Status and plan for CEPC vertex detector

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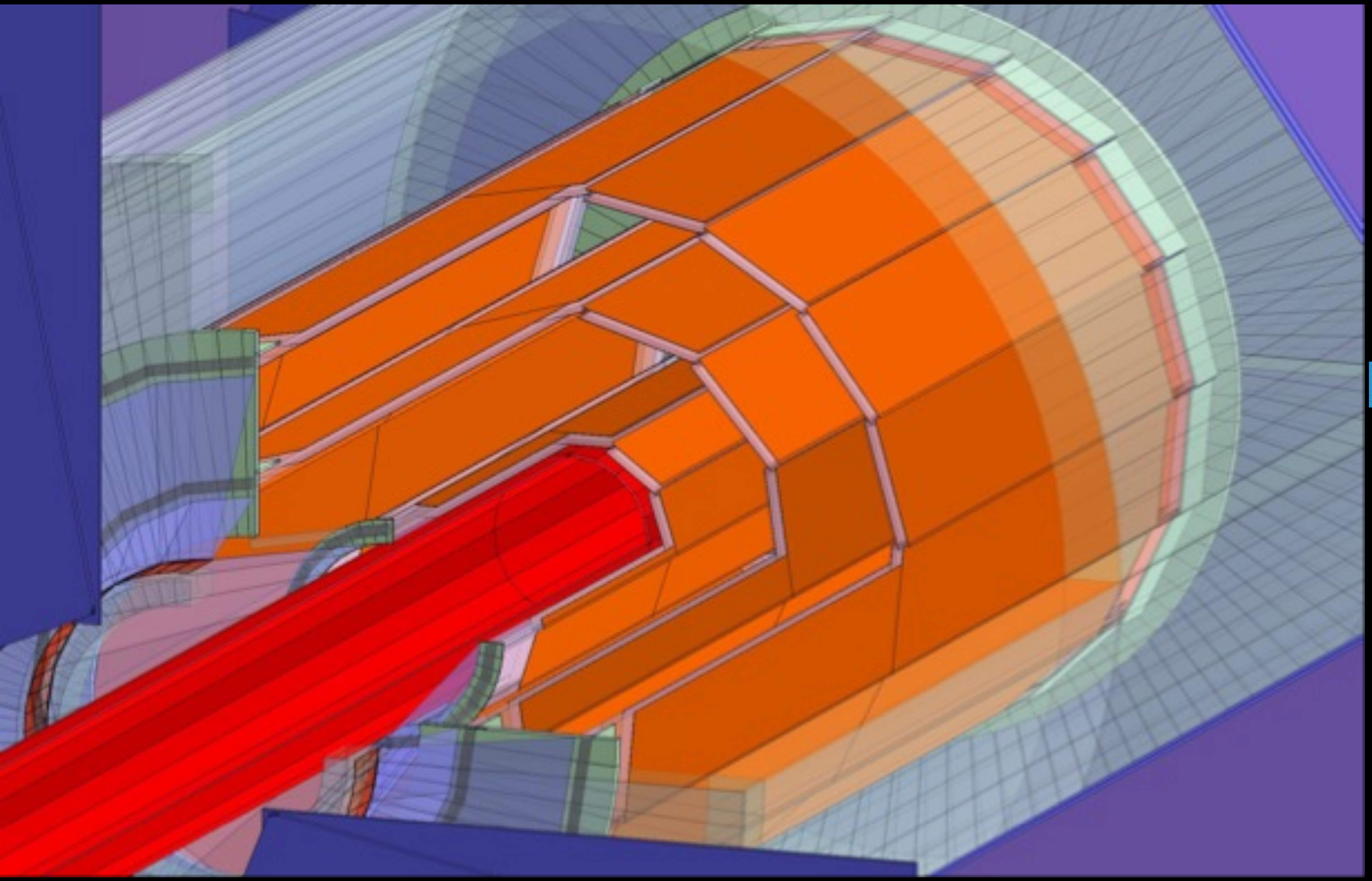
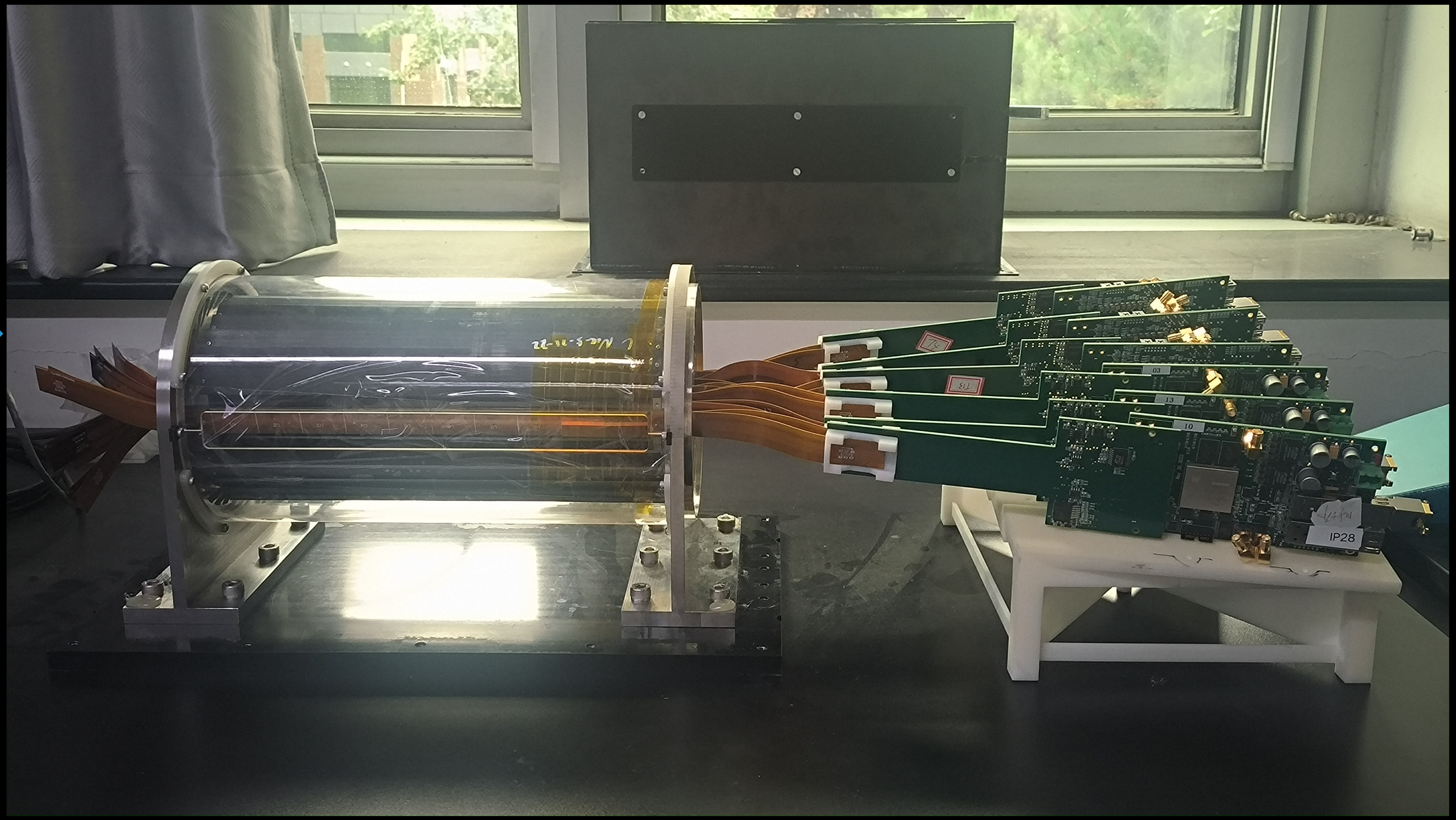
For the CEPC vertex detector prototype team

Overview of CEPC vertex detector R & D

CEPC design (2016)



Vertex detector prototype (2023)



Plan toward TDR

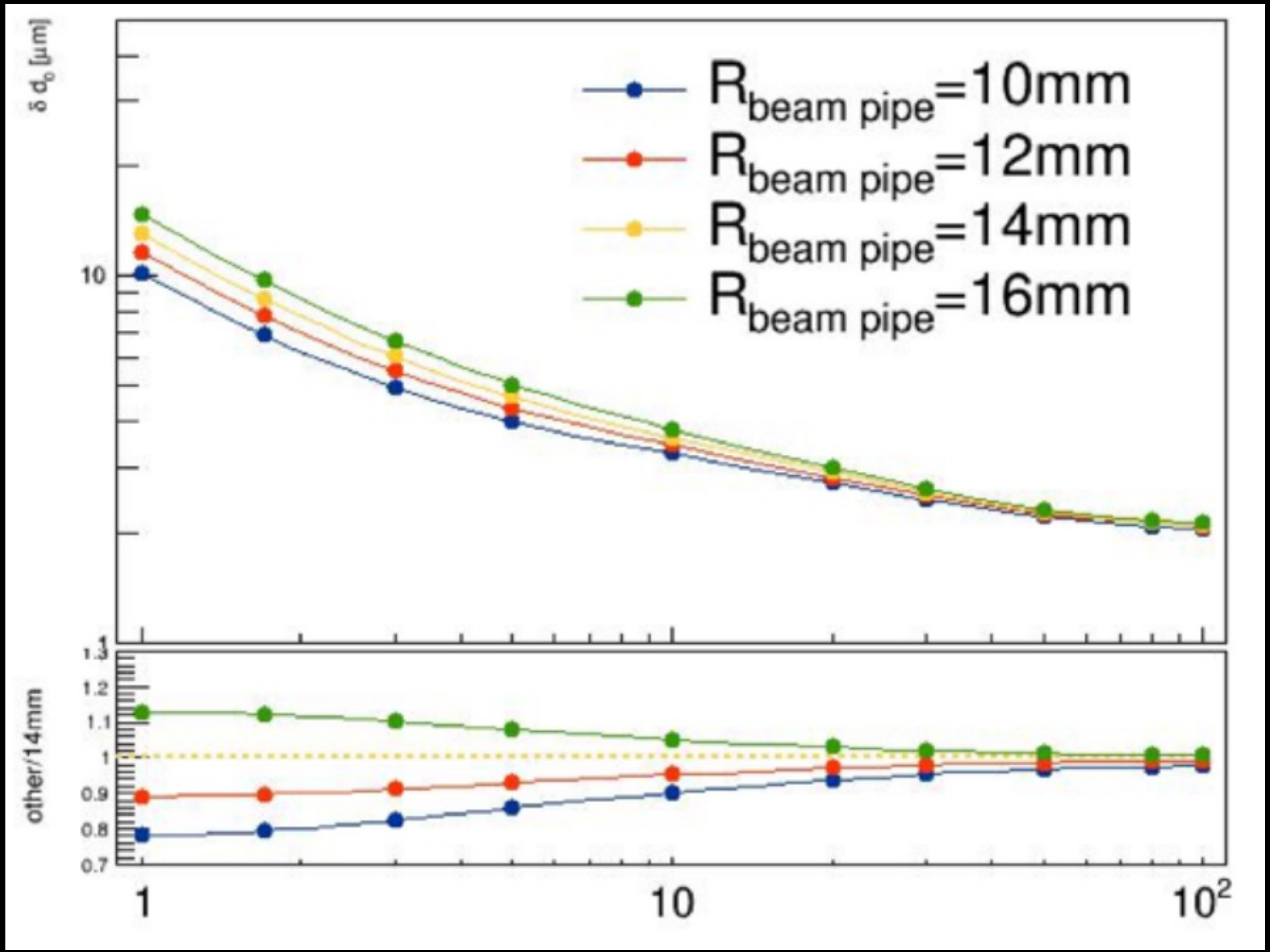
- Major change from CDR to TDR
  - Beam pipe diameter: 28mm (CDR) → 20mm (TDR) (reduce 30%)
  - Instant Luminosity per IP:
    - Z pole: 32×10^{34} $cm^{-2}s^{-1}$ (CDR) → 192 $\times10^{34}$ $cm^{-2}s^{-1}$ (TDR, 50MW) (6 times increase)
    - ZH: 5.6×10^{34} $cm^{-2}s^{-1}$ (CDR) → 8.3 $\times10^{34}$ $cm^{-2}s^{-1}$ (TDR) (~1.5 times increase)

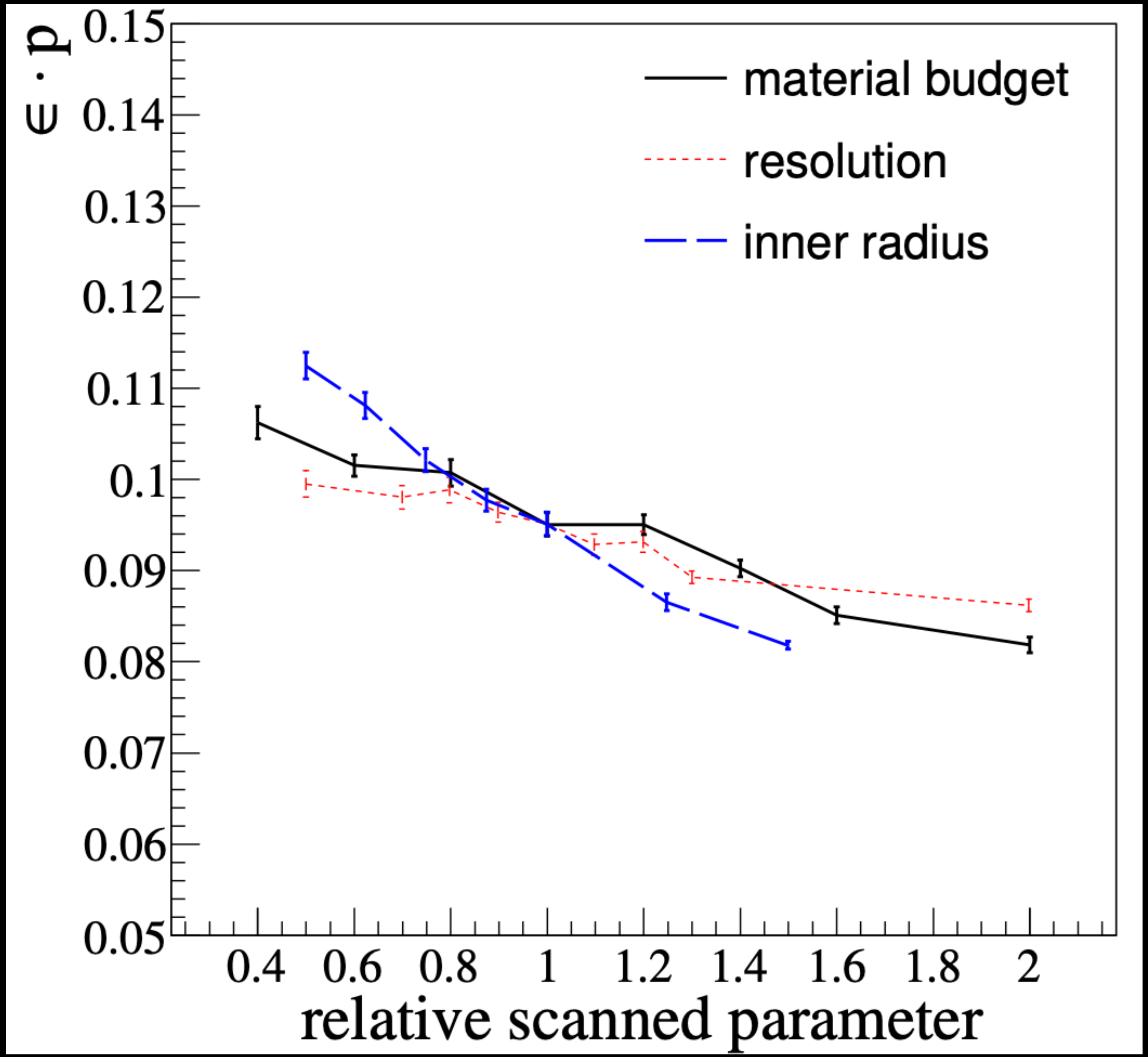
- Action item
  - Optimize the geometry
    - Whether we can reduce the radius of the first vertex layer , put it close to beam pipe
      - First vertex layer: Radius=12mm (TDR candidate) or Radius =16mm (CDR design) ?
  - Estimate the hit rate from background
  - Fluence and total ionization dose estimation

