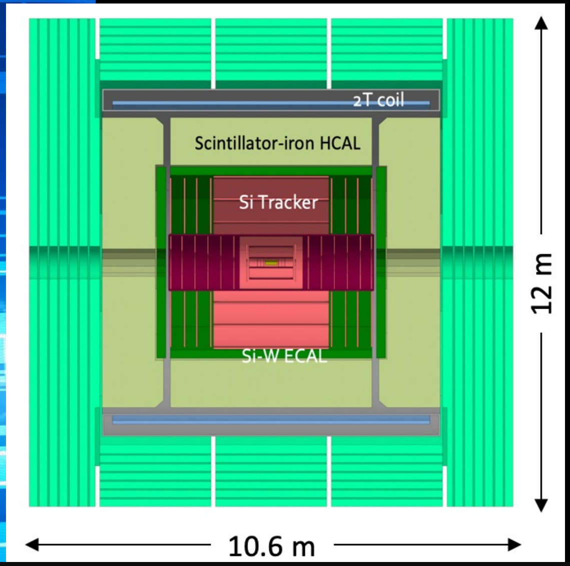
Si tracking and vertexing R&D for FCC

Daniela Bortoletto

FCCee Proto-Detector Concepts

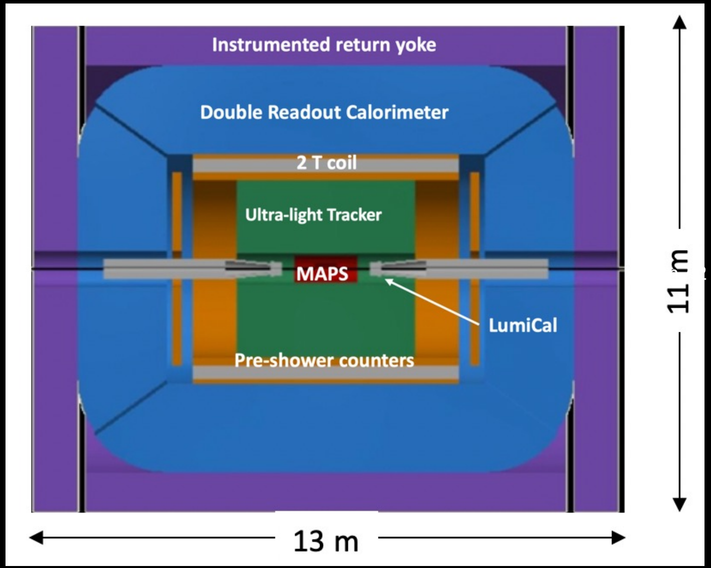
CLD



ILC → CLIC detector →CLD
- Full silicon vertex and tracker
- High granularity silicon-tungsten ECAL and scintillator-steel HCAL
- Large 2 T coil surrounding calorimeters
- Instrumented return-yoke for muon detection

Possible detector optimizations
- PID -$\mathcal{O}$(10 ps) timing and/or RICH….

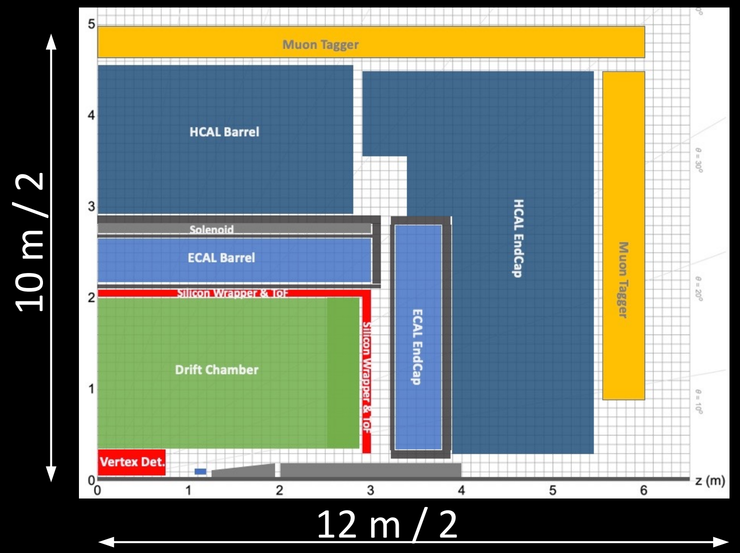
IDEA



- Si vertex detector
- Ultra light drift chamber with powerful PID
- Silicon wrapper (with PID?)
- Light, thin 2T coil inside calorimeters
- Pre-shower detector MPGC
- Dual-readout calorimeter; copper-scintilating/Cherenkov fibres
- Instrumented yoke with MPGC for muon detection

New

Noble Liquid ECAL based



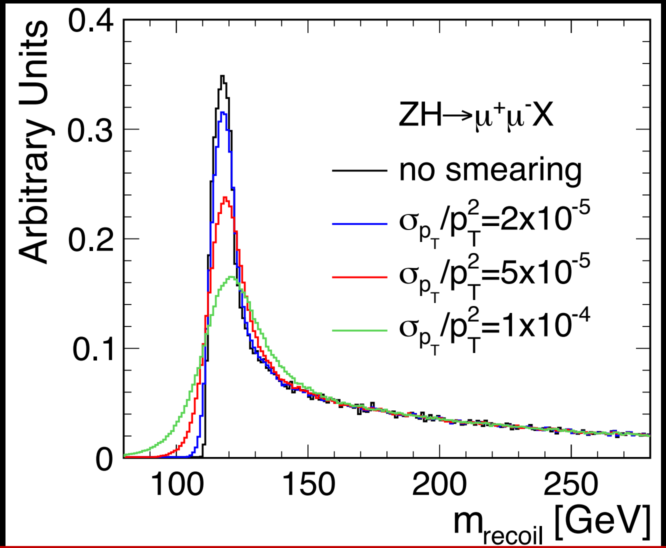
- Silicon vertex detector
- Low X_0 drift chamber with with particle ID
- Light, thin 2T coil inside same cryostat as ECAL
- High granularity Lead/Noble Liquid (LAr, possibly LKr) ECAL
- HCAL and muon systems to be specified

FCC-ee CDR: https://link.springer.com/article/10.1140/epjst/e2019-900045-4

Physics Requirements for Tracker and Vertex Detectors

Higgs Physics:
- Z Coupling at ‰ level
- Couplings to b and c at % level
- Invisible decays discovery at 0.18%

- Excellent momentum resolution for HZ reconstruction $\sigma_{P_T}/P_T^2 \simeq$ 2 x 10^{-5} / GeV with B field limited to 2 T
- Superior impact parameter resolution for c and b tagging $\sigma_{d_0} = 5 \oplus 10 - 15/(p[GeV]\sin^{3/2}\theta)\ \mu m$



Ultra precise QCD and EW Physics (8 x 10^{12} Z)

- Momentum resolution M.S. limited
- Track angular resolution < 0.1 mrad (beam energy spread from μμ < 1 MeV)

For silicon: 1-2% X_0/layer and ~ 7 μm point resolution

Heavy Flavour Physics: 10^{12} bb and 1.7 X10^{11} $\tau\tau$

- Superior impact parameter resolution for c, b tagging
- PID for b and τ physics

Feebly Coupled Particles (LLP)

- Far detached vertices (mm → m)
- More tracking layers, precise timing for velocity (mass) estimate

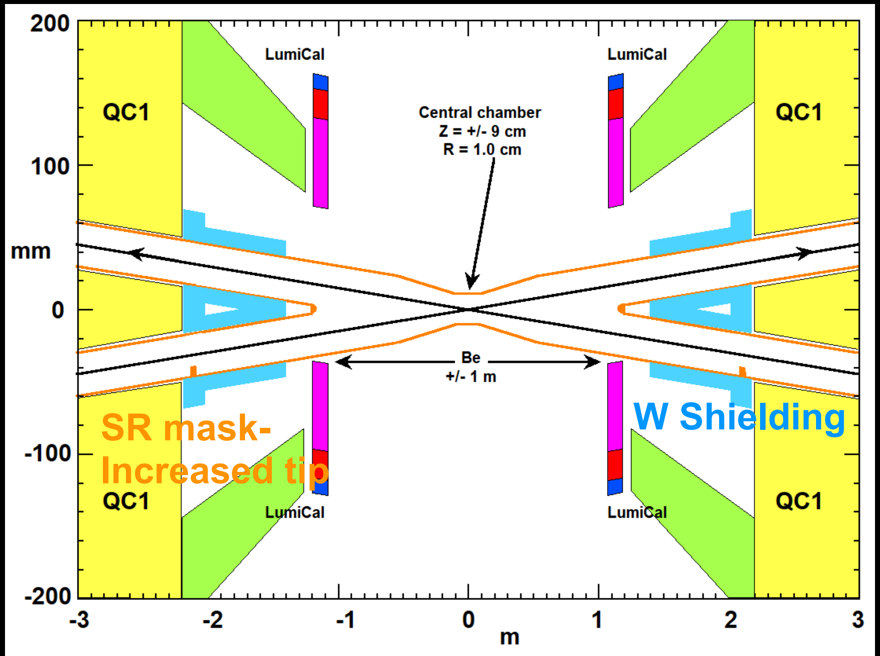
Track Timing of 6 ps could support PID, measurement of long lived particles, aid pattern reconstruction

Single point resolution in vertex detector ~3 μm and < 0.2% X_0/layer

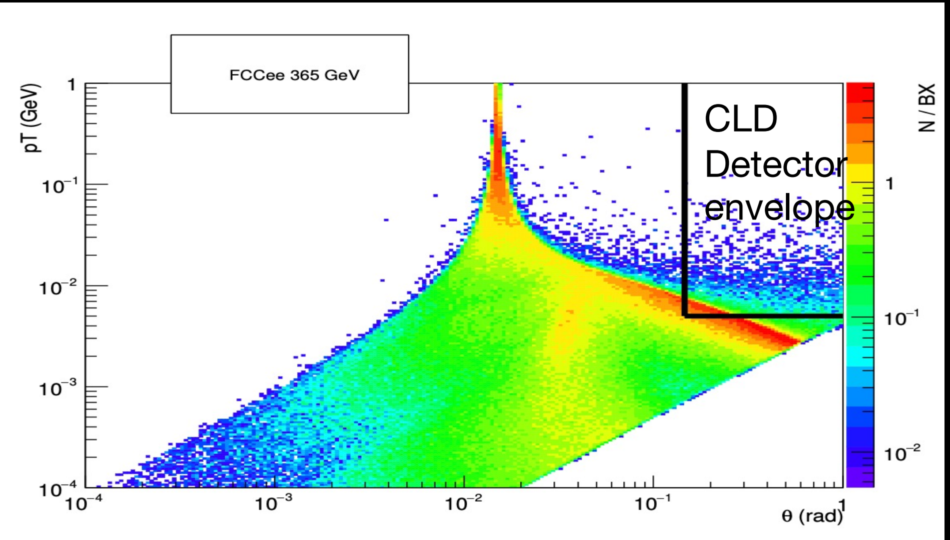
MDI Challenges

- Complex Machine Detector Interface (MDI)
  - first final focus quadrupole QC1 and two anti-solenoids inside the detector
- Backgrounds
  - beamstrahlung ⇒ photons
  - Real or virtual photon scattering ⇒ incoherent $e^{\pm}$ pair creation ⇒ limit on the radius of the IR beam pipe
  - $\gamma\gamma \rightarrow q\bar{q}$ ⇒ hadrons (jets)
  - Synchrotron radiation ⇒ photons (mitigated by MDI Design)
- Additional sources of background under study:
  - Beam- halo
  - Backscattering
  - Beam-gas scattering
  - From top –up injection
- Warning: Belle-2 discrepancies observed between simulations and first collisions

New beam pipe design with 1 cm radius central chamber



CLD detector -1 cm beam pipe



Incoherent pair creation

MDI Challenges

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  - Backscattering
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  - From top –up injection
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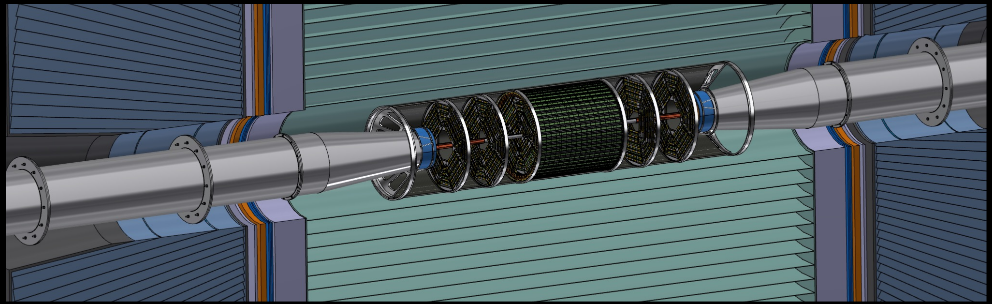
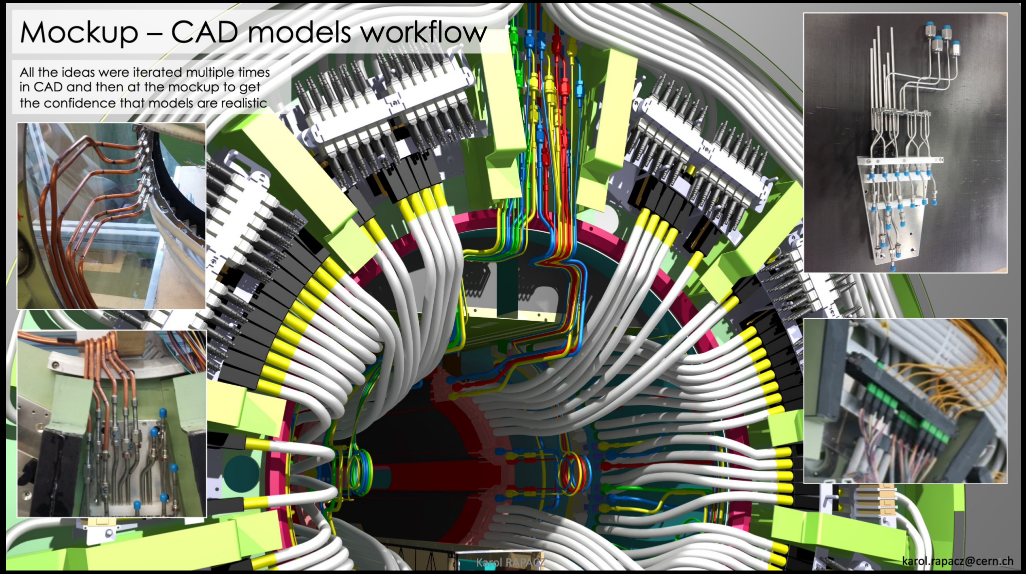
Ongoing work on mechanical model of the FCC-ee MDI for IDEA studying the insertion of vertex detectors



