The CMS MTD Endcap Timing Layer: Precision Timing with Low Gain Avalanche Diode Sensors

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on behalf of the CMS ETL group

22nd Particles and Nuclei International Conference

Outlook

★ *Precision timing at High-Luminosity LHC*

★ *The CMS MIP Timing Detector*

★ *The **CMS Endcap Timing Layer***

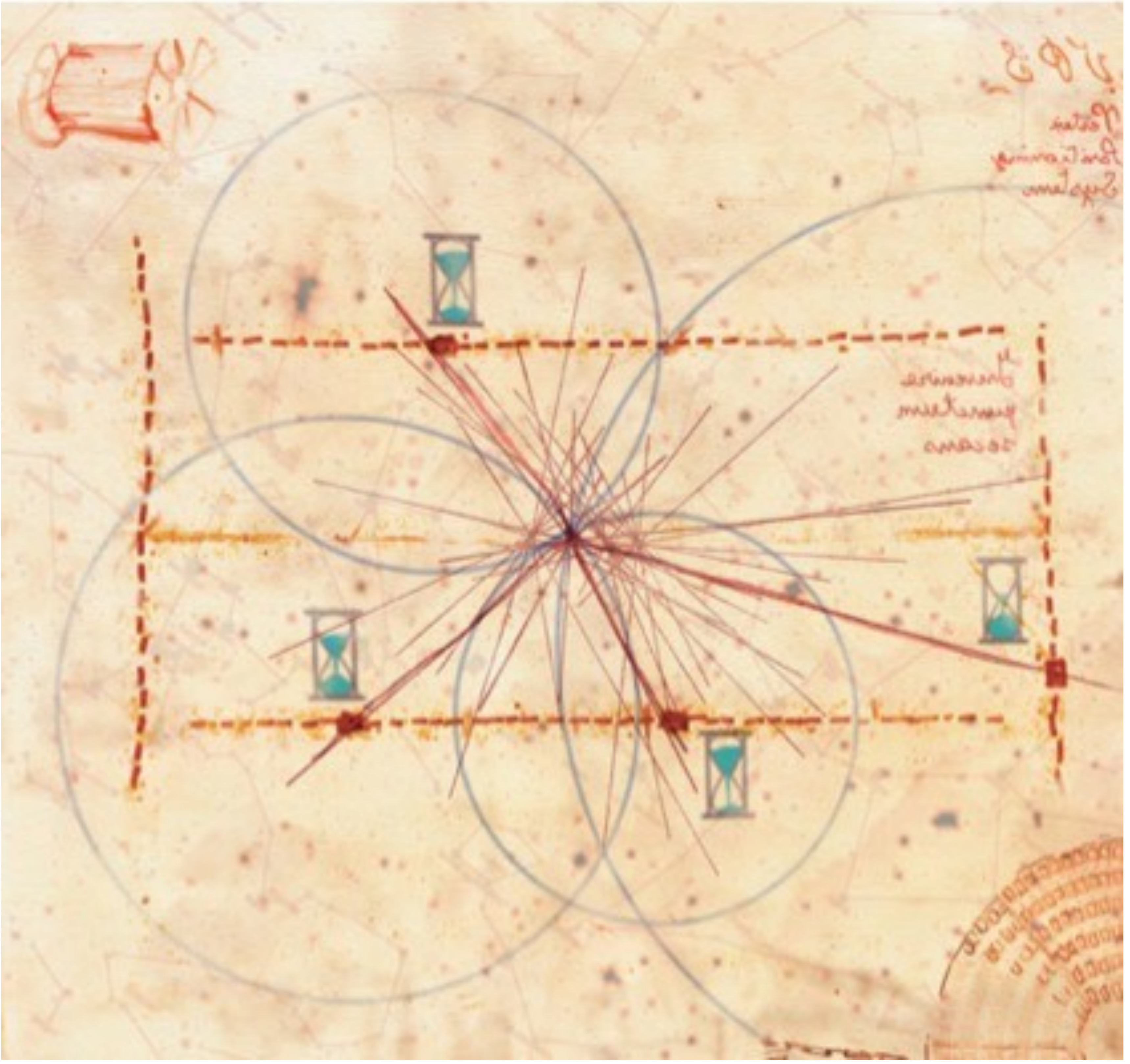
★ *The **ETL sensors***

- ✦ *Laboratory mesurements: uniformity, no-gain area, timing resolution*
- ✦ *Test beam results*

★ *The **ETL read-out ASIC***

- ✦ *ETROC0 and 1, specifications and test beam results*

★ *Conclusions*



Precision timing at High Luminosity LHC

At High Luminosity LHC instantaneous luminosity will increase of a factor ~5

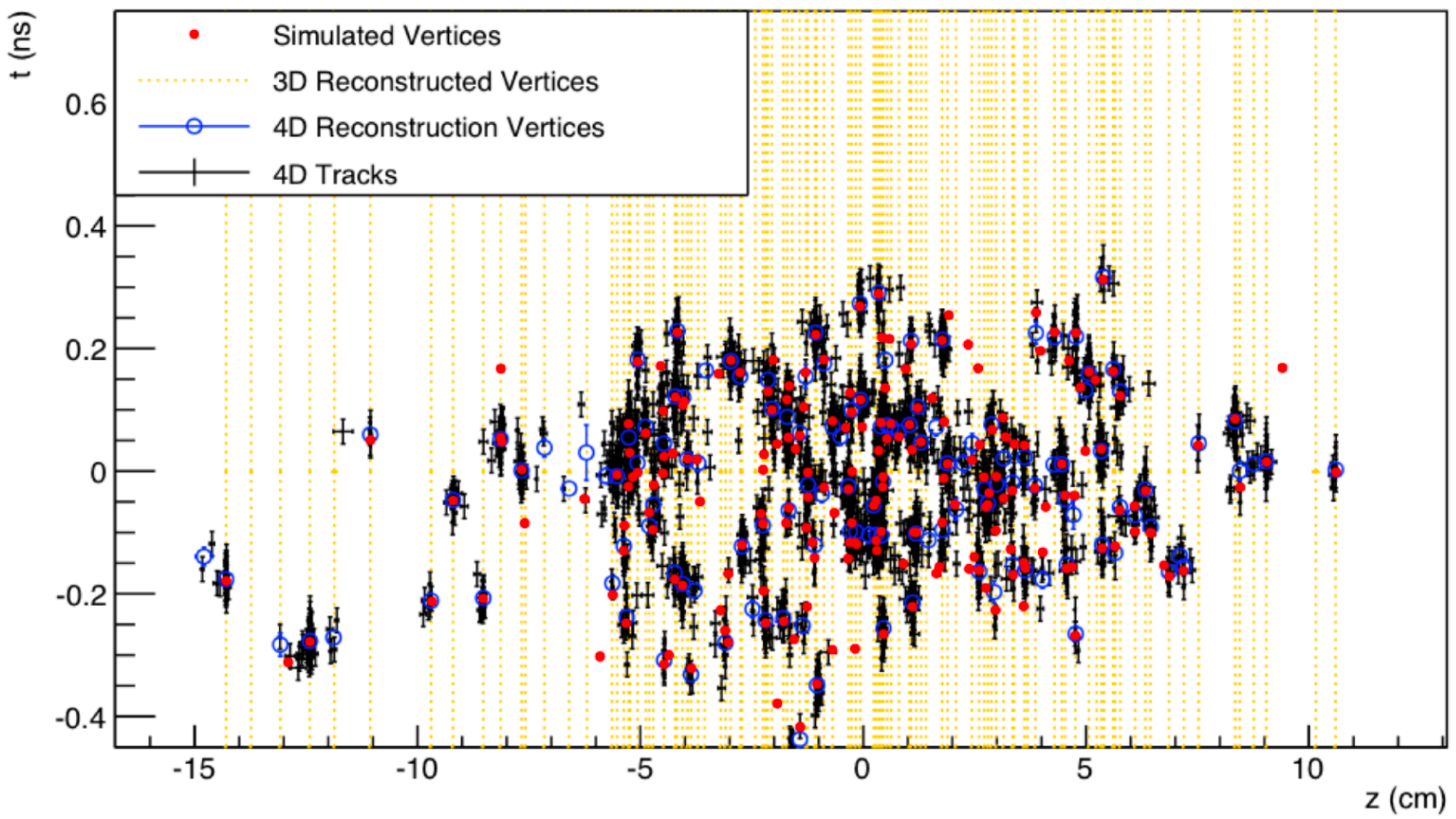
→ *140-200 proton-proton collisions in each bunch crossing*

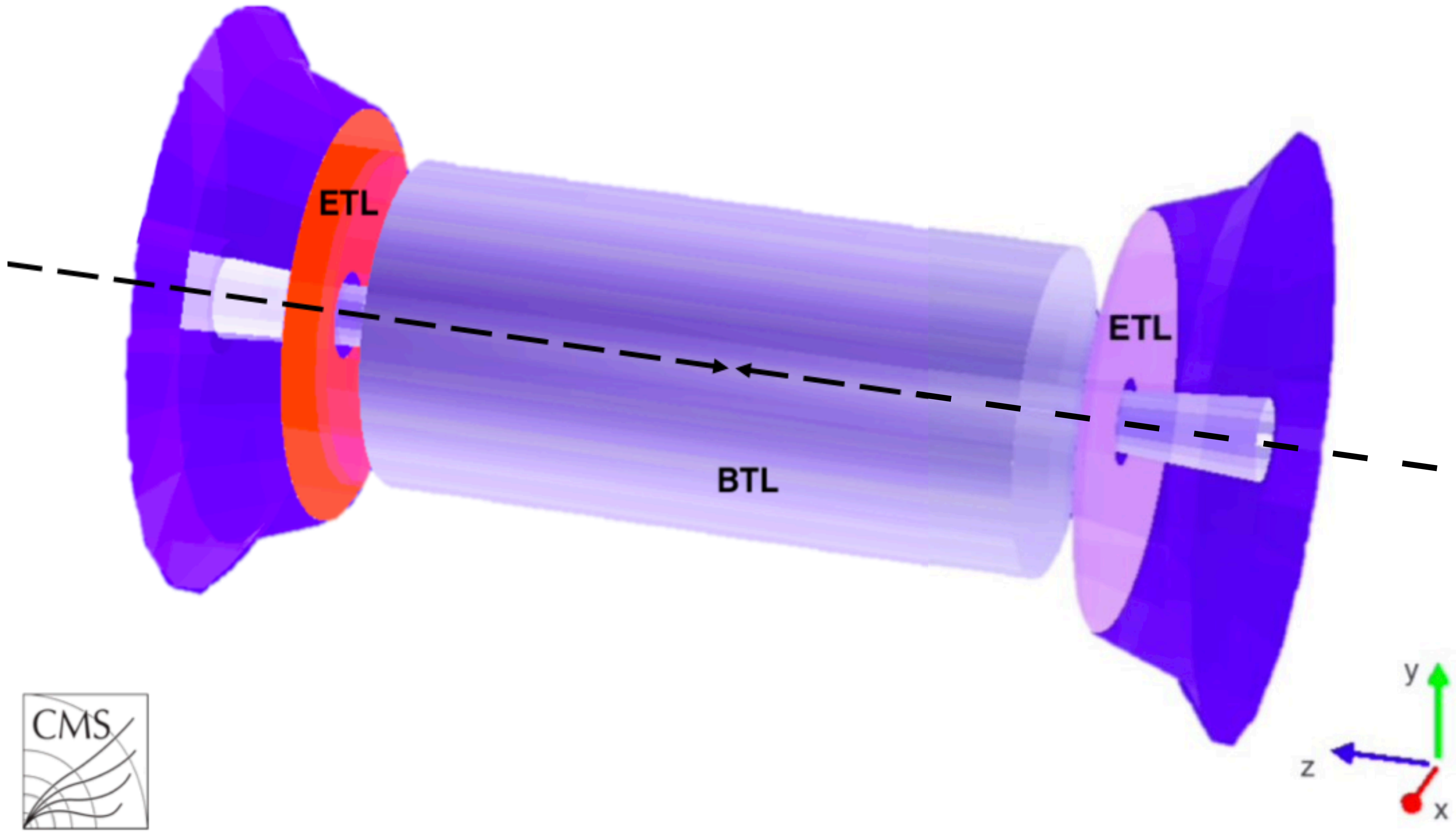
→ *difficulties in object reconstruction and particle identification due to tracks coming from nearby vertices*

Need to add timing information to separate events overlapped in space but happening at different times

→ *Creation of timing detectors providing 4D tracking*

→ *Minimum Ionizing Particle Timing Detector (MTD) for the CMS experiment*





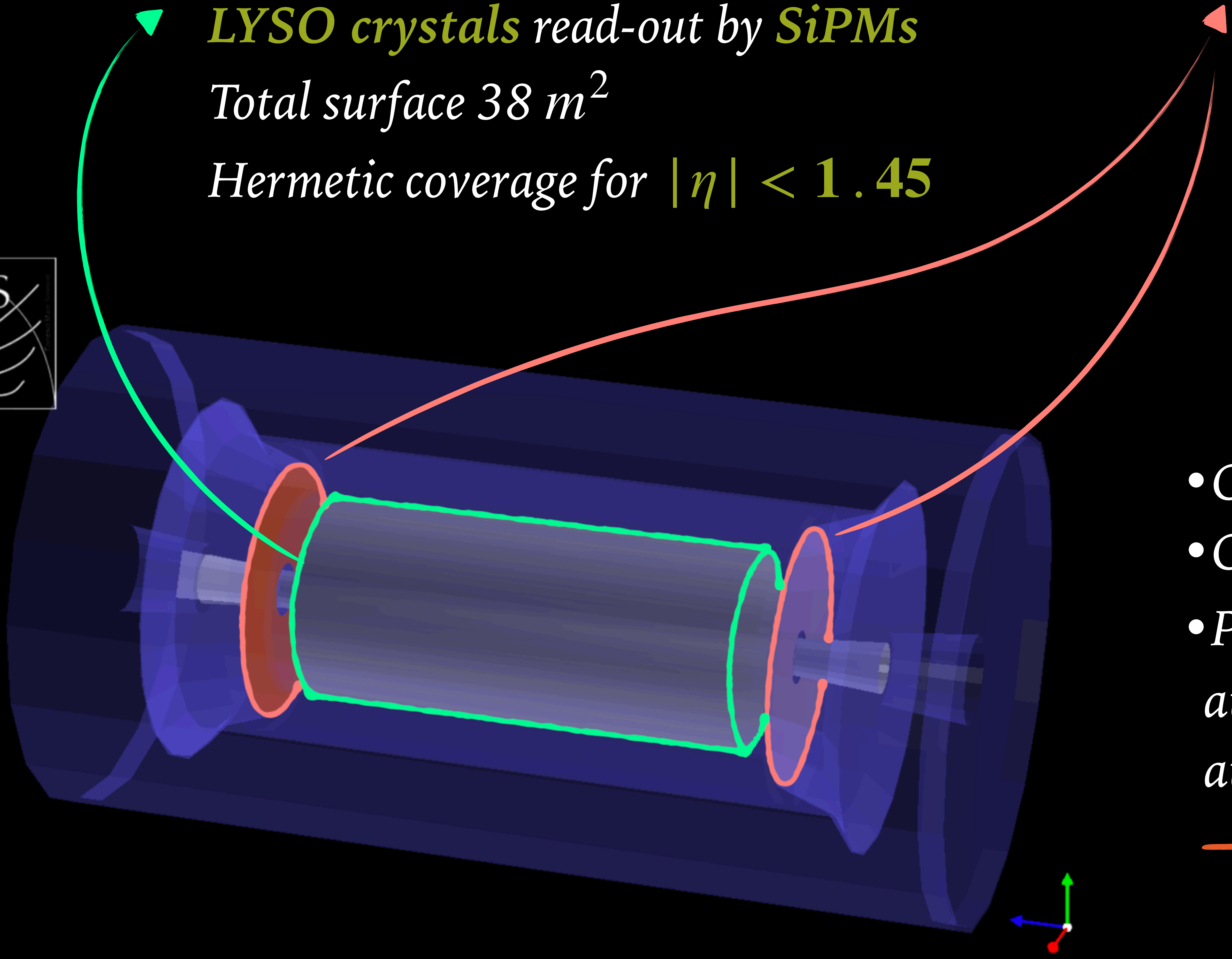
The CMS MIP Timing Detector

Barrel Timing Layer (BTL)

- *LYSO crystals* read-out by *SiPMs*
- Total surface 38 m^2
- Hermetic coverage for $|\eta| < 1.45$

Endcap Timing Layer (ETL)

- *Low Gain Avalanche Diodes* with ASIC readout
- Total surface 14 m^2
- Hermetic coverage for $1.6 < |\eta| < 3.0$



MTD will improve reconstruction by:

- Collecting timing information on charged particles
- Combining tracking with timing
- Providing a **timing resolution $\sigma_t \sim 30 - 40$ ps** at the start of HL-LHC, barrel degrades to 50-60 ps at end of HL-LHC

→ Mitigation of pile-up effect from HL-LHC

The CMS Endcap Timing Layer

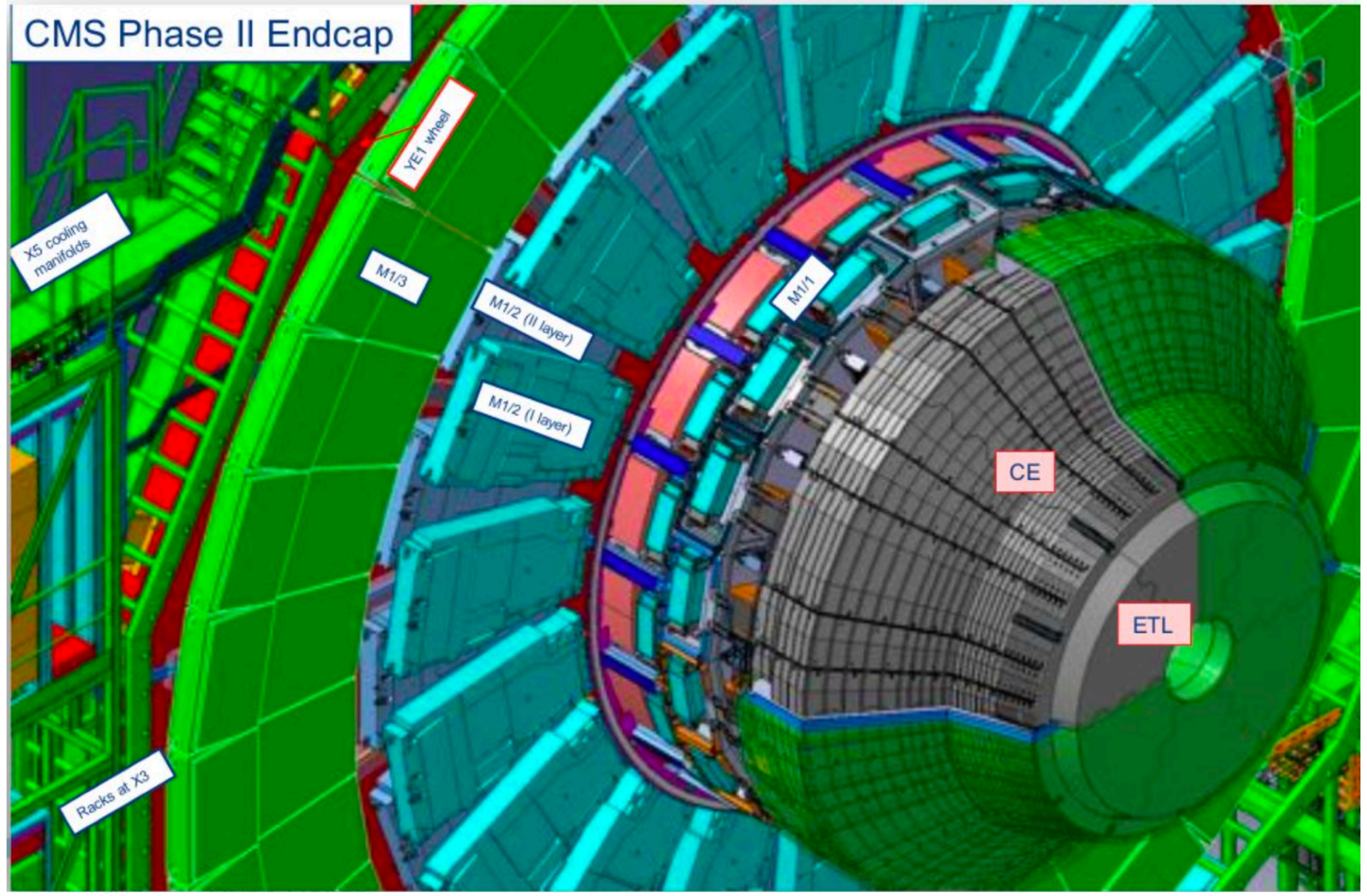
- ETL will be placed on the HGCAL nose
- **Two disks** for each endcap, covered in silicon sensors on **both sides**
- Hermetic coverage for $1.6 < |\eta| < 3.0$

