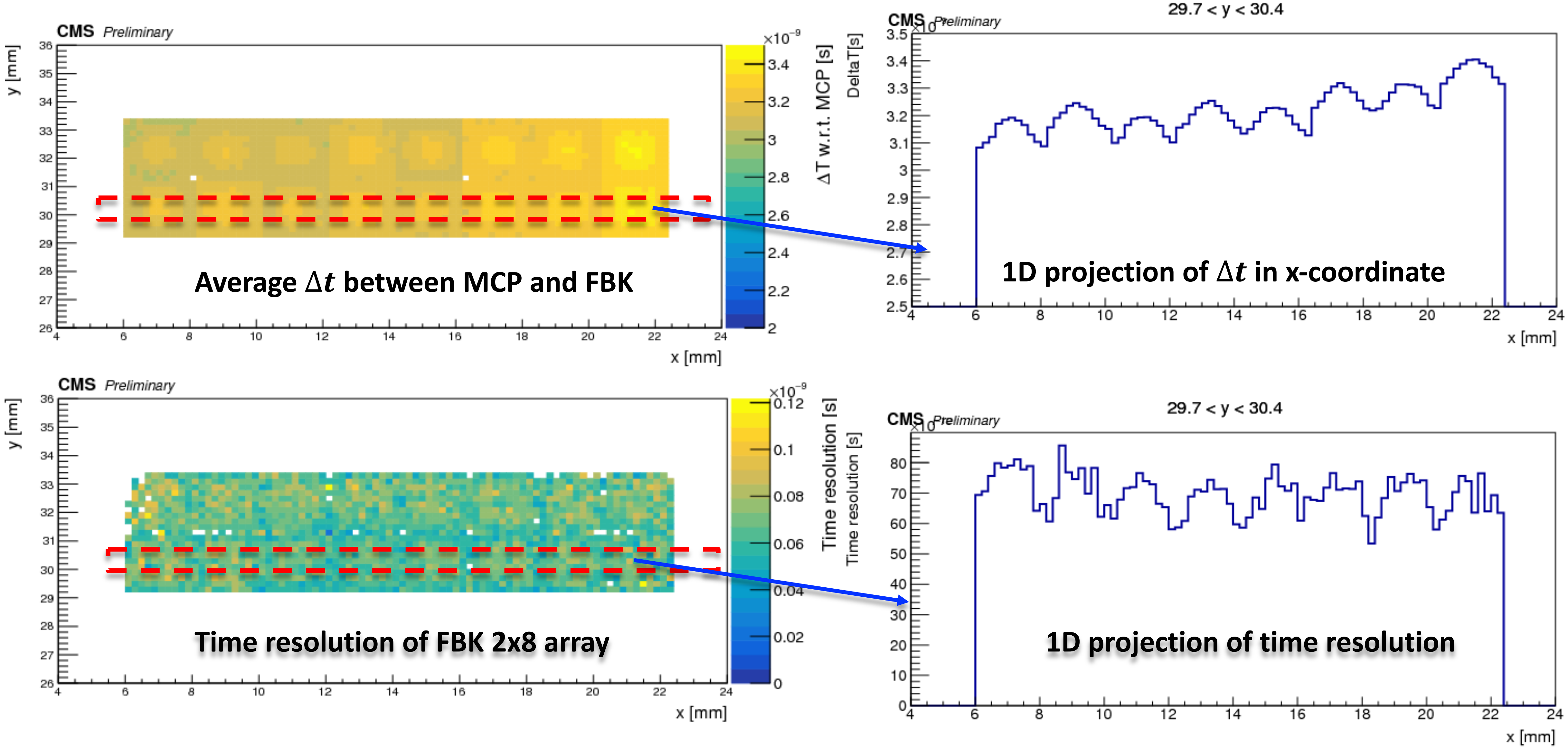


- LGAD, MCP time stamp
  - Larger signals (LGAD) reach threshold earlier
  - Constant Fraction Discriminator (CFD)
    -Threshold as fraction of peak amplitude