Vertex detector optimization for TDR

C-tagging performance

- 1st priority: Small inner radius, close to beam pipe (new baseline beam pipe radius=10um)
- 2nd priority: Low material budget <0.15% X0 per layer
- 3rd priority: High resolution pixel sensor： 3~5 μm
- Global Timing resolution of CEPC tracker: ~25ns (40MHz collision @ Z pole)

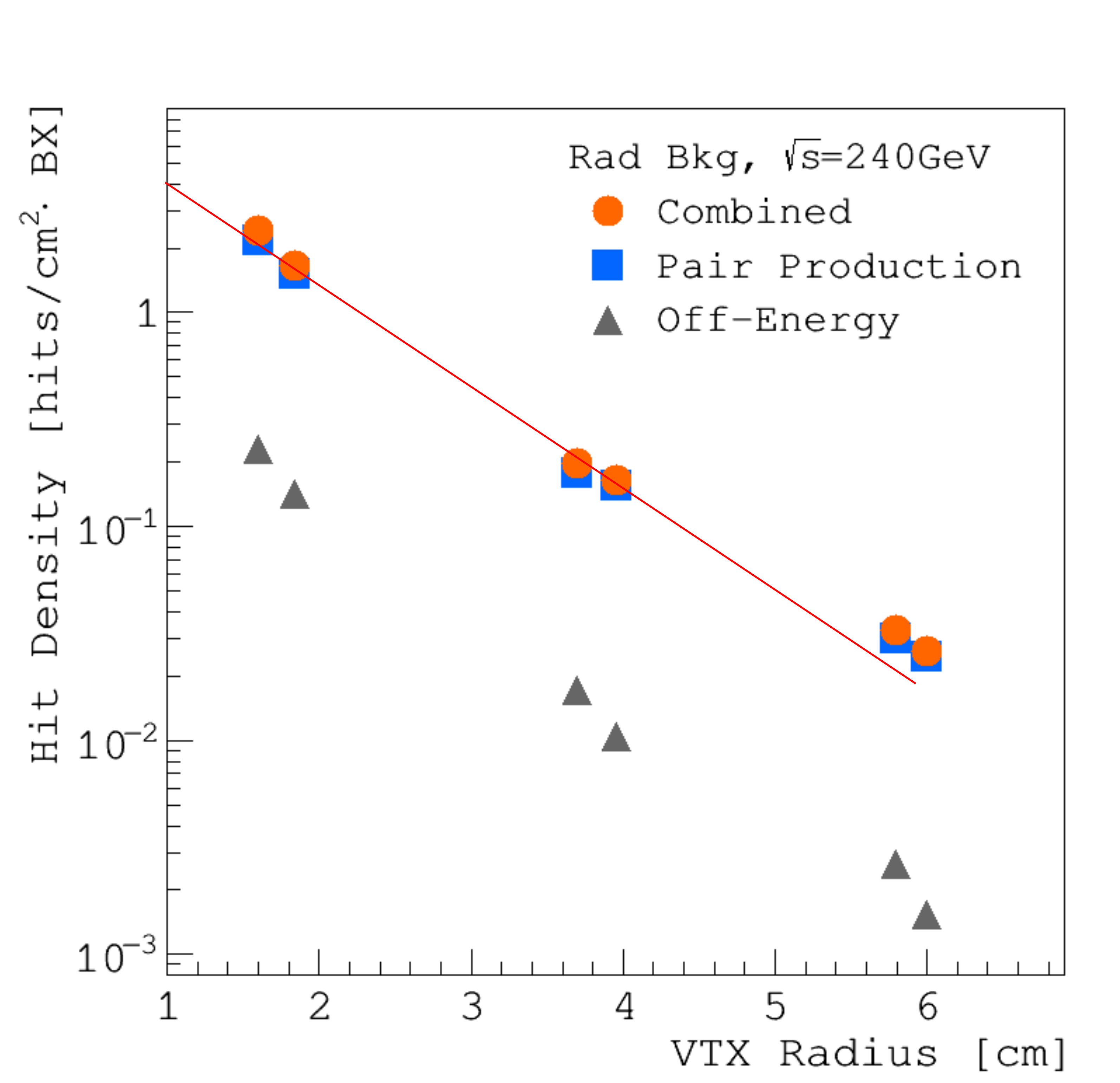




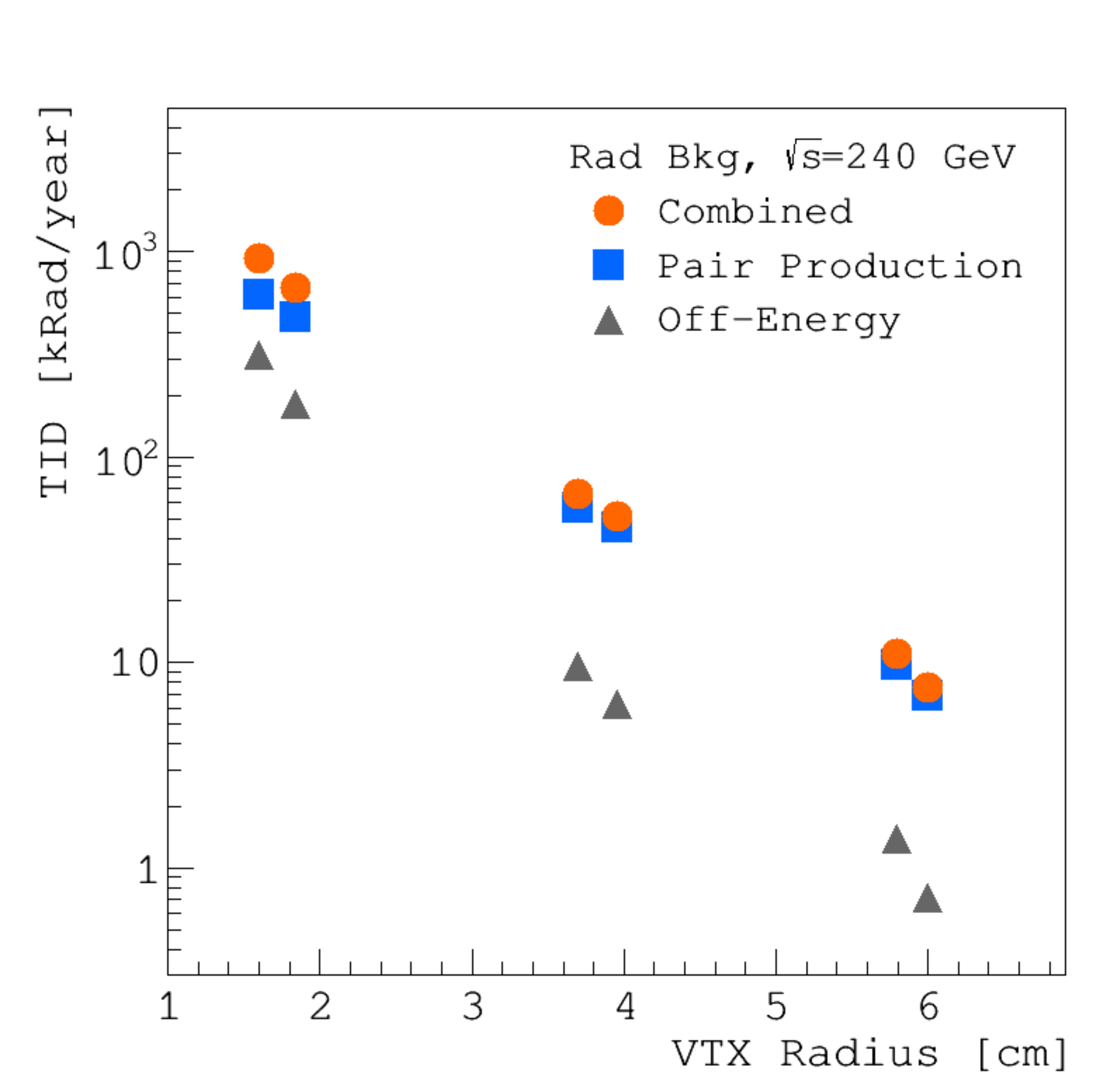
Hit rate and radiation from background (input for vertex)

- Waiting for the update on background estimation (Haoyu)
- First guess of background based on input (Haoyu)
  - Instant Luminosity increase → radiation hardness requirement increased, tiny impact on hit density
  - Beam pipe diameter: 28mm → 20mm : Expect 3-5 times larger hit density and radiation

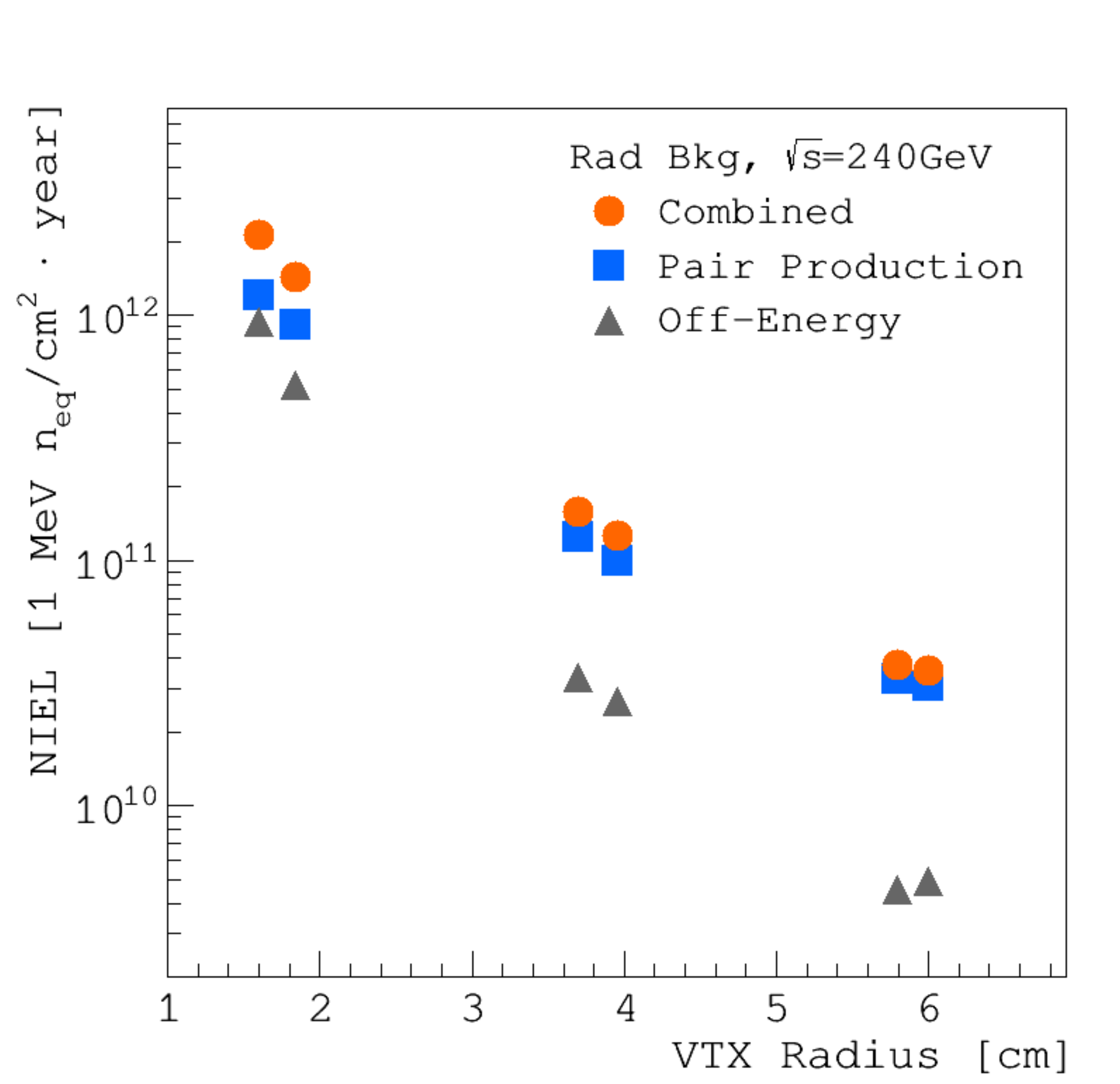
Hit density per crossing (CDR)



Total ionization dose (CDR)



Fluence (CDR)



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Hit rate and radiation from Background (CDR study, from Haoyu)

- Preliminary results on 1st layer of vertex. Safety factor of 10 applied.

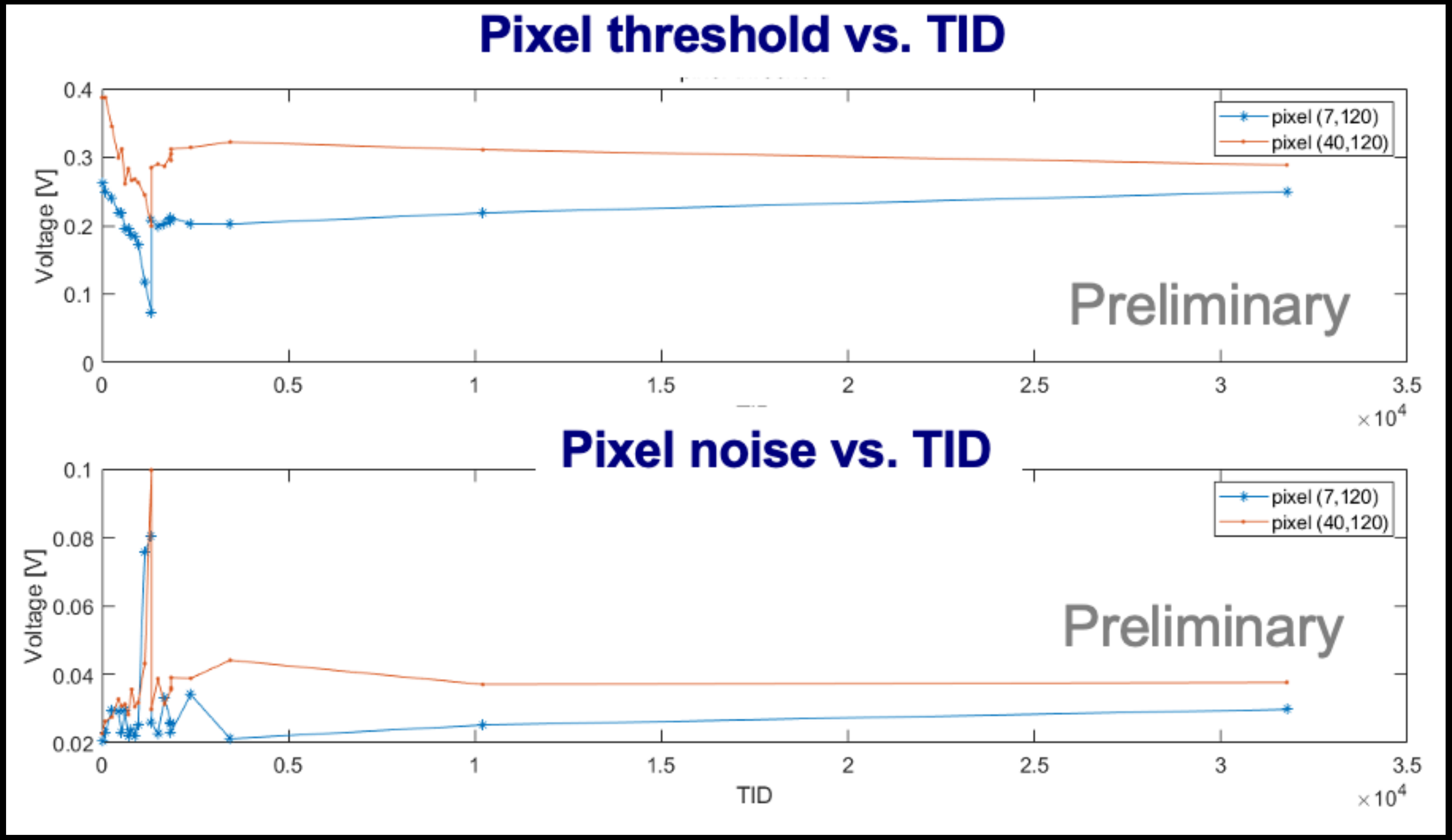
Background	Hit Density($cm^{-2} \cdot BX^{-1}$)			TID($Mrad \cdot yr^{-1}$)			1 MeV equivalent neutron fluence ($n_{eq} \times 10^{12} \cdot cm^{-2} \cdot yr^{-1}$)		
	Higgs	W	Z	Higgs	W	Z	Higgs	W	Z
Pair production	1.8	1.2	0.4	0.50	2.1	5.6	1.0	3.8	10.6
Beam Gas	0.4	0.4	0.2	0.36	1.3	4.1	1.0	3.6	11.1
Total	2.17	1.6	0.6	0.86	3.4	9.7	2.0	7.4	21.7

