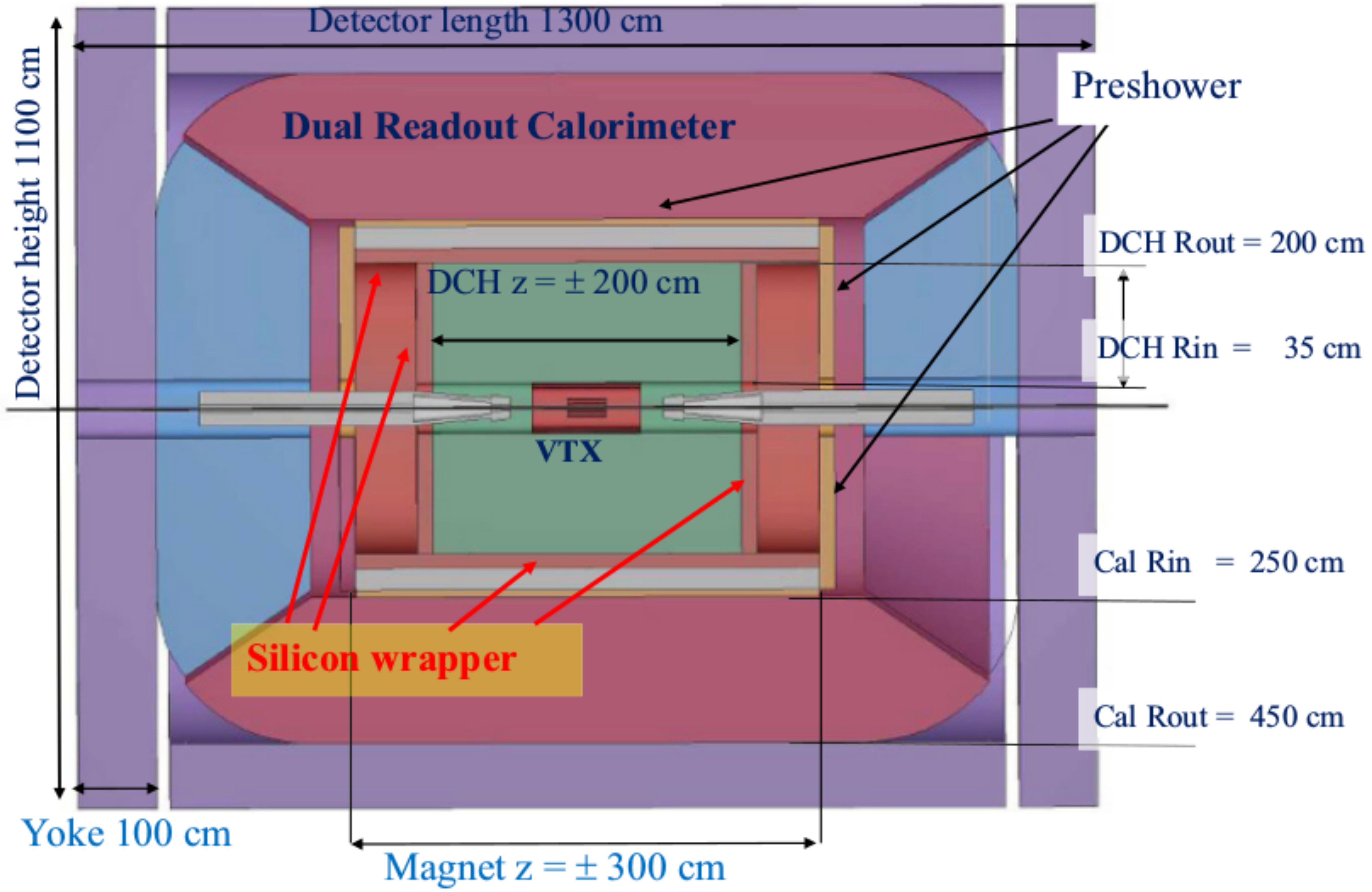
FUTURE CIRCULAR COLLIDER
Expanding our Horizons

LGAD detectors for tracking and timing

Enrico Robutti (INFN Genova), Roberta Arcidiacono (UPO & INFN Torino)

The IDEA silicon wrapper



In the IDEA concept, the drift chamber is complemented by an external tracking layer to:

- improve p_T resolution;
- provide absolute reference for tracks polar angles;
- extend tracking coverage at large $|\eta|$;
- possibly provide timestamp to associated tracks in the vertex detector $\Longrightarrow$ relax power requirements

~90 m² of silicon detectors (one layer)

- position resolution: up to now 7 μm in $r\phi$, 15 μm in z considered: still the reference?
- very low rate, O(1 kHz/cm²), low integrated dose expected

Silicon technology for the silicon wrapper

Baseline technology is DMAPS: synergy with vertex sensors

Total surface for silicon wrapper about 20 times that of vertex detector (or CMS "Phase-2" tracker)

- With similar pitch $\Longrightarrow$ $O(10^{11})$ channels

Are suitable alternative technologies available for consideration?

Resistive Silicon Detectors (RSD) can provide high-resolution position measurement with relatively large pitch

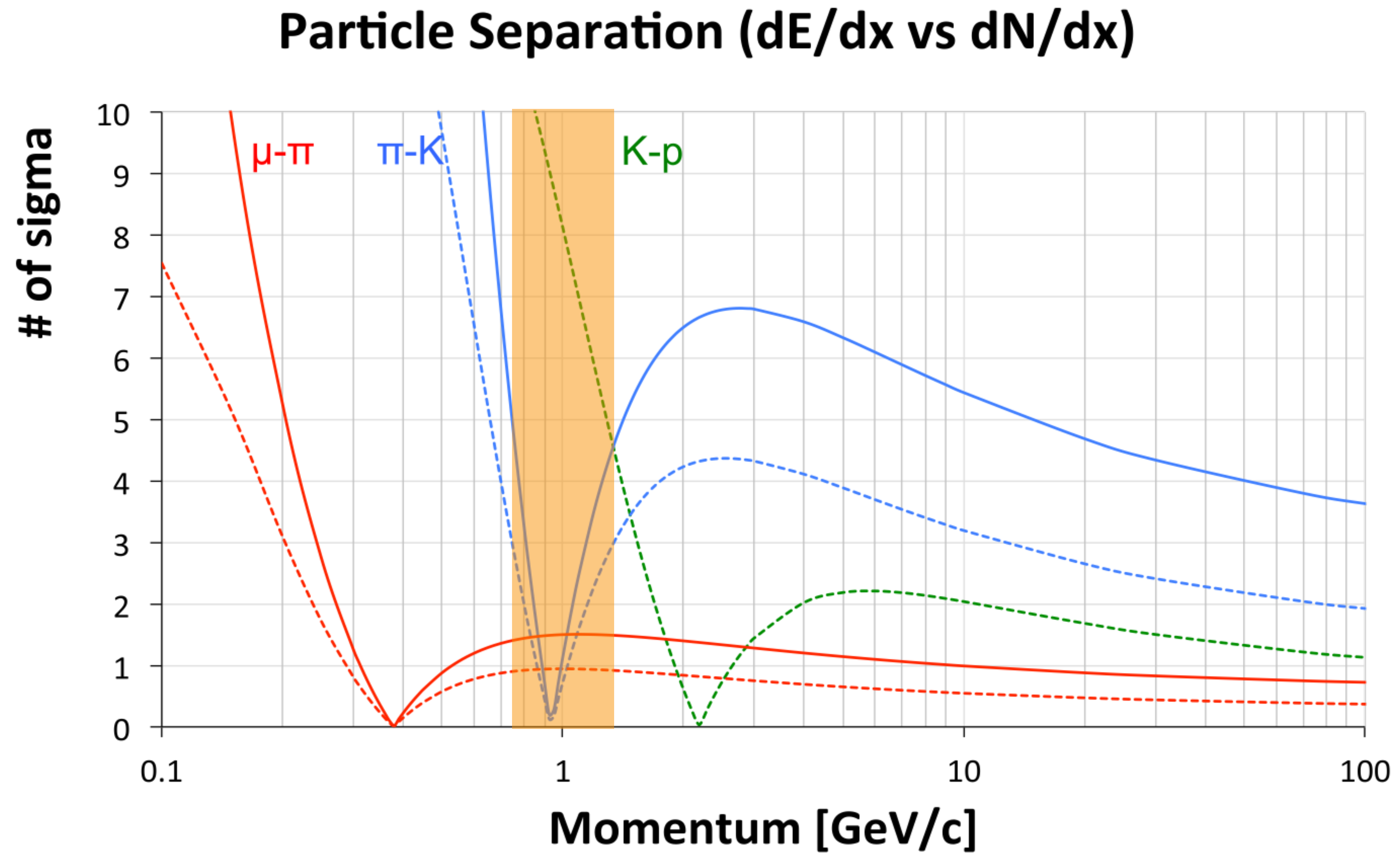
- Suitable for low occupancy environments
- Thin silicon layer(s) $\Longrightarrow$ comparable material thickness
- Precision time measurement possible
- Ongoing R&D on implementation in DMAPS structures

Time measurement in the silicon wrapper?

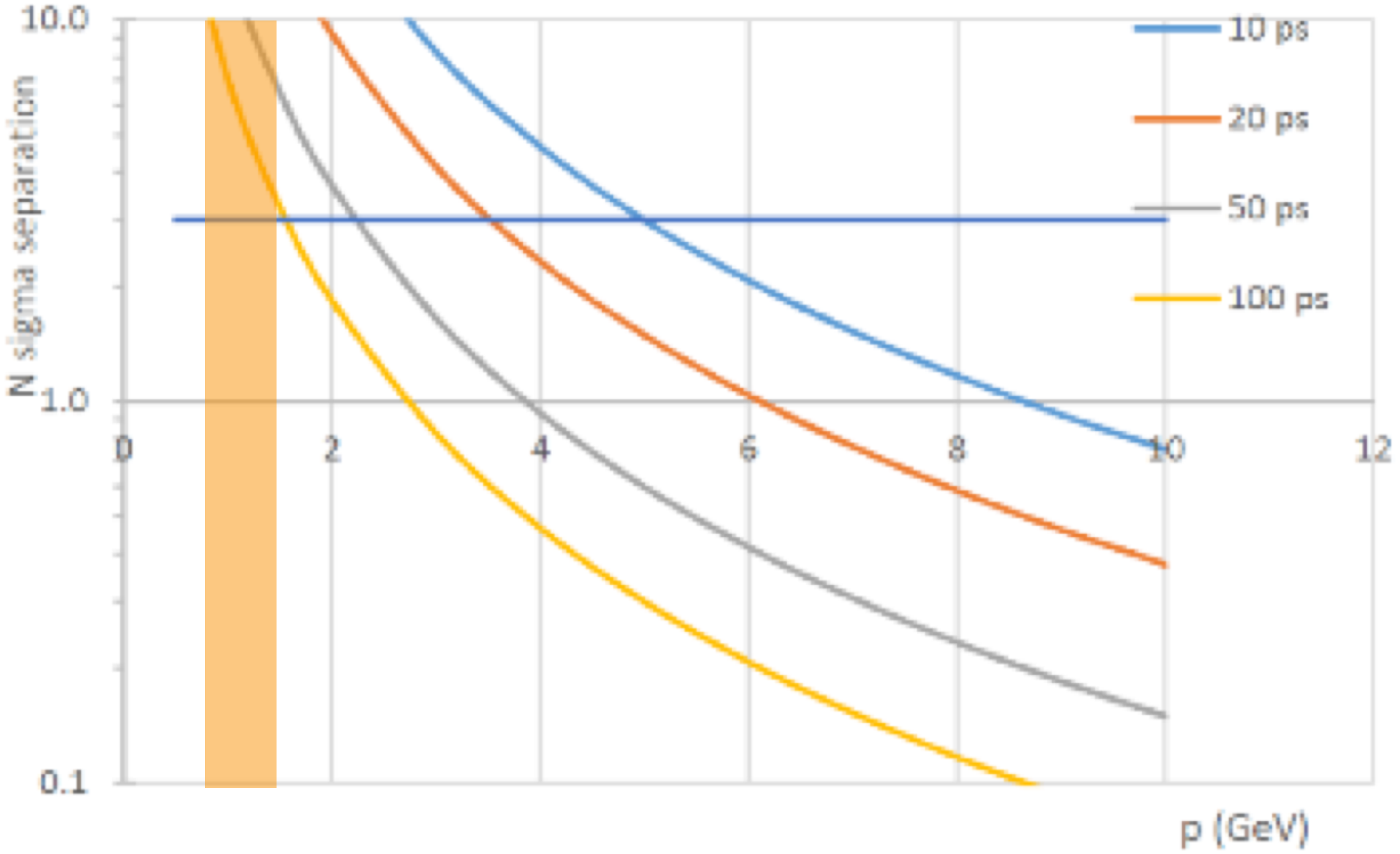
PID in IDEA (π-K, K-p separation) provided by the dE/dx or dN/dx (cluster counting) measurements in the drift chamber

Addition of a time measurements in the silicon wrapper (~2 m from the IP) would complement PID with a TOF system

- Few tens of ps resolution would “fill” the region around 1 GeV/c not covered by dN/dx for K-π separation
- Possible improvement of sensitivity in flavour physics studies; new handle for “exotic” signatures
- Note: with a 3 T magnetic field, 1-GeV particles in central region (θ ~ 90°) would barely reach the wrapper



