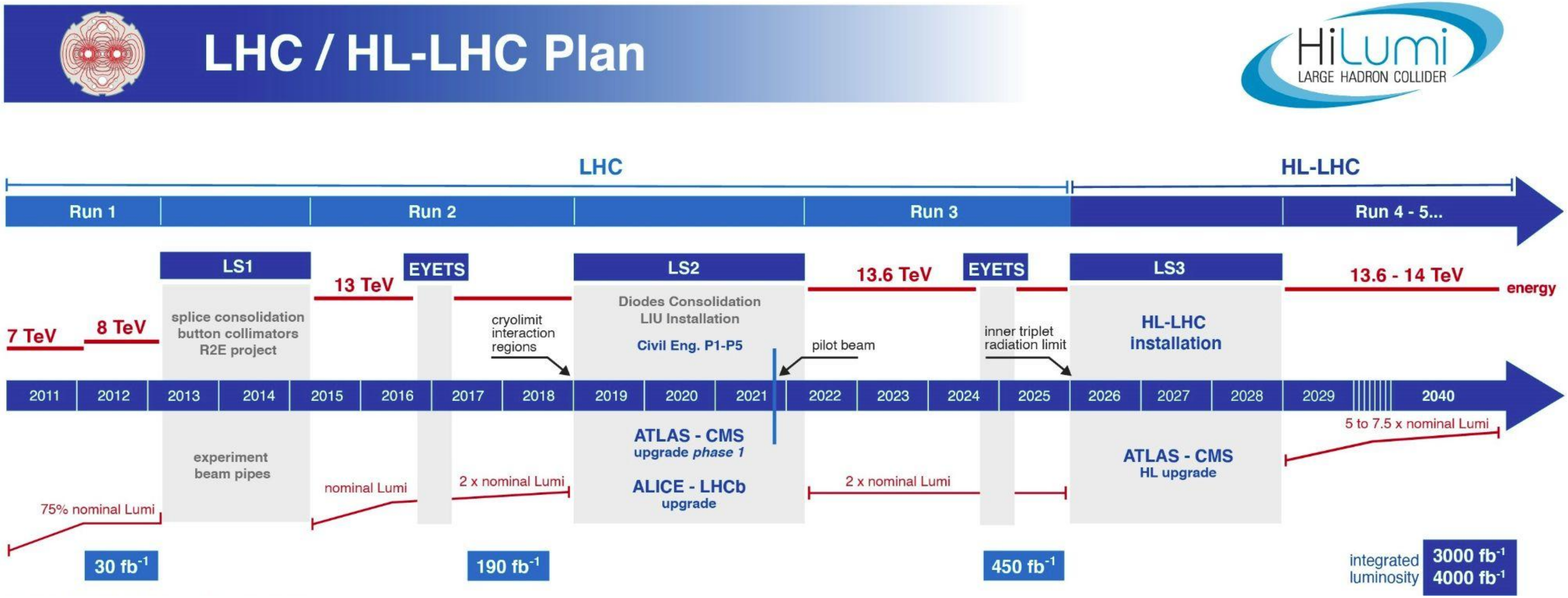
The Endcap Timing Layer detector for the CMS Phase-2 upgrade

Lazar Markovic on behalf of the CMS collaboration

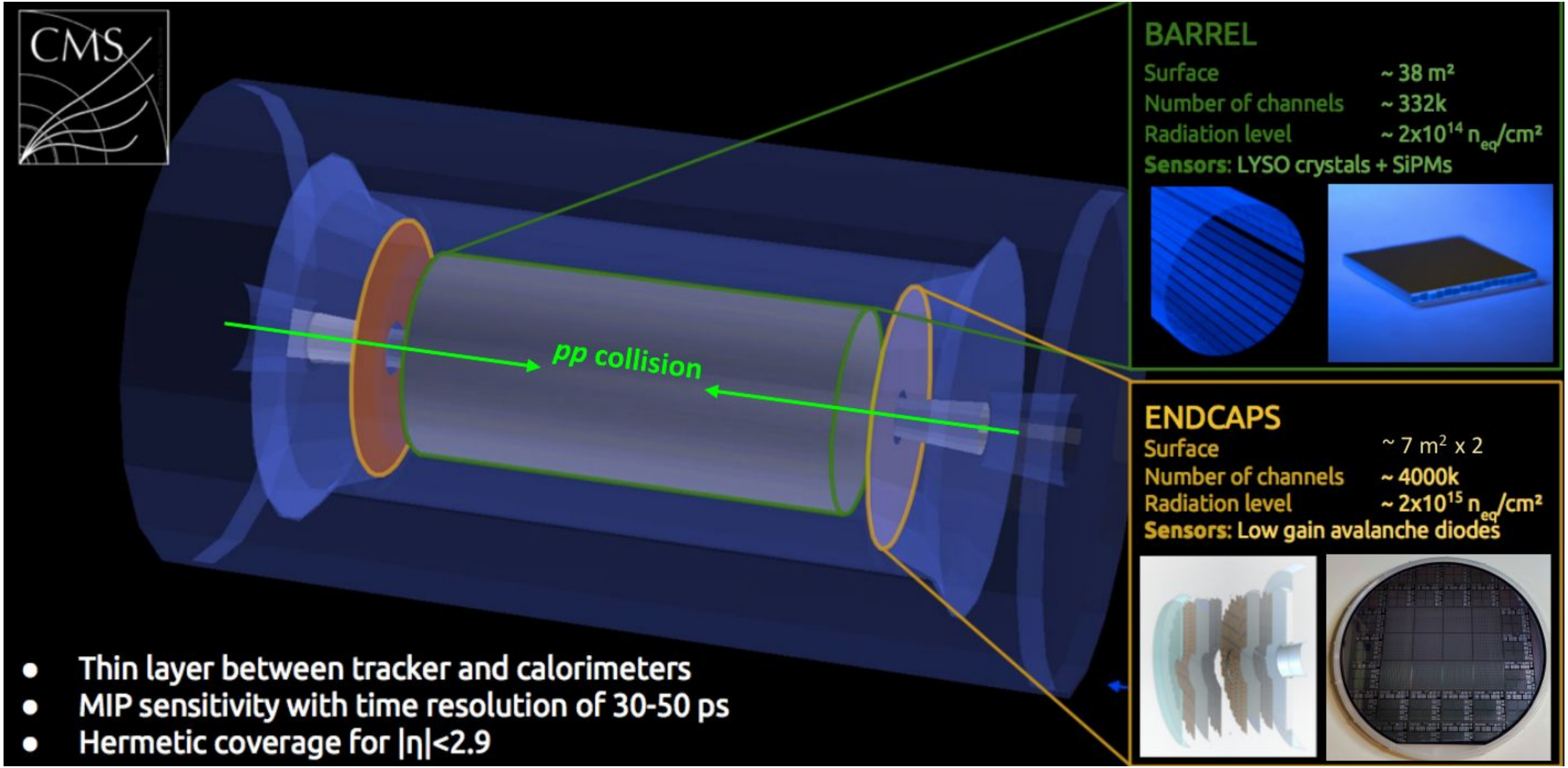
Elba Island, 31/05/2023, FAST 2023 workshop

High Luminosity LHC (HL-LHC)

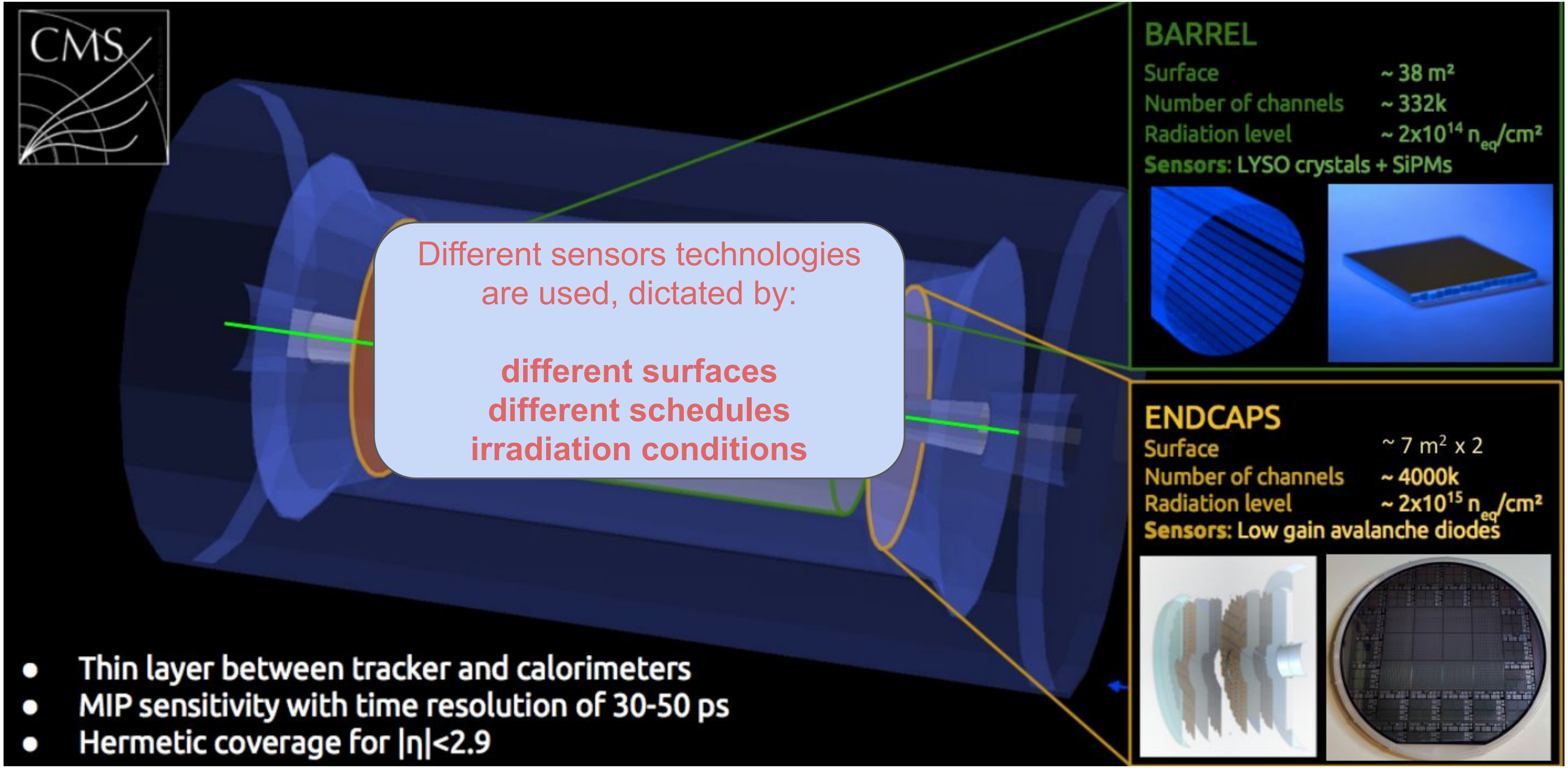


- ❖ Planned phase 2 upgrade will be done between 2026-28
- ❖ This talk is centered arround ETL of the CMS
- ❖ For why we need it, check out **Federico's** talk