Radiation hardness (Total ionization dose)

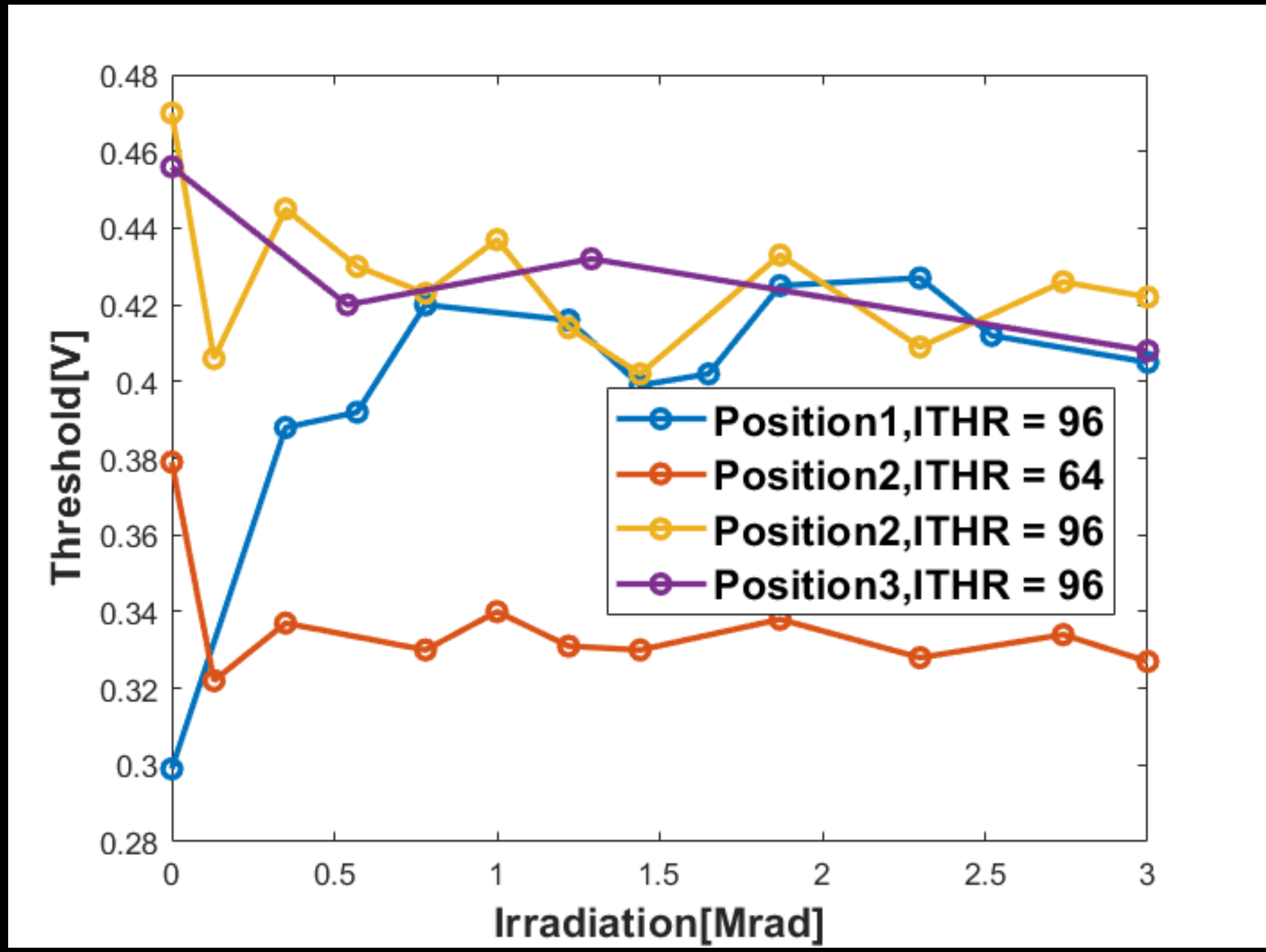
- First guess on Radiation requirement (need final input from Haoyu):
- Taichupix2 was irradiated in-situ tested up to 30 Mrad
- Based on LHC experience, chip have potential to survive serval hundred Mrad

Initial input on TID	First layer radius=16mm (CDR vertex design)	First layer radius=12mm (TDR design candidate)
ZH (240GeV)	~1 Mrad/year	3-5 Mrad/year
Z pole (91GeV)	~60 Mrad/year	200-300 Mrad/year

Taichupix2 irradiation test



Taichupix3 irradiation test
Pixel threshold vs. TID



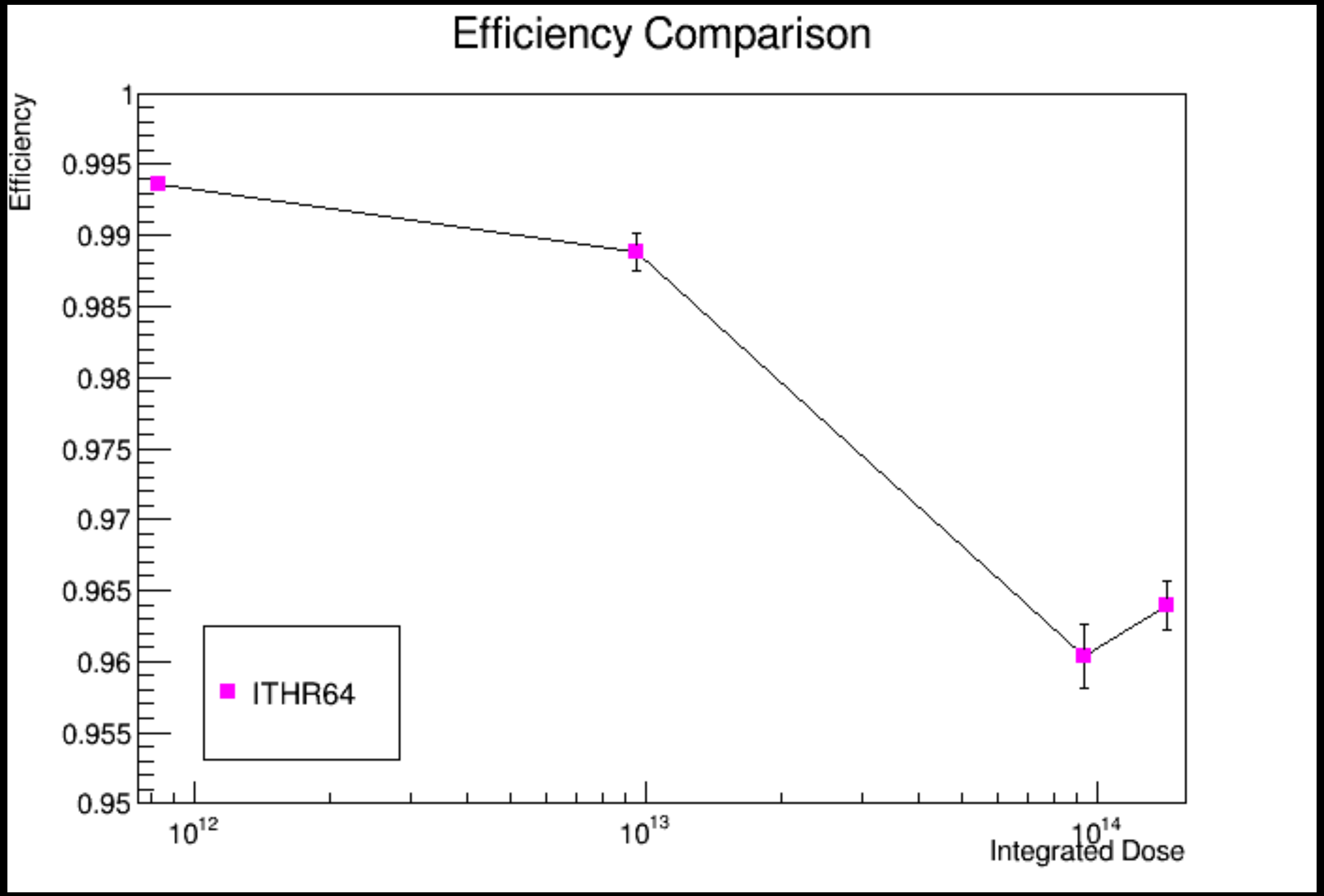
Radiation hardness (neutron Fluence)

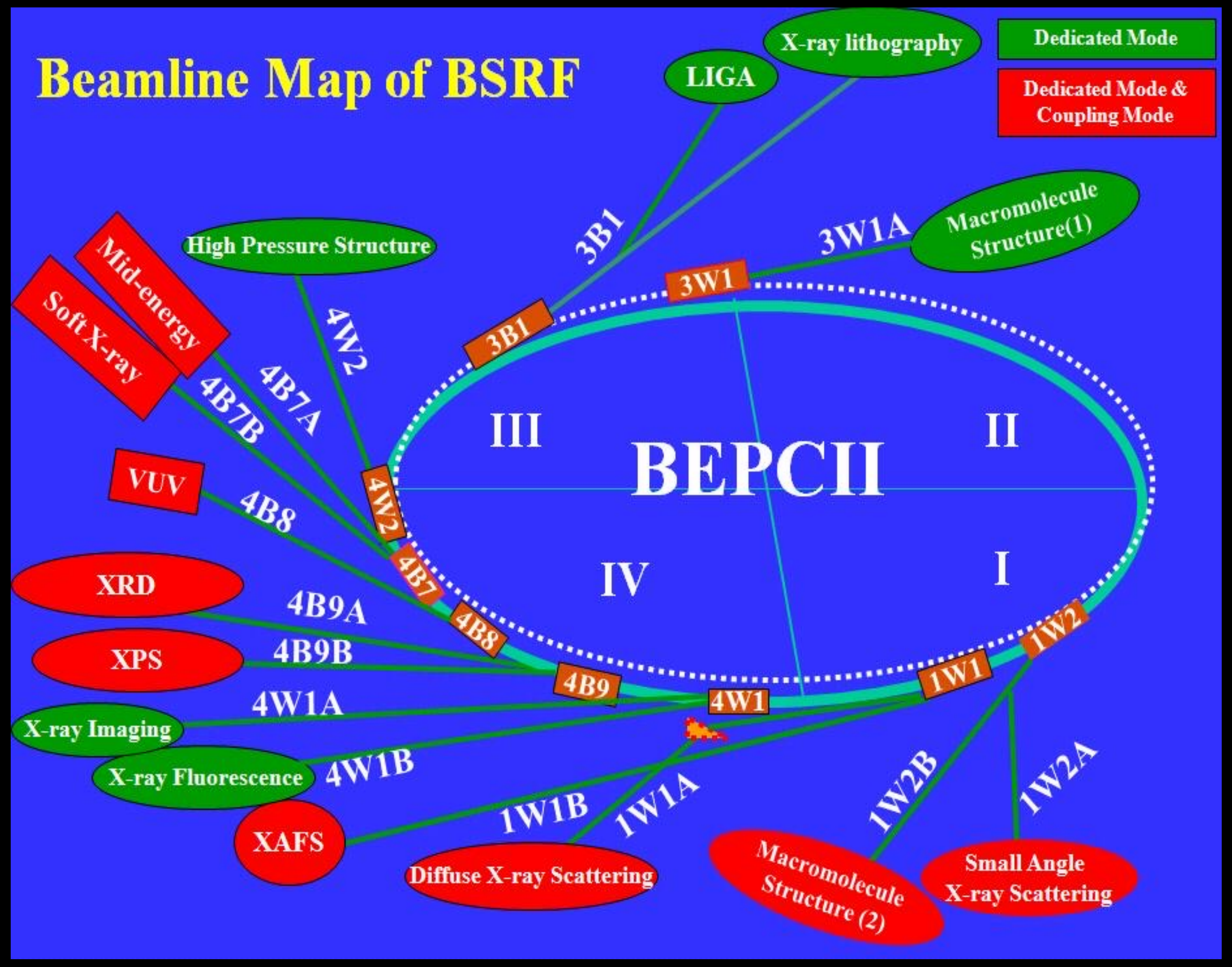
- First guess on Radiation requirement (need final input from Haoyu):
- CDR requirement: ~2*$\mathbf{10^{13}} \boldsymbol{n_{eq}} \cdot \boldsymbol{cm\text{-}2 \cdot yr}$
- TDR requirement: 1-6 *$\mathbf{10^{14}} \boldsymbol{n_{eq}} \cdot \boldsymbol{cm\text{-}2 \cdot yr}$ (depending on radius)
  - Whether CEPC MAPS sensor can survive $\mathbf{10^{14}} \boldsymbol{n_{eq}} \cdot \boldsymbol{cm\text{-}2}$?

neutron fluence $\boldsymbol{n_{eq}}\ \mathbf{10^{12}} \cdot \boldsymbol{cm\text{-}2 \cdot yr}$	First layer radius=16mm (CDR vertex design)	First layer radius=12mm (TDR design candidate)
ZH (240GeV)	3	9-15
Z pole (91GeV)	120	360-600

Radiation hardness (neutron Fluence)

- Beam test for irradiated TaichuPix @BSRF (Nov 2023)
  - Radiation of Taichu @ CSNS (up to $1.5*\mathbf{10^{14}} \boldsymbol{n_{eq}}$)
  - DUT is irradiated TaichuPix with modified process
  - Preliminary result
    - Efficiency >99% @ $\mathbf{10^{13}} \boldsymbol{n_{eq}}$
    - Efficiency >95% @ $1.5*\ \mathbf{10^{14}} \boldsymbol{n_{eq}}$





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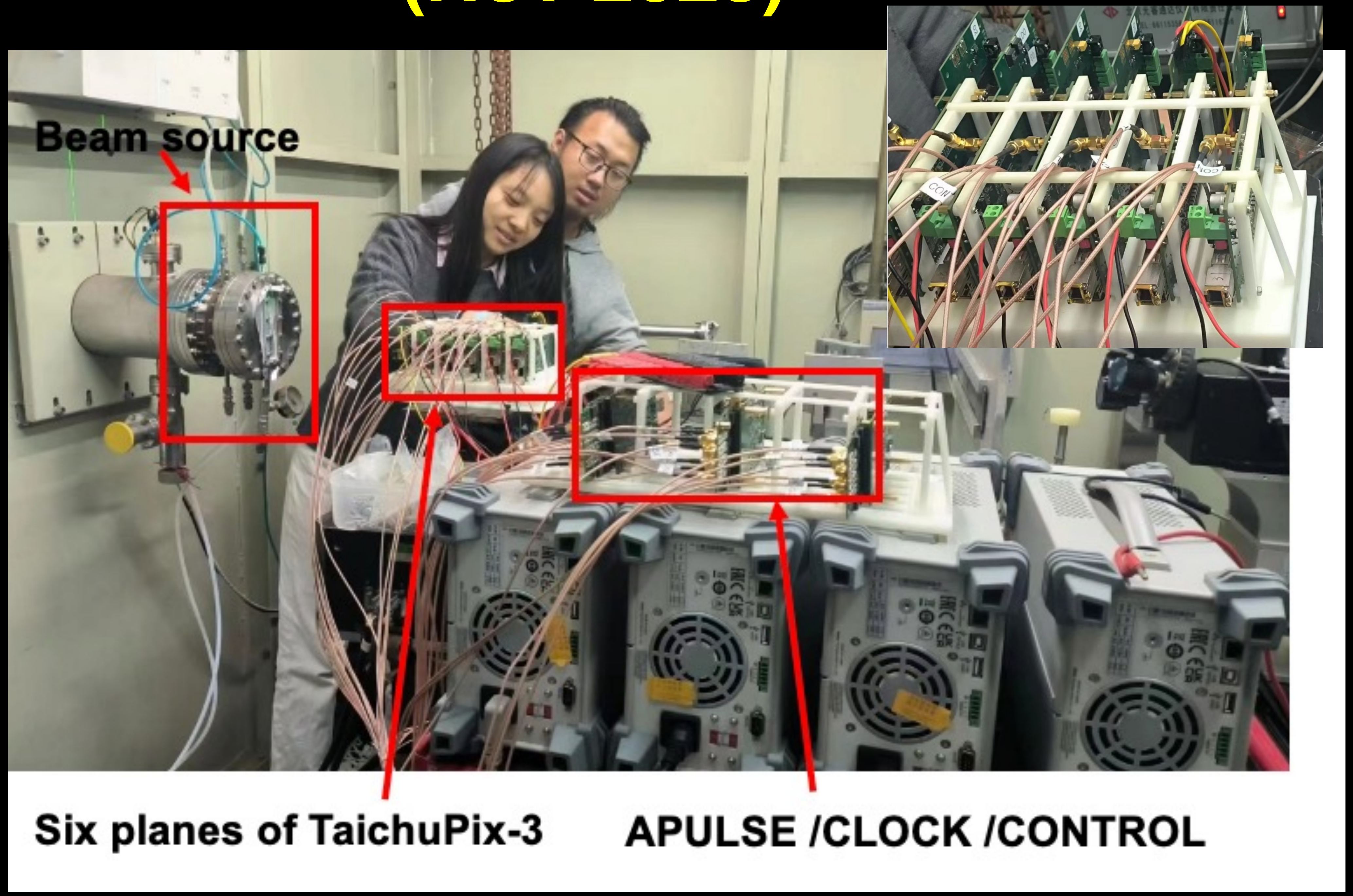