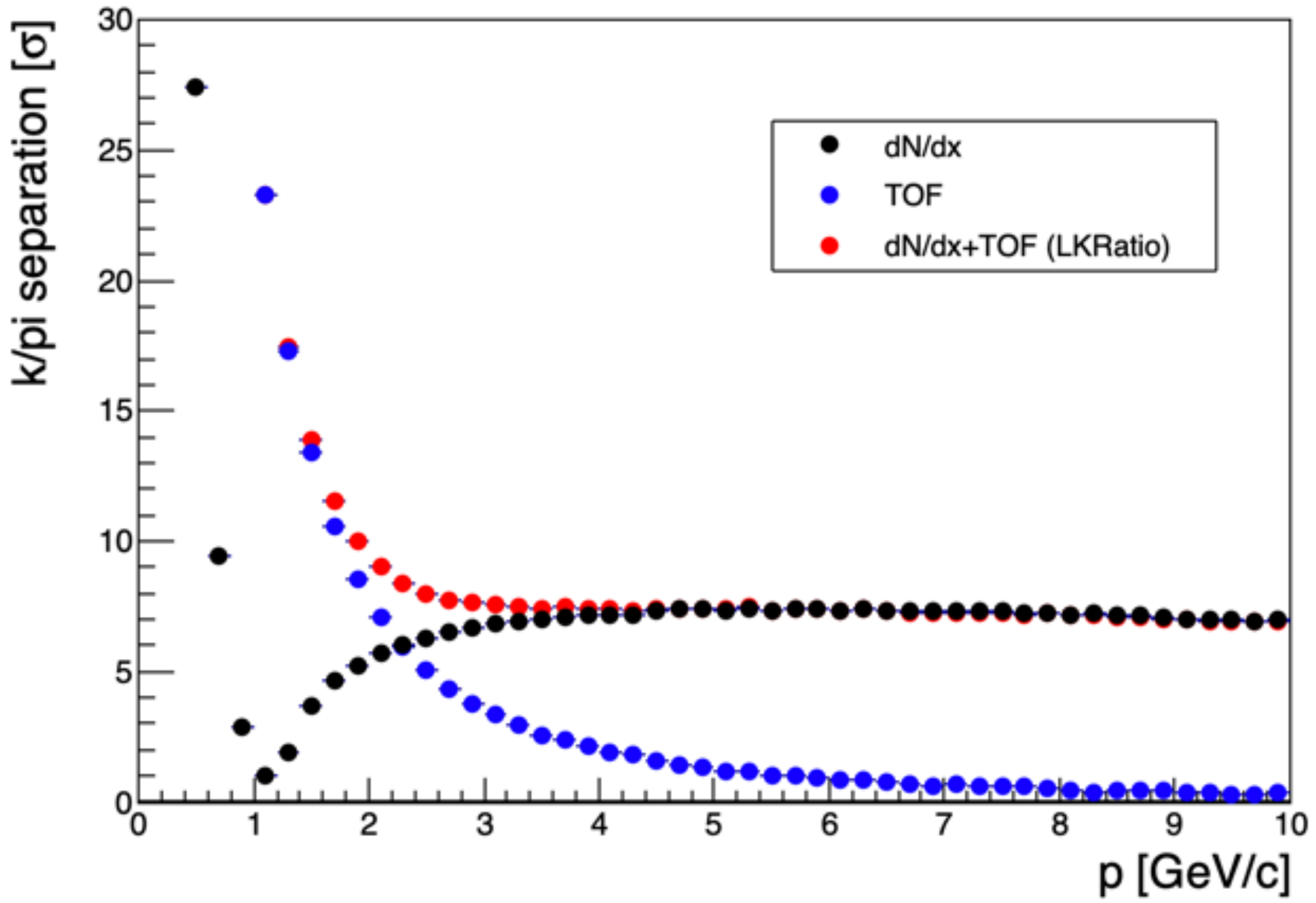
Momentum [GeV/c]



TOF integration in simulation

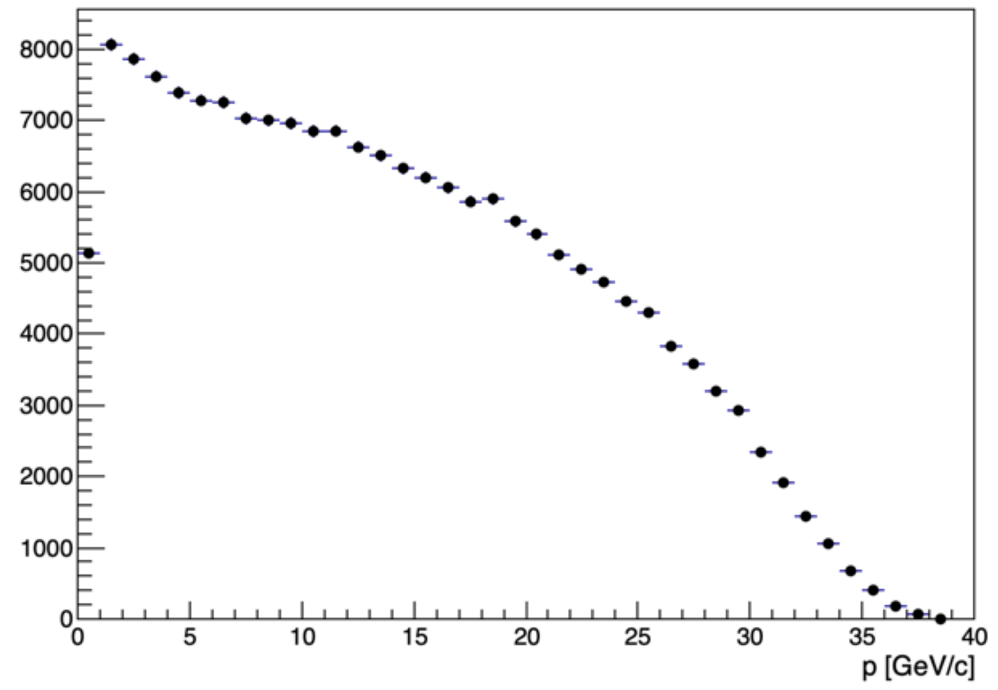
Studies ongoing on benchmark channel $B_s \rightarrow D_s K$

- In general, as expected, inclusion of TOF nicely extends π-K separation
- In this channel, K and π spectra are hard, well into the dN/dx discrimination region $\Longrightarrow$ TOF contribution is marginal
- But little doubt additional timing handle can be used if available in channels with softer spectra, LLP searches,…

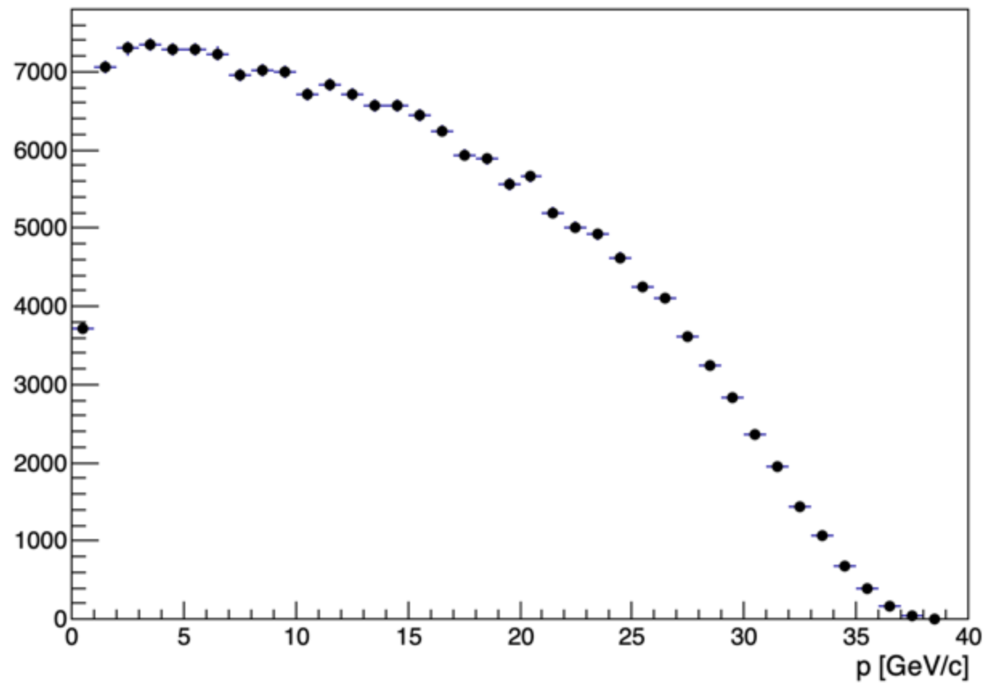


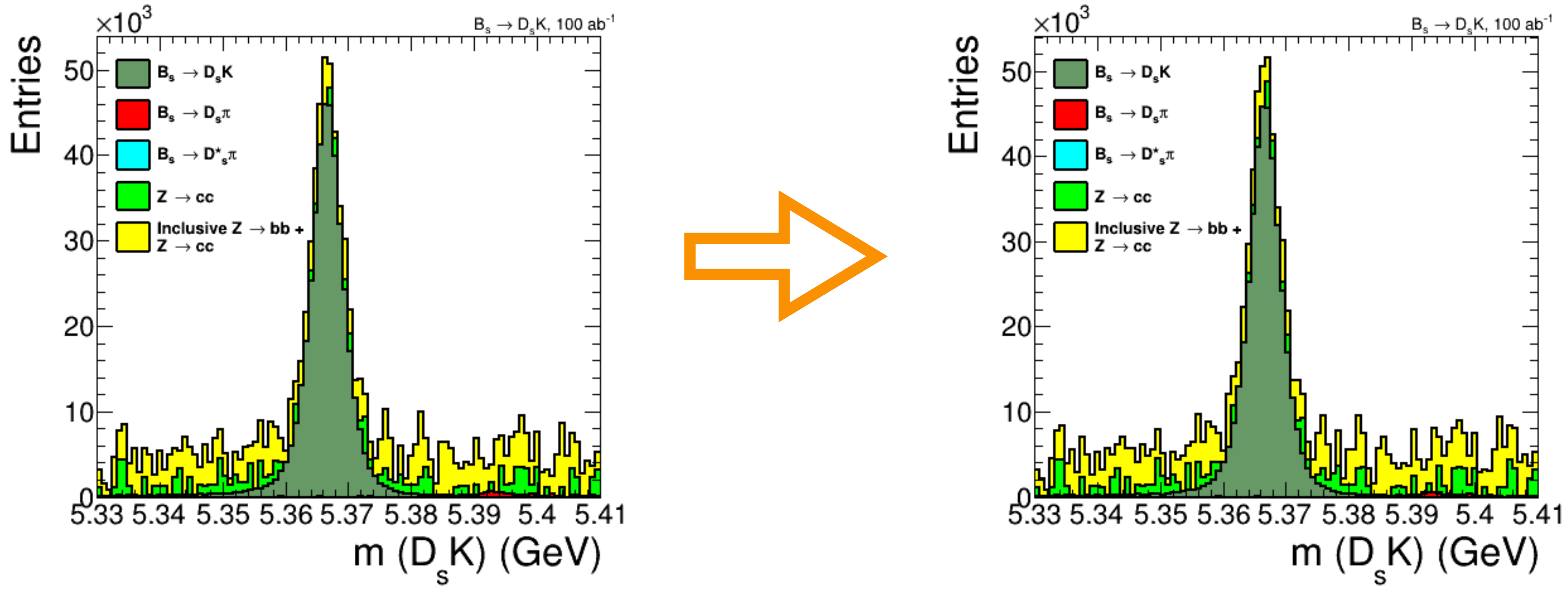
A. Coccaro, F. Parodi, E. Perez

π



K





Which technology for the silicon wrapper?

A potential candidate technology for the space-time detector for IDEA is the resistive **AC-coupled LGAD sensor** (aka **R**esistive **S**ilicon **D**etector)

INFN has historically a leading role in the development of LGAD detectors

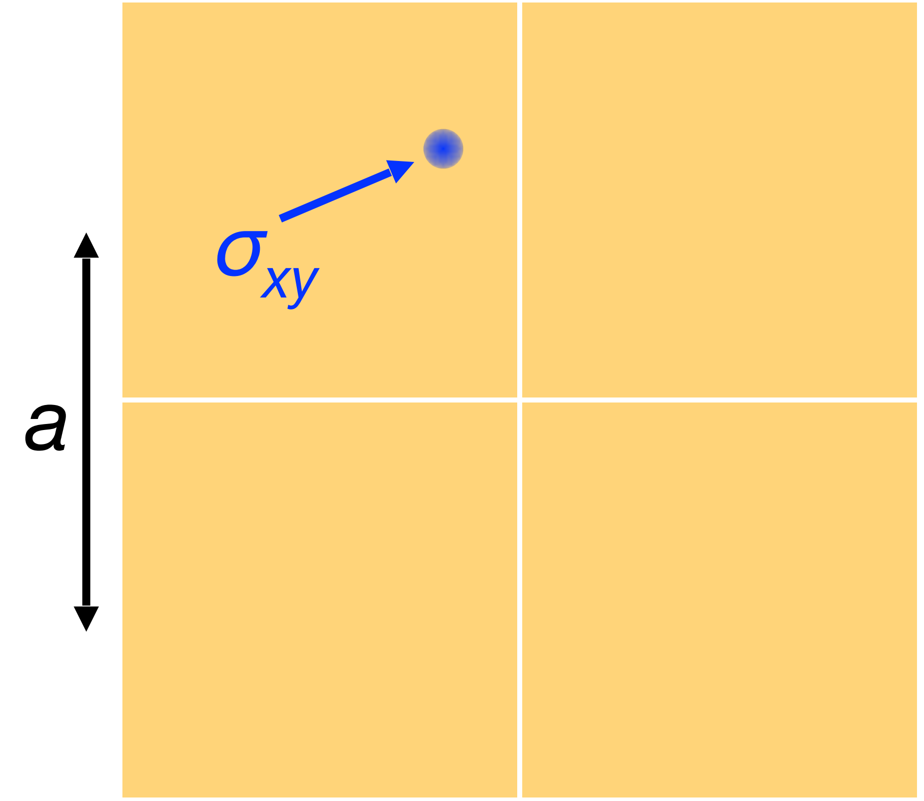
Dominant contribution in design, test, simulation studies from Torino, Perugia groups, in collaboration with FBK

First AC-coupled LGADs prototyped by FBK in 2019

More recently, additional foundries such as **HPK, BNL, IHEP, and CNM** have joined this line of research, prototyping AC-LGADs.

