Status of LGAD sensor testing and testing plan in Korea

Jae Hyeok Yoo (Korea University)

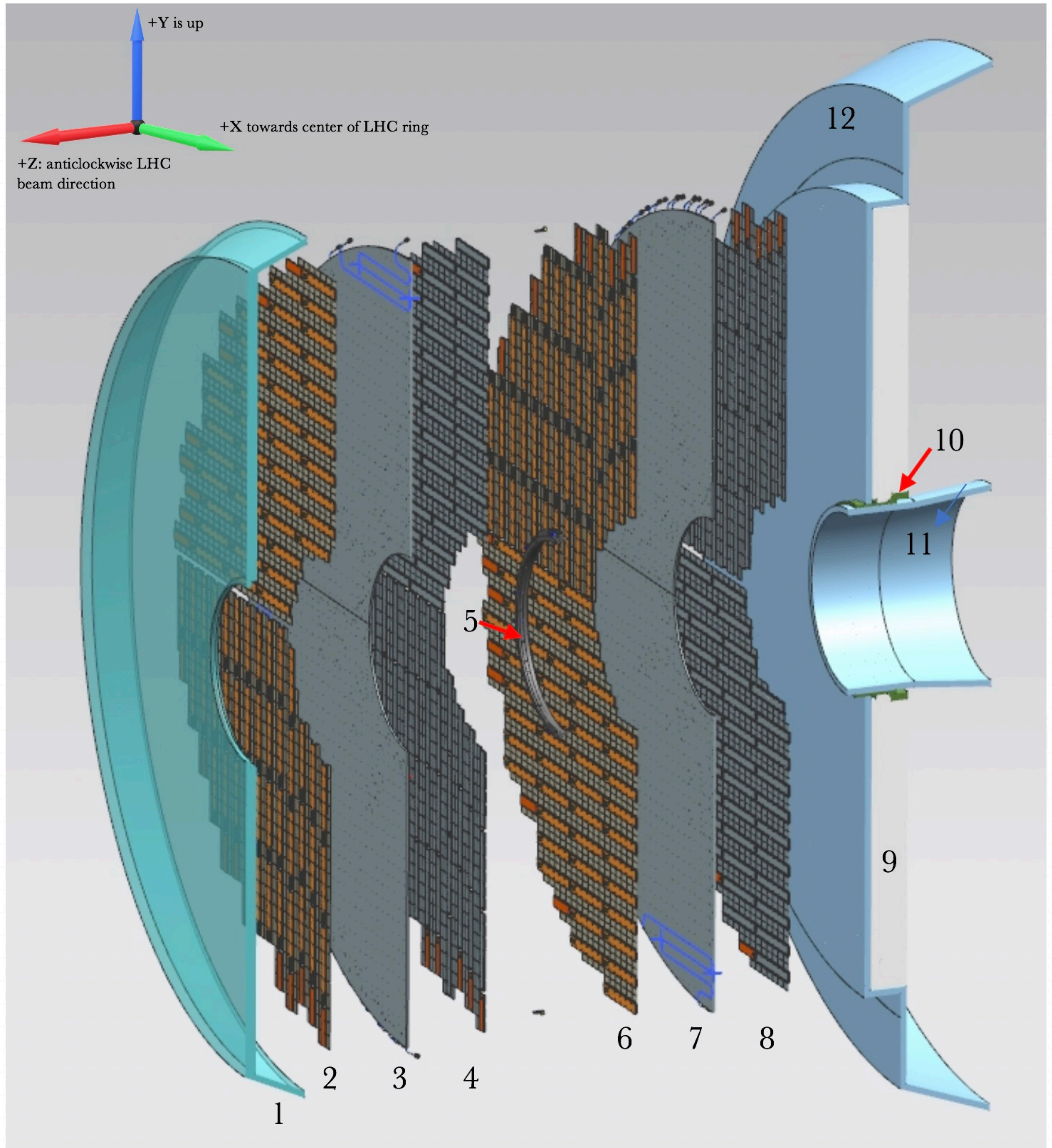
11/5/2020
2020 KPS Fall Meeting Focus Session
“Cornerstone for future collider projects”

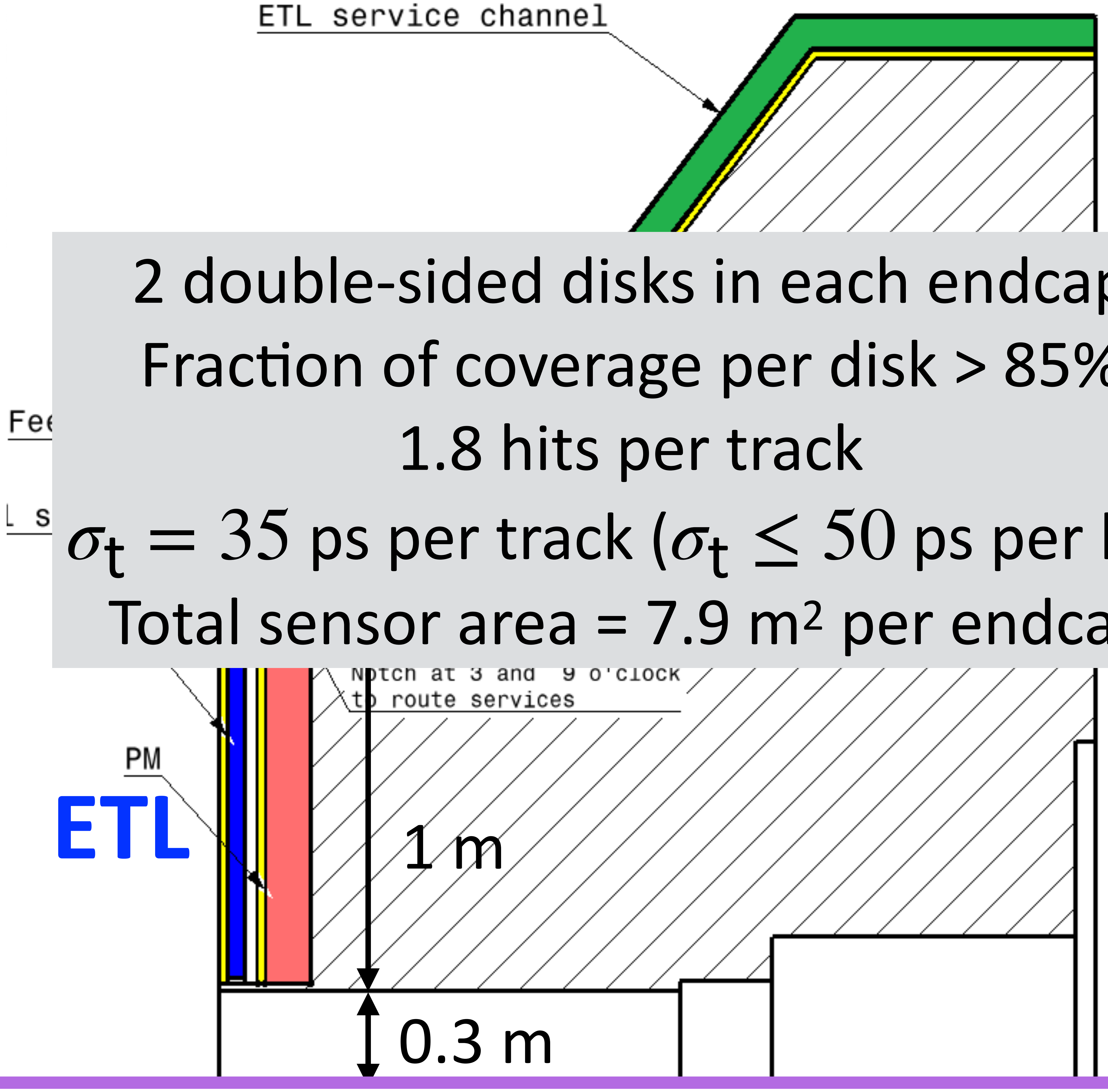
Endcap Timing Layer (ETL)

η coverage: 1.6 - 3.0
3 m from IP
Width = 4.5 cm

Endcap Timing Layer (ETL)

1: ETL Thermal Screen
2: Disk 1, Face 1
3: Disk 1 Support Plate
4: Disk 1, Face 2
5: ETL Mounting Bracket
6: Disk 2, Face 1
7: Disk 2 Support Plate
8: Disk 2, Face 2
9: HGCal Neutron Moderator
10: ETL Support Cone
11: Support cone insulation
12: HGCal Thermal Screen





2 double-sided disks in each endcap

Fraction of coverage per disk > 85%

1.8 hits per track

$\sigma_t = 35$ ps per track ($\sigma_t \leq 50$ ps per hit)

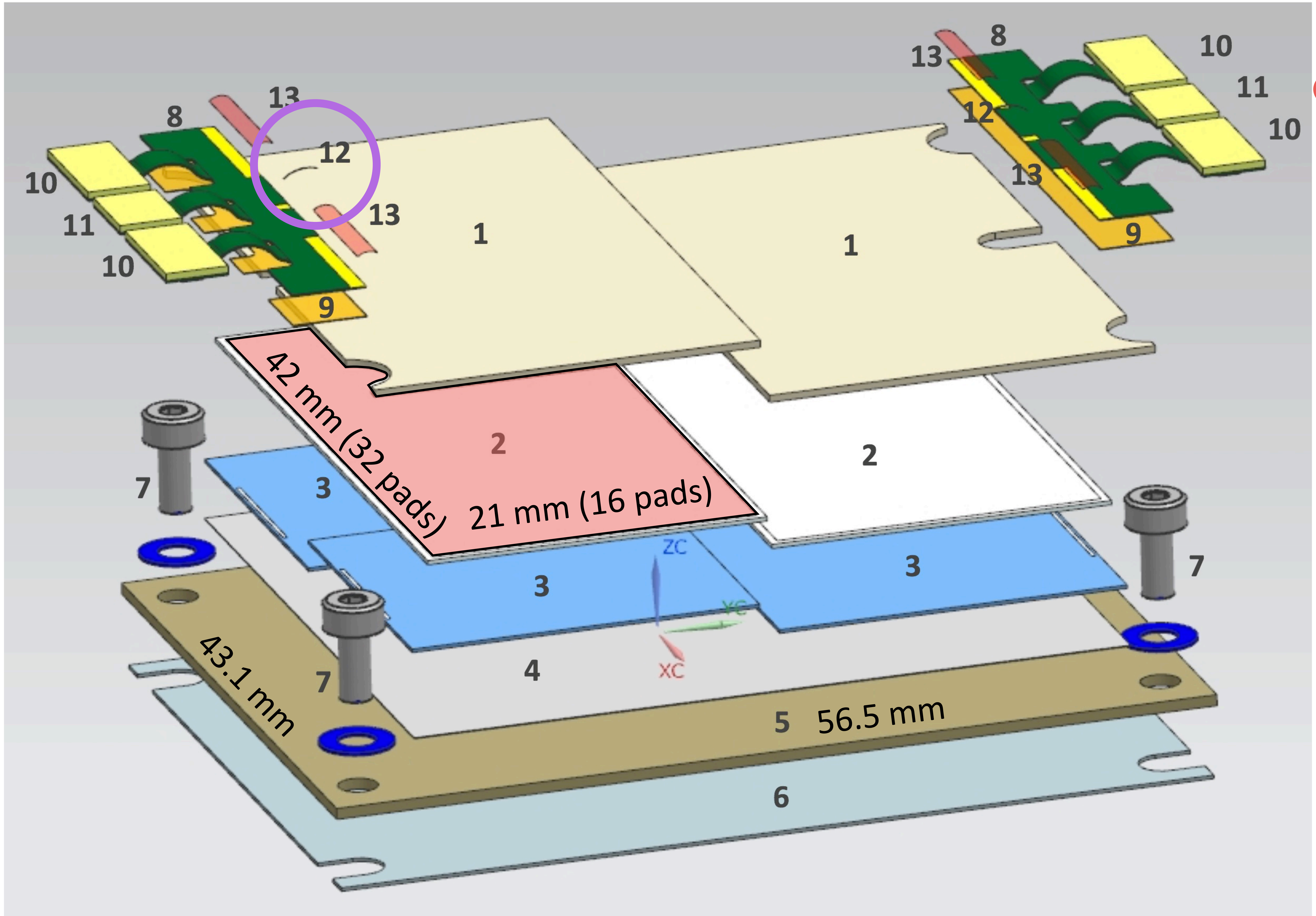
Total sensor area = 7.9 m² per endcap

IP

beamline

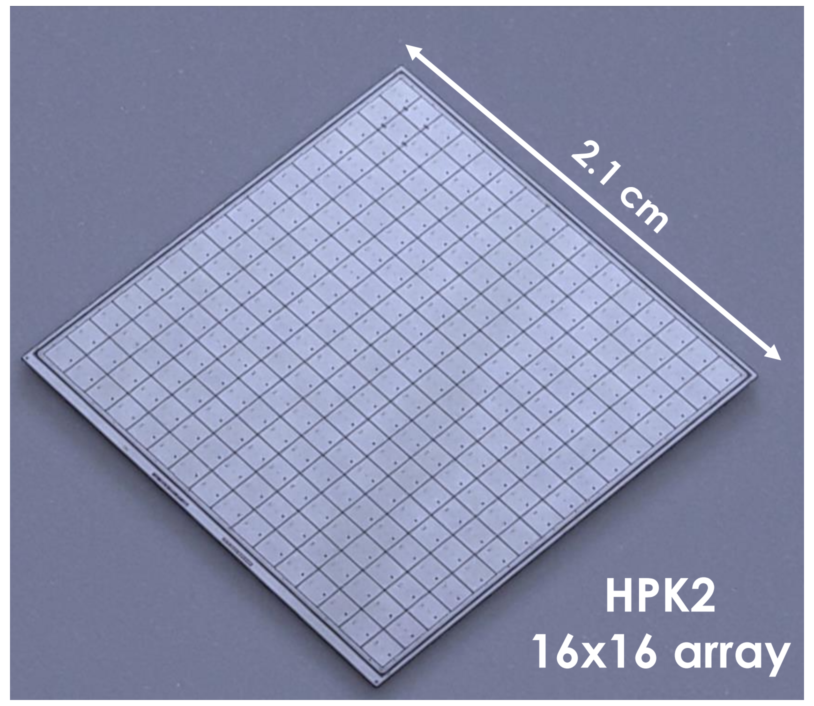
3 m

LGAD sensors in module



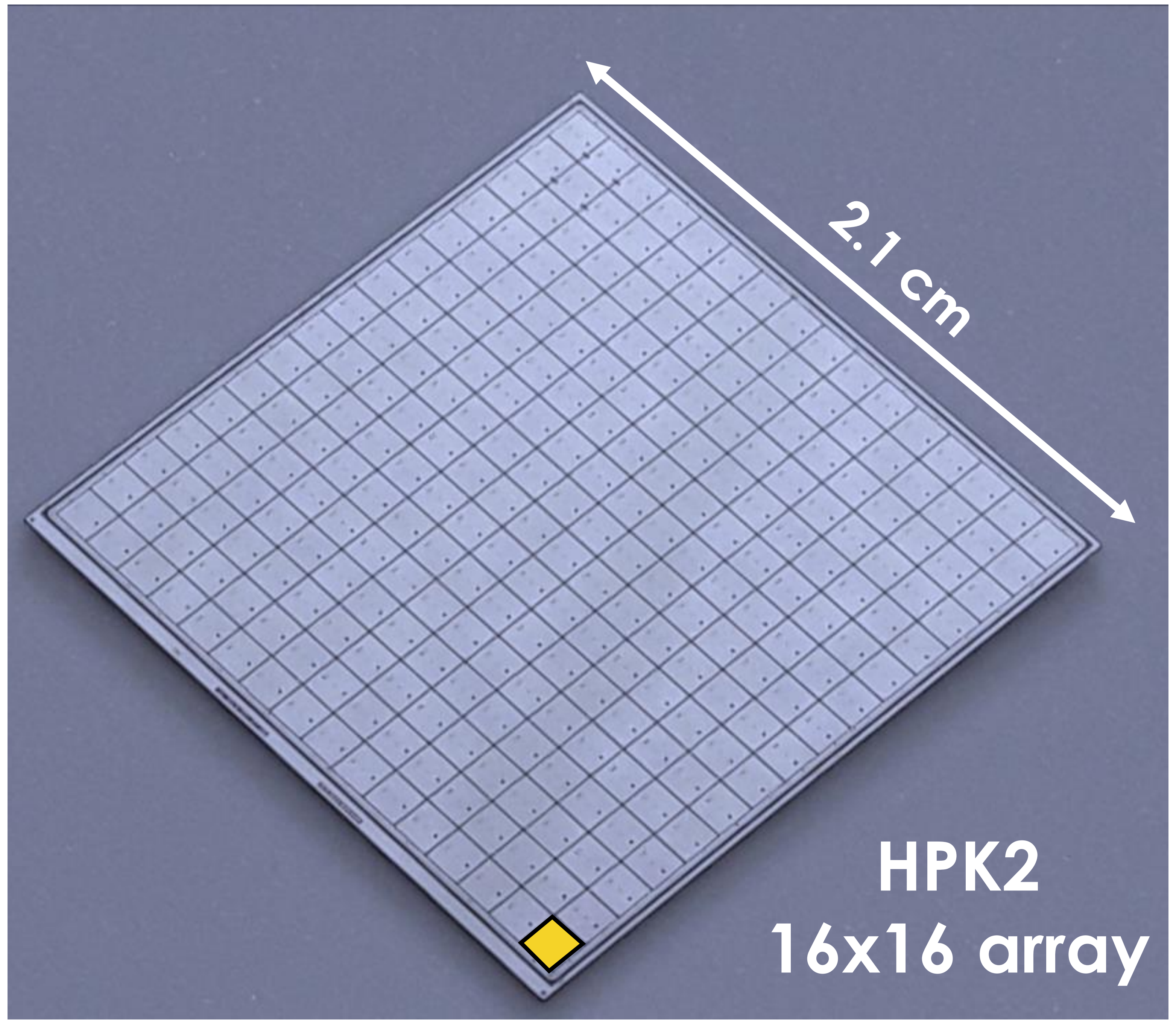
1: AlN module cover
2: LGAD sensor
3: ETL ASIC
4: Mounting film
5: AlN carrier
6: Mounting film
7: Mounting screw
8: Front-end hybrid
9: Adhesive film
10: Readout connector
11: High voltage connector
12: LGAD bias voltage wirebond
13: ETROC wirebonds

