Solid states and gaseous tracking detectors

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Detector concepts

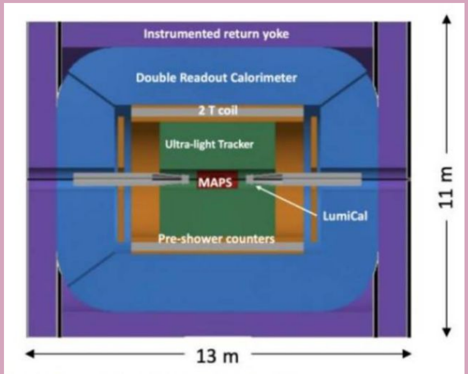
Solid-state devices are the choice for vertexing.

Solid-state and **gaseous detectors** are proposed for the tracking systems:

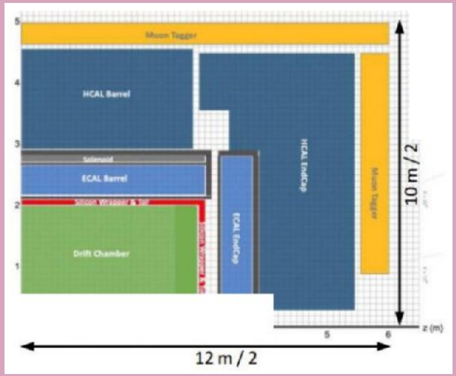
- **IDEA**, **ALLEGRO** and **ILD** are considering gaseous detectors
- **CLD** and **MuCol** are inheriting the CLIC design with a solid-state approach

Gas detectors are mainly proposed for the muon system.

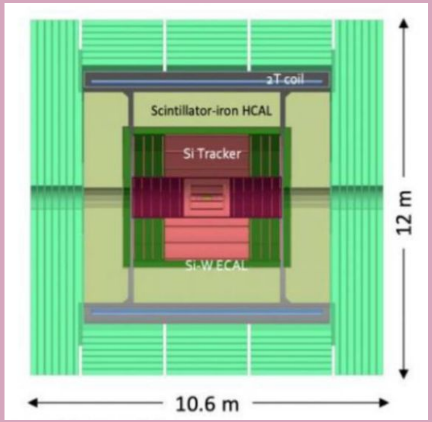
IDEA



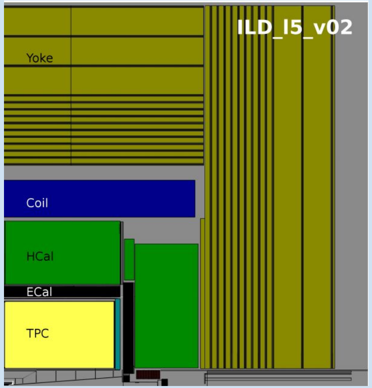
ALLEGRO



CLD



ILD



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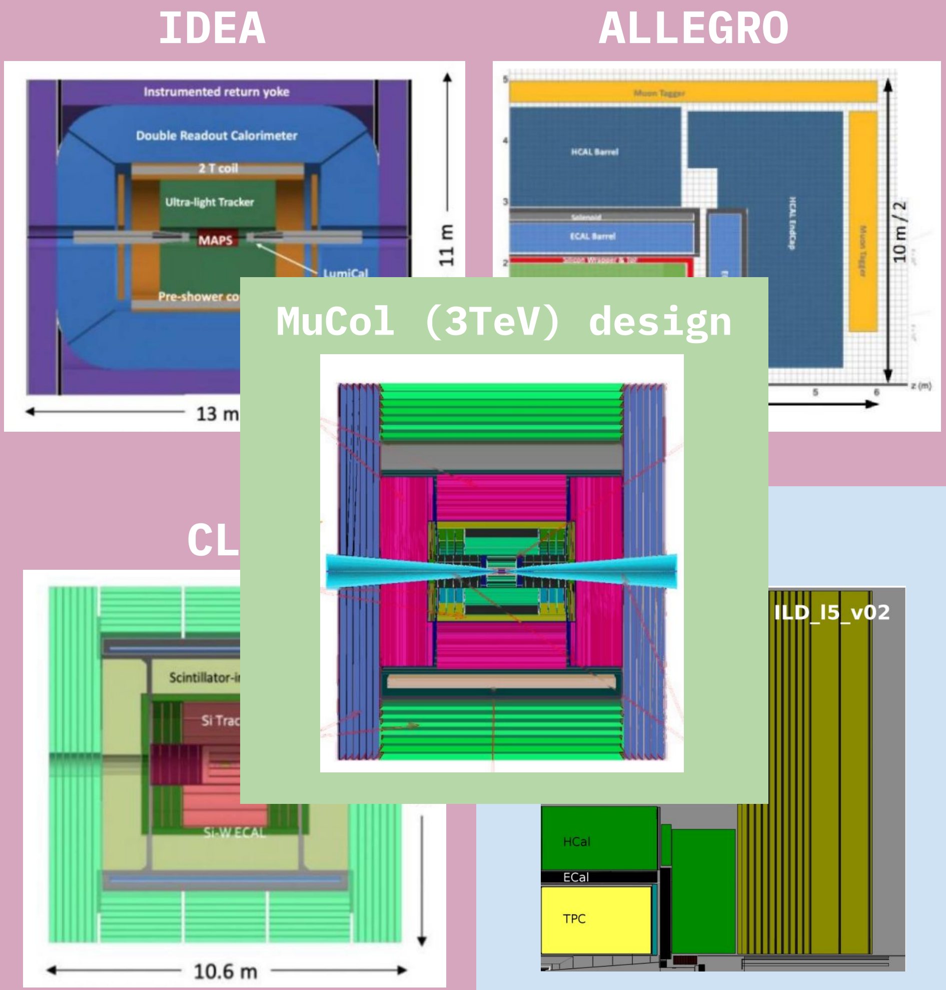

List of technologies/application

Solid-state detectors

Vertexing / Tracking / TOF	-> FD-MAPS, HV-CMOS, LGAD, RSD, bended

Gaseous detectors

Tracking	-> Drift chamber, TPC, Straw tubes
Muon system	-> µRWELL, RPC, Drift tube, Micromegas
TOF	-> Picosec, MRPC
Calorimetry	-> MPGD

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Requirements

Higgs boson tagging and BR into invisibles sets requirements on:

- Tracking and vertexing performance
- Material in the tracking volume.
- Magnetic field (and thickness of solenoid)

Transparency against multiple scattering and high precision momentum measurement play an important role.

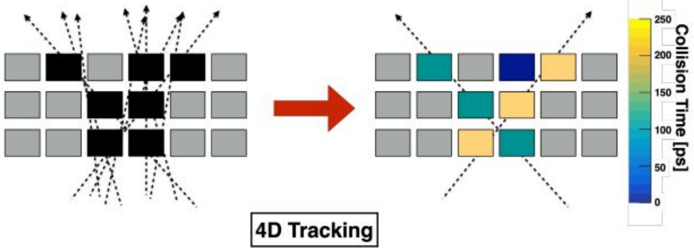
Particle identification interplay needed together with the tracking system.

High background level requires 4D tracking (MuCol) to remove combinatorial track reconstruction problem.

	Critical detector	Requirement
$ZH \rightarrow \ell^+\ell^- X$	Tracker	$\frac{\sigma(p_T)}{p_T^2} \sim \frac{0.1\,\%}{p_T} \oplus 2 \cdot 10^{-5}$
$H \rightarrow b\bar{b}, c\bar{c}$	Vertex	$\sigma_{r\phi} \sim 5 \oplus 15(p \sin\theta^{\frac{3}{2}})^{-1}[\mu m]$

$$\frac{\Delta p_T}{p_T}\Big|_{res.} \approx \frac{12\,\sigma_{r\phi}\,p_T}{0.3\,B_0 L_0^2}\sqrt{\frac{5}{N+5}}$$

$$\frac{\Delta p_T}{p_T}\Big|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{0.3\beta\,B_0 L_0}\sqrt{\frac{d_{tot}}{X_0 \sin\theta}}$$



Solid state detector

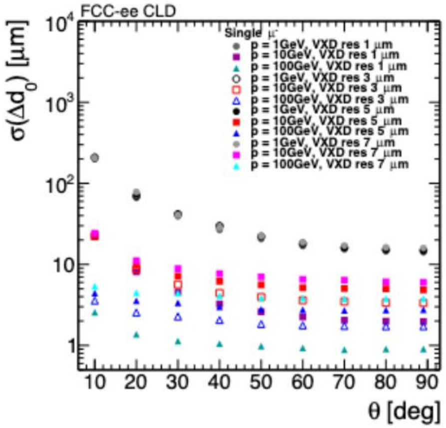
Gaelle Boudoul

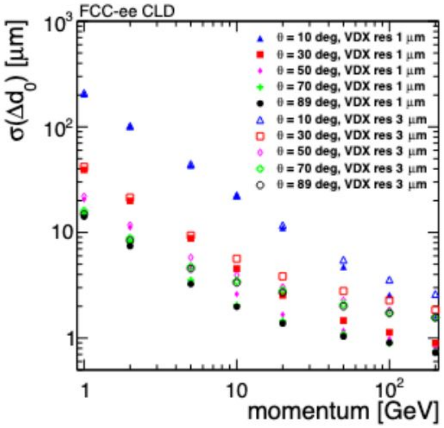
Silicon detector are the unique choice for the vertex detector to fulfil the requirements.