MTD design


CMS
pp collision
BARREL
Surface ~ 38 m²
Number of channels ~ 332k
Radiation level ~ 2x10^14 n_eq/cm²
Sensors: LYSO crystals + SiPMs
ENDCAPS
Surface ~ 7 m² x 2
Number of channels ~ 4000k
Radiation level ~ 2x10^15 n_eq/cm²
Sensors: Low gain avalanche diodes
Thin layer between tracker and calorimeters
MIP sensitivity with time resolution of 30-50 ps
Hermetic coverage for |η|<2.9

MTD design


CMS
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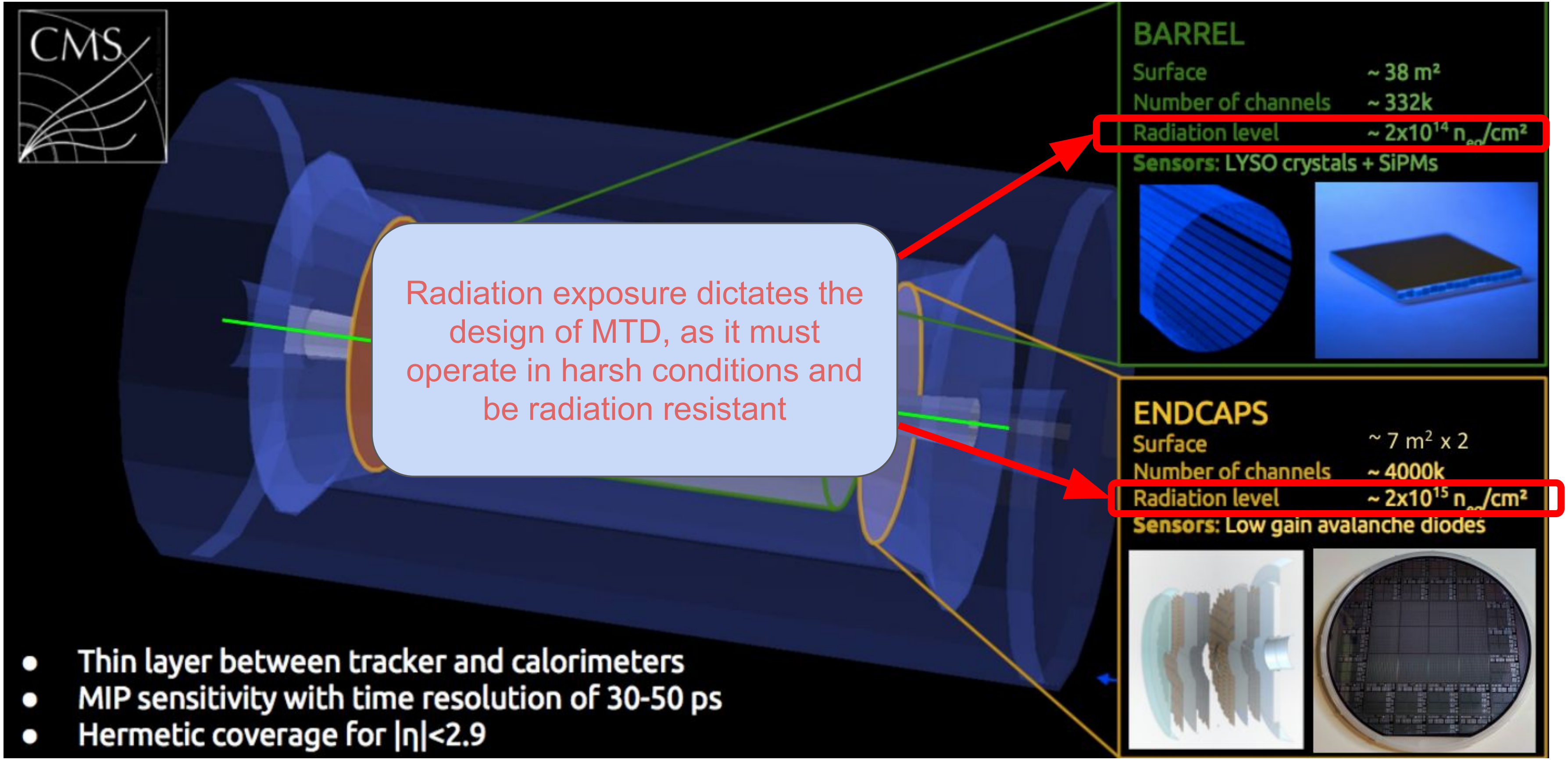
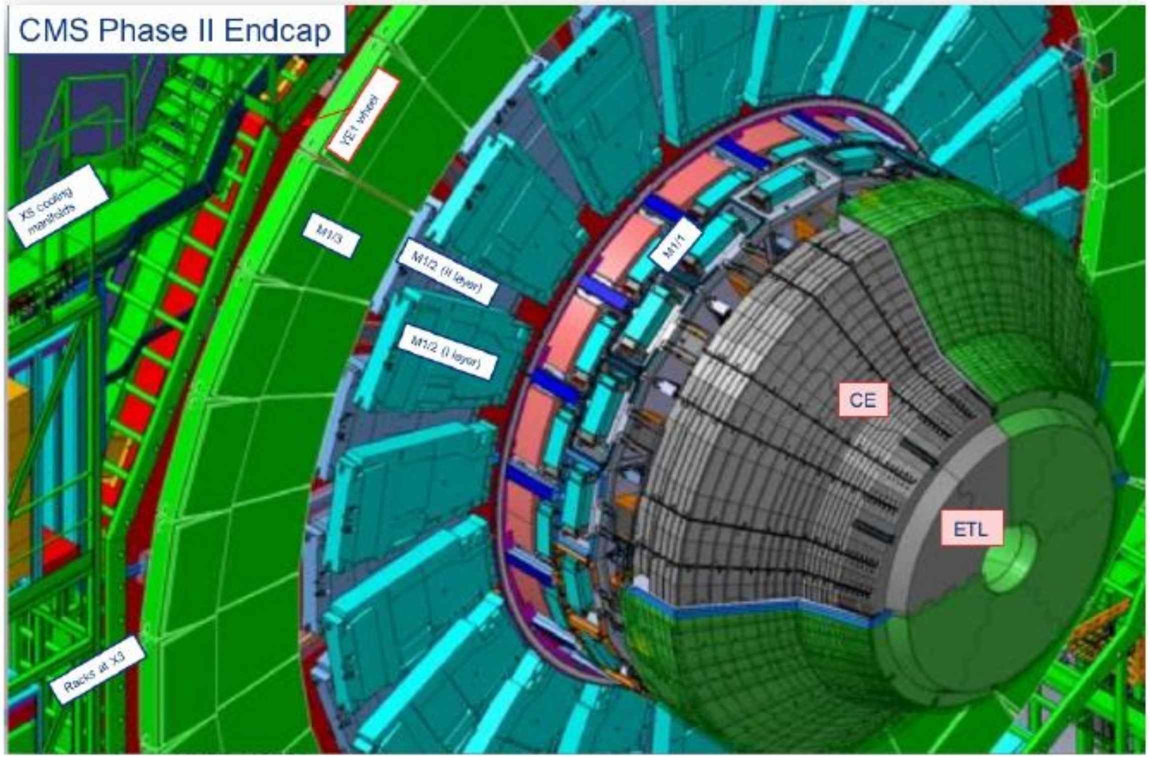
Surface ~ 7 m² x 2
Number of channels ~ 4000k
Radiation level ~ 2x10^15 n_eq/cm²
Sensors: Low gain avalanche diodes
Different sensors technologies are used, dictated by:
different surfaces
different schedules
irradiation conditions
Thin layer between tracker and calorimeters
MIP sensitivity with time resolution of 30-50 ps
Hermetic coverage for |η|<2.9

MTD design

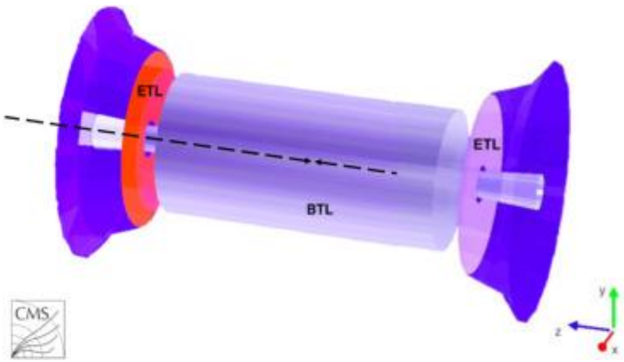


Radiation exposure dictates the design of MTD, as it must operate in harsh conditions and be radiation resistant