32x16=

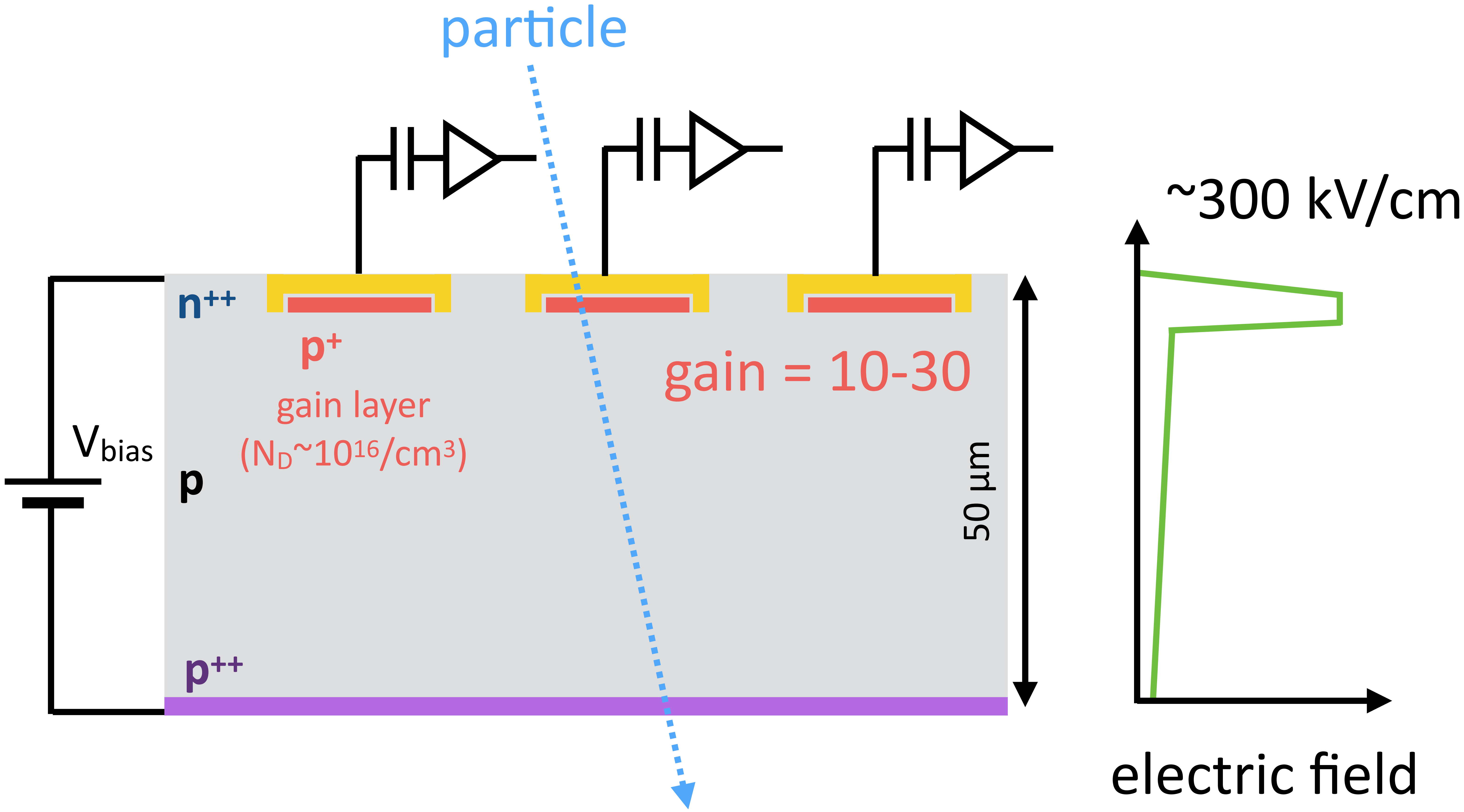


x2

LGAD sensor



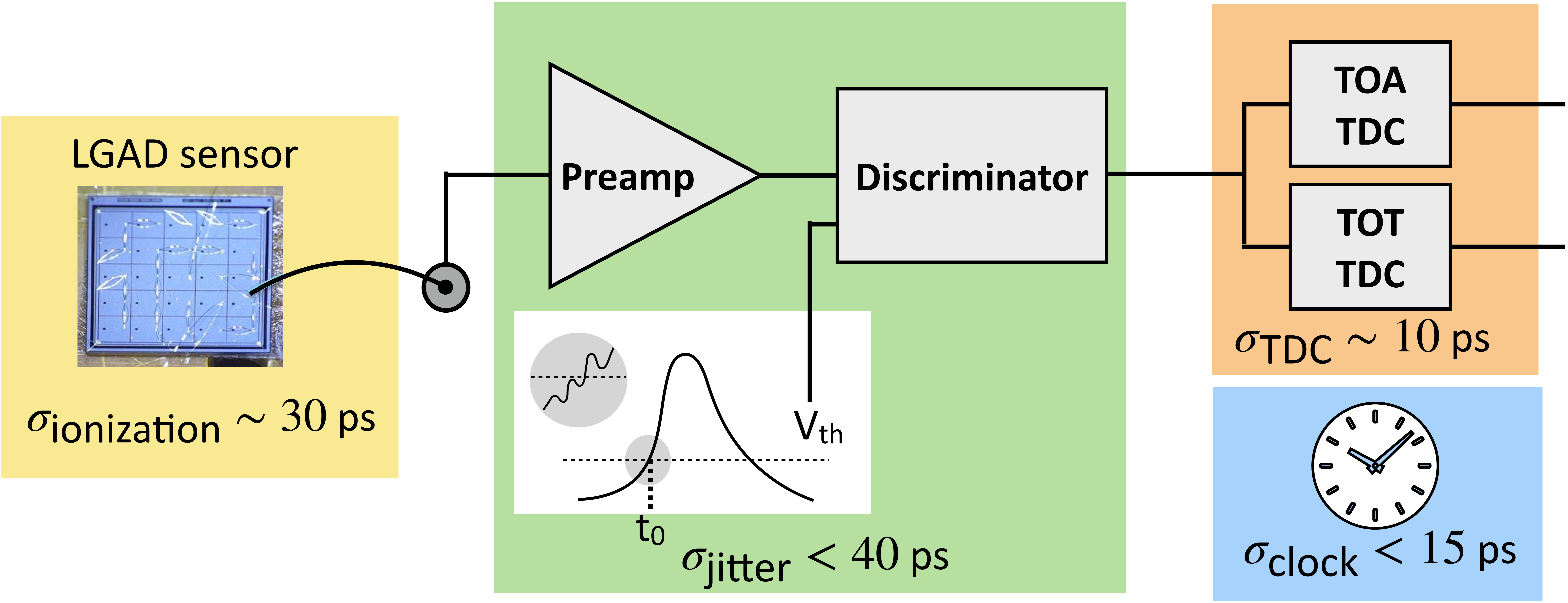
one pad (pixel) = 1.3x1.3 mm²



Parameters that affect time resolution

How to obtain 50 ps resolution per hit

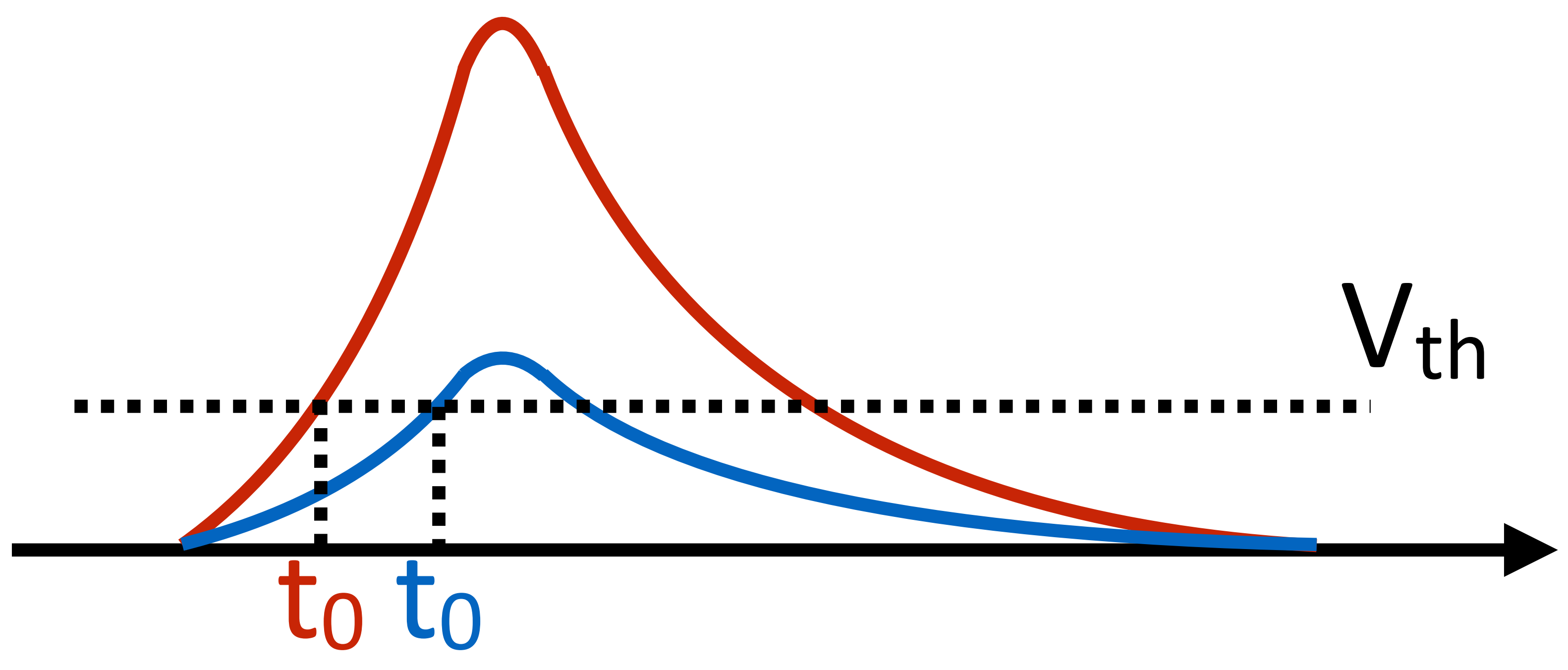
$$\sigma_t^2 = \sigma_{\text{ionization}}^2 + \sigma_{\text{jitter}}^2 + \sigma_{\text{TDC}}^2 + \sigma_{\text{clock}}^2$$



Parameters that affect time resolution

$$\sigma^2_{\text{ionization}} = \sigma^2_{\text{time walk}} + \sigma^2_{\text{Laudau noise}} + \sigma^2_{\text{Distortion}}$$

Illustration of time walk

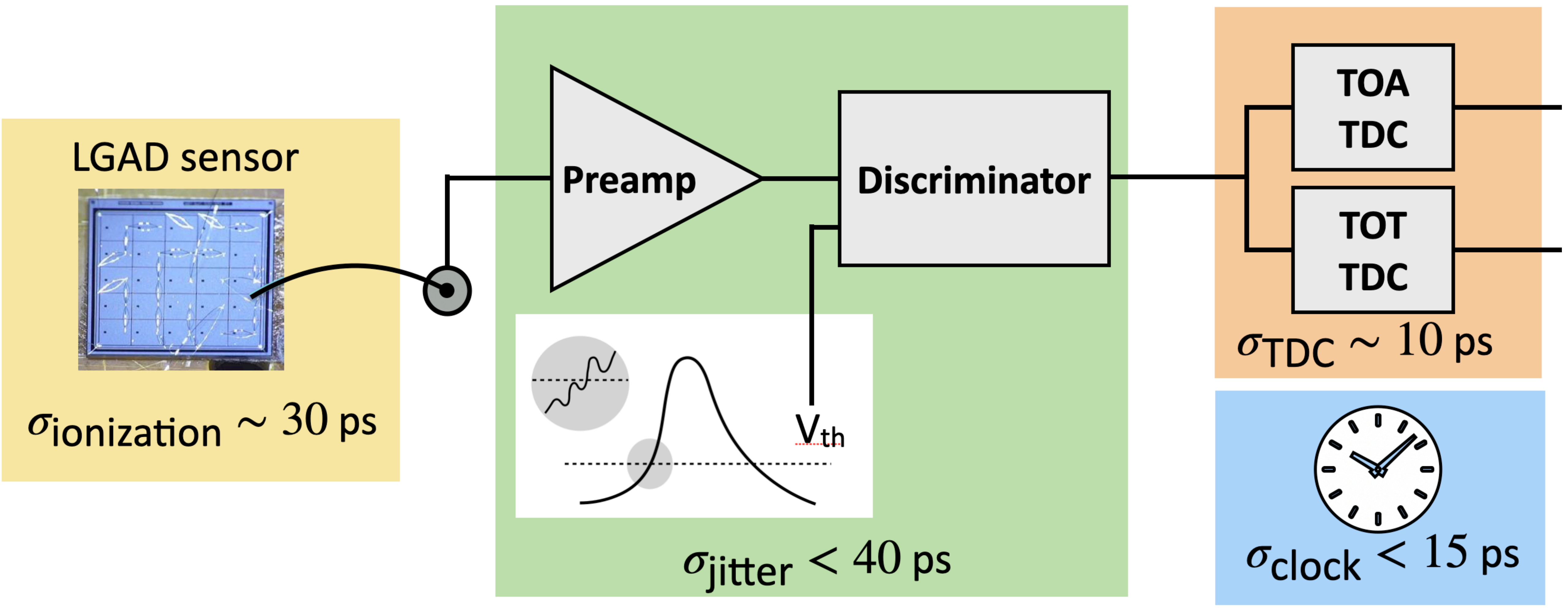


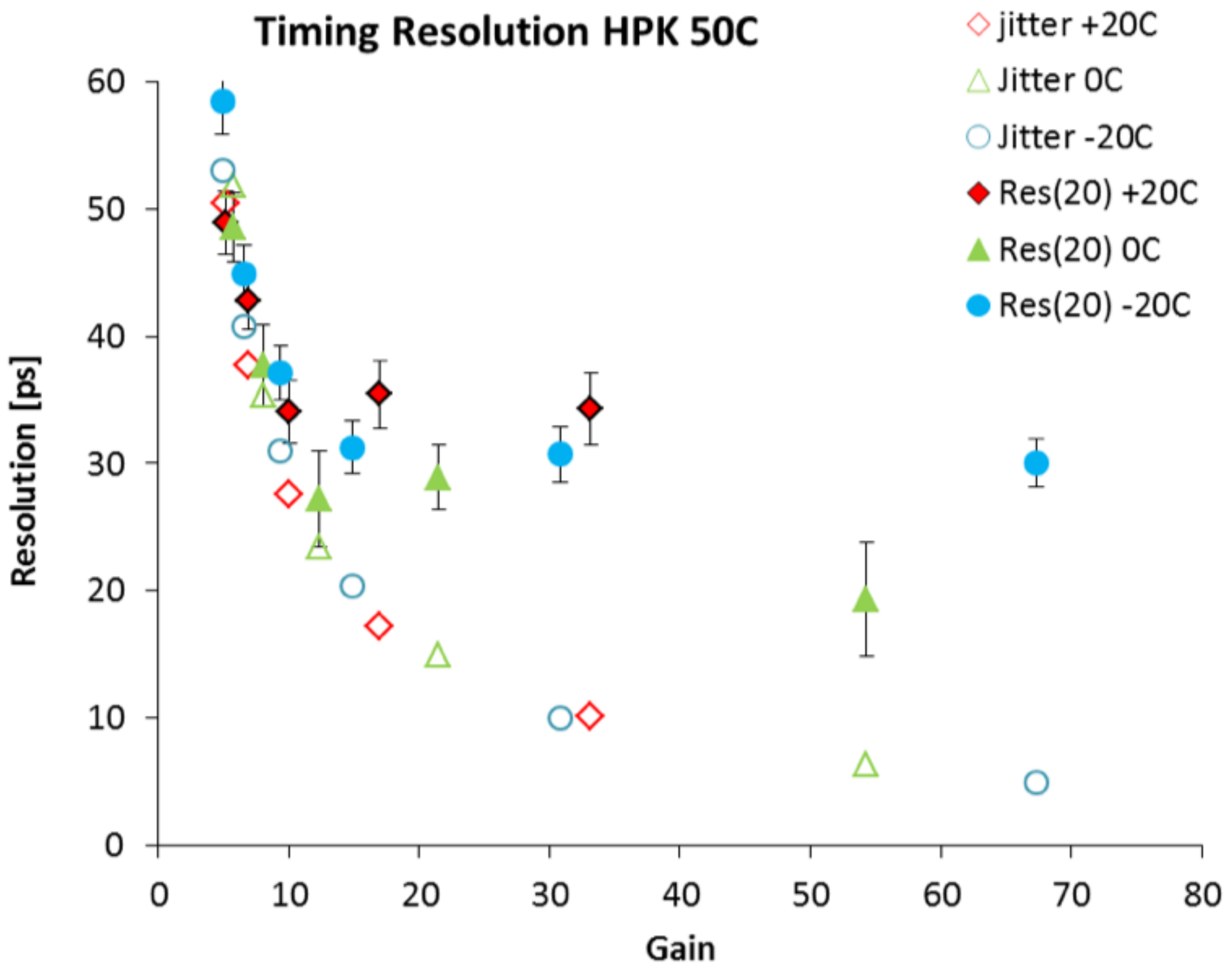
- Total number and local density of e-h production vary event by event basis
  - Can cause change in signal amplitude (time walk) and irregularities in current signal (Landau noise)
  - Time walk minimized by fast slew rate and low intrinsic noise (also in readout chain)
  - Laudau noise needs to be measured carefully
- Distortion of signal shape caused by non-uniform drift velocity and weighting field
  - Reduced by (1) saturated drift velocity with high field and (2) uniform weighting field using parallel-plate geometry

Main contributor to time resolution

How to obtain 50 ps resolution per hit

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





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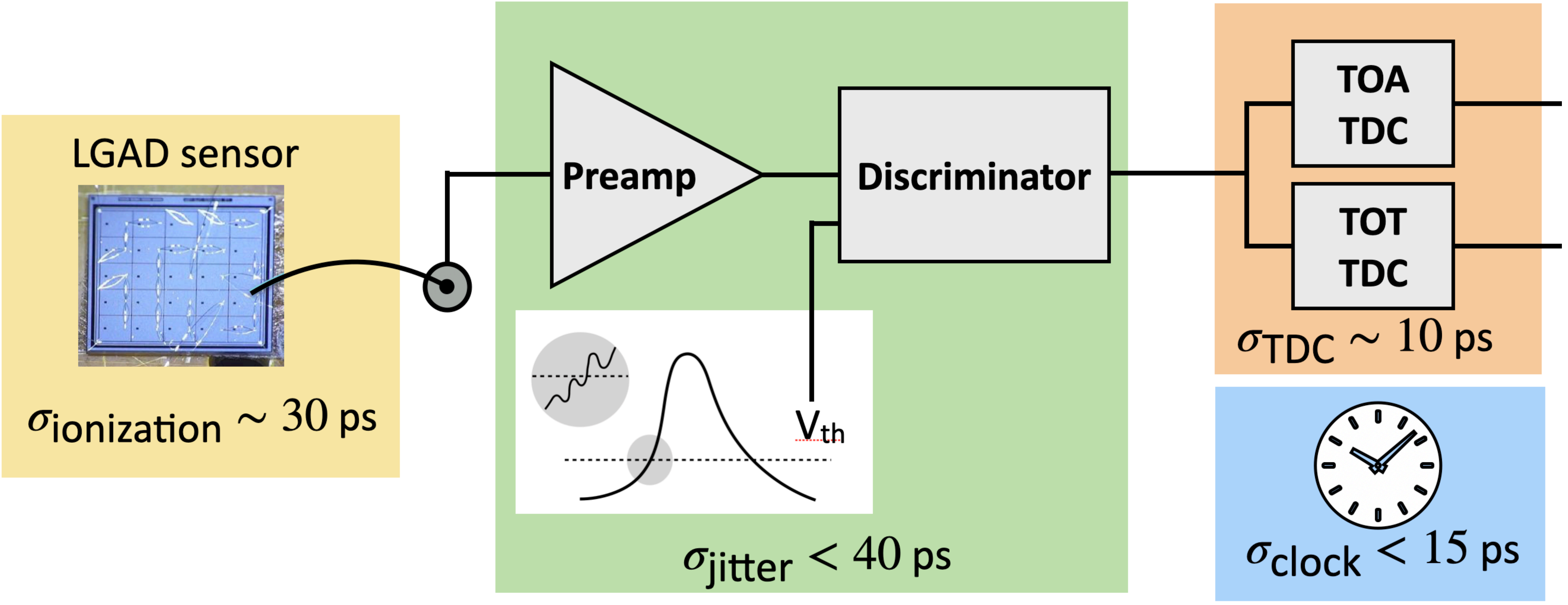