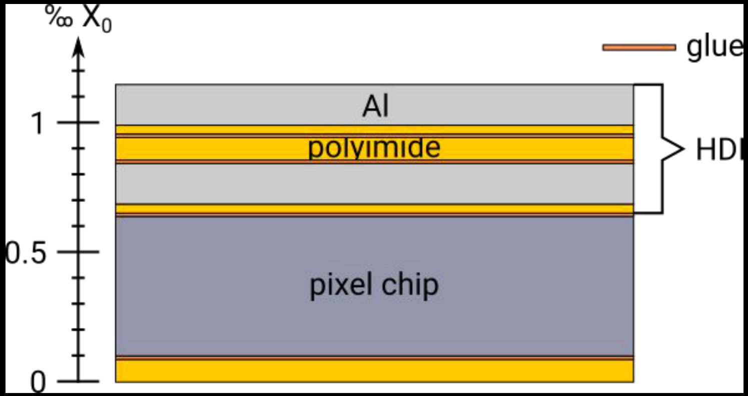
Full-scale IR mock-up to be realised at Frascati

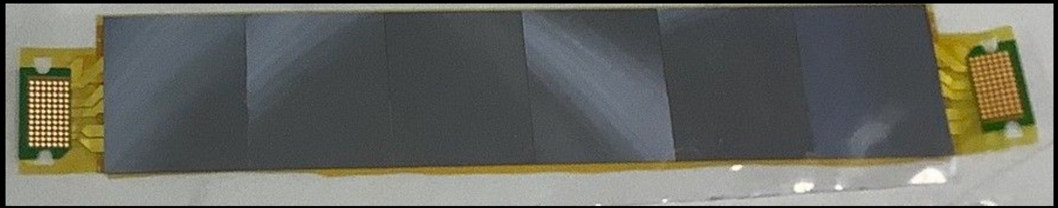


Example of CMS IR mock-up

Physics Goals & Challenges

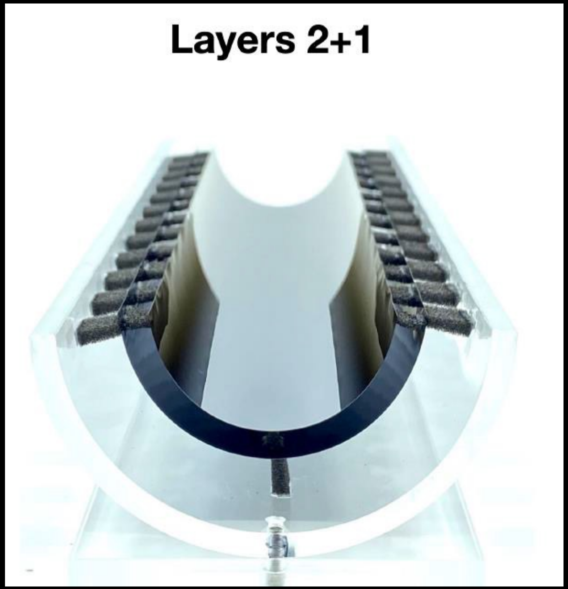
- Spatial Resolution
  - Inner and outer radius are key factors
  - Minimize Material
  - Monolithic CMOS detectors (R&D chip design costs, complexity, connection to foundries)
  - < 20 mW/cm^2 for air flow cooling to minimize material
- Time resolution (needs power)
- Cooling & geometrical acceptance
- Physics rates at Z resonance ~ 100 kHz
- <3.4 Mrad & 6.2x10^{12} n_{eq}/cm^2 per year at inner most layer
- Detector Optimization
  - Conflicting requirements (material, cooling, services, mechanics, etc.) require cooperation between physicists/chip designers/thermo//mechanical engineers/DAQ experts
- Time scale
  - Avoid the Never Ending R&D
  - Avoid to be too conservative





Mu3e

- Thinned sensors
- Kapton/flex
- Helium colling
- 0.115% X_0/layer

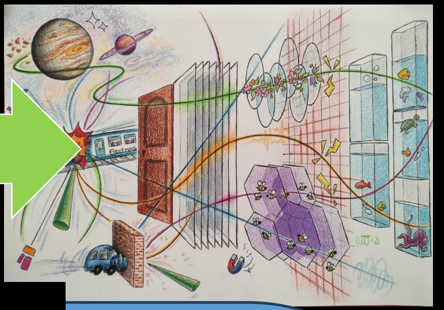


ALICE ITS3

- Stitched sensors
- Curved wafer-scale ultra-thin sensors in cylindrical layers
- 0.05% X_0/ layer
- TID ≈ 3Mrad and 2x10^{13} 1 MeV n_{eq} /cm^2.

ECFA detector roadmap

Implementation of the ECFA roadmap for Solid State Detectors



DRDT3.1: Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors

DRDT3.2: Develop solid state sensors with 4D-capabilities for tracking and calorimetry

DRDT3.3. Extend capabilities of solid state sensors to operate at extreme fluences

DRDT3.4. Develop full 3D-interconnection technologies for solid state devices in particle physics.

DRD3

- **WG1:** Monolithic CMOS Sensors
- **WG2:** Sensors for Tracking & Calorimetry
- **WG3:** Radiation damage & extreme fluences
- **WG6:** Non-silicon based detectors
- WG7: Interconnect and device fabrication
- **WG4:** Simulation
- **WG5:** Characterization techniques, facilities
- **WG8:** Dissemination and outreach

https://indico.cern.ch/event/1214410/

Proposal to be completed at the end of June

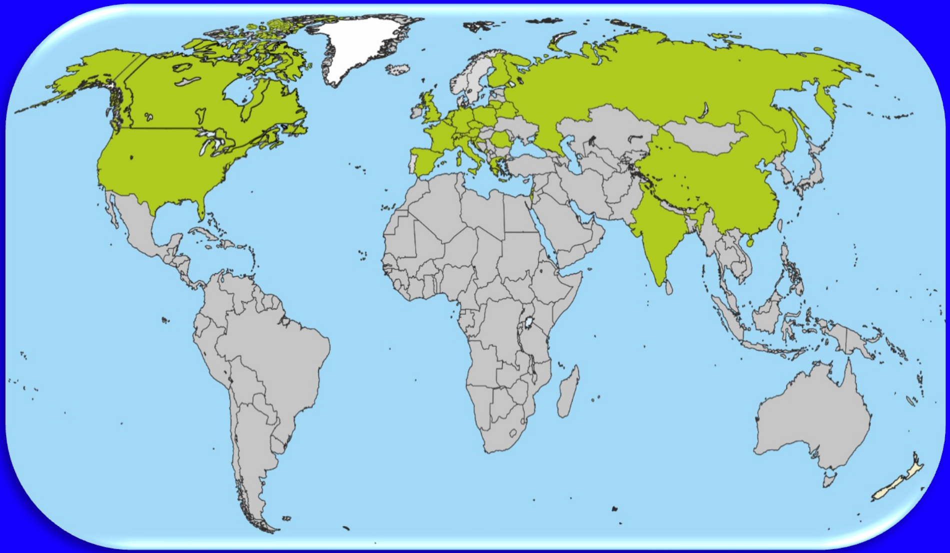
From RD50 to DRD3

DRD3

Status: 17.3.2023

RD50

- 65 institutes; 438 members
  - 50 in Europe
  - 8 in North America
  - 7 in Asia



57 RD50 institutes*
(88% of RD50)

+ 35 other institutes

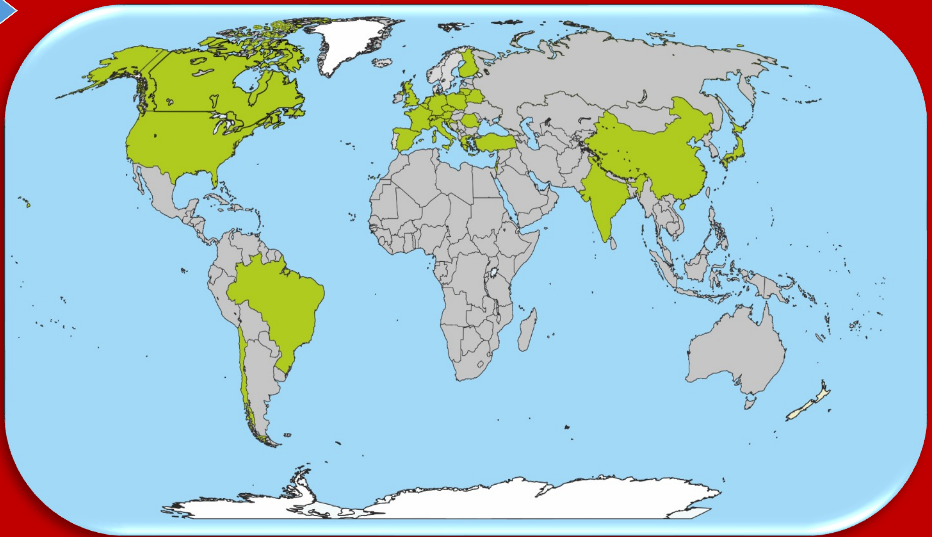
In DRD3 ≈ 62% will be former RD50 members

[*] 4 institutes included that did not send a questionnaire yet

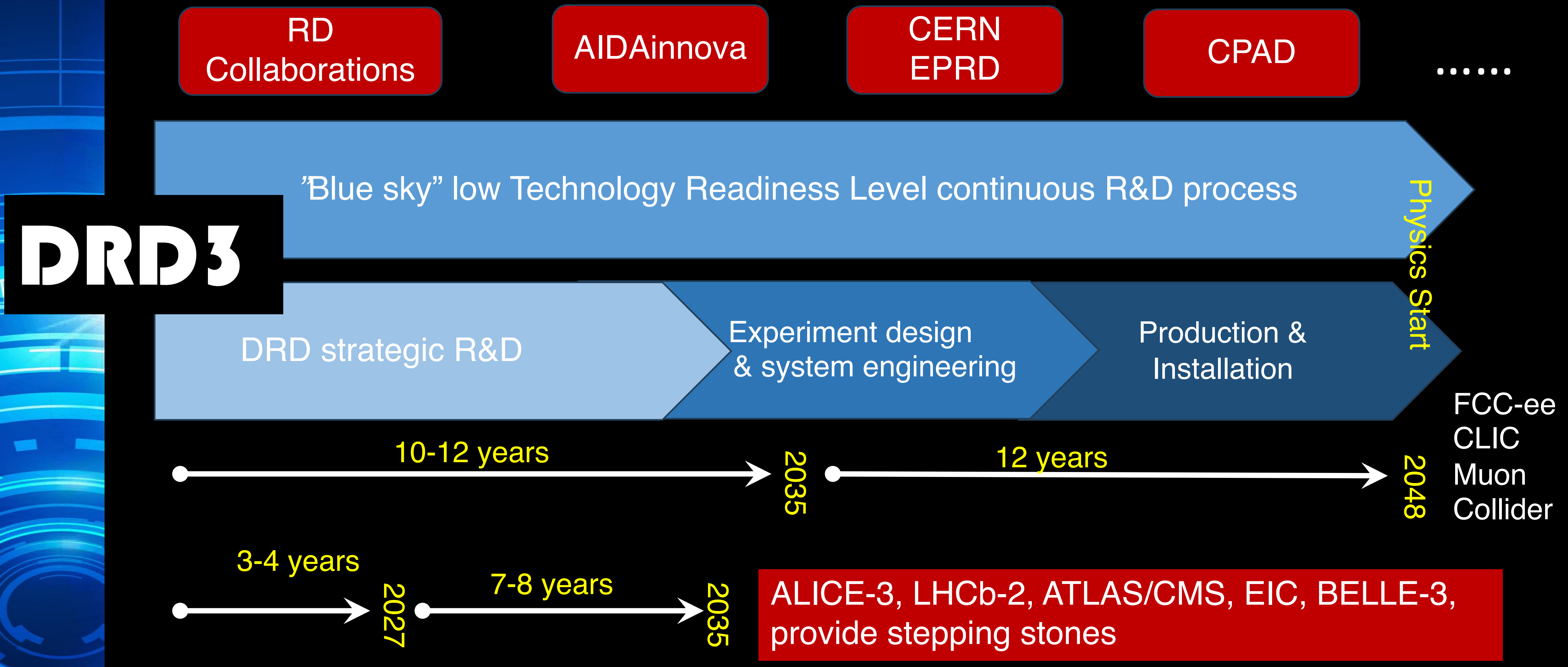
DRD3

(expression of interest)

- 92 institutes* (+27 institutes)
  - 68 in Europe (+18)
  - 12 in North America (+4)
  - 9 in Asia (+2)
  - 3 in South America (+3)

