# Status overview of Korean group activities for MTD ETL


**Dong Ho Moon**

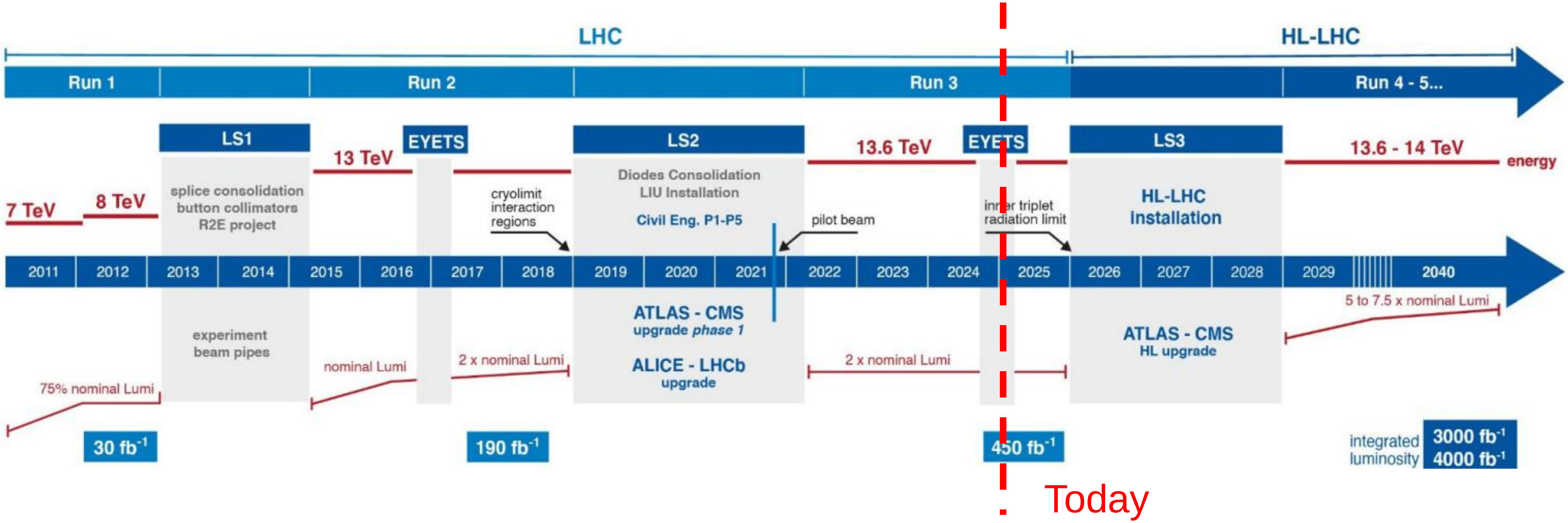
**On behalf of CMS collaboration**

**Chonnam National University**


**2025/01/15 ATHIC 2025 @ Odisha, India**

# High Luminosity LHC Era is coming

- LHC beam optics and injectors are upgrade to increase the intensity
  - Purpose to increase the LHC performance to maximize the potential for new discoveries after 2029
  - The luminosity will increase from 1.7 x $10^{34}$ $cm^{-2}s^{-1}$ up to 7.5 x $10^{34}$ $cm^{-2}s^{-1}$
  - Current collected data (2009-2025) : ~ 400 $fb^{-1}$
  - Target luminosity (2029-2042) : > 3000 $fb^{-1}$ (1 year data equivalent to ~ 10 years of collected data)



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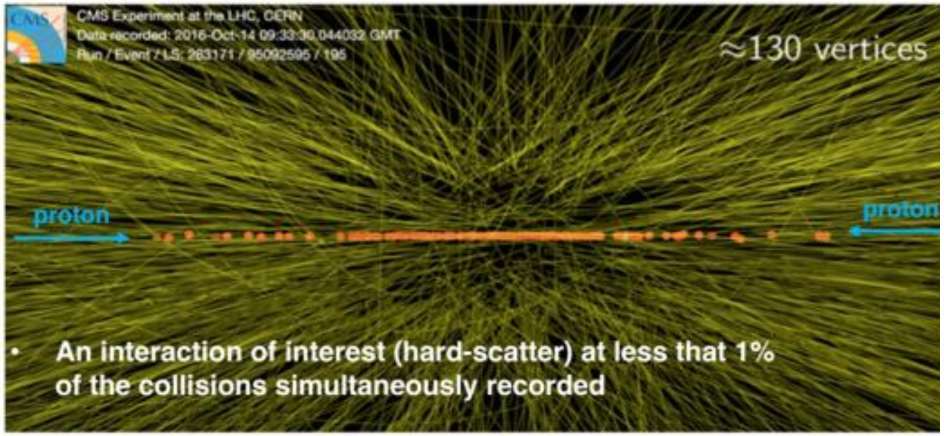
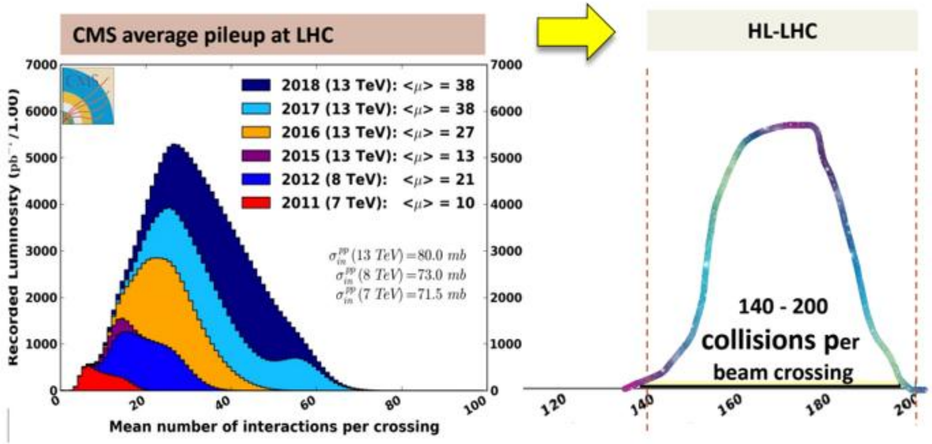
  - ~130 vertices in one bunch collisions
  - Need to weed out the experimental observables in pileup events

**Real life event at the LHC emulating HL-LHC conditions**



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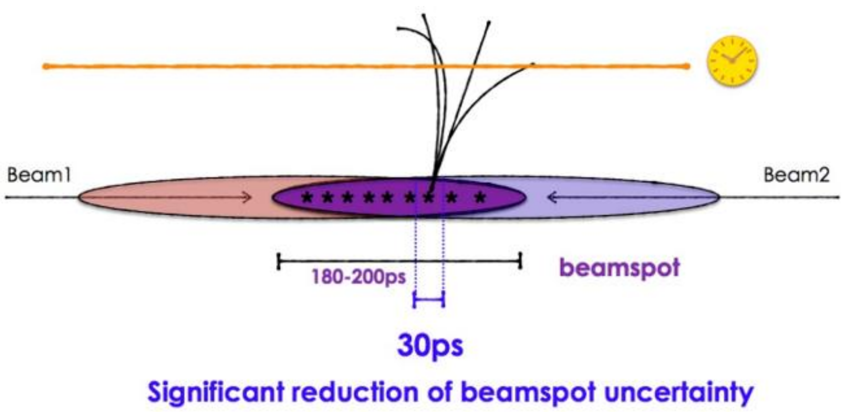


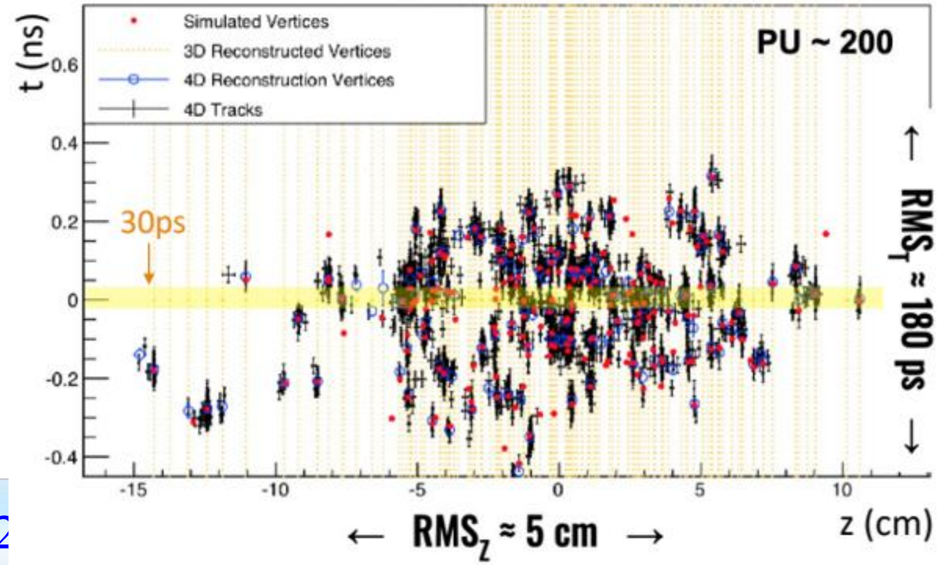

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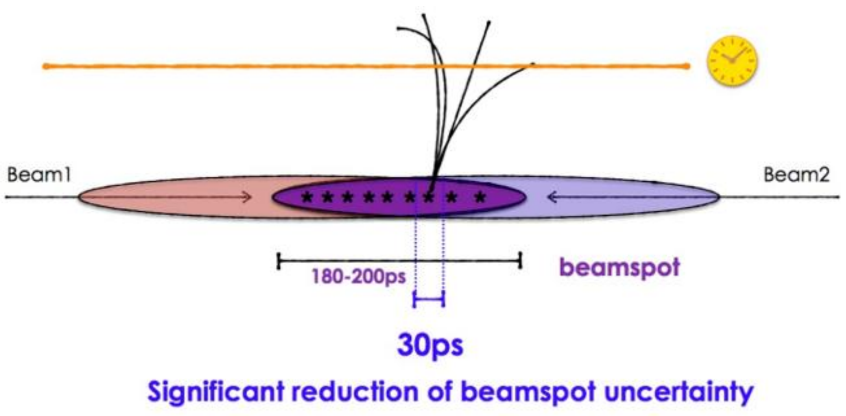
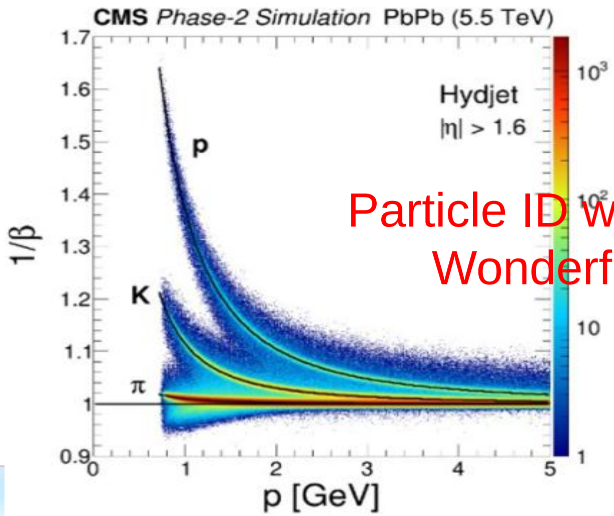
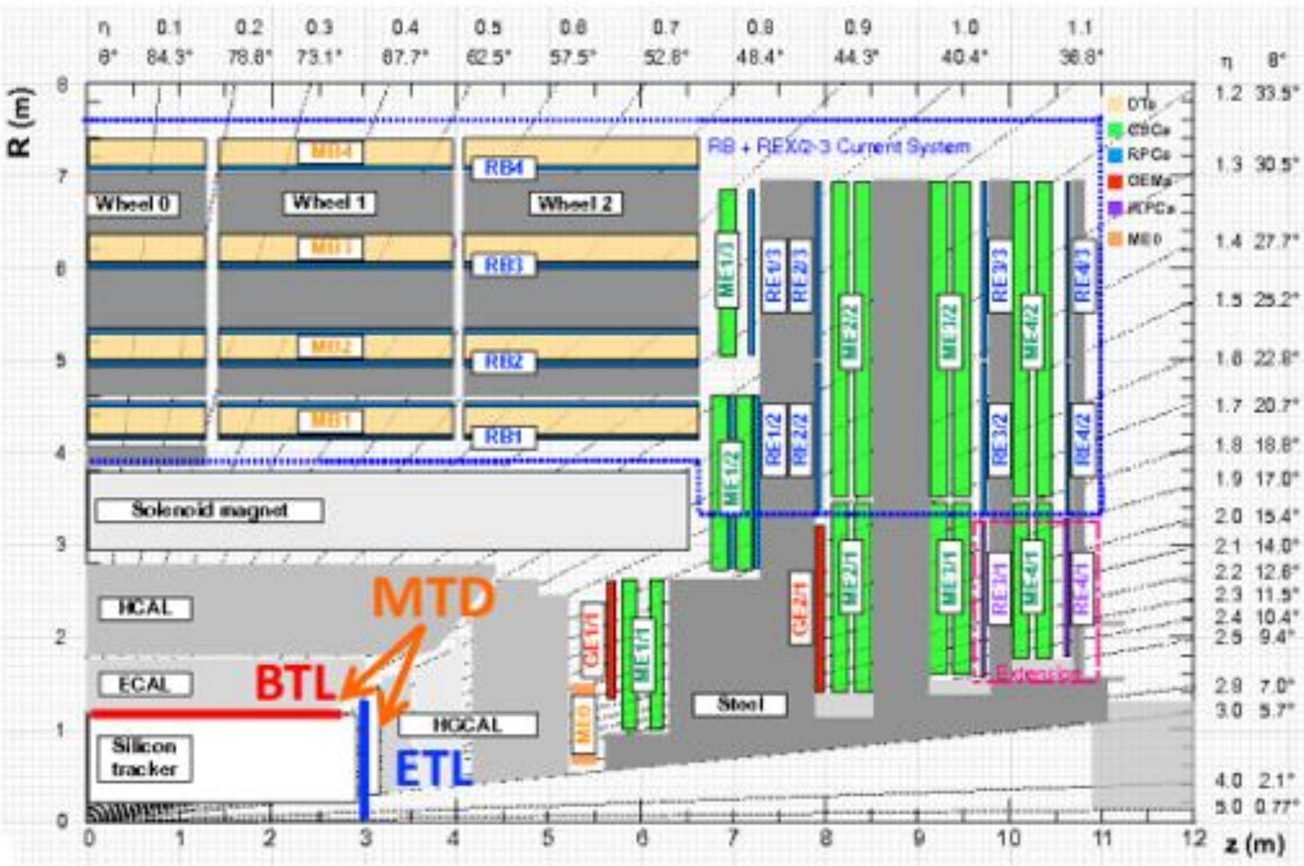