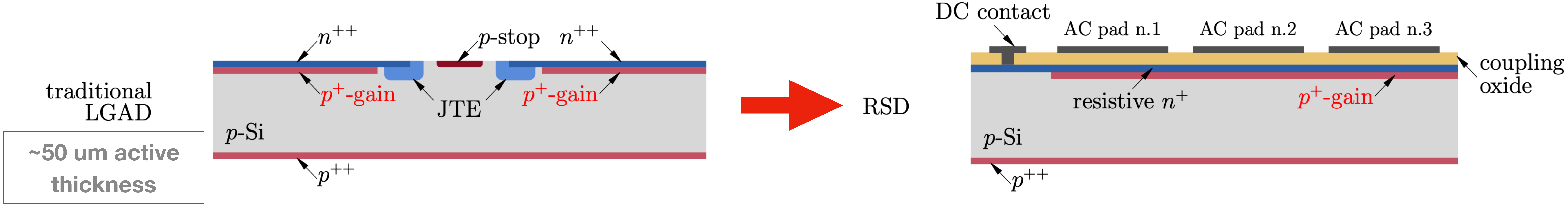
RSD main characteristics:

- **excellent position resolution with reduced number of channels σ_{xy} = 3-5% *a*;**
- **timing resolution and radiation hardness similar to "standard" LGADs;**
- **suitable for low-density hit environment**



AC-LGAD, or Resistive Silicon Detectors

LGAD with AC coupled read-out: a resistive layer is needed for charge collection $\Longrightarrow$ similar concept to gas detectors such as RPCs



- Single, uninterrupted diode $\Longrightarrow$ device with 100% Fill Factor
- Metal read-out pads coupled to the sensor through an oxide layer
- Resistive n^{+} layer

➡ intrinsic signal sharing

- Continuous gain layer spreading across the active area ➡ internal charge multiplication

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Direct charge induction on the resistive layer, **large > 5 fC (gain 10-30) & fast (~1 ns) signal**

Signals are induced on the AC-coupled metal pads: the shape and segmentation of the read-out pads defines the spatial resolution

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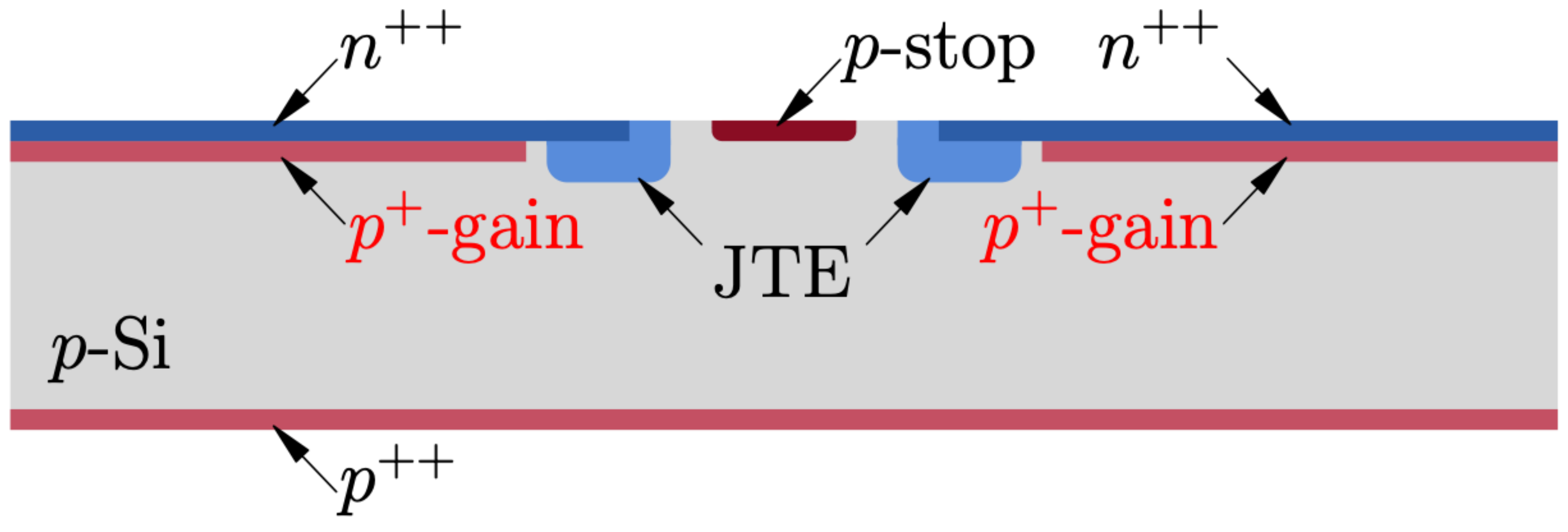
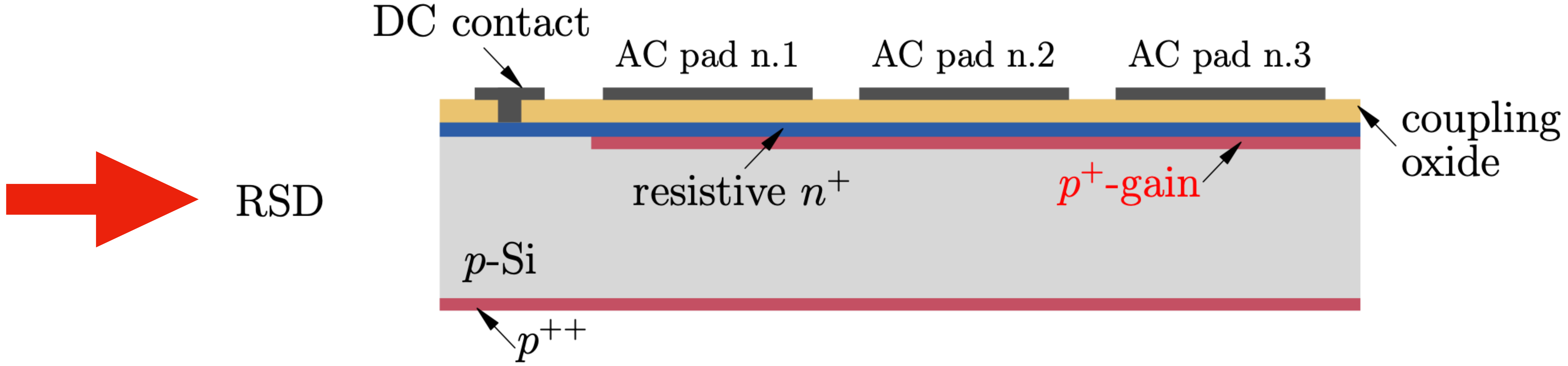
traditional LGAD

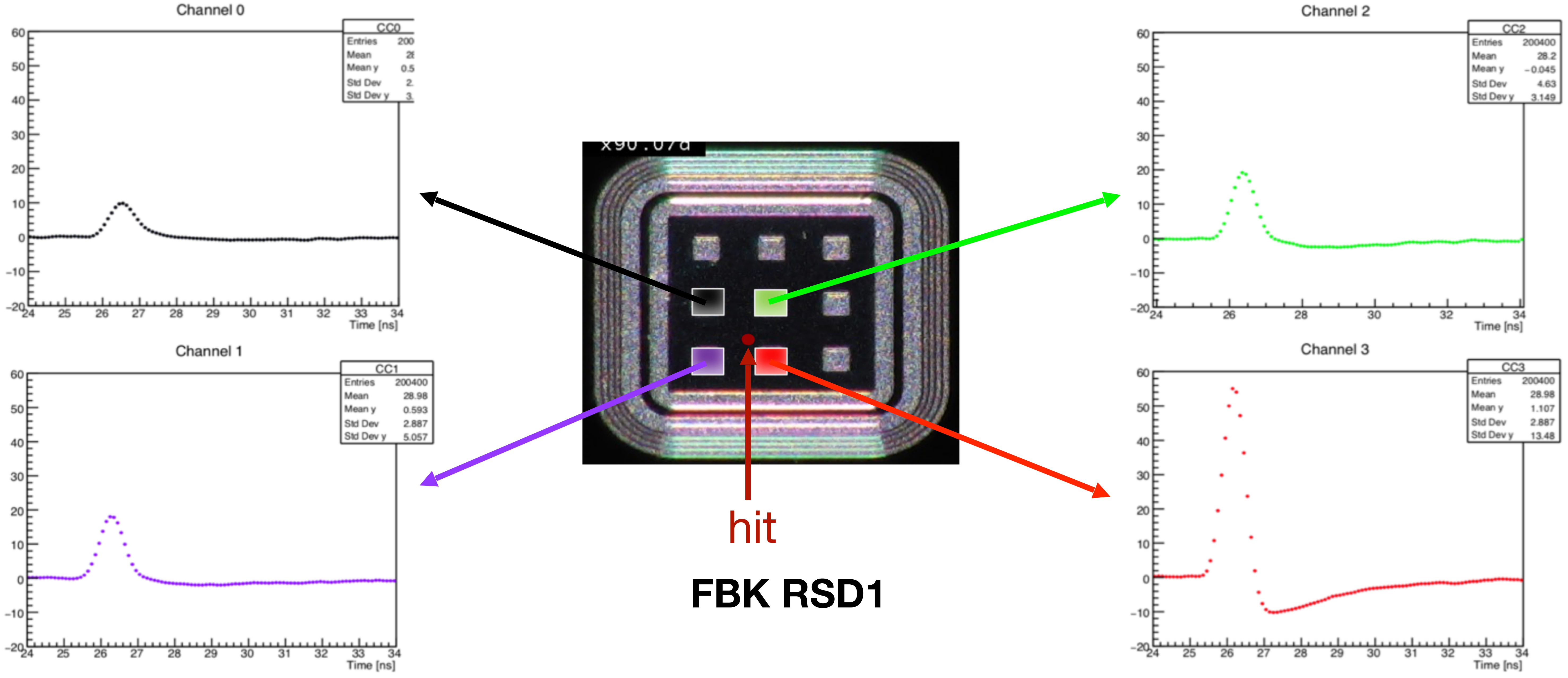
~50 um active thickness





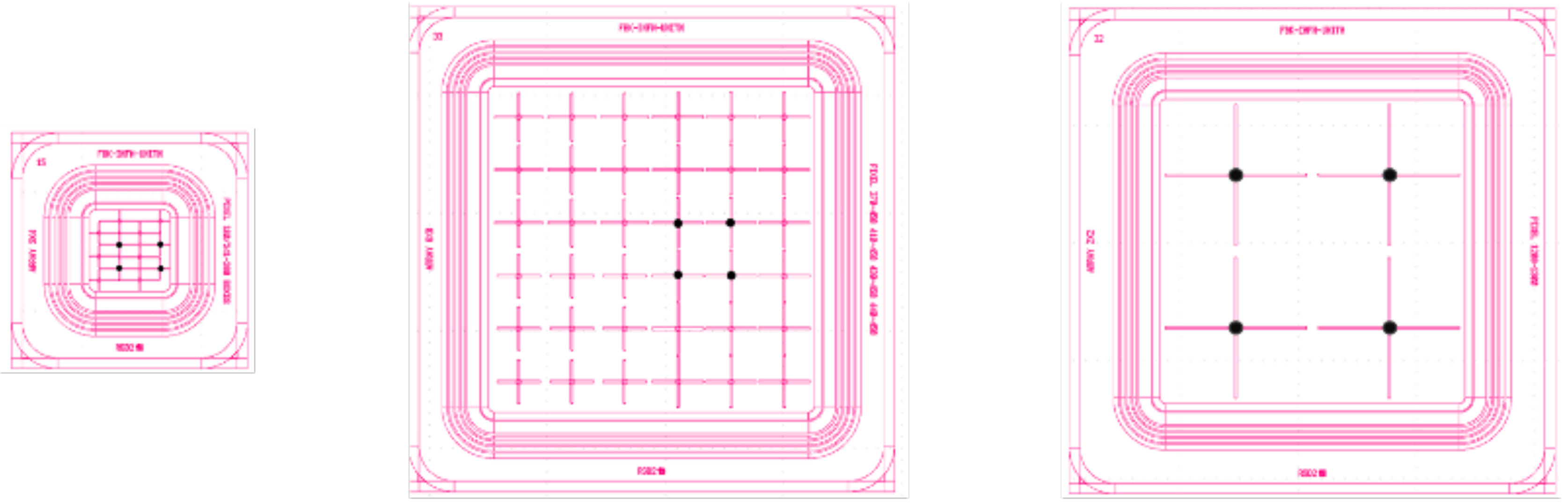
Signal is shared among nearby pads $\Longrightarrow$ position reconstructed by properly weighting signals

- requires calibration and corrective algorithms to reach the best accuracy



AC-LGADs from FBK: RSDs

FBK RSD2 (2021) best design: swiss cross electrodes.
Position performance have been explored with laser and several test beams.