MTD ETL Design



Endcap region of the CMS detector: ETL will be mounted on the CE nose

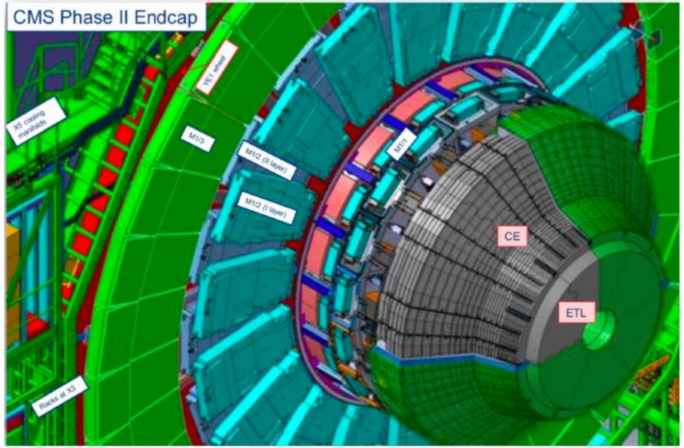


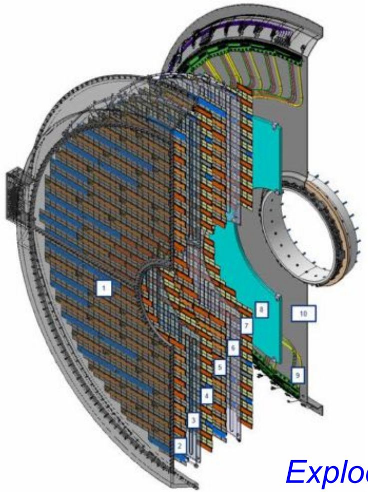
MTD design scetch

MTD ETL Design

- ETL will be mounted on the nose HGCAL
- Coverage:
  - z = 3 m from pp interaction
  - 0.315 m < R < 1.2 m
  - Surface ~ 14 m2

- 2 double-sided disks for each side
  - double-sided disk → large geometrical acceptance
  - 2 disks to achieve target time resolution:
    - Single hit resolution < 50 ps
    - track resolution < 35 ps

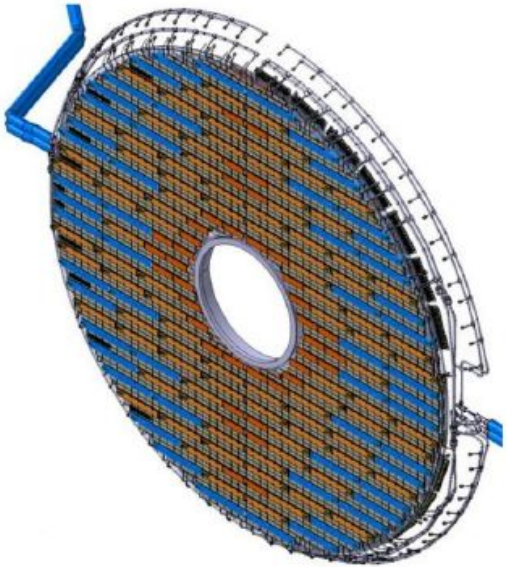




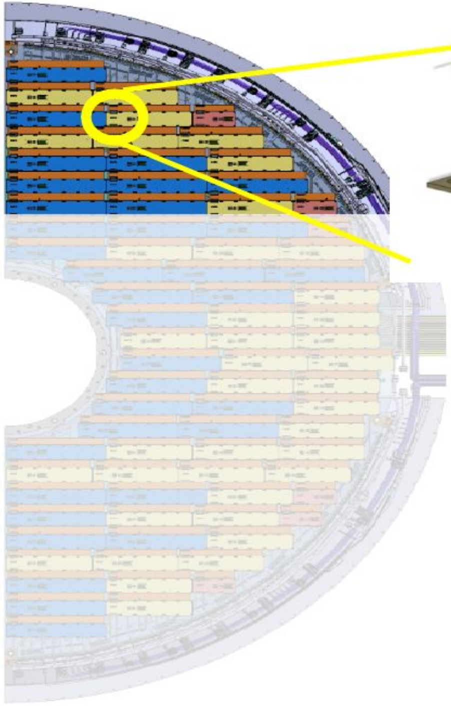
Element	
1	Thermal screen
	Gap between thermal screen and Face 1
2	Face 1 - active layer
3	Front disc
4	Face 2 - active layer
	Gap between Face 2 and Face 3
5	Face 3 - active layer
6	Back disc
7	Face 4 - active layer
	Gap between Face 4 and ETL front moderator
8+9	Patch panels 0 + cables [9] + ETL front moderator
10	ETL back support plate
	Gap between ETL back support plate and CE thermal screen

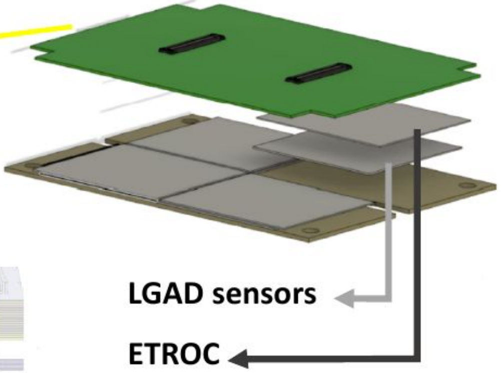
Exploded view of one of the ETL disks

MTD ETL Design

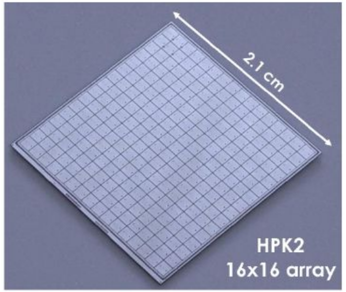


ETL disk





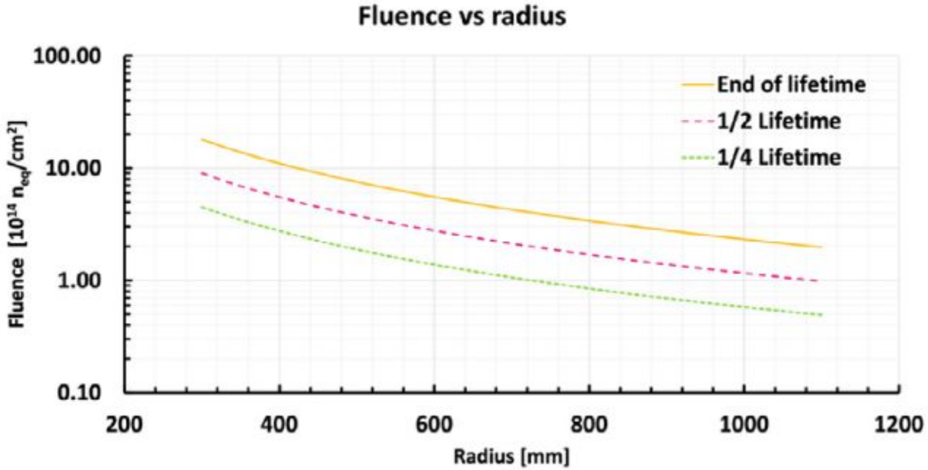
Zoomed in view of the ETL disk



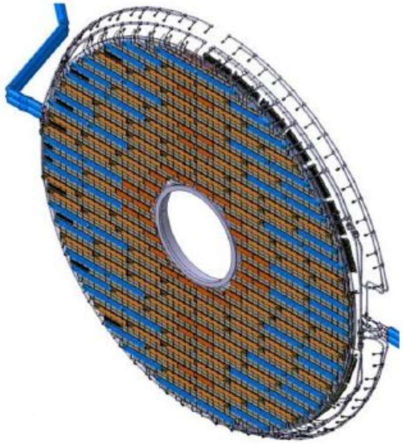
LGAD sensor matrix

MTD ETL Design

- 0.31 m < R < 1.2 m
- Fill-factor > 95 % (ratio of active and total detector surface)



Fluence vs radius of the ETL disk

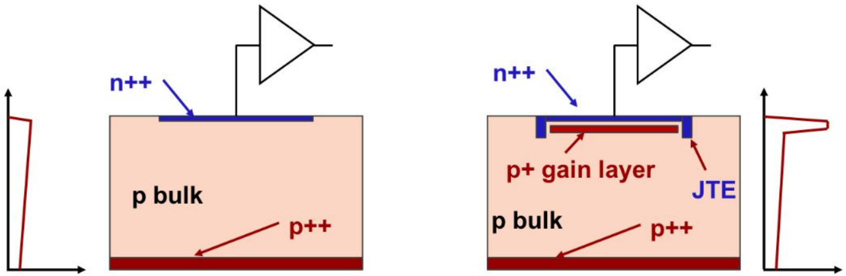


ETL disk

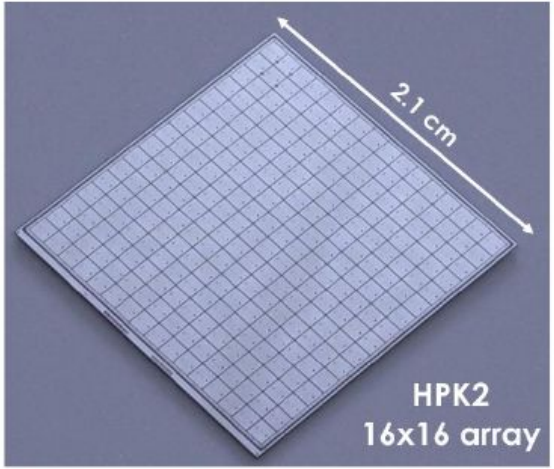
- Degradation of perfomanses begins at ~ $1\text{x}10^{15}\ n_{eq}/cm^2$
- ~88% ETL will be exposed to < $1\text{x}10^{15}\ n_{eq}/cm^2$
- About ~12% of ETL will be exposed to > $1\text{x}10^{15}\ n_{eq}/cm^2$
- Tolerable is ~$1.7\text{x}10^{15}\ n_{eq}/cm^2$

LGADs: Sensors for ETL

- The ETL sensor will be a 16x16 pad matrix of LGAD sensors
- 1.3 x 1.3 mm^2 pad size
- From the beginning to the end of HL-LHC lifetime, sensors expected to:
  - Achieve single hit time resolution < 50 ps when coupled to the ASIC (30-40 ps for the bare sensor)
  - Deliver > 8 fC of charge
- LGADs suited for radiaton: unchanged performance up to 1.5E15 n_{eq}/cm^2, and then slight slow degradation