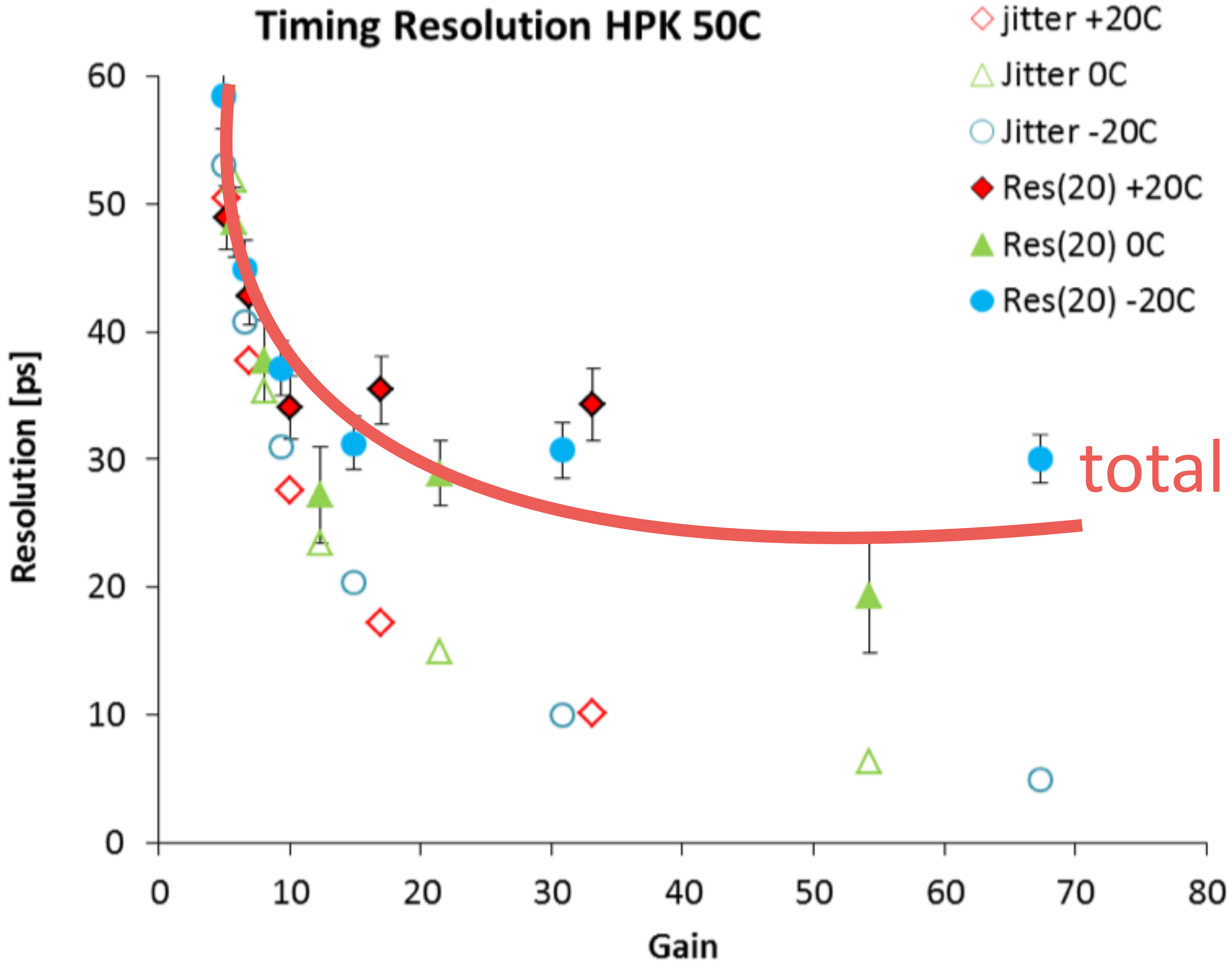

Main contributor to time resolution

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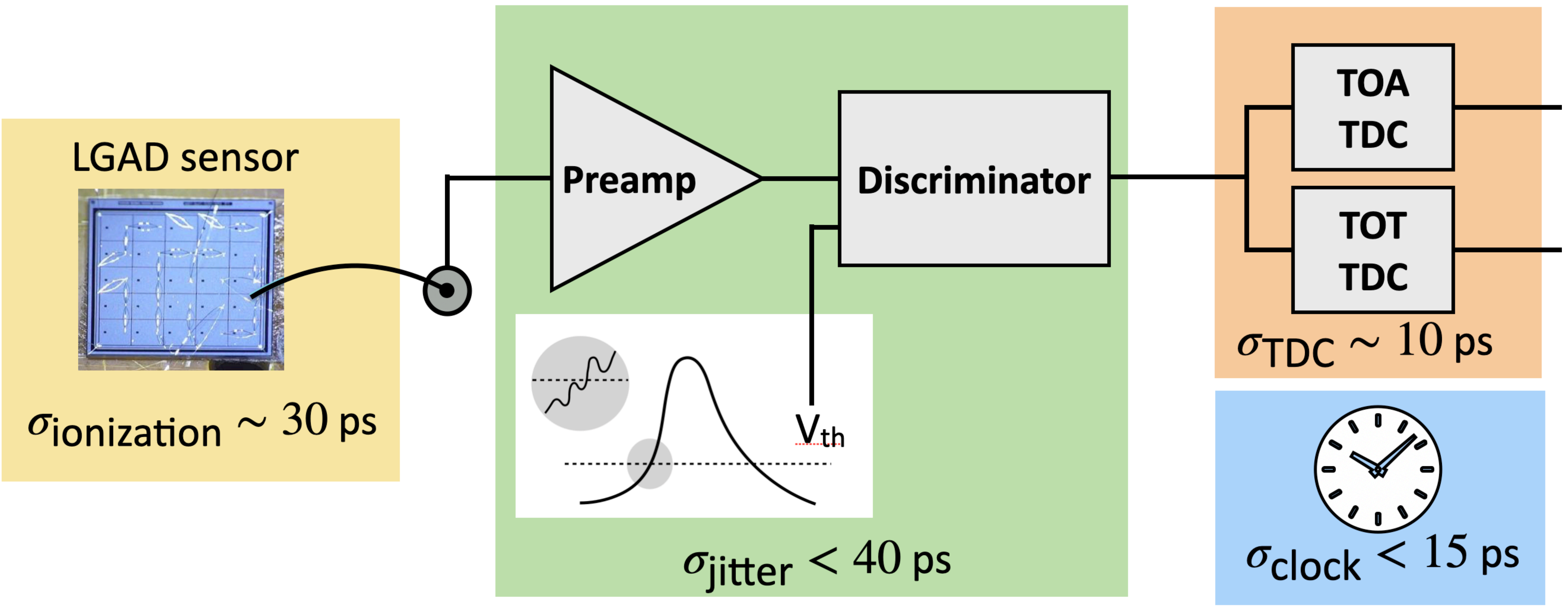

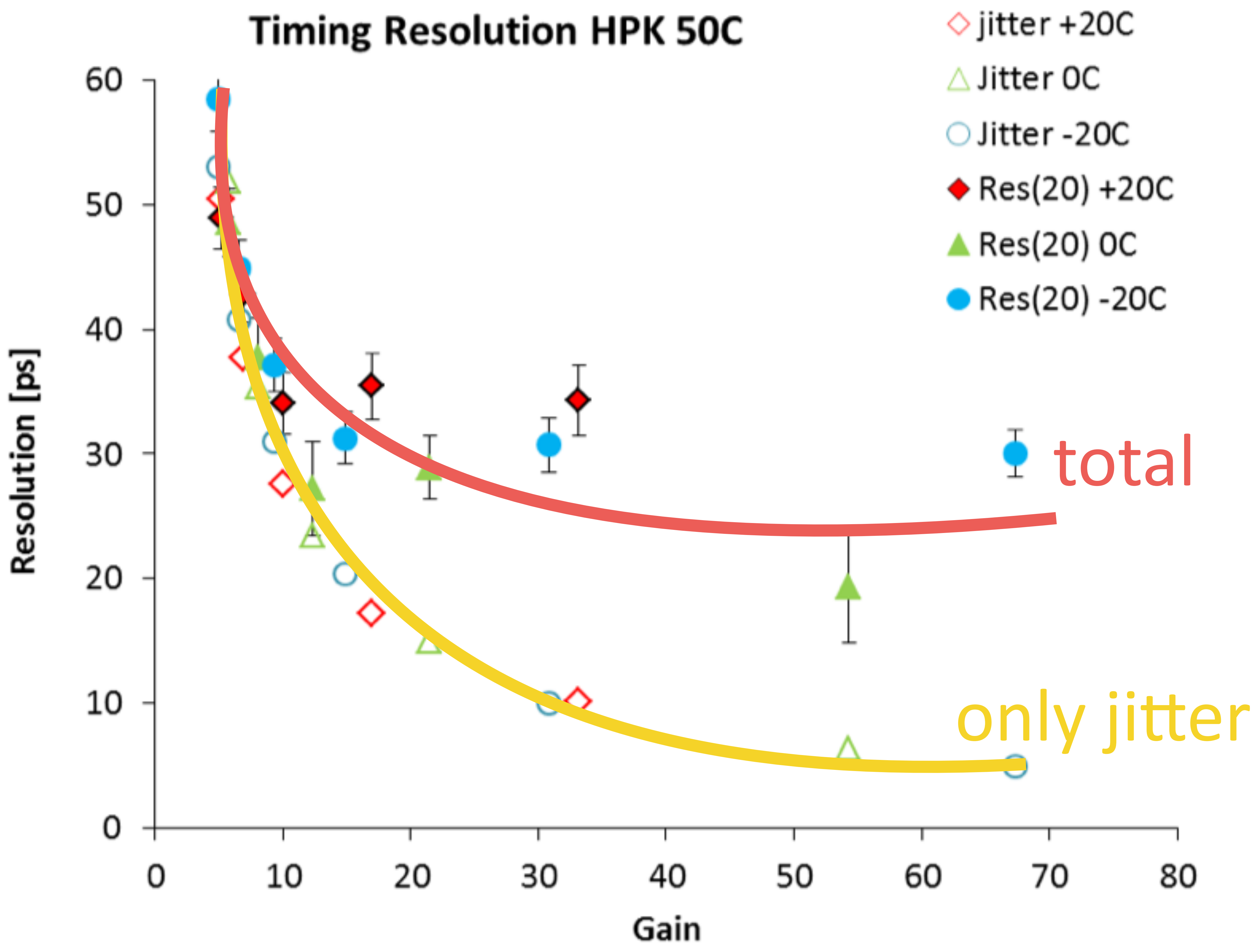

Main contributor to time resolution

How to obtain 50 ps resolution per hit

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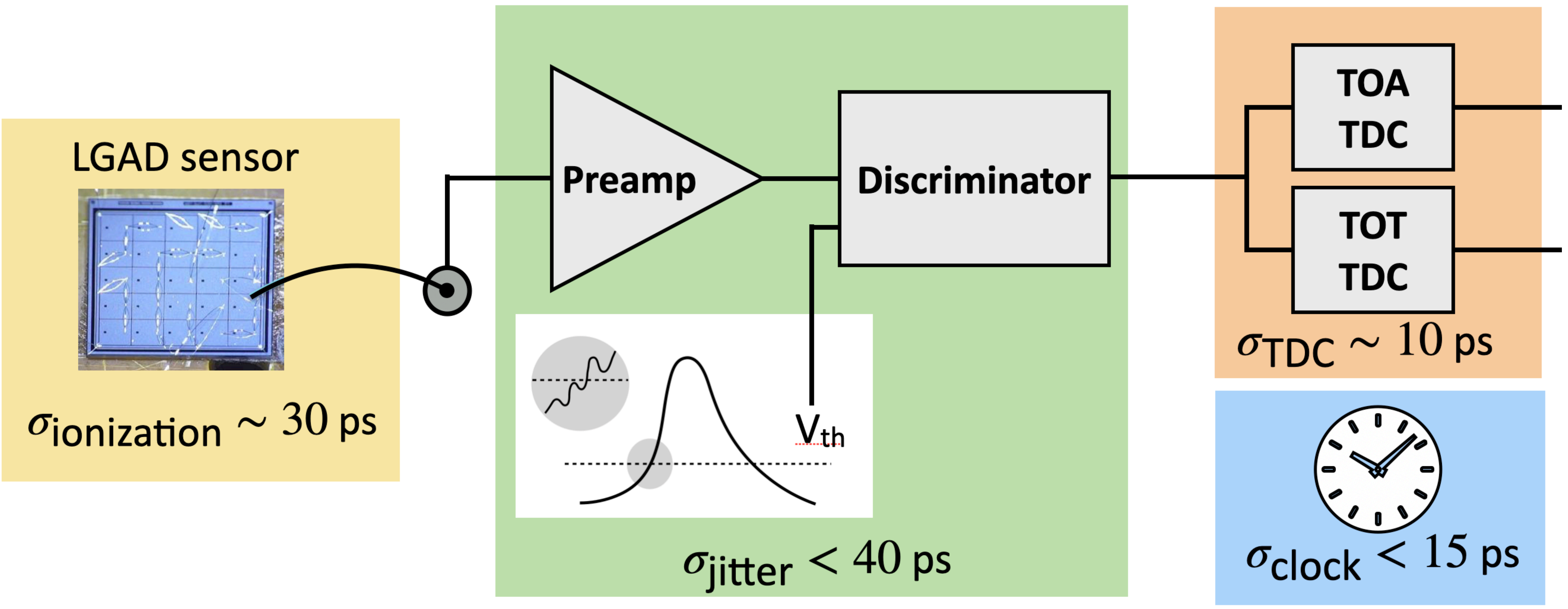
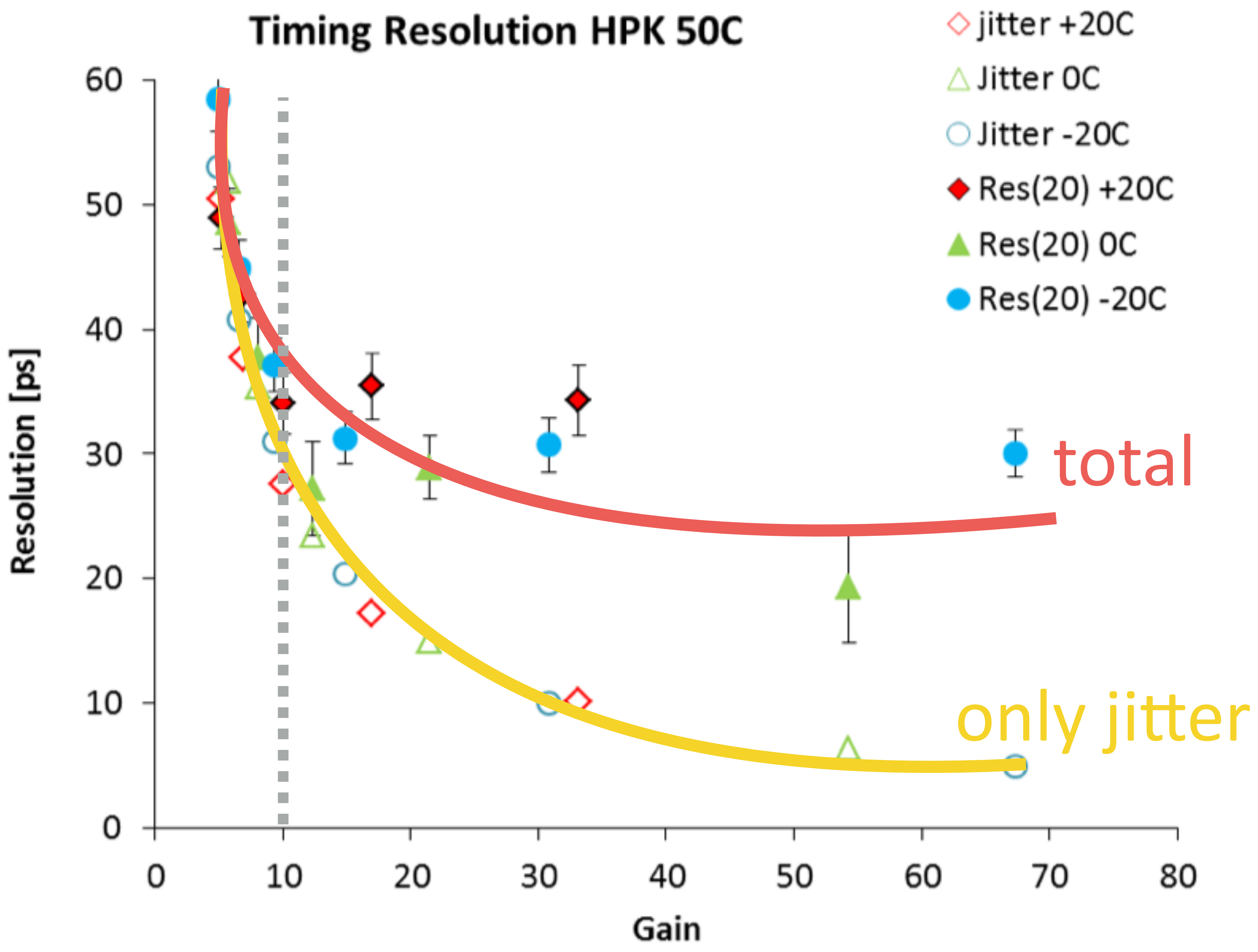


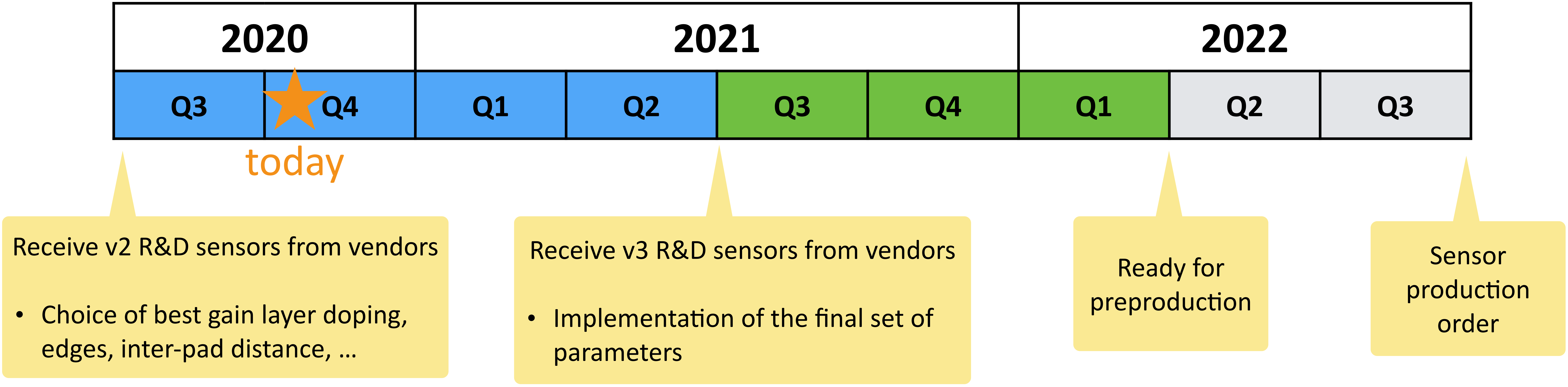


In gain > 10, main contribution is sensor resolution (dominated by Landau fluctuations)

Sensor manufacturers and testing goals

- Manufacturers: Centro Nacional de Microelectronica (CNM), Fondazione Bruno Kessler (FBK), Hamamatsu Photonics (HPK) and potentially Novel Device Laboratory (NDL)
- The design of sensors needs detailed optimization to achieve high gain, low noise, and uniform response
- Parameters to be studied and optimized for sensor development
  - **Fill factor (active area/total area)**: high fill factor to increase number of two-hit tracks (small gap, edge)
  - **Hit efficiency and signal uniformity**: high and uniform gain within the pad, sensor, and wafers
  - **Gain and noise**: high gain and low noise crucial for electronics to achieve excellent time resolution
  - **Longterm stability**: stability may be affected by annealing effect
  - **Failure modes**: high V_{bias} might lead to detector damage, *e.g.*, irradiated sensors can die during operation
  - **Time resolution**: use custom low-noise FE boards to measure sensor's time resolution

Schedule of sensor testing

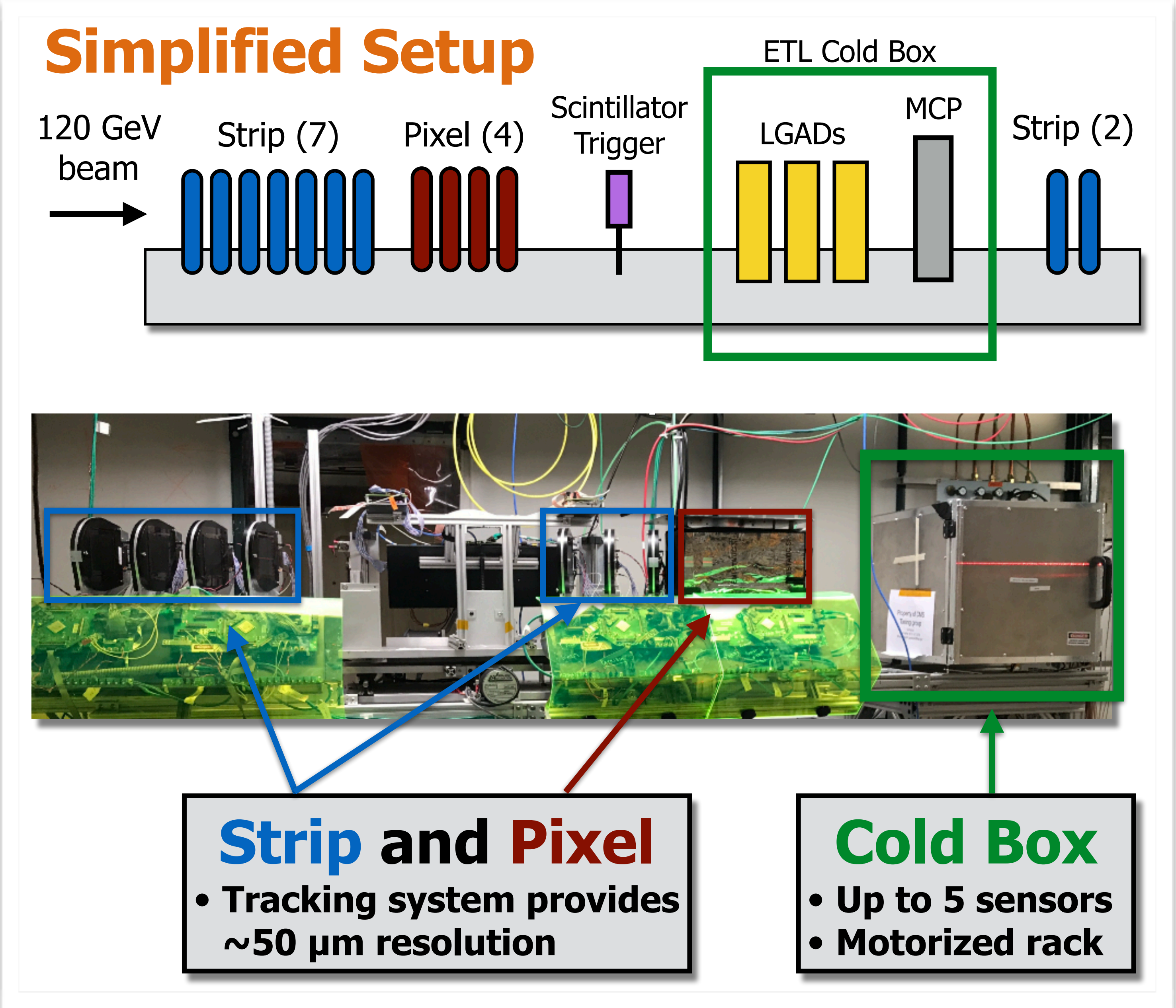


How are sensors tested?