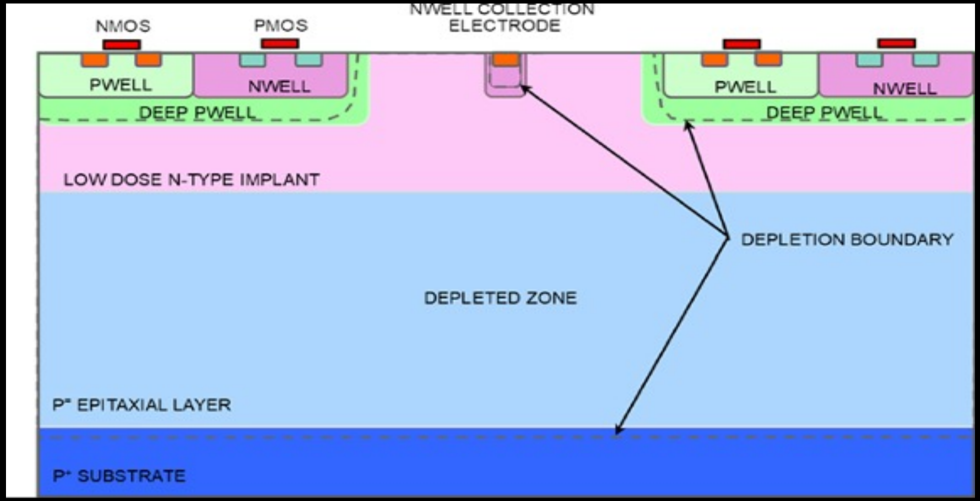


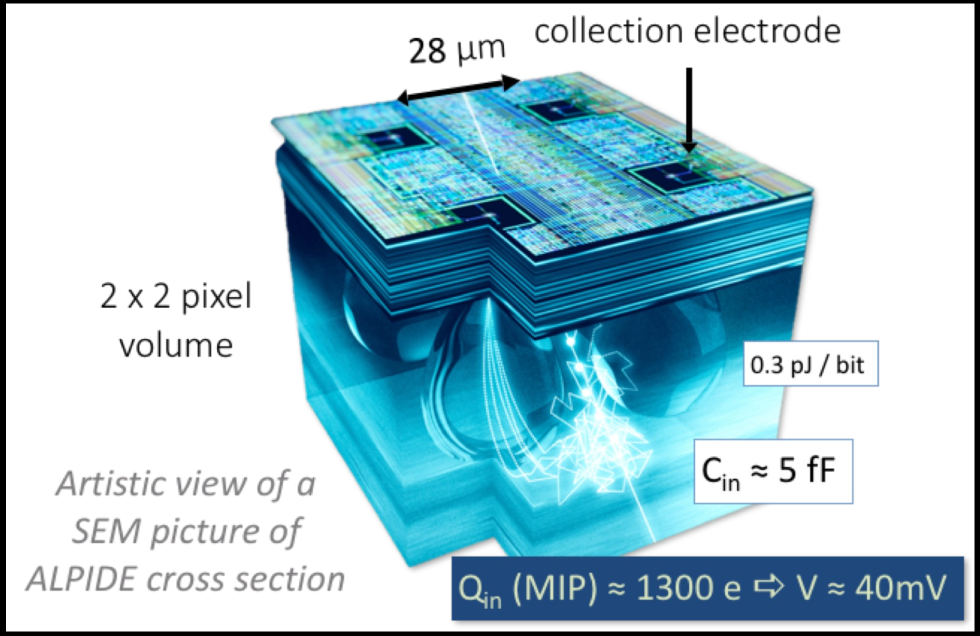
From DRD to next collider experiments



CMOS DMAPS Small Electrode

- State-of-the-art ALPIDE sensors for ALICE ITS on TJ 180 nm imaging process
  - 27x29 µm^2 pixels
  - high-resistivity (> 1kΩ cm) p-type epitaxial layer (≈25 µm thick) on p-type substrate
  - Partial depletion by applying 6 V
  - Small n-well diode (2 µm diameter)
    - Low capacitance
    - Better S/N
    - Faster/ lower power/ smaller pixels
  - Largest CMOS MAPS detector ever built (≈ 10 m^2)
  - Very low mass support achieving 0.35%X_0/Layer

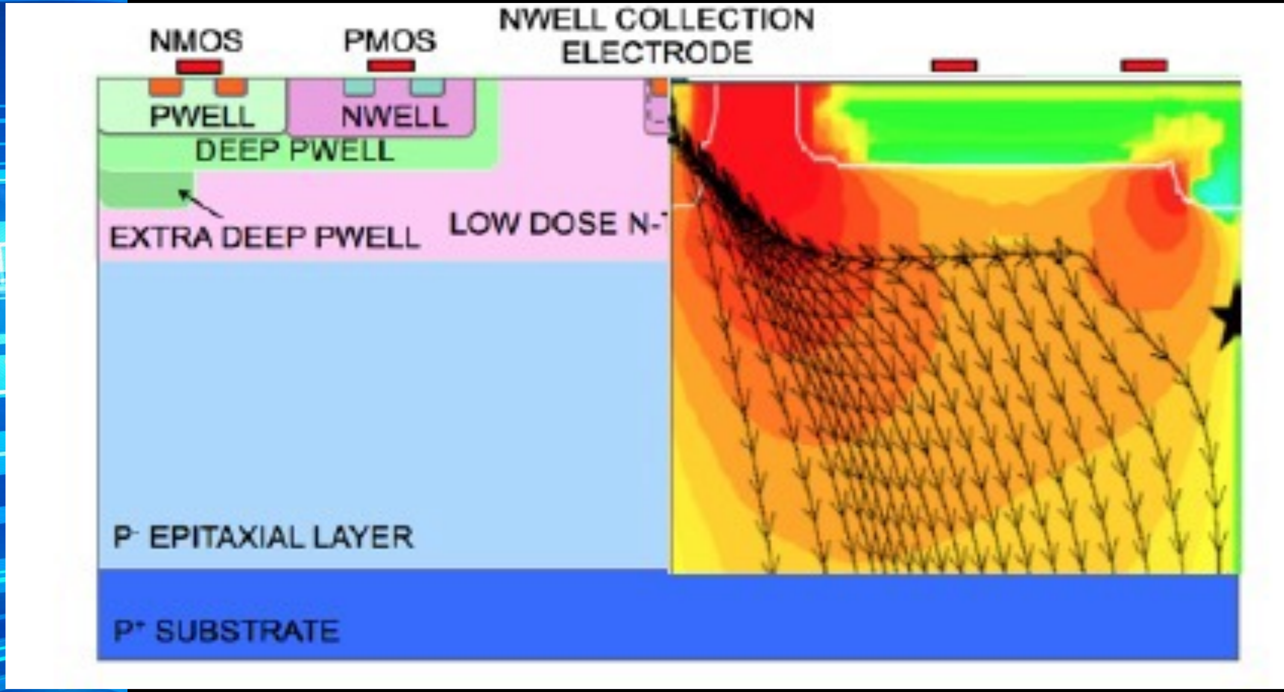




CMOS DMAPS Small Electrode

Modified TJ process to improve radiation hardness

- MALTA 2 (epitaxial and CZ)



CMOS DMAPS Small Electrode

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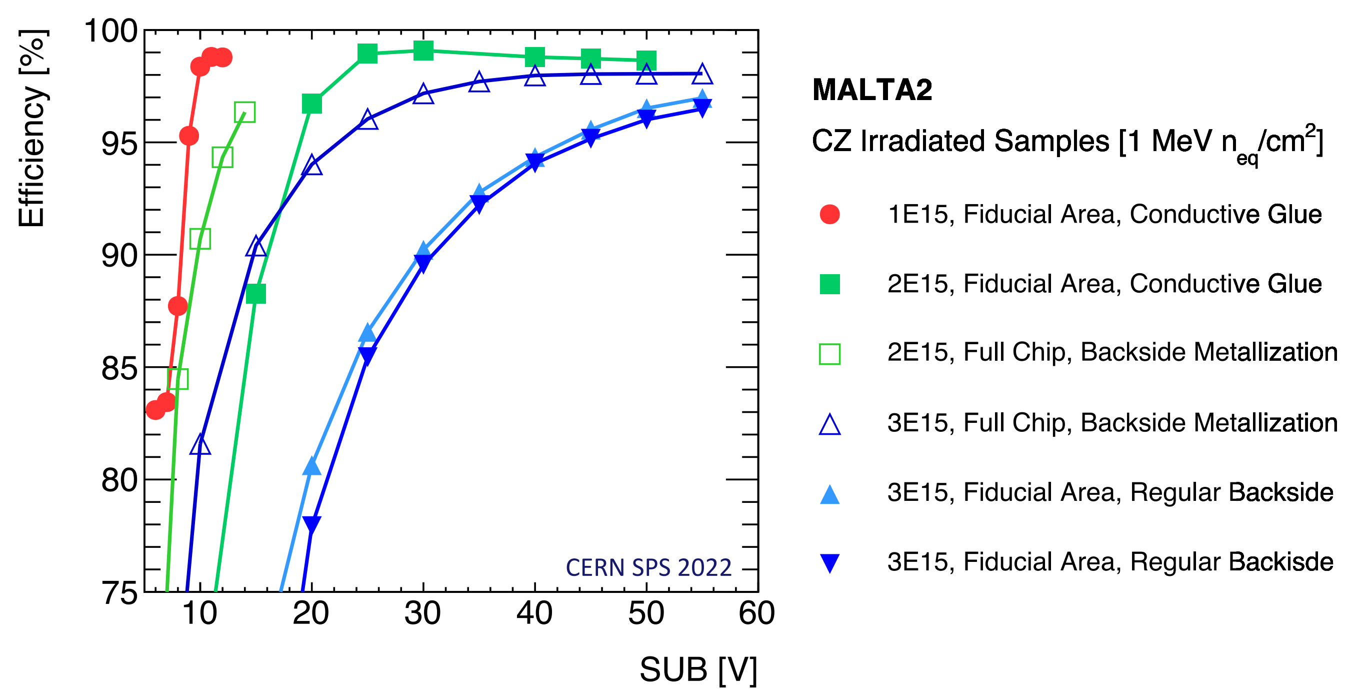
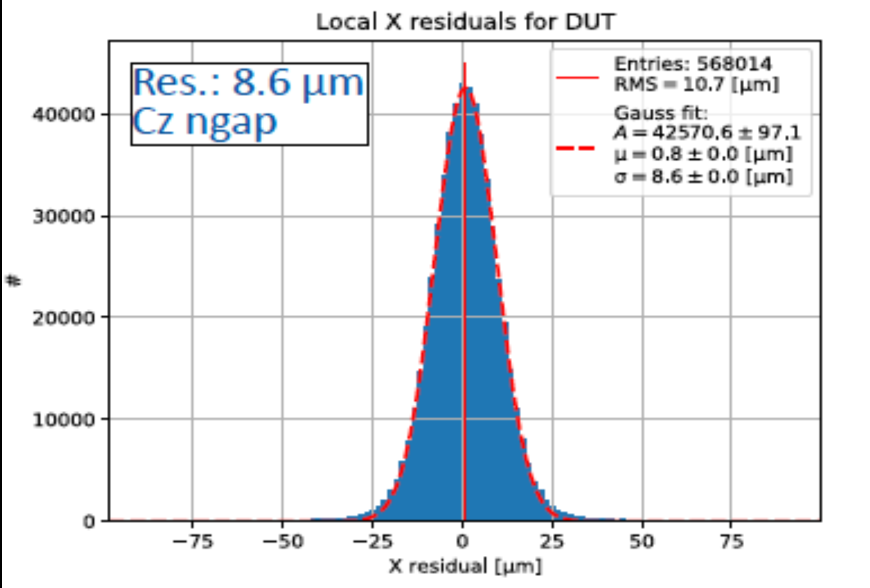
- MALTA 2 (epitaxial and CZ)



Average efficiency of irradiated MALTA2 on Czochralski substrate versus SUB voltage

Efficiency @3E15 n_{eq}/cm^2 > 95% in 25ns

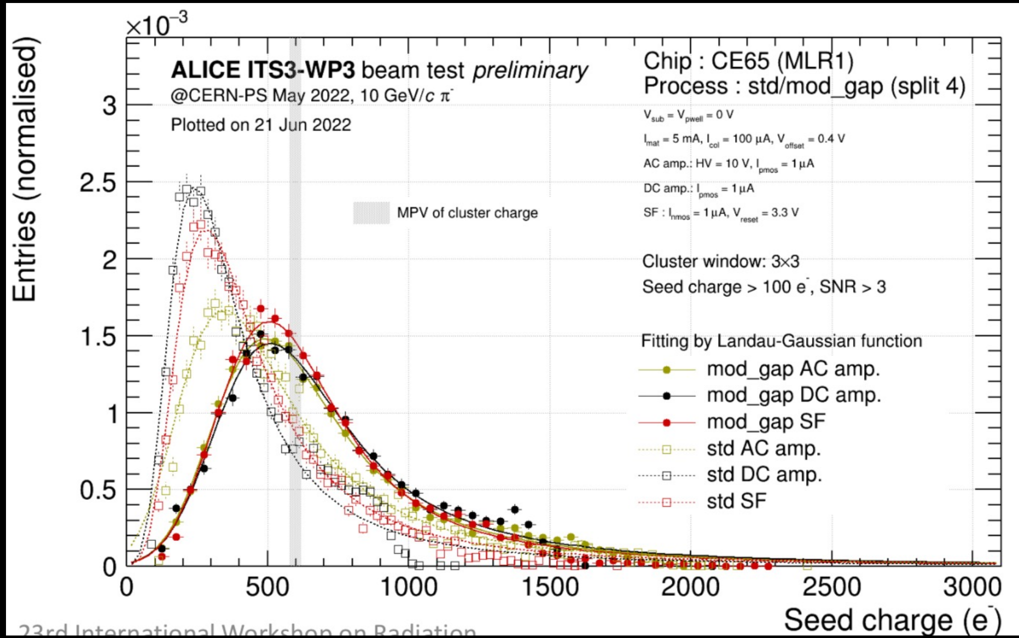
- TJ-MONOPIX2- large chip (2× 2 cm^2) column drain readout
- Pixel size 33x33 μm^2
- 25 µm p-type epitaxial layer (1 kΩ cm) grown on a low-resistivity substrate, C=3-4 fF