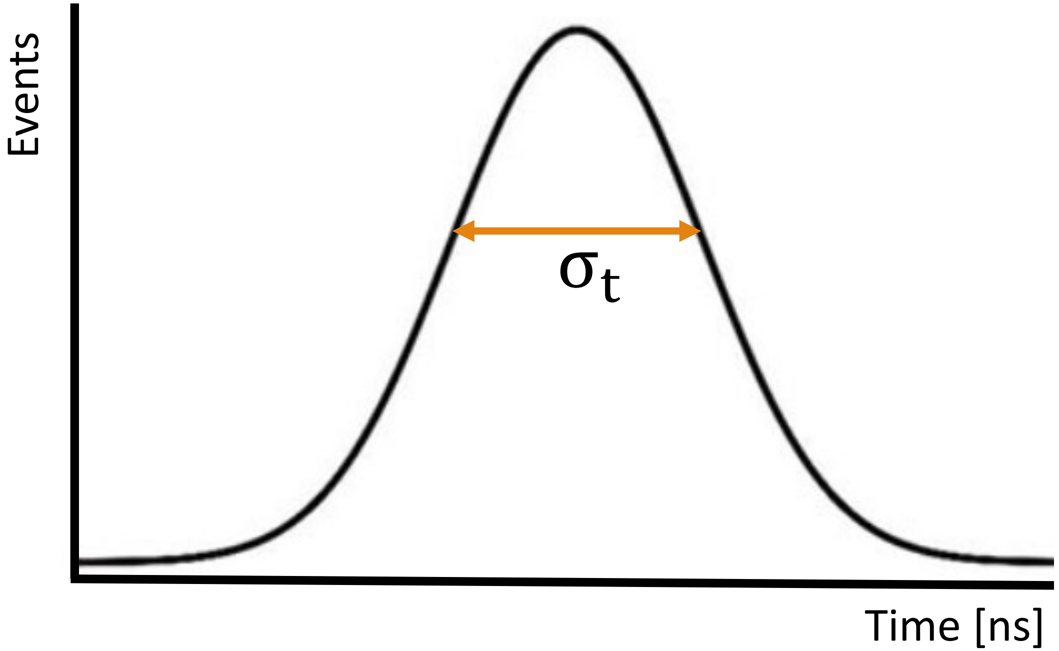
Irradiated FBK 2x8 arrays sensor test – Timing performance



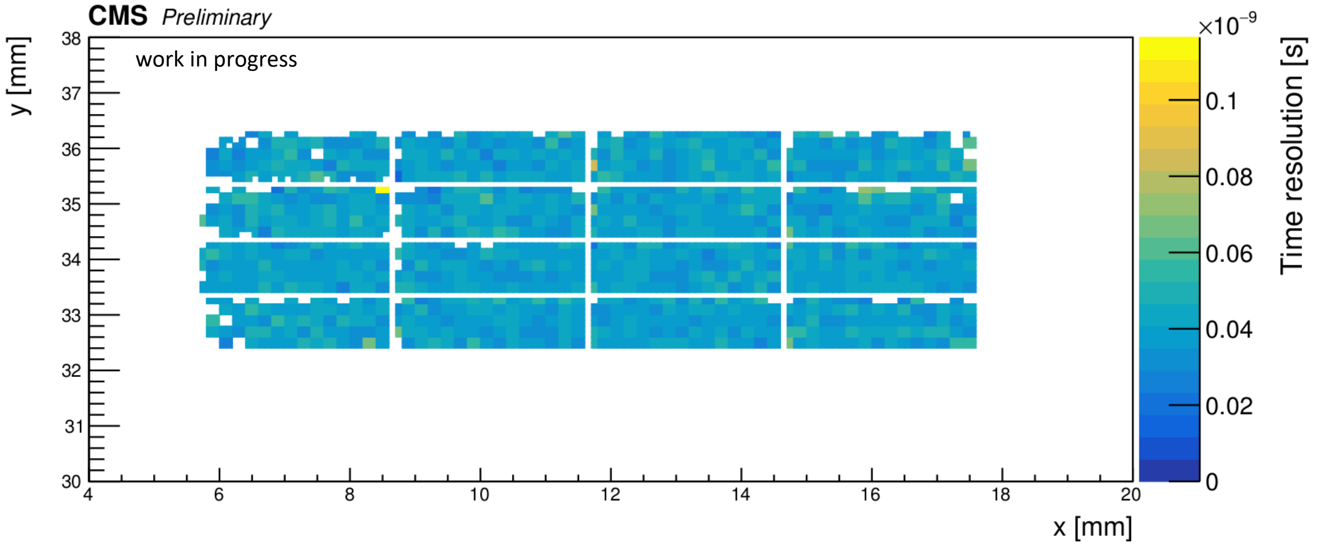
- Latest FBK production maintains less than 40 ps resolution for the entire lifetime

Time Resolution of HPK LGAD Sensor

- Time resolution is obtained between timestamp of LGAD and MCP
- Δt distribution fit with Gaussian to obtain width σ_t
- Uniform at ~40 ps on 16-channel board