Probe station

https://www.micromanipulator.com/wafer-probe-station/

Test beam setup @ FNAL



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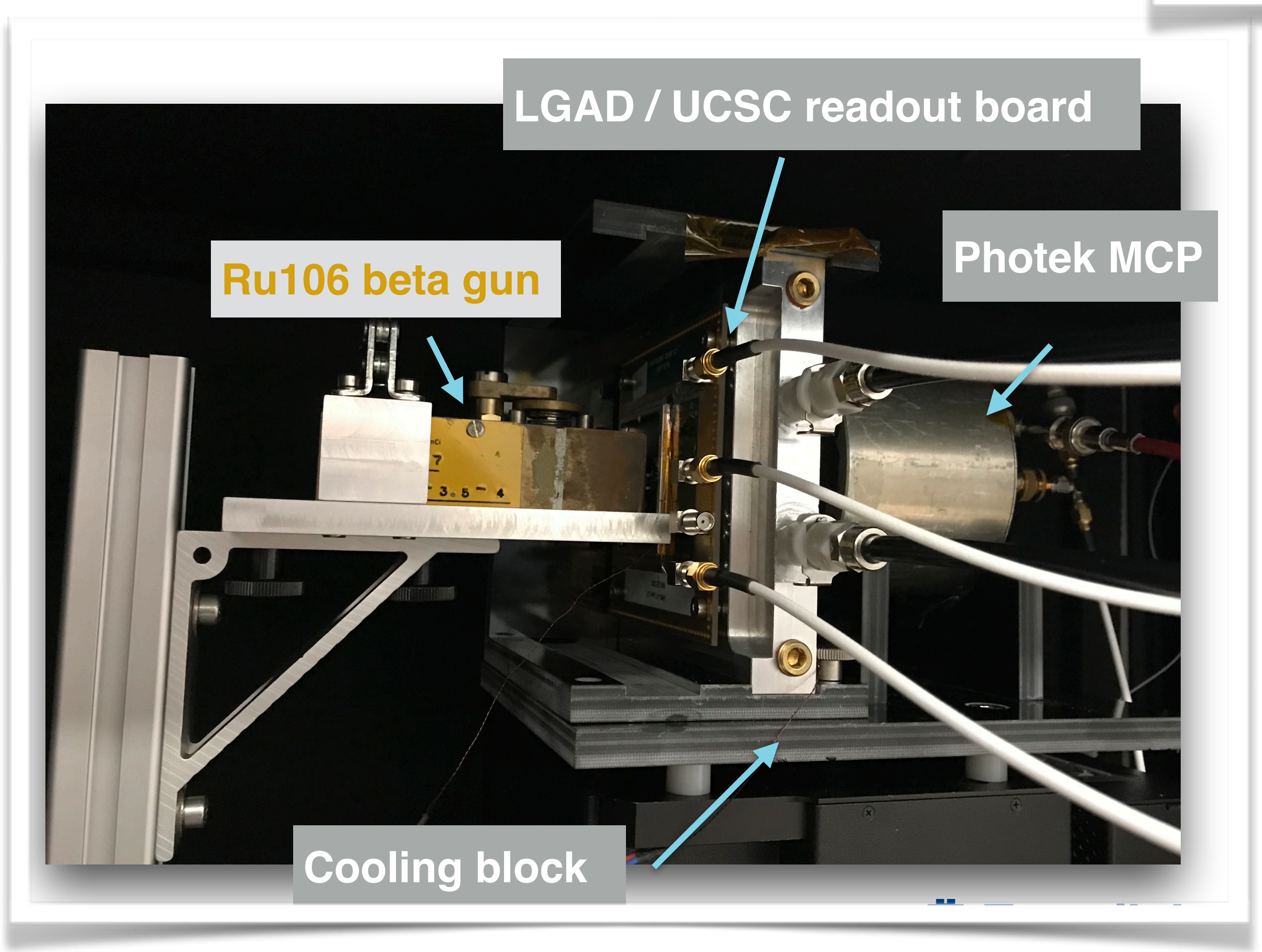
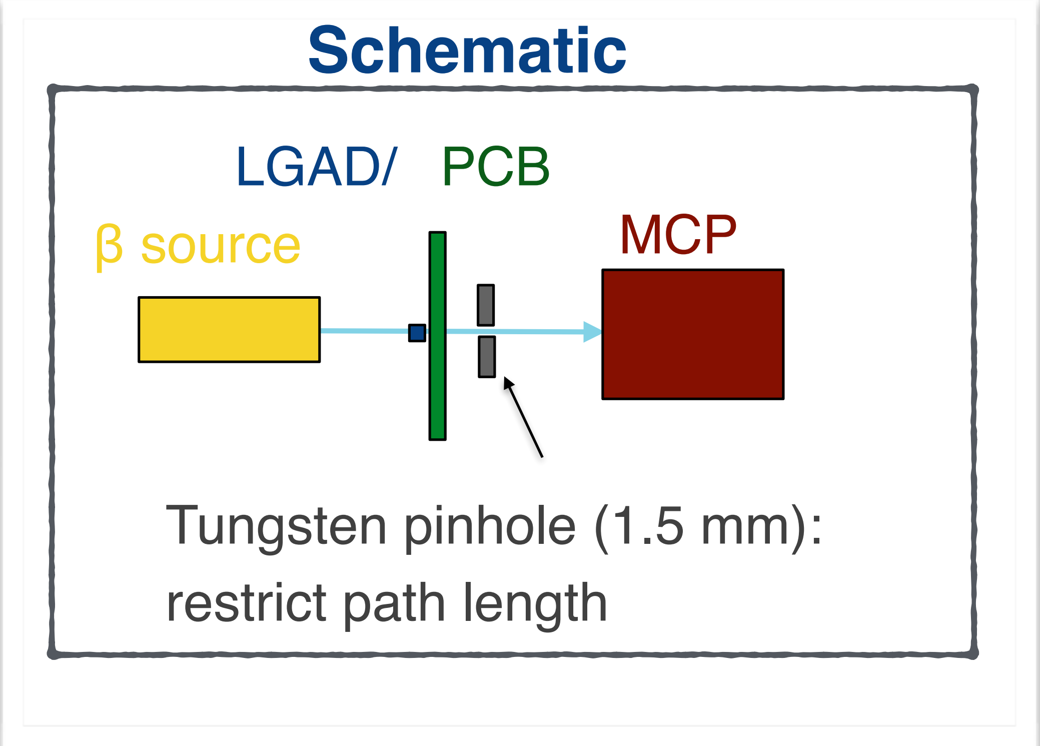
Beta source test setup @ FNAL



Ryan Heller



- Probe station
  - Measure IV and CV curves
  - Data provided by manufacturers
- Test beam
  - Measure gain, hit efficiency, timing
  - At FNAL, 1-2 times per year
- Beta source
  - Measure gain, timing
- Laser
  - Measure uniformity of gain, inter-pad gap

Testing results - FNAL test beam

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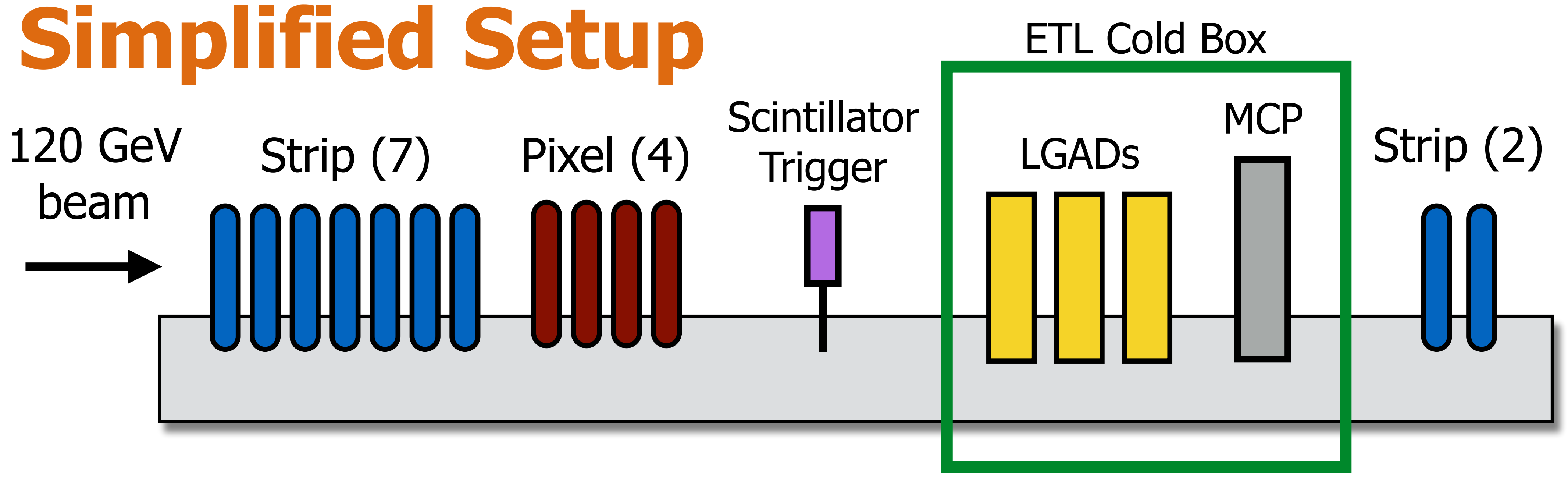
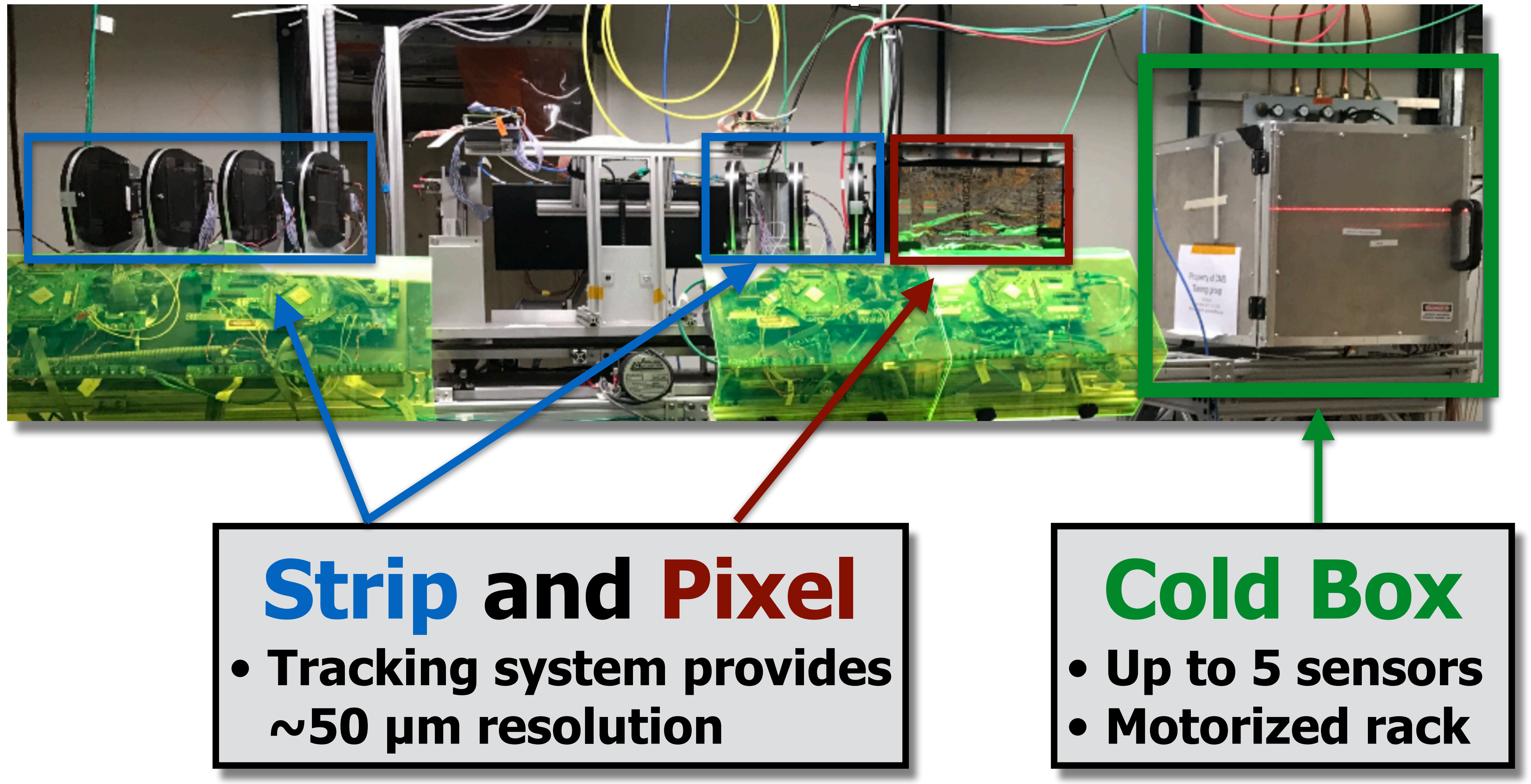
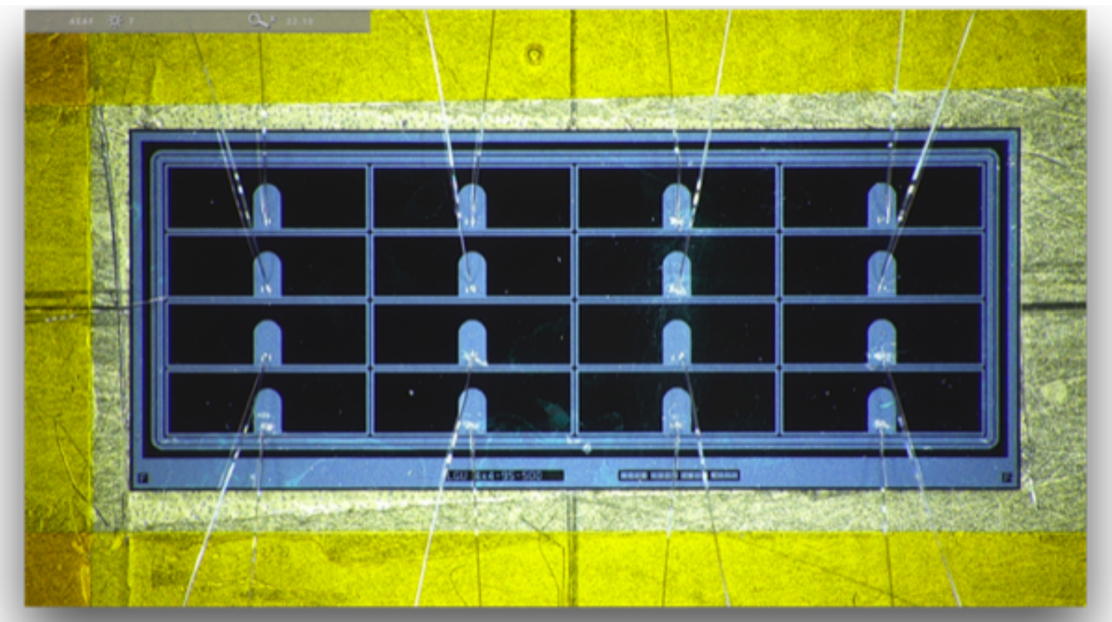
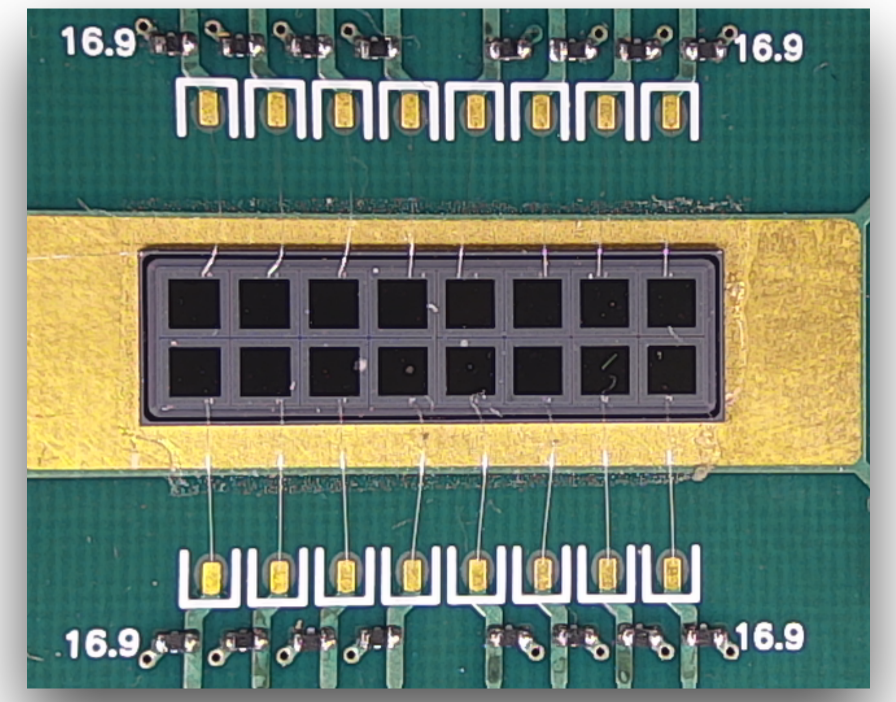
Simplified Setup