E filed Traditional Silicon detector VS LGAD **E** field

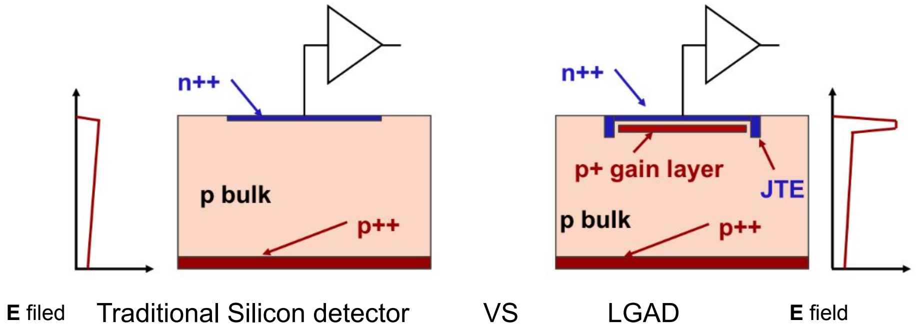


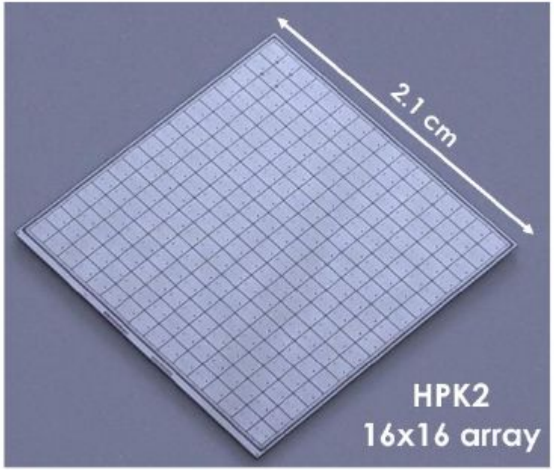
LGADs: Radiation affected performance

- ❖ There are two major effects that affect the performance:
  - ➢ **Gain layer depletion**
  - ➢ **Single Event Burnout (SEB)**

- ❖ **Gain layer** can be "recovered" by increasing the bias V_{bias} (see following slides) and using carbon to harden it

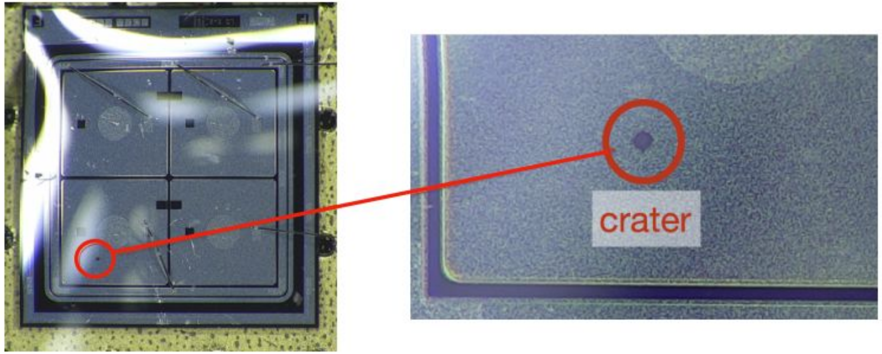
- ❖ **SEB** can be avoided by carefully choosing V_{bias} range (see following slides)

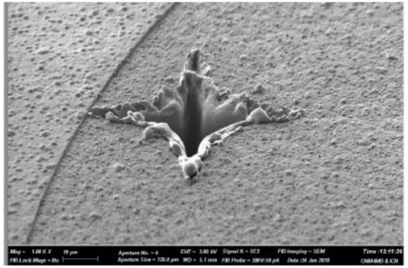


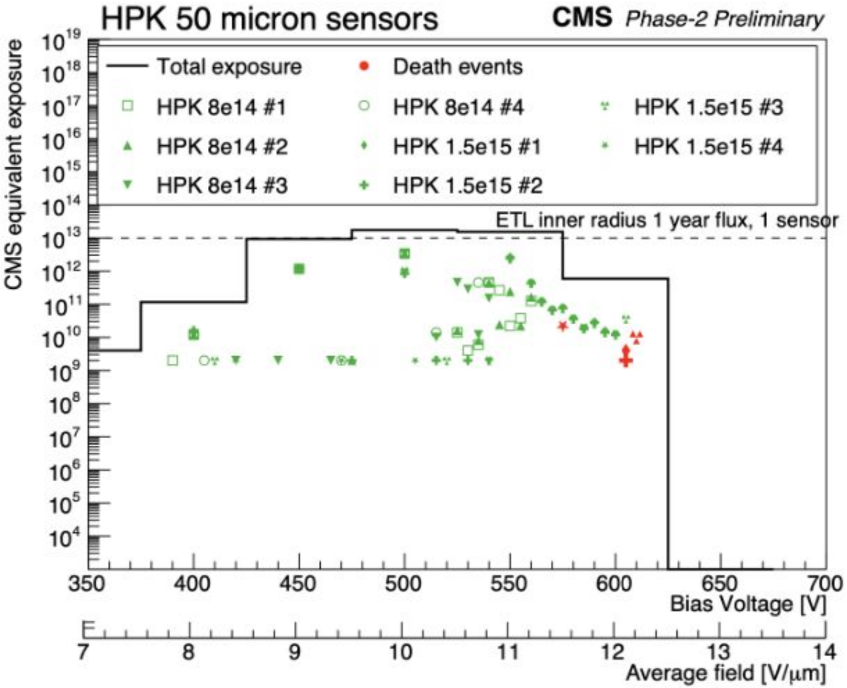


SEB

- High-rate test beam at FNAL demonstrate survival of irradiated LGADs at > 11 V/µm under a flux corresponding to ~1 year running for the sensors in ETL inner region



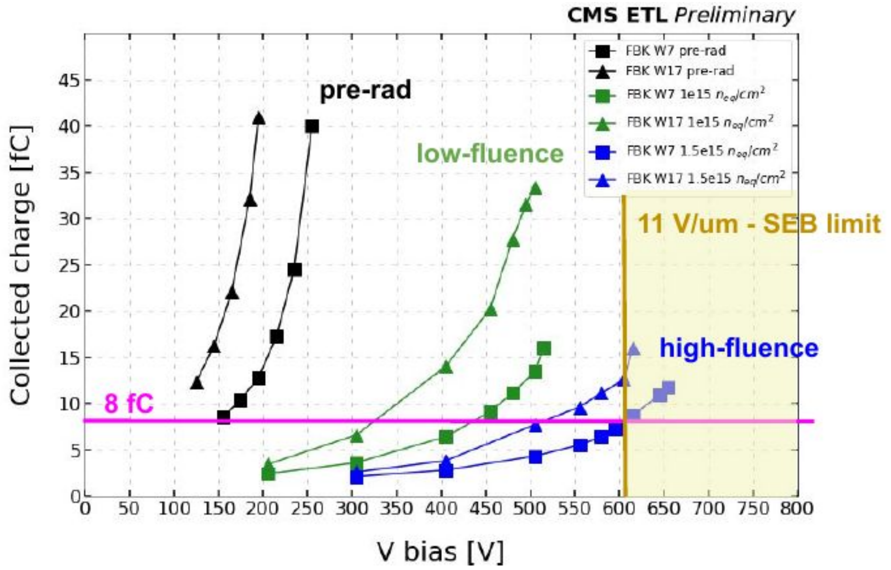


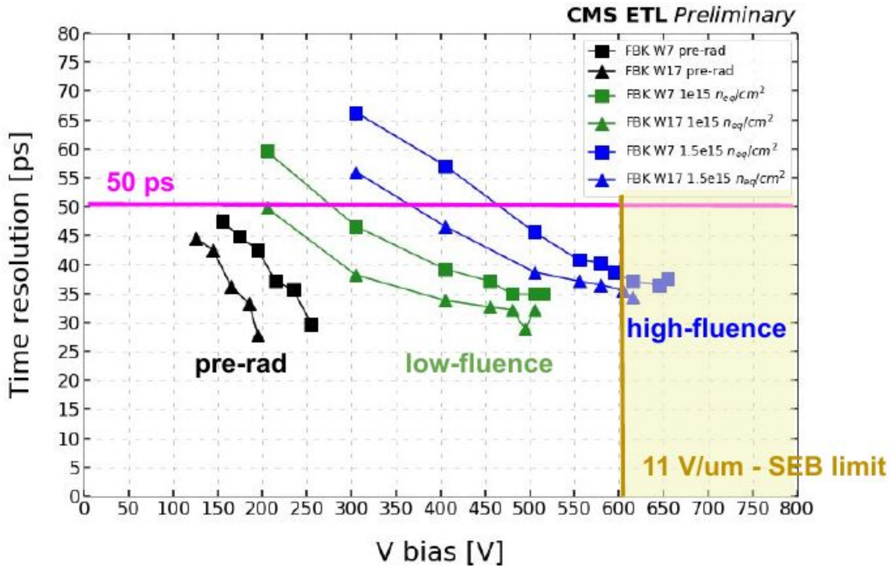


Lazar Markovic, *The Endcap Timing Layer detector for the CMS Phase-2 upgrade*, 2023 FAST Workshop, 31/05/2023

Performance of LGADs

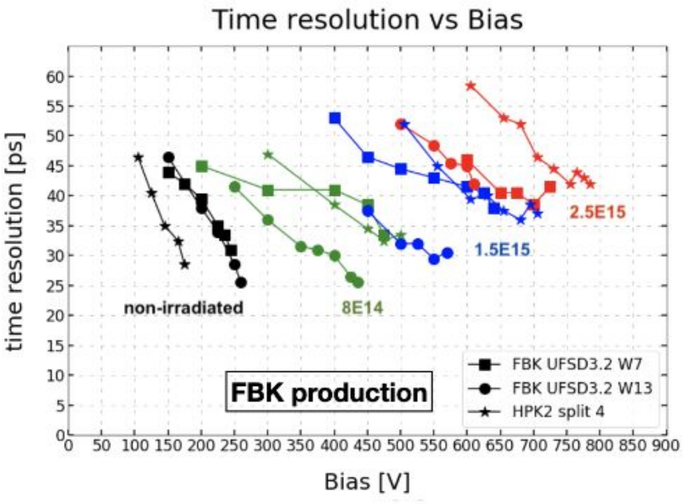
- Not safe regime due to Single Event Burn-out process affecting LGADs
  - E bulk < 11 V/µm
  - An incoming particle releases a lot of energy over a small volume, 5-10 µm
  - The local electric field is high enough to create a conductive channel
  - The energy stored in the sensor capacitance discharges burning the sensor

