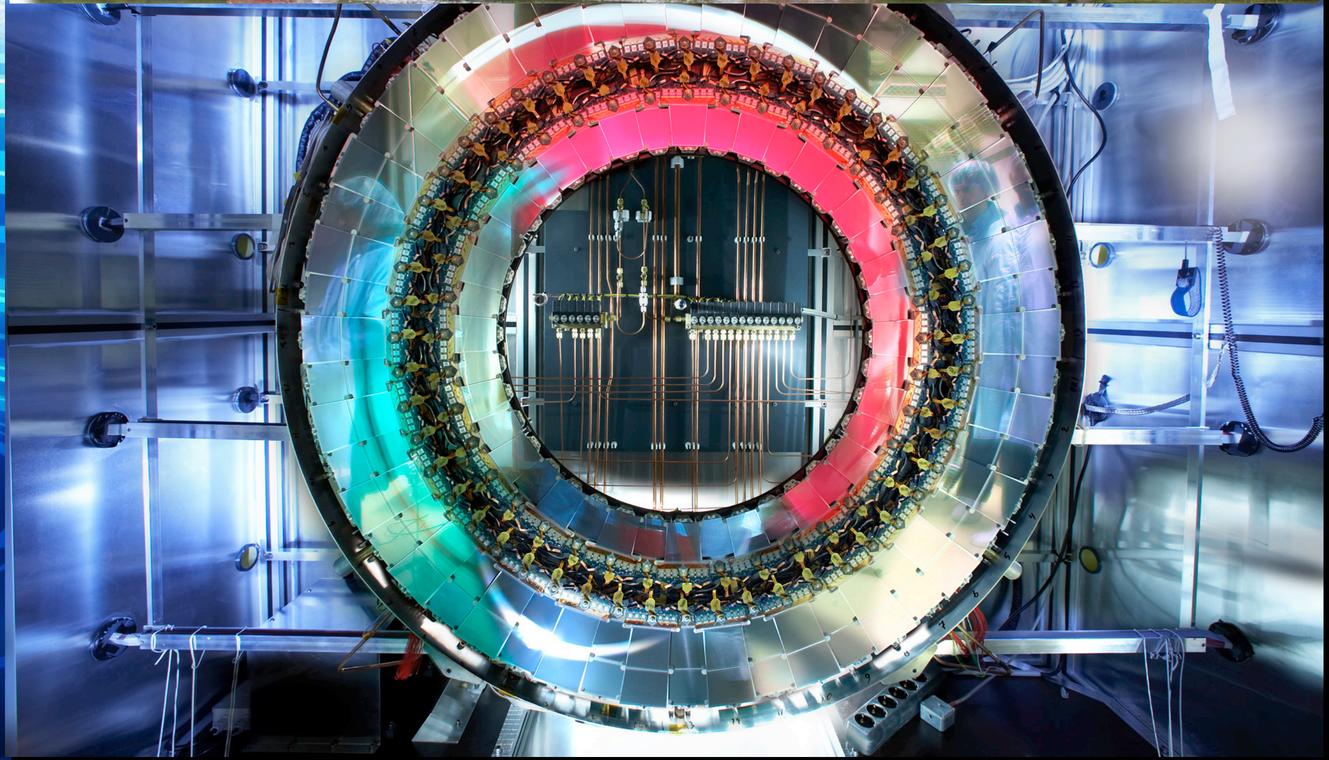
UNIVERSITY OF OXFORD

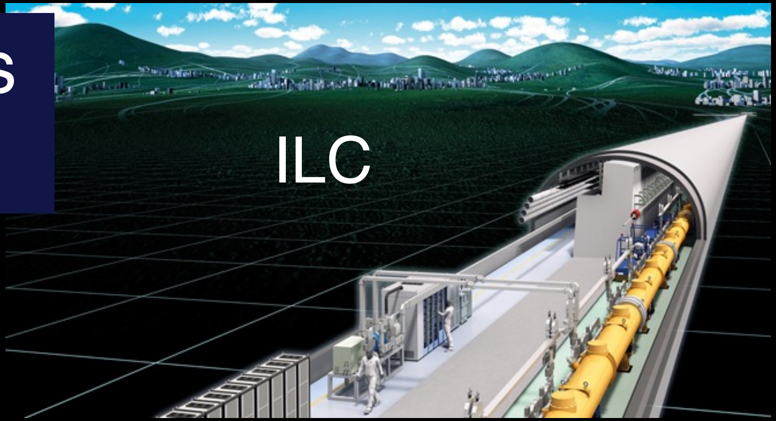


Detector Challenges at Future Colliders and recent R&D Highlights

Daniela Bortoletto

Possible Future Facilities

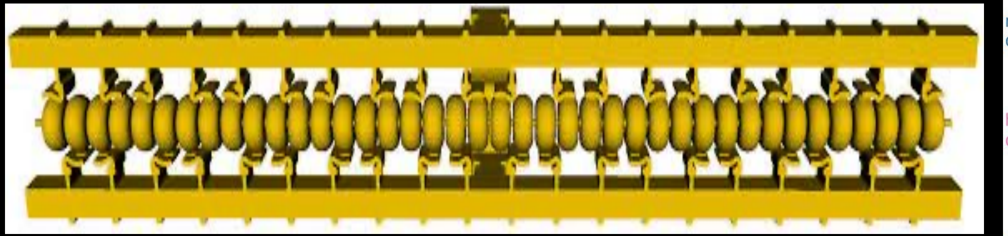
e+e- Higgs Factories



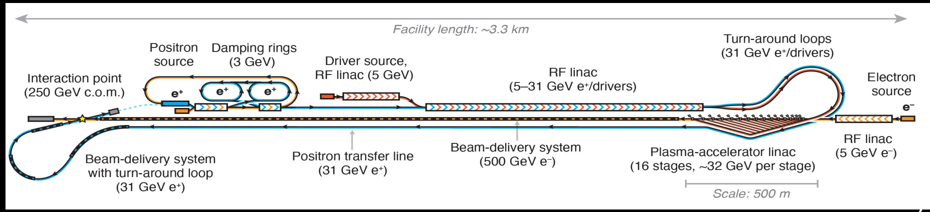
From Higgs Factories to 100 TeV hadron colliders

CLIC

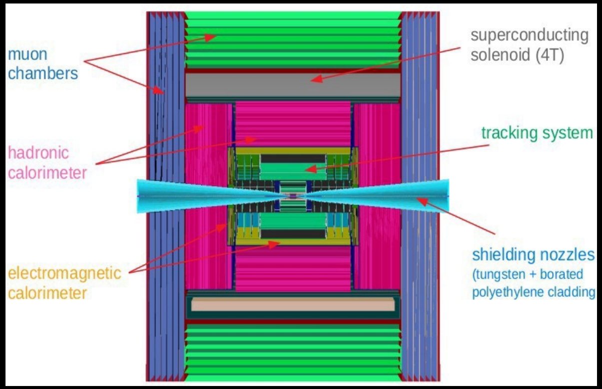
C3



HALHF



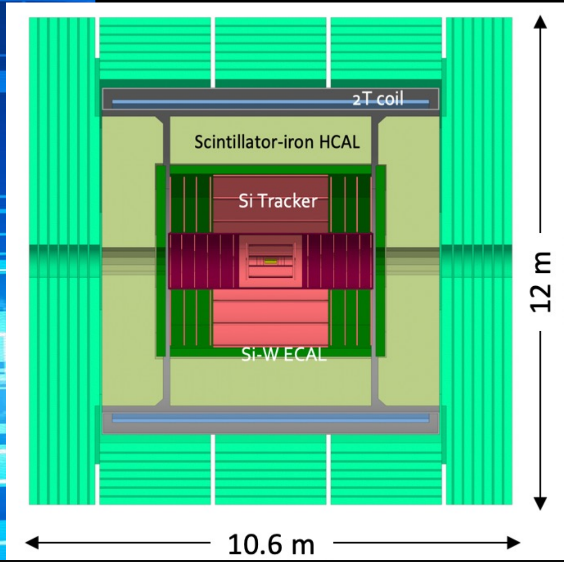
Muon Collider



FCC-ee/ FCC-hh/ FCC-eh

FCCee Proto-Detector Concepts

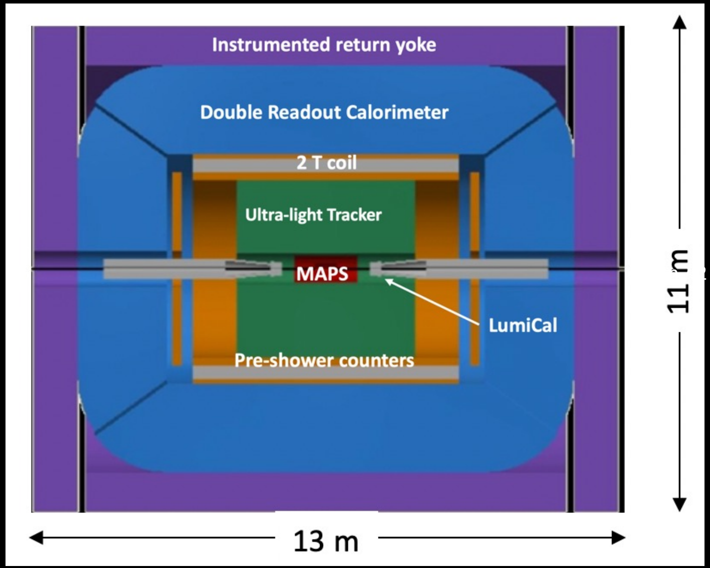
CLD



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

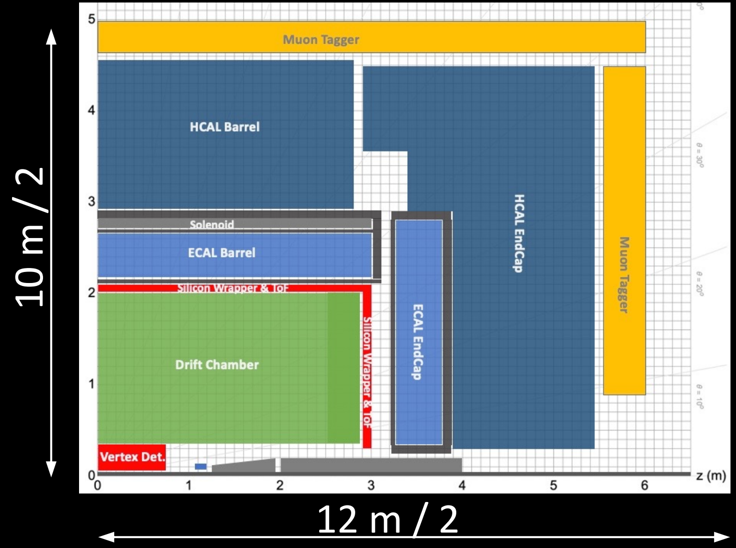
Possible detector optimizations
- PID -$\mathcal{O}$(10 ps) timing and/or RICH….

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-scintillating/Cherenkov fibres + possible crystal ECAL
- Instrumented yoke with MPGC for muon detection

ALLEGRO

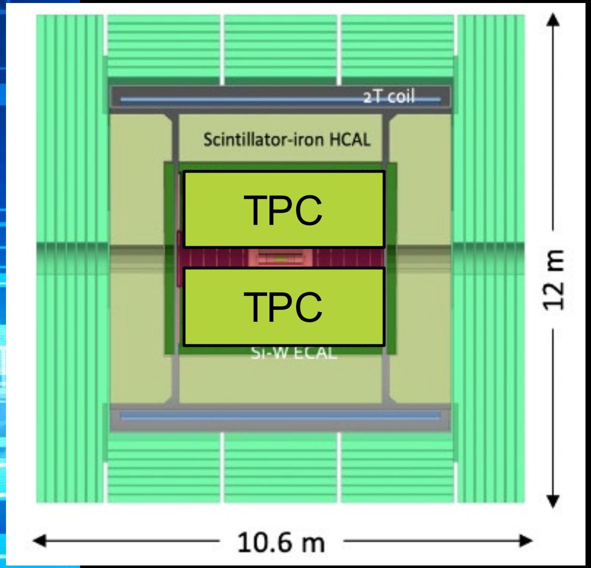


- Silicon vertex detector
- Low X_0 drift chamber with particle ID (or Si)
- Light, thin 2T coil inside the same cryostat as ECAL
- High granularity Lead/Noble Liquid (LAr, possibly LKr) ECAL
- HCAL steel and scintillator layers (Similar to ATLAS TileCal)
- muon systems to be specified

FCCee Proto-Detector Concepts

CLD: https://arxiv.org/abs/1911.12230
IDEA: https://pos.sissa.it/390/819
ALLEGRO: Eur.Phys.J.Plus 136 (2021) 10, 1066, https://arxiv.org/abs/2109.00391

CLD/ ILD'



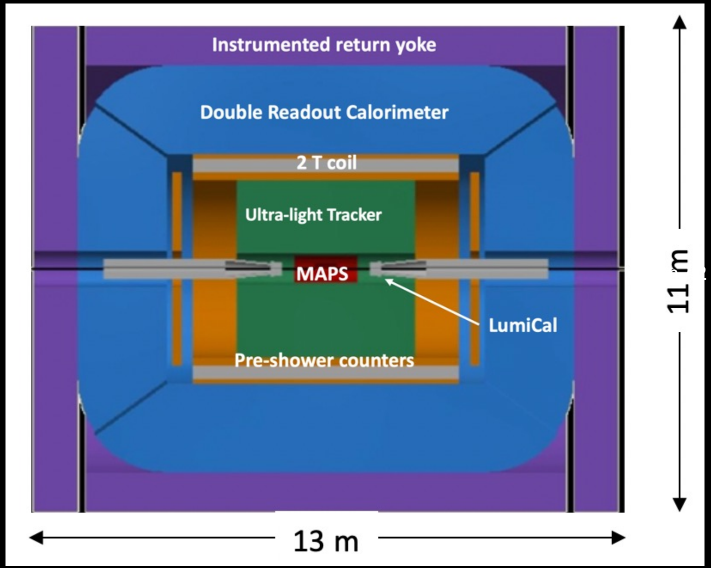
ILC → CLIC detector →CLD

- Full silicon vertex +tracker/study TPC
- 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



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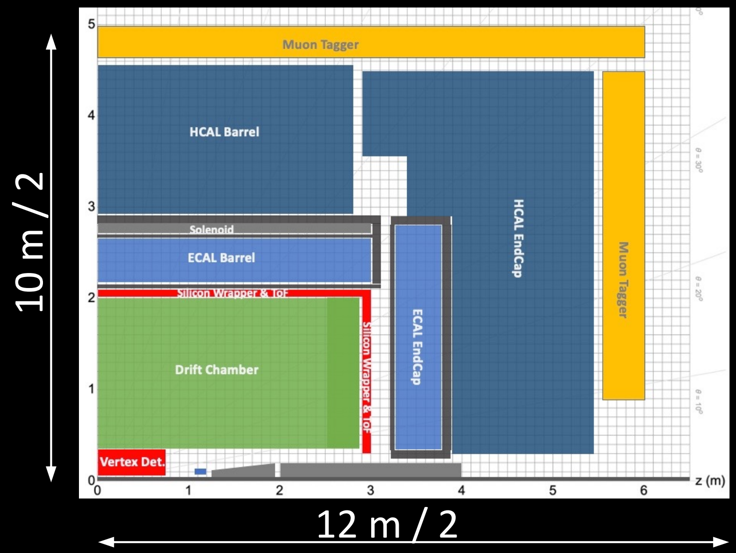

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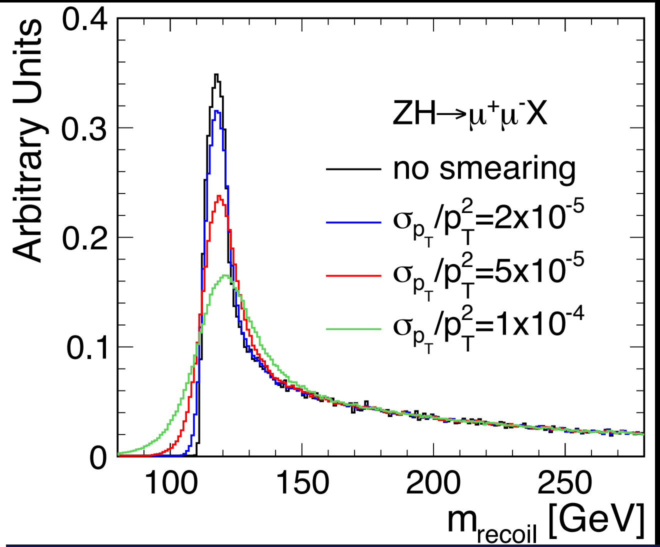
- muon systems to be specified

Requirements FCCee

Higgs Physics:
- Z Coupling at ‰ level
- Higgs couplings (b,c,s?)
- Invisible decays
- Self-coupling
- ee→ H

- Excellent σ_{P_T} for HZ reconstruction $\sigma_{P_T}/P_T^2 \simeq$ 2 x 10^{-5} / GeV with B field limited to 2 T
- Jet **energy** resolution of 3-4% for Z/W separation
- Superior impact parameter resolution for c and b tagging $\sigma_{d_0} = 5 \oplus 10 - 15/(p[GeV] \sin^{3/2}\theta)\ \mu m$
- PID



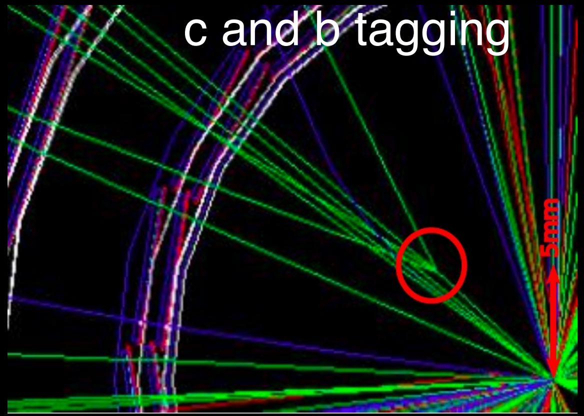
For silicon: 1-2% X_0/layer and ~ 7 μm point resolution

Ultra precise QCD and EW Physics (5 x 10^{12} Z)
- m_Z, Γ_Z, m_W, m_{top},…….

- Momentum resolution M.S. limited
- Track angular resolution < 0.1 mrad
- Absolute **luminosity** normalization to 10^{-4}
- Stability of B-field to 10^{-6}

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

- Superior impact parameter resolution
- ECAL resolution at few %/sqrt(E)
- Excellent π^0/γ separation for **tau identification**



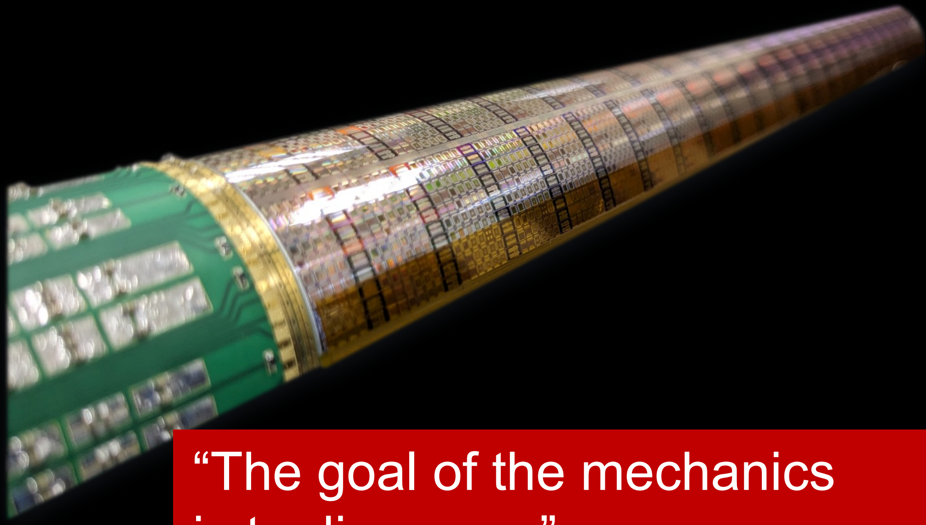
BSM
- feebly interacting particles with masses below m_Z
- Axion-like particles, dark photons, Heavy neutral leptons
- Long lifetimes LLPs

- Sensitivity to far detached vertices
  - **Tr**acking: more layers, “continuous" tracking
  - Calorimeter: granularity, tracking capability
  - Large decay length → extended decay volume
- Precise timing
- Hermeticity

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

Vertex Detectors Challenges

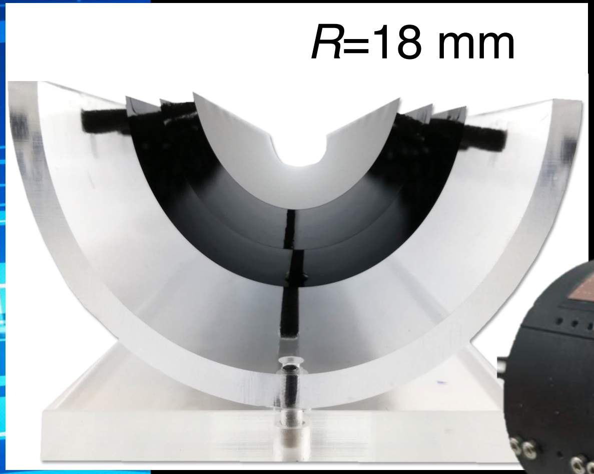
- Spatial Resolution
  - Inner and outer radius, and material minimization are key factors
  - Monolithic CMOS detectors (R&D chip design costs, complexity, connection to foundries)
  - < 20 mW/cm^2 for air flow cooling to minimize material
- Detector Optimization
  - Conflicting requirements (material, cooling, services, mechanics, etc.) need cooperation between physicists/chip designers/thermo/mechanical engineers/DAQ experts
- Beam-induced background: rate issue
  - incoherent pairs dominant with a yield rate of 400 MHz / cm^2
  - bandwidth 25 GB/s per module
- "Untriggered operation seems difficult"
- if confirmed: strong impact on all systems



"The goal of the mechanics is to disappear"

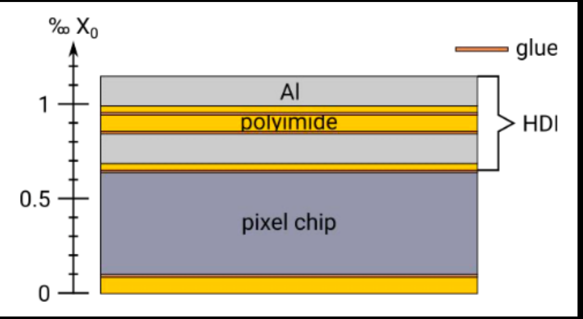
Stepping stones

ALICE ITS3

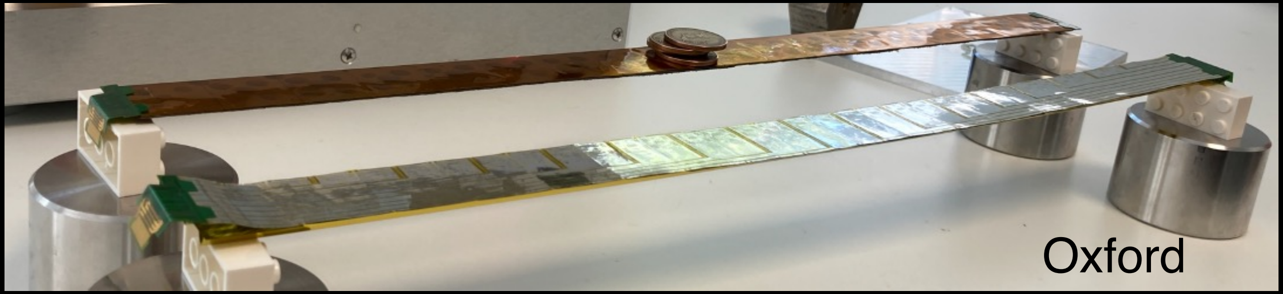


- Stitched 65 nm sensors
- Curved wafer-scale ultra-thin sensors in cylindrical layers
- 0.05% X_0/ layer
- TID ≈ 3Mrad and 2×10^{13} 1 MeV n_{eq} /cm^2.