(A) (B) (C)

Space resolution depends on several factors: electrodes pitch and geometry; electronics noise; signal digitisation; reconstruction algorithm.

x-y coordinates reconstructed using the "charge asymmetry" method + correction (migration matrix or sharing template, to correct algorithm induced distortion effect)

R. Arcidiacono et al, "High precision 4D tracking with large pixels using thin resistive silicon detectors", NIM A 1057 (2023) https://doi.org/10.1016/j.nima.2

Space resolution with RSDs

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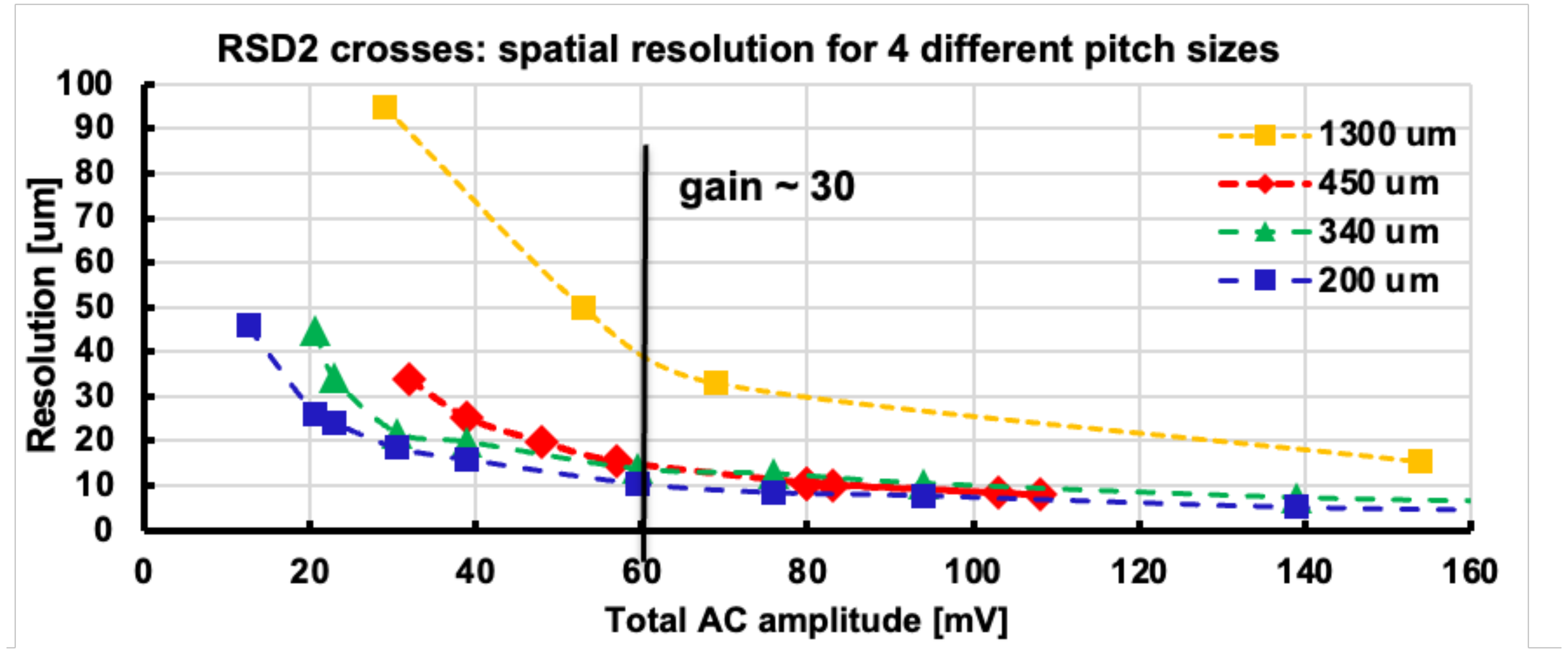
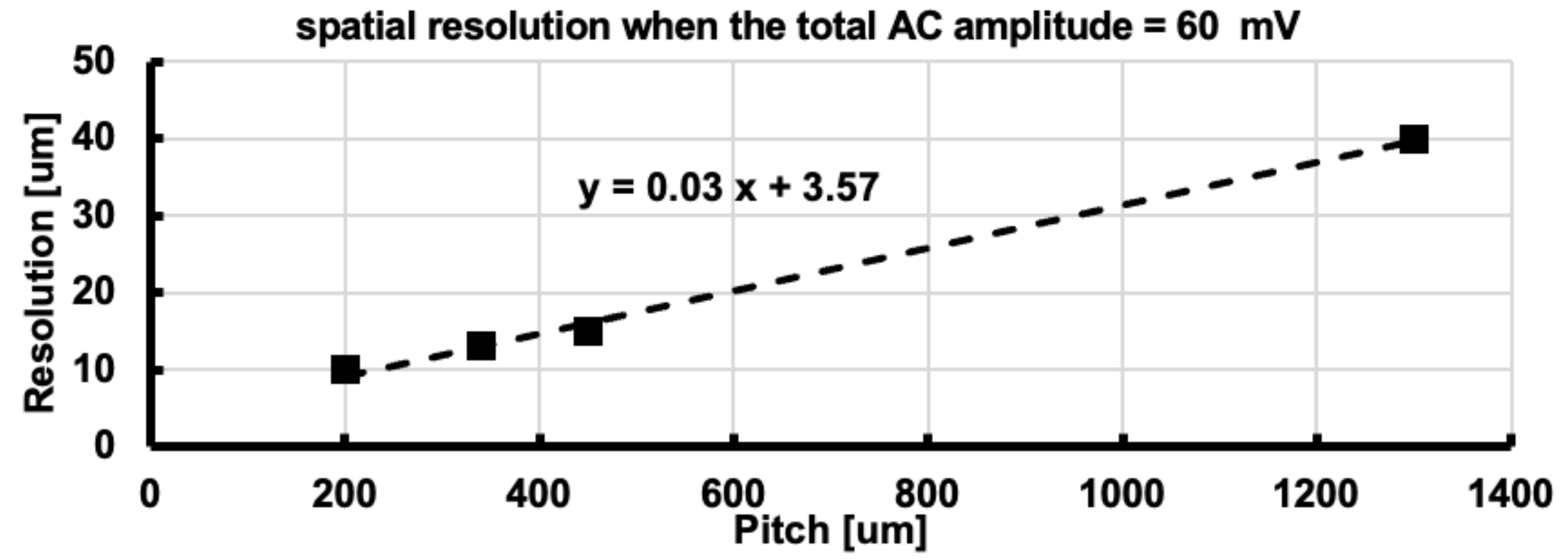
Results using TCT setup (laser)

RSDs at gain = 30 achieve a spatial resolution of about 3% of the pitch size

- 1300 x 1300 mm²: s_x ~ 40 µm
- 450 x 450 mm²: s_x ~ 15 µm





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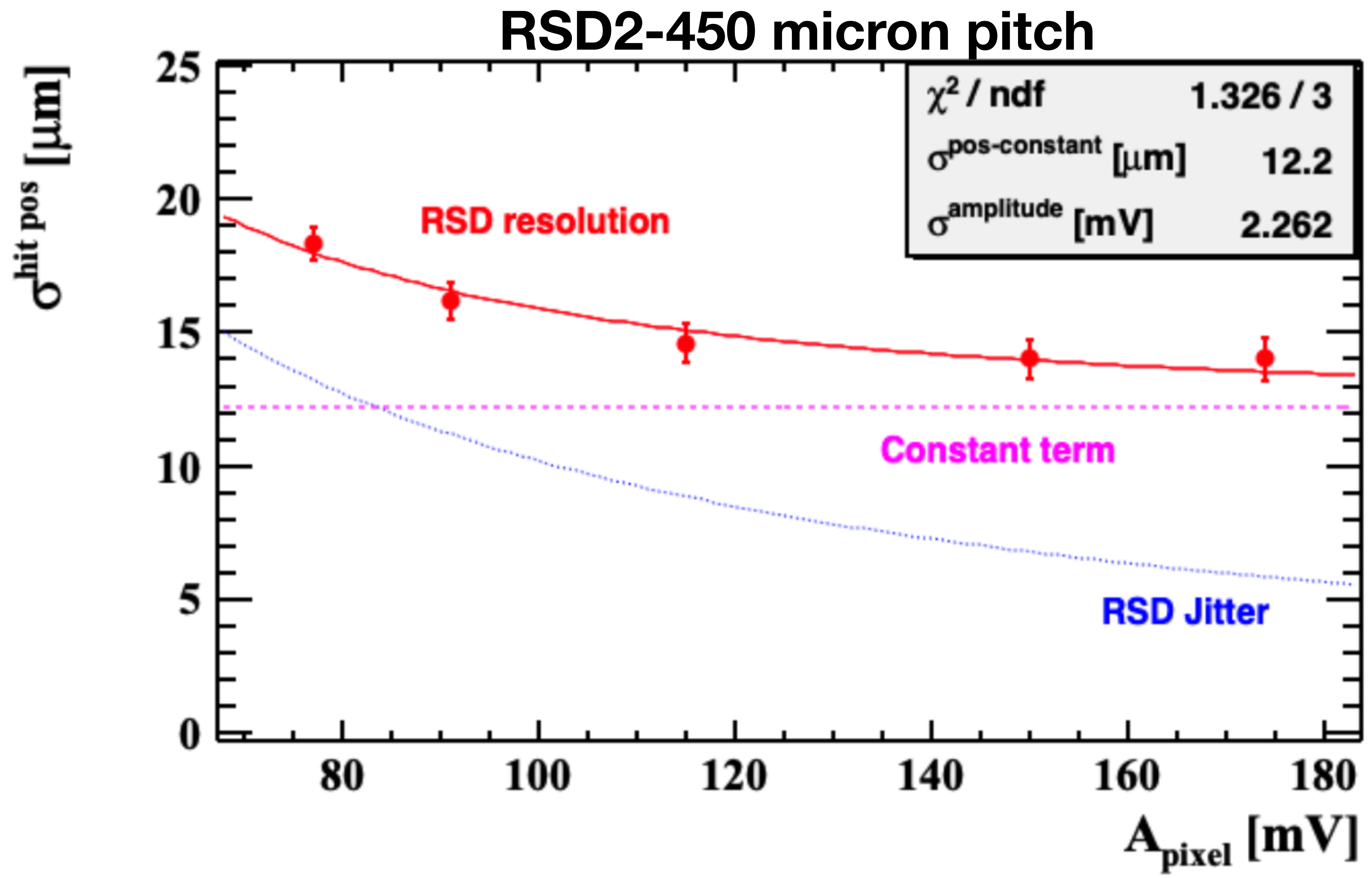
Position performance have been explored with laser and several test beams.

Results with electron testbeam (DESY)

RSD2-450, pixel 450 x 450 um^2 16 electrodes
16ch FAST2 Board (INFN Torino) + CAEN Digitizer

The constant term dominates the resolution $\sigma_{constant}$ ~ 13 µm
It includes mis-alignment RSD-Tracker, sensor and electronics non uniformity, etc…

Resolution around 3%-4% **of the pitch.**



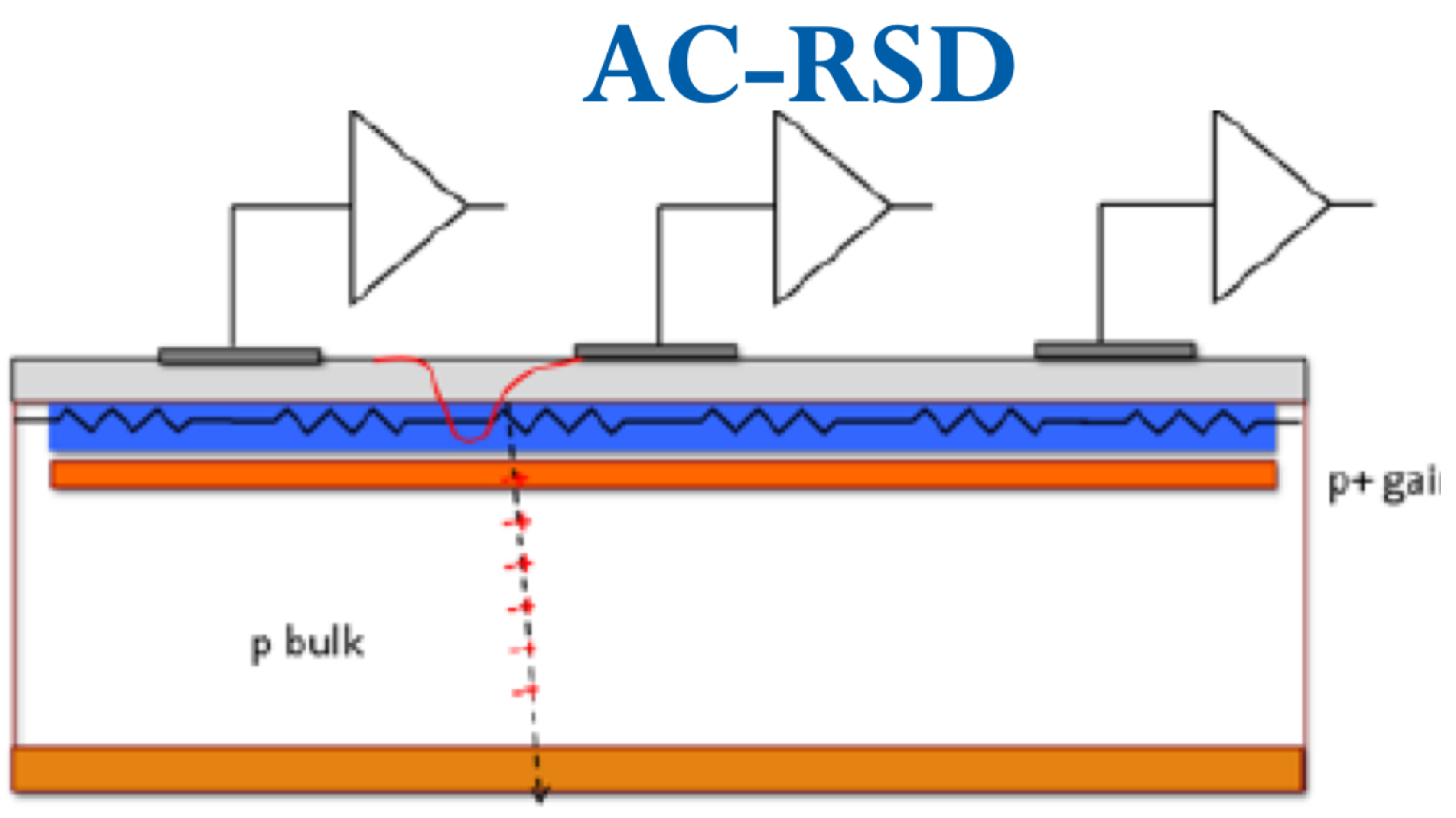
$$\sigma^{\text{hit pos}} = \sqrt{(\sigma^{\text{pos-constant}})^2 + (\frac{\sigma^{\text{amplitude}} \times \text{pitch}}{\Sigma_i^4 A_i})^2}.$$

L. Menzio et al, "First test beam measurement of the 4D resolution of an RSD 450 microns pitch pixel matrix connected to a FAST2 ASIC",)NIMA 1065 (2024), 169526

Next evolution (R&D) at FBK: DC-RSD

RSD sensors show some non-ideal features:

- Signal spread may involve a large (>4) and variable number of electrodes, leading to slight deterioration and a spatial resolution which is position-dependent
- Baseline fluctuations (leakage current collection only at the edge)
- The bipolar nature of the signals, with rather long tails during the discharge



