Precision Timing for PPS2 at HL-LHC

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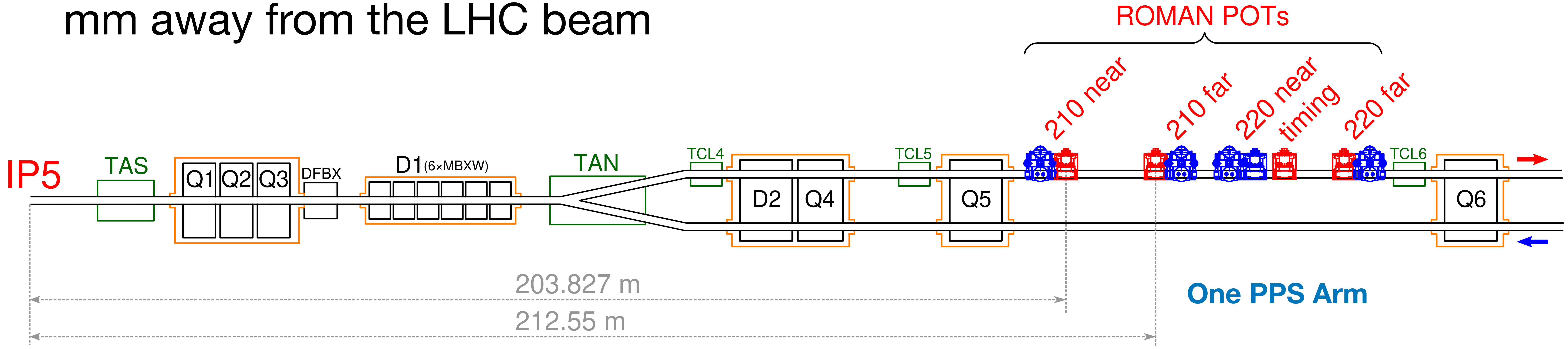
LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS

Fermilab

Precision Proton Spectrometer

- Current PPS detector originated from a collaboration between CMS and TOTEM
- It is fully integrated in CMS and has been taking data since 2016
- It provides precision tracking and timing in the very forward region on both sides of CMS
- Detectors located approximately 200m from the interaction point and a few mm away from the LHC beam



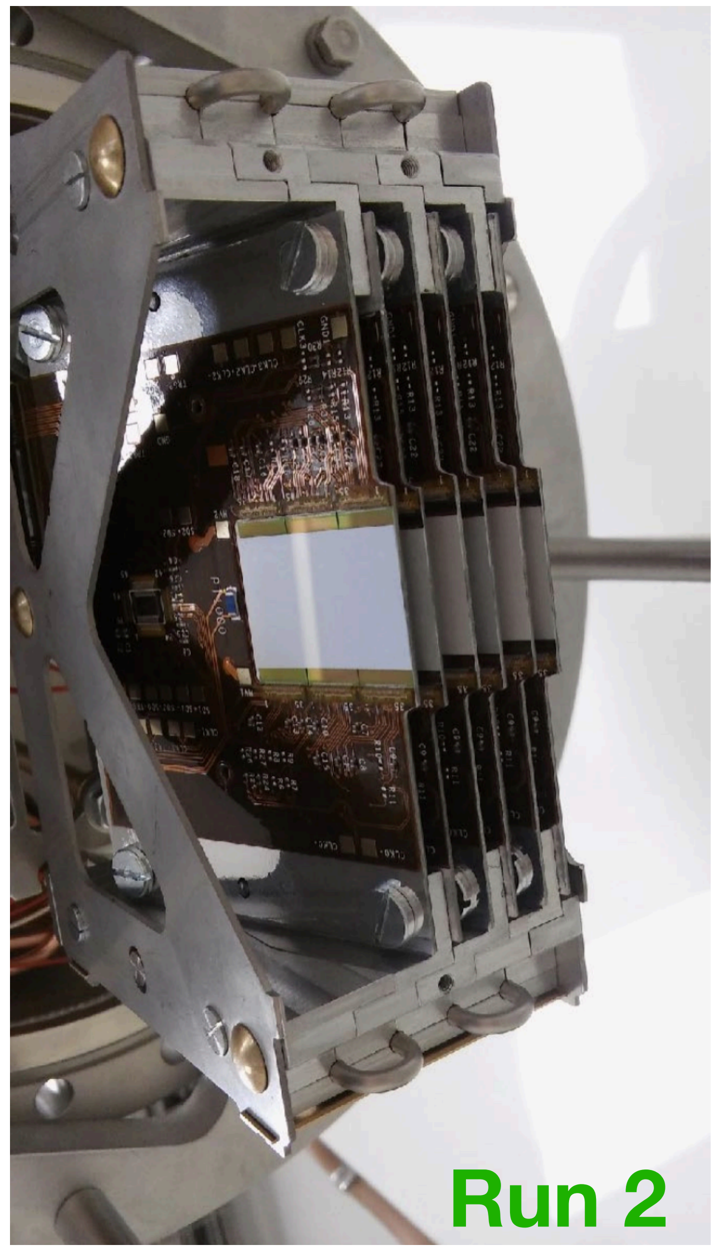
PPS Detectors

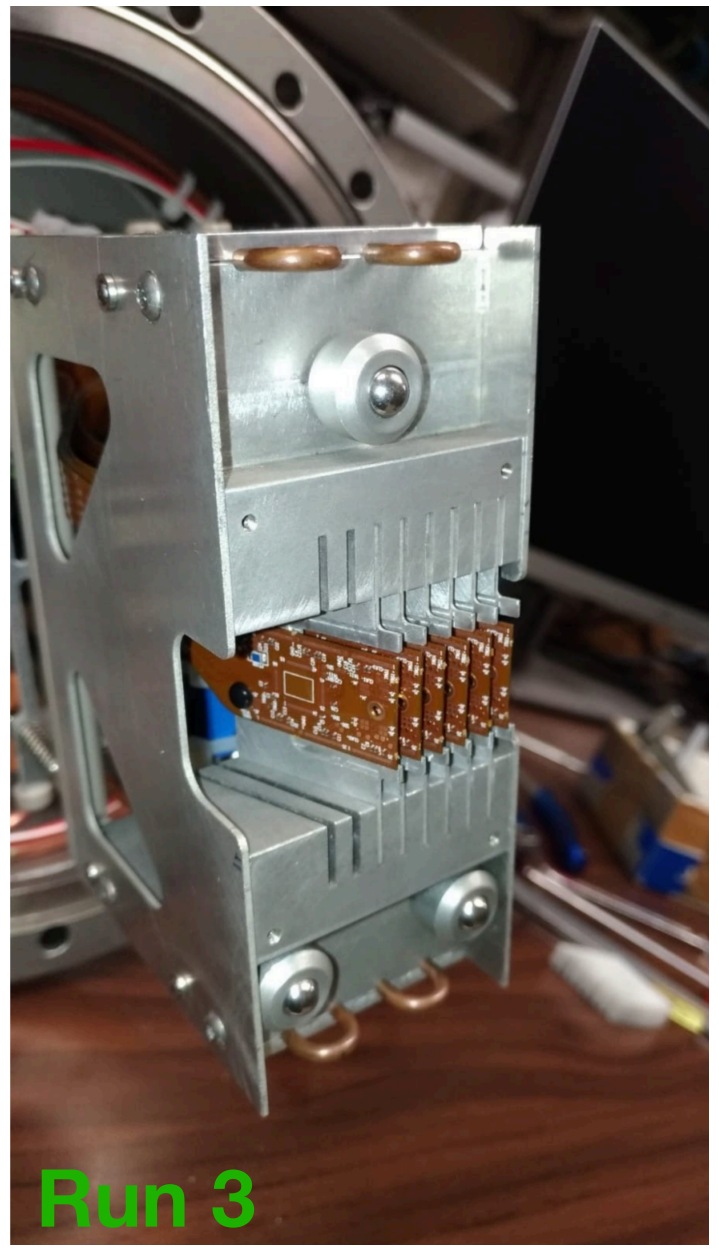
Tracking

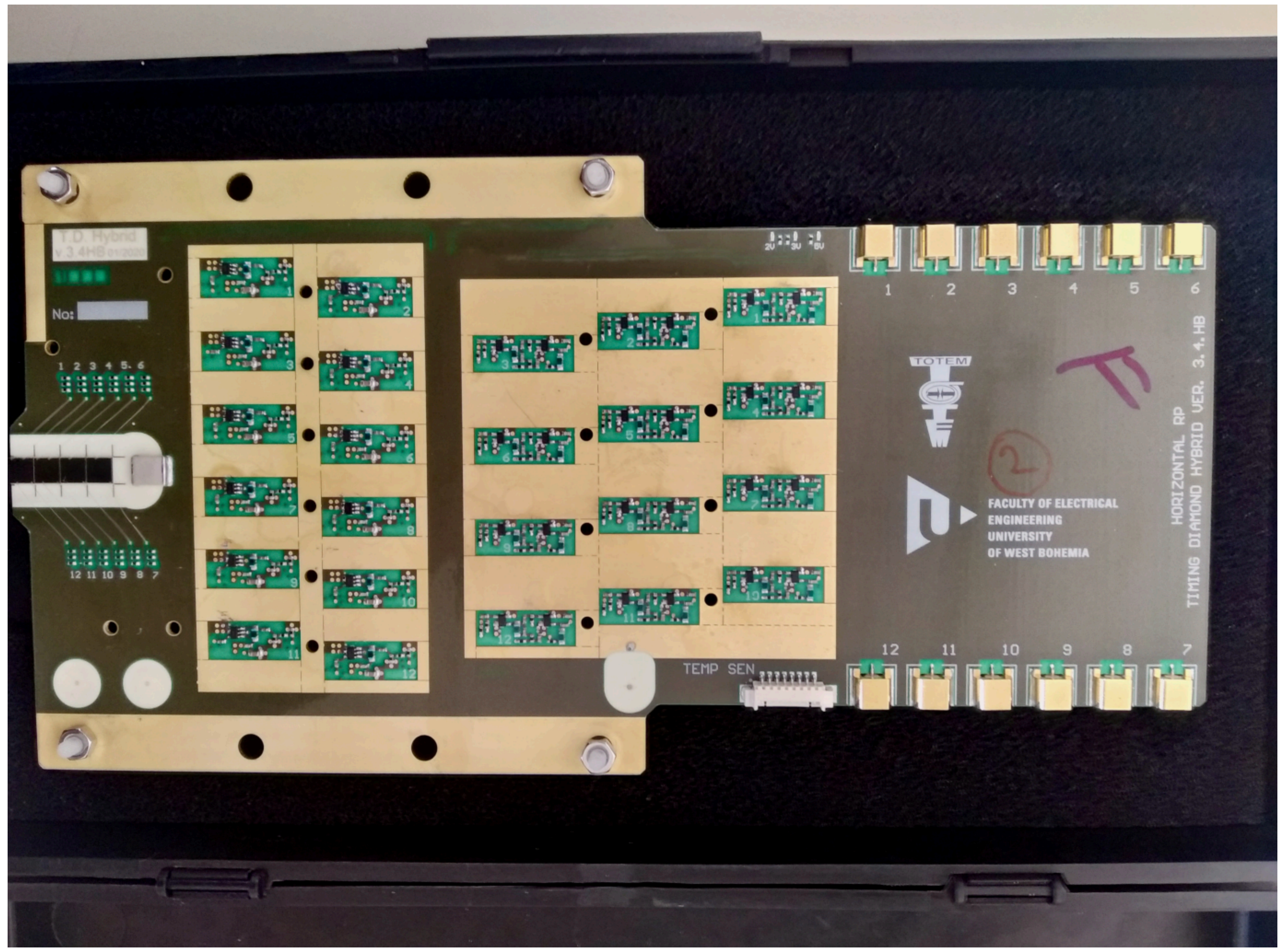
- Based on 3D Silicon Pixel sensors
- 6 planes per roman pot
- 2 tracking roman pots per arm

Timing

- Based on scCVD Diamond detectors
- 3/4 planes per roman pot
- 2 timing roman pots per arm

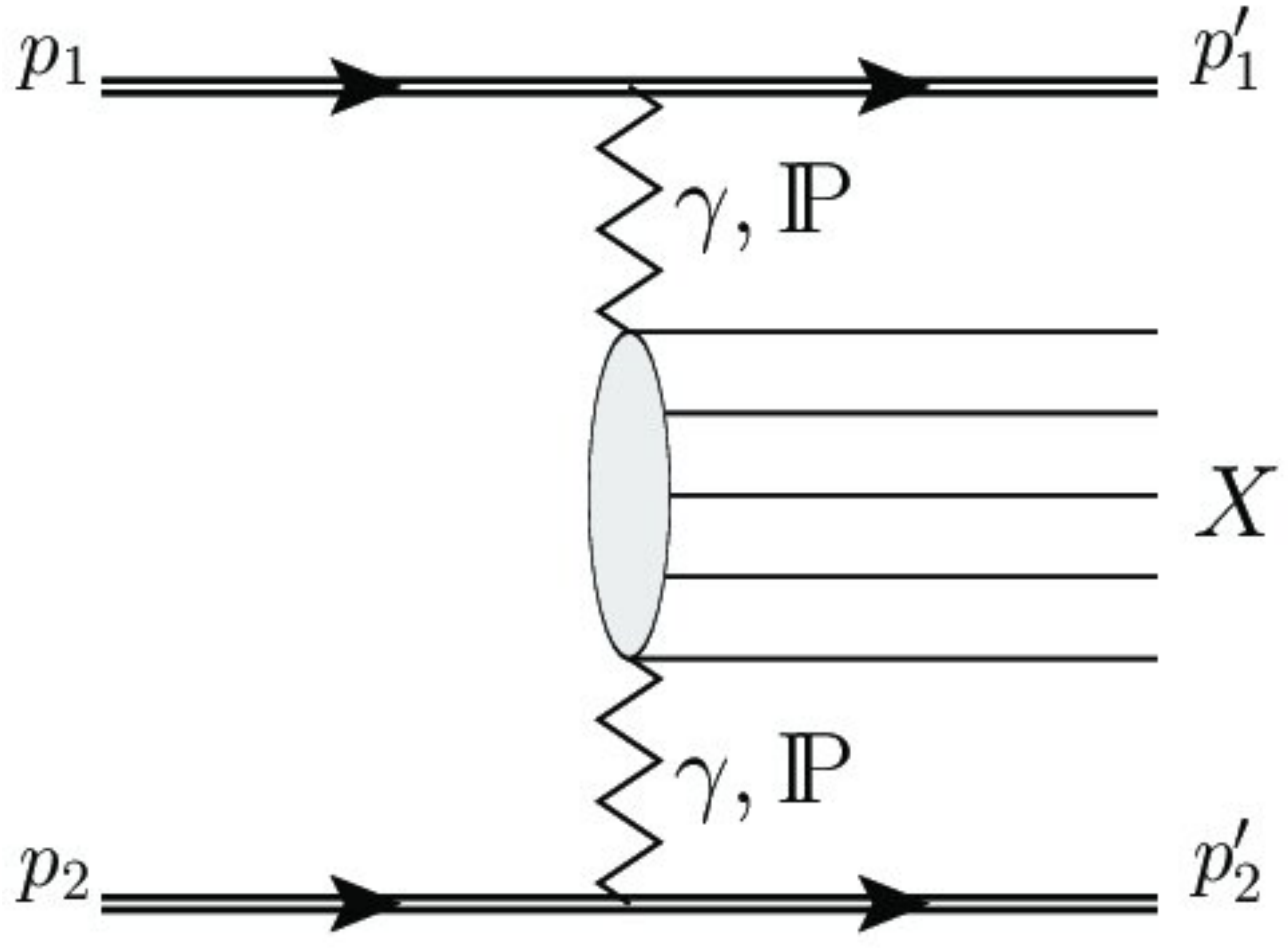






Physics with PPS

- Main goal: study Central Exclusive Production (CEP) events in proton-proton physics
    - Events where the two protons interact through the exchange of photons/pomerons and do not dissociate in the interaction
    - Protons are slightly deflected in the interaction and “go down” the LHC beampipe, where they are detected by PPS
    - The difference in time of arrival between the two protons measured by PPS is correlated to the vertex position of the tracker for pileup rejection
    - Clean event signature from the X state



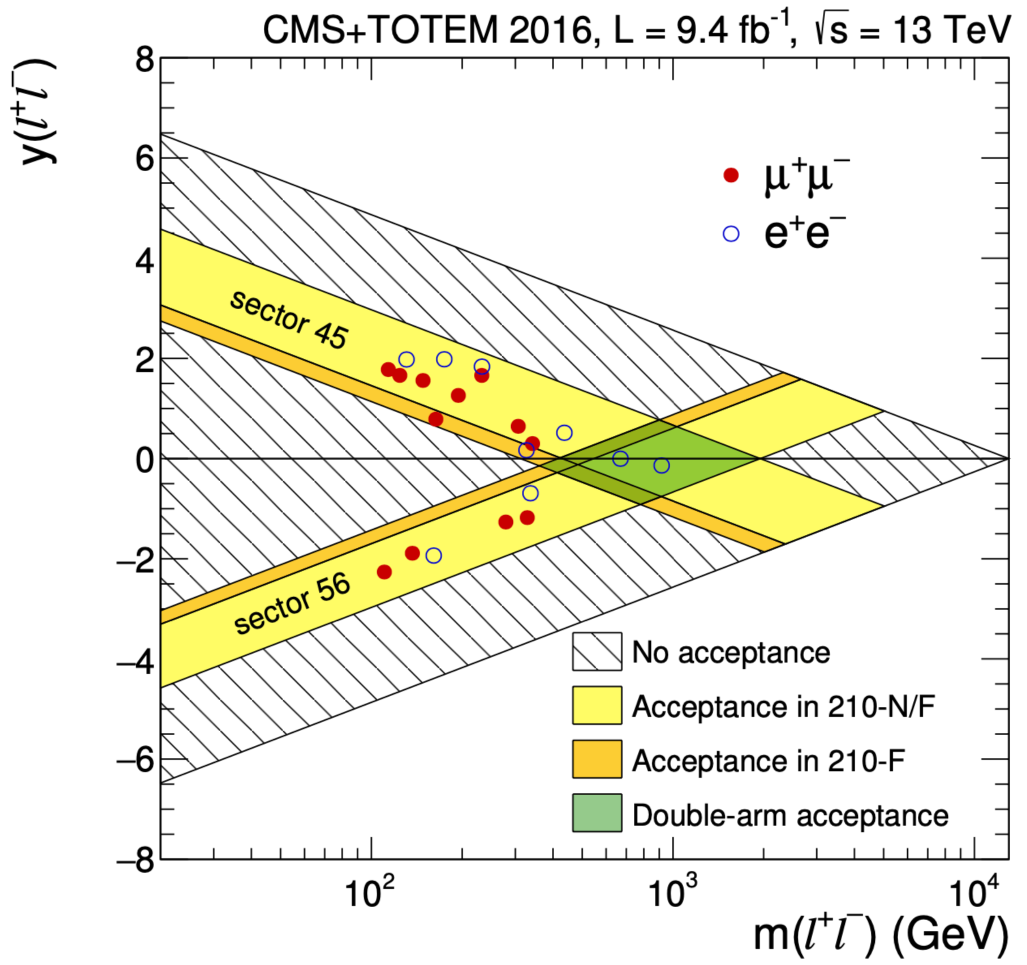
- Event kinematics are well reconstructed through the proton reconstruction and can be compared to the event in the central detector

Selected PPS Results

Observation of dimuon and dielectrons in 2016 data

JHEP 07 (2018) 153

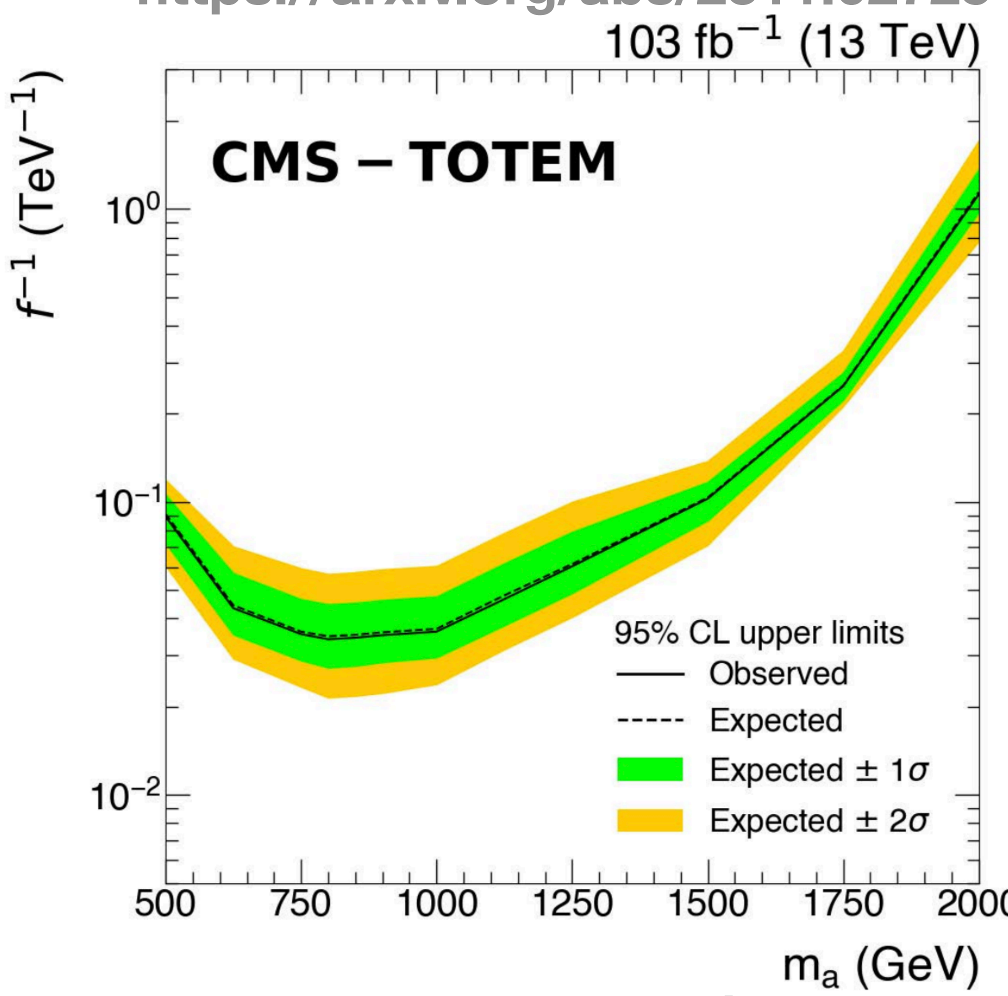
https://doi.org/10.1007/JHEP07(2018)153



Diphotons and AQGCs/ALPs (Run2 data)