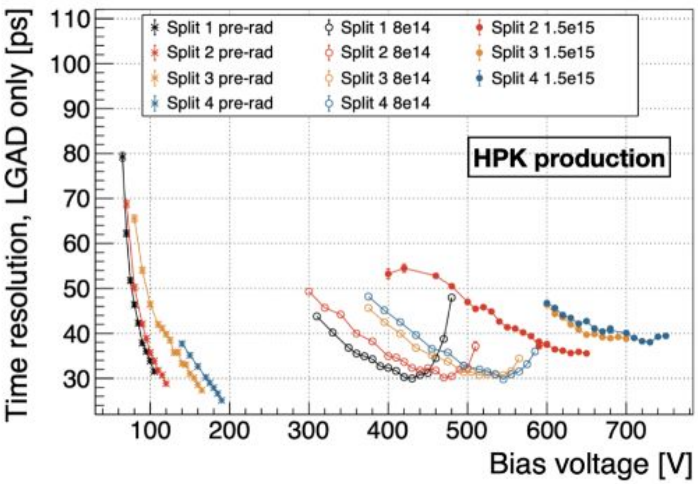




Performance of LGADs

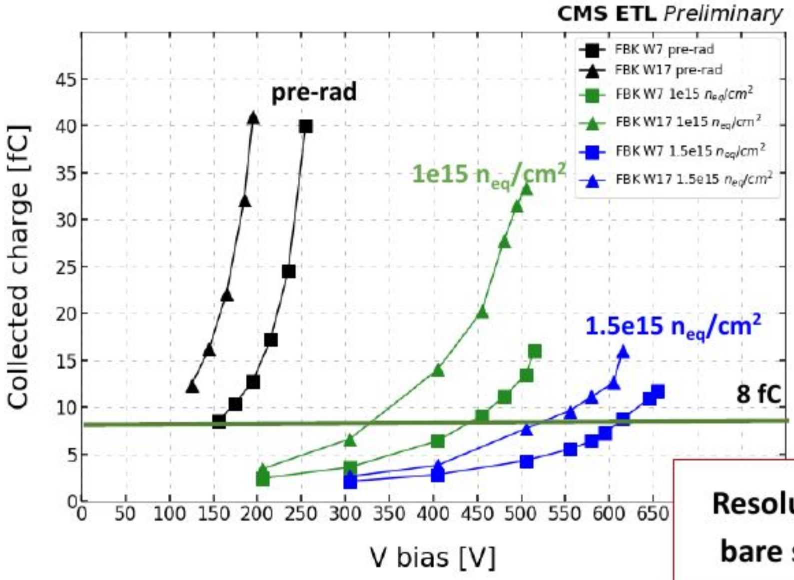
- Timing resolution measurements have been performed in Torino and at Fermilab
  - Using beta-source setups ^{90}Sr (2 MeV)
  - Very fast low noise electronic
  - Temperature -25 °C
  - For different fluencies

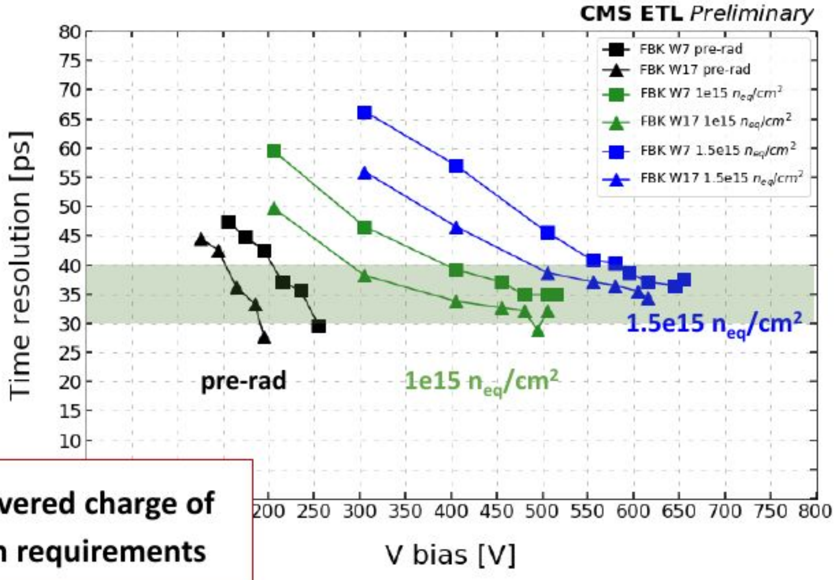




Performance of LGADs

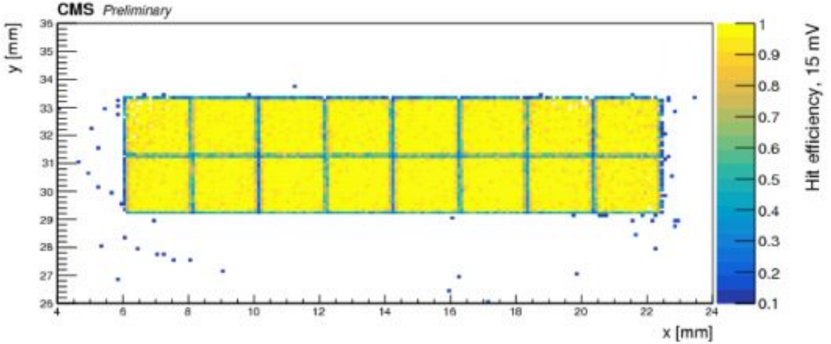
Example of MS sample performance: FBK (55 microns thick) measured with a beta-source setup





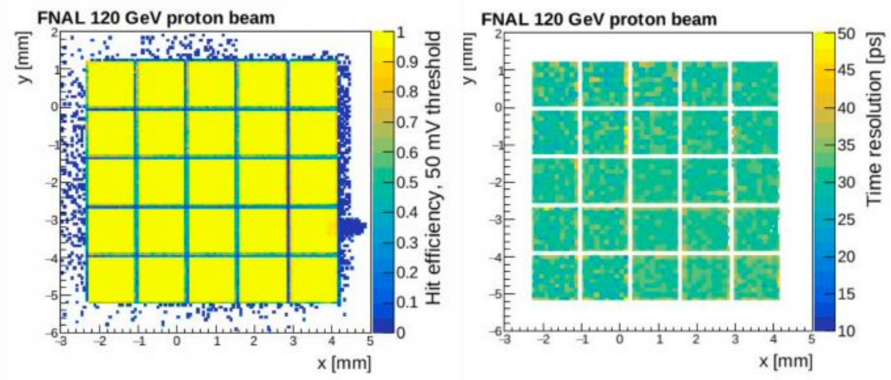
Resolution and delivered charge of bare sensors within requirements

Performance of LGADs

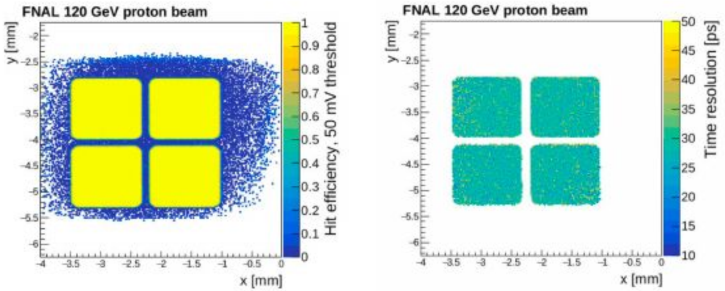


FBK 2×8 array (first prototype sensor production)

Irradiated 8e14 n_{eq}/cm^2



Non-irradiated FBK 5x5 array



Non-irradiated IHEP IME 2x2 array

- Maps measured at FNAL
- Resolution for non irradiated sensors ~ 30 ps
- Hit efficency
  - reaches ~ 100 % for non irr.
  - reaches ~ 99 % for irr.

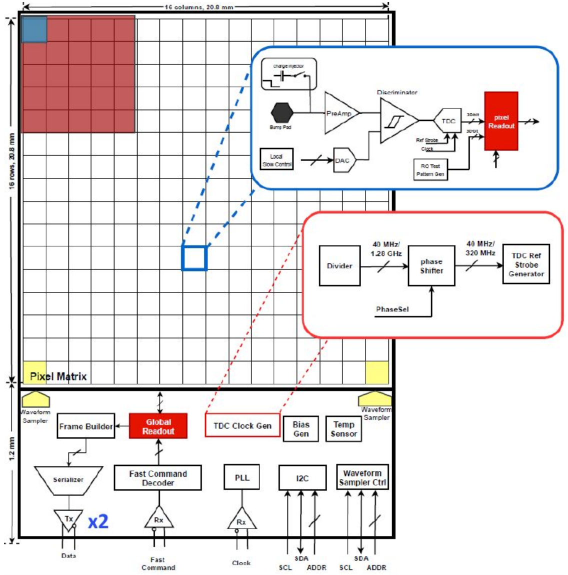
ETL Read-Out Chip (ETROC)

- ETROC is the ETL read-out ASIC

- Electronics needs to read all the channles, it's brand new, never been done before

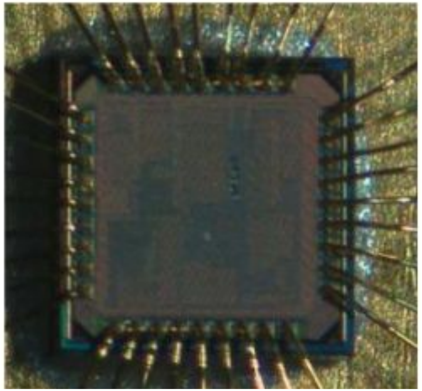
- **ETROC+LGAD** should achieve a time resolution **< 50 ps** per single hit
  - 65 nm technology, 100 MRad (TID spec)
  - low noise + fast rise time
  - power budget: 1 W/chip, 3 mW/channel
  - ETROC measures arrival time of signal (6 –20 fC)
  - **ASIC** contribution to time resolution **< 40 ps**
  - L1 buffer latency: 12.5 us
  - ENC = ~ 0.3 fC