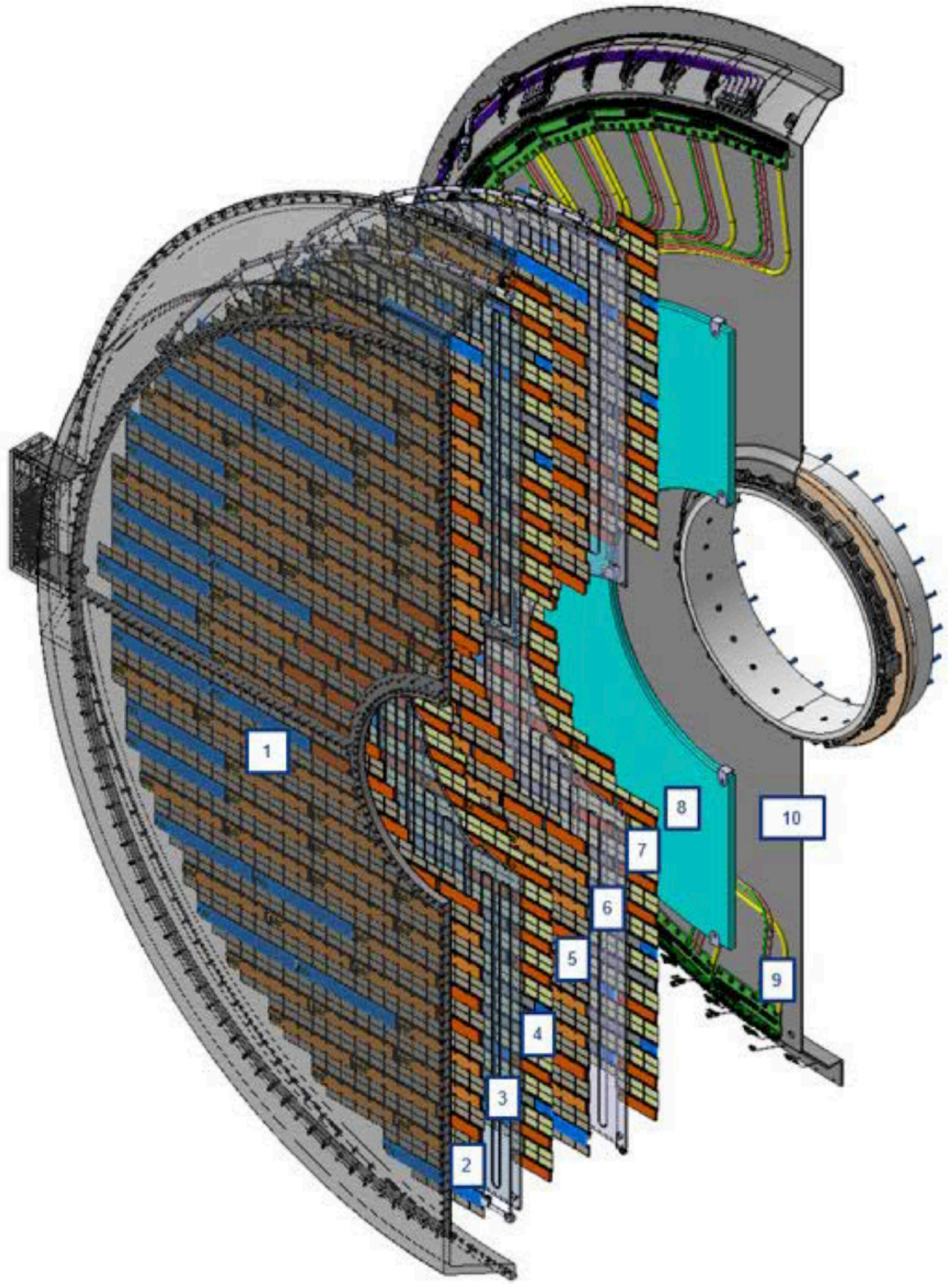
Ensure 2 hits for each track

Single-hit resolution <50 ps

$$\sigma_{single\ hit} = \sqrt{\sigma^2_{sensor} + \sigma^2_{readout}} \text{ with } \sigma_{sensor} \sim 30 - 40\ ps$$

Track resolution <35 ps

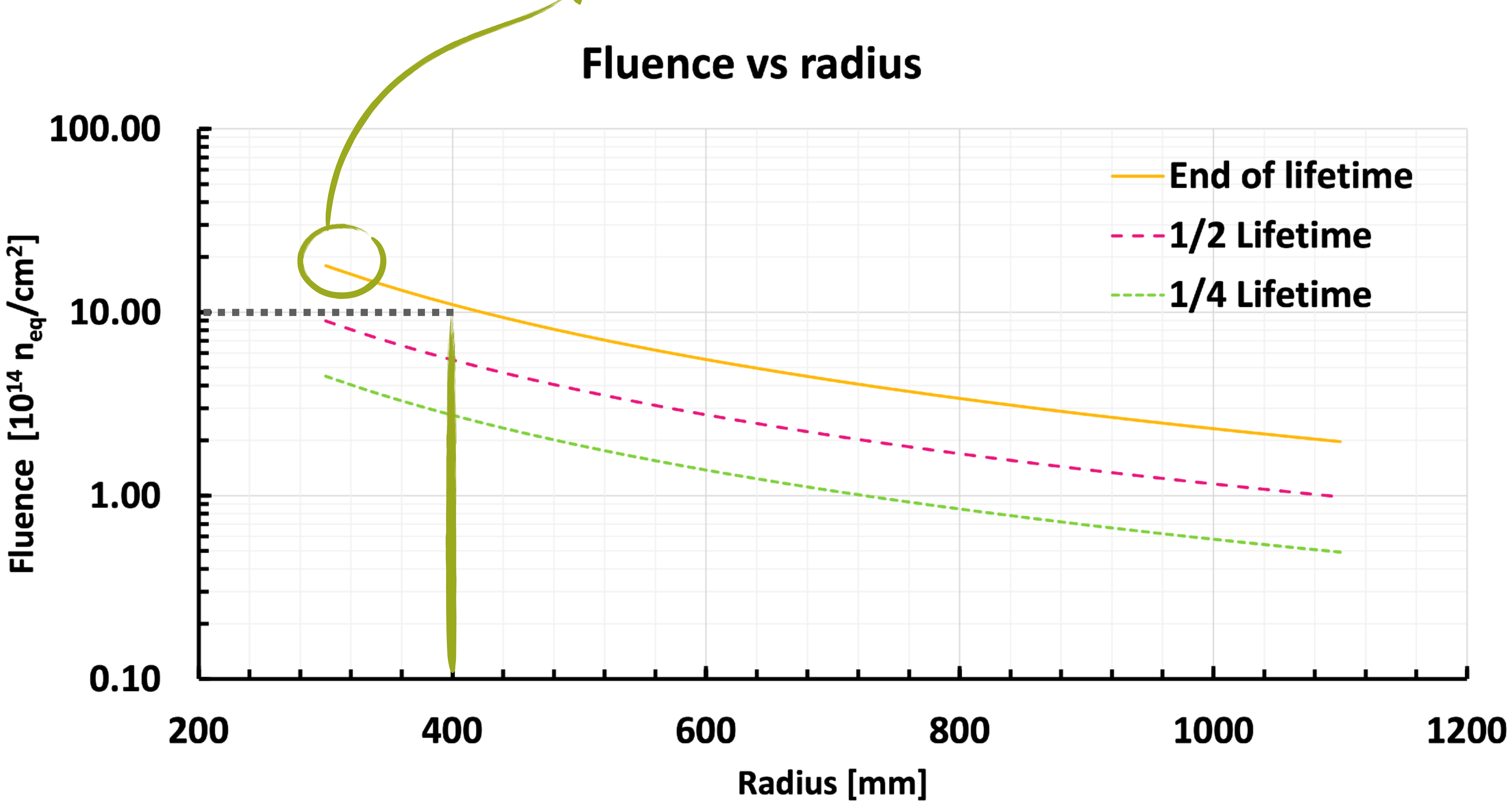




Element	
1	Thermal screen
	Gap between thermal screen and Face 1
2	Face 1 - active layer
3	Front disc
4	Face 2 - active layer
	Gap between Face 2 and Face 3
5	Face 3 - active layer
6	Back disc
7	Face 4 - active layer
	Gap between Face 4 and ETL front moderator
8+9	Patch panels 0 + cables [9] + ETL front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

The CMS ETL radiation environment

ETL will reach fluences $1.7 \times 10^{15}\ \mathrm{n_{eq}/cm^2}$ *in its inner region* $(|\eta| = 3.0)$ *at the end of the HL-LHC program*



Maximum fluence reaches $2.5 \times 10^{15}\ \mathrm{n_{eq}/cm^2}$ *when a 50% safety factor is applied*

Only a small fraction of the detector surface will reach fluences higher than $1 \times 10^{15}\ \mathrm{n_{eq}/cm^2}$ *after 1/2 lifetime*

The CMS Endcap Timing Layer

*ETL will contribute to **maintain CMS present performance also in HL-LHC environment**:*

- ***Fill-factor*** *(ratio between active and total detector area)* **> 95%**

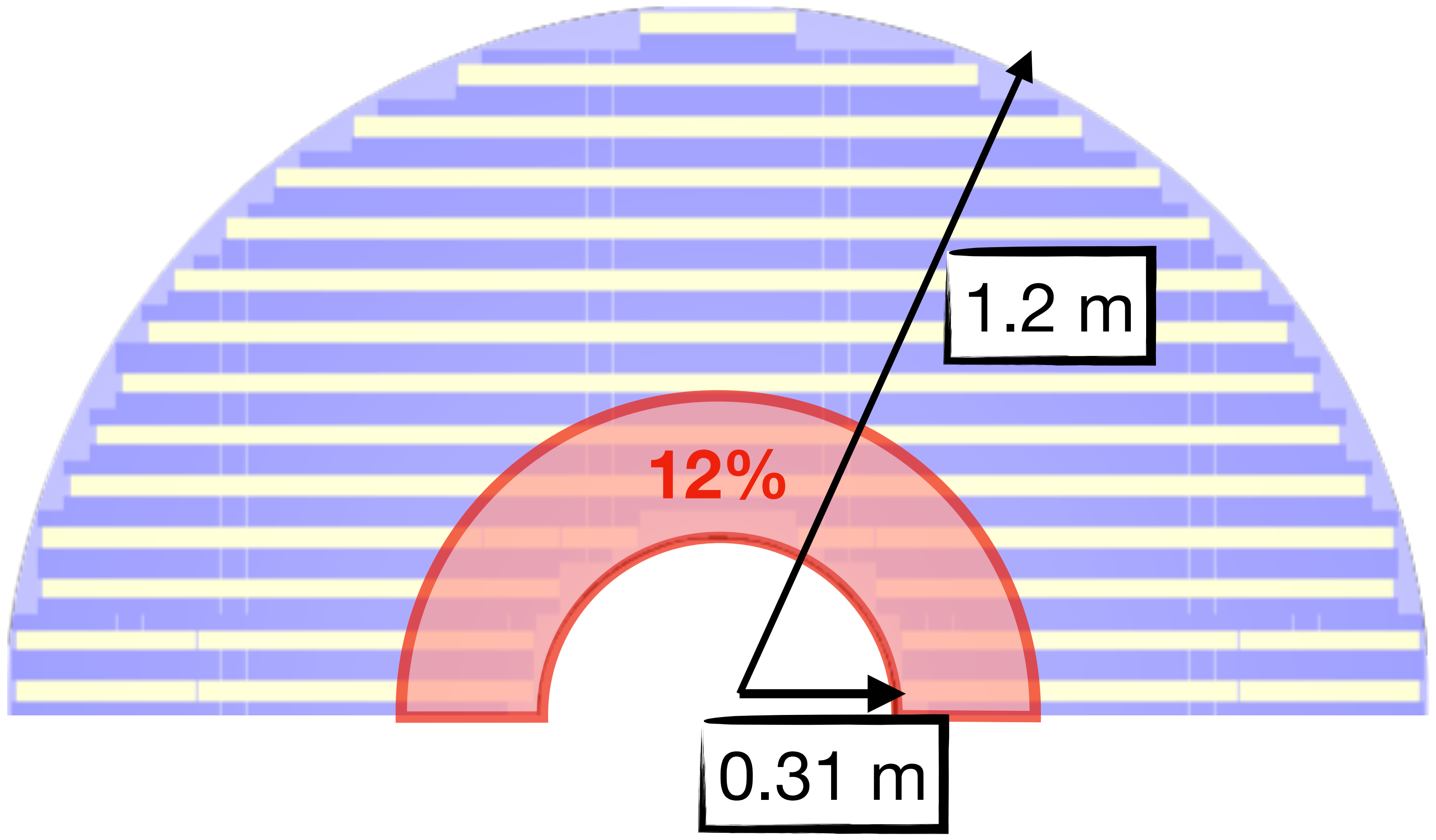
- ***Low occupancy*** *(<0.1% low η, 1% highest η) to avoid double hits and ambiguous time assignment*

- *Radiation tolerance up to* $\mathbf{1.7 \times 10^{15}\ n_{eq}/cm^2}$ *at* $|\eta| = 3.0$

  Large part of ETL will be exposed to less than $\mathbf{1 \times 10^{15}\ n_{eq}/cm^2}$

  → ***Only 12% of ETL surface will reach higher fluences***

  Operating temperature below -25°C



- *Design allowing to access the detector for maintenance*

  → ***Independent volume*** *isolated and operated separately from HGCAL*

ETL sensors

*ETL will be instrumented with **Low Gain Avalanche Diodes** (LGADs) optimized for timing measurements*

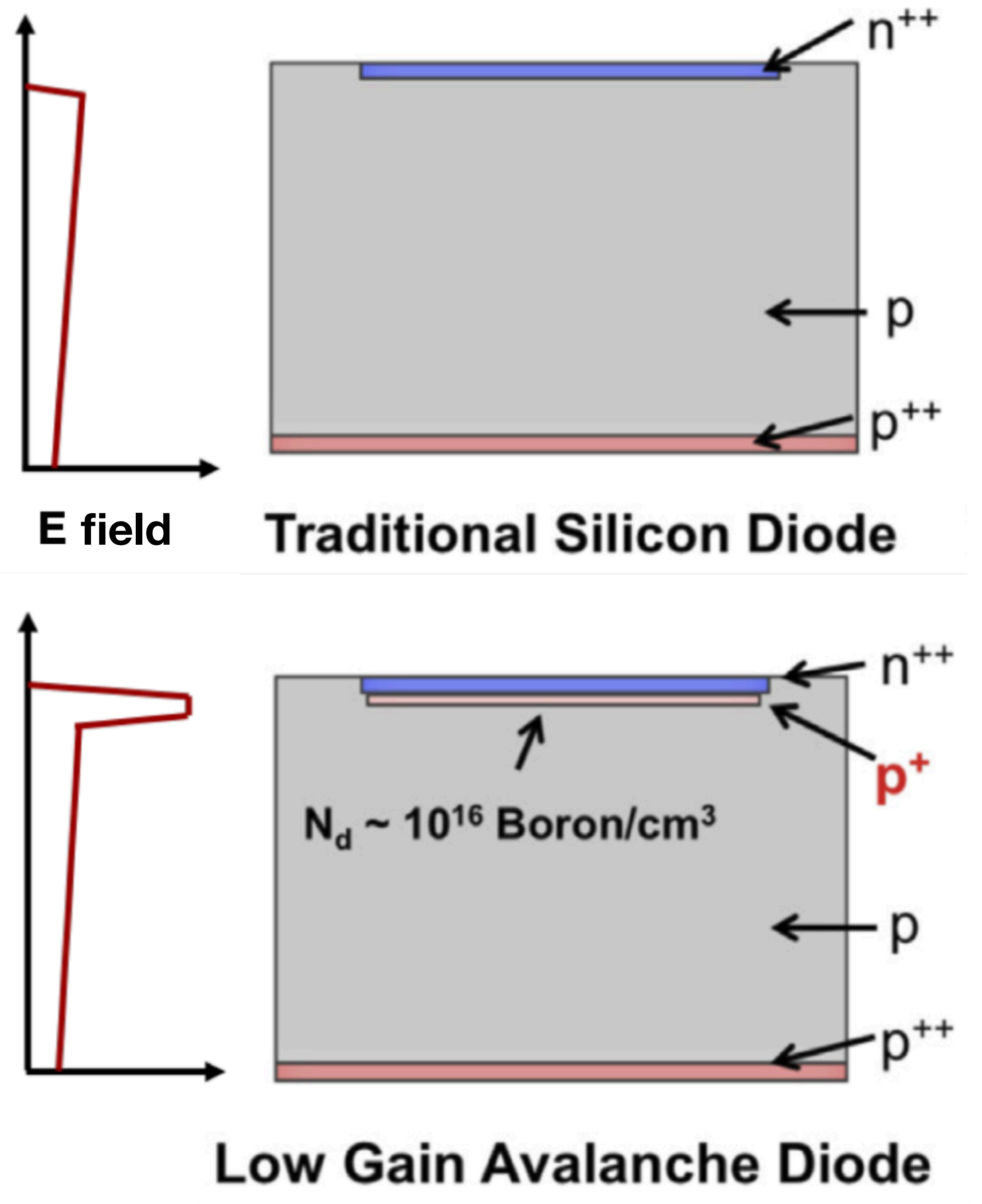
***LGADs** are provided with a **gain layer**, a highly-doped thin layer near the p-n junction*

→ *High local electric field producing **charge multiplication***

→ ***Moderate gain factor 10-30** to maximize signal/noise ratio*

***Sensor requirements**:*

- ***Pad size determined by occupancy and read-out electronics*** *(rather large capacitance, 3-4 pF)*
- ***Gain uniformity***
- ***Low leakage current** to limit power consumption and noise*
- *Provide **large and uniform signals**, >8 fC when new, >5 fC after highest irradiation point*
- *Minimized "no-gain" area, **interpad distance < 50 µm***



The final sensor will be a 50 µm-thick 16 × 16 pad array with 1.3 × 1.3 mm² pads

ETL sensor prototypes

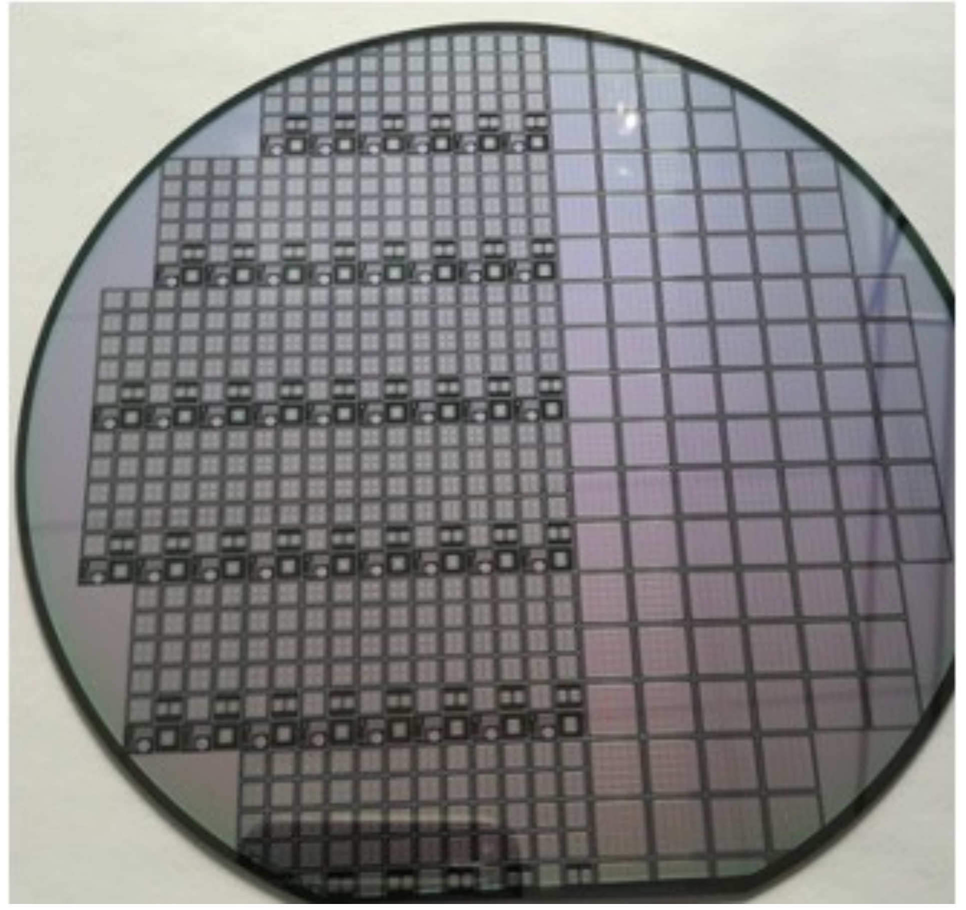
R&D studies to define the details for the final ETL sensor design are ongoing

Large size prototypes have been produced by different vendors: FBK (Italy), HPK (Japan)

*Latest **FBK** production:*

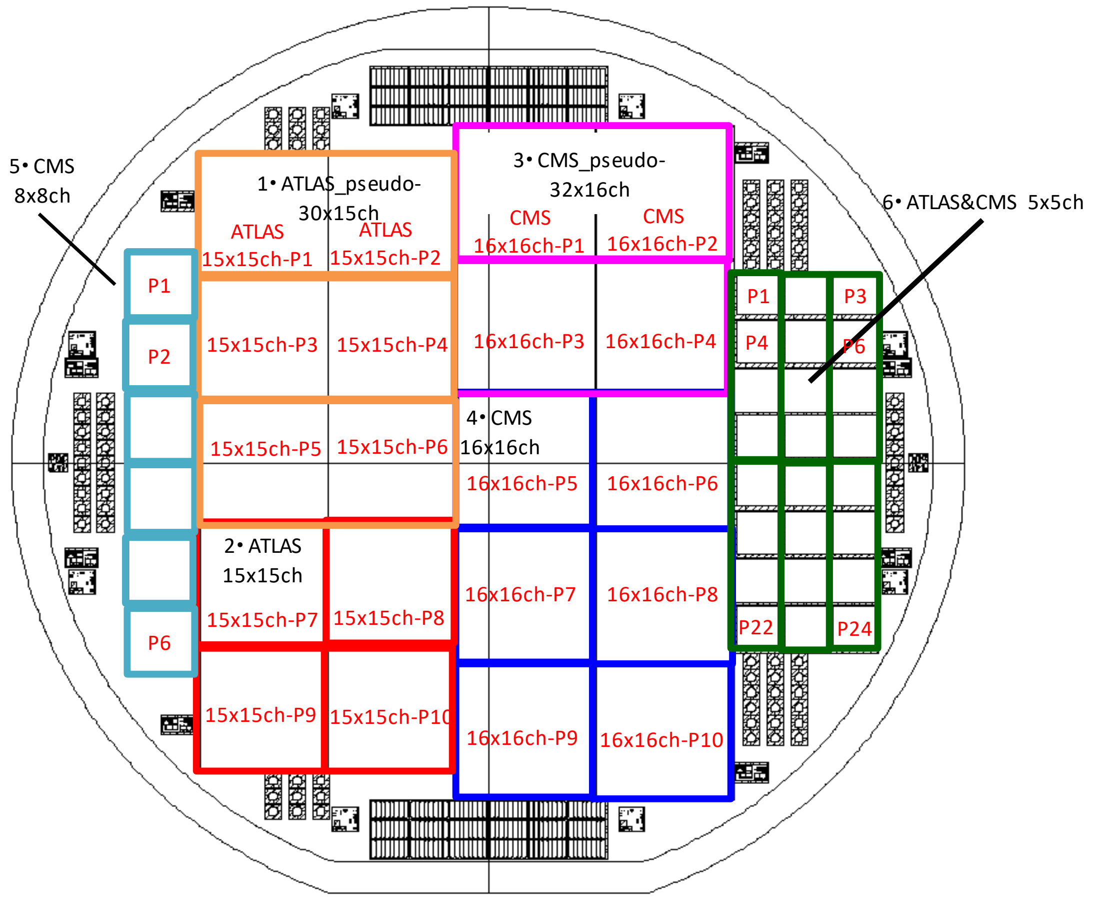
- *gain layer* implants with different doses and depths
- *Carbon* coimplantation in gain layer (enhanced radiation resistance)
- 9 layouts for the *interpad design*