Submitted to PRD

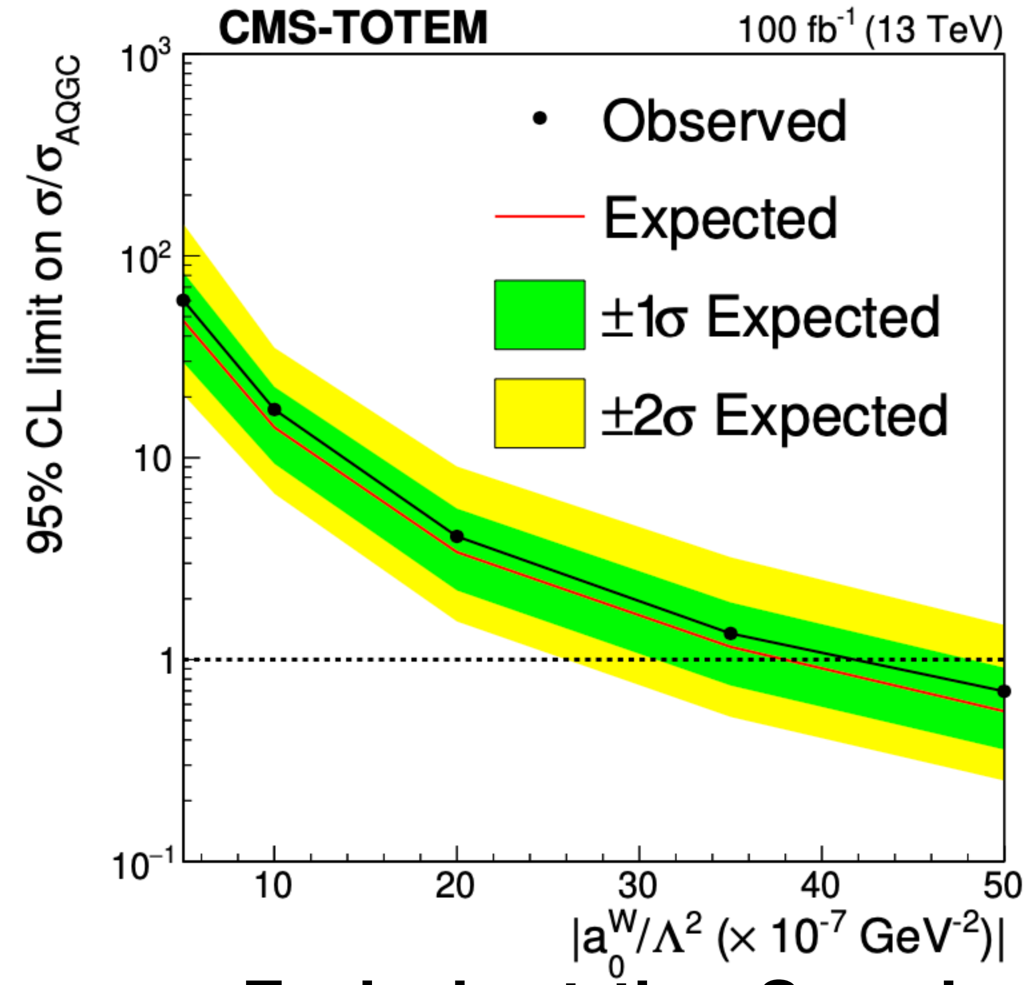
https://arxiv.org/abs/2311.02725



WW/ZZ all-hadronic Search and AQGC

JHEP 07 (2023) 229

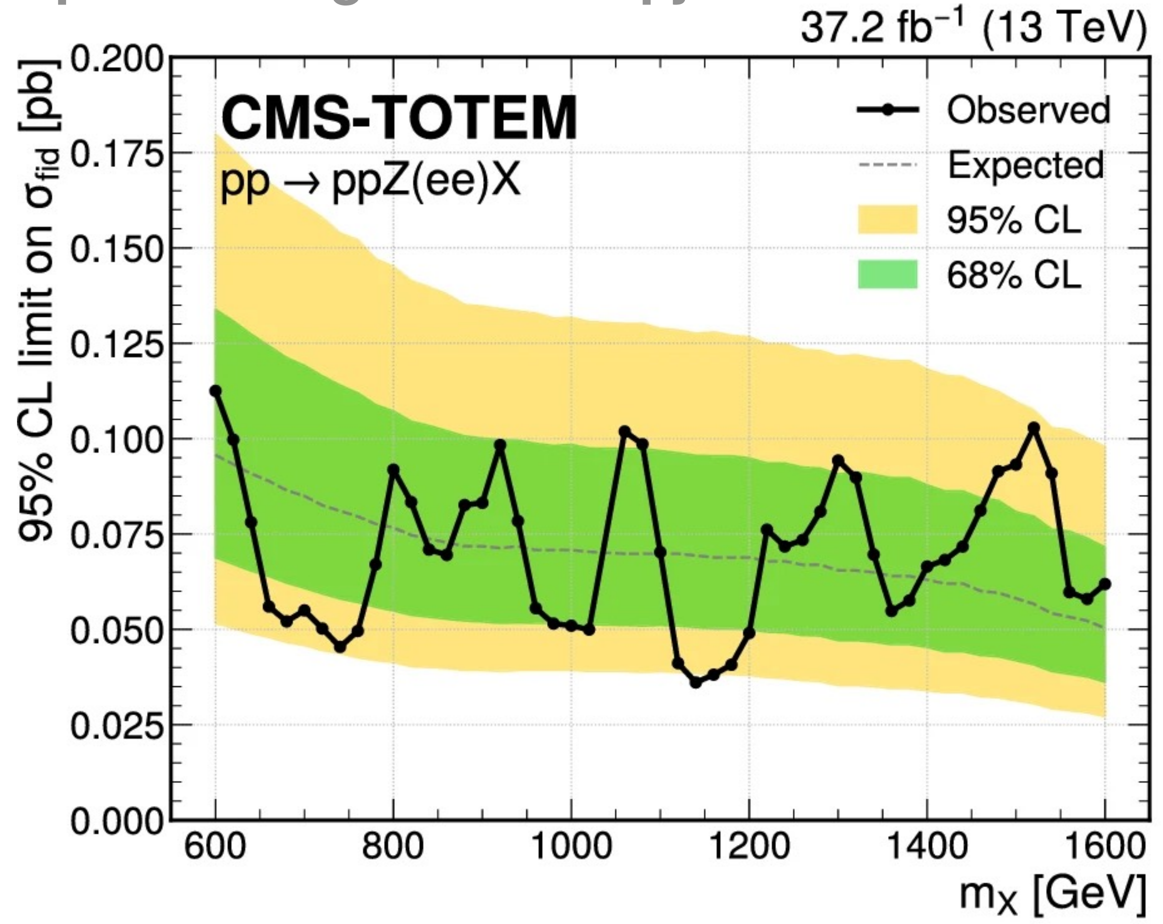
https://doi.org/10.1007/JHEP07(2023)229



Z+X and γ+X Missing Mass search

Eur. Phys. J. C 83 (2023) 827

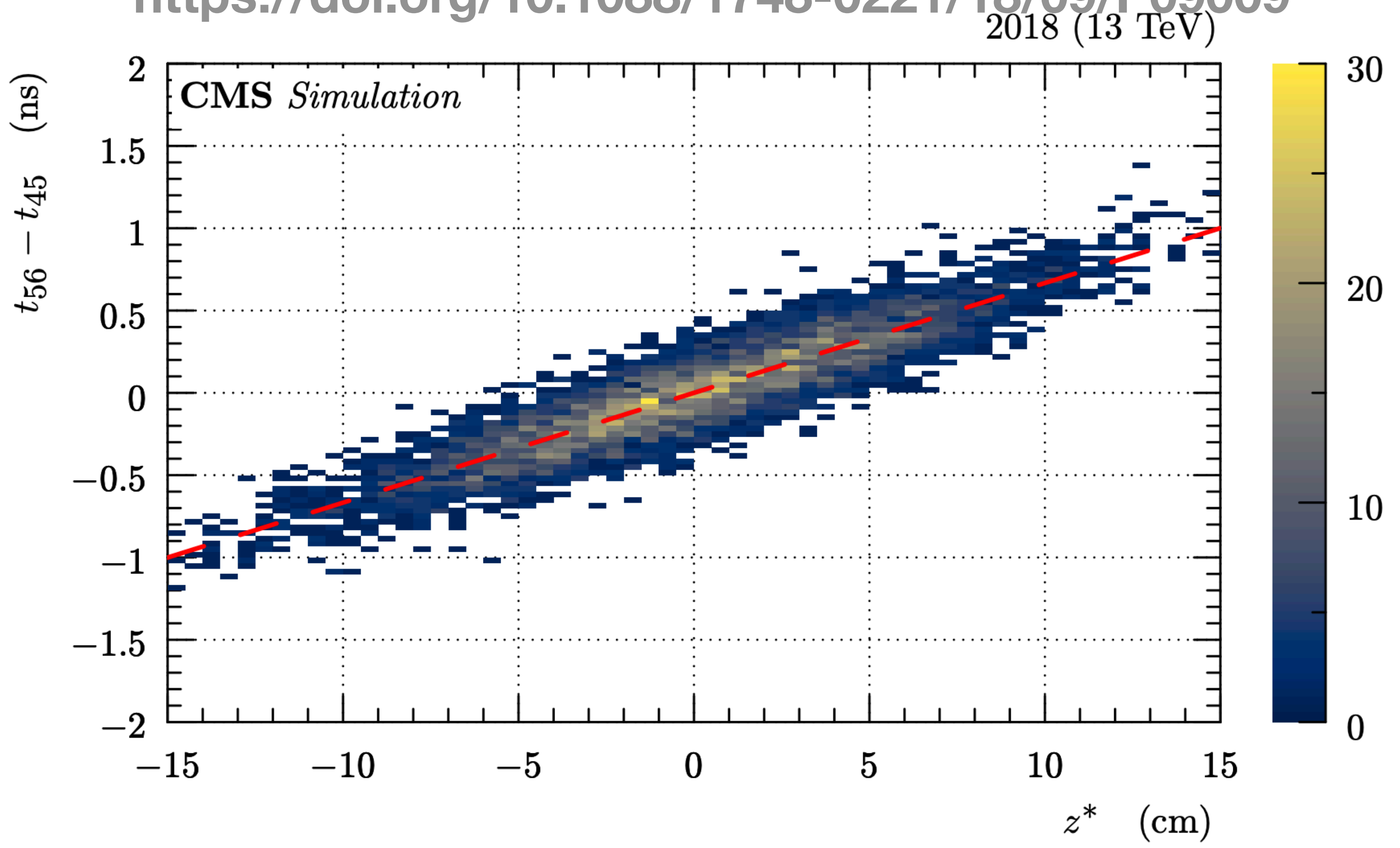
https://doi.org/10.1140/epjc/s10052-023-11687-5



Proton Reconstruction (Run 2 data)

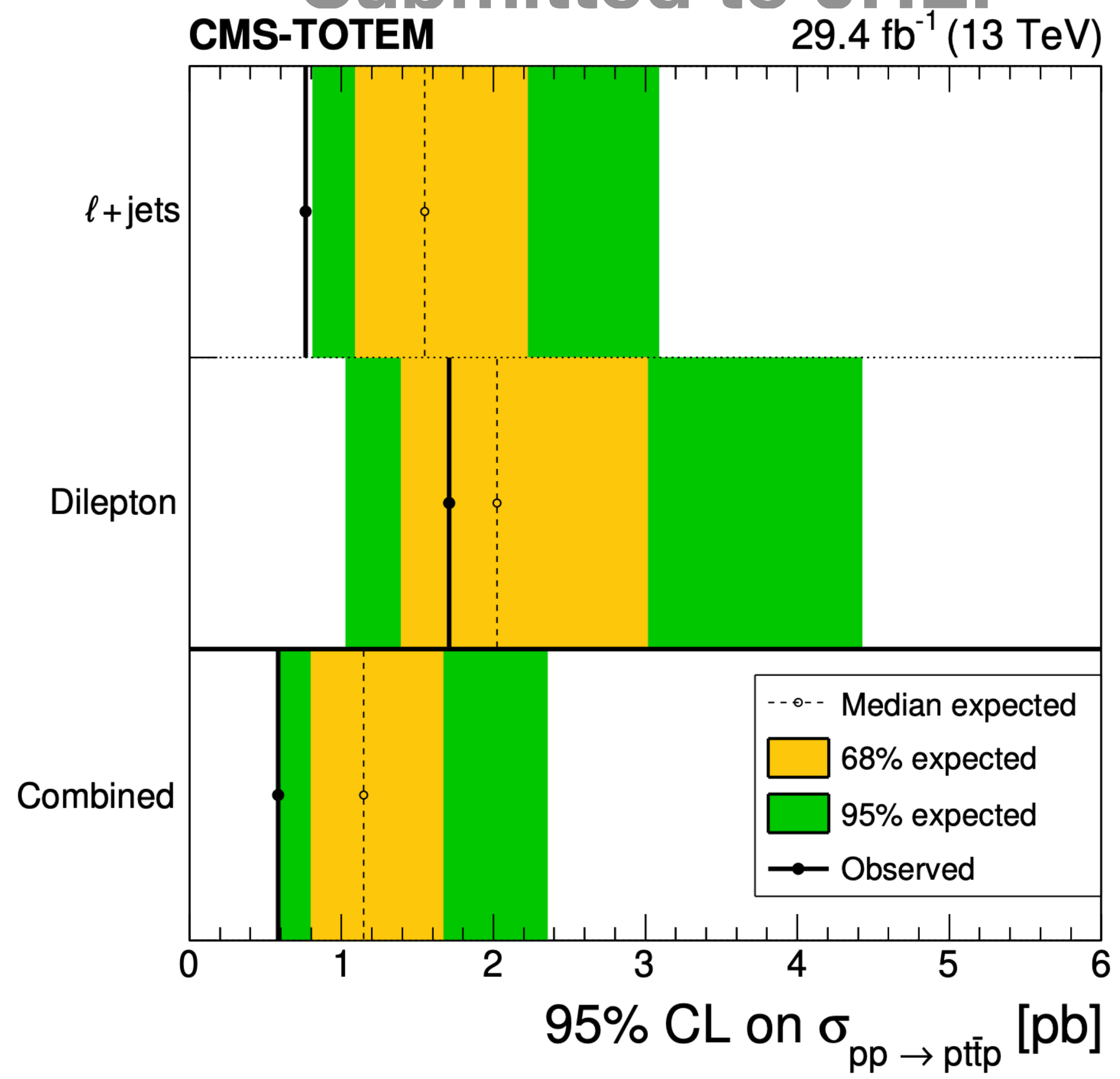
JINST 18 (2023) 09, P09009

https://doi.org/10.1088/1748-0221/18/09/P09009



Exclusive t-tbar Search

Submitted to JHEP



PPS2 Expression of Interest

CMS Note 2020/008 (arXiv 2103.02752)

Available on CMS information server CMS NOTE -2020/008

The Compact Muon Solenoid Experiment

CMS Note

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

26 November 2020 (v3, 09 December 2020)

The CMS Precision Proton Spectrometer at the HL-LHC – Expression of Interest

The CMS Collaboration

Abstract

The CMS Collaboration intends to pursue the study of central exclusive production (CEP) events, $\mathrm{pp} \to \mathrm{pXp}$, at the High-Luminosity LHC (HL-LHC) by means of a new near-beam proton spectrometer. In CEP events, the state X is produced at central rapidities, and the scattered protons do not leave the beam pipe. The kinematics of X can be fully reconstructed from that of the protons, which gives access to final states otherwise not visible. CEP allows unique sensitivity to physics beyond the standard model, e.g. in the search for anomalous quartic gauge couplings, axion-like particles, and in general new resonances.

CMS has been successfully operating the Precision Proton Spectrometer (PPS) since 2016; PPS started as a joint CMS and TOTEM project, and then evolved into a standard CMS subsystem. The present document outlines the physics interest of a new near-beam proton spectrometer at the HL-LHC, and explores its feasibility and expected performance. The document has been edited by the members of the PPS group and builds on their experience in the construction and operation of PPS.

Discussion with the machine groups has led to the identification of four locations suitable for the installation of movable proton detectors: at 196, 220, 234, and 420 m from the interaction point, on both sides (in this document these locations always imply both sides, unless otherwise noted). The locations at 196, 220, and 234 m can be instrumented with Roman Pot devices similar to the ones presently used. The 420 m location requires a bypass cryostat (which has been developed for other locations in the LHC) and a movable detector vessel approaching the beam from between the two beam pipes.

Acceptance studies indicate that having the beams cross in the vertical plane at the interaction point, as implemented after Long Shutdown 3, is vastly preferable over the present horizontal crossing. This gives access to centrally produced states X in the mass range 133 GeV−2.7 TeV with the stations at 196, 220, and 234 m. The mass range becomes 43 GeV−2.7 TeV if the 420 m station is included, which makes it possible to study central exclusive production of the 125 GeV Higgs boson. This is a major improvement with respect to the current mass range of 350 GeV−2 TeV.

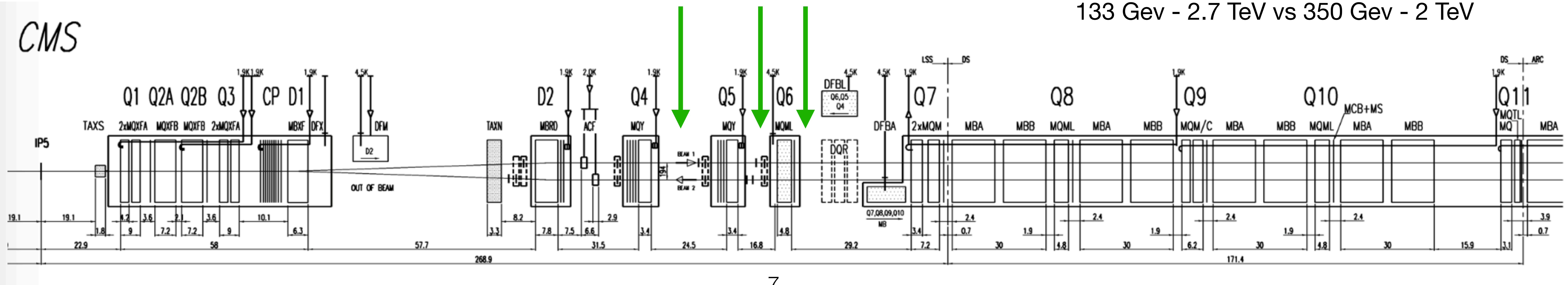
The radiation background has also been studied. Radiation hardness is required for all components in the tunnel. Service work during short technical stops will not be possible. The irradiation dose rate will be very strongly peaked near the beam. Detectors should therefore be vertically shifted with a

PPS2 and HL-LHC

- Interest in PPS2@HL-LHC since at end of Run 3, most PPS results will still be limited by statistical uncertainty
- During LS3 the beampipe and magnets around CMS will be removed and replaced
  - The current PPS detector will be removed, allowing for a new PPS2
- During one year of HL-LHC data taking, an integrated luminosity of 300 fb^{-1} is expected
- Increased pileup (up to 200) requires precision timing for pileup mitigation
- Locations in the new design have been identified as possible stations for PPS2:
  - 196 meters from the IP
  - 220 meters from the IP
  - 234 meters from the IP
  - Possible staged construction at 420 meters from the IP
  - 2 Roman Pots per station

Additional stations provide PPS2 a larger mass acceptance range than PPS

133 Gev - 2.7 TeV vs 350 Gev - 2 TeV



PPS2 Synergies with MTD

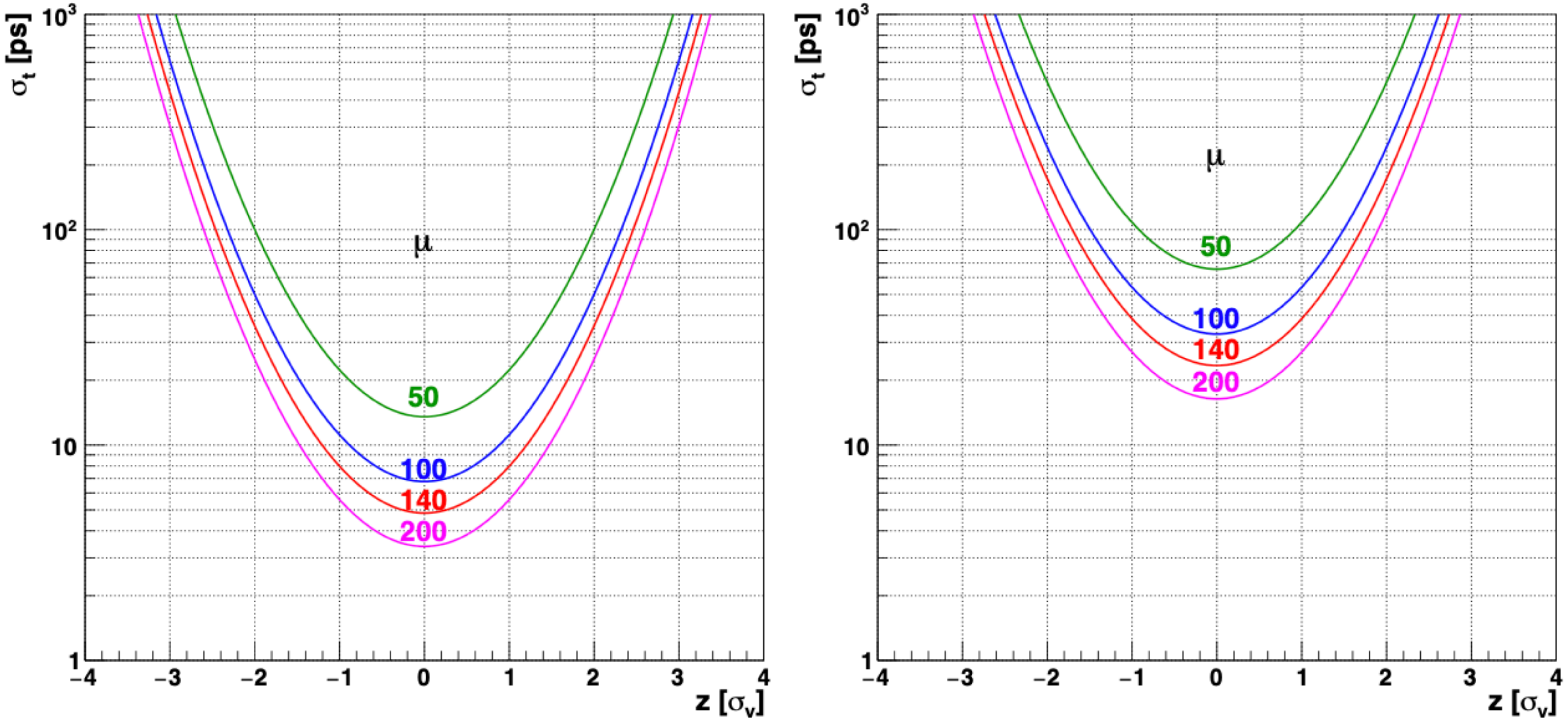


Figure 47: Time resolution required per spectrometer arm to resolve the mean vertex distance at a position z (in units of the longitudinal vertex width σ_v) from the IP centre. Four different pileup multiplicities are shown: $\mu = 50$ (LHC Run 2), 100, 140 (nominal HL-LHC performance), and 200 (ultimate HL-LHC performance). Left: for standalone PPS timing. Right: combining the PPS timing with the MTD system, selecting a time-slice of $\pm 50\,\mathrm{ps}$ around the central bunch crossing time.

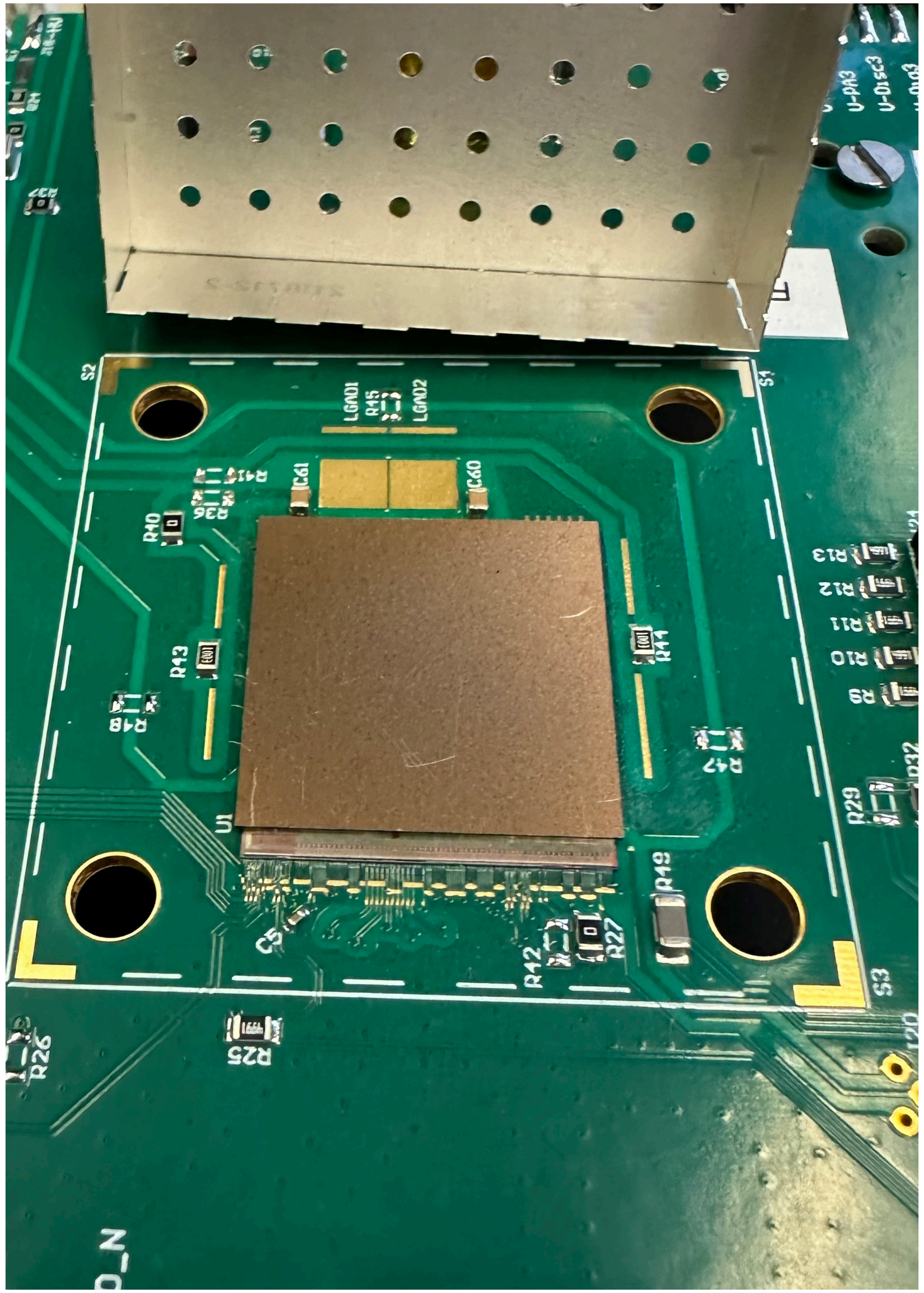
Taken from CMS Note 2020/008 (arXiv 2103.02752)

PPS2 LGAD approach to Precision Timing

- Goal: Use Low Gain Avalanche Diodes (LGAD) for timing measurement in PPS2
  - reuse as much as possible from ETL@CMS, who are pursuing an LGAD approach as well
  - may require customization of the LGAD sensor
  - PPS2 Expression of Interest → O(15 ps) per PPS2 arm → O(10) ETL+LGAD/station; 80 total
- Advantages:
  - Leverage knowledge and expertise being developed within CMS on LGADs for ETL
  - Reuse full DAQ chain currently being developed for ETL: ETROC, FED, firmware, etc
- Challenges:
  - Extremely non-uniform flux
  - Large radiation dose
- Already started Irradiation studies on LGAD and ETROC