Mu3e

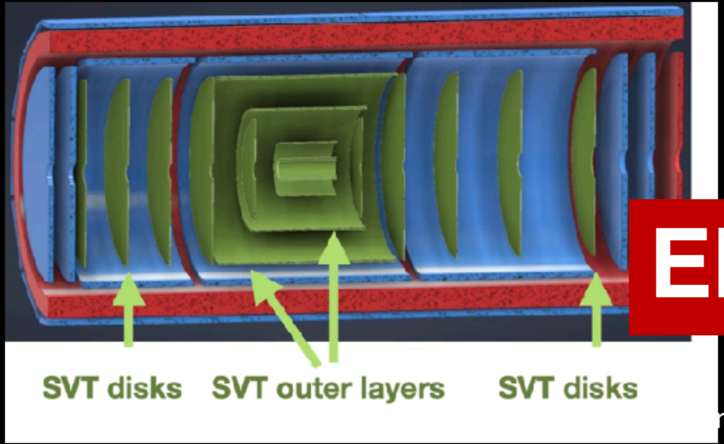


- Baseline:
  - Thinned 180 nm MAPS
  - Chip glued on Al/Kapton flex
  - 25 μm Kapton support
  - Helium cooling
  - 0.115% X_0/layer



Kapton V-folds
- Difficult to fabricate
- Enough structural integrity for 18 chip ladders

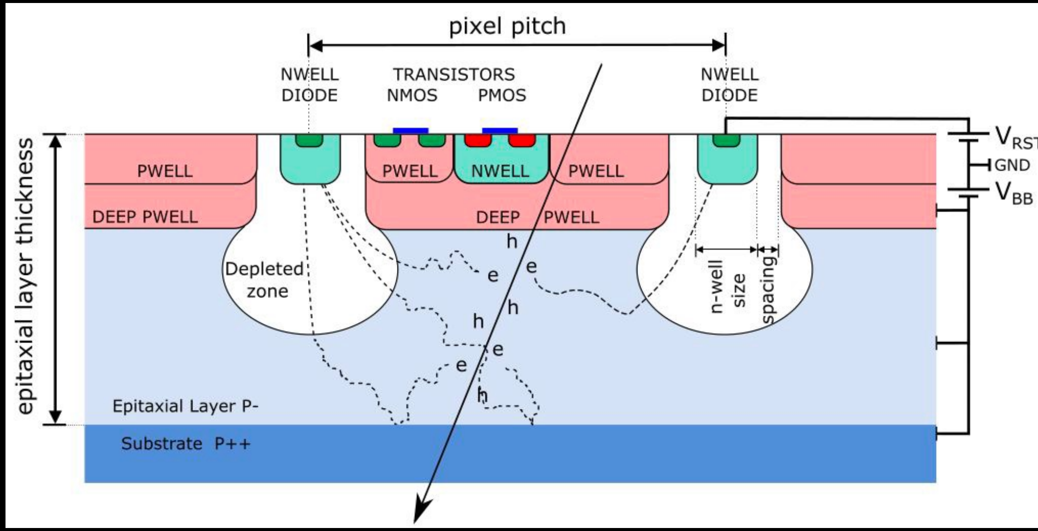
Carbon-fibre u-folds (25 μm thin)
- Lower mass than kapton



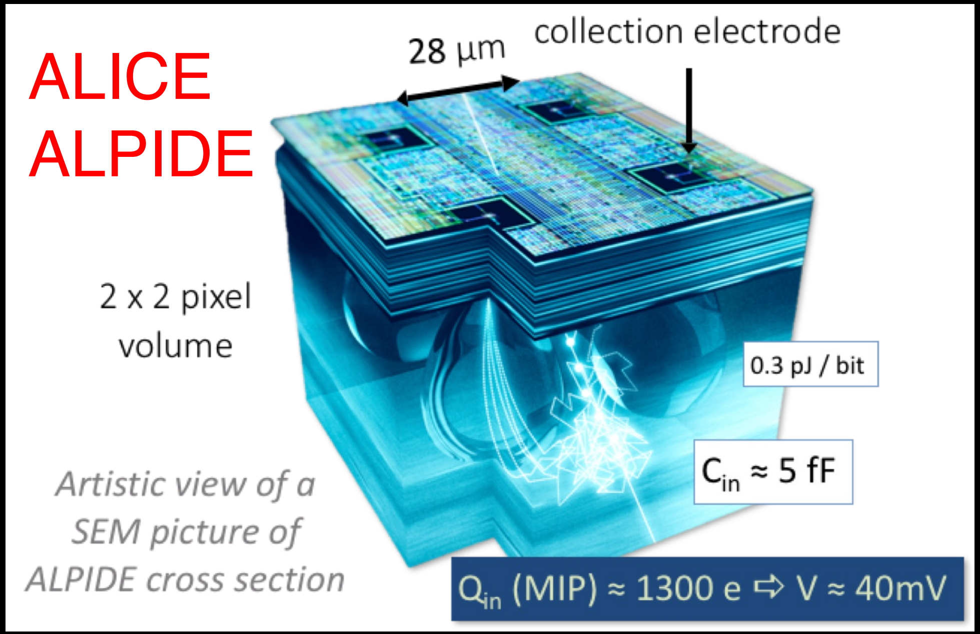
EIC Epic SVT

CMOS DMAPS Small Electrode

- State-of-the-art ALPIDE sensors for ALICE ITS 2 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)
  - Largest CMOS MAPS detector ever built (≈ 10 m^2)
  - Very low mass support achieving 0.35%X_0/Layer



- TPSCo 65 nm (Tower) for ITS3
- Benefits : 65 nm vs 180 nm
  - Better spatial resolution due to smaller feature size.
  - Larger wafers : 300 mm vs 200 mm → final sensor : 27x9 cm^2.
  - Lower power supply: 1.2 V vs 1.8 V → Low power consumption.
  - Lower material budget : thinner sensitive layer (~10 μm).
- Stitching and 7 metal layers
- Process modifications for full depletion:
  - Standard (no modifications)
  - Modified (low dose n-type implant)
  - Modified with gap (low dose n-type implant with gaps)



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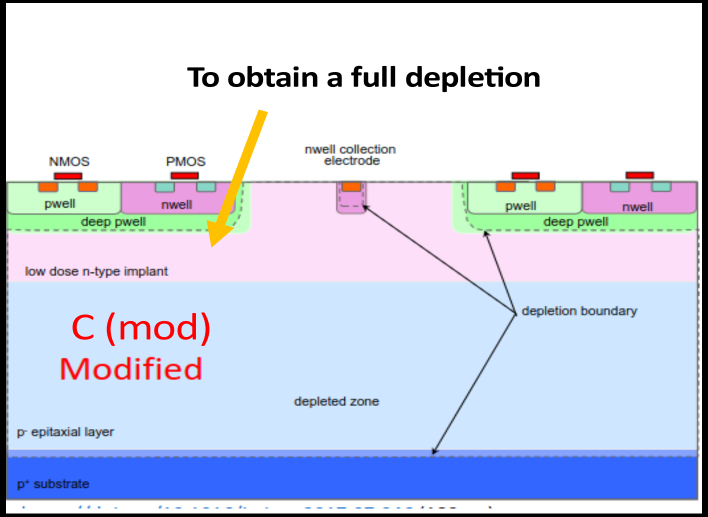
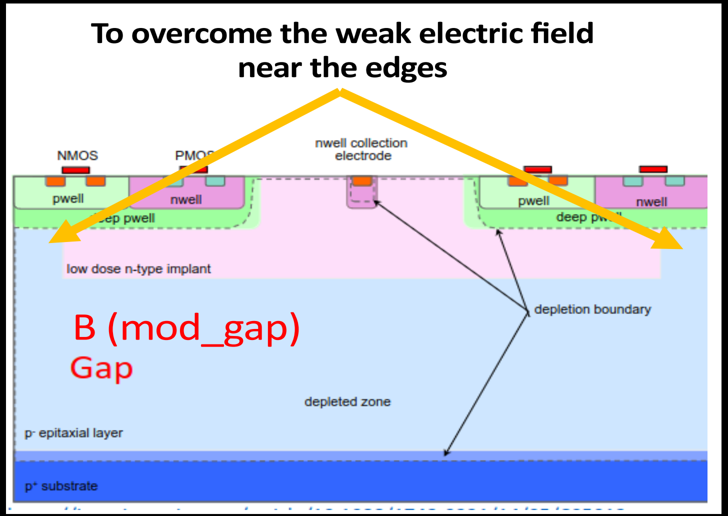


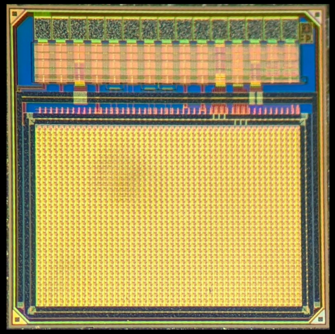


Studied in the 180 nm TJ with MALTA. T-J Monopix, OBELIX (Optimized BELle II pIXel sensor)

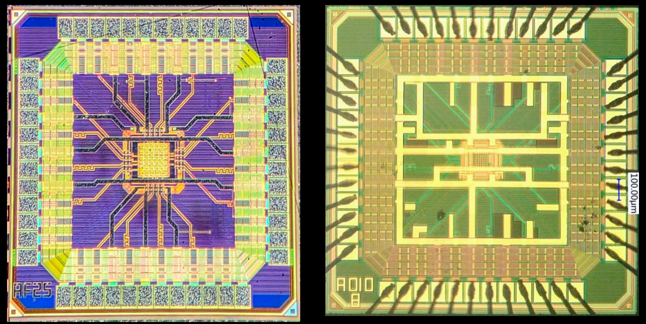
CMOS DMAPS Small Electrode

- Large collaborative effort (CERN + 24 institutions) and two submissions so far:
  - Multi Layer Reticule MLR1 (2020): sensor 10-25 μm pitch, 10 μm epi and checking process modifications
  - Engineering run (ER1) to check stitching with two prototypes
    - MOSS: 14mm x 259mm prototype
    - MOST: 2.5mm x 259mm prototype

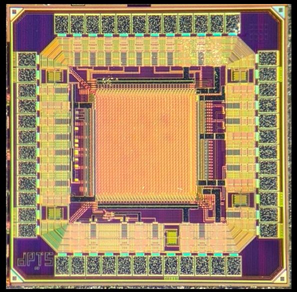
MLR1



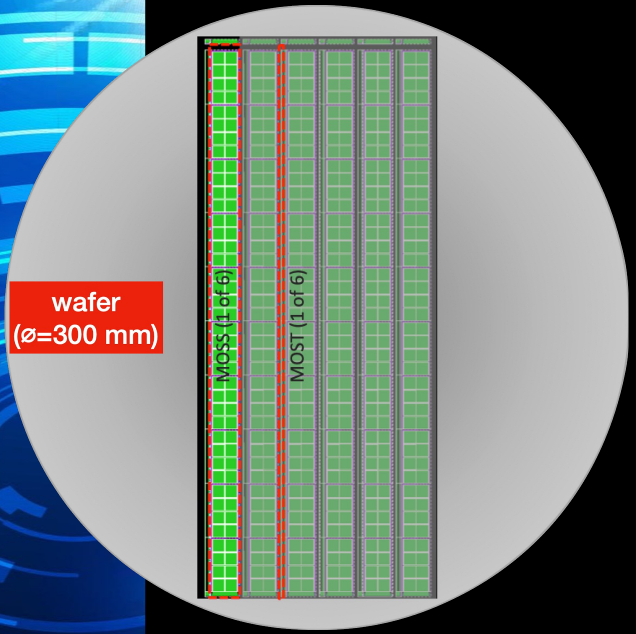
Circuit Exploratoire



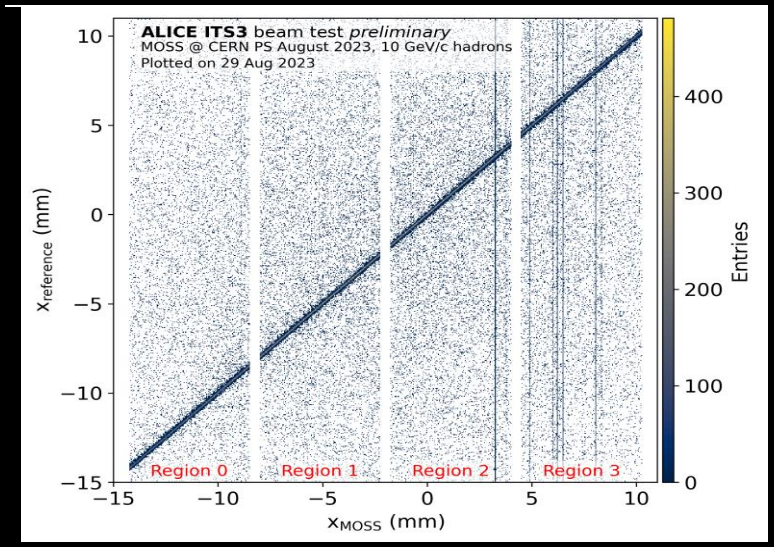
Analogue Pixel Test Structure



Digital Pixel Test Structure

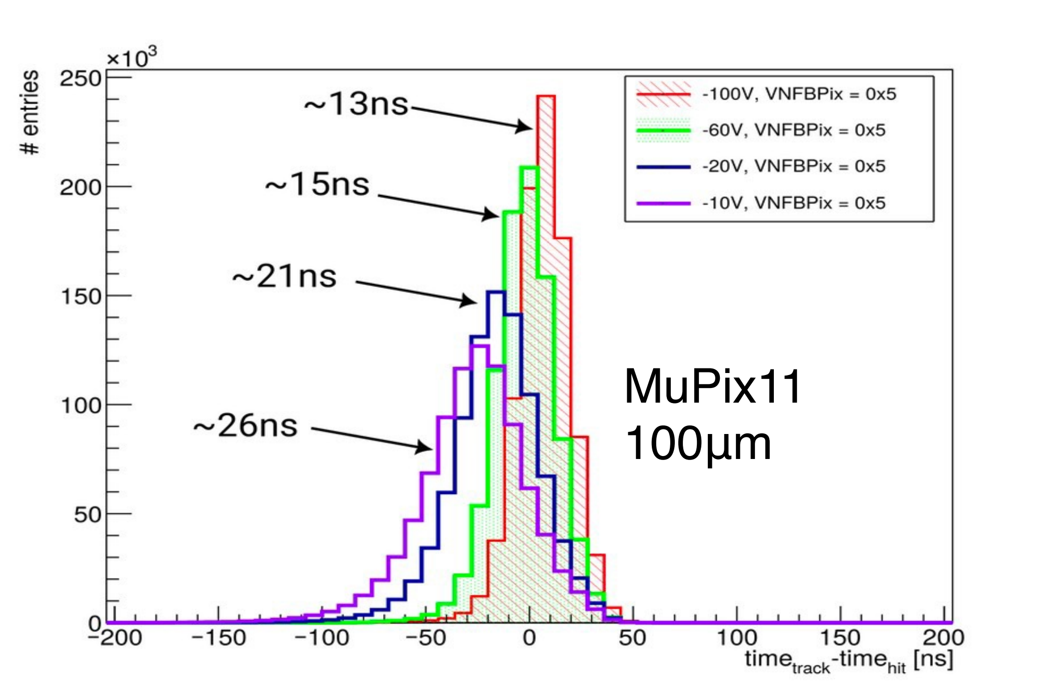


Hit x-coordinate correlation between MOSS and reference ALPIDE telescope



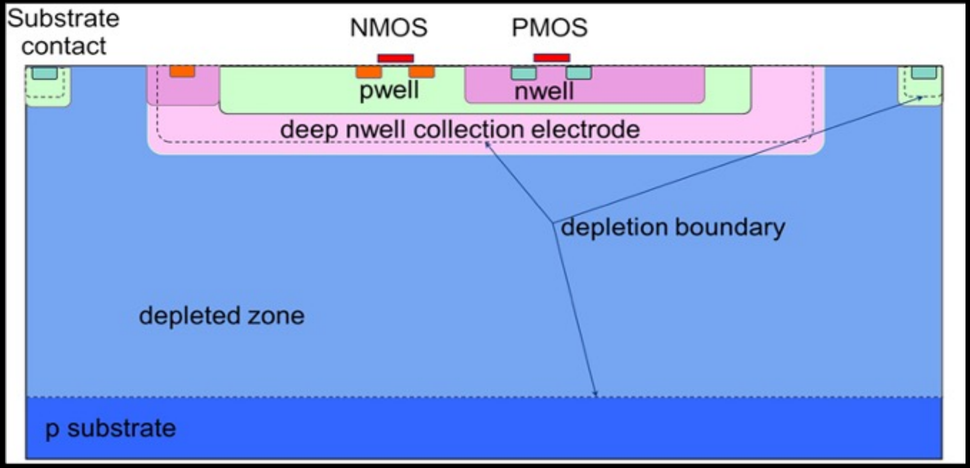
CMOS DMAPS Large Electrode

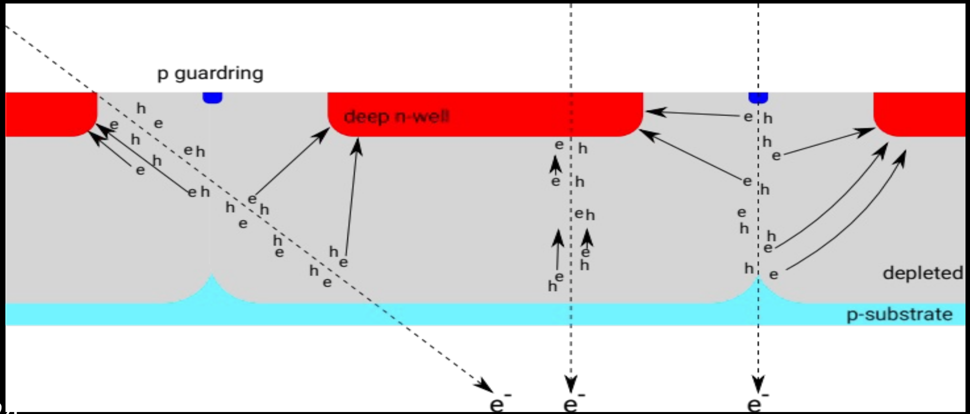
- State-of-the-art MUPIX11 for the Mu3e experiment on TSI semiconductor H18
  - 80x80 μm^2 pixels 50µm thick
  - Time resolution<20 ns
  - 0.115% X_0/layer and efficiency>99%



