VRIJE UNIVERSITEIT BRUSSEL

University of Zurich[UZH]

Characterising Analogue MAPS Fabricated in 65 nm Technology and Opportunities for FCC-ee

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NBI Seminar | 11.11.2024

FUTURE CIRCULAR COLLIDER

ALICE

FCC-ee

A lepton collider after LHC is a **priority** to test SM to the **ultimate precision**, especially focussing on the **Higgs boson**.

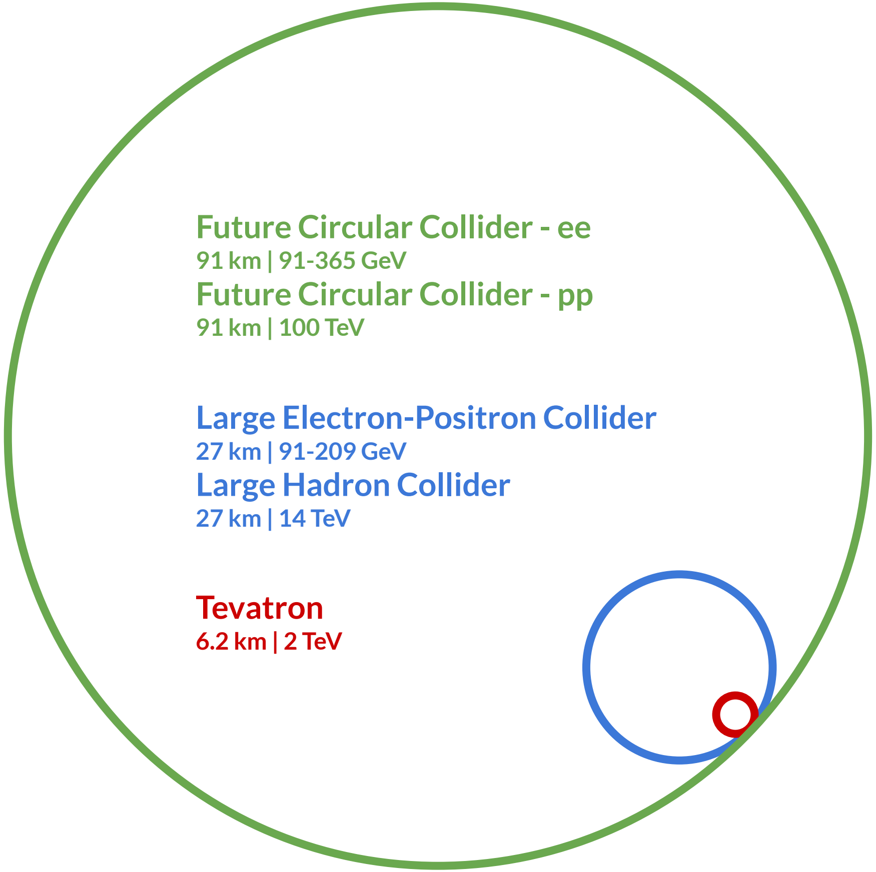
First stage of the integrated FCC program.

Up to **four** possible interaction points.

Planned to run at **four center-of-mass energy** modes.

Four year run at & around the *Z* resonance, About **half a LEP dataset per minute**.

Presents **novel challenges** to reduce **systematic effects** from detectors.



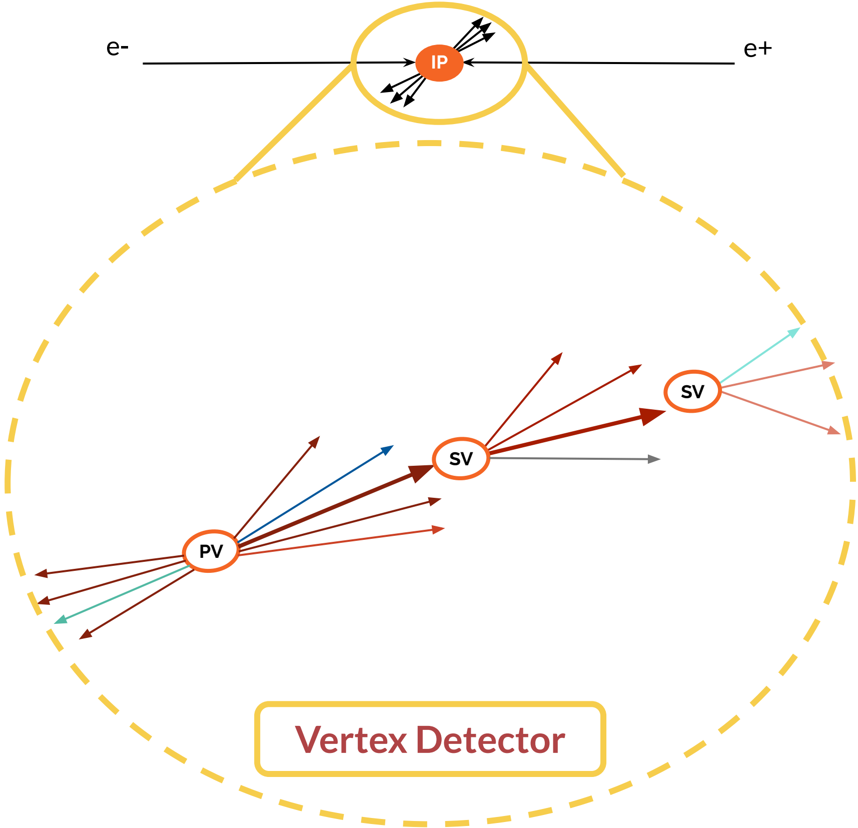
Vertexing

Most heavy **hadrons decay** very **close to the interaction point**.

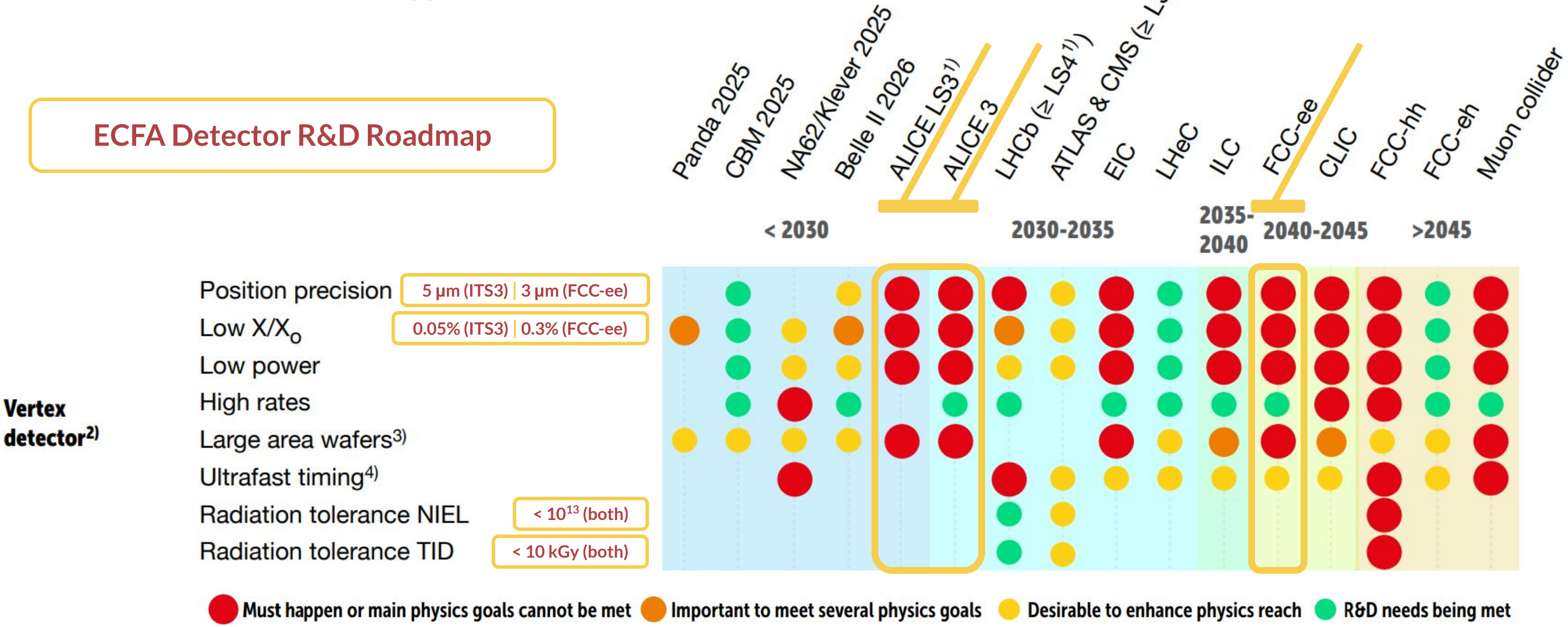
Excellent vertex detectors needed for precise reconstruction of these decay vertices.

Three detector concepts are being studied. All share the vertex detector requirements.

- **Very low resolution** → for precise tracking
- **Minimal material budget** → to reduce multiple scattering
- **High granularity** → high density of tracks near decay vertices



Detector Requirements and Goals



- Requirements for ALICE ITS3 & FCC-ee vertex detectors are congruous
- ALICE ITS3 & ALICE 3 can be a stepping stone for the FCC-ee vertex detectors

Symbiosis with Lepton Colliders

ALICE is a prototype for **lepton colliders** with similar requirements:

- Moderate radiation environment
- Low material budget and high spatial resolution is crucial
- First layer closer to the beam pipe for better IP resolution

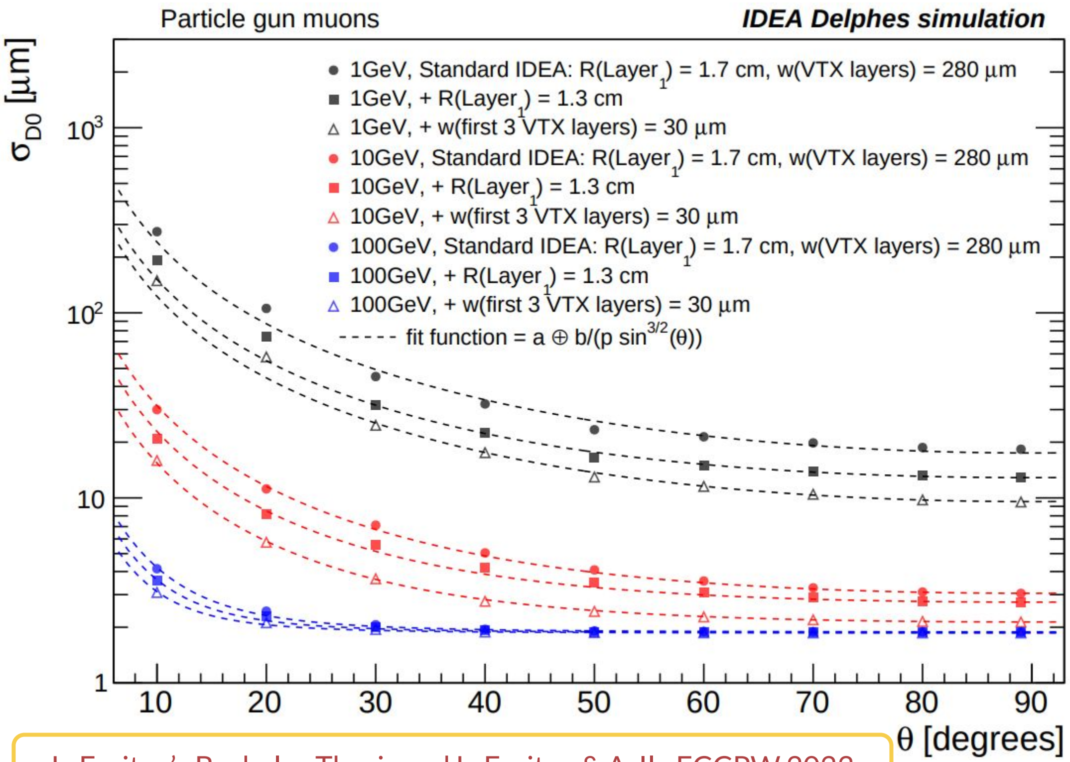
Future collider groups joined the ITS3 efforts