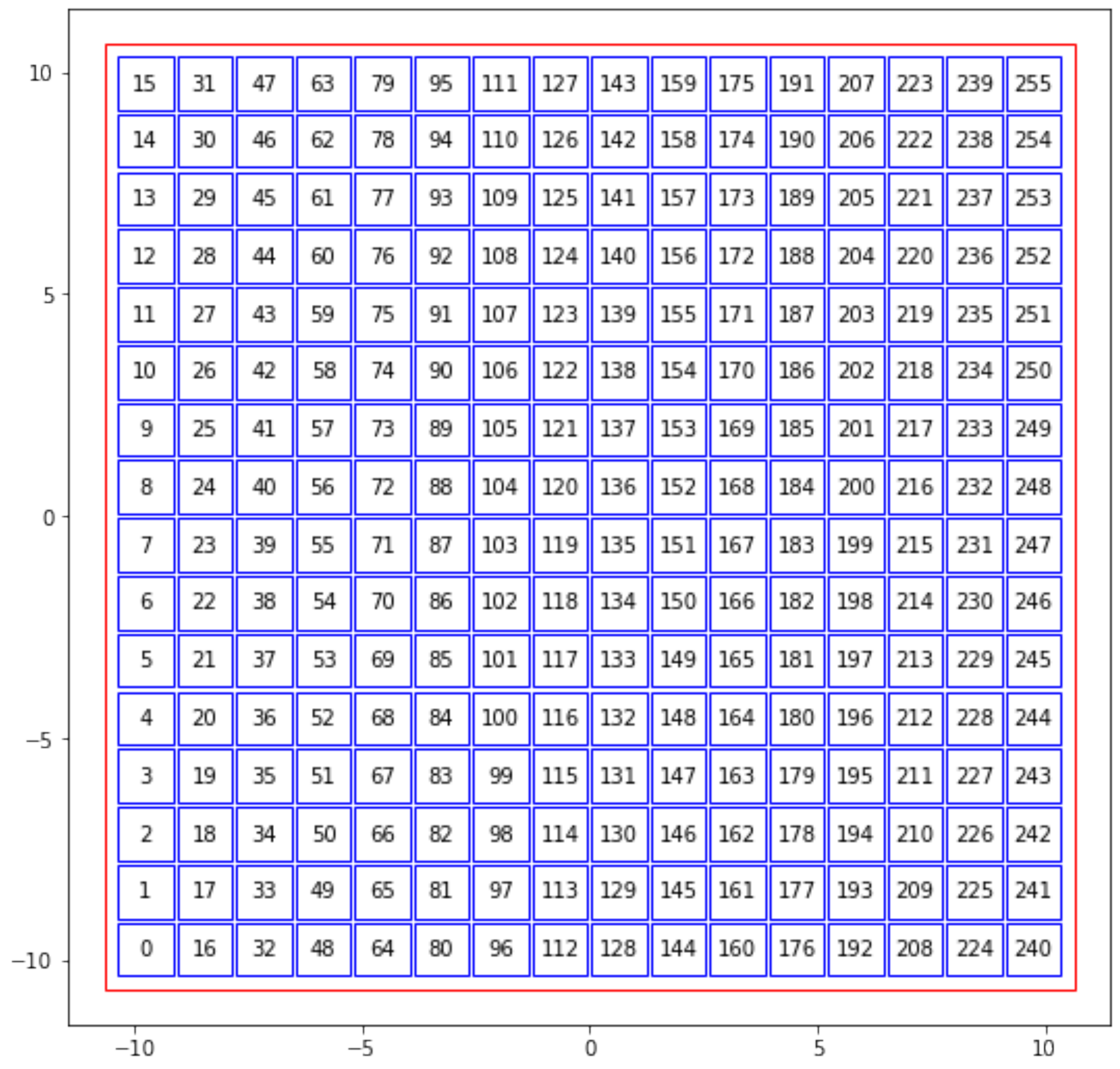
Use ETL Design for PPS2

- ETROC bump bonded to an LGAD sensor
- 16x16 square array of channels (both ETROC and LGAD)
- Each pad 1.3x1.3 mm^2 → 20.8x20.8 mm^2 LGAD size
- ETROC dimensions 21x23 mm^2
- Current prototype is ETROC2, already a full size chip with all features implemented
- LGAD radiation hardness ~2x10^{15} neq/cm^2



ETL LGAD Geometry

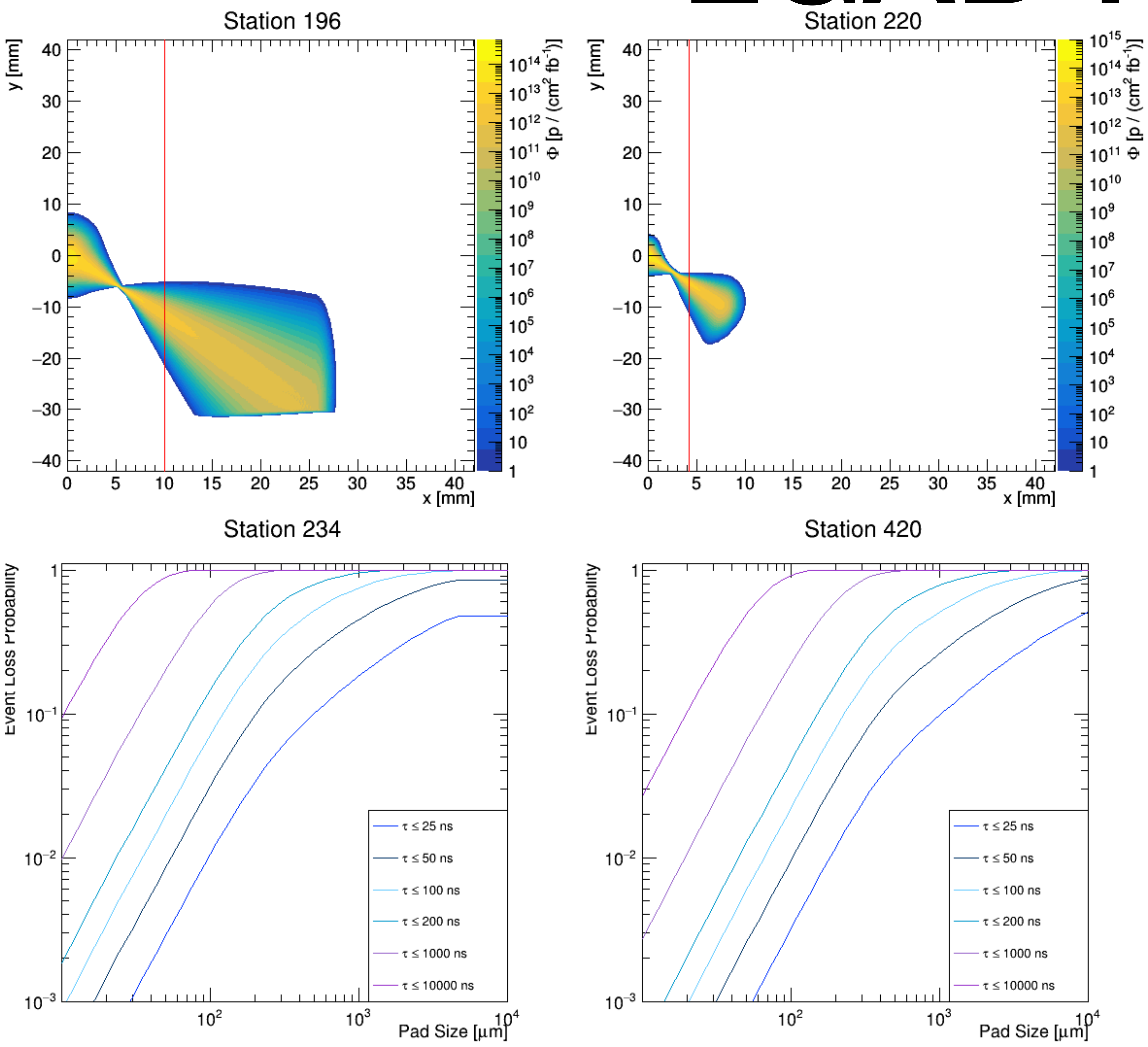
- Each sensor covers an area of 21x21 mm^2:
  - 16x16 pads or channels
  - Each pad 1.3x1.3 mm^2
- Realistic geometry has inactive regions:
  - Interpad Distance: depends on technology ~100 μm for standard LGAD
  - Guard Ring: smallest is ~300 μm



Trench Isolated (TI) LGAD can reach an interpad distance of ~10 μm, not pursued for ETL

PPS2 LGAD Segmentation and Radiation Tolerance Studies

LGAD Pad Size



- Calculated flux map data, for all 4 stations; flux from diffractive processes only, no other processes considered (referred to as background in subsequent slides)
- HL-LHC beam at position (0, 0)
- Red line marks approximate edge of the detector
- Use fluxes to estimate pad occupancy vs pad size

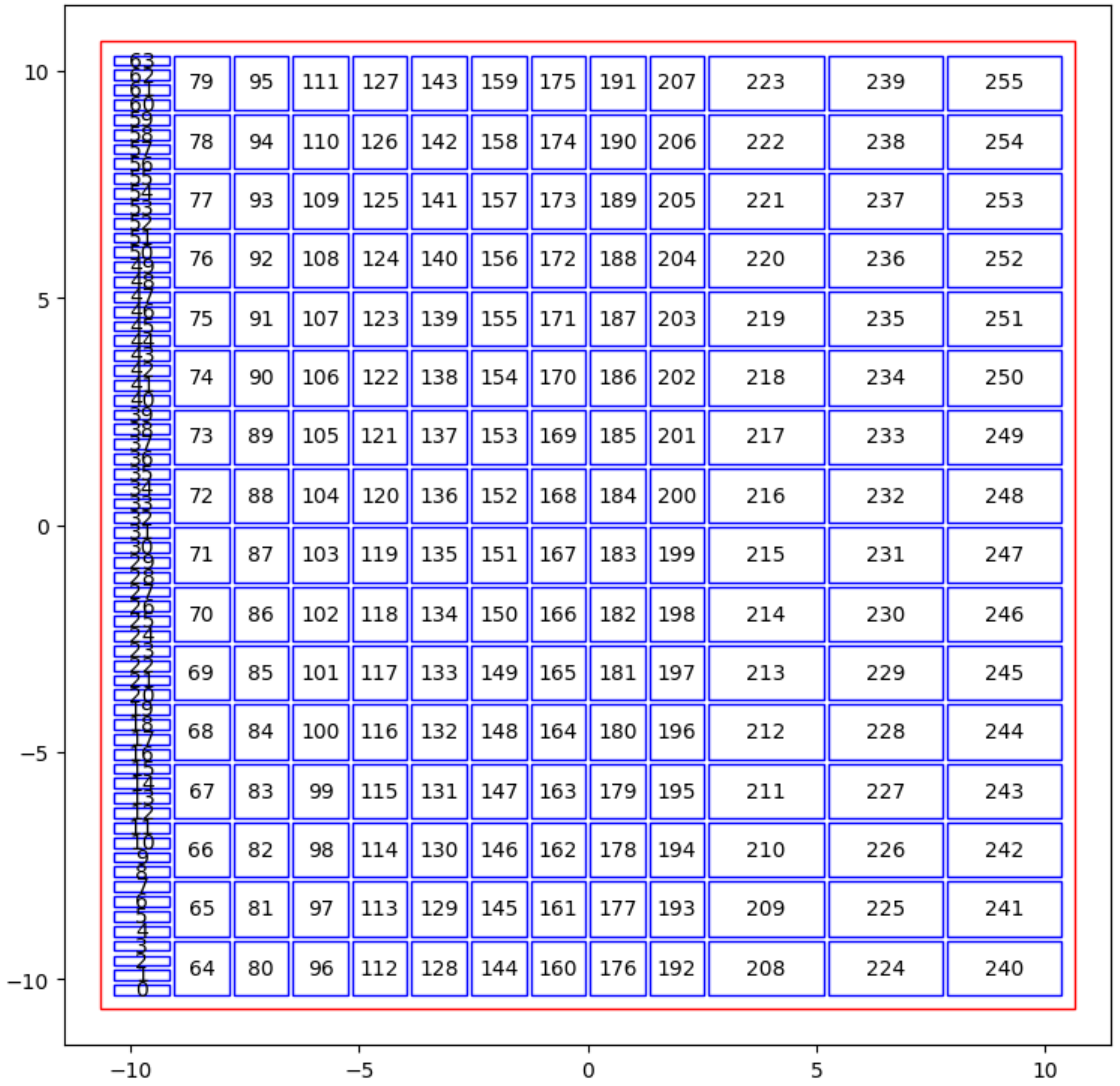
- Pad occupancy, detector deadtime and event loss probability are related:

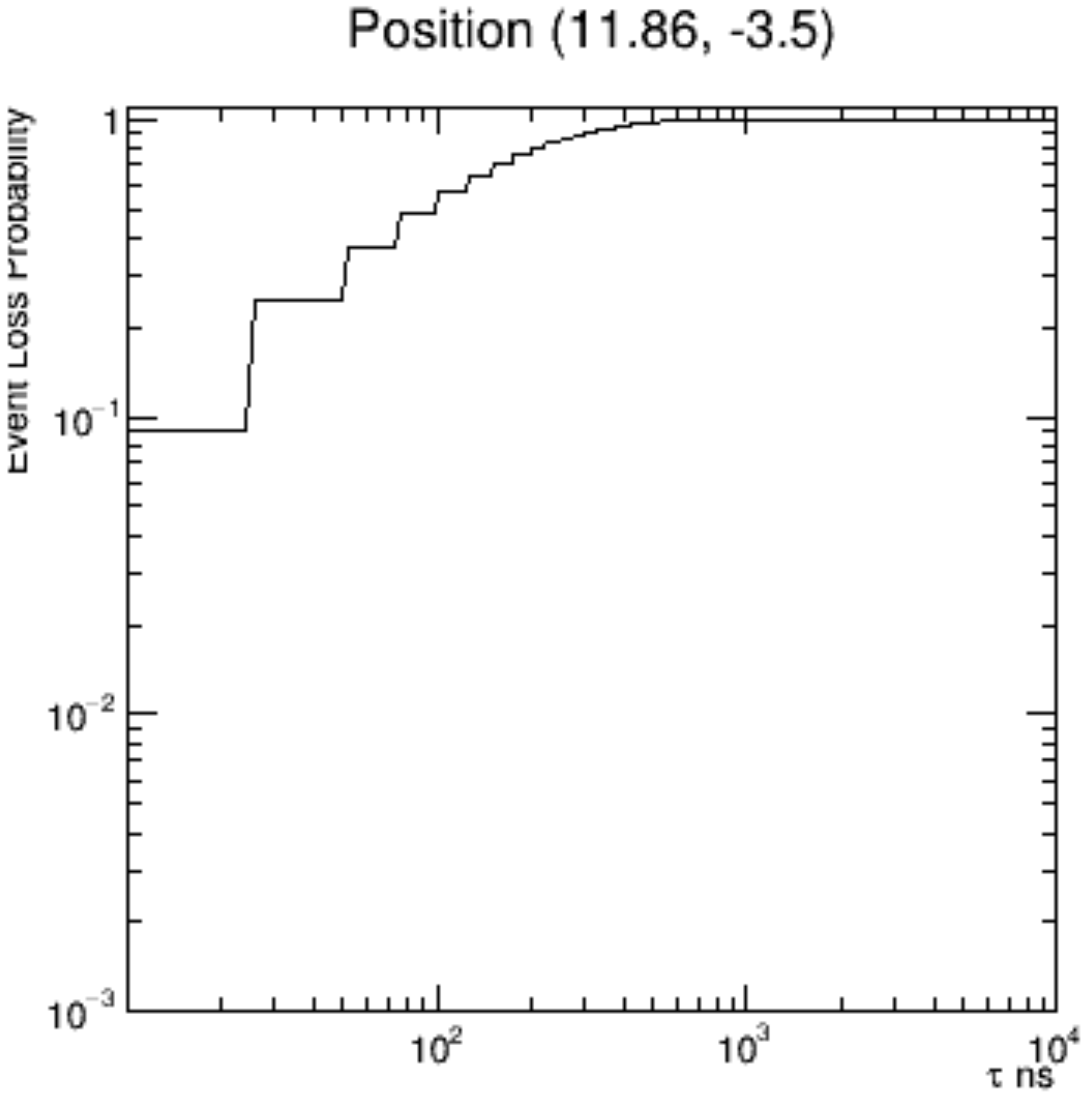
$$P(\geq 1\,\text{extra p within}\,\tau) = 1 - \frac{\mu^2}{\left(1 - e^{-\mu}\right)^2} e^{-2\mu\left[\text{int}\left(\frac{\tau}{\Delta t}\right)+1\right]}$$

- Reducing the pad size is fundamental in order to efficiently take data, particularly for the first pad column

Proposed PPS2 LGAD Geometry

- Split first column of pads into 4 to mitigate high occupancy
- Merge last columns to maintain same number of channels
- Interposer is required to interface with ETROC
- Other LGAD designs are being considered





Currently in discussion with FBK about the feasibility and possibility of such a production

Active Area Optimization

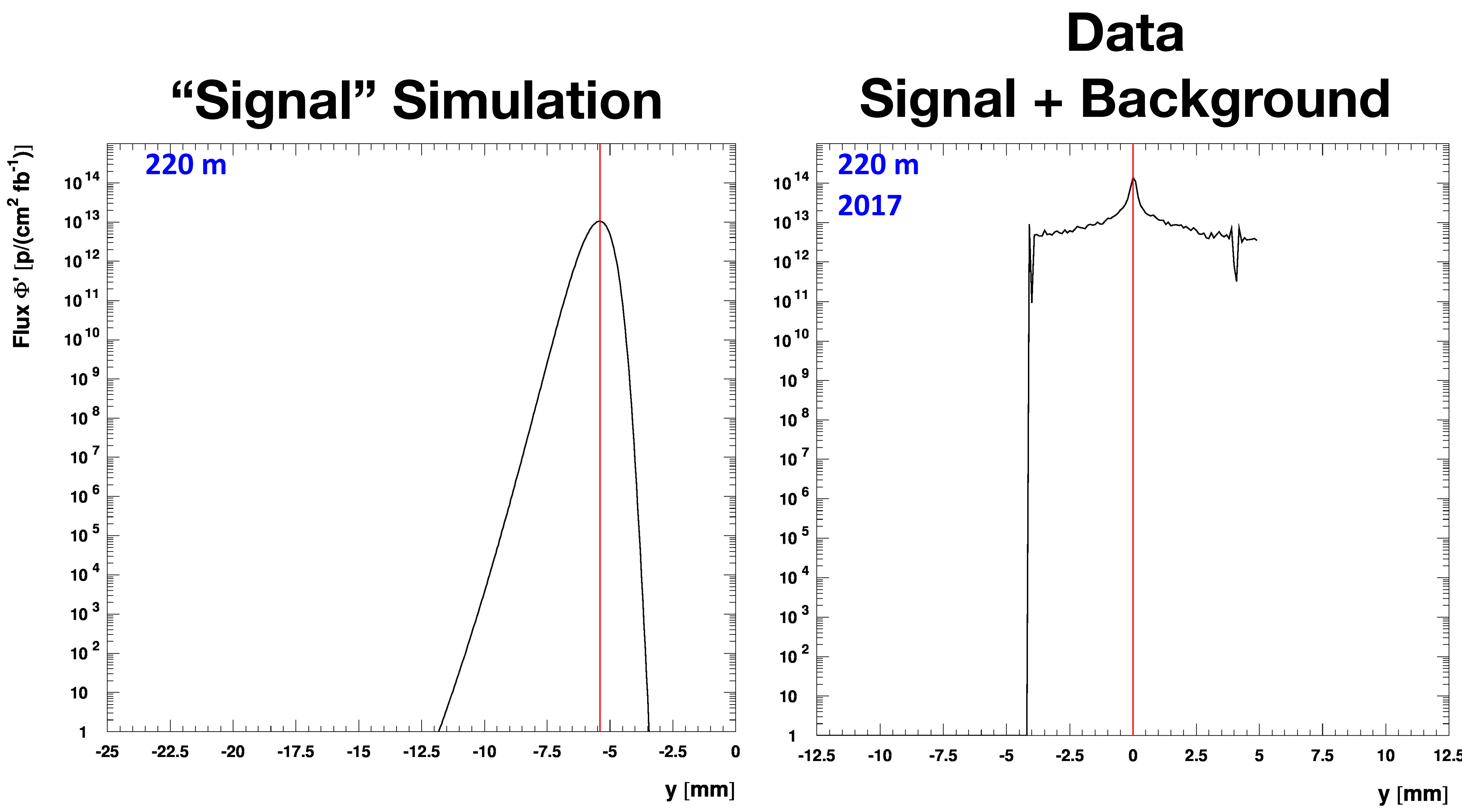
- For a “Standard LGAD”, the interpad distance (space between pads) is approximately 100 µm
  - This gives a standard ETL LGAD a fill factor of approximately 85%
  - With PPS2 segmentation, the overall fill factor is ~81%, but the fill factor of the first column is ~64%

- A TI-LGAD can achieve interpad distances as low as 10 µm
  - PPS2 LGAD can reach an overall fill factor of ~**98%** and a fill factor of the first column of ~**96%**

- Reducing the interpad spacing is fundamental to achieve good efficiency, so TI-LGADs are the preferred option for PPS2

Background Flux

- Studies with 2017 data: Background ~5×10^{12} p/(cm^2 fb^{-1})



- Background+Signal covers smaller range than signal only:
  - Mitigates issues with non-uniform irradiation
  - Increases the total irradiated dose

- To improve background characterization, use 2018 data and study dependence on beam properties
  - Initial results show dependence only on integrated luminosity, no dependence of background flux on beam parameters: number of circulating bunches, β*, …

- Assuming HL-LHC background is similar to 2017 → after 300 fb^{-1}, dose from background ~**1.5×10^{15} p/cm^2**

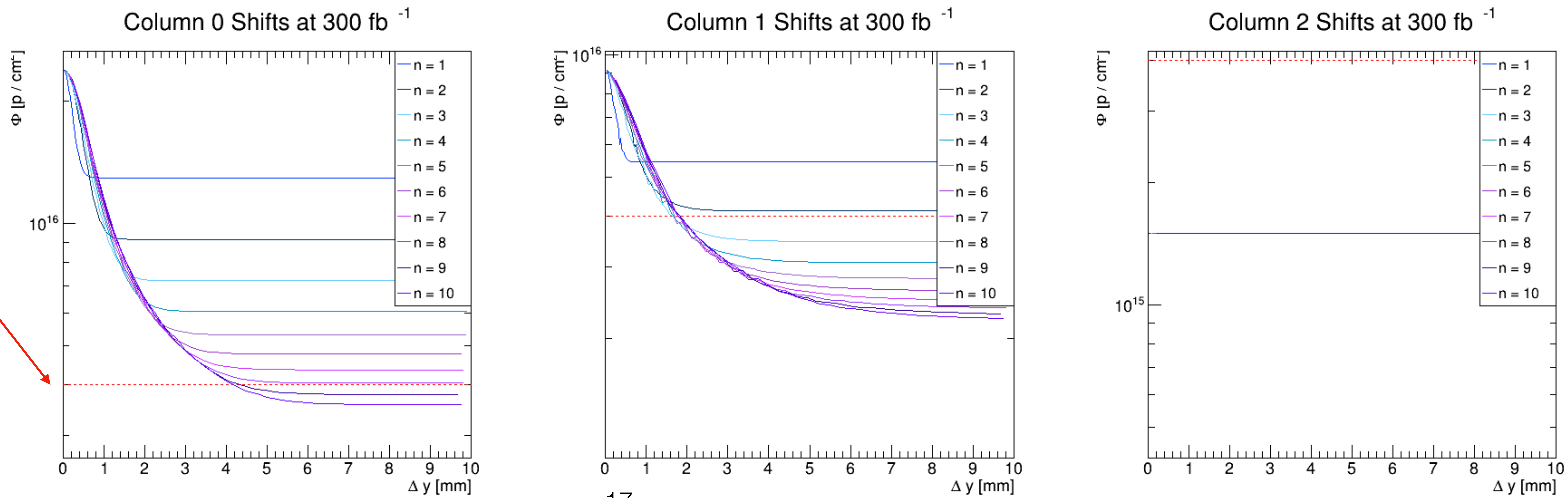
Radiation Damage Mitigation

- LGAD sensors can withstand maximum flux:
  - ~2×10^{15} neq/cm^2 ≅ 4×10^{15} p/cm^2 (1 neq ≝ 1 MeV n; p ≈ p > 10 GeV)
- The 234 station will exceed this value in less than one year of HL-LHC (300 fb^{-1}), the 220 station is close and will exceed when accounting "background flux"
- The sensors need to be vertically shifted periodically throughout the year to spread the peak flux and mitigate the damage effects

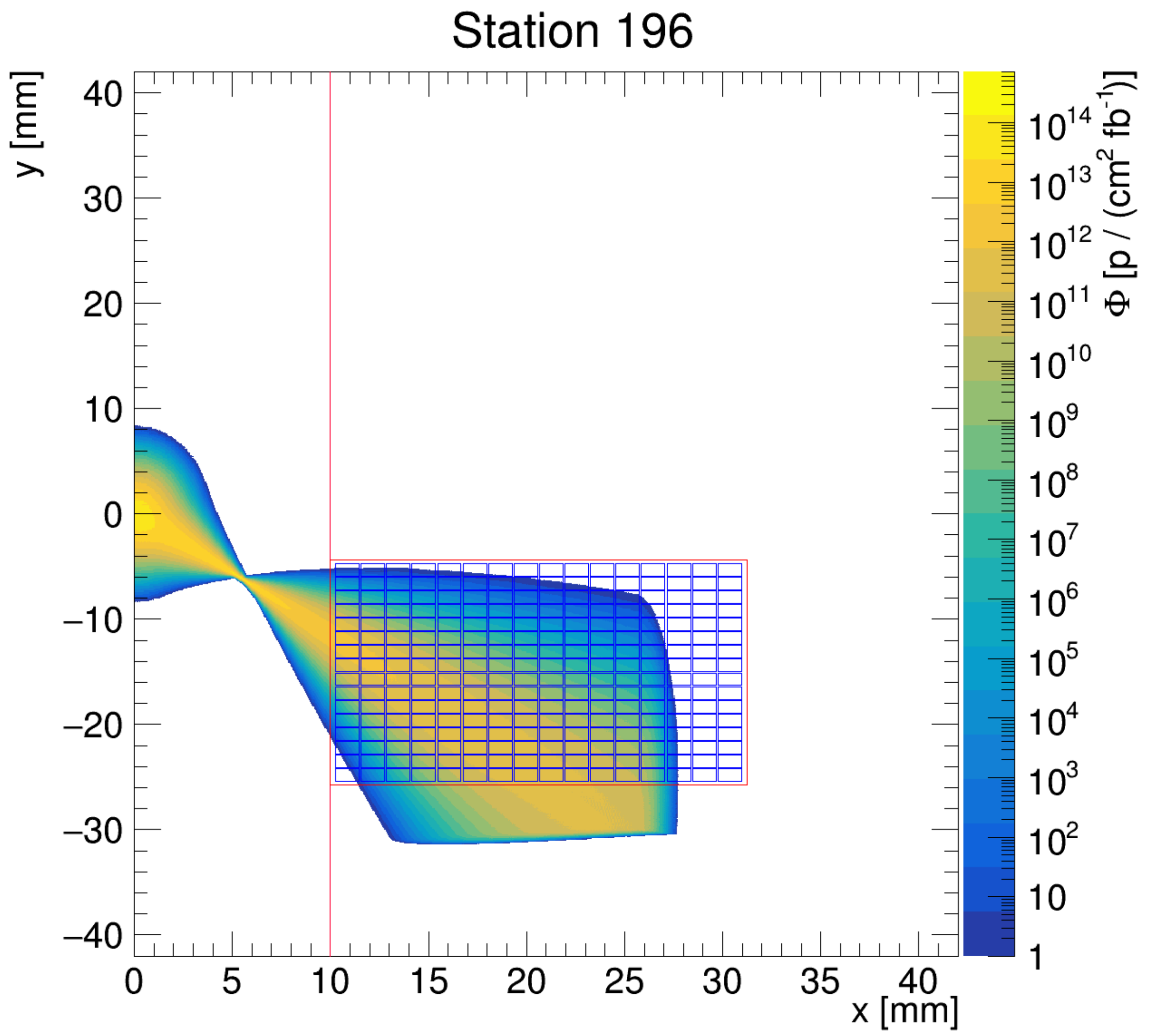
Station 234
(with background)