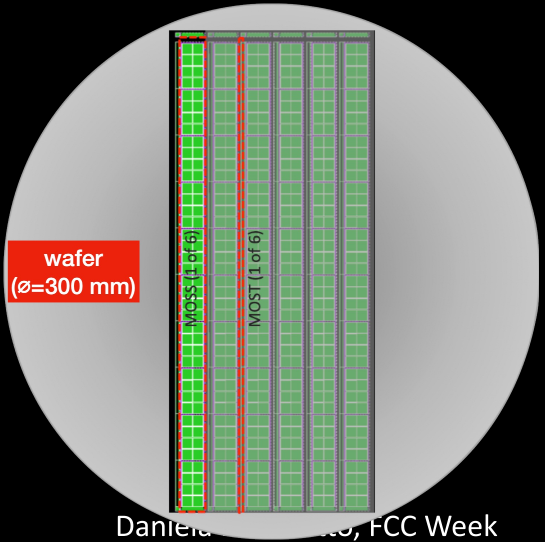


- OBELIX (Optimized BELle II pIXel sensor
  - Total Ionizing Dose (TID) 100 kGy/year
  - Non-Ionizing $5x10^{13}$ n_{eq}/cm^2/year
  - Hit rates up to 120 MHz/cm^2

CMOS DMAPS Small Electrode

- TPSCo 65 nm (Tower) for ITS3
- Exploring the new technology (large collaboration effort, CERN + 24 institutions) including stitching
- Two submissions so far
  - Multi Layer Reticule MLR1 (2020) sensor 10-25 μm pitch, 10 μm epi Checking process modifications
  - Engineering run (ER1) to check stitching

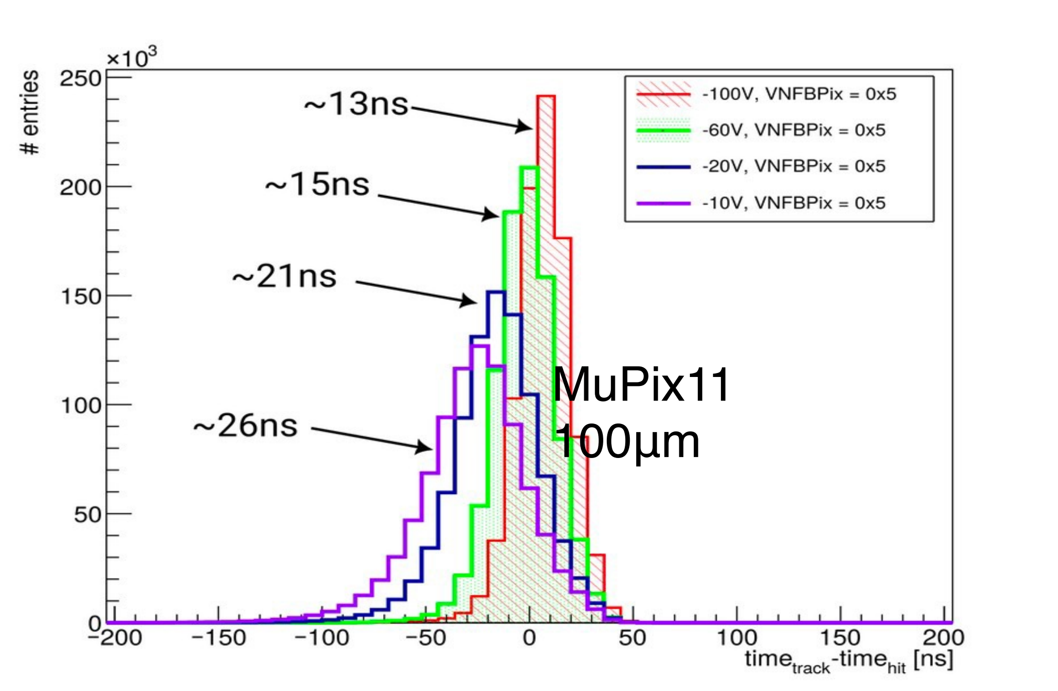




See talks this afternoon

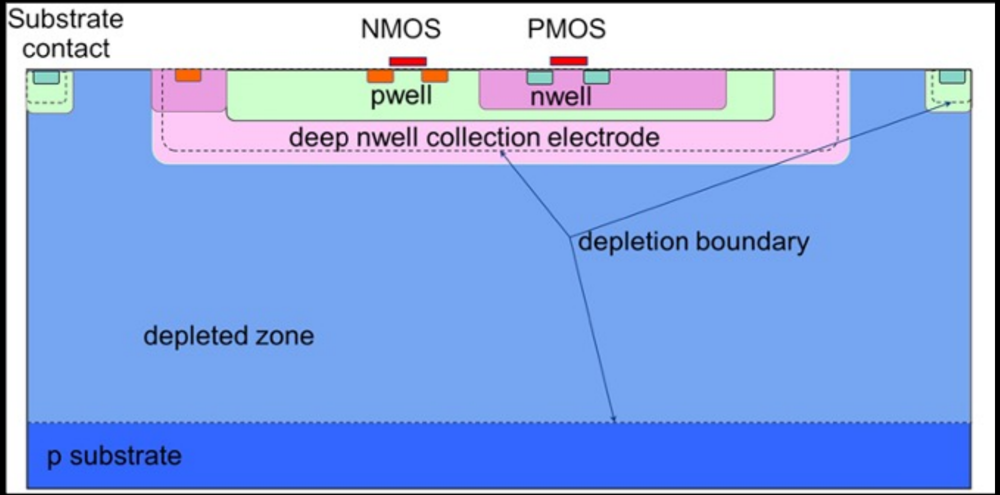
CMOS DMAPS Large Electrode

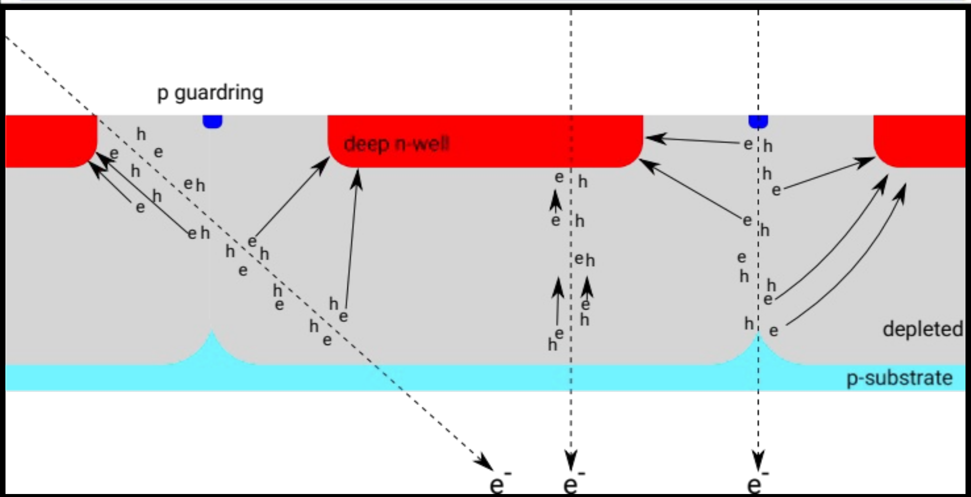
- State-of-the-art MUPIX11 for the Mu3e experiment on TSI semiconductor H18
  - 80x80 μm^2 pixels 50μm thick
  - Time resolution<20 ns
  - 0.115% X_0/layer and efficiency>99%



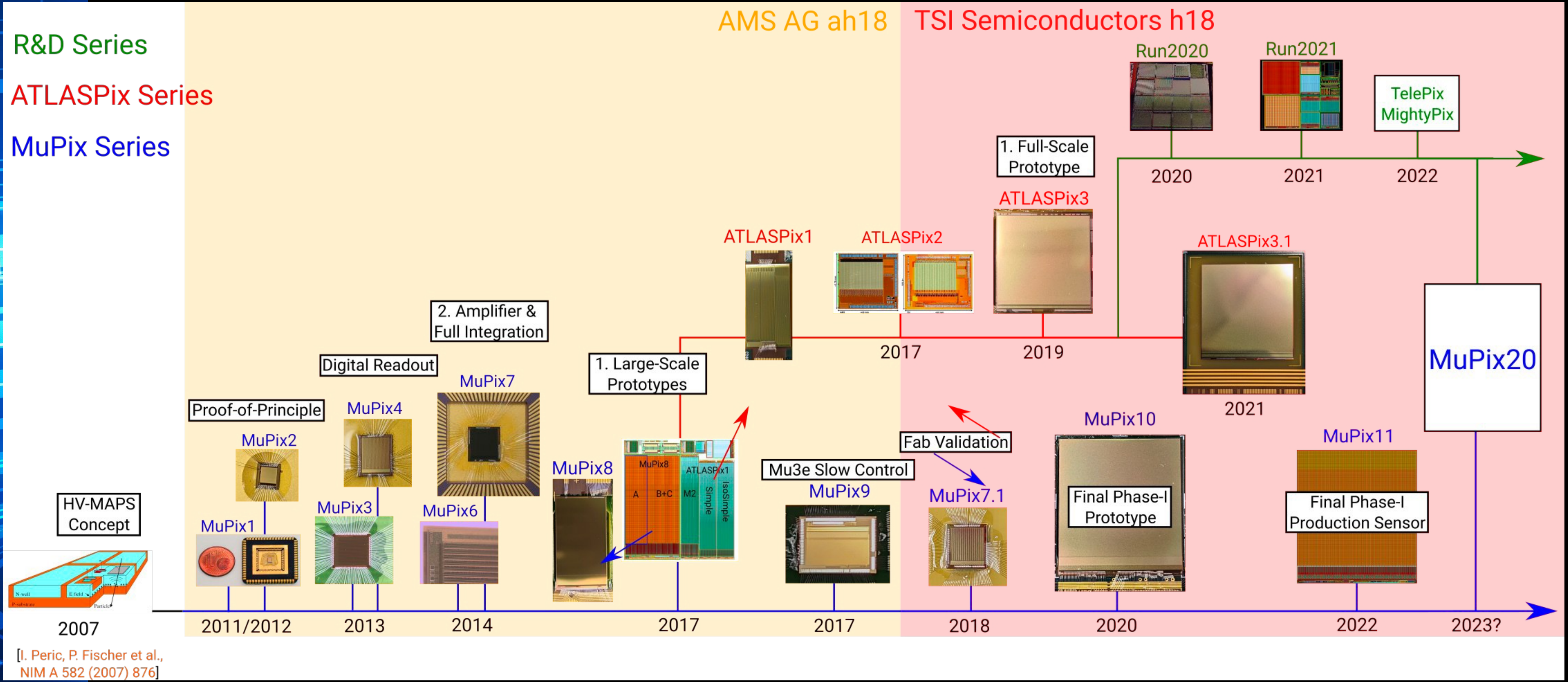
Large electrode:

- Low ohmic substrates (10-400 Ωcm)
- High voltages up to 100V
- More radiation hard





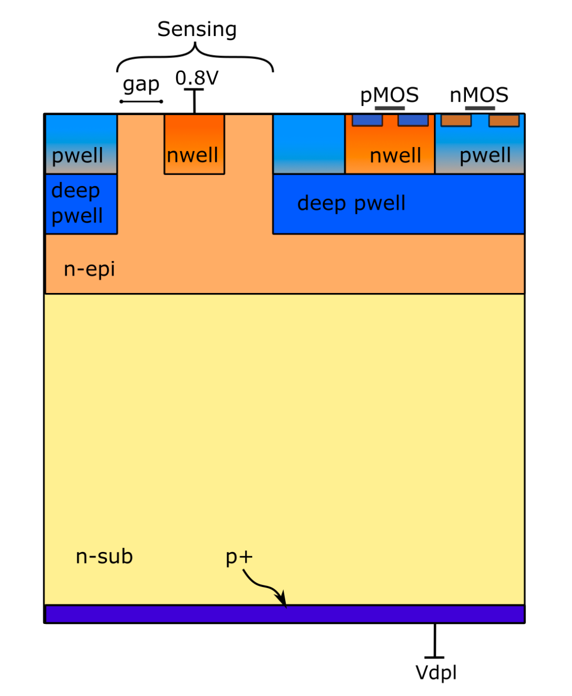
ATLASPiX/MuPix Series

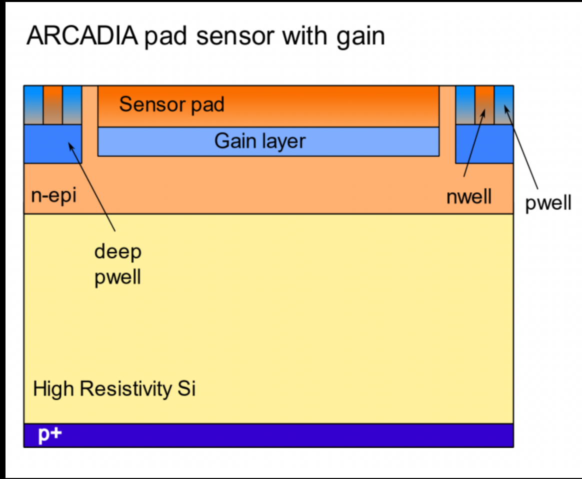


[I. Peric, P. Fischer et al., NIM A 582 (2007) 876]