Hit density

- First guess on Radiation requirement (need final input from Haoyu):
- CDR : ~2 hits cm^{-2} BX^{-1}
- TDR requirement: 2~10 hits cm^{-2} BX^{-1}(depending on radius)

Hit density Hits cm^{-2} BX^{-1}	First layer radius=16mm (CDR vertex design)	First layer radius=12mm (TDR design candidate)
ZH (240GeV)	~2	6-10
Z pole (91GeV)	0.6	1.8-3

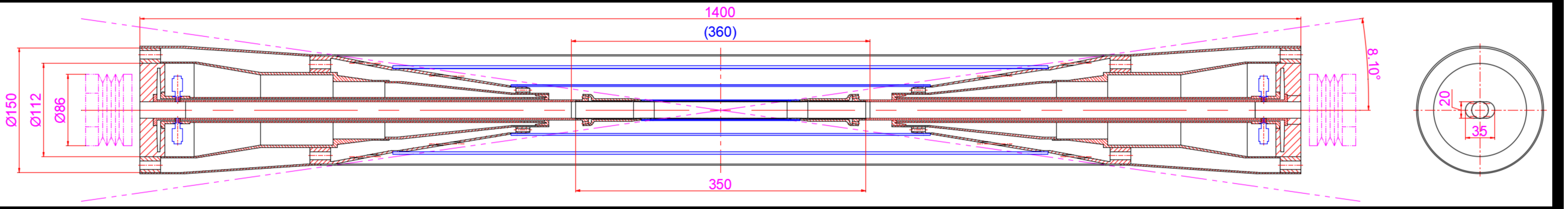
Data rate per chip (triggerless)	First layer radius=16mm (CDR vertex design) From Weiwei	First layer radius=12mm (TDR design candidate)
ZH (240GeV)	1.3 Gbps	4-6.5 Gbps
Z pole (91GeV)	2.6 GBps	8-13 Gbps

Summary： Action item

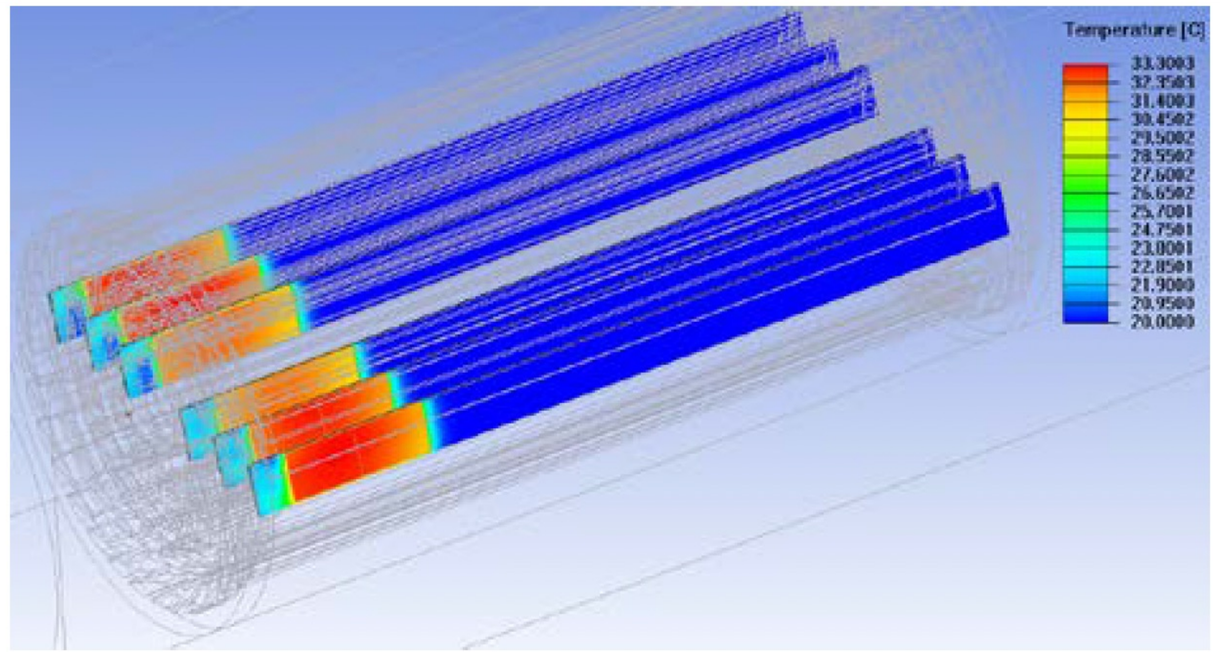
- Based on initial input of background, compare advantage and disadvantage of different layout
  - First layer radius 12mm Vs 16mm
  - Still waiting for final input of background from MDI group (Haoyu)

- Revisit vertex time resolution and occupancy, spatial resolution requirement
  - Roadmap for R & D (Taichu –like/ Jadepix –like architecture)
  - Finalize the readout architecture design (need to consider trigger design)

- Integration vertex design with beam pipe in MDI region
  - For Cooling design and support structure, Cabling, and frontend boards location



Prototype cooling simulation： Max 33.3 ℃



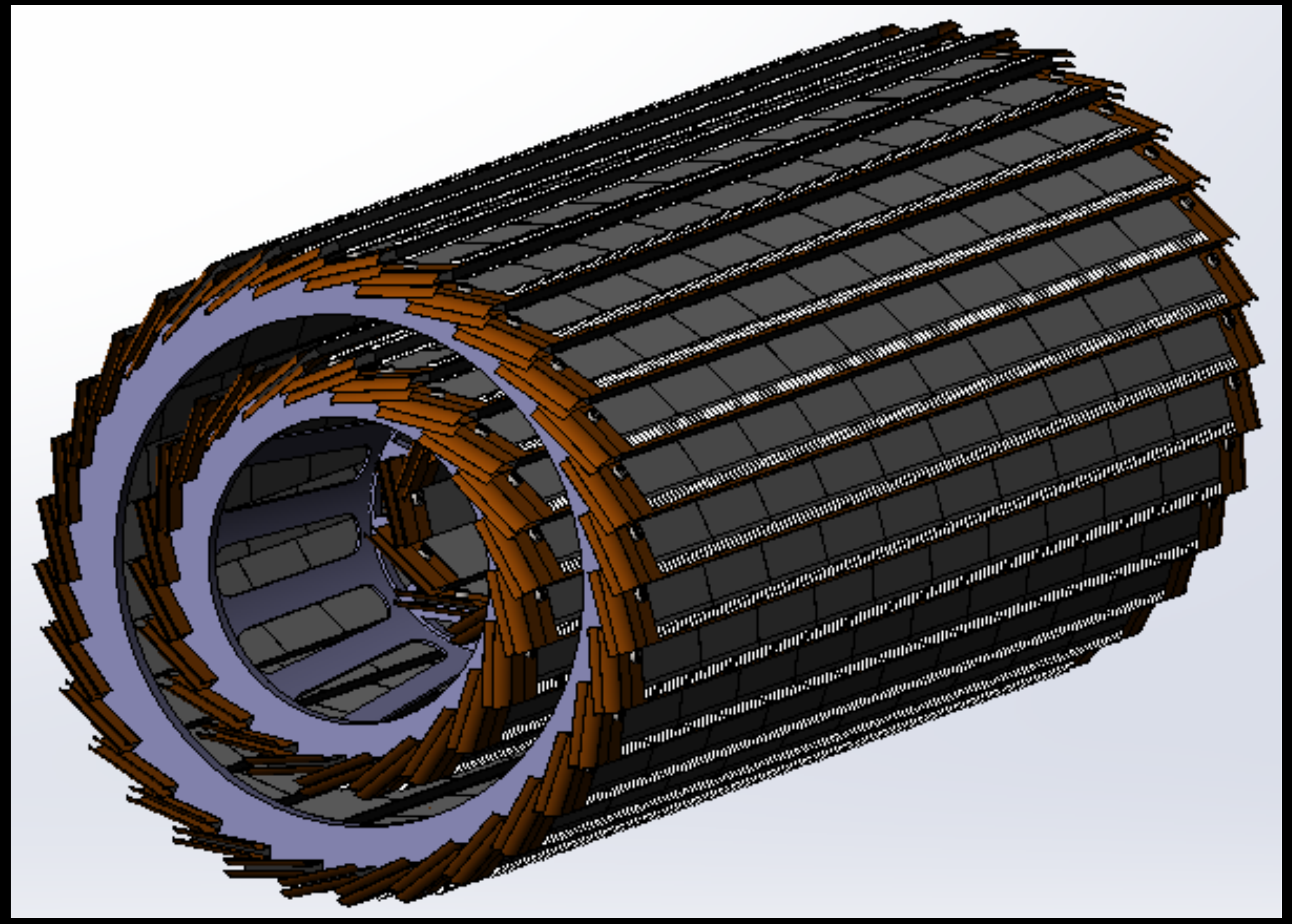
Air cooling for CEPC vertex detector

- **Air cooling is baseline design for CEPC vertex detector**
- **Sensor Power dissipation:**
  - Taichupix design : ≤ 100 mW/cm². (trigger mode), ≤ 150 mW/cm² (triggerless mode),
  - Taichupix measured result: ~60 mW/cm²(triggerless mode, 17.5MHz)
  - CEPC final goal : ≤ 50 mW/cm²
- Cooling simulations of a single complete ladder with detailed FPC were done.
  - Need 2 m/s air flow to cool down the ladder

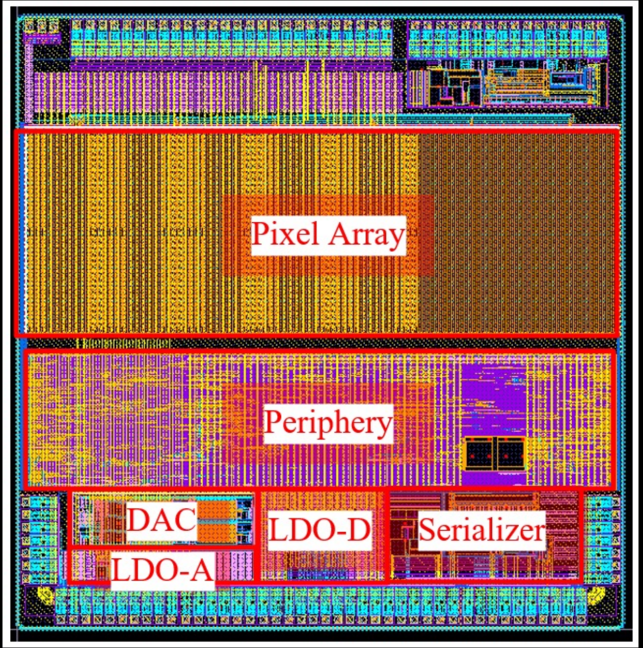
Max temperature of ladder (℃) (air temperature 5 ℃)					
Air speed (m/s) / Power Dissipation (mW/cm2)	5	4	3	2	1
100	19.6	21.8	25.0	*30.6*	*43.4*
150	26.9	30.1	35	*43.4*	*62.6*