M. Mager
FCCW2023

D. Contardo
FCCW2023

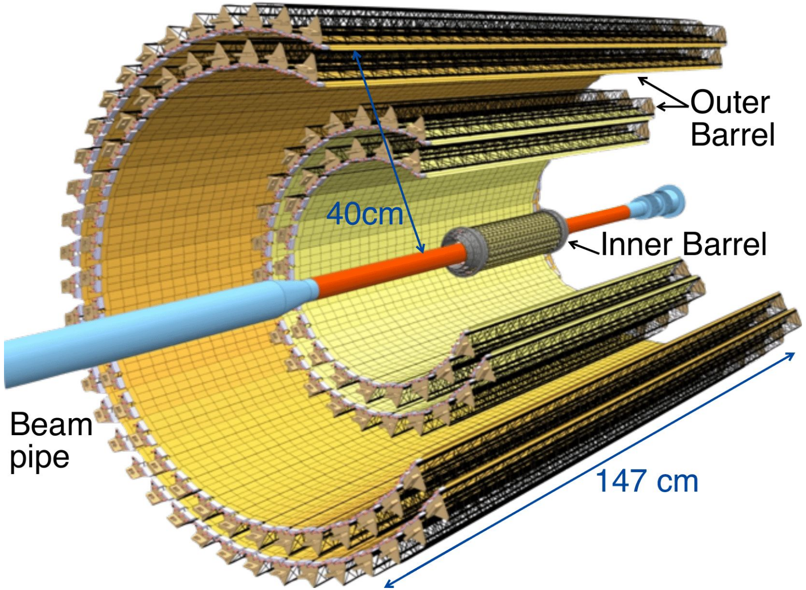
F. Palla
FCCPW2024

A. Ilg
FCCPW2024



L. Freitag's Bachelor Thesis and L. Freitag & A. Ilg FCCPW 2023

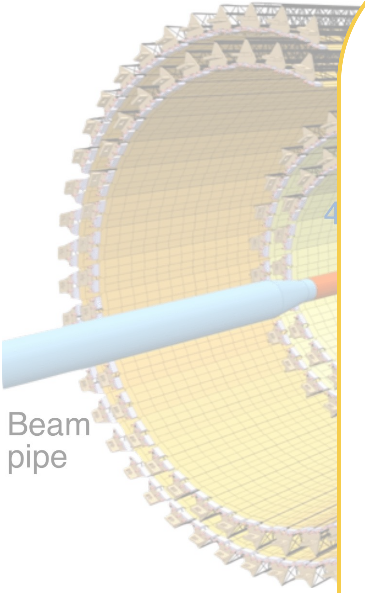
ITS2 → ITS3

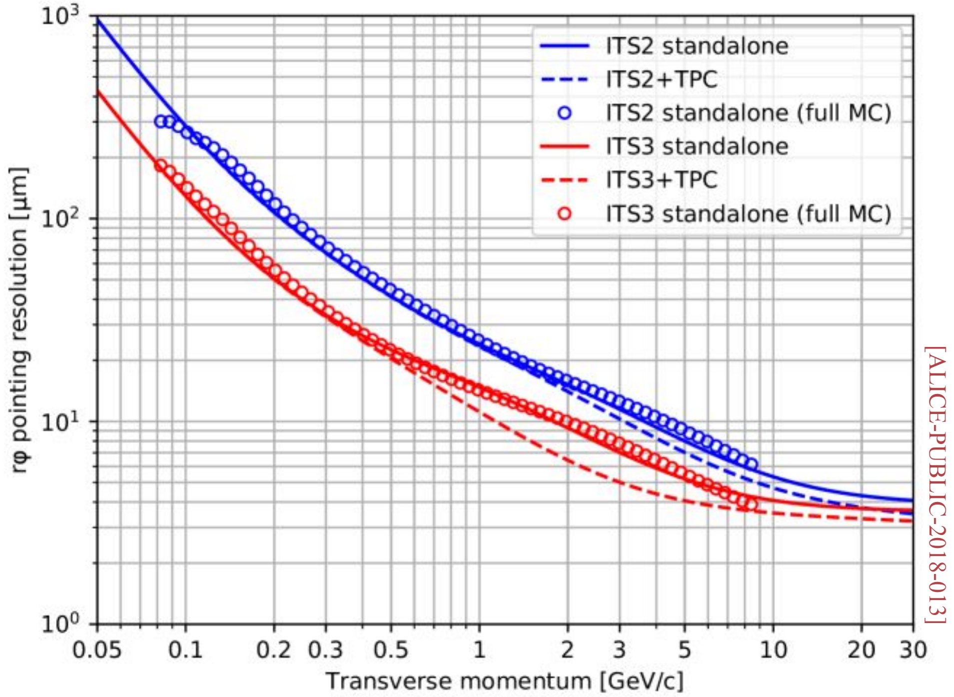


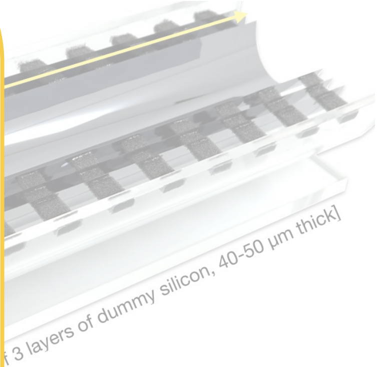
only 1/7th of the material budget

- Replacing the barrels by real half-cylinders
  - using bent, thin silicon
- Rely on stitched wafer-scale sensors
  - in 65 nm technology

ITS2 → ITS3







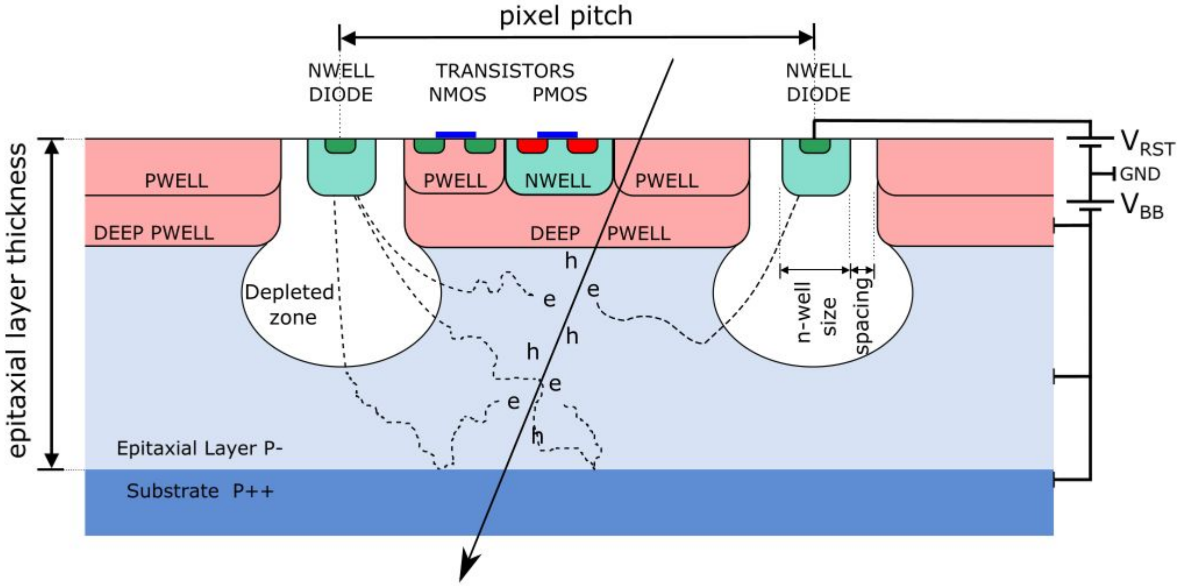
only 1/7th of the material budget

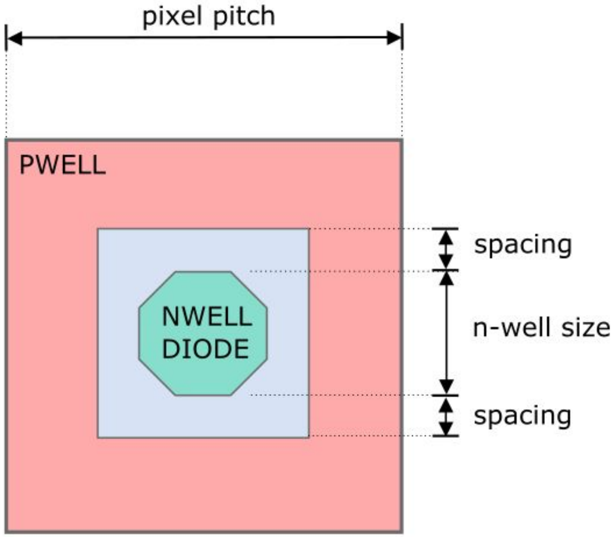
- Replacing the … ale sensors
  - using be… gy

Improvement of factor 2 over all momenta

https://doi.org/10.1016/j.nima.2020.164859

Monolithic Active Pixel Sensor (MAPS)





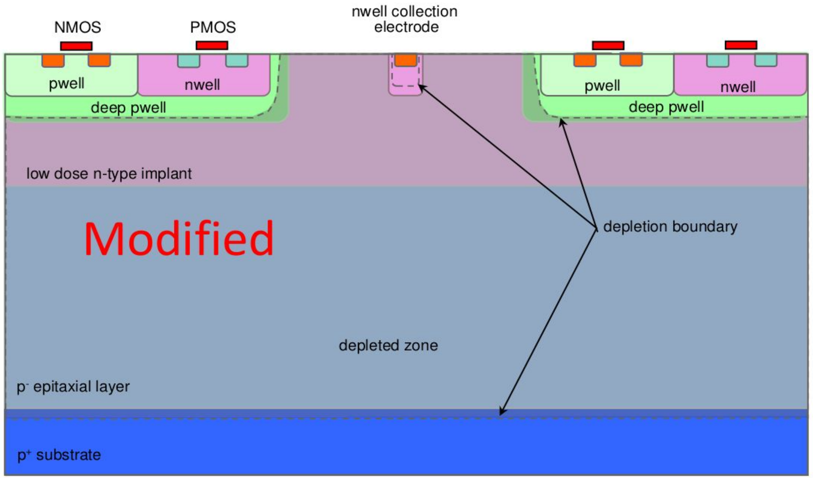
- Deep PWELL shields the CMOS circuitry from collecting charge
- Low capacitance of the small collection electrode results in lower power consumption
- Applying substrate bias increases depletion and also improves radiation tolerance
- Further modifications needed for the full depletion of the sensitive layer

http://dx.doi.org/10.1016/j.nima.2017.07.046

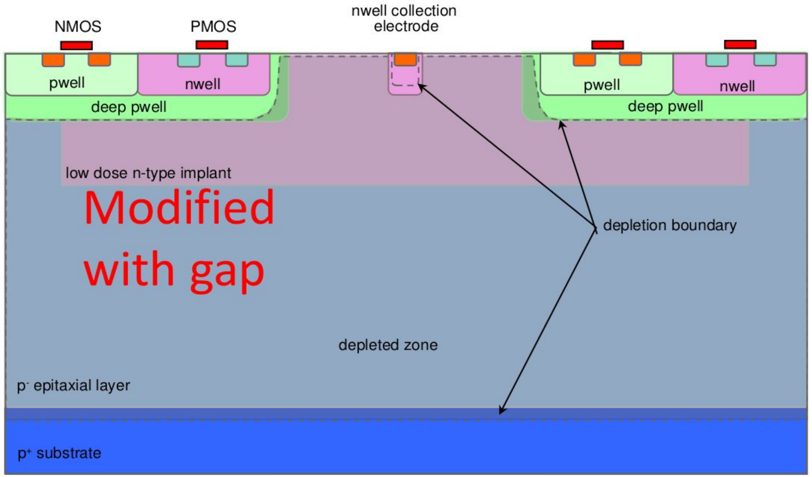
Process Modifications

TPSCo 65 nm Process

- To reach full depletion



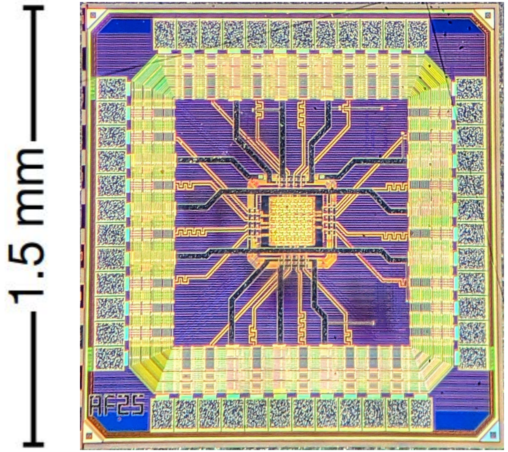
- More control over charge sharing



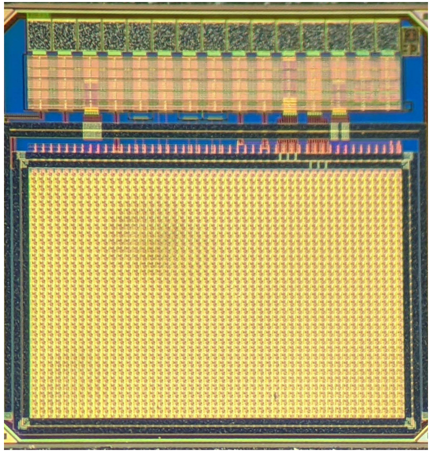
more charge sharing

faster charge collection

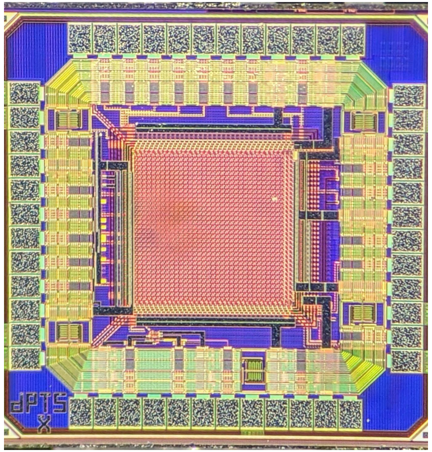
ITS3: Pixel Prototype Chips



doi.org/10.1088/1748-0221/18/01/C01065
doi.org/10.1016/j.nima.2024.169896



doi.org/10.1016/j.nima.2022.167213



doi.org/10.1016/j.nima.2023.168589

APTS

- 6x6 pixel matrix
- Direct **analog readout** of central 4x4 pixels
- Pitch: 10, 15, 20, 25 µm