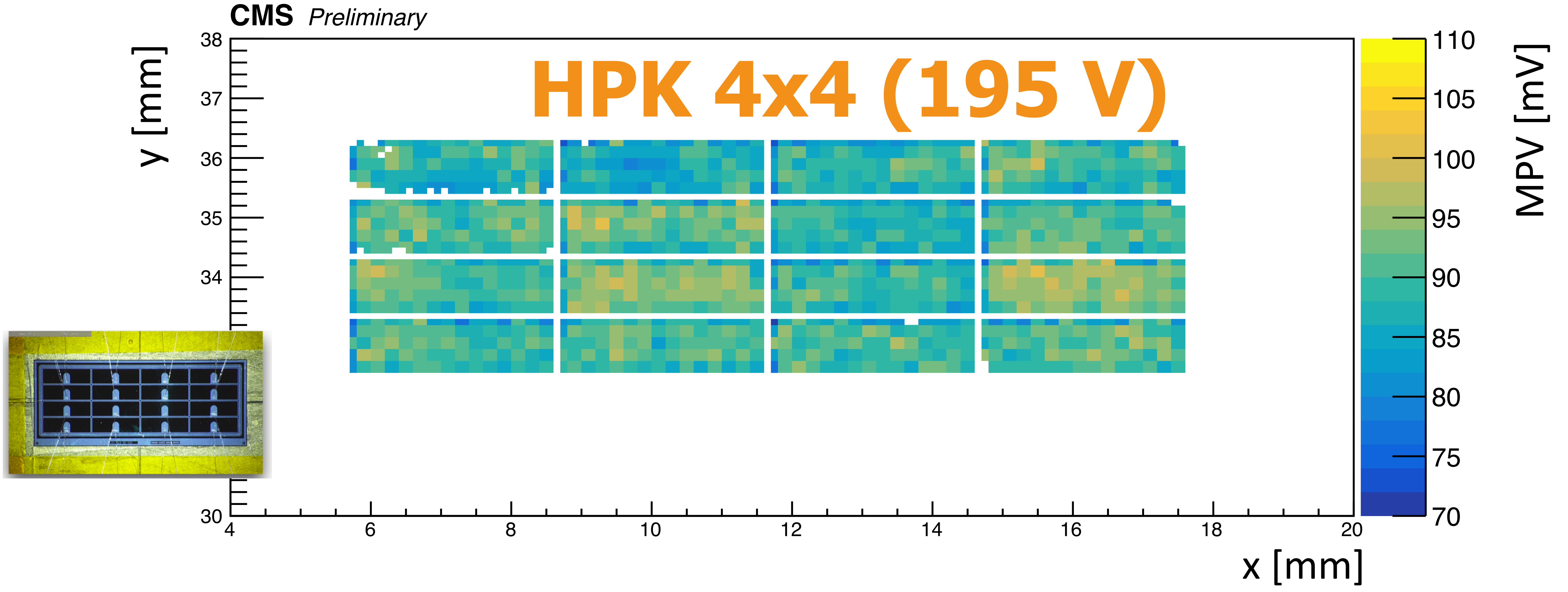
HPK type 3.1 4x4 LGAD array

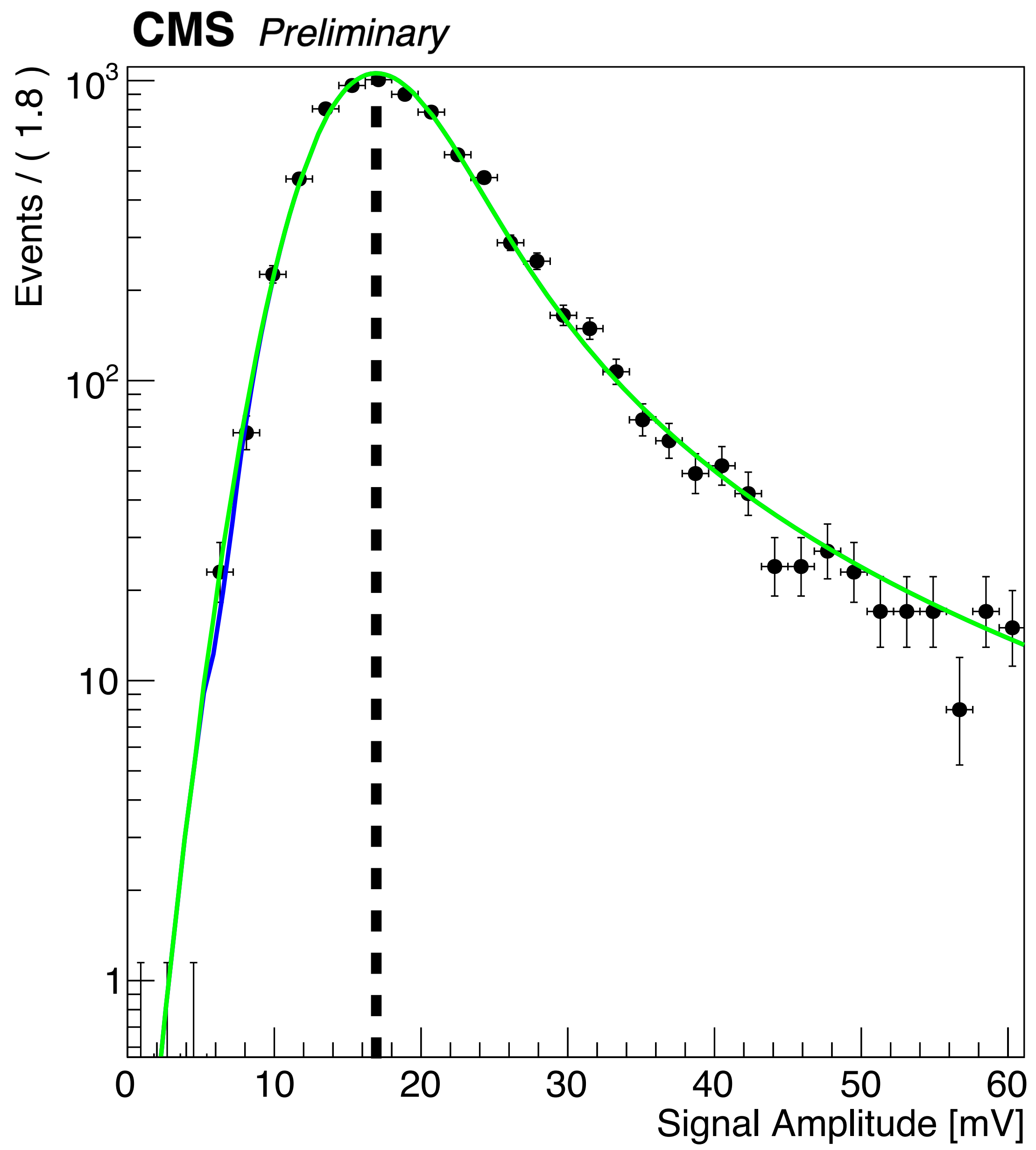


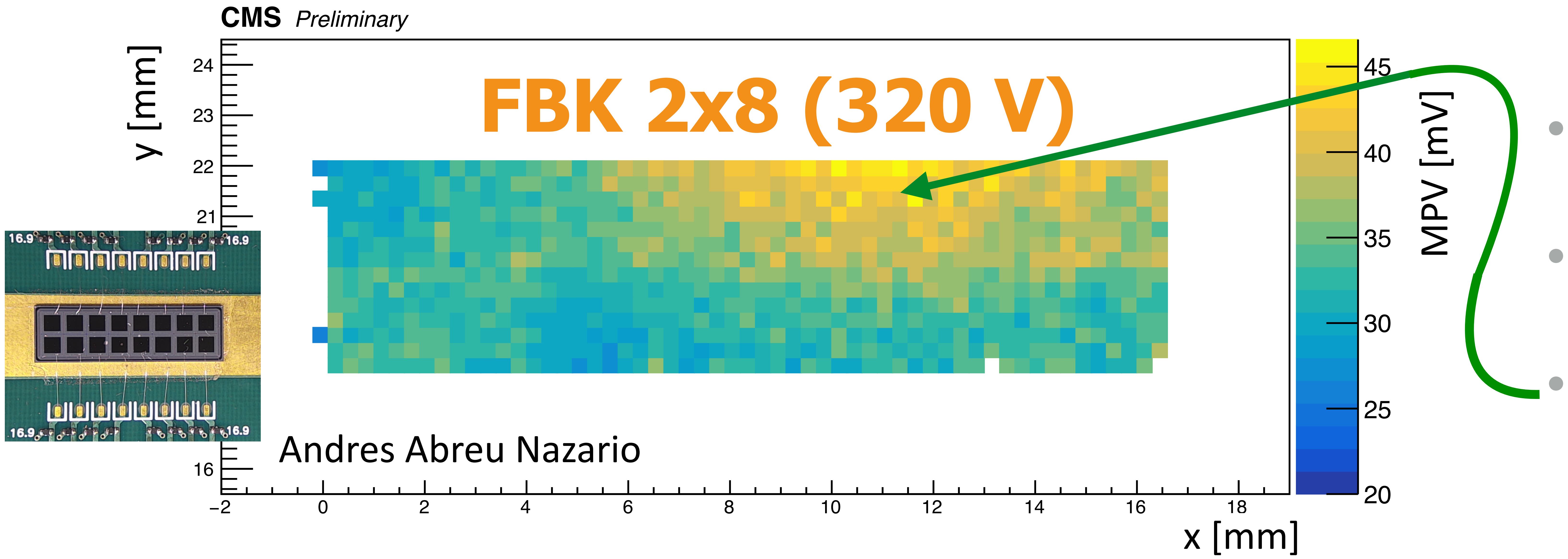
FBK 2x8 LGAD array

- Tested sensors: 16-ch HPK and FBK arrays
  - Pad size (earlier test sensors) : 1x3 mm^2 (HPK) and 2x2 mm^2 (FBK)
- Results from FNAL test beam
  - 120 GeV proton beam, MCP PMT as a time reference (res ~10 ps), strip+pixel tracking system

Testing results - gain uniformity

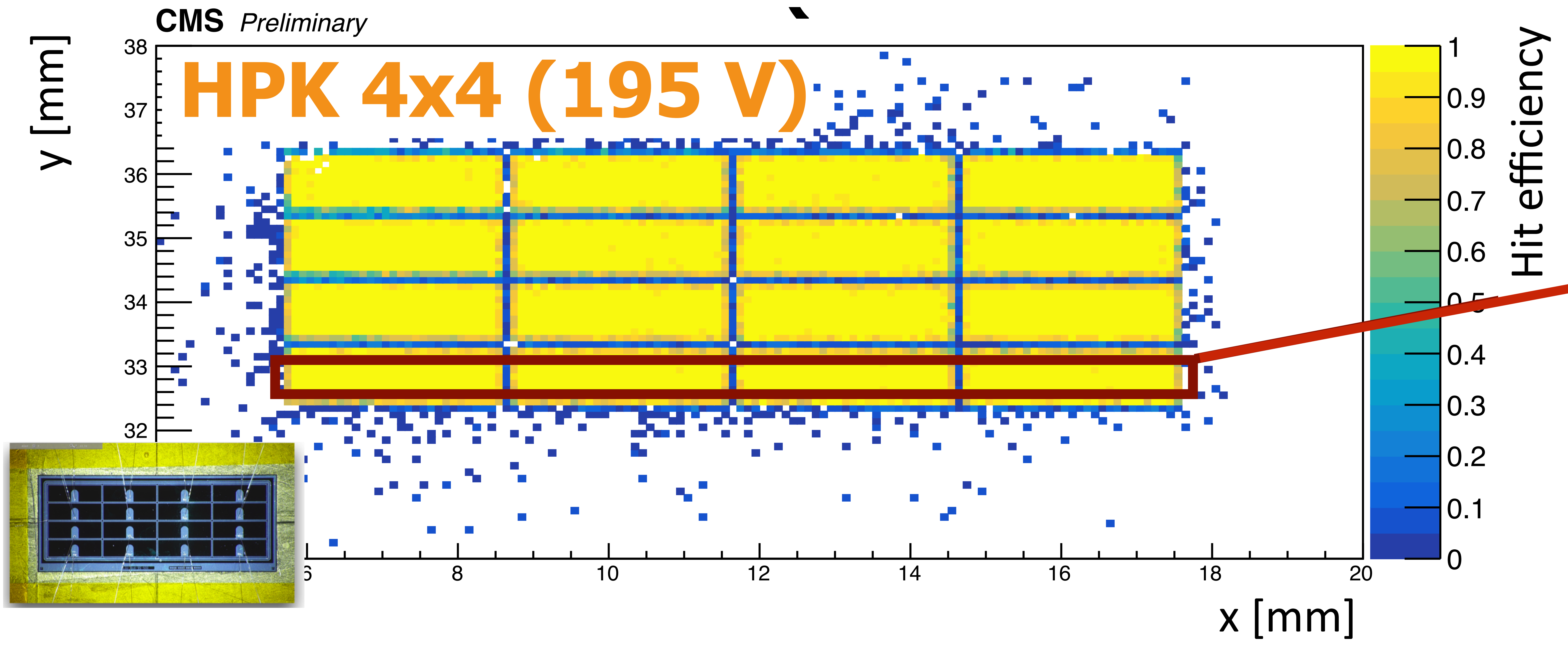


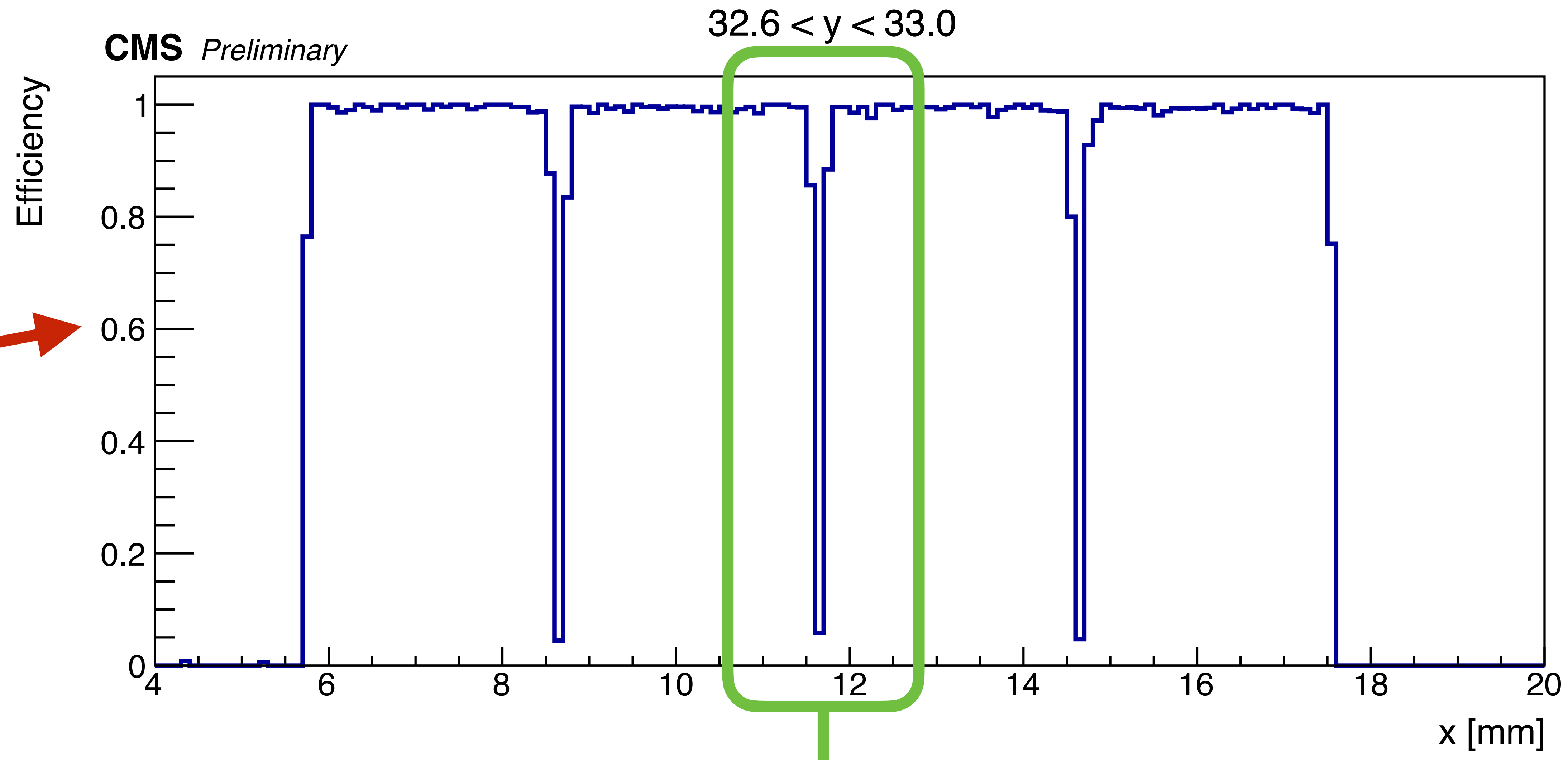


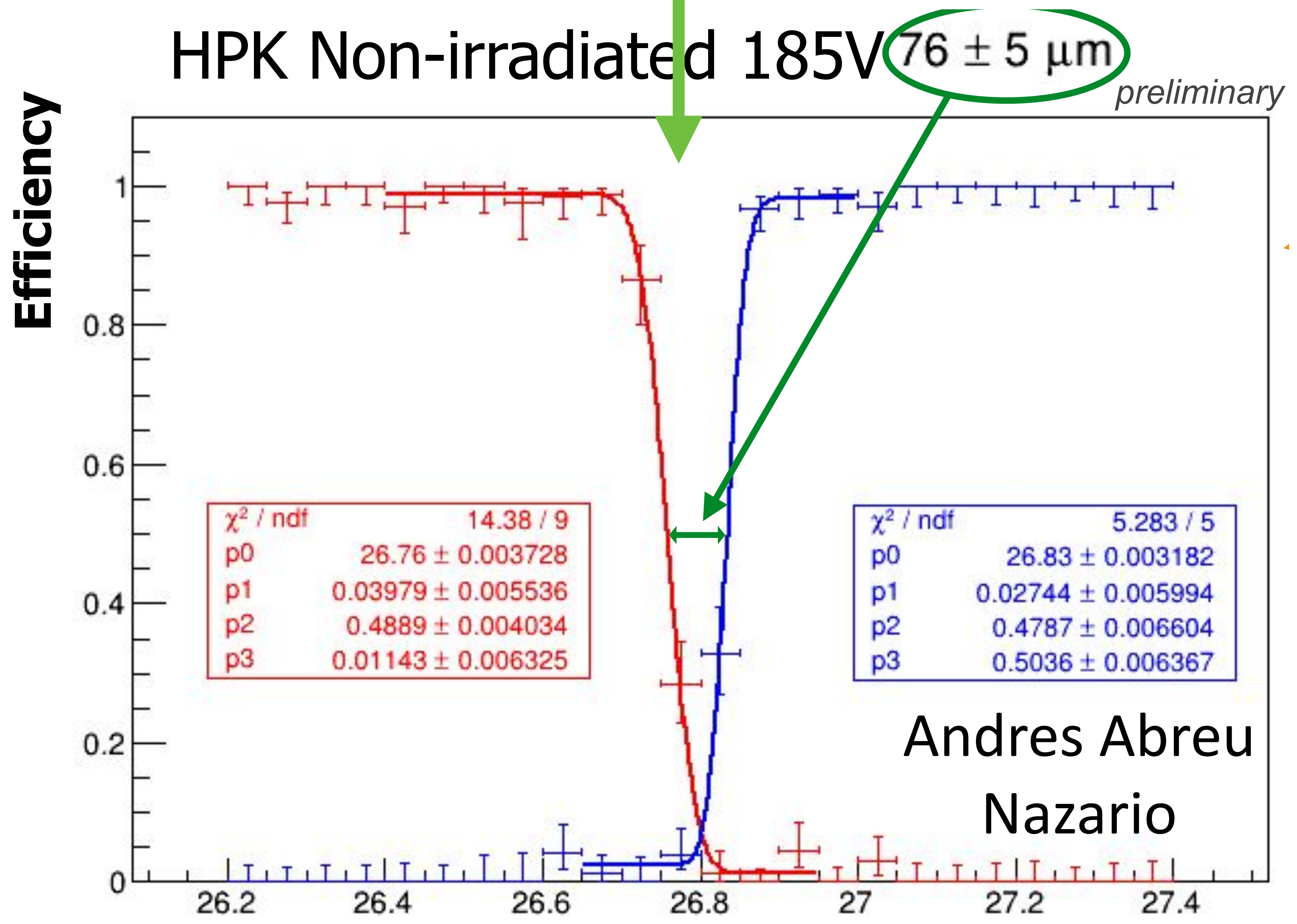


- Find the MPV of signal MAX
- HPK: gain uniform at 5% level
- FBK: hot spot due to variation in doping concentrations