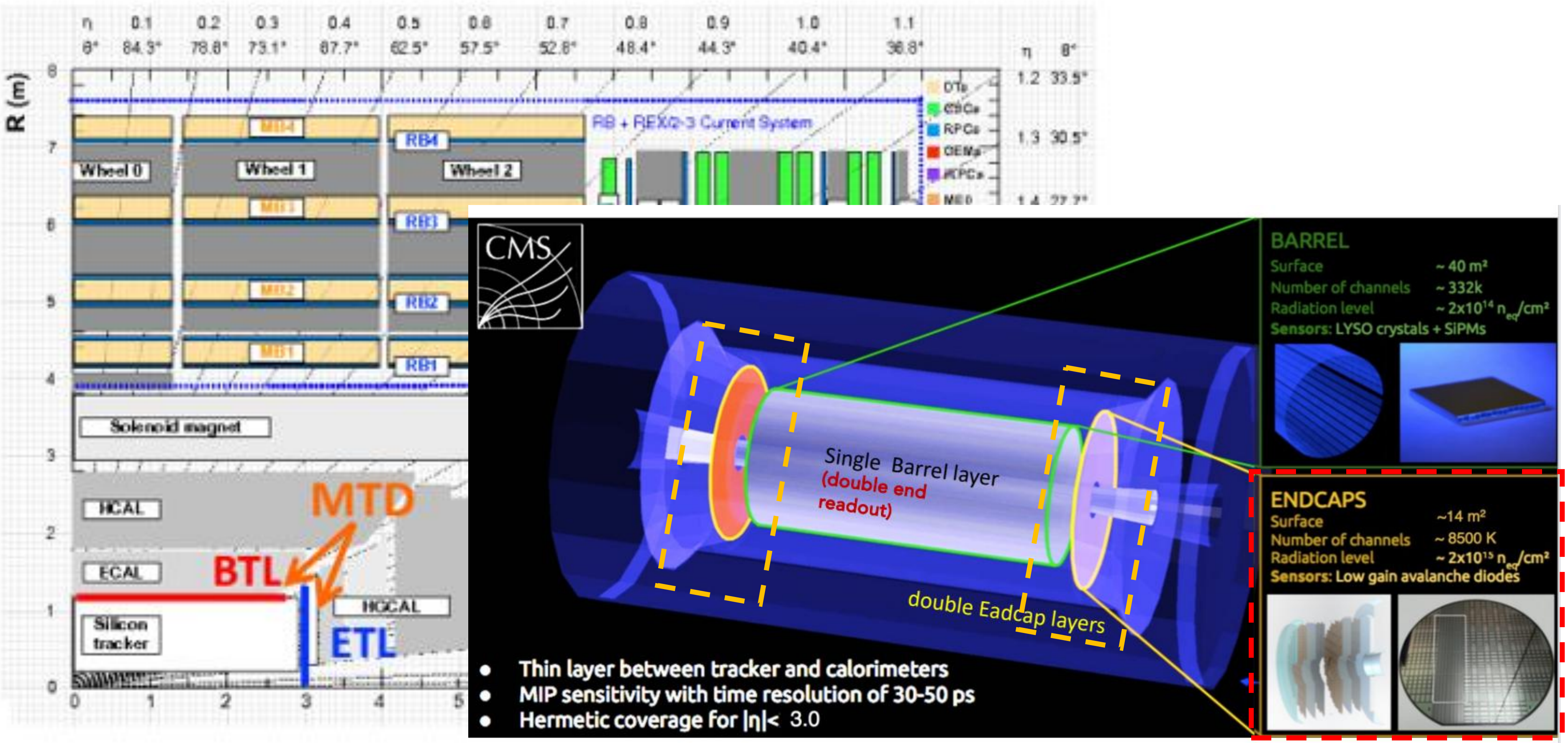

Particle ID will be possible !!!
Wonderful advantage for
Heavy ion crew

# Mip Timing Detector (MTD)




- MTD will be installed at the space between tracker and calorimeter.
- Barrel Timing Layer (BTL) : LYSO crystal + SiPM
- Endcap Timing Layer (ETL) : LGAD sensor + ASIC (ETROC)

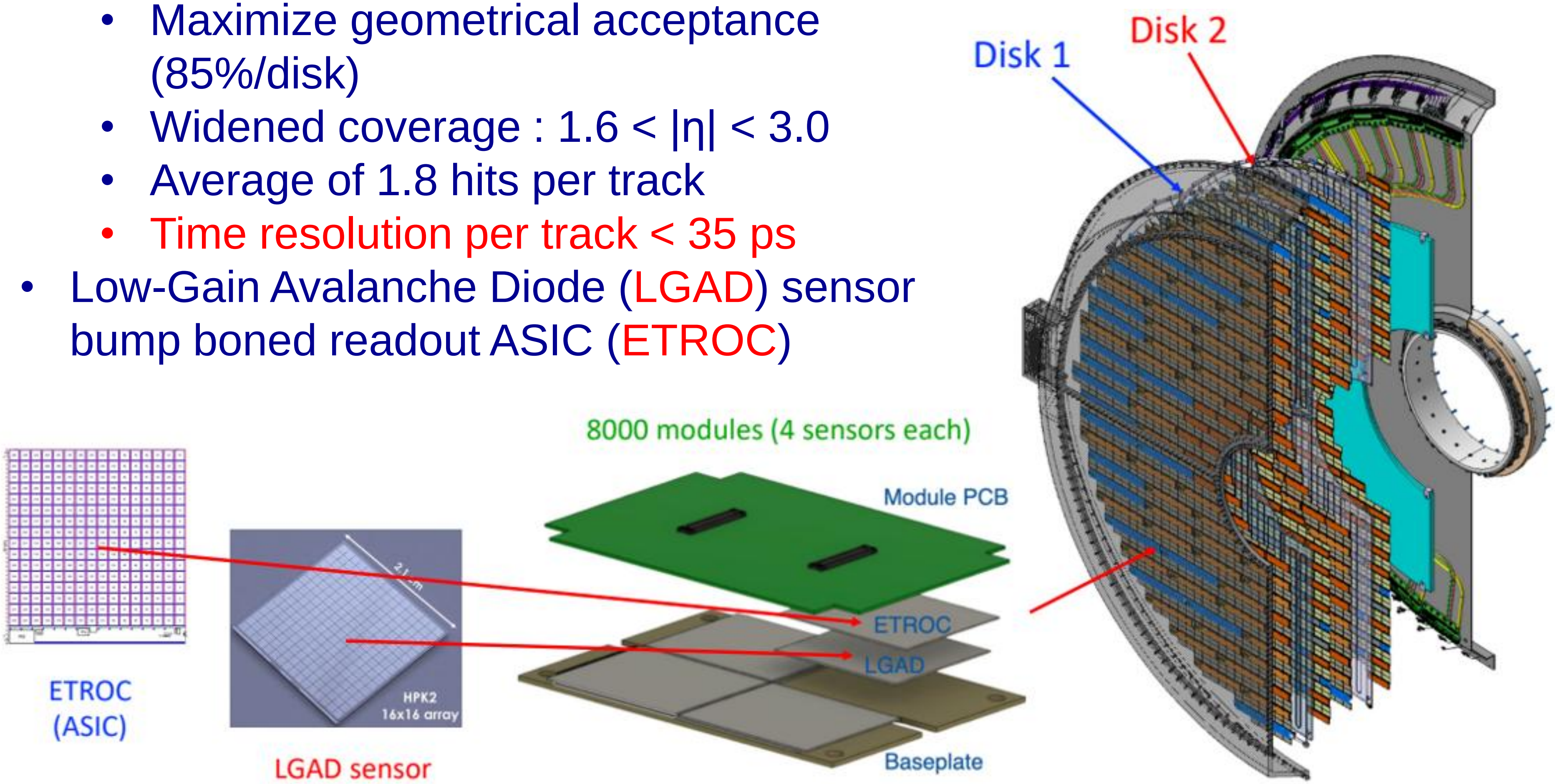
# Mip Timing Detector (MTD)



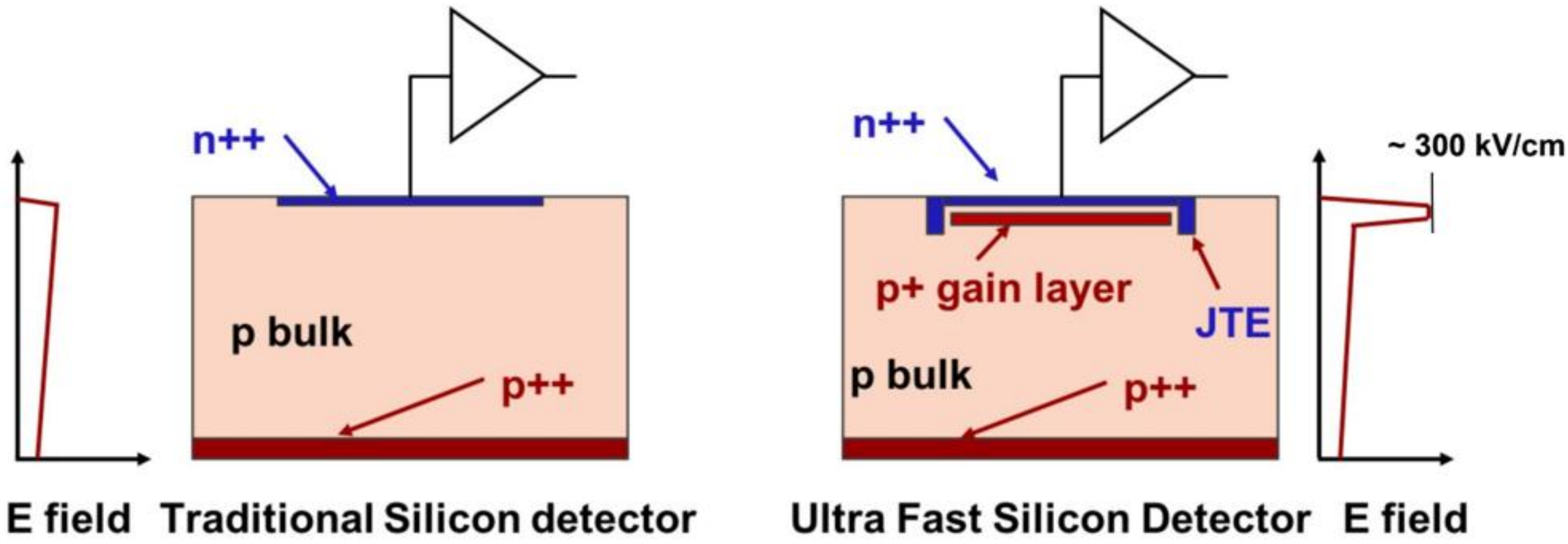

- MTD will be installed at the space between tracker and calorimeter.
- Barrel Timing Layer (BTL) : LYSO crystal + SiPM
- Endcap Timing Layer (ETL) : LGAD sensor + ASIC (ETROC)
- Korean CMS group is responsible for 25 % of MTD Endcap Timing Layer (ETL) production.