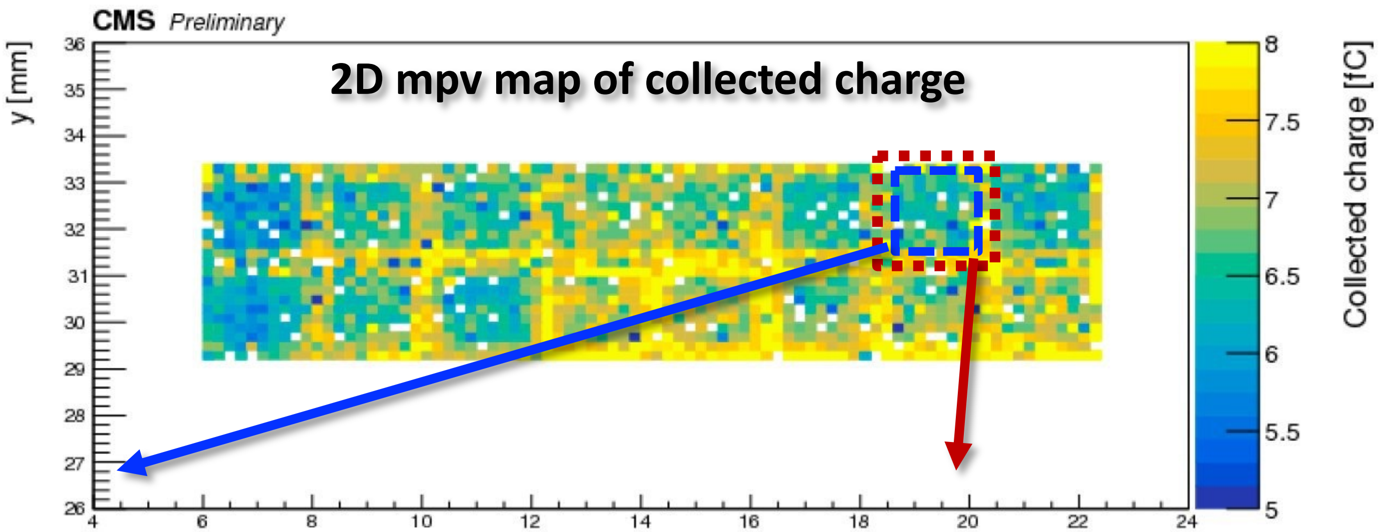


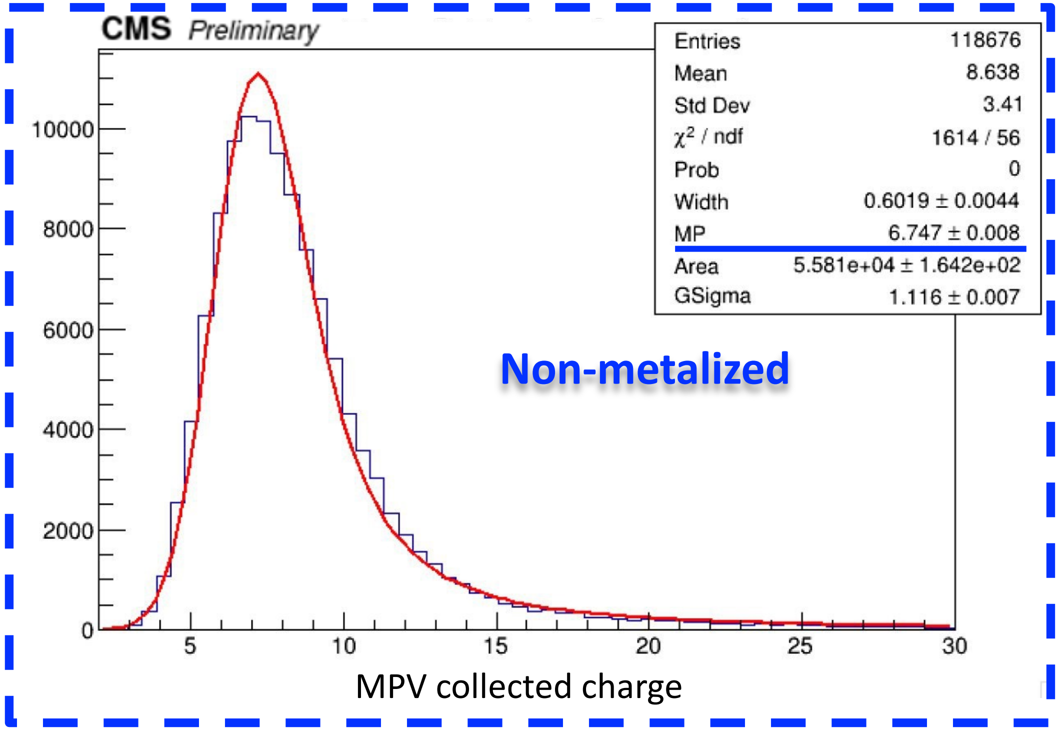
HPK type 3.1, 4x4 array ($3\times1\ mm^2$ pads)