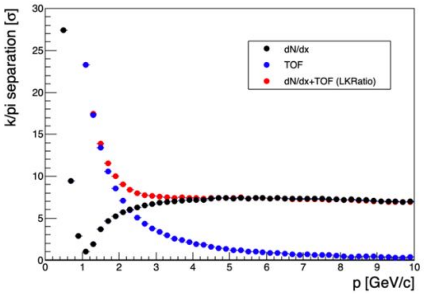
Material budget plays an important role but R&D is ongoing to reduce its impact.

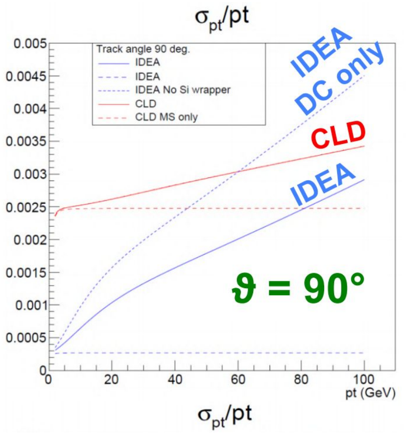
Timing performance for TOF measurement enhance the PID where dE/dx and dN/dx fail

I did a personal selection on the technology discussed in the next slides: FD-MAPS, LGAD, HV-CMOS, AC-LGAD, bended.





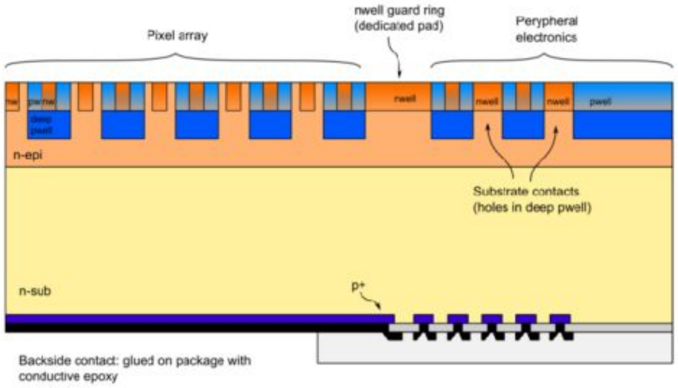


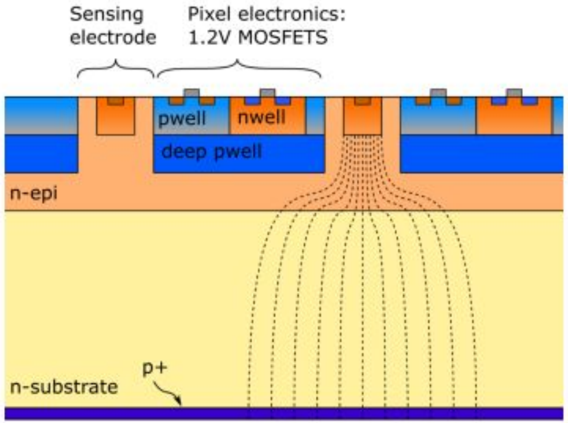


ARCADIA

Advanced **R**eadout **C**MOS **A**rchitectures with **D**epleted **I**ntegrated sensor **A**rray
Fully Depleted Monolithic Active Pixel CMOS sensor technology platform allowing for:

- Active sensor **thickness** in the range 50 µm to 500 µm
- Operation in **full depletion** with fast charge collection by drift
- Small collecting electrode for optimal signal-to-noise ratio
- **Scalable readout** architecture with ultra-low **power capability** O(10mW/cm^2)
- Compatibility with standard CMOS fabrication processes
- Technology: **LF11is 110nm CMOS**





ARCADIA Demonstrator layout

Vertex

Manuel Rolo

Matrix

- 512x512 pixels, Double Column arrangement
- **25x25 μm² pixels**
- Clockless

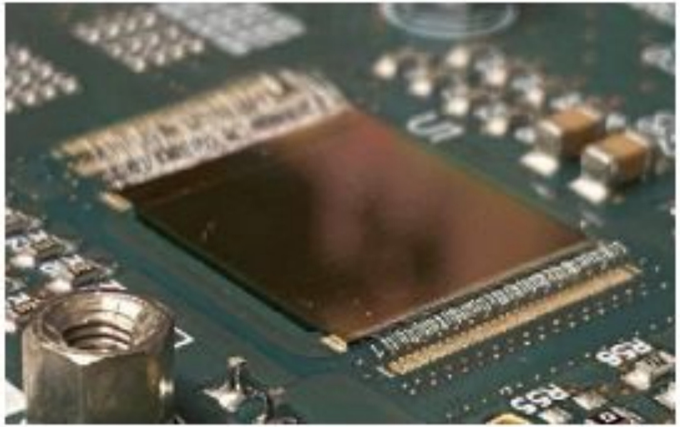
End of Sector
(x16) Reads and Configures 512x32 pixels

Sector Biasing
(x16) Generates I/V biases for 512x32 pixels

Periphery

- SPI, Configuration, 8b10b enc, Serializers
- Triggerless data-driven readout
- **Event rate up to 100 MHz/cm²**
- High-rate operation (16 Tx): **17-30 mW/cm²**
- Low-power operation (1 Tx): **10 mW/cm²**

Bottom Pad Frame
Stacked Power and Signal pads



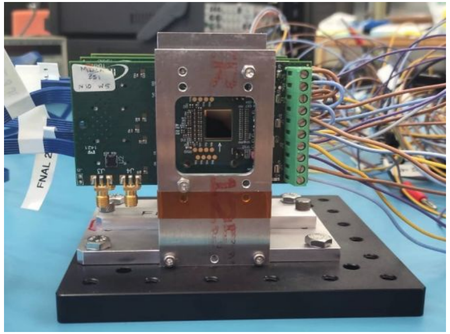
Test beam at FNAL (120 GeV protons)

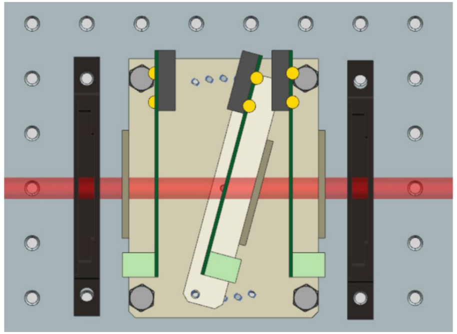
Telescope with 3 ARCADIA-MD3 200 μm thick sensors

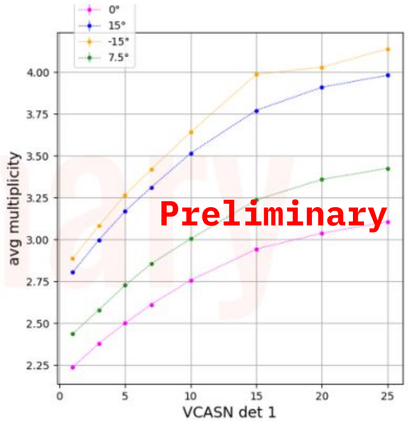
Threshold, sensor HV and incidence angle parameterization: study of cluster size, collection efficiency, spatial resolution

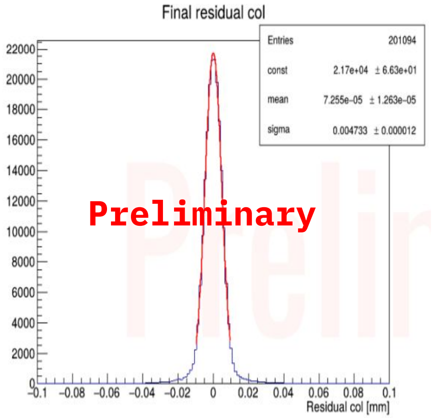
Single-point resolution ~4.7 μm
@VCASN = 5 (~ 600 e-)
and angle of tilt = 0°

Average efficiency 0.9941 ± 0.0003









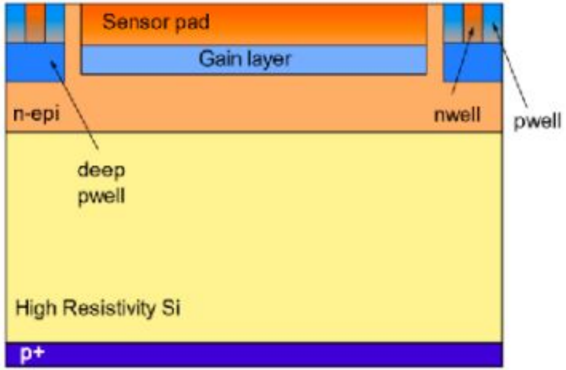
ARCADIA MadPix

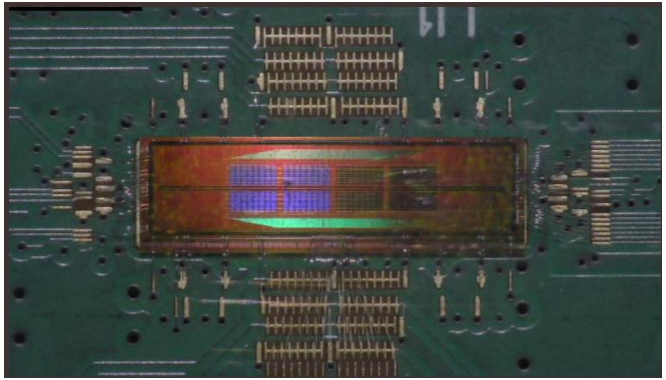
Monolithic CMOS **A**valanche **D**etector **PIX**elated Prototype for ps Timing Application

MadPix prototype with gain layer and integrated electronics

Advantages of **CMOS LGAD** are a reduced material and cost together with a cheaper assembly through a monolithic approach

Add-on p-gain implant underneath the n+ collecting electrode to **push the timing performances**