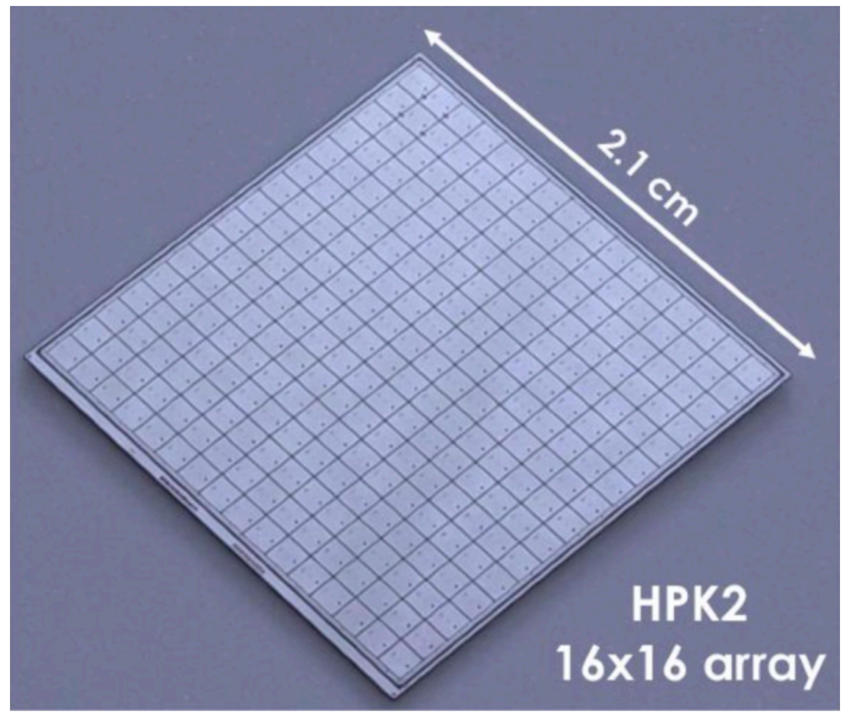
Wafer #	Thickness	DEPTH	Dose Pgain	Carbon	Diffusion
1	45	Standard	0.98	1.*A	CH-BL
2	45	Standard	0.98	1*A Spray	CH-BL
3	45	Standard	0.98	0.8*A	CH-BL
4	45	Standard	0.98	0.4*A	CH-BL
7	55	Standard	0.98	1.*A	CH-BL
8	45	deep	0.70	1.*A	CBL
9	55	deep	0.70	1.*A	CBL
10	45	deep	0.70	0.6*A	CBL
11	45	deep	0.70		BL
12	45	deep	0.74	1*A	CBL
13	45	deep	0.74	0.6*A	CBL
14	45	deep	0.74	1.*A	CBH
15	55	deep	0.74	1.*A	CBH
16	45	deep	0.74	0.6*A	CBH
17	45	deep	0.74		BH
18	45	deep	0.78	A	CBH
19	45	deep	0.78	0.6*A	CBH



*Latest **HPK** production:*

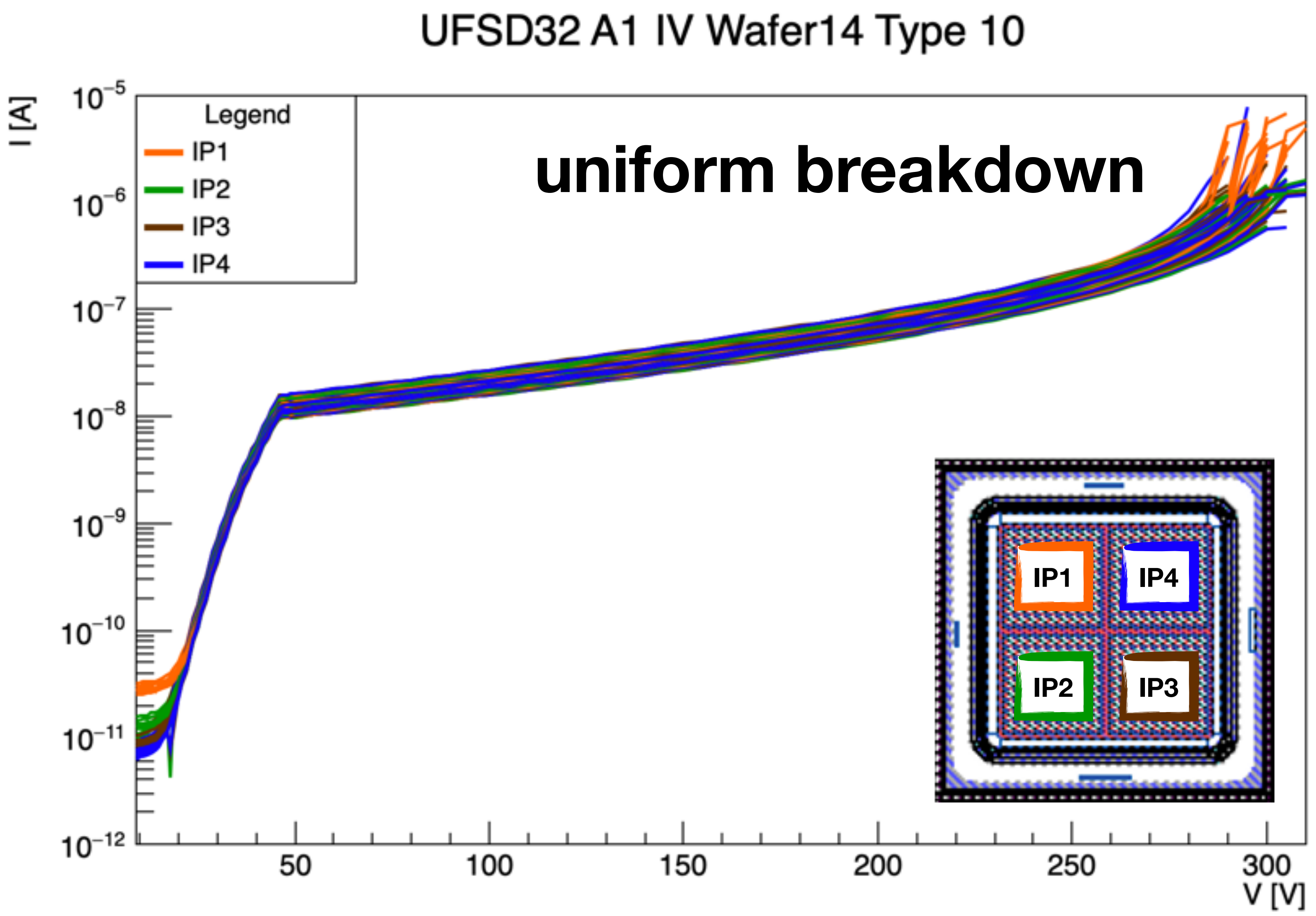
- 4 *gain layer* doses
- No *Carbon* coimplantation
- 4 layouts for the *interpad design*, 2 edges layouts





Laboratory measurements: uniformity

*Devices are tested **on wafer** and **after dicing** with probe stations*

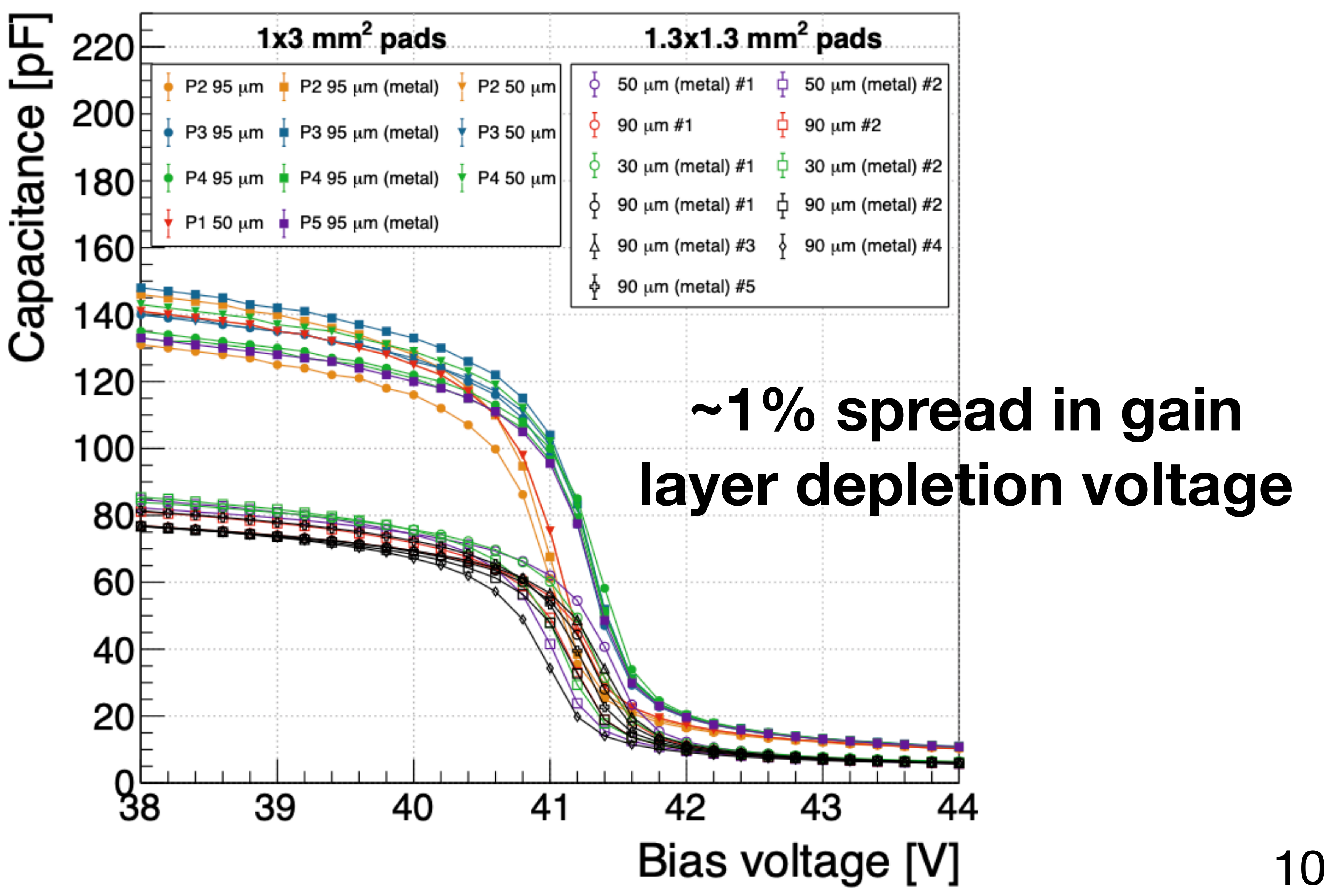


For each wafer and device type we consider:

- ***Breakdown distributions*** *for every structure or pad*
- ***current distributions*** *of every single pad at* ***a fixed value of bias***
- ***depletion voltage distributions*** *of each pad, extracted from C(V) curves*

→ ***Latest LGAD productions are highly uniform and with low leakage current for both FBK and HPK***

→ *well within required specifications*



More results of laboratory measurements on no-gain distance in the backup

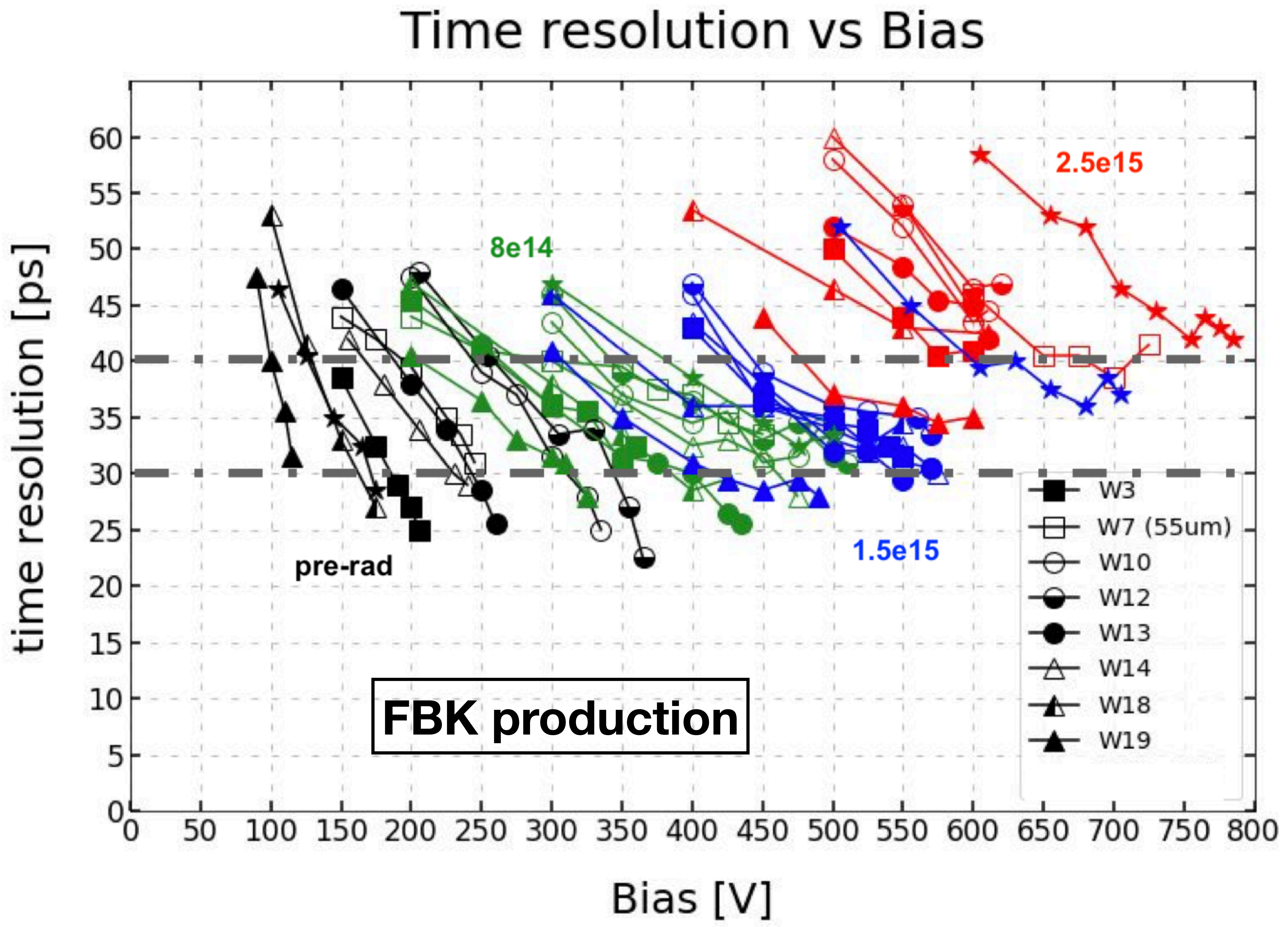
Laboratory measurements: timing resolution

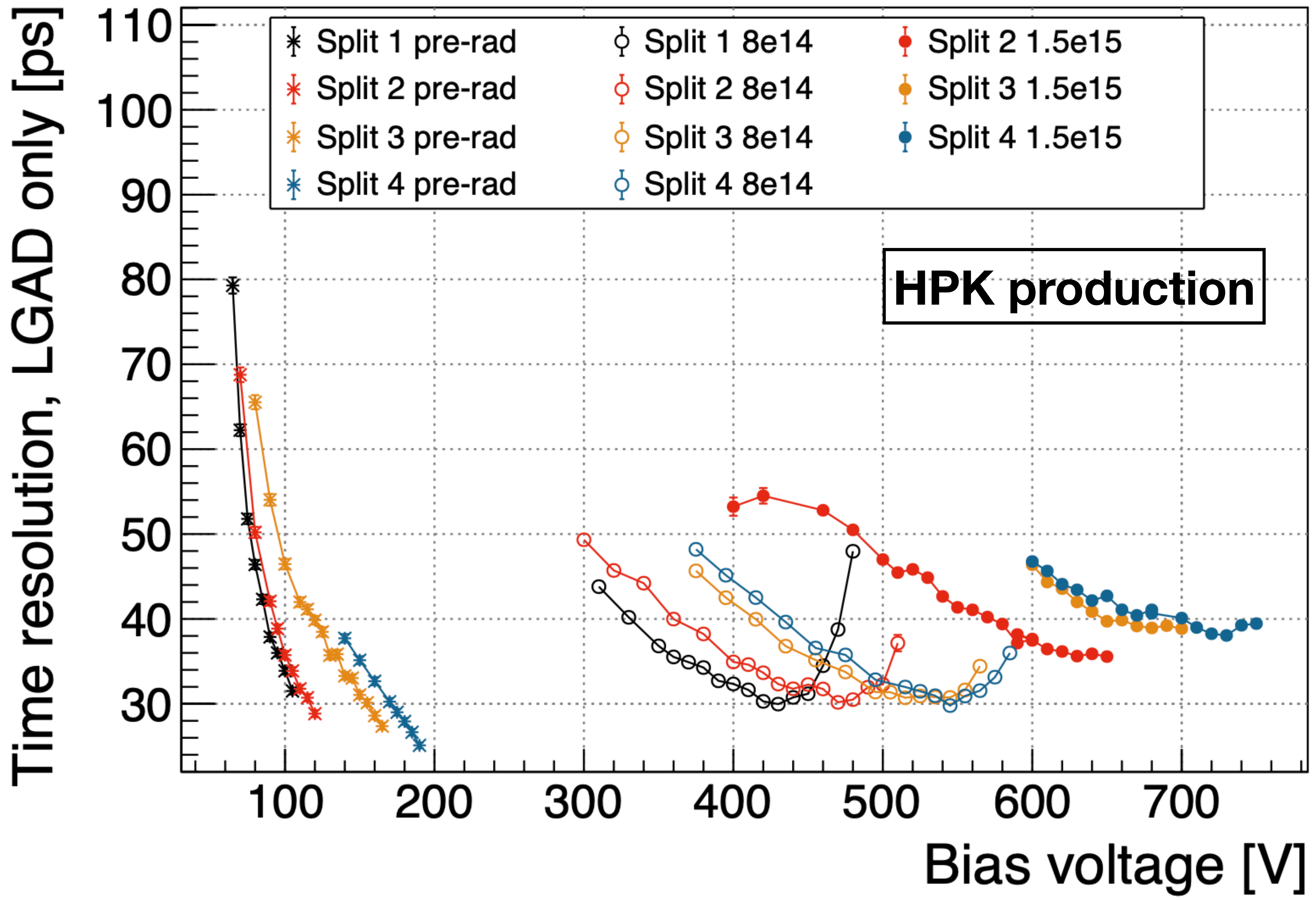
Sensor performances are benchmarked using very fast low noise electronics

→ *results might be different with the ETL ASIC*

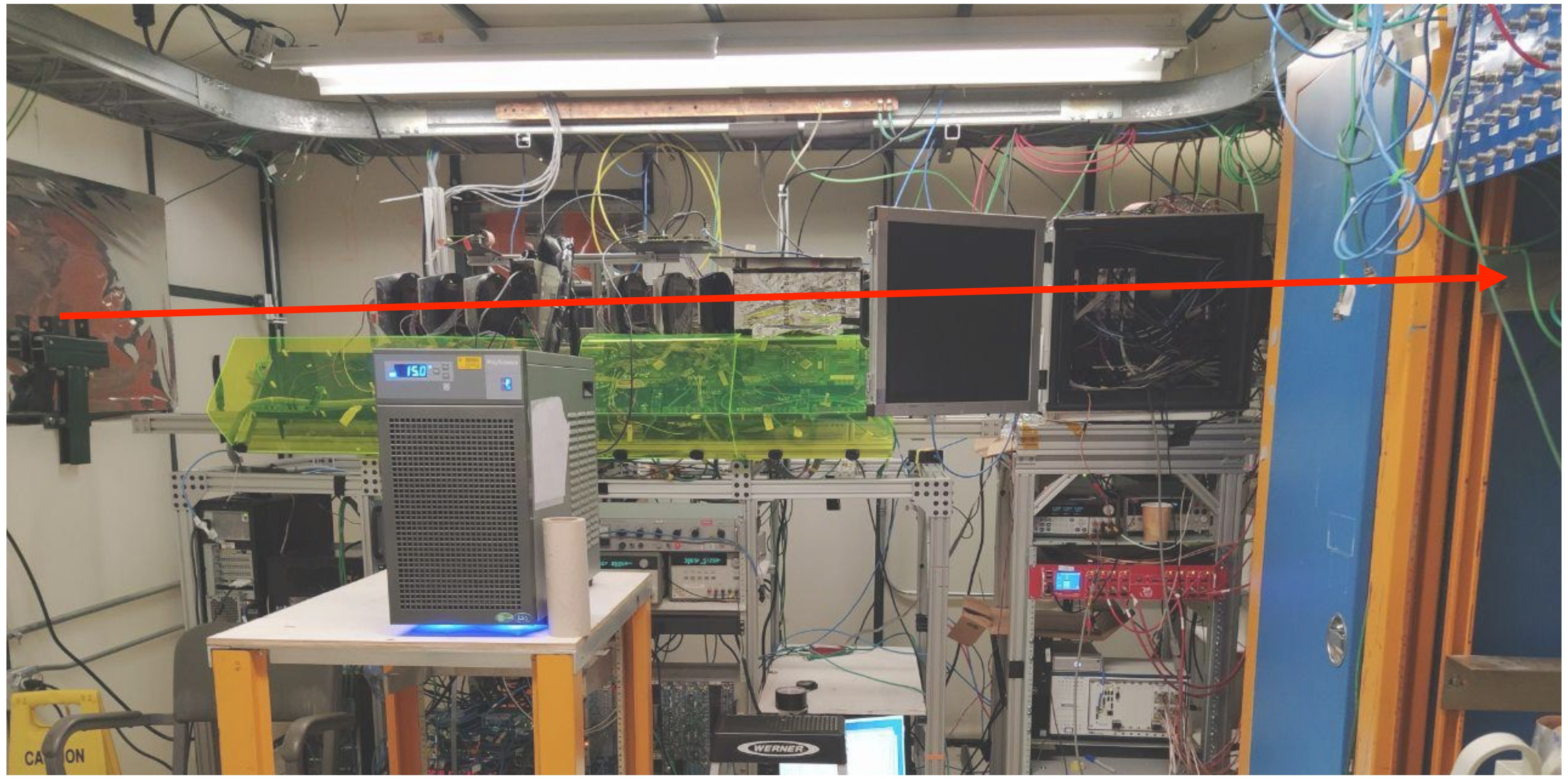
*Measurements performed with **Beta-source setups** based on **Sr90 sources** in Torino and at Fermilab*