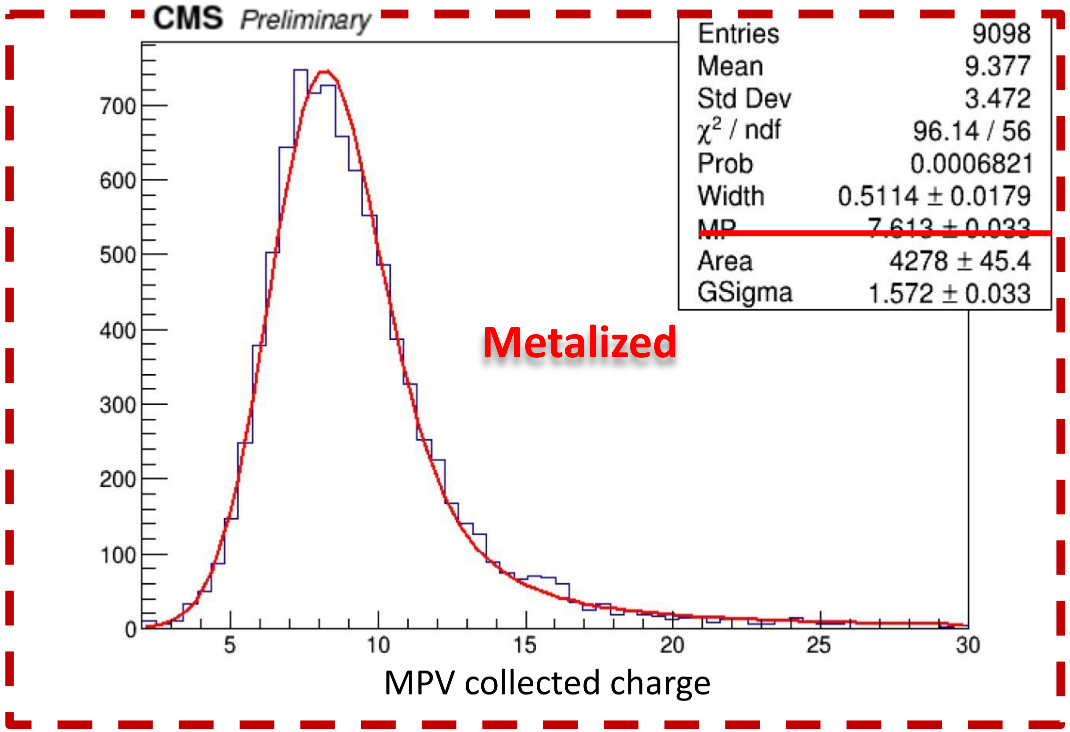


Irradiated FBK 2x8 arrays sensor test – Collected charge

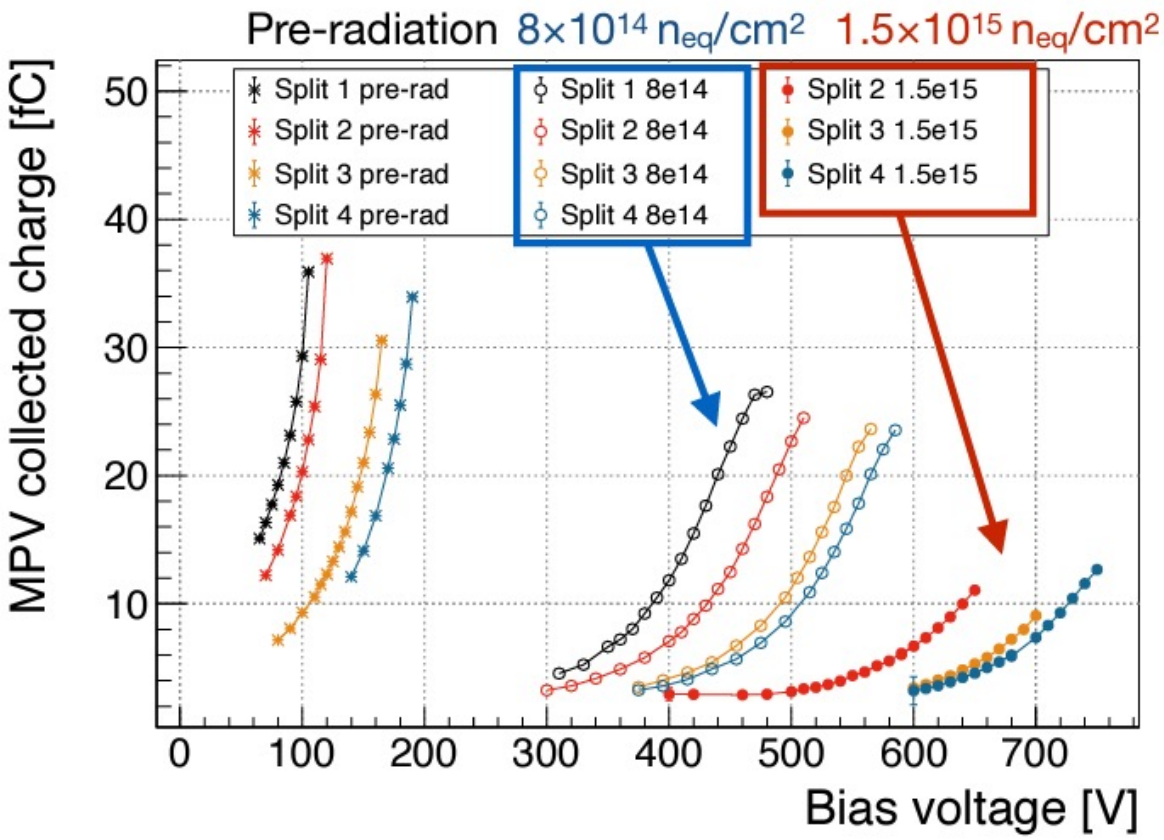
- MPV collected charge
  - Metalized region
    MPV peak ~7.6 fC
  - Non-metalized region
    MPV paek ~ 6.7 fC
- Latest prototype sensor
  - 10 fC with a whole lifetime in the detector