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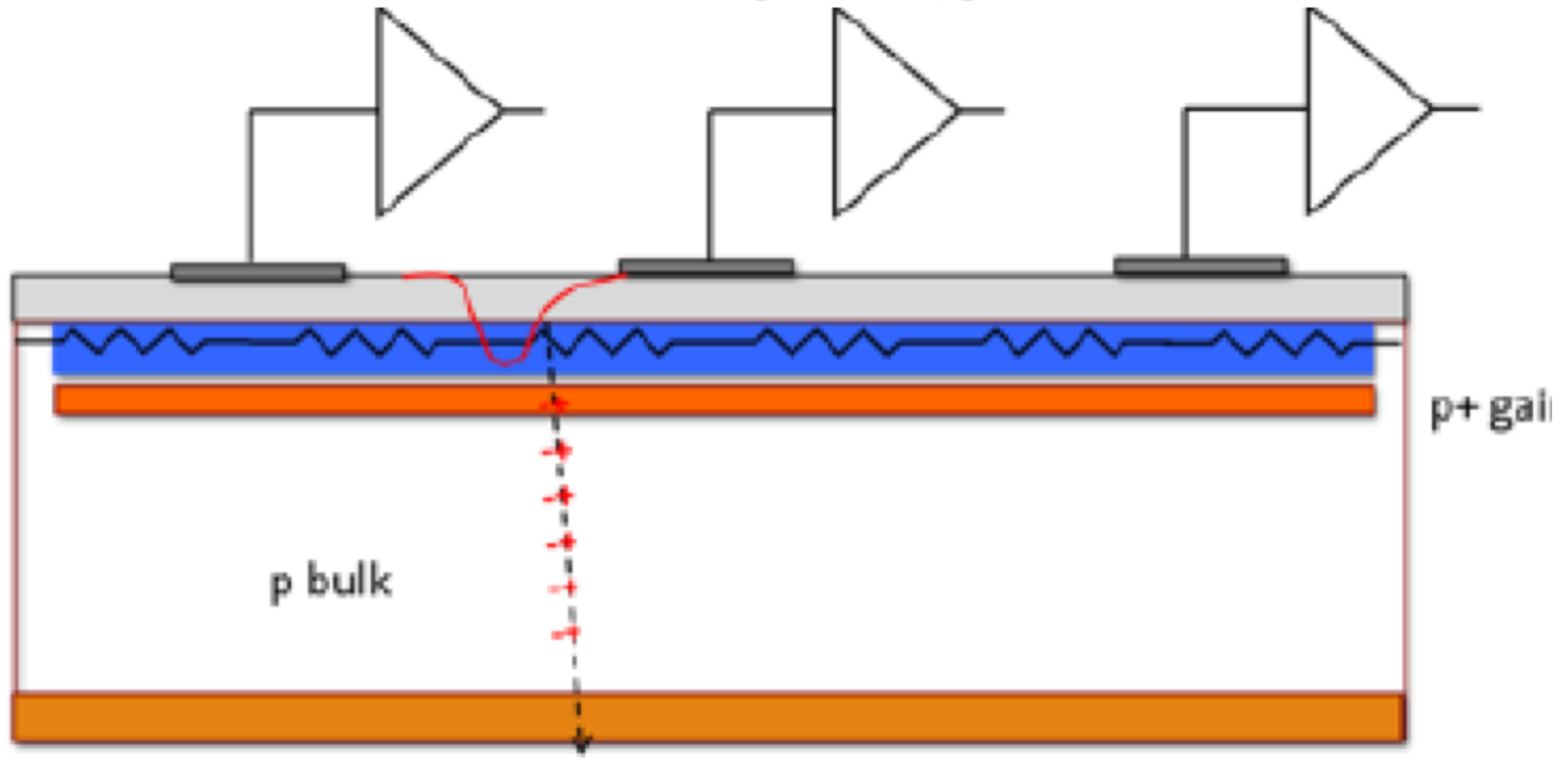
DC collection of signals, with low resistivity paths to readout pads ⟹ DC-RSD design

- Signal is confined: charge sharing in a predetermined number of pads
- the leakage currents is removed locally at each electrodes
- No bipolar signal → 1 ns-long pulses

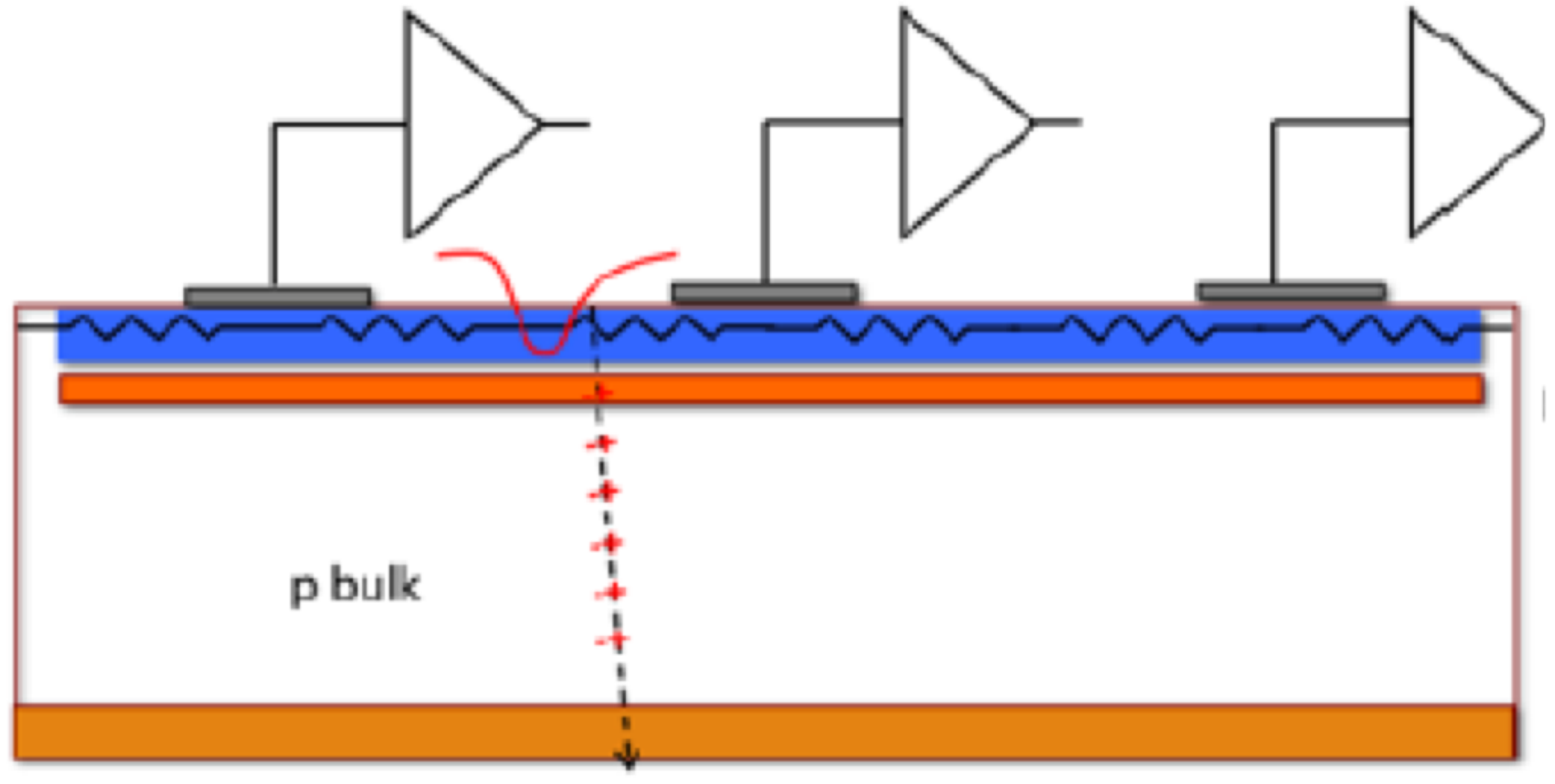
→ uniform performance and scalable to large devices

Extensive simulation studies performed to optimise design: resistive path, charge sharing, electrodes geometry, confinement method…

AC-RSD



DC-RSD



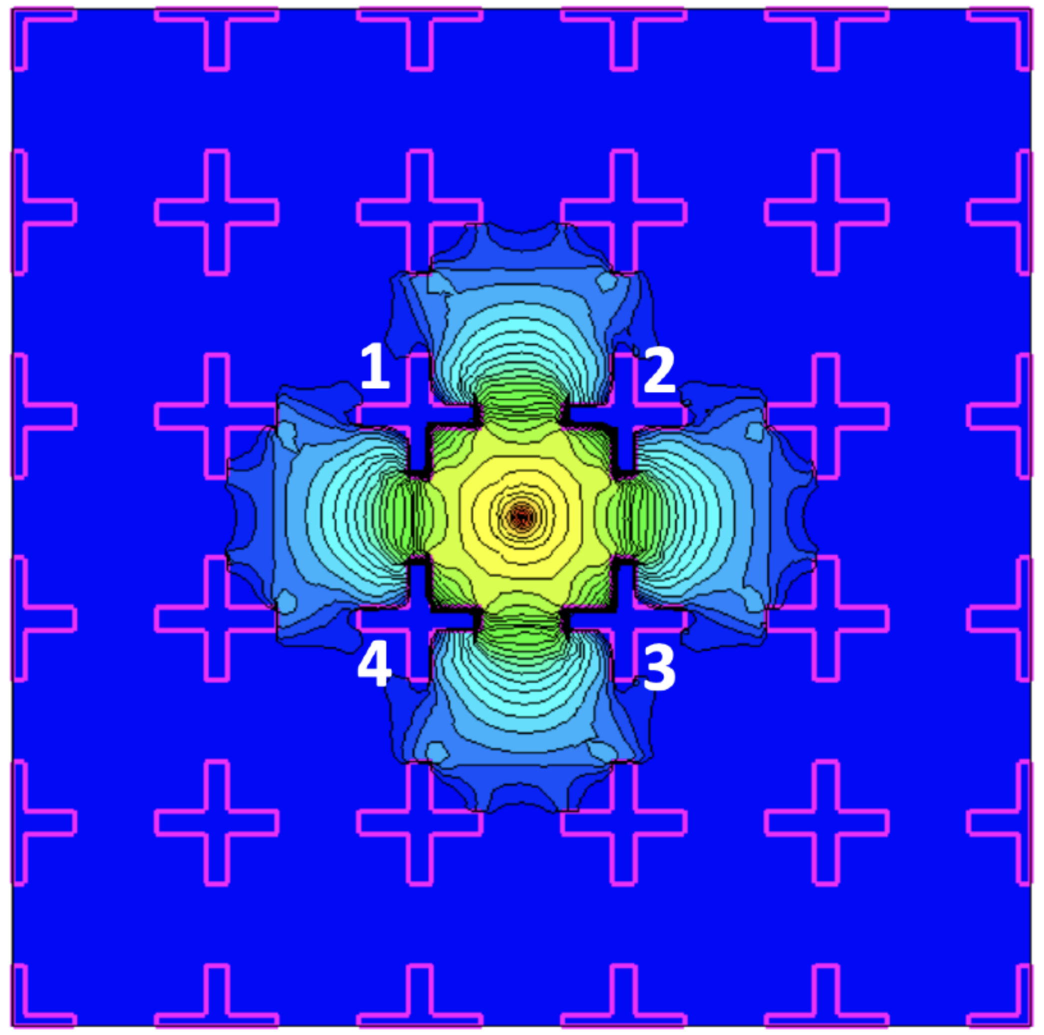
Status of DC-RSD production

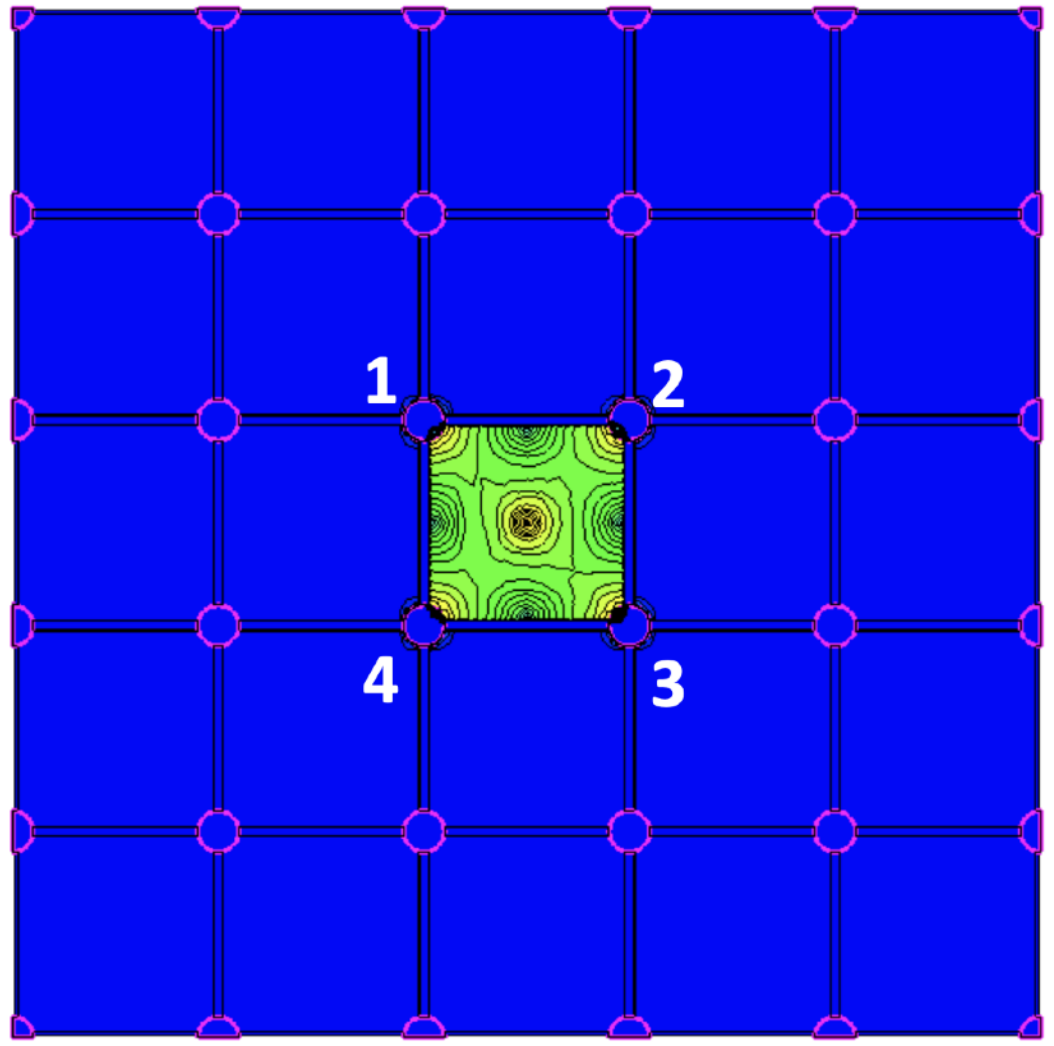
DC-RSD development started in the framework of the **4DinSiDe** (PRIN, 2017) and is now continuing with the **4DSHARE project** (INFN CSN5, PRIN 2022)