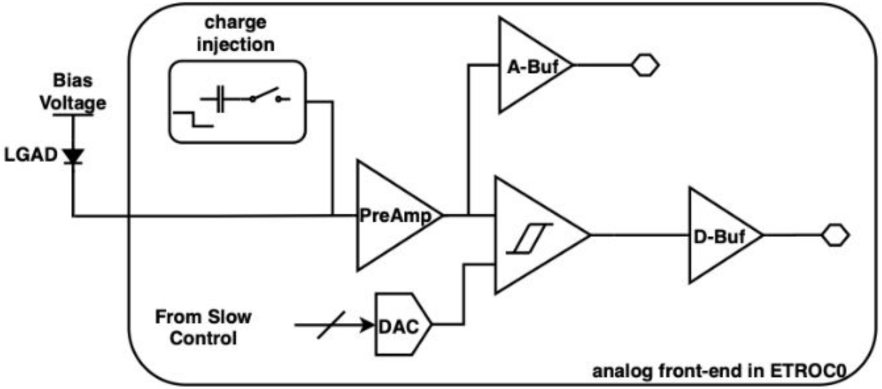
- ETROC is developed in stages (ETROC0/1/2/3)



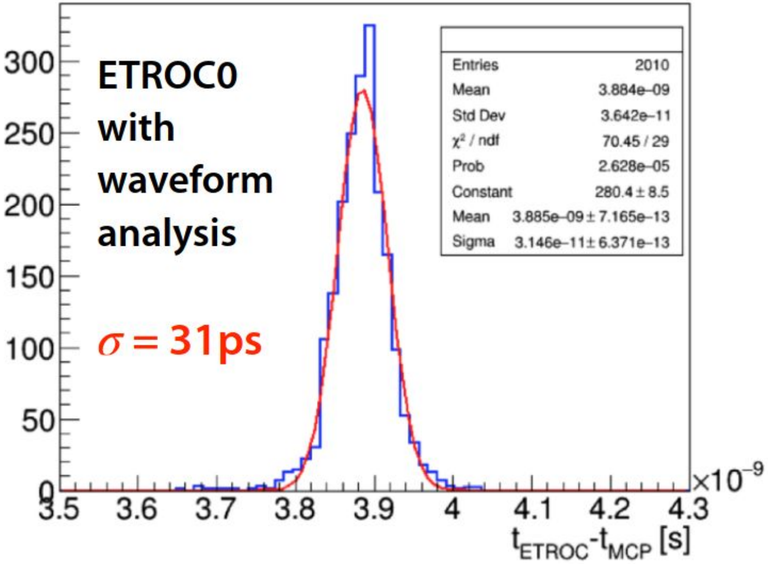
Showcase of ETROC 2 design

ETROC0

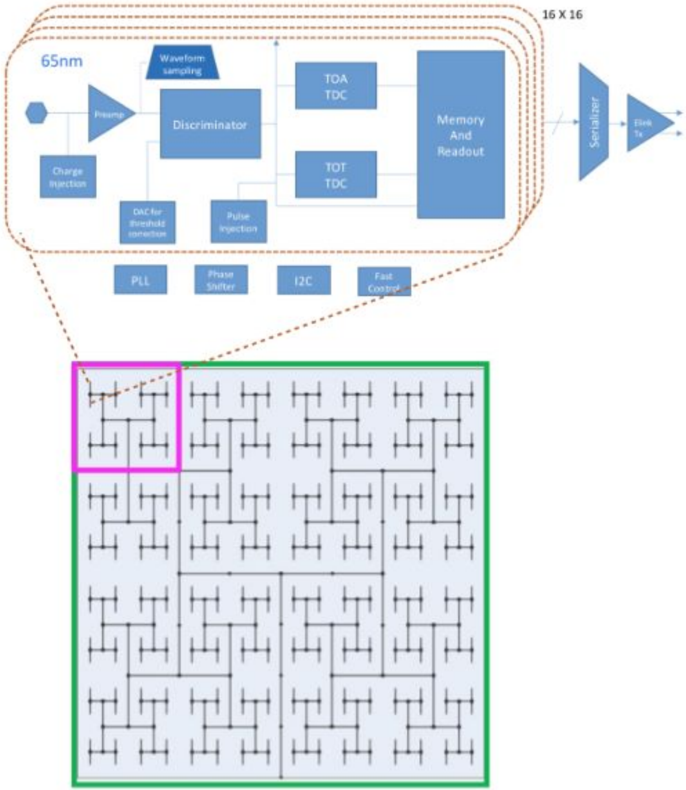




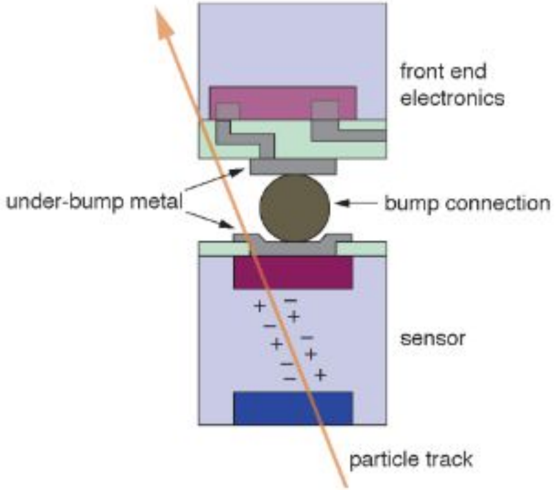
- ETROC0
  - ➢ Single analog channel
  - ➢ Pre-amp + discriminator
  - ➢ TID up to 100 Mrad
  - ➢ 30 ~ 40 ps time resolution in test beam



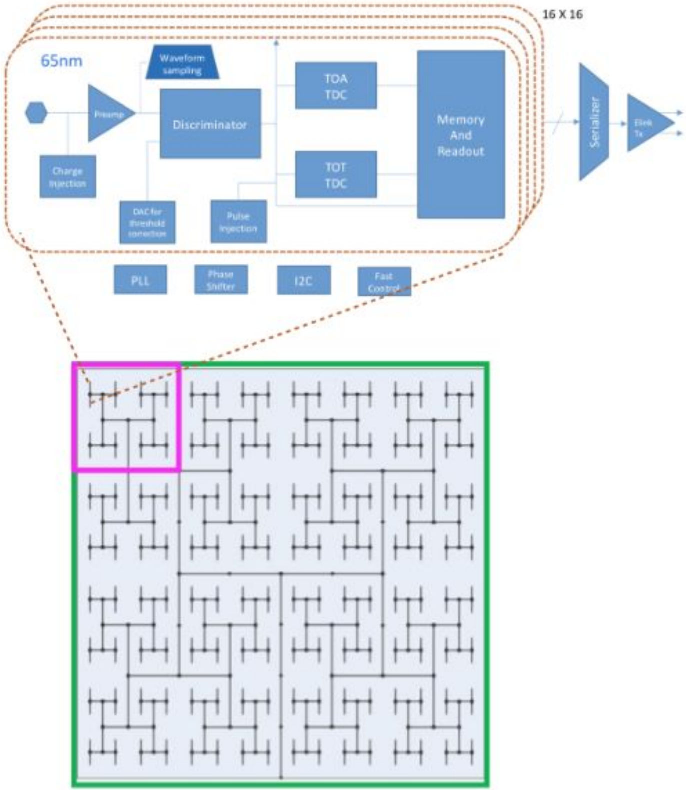
ETROC1

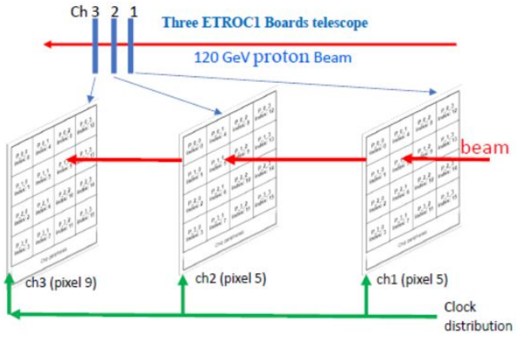


- ❖ ETROC1: with TDC, 4x4 channel - clock tree
- ❖ ETROC1 proved to be able to reach **~40 ps** resolution when coupled to LGAD (measured at FNAL with 120 GeV proton beam)

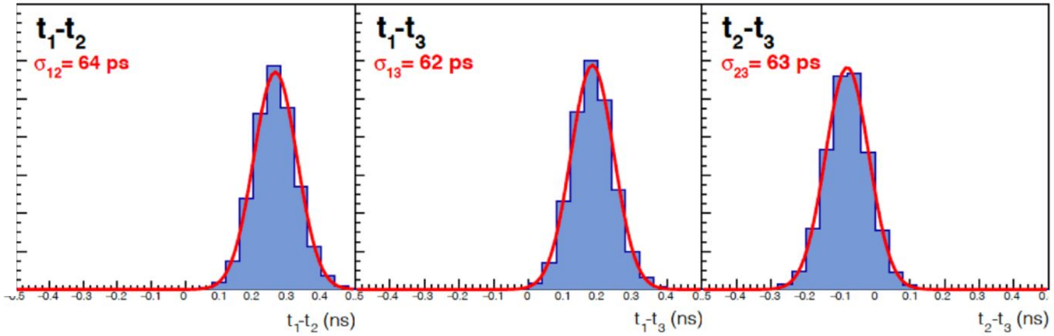


ETROC1

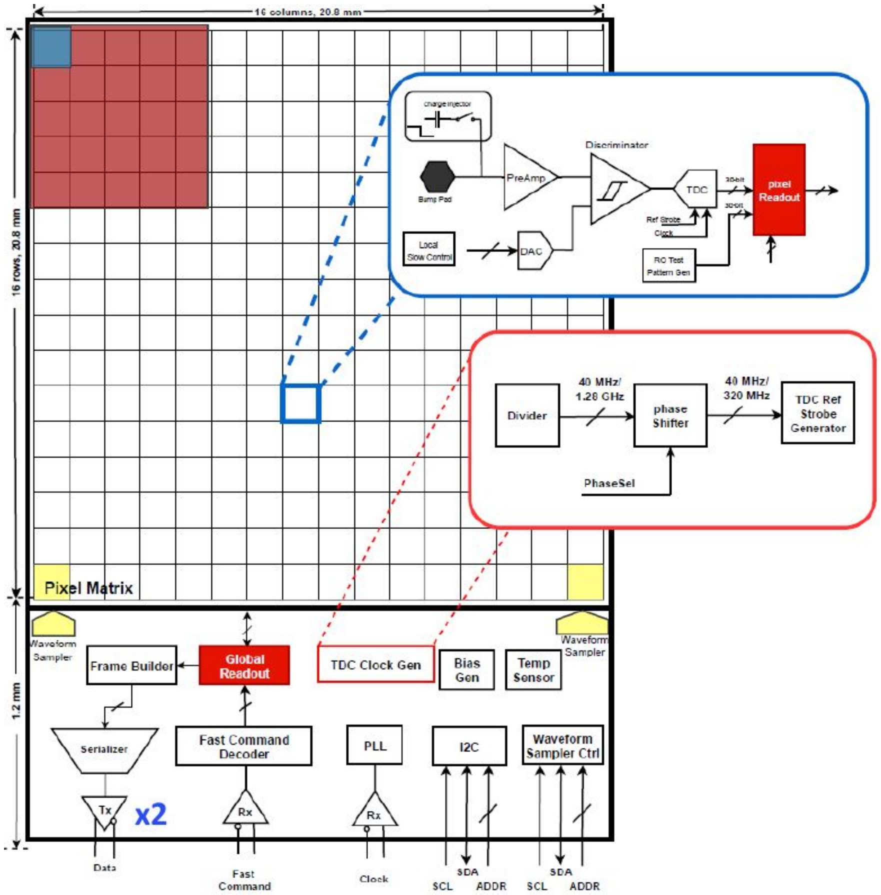




$$\sigma_i = \sqrt{0.5 \cdot (\sigma_{ij}^2 + \sigma_{ik}^2 - \sigma_{jk}^2)} \quad \sim 42 - 46 \text{ ps}$$