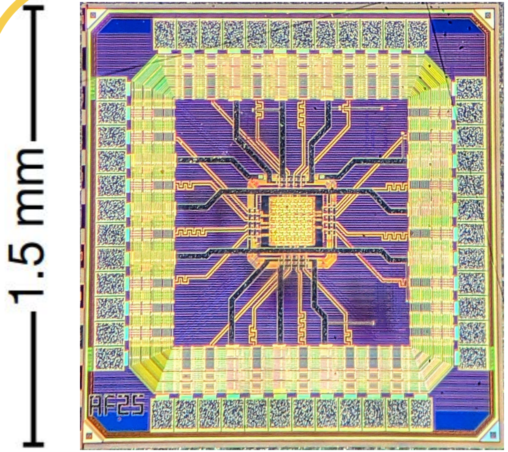
CE65

- 64x64 [v1], 48x32 [v1], 48x24 [v2] pixel matrix
- Rolling shutter **analog readout**
- Pitch: 15, 25 µm

DPTS

- 32x32 pixel matrix
- Asynchronous **digital readout** with ToT
- Pitch: 15 µm

ITS3: Pixel Prototype Chips



doi.org/10.1088/1748-0221/18/01/C01065
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APTS

- 6x6 pixel matrix
- Direct **analog readout** of central 4x4 pixels
- Pitch: 10, 15, 20, 25 µm

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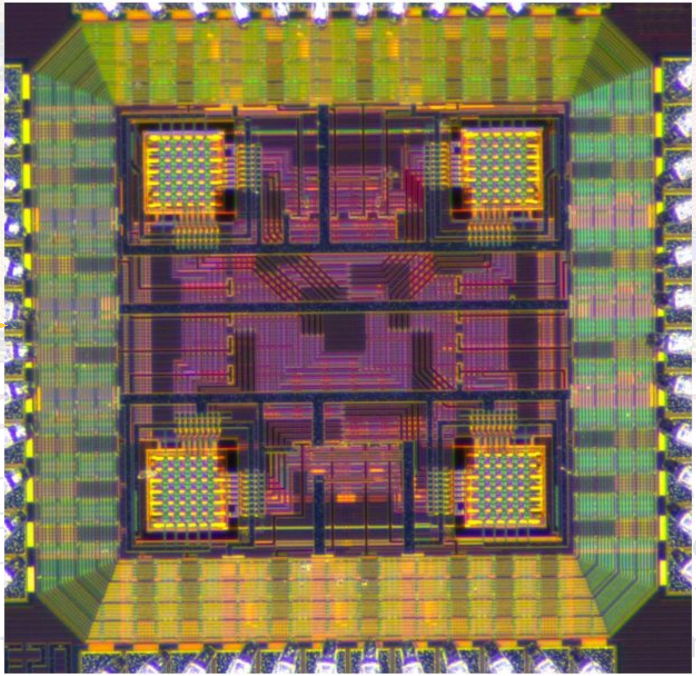
APTS-Multiplexer



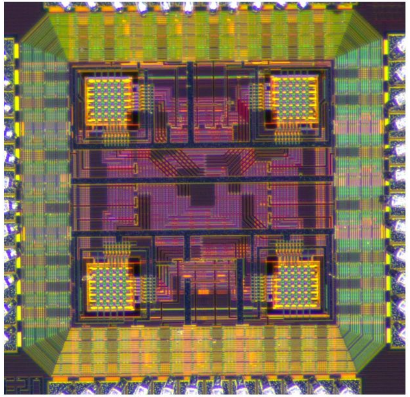
- 64x64 [… 48x24 […
- Rolling … **readou** …
- Pitch: 15, 25 µm

…l matrix … ous **digital** … th ToT

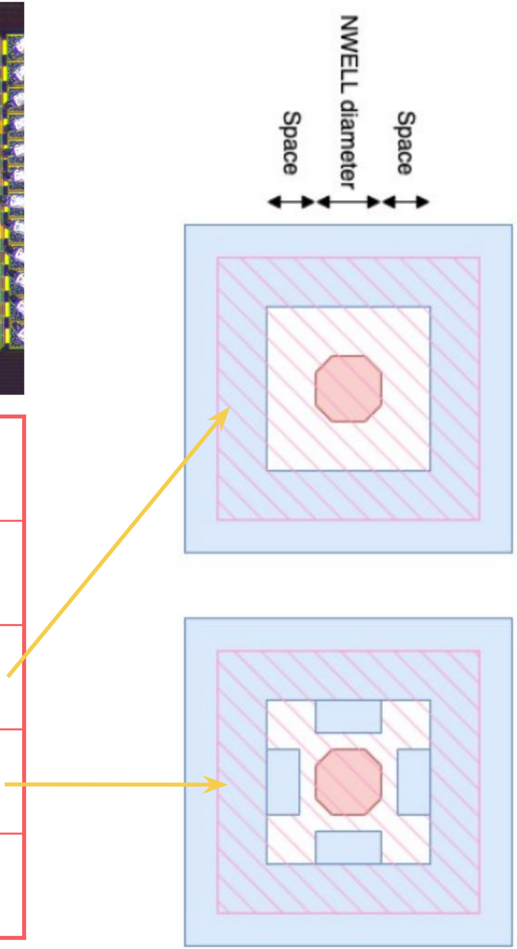
APTS-SF Multiplexer

One out of the four sensor variants can be read out at a time by selecting an output with the 2-bit multiplexer.

Slightly higher noise due to larger current.



--mux	Selected Matrix	Sensor Variant
0	Left Top	Larger NWELL Collection Electrode
1	Left Bottom	Reference
2	Right Top	Finger-shaped PWELL Enclosure
3	Right Bottom	Smaller PWELL Enclosure



Testing Small-Scale Sensors

With Fe-55 Radioactive Source

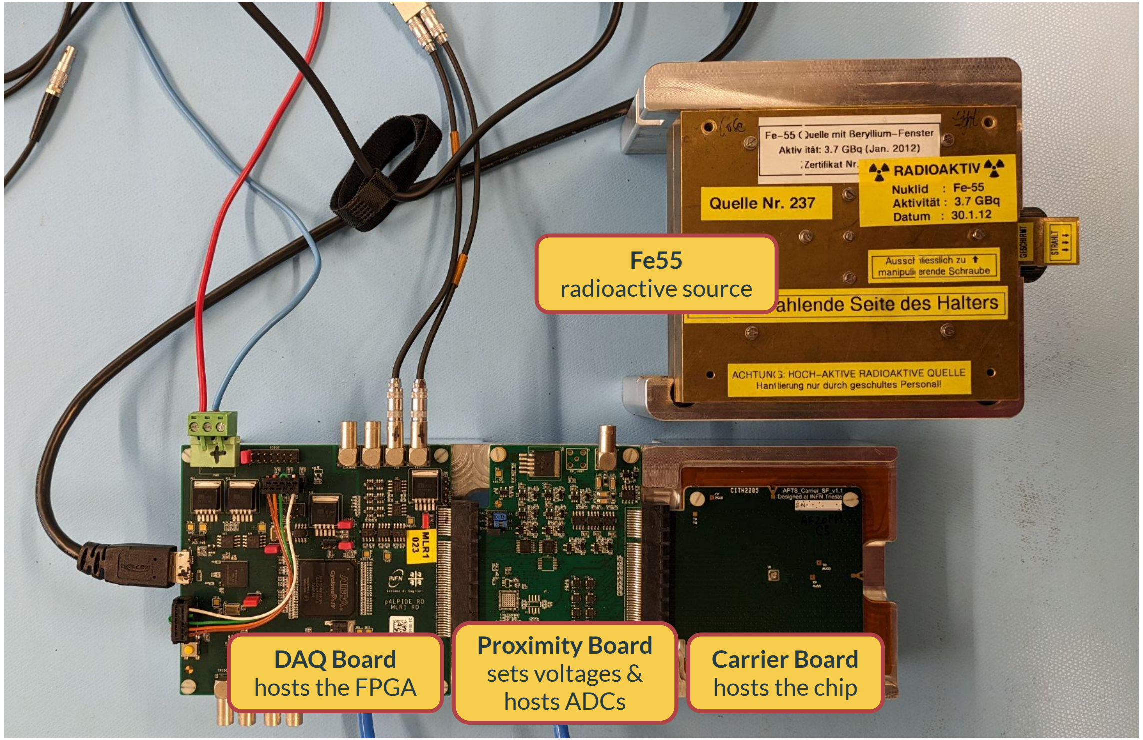
Measurement Setups

The measurement of the **Fe55 spectrum** is used to **calibrate** the sensor readout to the collected charge at different **bias voltages**.

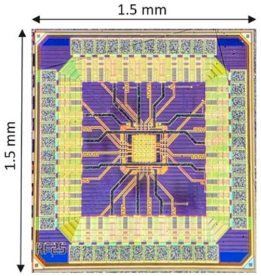
Water cooling used to set a **standard temperature** during tests (16°-20°C).

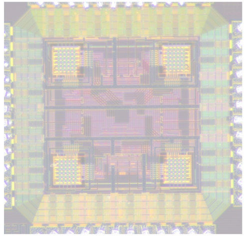
- MLR1 **DAQ Board** → hosts the **FPGA**
- APTS **Proximity Board** → sets voltages and hosts **ADCs** for readout
- **Carrier Board** → hosts the chip

Using 210 MBq **Fe55 Source**

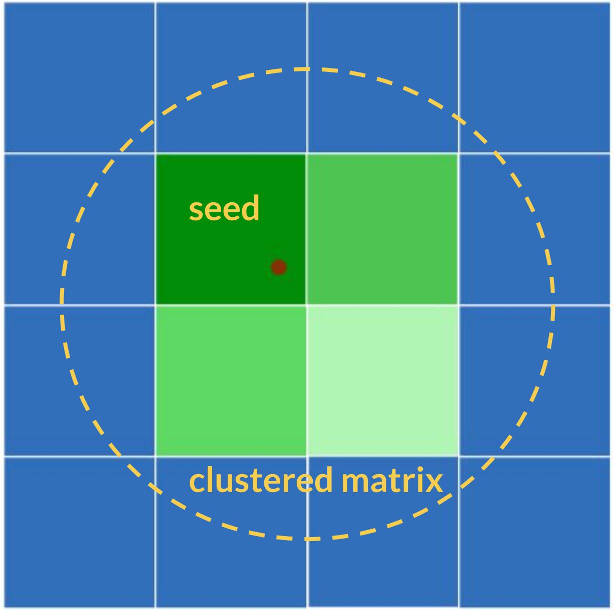


Clustering and Charge Sharing





incident charged particle

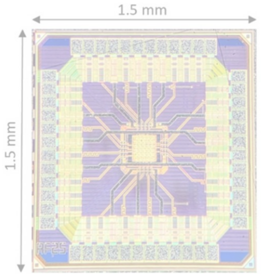


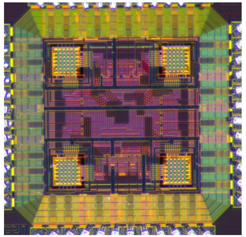
Seed
Pixel with the highest collected charge passing a threshold

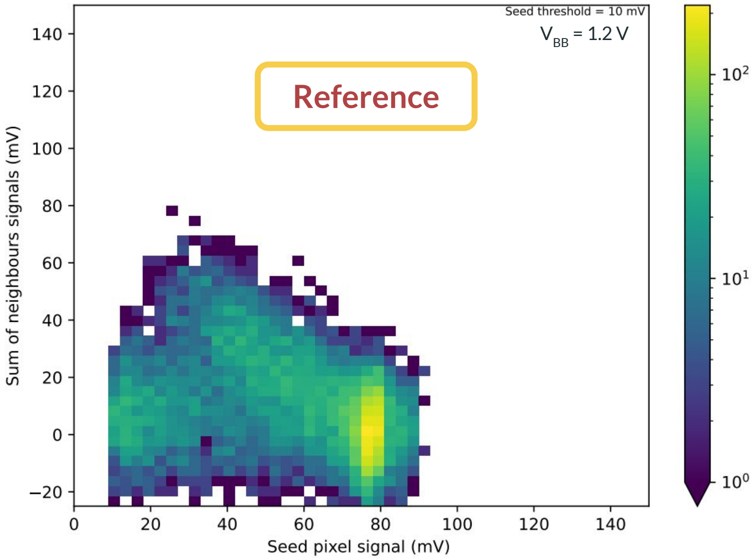
Clustered matrix
Set of seed and neighbouring pixels collecting charge greater than a threshold

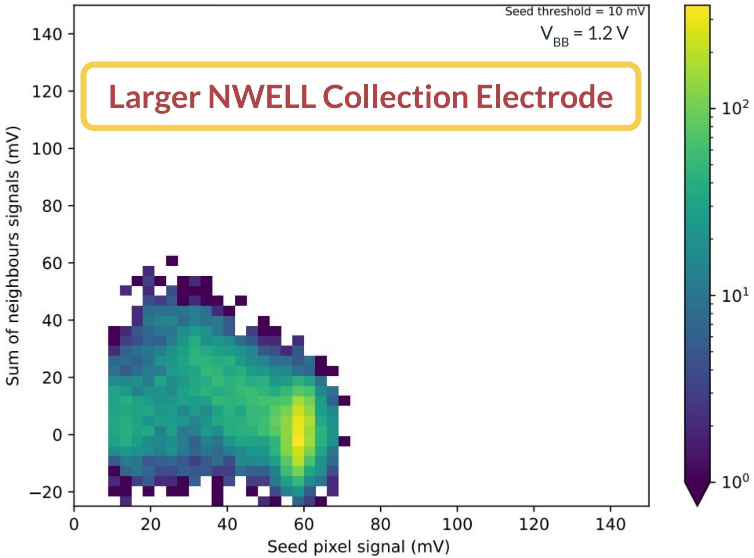
Pro: improved spatial resolution | **Con:** worse efficiency at higher thresholds

Clustering and Charge Sharing (APTS)









- A larger collection electrode results in most of the charge getting collected by the seed pixel and the charge sharing with the neighbouring pixels is minimal

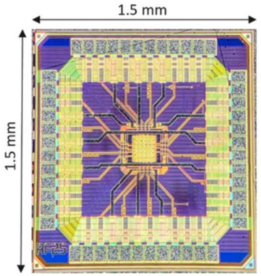
Charge Collection (APTS)

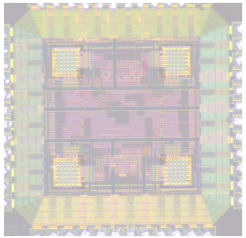
The entire generated charge is collected pointing to the near-full depletion of the sensitive layer.