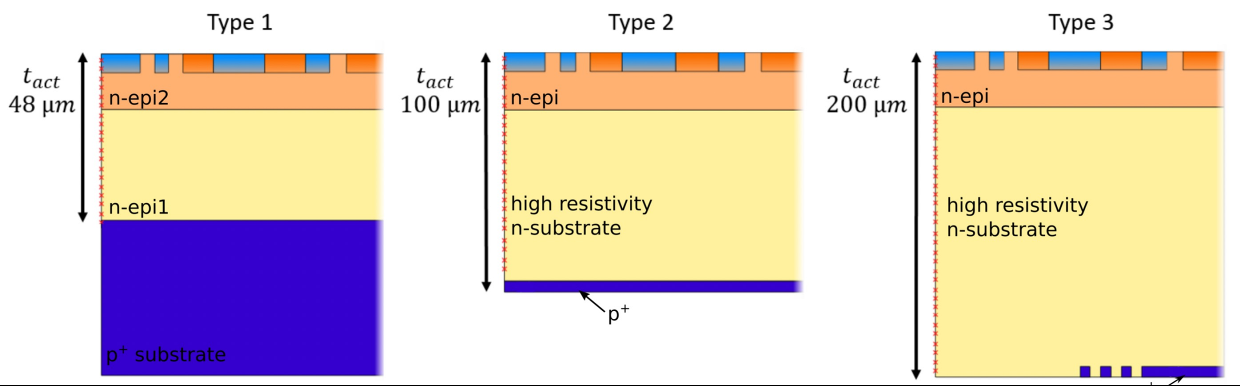
ARCADIA

- Lfoundry 110 nm CMOS process with 1.2 V transistors, developed between INFN and LFoundry
- fully depleted, charge collection by drift
- backside processing (diode+GR)
- low resistivity epi-layer
- Pixel pitch *25* μm pitch
- sensor diode about 20% of total area
- low power <50mW/cm^2, to allow air cooling
- side- buttable' to accommodate a 1024x512 silicon active area (2.56x1.28 cm^2)
- Demonstrator 512 x 512





Wafer splits with gain layer to explore < 100 ps



23 wafers produced in first 2 production runs, 3 types/thicknesses

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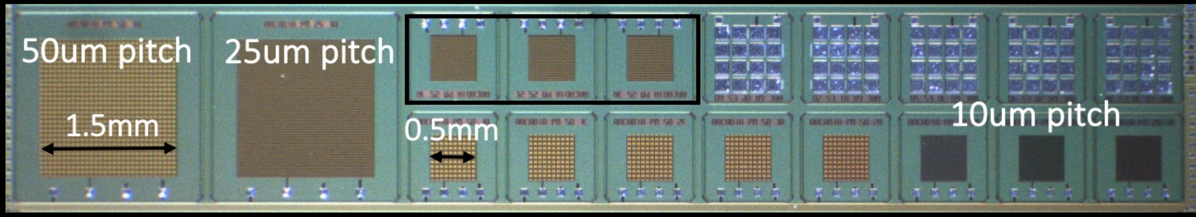
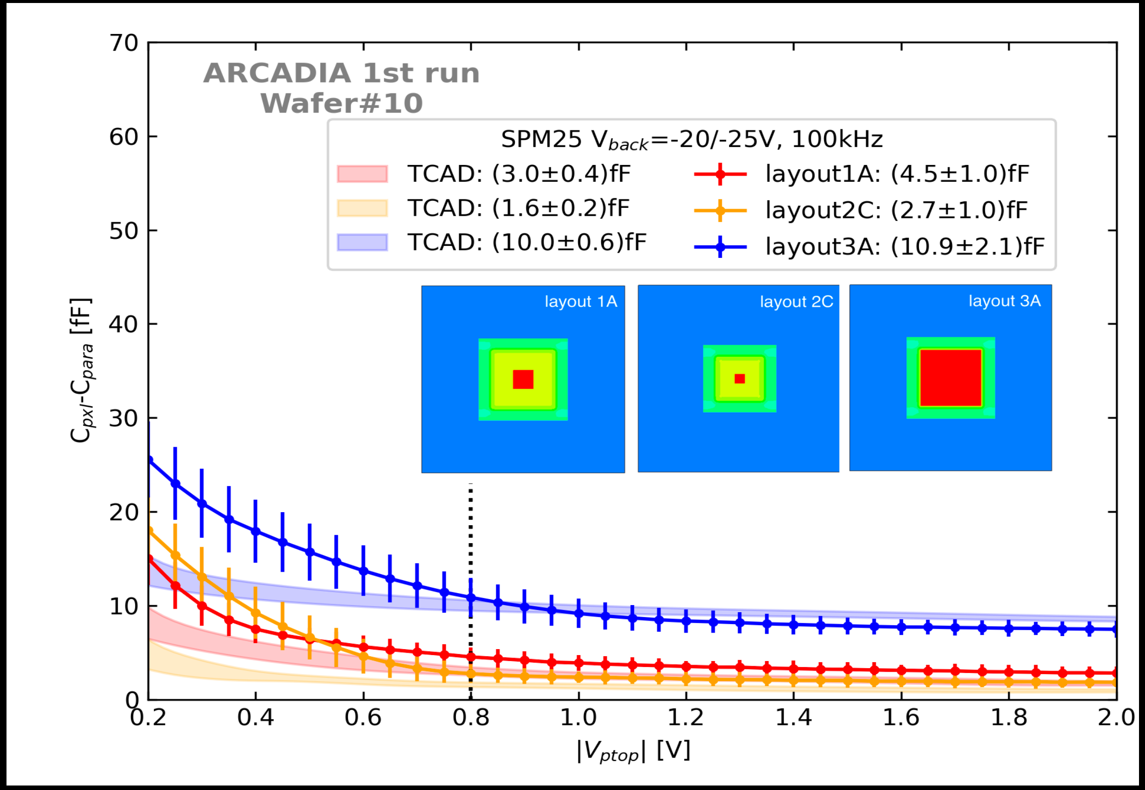
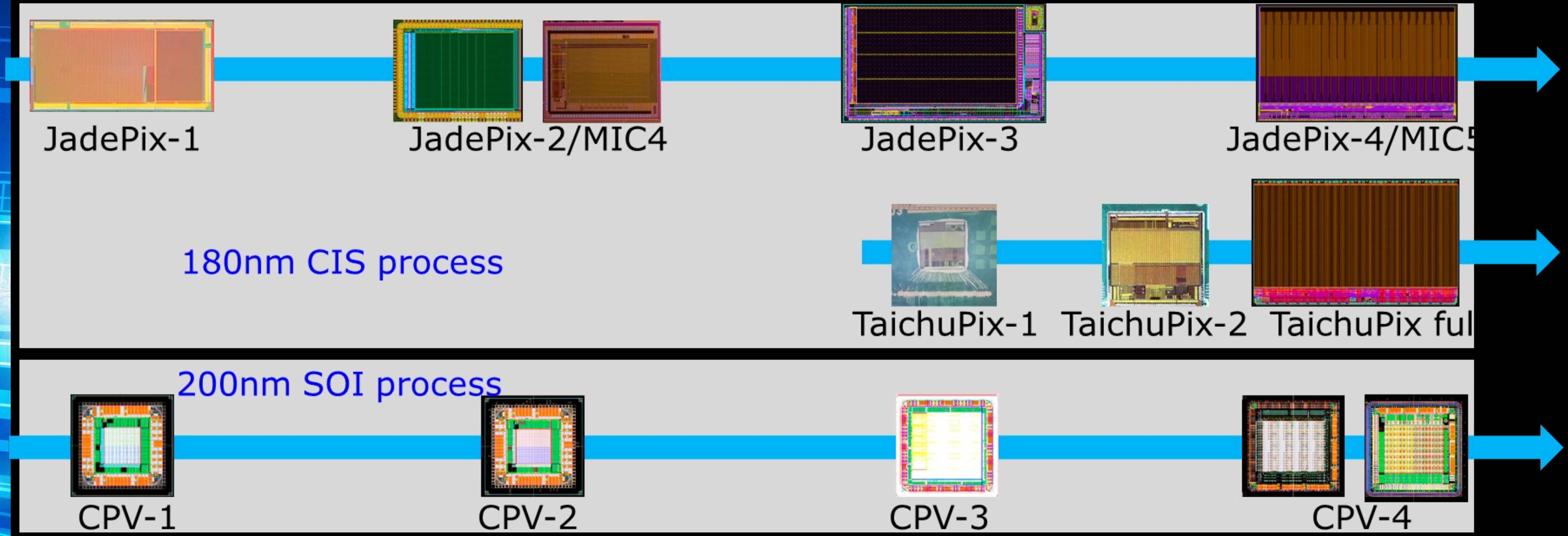




stable operation at full depletion, and good agreement with TCAD simulations

DMAPS for CEPC



DMAPS for CEPC

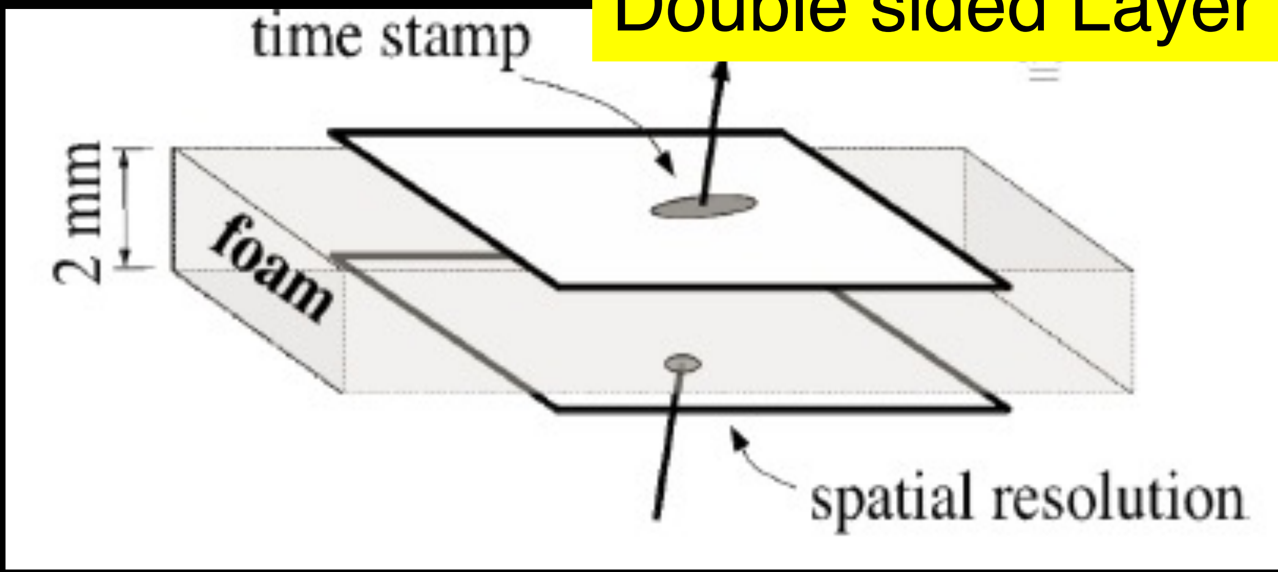
JadePix Tower 180 nm

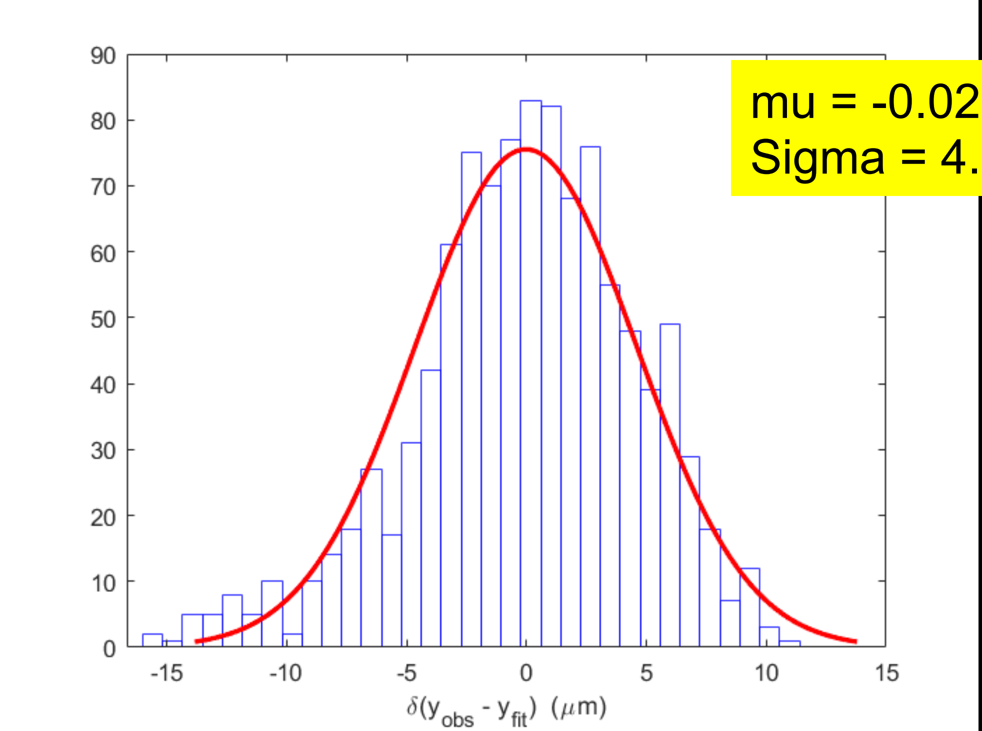
- JadePix-3
  - Fine pitch(16 x 23 μm^2) & low power sensor for spatial resolution
  - **s**.p.< 3 μm achievable
  - rolling shutter
- JadePix-4/MIC5
  - A faster sensor to provide time-stamp
  - s.p. < 5μm, 1μs integration time
  - row address encoder

TaichuPix sensor Tower 180 nm

- 3 round of sensor prototyping
- Pixel 25 μm ×25 μm
- Column-drain readout for pixel matrix