# Design of MTD ETL

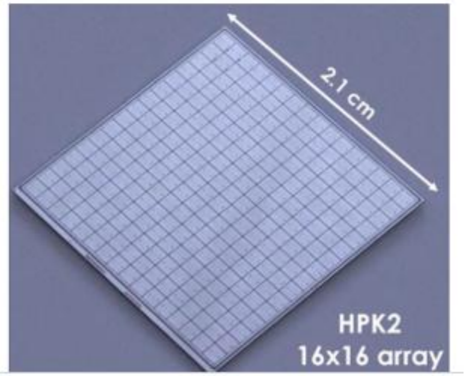
- Two double-sided disks for each side
  - Maximize geometrical acceptance (85%/disk)
  - Widened coverage : $1.6 < |\eta| < 3.0$
  - Average of 1.8 hits per track
  - Time resolution per track < 35 ps
- Low-Gain Avalanche Diode (LGAD) sensor bump boned readout ASIC (ETROC)



# Low Gain Avalanche Diode (LGAD) sensor




- LGAD characteristics
  - 16x16 pixel matrix, 1.3x1.3 mm$^2$ pixel size
  - Highly improved radiation tolerance
  - Very low gain factor (10-30) : excellent S/N ratio
  - Thin implanted gain layer (35-50 μm)
  - Gain uniformity (>8 fC of charge)
- Additional gain layer : highly boron-doped thin layer
  - Able to generate the high E filed enough charge multiplication



# Korean CMS MTD Group


경북대학교
KYUNGPOOK NATIONAL UNIVERSITY

고려대학교
KOREA UNIVERSITY

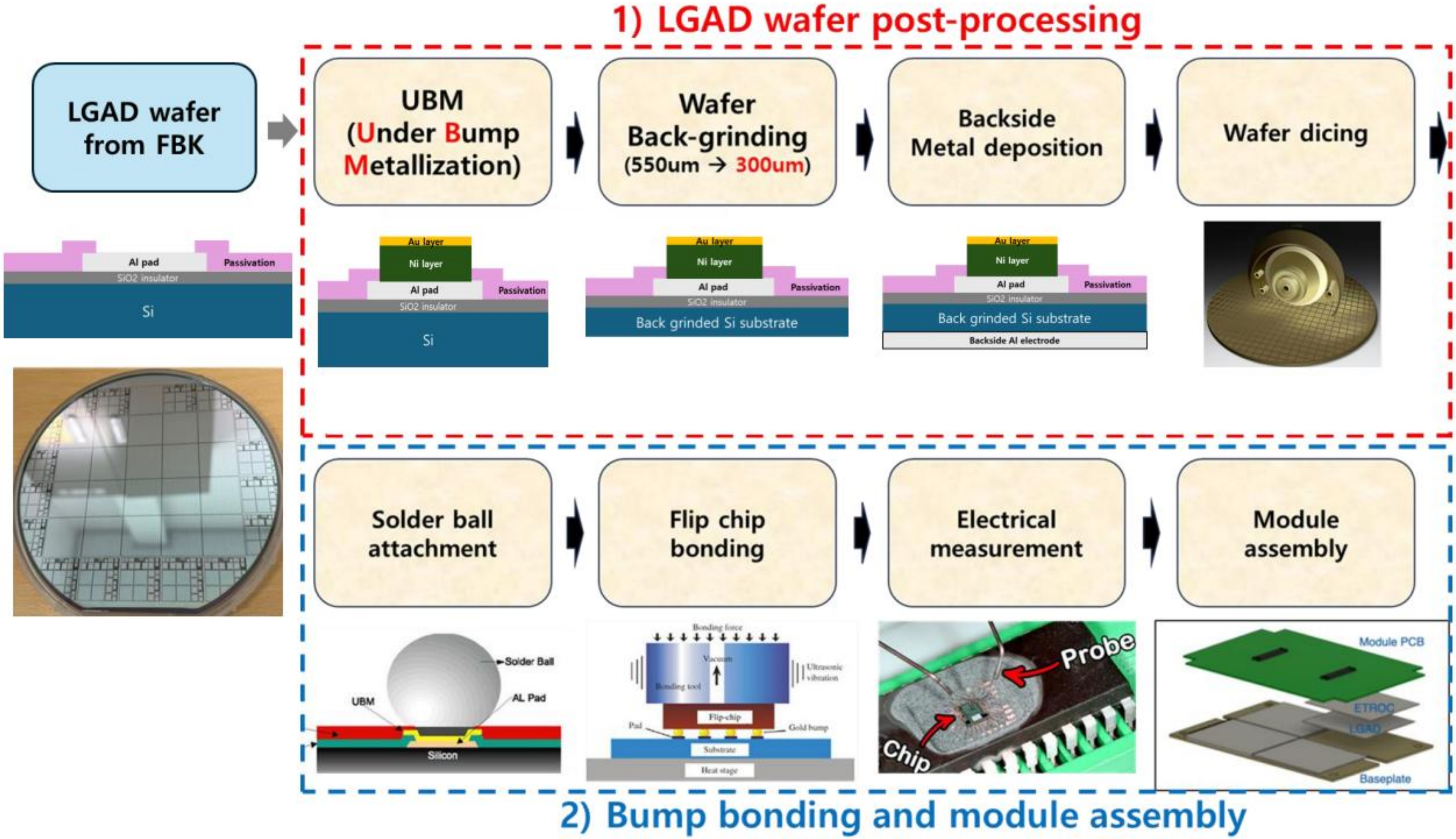
강릉원주대학교
GANGNEUNG-WONJU NATIONAL UNIVERSITY

전남대학교
CHONNAM NATIONAL UNIVERSITY

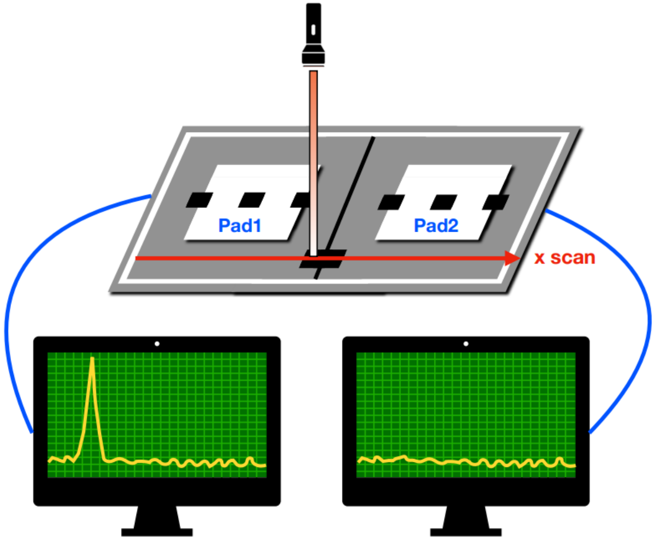
- Held 1st intensive MTD workshop in Gangneung, Korea
- 4 institutions and ~ 20 members

# Korean CMS MTD Group Contributions

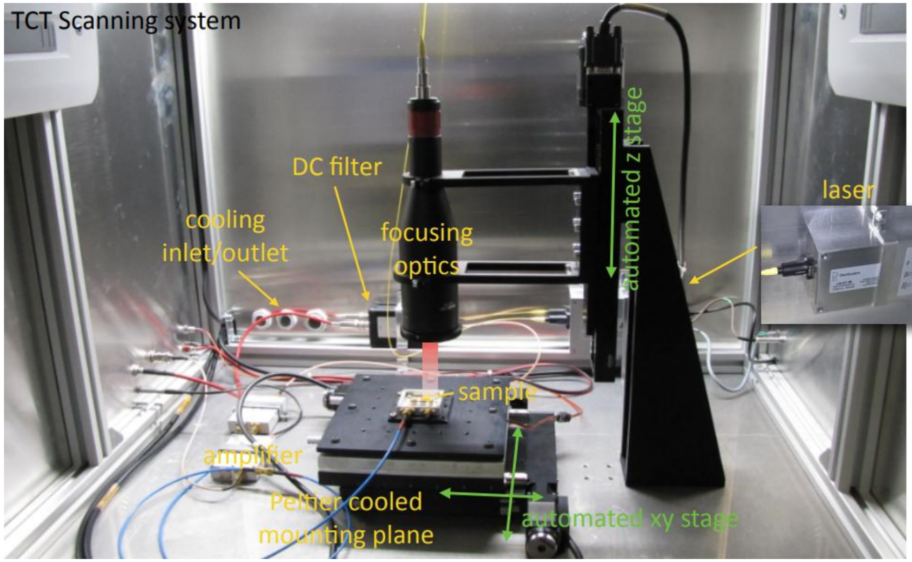
- Participated wafer market survey
- LGAD post-processing, bump bonding and module assembly

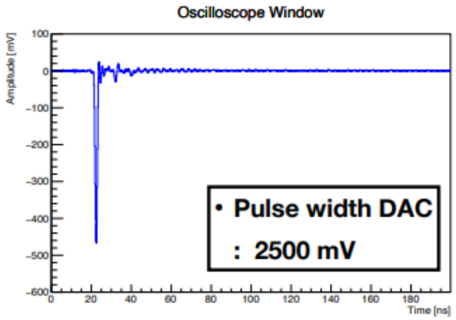


# Market Survey for wafer companies

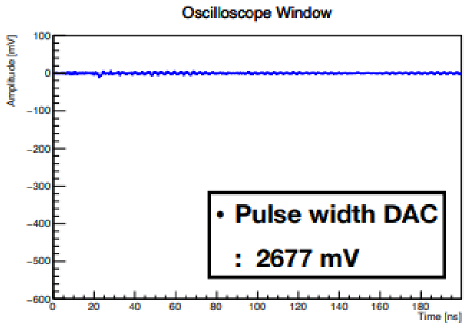



- Signal from pad1
- Signal from pad2

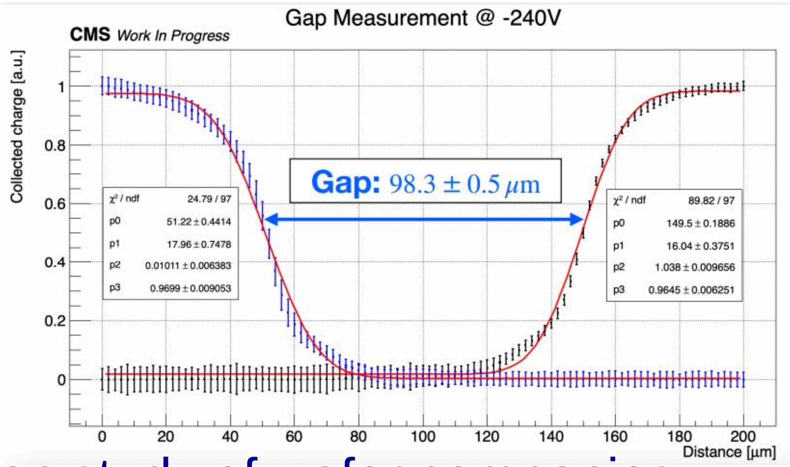



- Area: ~600 pWb → ~250 MIPs

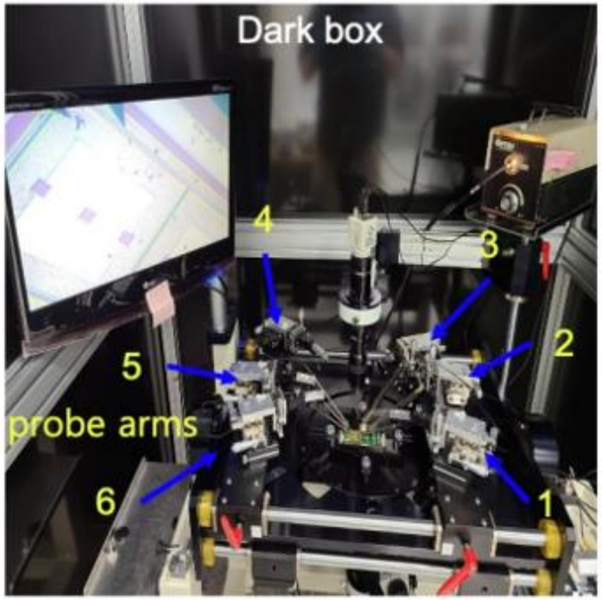



- Area: 17.7 pWb → ~7 MIPs

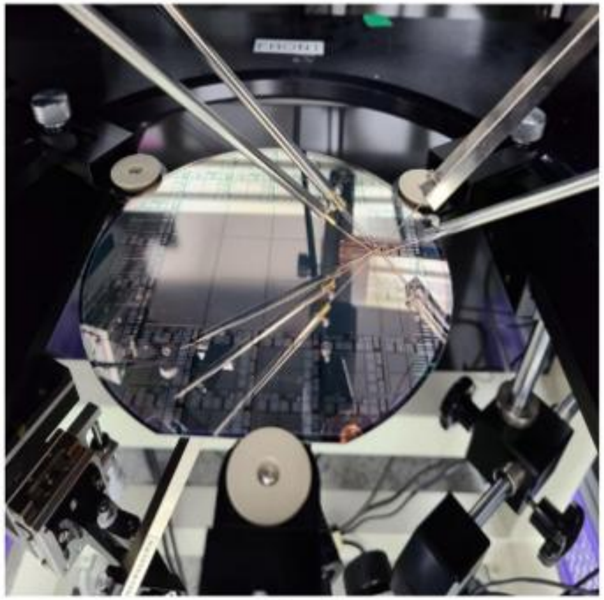



- Contributed to market survey : comparison study of wafer companies.