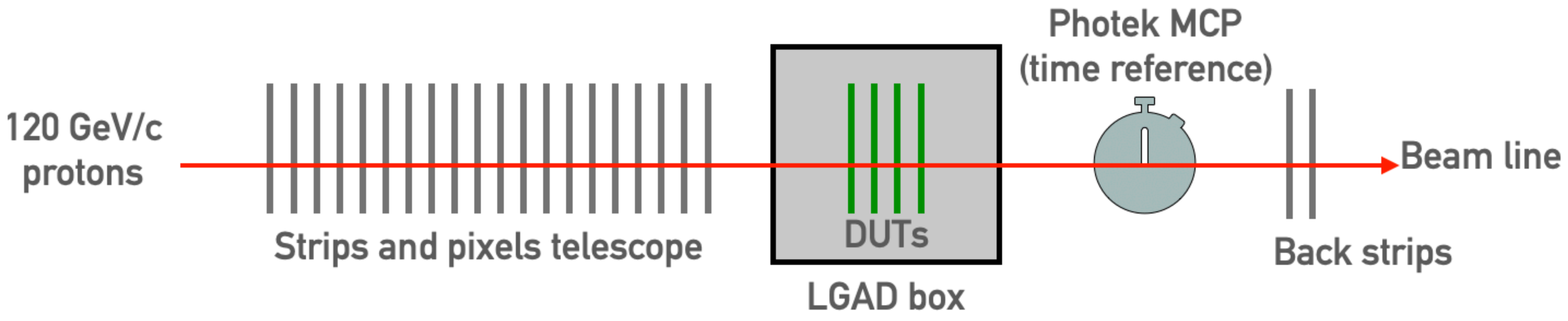
*Most performing prototypes can reach a **timing resolution <40 ps** up to fluences of **2.5e15 n_{eq}/cm^2***





Test beam





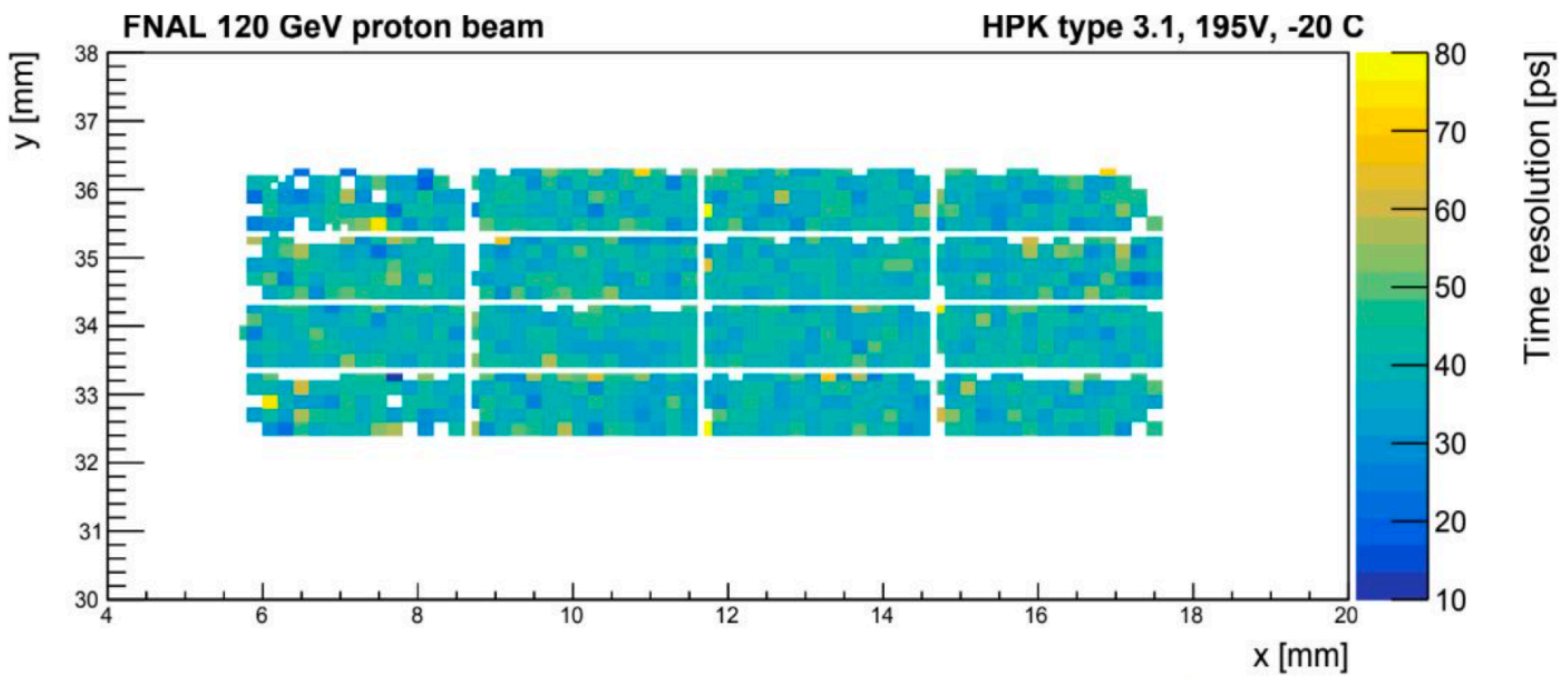
Fermilab test beam facility:

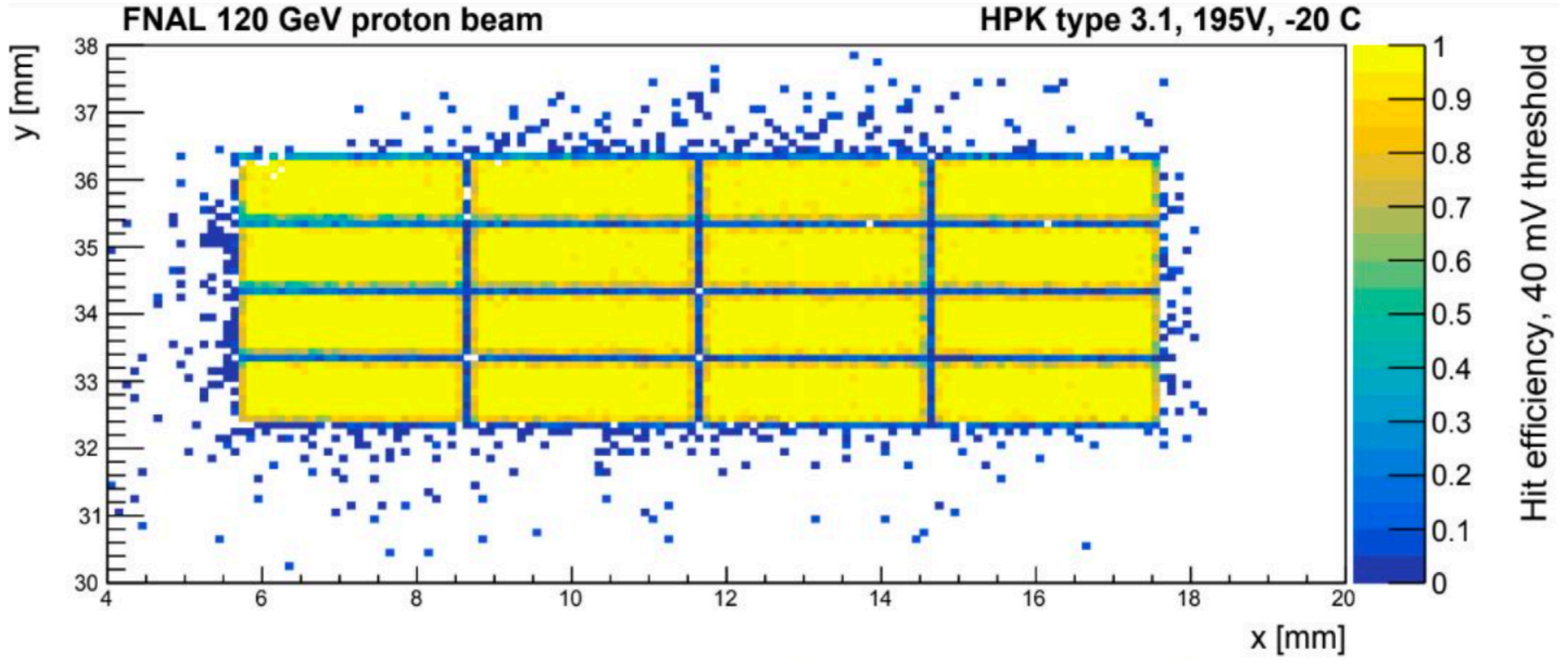
- *120 GeV/c proton beam*
- *Trigger provided by independent scintillator*
- *Precise tracking performed with strips and pixels telescope*
- *Timing resolution measurements with high speed Photek Micro-Channel Plate as reference providing timestamp with 10 ps resolution*
- *Cold box with LGADs under test*

→ *Study of a limited number of sensors with high precision*

Test beam

New HPK 4×4 array

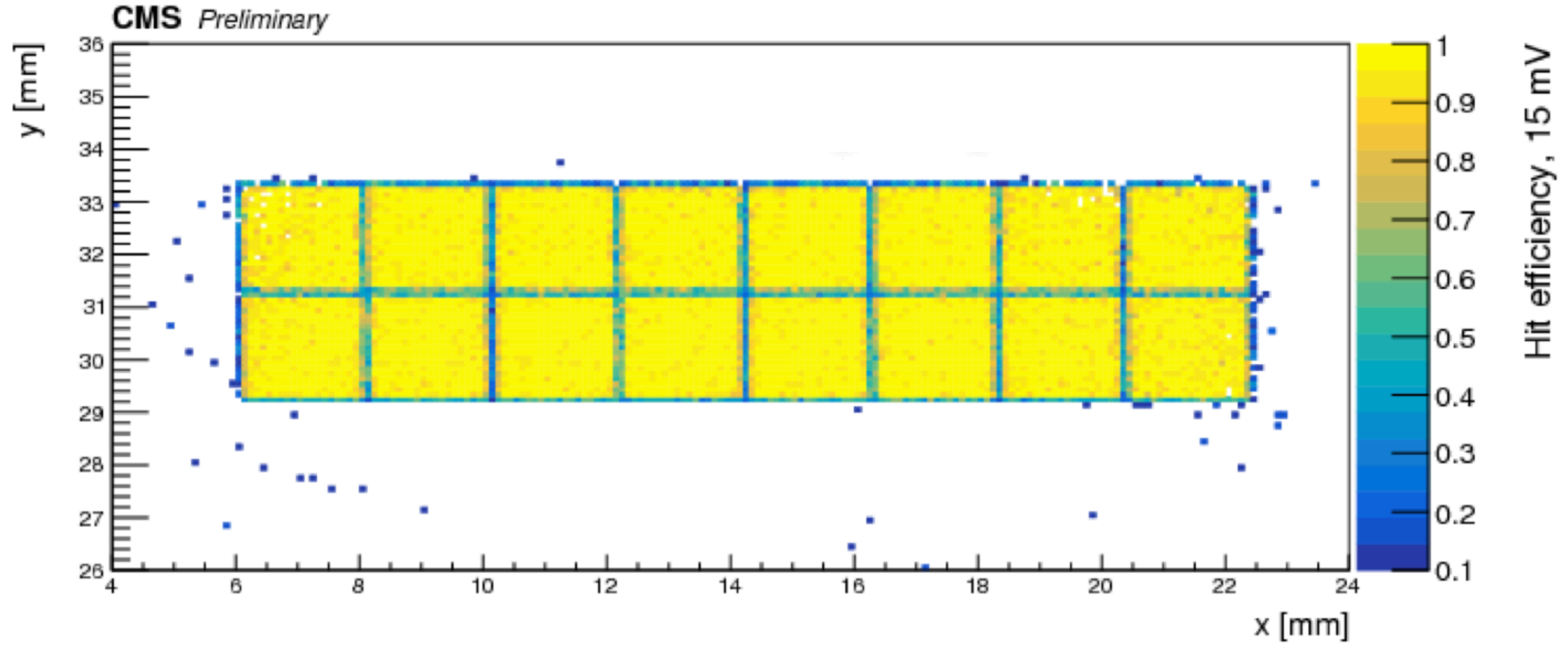




Uniform ***timing resolution*** *map with* $\sigma_t \sim$ **40 ps** *for new devices*

Uniform ***hit efficiency*** *reaching* ***~100%*** *in new sensors and* ***~99%*** *after irradiation*

→ *LGADs are highly uniform and efficient, able to reach target resolution on large multi-pad arrays*



FBK 2×8 array (first prototype sensor production)

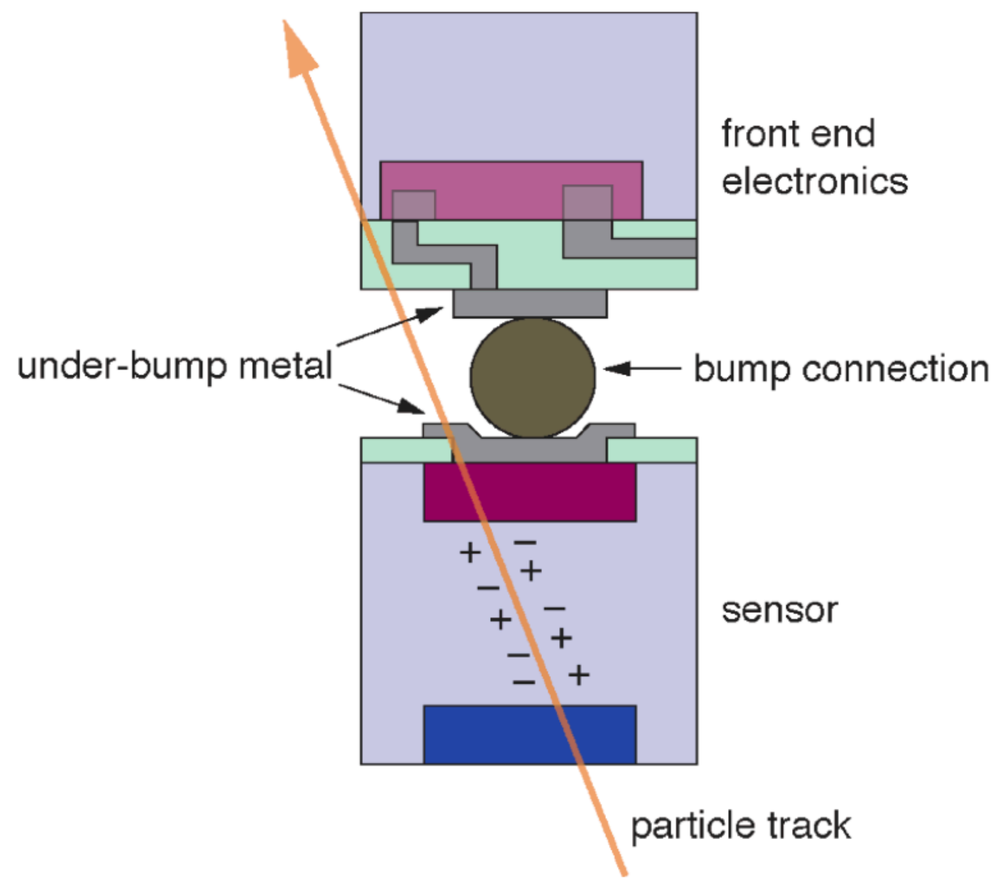
Irradiated 8e14 n_{eq}/cm^2

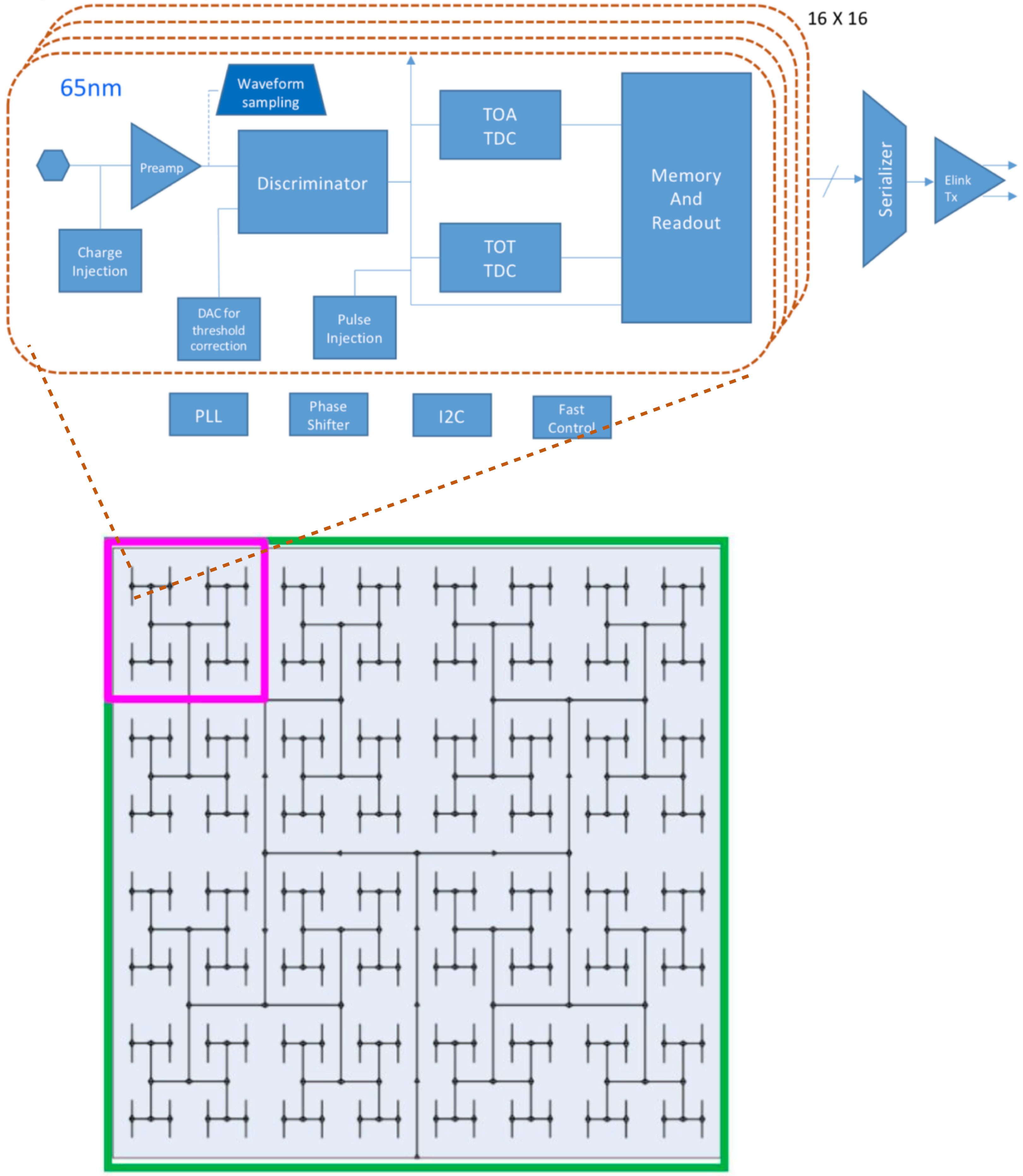
ETL read-out ASIC

*The **Endcap Timing Layer Read-Out Chip** (ETROC) is the ETL read-out ASIC*

Goal: reach time resolution $\sigma_t < \mathbf{50\ ps}$ *per single hit*

- *Low noise and fast rise time*
- *Power budget: 1 W/chip, 3 mW/channel*





*Three prototype versions before the **final full-size** 16×16 **chip**:*

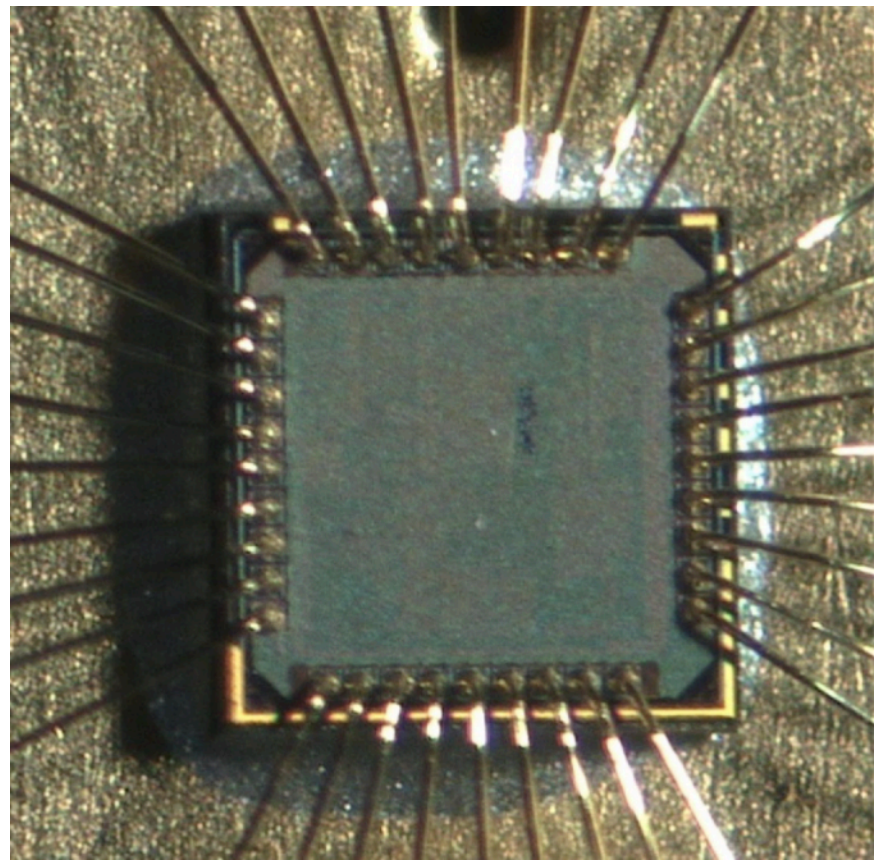
✓*ETROC0 and ETROC1 produced and tested*

