FCC-ee Silicon Tracking Detector Overview

2025 European Edition of the International Workshop on the Circular Electron-Positron Collider
Barcelona, 16 June 2025

Attilio Andreazza - Università di Milano and INFN

For the FCC Physics Experiments and Detectors Working Group

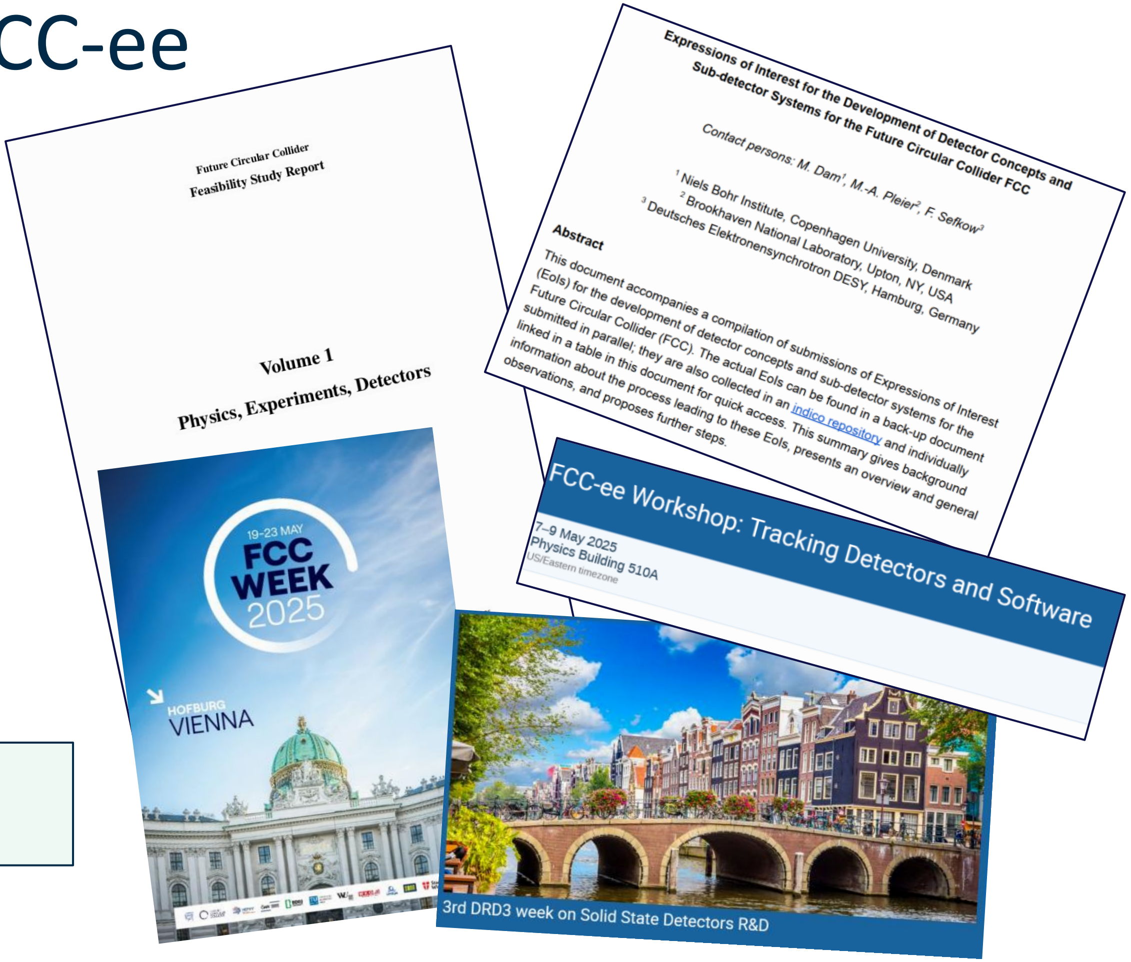
FUTURE CIRCULAR COLLIDER

INFN MILANO

UNIVERSITÀ DEGLI STUDI DI MILANO
DIPARTIMENTO DI FISICA

Outline

- Requirements for tracking at FCC-ee
- Silicon tracking in the FCC-ee Detector concepts
- Inner Vertex Detector layouts
- Challenges for outer trackers
- Conclusions and outlook

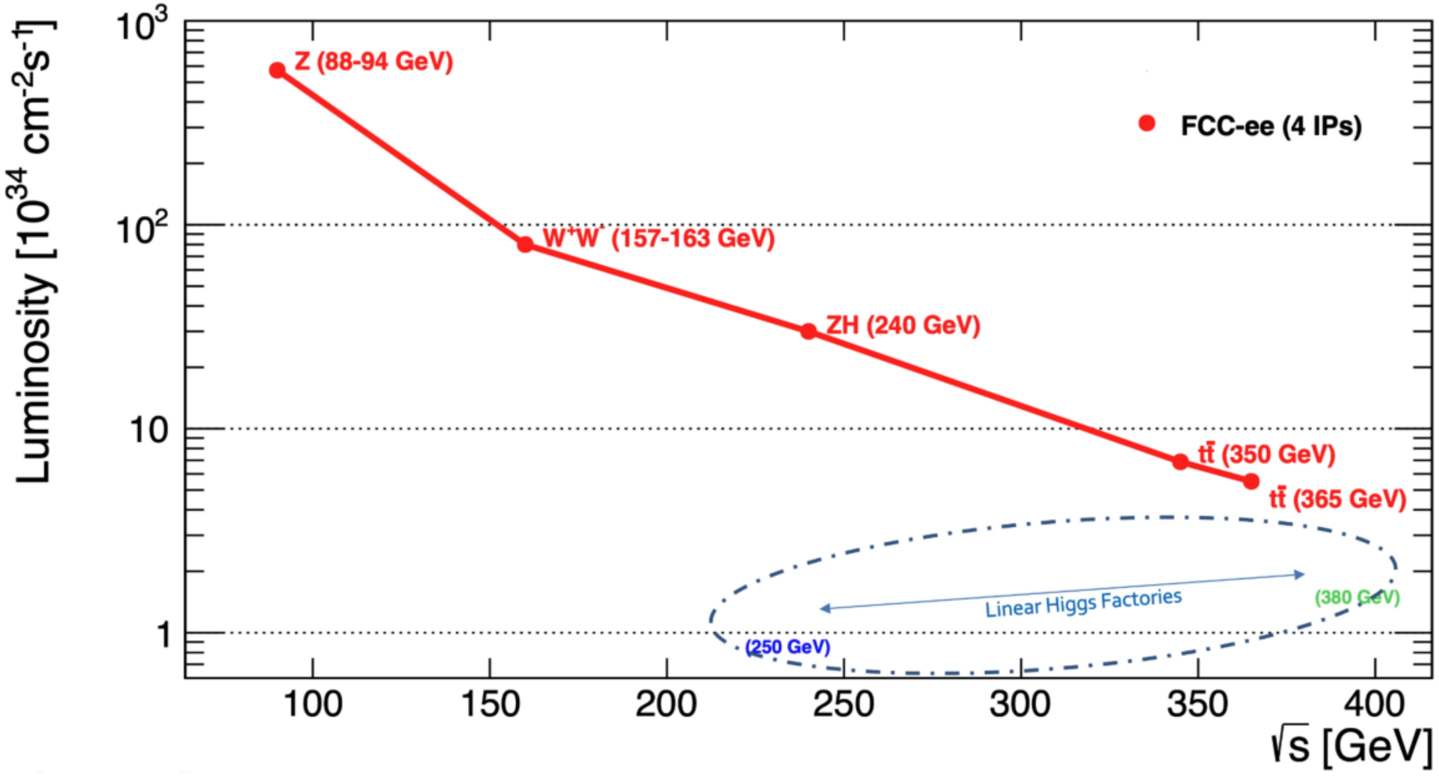


Disclaimer: cannot summarize in 20' all the ongoing R&D activities, apologies for the R&D lines underrepresented in this overview

- Material from FCC-ee Feasibility Study Report, FCC inputs to the European Strategy 2026 Update and recent FCC and DRD3 workshops

Physics requirement at Higgs Factories

- Rich physics program at future Higgs Factories
  - ZH, but also tera-Z, WW and $t\bar{t}$ threshold
- Physics performance *mostly* determined by the Higgs physics program
- Operating conditions (data rate, background) constrained mainly from the high-luminosity at the Z pole



- Impact parameter resolution

$$\sigma_d < 3\ \mu\text{m} \oplus \frac{15\ \mu\text{m}\cdot\text{GeV}}{p\sin^{3/2}\theta}$$

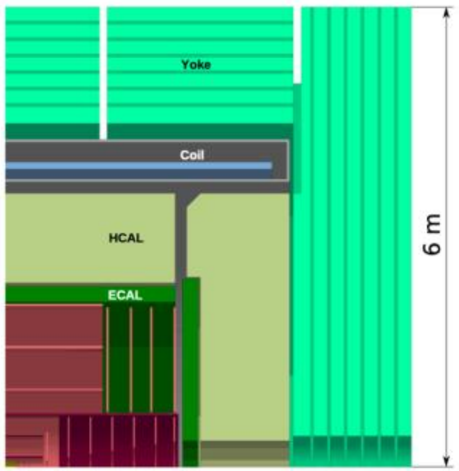
- Momentum resolution

$$\frac{\sigma_p}{p} < 2\cdot 10^{-5}\text{GeV}^{-1}p \oplus \frac{b}{\sin\theta}$$

- Hit rate near to the beam-pipe ~**200 MHz/cm²** (background dominated)
- Bunch spacing: **27 ns** at Z peak
- Z production rate ~**100 kHz**

Detector Concepts

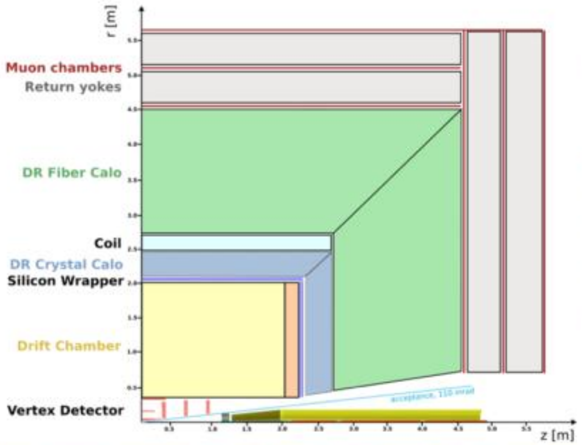
CLD



- Well established design
  - ILC → CLIC detector → CLD
- Full Si VXD + tracker
- CALICE-like calorimetry – very high granularity
- Coil outside calorimetry, muon system
- Possible detector optimizations
  - Improved σ_p/p, σ_E/E
  - PID: precise timing and RICH

arXiv:1911.12230

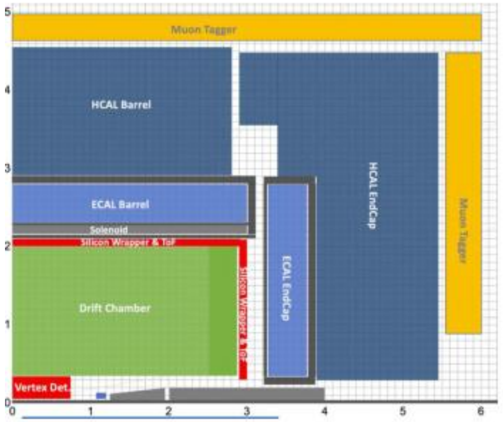
IDEA



- Design developed specifically for FCC-ee and CEPC
- Si VXD; ultra-light drift chamber with powerful PID
- Crystal ECAL w. dual readout
- Compact, light coil;
- Dual readout fibre calorimeter
- Muon system

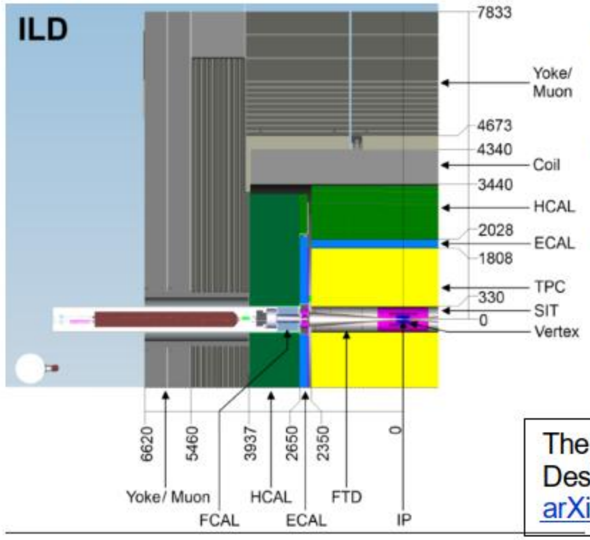
https://doi.org/10.48550/arXiv.2502.21223

Allegro



- Still in early design phase
- Design centred around High granularity **Noble Liquid ECAL**
  - Pb+LAr (or denser W+LKr)
- Si VXD
- Tracker: Drift chamber, straws, or Si
- Steel-scintillator HCAL
- Coil outside ECAL in same cryostat
- Muon system