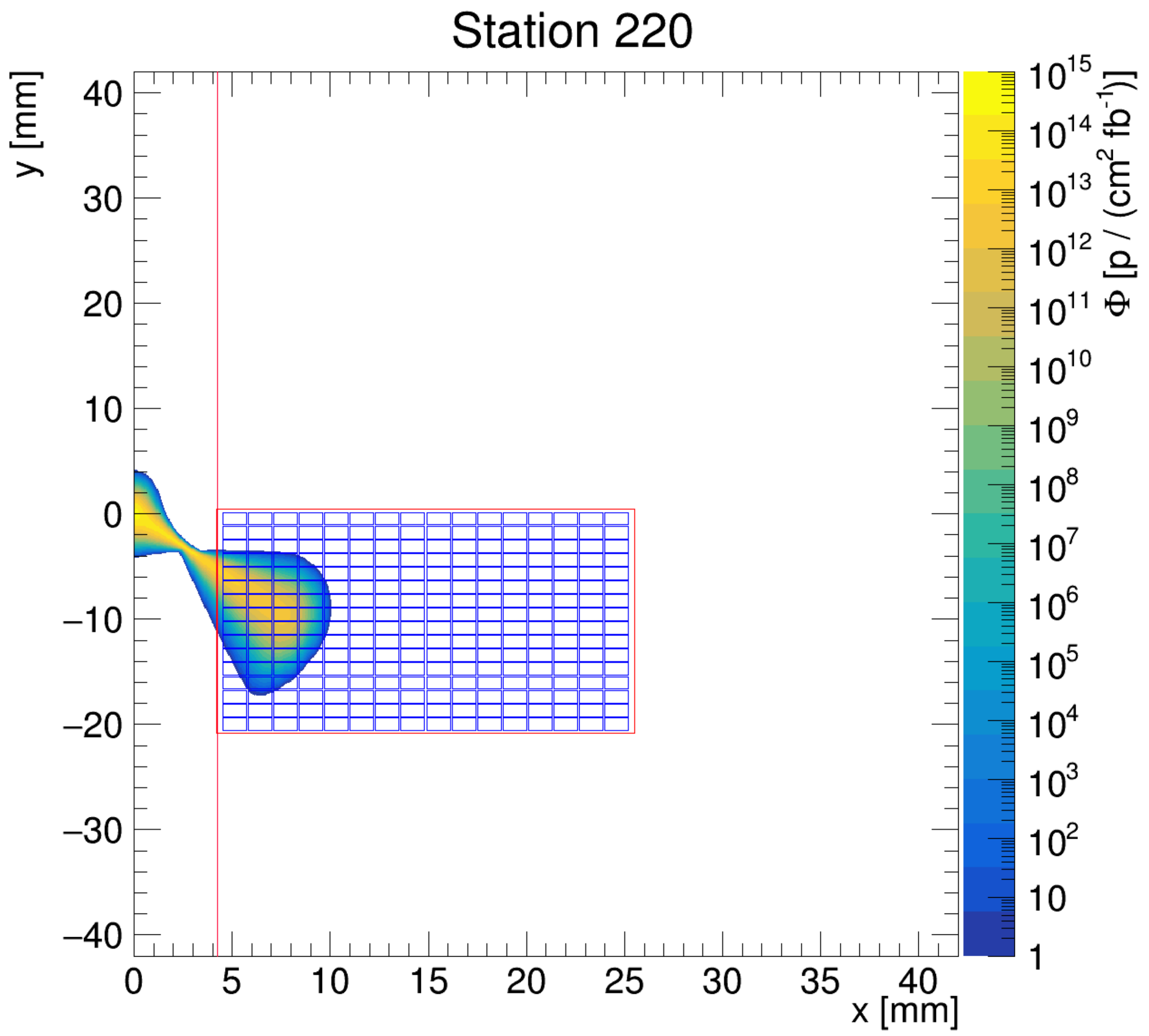
LGAD Radiation Limit

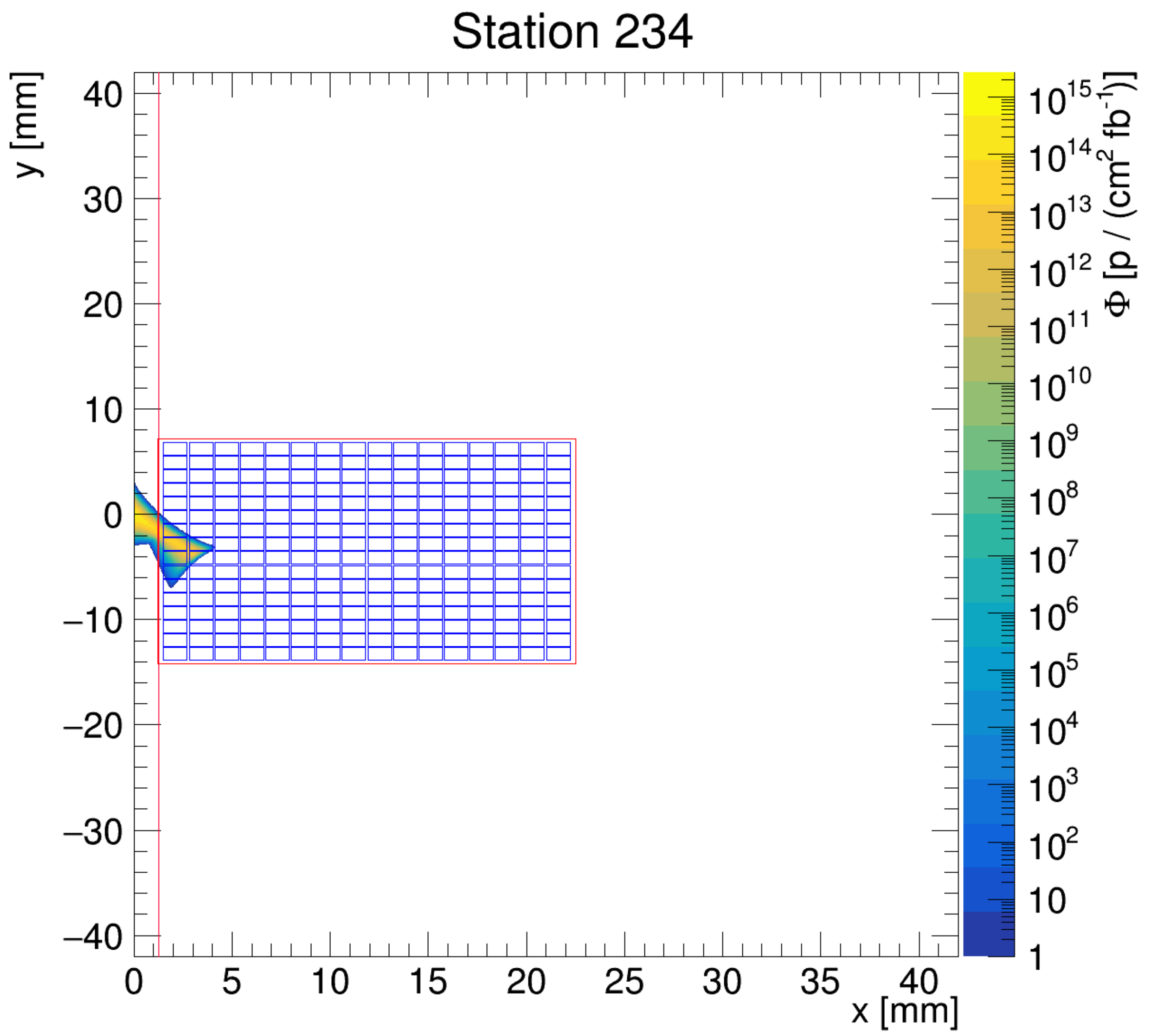
At least 9 shifts required throughout a year of HL-LHC



Sensor Position





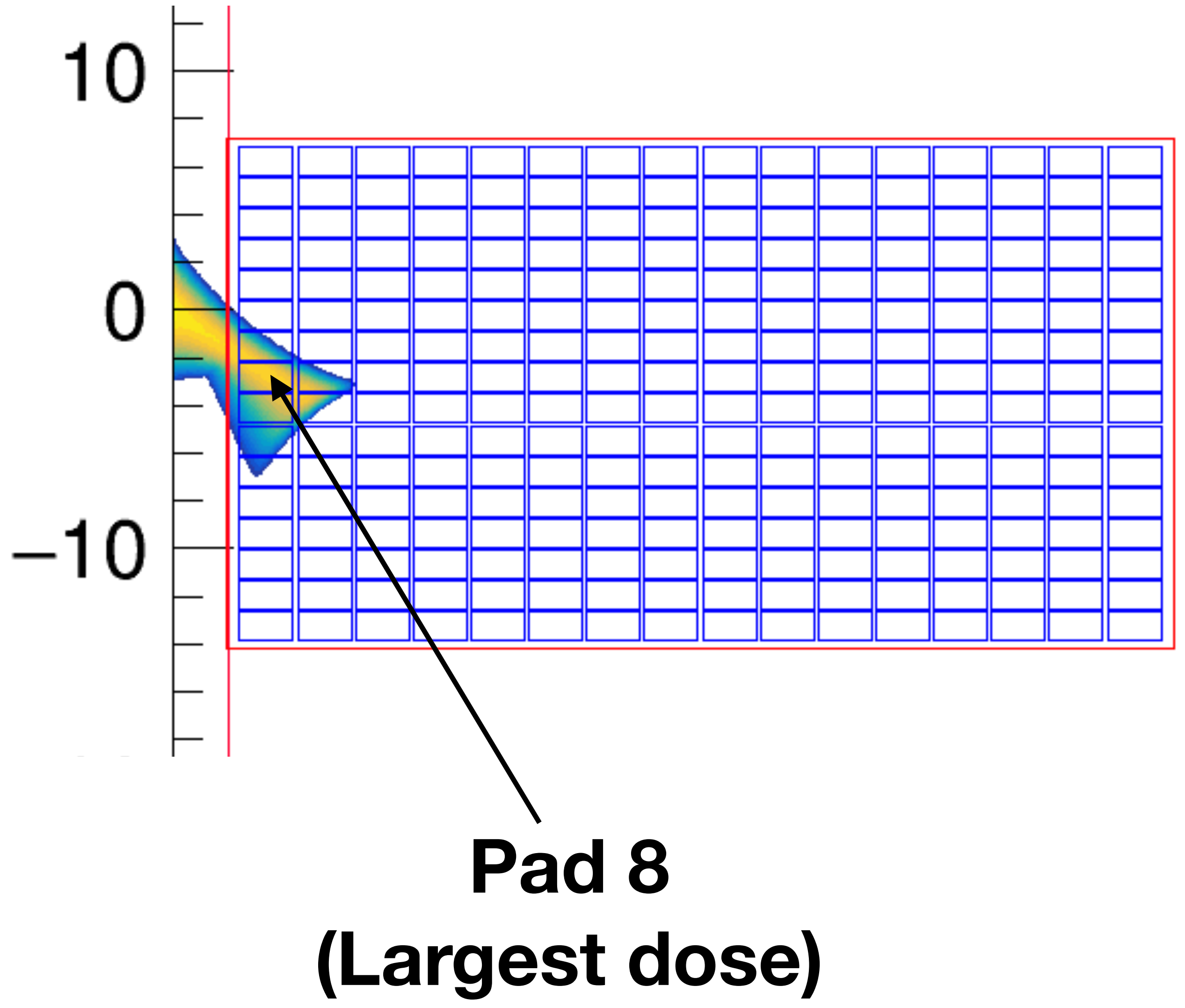


- Single sensor covers full acceptance for all stations, except 196 m
  - Stack multiple sensors with offsets to get full coverage or place additional sensors side-by-side
- Other stations require periodic vertical shifts to mitigate radiation damage
  - 220 m: 1 shift (0 without background)
  - 234 m: 9 shifts (5 without background)

LGAD Operation Voltage

- Absolute maximum voltage (burn-out): 688 V (12.5 V/μm @ 55 μm)
- Consider flux map in pad 8 and estimate minimum bias voltage to obtain 8 fC and estimate breakdown bias voltage, for different integrated luminosities:
  - 100 fb-1: 338-436 V
  - 200 fb-1: 483-537 V
  - 300 fb-1: 656-650 V
    - the minimum voltage is above the breakdown voltage, only slightly, so the most irradiated regions of the pad will be inefficient
- The analysis above not yet extended to full sensor

ETL-Like Sensor
Standard LGAD
234 m Station
6 Shifts - 7 Positions
Shifts by 1.3/2



Based on data from the ETL LGAD Market Survey shared by Roberta Arcidiacono

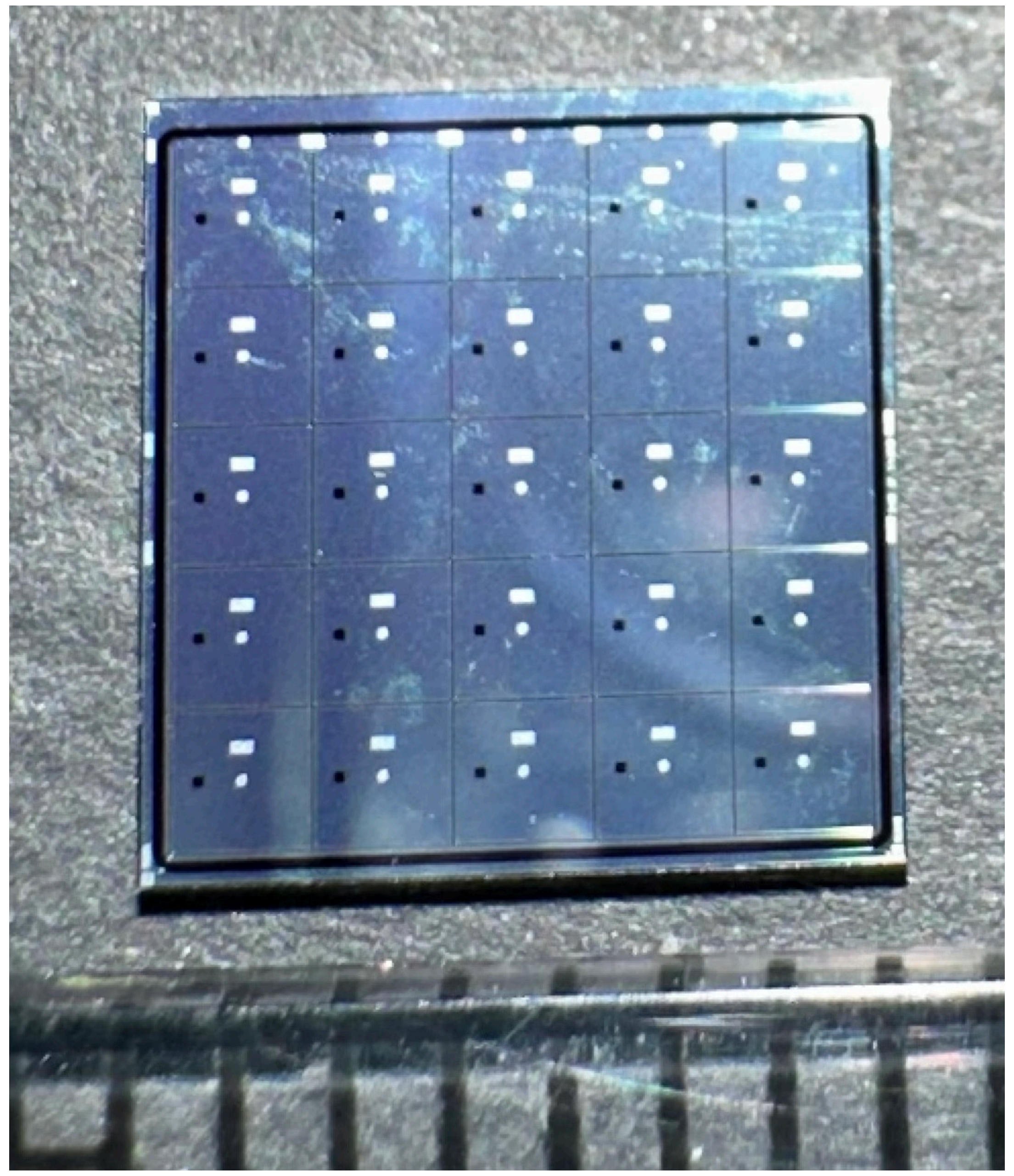
LGAD Irradiation

LGAD Samples

- 5 LGAD samples from FBK-UFSD4 production
  - Samples from Wafer 18 - Observed to be most radiation hard wafer from UFSD4

- Each sample is a matrix of 5x5 pixels, each pixel is a square with 1.3 mm side. Samples are a Standard LGAD design with ~100 μm interpad

- Samples have different characteristics:
  - Guard ring design (GR3_0 or GR3_1)
  - LGAD Interpad design (T9 or T10)

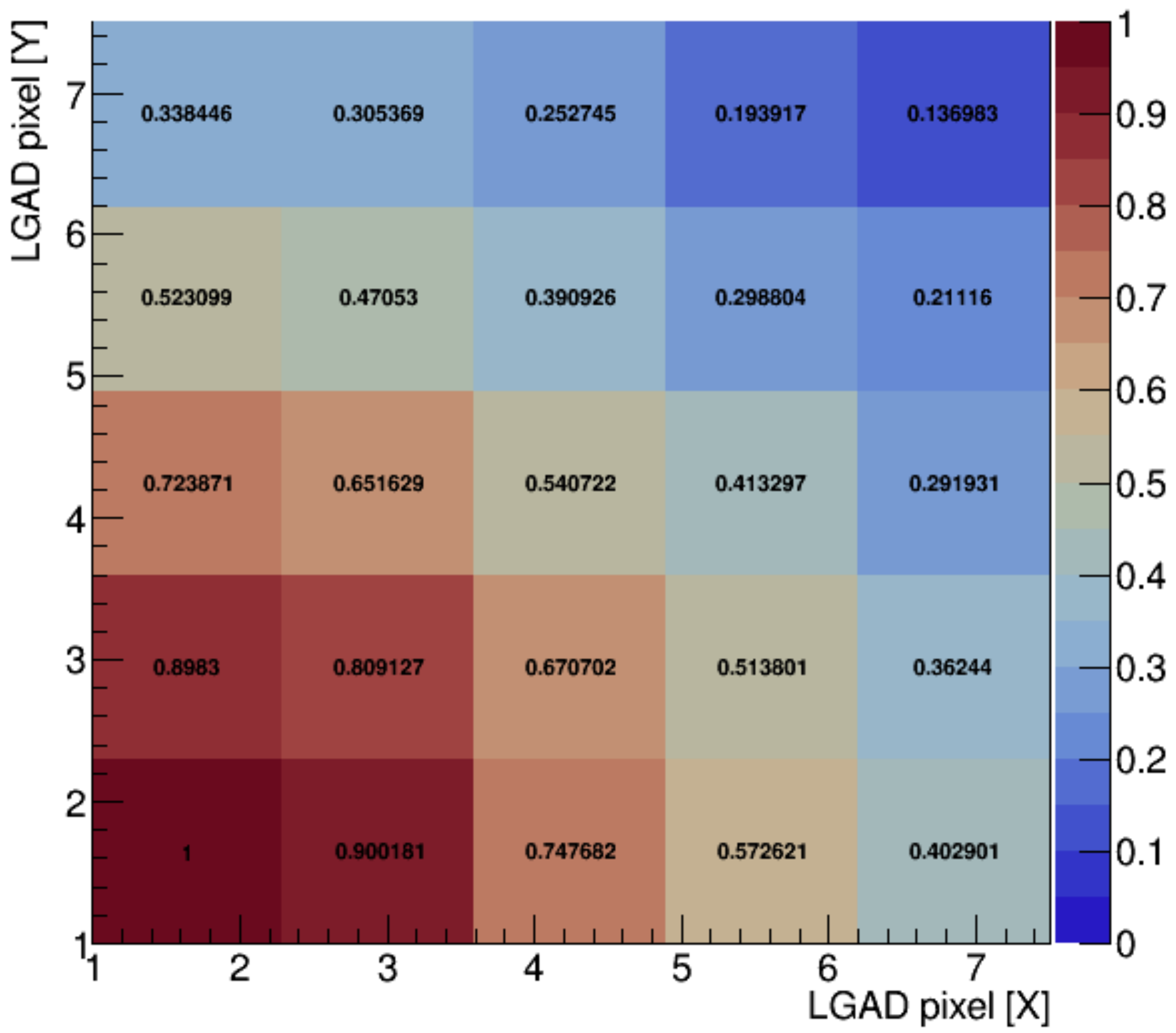


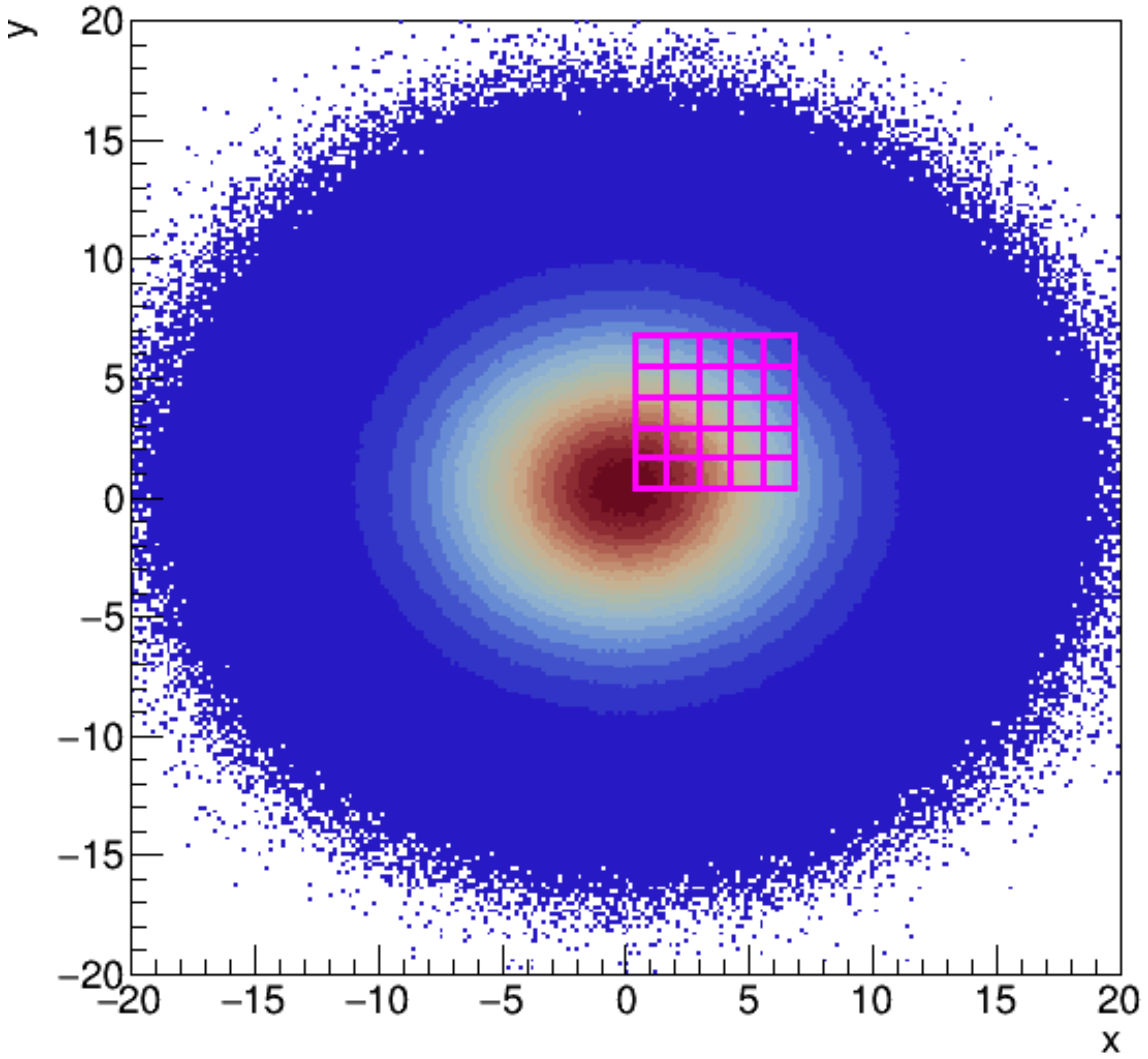
Samples provided by Roberta Arcidiacono

LGAD Irradiation

- Irradiation performed at IRRAD facility at CERN
- Irradiated 4 of the LGADs with a non-uniform field, sensor offset from the center of the beam
- Irradiation dose spans approximately 1 order of magnitude

Sample Name	Reference	Peak Irradiation
PPS_LGAD_01	FBK UFSD4 W18 GR3_1 T9 6-4	1E16 p/cm^2
PPS_LGAD_02	FBK UFSD4 W18 GR3_1 T10 6-4	5E15 p/cm^2
PPS_LGAD_03	FBK UFSD4 W18 GR3_0 T9 6-4	NA
PPS_LGAD_04	FBK UFSD4 W18 GR3_0 T10 6-4	1E16 p/cm^2
PPS_LGAD_05	FBK UFSD4 W18 GR3_0 T9 4-6	5E15 p/cm^2