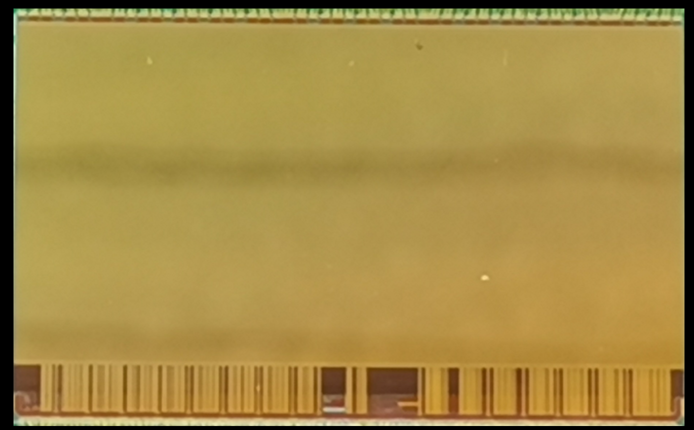
Overview of CEPC vertex detector R & D

Vertex detector Prototype for beam test

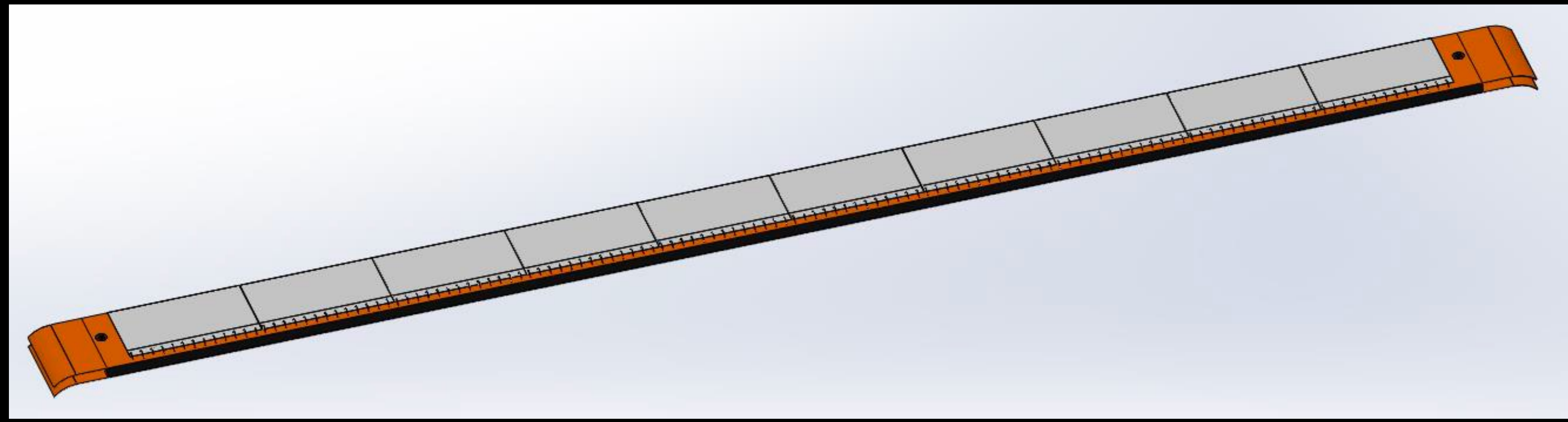


CMOS imaging sensor prototyping

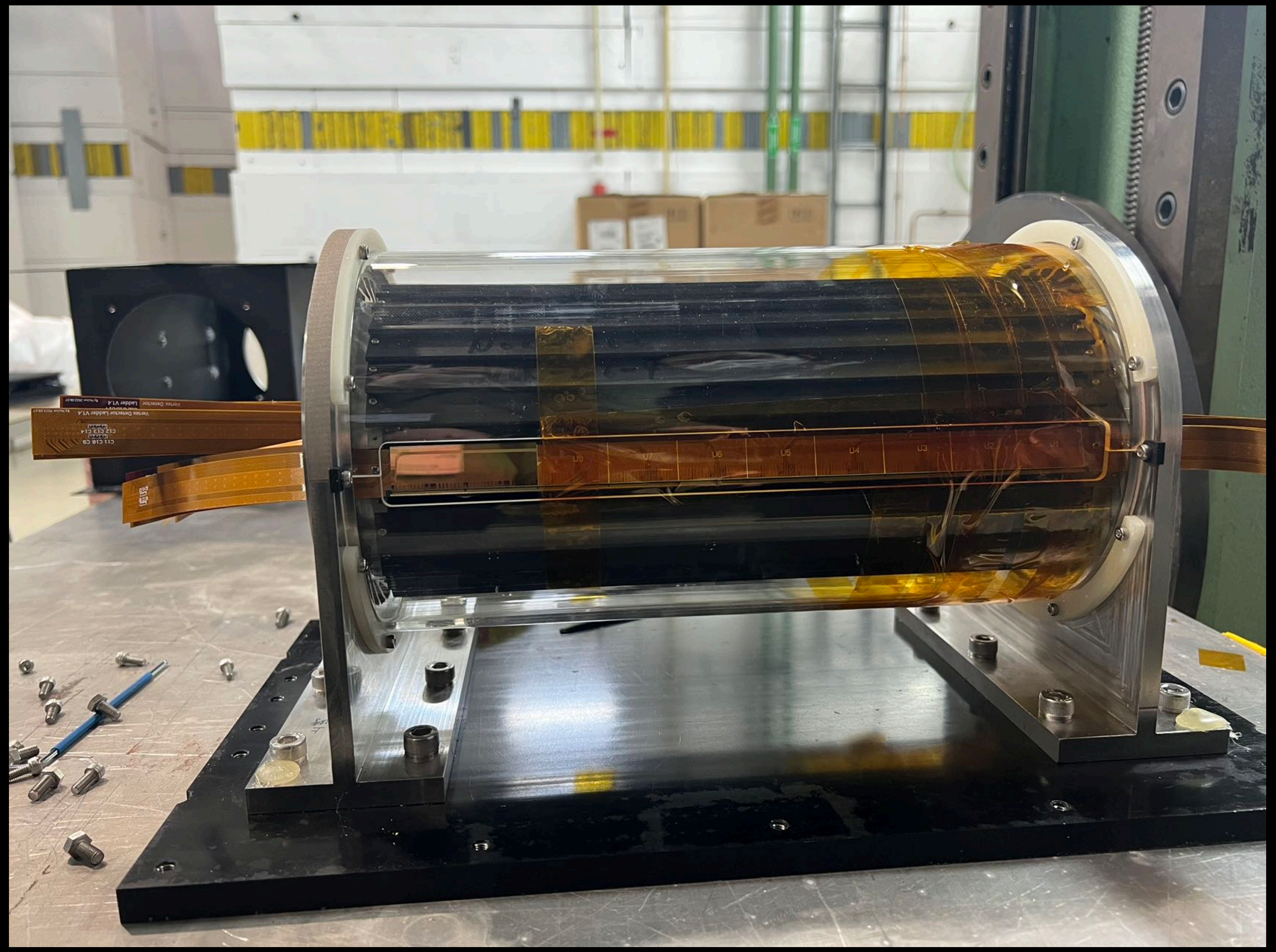




Detector module (ladder) Prototyping



Ladder readout system



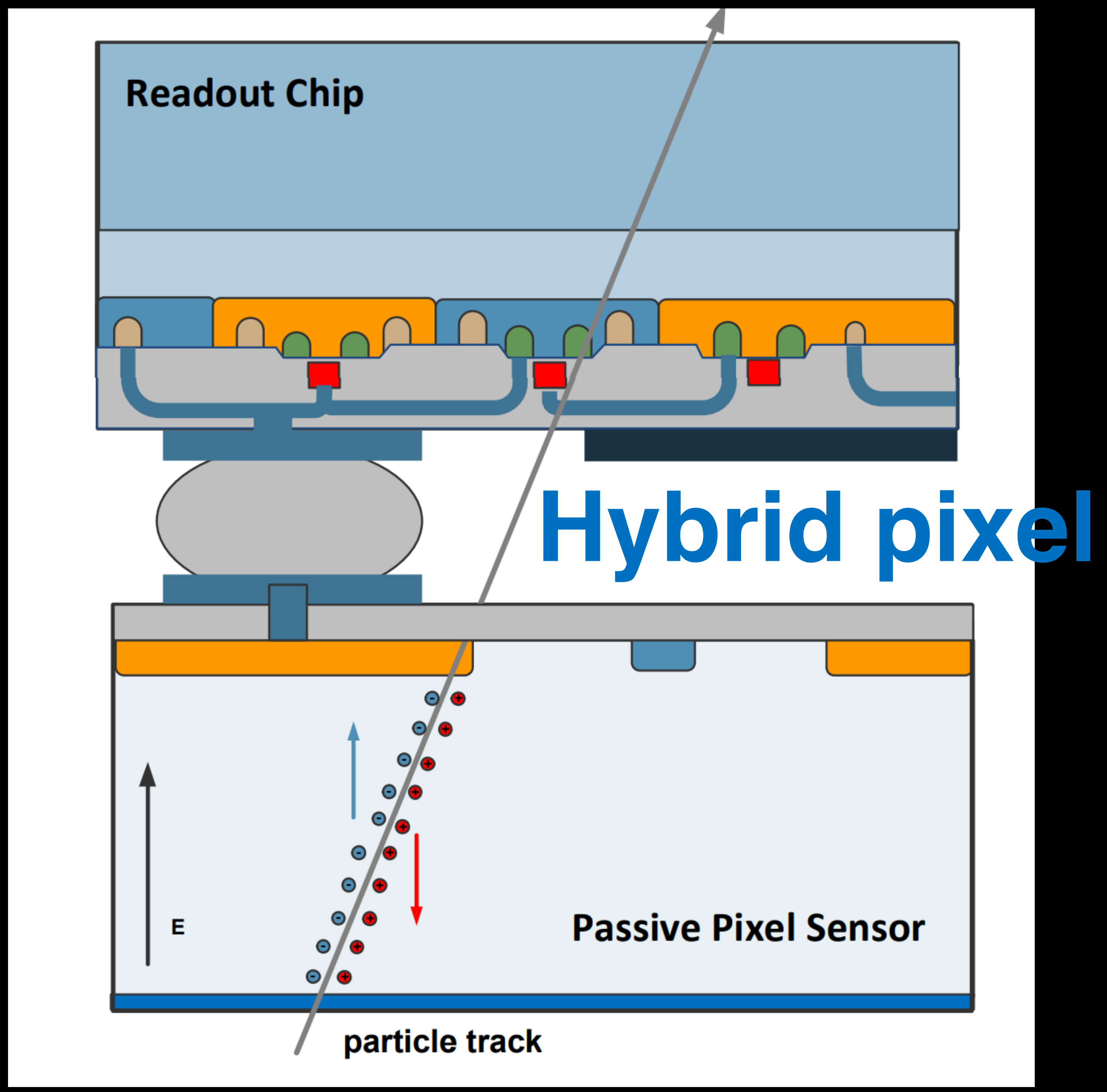
- Design CMOS imaging sensor chip
- Detector Module prototyping
- Vertex Detector assembly and testbeam

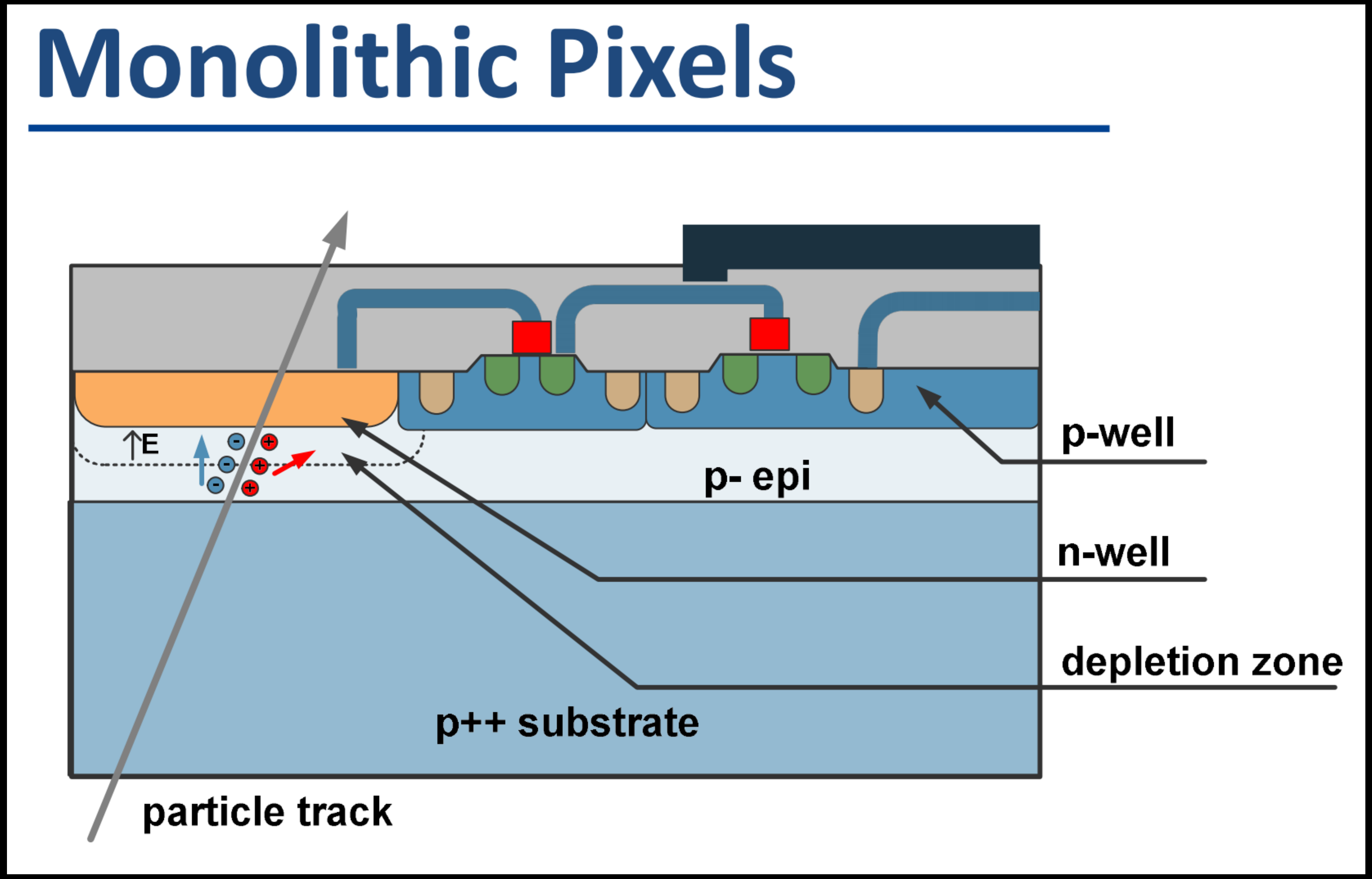
Research Team in MOST2 silicon project

Institutes	Tasks
IHEP	**Full CMOS chip modeling, Pixel Analog, PLL block Detector module (ladder) prototyping Data acquisition system R & D Vertex detector assembly and commissioning Irradiation, test beam organization**
IFAE(Spain)/CCNU	**CMOS sensor chip: Pixel Digital**
NWPU	**CMOS sensor chip: Periphery Logic, LDO**
ShanDong University	**CMOS sensor chip: Bias generation, TCAD simulation Sensor test board design**
Nanjing University	**Irradiation, test beam**

CMOS Monolithic pixel sensor

- Conventional Hybrid pixel technology at Large Hadron Collider
  - Need to bump bonding with readout ASIC
  - Typical pixel size >=50µm, much more difficult for bump bonding with smaller pixels
- CMOS Monolithic pixel (CIS process) is ideal for CEPC application
  - Sensor and ASIC high integrated in one chip, easier for detector assembly
  - Can have compact structure in pixel array design.
    - Pixel size can be reduced to 25um or below → can achieve better spatial resolution





CMOS Sensor chip R & D

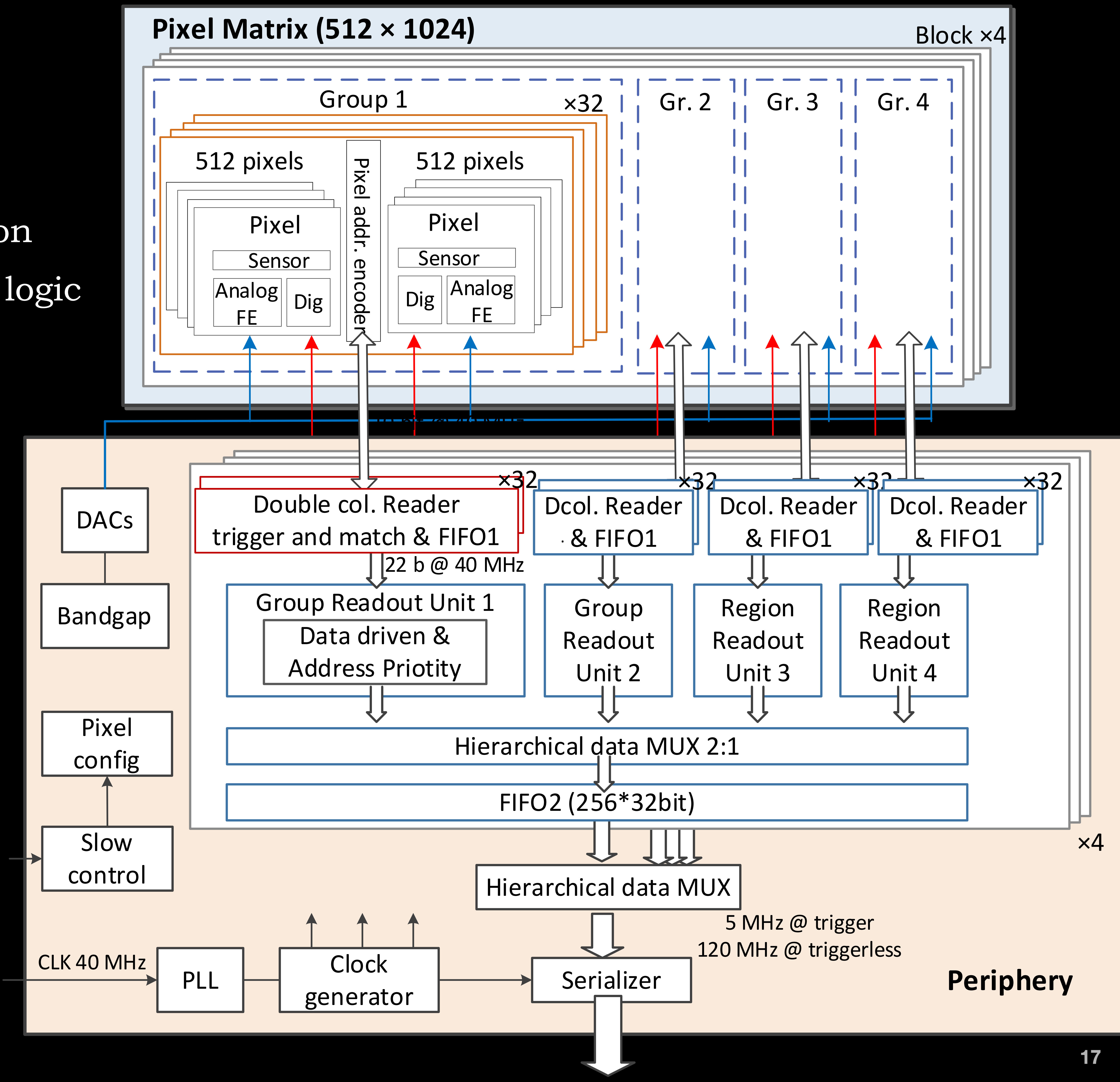
- The existing CMOS monolithic pixel sensors can't fully satisfy the requirement
- Major Challenges for the CMOS sensor
  - Small pixel size -> high resolution (3-5 μm)
  - Radiation tolerance **(per year):** **>**1 Mrad
  - High readout speed -> for high luminosity CEPC Z pole running (40MHz)