ETROC2



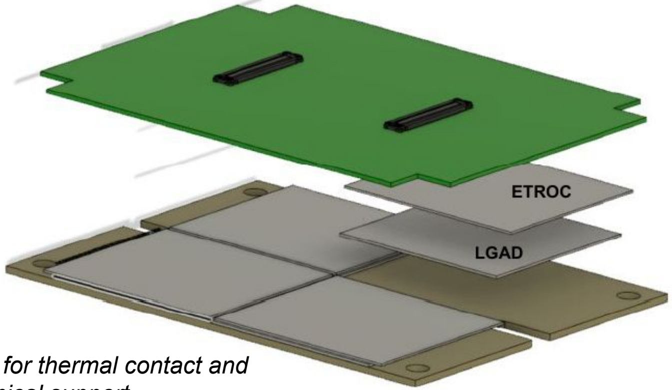
- ❖ ETROC2: full size, full functionality
- ❖ ETROC2 + LGAD testing coming soon 2023/24:
  - ➢ First, beta source and laser tests with wire-bonded LGAD
  - ➢ Build experience and debug → bump-bonded LGAD in beam

ETROC0: single analog channel
ETROC1: with TDC, 4x4 channel - clock tree
ETROC2: full size, full functionality
ETROC3: final chip!

ETROC Assembly

- Modules are based on 4 16x16 pixel LGAD sensors,bump bonded to one ETROC each
- Sensors are glued on AlN baseplate and in thermal contact with the cooling
- Wire bonds to PCB Modules are directly connected to multi-module readout board that sits on top disk
- Readout board based on CERNs rad-hard Low Power Gigabit Transceiver (lpGBT) and Optical Link Module (VTRx+)

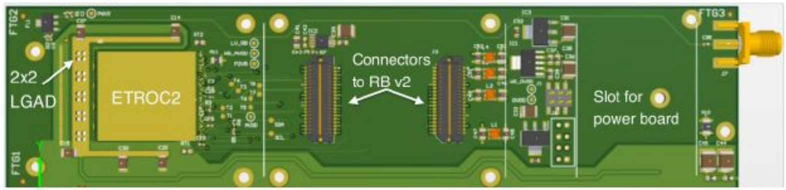
module PCB (allows connection to the read-out board)

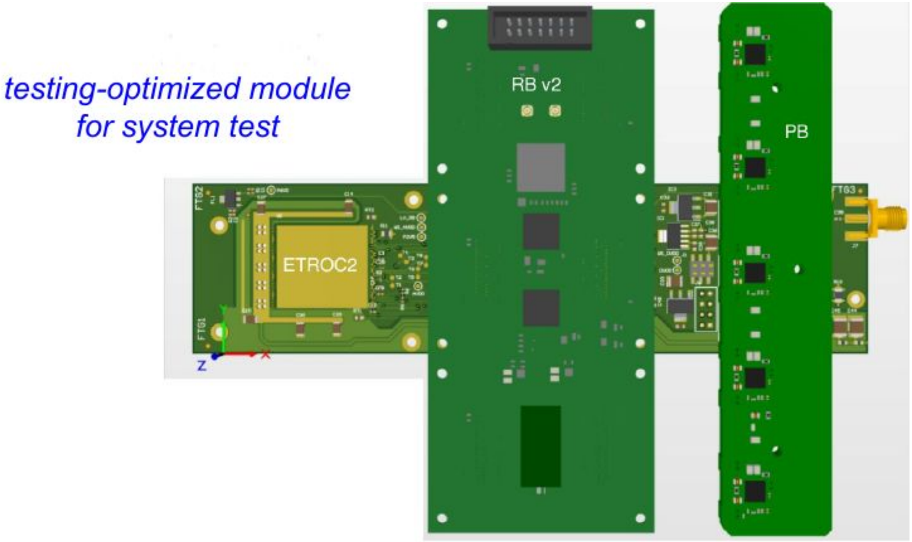


ceramic baseplate for thermal contact and mechanical support

ETROC2

- ❖ Designing a testing-optimized module compatible with ETROC2, read-out board and power board, and with a bump-bonded 16x16 → will enable a full system test!





Summary

- ❖ The design of MTD is heavily influenced by harsh conditions of radiation
- ❖ LGAD sensors will be used, providing resolution of < 50 ps, with collected ~10 fc of charge
- ❖ MS performanse gives good results (shown for FBK)
- ❖ ETROC1 + LGAD reaches desired resolution of ~ 40-50 ps
- ❖ Full-size read-out chip ETROC2 arriving soon
- ❖ Top priority of the next months: validation of LGAD + ETROC2 based prototypes

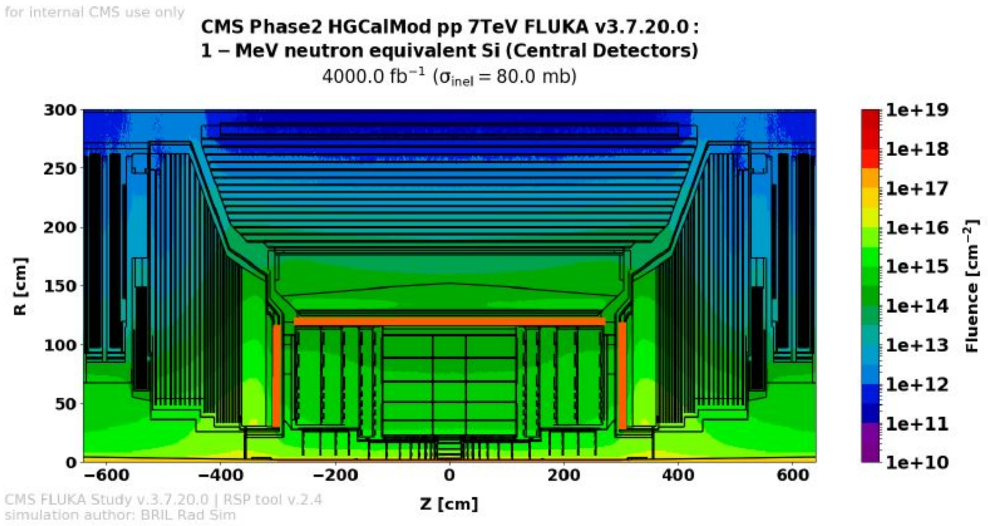
THANK YOU FOR YOUR ATTENTION

BACKUP

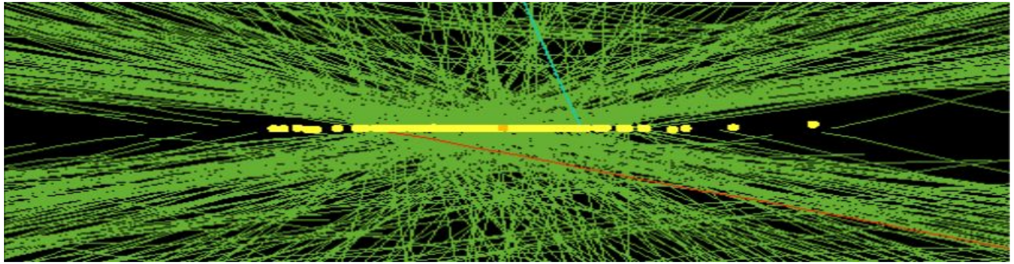
High Luminosity LHC (HL-LHC)

- Up to **5x** higher vertex density

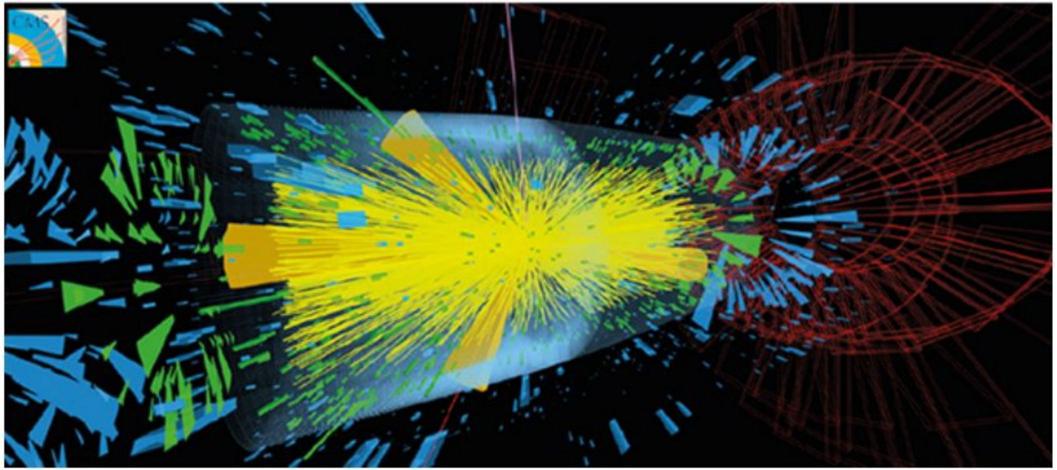
- Unprecedented radiation levels
  - ~10x higher then presen LHC
  - Expected fluence up to several 10^{16} neq/cm^2