The first proof-of-concept production at FBK is close to completion (Nov/24)

- The solution selected to achieve the containment: use of Isolating Trenches (like in TI-LGADs or SiPM)

3D-TCAD simulation comparing
DC-RSD without (left) and with (right) isolating trenches





F. Moscatelli et al, https://www.sciencedirect.com/science/article/pii/S0168900224003061 (2024)

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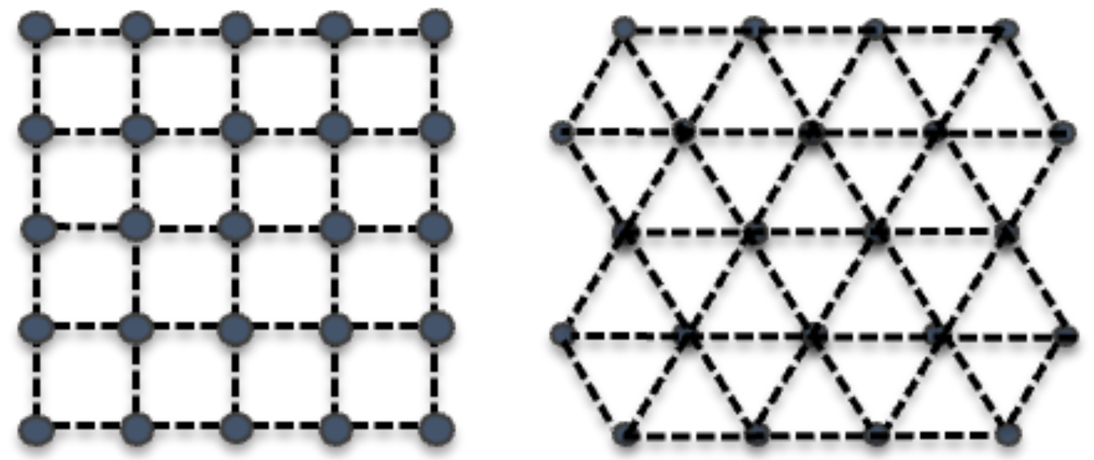
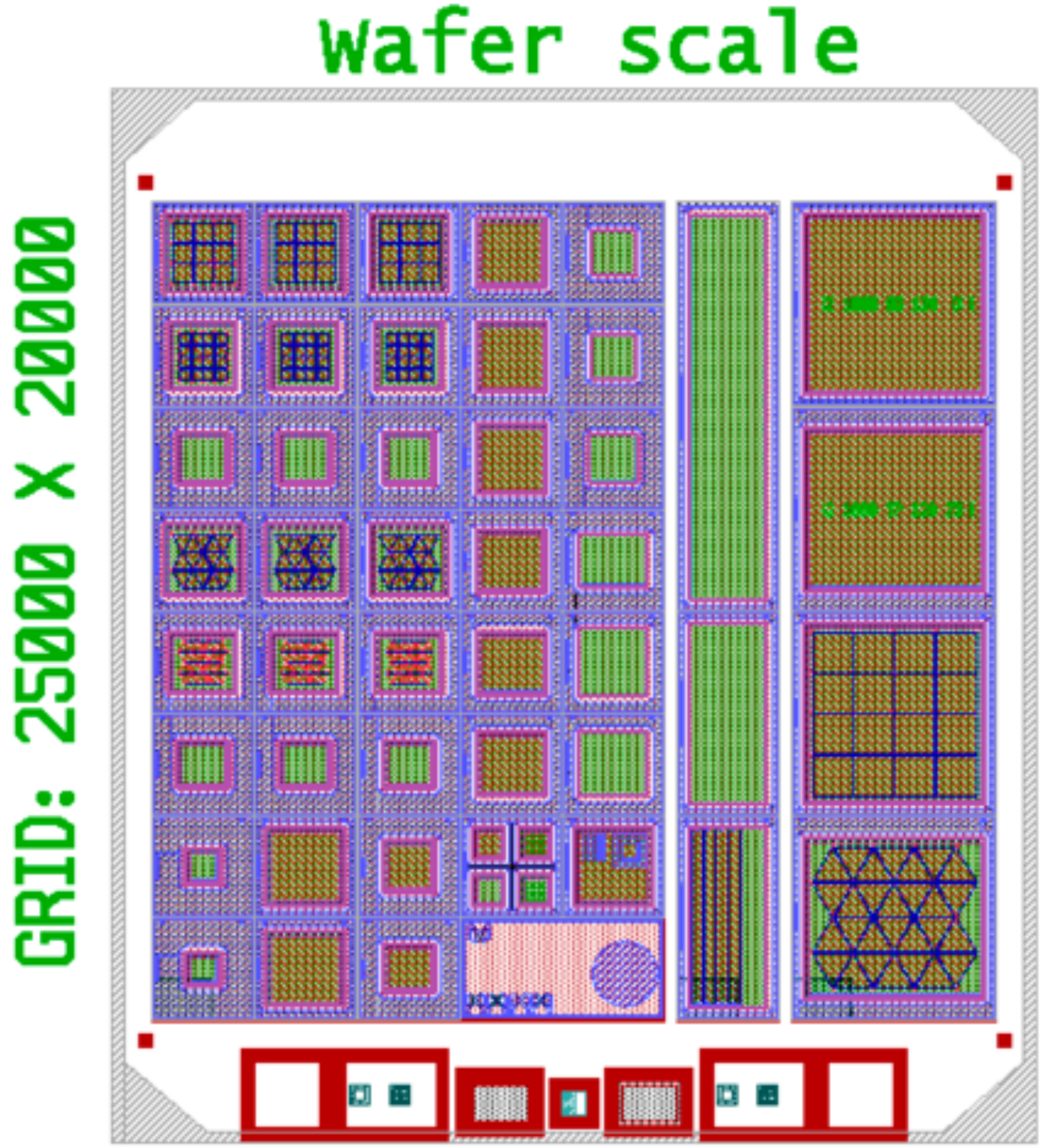
- Several test structures implemented:
  - devices with squared or hexagonal matrix of electrodes (dot-like), without and with isolating trenches, multiple pitch options
  - strips with multiple pitch options, and different electrode layout

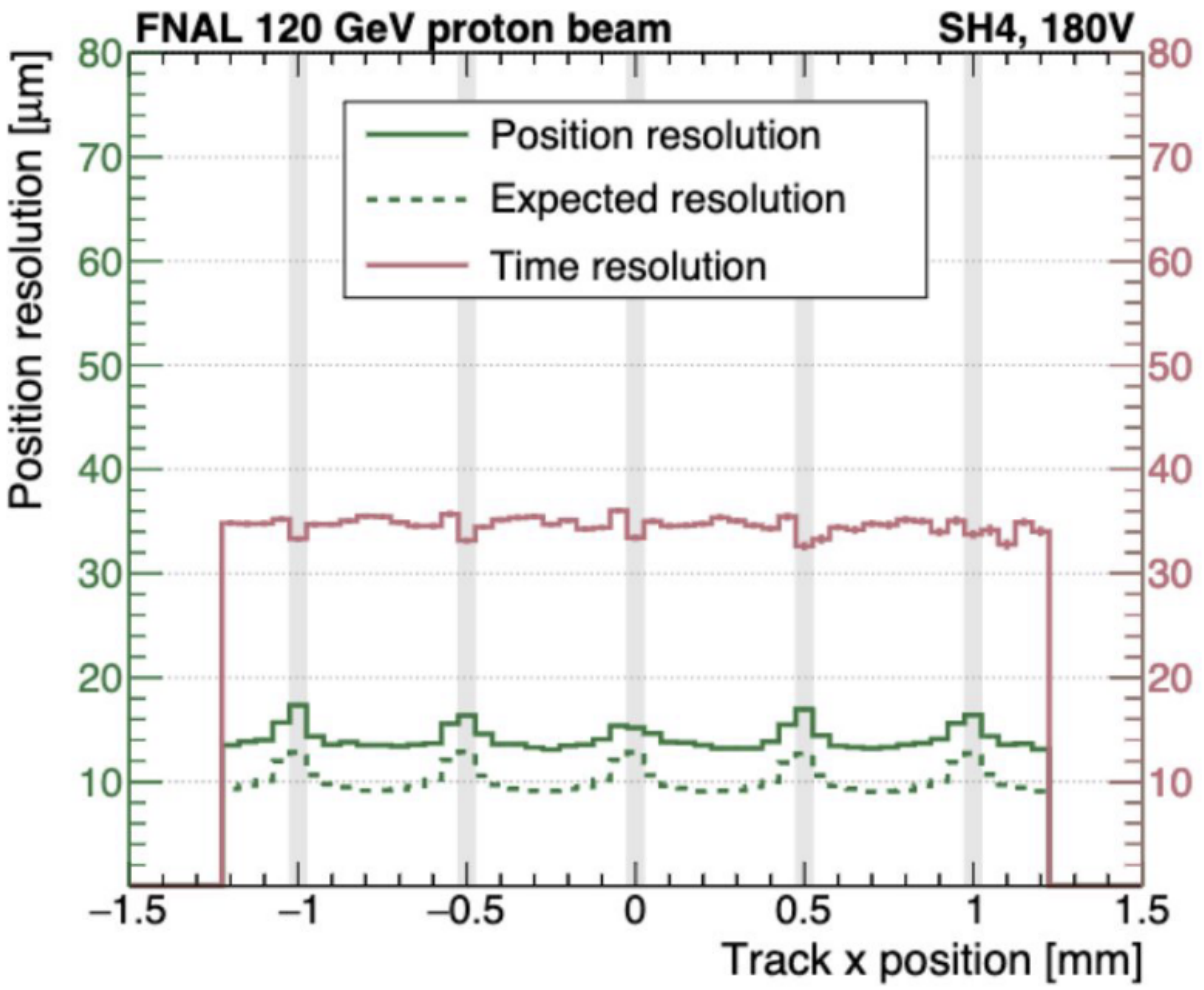


squared or hexagonal matrix

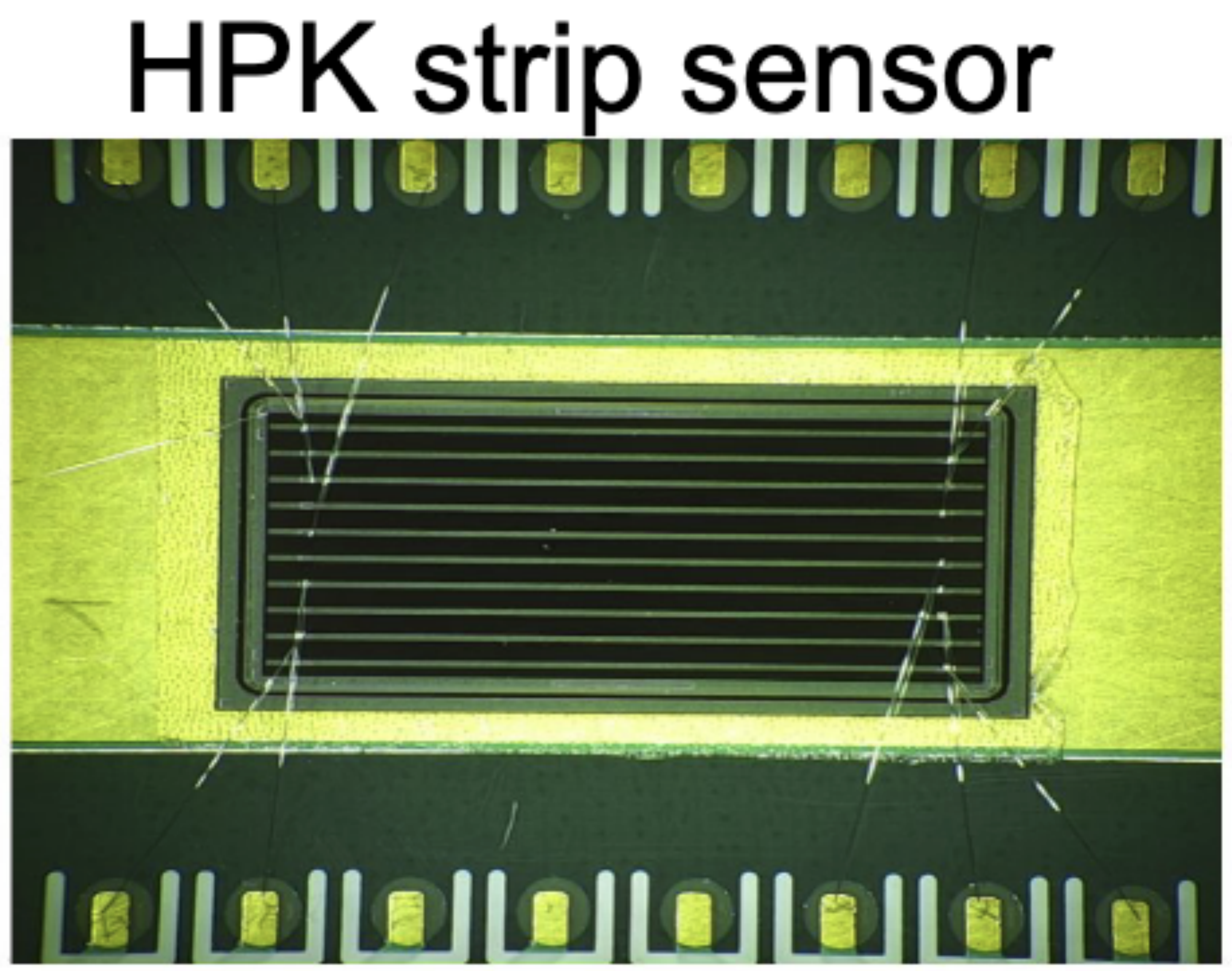


AC-LGADs from HPK

- Target application: EIC
- Here showing the "charge-sharing approach" type (as in FBK RSD - small metal pad size), for low occupancy colliders.
- **Strips** 1 cm length, **500 μm pitch, 50 μm metal width**, 50 μm active thickness