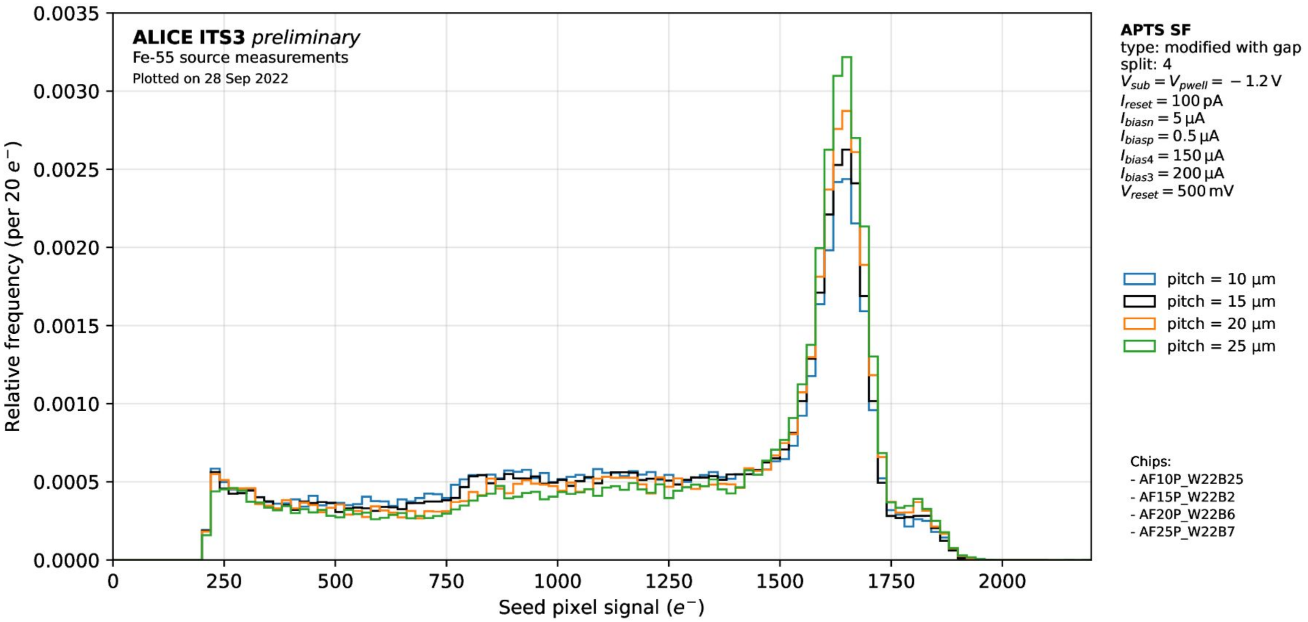
All pitches/geometries show similar results indicating efficient charge collection.

Allows to choose for the optimal pitch for the final sensor.

Sensor geometry with higher capacitance leads to lower signal in mV.







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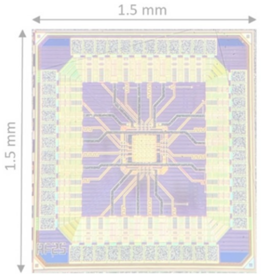

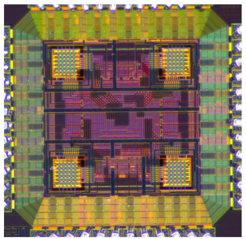

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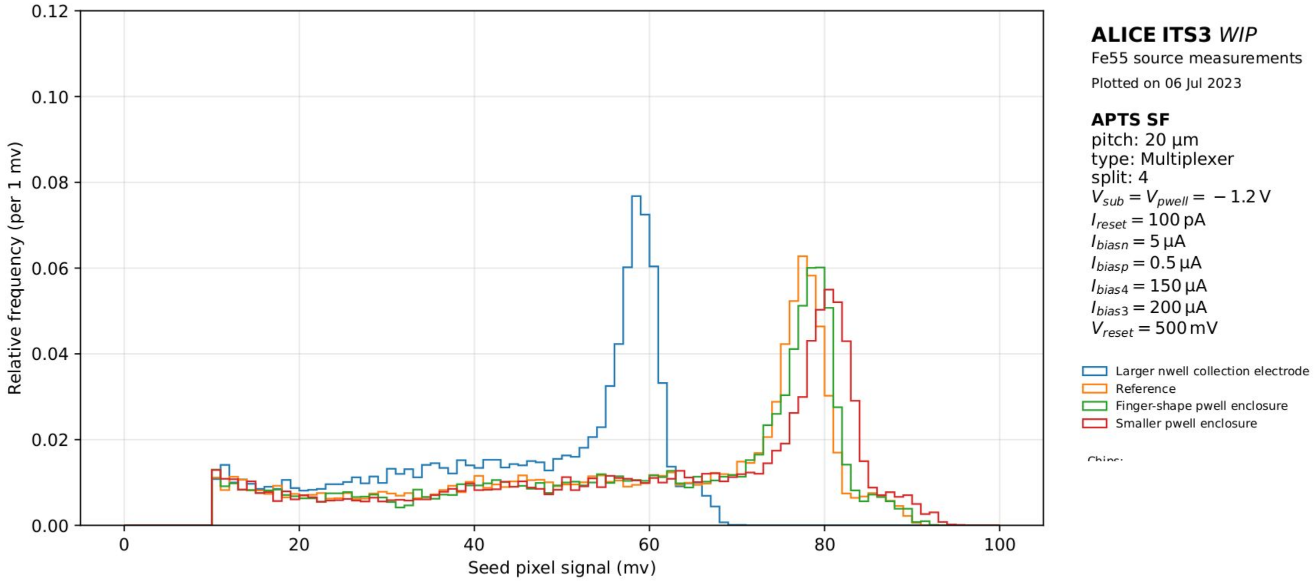
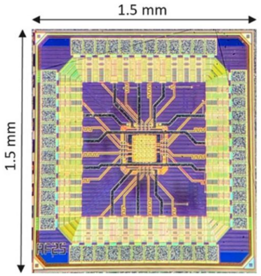
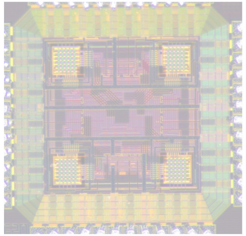


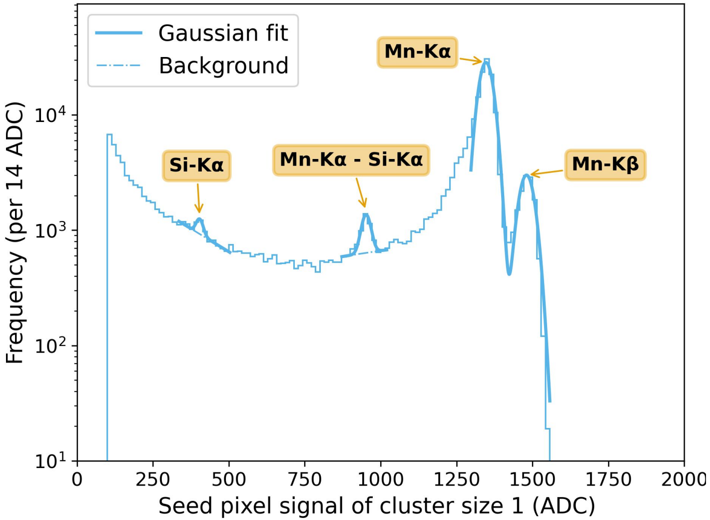
Expect **better radiation tolerance** in sensors with **larger collection electrode**

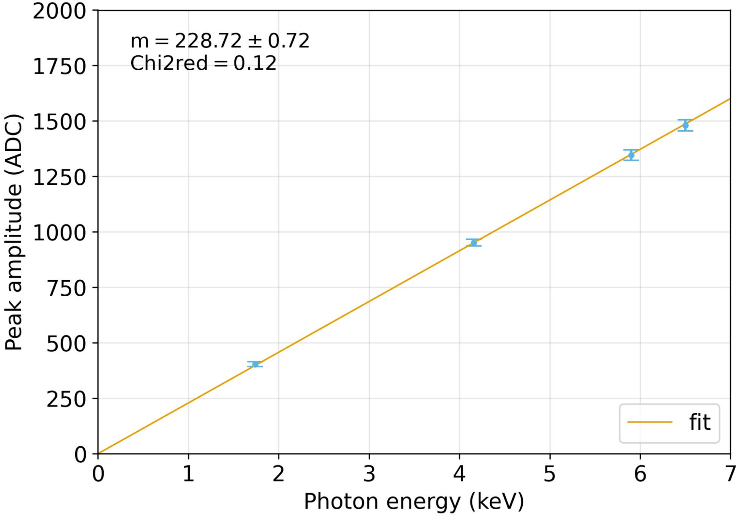
Energy Calibration and Linearity of Pixel Response (APTS)





- Only **central 4 pixels** considered to avoid edge effects.
- **Mean** of the most prominent **Mn-Kα peak** used to convert **ADC units into e⁻**.
- Demonstrated the **linearity of energy calibration**.





Testing Small-Scale Sensors

With Hadron Testbeams

Measurement Setups

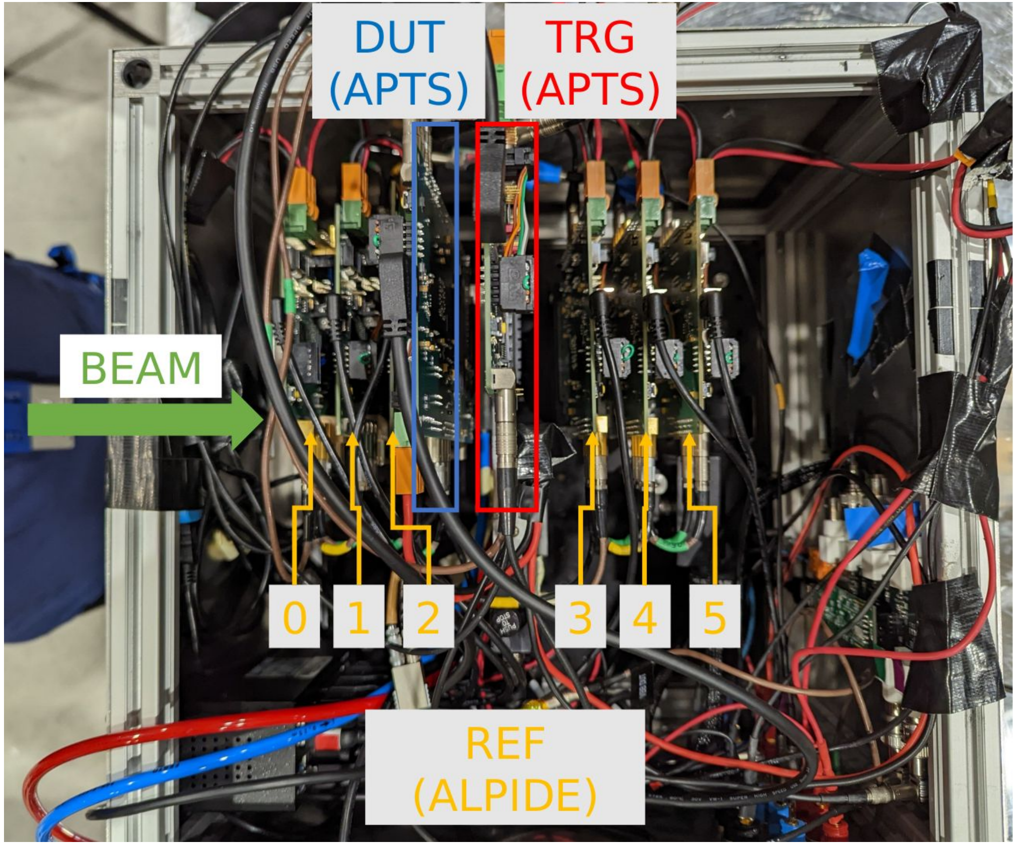
1 DUT at a time at the temperature of 16°C measured very close to the sensor