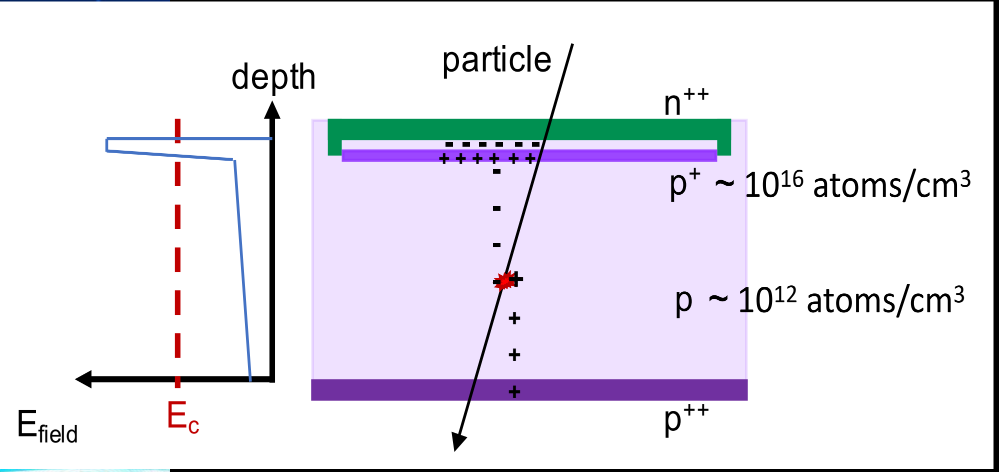
Double sided Layer



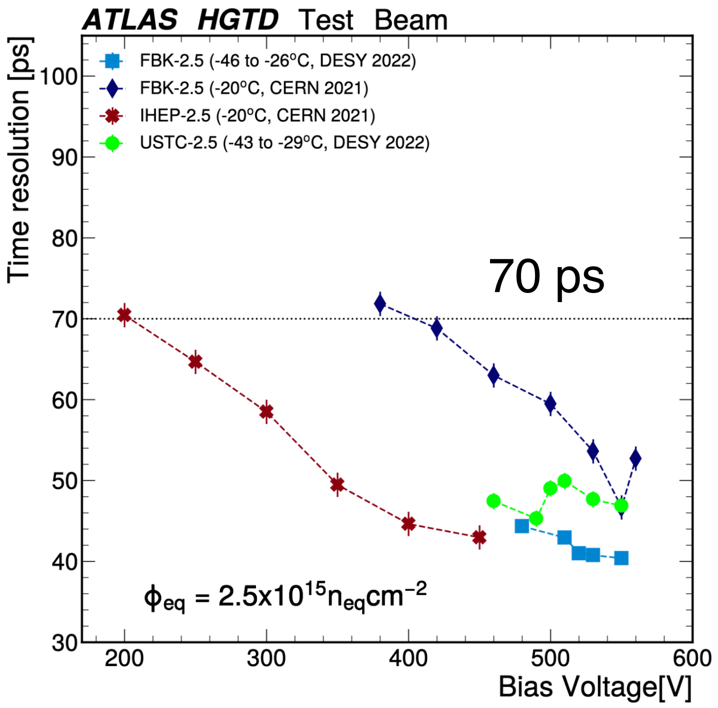


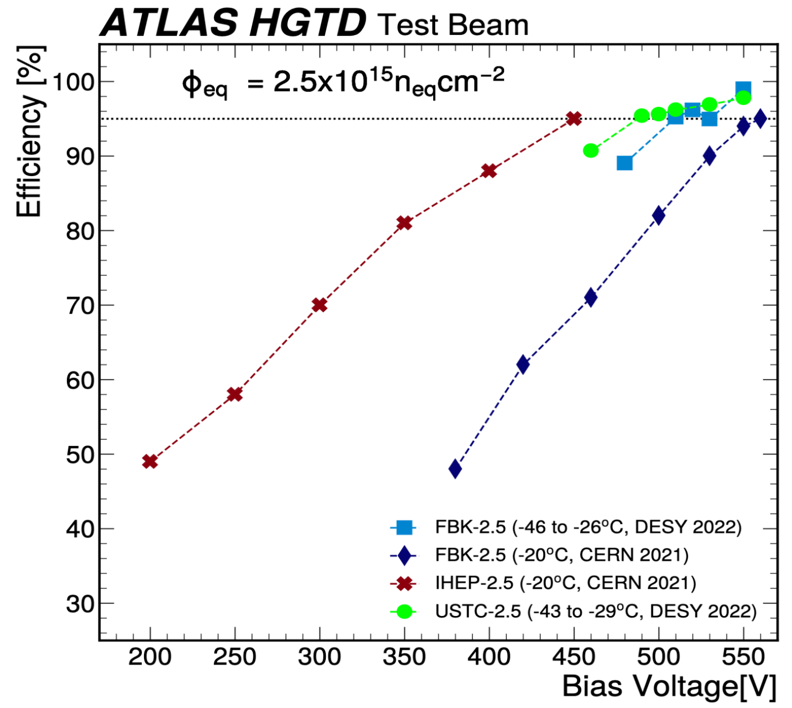
mu = -0.02 μm
Sigma = 4.6 μmm

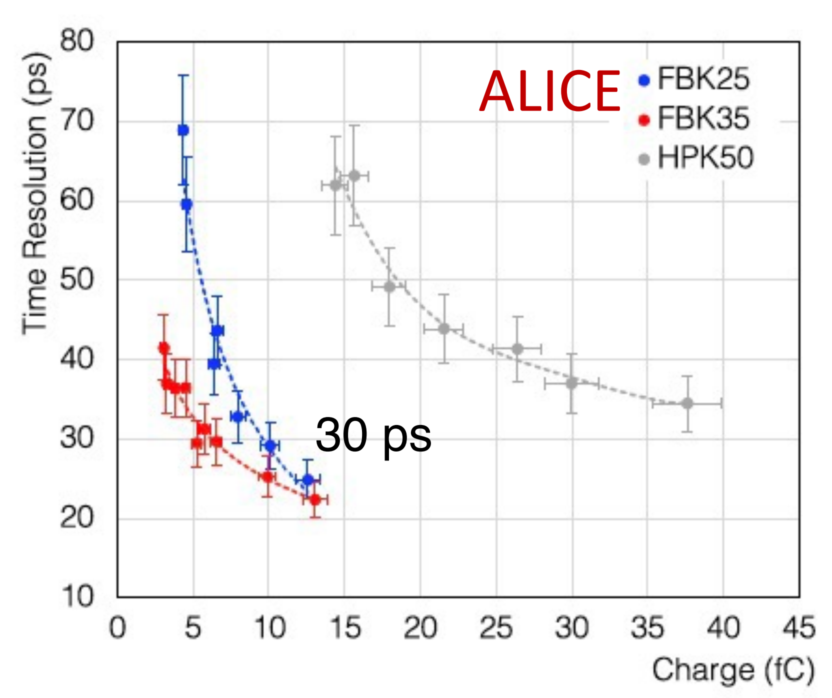
Sensors with gain



- State of the art sensors for HGTD (ATLAS) and CMS endcap MIP Timing Detector (MTD) - Pixel size 1.3 mm x 1.3 mm
- Time resolution: measured with a time reference device < 50 ps even after $2X10^{15}\ n_{eq}/cm^2$
- R&D for ALICE TOF
  – 25 and 35 µm thick prototypes show time resolution < 25 ps
  – Sensors of 10 µm in preparation

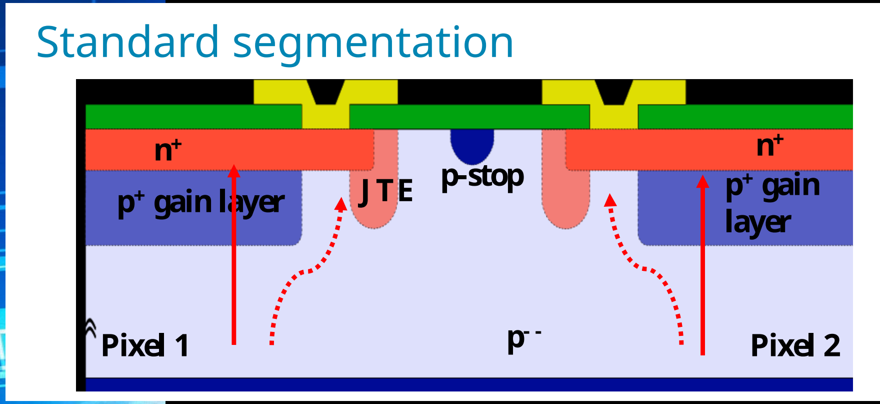


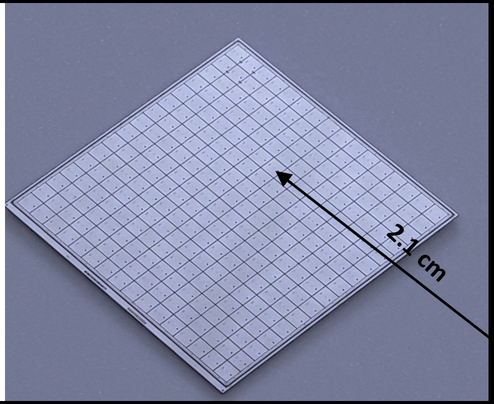




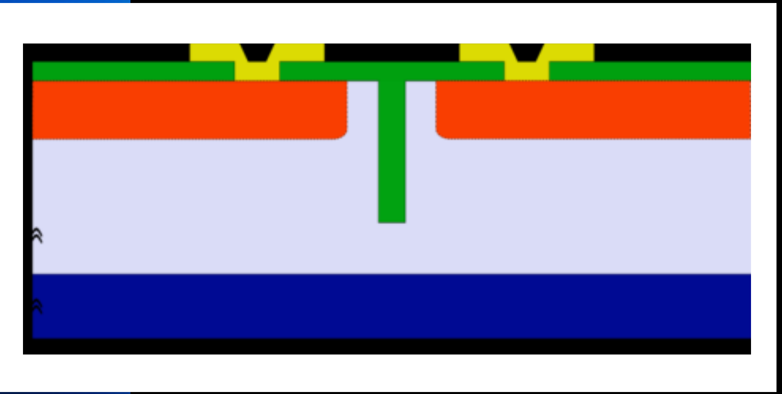
Sensors with gain

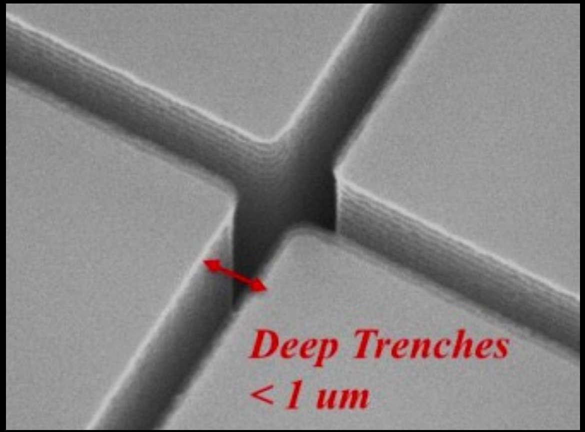
JTE + p-stop design (no gain area)



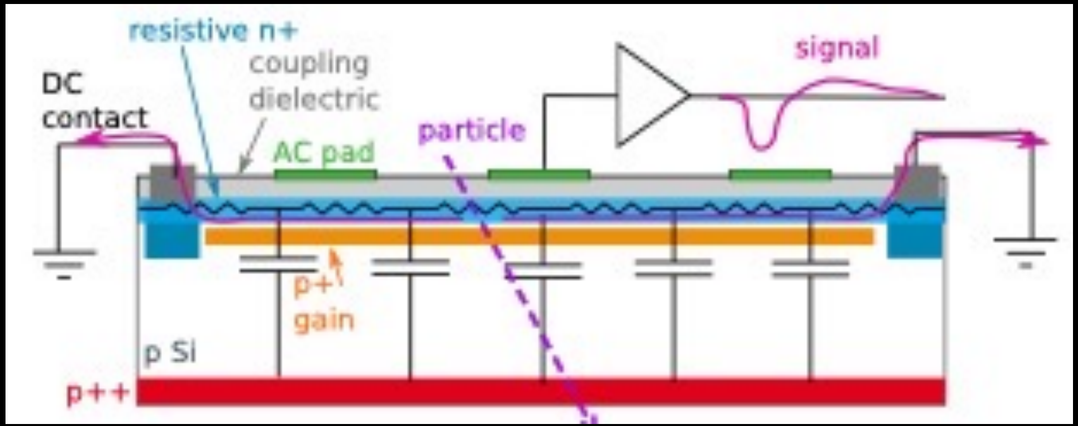


Trench-isolated design (trench filled with Oxide)

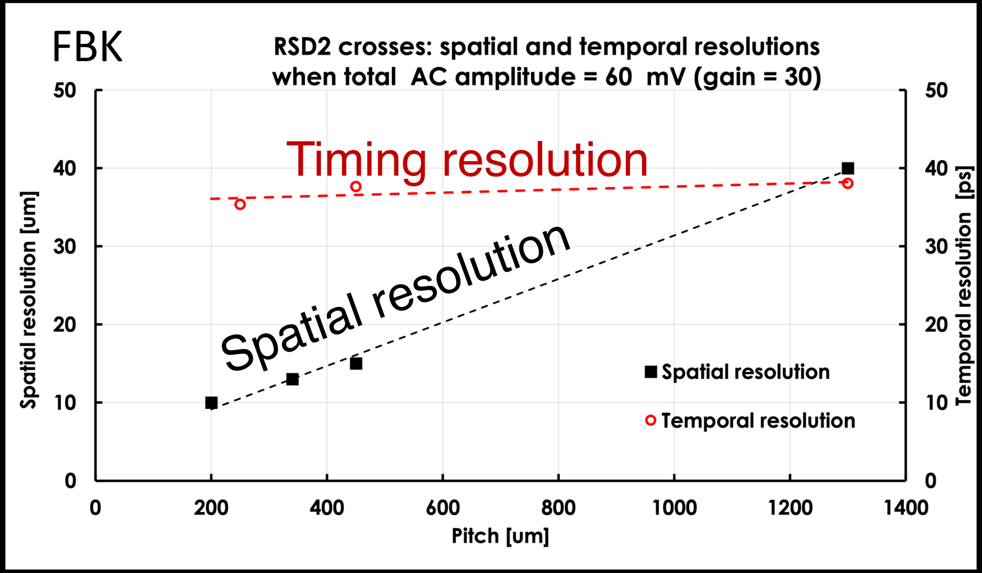




Resistive AC LGAD



- Continuous resistive n+ implant
- Readout: AC-coupling through dielectric layer
- Segmentation obtained by position of the AC pads