Testing results - hit efficiency, inter-pad gap



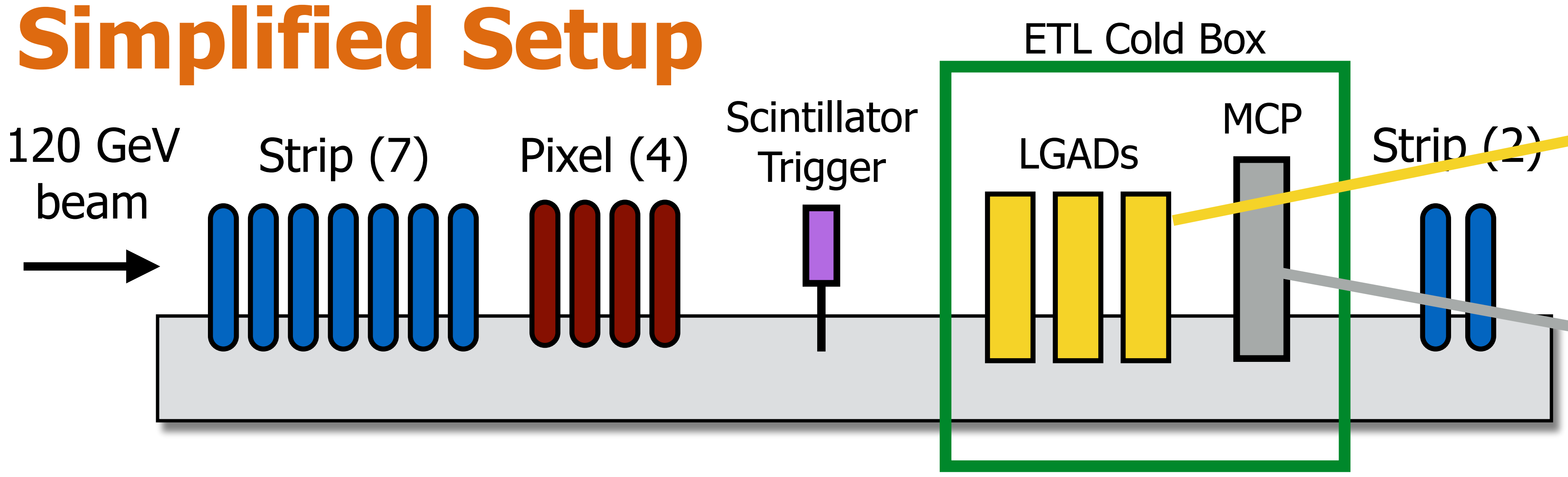


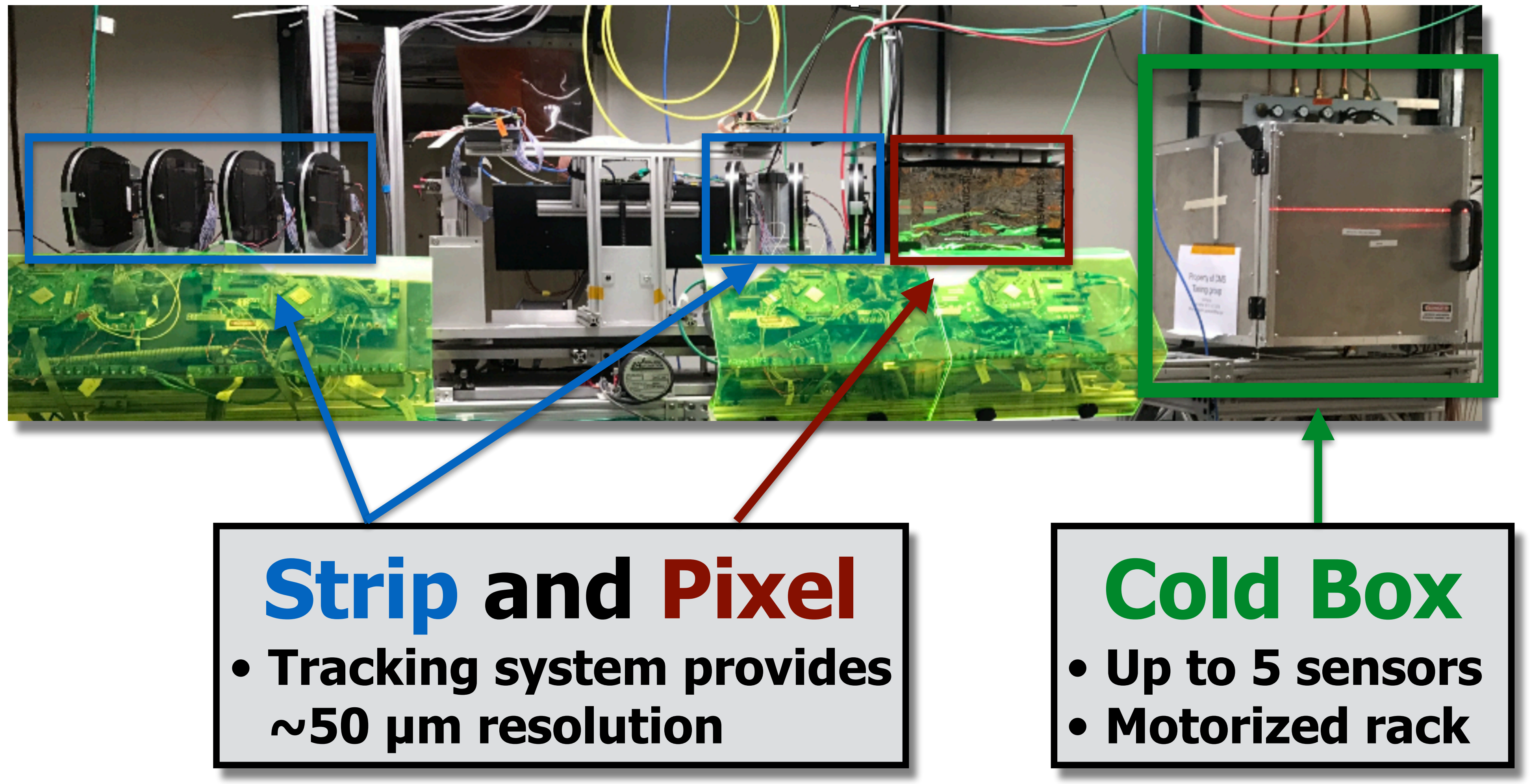


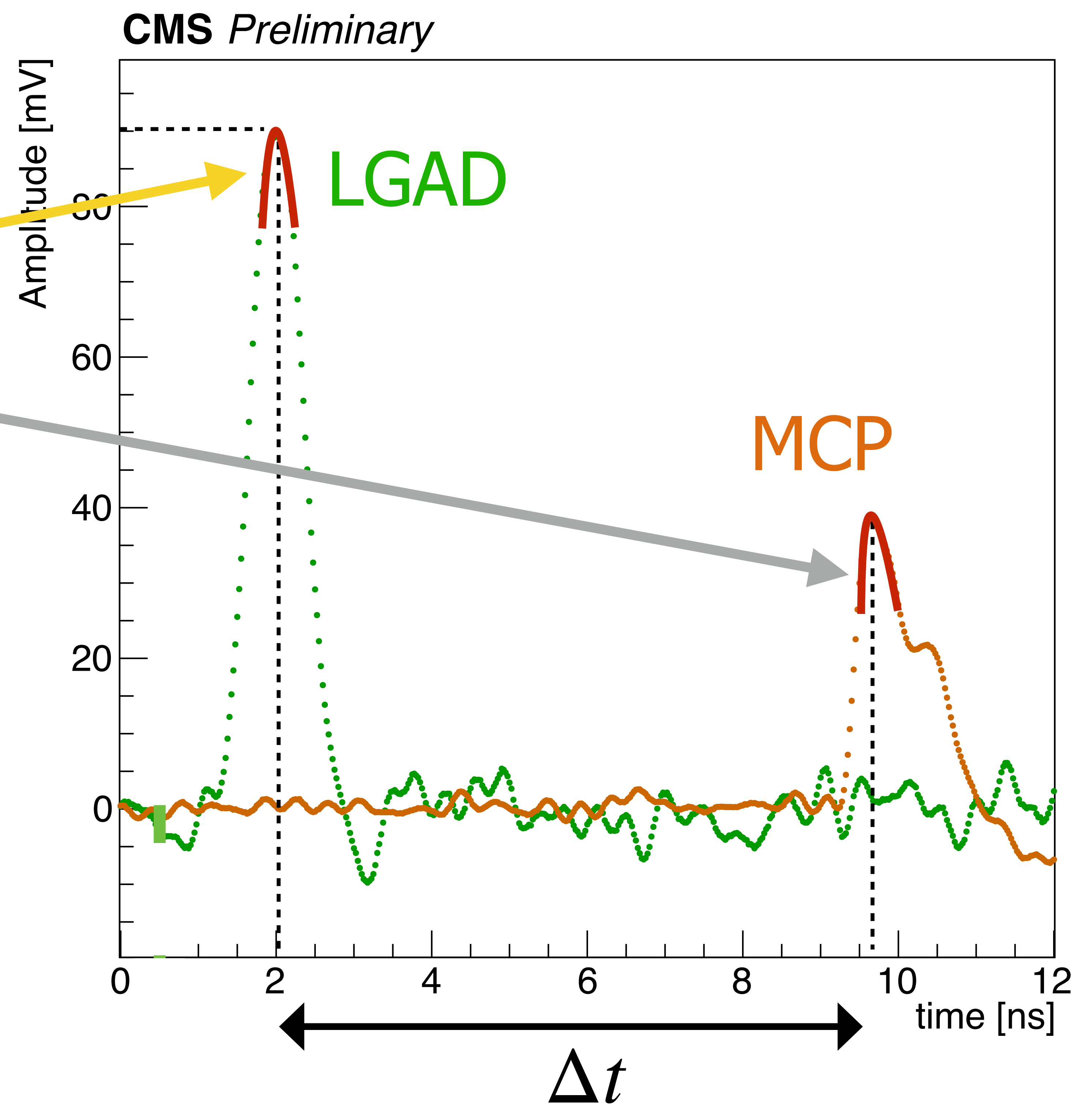
- Hit efficiency > 99%
- Efficiency between pads => coverage loss due to gap
- Meet the sensor specification (< 90 um)

Testing results - timing

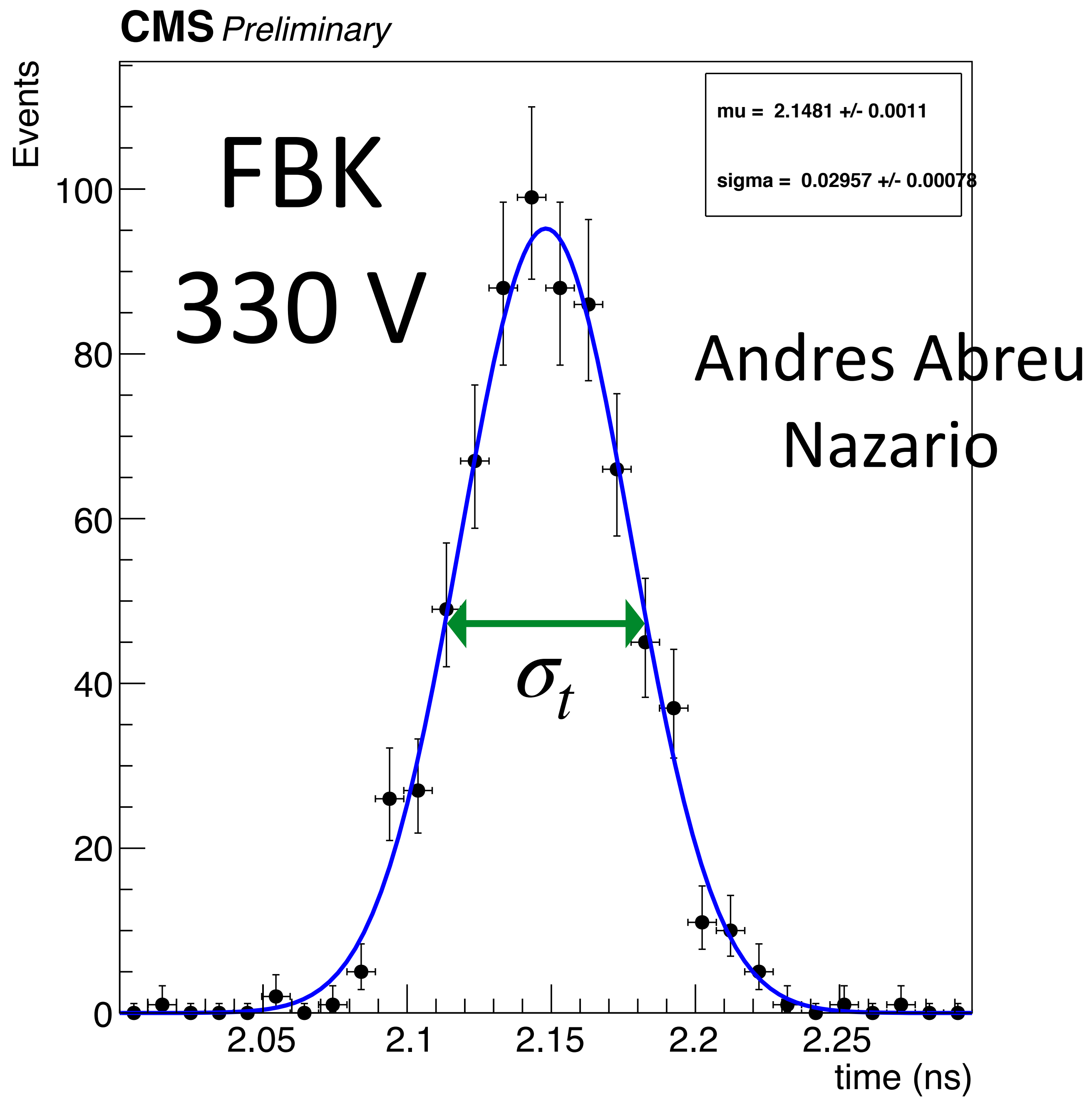
Simplified Setup







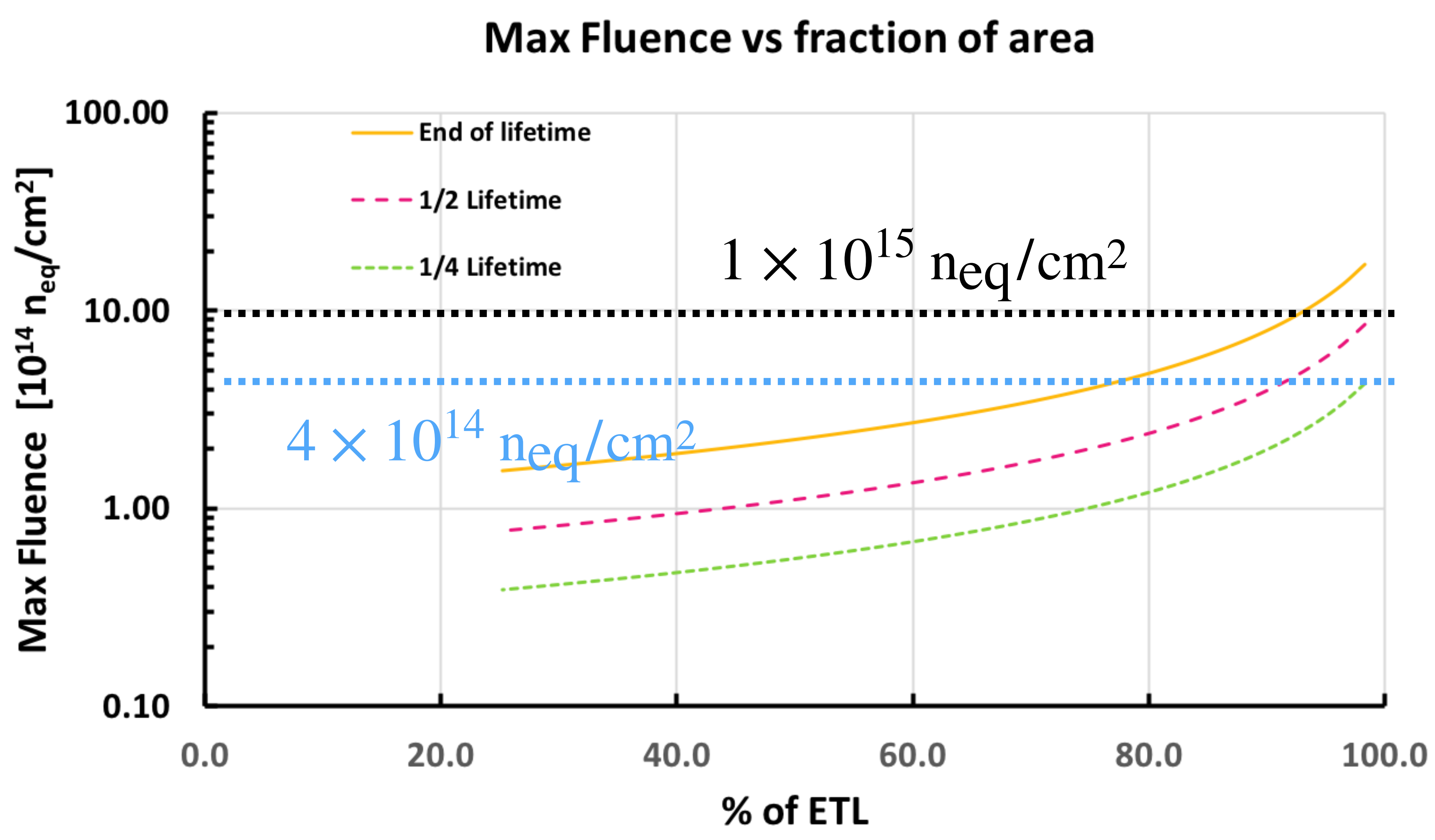
Δt: time difference between LGAD and MCP PMT

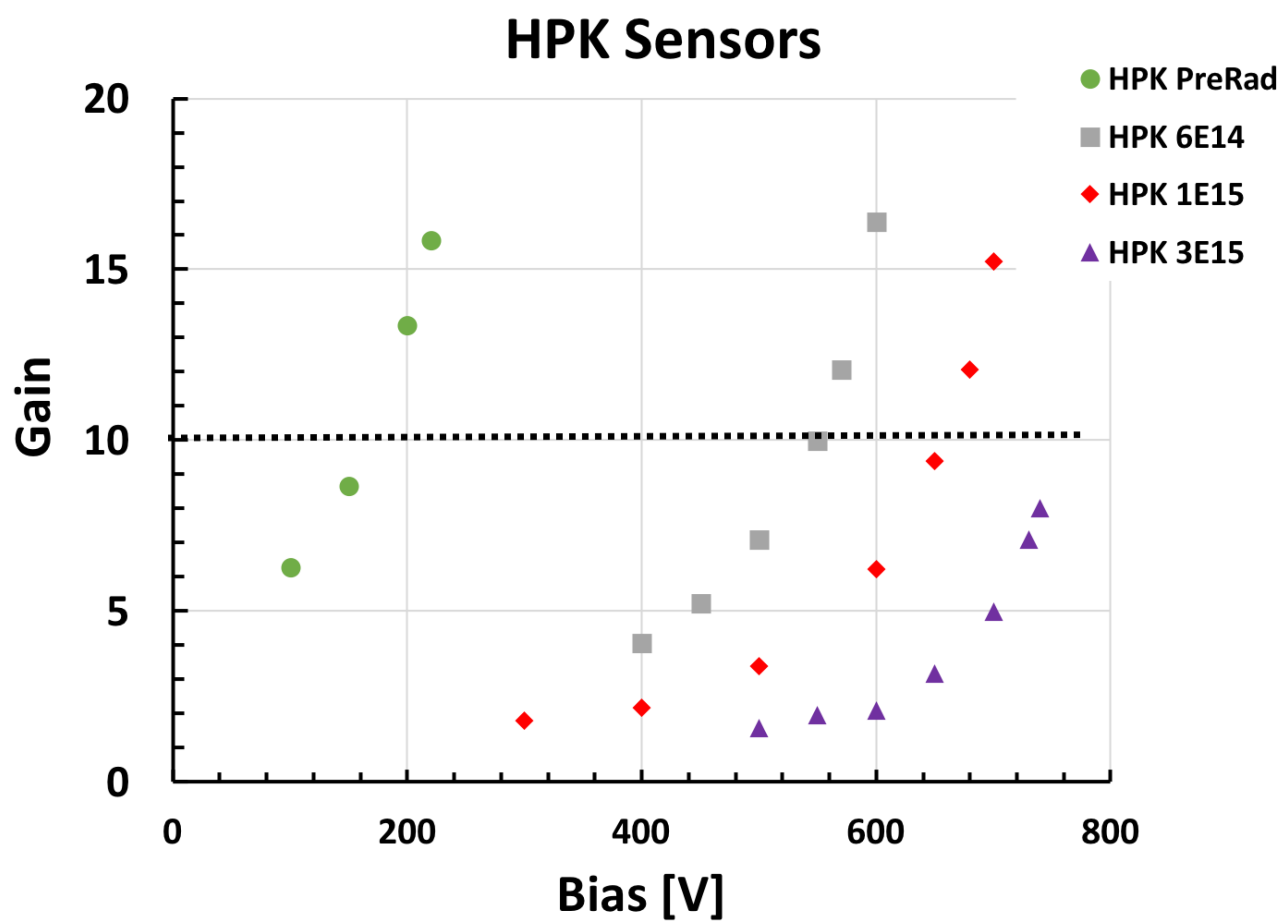


Gaussian fit to extract time resolution (σ_t)