Eur.Phys.J.Plus 136 (2021) 10, 1066, arXiv:2109.00391

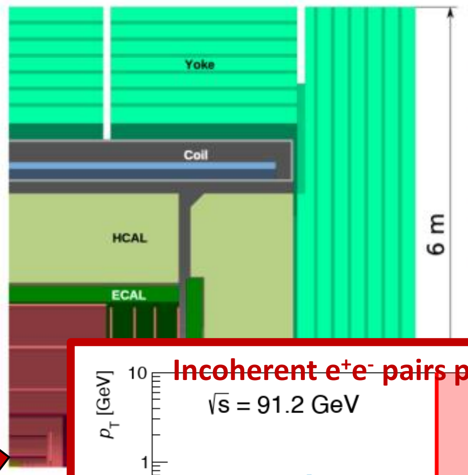


- Designed originally for operation at the ILC
- Together with SiD, ancestor of CLD.
- Main difference and signature element:
  - Large-volume time projection chamber (TPC)

The International Linear Collider Technical Design Report - Volume 4: Detectors
arXiv:1306.6329

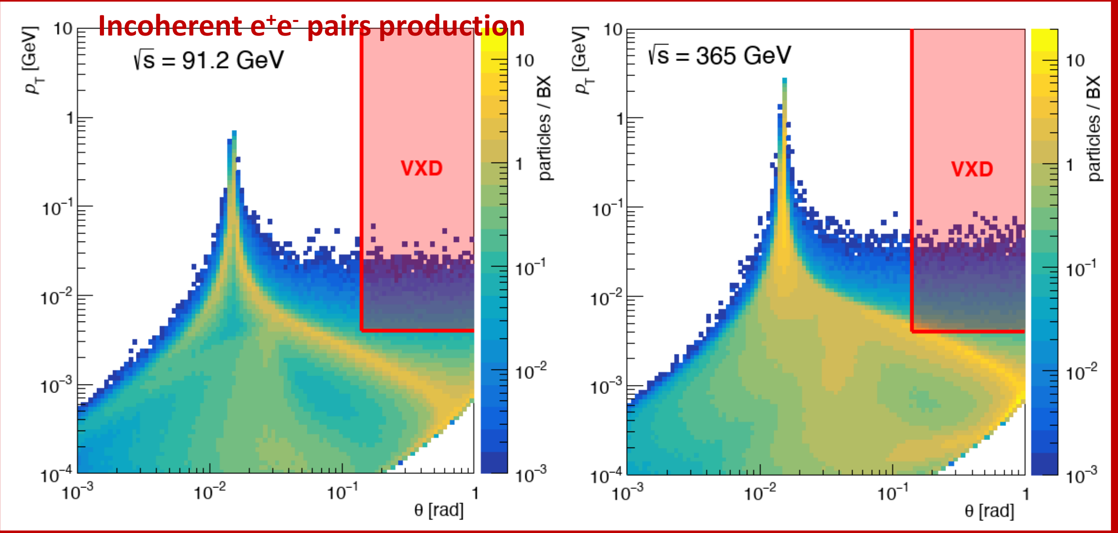
Detector Concepts

CLD



inner vertex region (R=1-6 cm)
- 3-5 μm resolution
- rate O(200 MHz/cm²)
- very low material <1% X_0

- granularity
- Coil outside calorimetry, muon system
- Possible detector optimizations
  - Improved σ_p/p, σ_E/E



AL

- Steel-scintillator HCAL
- Coil outside ECAL in same cryostat
- Muon system

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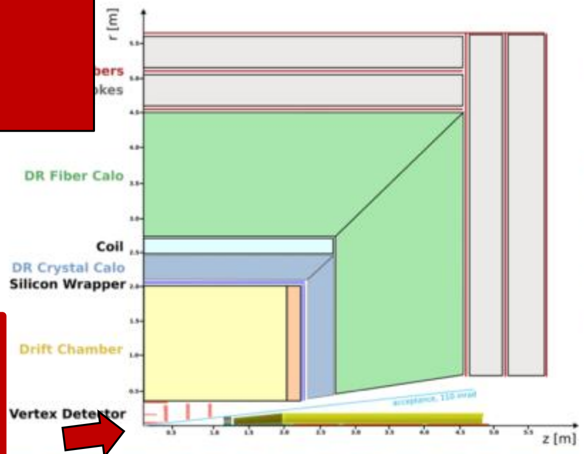

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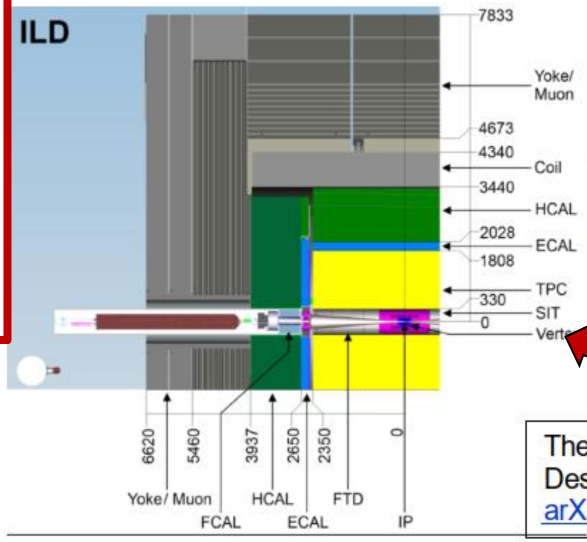
ILD



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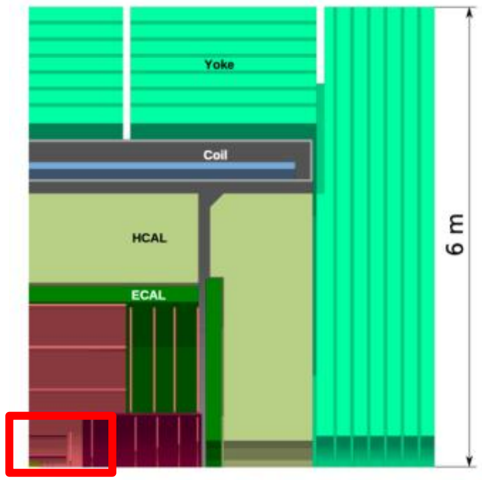
Detector Concepts

outer vertex detector (R=10-70 cm)
- ~7 μm resolution
- 27 ns timestamp
- material is still a concern

CLD



granularity
- Coil outside calorimetry, muon system
- Possible detector optimizations
  - Improved σ_p/p, σ_E/E
  - PID: precise timing and RICH

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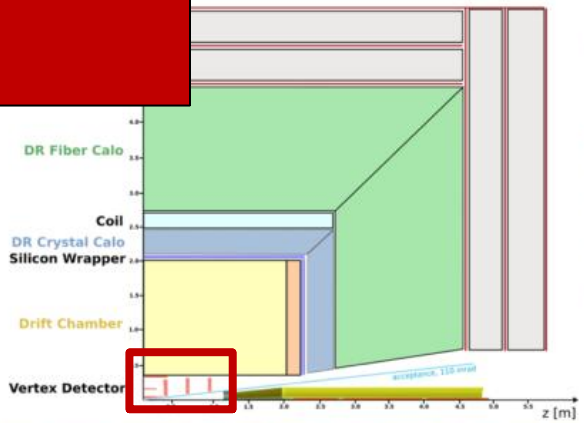
EA



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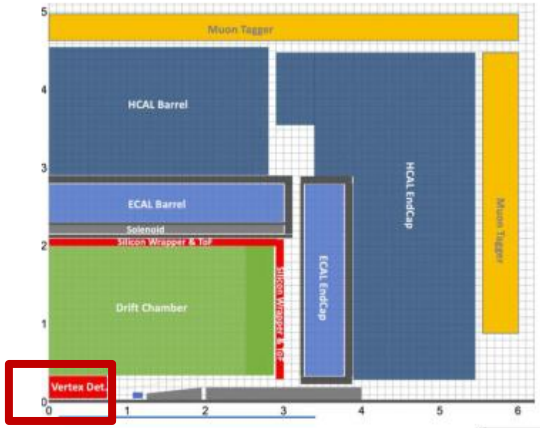

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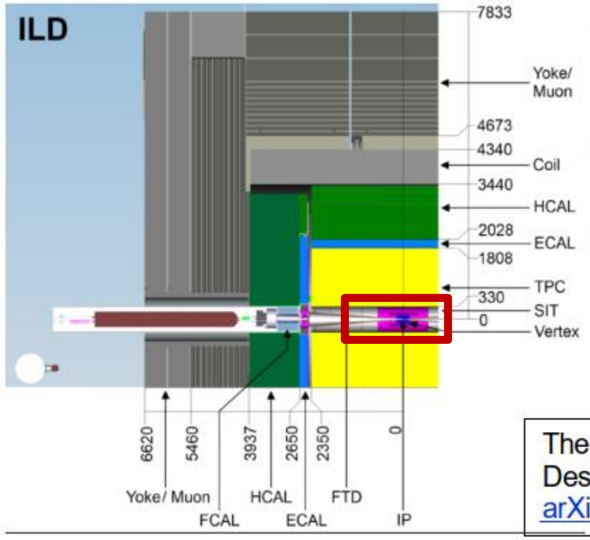

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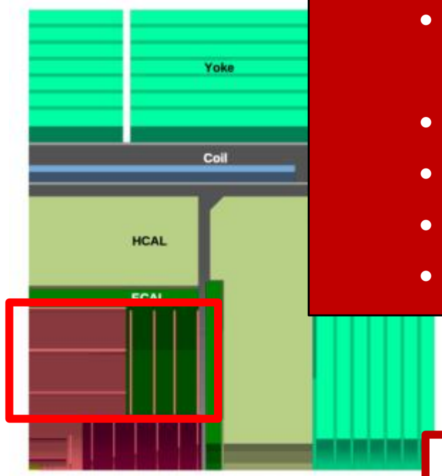
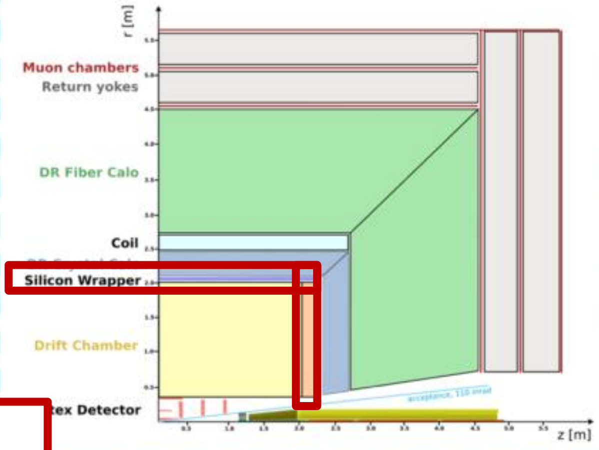


large area tracker (R,z up to 200 cm)

- full Si tracker or Si wrapper around gas chamber
- surface O(100 m^2)
- significant power consumption
- ~7 µm resolution
- 27 ns timestamp

- PID: precise timing and RICH

IDEA



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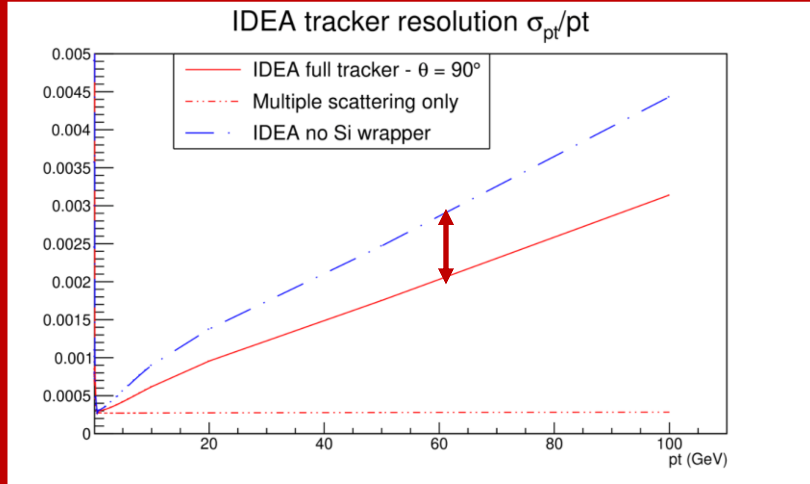

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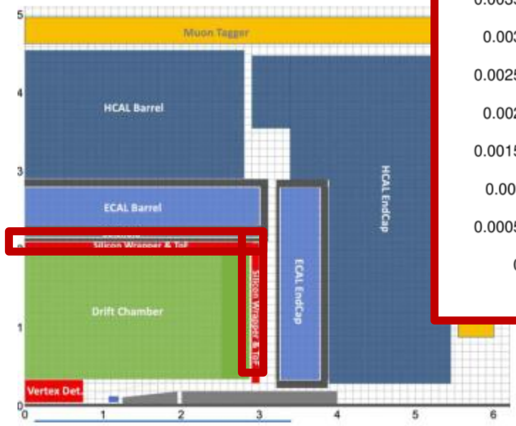