  ✓ ***ETROC0: single analog channel***

  ✓ ***ETROC1: full front-end with TDC and*** 4×4 ***clock tree***

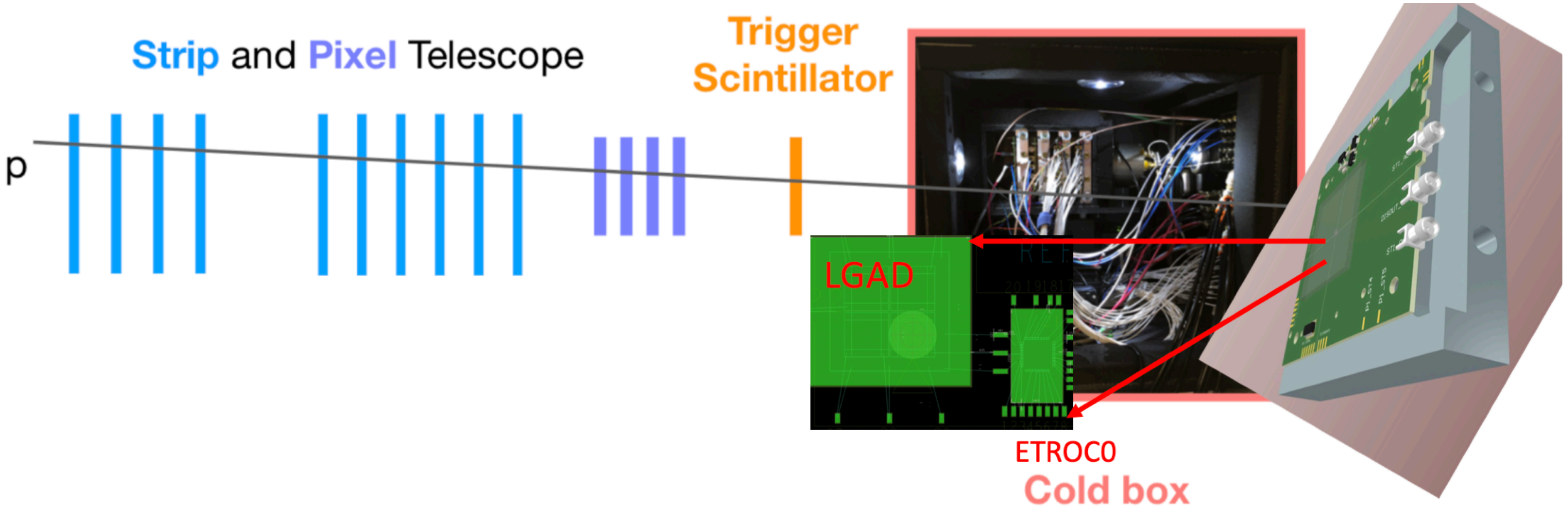
➡ ***ETROC2 design in progress: full functionality + full size***

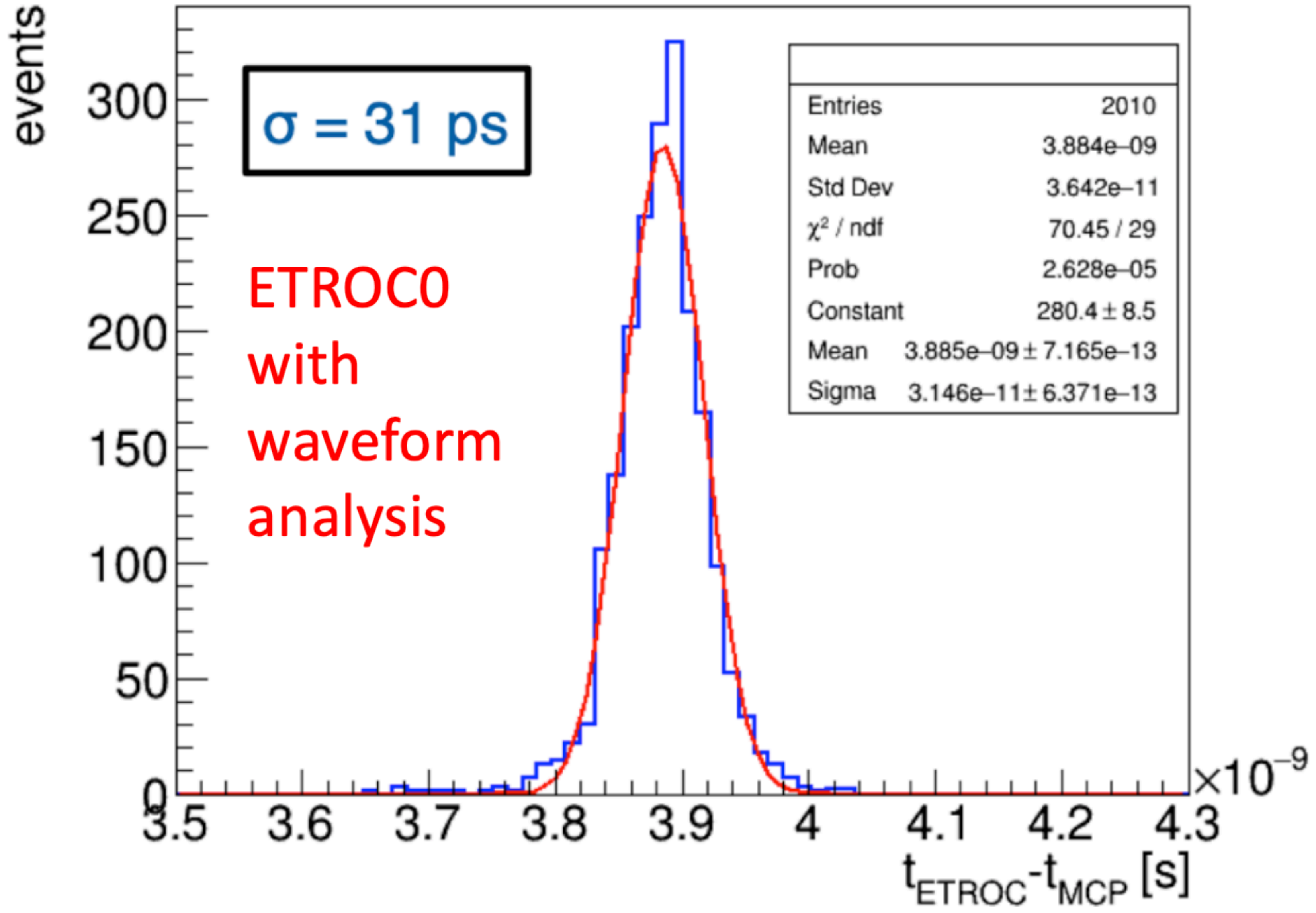
ETROC0



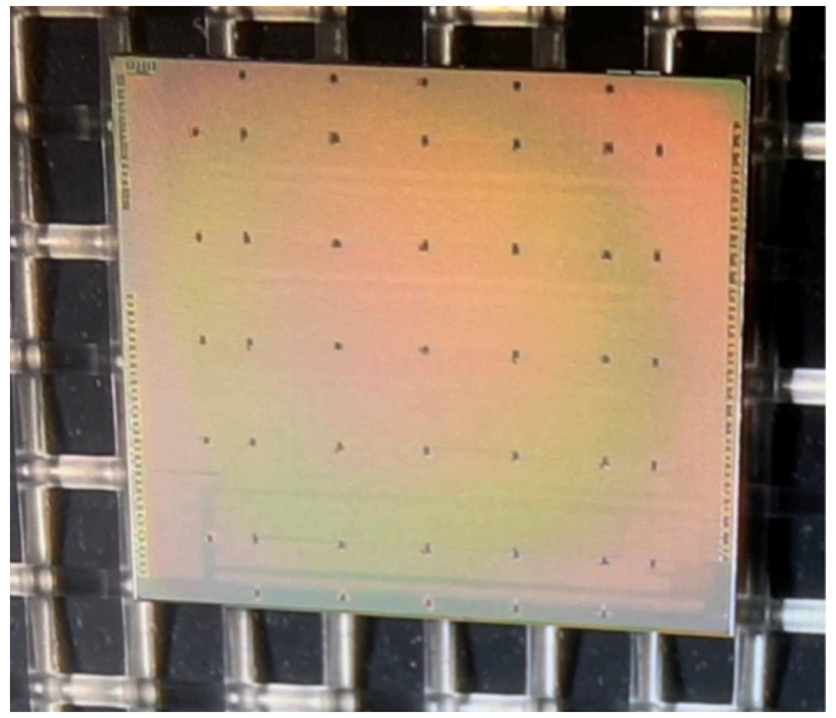
Goal: measure core front-end analog performance

- *Jitter measurements agree with chip post-layout simulation*
- *Power consumption for preamp and discriminator consistent with expectation*
- *31 ps timing resolution achieved at FNAL test beam with ETROC0+LGAD*



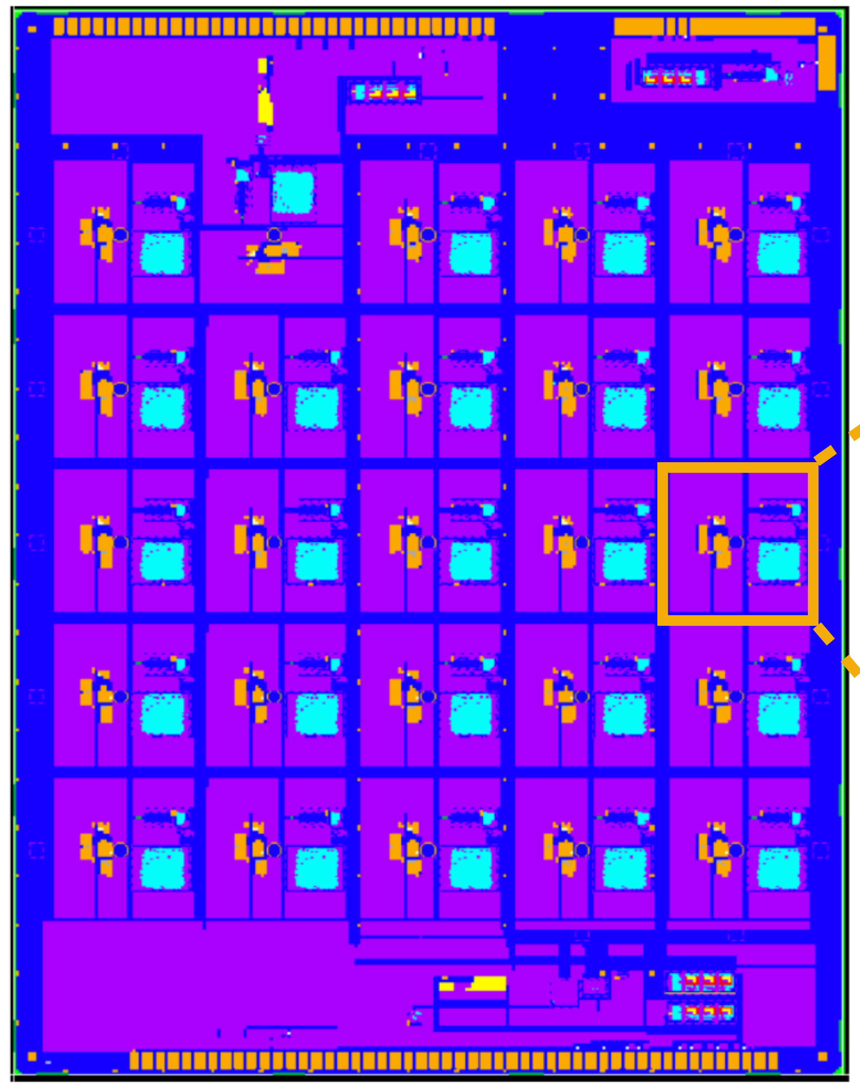


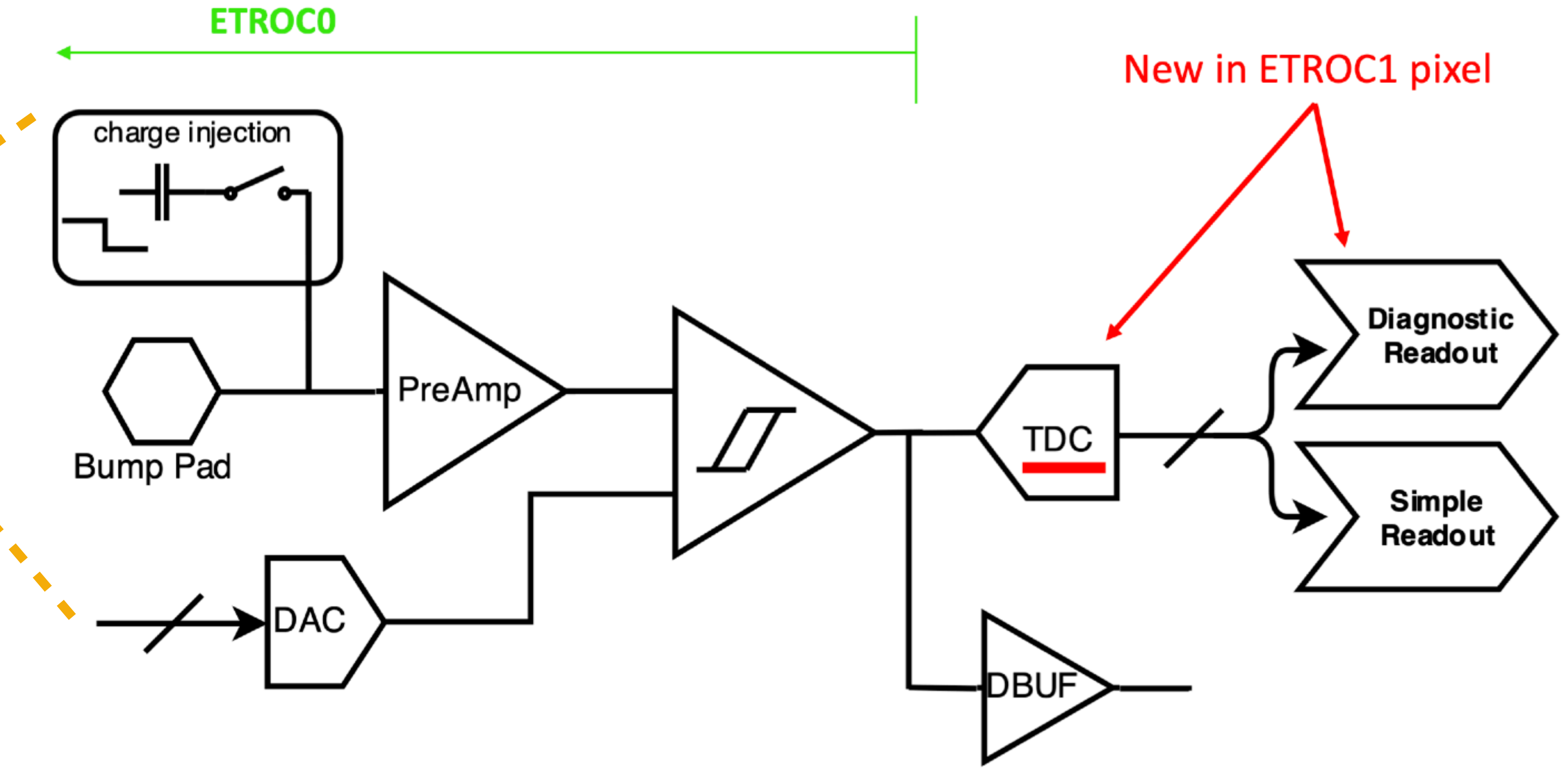
ETROC1



ETROC1 is the second prototype version: 4x4 pixels + TDC

- *Uses ETROC0 front-end*
- *ETROC **TDC brand new design optimized for low power***
- *Low power achieved using simple delay cells with **self-calibration***
- *Achieved **TDC resolution ~6 ps***



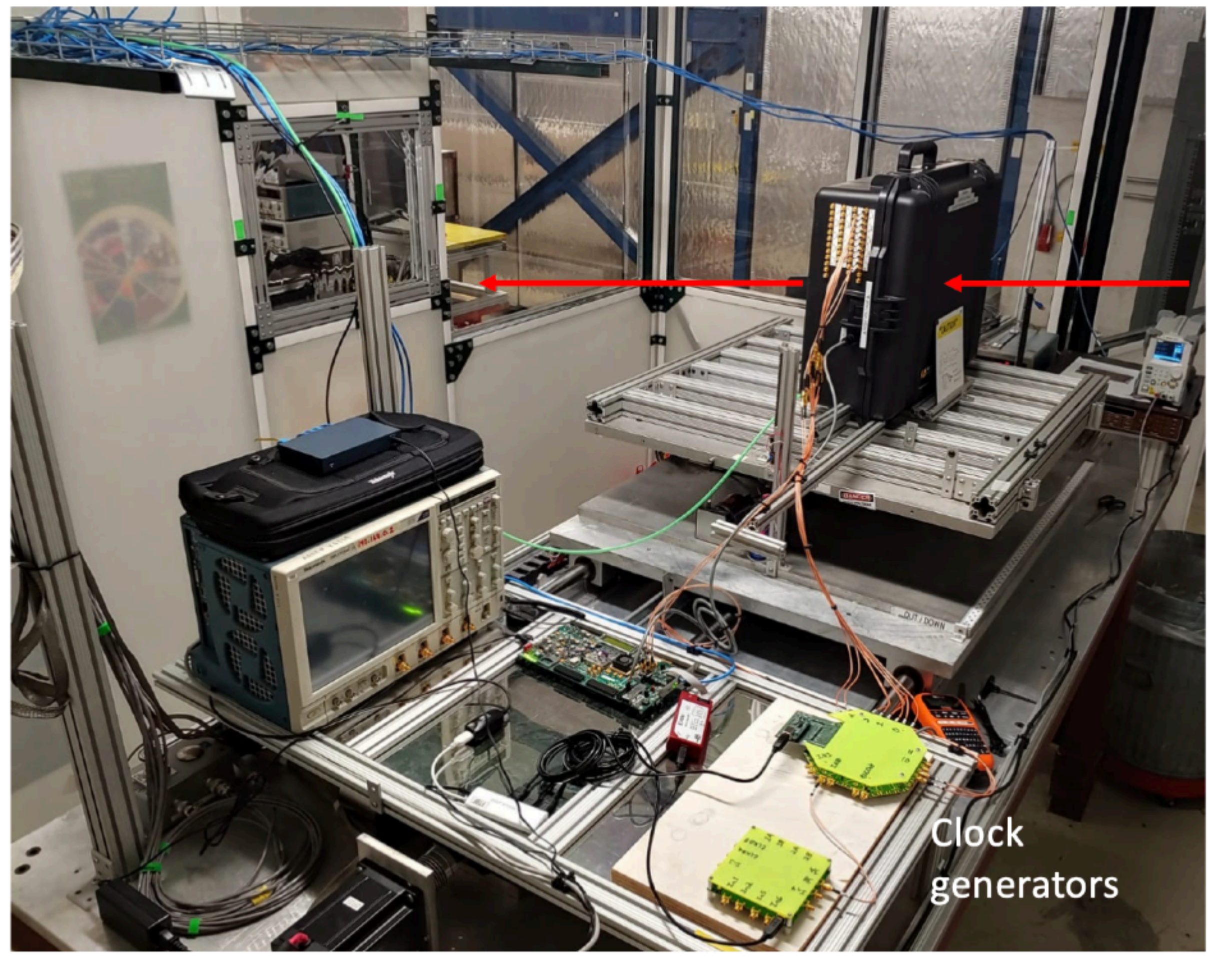


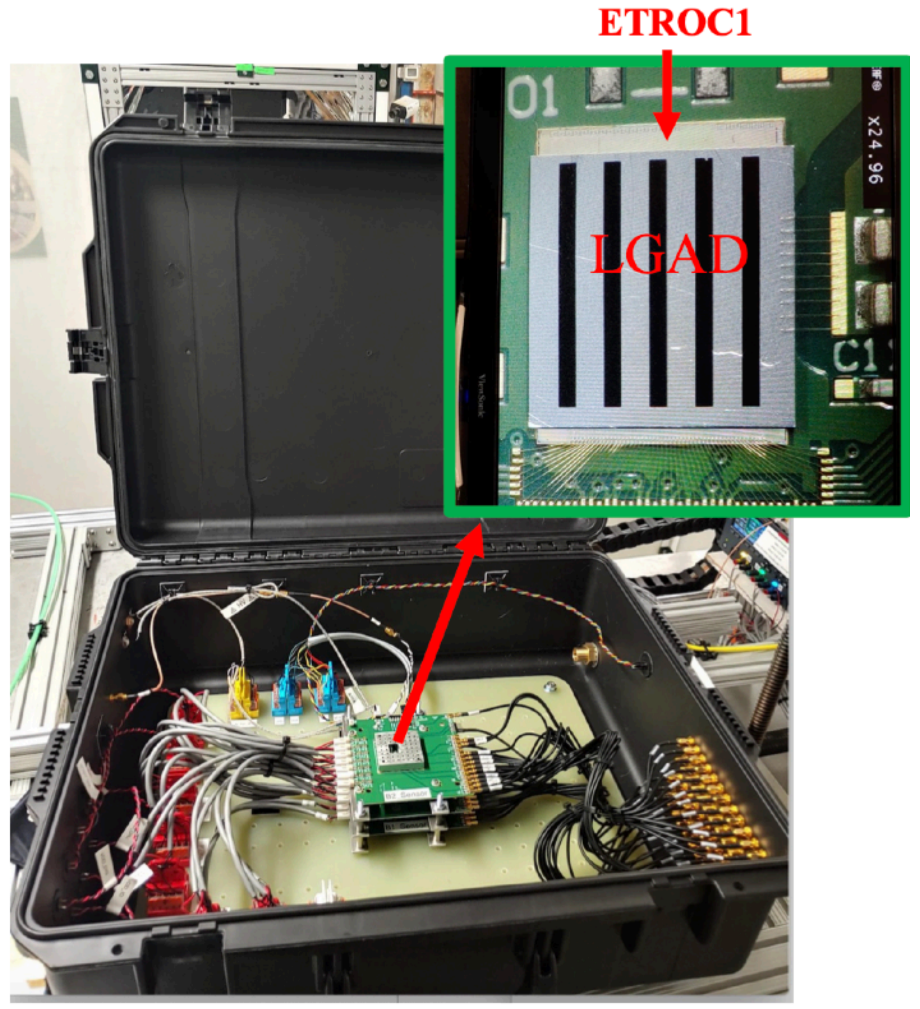
40 MHz noise observed on bump-bonded ETROC1 + LGAD

- *Coupled through the sensor due to 40MHz clock activity in the circular buffer memory*
- *The noise is very high and is suppressed by a discriminator threshold of ~8 fC*