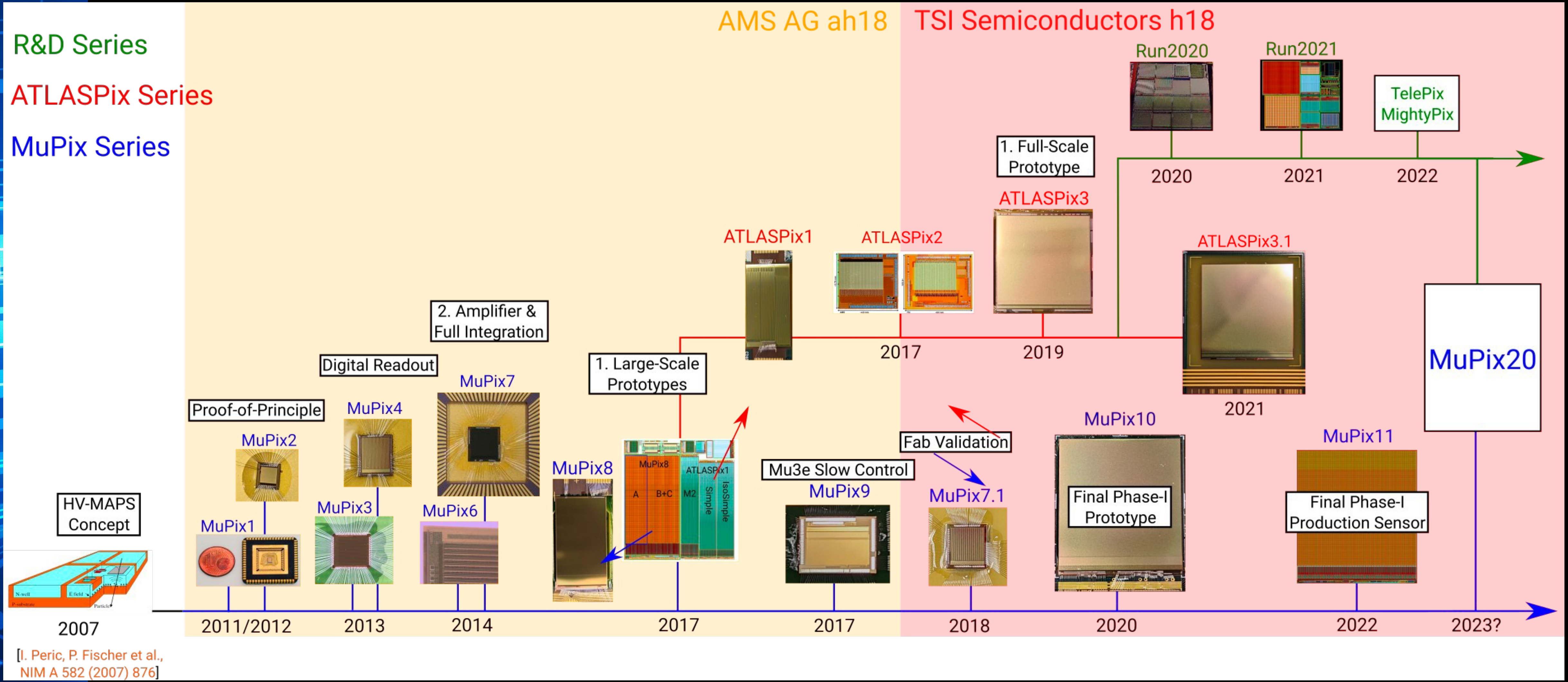
Large electrode:

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

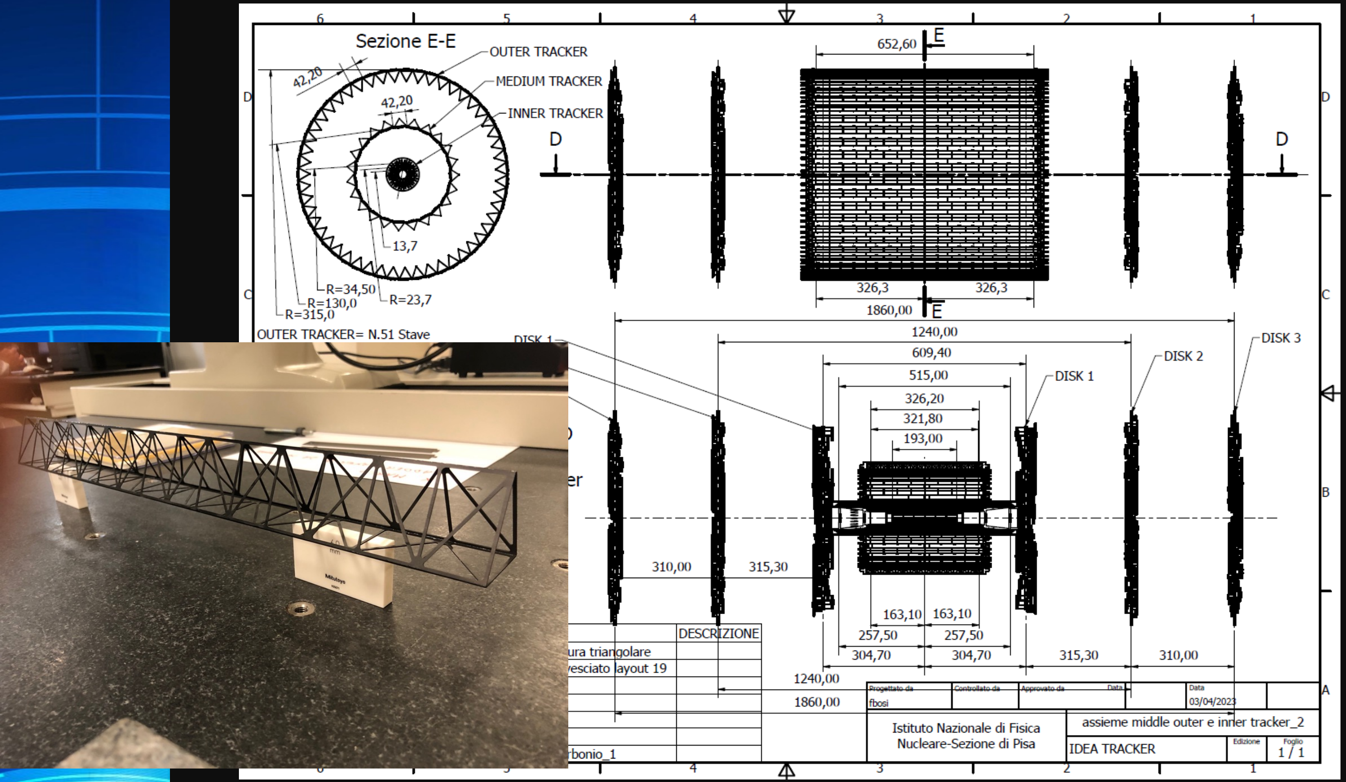




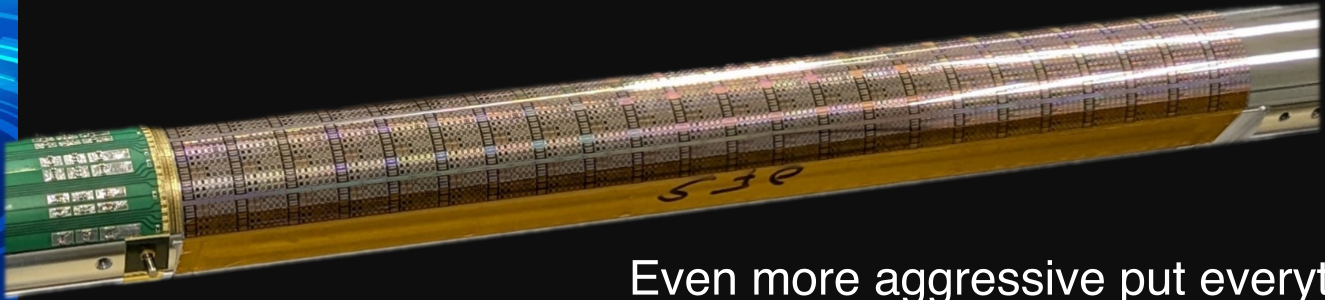
ATLASPiX/MuPix Series



IDEA VERTEX DETECTOR



- A detailed layout of IDEA VERTX detector was used for the midterm feasibility study
- **Outer vertex tracker:**
  - Modules of $50 \times 150\ \mu m^2$ pixel (ATLASPix)
  - 2 barrel layers: 13 cm and 31.5 cm radius
  - 3 disks per side
- **Inner Vertex detector:**
  - Modules of $25 \times 25\ \mu m^2$ pixel (ARCADIA)
  - 3 barrel layers at 13.7, 22.7 and 34.8 mm radius

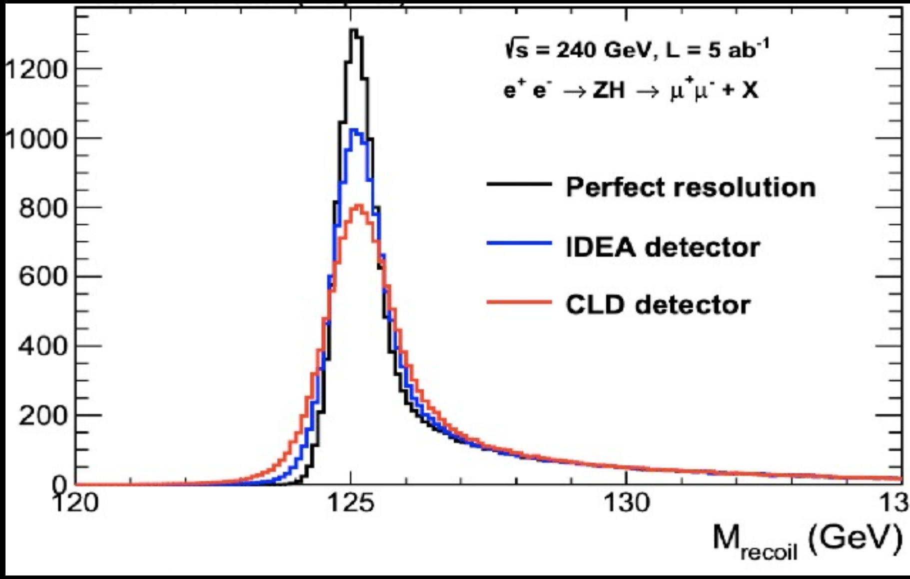


- Work starting to evaluate a configuration similar to ALICE ITS3

Even more aggressive put everything in beam pipe with a secondary vacuum (ALICE IRIS)

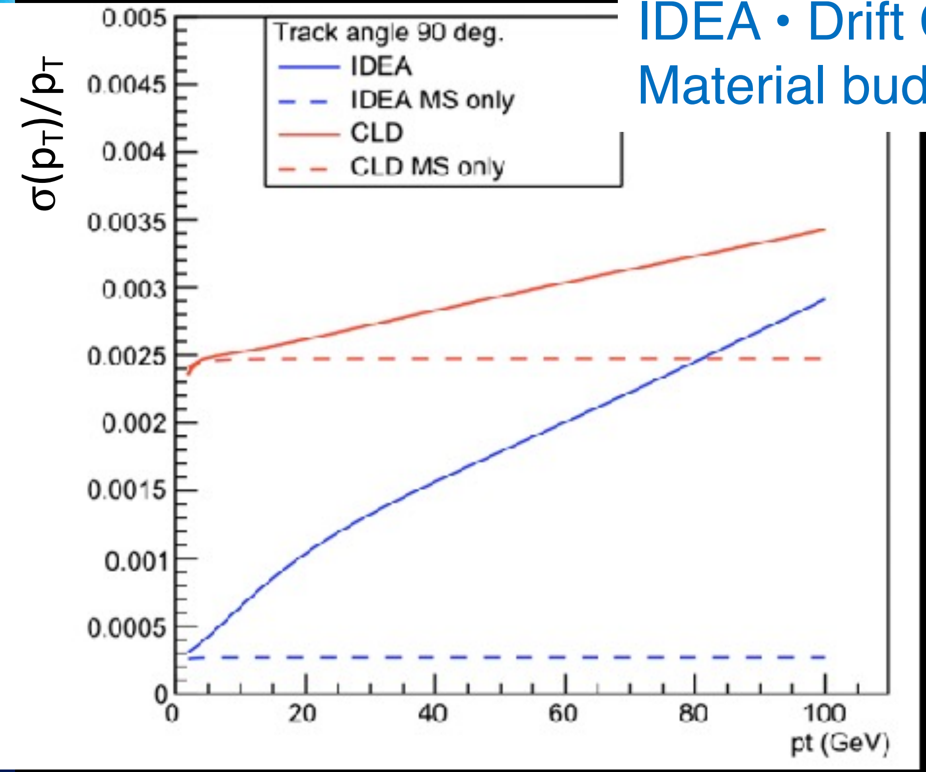
FCC-ee Tracking optimization

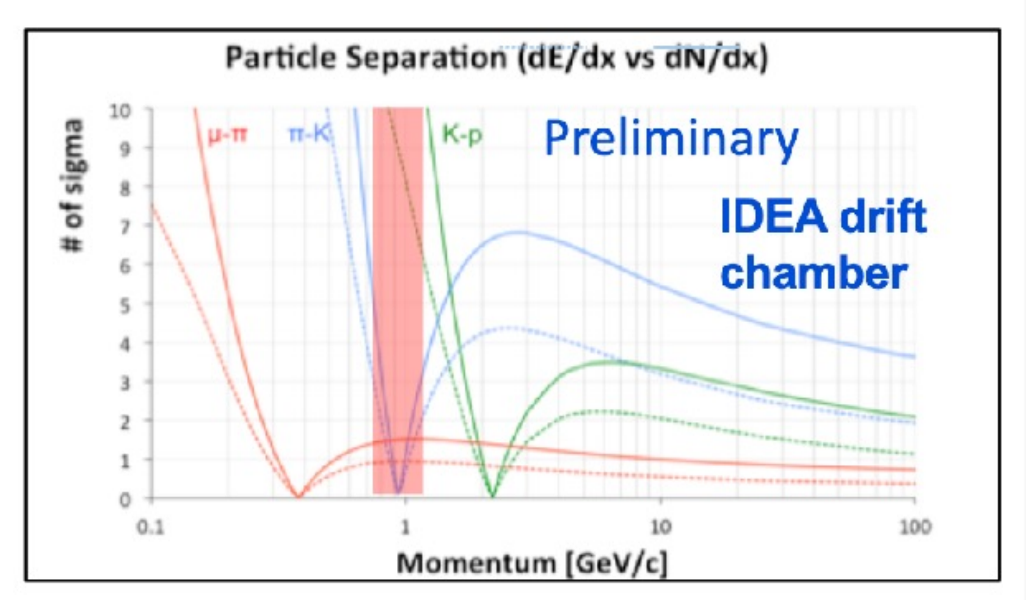
- Low material (transparency) wins over single point resolution over most of relevant momentum range
- Particle ID via dcdx or dN/dx (cluster counting) complement ToF



CLID - All Si Tracker total material budget 11%

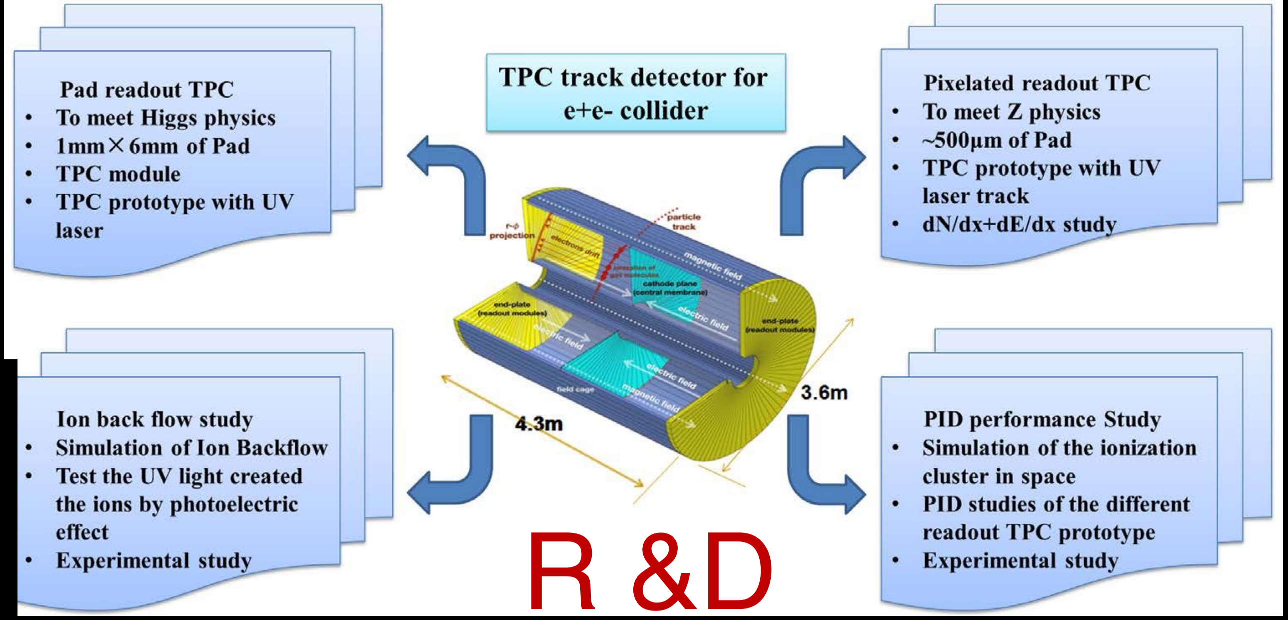
IDEA • Drift Chamber Material budget is < 2%



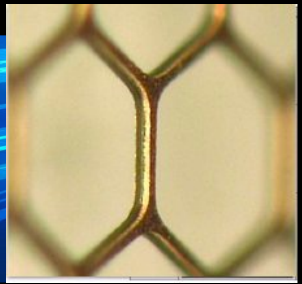


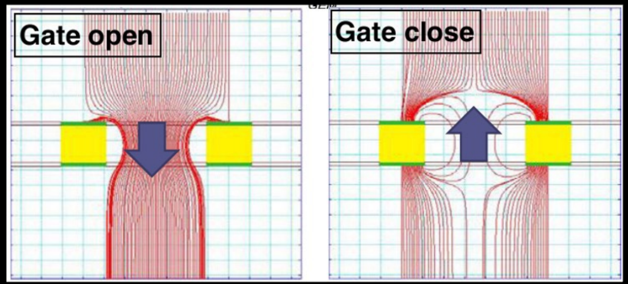
TPC R&D for e^+e^- future colliders

- TPC can meet tracking specification specifications of e^+e^- colliders:
  - $\sigma_{1/pt}$ ~10^{-4} $(GeV/c)^{-1}$ with TPC alone
  - σ_{point}<100 μm in rϕ
  - dE/dx resolution < 4% and cluster counting
- Prototype at DESY to compare different technologies
  - GEM, MM, GRIDPIX
- Ions from gas amplification stage build up discs leading to 60 μm track distortion: GEM-gate are an option

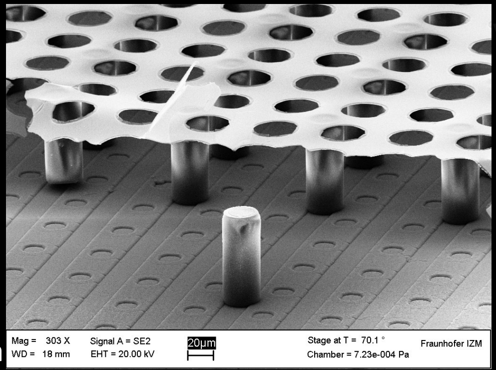


- TPC for CEPC/FCC: challenges for Z pole running(@10^{36}):
  - Pixelated readout brings high spatial resolution, high rate capability, 3D track reconstruction, better dE/dx and dN/dx
  - Challenges: cost, complexity of readout electronics

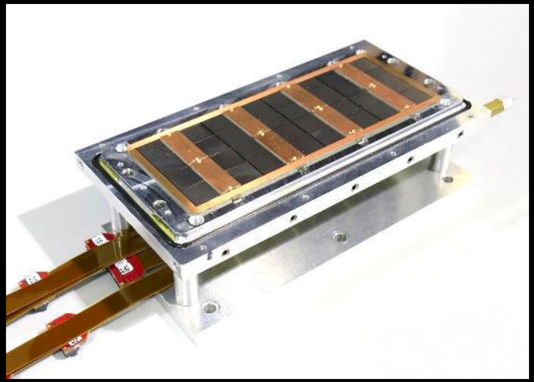




- Gating GEM gate opens 50 μs before the 1st bunch and closes 50 μs after the last bunch (possible because of ILC beam structure).