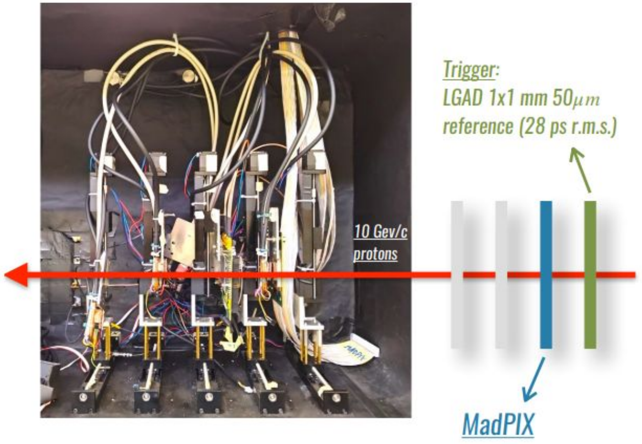


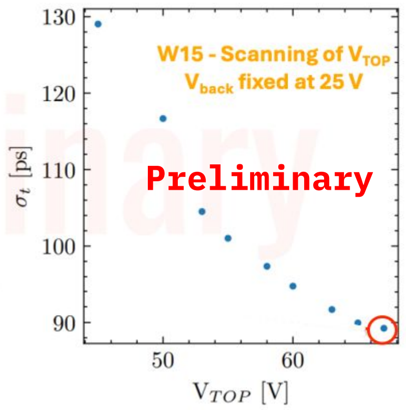
First small-scale **demonstrator**
- 4x16 mm^2 and **250 x 100 μm^2** pixel pads
- 8 matrices (64 pixel pads each) implementing different sensor and front-end flavours
- 64 analogue outputs on each side

ALICE3 TOF Test beam @ CERN PS in October 2024. **Timing resolution** measured < 75 ps (very preliminary results)

48 µm thick active layer on a p+ substrate, timing resolution is sensor limited

FEE jitter ~ 20 ps r.m.s. measured with laser





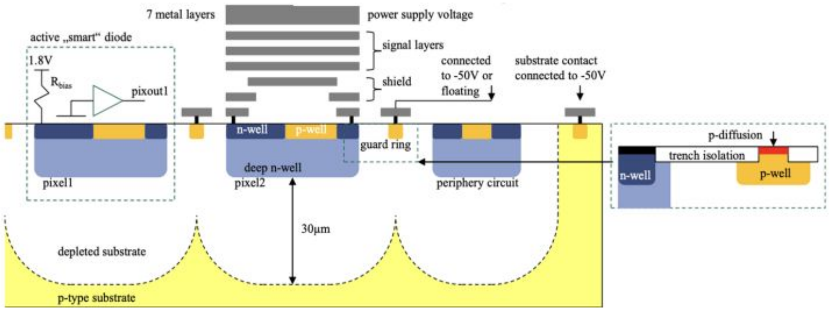
ATLASPIX3

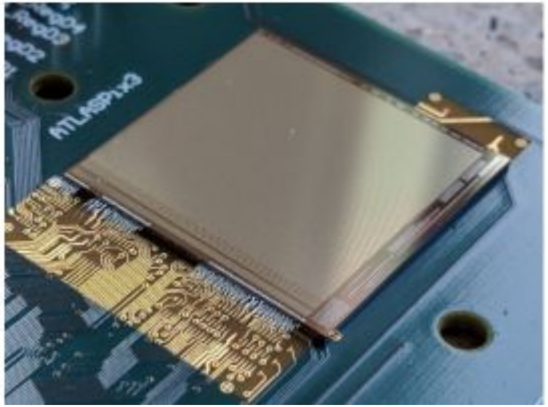
ATLASPix3 was developed for ATLAS ITk, now used widely as HV-CMOS demonstrator.

General features

- TSI 180 nm **HV-CMOS technology**
- full-reticle size 20×21 mm^2 **monolithic pixel sensor**
- 132 columns of 372 pixels
- pixel size 50×**150µm**^{2} (25×150µm^2 on recent prototypes)
- **breakdown voltage ~-60 V**
- up to 1.28 Gbps downlink
- 25 ns timestamping
- analog pixel matrix, digital processing in periphery
- Threshold can be tuned to 800e, with dispersion ~60e, noise ~ 70e

Both triggerless and triggered readout modes





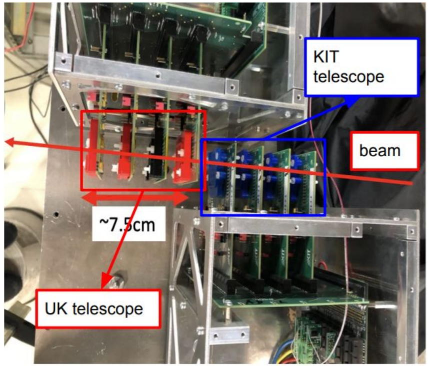
ATLASPIX3 Test Beam

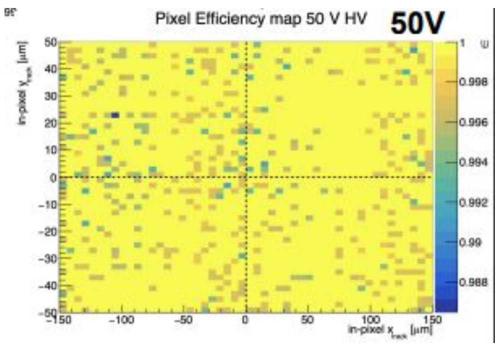
Two telescopes (KIT and UK) in standalone systems tested at DESY with electron beams.

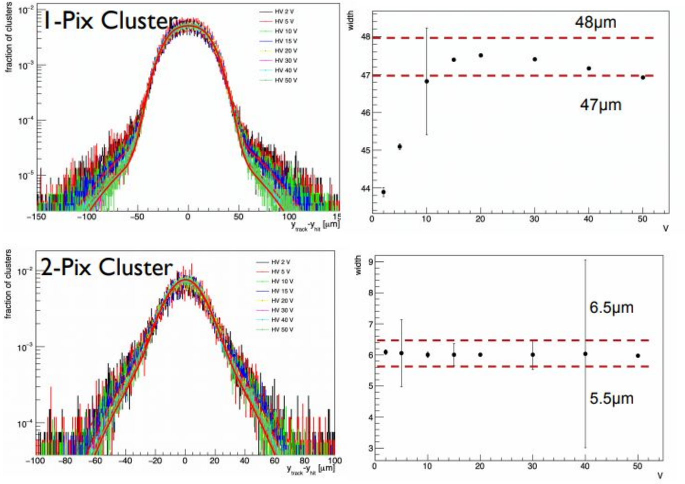
For the presented data analysis a 3-6 GeV electrons beams is used and perpendicular beams.

Resolution depends on the cluster size.

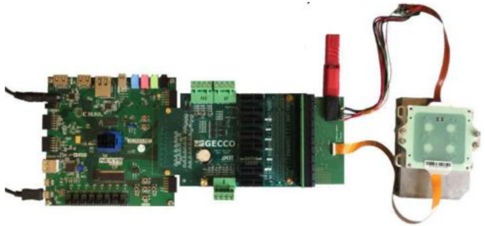
Overall efficiency > 99% achieved after 20V