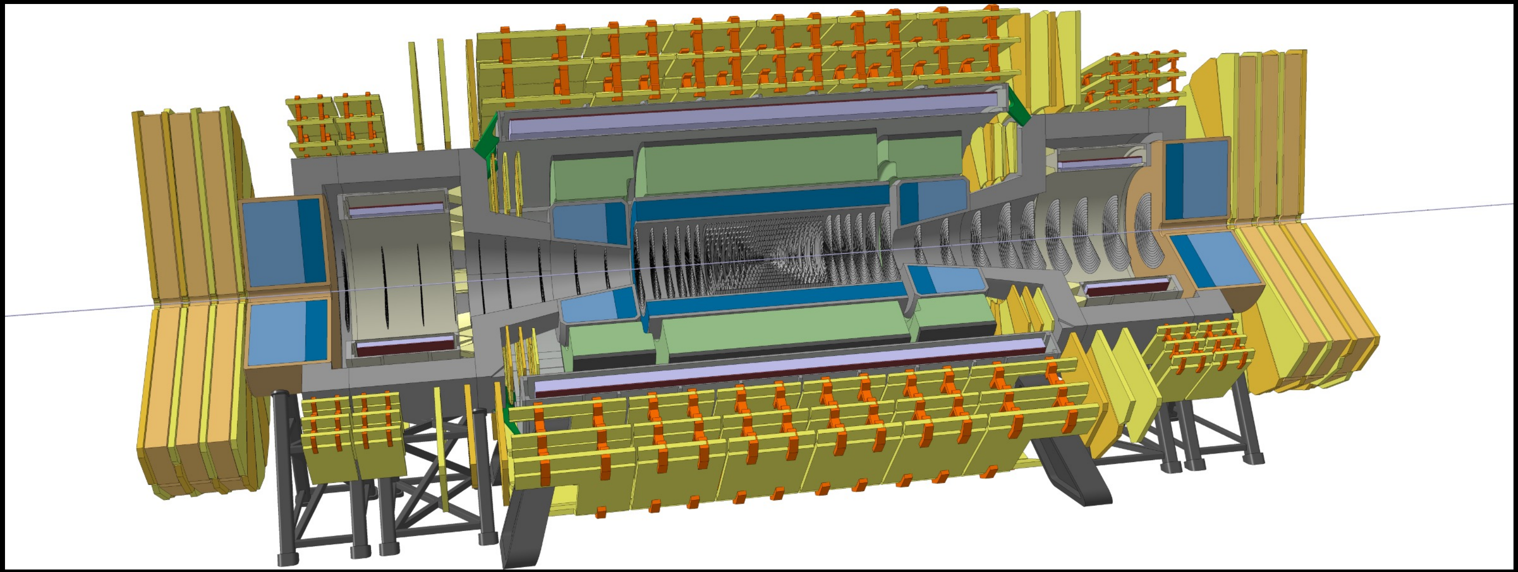


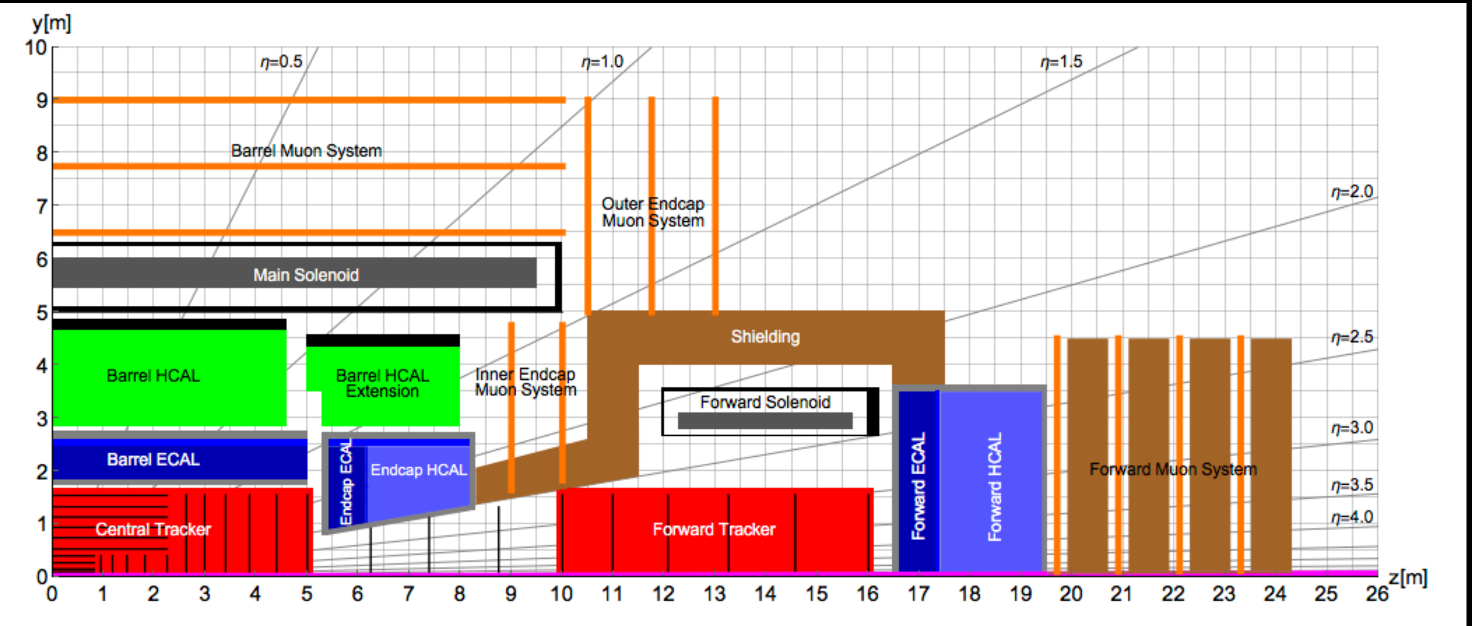
Cartiglia

FCC-hh Detector Concept

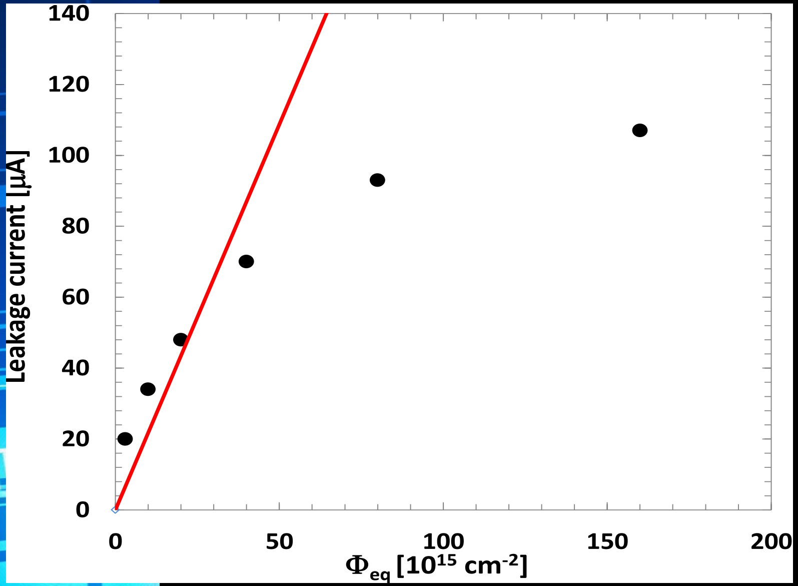
50 m long, 20 m diameter

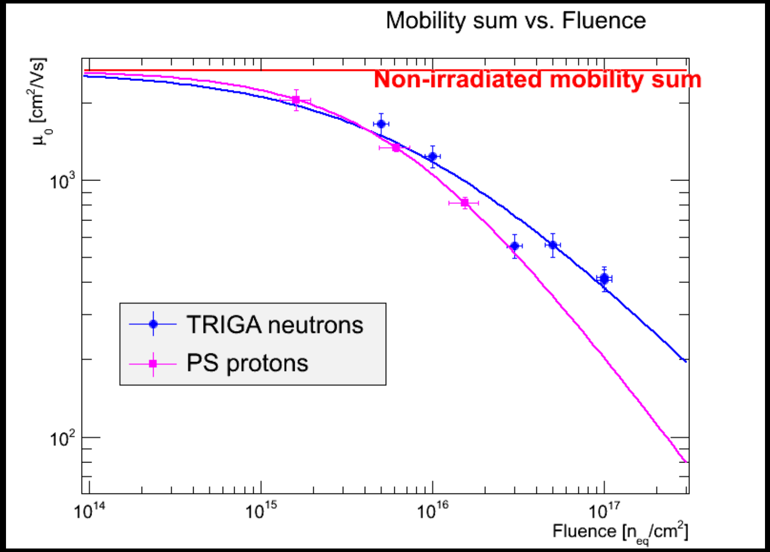
- More forward physics → large acceptance
  - Tracking and calorimetry up to $|\eta| < 6$
- Achieve σ_{p_T} / p_T = 10-20% @ 10 TeV
- Physics objects more boosted
  - high granularity (both in tracker and calorimeters)
- Goal 30/ab @100Tev
- Tracker: first IB layer (2.5 cm- 10 GHz/cm^2 charged particles): ~6E10^{17}/cm^2 and 300 MGy TID
  - HL-LHC = 20 x LHC
  - FCC = 30 x HL-LHC
- Pileup of 1000 → Timing will be essential

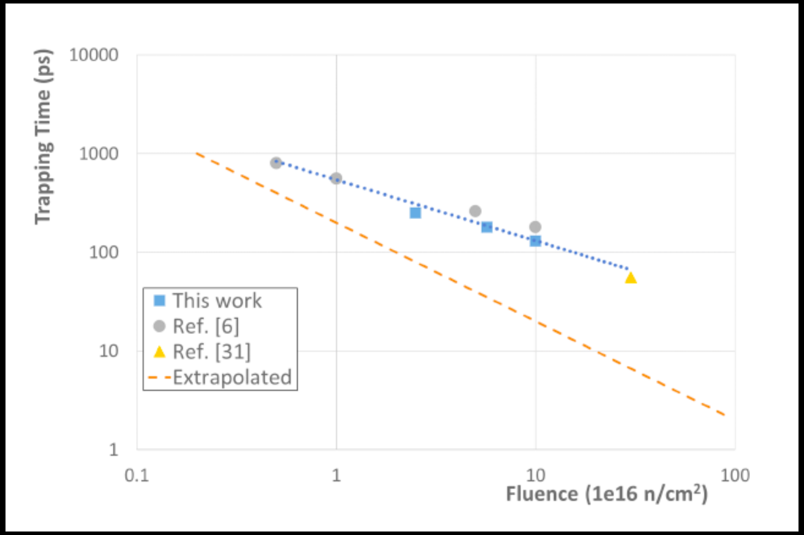




R&D on silicon at Extreme fluences







- Leakage current
  - n^+p "spaghetti" strips, 300 μm
  - Observation not compatible with extrapolations: Leakage current "saturating"

- Mobility reduction
  - Mobility decrease worse for protons

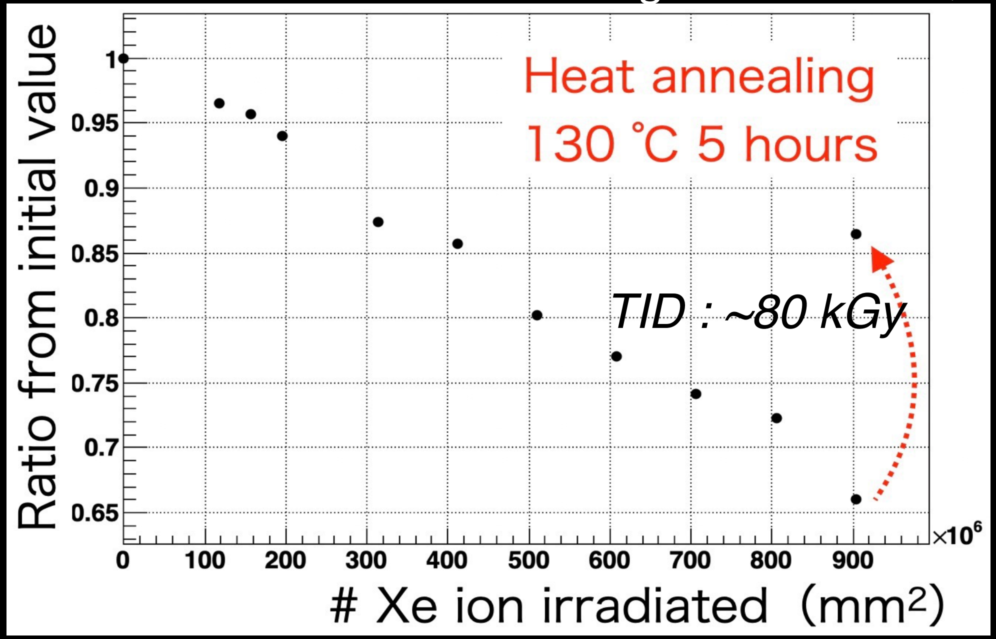
- Trapping time
  - Order of magnitude smaller than extrapolated