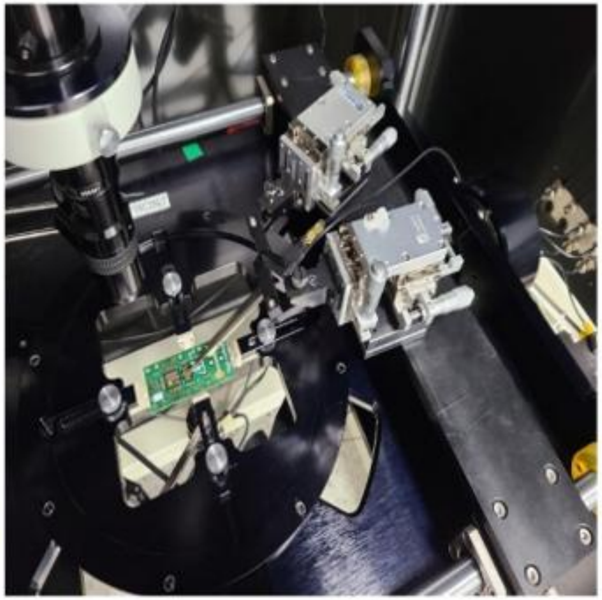
# Test setup for wafer and sensor level




• Overview



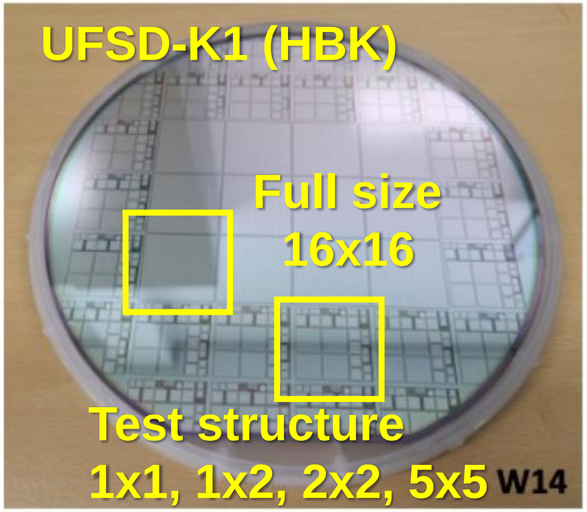
• wafer tray

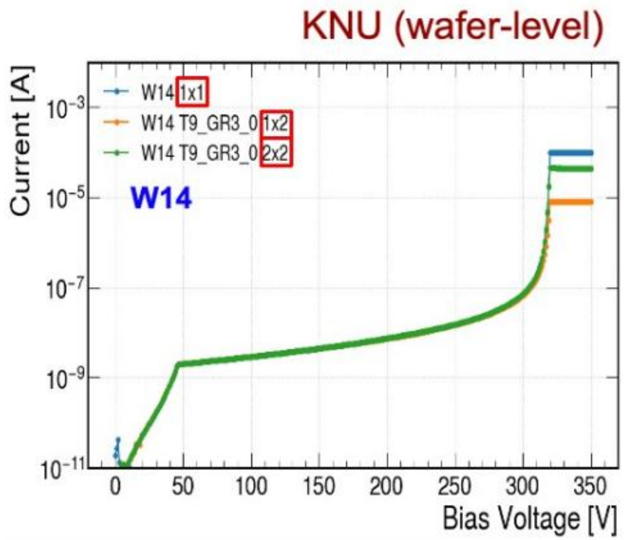


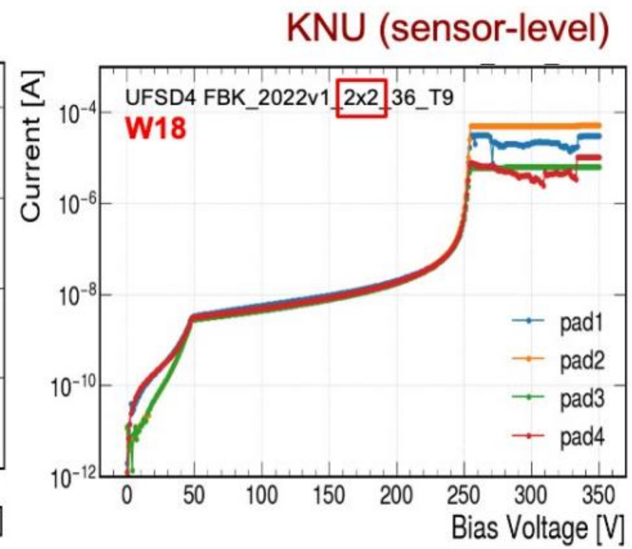
• sensor tray

- Six probe arms that use magnets to connect with the station
  - Signal read-out, bias voltages supplying, and 4 for grounding
- Two types of tray available for wafer-level and sensor-level tests
- KCMS will prepare a probe card and switching matrix for 16x16 sensors

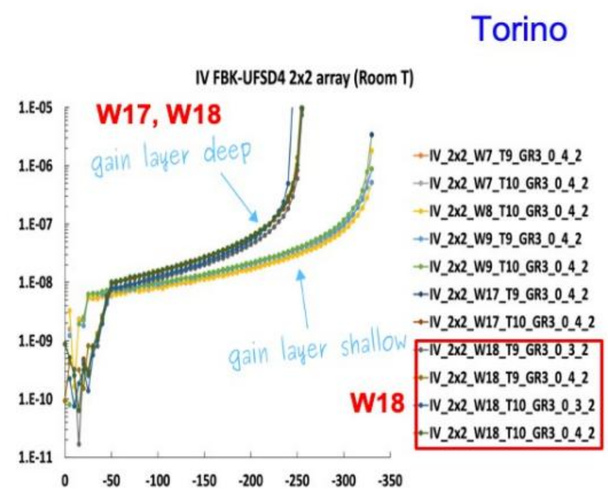

# Test results for wafer and sensor level



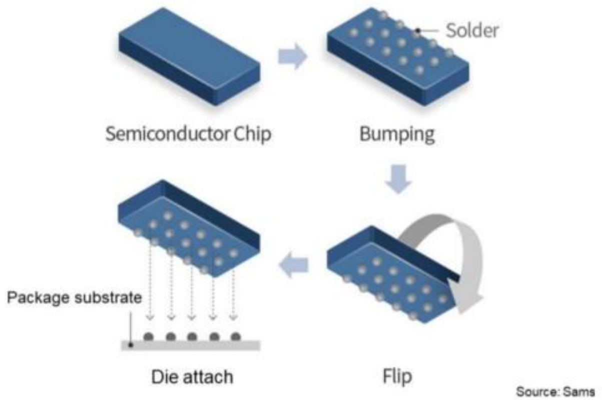



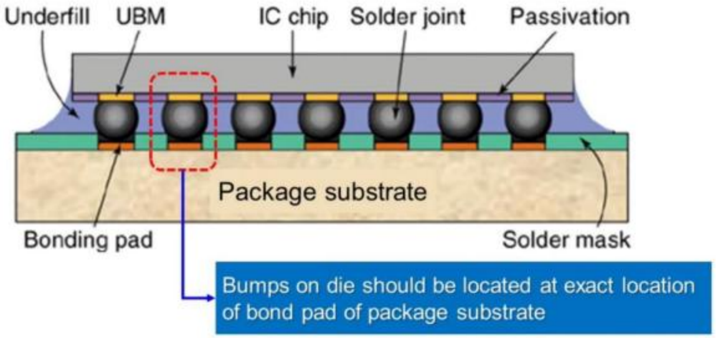



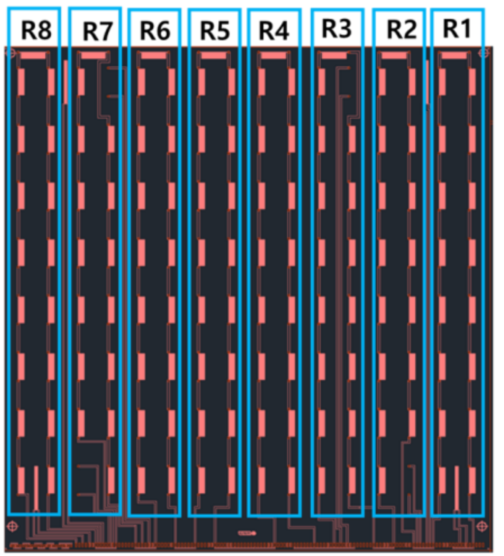

- Bias voltage applied from 0 V to -350 V
- Tested in room temperature
- Breakdown voltage
  - $V_{BD}$ ~ 320 V in W14 and $V_{BD}$ ~ 250 V in W18
  - Not depending on the sensor structures in the W14
- Comparable with Torino group results



# Bumping and flip chip bonding



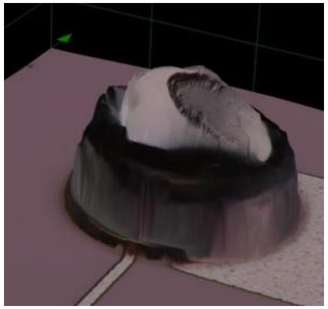




ROIC dummy device

Unit : Ohm

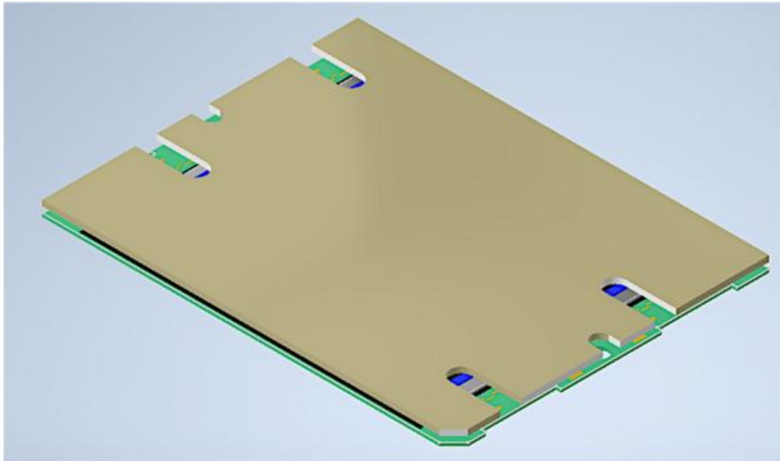
| Sam-ple | R1 | R2 | R3 | R4 | R5 | R6 | R7 | R8 |
|---|---|---|---|---|---|---|---|---|
| S1 | 808 | 276 | 253 | 185 | 20 | 21 | 215 | 516 |
| S2 | 291 | 33 | 37 | 202 | 57 | 27 | 240 | 440 |

Resistance test

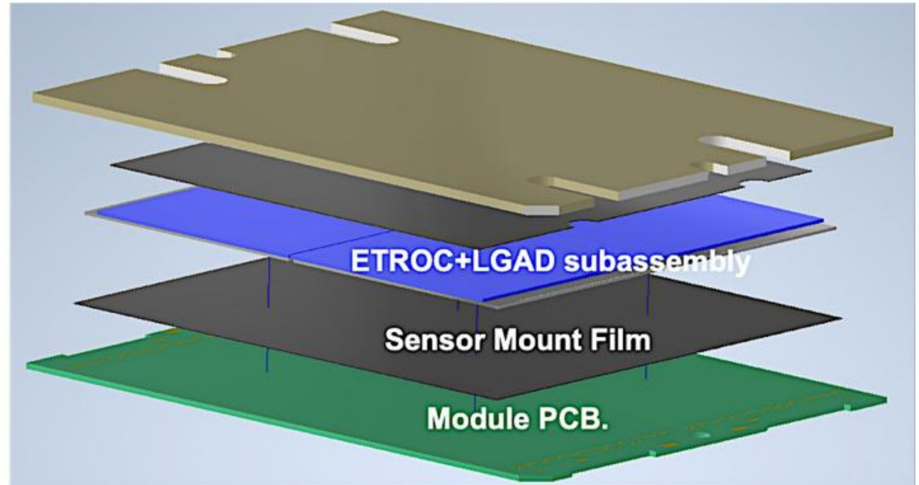



- Bump bonding test with dummy wafers
  - Searching for appropriate venders
- Resistance test, 3D imaging inspection

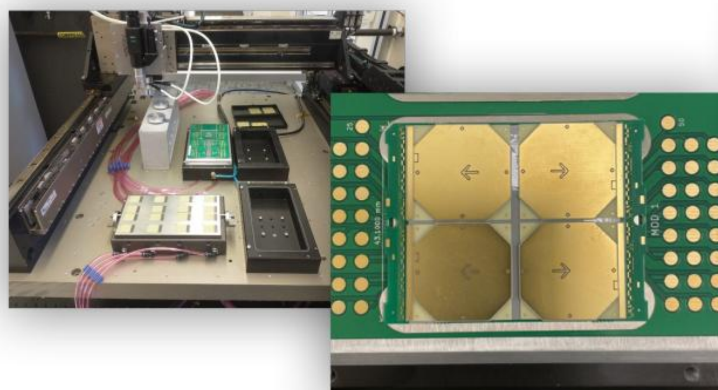
# Module assembly



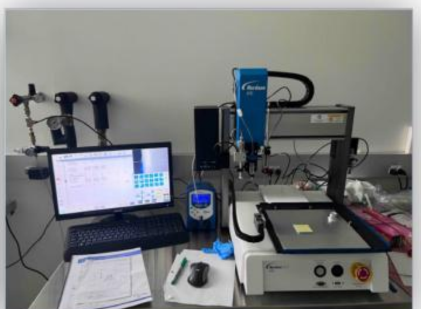
PCB + subassembly



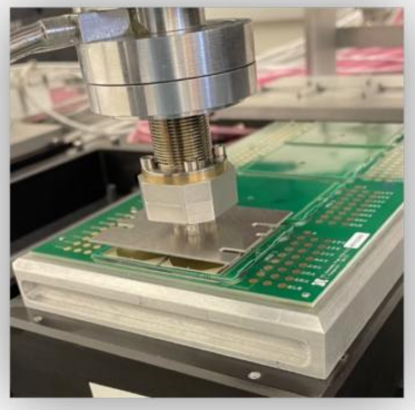

Basic scheme of a module



Pick & place sensor + PCB

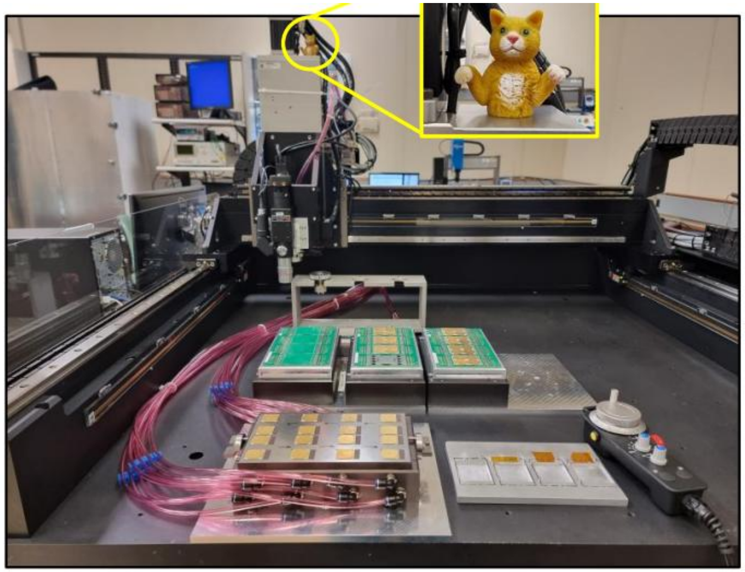


Wirebond and encapsulating

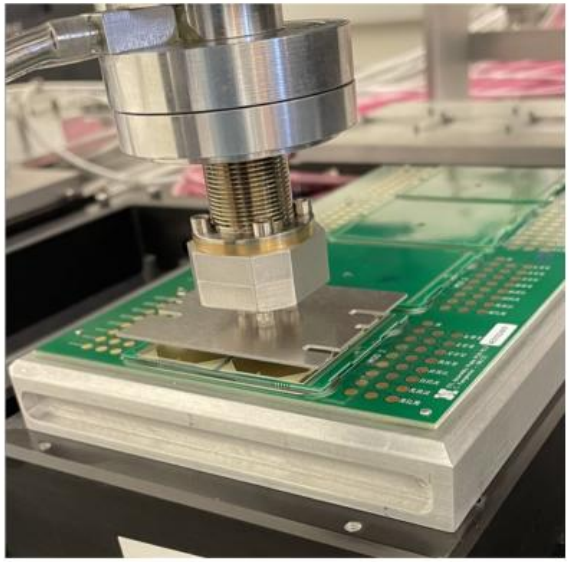


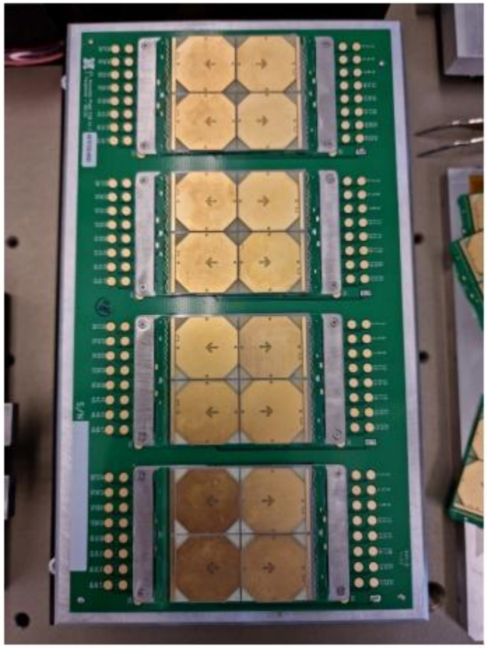
Apply film to baseplate, pick and place, and cure film