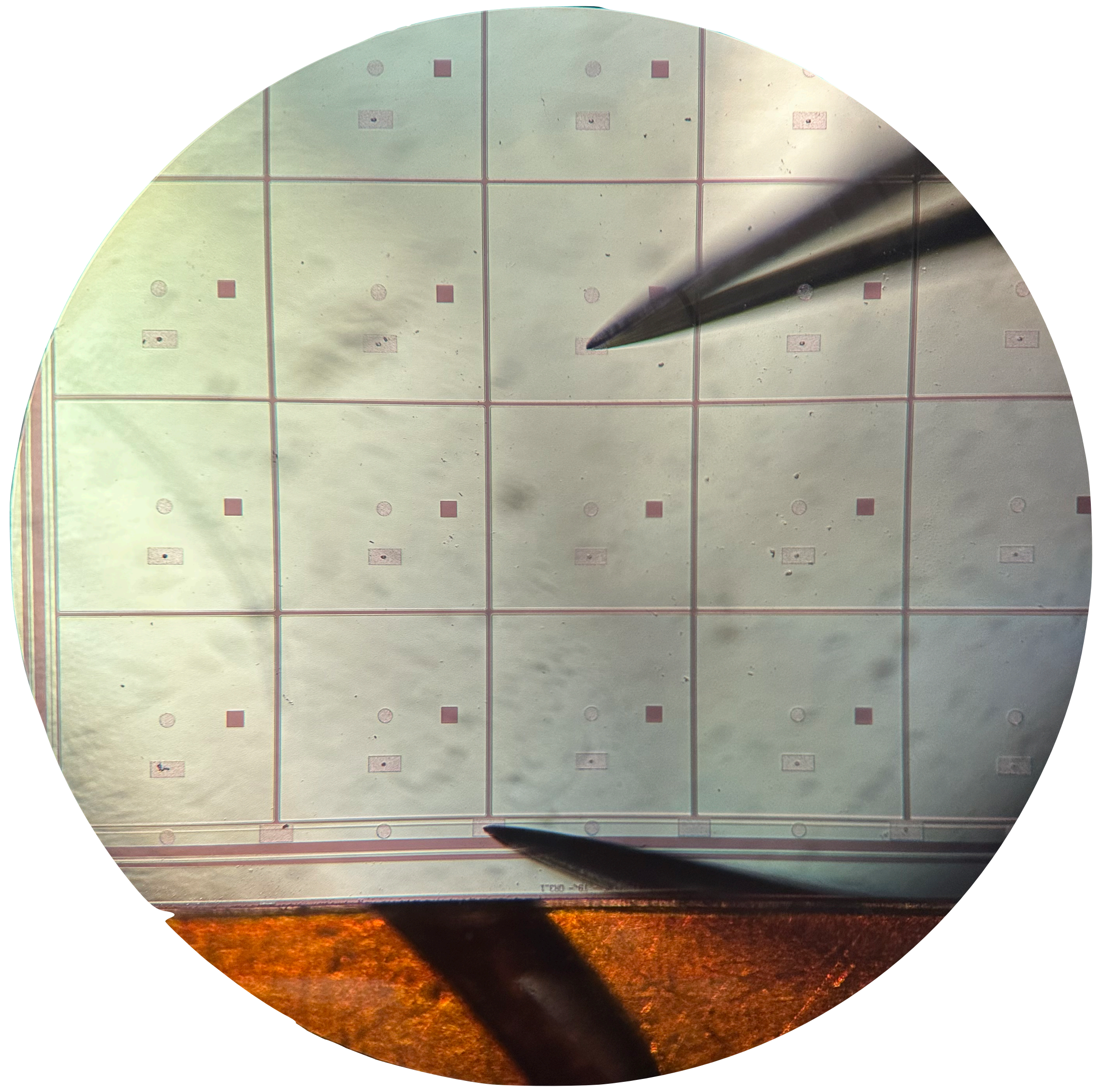


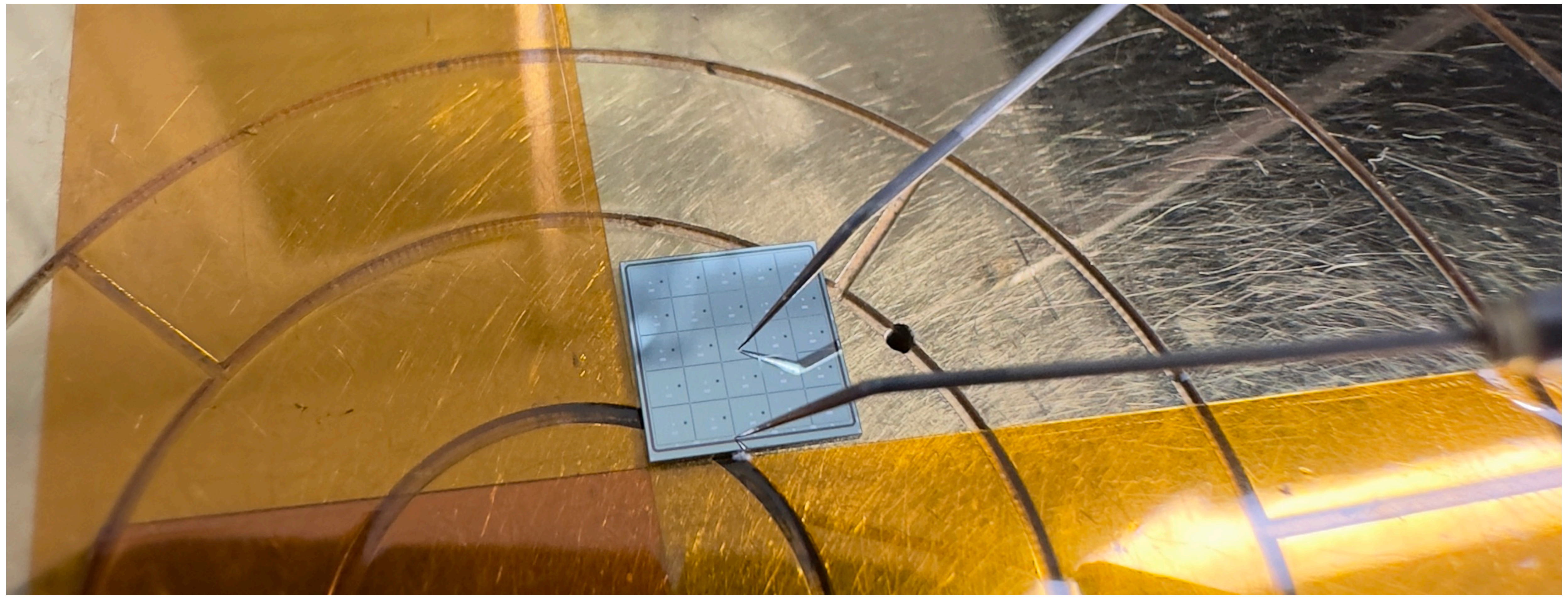
Beam profile measured from spills used to irradiate the samples

LGAD Measurements

- Before and after irradiation, characterise CV and IV curves of LGAD pads
  - Focus on pads along the diagonal to evaluate effect of irradiation gradient

- CVIV measurement system from CERN SSD lab was used:
  - Only 2 probe needles available, together with chuck connection for HV supply
  - Connect 1 needle to guard ring and the other needle to the pad under study, floating pads around the pad of interest slightly affect the measurement

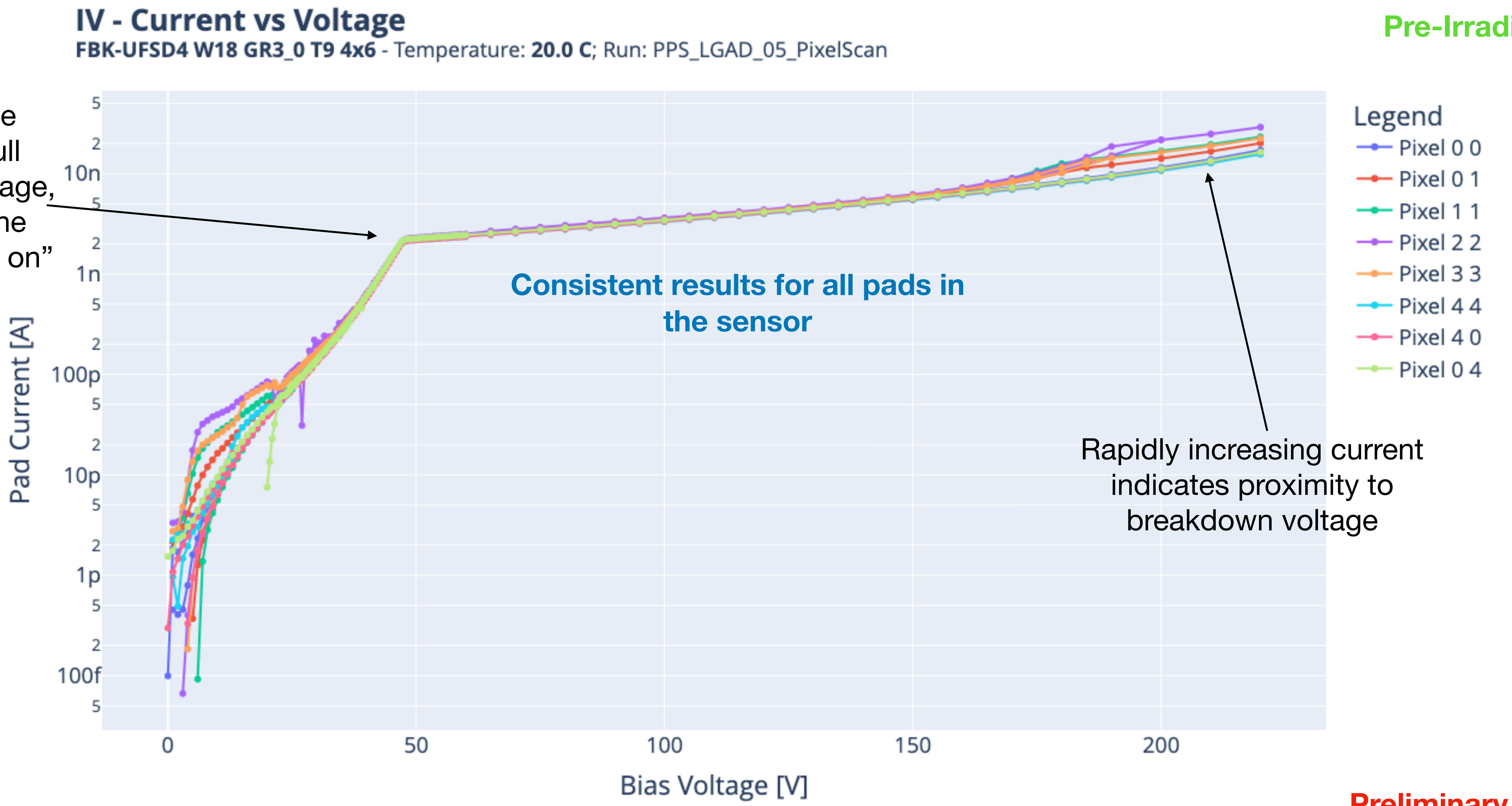




IV Curves of Pads in 1 Device

Pre-Irradiation

Knee shape indicates full depletion voltage, i.e. where the sensor "turns on"



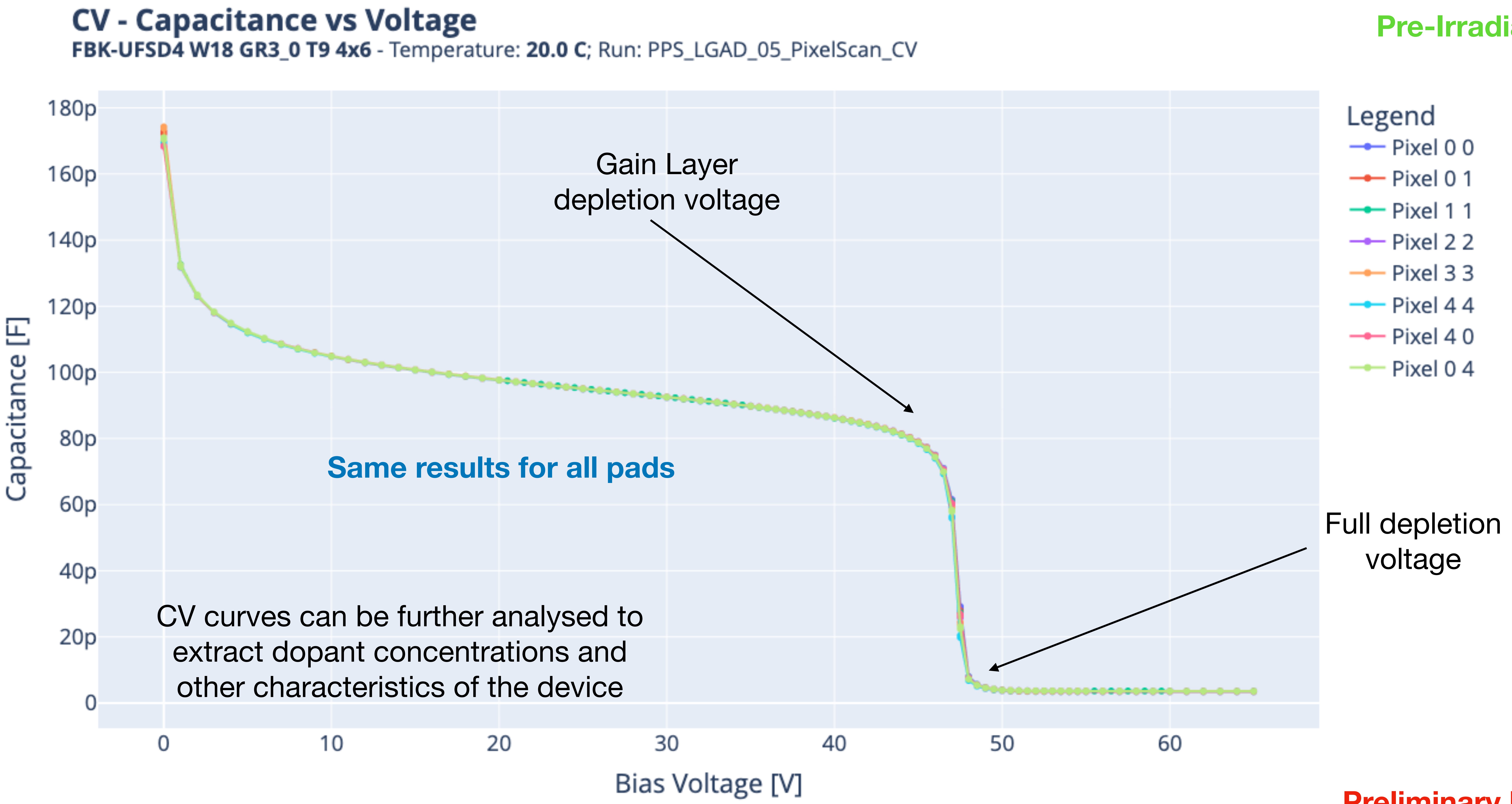
Consistent results for all pads in the sensor

Rapidly increasing current indicates proximity to breakdown voltage

Preliminary Results

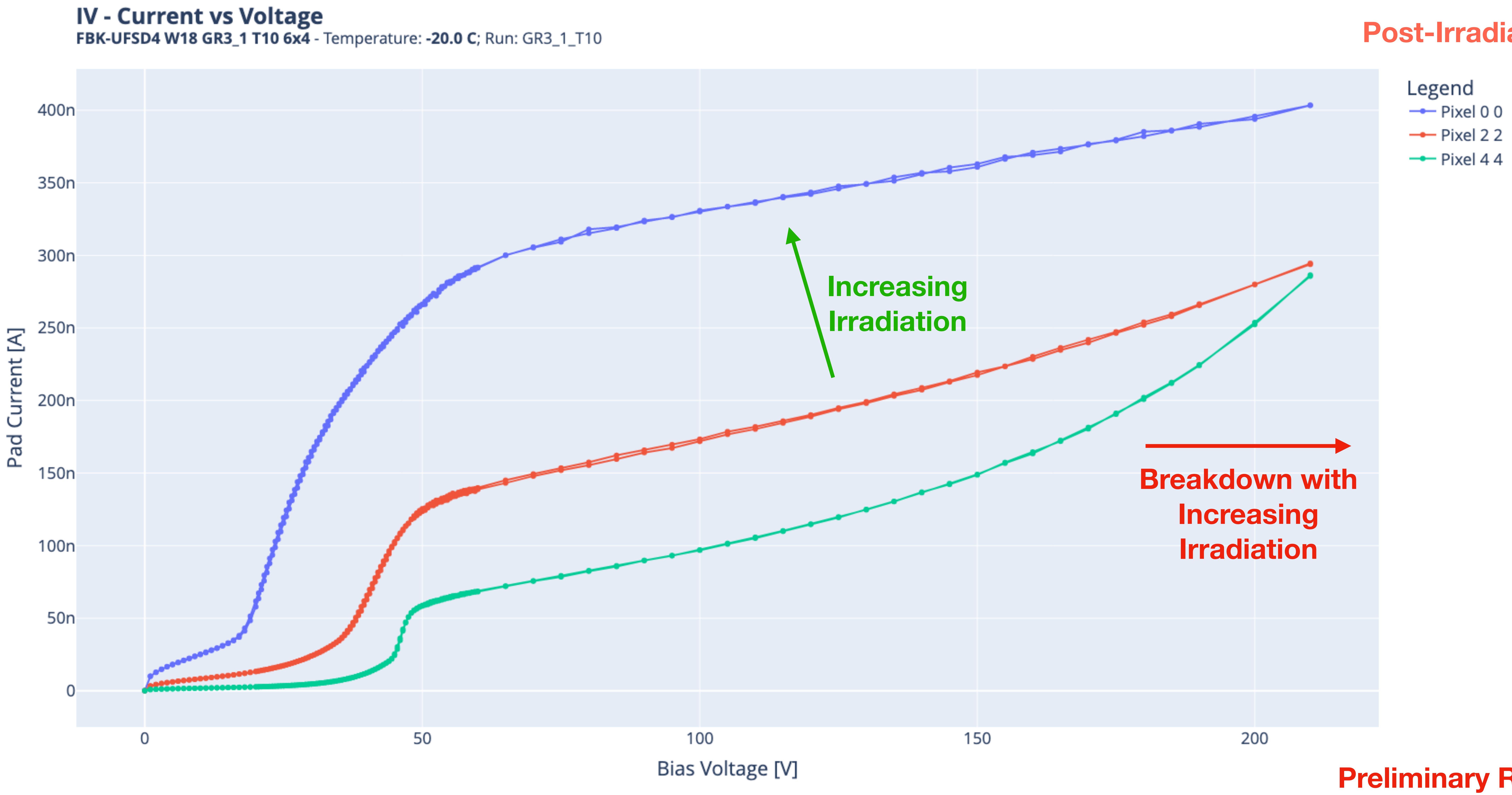
CV Curves of Pads in 1 Device

Pre-Irradiation



Preliminary Results

IV Curves of Pads in 1 Device



Post-Irradiation

Preliminary Results

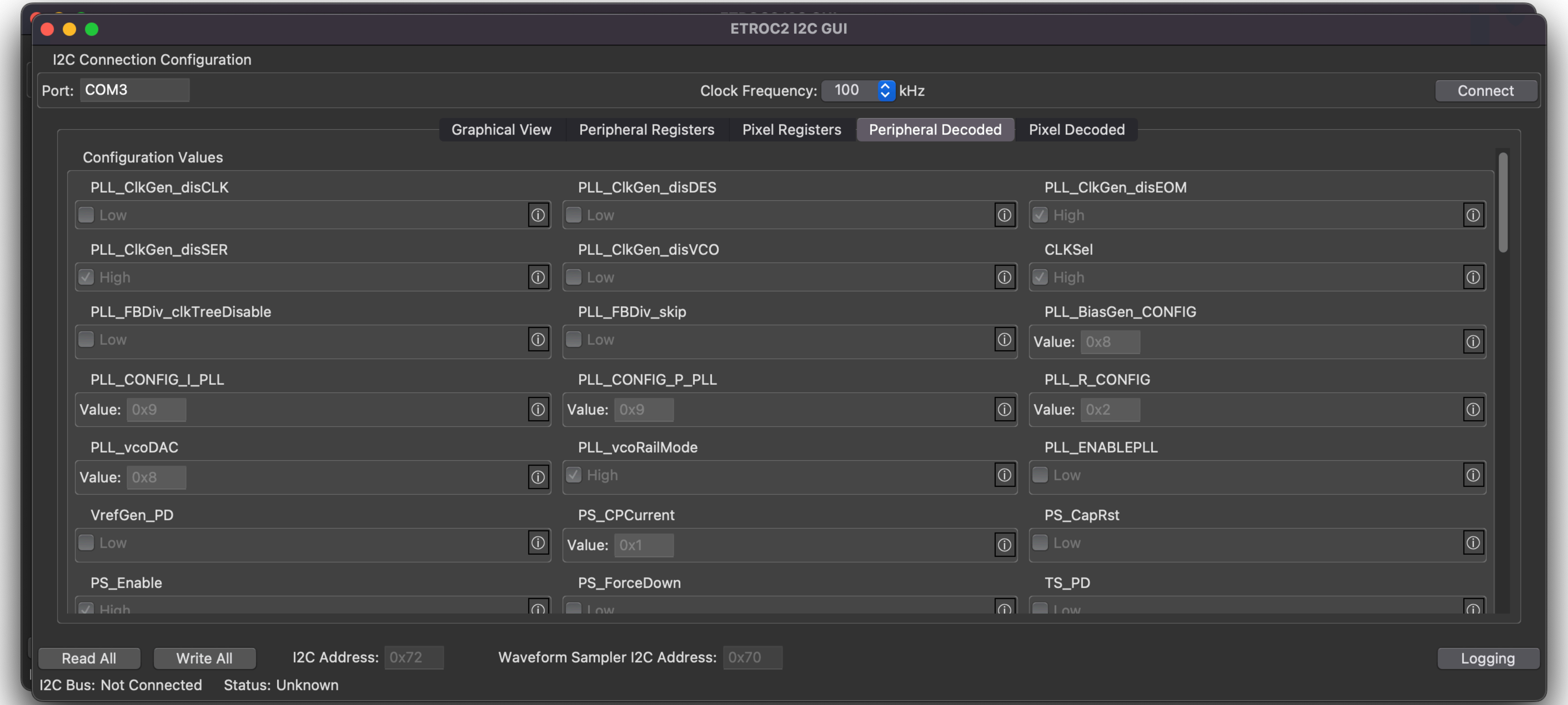
ETROC

ETROC Activities

- Collaborating with the Fermilab group developing ETROC
  - Developed a GUI and python library to configure any chip over I2C, specifically ETROC chips (ETROC1, ETROC Emulator, ETROC2)
  - Contributing to ETROC Operations: the DAQ and software development necessary for ETROC test systems (telescopes and test benches)
  - Participating in test beam activities, TID campaigns and others
  - ETROC integration with AIDA Telescope system - EUDAQ: Scheduled for next week

ETROC GUI

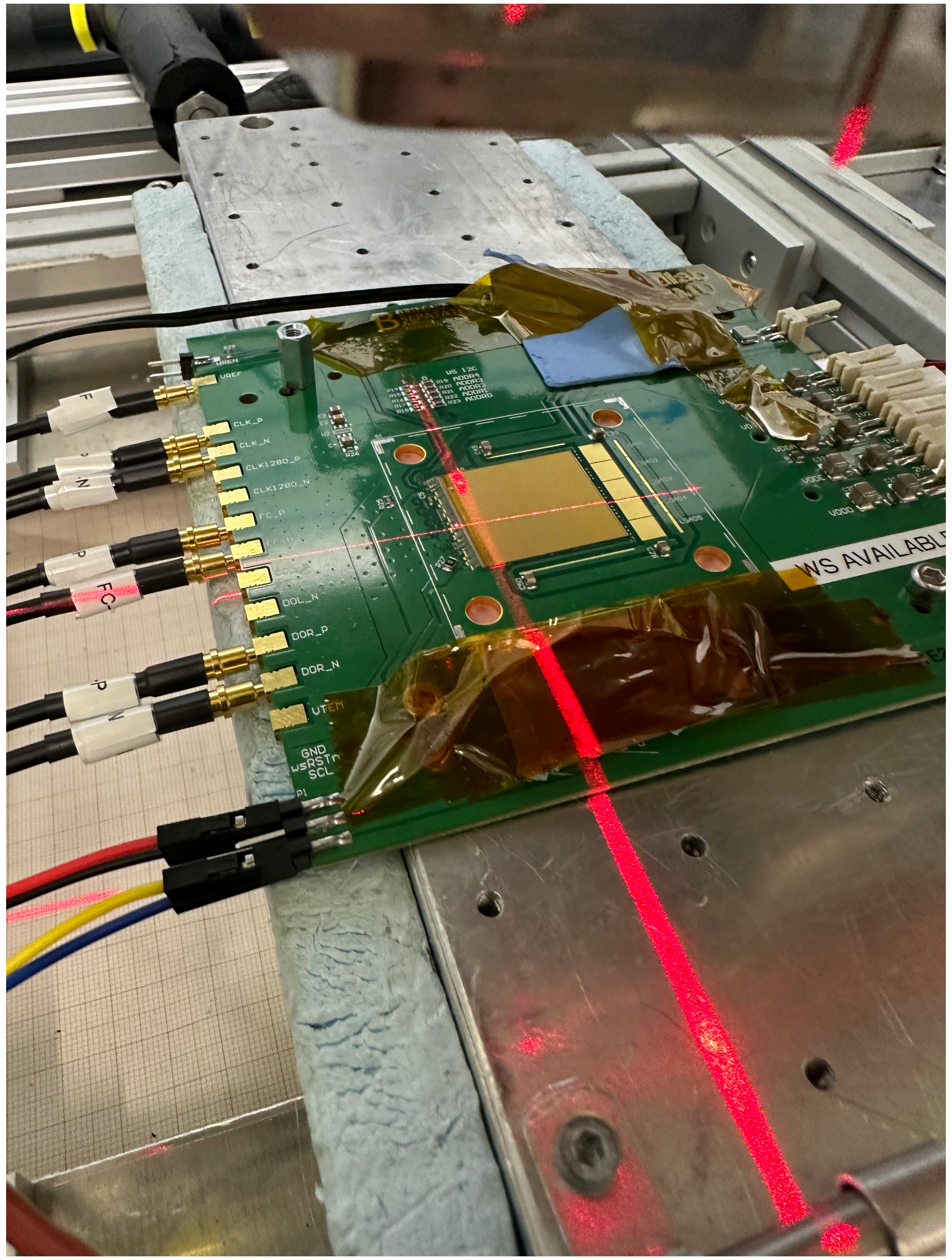
- GUI is able to communicate with any chip over I2C, with minor configuration required for other chip types