- Expected fluence dictates the technologie development for subdetectors



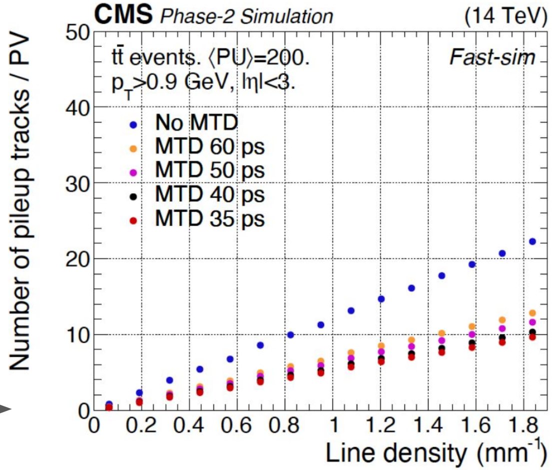
Motivation for Tracker upgrade



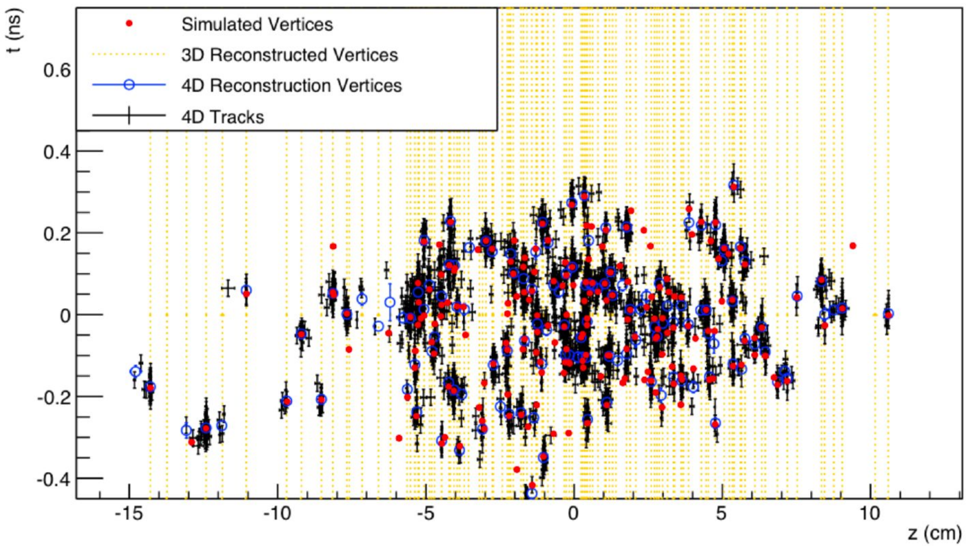
VBF H→τ τ
simulation 200 pp pile-up

Interactions are distributed over time (and space) with an RMS of **180-200 ps**

Simulation: Number of pileup tracks incorrectly associated with the hard interaction vertex as a function of the collision line density for different time resolution and time reconstruction efficiency of 0.85



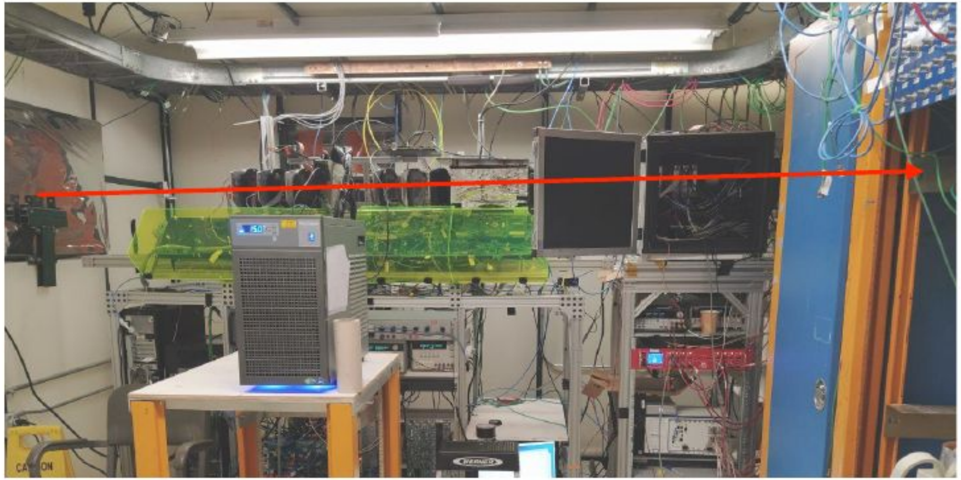
Motivation for Tracker upgrade

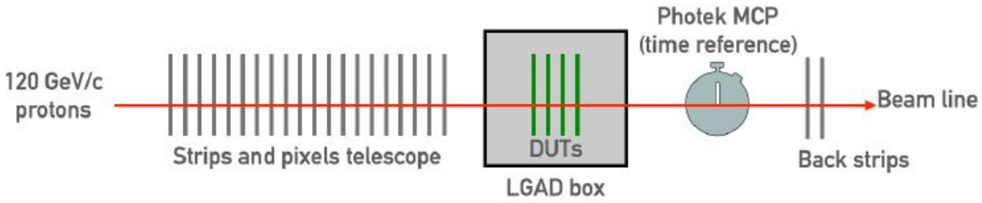


With a resolution of **35 ps**, vertex merging is reduced from **15%** in space to **1%** in space-time, as in the current operating mode of the LHC

- The MIP Timing Detector (**MTD**)
  - Will measure the time of passage of charged particles with a resolution of **30-40 ps**
  - This precision will decrease to **50-60 ps** towards the end of the HL-LHC operation
  - In addition to being "fast", it must be able to withstand harsh conditions/radiation
  - Charged tracks/vertices association with photons and hadronic showers

LGAD sensors - FermiLab test



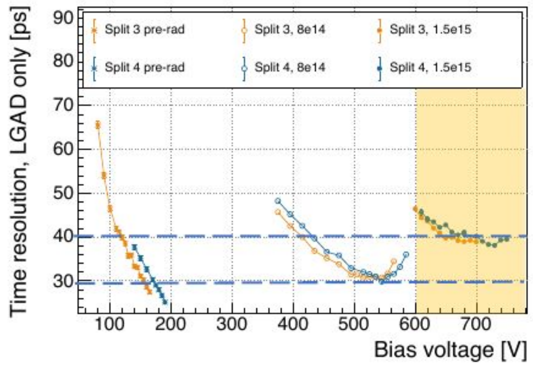


- ❖ Proton beam 120 GeV/c
- ❖ Scintilator used as a trigger
- ❖ Telescope monitors the position
- ❖ MCP (resolution 10ps) for time reference
- ❖ Cooling chamber

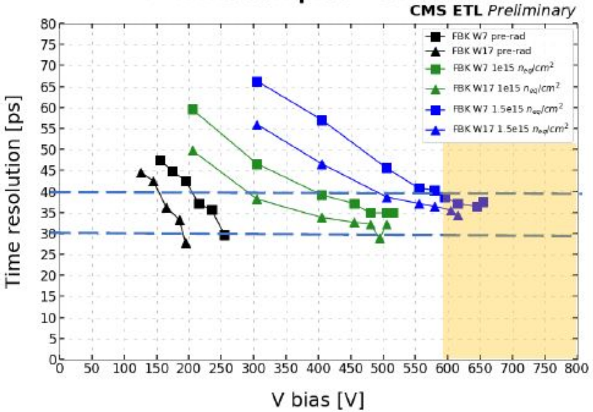
2021

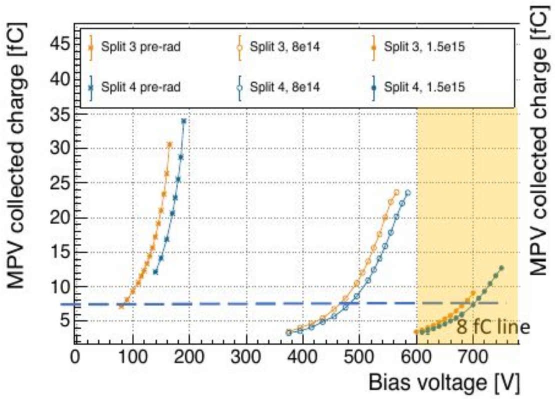
LGADs: Time resolution - charge collected

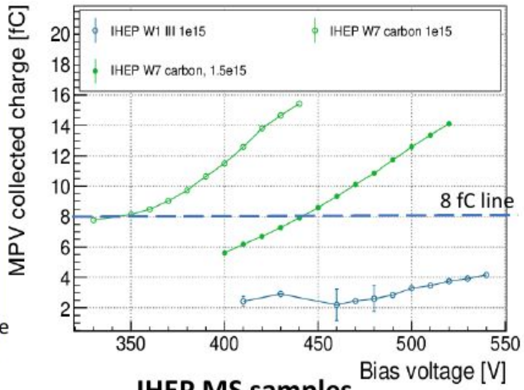
HPK MS samples – HPK2



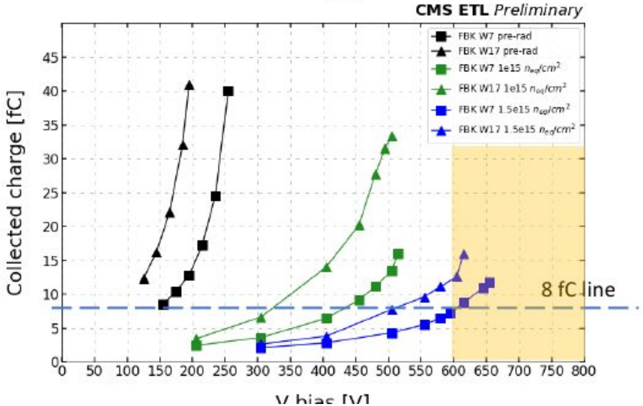
FBK MS samples – UFSD4







IHEP MS samples



Desy TeastBeam, November 2022

Siviero F. , MTD ETL sensors qualification and test plans, CMS upgrade Days 2023

- **First test beam ever with 16x16 LGADs**
  - Previous ones only with small prototypes
- Three vendors tested: HPK, FBK, IHEP-IME
- Very nice agreement with previous results from small prototypes
- All sensors achieved the target performance both in terms of time resolution and delivered charge