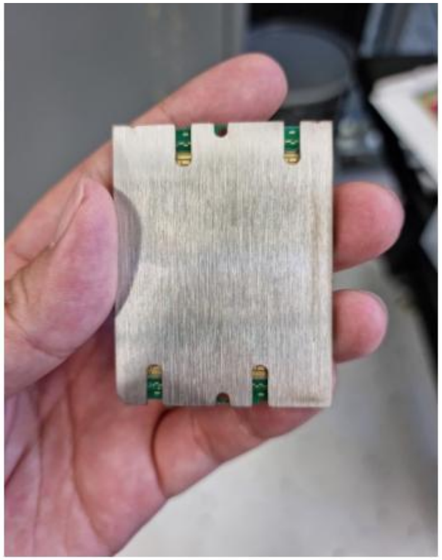
# Module assembly



Robotic gantry (SiDet, FNAL)

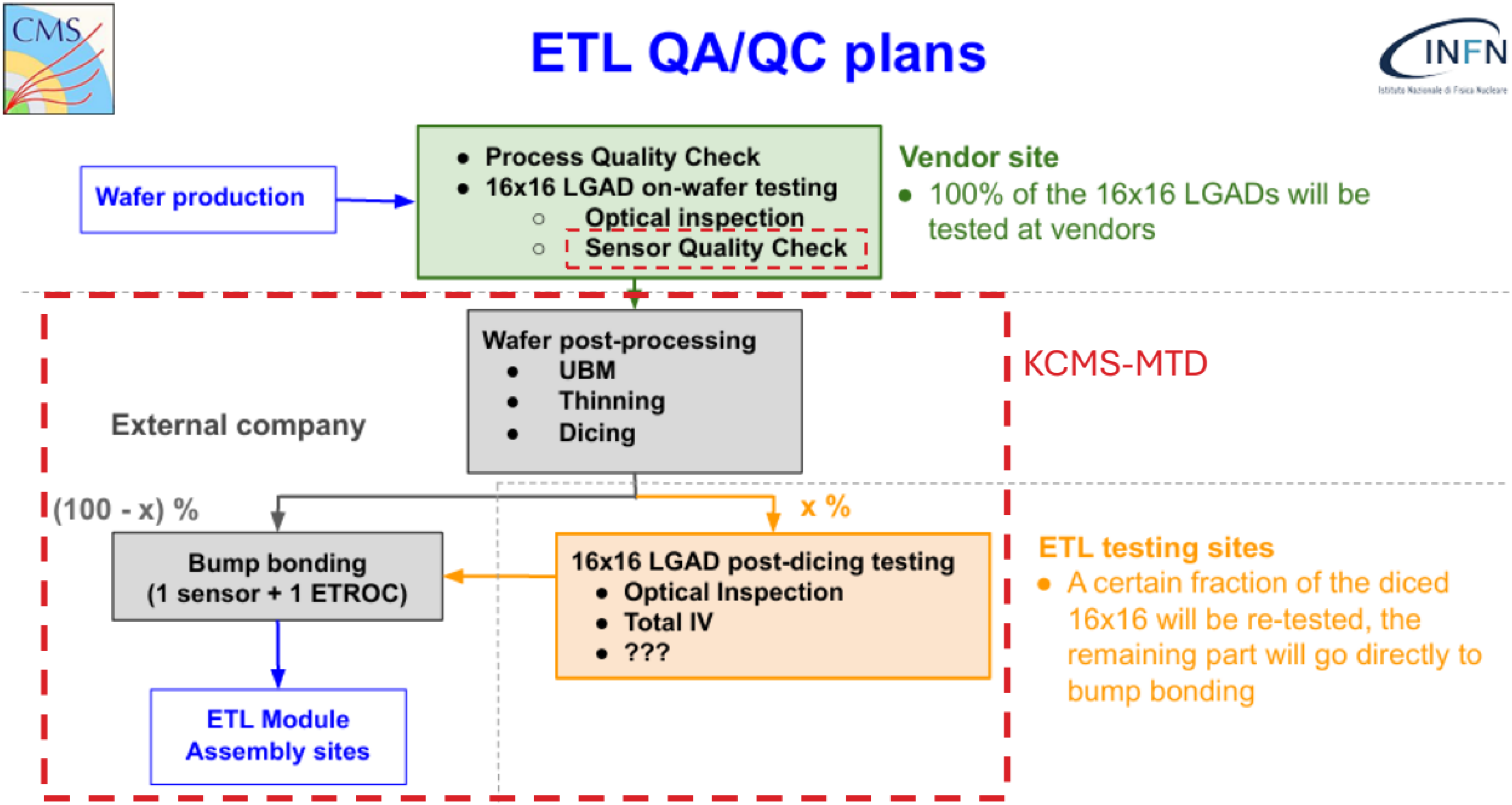






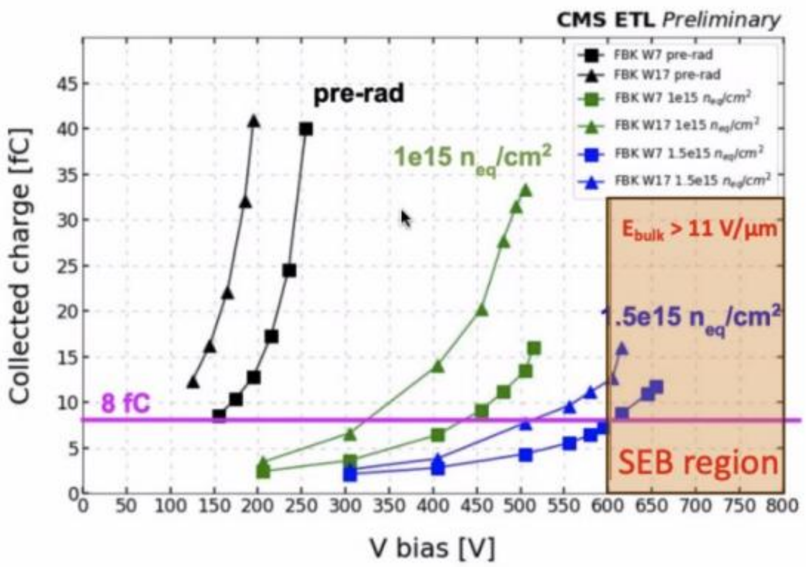
- Visiting Fermi Lab. to participate assembly process
- Preparation of the full assembly process is completed and ready to go.
- 50% throughput demonstration with mockup components ongoing at assembly sites.
- Robotic gantry shows good subassembly alignment below the 100 μm limit.

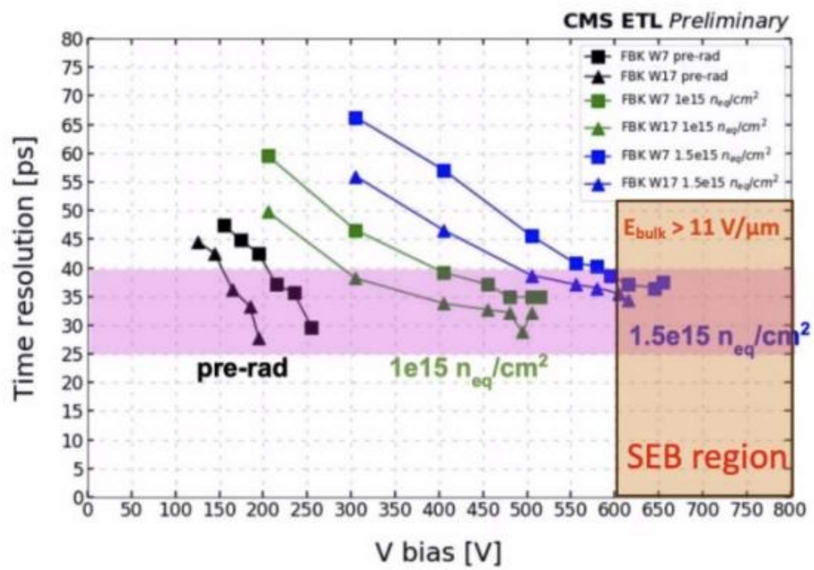
# QA/QC preparation at Korea site




- Building Quality Assurance (QA)/Quality Control (QC) facility in Korea
  - Leakage current, breakdown voltage, $V_{GL}$ uniformity etc.

# Irradiation test in KOMAC



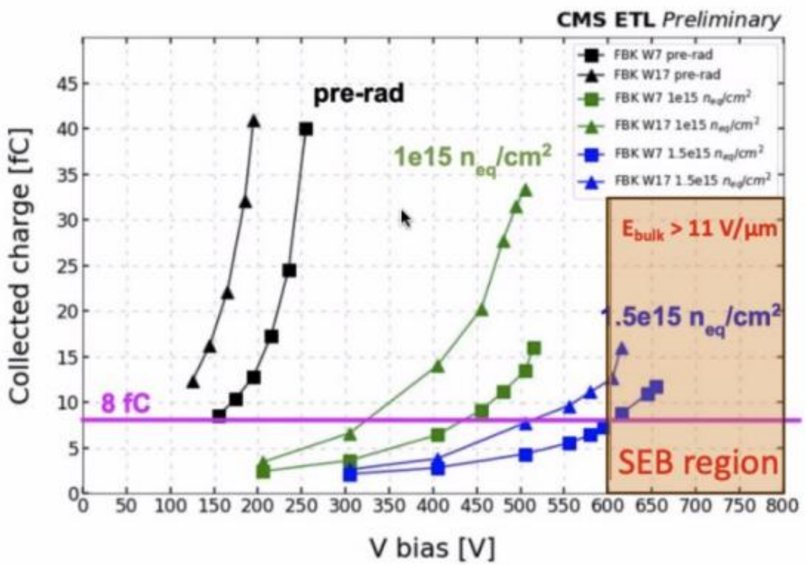



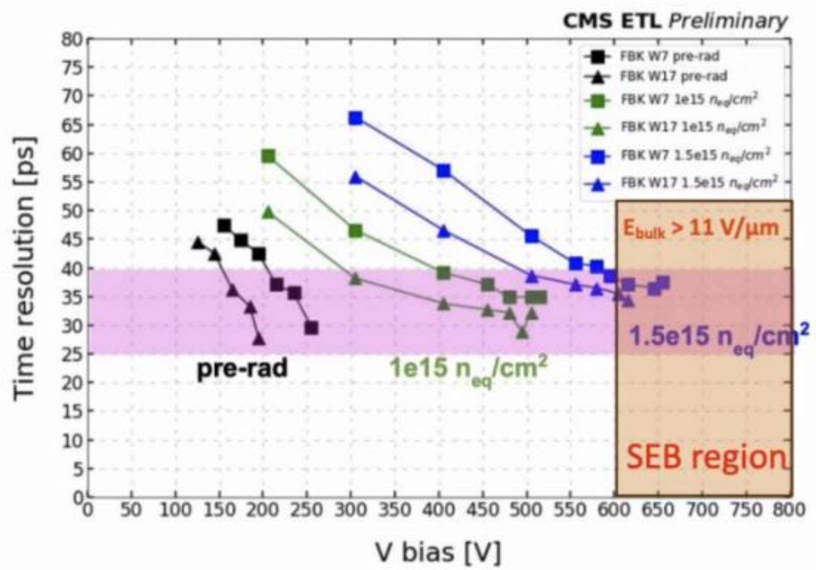

- Irradiation damage has been tested with beta source ($^{90}$Sr) at FBK
- Single event burn-out (SEB) observed at high radiation environment
- Follow up irradiation test has been carried out at KOMAC facility in Korea (100 eV proton beam)


KOMAC accelerator

- Beam size : 30 mm
- Beam flux : $10^{10}$ ~ $10^{11}$ /pulse
- Beam energy : 20 MeV, 100 MeV

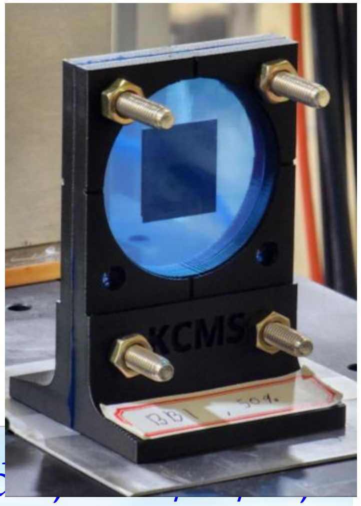
# Irradiation test in KOMAC

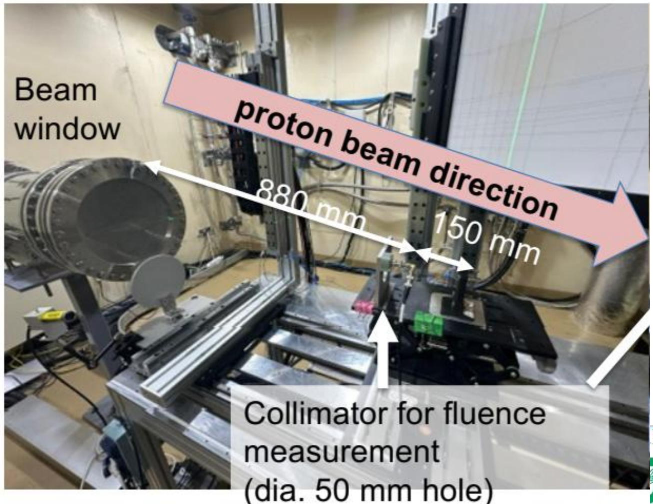



- Follow up irradiation test has been carried out at KOMAC facility in Korea (100 MeV proton beam)
  - 2 LGAD itself
  - 2 Bump-bonded dummy wafer + chip

  UFSD-K1 (after post process)




- Analysis is ongoing.