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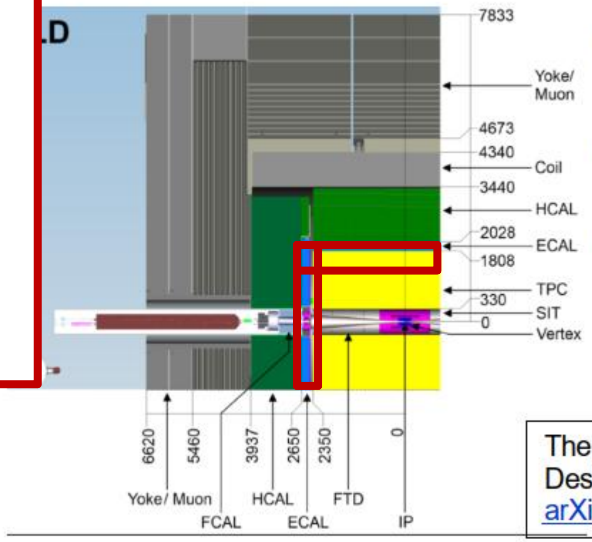

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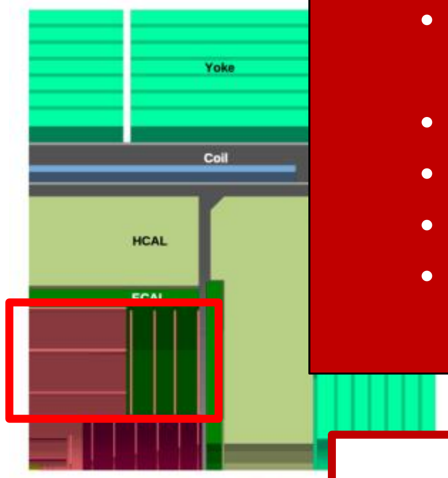
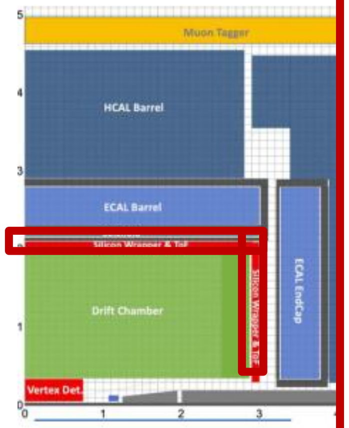


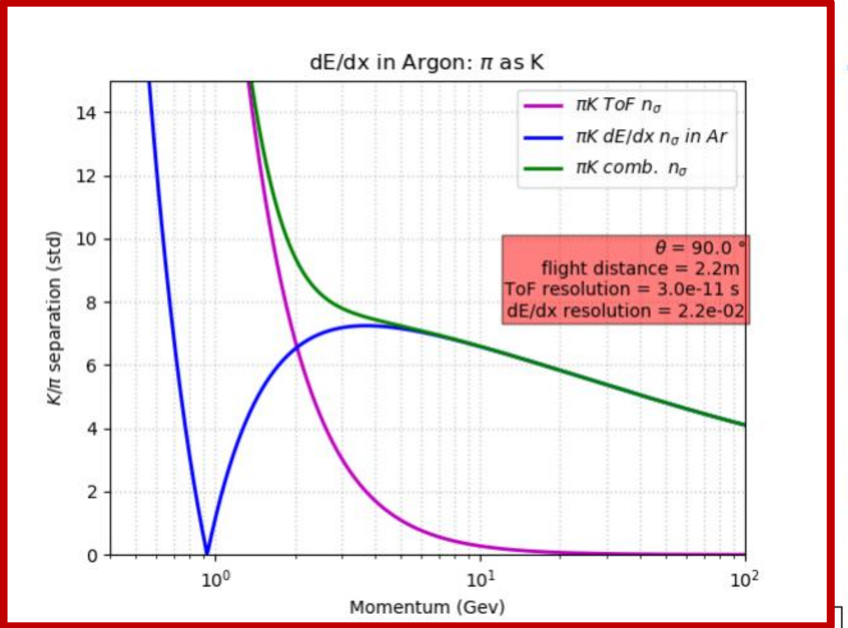
large area tracker (R,z up to 200 cm)

- full Si tracker or Si wrapper around gas chamber
- surface O(100 m^2)
- significant power consumption
- ~7 μm resolution
- 27 ns timestamp

  option for TOF measurement

Allegro





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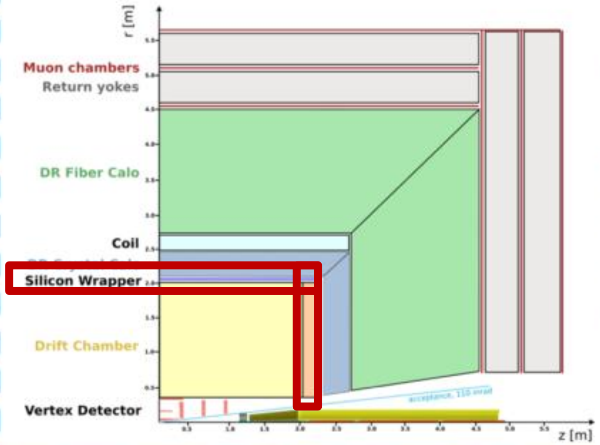

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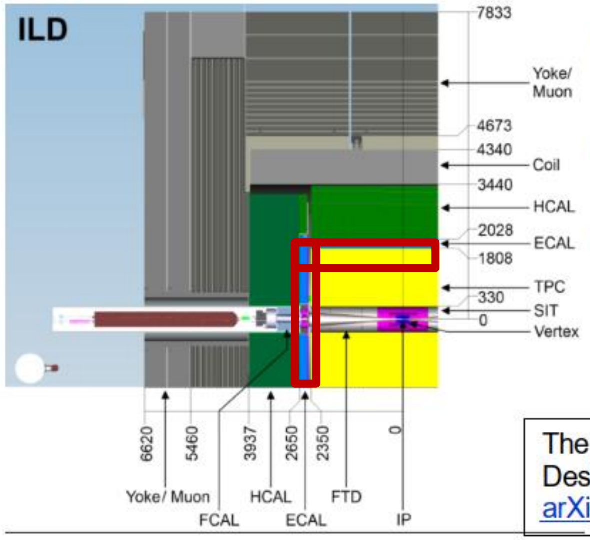

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Inner Vertex Detector EOI

Expression of Interest for a
lightweight vertex detector for FCC-ee

Involved Laboratories:
Italy: INFN - Genova, Frascati, Milano, Padova, Perugia, Pisa, Torino, Trieste-Udine
Switzerland: ETH Zurich, Paul Scherrer Institute, University of Zurich
United States of America: Brown University, BNL, FNAL, LBNL, MIT, SLAC, Stony Brook University

Expression Of Interest for a Vertex Detector at FCCee :
FCC Snail-shape vErtEx Detector (FCC-SEED)

[1]Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
[2]CNRS/IN2P3, CPPM, Aix-Marseille University, Marseille, France
[3]Institut de Physique des 2 Infinis de Lyon - CNRS/IN2P3, 69100 Villeurbanne, France
[4]Laboratoire de Physique Nucléaire et de Hautes Énergies UMR 7585, France
[5]laboratoire AstroParticule et Cosmologie, France

- Depleted Monolithic Active Pixel Sensors (DMAPS)
- Very thin sensors: curved geometries
- Low power architectures: air cooling
- Integration with machine is a key aspect

Expression of Interest for

FCC-ee Machine-Detector-Interface (MDI) Integration

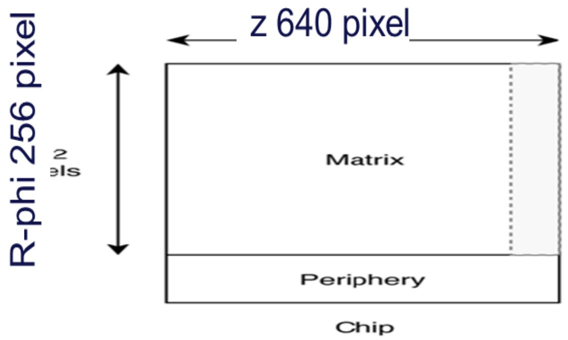
Involved Laboratories

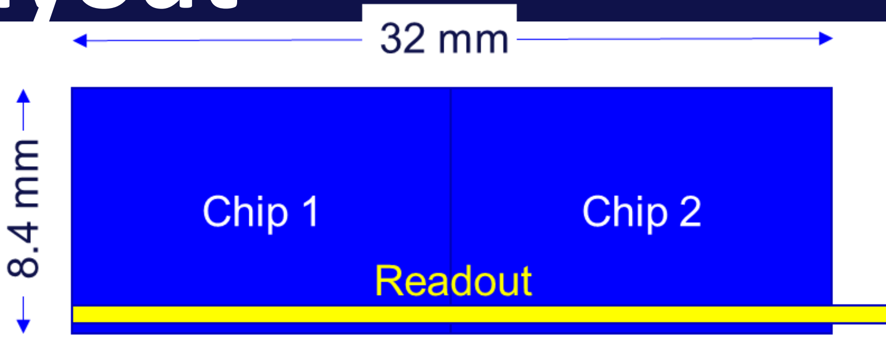
Italy: INFN Laboratori Nazionali di Frascati, Pisa

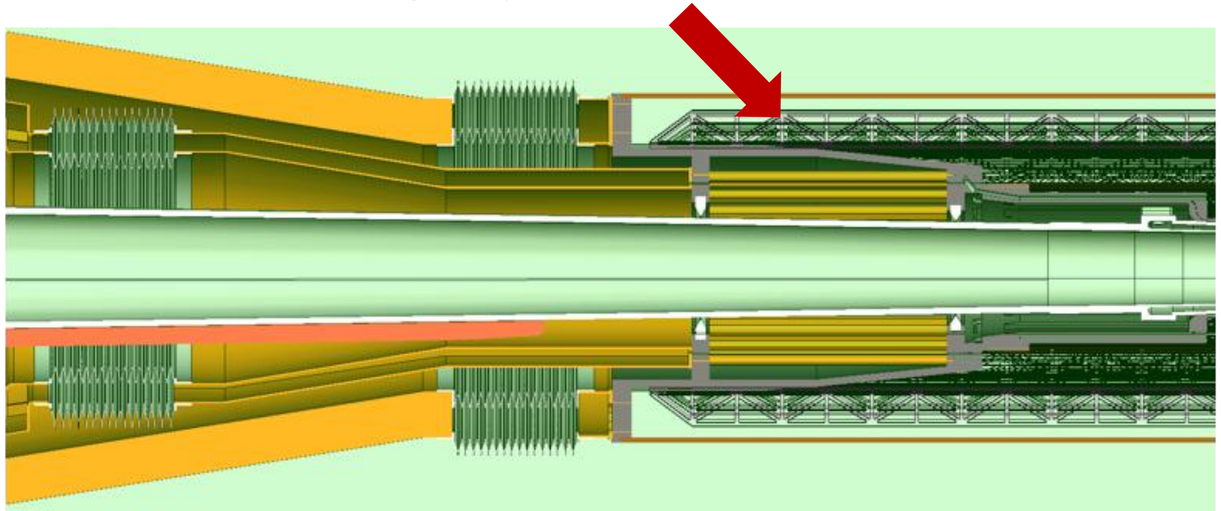
United States of America: BNL, FNAL, JLAB, SLAC

IDEA vertex layout

- Module based on LF110 nm DMAPS
  - 25x25 μm^2 (ARCADIA MD3 layout)
- 3 barrel layers
  - 13.7, 23.7, 34/35.6 mm radii
- Sensor loaded on thin carbon-carbon support and flex PCB for powering and readout
  - Alice/Belle2 like stave approach
- Light truss structure to provide mechanical rigidity to the stave