	ALPIDE	ATLAS-MAPS (MONOPIX / MALTA)	MIMOSA
Pixel size	✓	X	✓
Readout Speed	X	✓	X
TID	X (?)	✓	✓

TaichuPix readout architecture

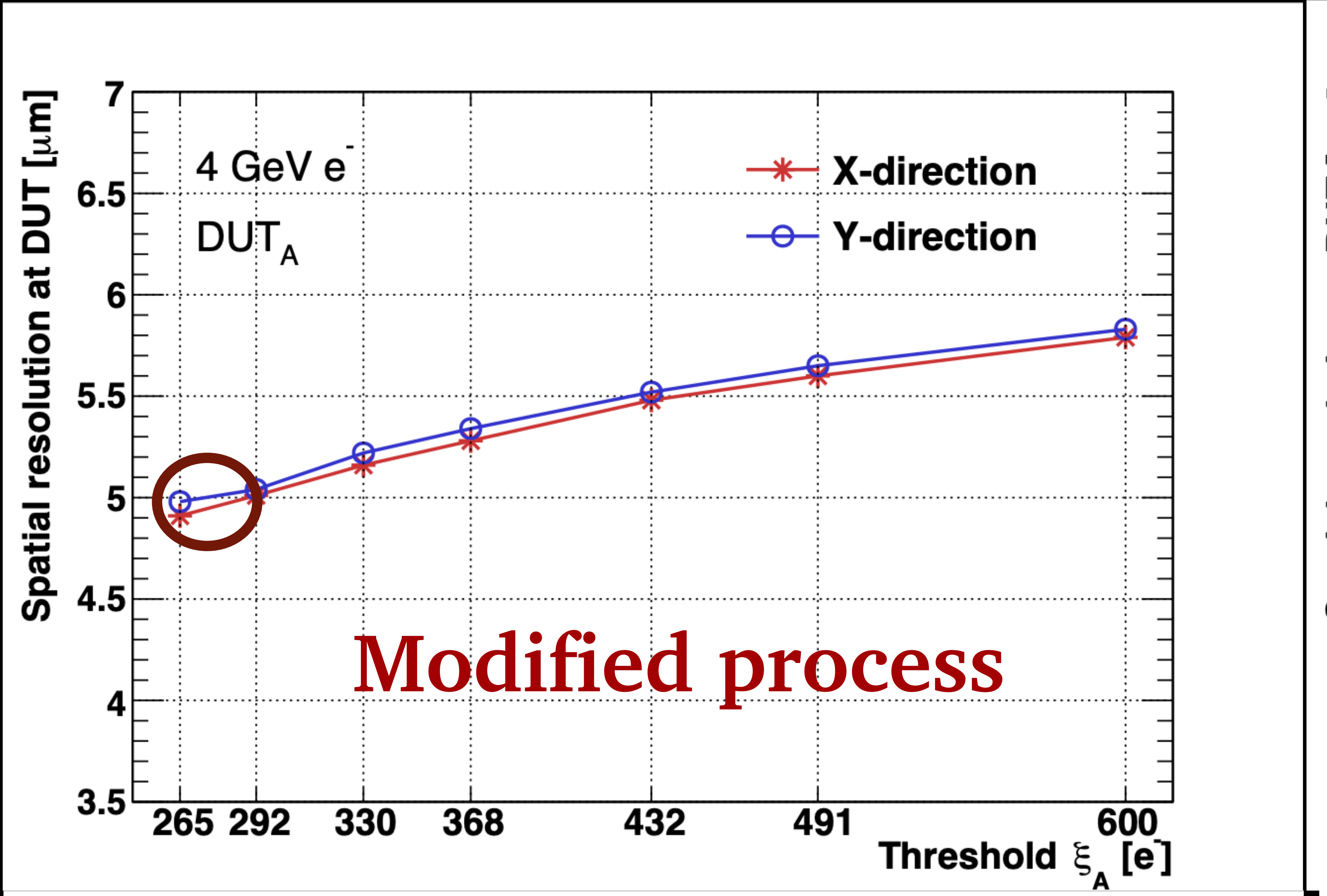
- **High resolution and high data rate**
- **Data-driven readout design**

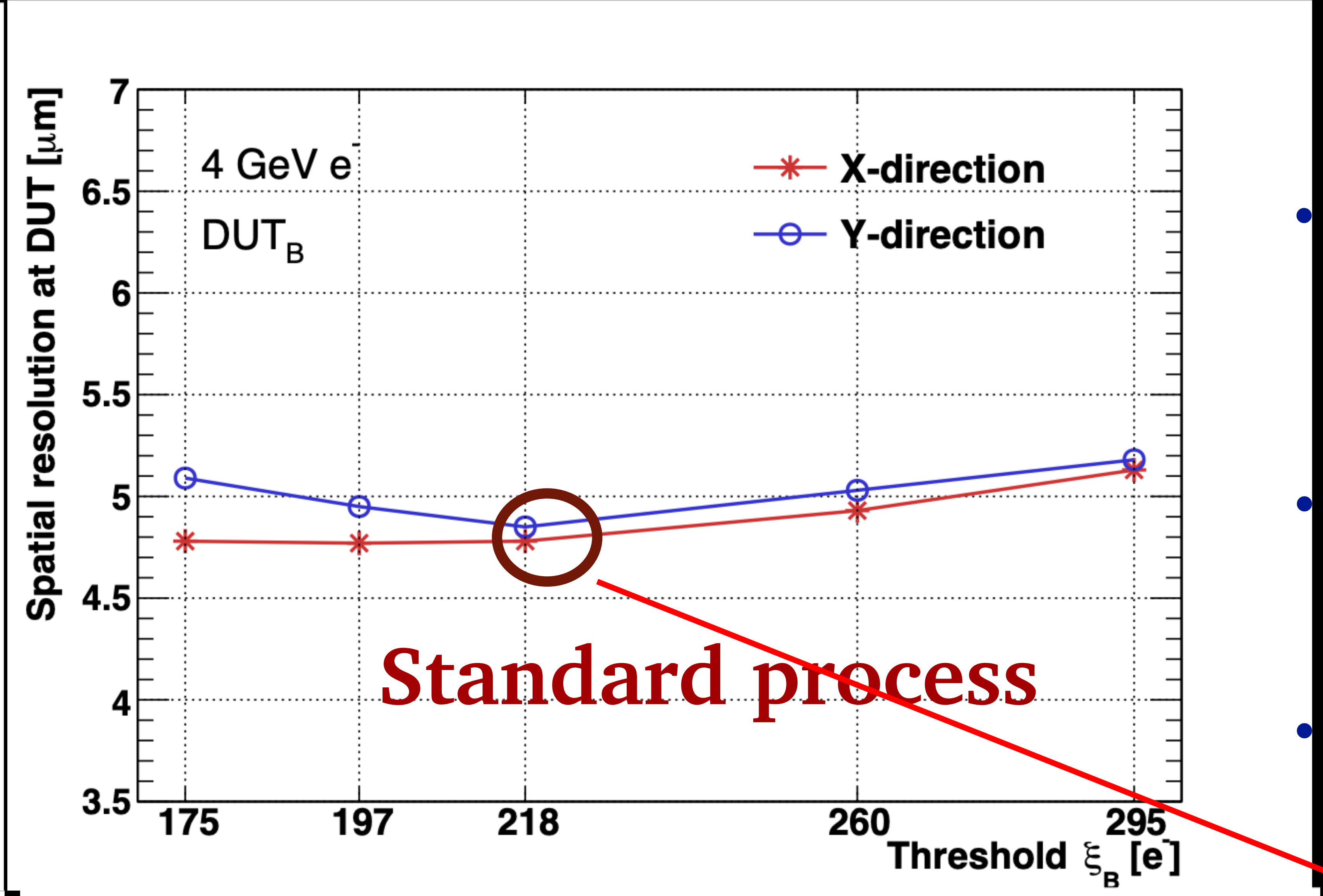
- **Pixel 25 μm × 25 μm**
  - Continuously active front-end, in-pixel discrimination
  - Fast-readout digital, with masking & testing config. logic
- **Column-drain readout for pixel matrix**
  - Priority based data-driven readout
  - Readout time: 50 ns for each pixel
- **2-level FIFO architecture**
  - L1 FIFO: de-randomize the injecting charge
  - L2 FIFO: match the in/out data rate
  - between core and interface
- **Trigger-less & Trigger mode compatible**
  - Trigger-less: 3.84 Gbps data interface
  - Trigger: data coincidence by time stamp
    only matched event will be readout
- **Features standalone operation**
  - On-chip bias generation, LDO, slow control, etc.



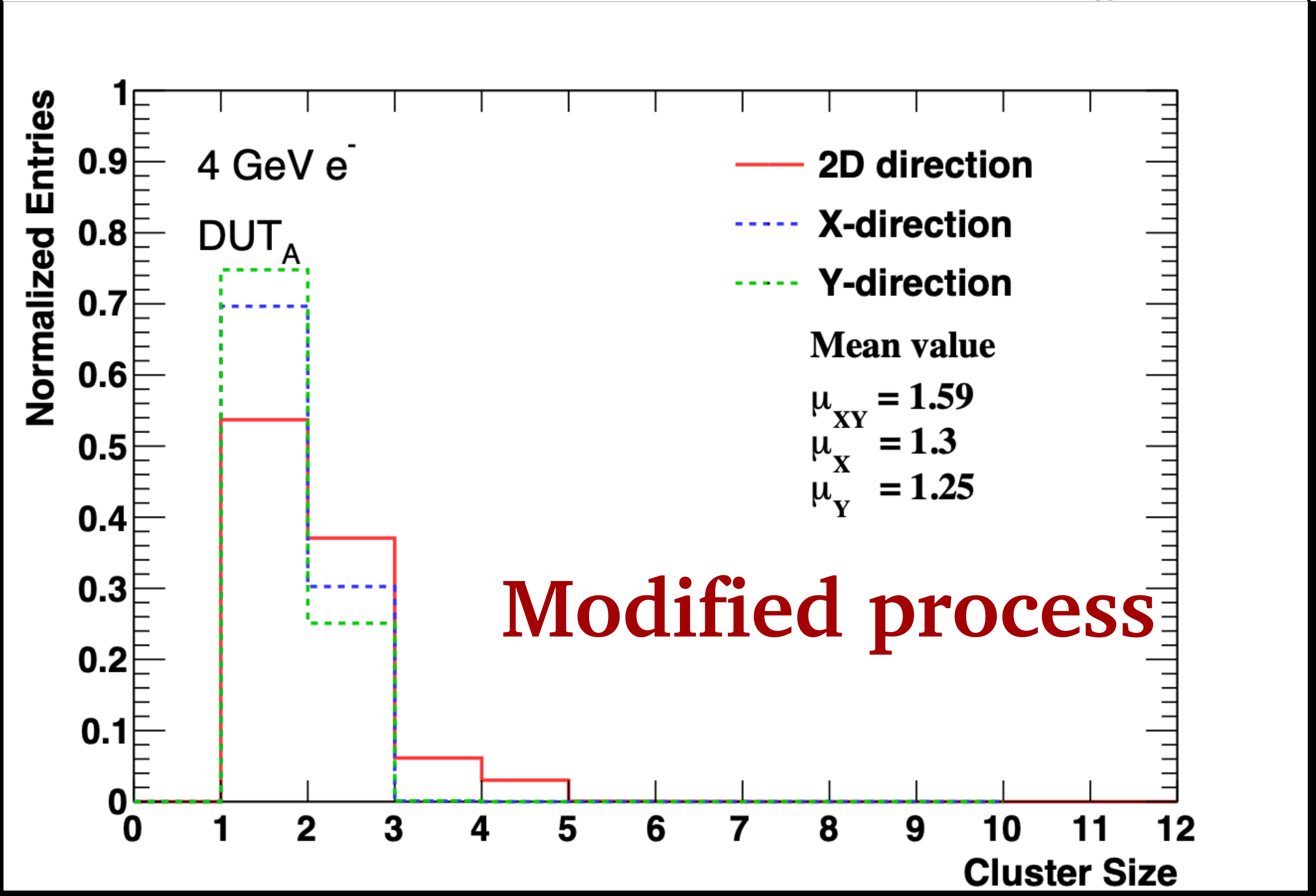
Spatial resolution and cluster size VS threshold

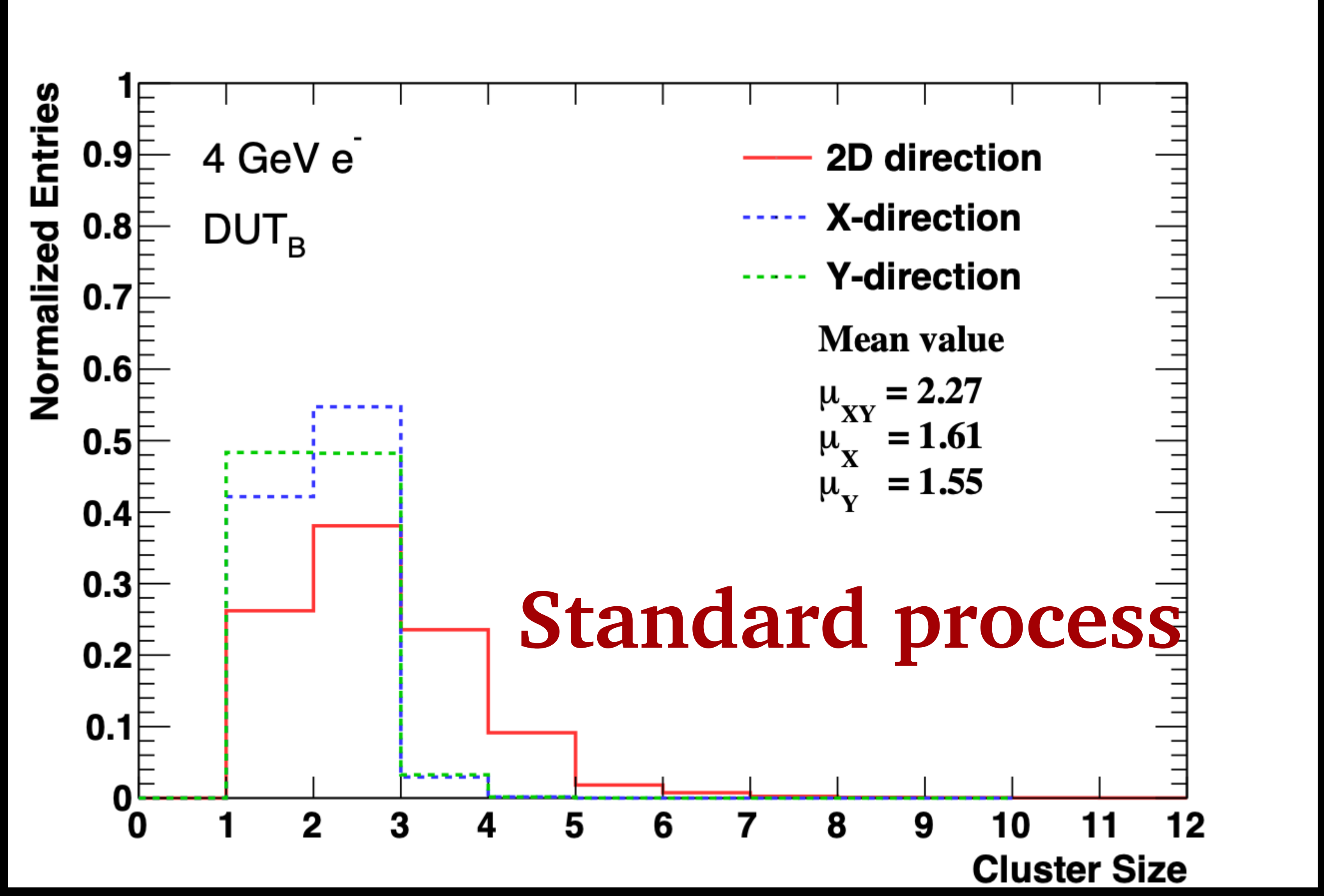
- The spatial resolution extracted by the unbiased residual distribution after substracting the track uncertainty→ **The spatial resolution less than 5 um**