- $\sigma_{Spatial}$ **= 15 um** (x-axis) very uniform
- σ_{Time} **= 35 ps** very uniform



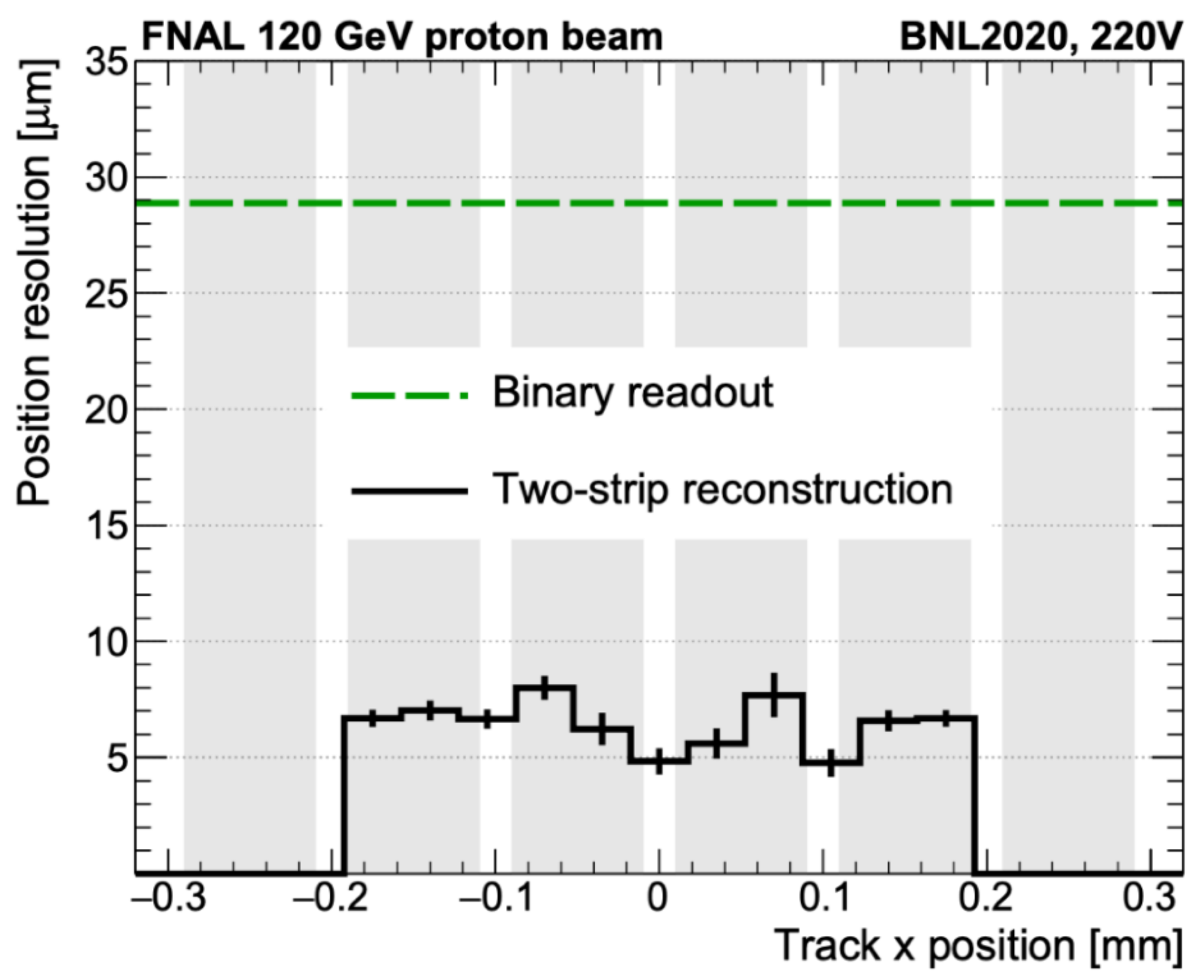
500 um pitch variable metal width and active thickness

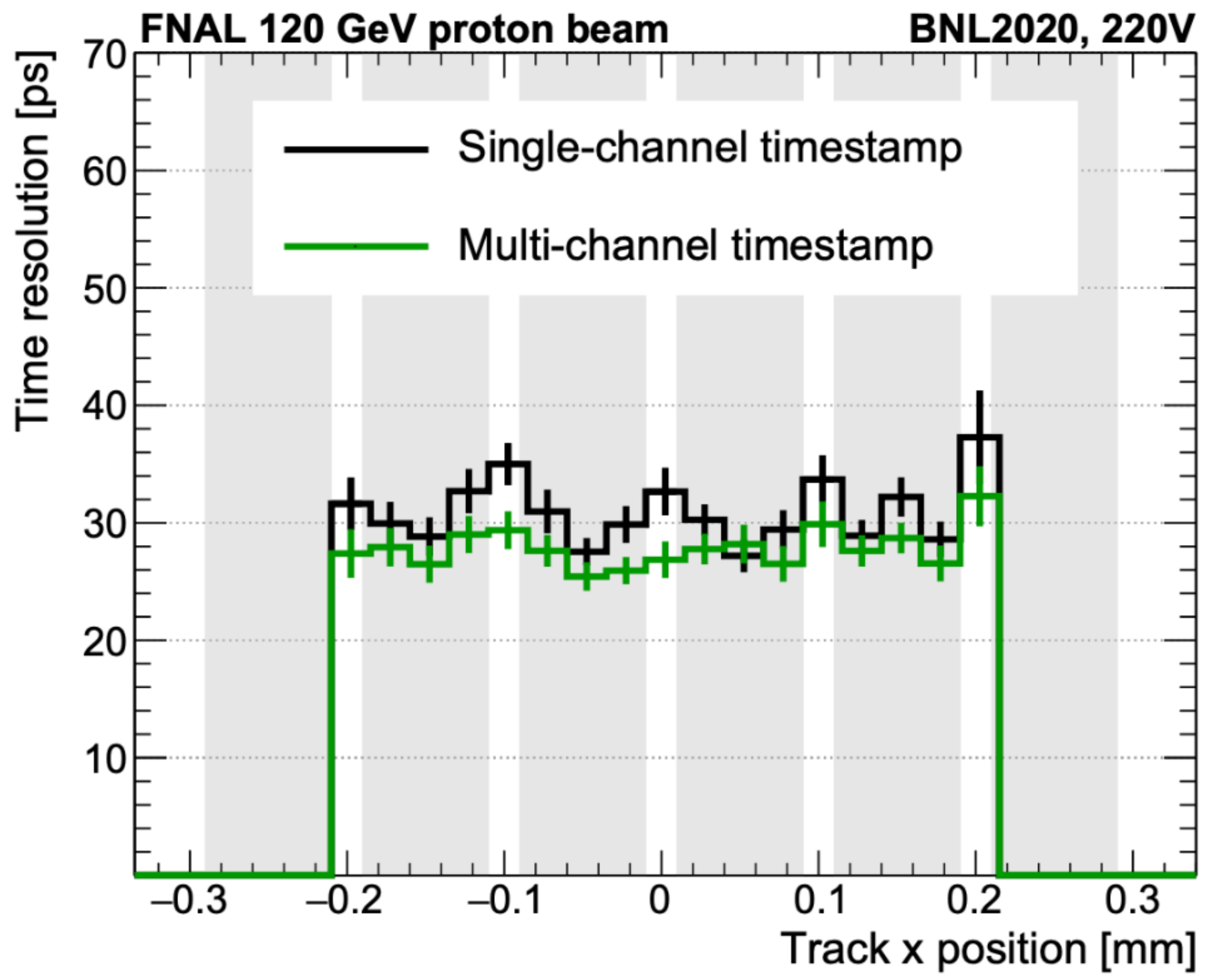
- Similarly good results obtained with a 20-μm active thickness (very thin!!!) **pixel matrix 500-μm pitch , 150 μm electrode pads:**
- quite uniform performance
- $\sigma_{Spatial}$ **~ 21 μm**
- σ_{Time} **~21 ps**

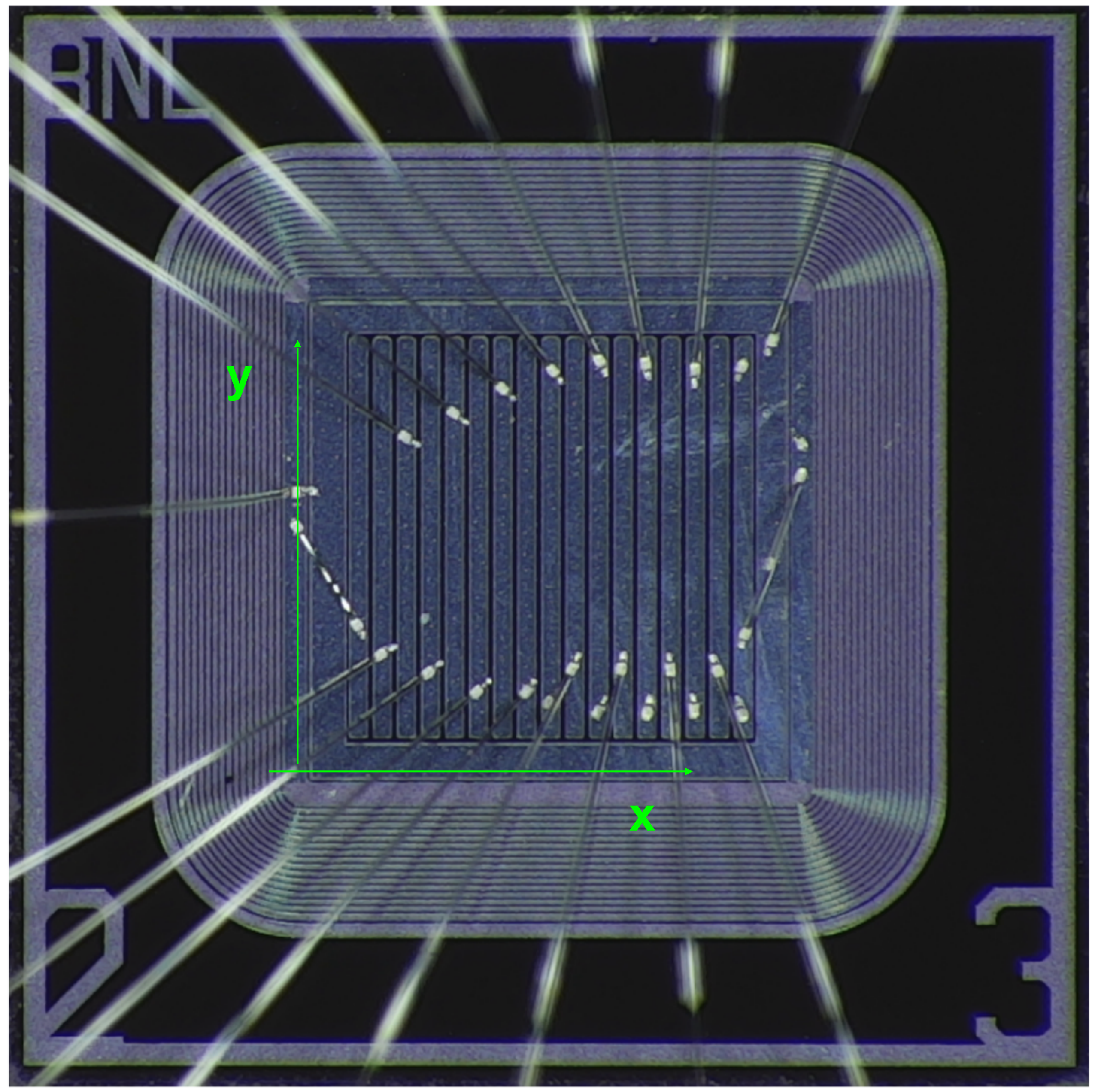
https://lss.fnal.gov/archive/2024/slides/fermilab-slides-24-0039.pdf

AC-LGADs from BNL

- Target application: EIC
- Results from a FNAL test beam (link) on **BNL production**