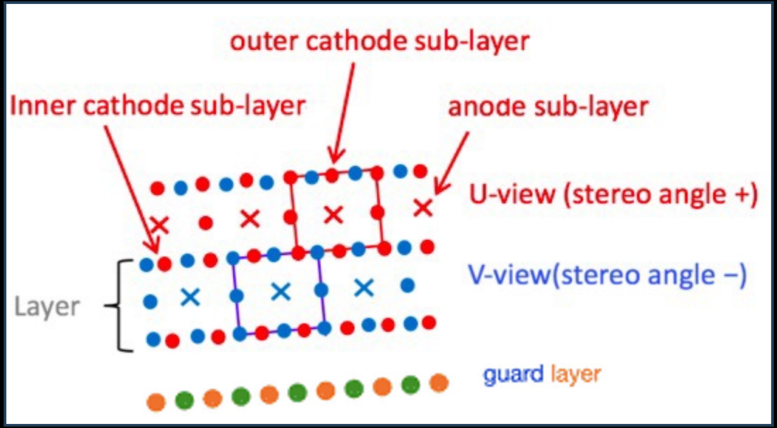


GridPIX:
- Bump bond pads used as charge collection anodes
- Readout with TimePix



Tracking with PID: Drift chambers

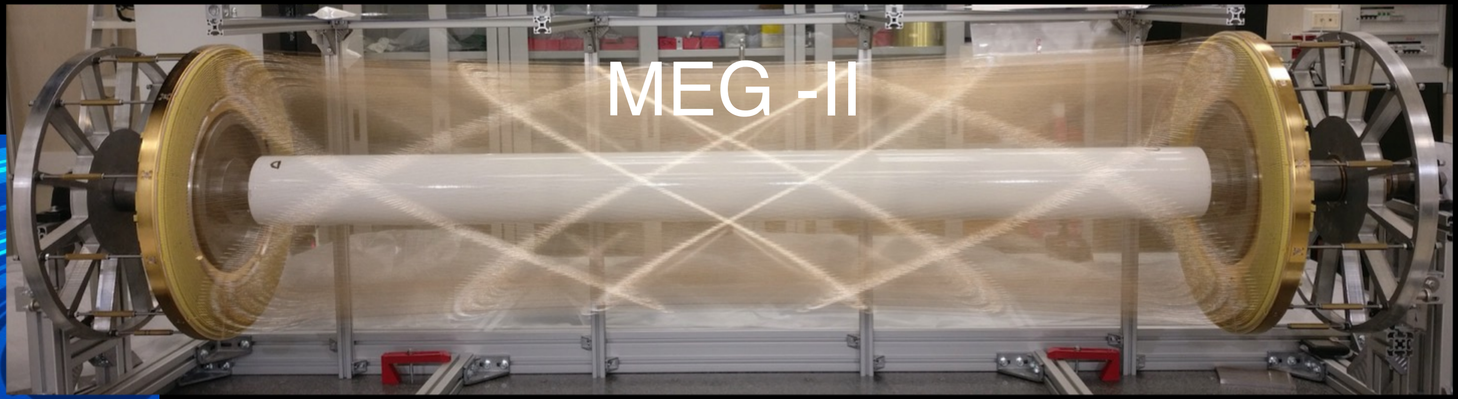
- IDEA: novel cylindrical drift Chamber under study for FCC-ee/CEPC/SCTF based on MEG-II DCH
  - High granularity, low-mass
  - He 90% - iC4H10 10%
- Requires non standard wiring procedure and a feed-through-less wiring system.
- Separation of gas containment and wire support enables ≈ 10^{-3} X/X_0 for inner cylinder and ≈ 10^{-2} X/X_0 for end-plates (with FEE, HV supply and)cables



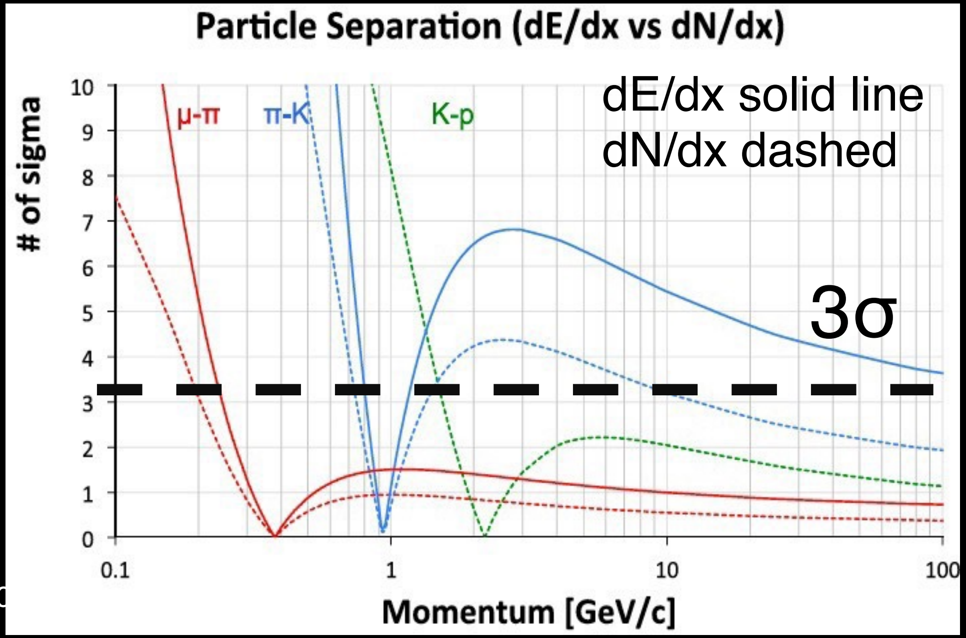
Wires with + and – orientation yield better E-field isotropy and smaller ExB asymmetries

343,968 wires in total

- $\sigma(p_T)/p_T \approx 0.3\%$ for 100 GeV/c muons
- $\sigma(dE/dx)$ = 4.3 % and $\sigma(dN/dx)$ = 2.2 % (at ε_N = 80 %)



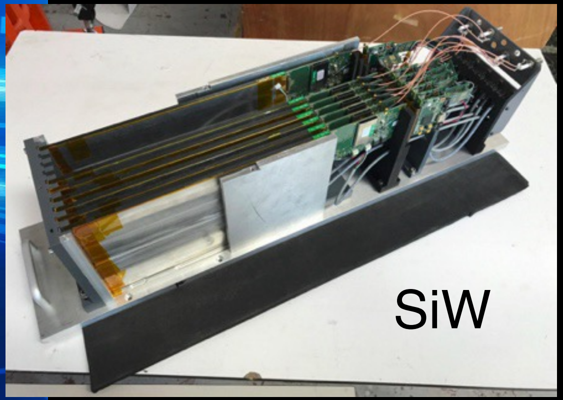
R&D: challenging mechanic, development of suitable FE and Data reduction for clustering with FPGAs, Test beams



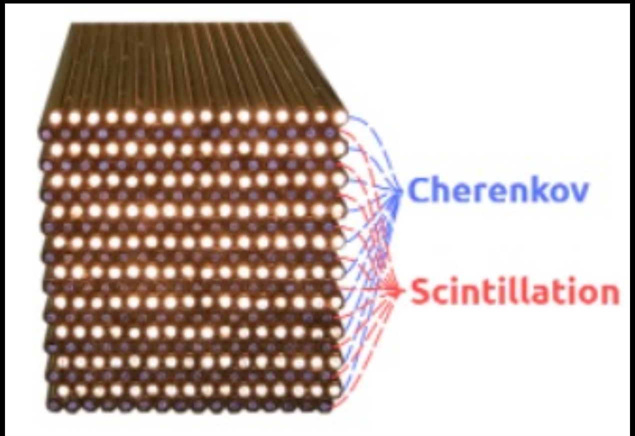
CALORIMETRY

- All proto-detectors plan to implement particle flow reconstruction
- Energy resolution for photons (down to 200-300 MeV)and neutral hadrons
- Dynamic range: 200 MeV – 180 GeV (at the LHC 6 TeV jets)
- Granularity: PID, disentangle showers for PFlow
- Hermeticity, uniformity, stability, easy to calibrate

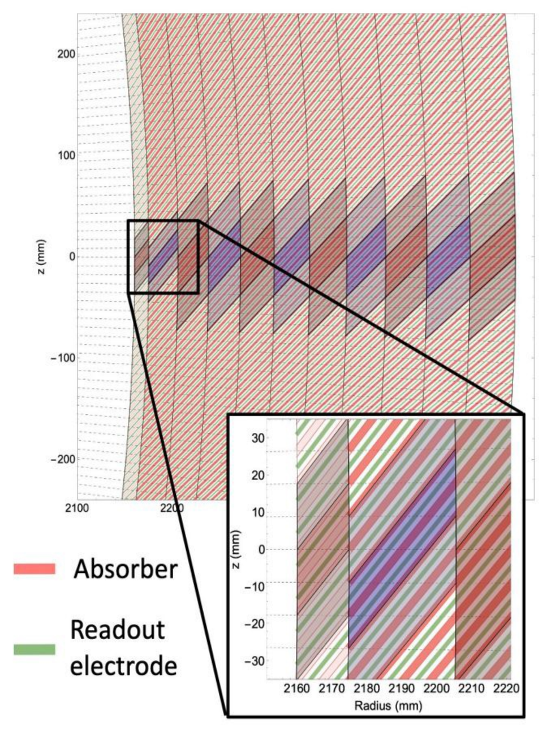
CLD – CALICE
“imaging” calorimeter



IDEA- Dual readout

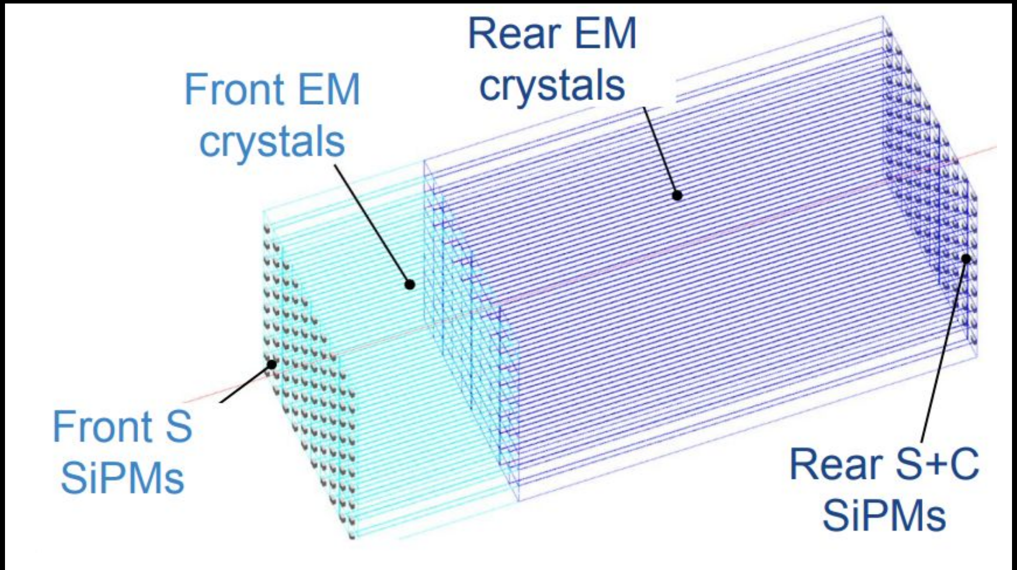


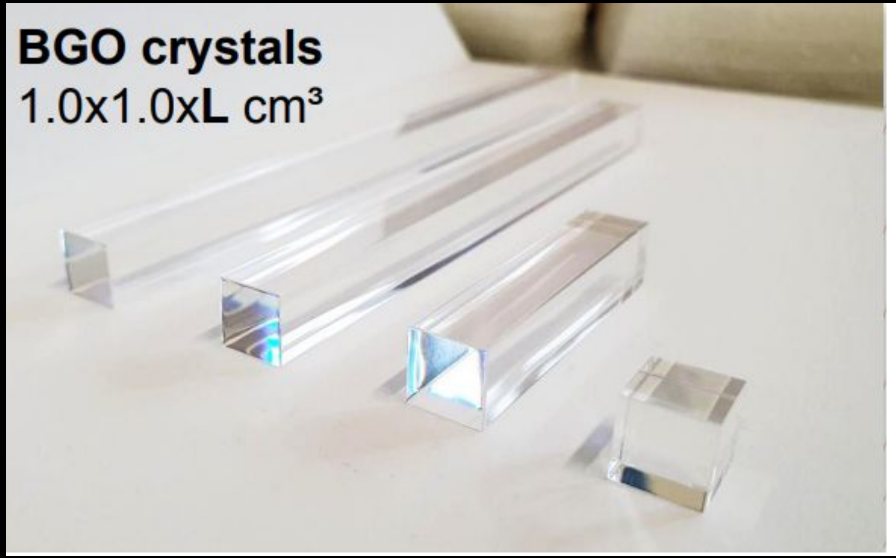
ALLEGRO:
High granularity Lead/Noble Liquid + steel and scintillator layers



CalVision

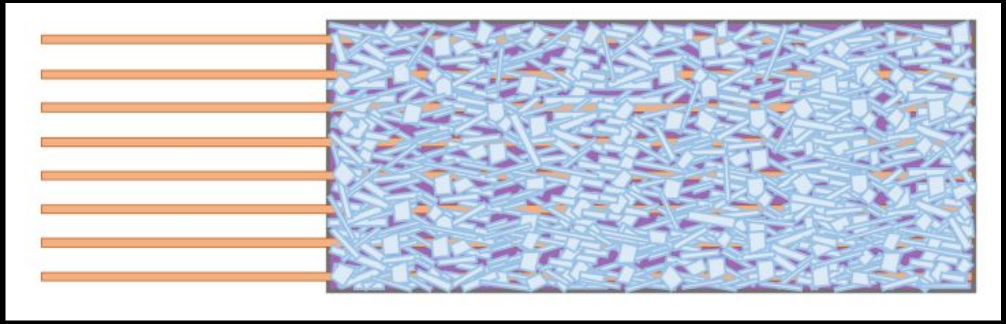
- Homogeneous EM calorimeter based on segmented crystals with dual-readout
    - High-density scintillating crystals with good Cherenkov yield
    - Dedicated optical filters and SiPMs to read S and C from the same active element
    - Promise 3%/√E + DR capability
    - Synergies within Calvision, IDEA and CERN Crystal Clear collaborations
- Main R&D Topics
    - – Identification of optimal crystal, optical filters and SiPM candidates
    - – Proof-of-concept with lab measurements and prototypes
    - – EM scale prototype for beam test



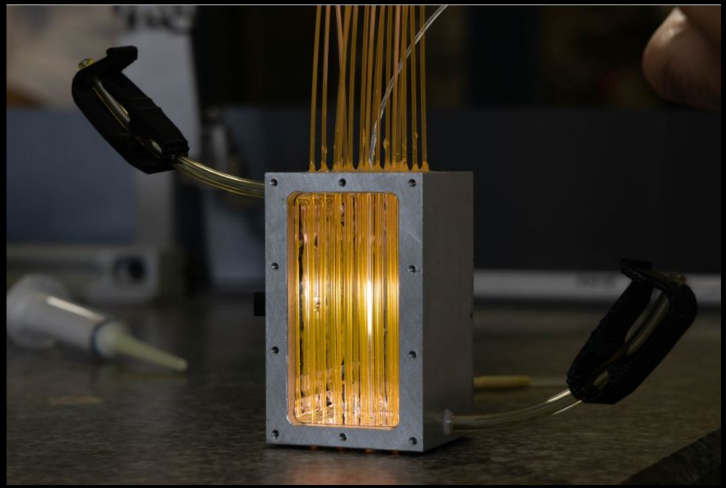


GRAiNITA

- Use grains of inorganic scintillating crystal readout by wavelength-shifting fibers
- Light spatially confined by refraction/reflections

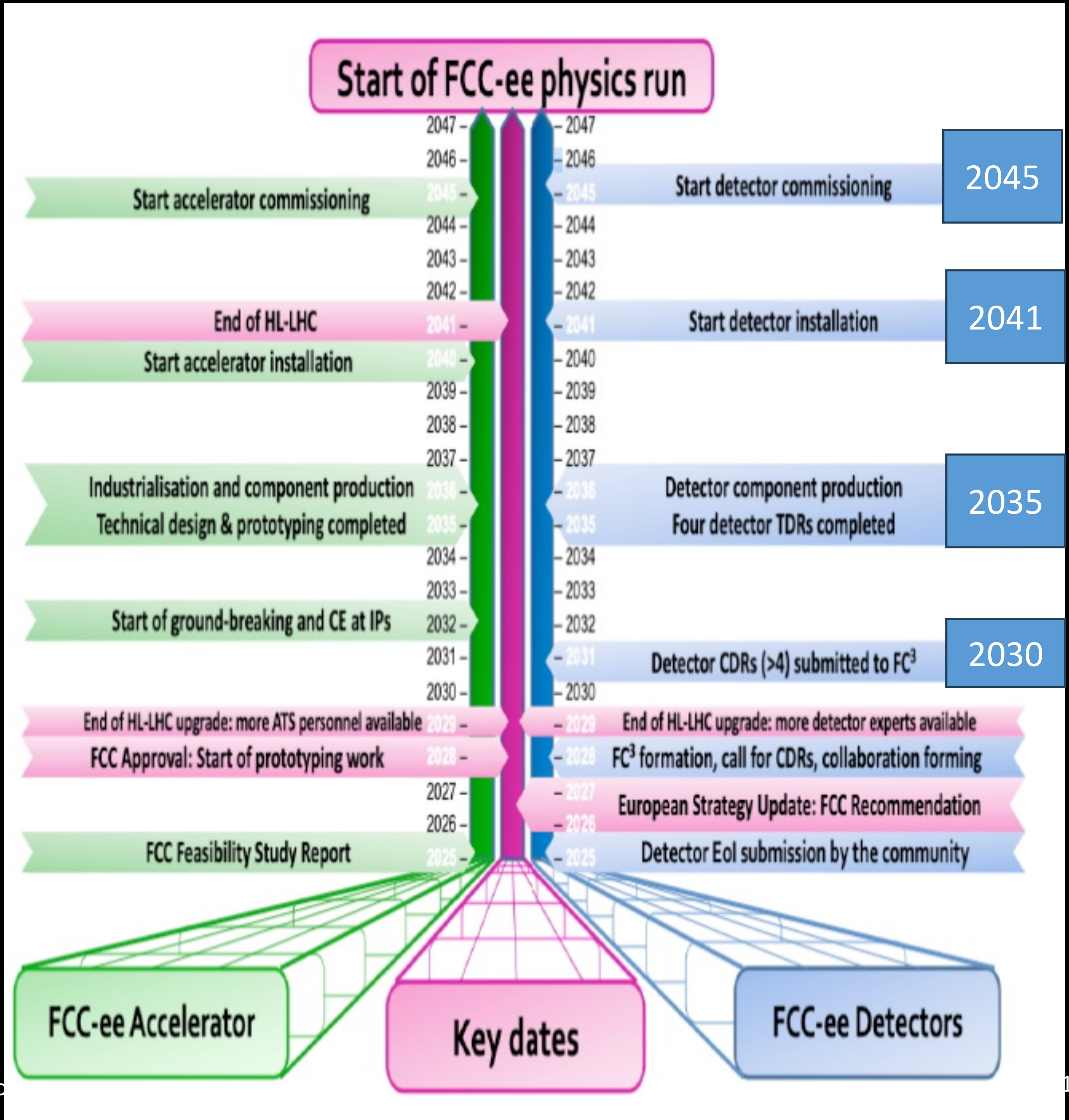


- Excellent expected EM resolution: 2-3%/√E
  - Using BGO or $ZnWO_4$ crystals
  - First small 16-channel prototype used with cosmics
- Main R&D topics
  - R&D on crystal grains
  - Aim for larger prototype to validate on testbeam



Outlook

- A lot of R&D ongoing covering all future colliders
- R&D now been organized along:
  - DRD collaborations at CERN
  - RDC collaborations in the USA
  - Many initiatives in other countries



EXTRA MATERIAL

CALORIMETRY

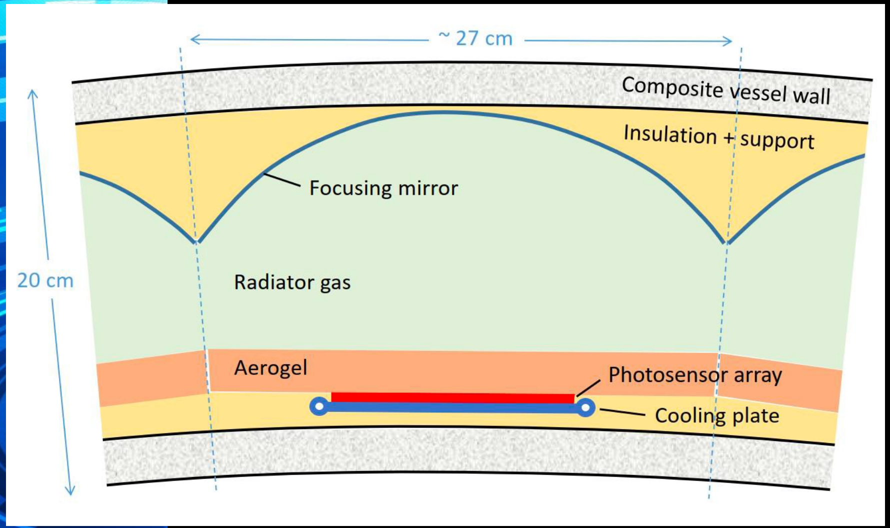
- Energy resolution for photons (down to 200-300 MeV)and neutral hadrons
- Dynamic range: 200 MeV – 180 GeV (at the LHC 6 TeV jets)
- Granularity: PID, disentangle showers for PFlow
- Hermeticity, uniformity, stability, easy to calibrate