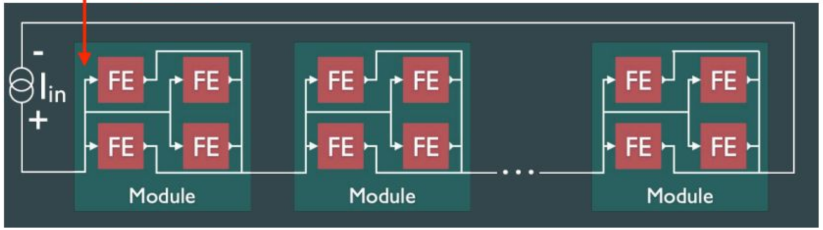


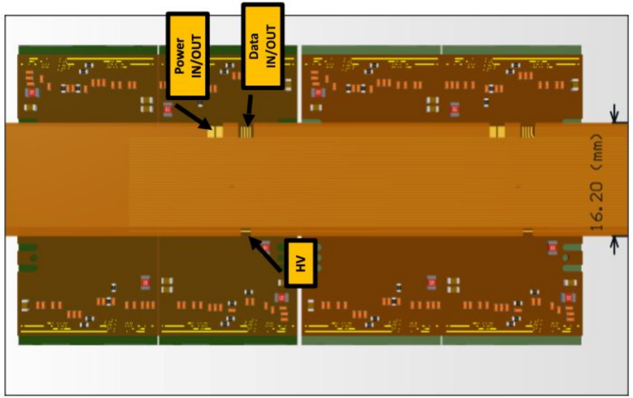




ATLASPIX3 Quad module





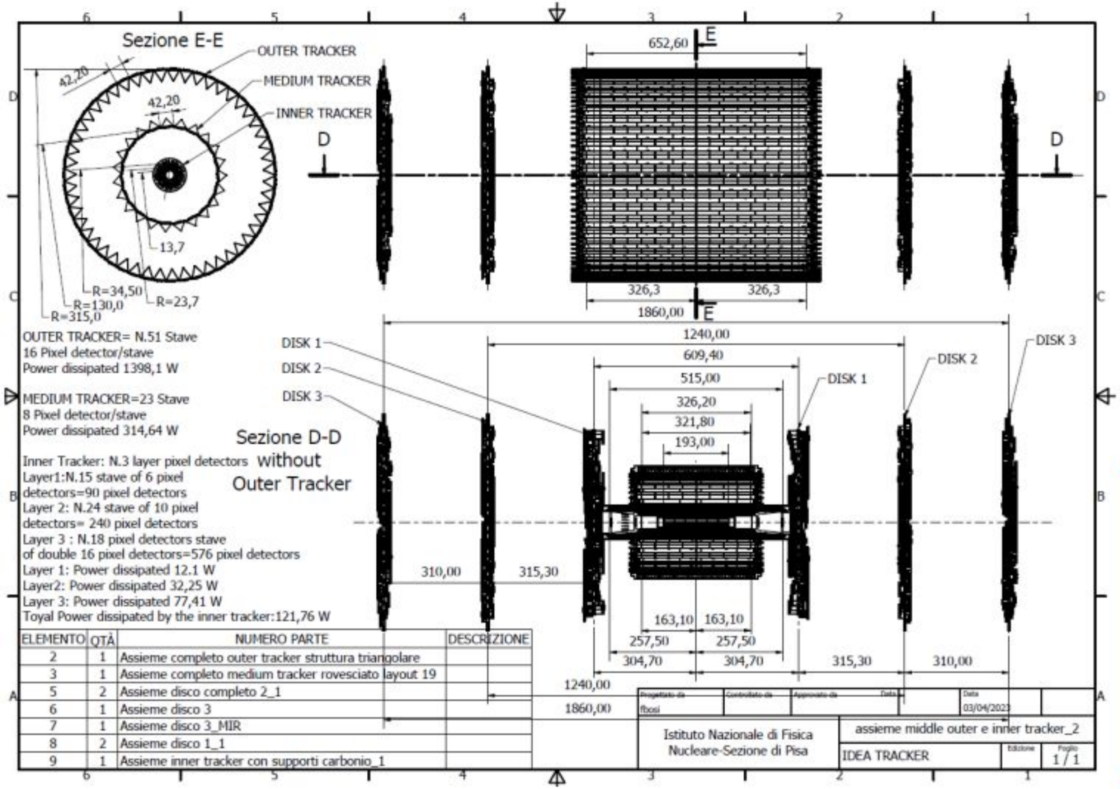


Multi-chip module assembly

- **aggregates electrical services and connection for multiple sensors**
- quad module, inspired by ATLAS ITk pixels
- implemented interface to readout system
- developed software for module
- **no degradation of performances for quad modules**
- ATLASPix3 has serial powering capabilities
- **SP operation is not affected**

Silicon layout IDEA and Allegro

Fabrizio Palla



Outer vertex tracker:
ATLASPix3 based

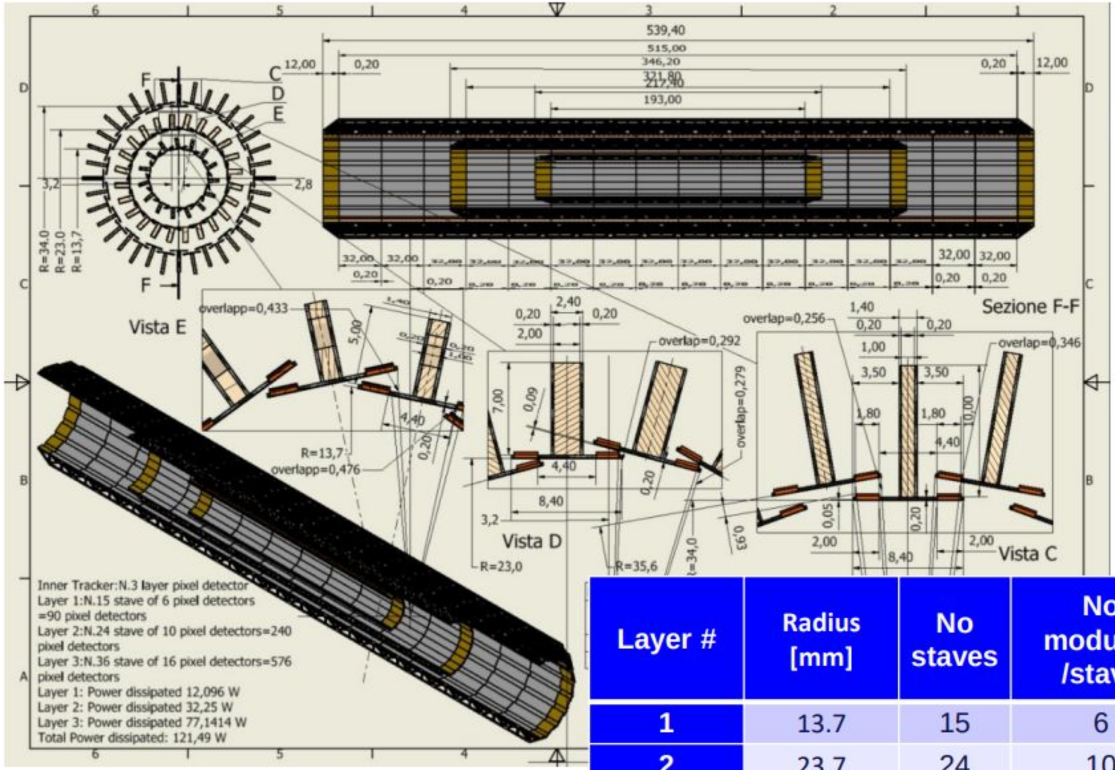
Modules of $50 \times 150\ \mu m^2$ pixel size
- Intermediate barrel at 13 cm radius
- Outer barrel at 34.5 cm radius
- 3 disks per side

Inner Vertex detector:
ARCADIA based

Modules of $25 \times 25\ \mu m^2$ pixel size

3 barrel layers at
- 13.7, 23.7 and 34/35.6 mm radius

Silicon layout IDEA and Allegro



Total thickness per layer 0.25% X/X0

Carbon Fibre ~60 %

Silicon: ~20%

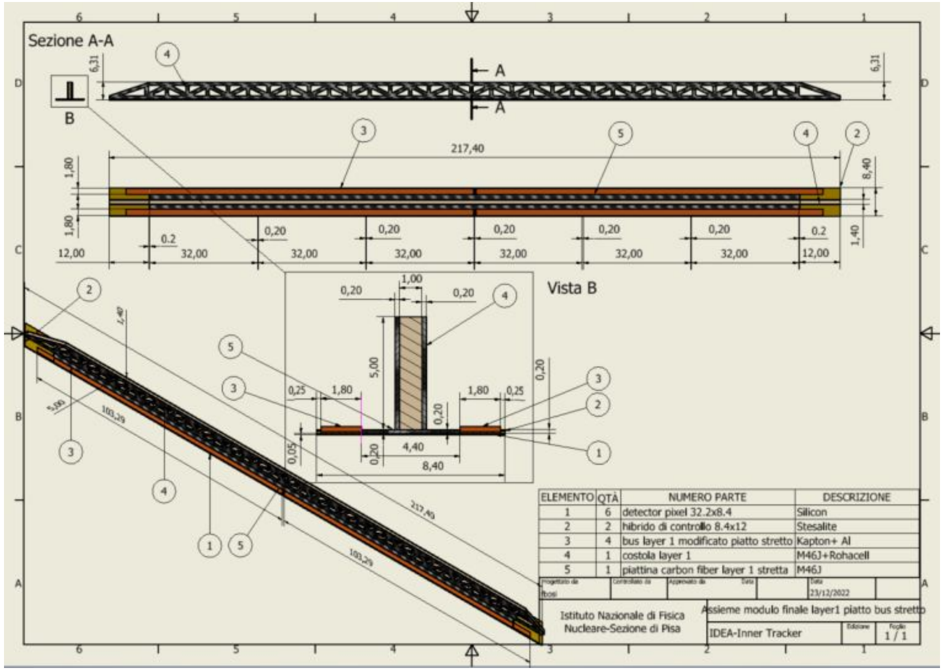
Power and readout bus: ~20%

Layer #	Radius [mm]	No staves	No modules /stave	Total Length [mm]	Active Area [cm²]	Power [W]
1	13.7	15	6	217.40	241.92	12
2	23.7	24	10	346.20	645.12	32
3	34 & 35.6	36	16	539.40	1548.29	77

Silicon layout IDEA and Allegro

Fabrizio Palla

- Reticular lightweight support to provide stiffness
- Thin carbon fiber walls interleaved with Rohacell
- 2 buses (data and power) 1.8 mm wide and 250 µm thick (50 µm Al, 200 µm kapton) per side
- Inspired to low mass hybrid R&D Sensors facing interaction point w/o any other material in front
- Readout chips either sides
- Air cooled



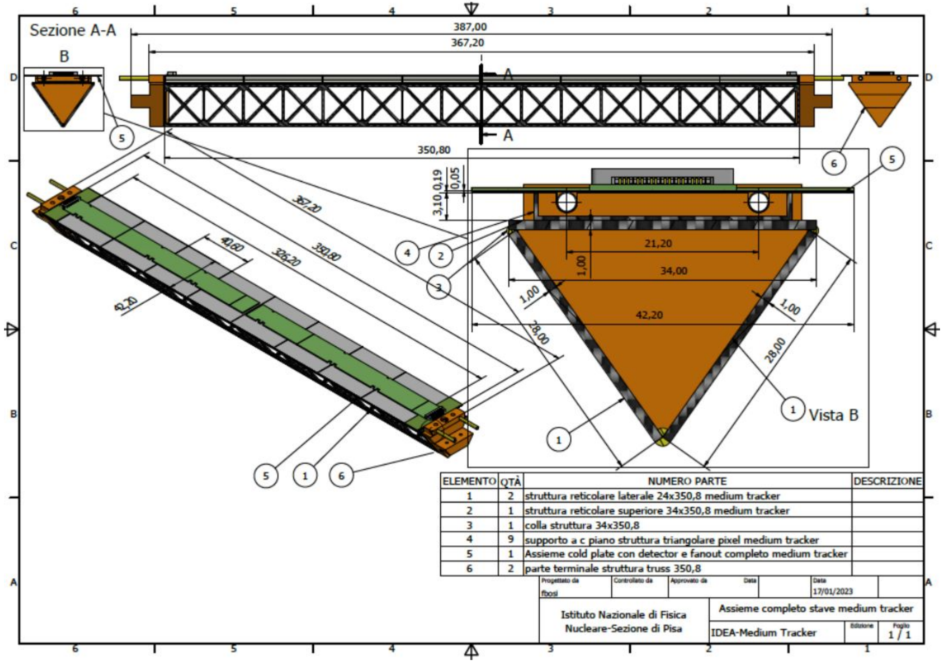
Silicon layout IDEA and Allegro

- Middle Barrel At 13 cm radius
- Similar for outer barrel

- 22 staves of 8 modules each.
- Lightweight reticular support structure (ALICE/Belle-II like)