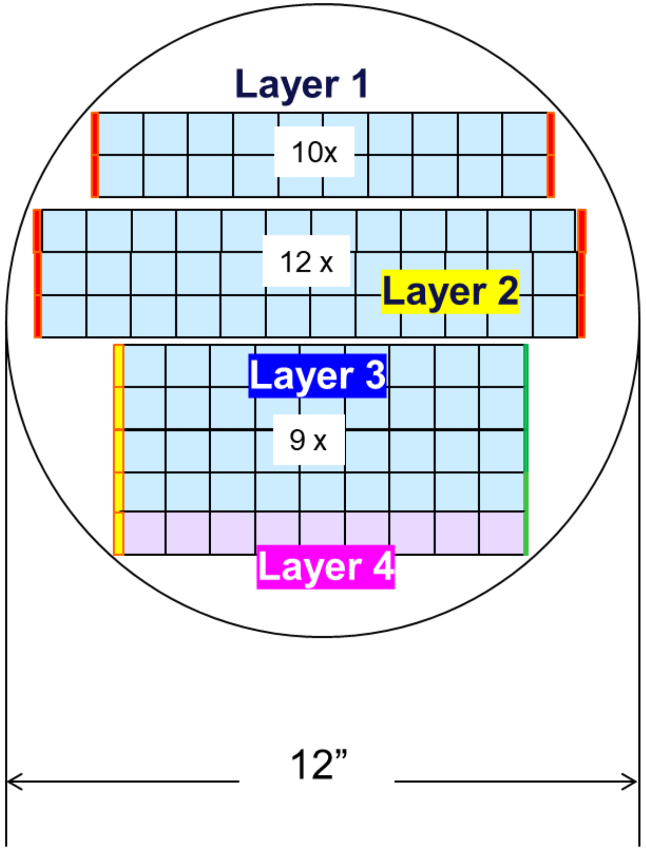


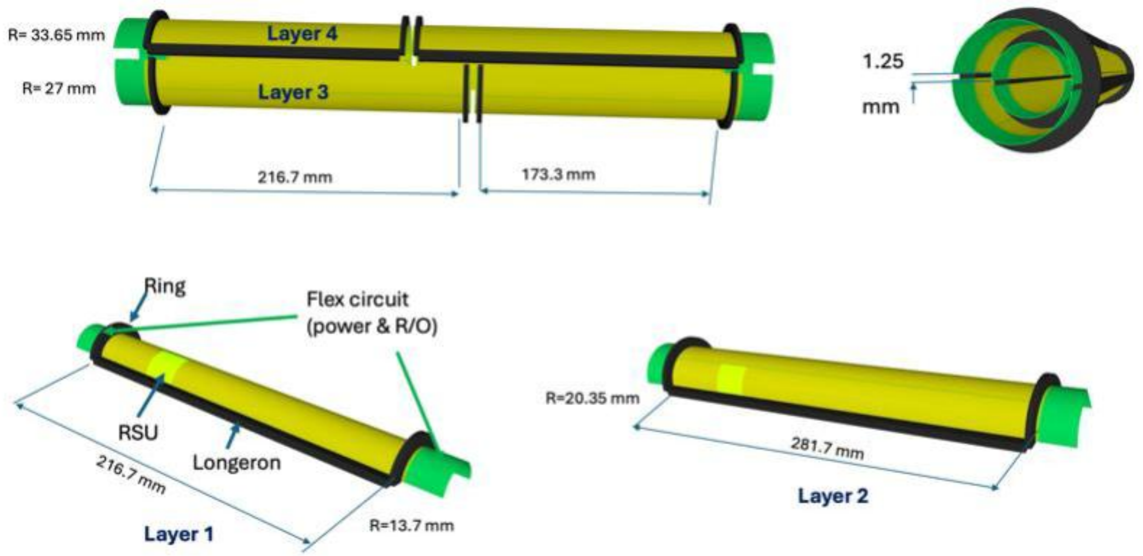


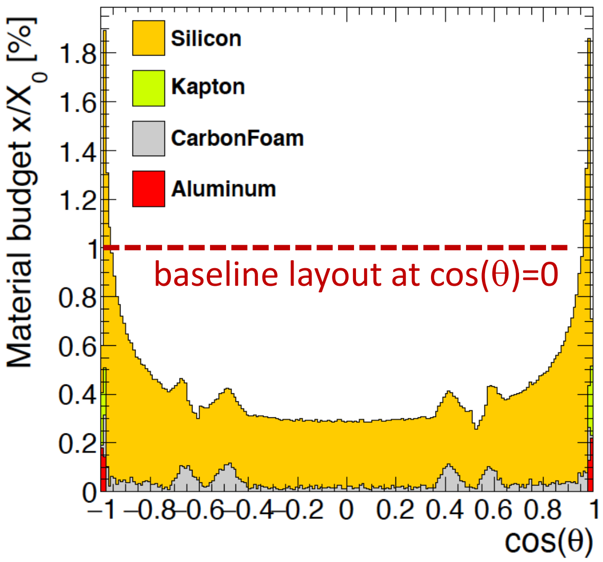
- Total detector weight 285 g
- 0.25% X_0 thickness per layer
  - Chips ~0.05% X_0, readout and power bus ~0.06% X_0
- Total power consumption 121 W
- **Air cooling is possible**
- Mockup construction and testing of the concept ongoing (LNF, Pisa, Perugia)

Curved vertex layout (stitched sensors)

- Curved layout inspired by ALICE ITS3 developments
  - adapted to the FCCee interaction region geometry and tracking coverage
  - DMAPS in TPSCo 65 nm technology
  - 20.5x21.7 mm^2 stitched pixel-matrix cell (MOSAIX-like)
  - 4 layers
  - Highest radii layers split in two sections due to wafer size and staggered to recover hermeticity
  - drastic improvement in material budget



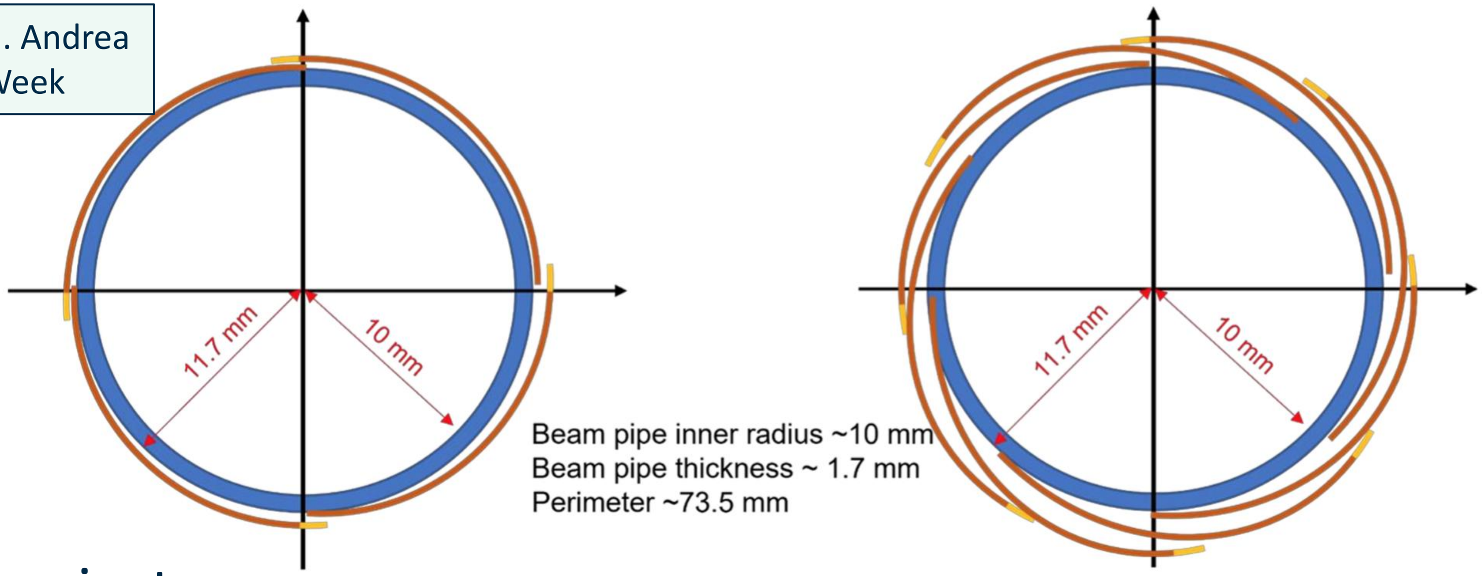




Snail-shaped vErtEx Detector (SEED)

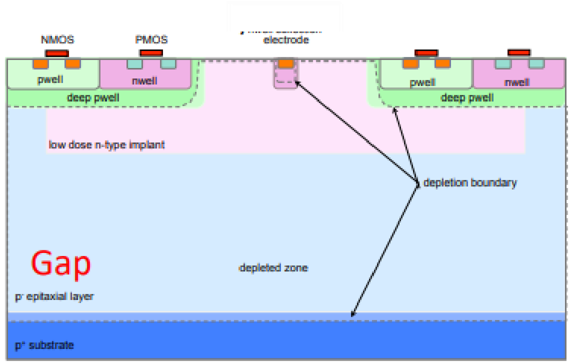
- Low material and fully hermetic layout
- Flexible in sensor size and detector layout

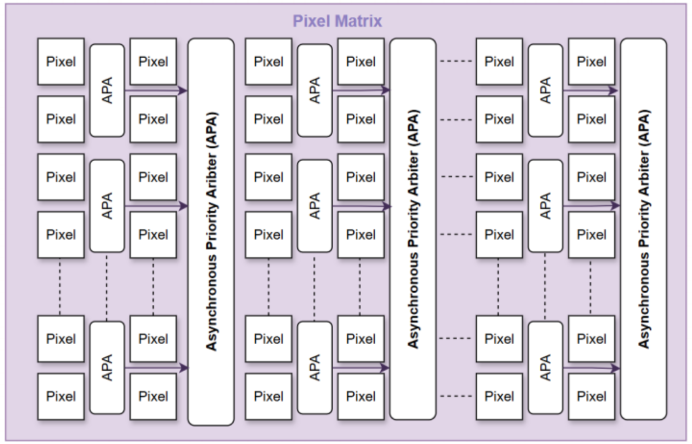
A.G. Besson and J. Andrea
8th FCC Physics Week



- Sensor developed within the DRD3 project:
  OCTOPUS: **O**ptimized **C**MOS **T**echnology f**O**r **P**recision in **U**ltra-thin **S**ilicon
  - TPSCo 65 nm technology
  - 3 μm resolution → 20 μm pixel pitch
  - fully asynchronous readout in the pixel matrix to reduce powe consumption
  - 50 μm silicon material

F. Guezzi
3rd DRD3 week





Silicon Tracking EOI

Expression of Interest for the development of modules for Vertex detector and Silicon Wrapper with combined tracking and timing capability in LFoundry 110nm technology

Involved Laboratories:
Italy: INFN - Bologna, Milano, Padova, Pavia, Perugia, Pisa, Torino, TIFPA
United States: FNAL

Monolithic Active Strip Sensors

Bonn University, DESY, FH Dortmund,
TU Dortmund, Siegen University, Freiburg University

Expression of Interest
Towards Time of Flight MCMOS tracking layers for a detector at FCC-ee

[1]CEA-Saclay, IRFU/DPhP, Université Paris-Saclay, 91191 Gif sur Yvette cedex, France
[2]CEA-Saclay, IRFU/Dedip, Université Paris-Saclay, 91191 Gif sur Yvette cedex, France
[3]Institut de Physique des 2 Infinis de Lyon - CNRS/IN2P3, 69100 Villeurbanne, France

Expression of Interest for a large-area tracking and timing layer for an FCC-ee detector

Involved Laboratories:
Italy: INFN
Switzerland: CERN, Paul Scherrer Institute, University of Zurich
U.S.A.: Brandeis University Waltham, Brookhaven National Laboratory, SLAC National Accelerator Laboratory, University of California Santa Cruz, University of New Mexico

Expression of Interest in Development of Large Area Tracking Systems for FCC-ee Detectors

Santa Cruz Institute for Particle Physics
University of California, Santa Cruz

Particle beam telescope with versatile DMAPS chip
FCCee vertex detector demonstrator system

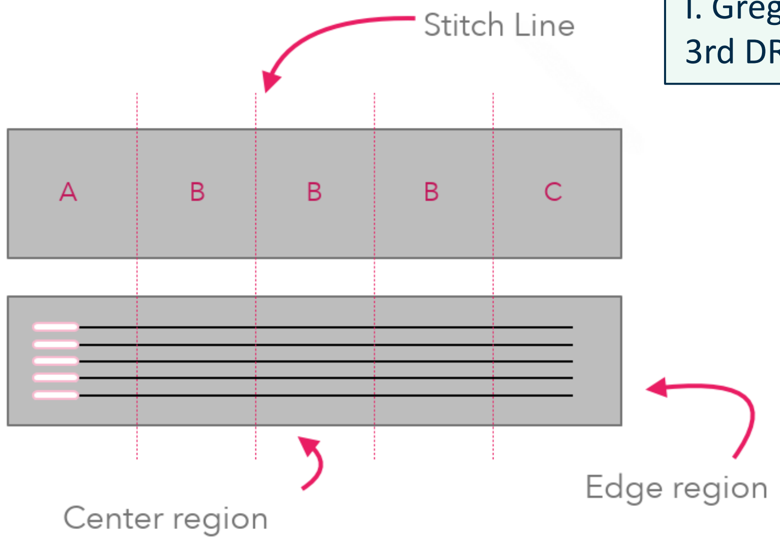
[1]Instituto Tecnologico de Aragon (ITA)
[2]Instituto Galego Fisica Altas Enerxias (IGFAE)
[3]Instituto de Fisica Corpuscular (IFIC, CSIC-UVEG)
[4]Instituto de Fisica de Cantabria (IFCA, CSIC-UC)