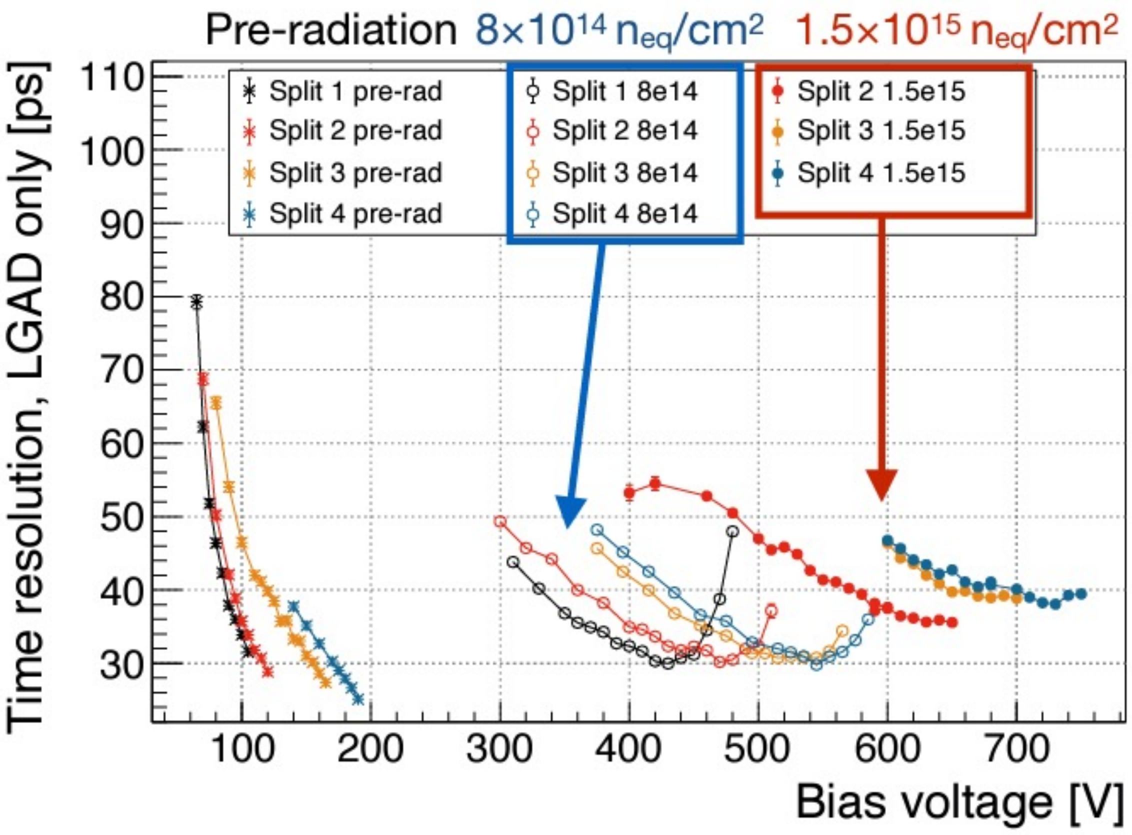






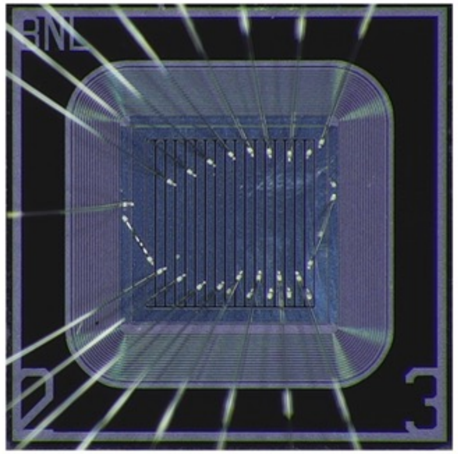
Radiation hardness test with HPK LGAD sensor