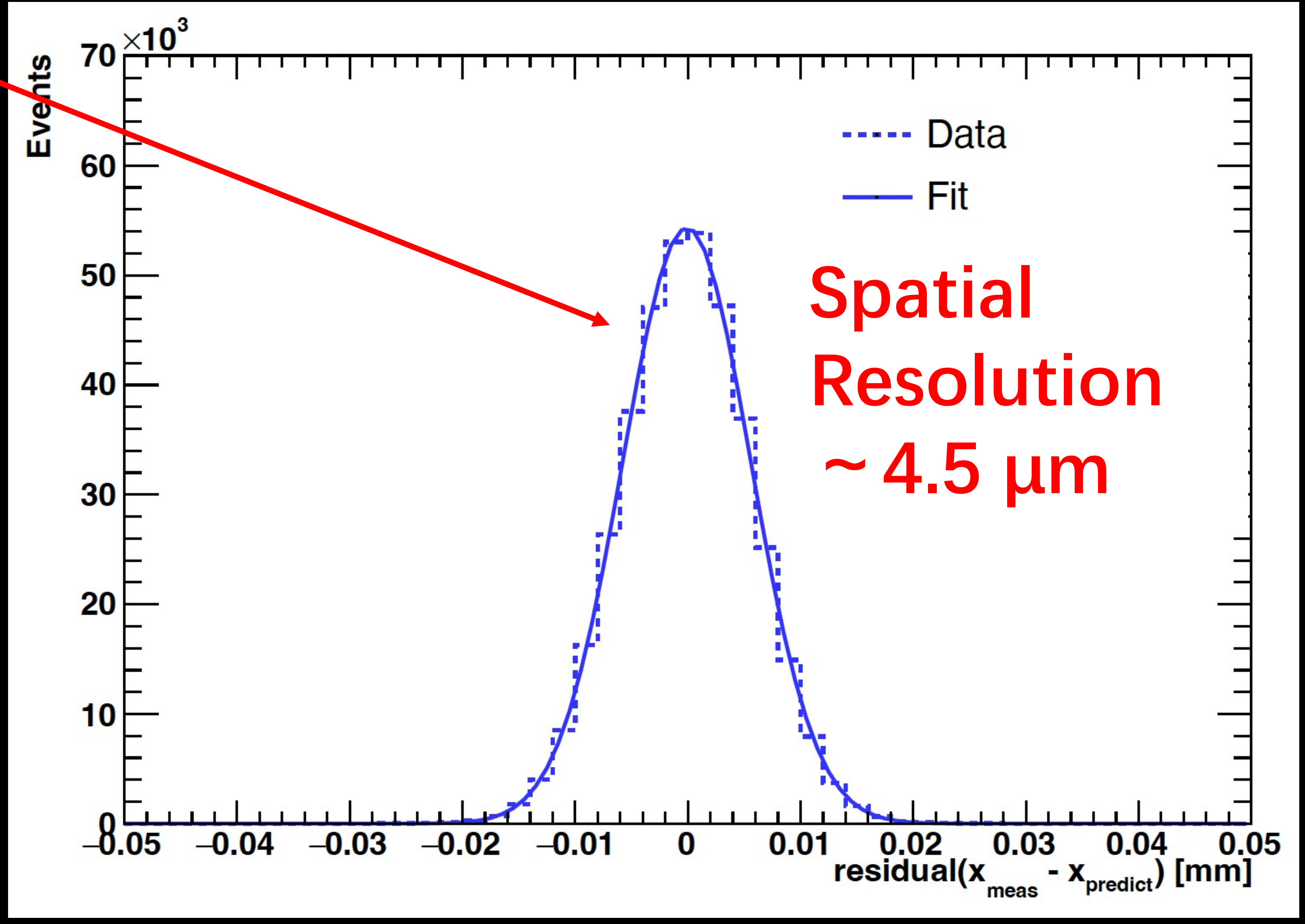




- **Less charge sharing effects in modified process with full depletion**
- **If lowering the threshold, cluster size will be dominated by noise**





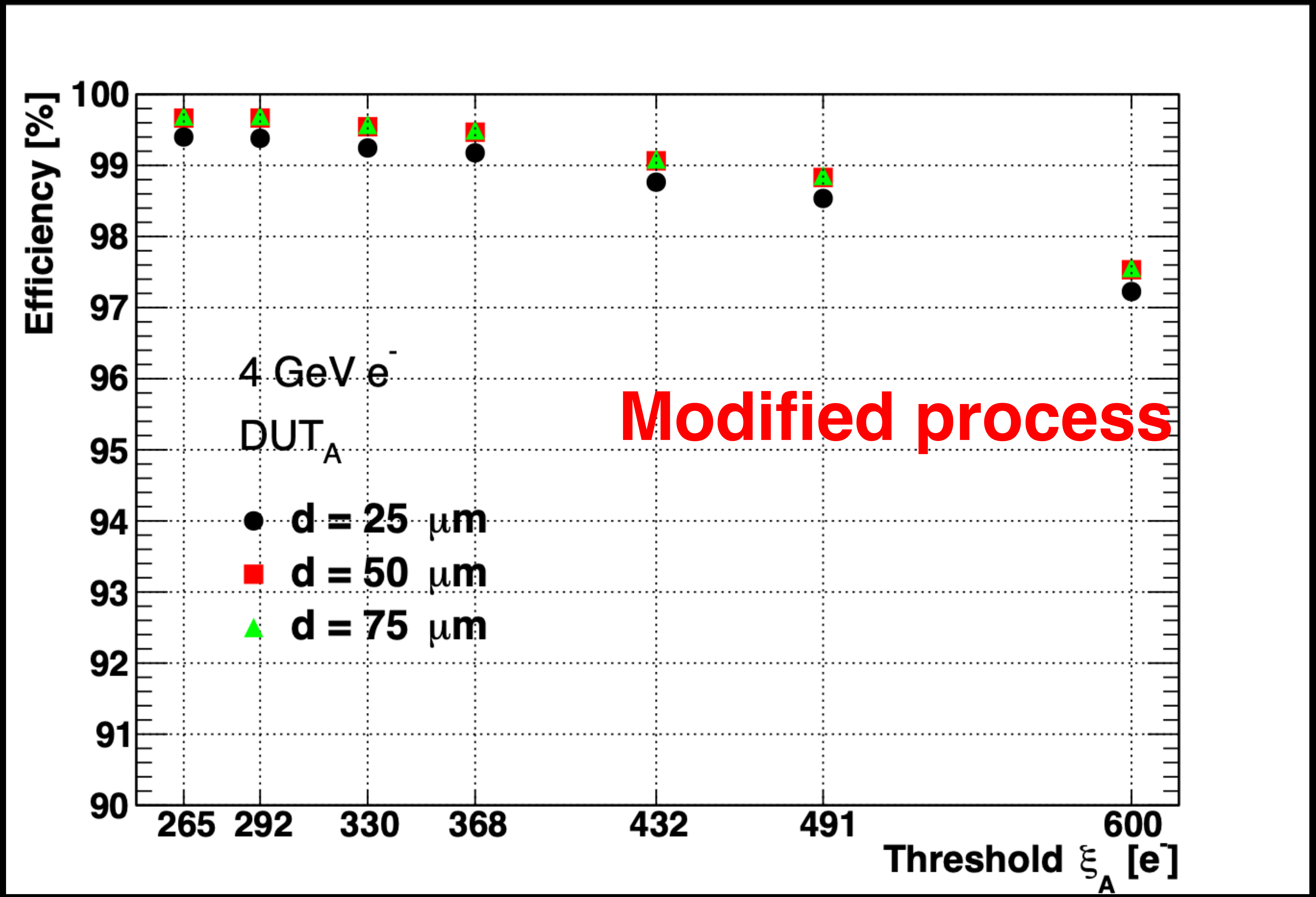


Hit Efficiency

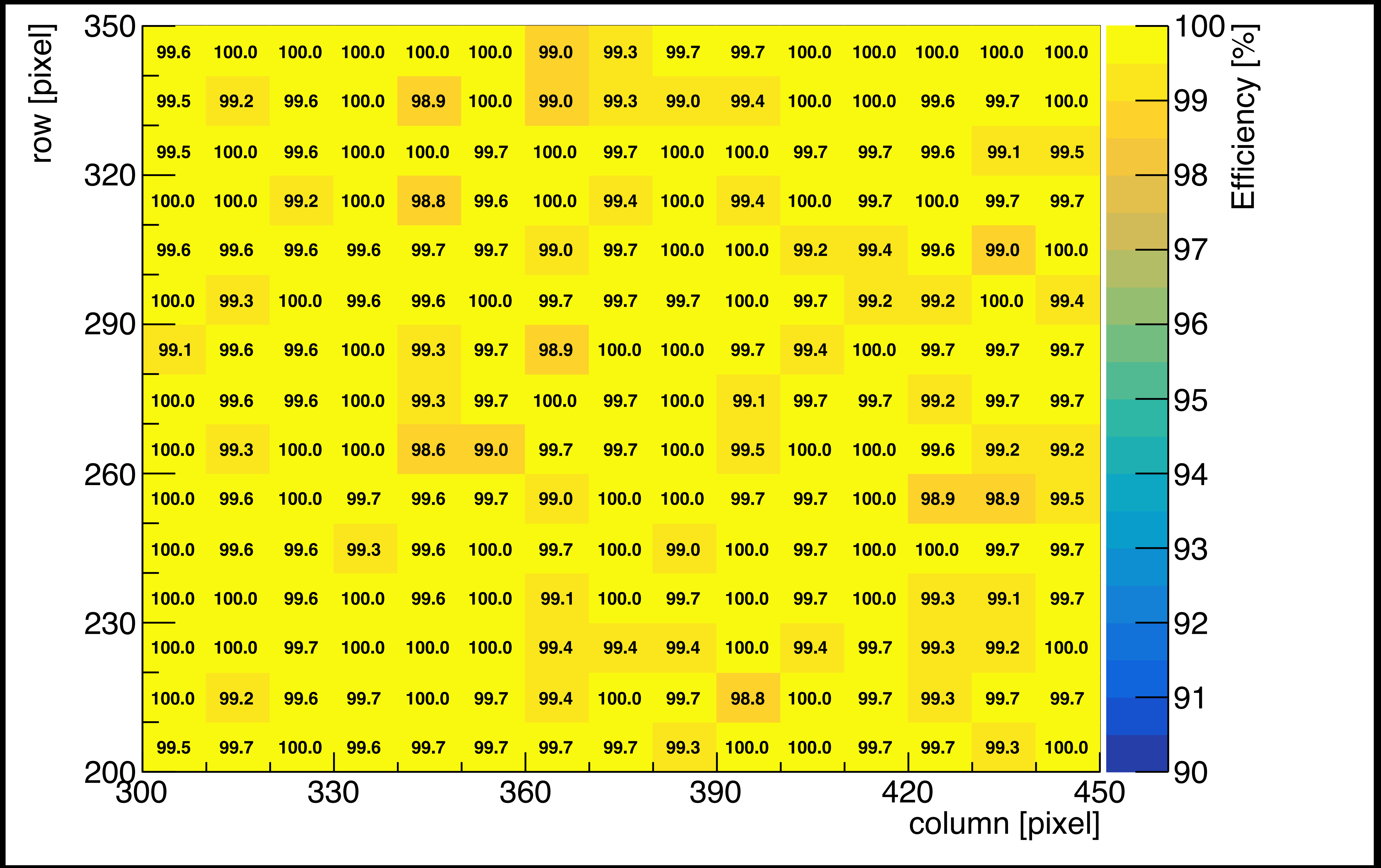
- Efficiency is the ratio of tracks that match the hit on the DUT within a distance around the predicted hit from the telescope to all tracks of the telescope
  - It can reach about 99.4% efficiency in optimized threshold

$$\epsilon = \frac{N^{matched\ Tracks}_{|x_{meas}, y_{meas} - x_{pre}, y_{pre}| < d}}{N^{Tracks}_{tel}}$$

Efficiency Vs threshold



Efficiency maps



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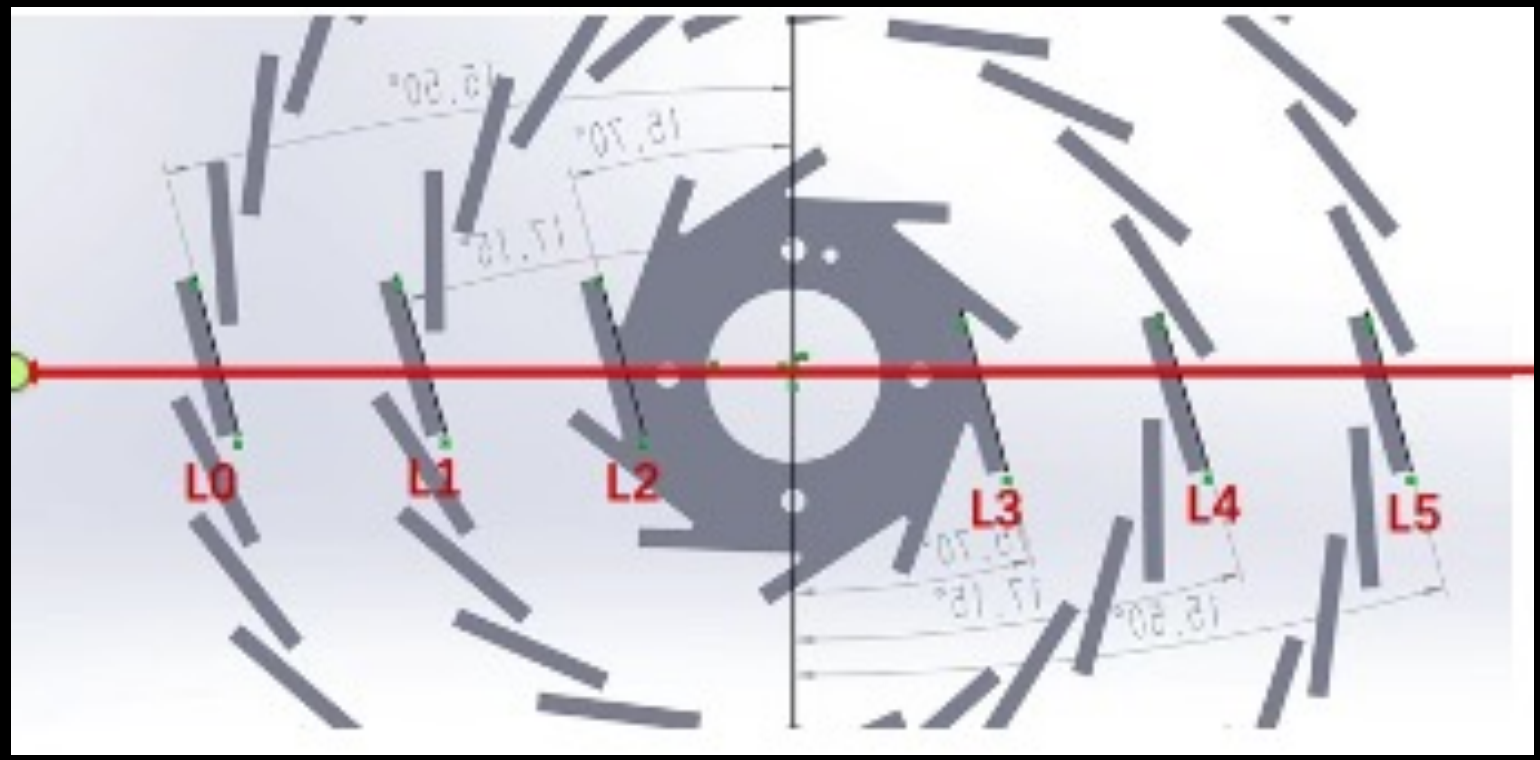
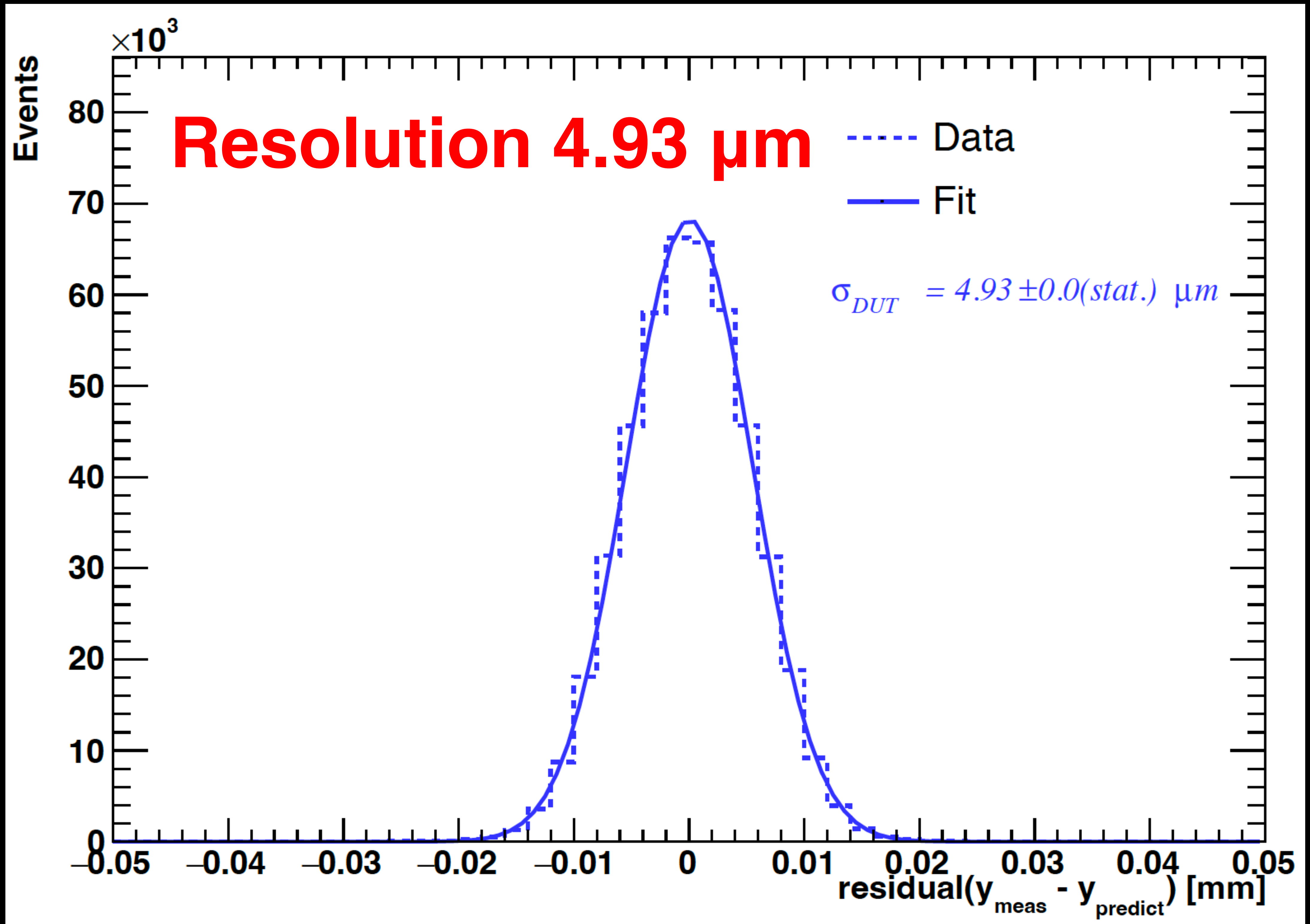
150	26.9	30.1	35	*43.4*	*62.6*