$\sigma_t = 30$ ps

Testing results - radiation hardness

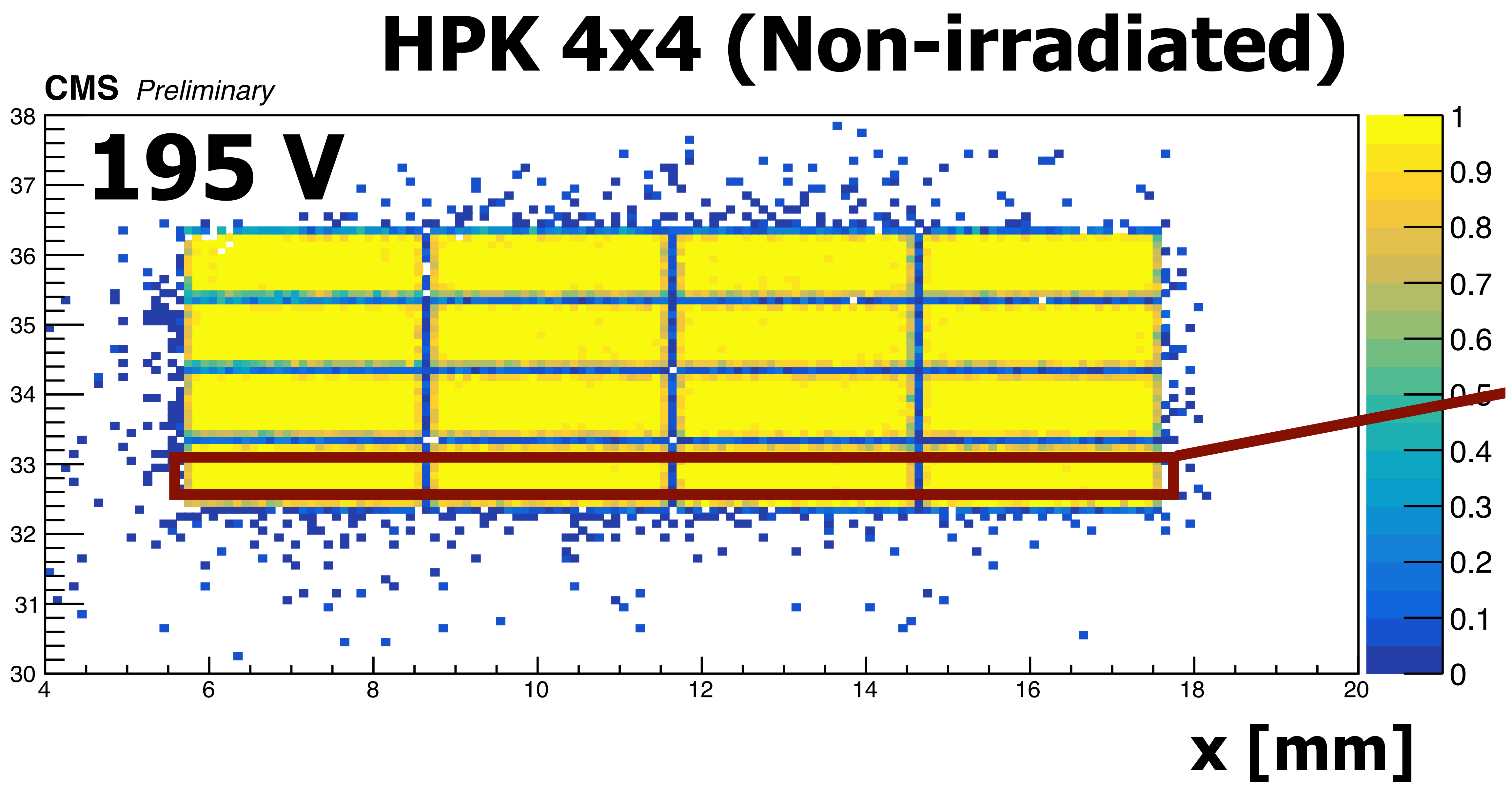


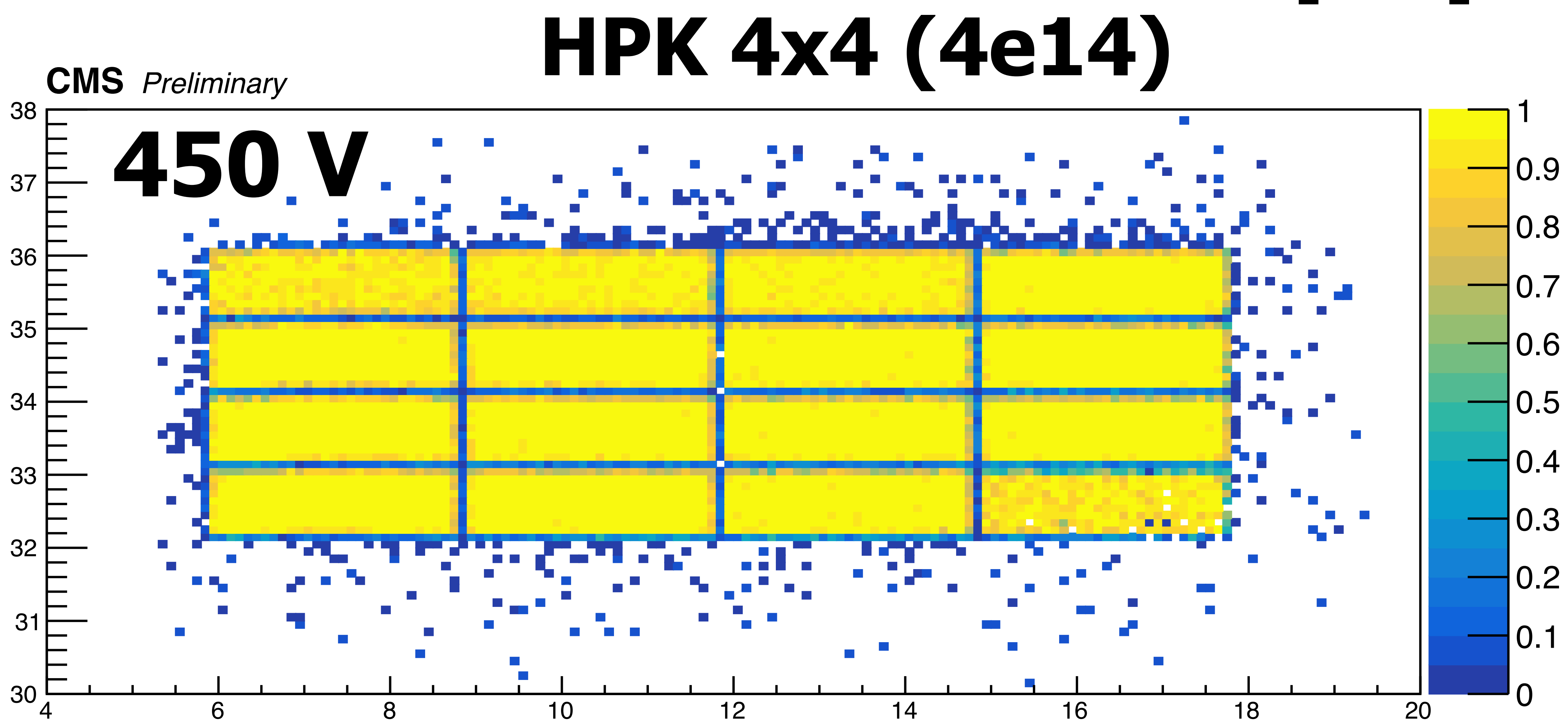


- Max expected fluence at the end of HL-LHC: 1.5×10^{15} n_{eq}/cm^2
- Radiation can cause decrease in gain (due to worse charge collection efficiency, change in doping profile) and higher noise (leakage current)

- To maintain the gain, need operate sensor at higher V_{bias}
- Is the sensor performance maintained by the end of LHC life? → Test irradiated sensors

Testing results - radiation hardness





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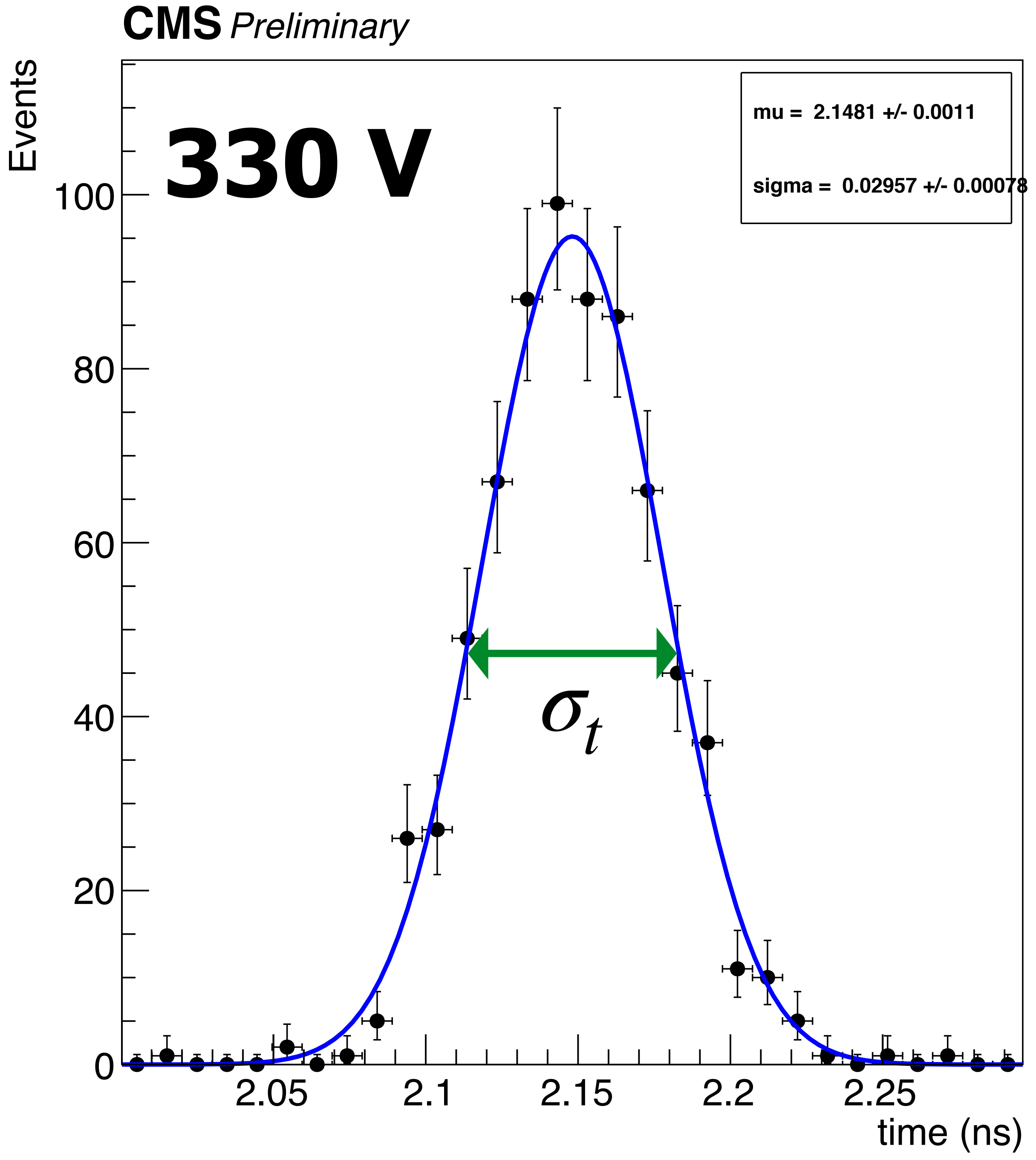
- Hit efficiency > 99% for most pads after 4×10^{14} n_{eq}/cm^2 of radiation
  - 4×10^{14} n_{eq}/cm^2: more than 50% of the sensors will have less fluence at the end of HL-LHC

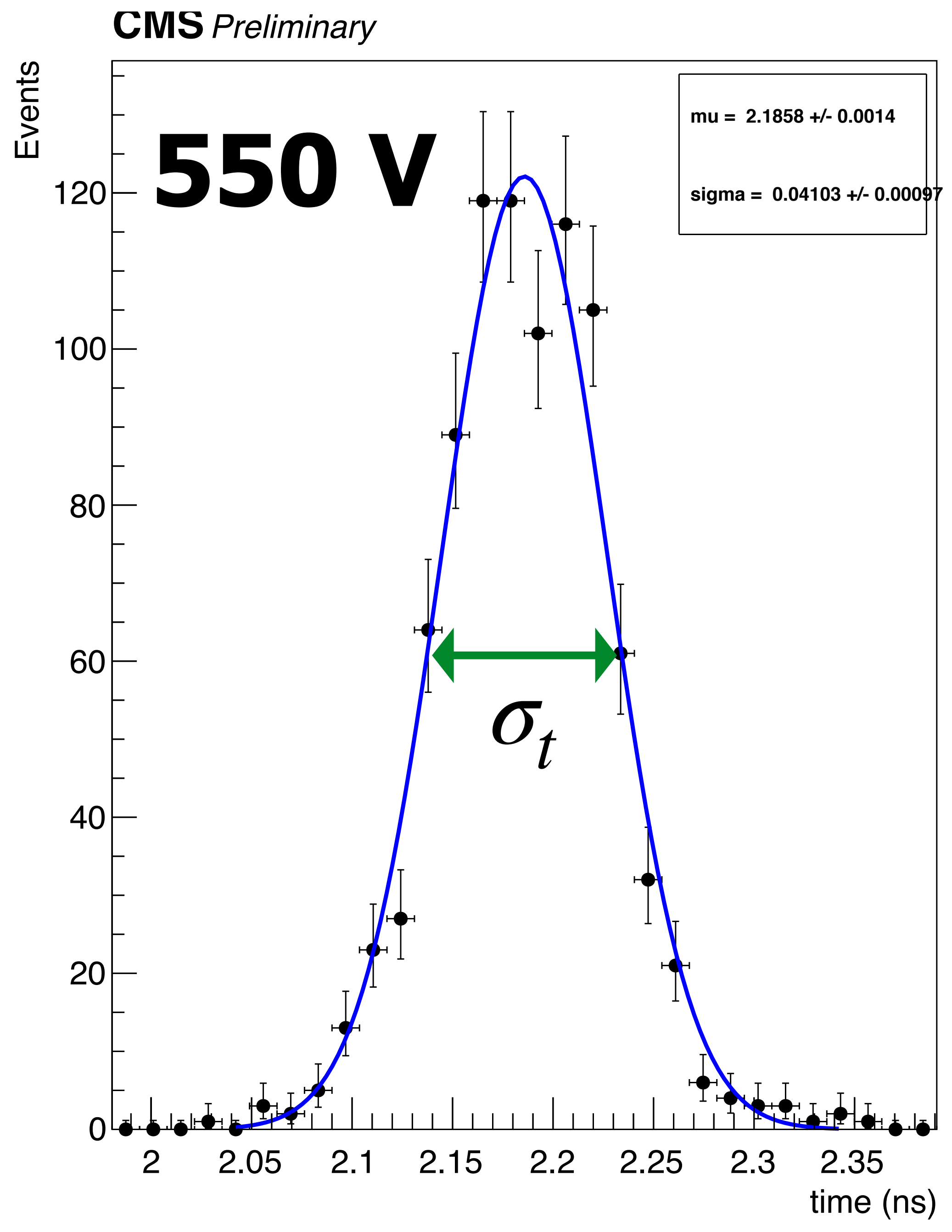
Testing results - radiation hardness

Time resolution before/after irradiation

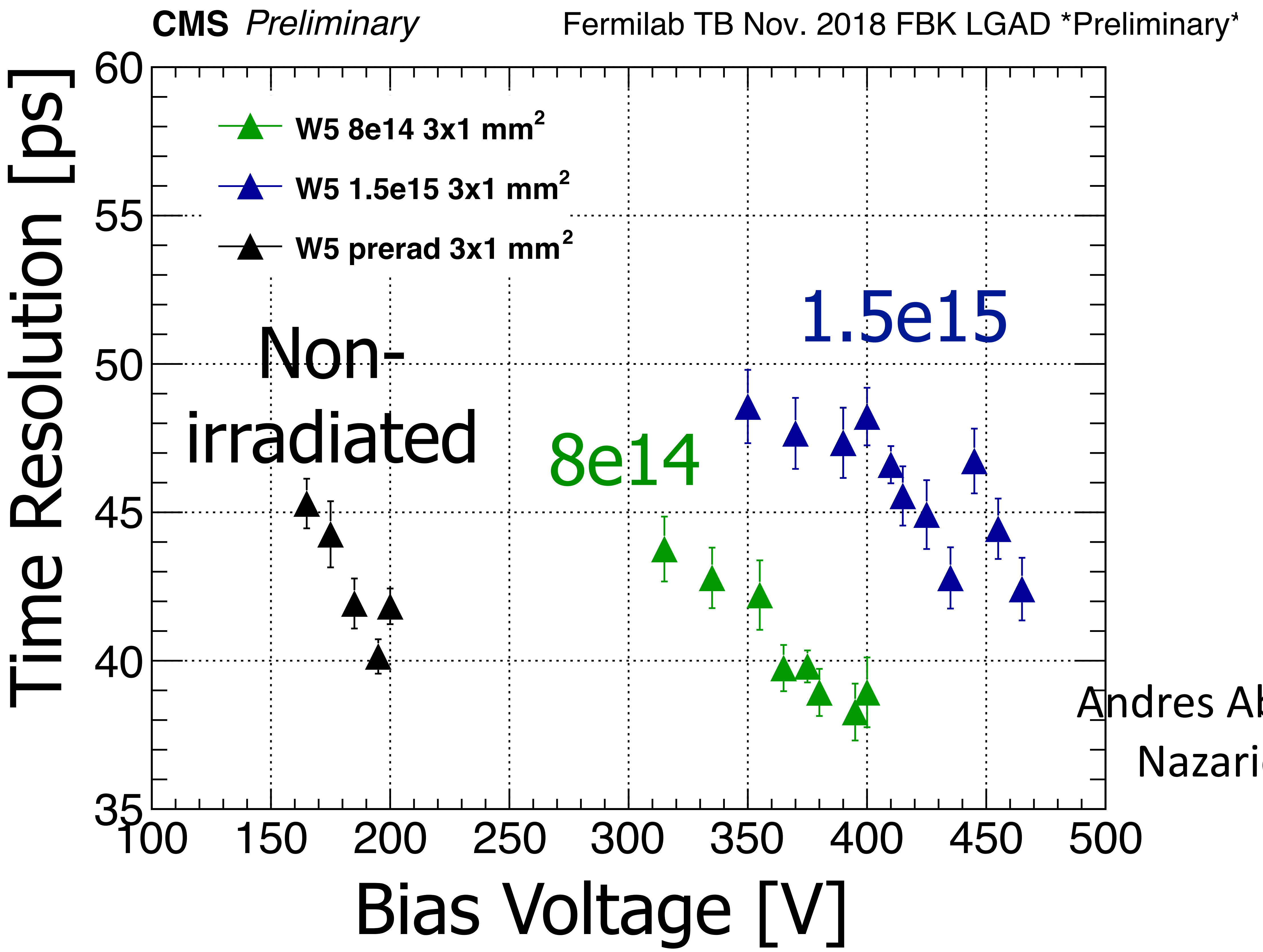
Non-irradiated $8 \times 10^{14}\ n_{eq}/cm^2$



$\sigma_t = 30$ ps



$\sigma_t = 41$ ps



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Larger V_{bias} (larger gain) => Smaller σ_t

Maintain timing performance by operating sensors at higher V_{bias}

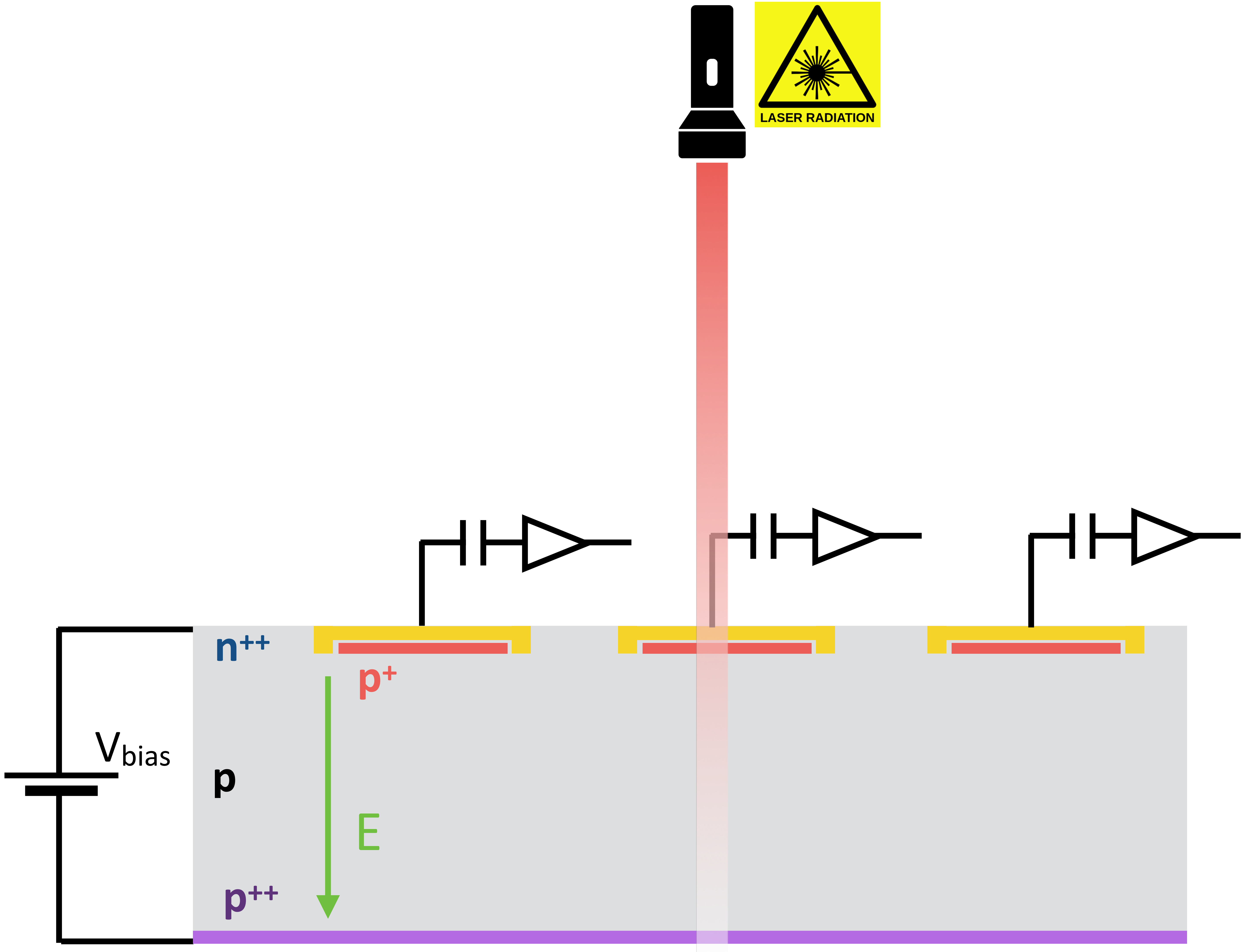
Sensor testing status and what's next

- What we learned so far: manufacturers can meet all required features
  - Doping uniformity: 1-2% variations in a wafer and among wafers
  - Sensors provide large signal (>15 fC) with low noise until the end of HL-LHC (1.5×10^{15} n_{eq}/cm^2)
  - Inter-pad gap: 50-100 um
- What needs to be tested in the current/next version of prototypes?
  - No degradation of performance up to 1.5×10^{15} n_{eq}/cm^2
  - Production uniformity, particularly, of large sensors (16x16 and 32x16 pads)
  - Longterm stability
- A few groups are contributing to the effort
  - Torino, FNAL, UCSB, Santander, Helsinki