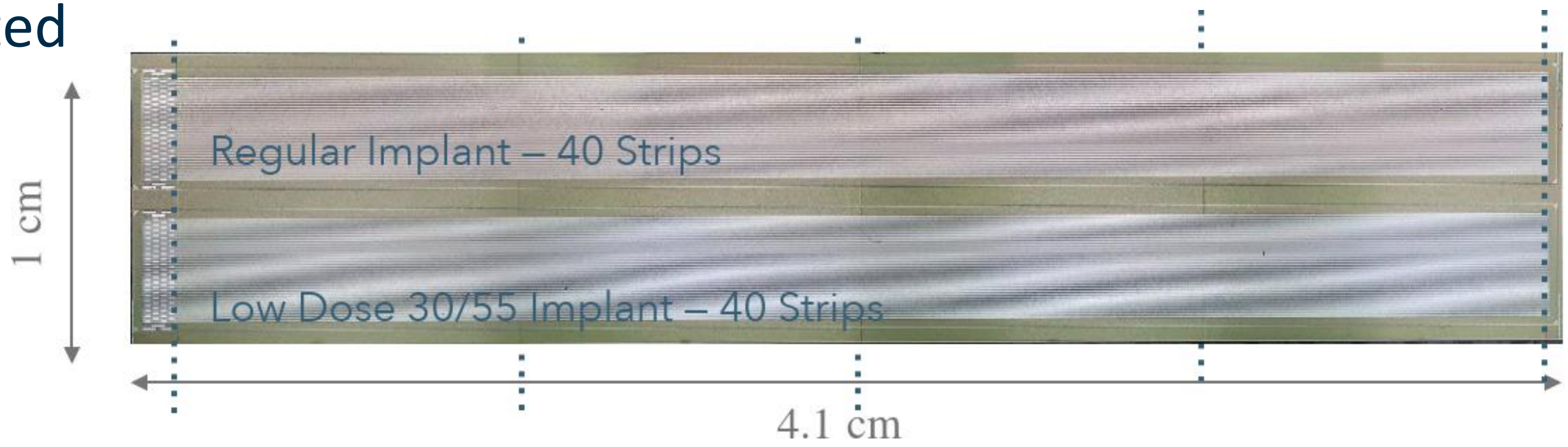
- Emphasis on timing capabilities
- Pushing towards integrated solutions whenever possible
- Also looking at new technologies and system aspects

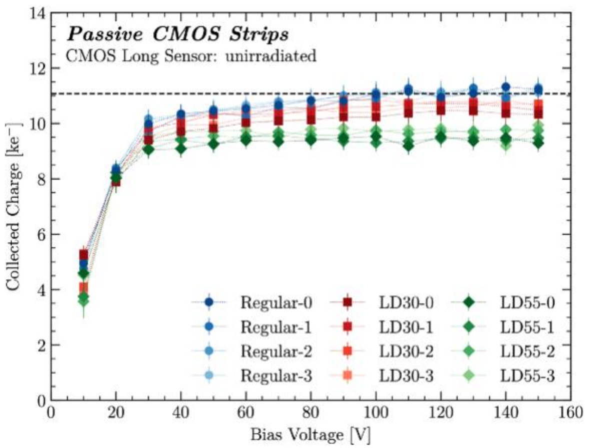
Monolithic Strip Detectors

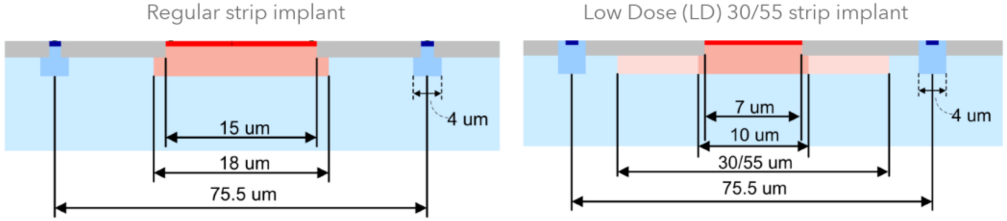
I. Gregor
3rd DRD3 week

- n-in-p sensor **150 nm LFoundry** technology
- 150 μm thickness, 75.5 μm strip pitch
- Different formats through **stitching** technique
- Develop an alternative technology strip detector fabrication for large area applications
- To fully profit from the use of a CMOS process the **front-end** should be implemented
  - Ease of module building
  - Reduction of material



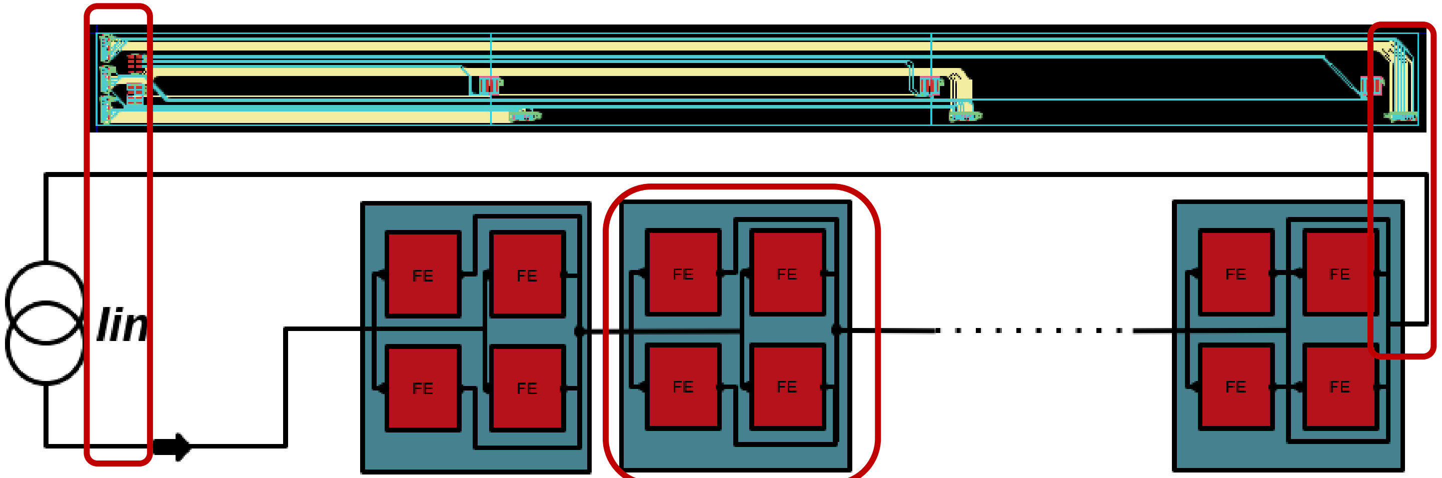


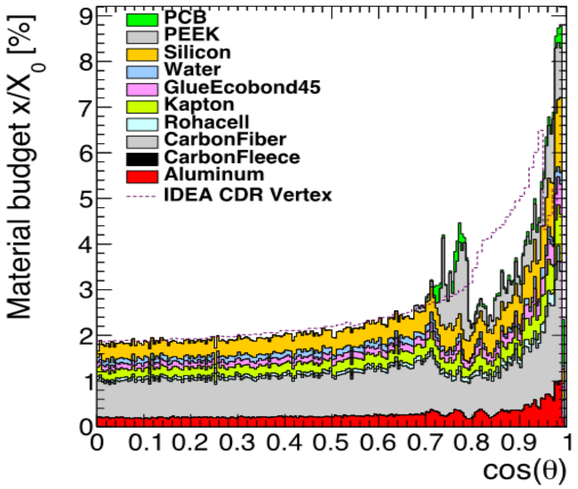


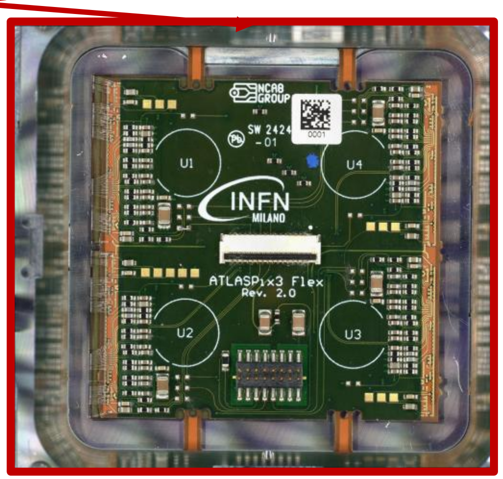


DMAPS Integration

- Prototyping with ATLASPIX3.1 sensors
  - TSI 180 nm CMOS process
  - Almost full-reticle size 2 × 2 cm^2
  - 150 mW/cm^2
- Multi-chip modules
  - Single LV and HV bias line
  - Common data-in LVDS lines: command, clock, synch, trigger
  - Individual modules data-out LVDS lines
  - AC coupling to DAQ
- On chip SLDO regulator: building a serial powering chain
- Experimenting with Al power and data bus to reduce X_0 thickness within the detector



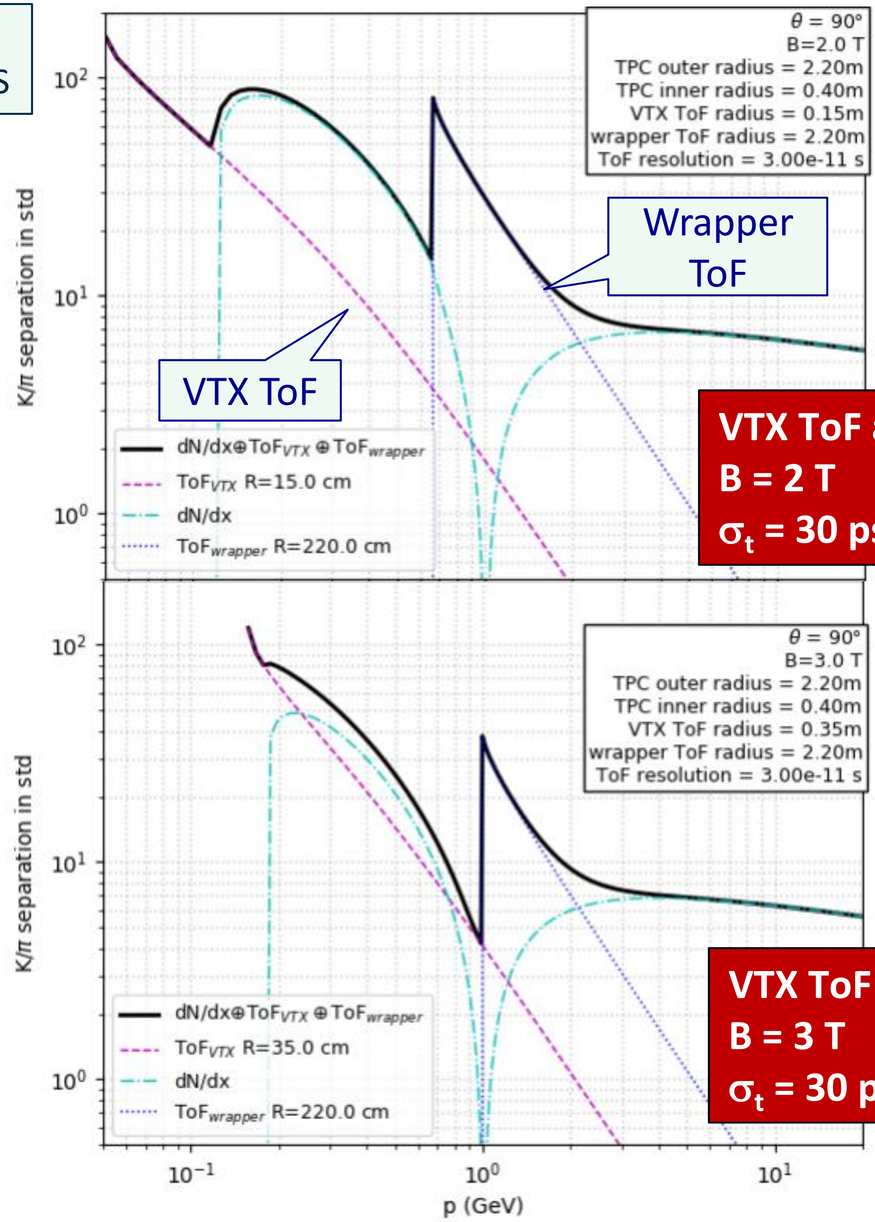




Timing Measurement

- dE/dx or dN/dx confusion region at 1 GeV
  - timing measurements at 30 ps level in the wrapper can solve the ambiguity
- Improve π/K separation at low momentum
  - light flavour tagging in $H \to q\bar{q}$
  - Flavour physics
- Low pT particles not reaching the central gas tracker
  - timing in the outer vertex layers
  - it can extend coverage to momenta below 100 MeV
  - particularly relevant if magnetic field increased to 3 T