- Readout chips either side
- Power budget ~342 W

- Total weight ~1 kg Water cooled (2 pipes of 2 mm diameter)
- Similar prototype built @ Pisa



Resistive Silicon Detectors

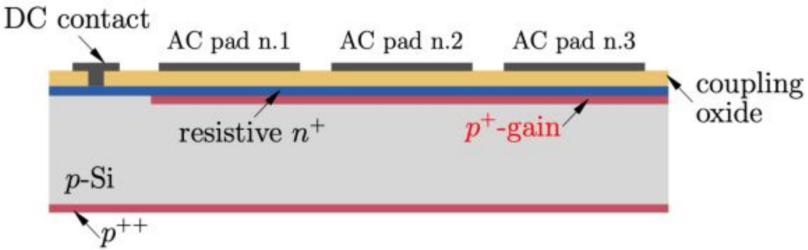
Tracker/TOF

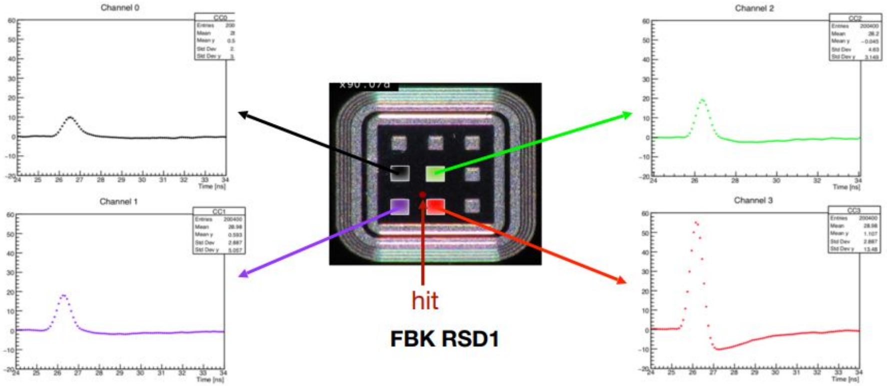
Enrico Robutti

Total surface for silicon wrapper about 20 times that of vertex detector and with similar pitch
$\Longrightarrow$ O(10^{11}) channels

Resistive Silicon Detectors (**RSD**), an **AC-coupled LGAD** sensor, can provide high-resolution position measurement with relatively large pitch

- Suitable for low occupancy environments
- Comparable material thickness
- Precision time measurement possible
- Ongoing R&D on implementation in DMAPS structures



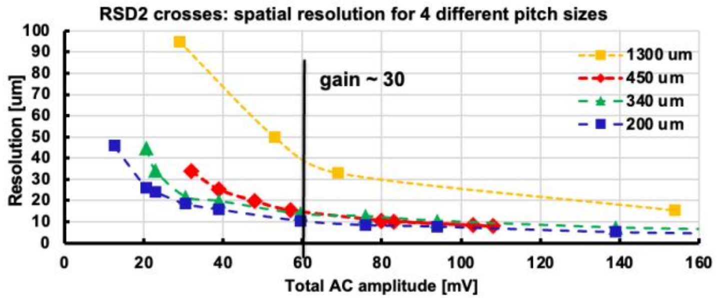


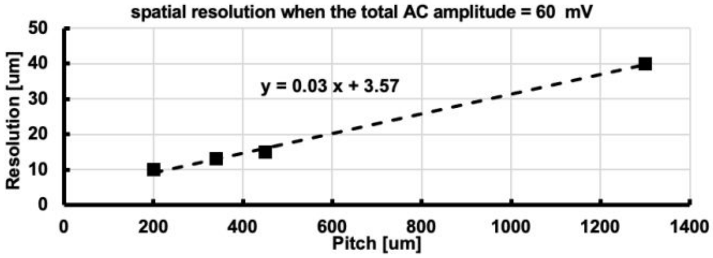
RSD Test Beam

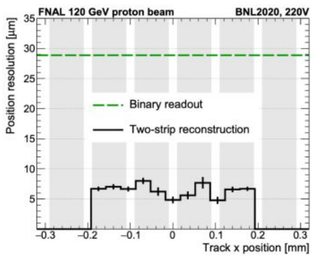
Position performance measured with laser and several test beams with 120 GeV proton beam @ FNAL

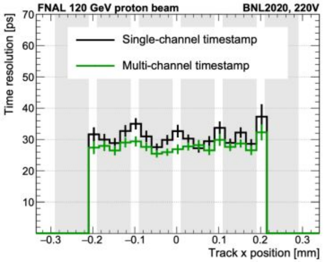
Different pitch size tested and with a gain of 30 **it achieves a spatial resolution of about 3% of the pitch size**.

The **time resolution** achieved is about **30 ps**, independently from the pitch used.









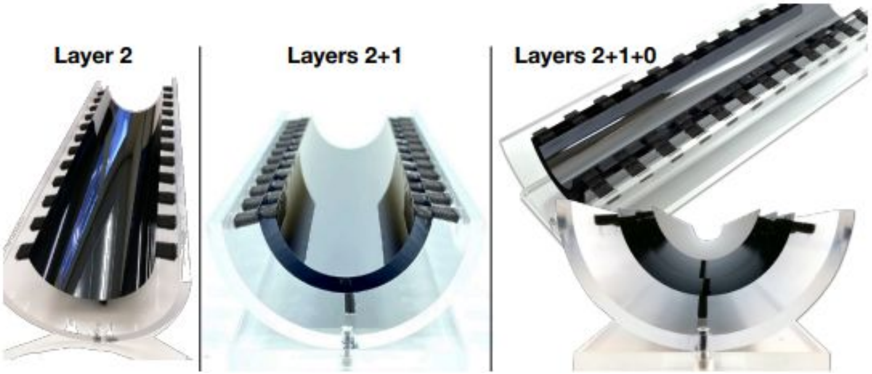
ALICE ITS3 layout-like

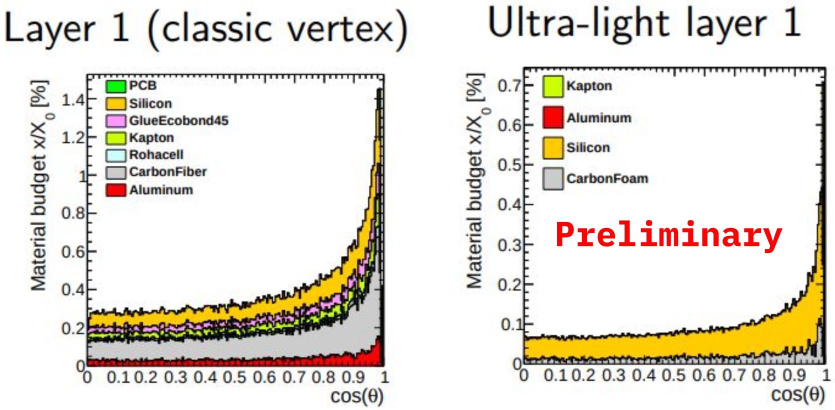
DMAPS in 65 nm TPSCo process with bended detector.

The **IDEA first layer has a smaller radius** comparing to ALICE, from 18 to 13.7 mm. Mechanically is okay, electrically to be demonstrated.

Proposal for FCC-ee to use **4 segments** (stitching)

Preliminary material budget evaluation measure a **reduction of about 3-5 times** with respect standard geometry.





OCTOPUS

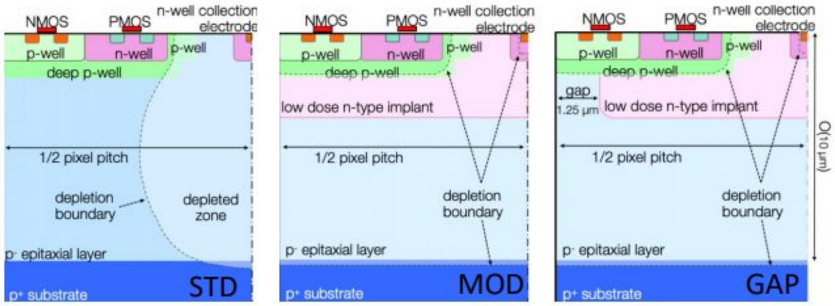
Vertex

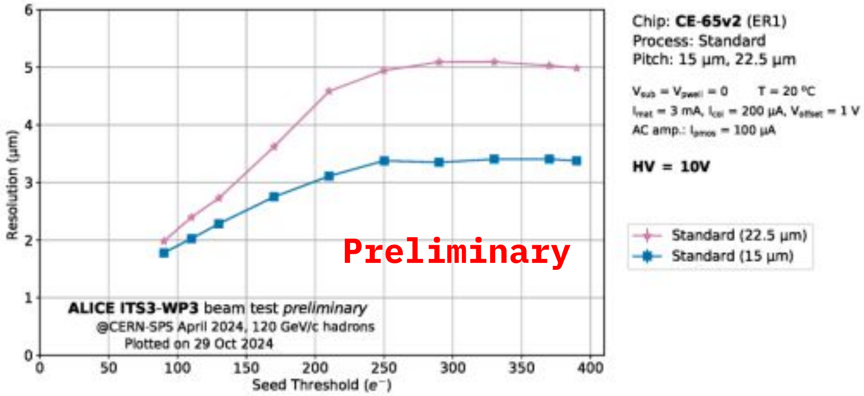
Serhiy Senyukov

Optimized **C**MOS **T**echnology f**O**r **P**recision in **U**ltra-thin **S**ilicon is a project for simulation, development and characterization of **MAPS** in **TPSCo 65 nm** CMOS Imaging Process targeting future Lepton Collider specifications with this focus:

- Single point resolution: 3 µm
- Time resolution: 5 ns
- Power dissipation: 50 mW/cm2
- Thickness: 50 µm
- Readout architecture scalable to large area
- 48 × 24 pixel chip with analogue readout
- **3 process variants (STD, MOD, GAP) for depletion control**
- 3 pixel pitches: 15, 18, 22.5 µm
- AC pixels with Vbias = (0; 10) V

Ongoing test beam campaign reported preliminary interesting results.