6 ALPIDEs (ITS2) as reference planes

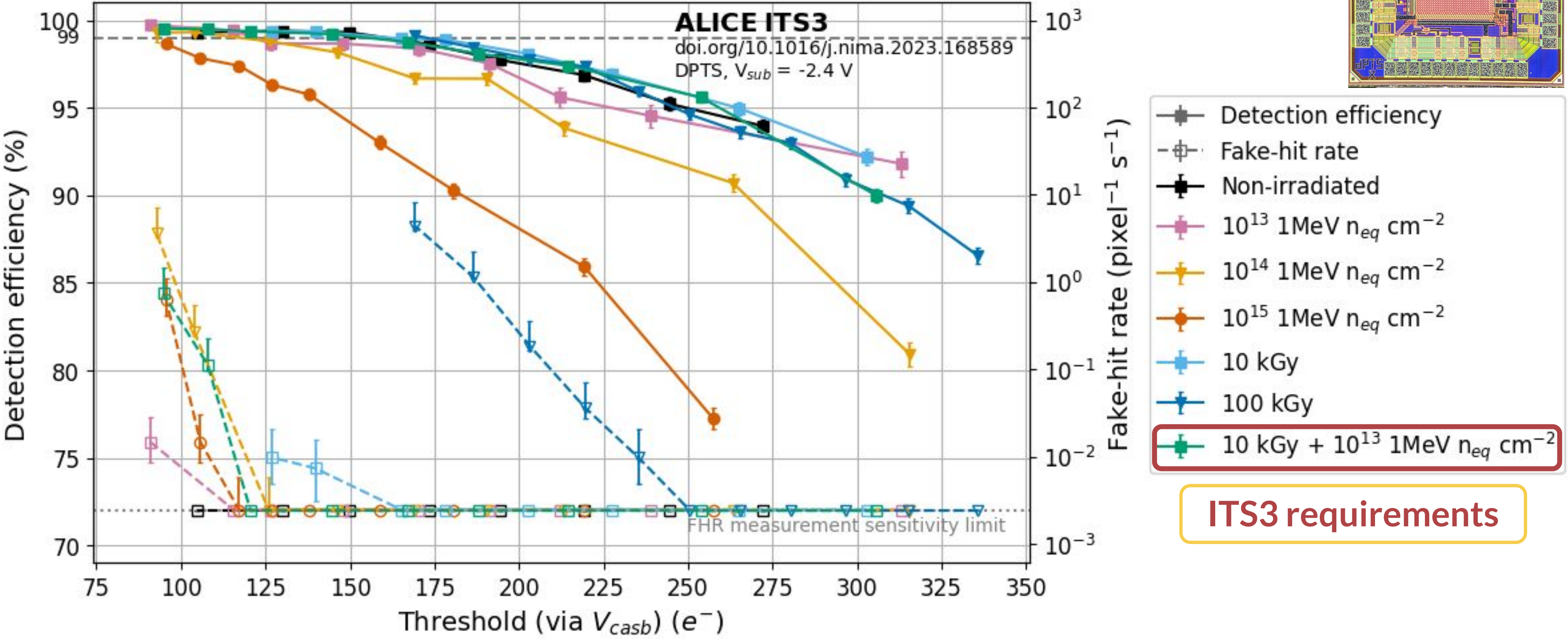
Trigger:

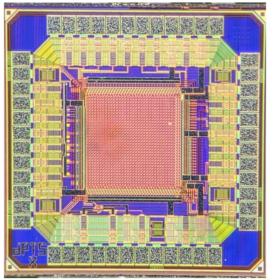
- **scintillator** to align the beam to the telescope
- **25μm** pitch APTS-SF sensor at bias voltage of **-1.2V** (near-full depletion) for **APTS**; larger area than all DUTs
- **15μm** pitch DPTS at **-1.2V** for **DPTS/CE-65**

Beam: **120 GeV hadrons** ar SPS, **10 GeV hadrons** at PS, and **0.8-5 GeV electrons** at DESY.



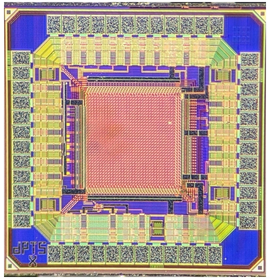
Detection Efficiency (DPTS)

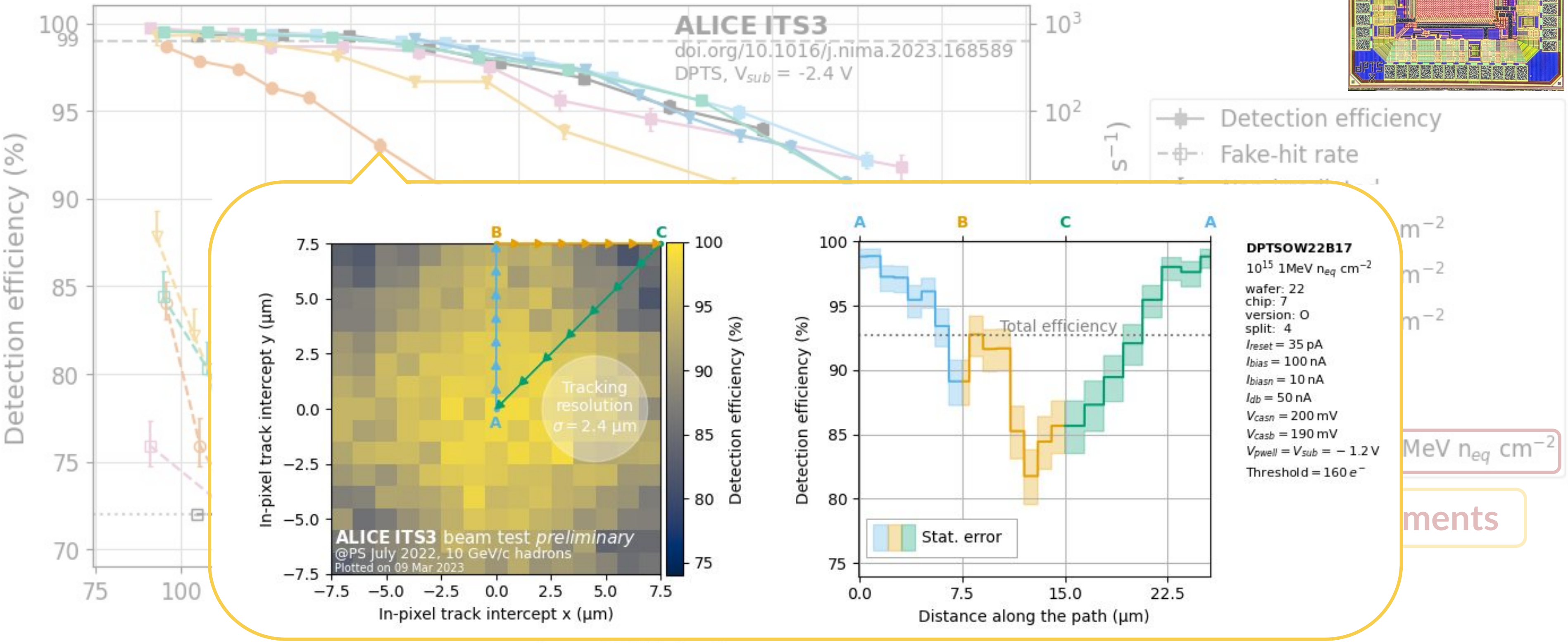




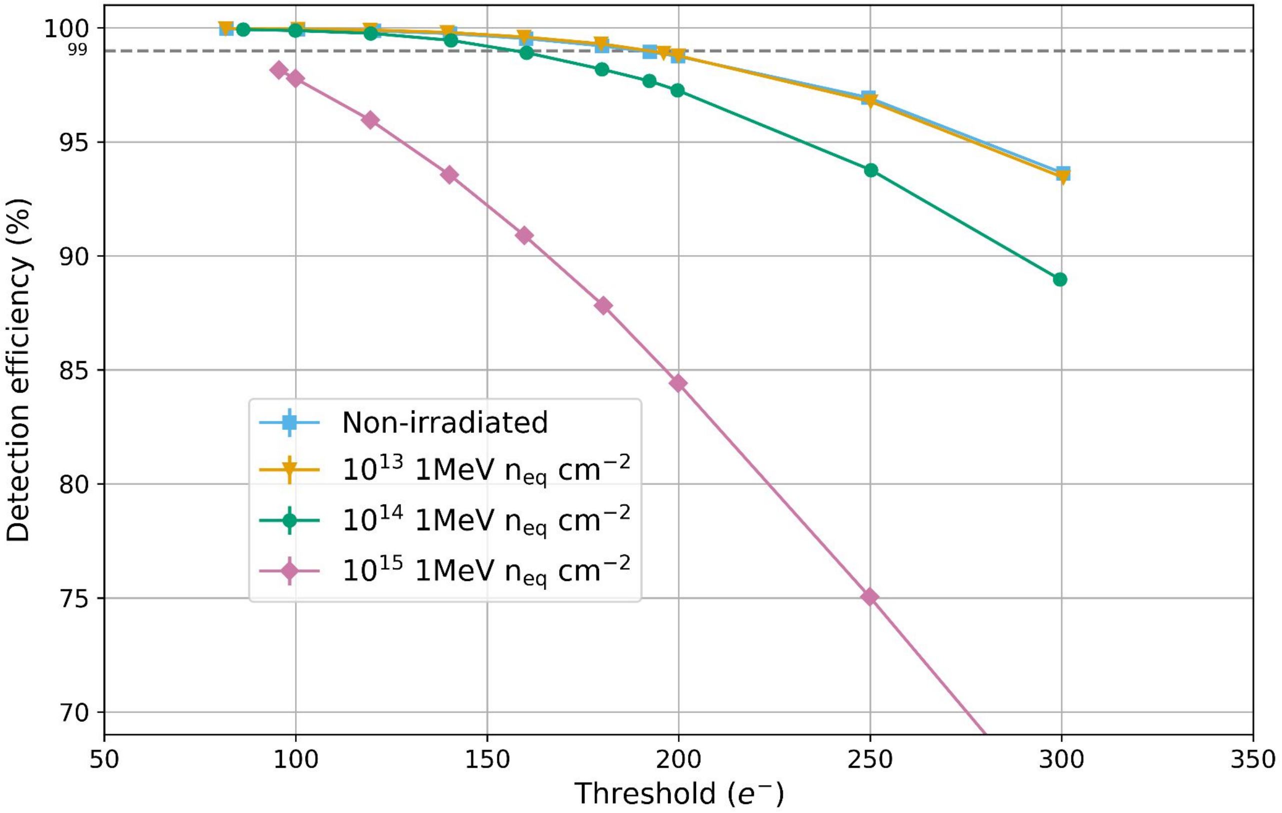
ITS3 requirements

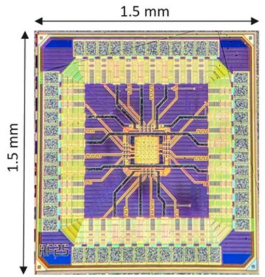
Detection Efficiency (DPTS)

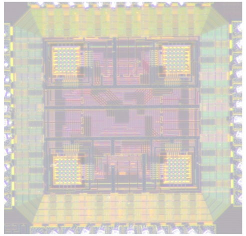




Detection Efficiency (APTS)

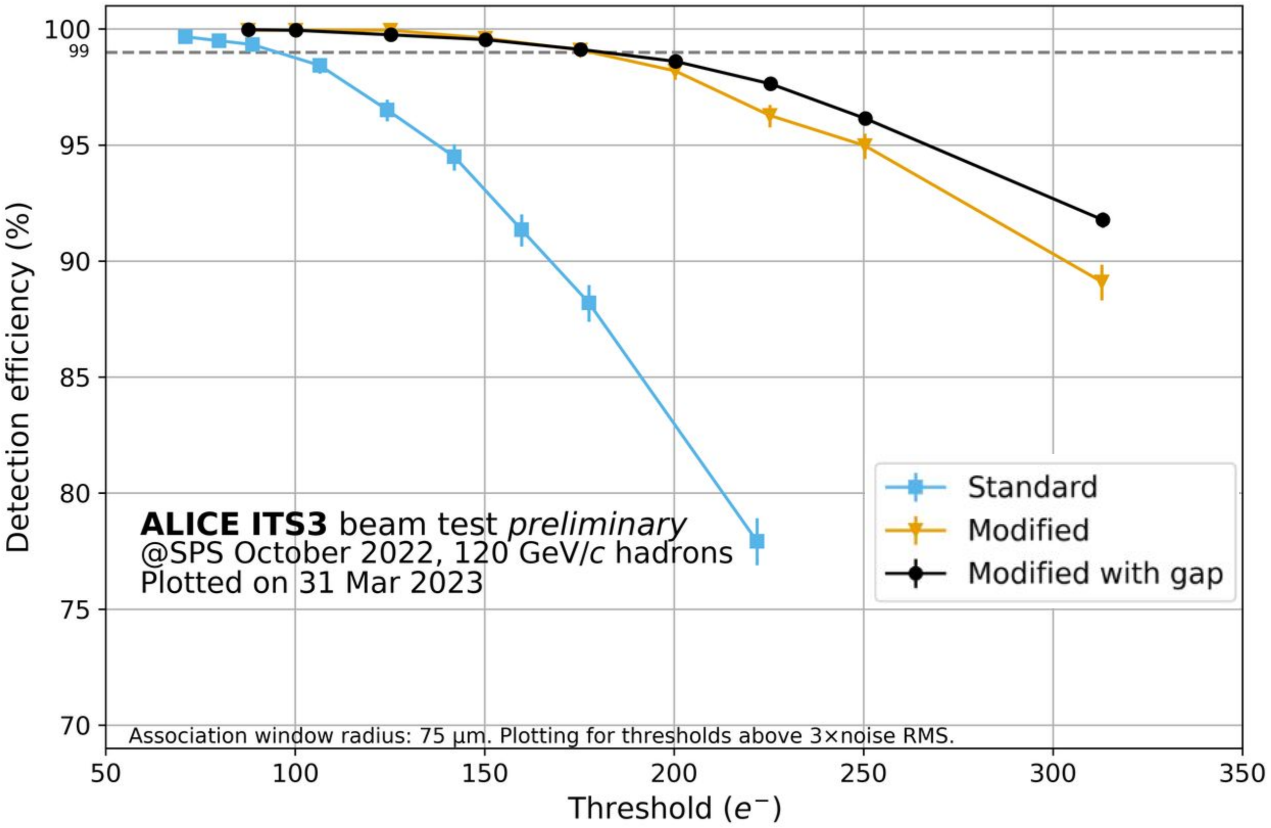


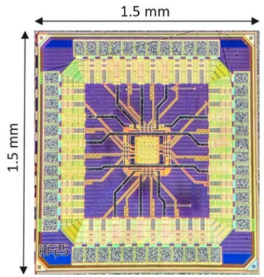


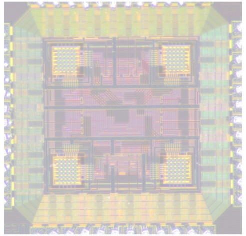


over 99% efficiency after **1e14 NIEL** irradiation

Detection Efficiency (APTS)