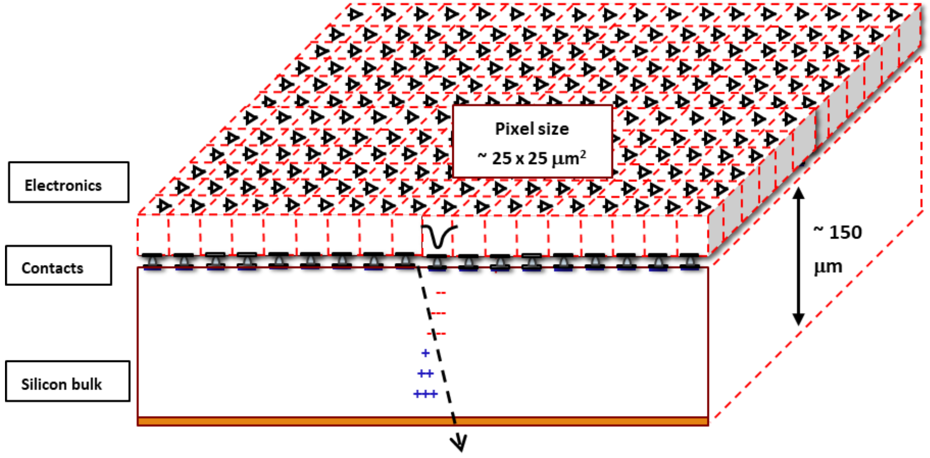
P. Schwemling
FCC-ee Tracking WS



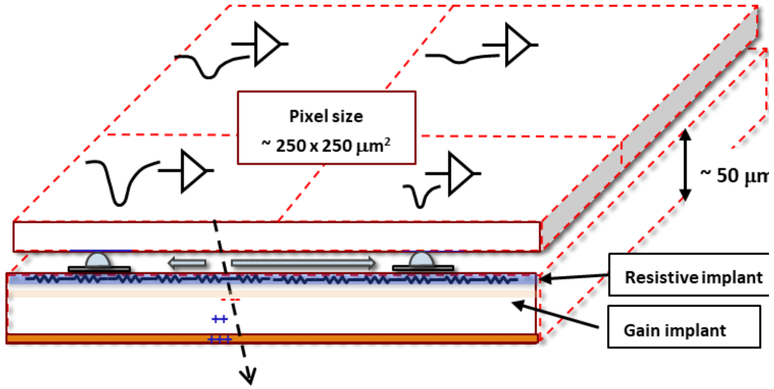
VTX ToF at 15 cm
B = 2 T
σ_t = 30 ps

VTX ToF at 35 cm
B = 3 T
σ_t = 30 ps

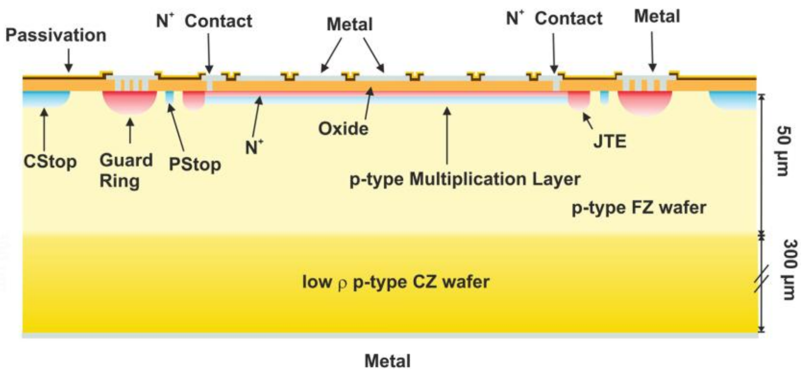
AC-LGADs for Tracking and Timing



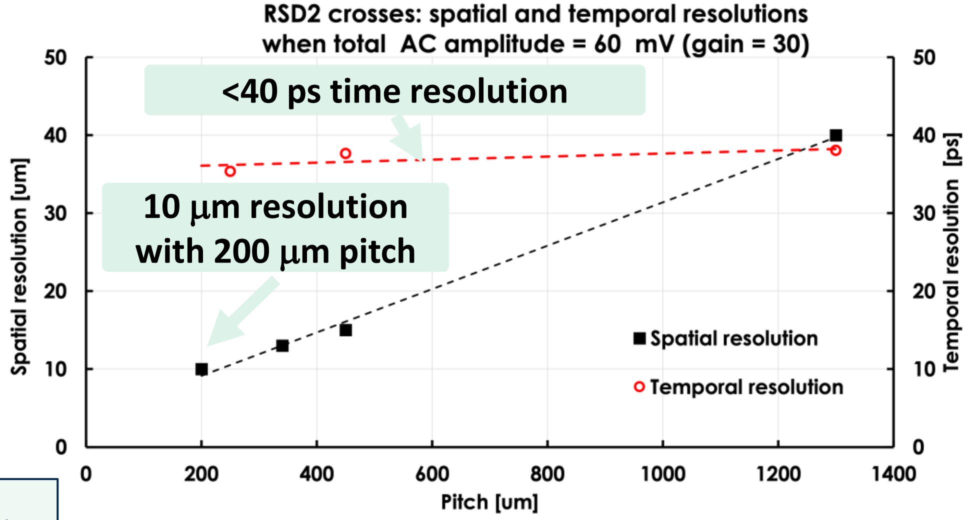
Standard Silicon Detector



Resistive Read-out Detector

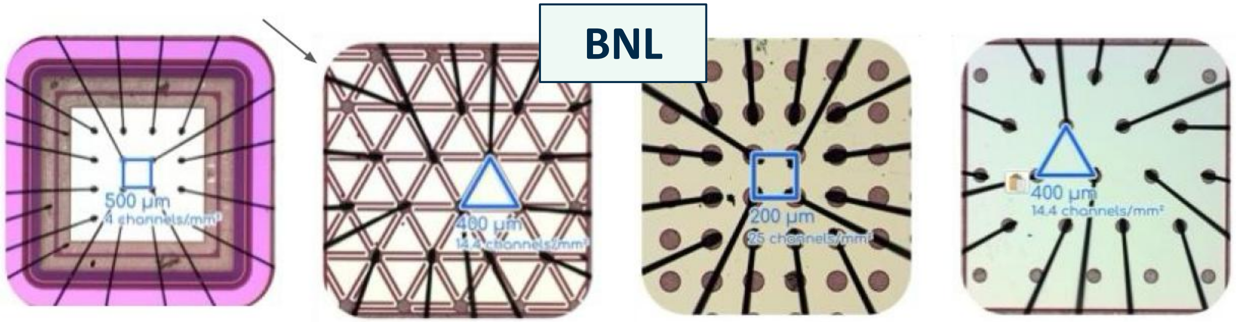


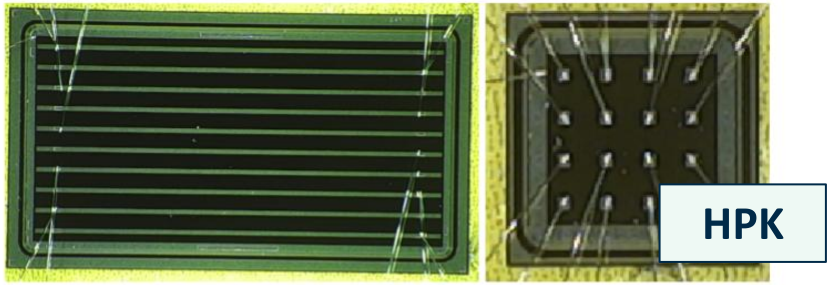
- Standard pixel detectors
  - **space resolution**: 30% pitch (binary), 15% pitch (charge interpolation)
- Resistive silicon detectors:
  - **space resolution**: ~5% of the pitch (deterministic charge sharing)
  - **time resolution**: 40 ps for 50 μm thin sensors



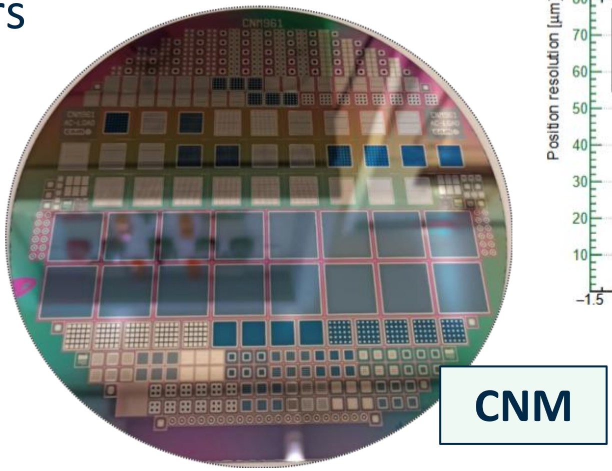
N. Cartiglia et al.
arXiv:2301.02968

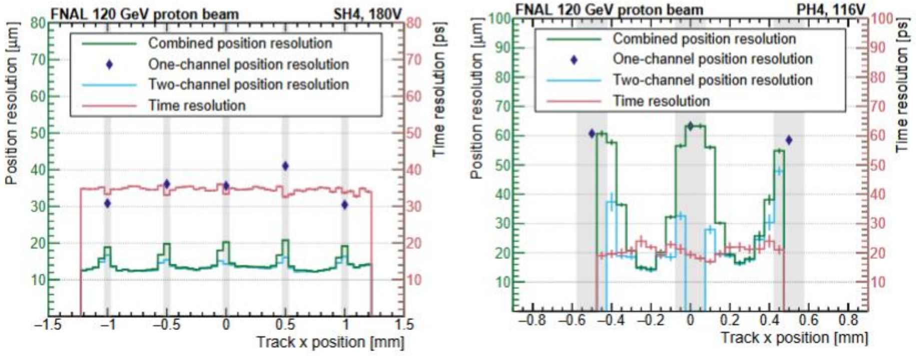
AC-LGADs for Tracking and Timing





- Many manufacturers and multiple flavours
  - strip, square pixels, triangular pixels
- Very high flexibility in detector design
  - developments for **ePIC TOF** systems
- Also DC-coupled electrodes
- Very active community in DRD3

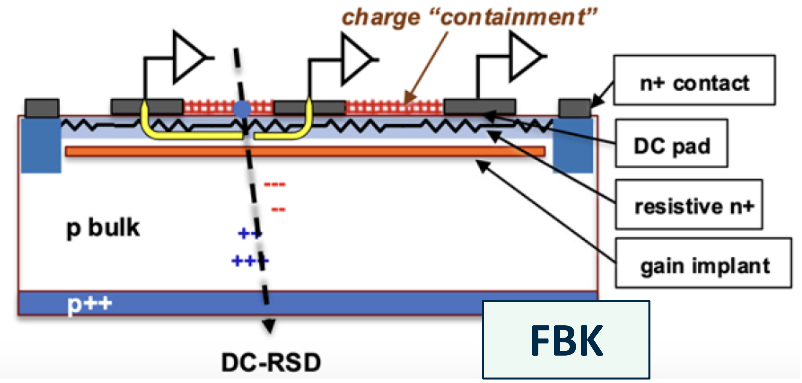




Expression of Interest for a large-area tracking and timing layer for an FCC-ee detector

Involved Laboratories:
Italy: INFN
Switzerland: CERN, Paul Scherrer Institute, University of Zurich
U.S.A.: Brandeis University Waltham, Brookhaven National Laboratory, SLAC National Accelerator Laboratory, University of California Santa Cruz, University of New Mexico

WG2 session at
3rd DRD3 week

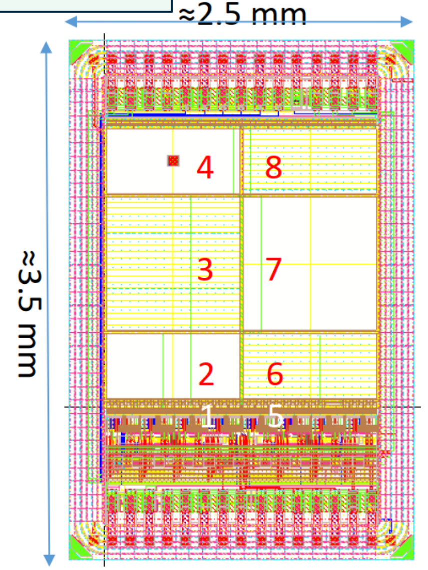


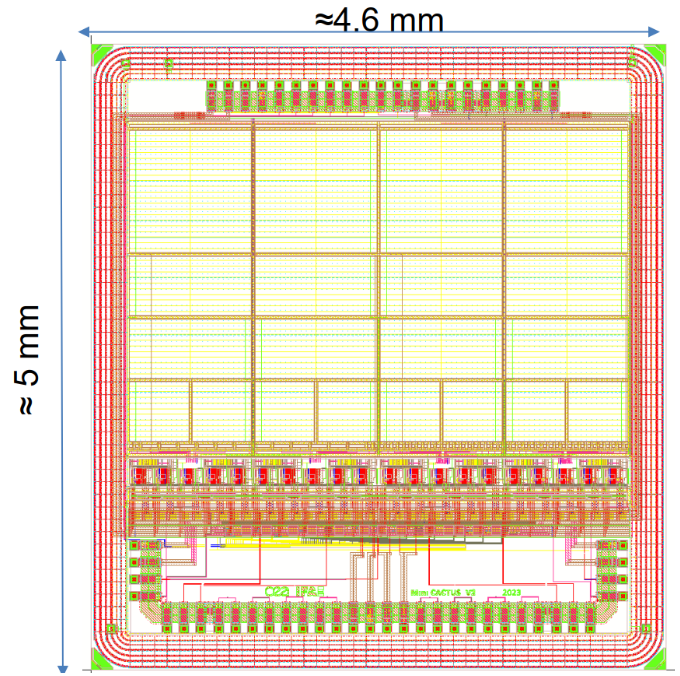
DC-RSD design:

- **Signal confined** through **containment structures** and **low resistivity paths** towards a predetermined number of readout electrode
- Leakage current removed locally through each electrodes
- **No-bipolar signal:** of 1-2 ns of duration in time as in standard LGADs

Monolithic CMOS Sensors for Timing

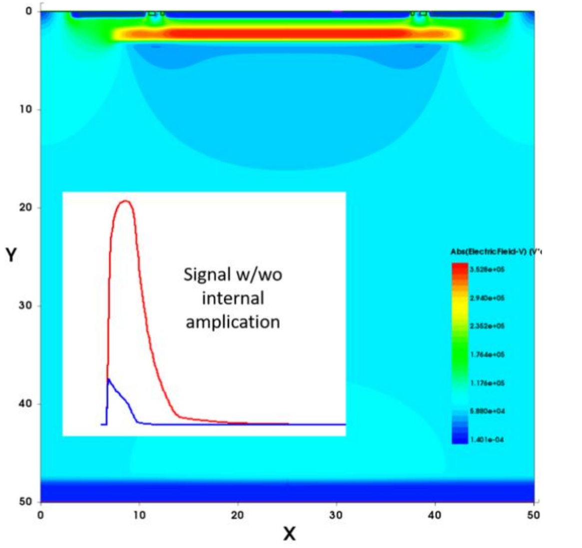
P. Schwemling
FCC-ee Tracking WS





CACTUS Chip Family

- LFoundry 150 nm node
- 60 ps reached **without internal amplification**
- Now testing the addition of a gain layer