Snail-shape vErtEx Detector

Vertex

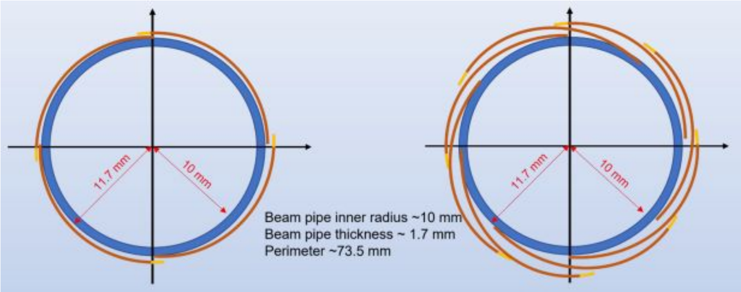
Serhiy Senyukov

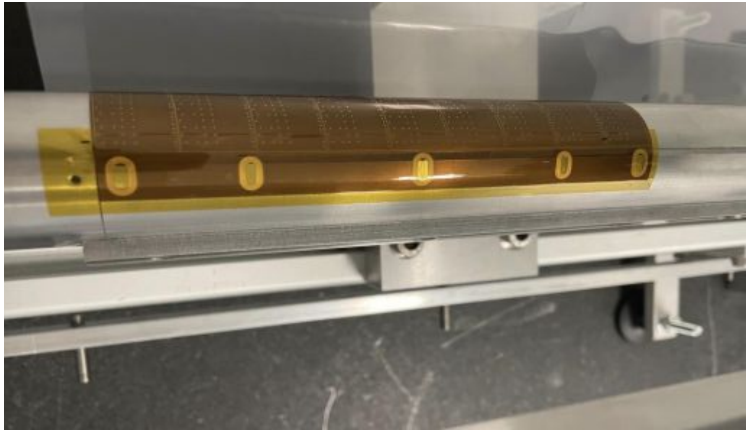
FCC-SEED is a full silicon ladders of 6/8 reticles

- With or without stitching along Z
- Ladders are bent to provide mechanical stiffness to build the layer and to reduce the material budget
- **Full r-phi coverage**
- Stitching yield less critical
- **Less constrain on the layer radius**

Project to build a prototype of a FCC-SEED layer using **MIMOSIS chips**

- Different thicknesses: 30/40/50 µm
- Different radii: 18/15/12/10 mm





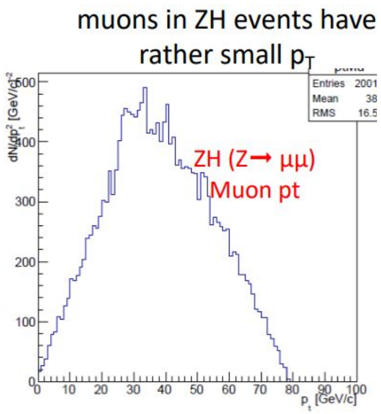
Gaseous detector

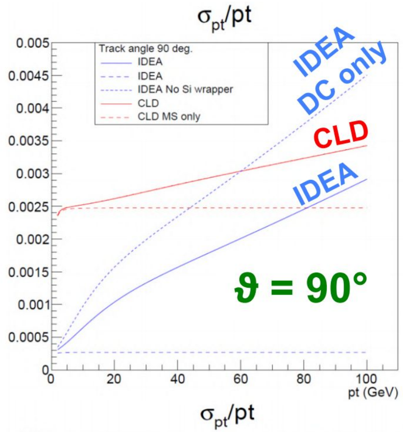
Gaseous detector are used for tracking purpose and also for muon measurement, timing and calorimetry.

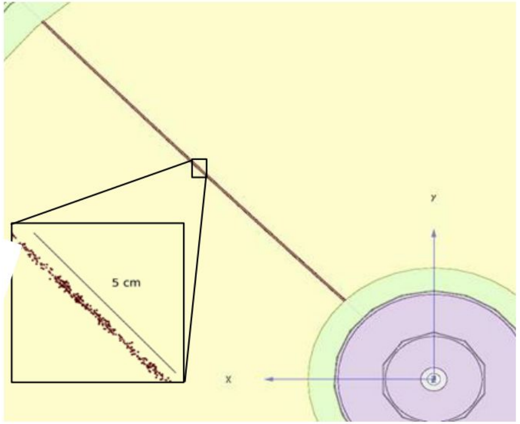
The **low material budget** reduce the contribution on multiple scattering and improves the momentum resolution

Multiple measurement of the track path O(100) allows together with the momentum measurement, the particle identification.

I did a personal selection on the technology discussed in the next slides: Drift chamber, Straw tube and TPC.







Drift Chamber

Tracking

Walaa Elmetenawee

Dimensions:
4m long (active volume)
35cm to 2m radius

Low material budget
- Barrel: ~ 1.6% X_0
- Forward directions: ~ 5% X_0

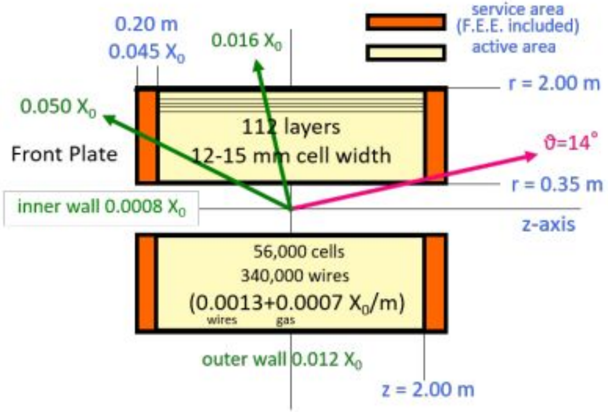
Stereo layout
- 112 layers ranging from 50 to 250 mrad

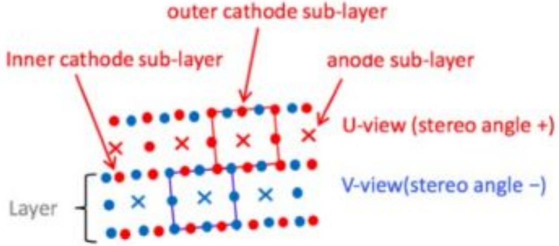
Operating gas mixture: He + 10% iC_4H_{10}
- Average drift velocity of ~ 2 cm/µs
  → drift time t_D < 400 ns

Sense vires: 20 µm diameter W(Au) =>56448
Field wires: 40 µm diameter Al(Ag) =>229056
F. and G. wires: 50 µm diameter Al(Ag) => 58464

Active volume: 56448 almost **squared drift cells (12 ÷ 14.5 mm)**

Expected resolution: σ_{xy} ~ 100 µm and σ_z ~ 1 mm





5 : 1 field-to-sense wire ratio

Drift Chamber mechanical structure

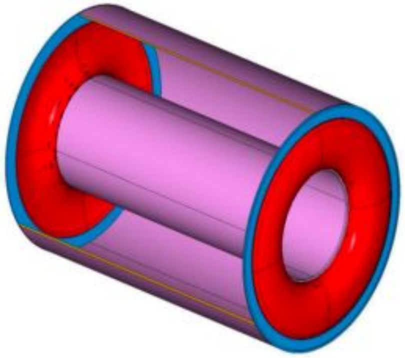
The mechanical design of the drift chamber is driven by two main objectives:

- Maximizing its transparency in terms of radiation length.
- Maximizing its mechanical stability by reducing to acceptable limits the deformations of the endplates under the total load of the wires.

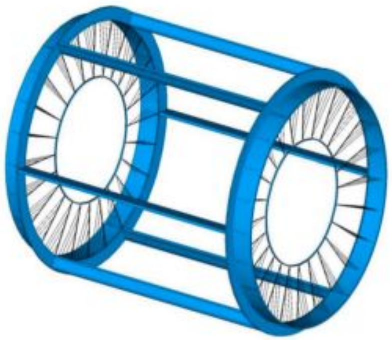
Gas containment: gas vessel can freely deform without affecting the internal wire position and mechanical tension.