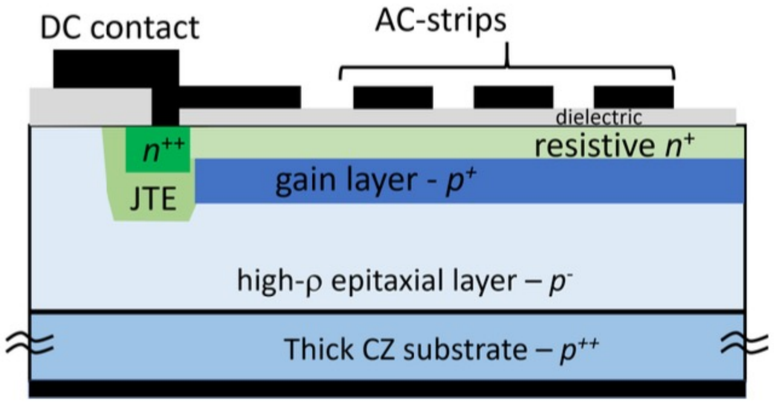
- Maintained LGAD performance by increasing Bias voltage.
- Time resolution of irradiated sensors can be achieved 40ps time resolution until the end of life at HL-LHC (1.5 x 10^{15} n_{eq}/cm^2).

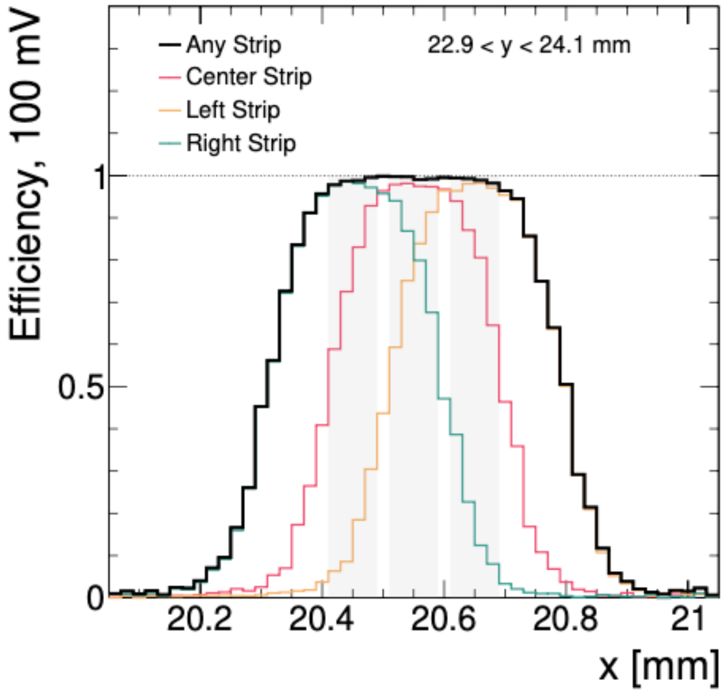
AC-LGAD strip sensor beyond CMS LGAD



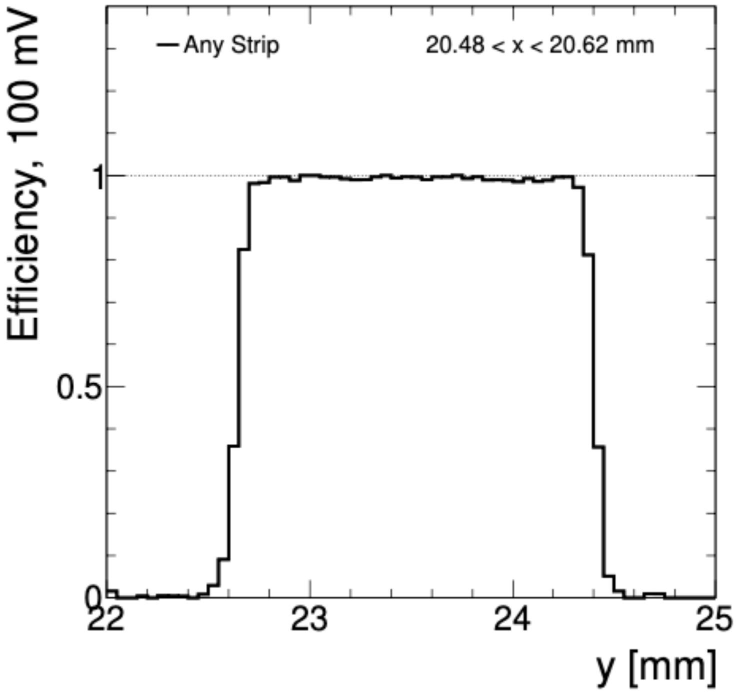
Photograph of the AC-LGAD sensor. The seventeen individual strips are referenced according to labels 0 to 16, from left to right.

Cross section of a segmented AC-LGAD. For simplicity, only three AC electrodes are shown, and the figure is not to scale.