# Summary and plan

- CERN-Korea CMS sign up MoU in 2022

**Memorandum of Understanding (MoU)**
**for Korea-CMS contribution**
**towards the MIP timing detector (MTD)**
**for the Phase-2 CMS Upgrade**

between
The CMS Collaboration at CERN, hereafter referred to as CMS, on the one hand
and
The CMS Korea Institutes, hereinafter referred to as KCMS, on the other hand and
hereinafter collectively referred to as Parties

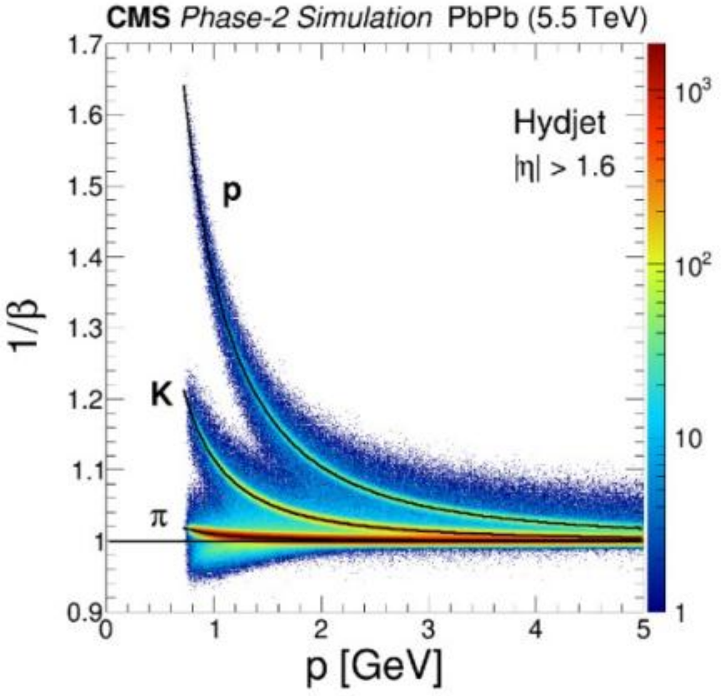


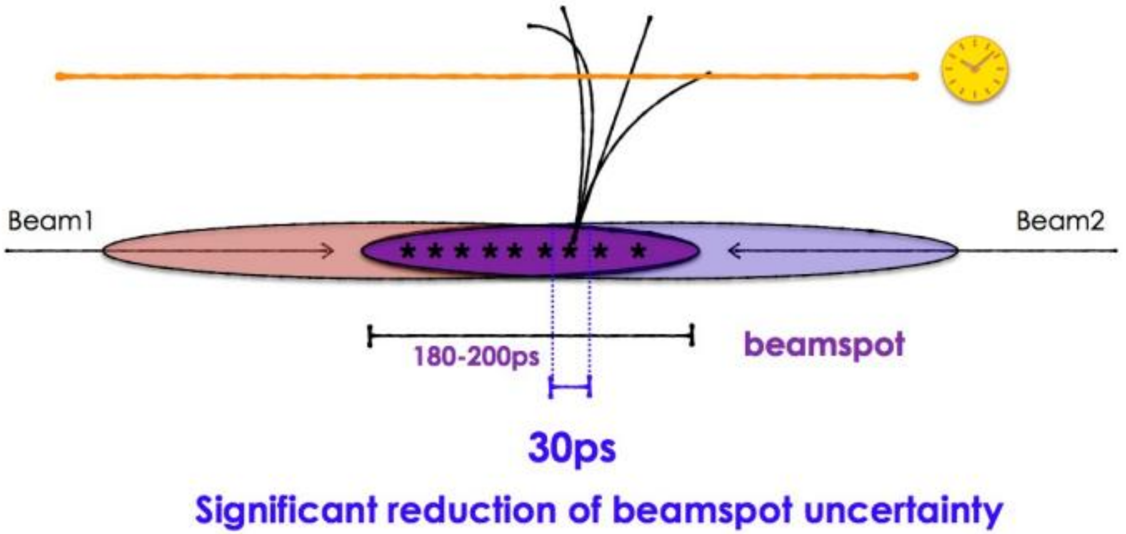
- Korea CMS is responsible for 25 % of LGAD sensor, post-process, module assembly of MTD ETL production.
  - 2.2 MCHF budge approved by National Research Foundation (NRF)
- First Korea-Italy LGAD sensors (UFSD-K1,K2) were produced, and evaluation is ongoing in Korea.
- QC/QC facility is ongoing to build.
- Irradiation test results are ongoing to analyze.

# Backup

# Advantage for heavy ion crew

## MTD Physics motivation: particle ID



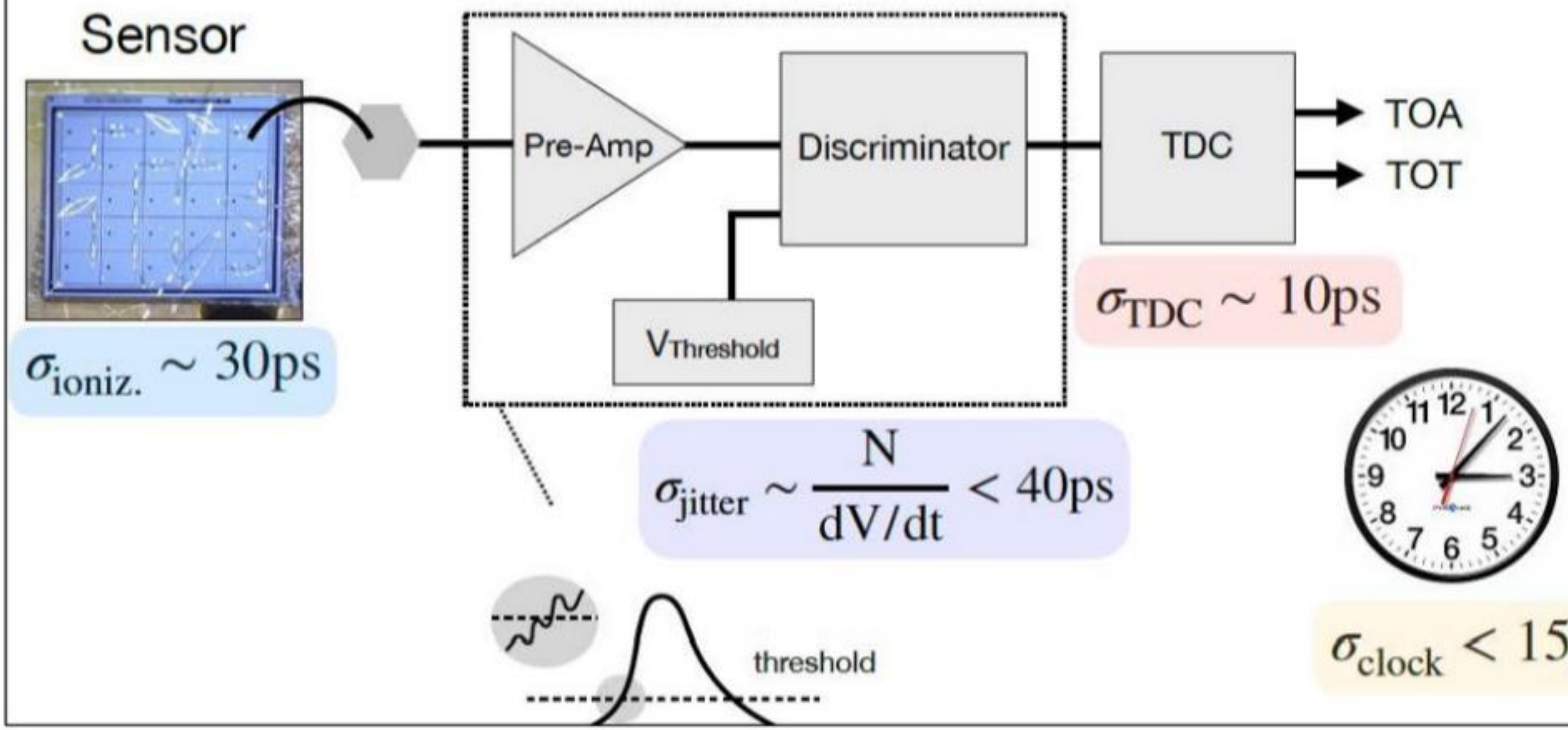




- MTD can provide significant improvement for particle ID
  - Heavy ion charm tag
- Significant gains for searches for long-lived new particles

# Timing Resolution

## ETL - Timing Resolution

$$\sigma_t^2 = \sigma_{\text{ionization}}^2 + \sigma_{\text{jitter}}^2 + \sigma_{\text{TDC}}^2 + \sigma_{\text{clock}}^2$$




$\sigma_{\text{ioniz.}} \sim 30\text{ps}$

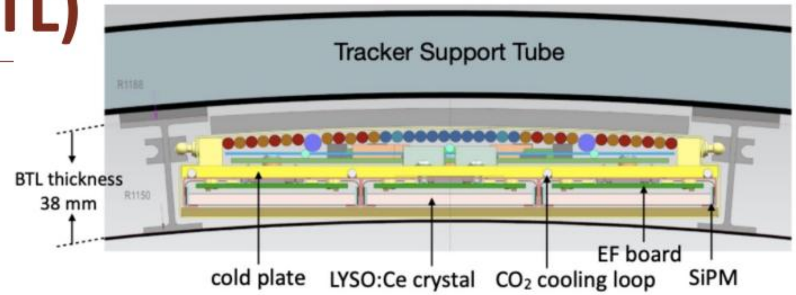
$\sigma_{\text{TDC}} \sim 10\text{ps}$

$\sigma_{\text{jitter}} \sim \frac{N}{dV/dt} < 40\text{ps}$

$\sigma_{\text{clock}} < 15\text{ps}$

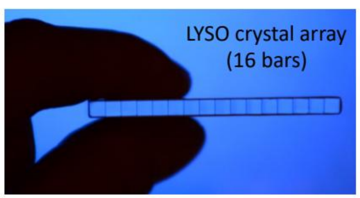
# MTD BTL

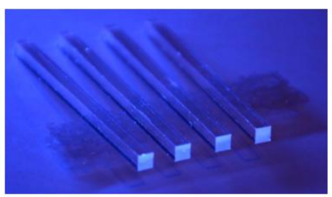
## MTD : Barrel Timing Layer (BTL)

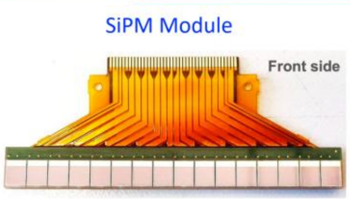


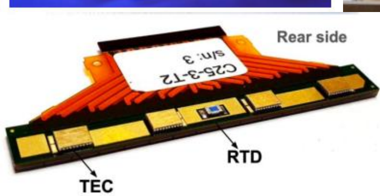

- 3.8 cm thin cylindrical detector
  - located inside the tracker support tube, $|\eta| < 1.45$
  - ~5 m long, 38 $m^2$ surface

- **LYSO crystal bars (166k)**
  - Cerium-doped lutetium yttrium orthosilicate (LYSO:Ce) scintillation medium
  - Well established in PET applications and vendors widely available
  - High radiation tolerance
  - $\tau_{rise}$ : ~100 ps, $\tau_{decay}$ : ~ 40 ns
  - High Light Yield : 40000 γ/MeV

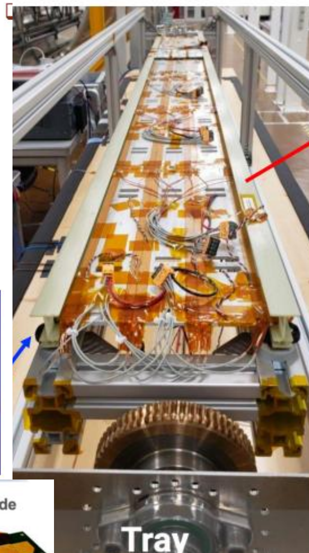


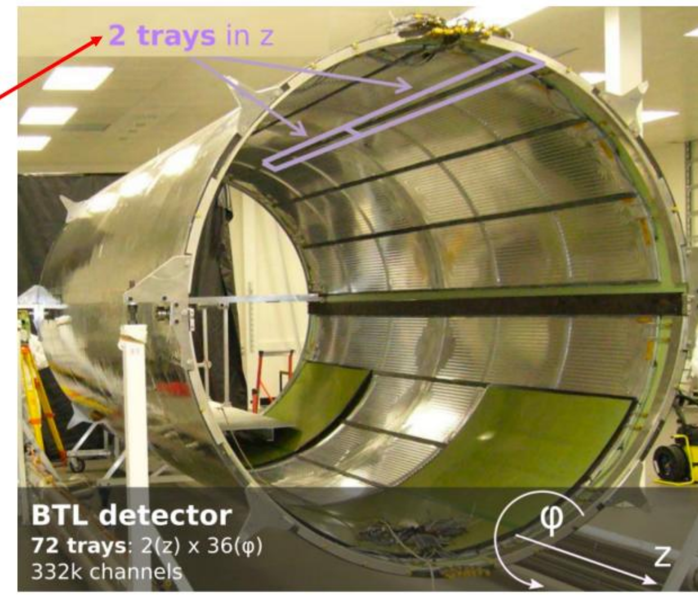





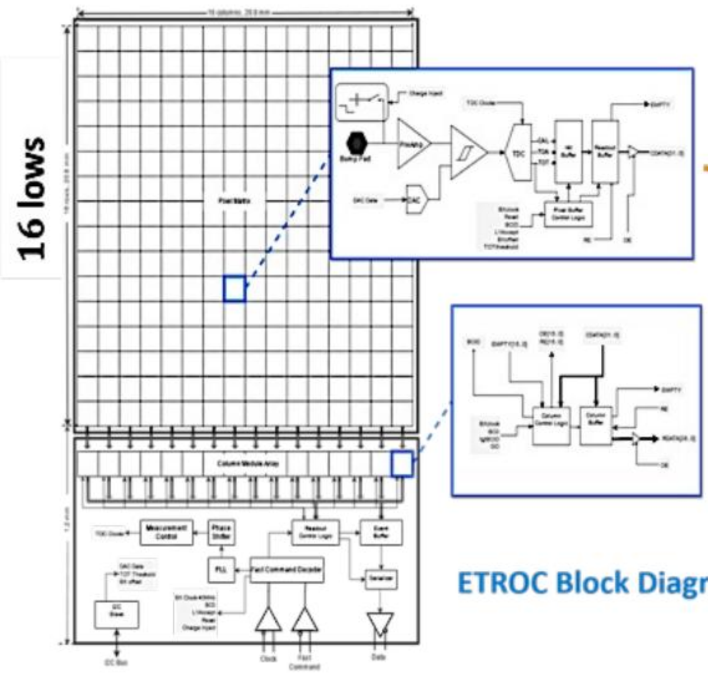




)24!