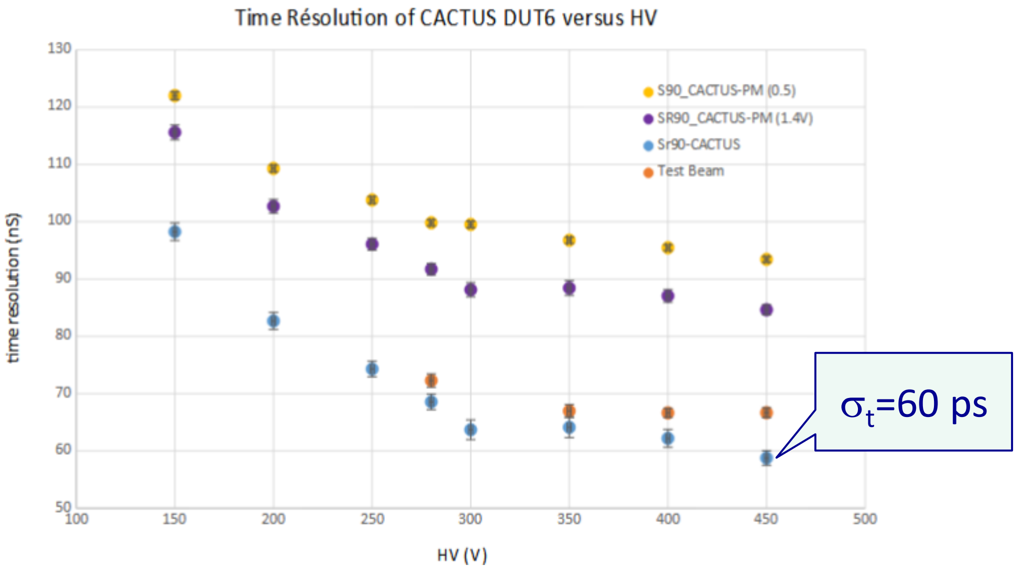


MiniCACTUS_v1

- small detector prototype designed in order to explore the possibilities of timing with non amplified large electrode designs
- FE integrated at column level

MiniCACTUS_v2

- ~ 2 times larger than MiniCACTUS
- 0.5 mm x 1 mm (baseline), 1 mm x 1 mm and 0.5 mm x 0.5 mm diodes
- 3 different preamps
- New multistage discriminator with programmable hysteresis



Monolithic CMOS Sensors for Timing

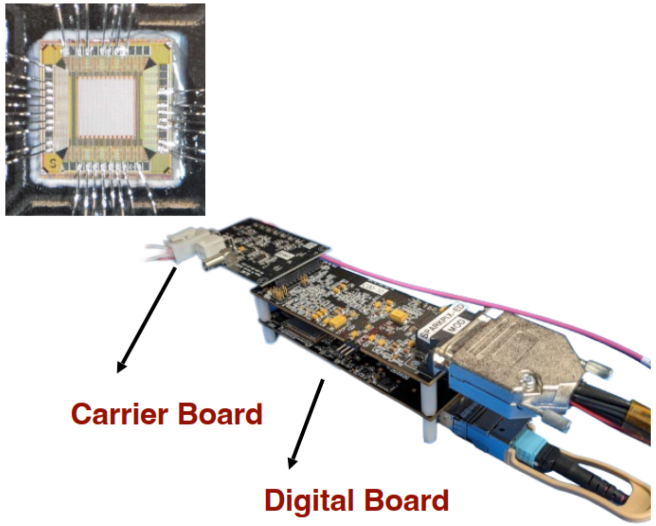
NAPA: **NA**nosecond **P**ixels for Large **A**rea sensors

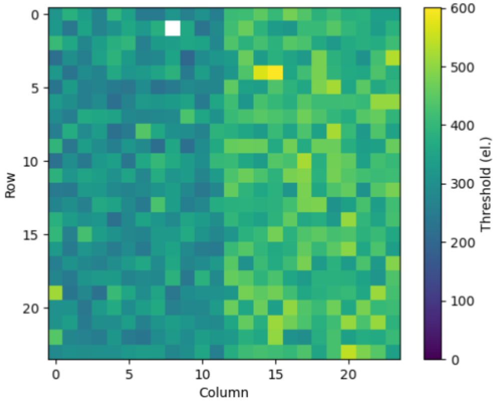
- TPSCo 65 nm node

NAPA_p1 performance

	Specification	Simulated NAPA-p1
Time resolution	1 ns-rms	0.4 ns-rms ✓
Spatial Resolution	7 μm	7 μm ✓
Noise	< 30 e-rms	13 e-rms ✓
Minimum Threshold	200 e-	~ 80 e- ✓
Average Power density	< 20 mW/cm^2	0.1 mW/cm^2 for 1% duty cucle ✓

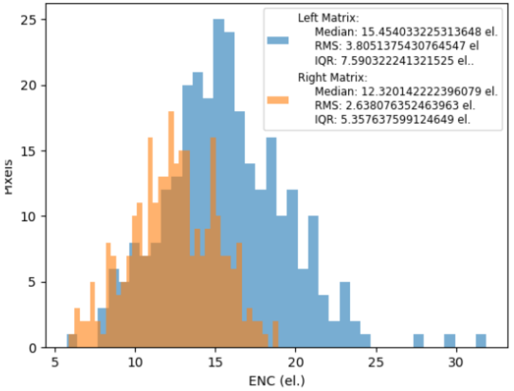
C. Vernieri
FCC-ee Tracking WS





Left Matrix: Nominal Pixel Variant

Right Matrix: Pixel Variant with DC leakage current compensation



DC leakage current variant has less nosie

NAPA_p2

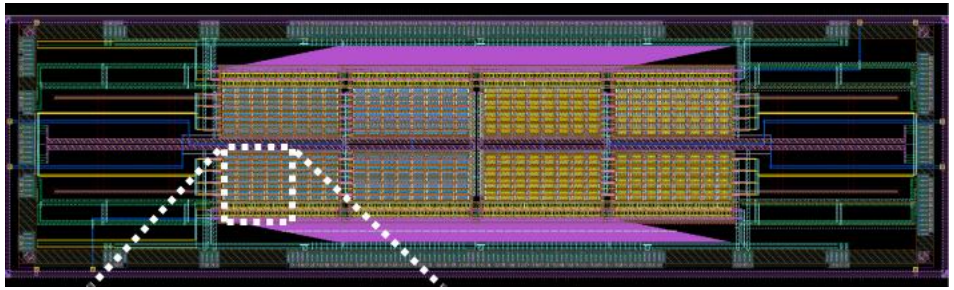
- Further improve timing resolution & power trade-off: goal is to achieve x10 improvement over current state-of-the-art
- Design of compact, low-power Time-to-Digital Converter (TDC).
- The chip contains a novel low-power and small-area Vernier delay line, which is the core building block of a sub-ns TDC, with a programmable time resolution as low as 20 ps.

Monolithic CMOS Sensors for Timing

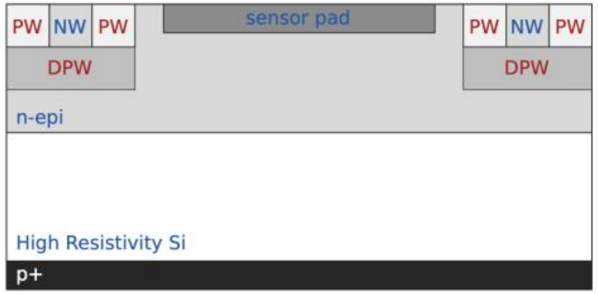
M. Mandurrino
FCC-ee Tracking WS

MADPIX: **M**onolithic CMOS **A**valanche **D**etector **PIX**elated Prototype for ps Timing Applications

- LF 110 nm node
- 8 matrices of 64 pixels
- 250 × 100 µm2 pads
- 0.18 mW/ch

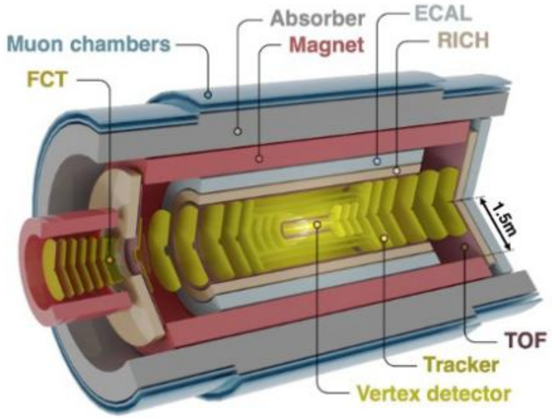


fully-depleted MAPS

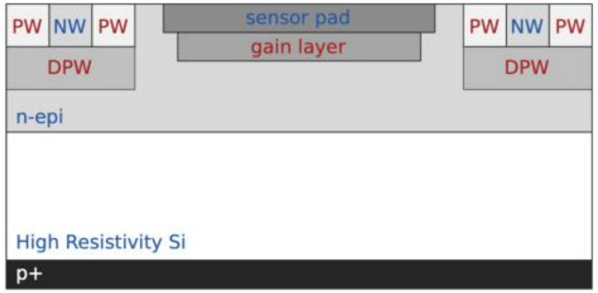


ALICE3 TOF detector:

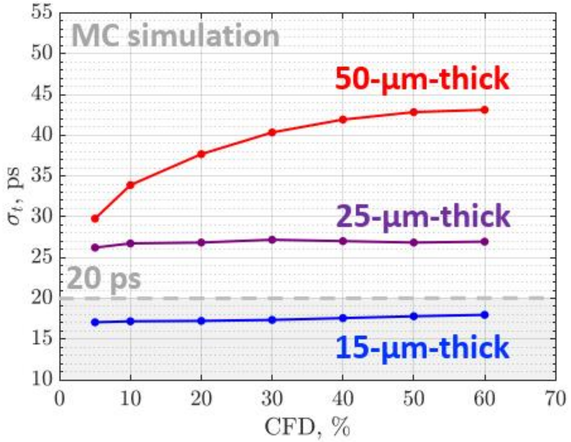
- high-resolution **tracking**
- **particle ID** at low $p_T \Rightarrow \sigma_t \sim 20$ ps



CMOS-LGAD



add-on ***p*-gain** implant
(**gain** target: **10 – 30**)



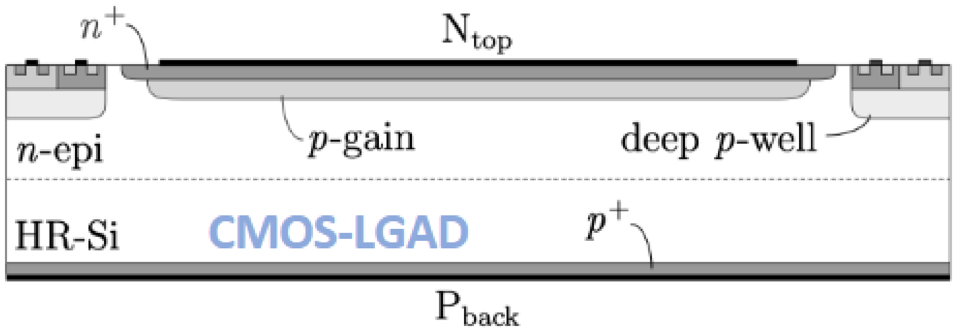
Monolithic RSD for Si Tracking

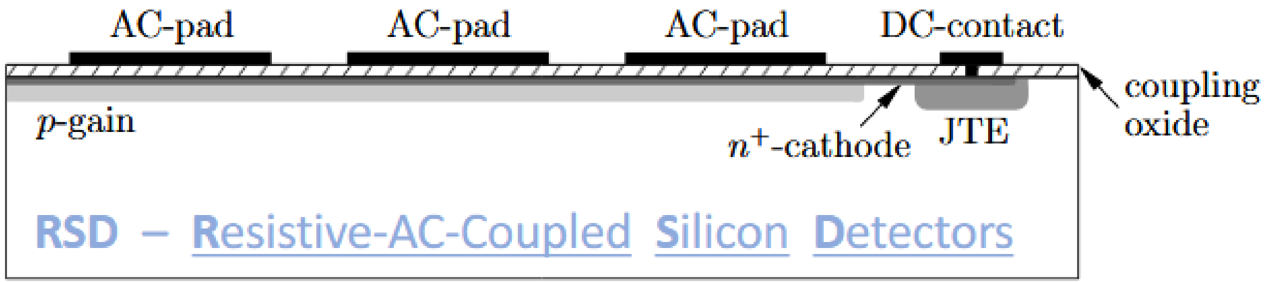
M. Mandurrino
FCC-ee Tracking WS

CMOS integration of the **LGAD technology** already demonstrated (in LF11is)