Wire cage: wire support structure not subject to differential pressure can be light and feed-through-less

Gas containment



Wire cage



Drift Chamber Cluster counting

Tracking | Walaa Elmetenawee

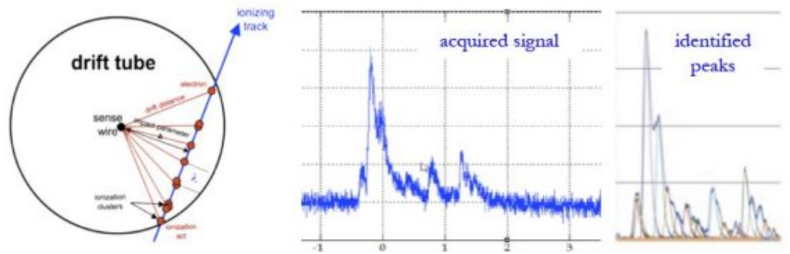
In **He based gas mixtures** the signals from each ionization act can be spread in time to few ns. With the help of a **fast read-out electronics** they can be identified efficiently.

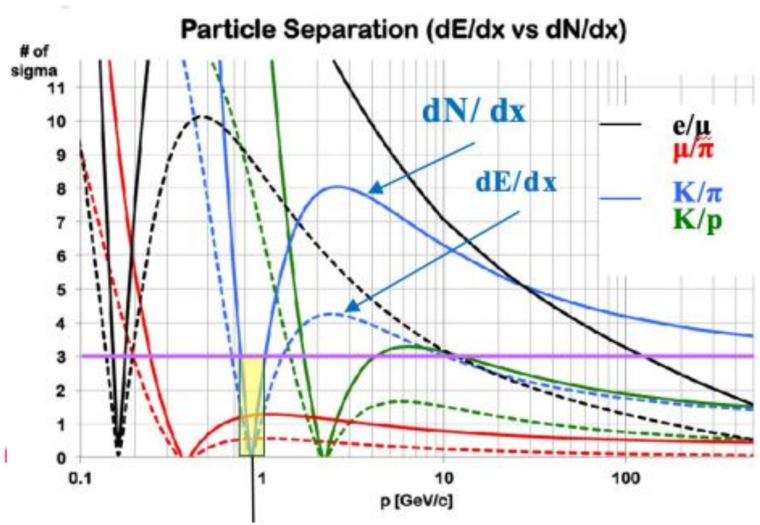
By counting the number of ionization acts per unit length (**dN/dx**), it is possible to identify the particles (P.Id.) with a better resolution w.r.t the dE/dx method.

Landau distribution of **dE/dx** originated by the **mixing of primary and secondary ionizations**, has **large fluctuations** and limits separation power of PID

Primary ionization is a Poisson process, has small fluctuations

The cluster counting is based on replacing the measurement of an ANALOG information (the [truncated] mean dE/dX) with a DIGITAL one, the number of ionisation clusters per unit length.





Drift Chamber Test Beam

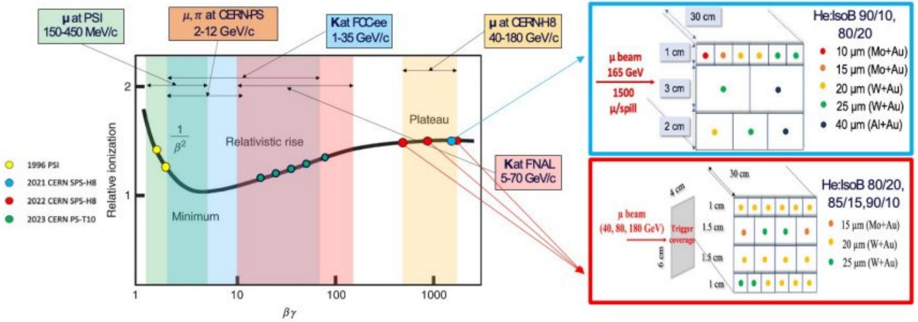
Beam tests to experimentally asses and **optimize** the performance of the **cluster counting/timing**.

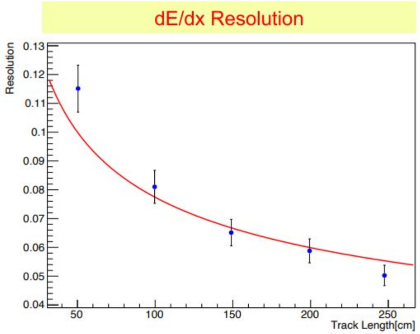
dE/dx measurement has an **optimized truncation empirically**: selected the distribution with 80% of the charges.

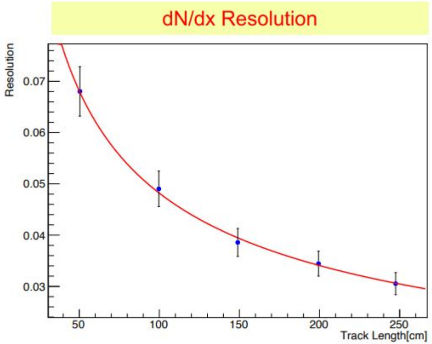
To accurately identify electron peaks, Derivative Algorithm (DERIV) and Running Template Algorithm (RTA) are developed.

A factor 2 improvement in the resolution using dN/dx method.

Needs to be demonstrate its performance in cell with large occupancy







Straw tube

Reasonable single hit resolution: 120 μm

Similar or better momentum resolution than the pixel detector due to more hits detected and a longer lever arm

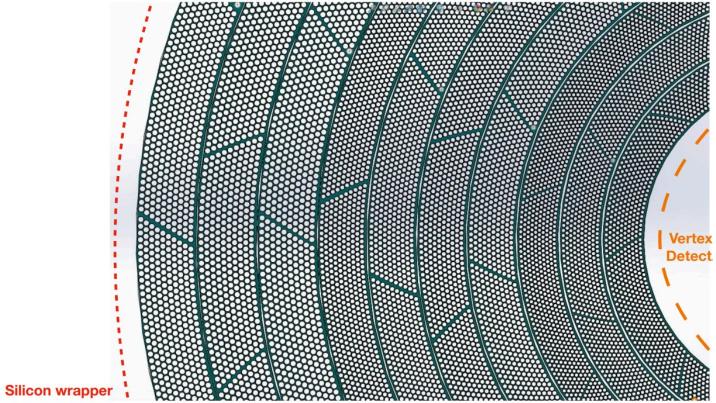
Low material and less multiple scattering with straws

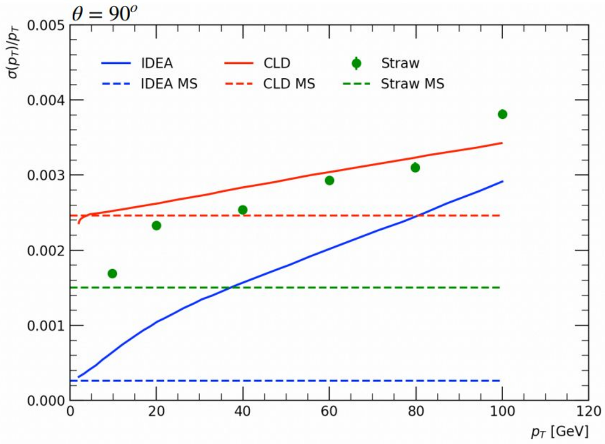
Particle identification (π-K, K-p identifications)

Mylar wall thickness of 12 μm and 100 layers means ~3 mm Mylar films ~1.2% X_0

Inner wall 0.05 μm Aluminum coating
Sense wire: radius of 10 μm Tungsten

Endplate supporting structure could be similar to DCH





Straw tube PID simulation

Tracking

Kevin Nelson

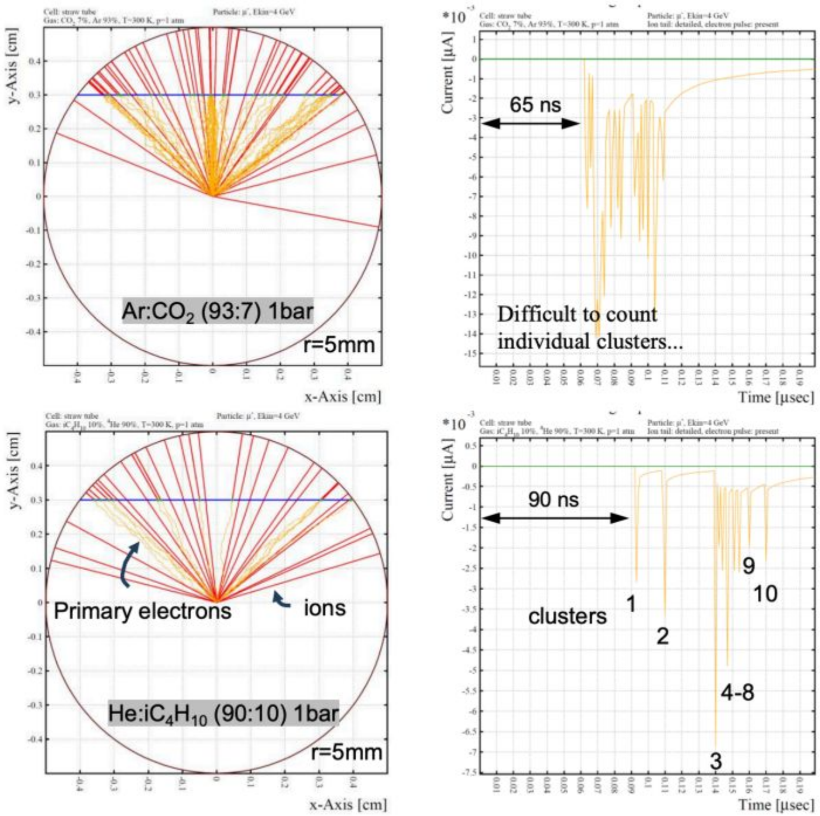
Ongoing Garfield simulation to provide essential inputs for the gas optimization and dE/dx(dN/dx) measurement for PID

- **Ar-based gas:**

high ionization density
(~40 clusters/cm)
moderate electron drift velocity
50 μm/ns (@E~2kV/cm)
Mean cluster arrival time separation:
~5 ns

- **He-based gas:**

lower ionization density
(~15 clusters/cm)
drift velocity
30 μm/ns (@E~2kV/cm).
Mean cluster arrival time separation:
~15 ns



Straw tube Test Beam

Test beam at CERN H4 & T9

Straw diameters: 5, 10, 20 mm to evaluate operation working points (high voltage, thresholds, gas)

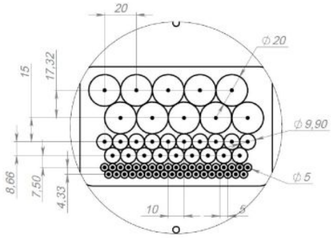
Tube-wall 36 µm coated with 20 nm gold and 70 nm copper

Central wire diameter 30 µm

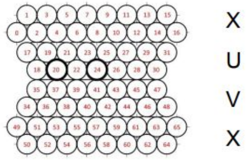
2 prototypes (from different production) of straw chambers used

Straw signal amplified by NIM amplifiers. Digitized by an oscilloscope. **Individual clusters could be seen from the raw signal**.