ETROC Irradiation

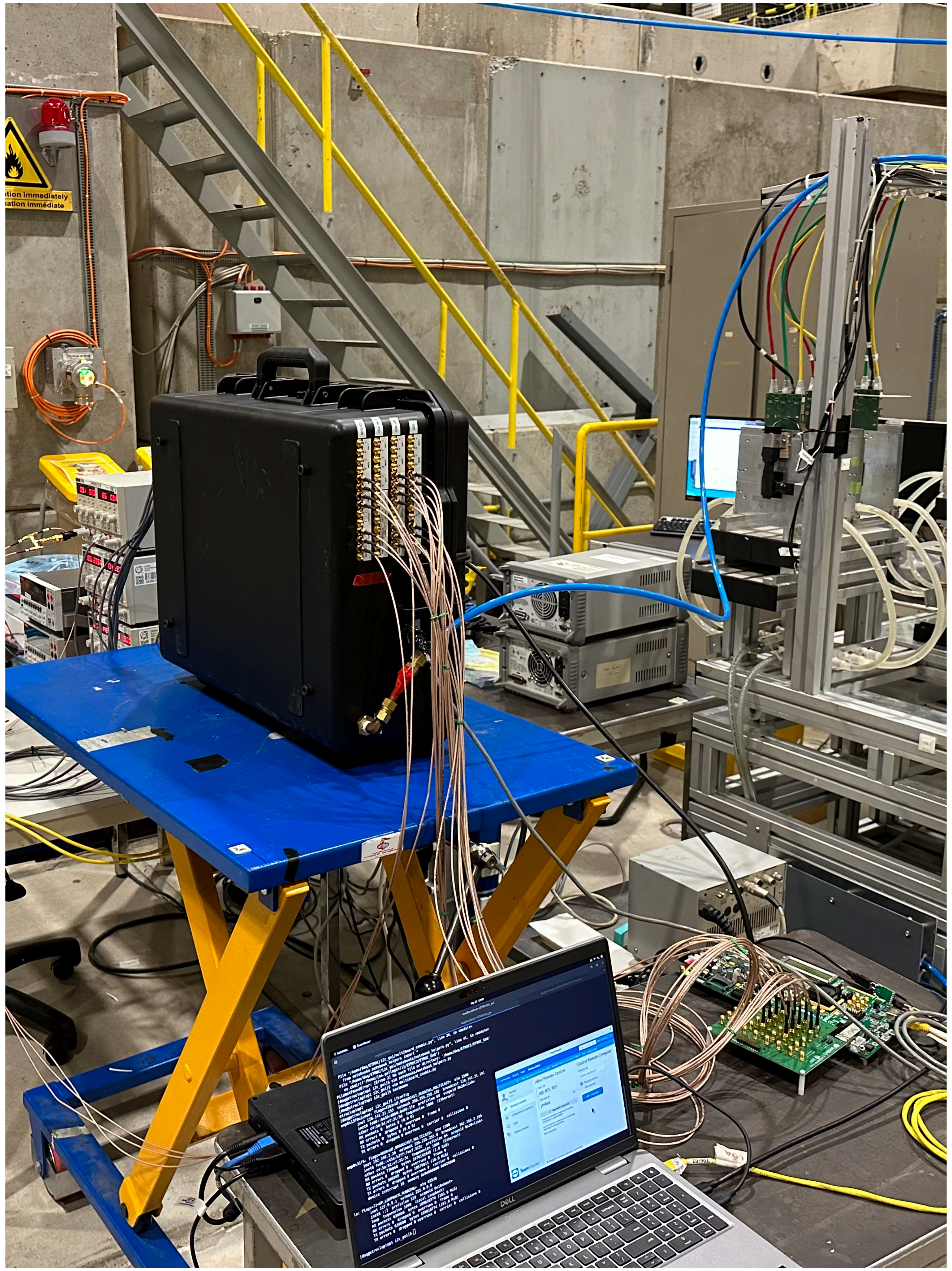
- Irradiated ETROC2 with X-Rays (ionizing radiation) at 4.1 MRad/h @ CERN

- Irradiation profile was non-uniform, one edge of the chip was irradiated and the remaining part received no irradiation, i.e. a highly non-uniform irradiation profile



ETROC Testbeam@CERN

- Testbeam performed at H6
- Telescope of 3 ETROC2 placed in beam
- The 3 ETROC were connected to an LGAD (2 bump bonded, 1 wire bonded) → Full system test
- Readout performed through FPGA and then to a computer
- Preliminary analysis shows excellent timing precision

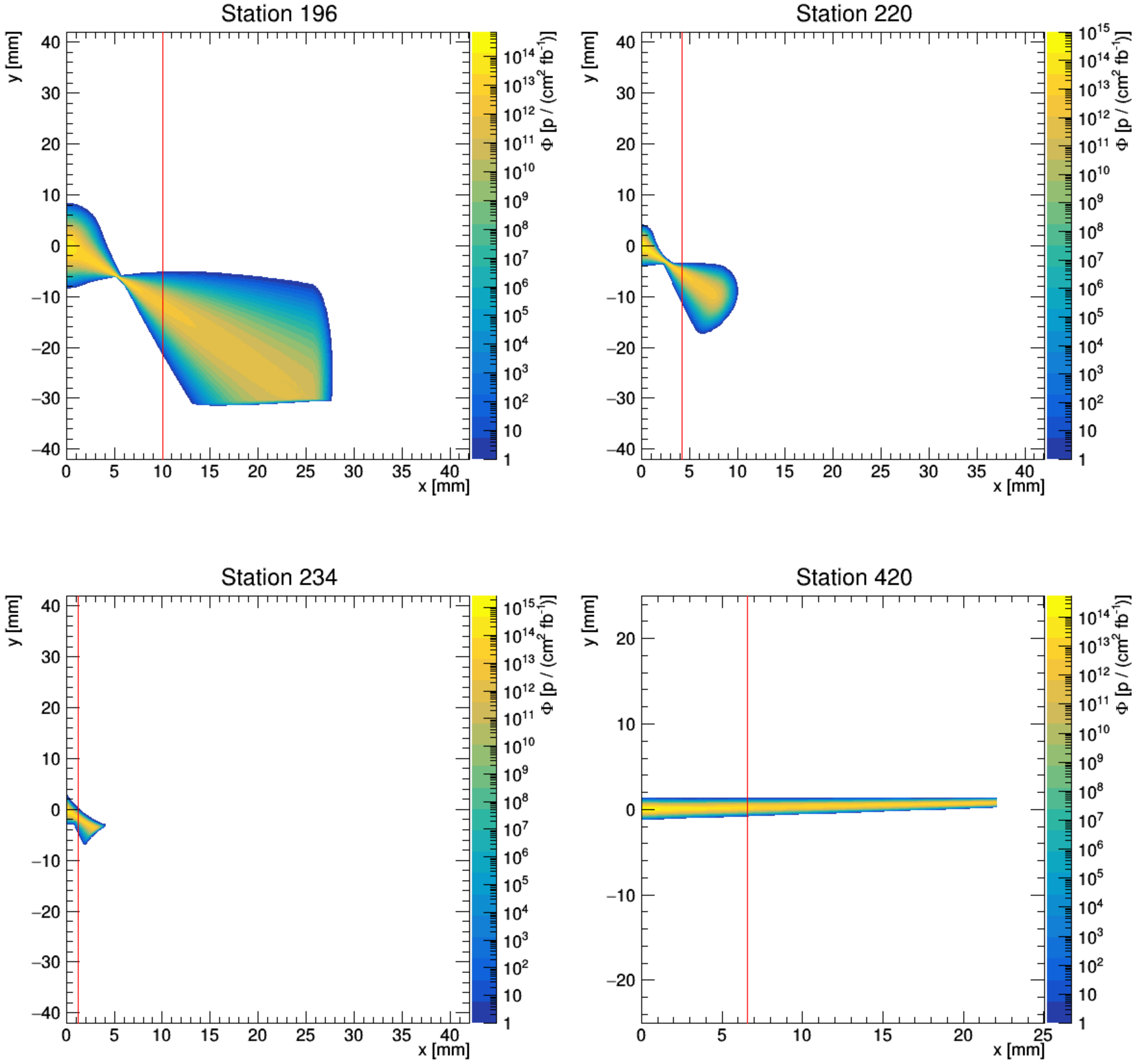


Summary and Future Plans

- PPS2 project fully approved since Fall 2023, with the goal of being ready for start of Run 4
- LGAD+ETROC is a robust and complete solution for precise timing measurement at PPS2
  - Includes sensors and readout electronics with compact and fine segmentation
- Many activities ongoing:
  - LGAD studies for PPS2
  - Irradiated LGAD measurements and data analysis
  - Planning and preparing for DESY testbeam with LGAD+ETROC2
  - Commissioning 2 telescopes with ETROC bump/wire bonded to LGAD sensors
- Future plans:
  - Study interposer feasibility and technologies or other LGAD options for PPS2
  - Characterise collected charge and time resolution of non-uniformly irradiated sensors
  - Obtain and characterise TI-LGAD with uniform/non-uniform irradiation

Backup

Proton Flux per PPS Station



- Original flux map data, for all 4 stations, provided by Mario Deile; flux from diffractive processes only, no background considered

- Red line marks approximate edge of the detector

- In station 234 the proton flux is most concentrated, thus being most challenging station

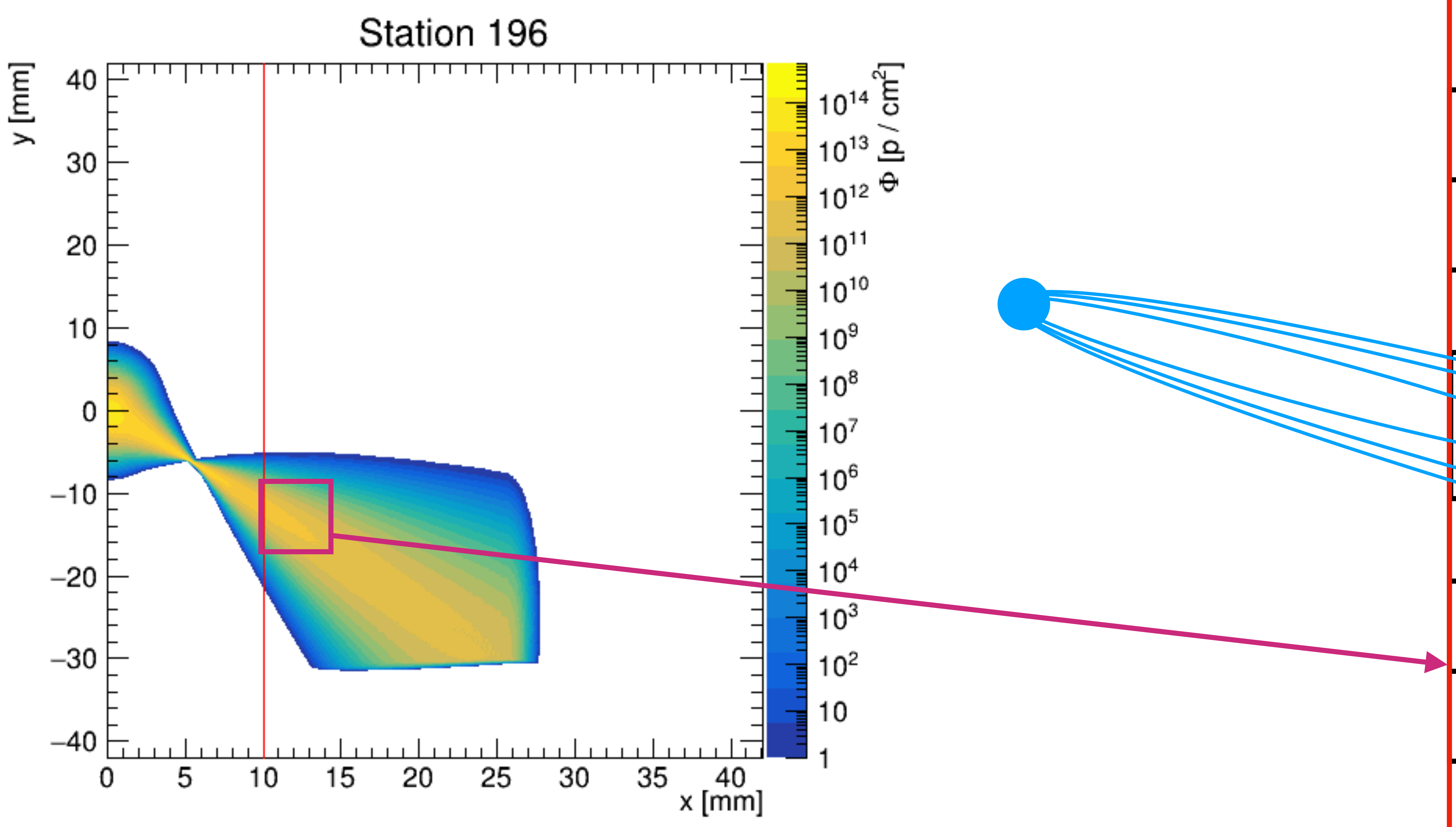
Sensor Pad Size

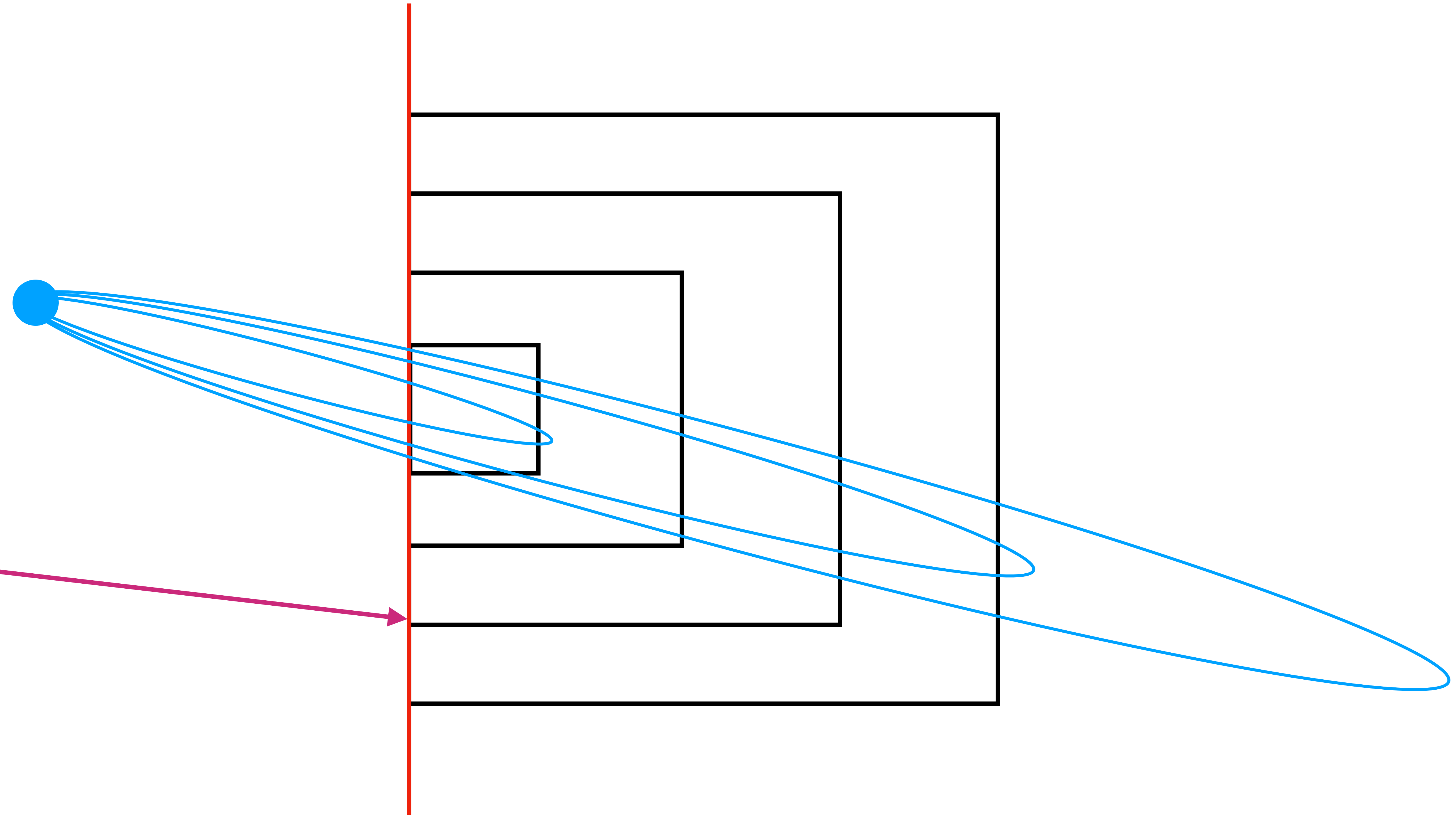
- The average expected occupancy (μ) for a single pad:
  - Particle fluence over 1 fb^{-1} can be converted to particle fluence for each bunch crossing with: $\Phi_{BX} = 1.6 \times 10^{-12}\, \Phi_{fb^{-1}}$
  - Center the pad at the position with maximum particle fluence on the sensor area (worst case scenario)
  - Calculate the pad occupancy in two different scenarios:
    - Assume uniform fluence over the whole pad area equal to the maximum fluence (worst case scenario):

$$\mu = \Phi_{BXmax} * A = \Phi_{BXmax} * l^2$$

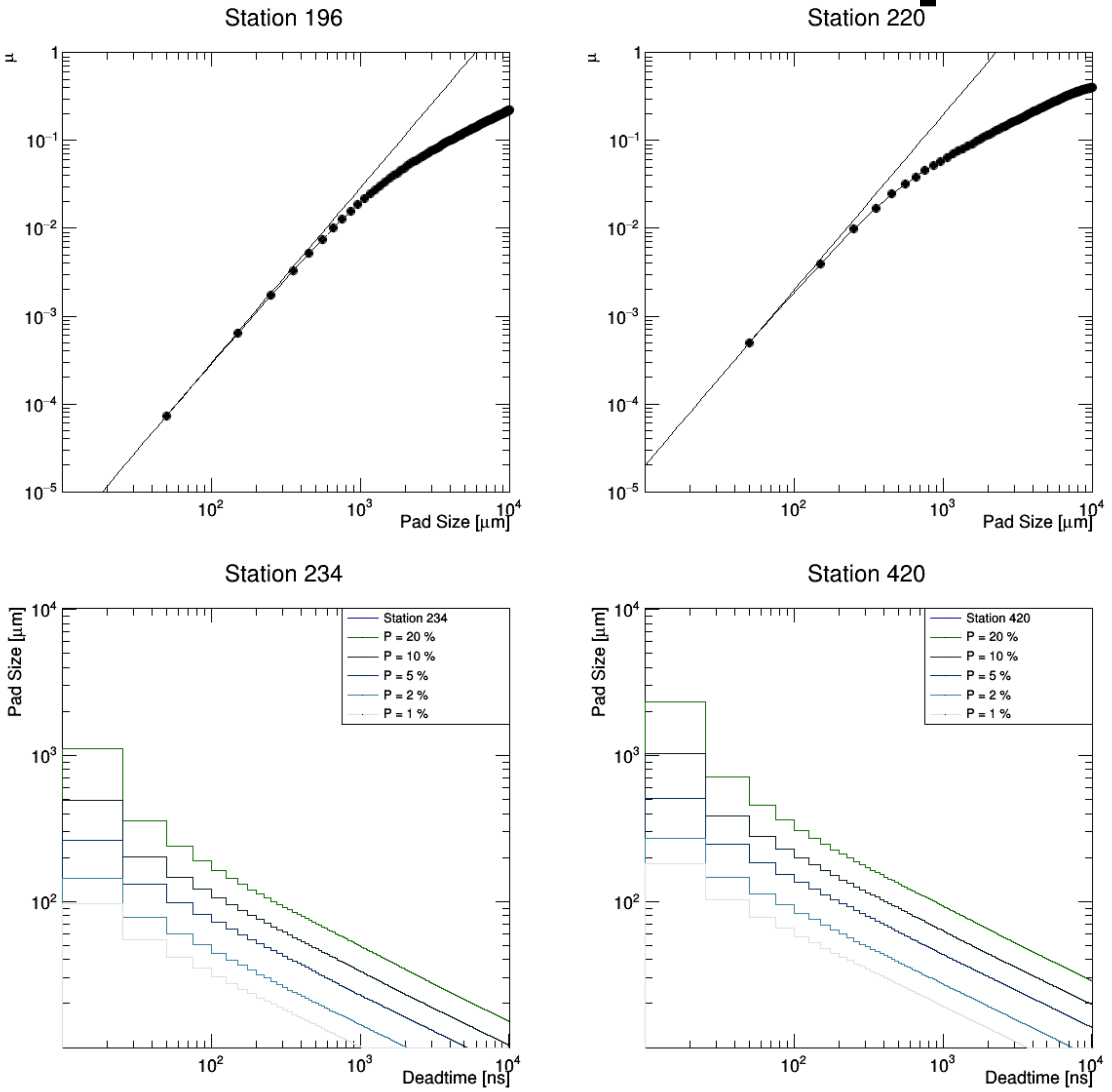
    - Integrate particle fluence map over the pad area: $\mu = \int_{x_{edge}}^{x_{edge}+l} dx \int_{-\frac{l}{2}}^{\frac{l}{2}} dy\, \Phi(x, y)$

Sensor Pad Position



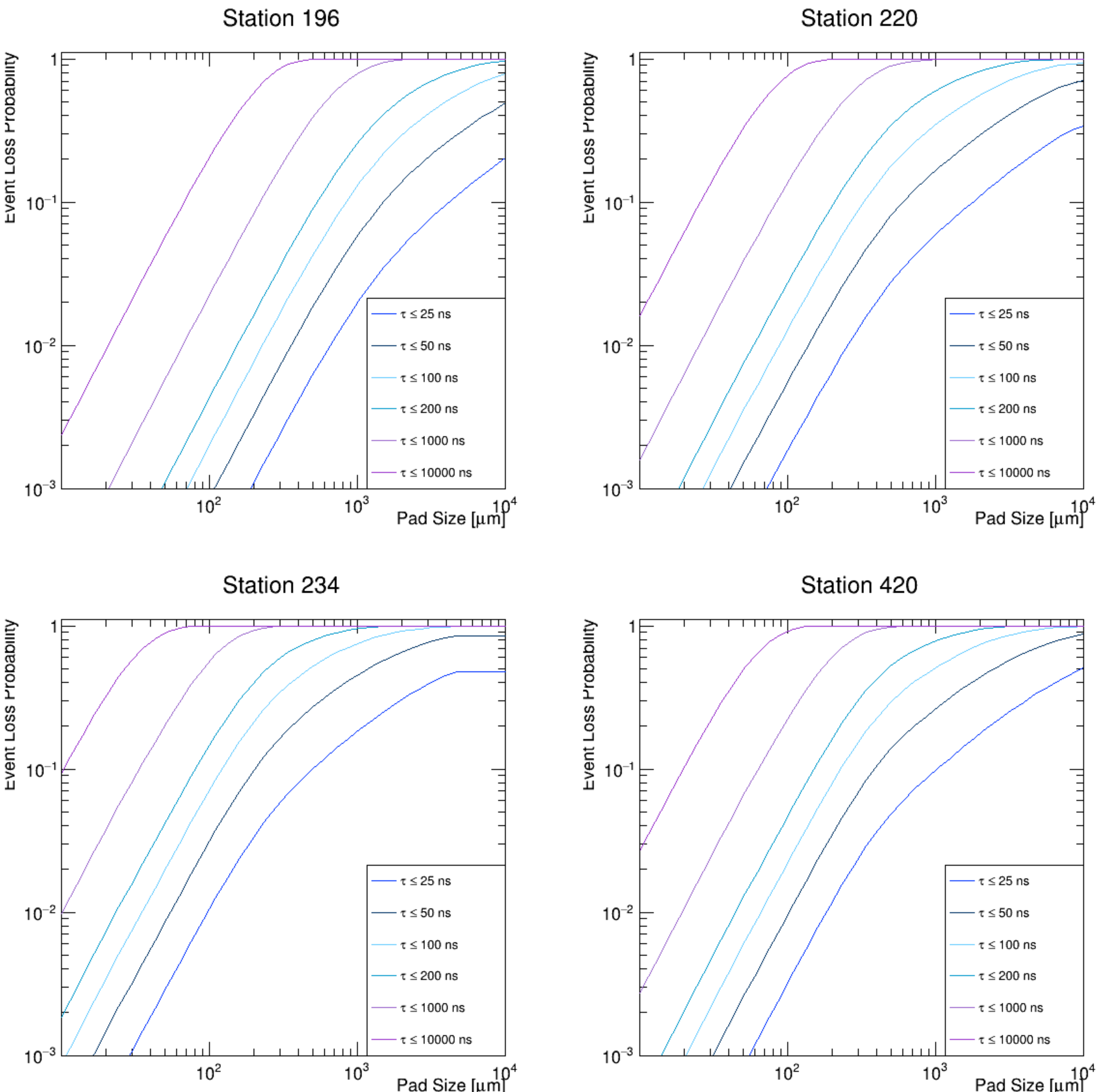


Pad Occupancy vs Pad Size



- Straight line assumes constant flux equal to the maximum flux on the detector surface
- Dots integrate the flux map for a square pad with the edge centered on the maximum, i.e. valid for the first column of pads in the sensor
- If the detector event loss probability is to be kept below 5%, the pad size must be smaller than ~300 μm (dominated by station 234)