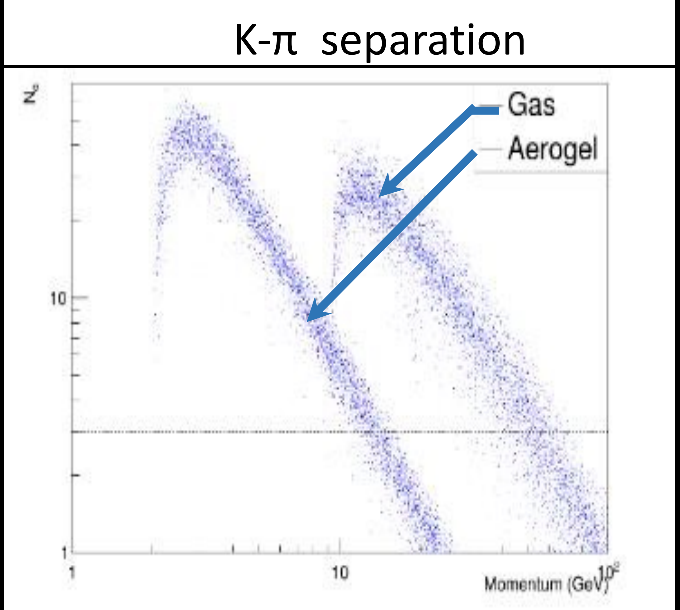
- SIW (baseline for CLD)
  - 40 layers, 1.9 mm tungsten absorber, 22 X0
  - 0.5 mm thick silicon sensors with 5×5 mm^2 granularity
  - $O(10^8)$ cells
    - Super high granularity for PFlow reconstruction
    - Tight integration: compact and hermetic
  - EM resolution ~17%/√E

- SiPM-on-tile / steel HCAL (Baseline on CLD and used in CMS HGCAL)
  - Builds on CALICE AHCAL prototype
  - Wrapped scintillator tiles directly read by SiPM
- **T-SDHCAL**
  - RPC-based semi-digital HCAL with timing capability
  - Builds on CALICE SDHCAL technological prototype
  - Use of more eco-friendly gases

ARC: Array of RICH Cells for FCC-ee

- RICH detectors are the gold standard for charged hadron ID at high momentum but implementation in a collider layout is difficult
- Reduction of Radial depth to 20 cm (and few % X_0 material) requires and ultra light pressure vessel for operating at 3.5 bar (carbon fibre composite)
- Challenge to arrange optical elements so that Cherenkov light focused onto a single sensor plane could be solved with a design inspired by the compound-eye of an insect
- Use spherical focusing mirrors: focal length = radius-of-curvature/2 → select radius-of-curvature R≈ 30 cm for radiator thickness of 15 cm

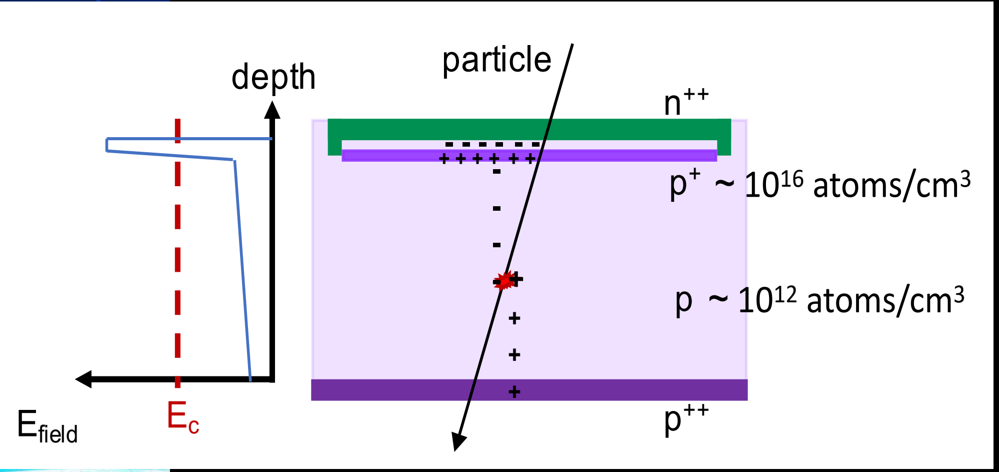




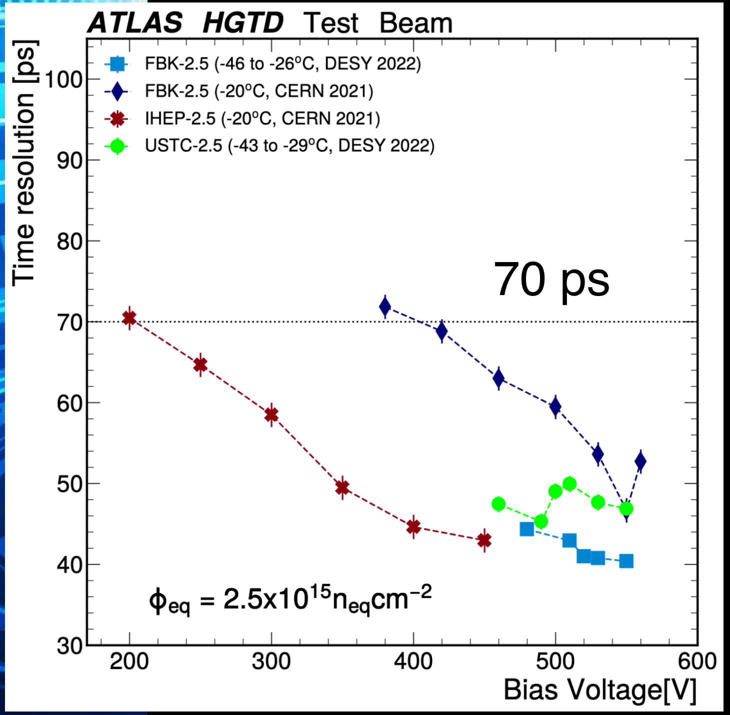
R&D:

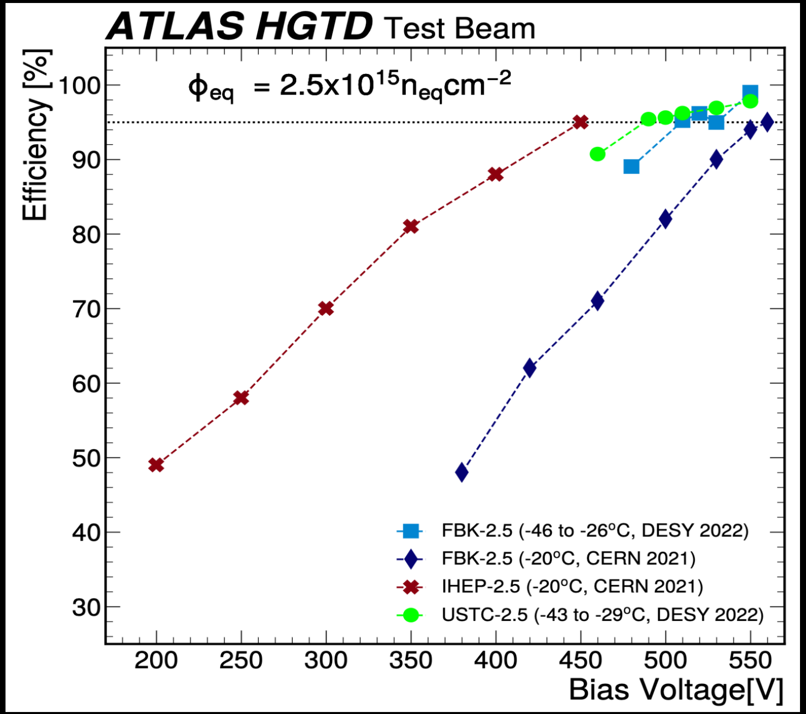
- Pressure vessel: leak tightness, minimizing material, safety aspects, access,
- Gaseous radiator: tuning choice of gas, operating temperature vs. pressure, chromatic resolution, use fluorocarbon with leak-free system vs. Xe (or other)
- Aerogel: clarity, choice of refractive index, developing large tiles, ensuring compatibility with the gaseous radiator
- Photosensor: SiPM PDE vs. wavelength, active area (e.g. microlenses), DCR, cooling

Sensors with gain

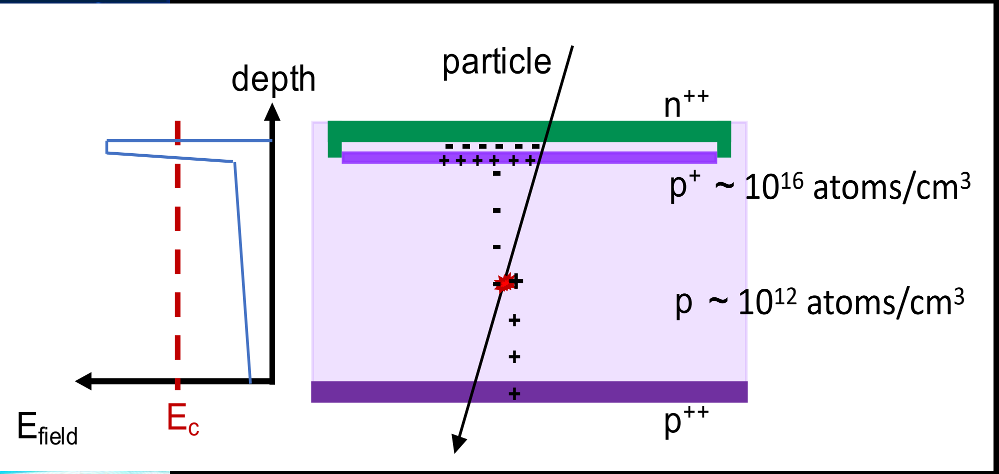


- State of the art sensors for HGTD (ATLAS) and CMS endcap MIP Timing Detector (MTD) - Pixel size 1.3 mm x 1.3 mm
- Time resolution: measured with a time reference device < 50 ps even after $2X10^{15}\ n_{eq}/cm^2$





Sensors with gain



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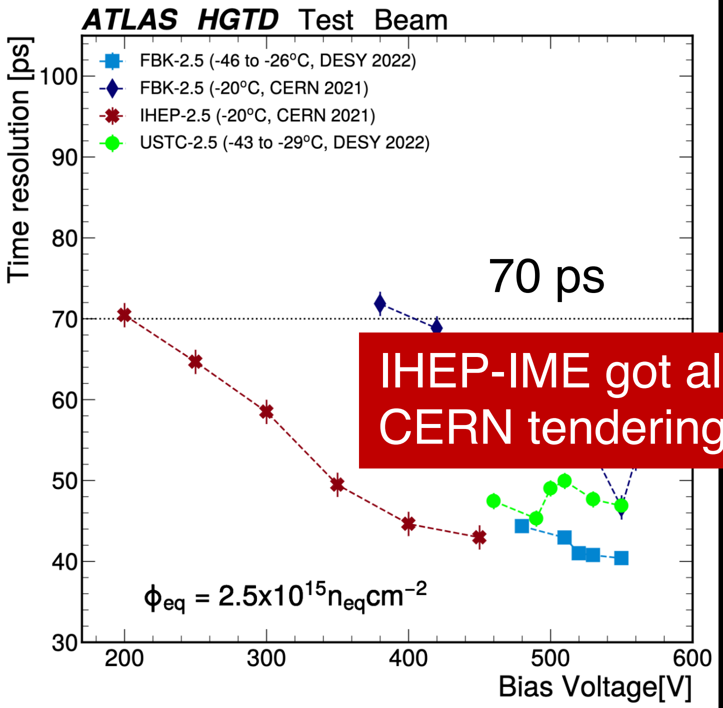
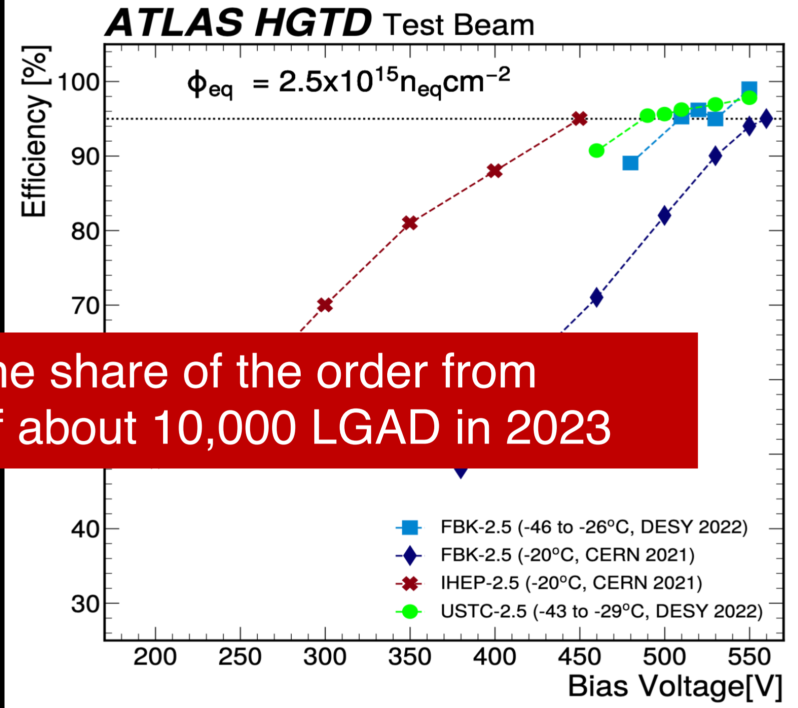
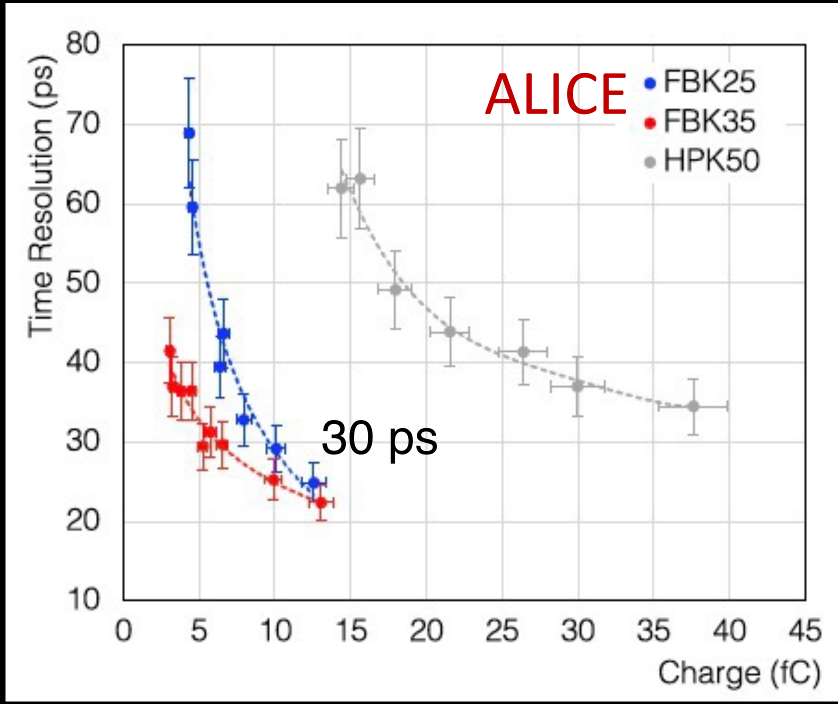
- Time resolution: measured with a time reference device < 50 ps even after $2X10^{15}\ n_{eq}/cm^2$
- R&D for ALICE TOF
  - 25 and 35 µm thick prototypes show time resolution < 25 ps
  - Sensors of 10 µm in preparation



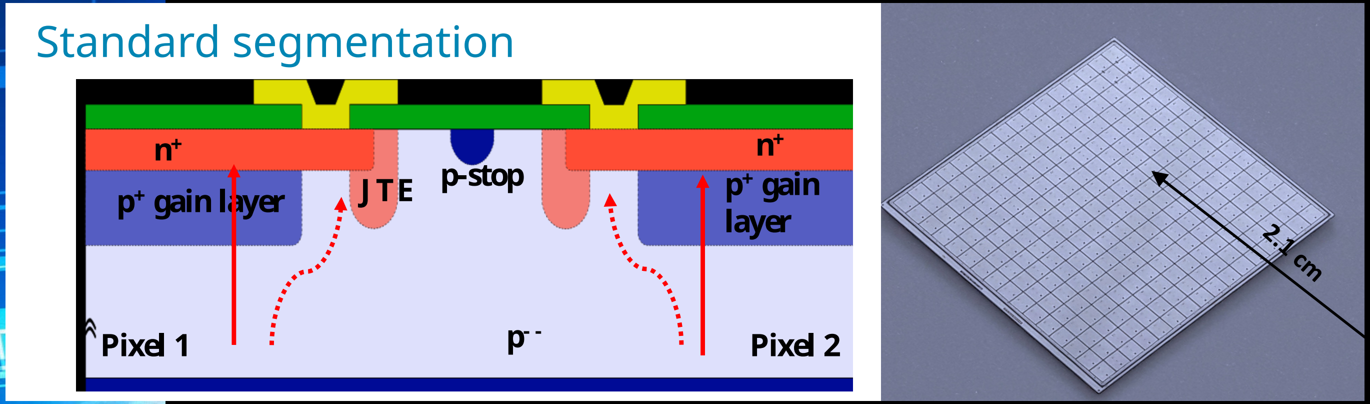


IHEP-IME got all the share of the order from CERN tendering of about 10,000 LGAD in 2023

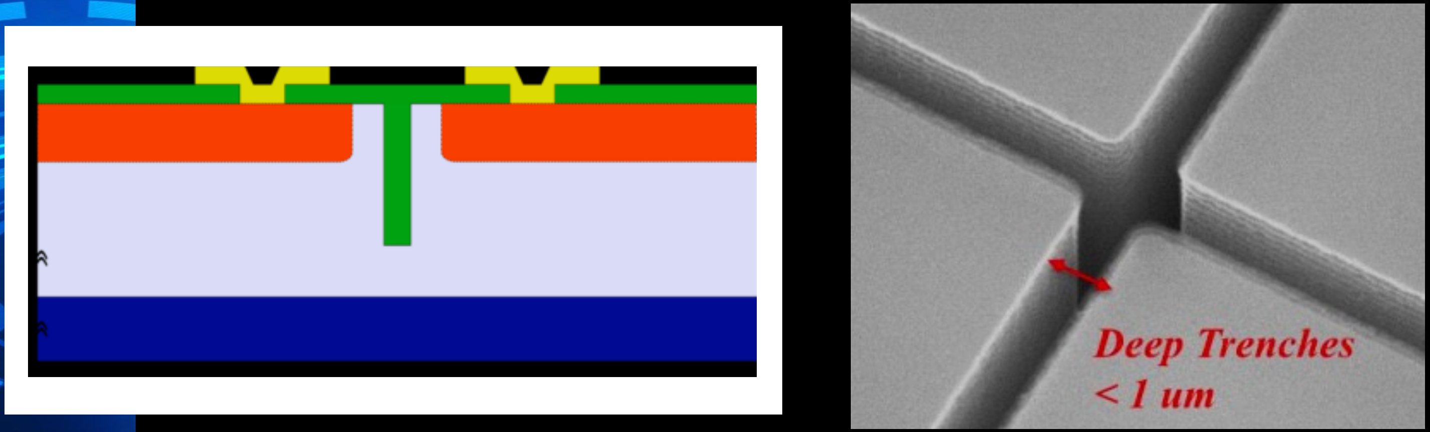


Sensors with gain

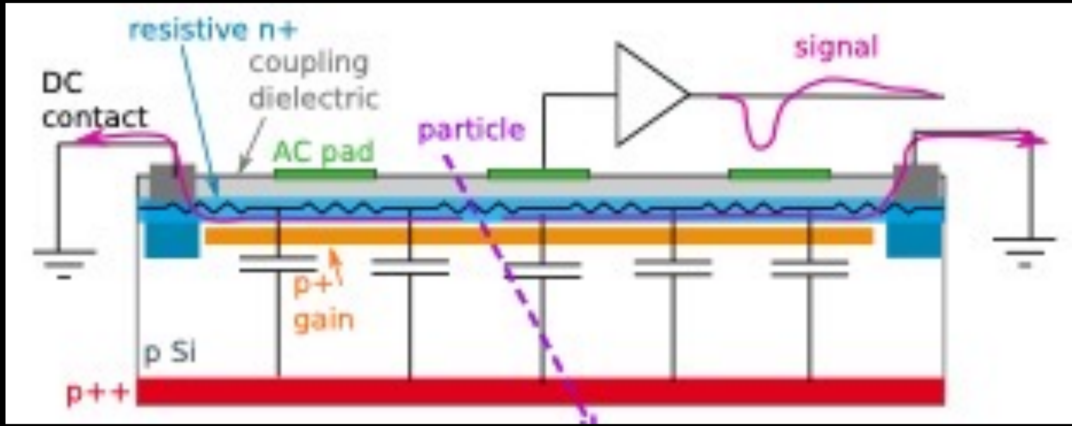
JTE + p-stop design (no gain area)



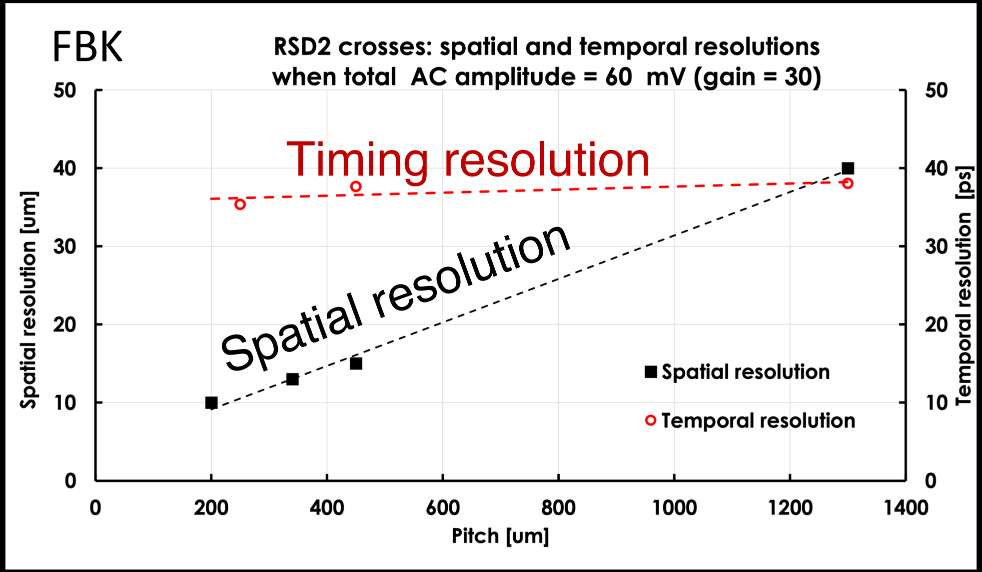
Trench-isolated design (trench filled with Oxide)