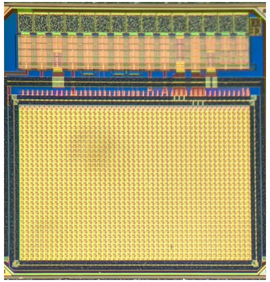


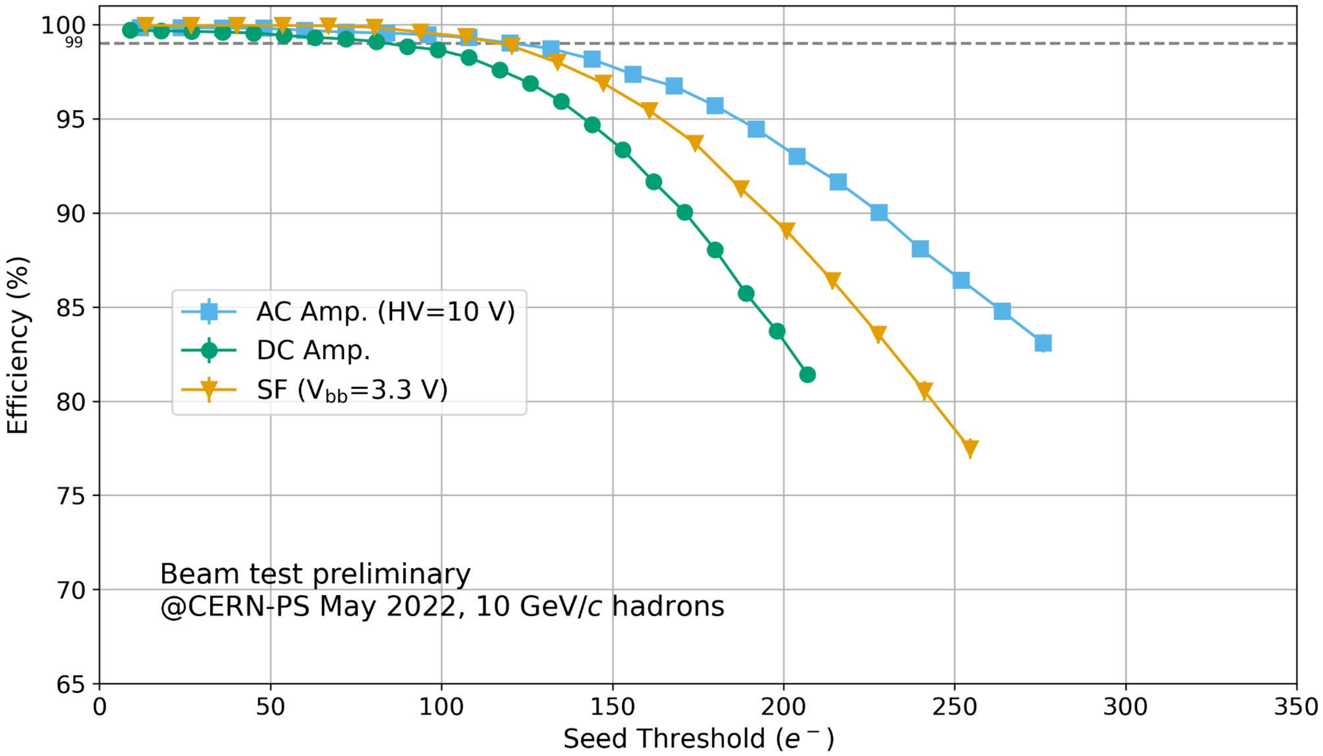


Process **modification** drastically **increases the range of operation** over 99% efficiency

Charge sharing causes efficiency to drop at higher threshold for the **standard** process

Detection Efficiency (CE-65)



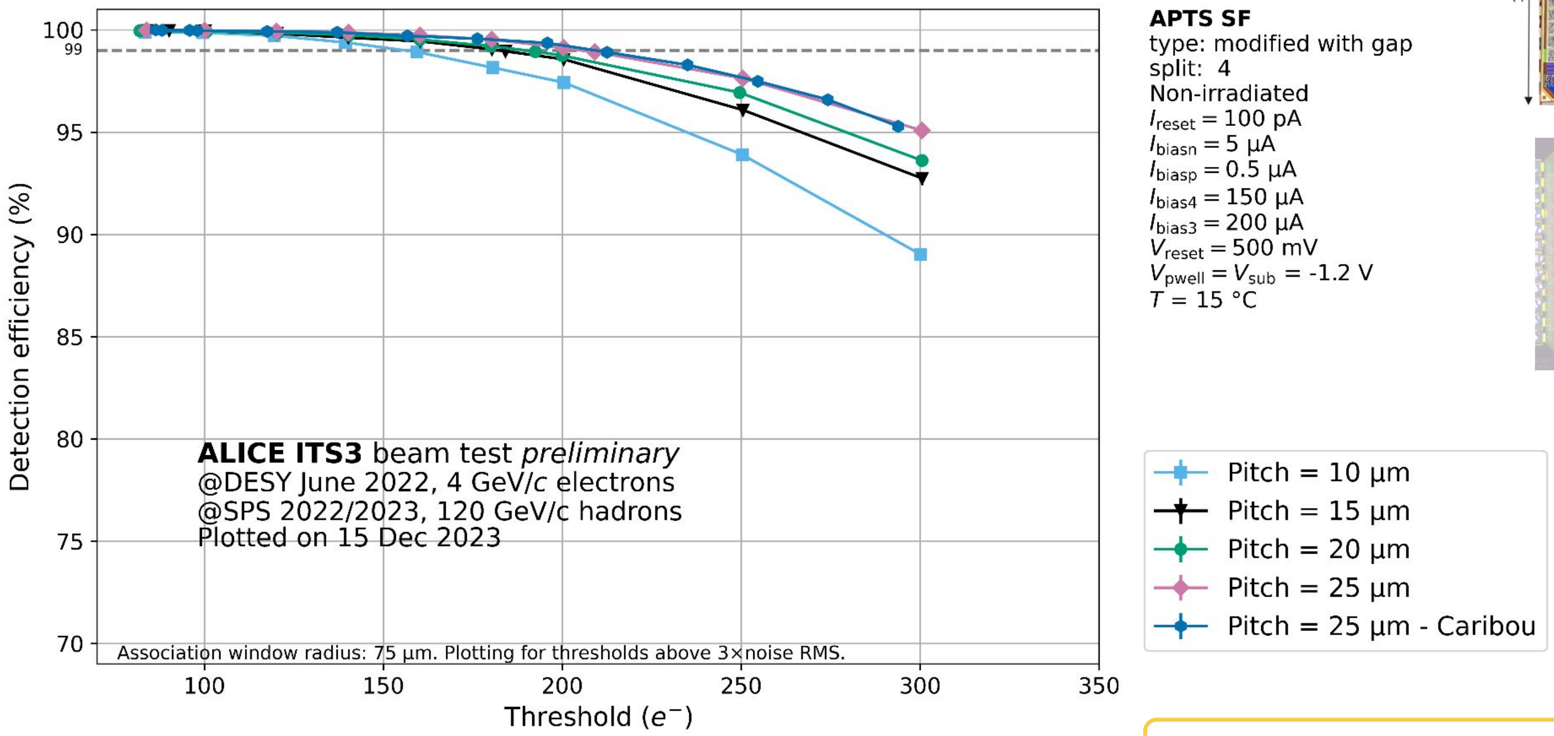


AC-coupled high voltage provides **full depletion**

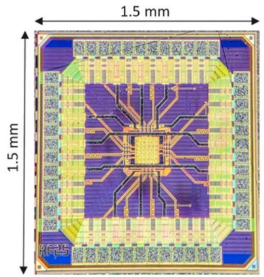
DC-coupled variant only reaches **partial depletion**

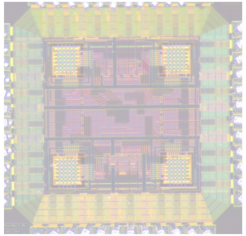
Depletion of the **SF** variant depends on **bias voltage**

Detection Efficiency (APTS)



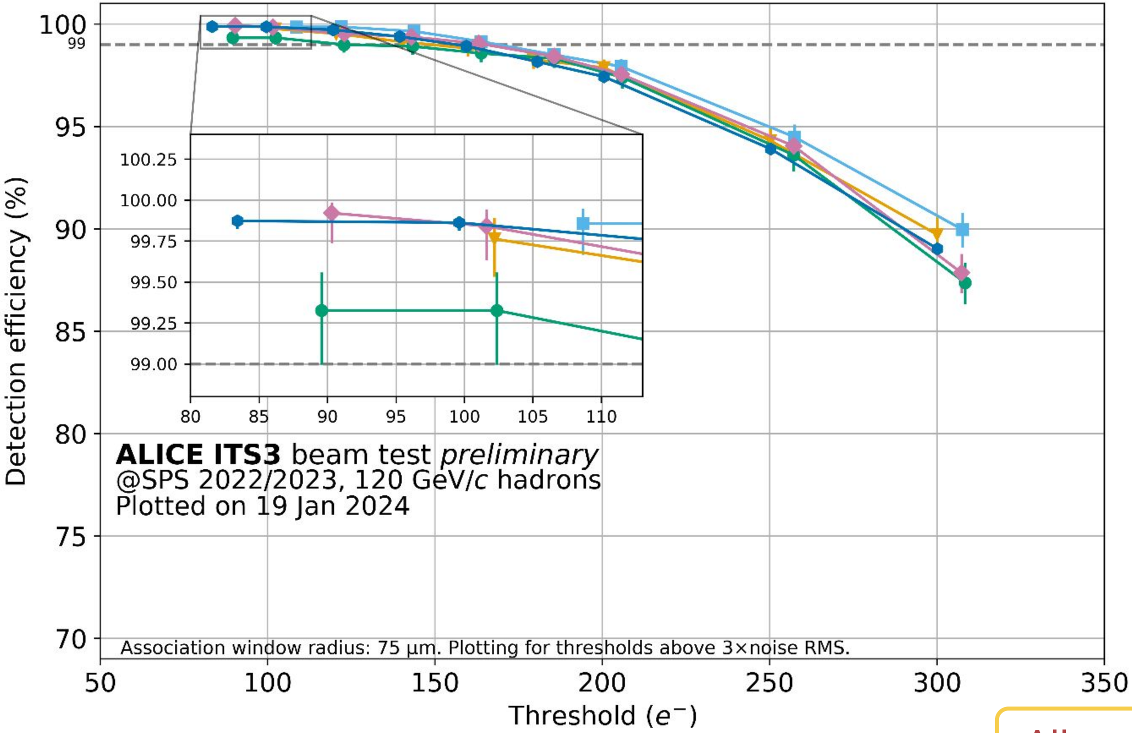
APTS SF
type: modified with gap
split: 4
Non-irradiated
I_{reset} = 100 pA
I_{biasn} = 5 µA
I_{biasp} = 0.5 µA
I_{bias4} = 150 µA
I_{bias3} = 200 µA
V_{reset} = 500 mV
V_{pwell} = V_{sub} = -1.2 V
T = 15 °C



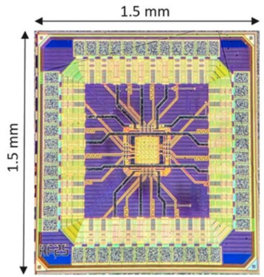


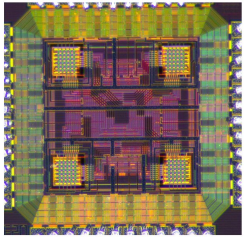
over 99% efficiency for all pitches

Detection Efficiency (APTS)



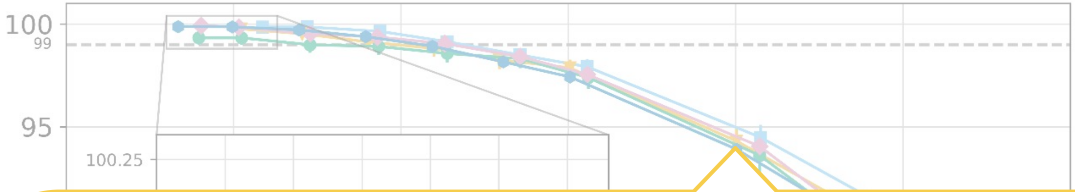
APTS SF
type: modified with gap
pitch: 10 µm
split: 4
Irradiation: None
$I_{reset} = 100$ pA
$I_{biasn} = 5$ µA
$I_{biasp} = 0.5$ µA
$I_{bias4} = 150$ µA
$I_{bias3} = 200$ µA
$V_{reset} = 500$ mV
$V_{pwell} = V_{sub} = -1.2$ V
T = 14°C



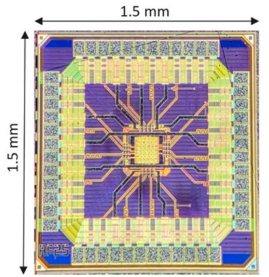


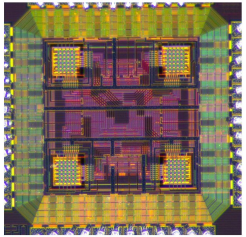
All geometries operable **over 99% efficiency**