(a) Combined efficiency in x direction.



(b) Combined efficiency in y direction.

Combined signal effciency of adjacent strips as a function of the proton track x and y position, for signals with amplitudes above a 100 mV threshold. In (a) individual strip effciencies are also shown, and vertical grey bands indicate the strip positions in the x-direction.

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AC-LGADs for Electron Ion Collider

- AC-LGAD based Time of Flight (TOF) can provide the Particle ID for every particle in EIC.
  - based on 30 ps timing resolution
  - Ideally coarse pitch (500 μm, 1-2 cm strips) for sparse readout
  - TOF can be used tracking layer (~20 μm resolution)
- TOF ID complements Cherenkov-based ID for soft particles.

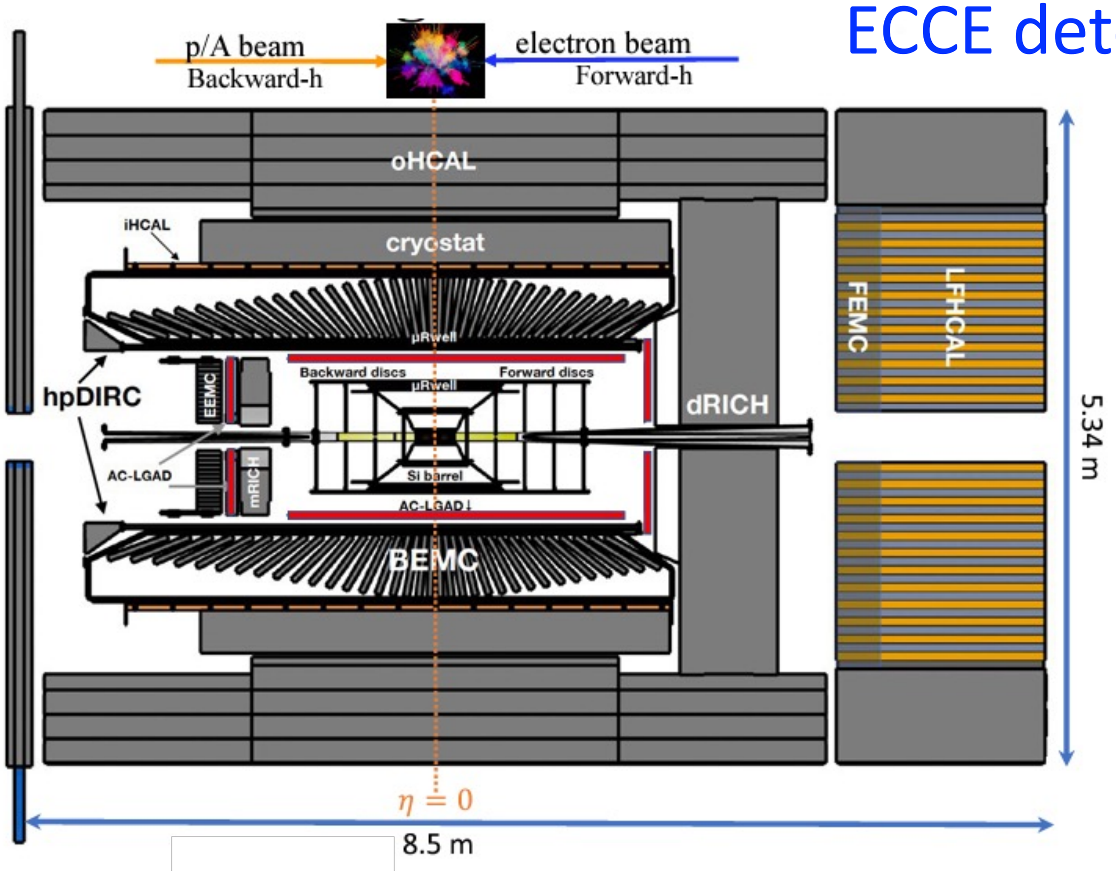
Tracking:
- Si MAPS
- AC-LGAD (~30 μm)
- μRWELL

PID:
- hp-DIRC
- mRICH
- dRICH
- AC-LGAD (~30 ps)

Calorimetry:
- SciGlass Barrel EMCal
- PbWO EEMCal
- Longitudinally separated EM+Hcal
- Inner HCal (instrumented frame)
- Outer HCal (sPHENIX re-use)