Resistive AC LGAD

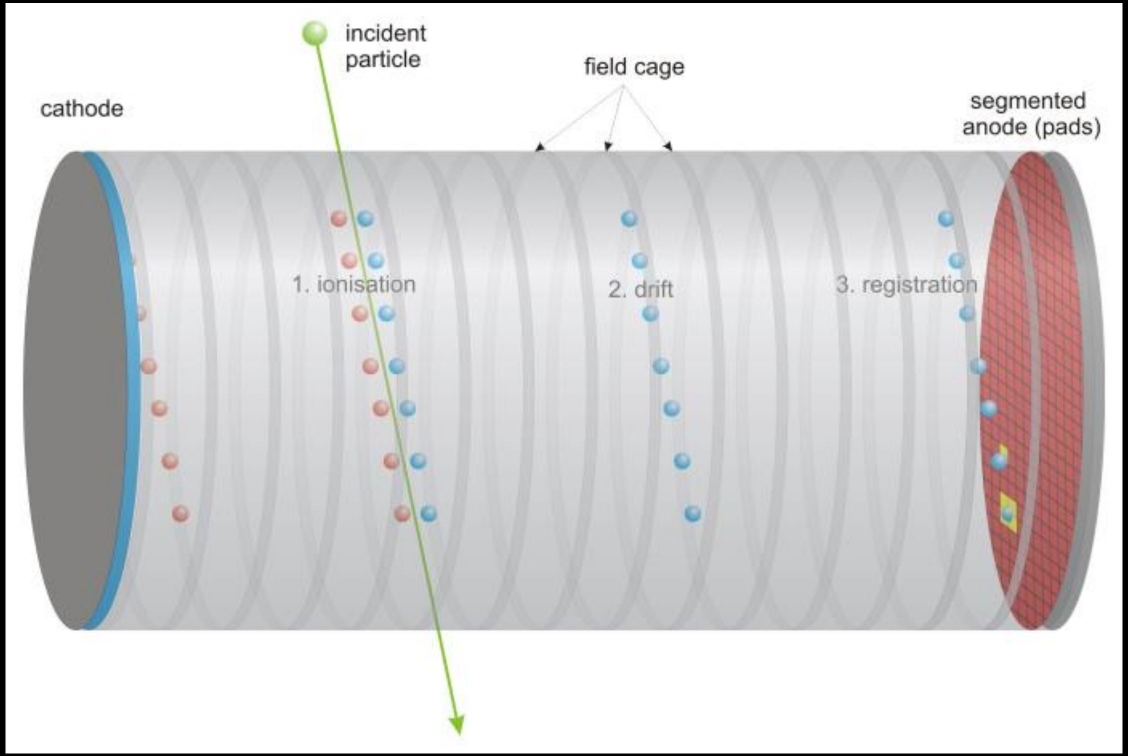


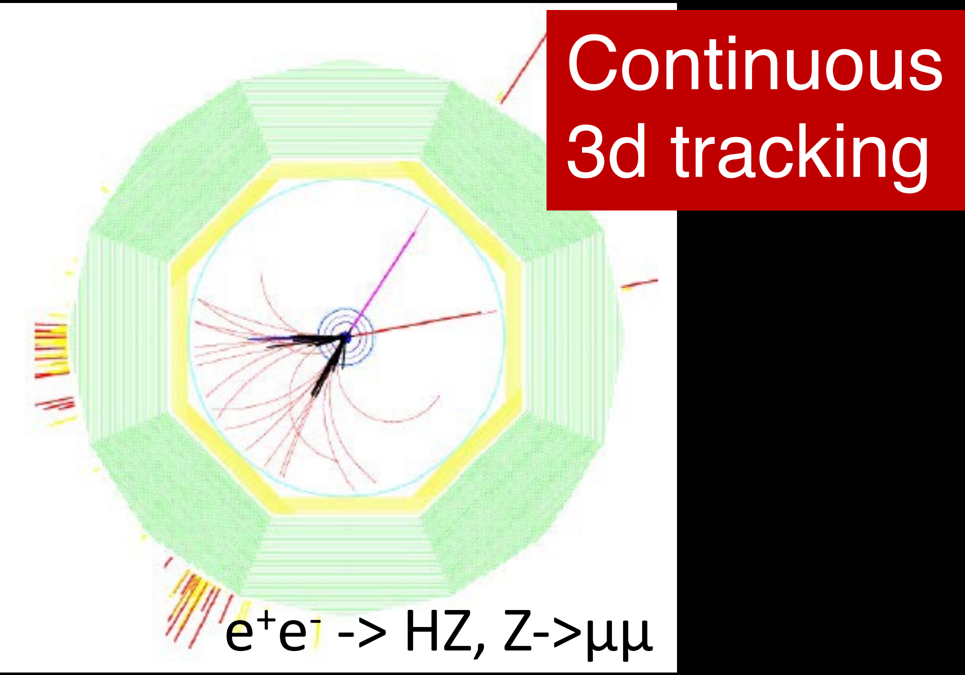
- Continuous resistive n+ implant
- Readout: AC-coupling through dielectric layer
- Segmentation obtained by position of the AC pads

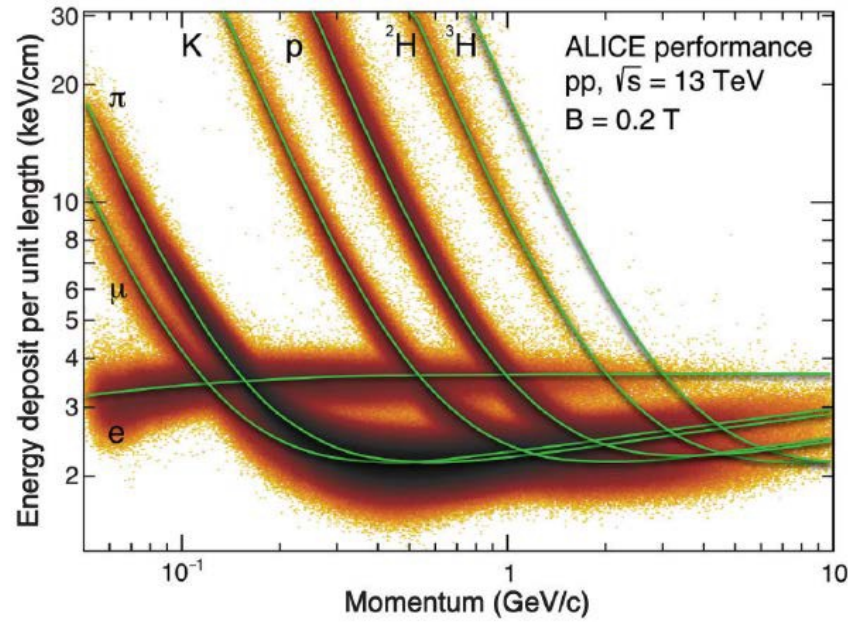


Cartiglia

TPC and ion back-flow



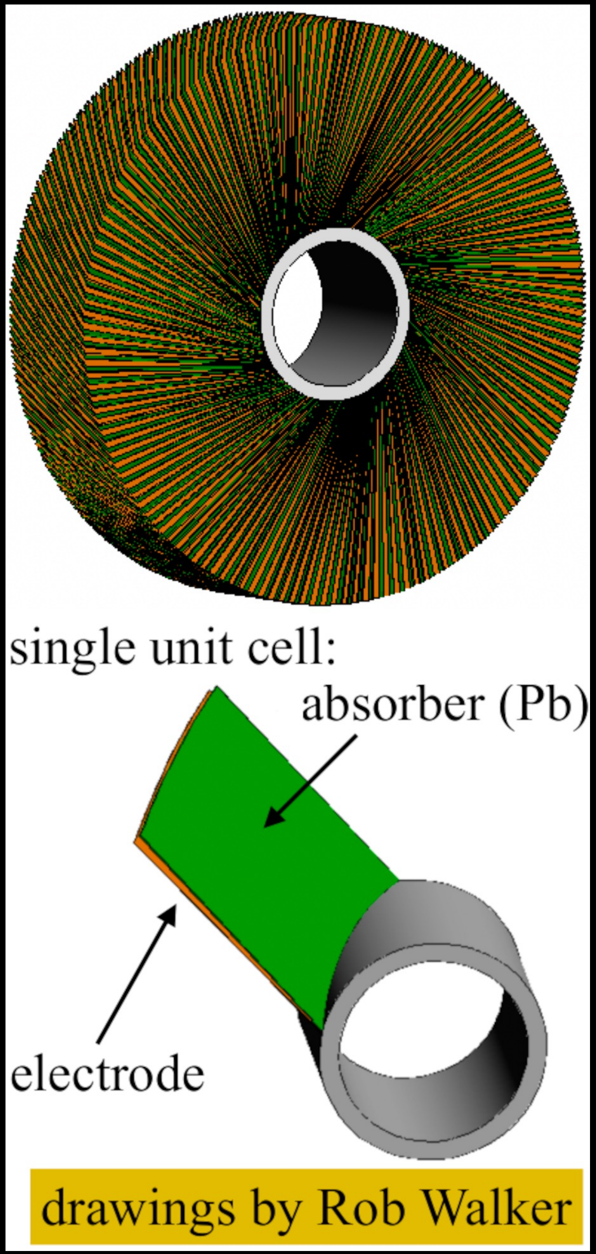




- Ions are produced in the amplification device. A fraction of them will flow back in the drift space and add to the primary ions produced by the charged tracks
- Ions drifting in the TPC's electric field are slow (m/s)
- Positive charge accumulates and gives rise to a space charge.
- Space charge is non-uniform producing transverse E field components which produce distortions

Particle Flow Calorimetry

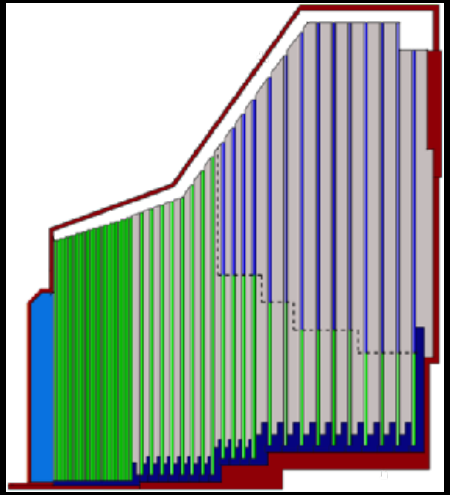
- **Liquid Argon + tiles**
  - Finer longitudinal sampling wrt ATLAS (4→12)
  - Warm or cold electronics
  - CALICE or ATLAS style scintillator tile HCAL
- **Fibre-based Dual Read-out with crystals in front**
  - Copper or steel matrix,
  - Cherenkov and scintillating fibres, SiPMs
  - Pointing geometry, superior PID
  - Longitudinal segmentation via timing
- **High granularity CALICE-style with embedded electronics**
  - silicon (pads or MAPS) ECAL, SiPM-on-Tile HCAL
  - strip ECAL, gas HCAL
  - synergies with CMS HGCAL upgrade



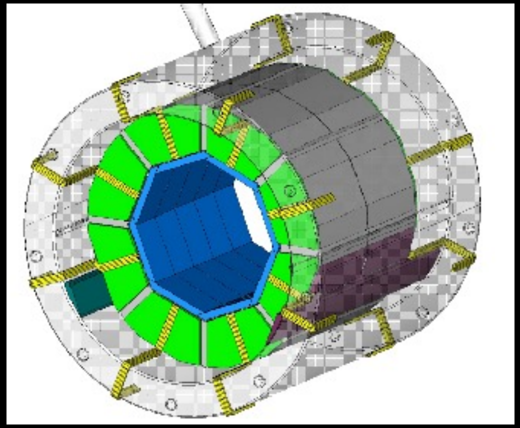
Challenges of High Granularity calorimetry

- **High channel is a challenge on all levels**
  - Production, test, calibration, software, management
  - Each step in size requires higher degrees of automation
- **Full imaging power requires both ECAL and HCAL inside the solenoid**
  - Much higher demands on compactness than in the CMS endcap
- Re-optimisation of sampling including cooling and services / dead spaces
-

CALICE AHCAL prototype **22’000** SiPMs



CMS HGCAL (2 end-caps) **280'000** SiPMs

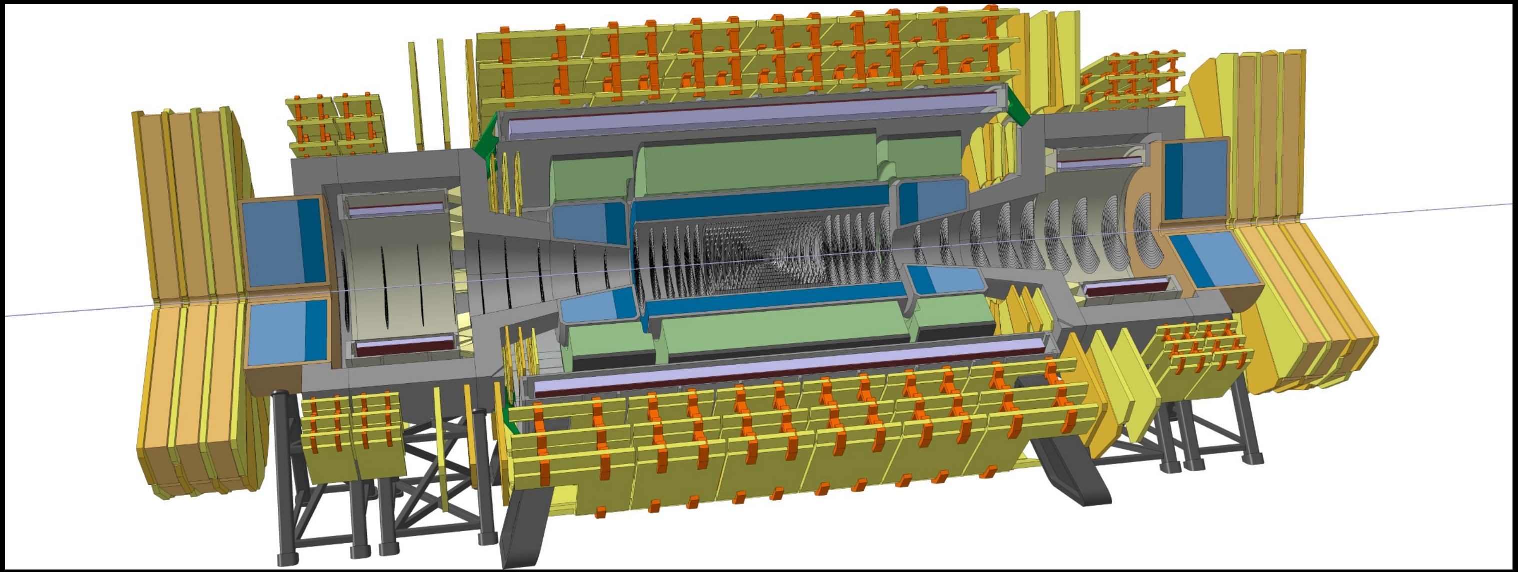


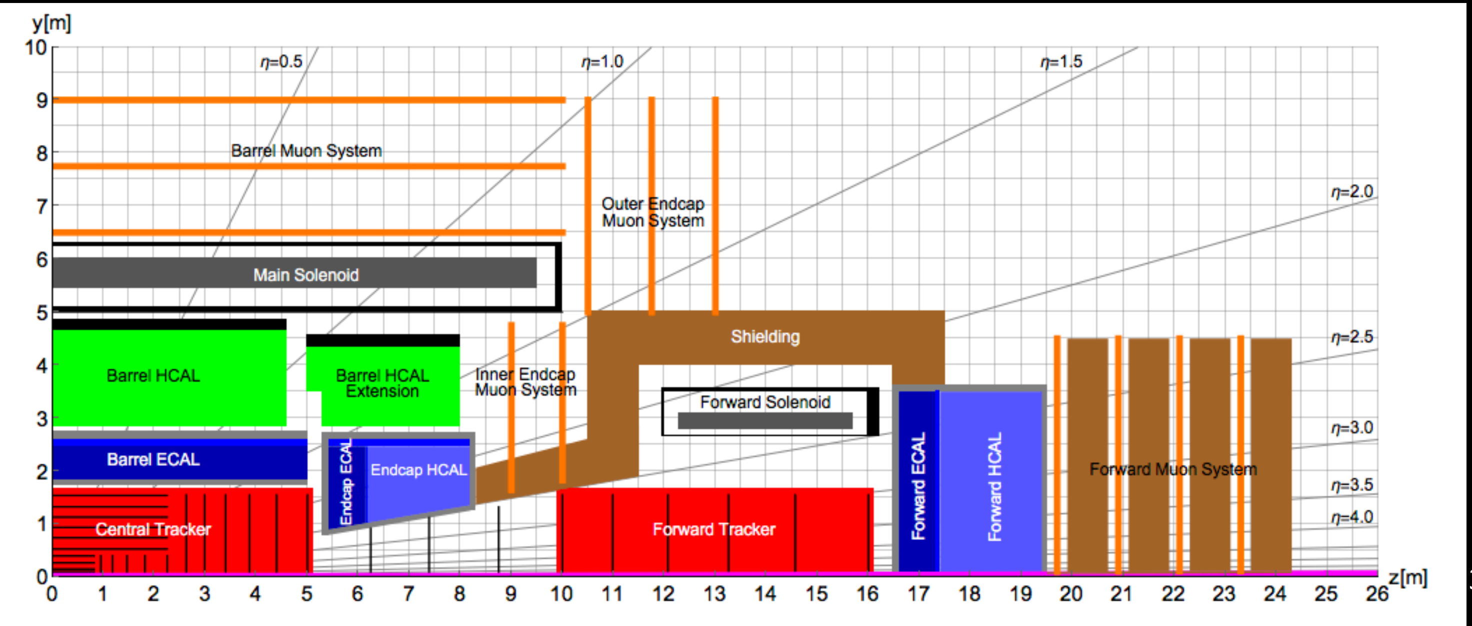
CLD / ILD HCAL barrel only **4’000’000 SiPMs**

FCC-hh Detector Concept

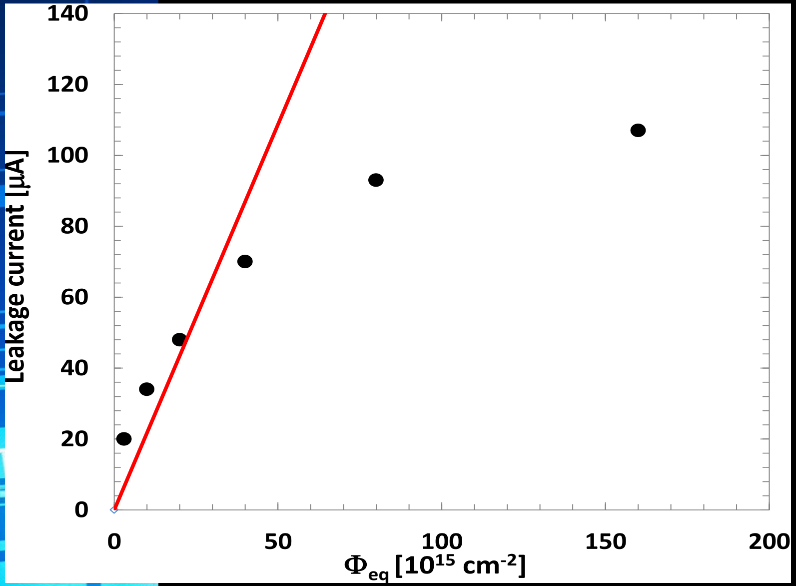
50 m long, 20 m diameter

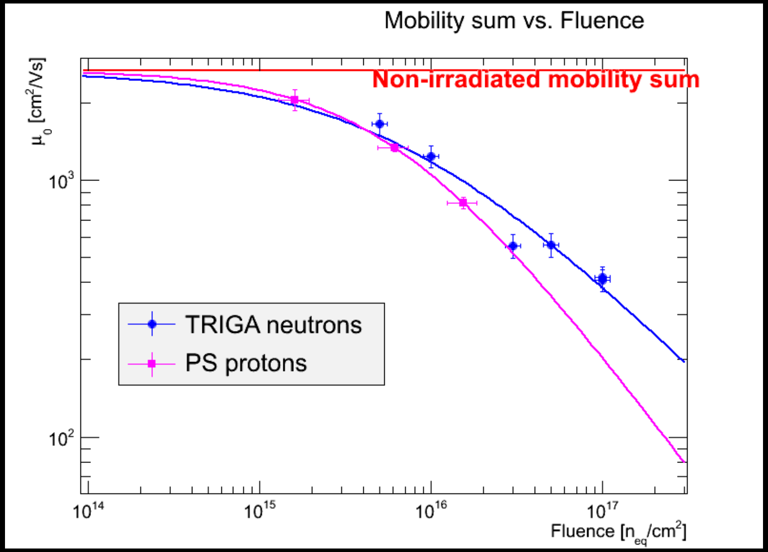
- More forward physics → large acceptance
  - Tracking and calorimetry up to $|\eta| < 6$
- Achieve σ_{p_T} / p_T = 10-20% @ 10 TeV
- Physics objects more boosted
  - high granularity (both in tracker and calorimeters)
- Goal 30/ab @100Tev
- Tracker: first IB layer (2.5 cm- 10 GHz/cm^2 charged particles): ~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