→ *under investigation*

ETROC1

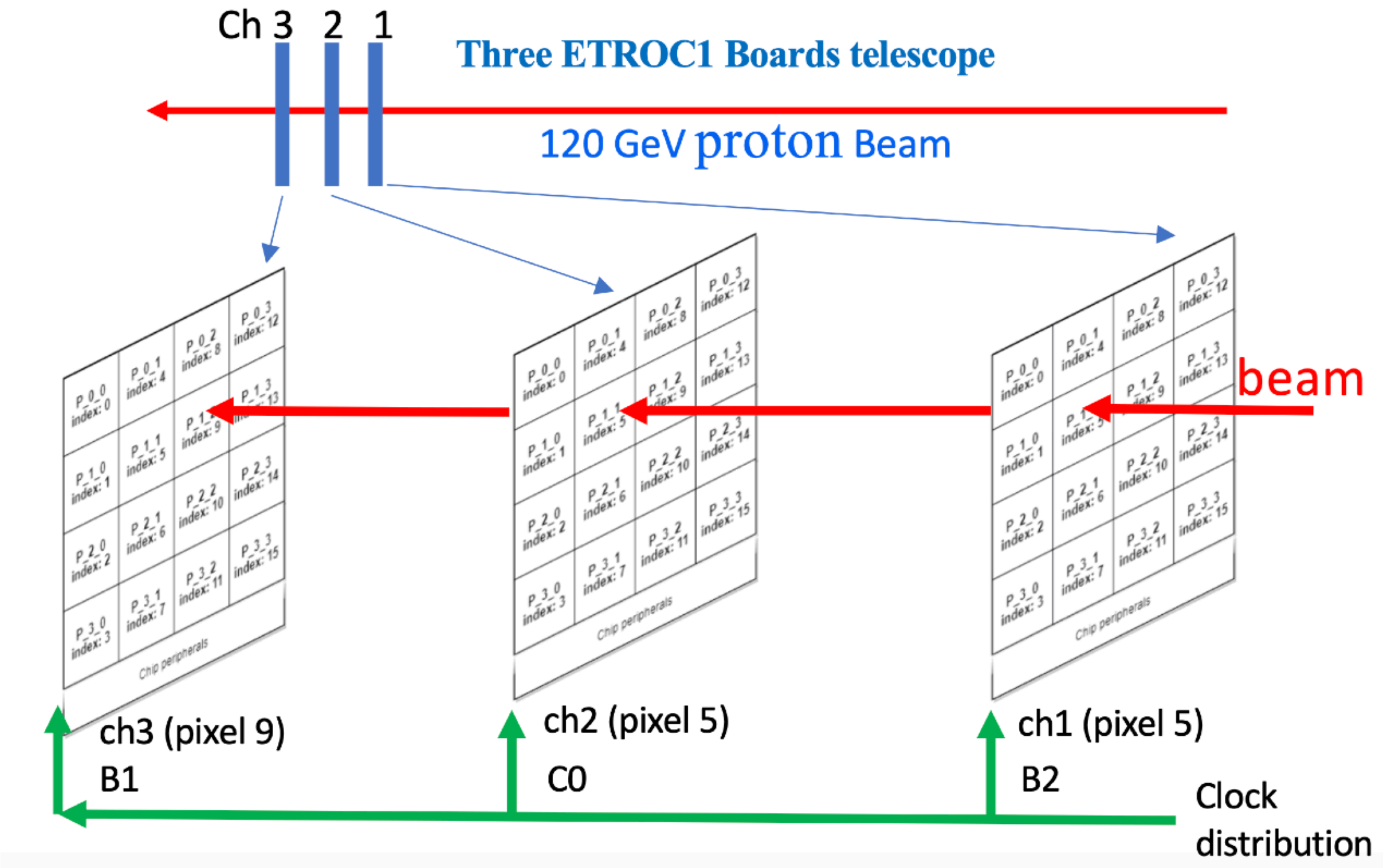


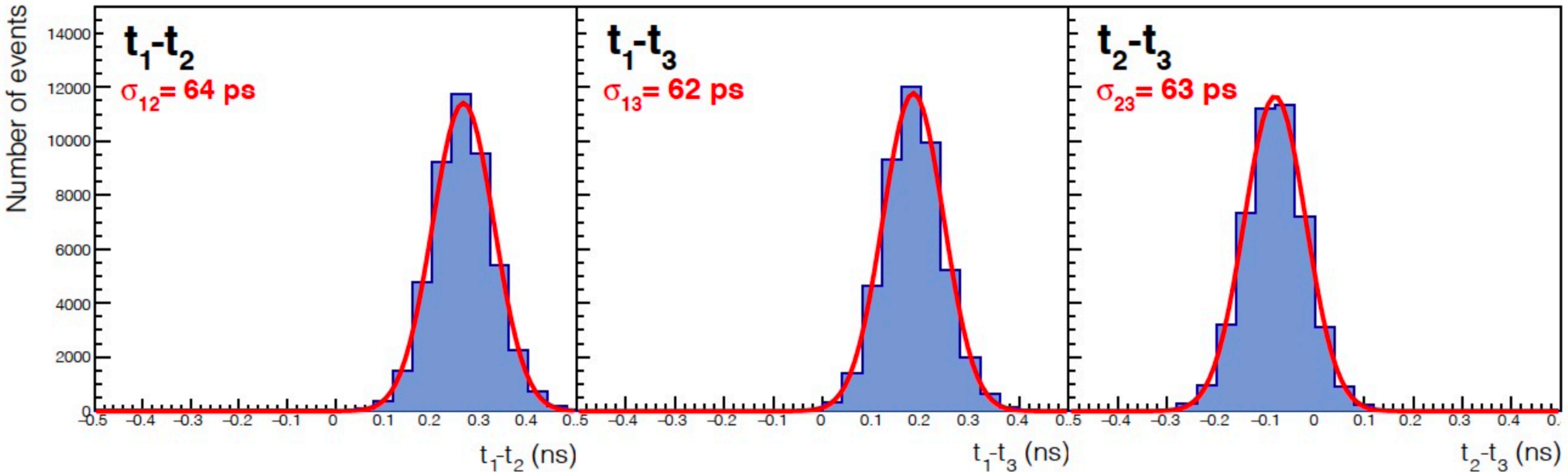


ETROC1 beam telescope at FNAL test beam facility

*From preliminary analysis of the data from ongoing beam test at FNAL, **the total time resolution per hit** for each LGAD+ETROC1 layer has reached:*

$$\sigma_i \sim \mathbf{42 - 46\ ps}$$





Conclusions

*The **CMS Endcap Timing Layer** will perform precise timing measurements of charged particles with single-hit **timing resolution <50 ps**, allowing the CMS detector to maintain its excellent performances in the very challenging environment of the HL-LHC*

*ETL will be instrumented with thin **Low-Gain Avalanche Diodes** (LGADs) read-out by **ETROC ASIC***

- *The latest LGAD productions have been measured both in the laboratory and at test beams, to ensure they meet all the specifications:*
  - ***Highly uniform sensors: low leakage currents, good gain, uniform breakdown voltage***
  - ***Timing resolution < 40 ps up to the end of lifetime***
  - *Test beam results show **100% efficiency** and **uniform timing resolution** across the whole active area of large LGAD arrays*

- *The **Endcap Timing Layer Read-Out Chip** (ETROC) is required to consume low power while providing excellent timing performances*
  - ***ETROC1** is the second prototype version: 4x4 pixels + low-power TDC :*
    - ***42-46 ps time resolution** measured at FNAL beam test*
  - ***ETROC2 design in progress** (submission in 2022)*

CMS

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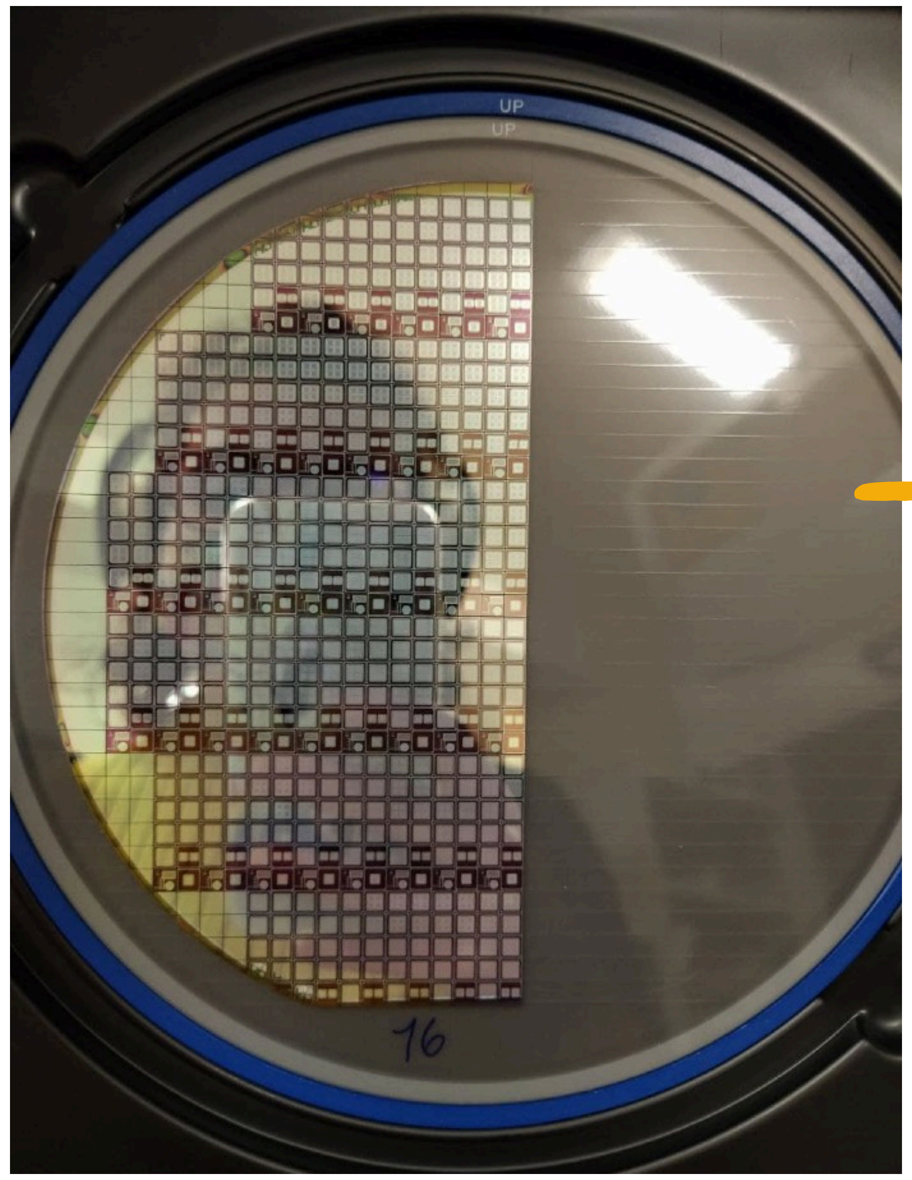
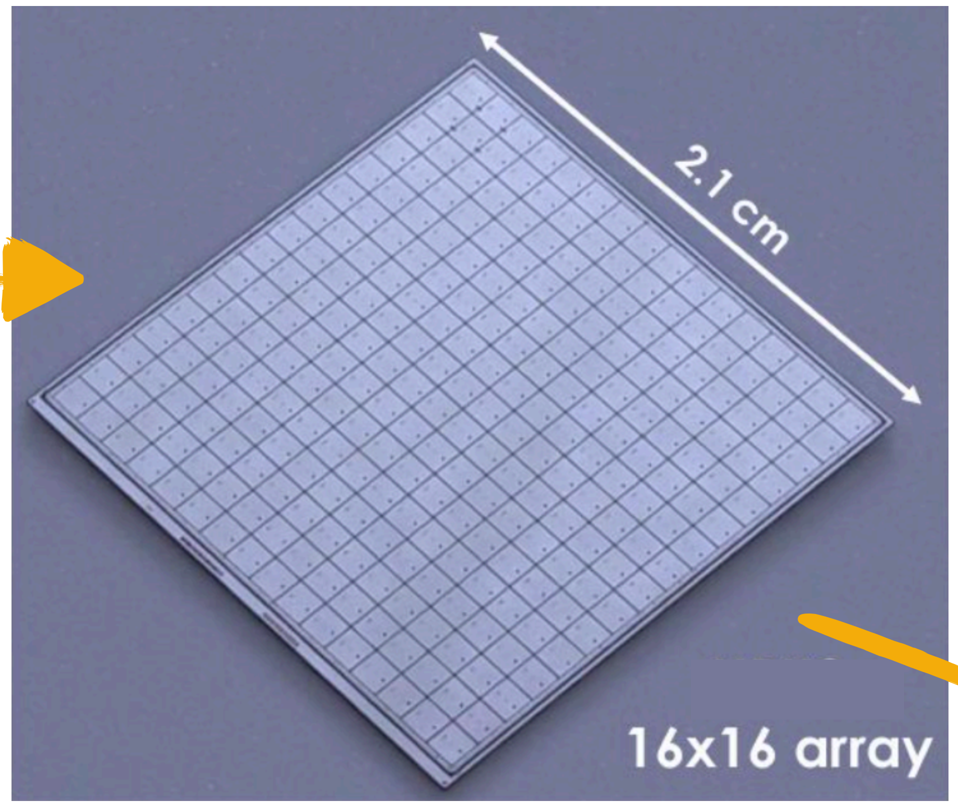
Backup

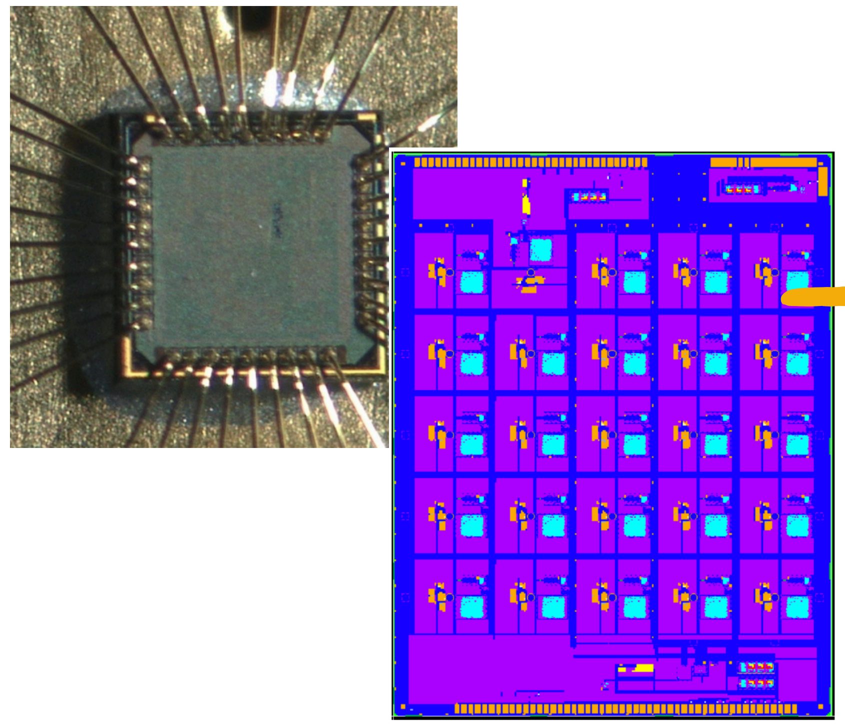
From R&D studies to the Endcap Timing Layer