Test beam results (April 2023)

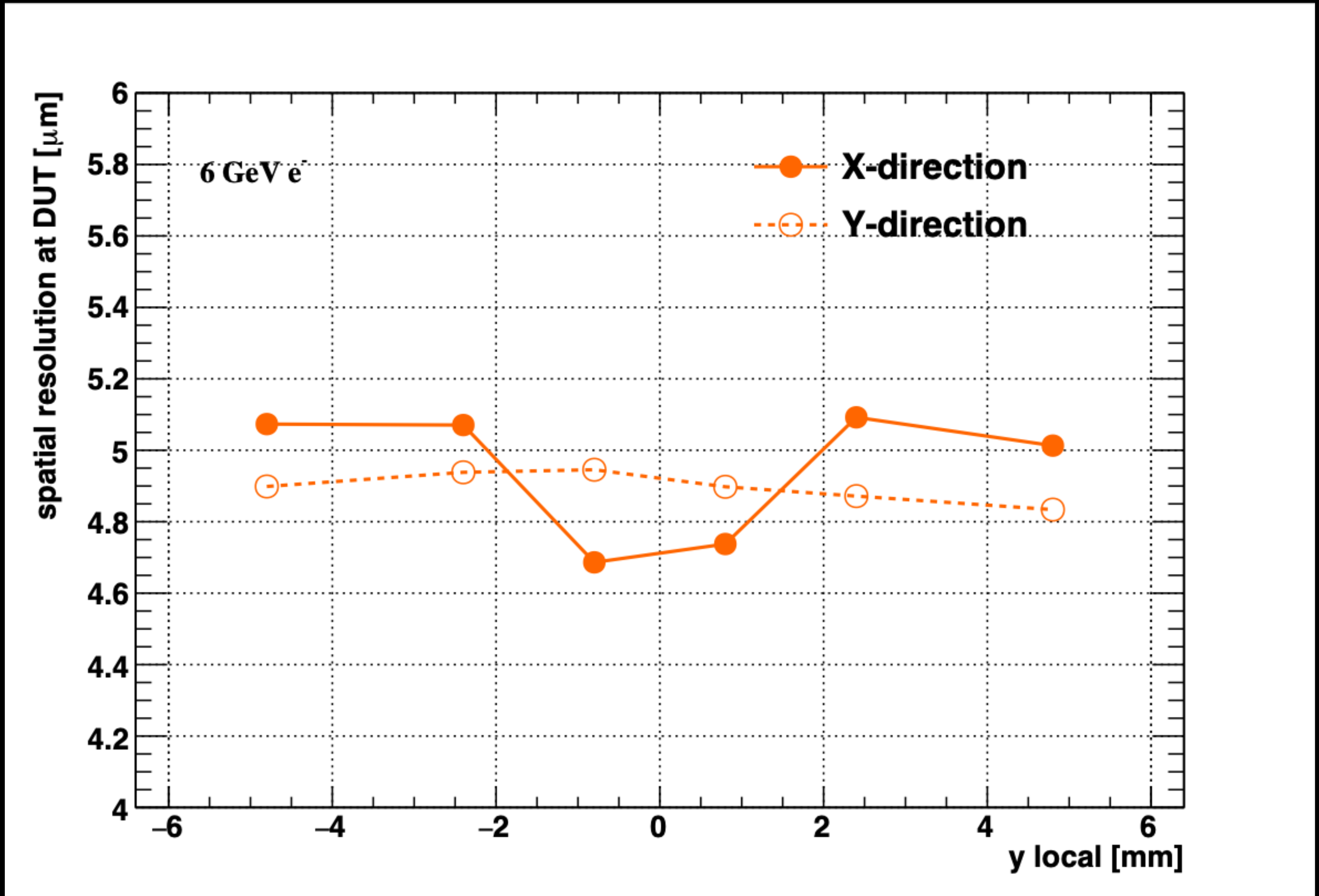
- Extract Spatial resolution from detector prototype testbeam data
  - One layer (L1) of TaichuPix used as Detector-Under-Test (DUT)
  - Other layers of vertex detector prototype used for track fitting
  - Spatial resolution reached 4.9μm (Y axis→ bending direction)
    - Spatial Resolution met the requirement (3-5μm)



Residual distribution in Y axis
DUT measured position – expected position from track



Spatial resolution vs hit positions
Y axis is bending direction



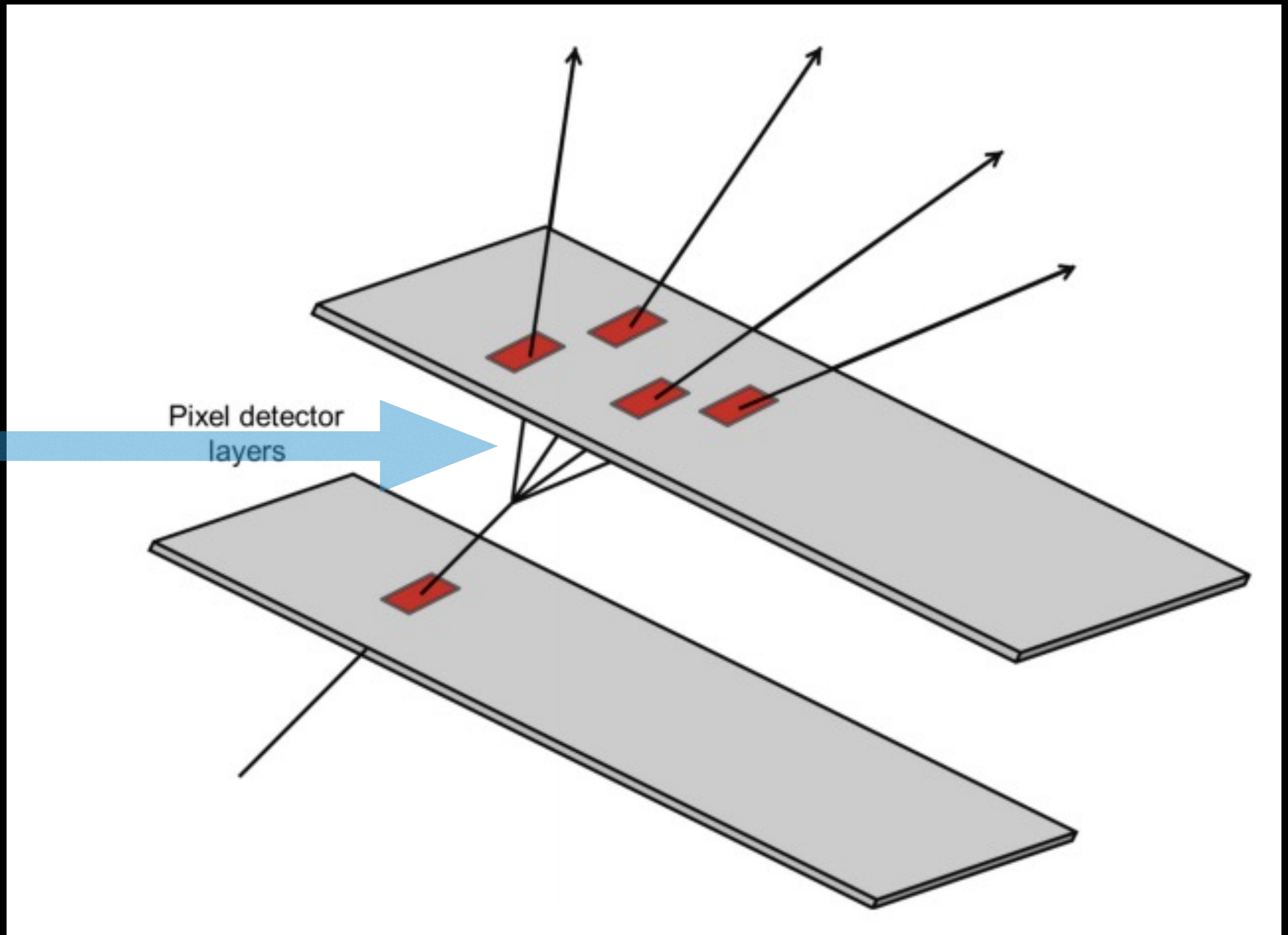
Backup

Road map of sensor R & D

- This talk focus on more TaichuPix based CEPC vertex detector prototype
- More details chip development in talks tomorrow in electronics section
- 3D-integrated pixel circuit for a low power and small pitch SOI sensor, Yunpeng LU
- Development of TaichuPix pixel chips for the first CEPC vertex detector prototype, Ying Zhang

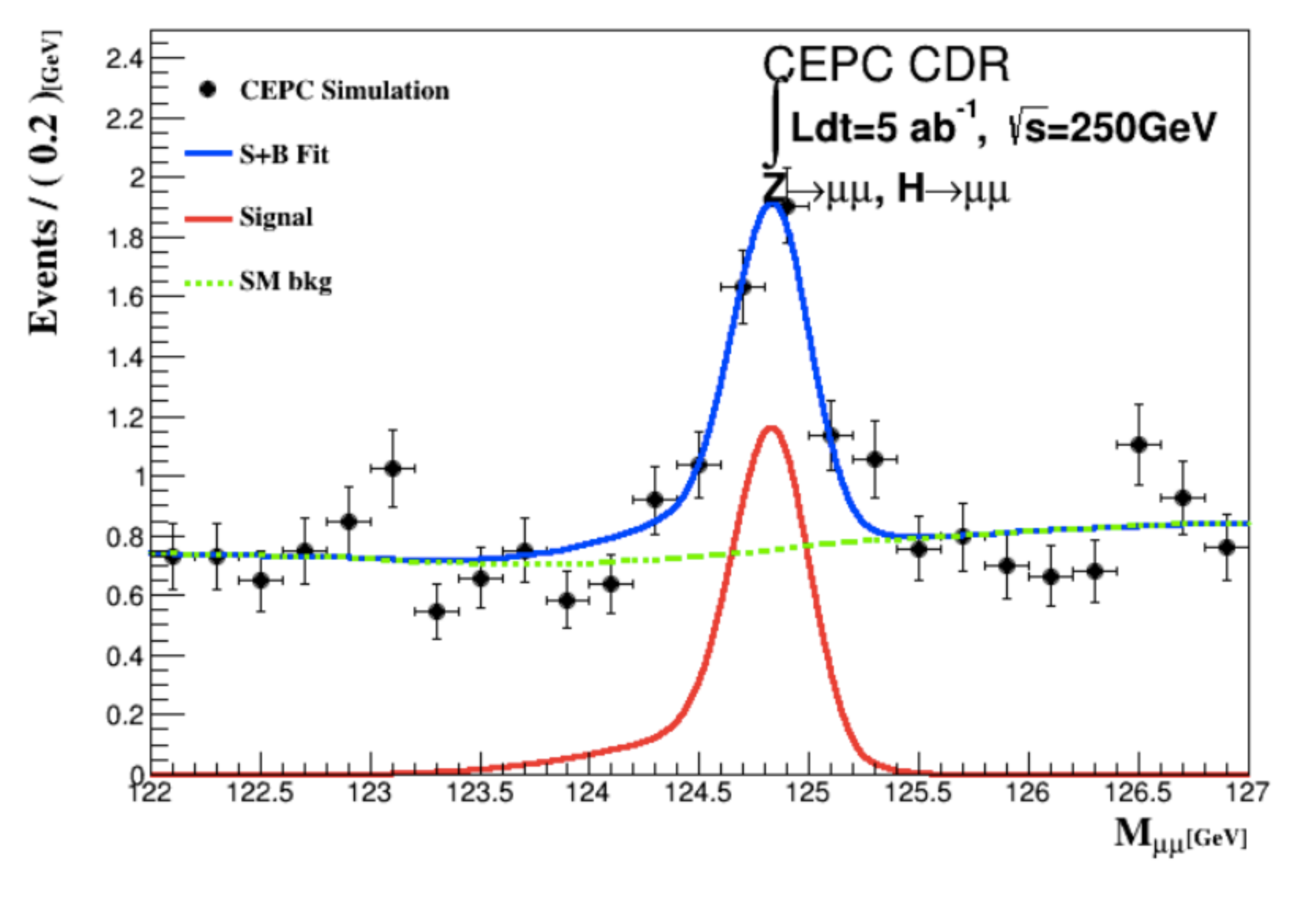
Vertex detector: Physics goal

- Produce a world-class vertex detector prototype
  - Small inner radius, close to beam pipe
  - Spatial resolution: 3~5 μm (pixel detector)
  - Low material budget <0.15% X0 per layer
  - Timing resolution: ~25ns (40MHz collision @ Z pole)



- Physics motivation
  - Higgs precision measurement
  - $H \rightarrow bb$ precise vertex reconstruction
  - $H \rightarrow \mu\mu$ (precise momentum measurement)

Need tracking detector with high spatial resolution



- Main technology
  - Develop the know-how in China to build such detector
  - High spatial resolution technology → pixel detector
  - Radiation resistance technology