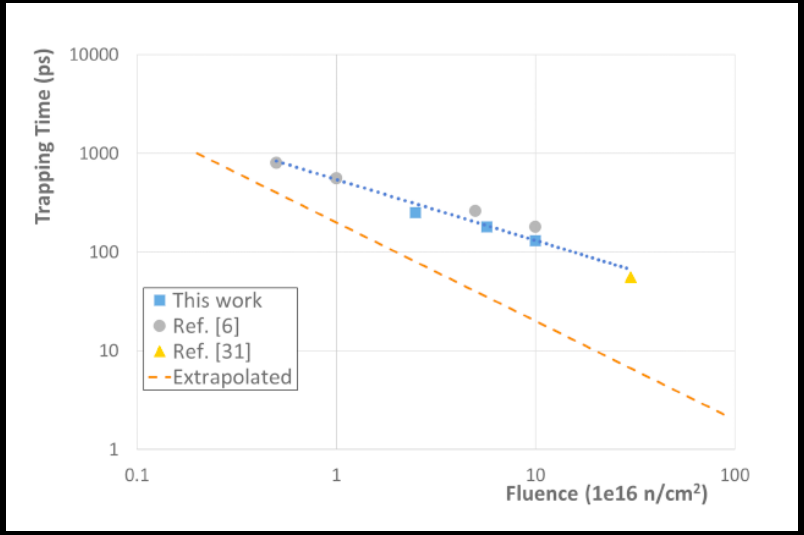




R&D on silicon at Extreme fluences







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

- Mobility reduction
  - Mobility decrease worse for protons

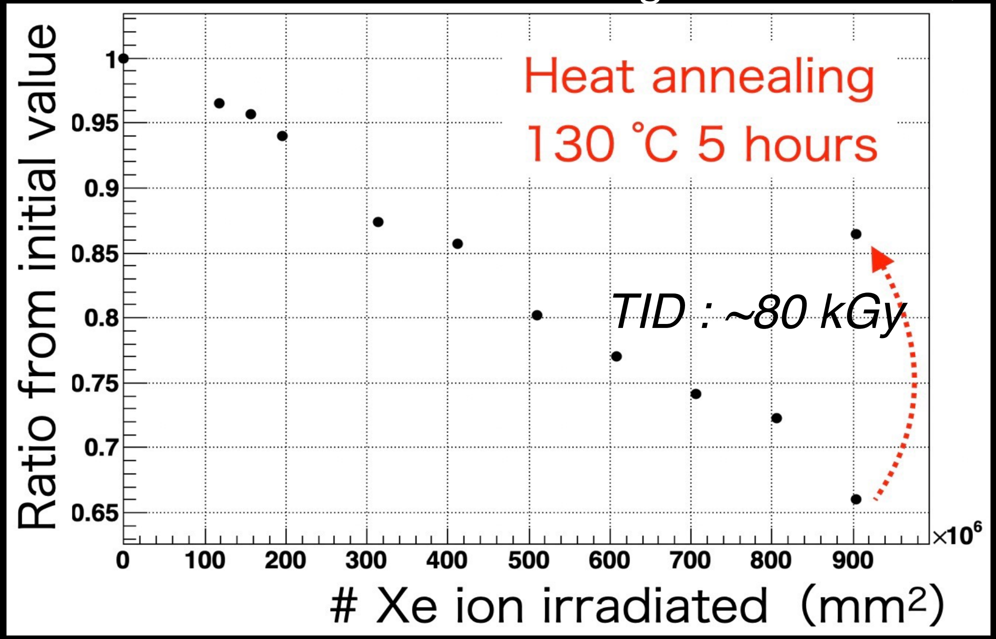
- Trapping time
  - Order of magnitude smaller than extrapolated

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

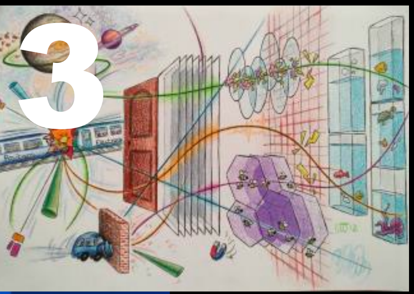
R&D on silicon at Extreme fluences

Manabu Togawa KeK and QPI

- 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



DRD



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

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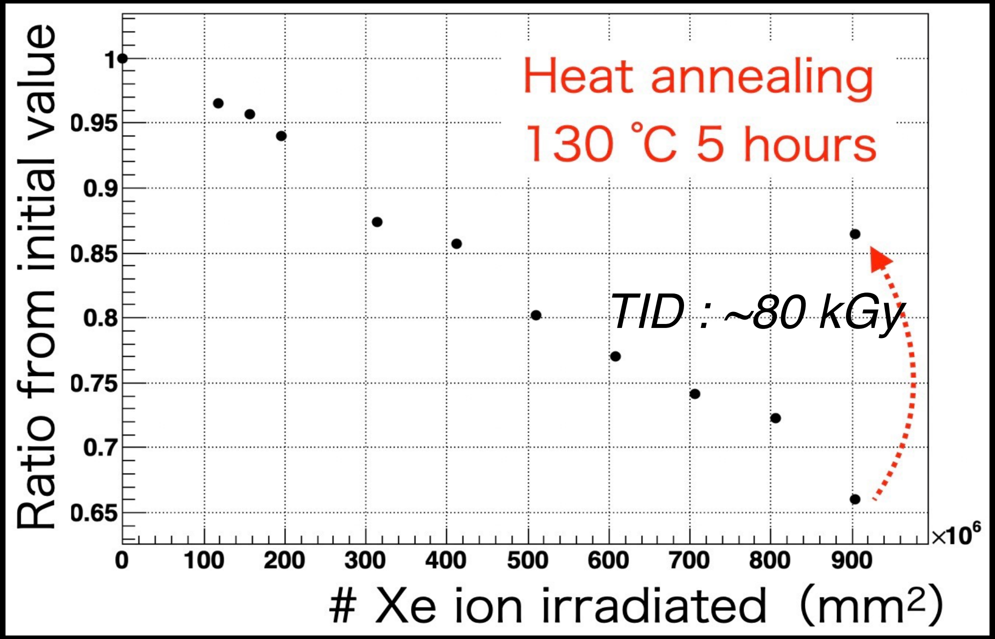
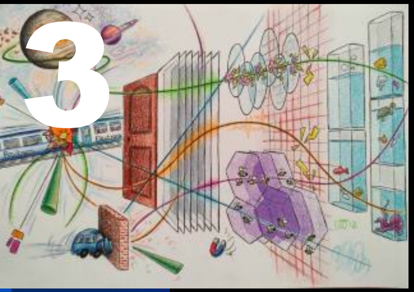
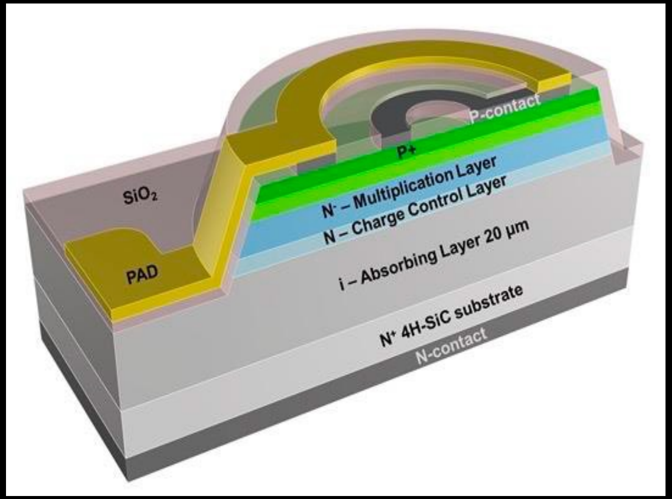


DRD SiC





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

Sensors with gain

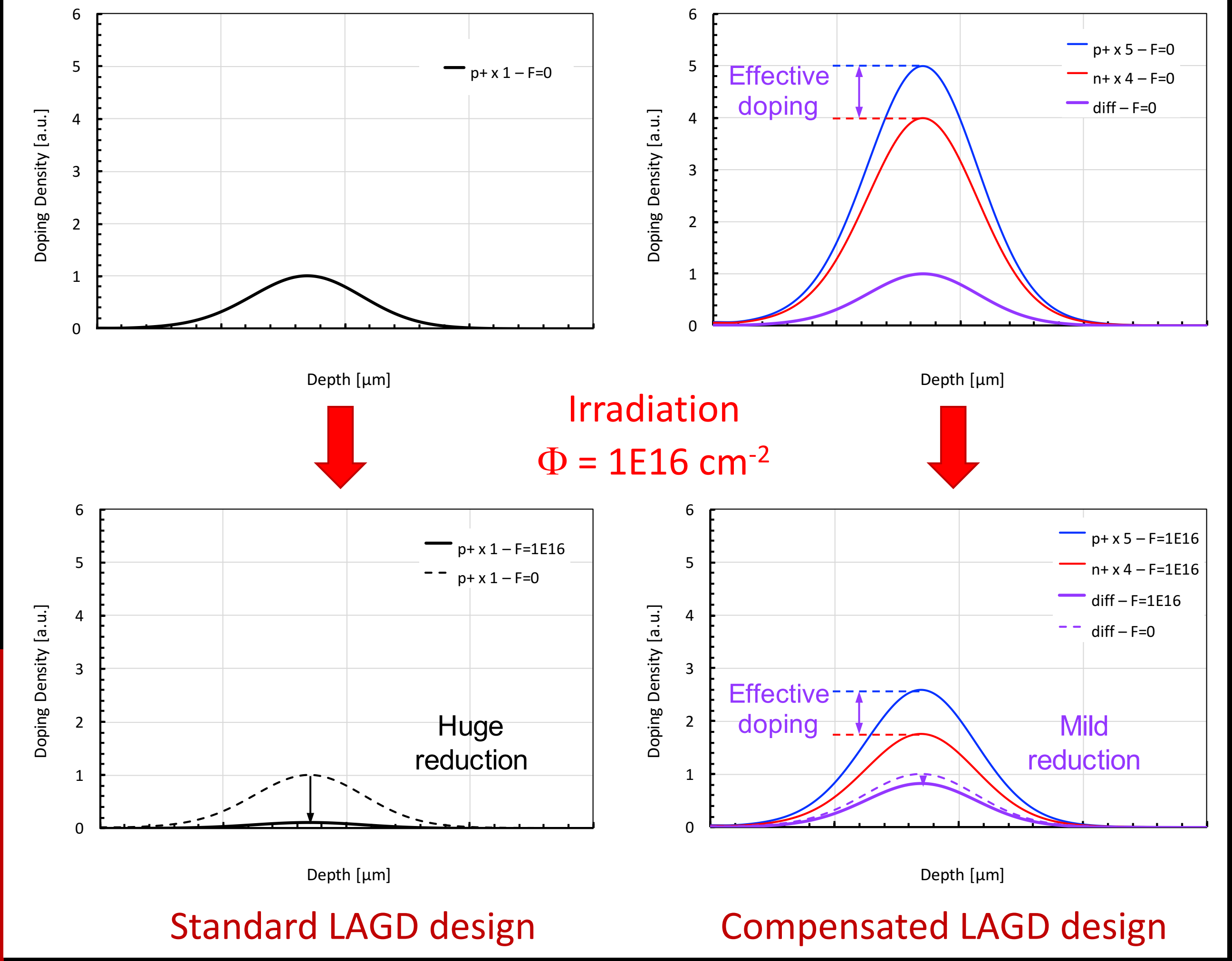
- The acceptor removal deactivates gain layer p+-doping with irradiation:

  $$p^{+}(\phi) = p^{+}(0)e^{-C_A\Phi} \text{ with}$$

  c_A =acceptor removal coefficient depends on defect engineering of the gain layer atoms

- Lowering c_A extends the gain layer survival to the higher fluences

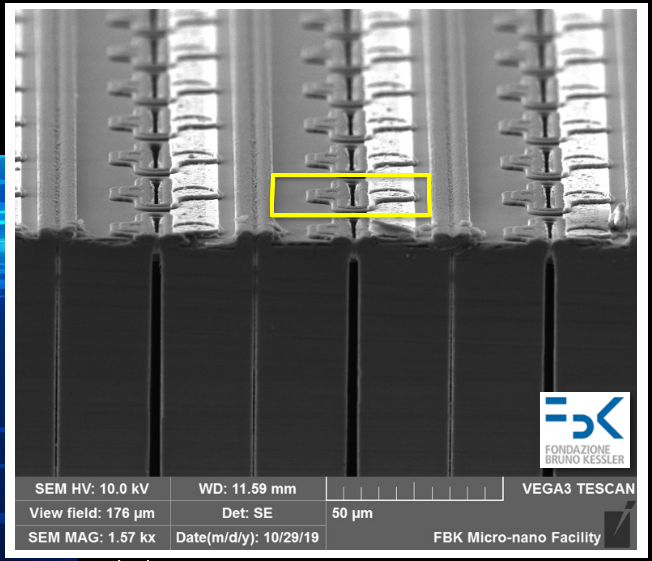
Compensated LGAD:
Use interplay between acceptor and donor removal to maintain constant gain layer doping density



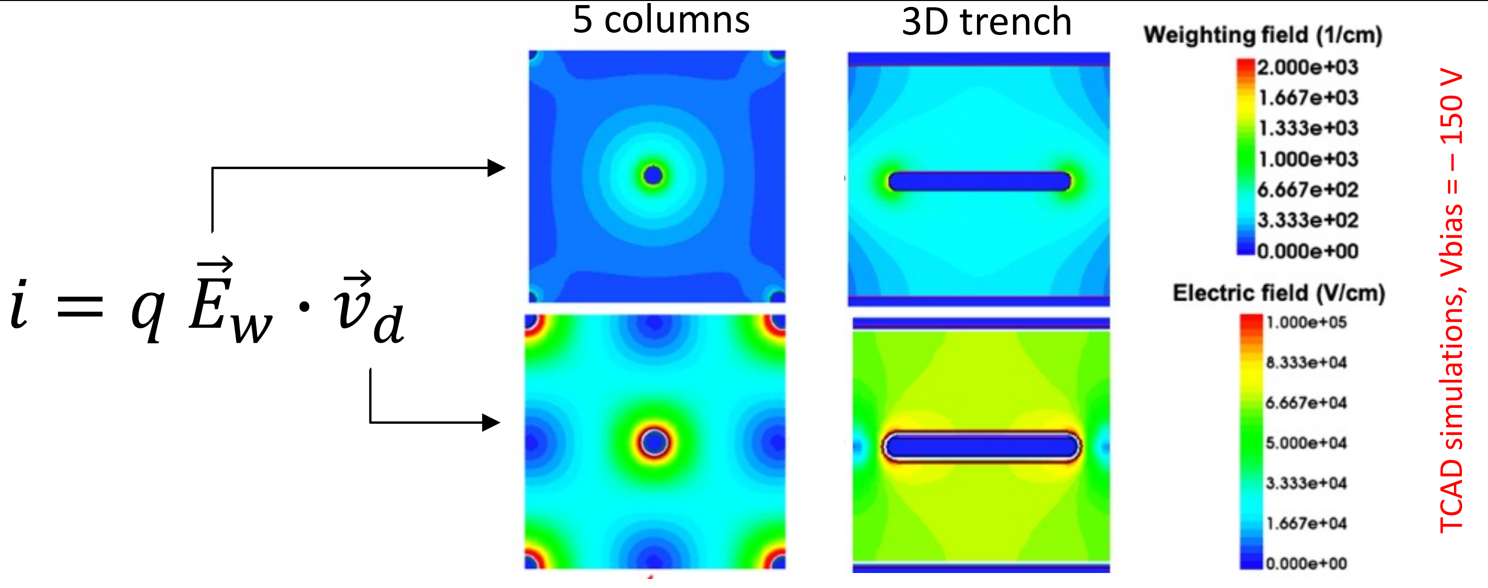
Fist submission done within AIDAInnova Blue sky programme: p^{+}–n^{+} doping densities needs tuning

TIMESPOT Trenched 3D

- 55 µm x 55 µm pixels (to be compatible with existing FEE, for example the Timepix family ASICs)
- In each pixel a 40 µm long n++ trench is placed between continuous p++ trenches used for the bias
- 150 µm-thick active thickness, on a 350 µm-thick support wafer
- The collection electrode is 135 µm deep
- Single sided (Si-Si) process with a support wafer



Comparison 3D and Trenched 3D sensors



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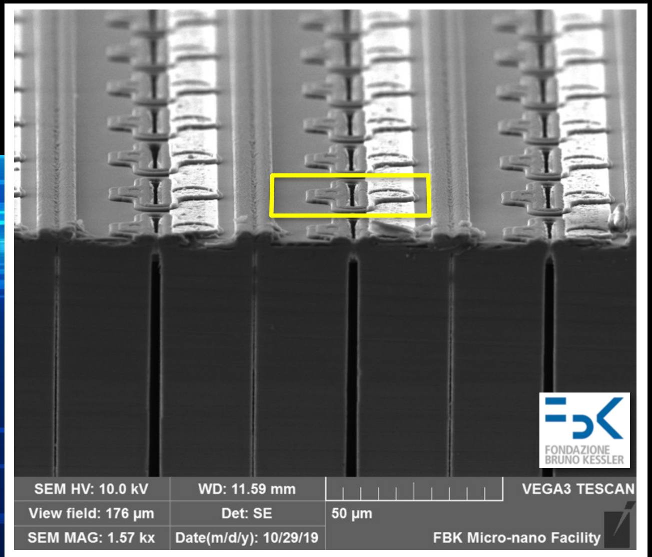
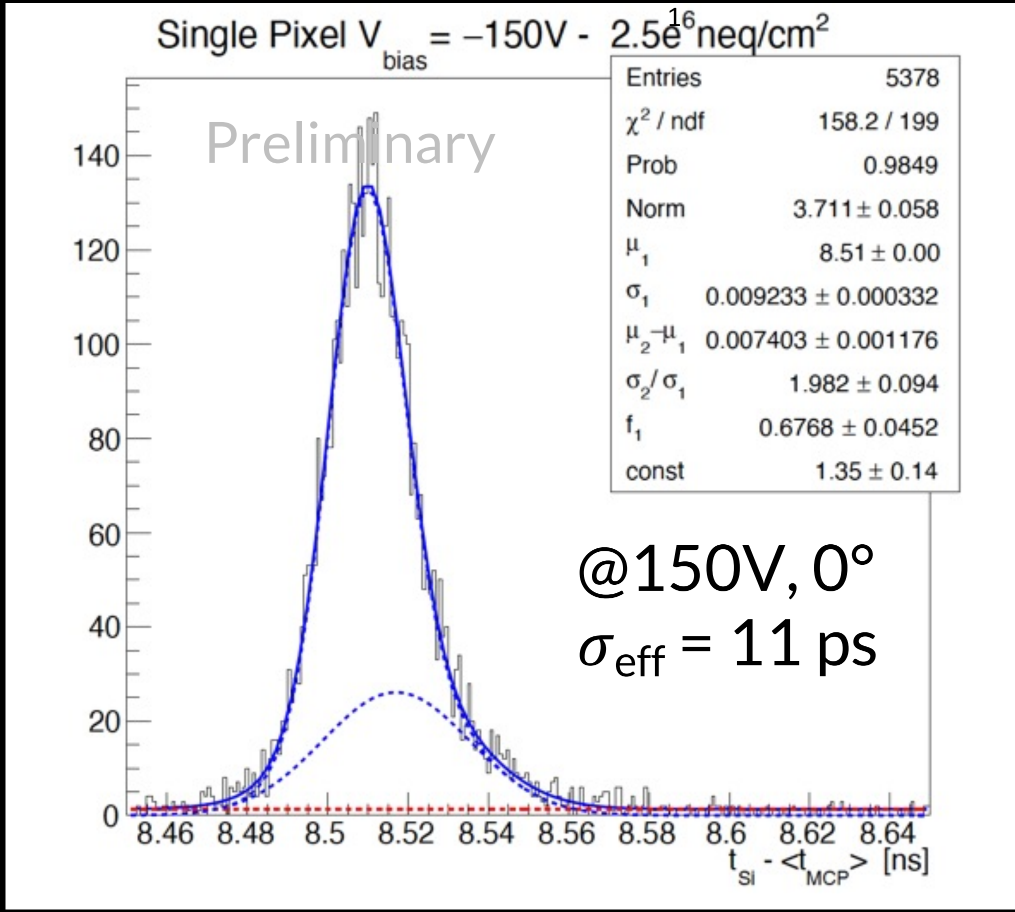