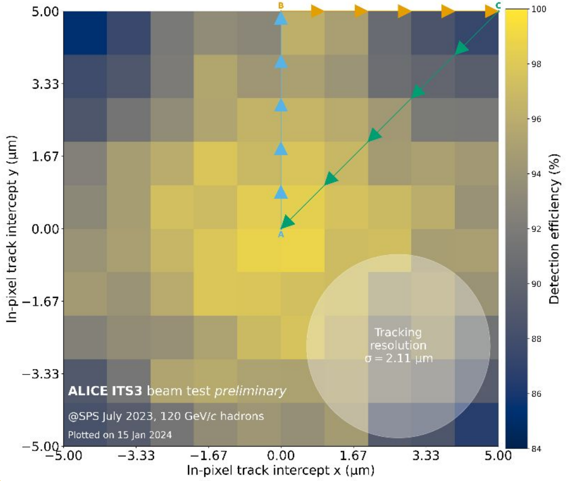
Detection Efficiency (APTS)

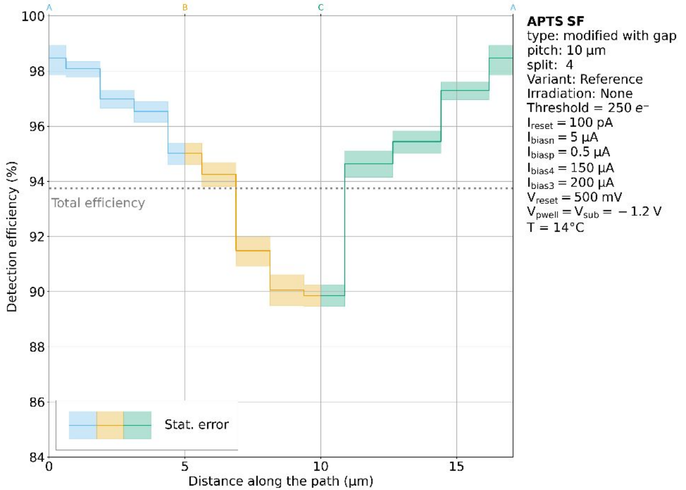


APTS SF
type: modified with gap
pitch: 10 µm
split: 4
Irradiation: None
I_{reset} = 100 pA
I_{biasn} = 5 µA









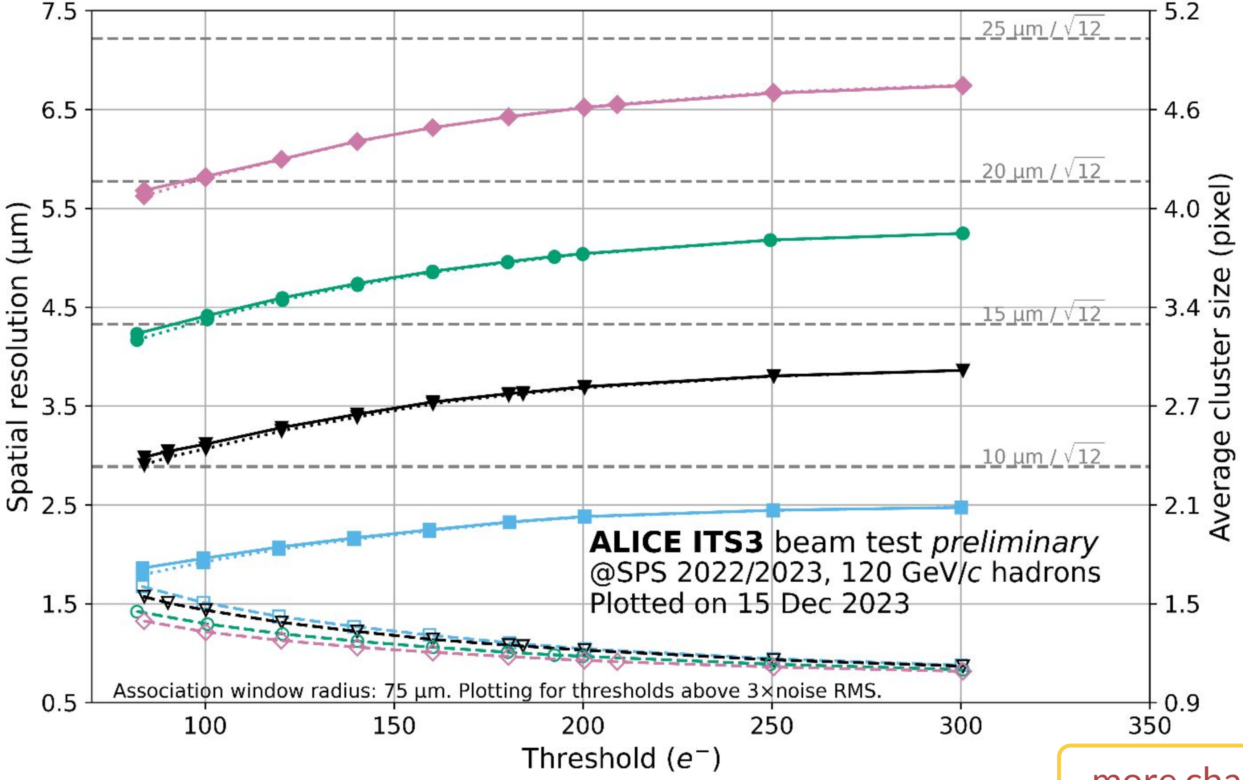
ollection electrode

WELL enclosure

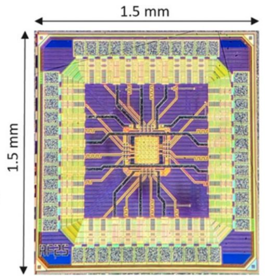
enclosure

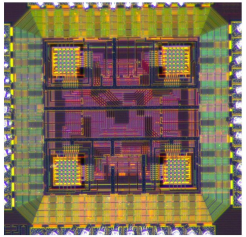
All geometries operable **over 99% efficiency**

Spatial Resolution (APTS)



APTS SF
type: modified with gap
split: 4
Non-irradiated
I_{reset} = 100 pA
I_{biasn} = 5 µA
I_{biasp} = 0.5 µA
I_{bias4} = 150 µA
I_{bias3} = 200 µA
V_{reset} = 500 mV
V_{pwell} = V_{sub} = -1.2 V
T = 15 °C





more charge sharing ⇨ improved resolution

Summary
&
Outlook

ITS2 (now)

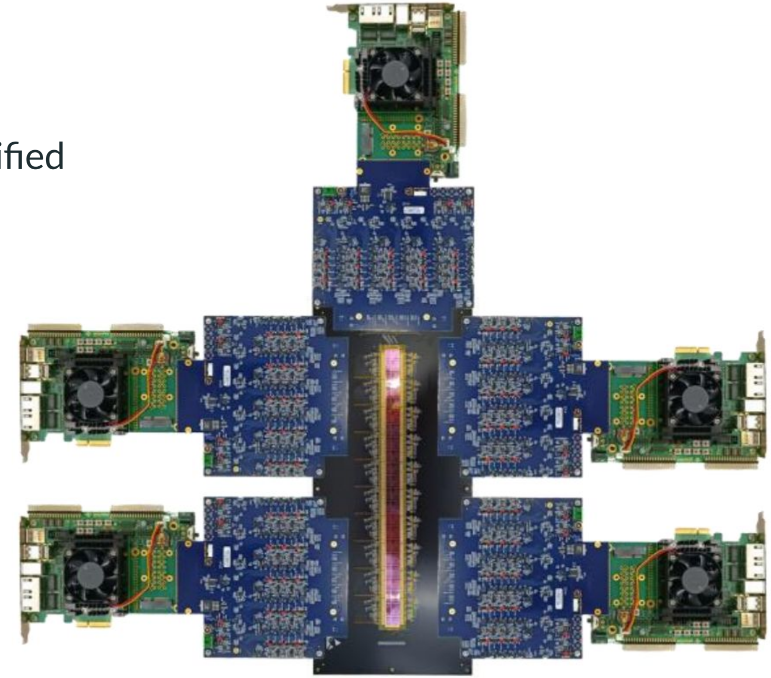
- 12.5 GPixel tracker based on the ALPIDE chip (180 nm technology MAPS)
- Stable, >99% functional

ITS3 (LS3)

- Bent MAPS demonstrated in testbeam, 65 nm process qualified
- Testing of stitched design started
- Assembly of wafer-scale sensors defined
- TDR now with LHCC

ALICE R&D on MAPS

- ALICE 3 with large-scale integration; 60 m^2 outer tracker
- Current and future ALICE detectors with large operational margins
- Symbiosis with the lepton collider community
- A good starting point for FCC-ee vertex detector R&D



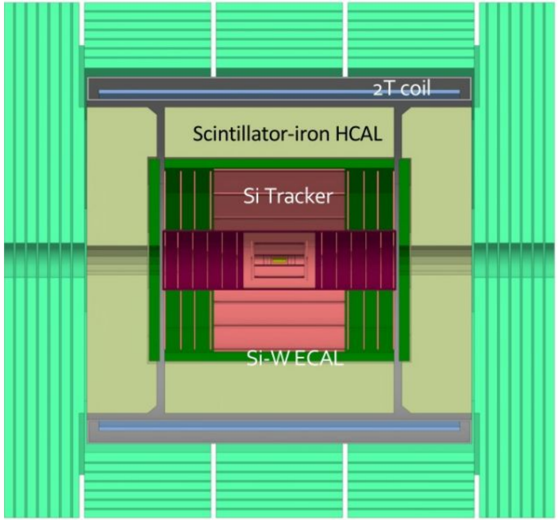
So long,

and **thanks** for all the fish

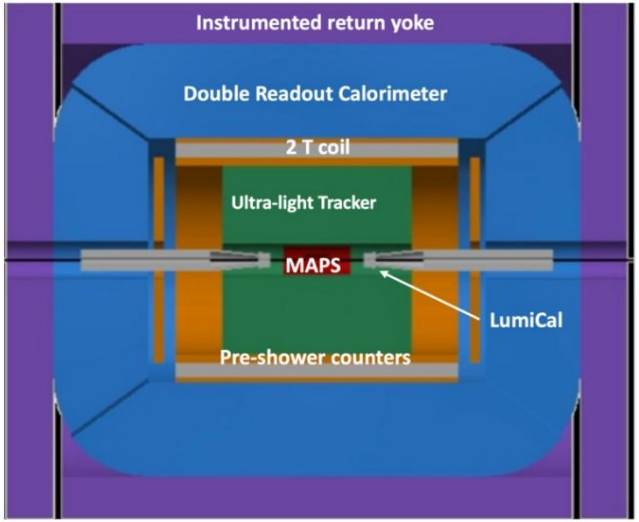
Back-up

FCC-ee Detector Concepts

Three detector concepts are being studied.



CLD

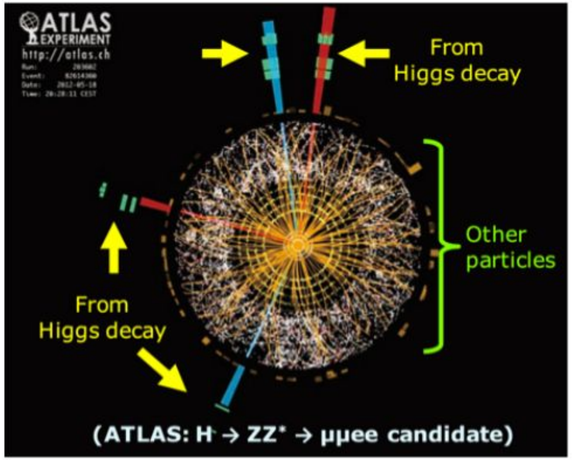


IDEA

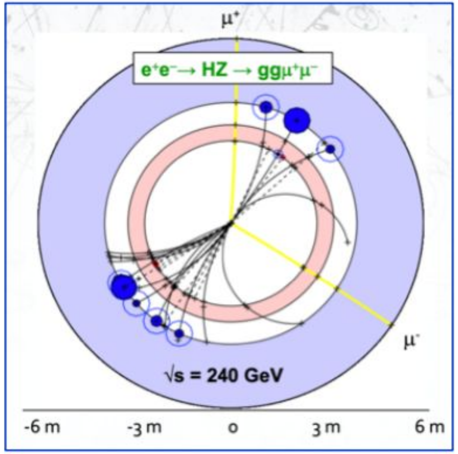
Allegro

Prelude: pp vs. e^+e^-

Higgs event in pp



Higgs event in e^+e^-



pp: look for striking signal in large background

- High rates of QCD backgrounds
  - Complex triggering schemes
  - High levels of radiation
- High cross-sections for coloured states
- High-energy circular pp colliders feasible
  - Large mass reach ➞ direct exploration
- S/B ≈ 10^{-10} before trigger; S/B ≈ 0.1 after trigger

e^+e^-: detect everything; measure precisely

- Clean experimental environment
  - Trigger-less readout
  - Low radiation levels
- Superiour sensitivity for electro-weak states
- Limited direct mass reach
- S/B ≈ 1 ➞ precision measurement
  - Exploration via precision

FCC-ee Physics Programme

"Higgs Factory" Programme

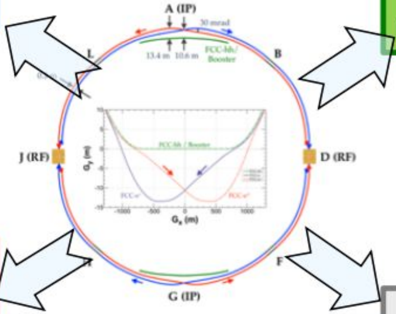
- At two energies, 240 and 365 GeV, collect in total
  - 1.2M HZ events and 75k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \rightarrow H$ @ $\sqrt{s}$ = 125 GeV