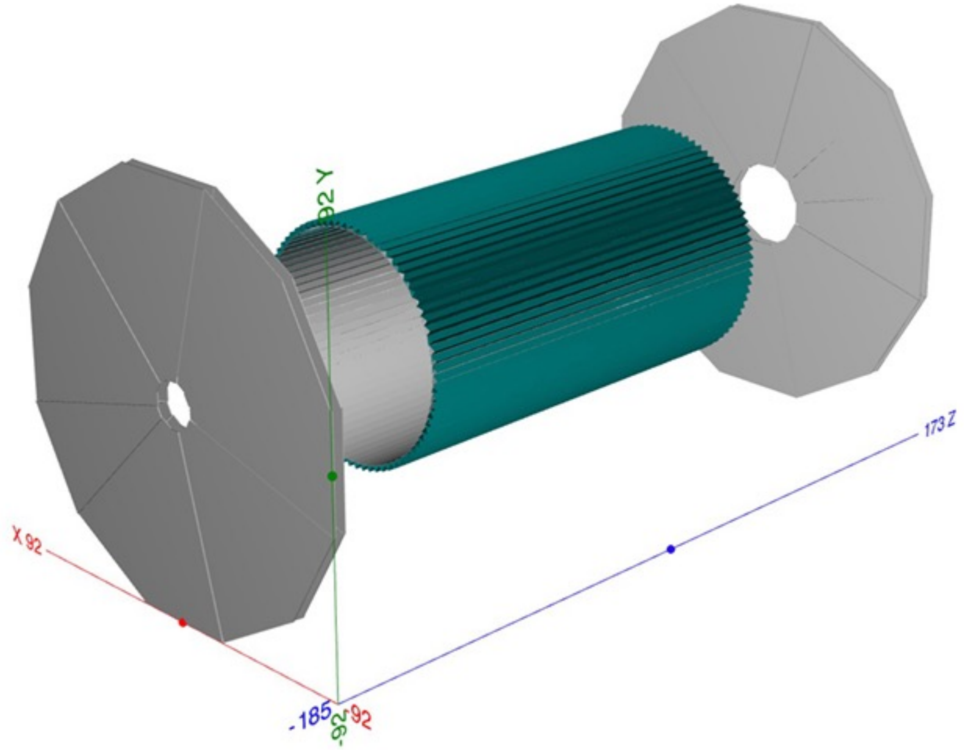
Different to LHC
- lower momentum
- lower occupancy
- less irradiation

ECCE detector



AC-LGADs for Electron Ion Collider

AC-LGAD TOF Detectors for EIC – eRD112



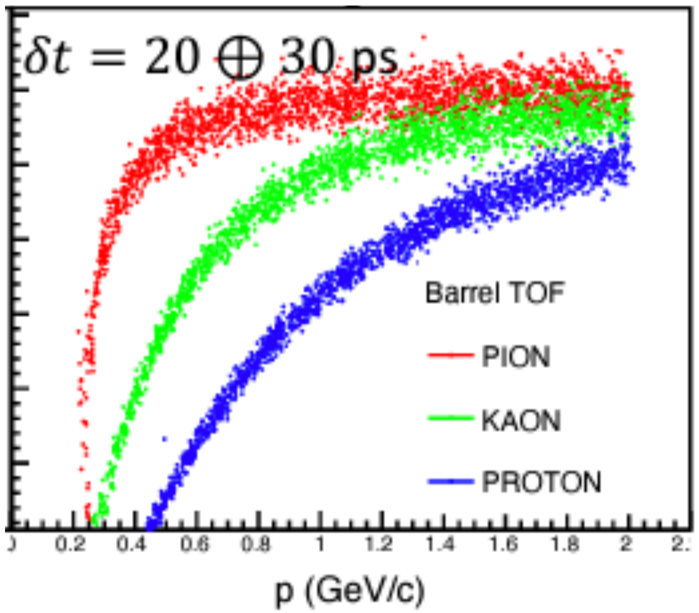
Barrel TOF
Single layer with 30 ps resolution and $2\%X_0$ material budget per layer

Forward TOF
Double layer with 25 ps resolution and $5\%X_0$ material budget per layer

Backward TOF
Double layer with 25 ps resolution and $5\%X_0$ material budget per layer

START Time
20 ps resolution

Barrel TOF simulation (eta=0)



Summary

- The CMS MIP Timing Detector will measure precision timing of charged particles produced inside CMS.
  - Provides significant pileup mitigation, furthering the experiment's mission in the HL-LHC era.
  - Brings new capabilities to CMS that could help to search new phenomena in the HL-LHC.
- BTL will be instrumented with LYSO crystals + SiPMs, read-out by the TOFHIR
  - Beginning of life performance (30-40 ps) within requirements
  - End-of-life performance (~ 60 ps) close to requirements → optimization of SiPM cell size ongoing
- ETL will be instrumented with LGADs read out by the ETROC
  - Performance at beginning and end of life within requirements (single hit resolution < 50 ps)
  - LGAD market survey done → Will enter a tender process soon.
  - Full-scale 16x16 ETROC2 arriving soon
- Common MTD DAQ system is being developed together for the ETL and BTL.
- Mechanical engineering of the full detector system is preparing.
- The development of CMS LGAD will have a positive impact on EIC.