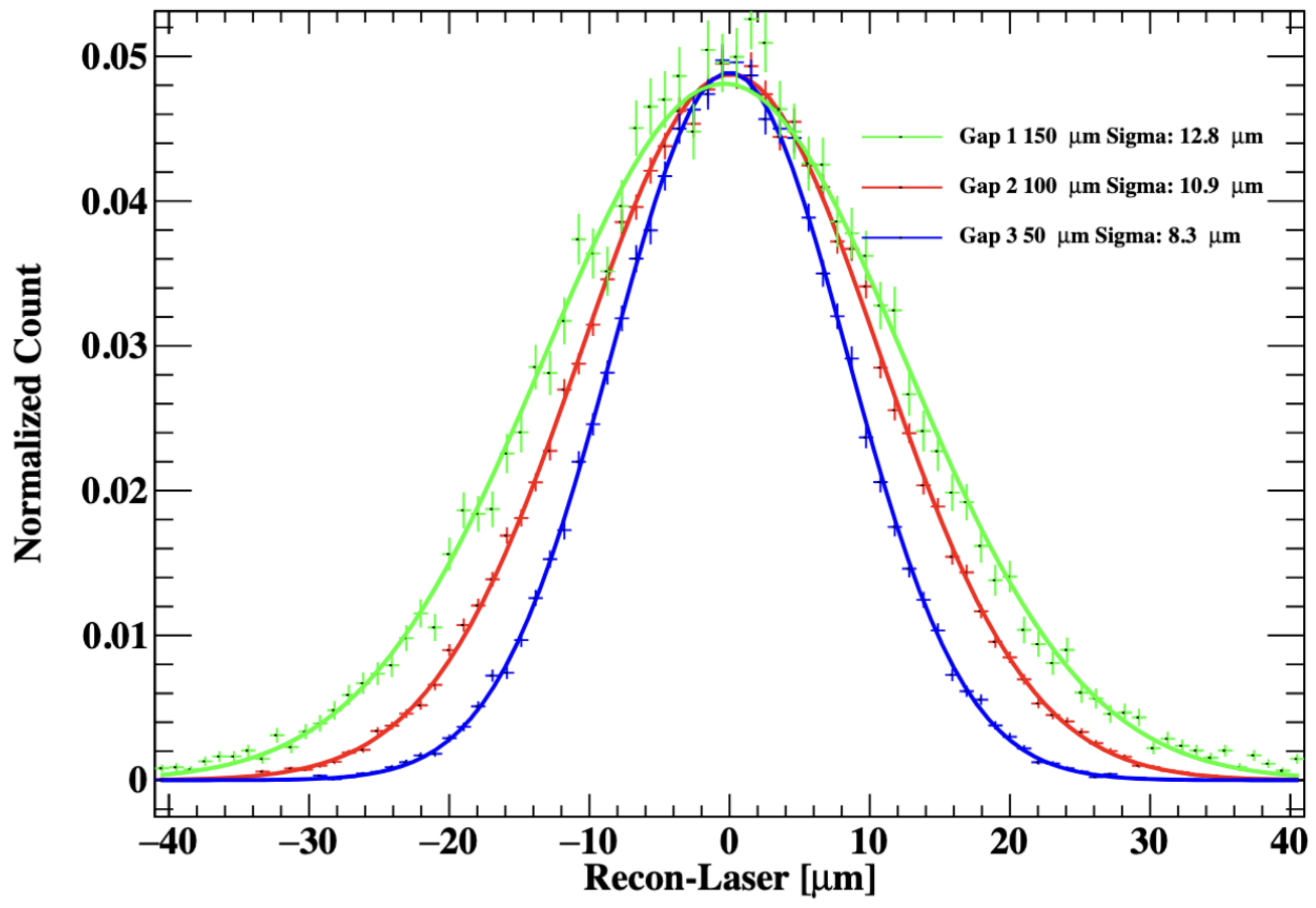


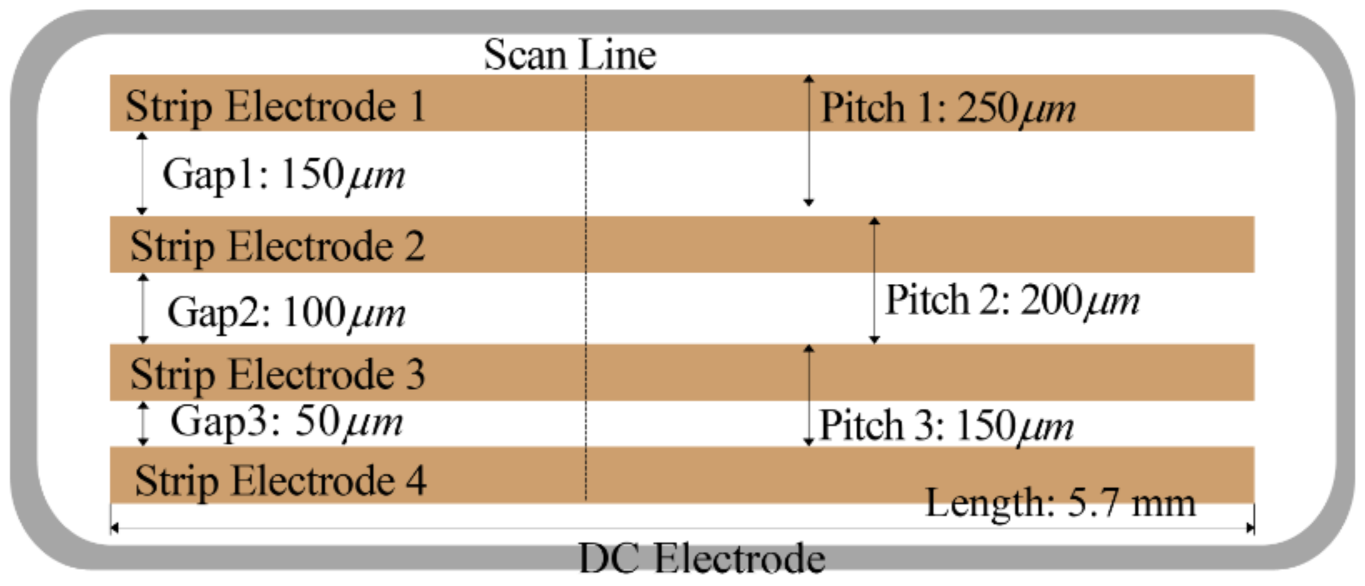
BNL sensor(2020): 100 um pitch strips (80 um metal)

- $\sigma_{Spatial}$ = 5-10 um along x-axis
- σ_{Time} = 30-40 ps
- Only 30% of the active area (central part) used used for the reconstruction
- New BNL prototypes (May 2023) under studies (optimized strips and pixel matrix with cross-like electrodes)

AC-LGADs from IHEP

- Target application: EIC
- AC-LGAD strips, 150 200 and 250 um pitch (5.7 mm long)
- Studied with pico-second laser test and beta source test



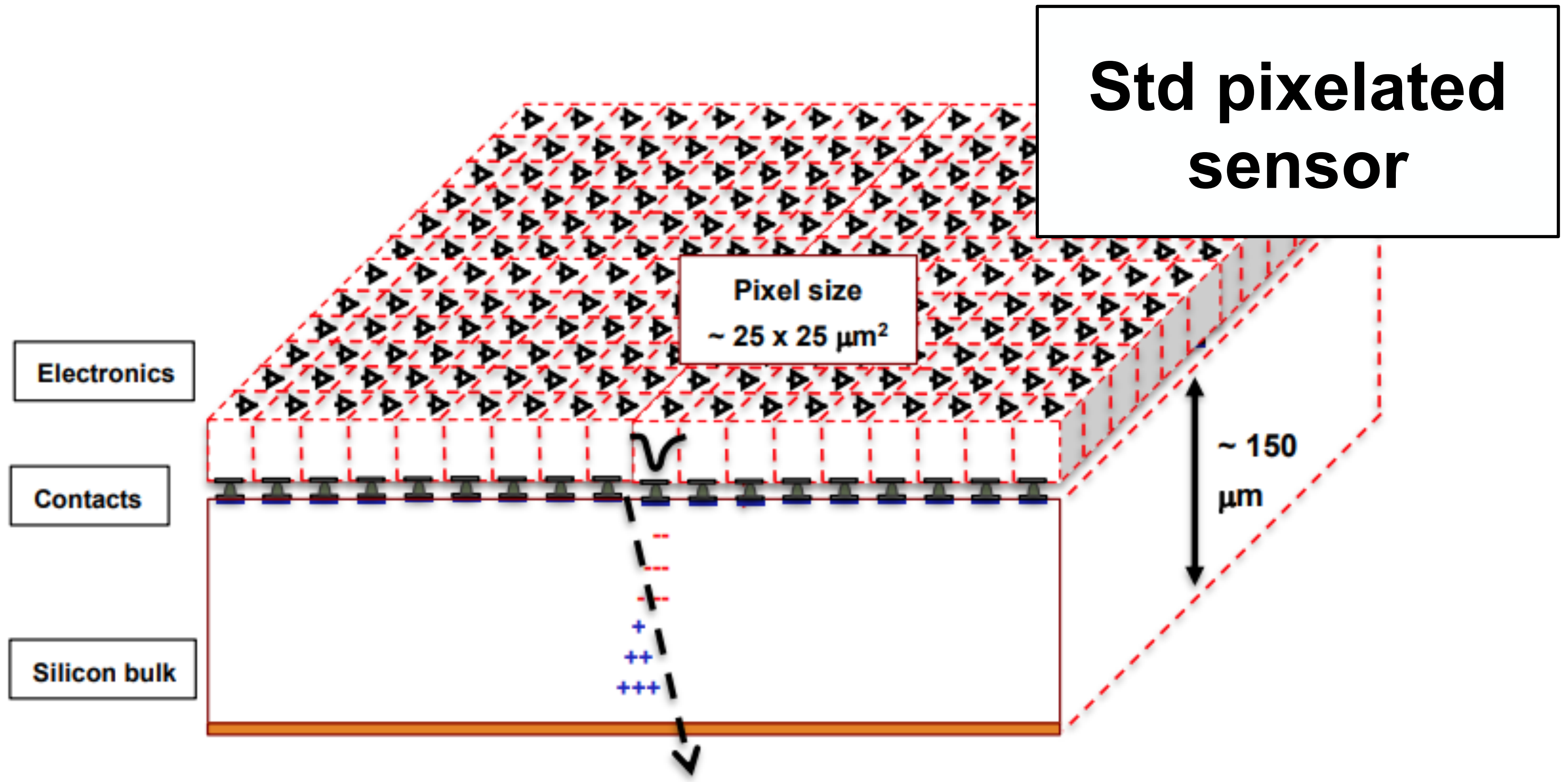


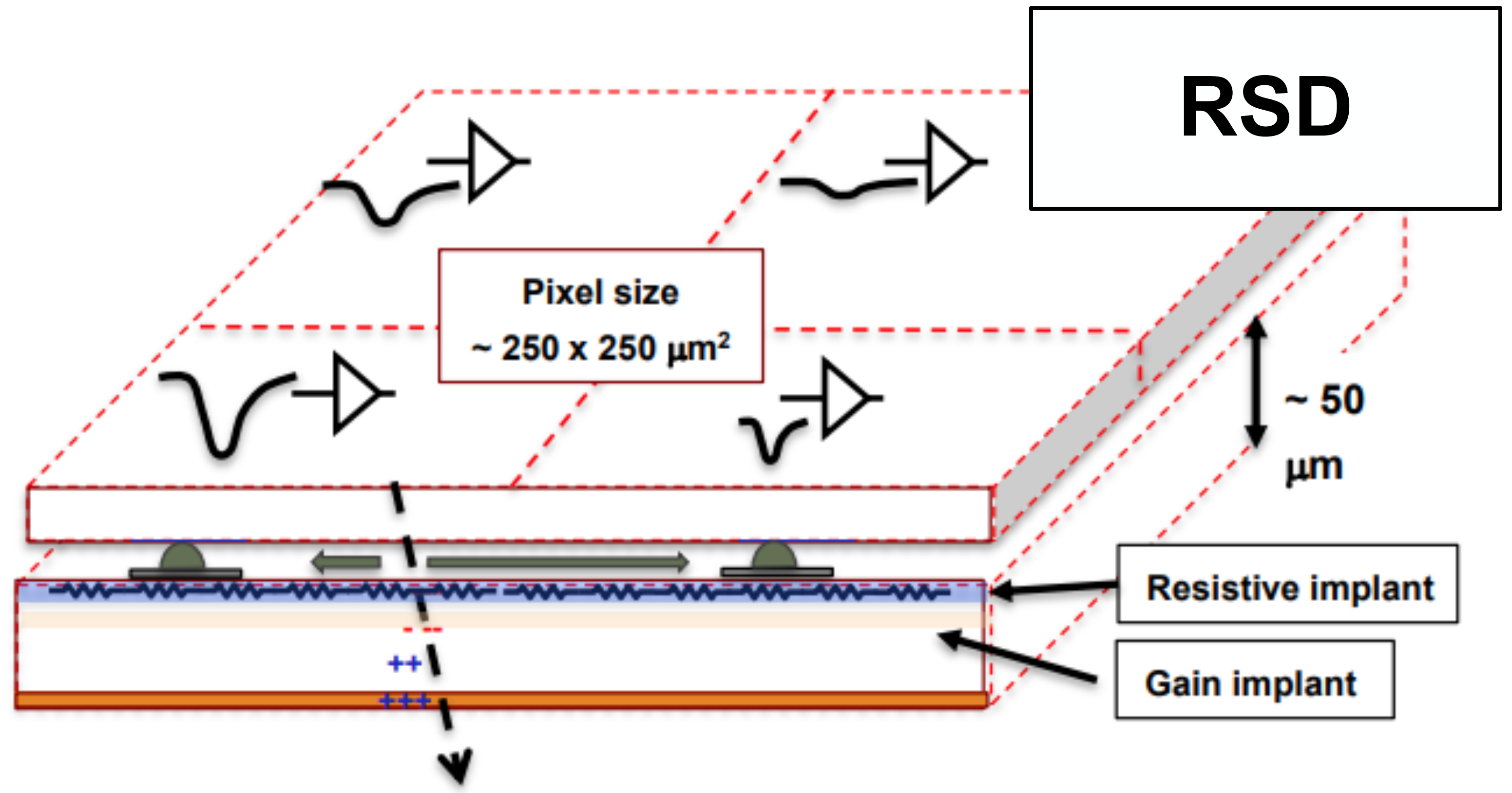
IHEP strip: variable pitch

May 2024 https://arxiv.org/pdf/2307.03894

- Timing resolution 37.6 ps
- Spatial resolutions pitch sizes of 150 µm, 200 µm, and 250 µm are 8.3 µm, 10.9 µm, 12.8 µm, respectively.

A new paradigm for silicon trackers





- **Binary read-out: σ_{Pixel} ~ 0.3·pitch**
- **AC-LGADs: σ ~ 0.03- 0.05 ·pitch**
- **AC-LGADs** time resolution → **30-40 ps**

similar space resolution with reduced number of read-out channels (a factor of ~100 less)

excellent time resolution

Conclusions

- Resistive read-out coupled to LGAD technology can enable accurate 4D-tracking
  - Large & fast signals shared among a constant number of pads, 100% fill factor
- State-of-the-art AC-coupled resistive LGADs studied with testbeam particles:
  - achieved 15 um spatial resolution and 50 ps time resolution with 450 microns pitch
  - achieved 15-20 um spatial resolution with 500 microns pitch strips

  → ideal for low-occupancy applications
- Many prototypes on the market
  - FBK, HPK, BNL and IHEP
- Possible improvement with the DC-coupled resistive LGAD (DC-RSD), soon to be tested, enabling larger scale devices.