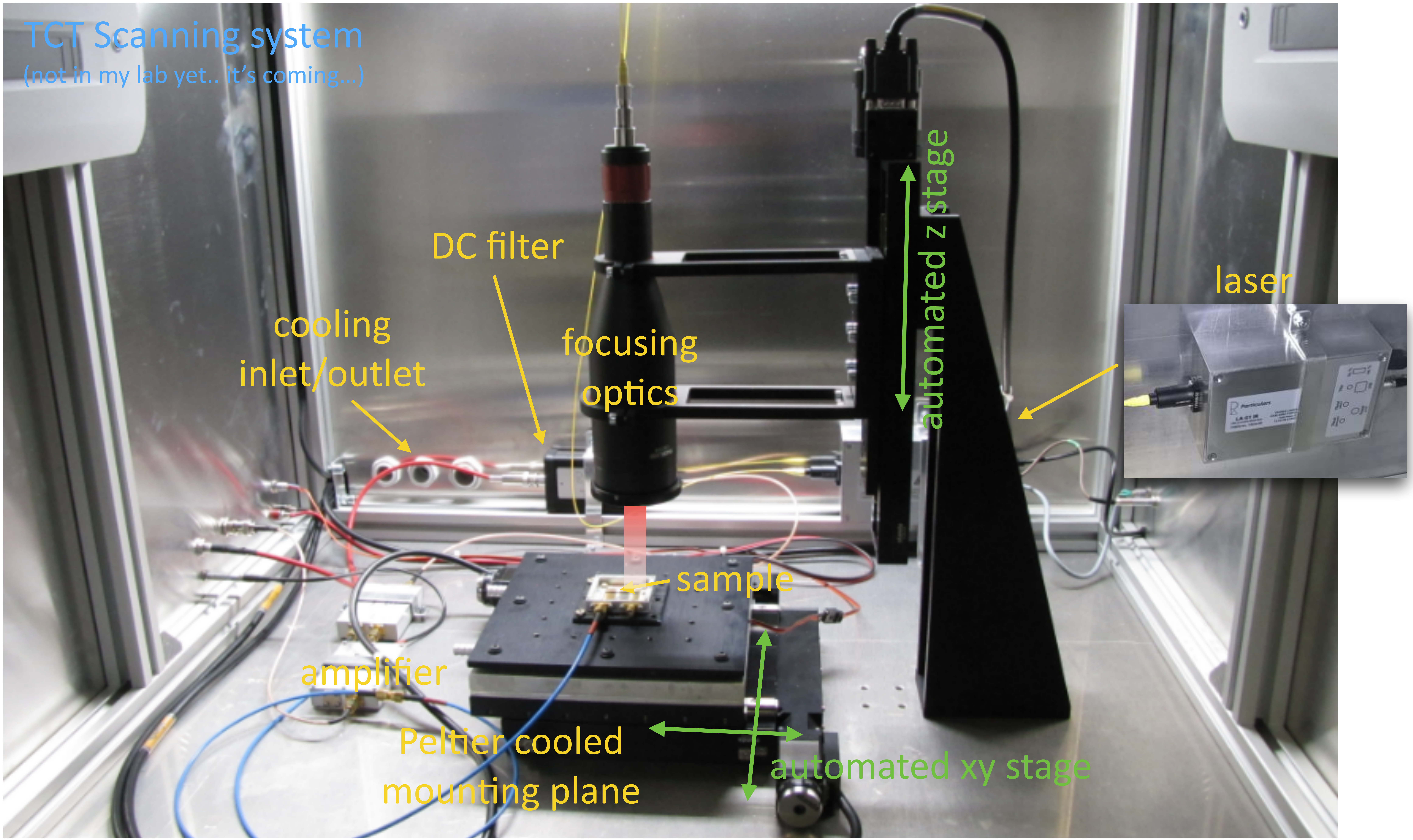
Sensor testing facility in Korea

- Setting up sensor testing facility using laser at Korea University
- Laser provides excellent position granularity to study inter-pad design and uniformity of sensors
  - Automated sample stage makes testing large sensors convenient
- Exploring possibility of using probe station

Basics of sensor testing using laser



- Shoot laser to LGAD sensor
  - Fast (pulse duration=350 - 4000 ps) and narrow (FWHM < 11 μm)
  - Wave length: 1064 nm (absorption depth in silicon = 1 mm)
  - pulse power: few - 100 MIPs (equivalent in 300 μm Si)
- Automated sensor position control
  - Moving range: 10x10x10 cm
  - Position resolution: < 1 μm
- Use Transient Current Technique (TCT) apparatus by Particulars
  - Can save time for setting up the facility


TCT Scanning system
(not in my lab yet.. it's coming...)
DC filter
cooling
inlet/outlet
focusing
optics
automated z stage
laser
sample
amplifier
Peltier cooled
mounting plane
automated xy stage

Sensor testing plan at KU

2020		2021				2022		
Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3

today

Receive v2 R&D sensors from vendors

- Choice of best gain layer doping, edges, inter-pad distance, …

Receive v3 R&D sensors from vendors

- Implementation of the final set of parameters

Ready for preproduction

Sensor production order

2020	2021		2022
Setup testbed	**gain expertises participating in v2 testing**	**contribute to v3 testing**	**longterm stability & large-scale system**

Person power: 1 faculty, 1 postdoc, 2 students

Summary and outlook

- ETL sensor testing is advancing well
  - Making a good progress in prototype v2 testing: vendors can meet the LGAD spec requirements
- Setting up sensor testing facility using laser at Korea University
  - Possibly start measurements this winter
  - Plan to make important contributions to prototype v3 testing!
- Exploring possibility of using probe station
- Close collaboration with sensor experts in FNAL, UCSB and Torino groups

References

CERN-LHCC-2019-003
CMS-TDR-020
29 March 2019
Revised 26 September 2019

A MIP Timing Detector for the CMS Phase-2 Upgrade

Technical Design Report

CMS Collaboration

IOP Publishing — Reports on Progress in Physics

Rep. Prog. Phys. **81** (2018) 026101 (34pp) — https://doi.org/10.1088/1361-6633/aa94d3

Review

4D tracking with ultra-fast silicon detectors

Hartmut F-W Sadrozinski[1,3], Abraham Seiden[1] and Nicolò Cartiglia[2]

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[2] INFN, Torino, Italy

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Received 5 June 2015, revised 29 June 2017
Accepted for publication 20 October 2017
Published 18 December 2017

CrossMark

Corresponding Editor Professor Steve Ritz

Characterization of Low Gain Avalanche Detectors for the CMS MIP Timing Detector

Andrés Abreu
On behalf of the CMS Collaboration
University Of Kansas

APS DPF Conference
Monday, July 29 2019

Development of the CMS MTD Endcap Timing Layer for the HL-LHC

Karri Folan DiPetrillo, on behalf of the CMS MIP Timing Detector group
ICHEP 2020
28 July 2019

Precision Timing with the CMS Endcap Timing Layer

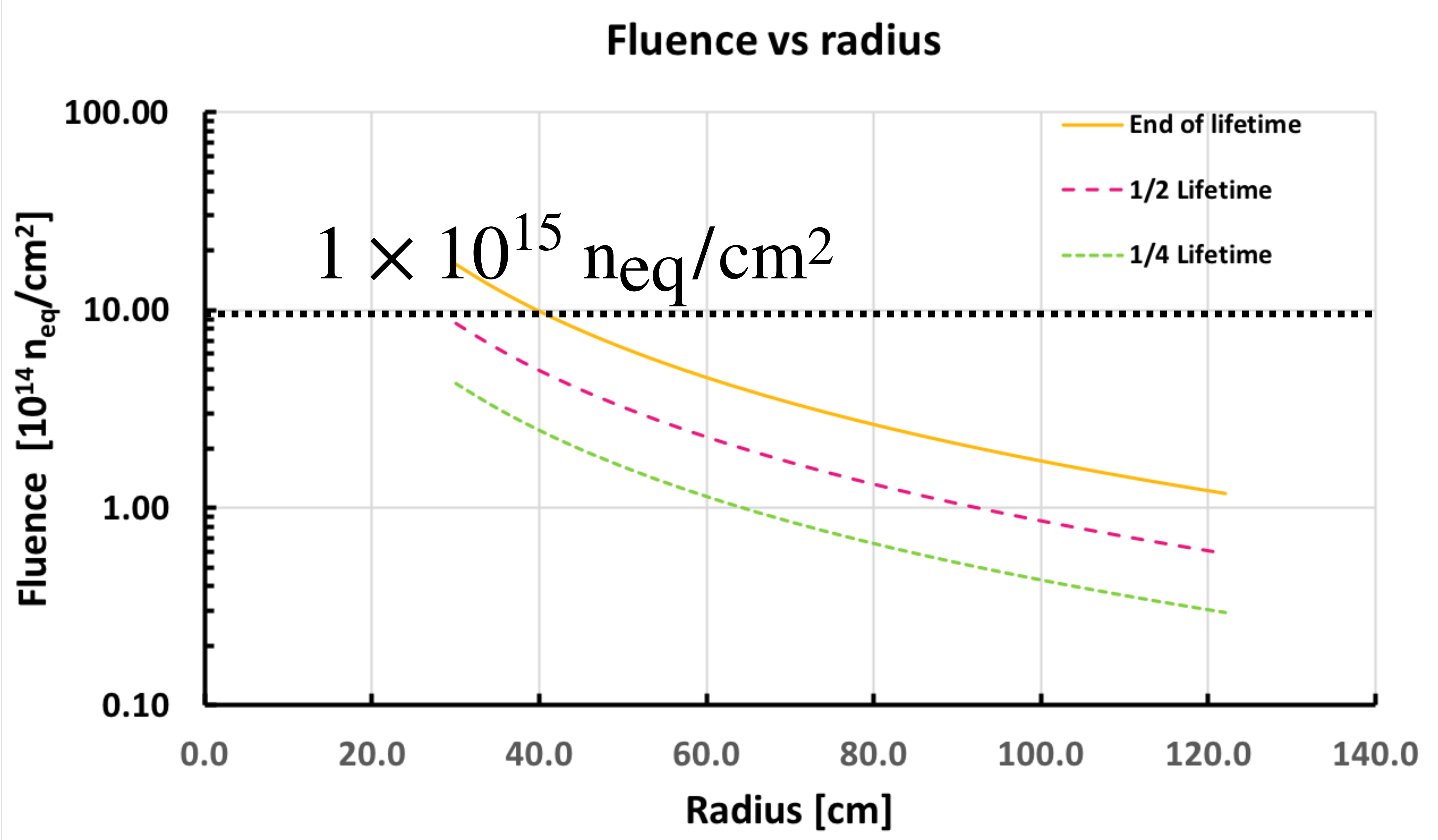
Ryan Heller on behalf of the CMS MIP Timing Detector group
Meeting of the APS Division of Particles and Fields
July 29 2019

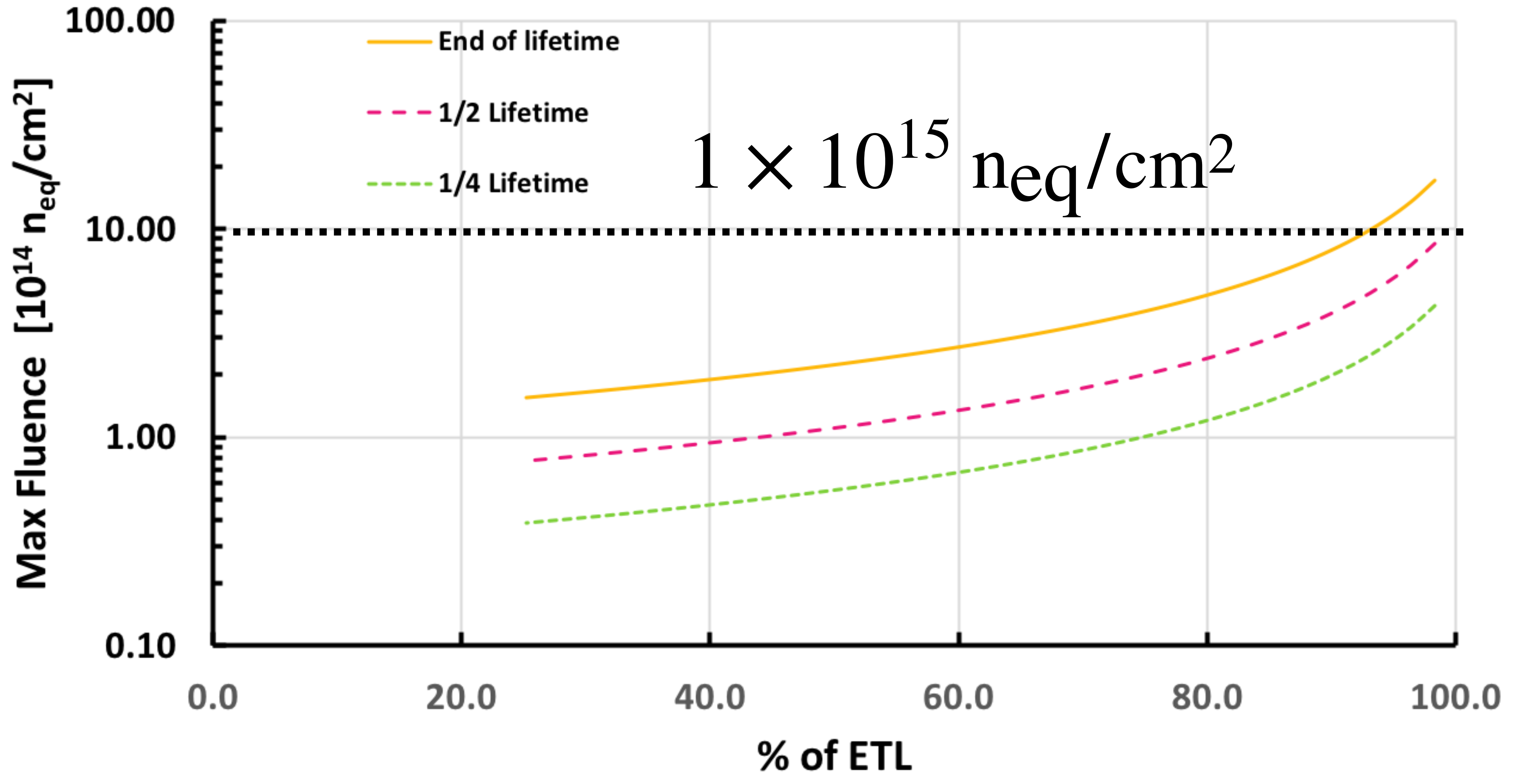
Key sensor characteristics

Depletion region thickness	50 μm	Minimize rise time, sufficient charge, gain uniformity
Pad size	1.3x1.3 mm^2	Minimize capacitance, Occupancy ~1%
Sensor size	2x4 cm^2 (16x32)	Optimize wafer usage
Interpad gap	< 90 μm	Fill factor > 85%
Time res. after irradiation	< 40 ps	up to $1.7 \cdot 10^{15}$ n_{eq}/cm^2

Karri Folan DePatrillo

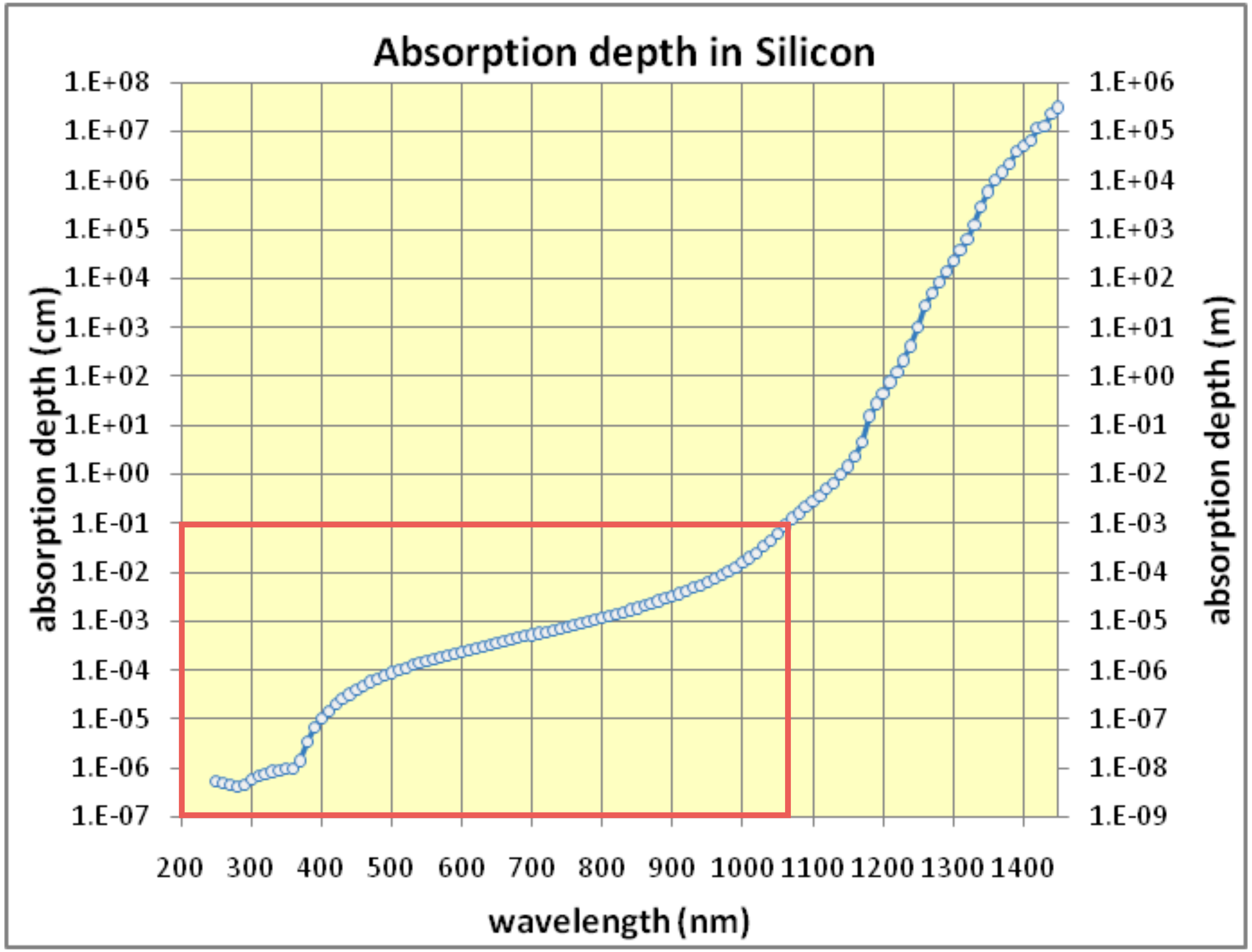
Radiation





- Fluence (n_{eq}/cm^2: 1 MeV neutron equivalent per cm^2) as a function of radius for 1/4, 1/2, and full lifetime of HL-LHC
- Until 1/2 lifetime, fluence is less than 1×10^{15} n_{eq}/cm^2 (top plot)
- Large fraction of ETL will receive mild dose
  - 50% of sensors: $< 5 \times 10^{14}$ n_{eq}/cm^2
  - 80% of sensors: $< 8 \times 10^{14}$ n_{eq}/cm^2
  - 10% of sensors: $> 1 \times 10^{15}$ n_{eq}/cm^2

Silicon absorption depth



https://www.pveducation.org/pvcdrom/materials/optical-properties-of-silicon