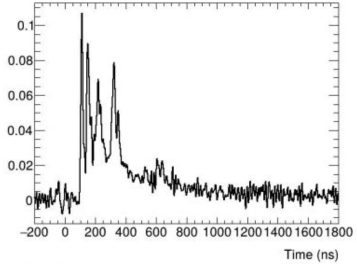
Cluster counting algorithm to be developed.



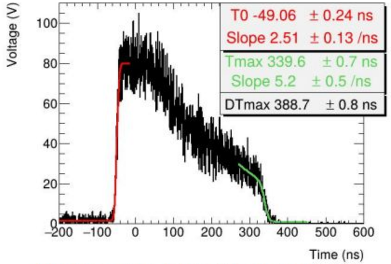
Prototype 1: 5 mm, 10 mm, and 20 mm tubes area



Prototype 2: 10 mm tube area only. Two planes of X, two planes of U (2°), two planes of V (−2°) and two planes of X.



Raw signal from the straw tube



First leading edge time spectrum

TPC

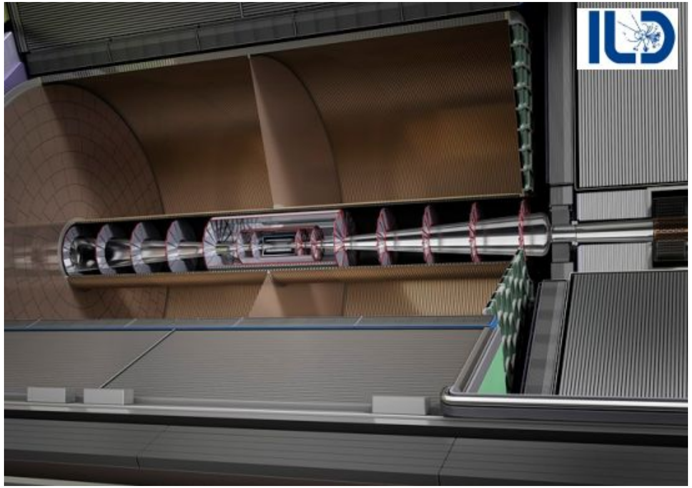
Time Projection Chamber
$0.3\text{m} < r < 1.8\text{m}$
$|z| < 2.4$ m

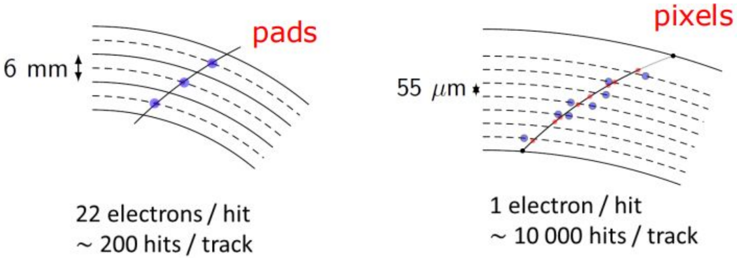
highly-redundant pattern recognition

dE/dx and dN/dx measurement PID

Material budget is
$0.01\ X_0$ TPC gas
$0.01\ X_0$ inner cylinder
$0.03\ X_0$ outer cylinder
$< 0.25\ X_0$ endplates (incl readout)

Note the very low budget in the barrel region. Material budget can be respected by different technologies like **GEM, MicroMegas and Pixels**





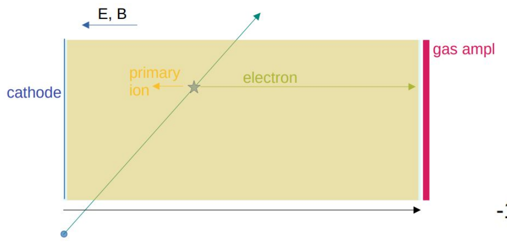
TPC operation and ion distortion

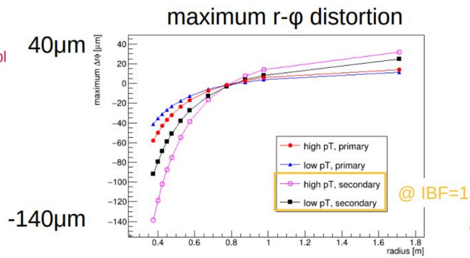
Large ionization at the Z peak produces a large ion density. As ions drift very slowly (O(m/s)) the TPC integrates a high ion space charge, which causes a transverse electric field, which in turn makes large distortions of the ionization electrons paths.

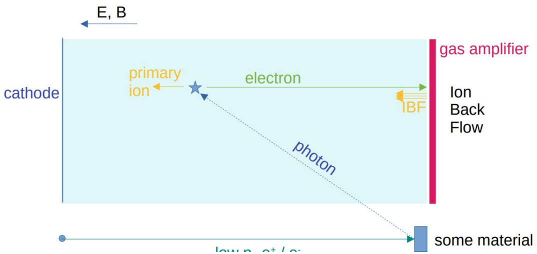
A distortions for the tracks at the Z pole, counting only the ionization from physics events is expected to be about 150 μm

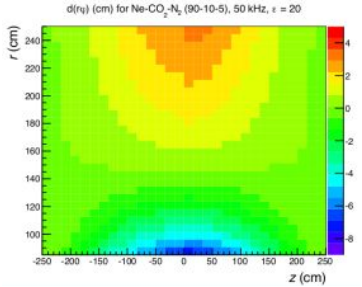
Beamstrahlung background produced ~200 times more ionization than hadronic Z decays and a distortion of 1-10 cm is estimated.

Correcting for this is necessary and is similar to what Alice attempts to do at the Pb-Pb run

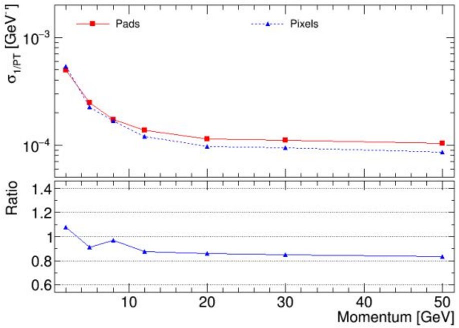


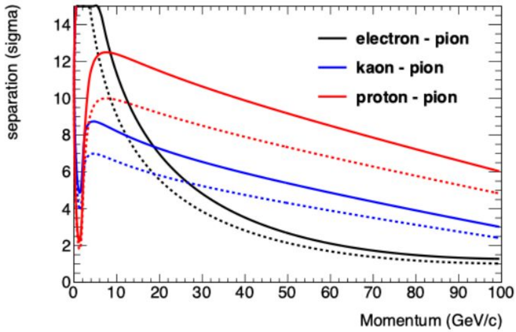






TPC momentum resolution and PID

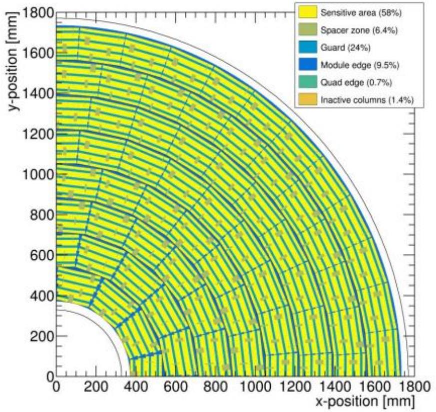




To study the performance of a large pixelized TPC, the pixel readout was implemented in the full ILD DD4HEP simulation with a coverage 59%.

The expected pion-kaon separation for momenta in the range of 2.5-45 GeV/c at $\cos\theta = 0$ is more than 5.5(4.5)σ

At a momentum of 100 GeV/c the separation is still 3.0(2.0)σ.



Conclusion

An overview on the ongoing activities for tracking system are presented.

The current prototypes performance are close to the FCC-ee requirement but R&D is mandatory to match this performance in the final detector. Collaboration between institutes and **DRDs** is a key element to develop the detectors for future lepton colliders and to enlarge the scientific community.

Silicon detector can achieve a few μm spatial resolution and tens ps time resolution if an amplification layer is used.

Bended silicon detectors can reduce significantly the material budget and provide full r-phi coverage.

Gaseous detectors, the best choice for a low material budget, need to face-off the stringent mechanical requirement on such a large area detector.

Beam induced background has to be take into account for the occupancy and its impact on dN/dx in drift chamber and straw tubes, for the ion distortion in the TPC.

Thank You!