Ultra Precise EW Programme & QCD

Measurement of EW parameters with factor ~300 improvement in *statistical* precision wrt current WA

- 5×10^{12} Z and 10^8 WW
  - m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W^{eff}$, R^Z_ℓ, R_b, α_s, m_W, Γ_W...
- 10^6 tt
  - m_{top}, Γ_{top}, EW couplings

Indirect sensitivity to new phys. up to Λ=70 TeV scale



Heavy Flavour Programme

- Enormous statistics: 10^{12} bb, cc; 1.7×10^{11} ττ
- Extremely clean environment, favourable kinematic conditions (boost) from Z decays
- CKM matrix, CP measurements, "flavour anomaly" studies, e.g. b → sττ, rare decays, CLFV searches, lepton universality, PNMS matrix unitarity

Feebly Coupled Particles - LLPs

Intensity frontier: Opportunity to directly observe new feebly interacting particles with masses below m_Z:

- Axion-like particles, dark photons, Heavy Neutral Leptons
- Signatures: long lifetimes – LLPs

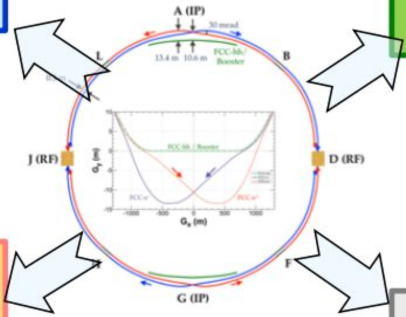
FCC-ee Detector Requirements

"Higgs Factory" Programme

- Momentum resolution at $p_T \sim 50$ GeV of $\sigma_{p_T}/p_T \simeq 10^{-3}$ commensurate with beam energy spread
- Jet energy resolution of 30%/√E in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

Ultra Precise EW Programme & QCD

- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. $\Gamma_{had}/\Gamma_{\ell}$) to 10^{-5}
- Momentum resolution "as good as we can get it"
  - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from μμ)
- Stability of B-field to 10^{-6} : stability of √s meast.



Heavy Flavour Programme

- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time measts.
- ECAL resolution at the few %/ √E level for inv. mass of final states with π^0s or γs
- Excellent π^0/γ separation and measurement for tau physics
- PID: K/π separation over wide momentum range for b and τ physics

Feebly Coupled Particles - LLPs

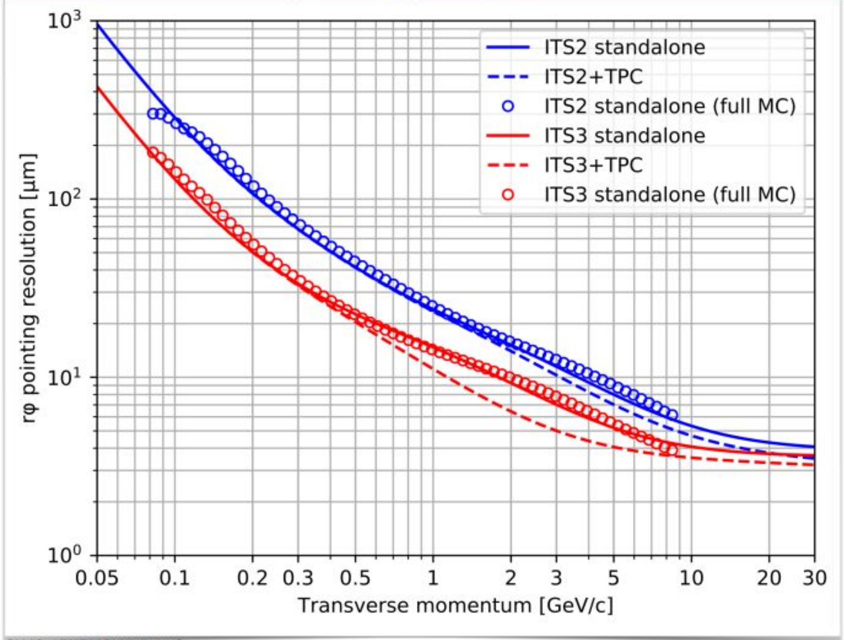
Benchmark signature: Z → νN, with N decaying late

- Sensitivity to far detached vertices (mm → m)
  - Tracking: more layers, continous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths ⇒ extended detector volume
- Precise timing for velocity (mass) estimate
- Hermeticity

ALICE ITS3

Performance improvement

pointing resolution



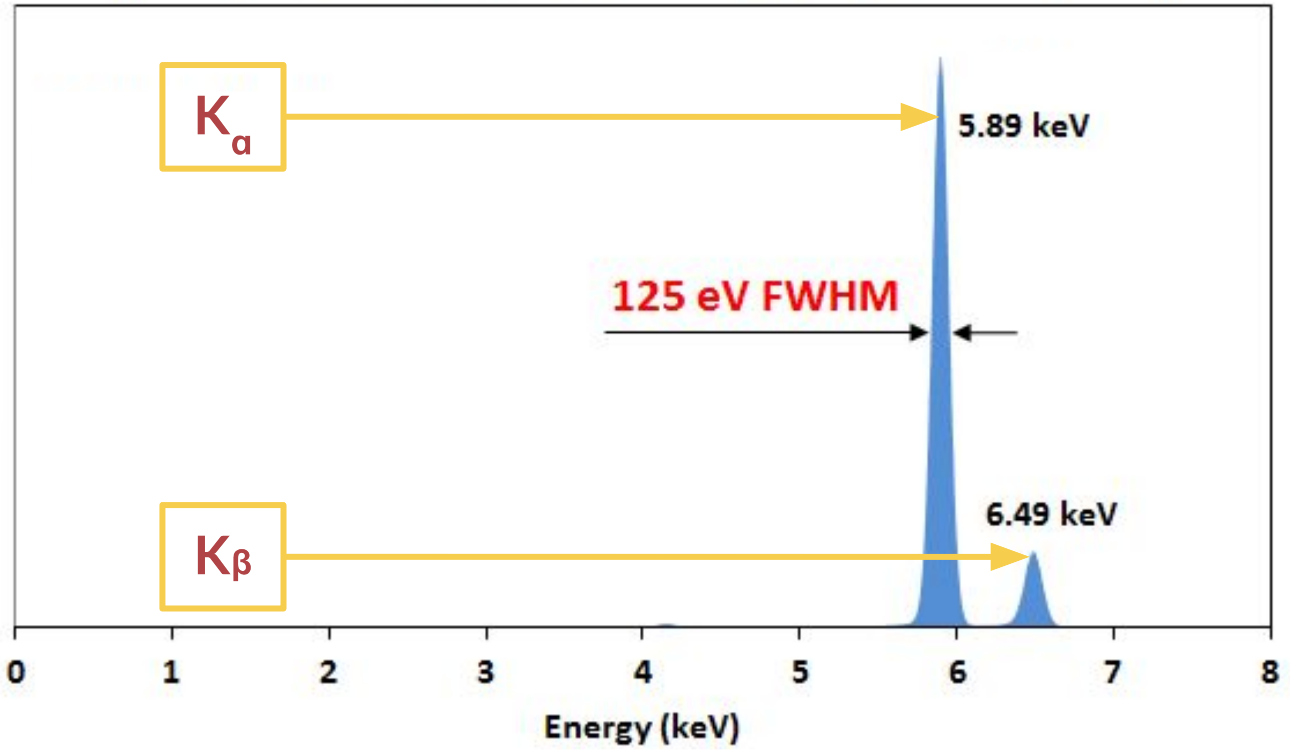
[ALICE-PUBLIC-2018-013]

improvement of factor 2 over all momenta

- Improvement of pointing resolution by:
  - drastic reduction of **material budget** (0.3 → 0.05% X_0/layer)
  - being **closer** to the interaction point (24 → 18 mm)
  - thinner and smaller **beam pipe** (700 → 500 μm; 18 → 16 mm)
- Directly boosts the ALICE core physics program that is largely based on:
  - low momenta
  - secondary vertex reconstruction
- E.g. Λ_c S/B improves by factor 10, significance by factor 4

Magnus Mager (CERN) | Si detector development for ALICE ITS3 and ALICE 3 | FCC week, London | 08.06.2023 | 13

Fe55 Spectrum



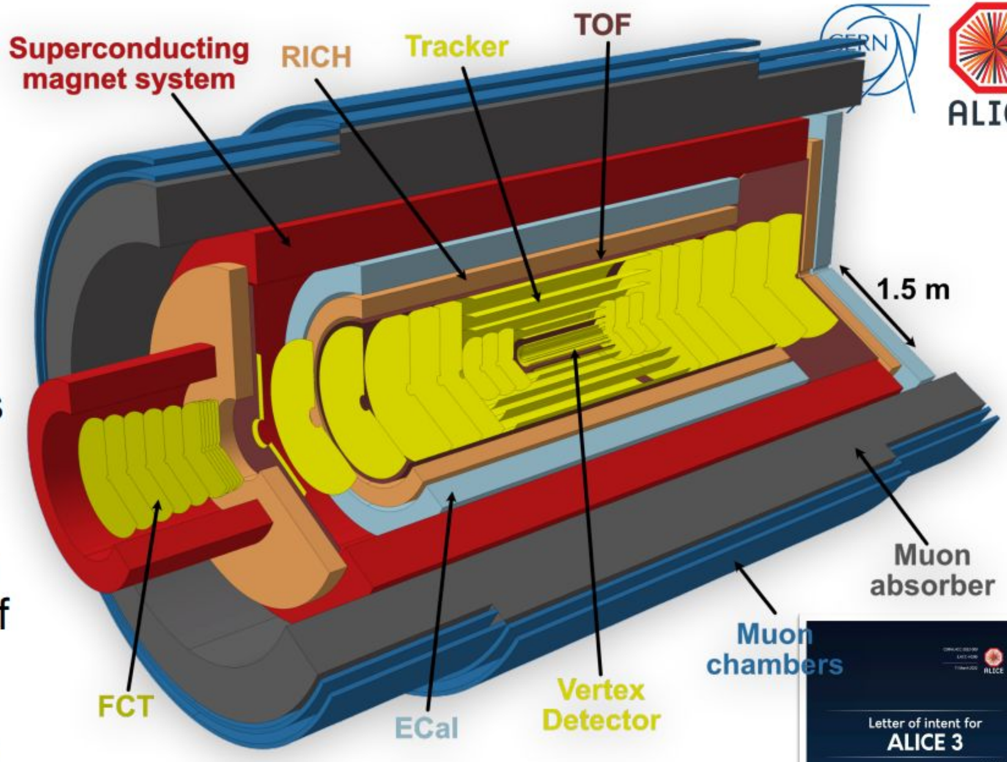
The measurement of the Fe55 spectrum is used to calibrate the sensor readout to the collected charge

- Number of electrons generated by Kα : 1640
- Number of electrons generated by Kβ : 1800

ALICE 3

LHC LS4 2033/34

- ALICE 3 is centred around a 60 m² MAPS tracker
  - innermost layers will be based on wafer-scale Silicon sensors "iris tracker", similar to ITS3 (but in vacuum)
  - outer tracker will be based on modules like ITS2 (but order of magnitude larger)
- *This is the next big and concrete step for this technology*



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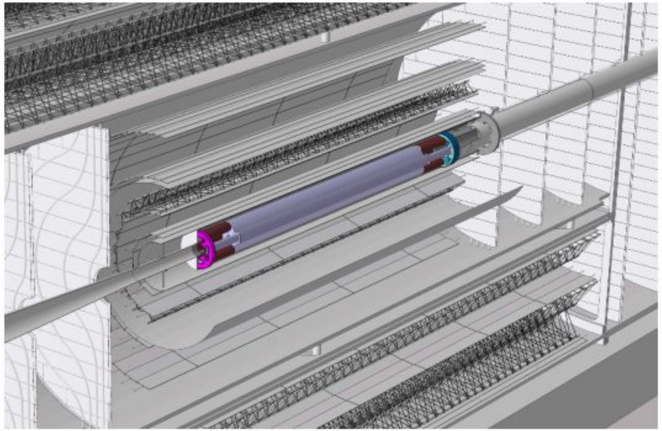
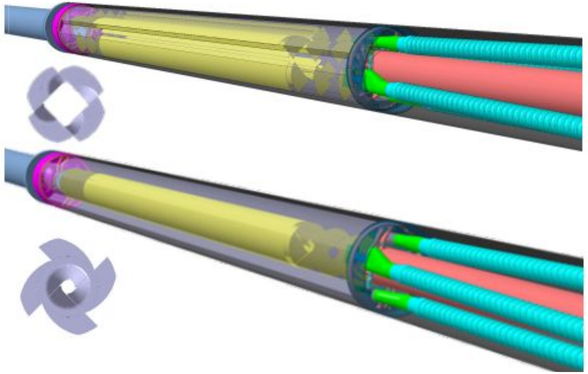
ALICE 3

vertex detector





- Based on wafer-scale, ultra-thin, curved MAPS
  - radial distance from interaction point: 5 mm (inside beampipe, retractable configuration)
  - unprecedented spatial resolution: ≈ 2.5 μm
  - … and material budget: ≈ 0.1% X_0/layer
  - at radiation levels of: ≈ 10^{16} 1MeV n_{eq}/cm^2 + 300 Mrad
  - and hit rates up to: 94 MHz/cm^2
- Unprecedented performance figures
  - largely leverages on the ITS3 developments
  - pushes improvements on a number of fronts

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