PPS Required LGAD Pad Size



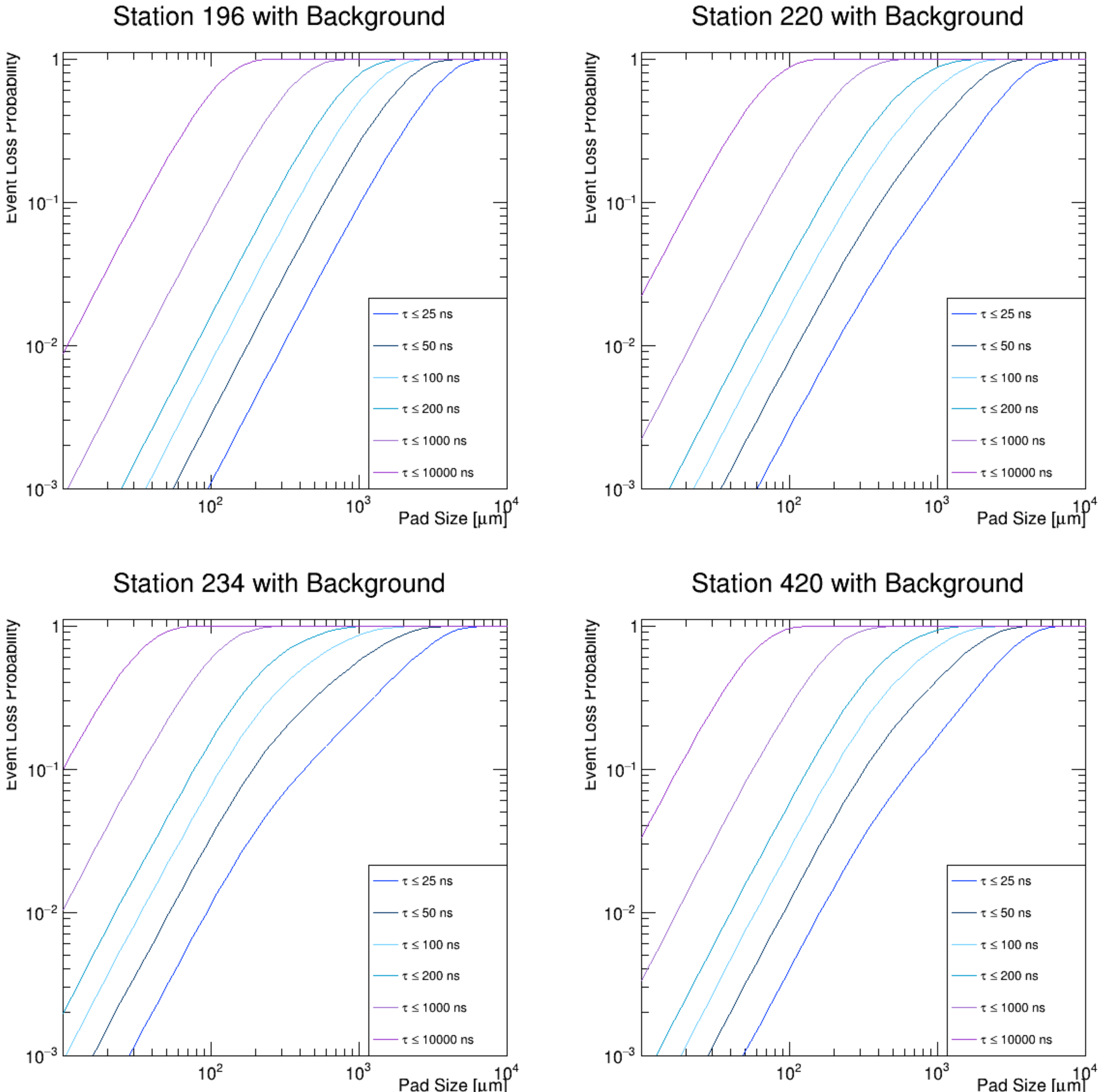
- Pad occupancy, detector deadtime and event loss probability are related:

$$P(\geq 1\,\text{extra p within}\,\tau) = 1 - \frac{\mu^2}{\left(1 - e^{-\mu}\right)^2} e^{-2\mu\left[\text{int}\left(\frac{\tau}{\Delta t}\right)+1\right]}$$

- For a detector deadtime below 25 ns, the standard ETL pad size (1.3 mm) gives a large event loss probability, particularly for station 234

- Reducing the pad size is fundamental in order to efficiently take data, at least for the first pad column

PPS Required LGAD Pad Size



- Adding the 2017 background, affects the prediction

Peak Dose

- Peak PPS2 dose (assuming diffractive flux maps) over 1 year of HL-LHC exceeds LGAD radiation tolerance (~2E15 neq ≅ 4E15 p/cm^2):
  - Station 196: 5.47E14 p/cm^2
  - Station 220: 3.72E15 p/cm^2
  - Station 234: 2.29E16 p/cm^2
  - Station 420: 6.35E15 p/cm^2
- Shift sensor vertically throughout the year to mitigate radiation damage

Radiation Damage Mitigation

- LGAD sensors can withstand maximum flux:
  - ~2×10^{15} neq/cm^2 ≅ 4×10^{15} p/cm^2

- The 234 and 420 stations will exceed this value in less than one year of HL-LHC (300 fb^{-1}), the 220 station is close and may exceed when accounting background flux

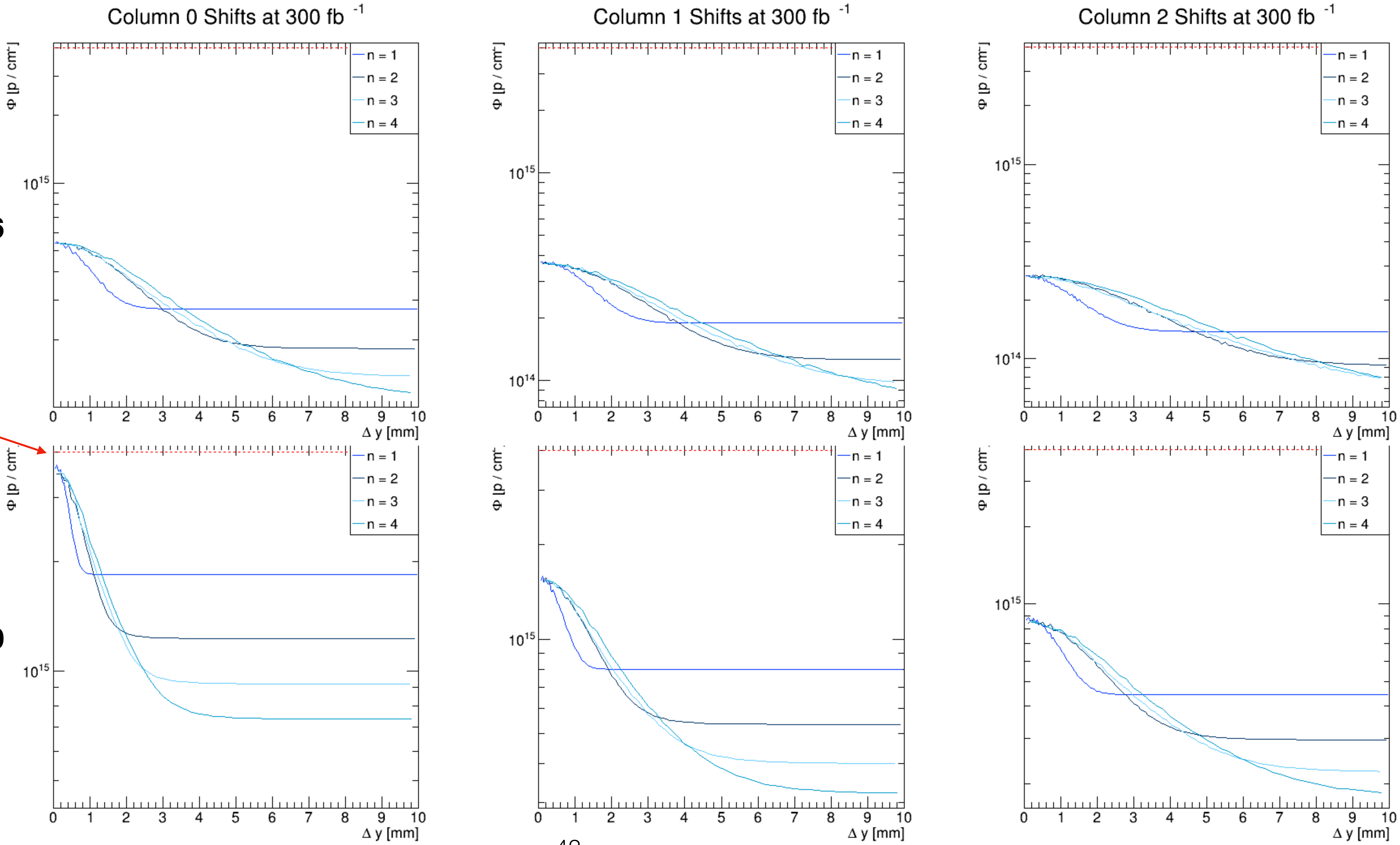
- The sensors need to be shifted periodically throughout the year to spread the peak flux and mitigate the damage effects

Sensor Shifts

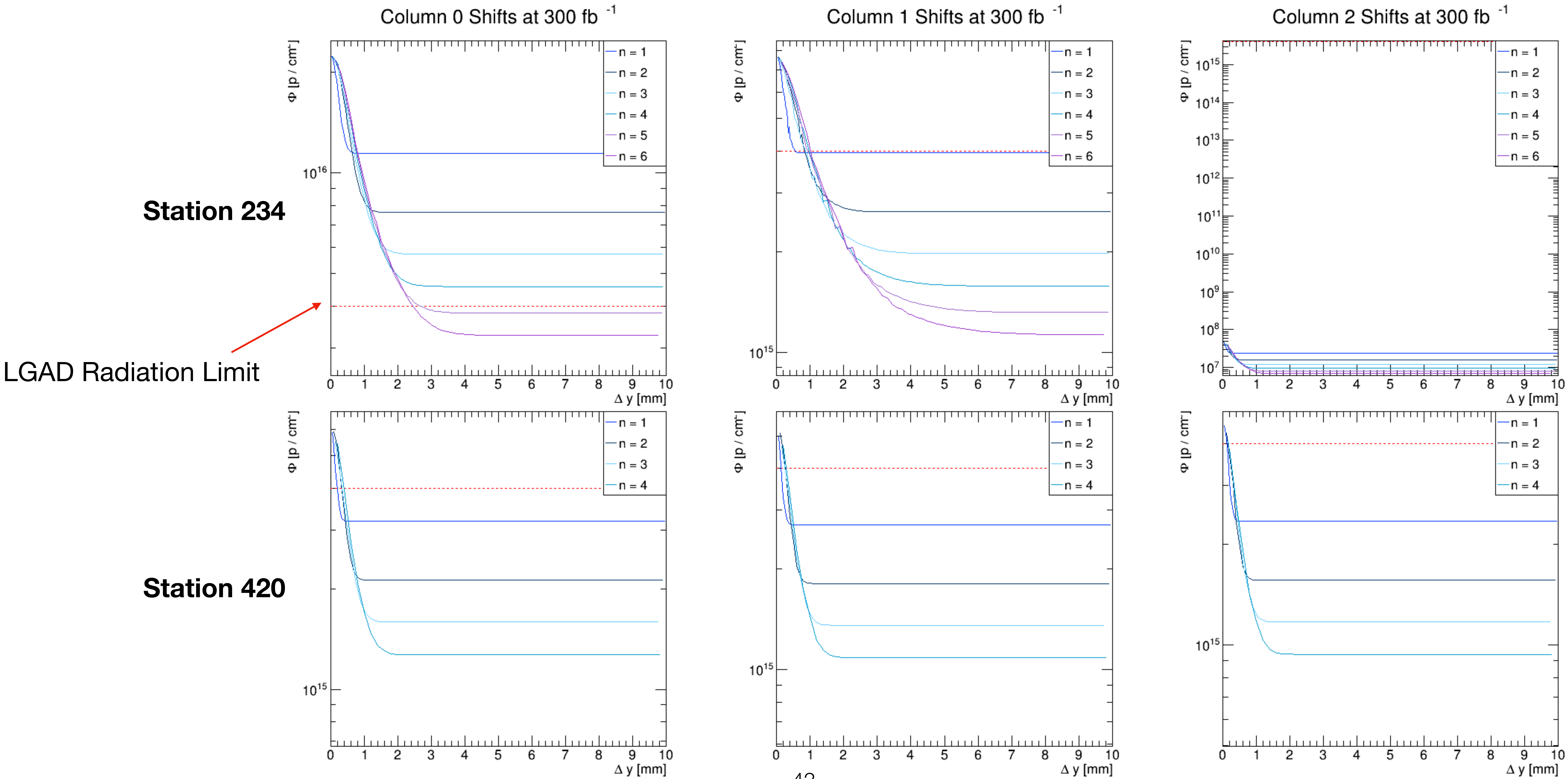
Station 196

LGAD Radiation Limit

Station 220



Sensor Shifts

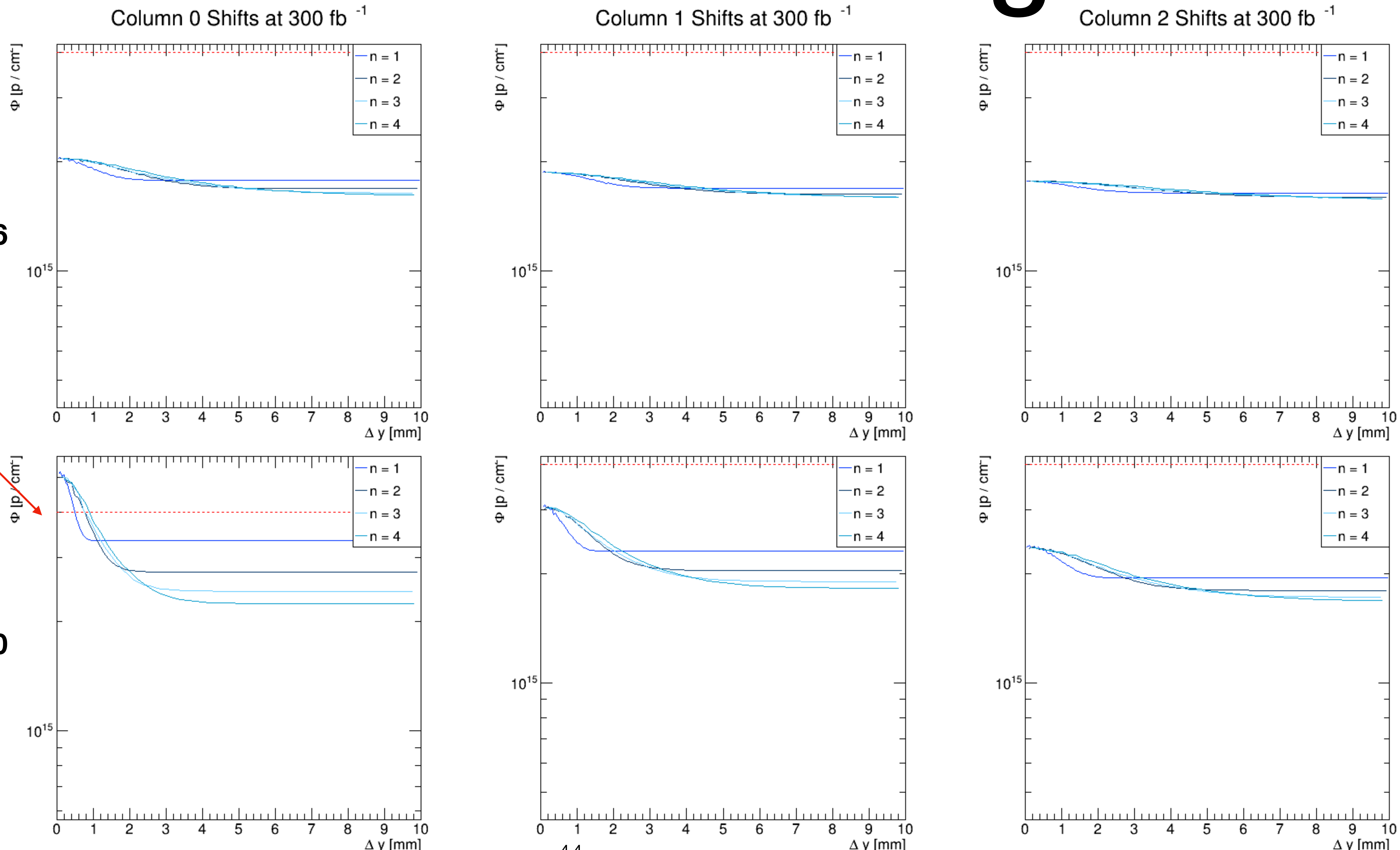


Sensor Shifts with Background

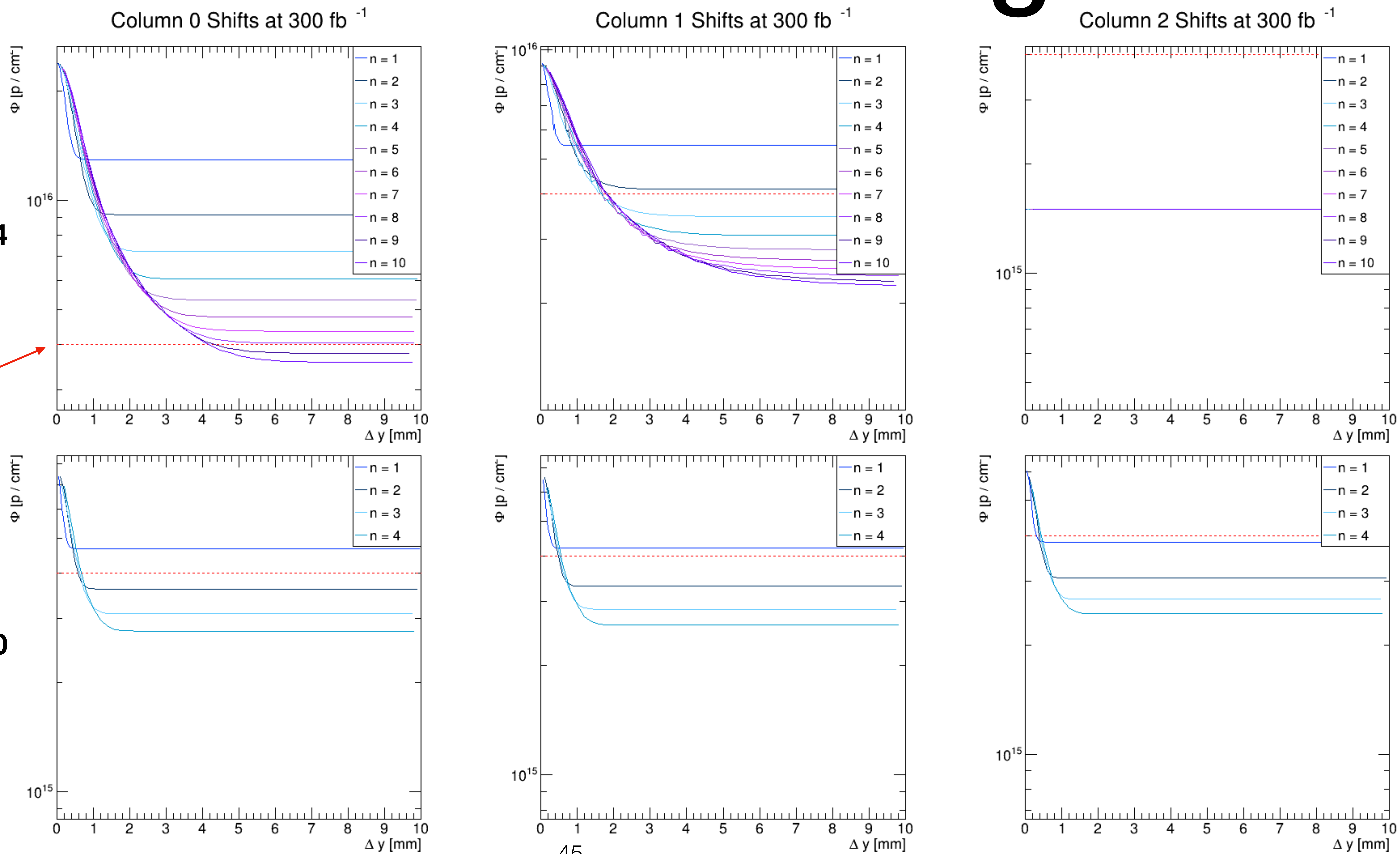
Station 196

LGAD Radiation Limit

Station 220



Sensor Shifts with Background



Station 234

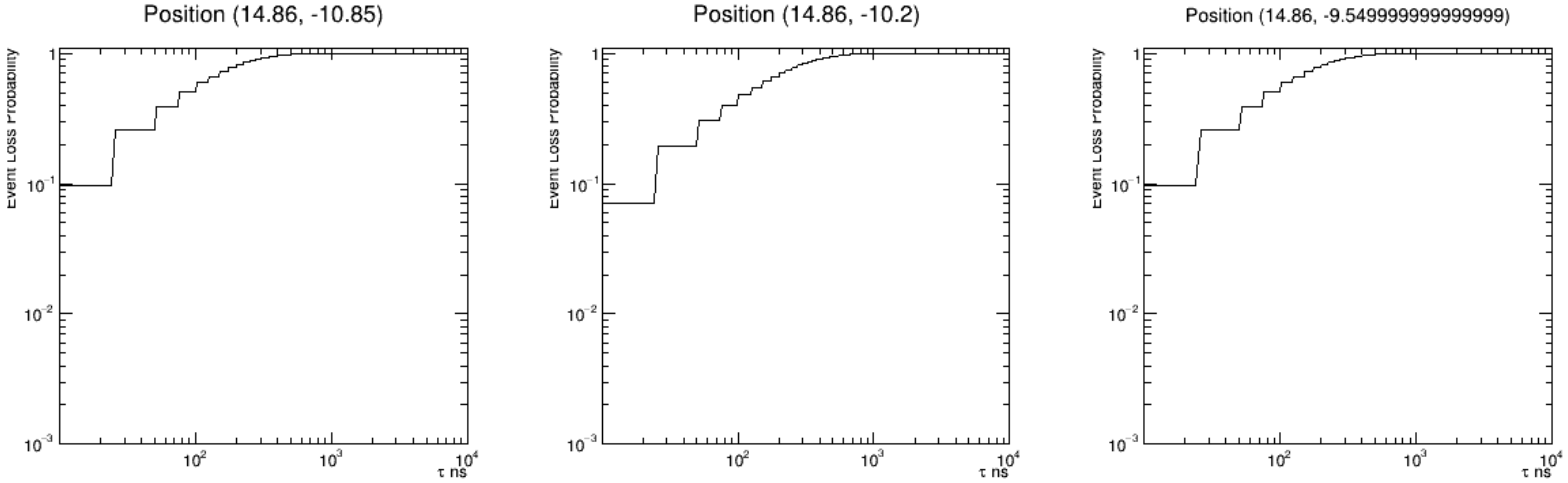
LGAD Radiation Limit

Station 420

Realistic Event Loss Probability

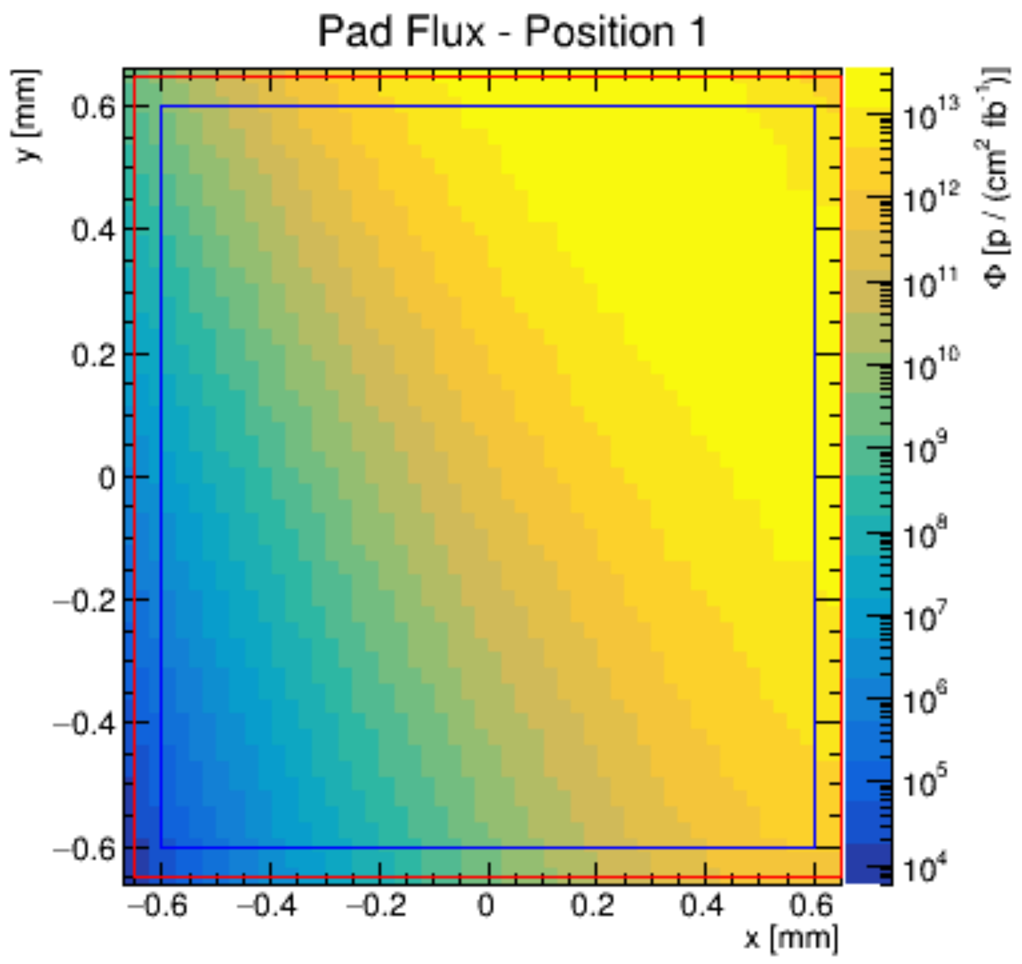
- Simulate realistic sensor in the different shift positions throughout the year
- Event loss probability depends on the sensor position, due to the 'blind' areas in the interpad spaces, less noticeable for TI-LGAD