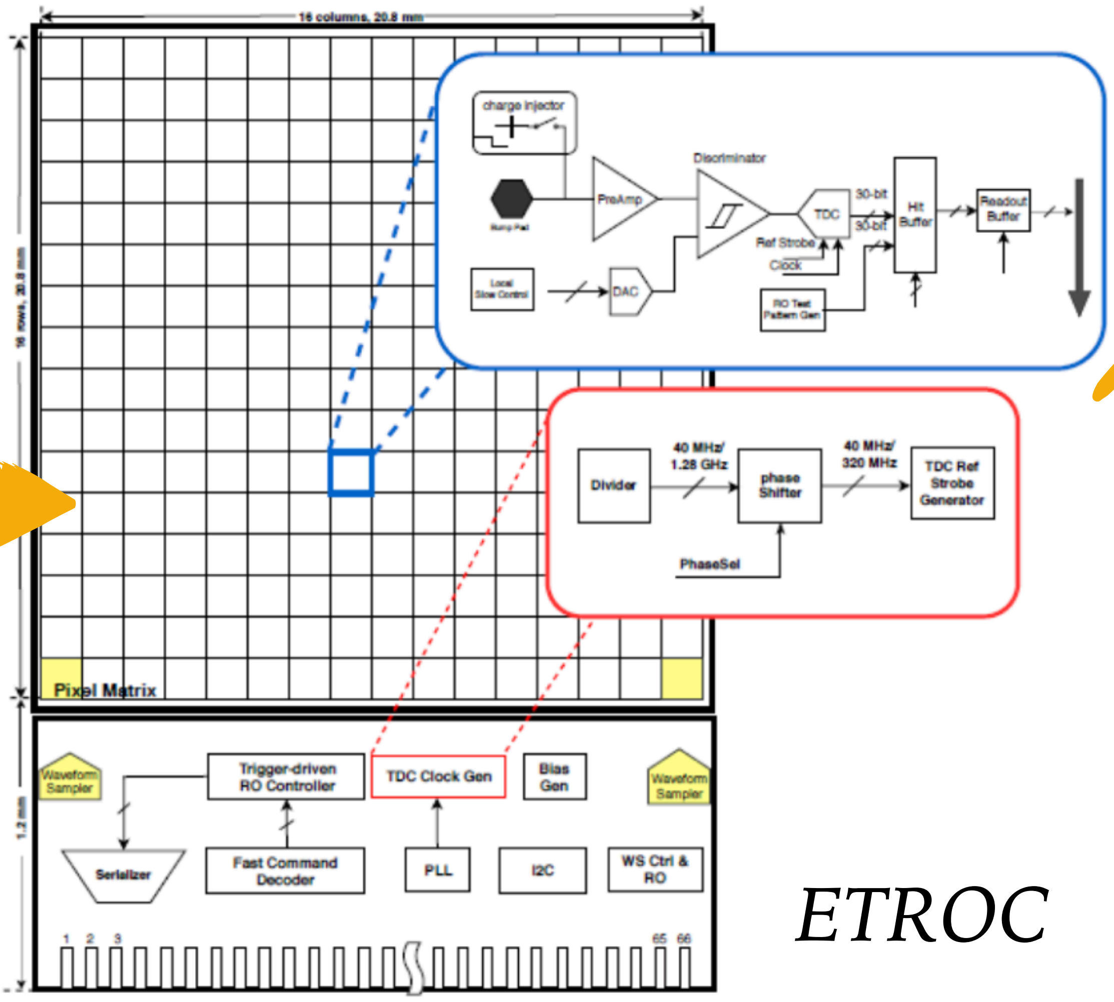


Final sensor

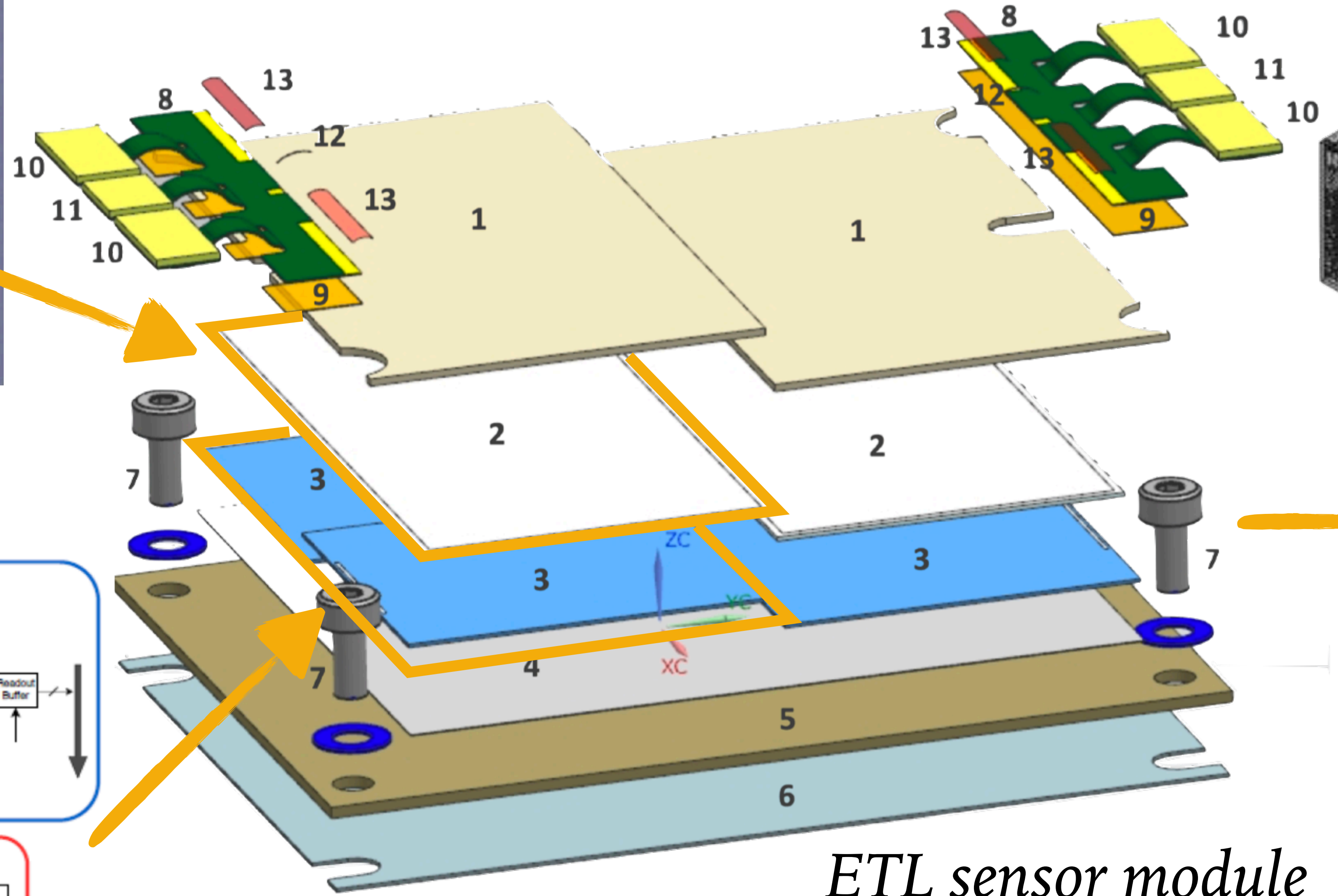


R&D productions

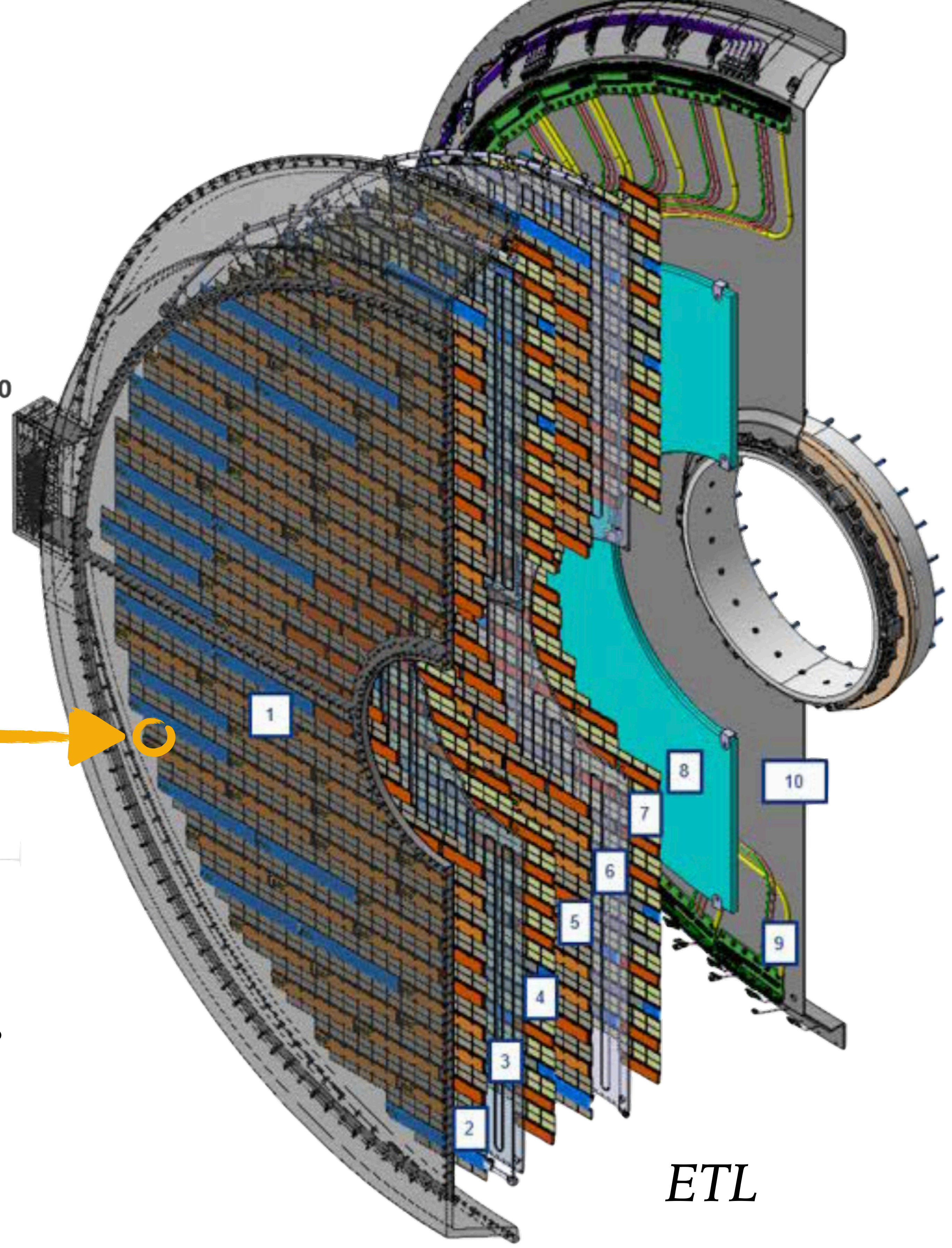




ETROC

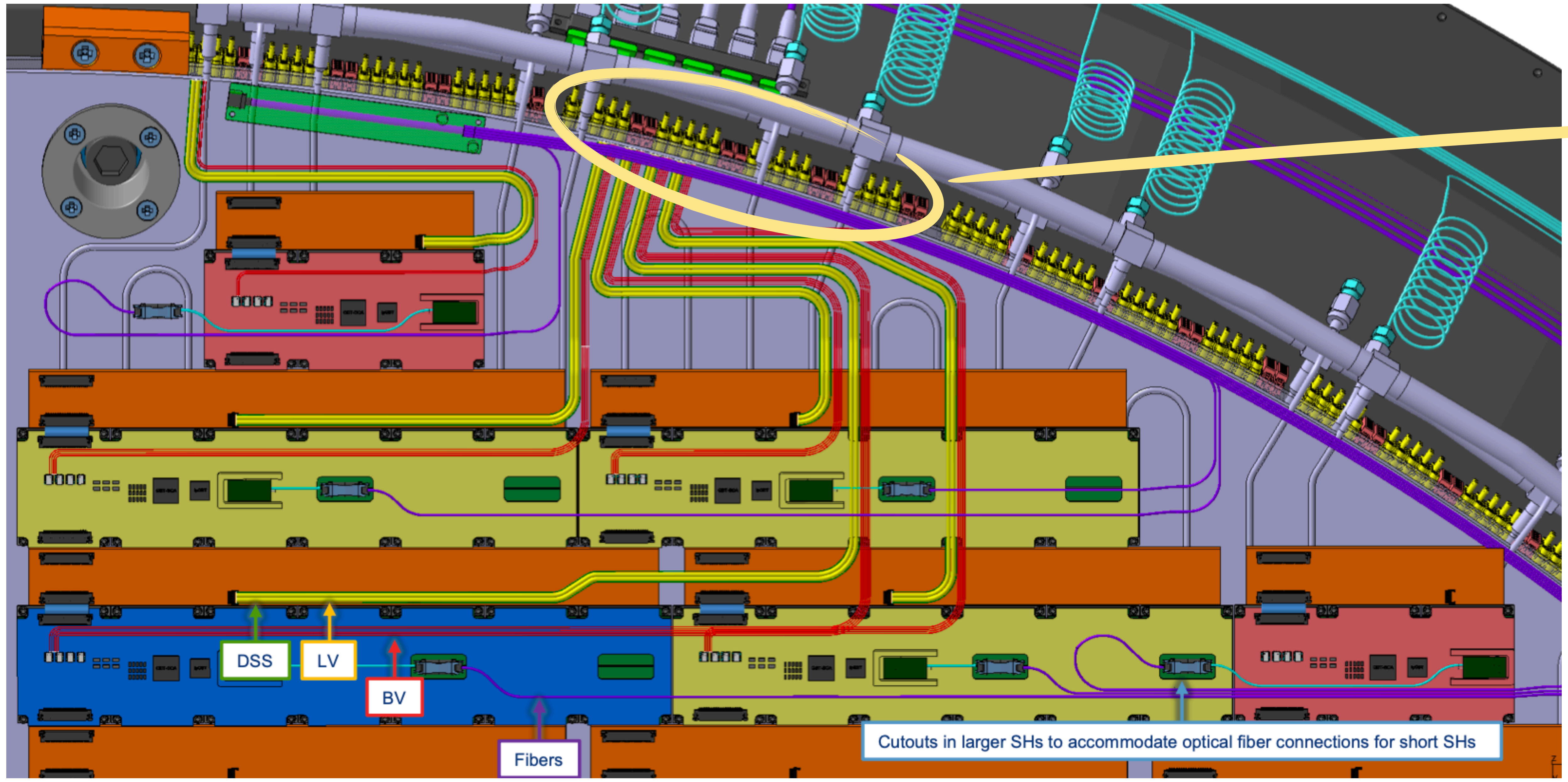


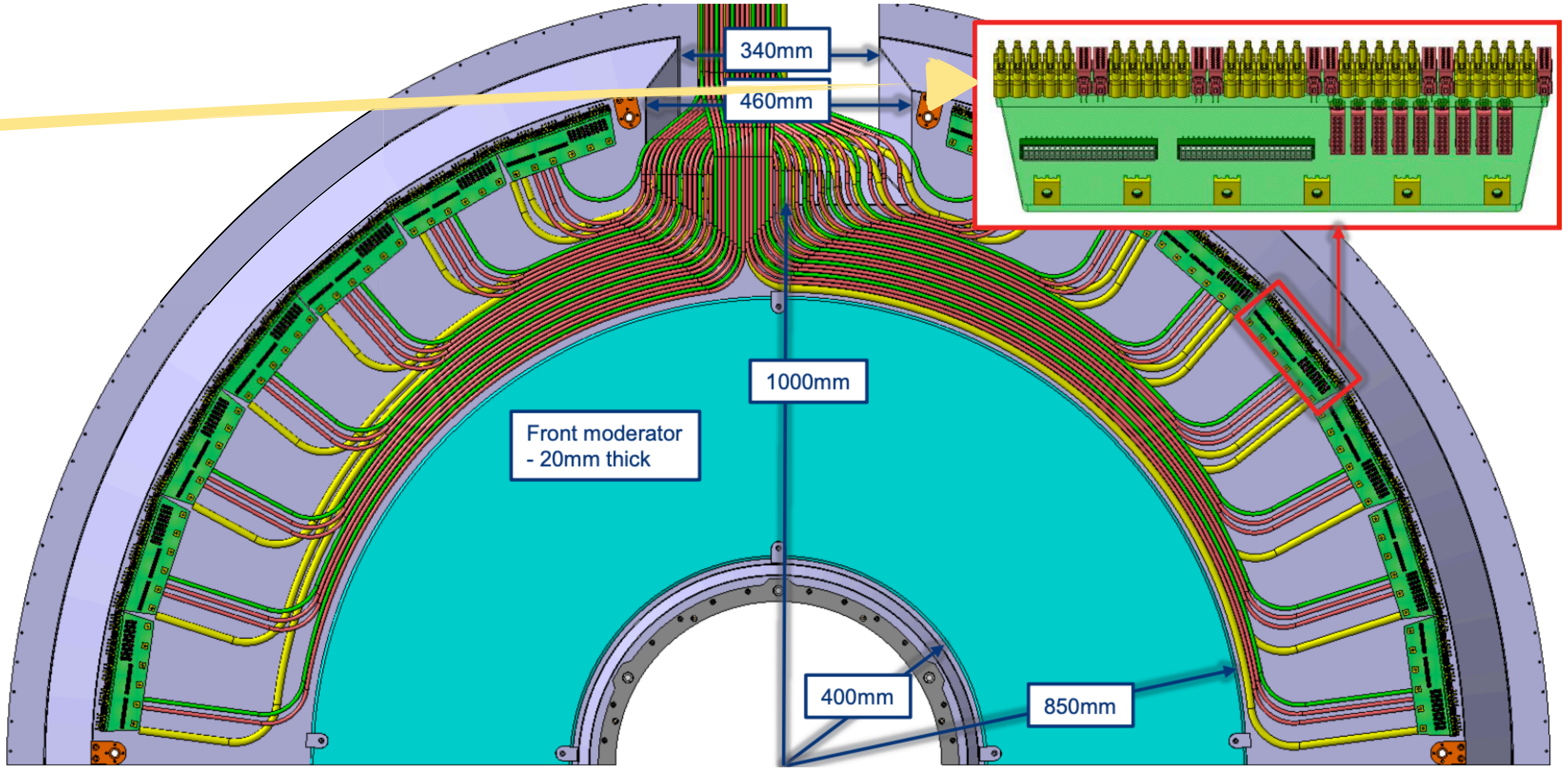
ETL sensor module

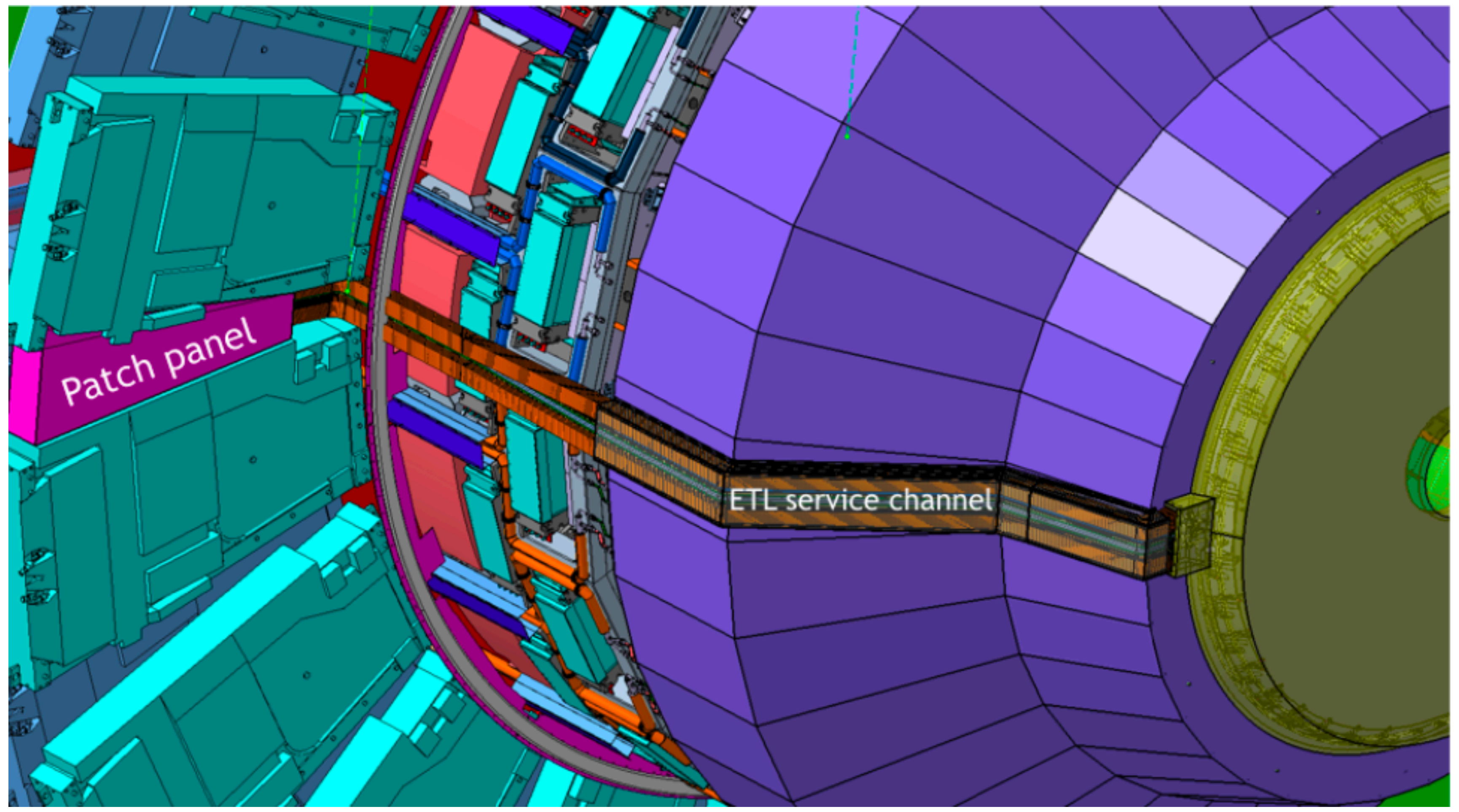


ETL

ETL services

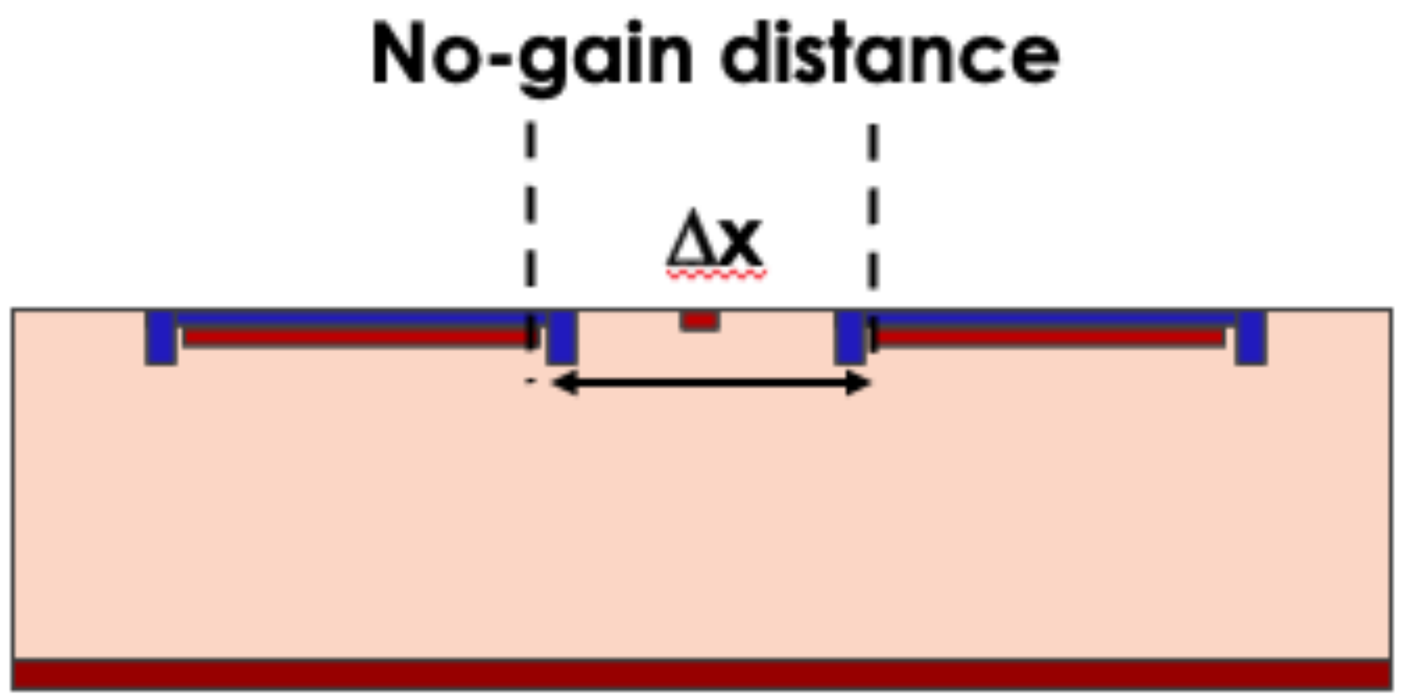


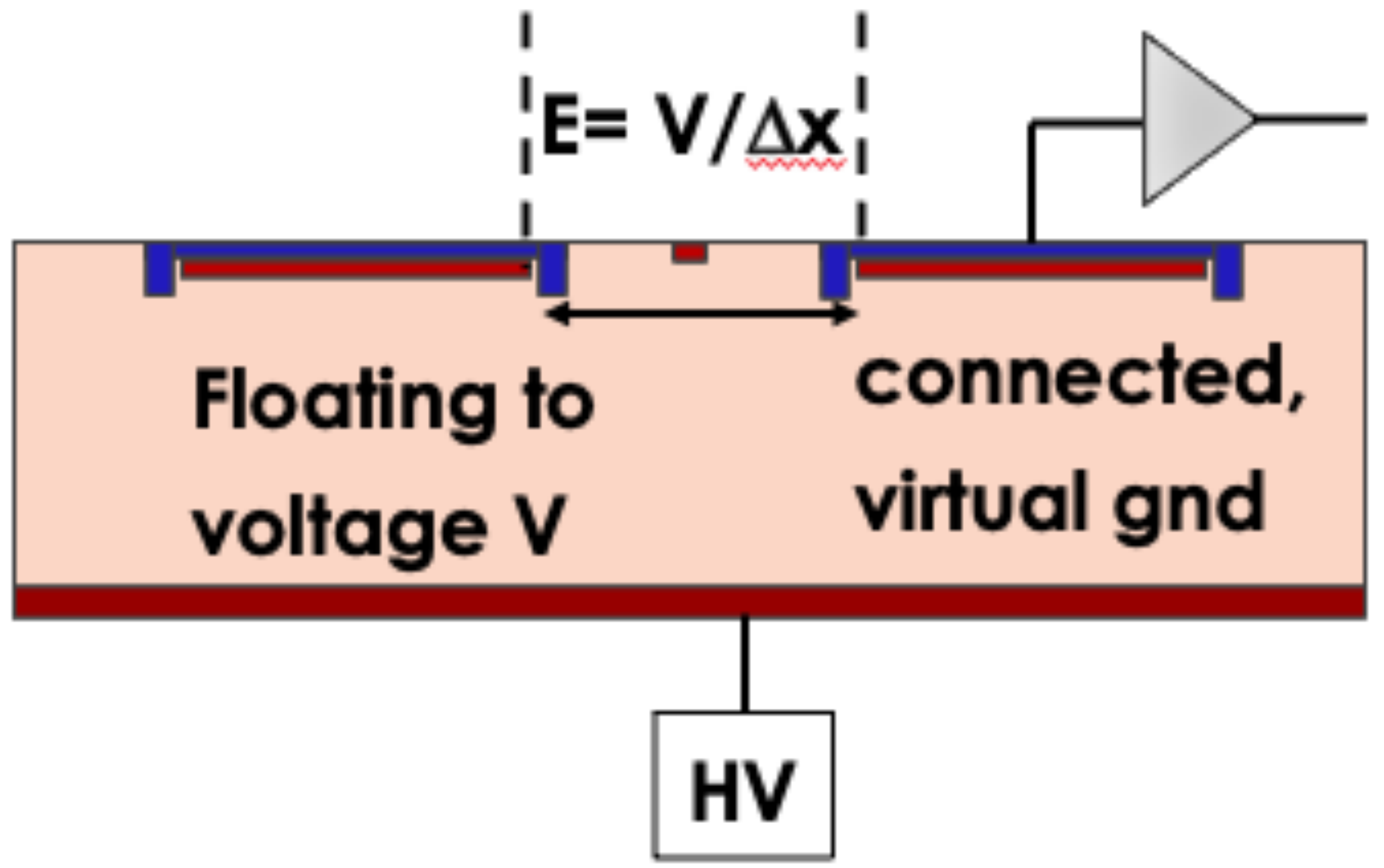


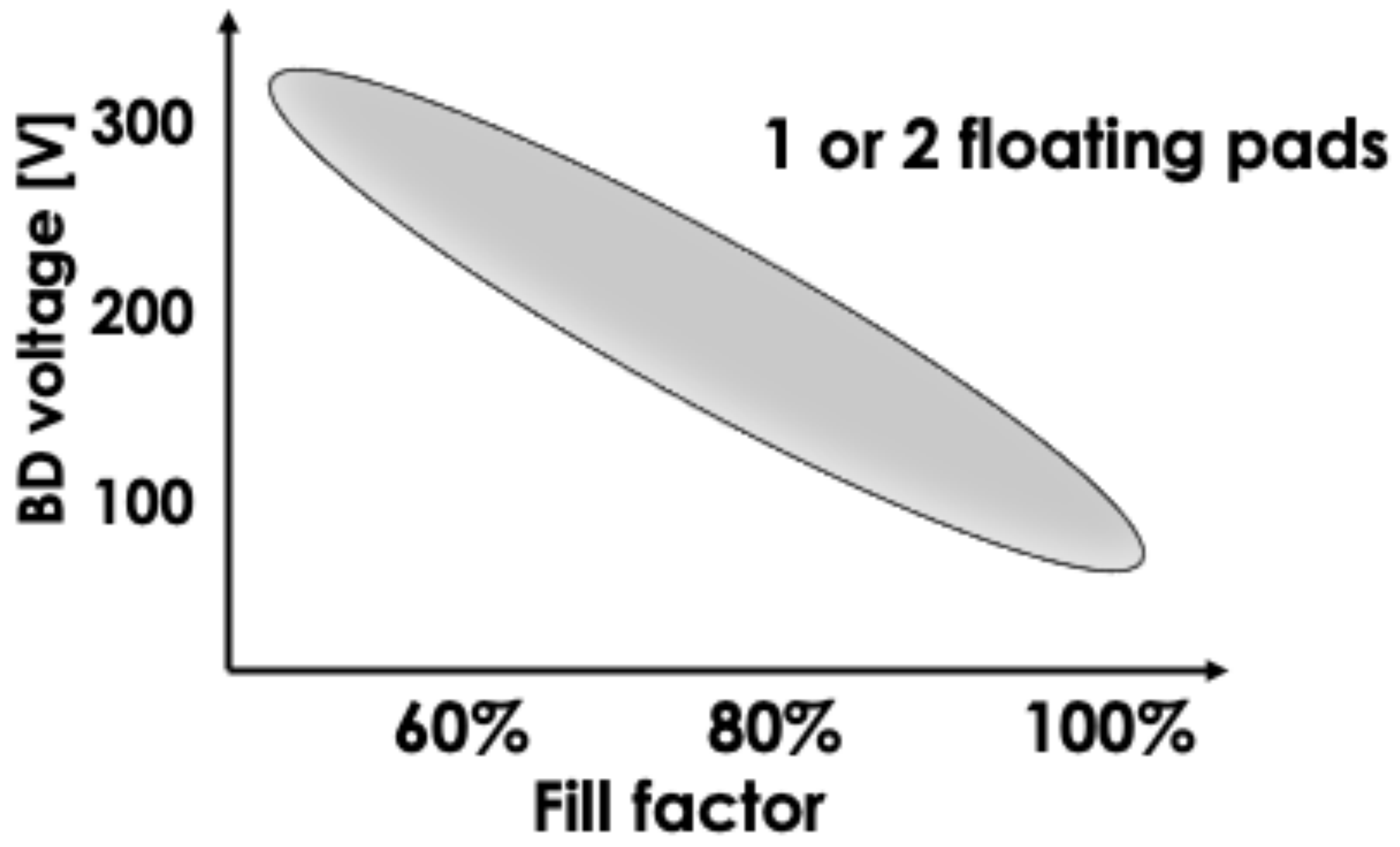


No-gain area and floating pad resiliency

Too narrow "No-gain" distances produce early breakdowns as floating pad resiliency gets worse