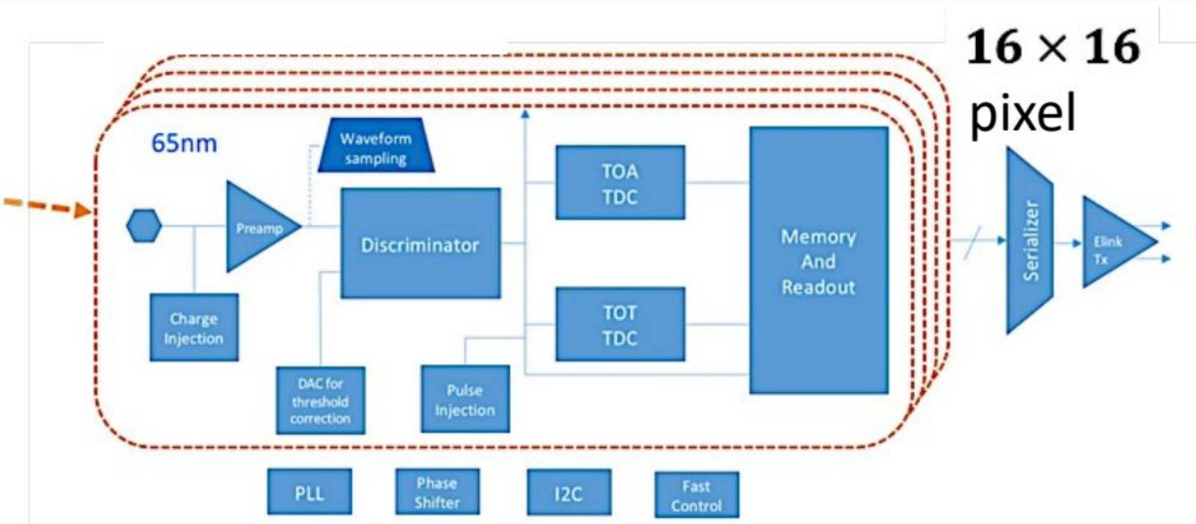


# Endcap Timing Layer ReadOut Chip (ETROC)



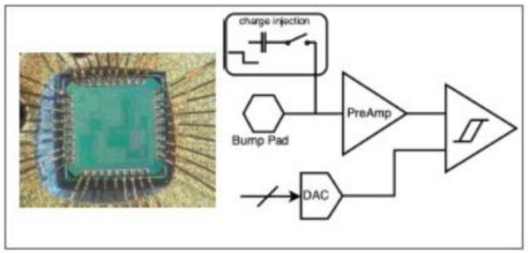

ETROC Block Diagram




- 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 - 20 fC
- TDC (time-to-digital converter) range
  - ~5 ns TOA (time of arrival)
  - ~10 ns TOT (time over threshold)

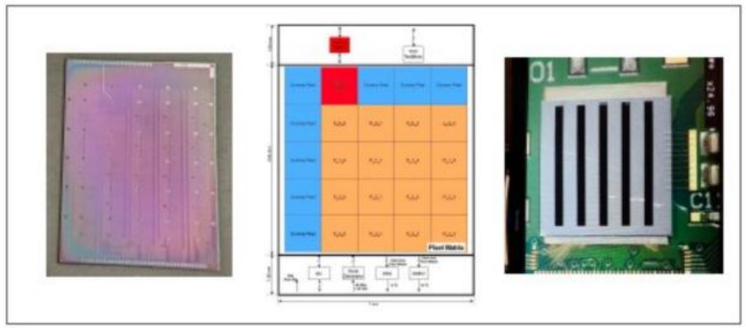
# ETROC Development Plan

## 2018
### ETROC0 (1x1)



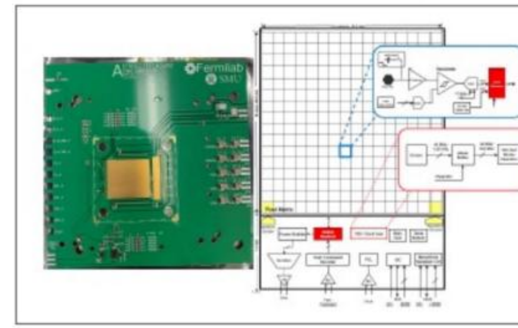

- Analog front-end only
- Wire-bonded with LGAD sensor reached ~33 ps time resolution per hit with preamp. waveforms
- Passed 100 Mrad TID

## 2020
### ETROC1 (4x4)



- Added low-power TDC and 4x4 H-tree for clock distribution
- Bump-bonded with LGAD sensor reached ~42 ps time resolution per hit with TDC data

## 2023
### ETROC2 (16x16)

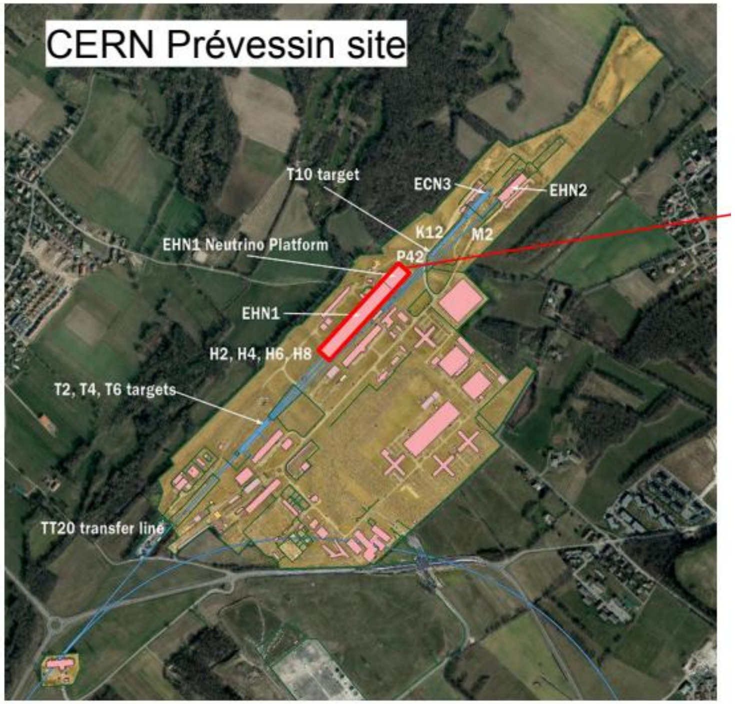


- First full-size chip (16x16) with all desired functionalities included
- All analog blocks silicon-proven; all digital blocks were verified in FPGA emulator

## ❑ ETROC3 : Final chip

- The same functionalities as ETROC2, with improvements based on what will be learned from extensive ETROC2 testing
- Submission scheduled for 2024

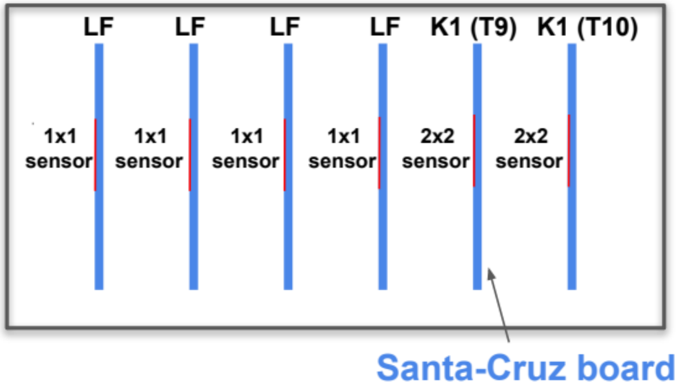
# ETROC test in Fermi Lab.

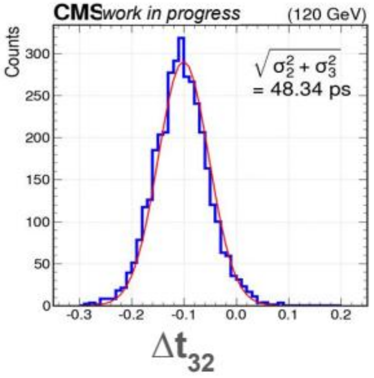



120 GeV Pion beam from SPS used for measurement of timing resolution of LGAD sensors

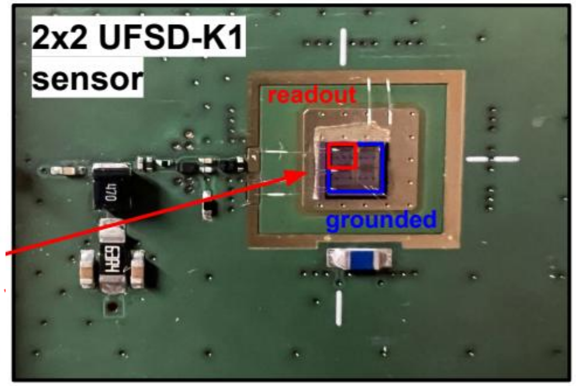
**Only single channel is connected to the signal readout for UFSD-K1 (T9), UFSD-K1 (T10) sensors**