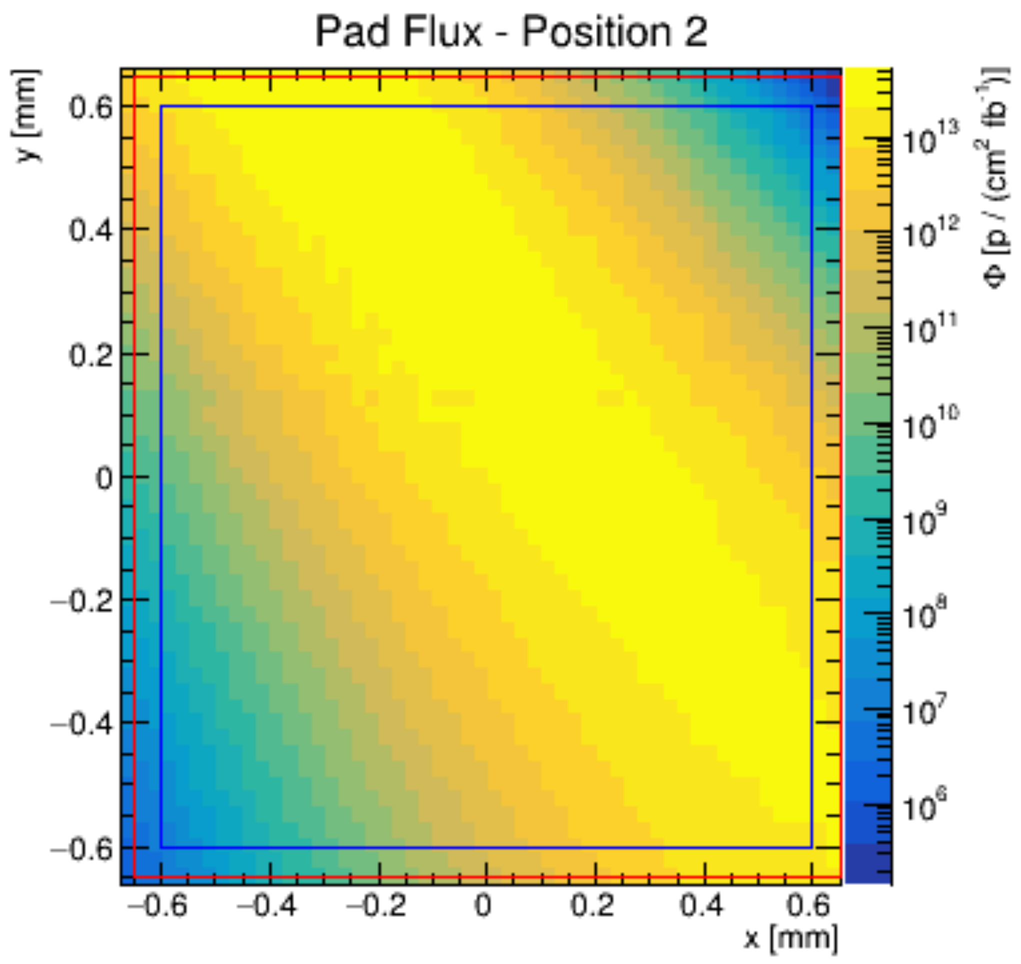
ETL-Like Sensor
Standard LGAD
220 Station
2 Shifts - 3 Positions
Shifts by 1.3/2

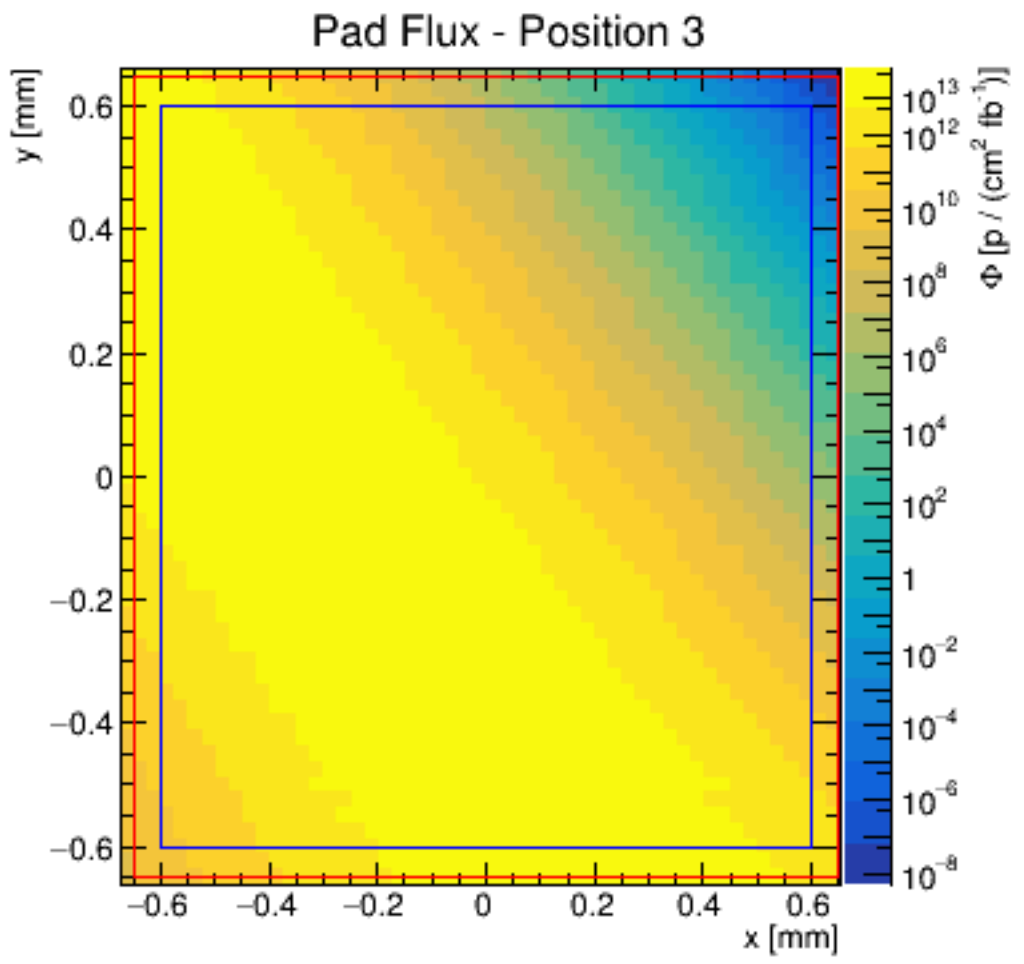


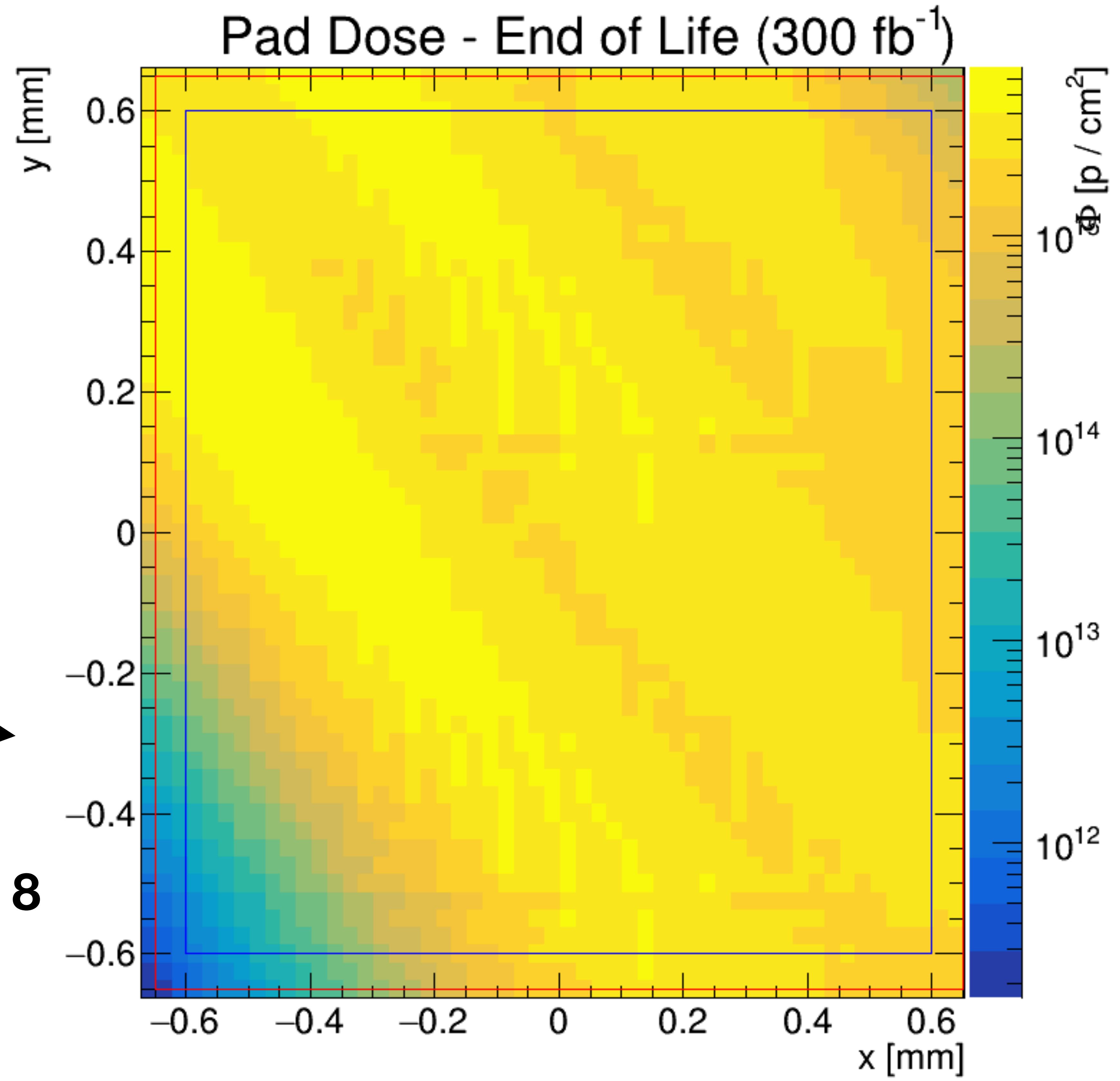
Pad Flux Maps

- The flux of every pad in each position is calculated and can be merged to get the pad dose at the end of a year of HL-LHC







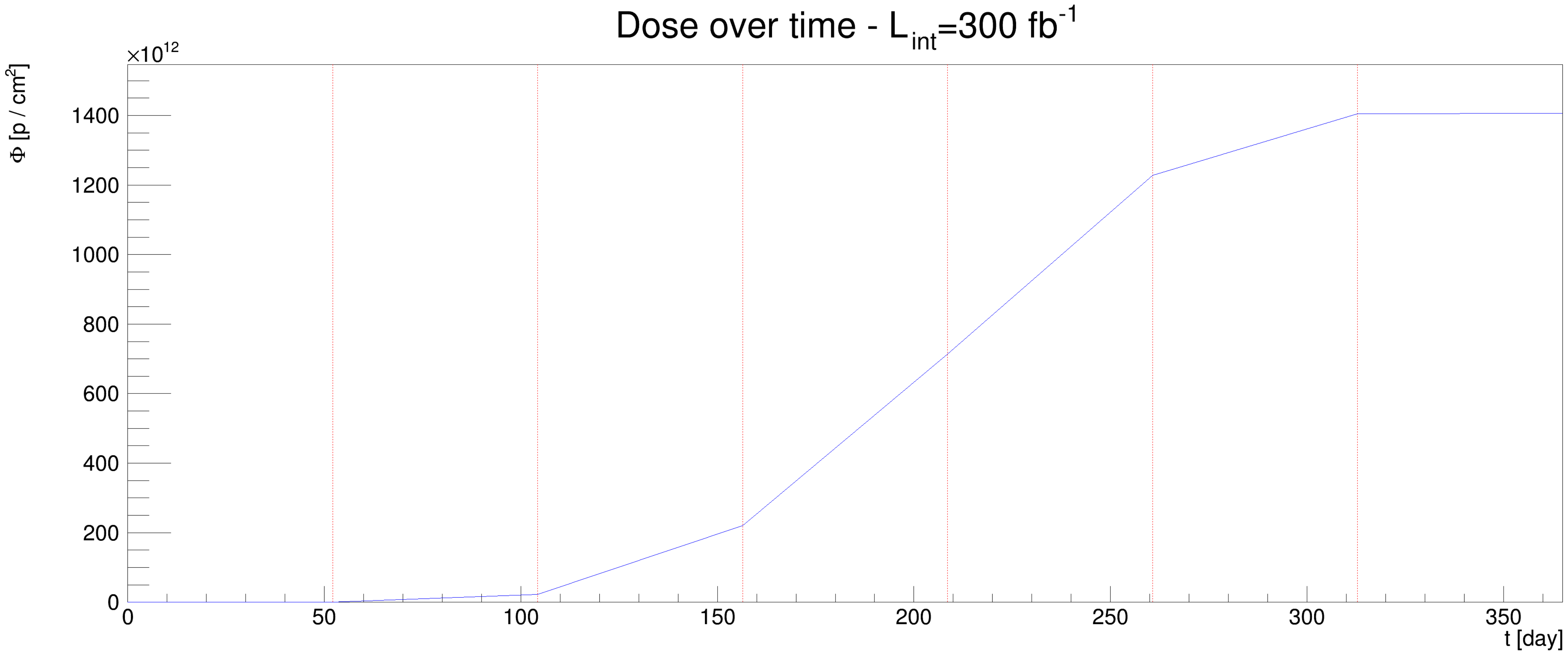


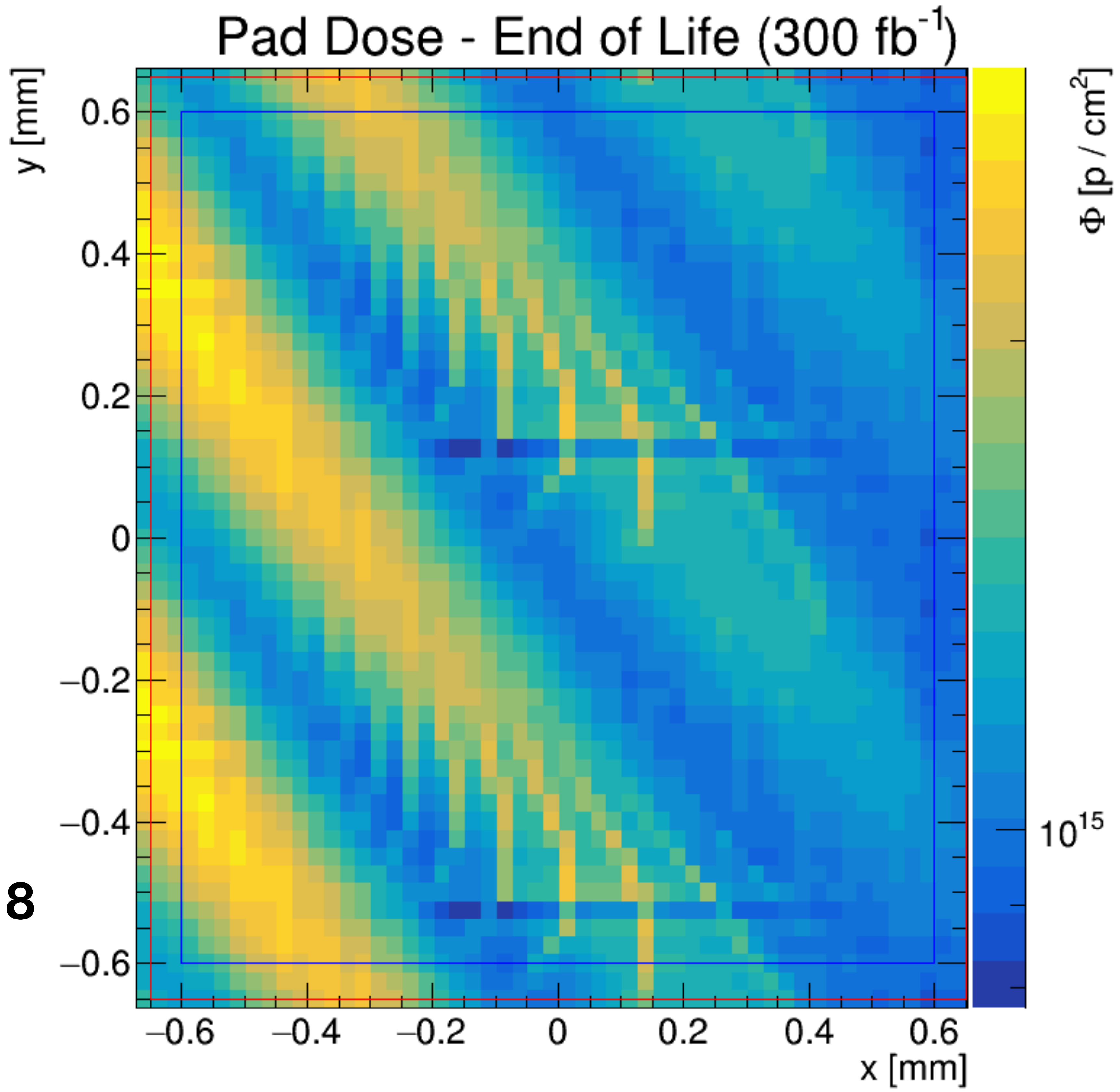
Pad 8

ETL-Like Sensor
Standard LGAD
234 Station
2 Shifts - 3 Positions
Shifts by 1.3/2

Pad Flux Maps

- Pad dose over time is also calculated



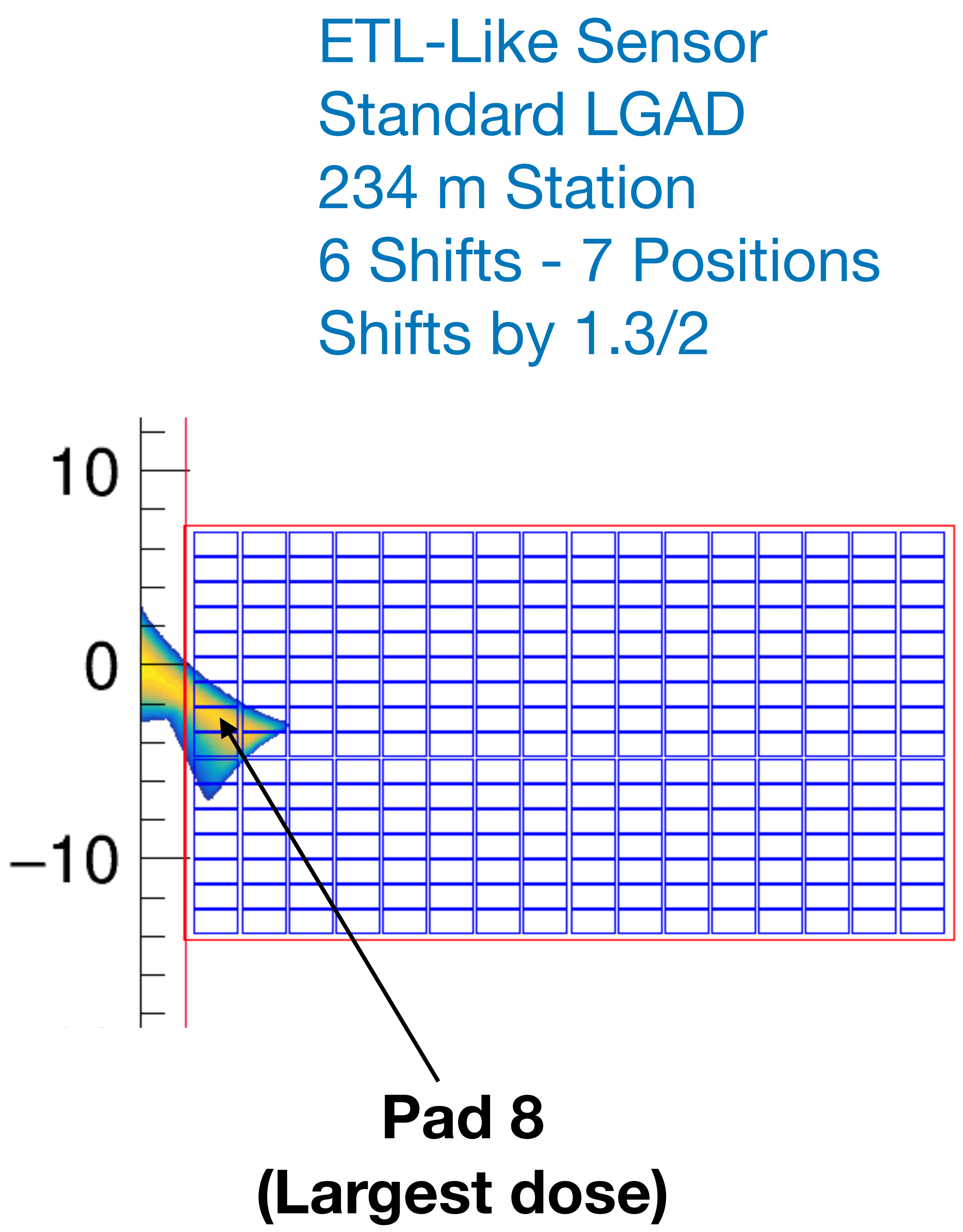


ETL-Like Sensor
Standard LGAD
234 Station
6 Shifts - 7 Positions
Shifts by 1.3/2

Pad 8

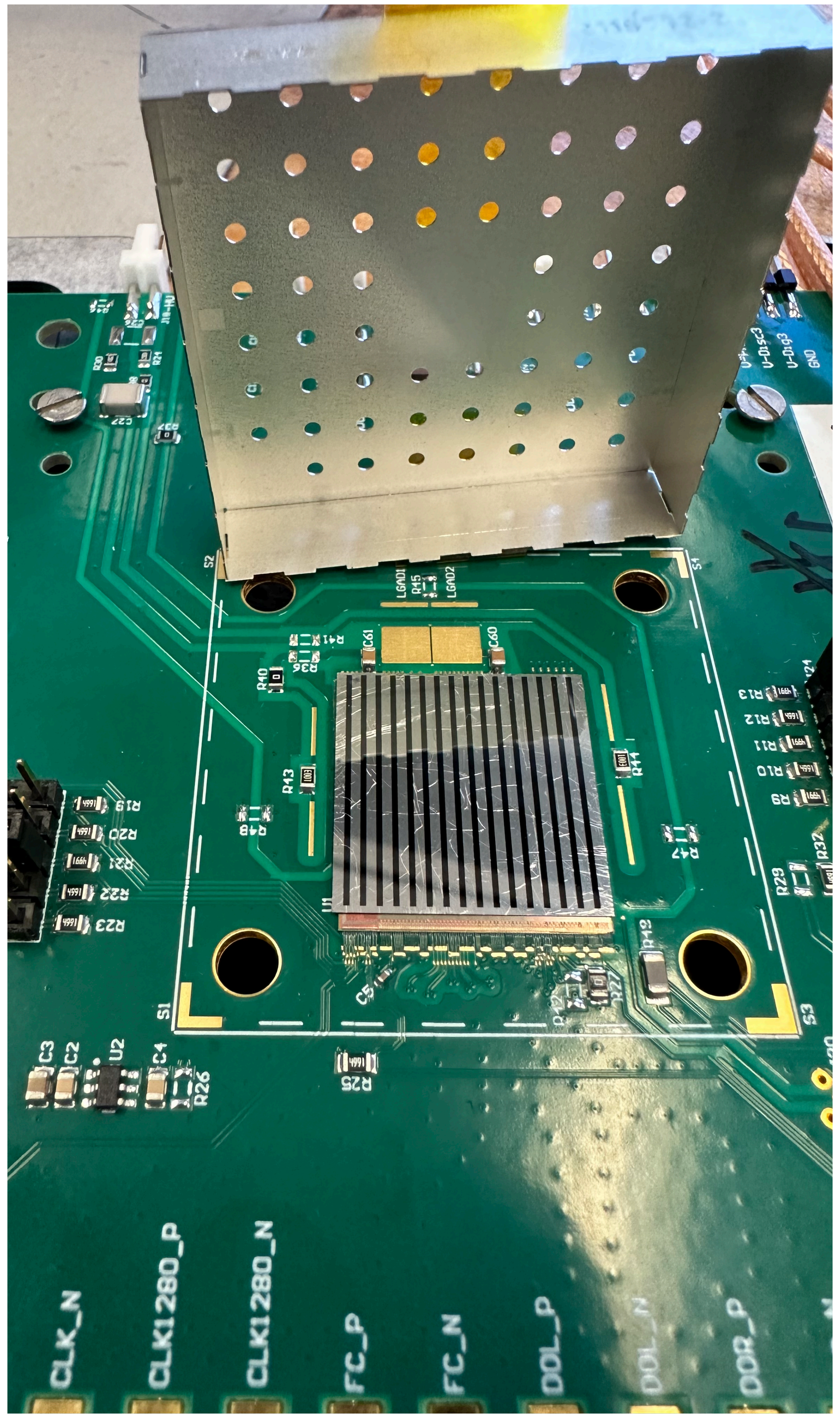
LGAD Operation Voltage

- Absolute maximum voltage (burn-out): 688 V (12.5 V/µm @ 55 µm)
- Consider flux map in pad 8 and estimate minimum bias voltage to obtain 8 fC and breakdown bias voltage, for different integrated luminosities:
  - 100 fb-1: 338-436 V (295-376 V without background)
  - 200 fb-1: 483-537 V (382-407 V without background)
  - 300 fb-1: 656-650 V (481-439 V without background)
    - the minimum voltage is above the breakdown voltage, only slightly, so the most irradiated region of the pad will be inefficient
- The analysis above not yet extended to full sensor



Based on data from the ETL LGAD Market Survey kindly shared by Roberta Arcidiacono

ETROC Power & PPS2 Considerations



- ETROC2 Power consumption:
  - ETROC2 Measurements:
    - Typical chips: 581 mW (low power); 738 mW (high power)
    - Corner chips: 779 mW (low power); 980 mW (high power)
  - Assume 20% variation for safety envelope
  - Consumption varies with irradiated dose
- LGAD also consumes some power in high rate conditions: 50 mW (current estimated maximum, assuming 500 V and 100μA)
- **LGAD + ETROC2 estimated maximum power (per pair): 1.226 W**
- 10 LGAD+ETROC layers per PPS2 station can provide O(15 ps) time resolution
  - For 220 and 234 Station: 5 Layers per RP (1 sensor each layer)
  - For 196 Station: 5 Layers per RP (2 sensors each layer)
  - 80 Sensors per year