From *I.Mandić et al., JINST 15 P11018 (2020)*

R&D on silicon at Extreme fluences

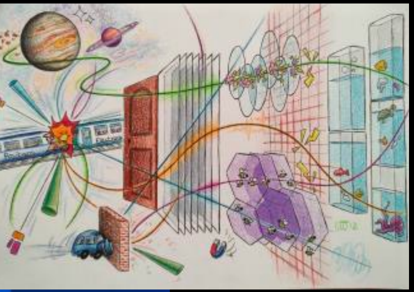
- CIGS(Cu,In,Ga,Se) was developed for solar cell
- Higher photon efficiency compared with Si and promising thin-film sensor
- Defects due to radiation degrades performance of sensor
- In the CIGS crystal, ions compensates defects with heat annealing and structural characteristics is recovered
- High radiation tolerance is expected

Manabu Togawa KeK and QPI



DRD3

WG3.6 on new materials:



- SiC Higher quality material available:
  - Power-efficient transistors in power supplies
  - Photovoltaic inverters
  - Electric car drive train
  - SiC-CMOS at Frauenhofer IIHS offers two MPW submissions per year
- Diamond and 2 D Materials (graphene)

- GaN :
  - Communications: cell phone chips, 5G base stations, LEO satellites, VSAT,
  - Automotive –LiDAR, power switches, power distribution
  - Aerospace –power amplifiers, radiation-hardened RF electronics
  - Military and defense –radar, military communications, electronic warfare

R&D on silicon at Extreme fluences

Manabu Togawa (KeK and QUP)

- CIGS(Cu,In,Ga,Se) was developed for solar cell
- Higher photon efficiency compared with Si and promising thin-film sensor
- Defects due to radiation degrades performance of sensor
- In the CIGS crystal, ions compensates defects with heat annealing and structural characteristics is recovered
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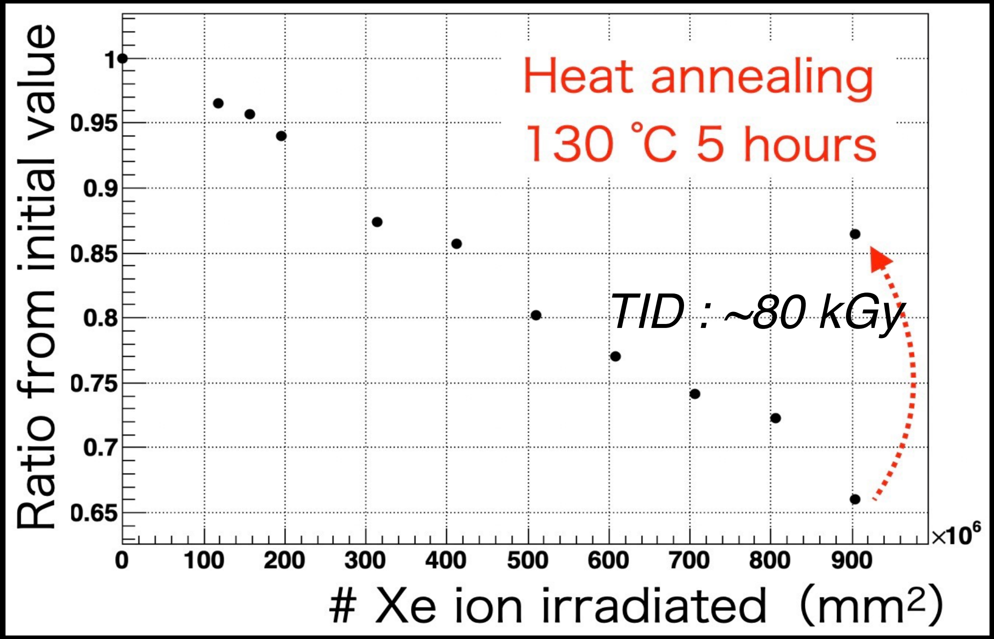
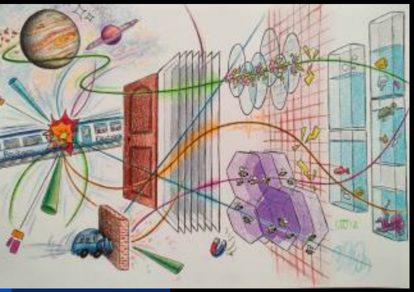
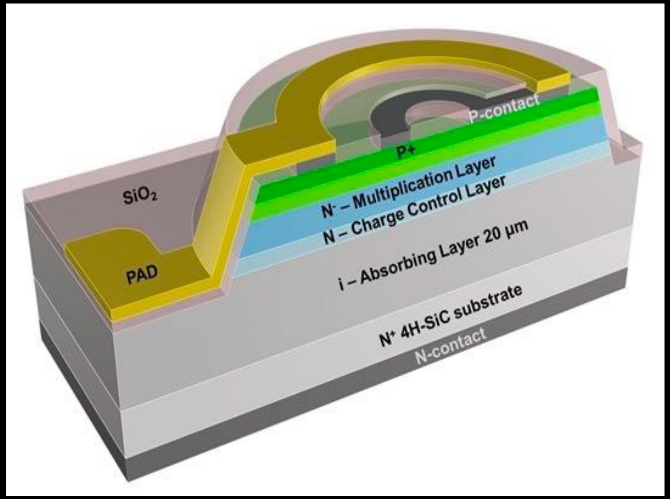


DRD3 SiC



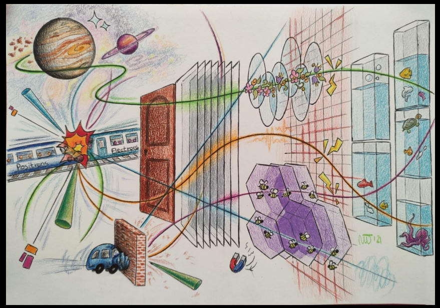


SiC LGADS

- Technological challenges:
  - —Only n-type substrates available
  - —Deep gain layer implant needs very high energy
- Progress at Nanjing University (NJU): gain <5 but early breakdown
- **New RD50 common project** for SiC-LGAD

Conclusions

DRD3



- R&D is ongoing
- DRD strategic R&D will provide more focus and hopefully dedicated funding for students, postdocs, professionals, researchers
- Light weight minimal mass support structures for tracking detectors are critical for FCCee physics
- Test beam & irradiation facilities are essential
  - Modernization of infrastructures
  - Coordination of upgrades between various laboratories
- Exploitation of running facilities to test prototypes in realistic environments
- More recognition of the importance of instrumentation needed

Technologies and work packages

DRDT 3.1	CMOS sensors	DRDT 3.2	Sensors for 4D tracking
WP1.1	TPSCo 65 nm	WP2.1	3D sensors
WP1.2	TowerJazz 180 nm	WP2.2	LGADs
WP1.3	LFoundry 150 nm		
WP1.4	TSI 180 nm		
WP1.5	LFoundry 110 nm		
WP1.6	IHP 130 nm		
DRDT 3.3	**Sensors for extreme fluence**	**DRDT 3.4**	**Demonstrator for 3D-integration**
WP3.1	Wide bandgap (SiC, GaN)	WP4.1	
WP3.2	Diamond	WP4.2	
WP3.3	Silicon		

- Finalizing proposal which includes deliverables and milestones

1st R&D phase, up to 2028-2029

Handle mandatory (independant) performance for strategic projects of 1st half of 2030's

Ball park generic performance targets* mandatory/desireable

Milestones	Tracking VD/CT	Timing Layer + Calorimeter
Heavy Ion	**M1** ultralight low power tracker pitch 10 - 30 µm @ O(100) MHz/cm^2, O(1) µs	**M2** O(20) ps (TL)
Flavour collider	ultralight low power tracker pitch 10 - 30 µm @ O(100) MHz/cm^2, O(1) ns	O(20) ps in (TL)
Lepton collider	e-e: ultralight low power tracker pitch down to <10 µm, @ O(100) MHz/cm^2 timing driven by power dissipation µ-µ: O(20) ps rates and irradiation tbc	O(10) ps in TL O(< 50) ps in calorimeter driven by power dissipation
pp collider	**M3** HL-LHC: 25-50 µm @ O(5) GHz/cm^2 5x10^{15} to 5x10^{16} neq/cm^2, 250 - 500 MRad timing O(<50) ps FCC-hh: < 10 - 20 µm @ 30 GHz/cm^2 4D tracking O(<10) ps up to O(10^{18}) neq/cm^2, up to O(50) GRad	**M4** HL-LHC: pitch O(<1) mm O(20) ps in TL, NIEL 5x10^{15} FCC-hh: 5D calorimeter O(<10) ps up to O(10^{18}) neq/cm^2, up to O(50) GRad

* ranges representative, ex. for VD and CT with more stringent constraints to be achieved in VD

2nd R &D phase, up to 2034-2035

Integration of 1st R&D phase performance in full 4D devices for stategic progams of the 2040 decade

Ball park generic performance targets* mandatory/desireable

Milestones	Tracking VD/CT	Timing Layer + Calorimeter
Heavy Ion	M1 ultralight low power tracker pitch 10 - 30 µm @ O(100) MHz/cm^2, O(1) µs	M2 O(20) ps (TL)
Flavour collider	ultralight low power tracker pitch 10 - 30 µm @ O(100) MHz/cm^2, O(1) ns	O(20) ps in (TL)
Lepton collider	M5 e-e: ultralight low power tracker pitch down to <10 µm, @ O(100) MHz/cm^2 timing driven by power dissipation µ-µ: O(20) ps rates and irradiation tbc	M6 O(10) ps in TL O(< 50) ps in calorimeter driven by power dissipation
pp collider	M3 HL-LHC: 25-50 µm @ O(5) GHz/cm^2 $5x10^{15}$ to $5x10^{16}$ neq/cm^2, 250 - 500 MRad timing O(<50) ps	M4 HL-LHC: pitch O(<1) mm O(20) ps in TL, NIEL $5x10^{15}$
	M7 FCC-hh: < 10 - 20 µm @ 30 GHz/cm^2 4D tracking O(<10) ps up to O(10^{18}) neq/cm^2, up to O(50) GRad	M8 FCC-hh: 5D calorimeter O(<10) ps up to O(10^{18}) neq/cm^2, up to O(50) GRad

* ranges representative, ex. for VD and CT with more stringent constraints to be achieved in VD

DRD3 Working Group's R&D Plan

- **WG 3.1: Monolithic CMOS sensors**
  - Spatial resolution of 3 μm
  - Timing precision of 20 ps
  - Readout architectures for 100 MHz/cm^2
  - Radiation tolerance of 10E16 n_{eq}/cm^2 NIEL and 500 MRad
- **WG 3.2: Sensors for tracking and calorimetry**
  - Spatial and temporal resolutions at extreme radiation levels
  - Reduction of pixel cell size for 3D sensors
  - 3D sensors with a temporal resolution of about 50 ps
  - Spatial and temporal resolutions at low radiation levels and low material and power budgets
  - LGAD sensors with very high fill factor and an excellent spatial and temporal resolution
  - LGAD sensors for Time of Flight applications
- **WG 3.3: Radiation damage and extreme fluence operation**
  - Build up data sets on radiation induced defect formation in WBG materials
  - Develop silicon radiation damage models based on measured point and cluster defects
  - Provide measurements and detector radiation damage models for radiation levels faced in HL-LHC operation
  - Measure and model the properties of silicon and WBG sensors in the fluence range 10E16 to 10E18 n_{eq}/cm^2

DRD3 Working Group's R&D Plan

- **WG 3.4: Simulation**
  - Flexible CMOS simulation of 65 nm to test design variations
  - Implementation of newly measured semiconductor properties into TCAD and MC simulation tools
  - Definition of benchmark for the validation of the radiation damage models with measurements and benchmark different models
  - Developing of bulk and surface model for 10E16 neq/cm2to 10E17 neq/cm2 NIEL
  - Collate solutions from different MC tools and develop algorithms to include adaptive electric and weighting fields
- **WG 3.5: Measurement and characterization techniques**
  - Development of new semiconductor characterization techniques is a priority for future detector developments
  - These techniques should enable high-resolution imaging and defect spectroscopy of semiconductor materials, as well as advanced characterization of charge transport properties
  - The Two Photon Absorption –TCT setup, Caribou DAQ system and the Ion Beam testing and irradiation facility at RBI have been identified as good examples and further improvements are being proposed
- **WG 3.6: Wide bandgap and innovative sensor materials**
  - 3D diamond detectors, cages/interconnects, base length 25 μm, impact ionisation
  - Fabrication of large area SiC and GaN detectors, improve material quality and reduce defect levels
  - Improve tracking capabilities of WBG materials
  - Apply graphene and/or other 2D materials in radiation detectors, understand signal formation

DRD3 Working Group's R&D Plan

- **WG 3.7: Sensor interconnection techniques**
  - Yield consolidation for fast interconnections
  - Demonstration of small pitch (< 30 μm) pixel interconnections
  - Demonstration of radiation hardness and thermomechanical constraints
  - Development of massless post-processing for commonly-used interconnection technologies
  - Bring part of the commonly-used interconnection technologies to specialised academic groups
  - Develop device-to-wafer interconnection technologies
  - Develop wafer-to-wafer in presently advanced interconnection technologies
  - Develop VIAS in multi-tier sensor/front-end assemblies
  - Develop connection techniques for post-processed devices
- **WG 3.8: Outreach and dissemination**
  - Disseminating knowledge on solid-state detectors to people working in high energy physics
  - Disseminating knowledge on solid-state detectors to high-school students and the general public

IDEA SI & ARCADIA

Vertex detector requirements:

- single point resolution of first layer < 3µm
- digital pixel with in-pixel discriminator 16 µm pitch
- material budget as low as possible
- 50 µm Si substrate thickness 0.15% X0/layer
- low power <50 mW/cm^2 for air cooling
- pixel readout time <10 µs due to 100 kHz event rate
- 25 ns time resolution for beam spacing @Z-pole
- inner layer at 16mm (maybe even closer)
- <3.4 Mrad & 6.2x10^{12} n_{eq}/cm^2 per year
- (factor 10 safety margin!)