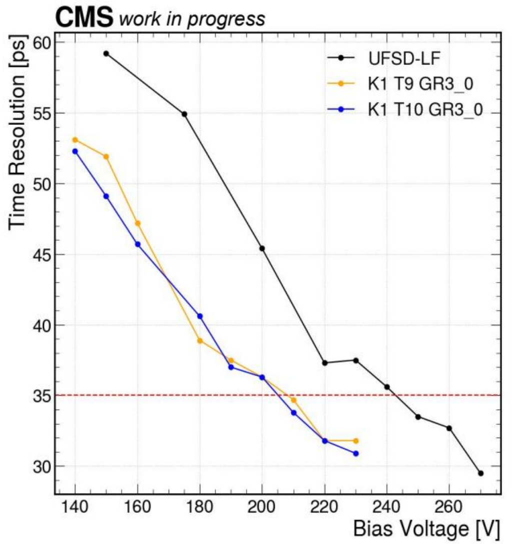
**Test module (6 slots)**



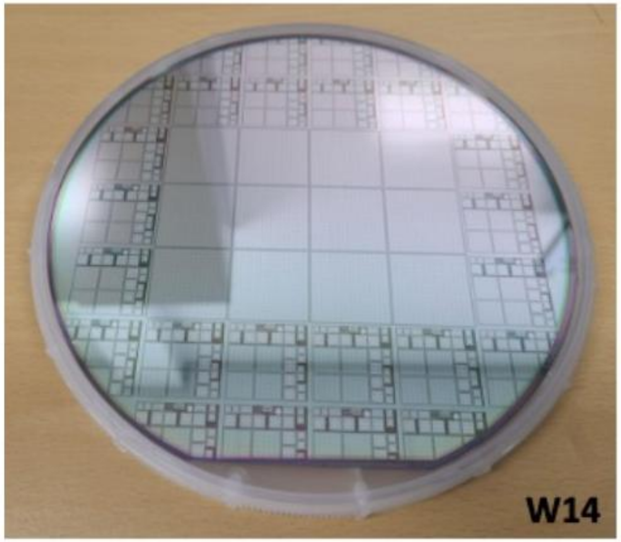




**Wire bonded to Santa-Cruz Board**

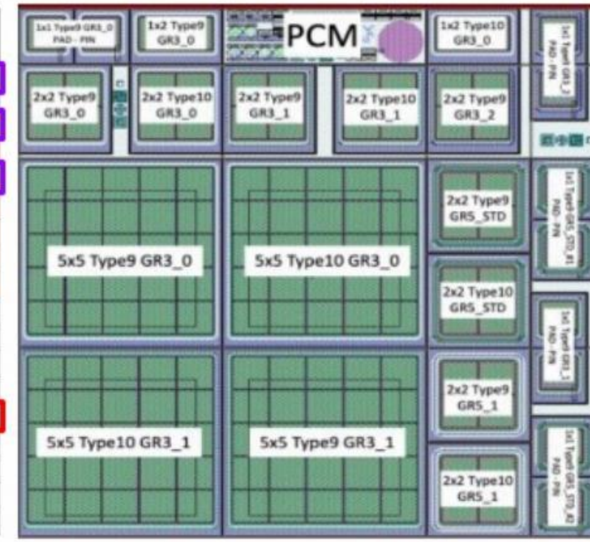


# UFSD4 (FBK, Italy) wafers test in Korea

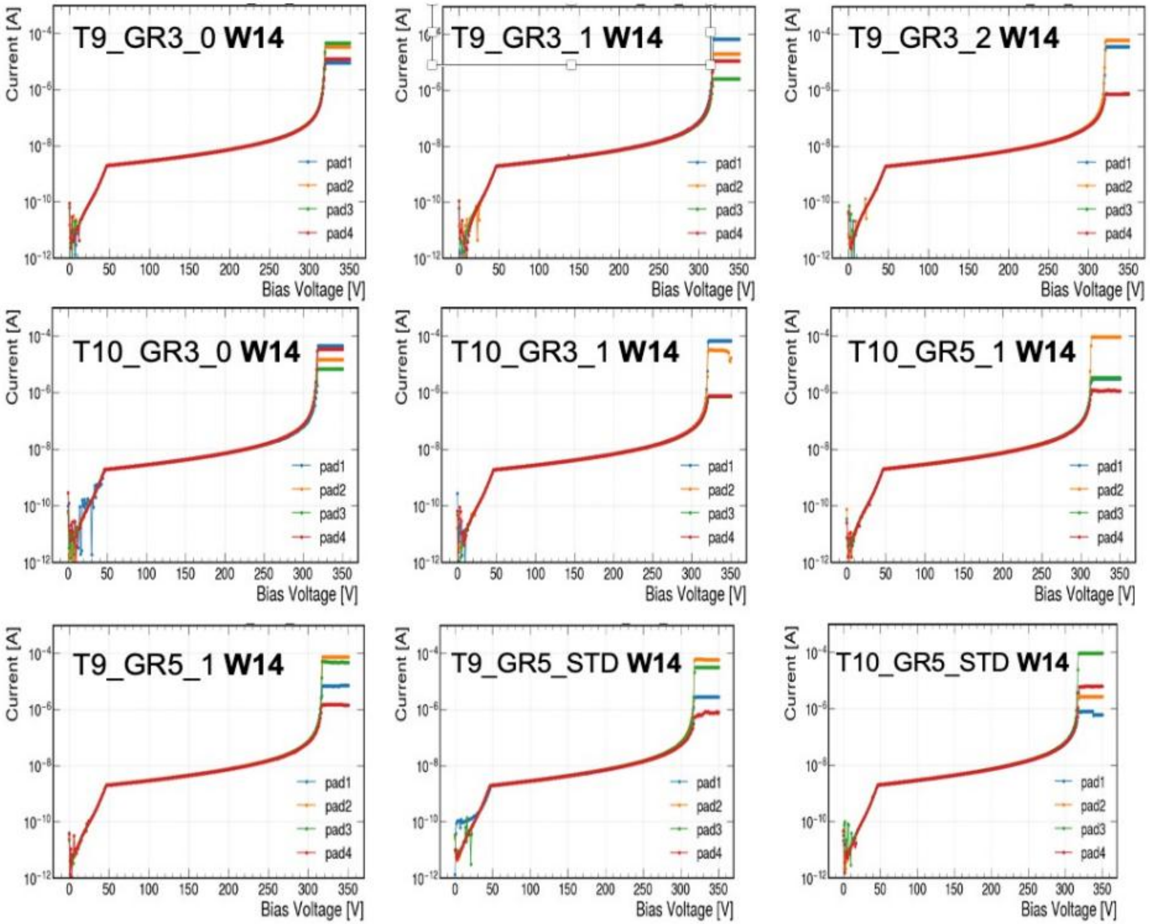



| Wafer Group | Wafer # | DI | Gain Layer Dose | Carbon | Diffusion |
|---|---|---|---|---|---|
| 1 | 1 | Shallow | 0.96 | 0.8 | CH-BL |
| 2 | 2 | Shallow | 1.00 | 1 | CH-BL |
| 3 | 3 | Shallow | 0.98 | 1 | CH-BL |
| 3 | 4 | Shallow | 0.98 | 1 | CH-BL |
| 4 | 5 | Shallow | 0.98 | 0.8 | CH-BL |
| 4 | 6 | Shallow | 0.98 | 0.8 | CH-BL |
| 4 | 7 | Shallow | 0.98 | 0.8 | CH-BL |
| 4 | 8 | Shallow | 0.98 | 0.8 | CH-BL |
| 4 | 9 | Shallow | 0.98 | 0.8 | CH-BL |
| 5 | 10 | Shallow | 0.98 | 0.8 + CS0.6 | CH-BL |
| 5 | 11 | Shallow | 0.98 | 0.8 + CS0.6 | CH-BL |
| 6 | 12 | Deep | 0.75 | 0.6 | CL-BL |
| 7 | 13 | Deep | 0.77 | 0.6 | CL-BL |
| 8 | 14 | Deep | 0.77 | 0.6 | CL-BL |
| 8 | 15 | Deep | 0.77 | 0.6 | CL-BL |
| 9 | 16 | Deep | 0.79 | 0.6 | CL-BL |
| 9 | 17 | Deep | 0.79 | 0.6 | CL-BL |
| 9 | 18 | Deep | 0.79 | 0.6 | CL-BL |

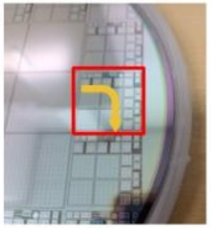


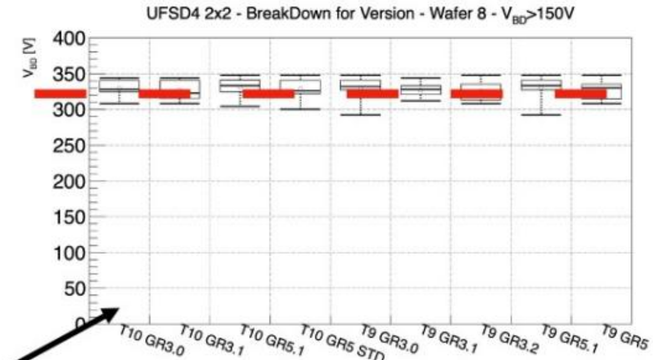

- The **Red box** represents the UFSD4 wafer #14 (W14), which has undergone wafer-level testing at KNU
- The **Purple box** represents three wafers which are shipped to CERN today for ETROC2 testing
- New 16 wafers (UFSD-K1), will be available for testing in a few weeks

# I-V measurement of 2x2 sensors in wafer level (UFSD4 W14) at KNU



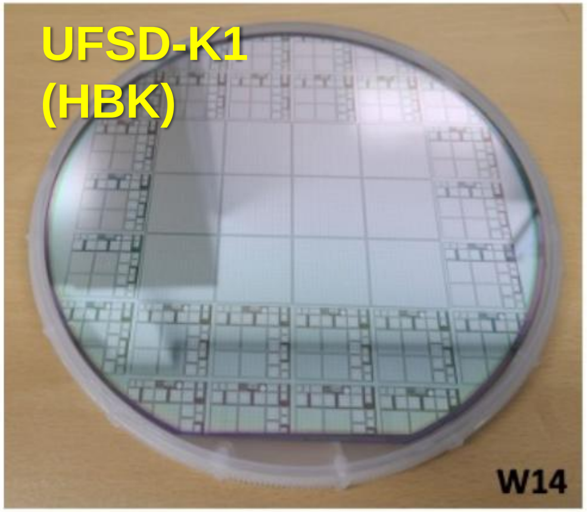

- Bias Voltage applied from 0 V to -350 V ($\Delta V$ = 1 V)
- Room temperature
- **Breakdown Voltage**
  - $V_{BD}$ ~ 320 V
  - The breakdown voltages are consistent in 2x2 sensors

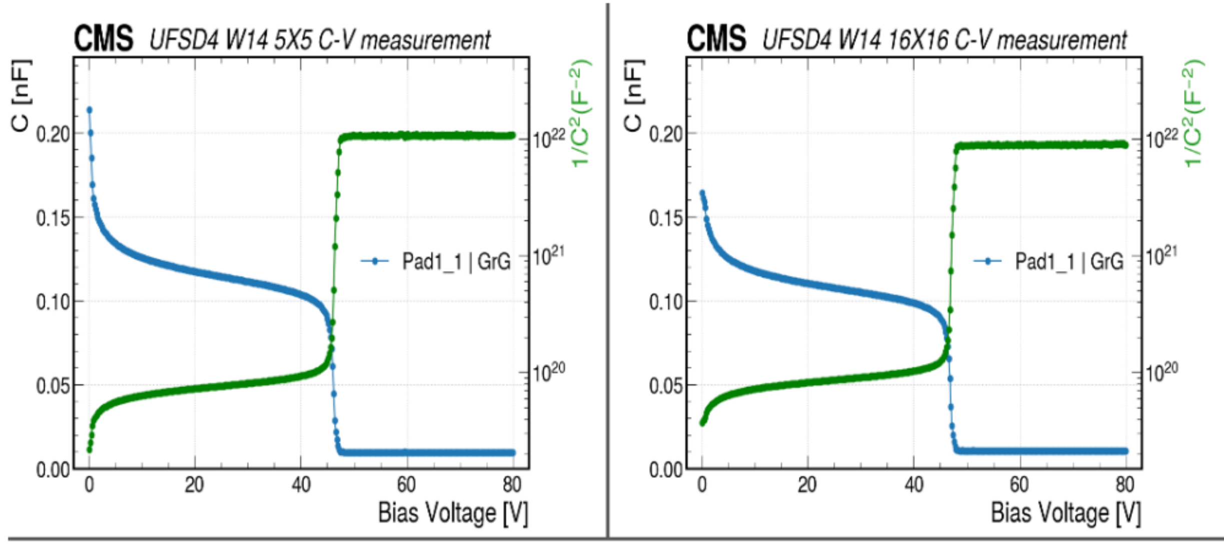




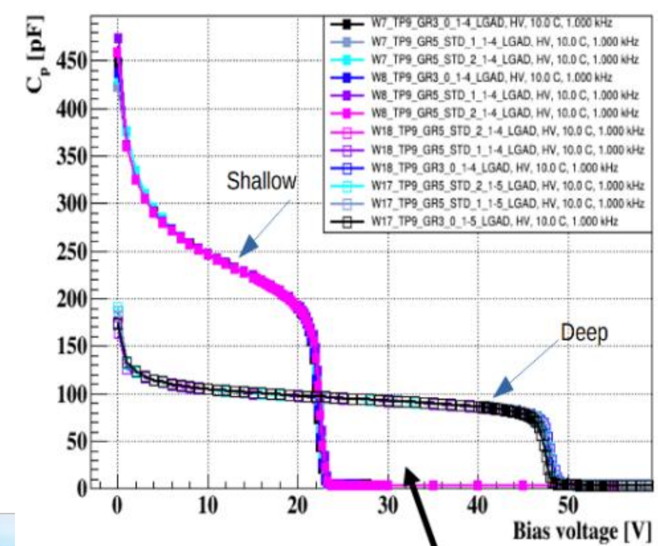

From Marta Tornago's talk, https://indico.cern.ch/event/1141394/

# Test results for wafer and sensor level



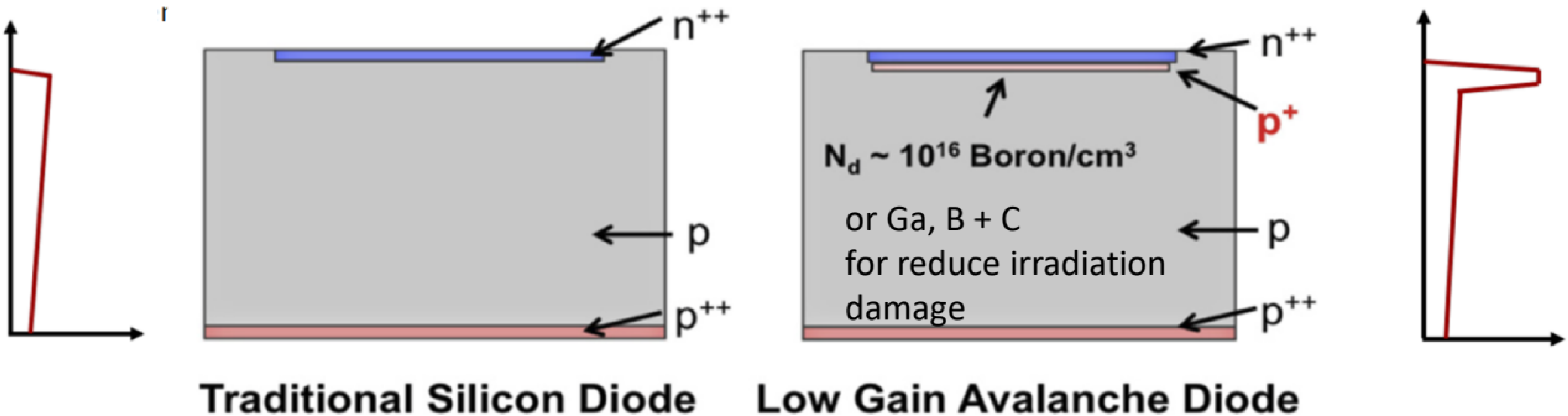

- ❑ Bias Voltage applied from 0 V to -80 V (**Δ**V = 0.2 V)
- ❑ AC frequency (10 kHz)
- ❑ Room temperature
- ❑ **Depletion Voltage**
  - o Gain layer depletion Voltage ~ 44 V
  - o Full depletion Voltage ~ 47 V



# Low Gain Avalanche Diode (LGAD) Sensors

## LGAD sensor design

- LGAD sensor on endcap timing layer
  - Provides timing information for next-generation detectors
- Thin implanted gain layer of overall thickness of 35–50 μm
  - Fast timing can be achieved in silicon diodes with a thin depletion region to have short drift times & fast rise time.
  - 50 μm thick depletion region gives < 500 ps rise time.
- E field amplification from internal p+ doping layer of silicon diode sensor
- Achieve a low-jitter, low noise with large signal
- Implement the internal gain of the sensor at 10-30 while providing 30-50 ps time resolution.



# PN Junction Diode