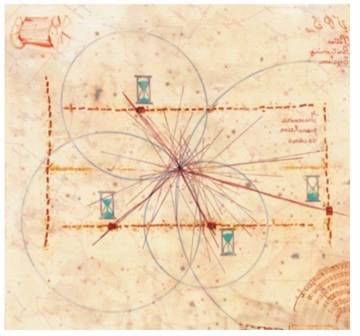




Need a compromise for interpad width:

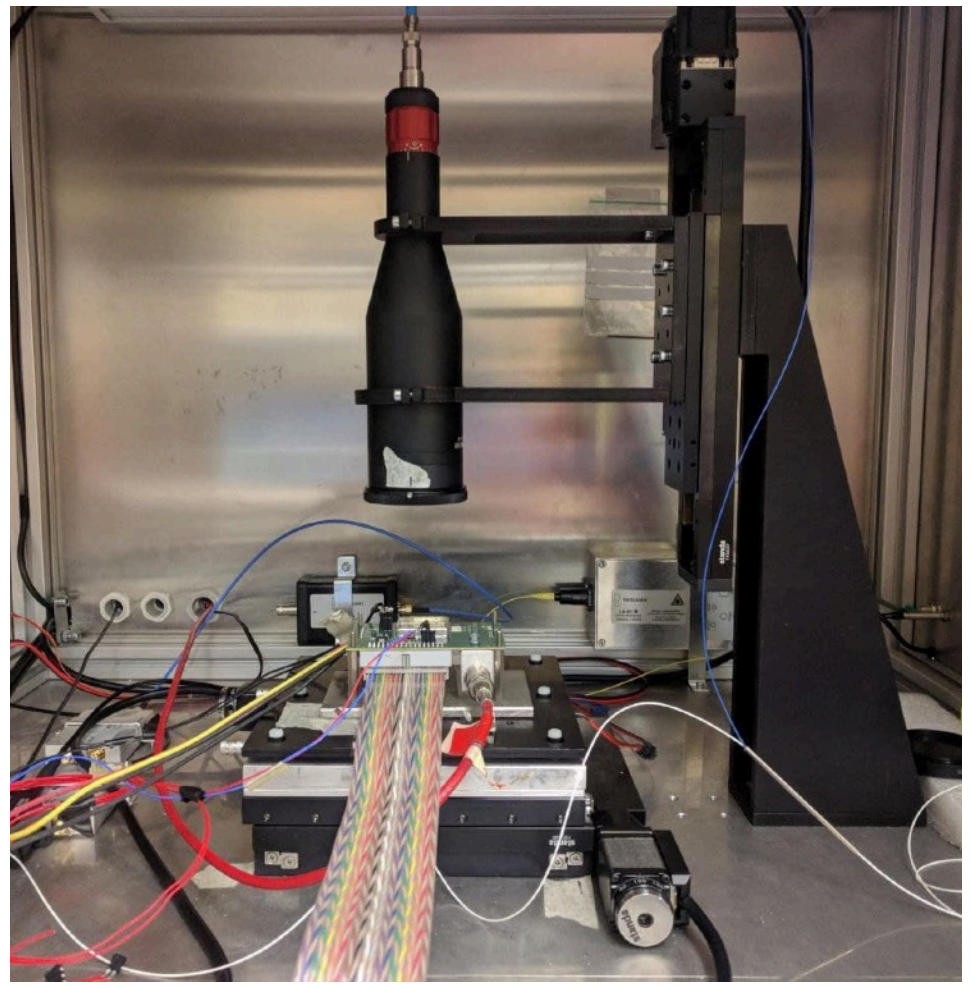
- *Narrow enough to allow ETL reaching >95% fill factor*
- *Large enough to avoid early breakdown due to bad floating pad resiliency*

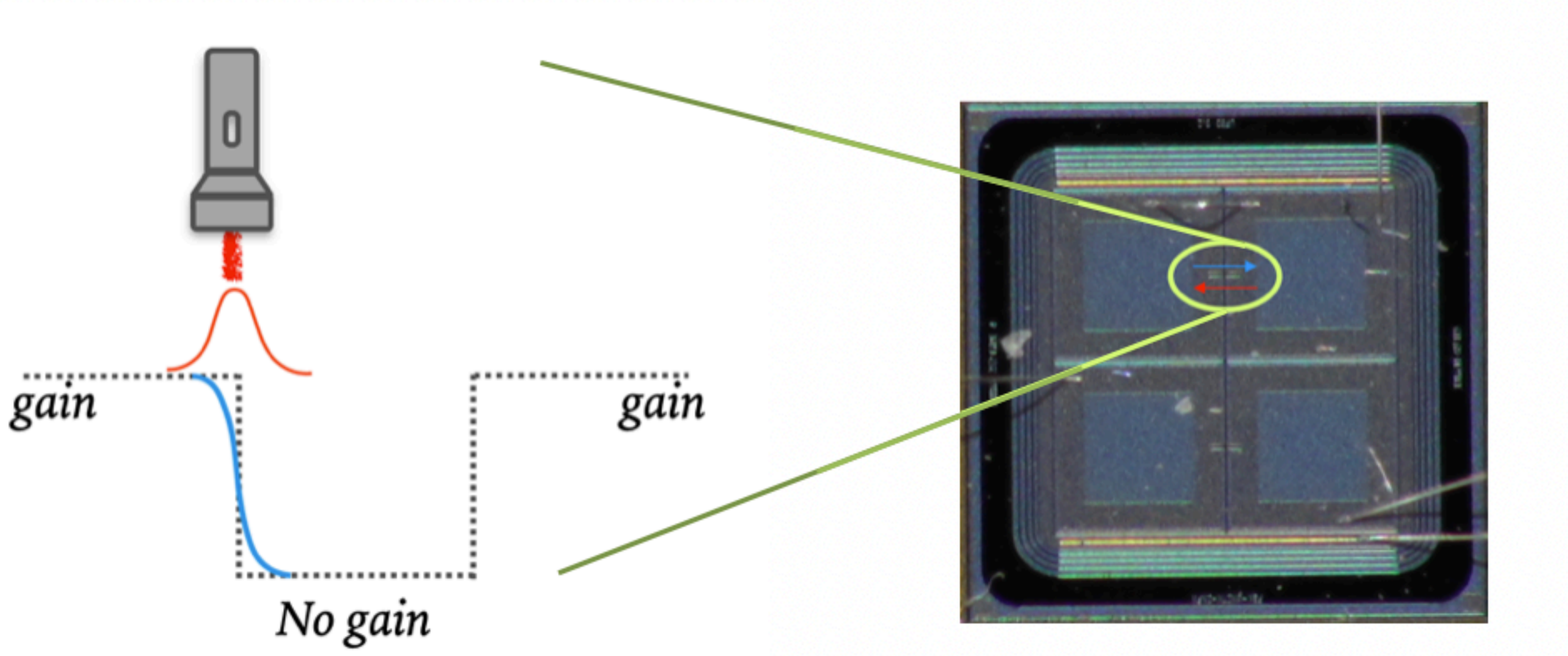
Laboratory measurements: no-gain area

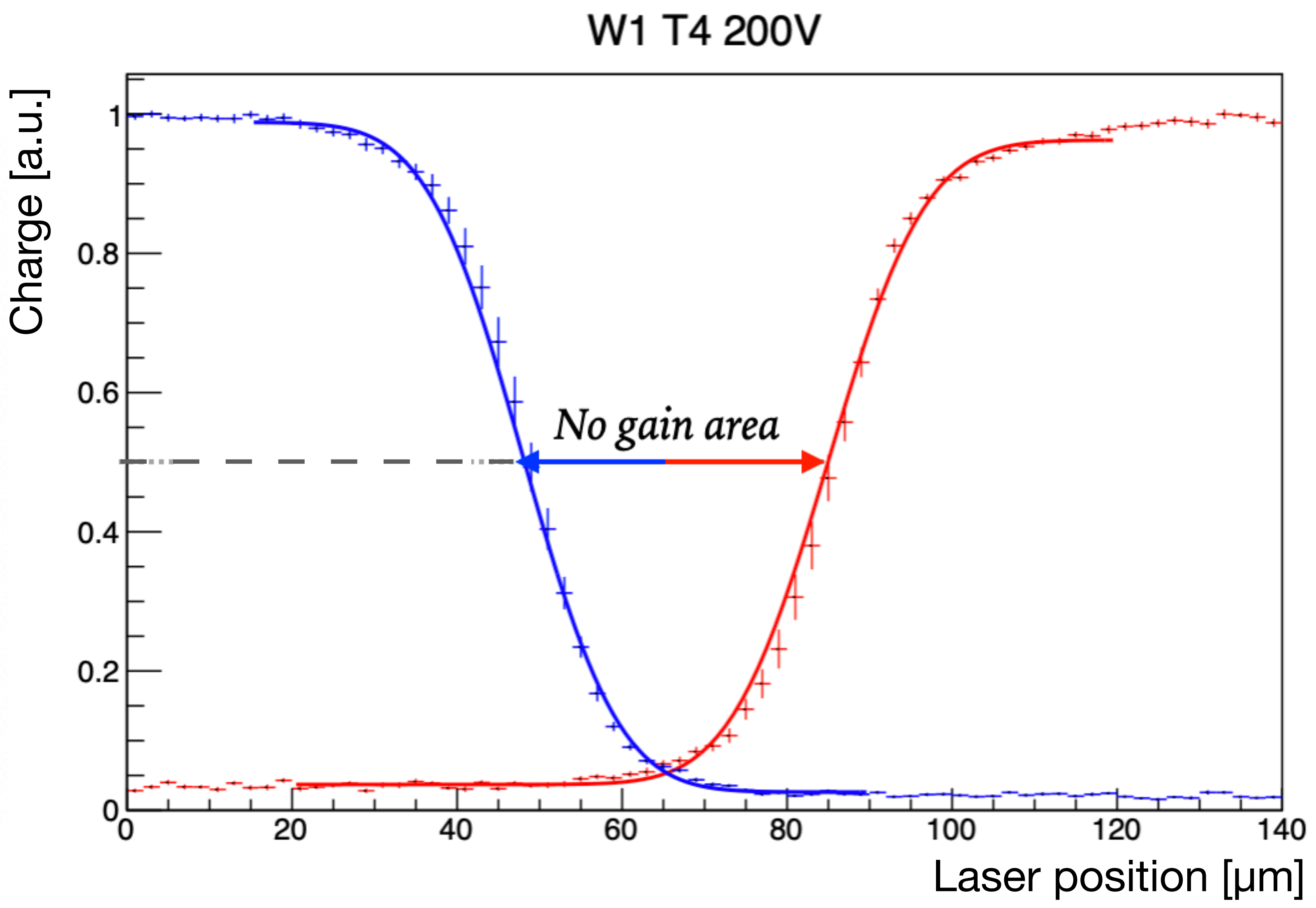


"No-gain" width measured with Particulars ***Transient Current Technique*** *setup*

- ***1D scan*** *with a* ***1060 nm picosecond laser*** *with* ***~10 μm spot*** *along the optical window between two pads*
- *Charge vs laser position fitted with an* ***S-curve****: convolution of* ***gain layer step function*** *and laser* ***gaussian beam profile***







Interpad area is evaluated as the ***distance between the points at 50% of the S-curve maximum*** *for the two measured pads*

Laboratory measurements: no-gain area

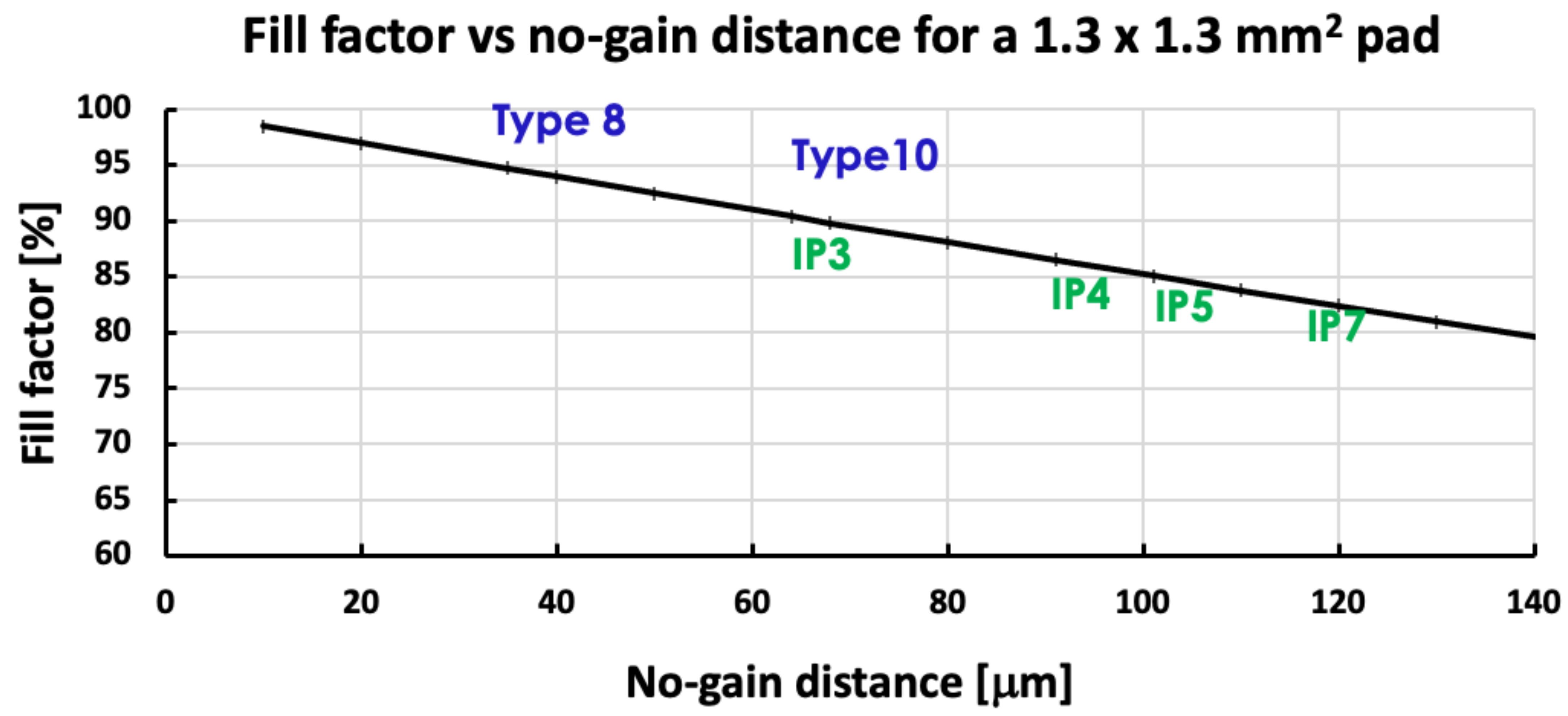
	Type (IP)	Vbias	No-gain [μm]	Fill factor	# Floating pad without effect in 2x2
UFSD3.2	T4	230	35.0	94.6%	?
UFSD3.2	T8	230	40.5	93.9%	?
UFSD3.2	T10	200	68.0	89.8%	?
HPK2	IP3	220	64.2	90.4%	2
HPK2	IP4	220	91.1	86.5%	all
HPK2	IP5	220	101.8	85%	all
HPK2	IP7	220	120.4	82.4%	all

No-gain area width results *from measurements on the latest productions*

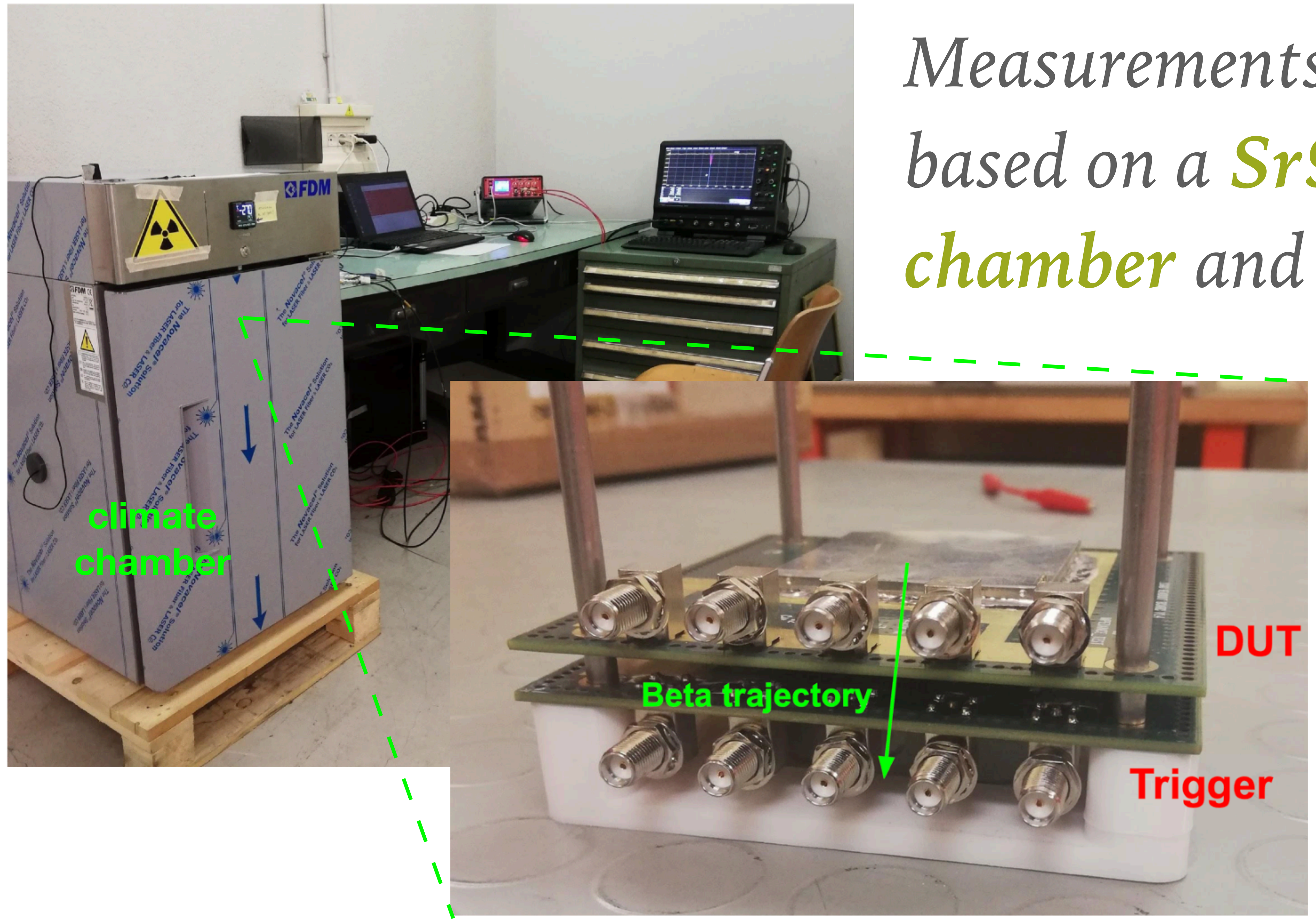
Smaller interpad designs:

- *Allow **better fill factor** for ETL*
- *Provide **worse protection from missing bumps***

→ *Need to perform the study after irradiation*



Laboratory measurements: timing resolution setups



*Measurements on FBK production performed with the **Torino Beta-source setup** based on a **Sr90 source** and provided with a **DUT+trigger telescope** in a **climate chamber** and an automated DAQ and analysis system*

*Results on FBK production obtained at **Fermilab SiDet Laboratory** with a setup equipped with a **Sr90 source**, **DUT** mounted on a **cooling block** and an **MCP** used as time reference and trigger*