Spatial resolution **~3% of sensor pitch** (allowing to relax the channel density)

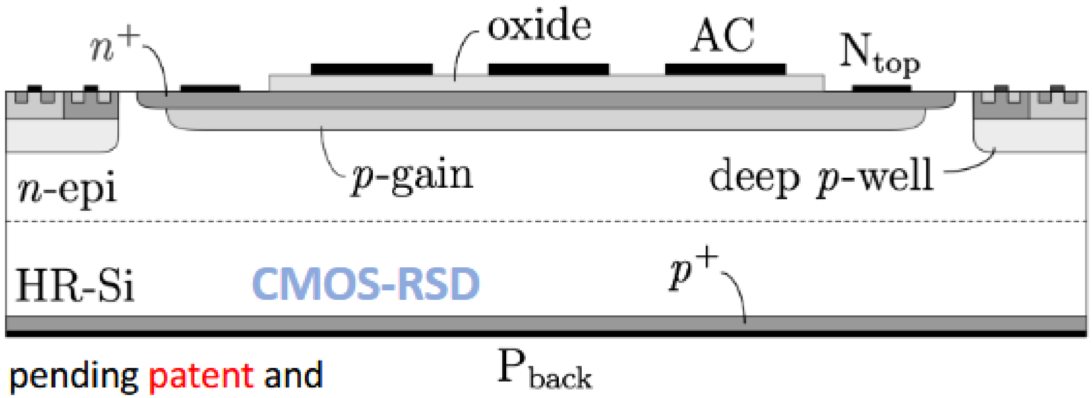
Time resolution similar to standard LGADs: **30-40 ps**





Plausible concurrent targets:

- **σ_t = 10-20 ps**
- **µm-level σ_x**
- **100% FF**



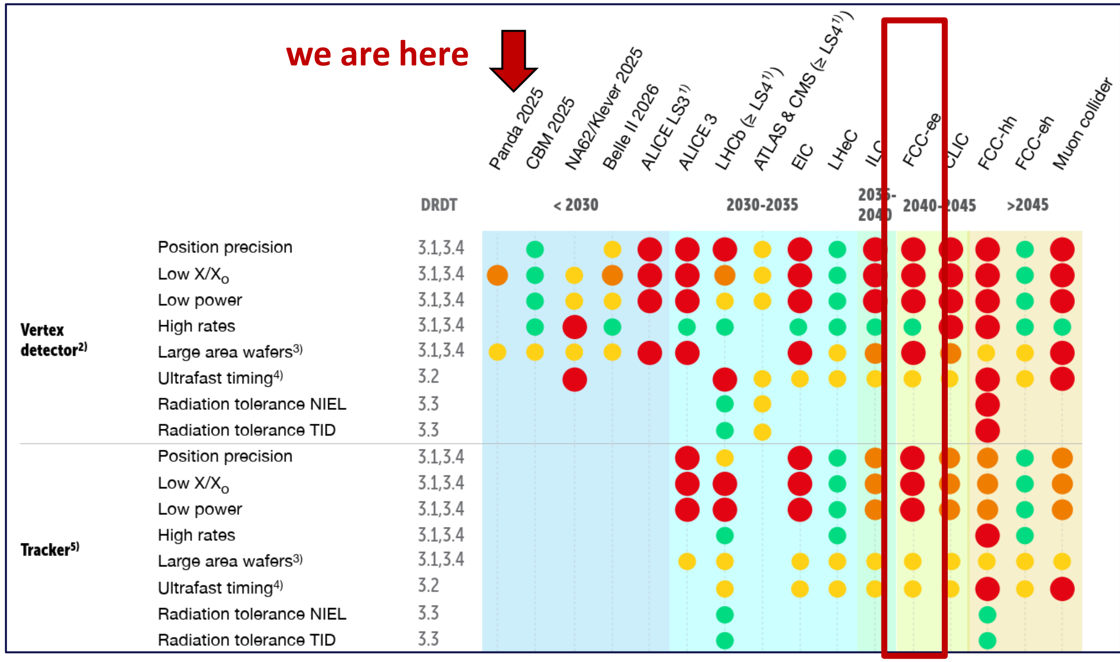
pending patent and extent of protection

Detector layout and process flow design activities are ongoing

First prototypes in next silicon production runs (std. CMOS process)

Summary and outlook

- The full exploitation of the FCC-ee physics potential of poses different challenges for the silicon tracking systems.
  - Extremely **high-resolution** and **low-mass** are needed for the **vertex detectors**
  - **System issues** will be the focus topics for the **large area detectors**
- **DMAPS** may be a material-effective and high-performance solution for the vertex region
- Many different options (**strips**, **DMAPS**, **RSD**) are investigated for the outer parts of the tracker
- The R&D program is well integrated within the DRD collaborations set up to implement the ECFA Detector R&D Roadmap, DRD3, DRD7 and DRD8
  - Framework for strategic R&D
  - Benefitting also from the developments for the upgrades of **existing experiments and new machines**



- Plenty of **fascinating electronics design and sensor development** will be needed to arrive to build a state-of-art detector within the time scale of future e^+e^- factories
- At the same time, it is possible to start addressing **system aspects** with already existing detectors

BACKUP

Accelerator parameters

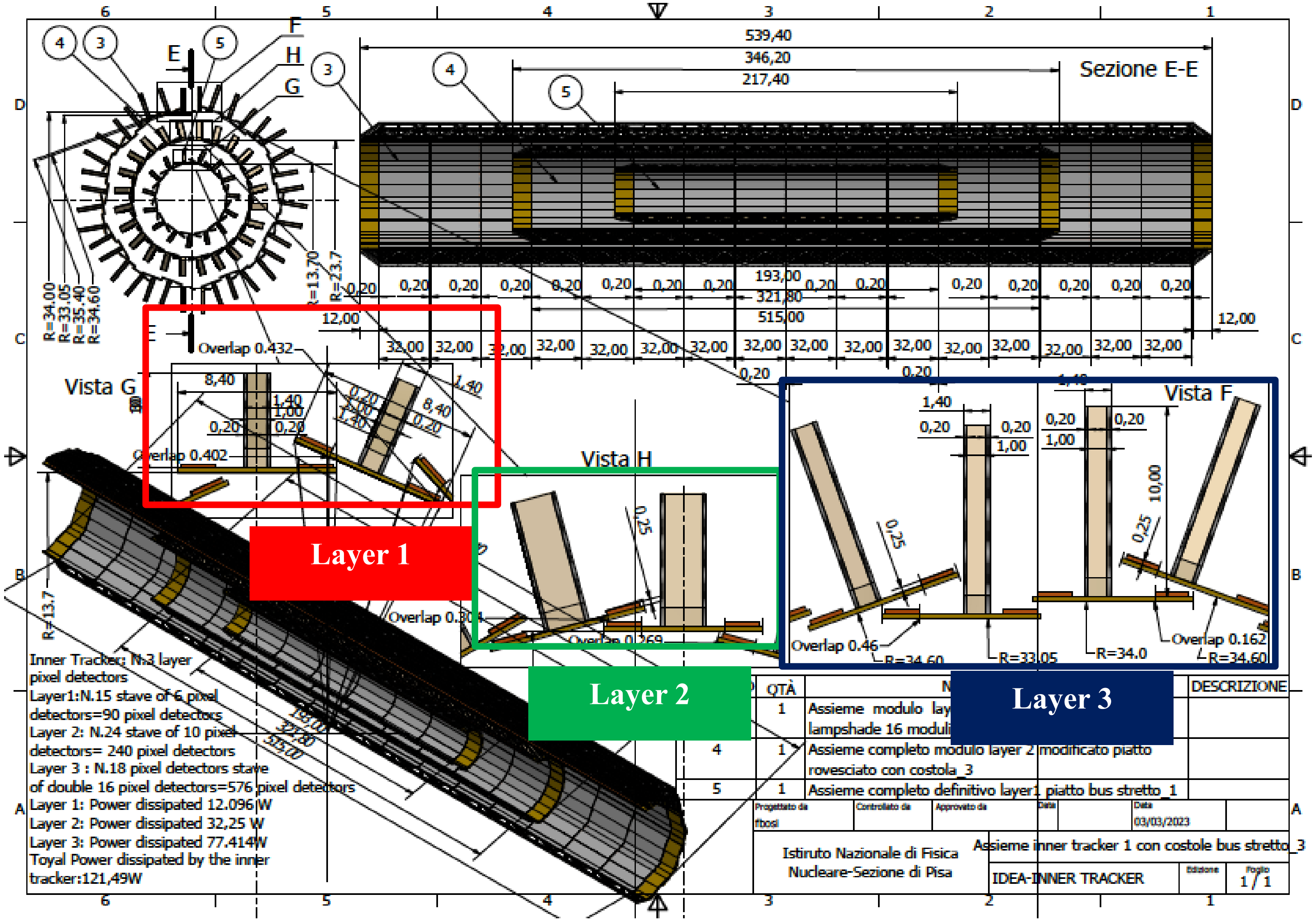
Working point	Z pole	WW thresh.	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94	157, 163	240	340–350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	140	20	7.5	1.8	1.4
Lumi/year (ab^{-1})	68	9.6	3.6	0.83	0.67
Run time (year)	4	2	3	1	4
Integrated lumi. (ab^{-1})	205	19.2	10.8	0.42	2.70
Number of events	6×10^{12} Z	2.4×10^{8} WW	2.2×10^{6} ZH + 65k WW $\rightarrow$ H	2×10^{6} $t\bar{t}$ + 370k ZH + 92k WW $\rightarrow$ H	

	Z	W^+W^-	ZH	$t\bar{t}$
Beam energy (GeV)	45.6	80	120	182.5
Luminosity / IP (10^{34} cm^{-2}s^{-1})	145	20	7.5	1.41
Beam current (mA)	1 294	135	26.8	5.1
Bunch number / beam	11 200	1 852	300	64
Bunch spacing (ns)	27	163	1 008	4 725
σ_x^* (μm)	9.5	21.8	12.6	36.9
σ_y^* (nm)	40.1	44.7	31.6	43.6
σ_z (mm) SR / BS	4.7 / 14.6	3.46 / 5.28	3.26 / 5.59	1.91 / 2.33
σ_δ (%) SR / BS	0.039 / 0.121	0.069 / 0.105	0.102 / 0.176	0.151 / 0.184

Overview of Detector Requirements

	Aggressive	Conservative	Comments
Beampipe	$X/X_0 < 0.5\%$	$X/X_0 < 1\%$	$B \to K^*\tau\tau$
Vertex	$\sigma(d_0) = 3 \oplus 15\,/\,(p\,\sin^{3/2}\theta)\,\mu m$ $X/X_0 < 1\%$	–	$B \to K^*\tau\tau$ R_c
	$\delta L = 5\,ppm$	–	$\delta\tau_\tau < 10\,ppm$
Tracking	$\sigma_p/p < 0.1\%$ for $\mathcal{O}(50)$ GeV tracks	$\sigma_p/p < 0.2\%$ for $\mathcal{O}(50)$ GeV tracks	$\delta M_H = 4\,MeV$ $\delta\Gamma_Z = 15\,keV$ $Z \to \tau\mu$
	t.b.d.	$\sigma_\theta < 0.1\,mrad$	$\delta\Gamma_Z(BES) < 10\,keV$
ECAL	$\sigma_E/E = 3\%/\sqrt{E}$	$\sigma_E/E = 10\%/\sqrt{E}$	$Z \to \nu_e\bar{\nu}_e$ coupling, B physics, ALPs
	$\Delta x \times \Delta y =$ $2 \times 2\,mm^2$	$\Delta x \times \Delta y =$ $5 \times 5\,mm^2$	τ polarisation boosted π^0 decays bremsstrahlung recovery
	$\delta z = 100\,\mu m$, $\delta R_{min} = 10\,\mu m\ (\theta = 20°)$	In-situ constraint with dilepton/diphoton events	alignment tolerance for $\delta\mathcal{L} = 10^{-5}$ with $\gamma\gamma$ events
HCAL	$\sigma_E/E = 30\%/\sqrt{E}$	$\sigma_E/E = 50\%/\sqrt{E}$	$H \to s\bar{s}, c\bar{c}, gg$, invisible HNLs
	$\Delta x \times \Delta y =$ $2 \times 2\,mm^2$	$\Delta x \times \Delta y =$ $20 \times 20\,mm^2$	$H \to s\bar{s}, c\bar{c}, gg$
Muons	low momentum ($p < 1$ GeV) ID	–	$B_s \to \nu\bar{\nu}$
Particle ID	$3\,\sigma$ K/π $p < 40$ GeV	$3\,\sigma$ K/π $p < 30$ GeV	$H \to s\bar{s}$ $b \to s\nu\bar{\nu}, \ldots$
LumiCal	tolerance $\delta z = 100\,\mu m$, $\delta R_{min} = 1\,\mu m$ acceptance 50–100 mrad	–	$\delta\mathcal{L} = 10^{-4}$ target (Bhabha)
Acceptance	100 mrad	–	$e^+e^- \to \gamma\gamma$ $e^+e^- \to e^+e^-\tau^+\tau^-(c\bar{c})$

Inner vertex layout



Outer Vertex Stave prototyping

Prototypes built for Belle II upgrade in Pisa

CF water-jet cut (by WatAJet Company)