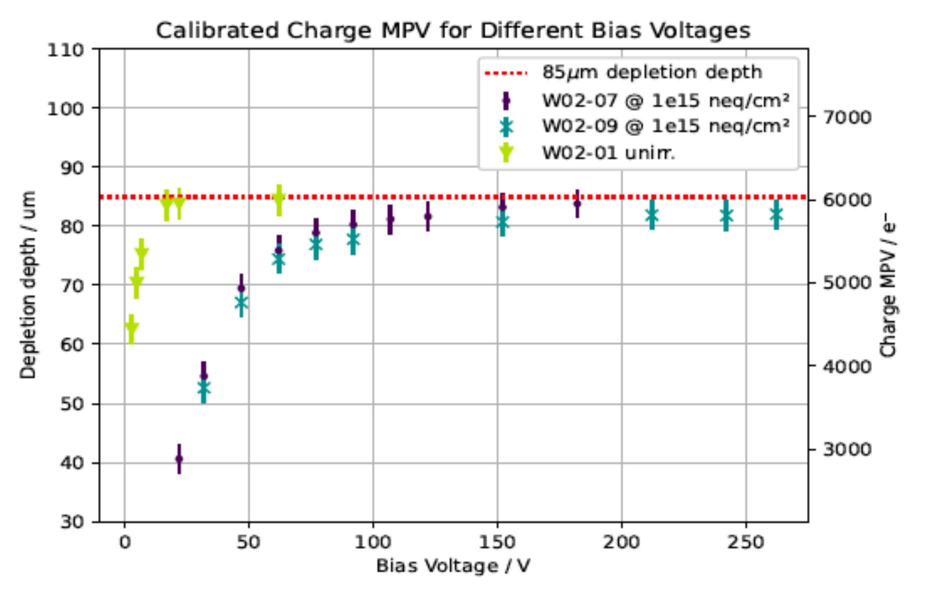


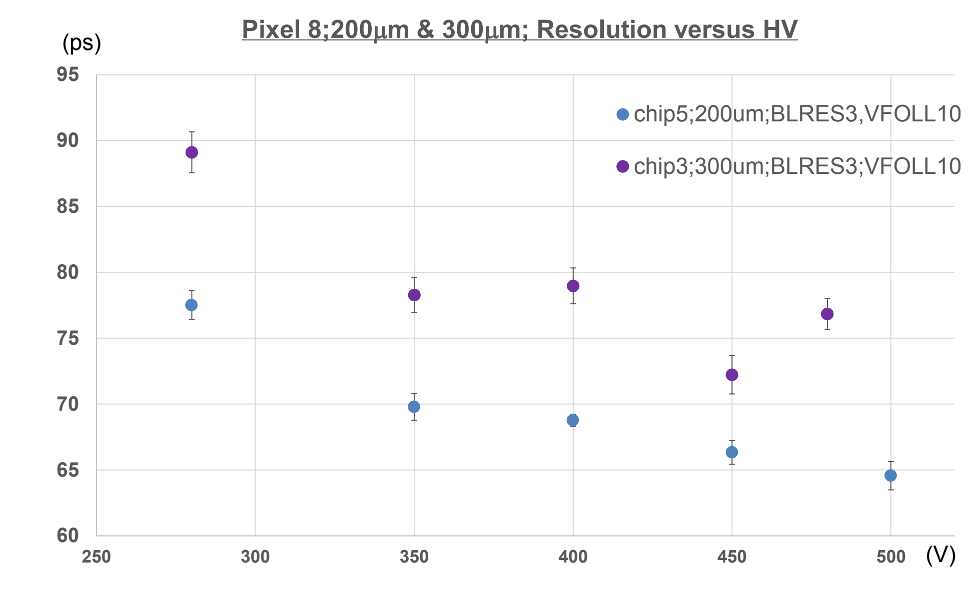
- 3D pixel time distribution w.r.t MCP-PMTs: symmetric with only a small tail
- σ = 11 ps measured at 150V on single pixels irradiated with fluences of $2.5 \cdot 10^{16}$ 1-MeV neutron equivalent

CMOS DMAPS Large Electrode

LFOUNDRY

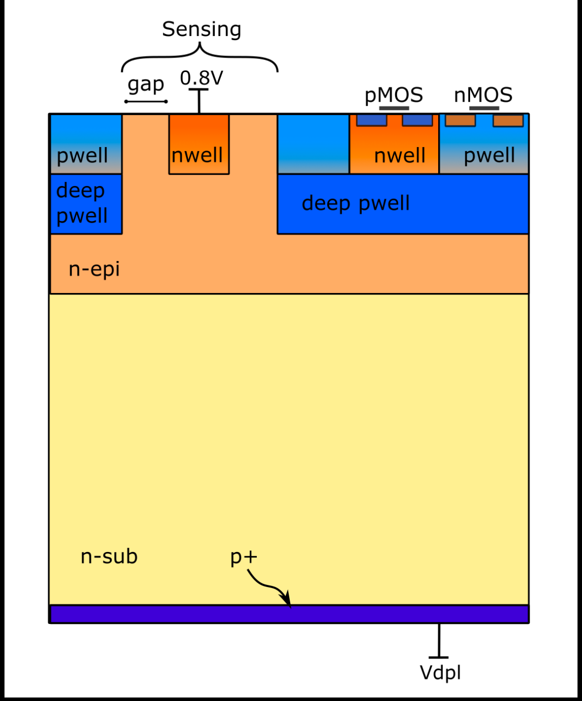
- LF-MONOPIX2 – 150 nm
  - Large & mature effort (1x 2 cm^2)
  - 50 x150μm^2 pixels - 100µm thick- C=250-300 fF
  - p-type substrate with a high resistivity (> 2 kΩ cm)
  - irradiated devices (1e15 n_{eq}/cm^2)
  - fully depleted @ 100 V bias (15 V unirr.)
- RD50 - Wafers with different resistivity (1.9 kΩcm, 3 kΩcm and 10 Ωcm), goal to achieve very small pixels (60 x 60 μm^2)
  - RD50-MPW1: test the LF150 process
  - RD50-MPW2: focus on the pixel and analog readout design
  - RD50-MPW3: increase size and include digital readout
- CACTUS - CMOS pixels for timing applications (~50 ps)
  - underestimation of parasitic capacitance/ bad S/N and 500 ps timing performance
  - Minicactus- small prototype to fix the problem

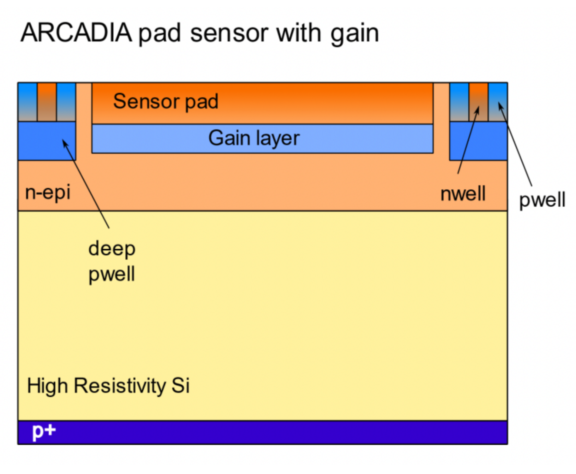




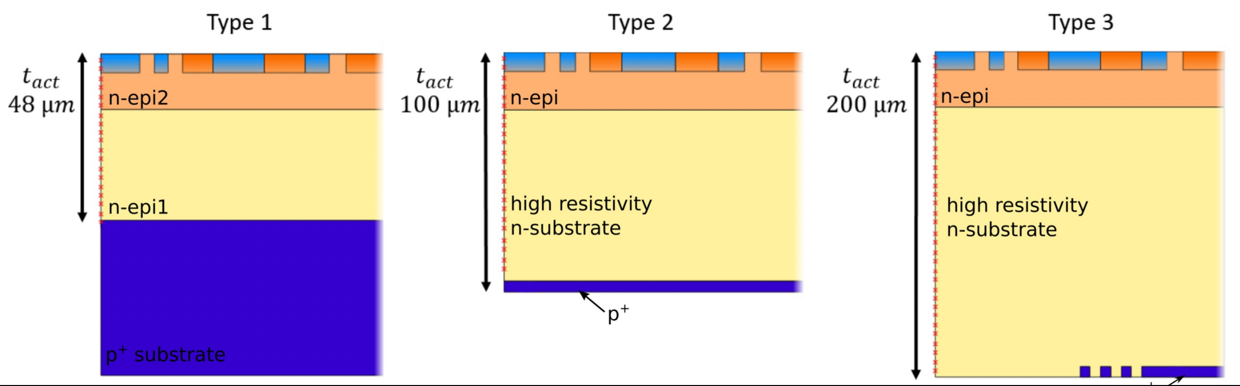
ARCADIA

- 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





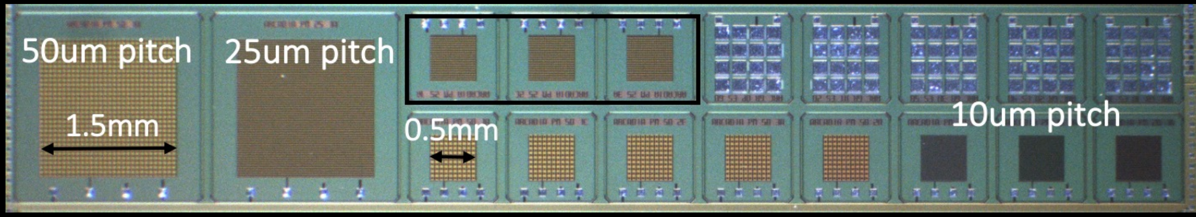
Wafer splits with gain layer to explore < 100 ps

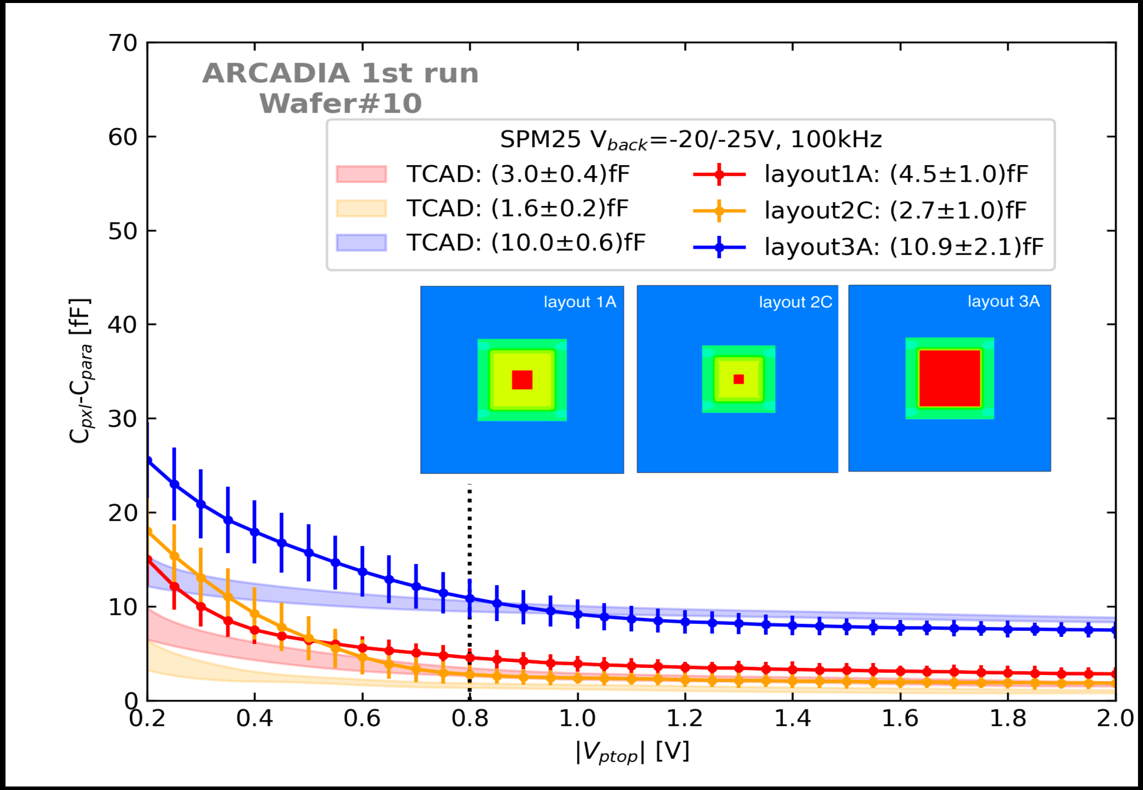


23 wafers produced in first 2 production runs, 3 types/thicknesses

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 (2.56Å~1.28 cm^2)
- Demonstrator 512 x 512





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

DMAPS for CEPC

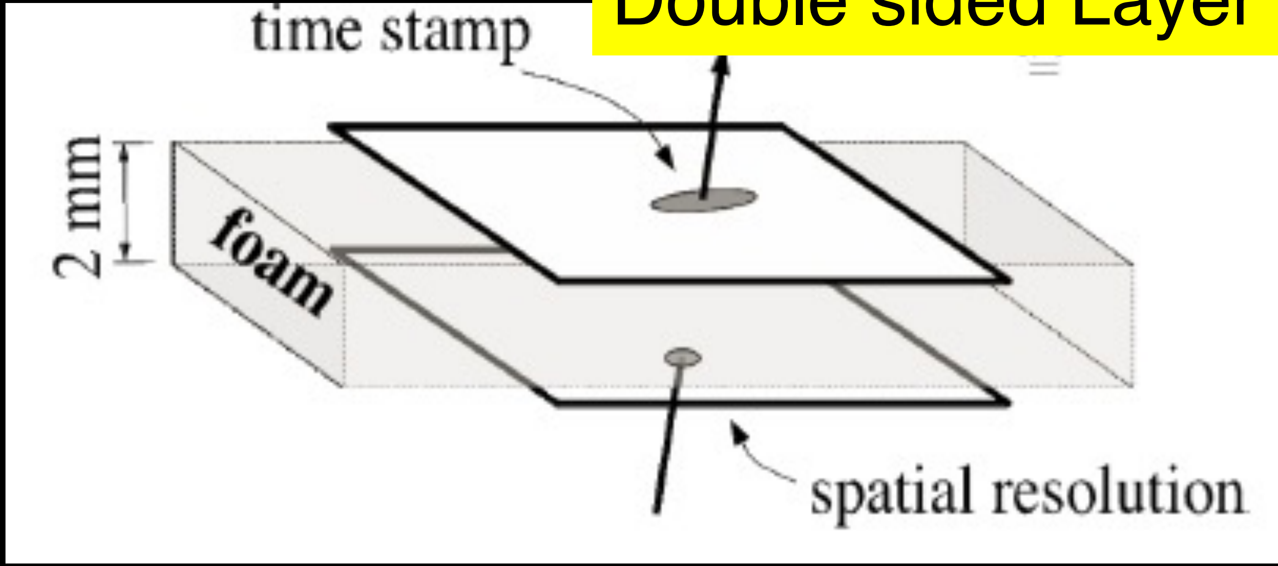
JadePix Tower 180 nm

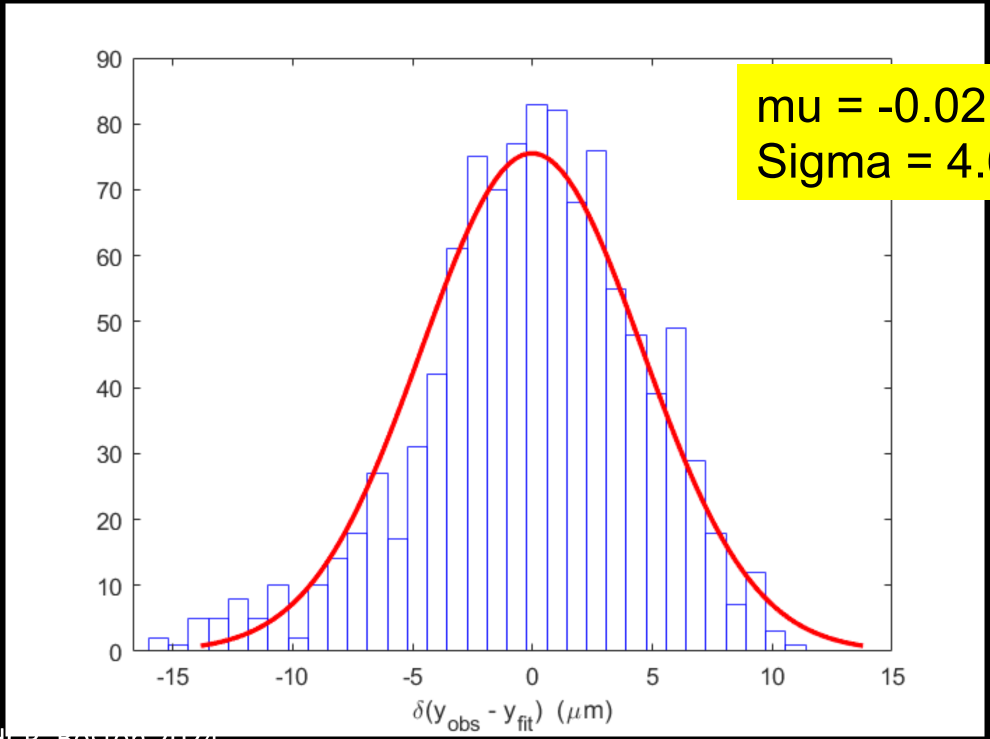
- JadePix-3
  - Fine pitch(16 x 23 μm^2) & low power sensor for spatial resolution
  - **s**.p.< 3 μm achievable
  - rolling shutter
- JadePix-4/MIC5
  - A faster sensor to provide time-stamp
  - s.p. < 5μm, 1μs integration time
  - row address encoder

TaichuPix sensor Tower 180 nm

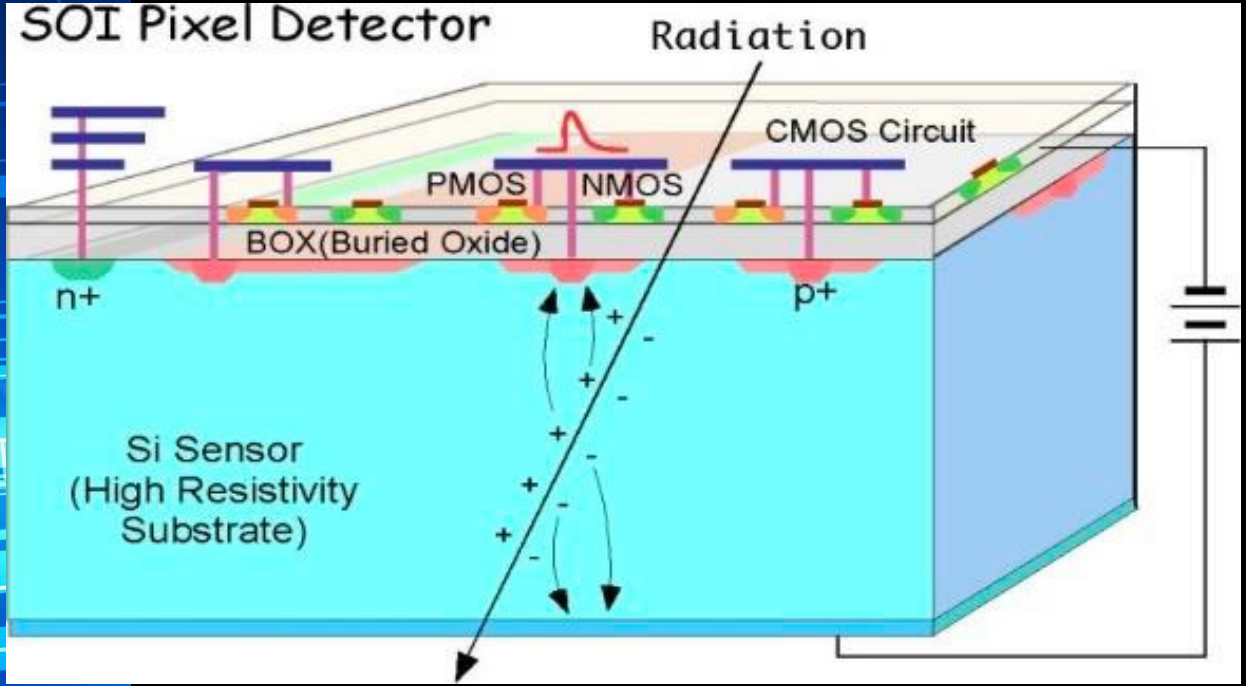
- 3 round of sensor prototyping
- Pixel 25 μm ×25 μm
- Column-drain readout for pixel matrix

Double sided Layer





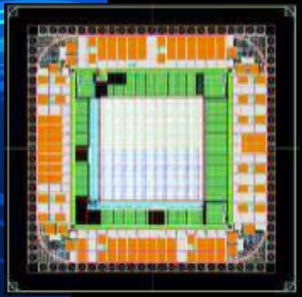
SOI for CEPC



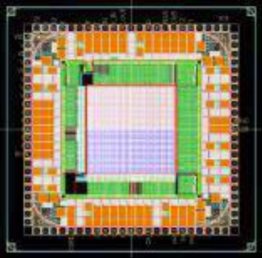
Silicon-on-Insulator technolog 0.2µm FD-SOI CMOS lapis Semiconductor Co. Ltd.

- High resistivity （>1 kΩ·cm) thick (50-500 µm) sensitive layer
  - High SIGNAL/low material budget possible;
- Fully depleted (high basing voltage > 100V possible)
  - fast collection
- Low power dissipation

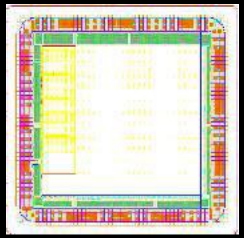
2015 2017 2019 2022



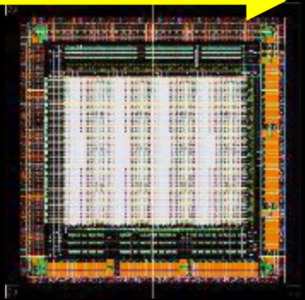
CPV1



CPV2



CPV3

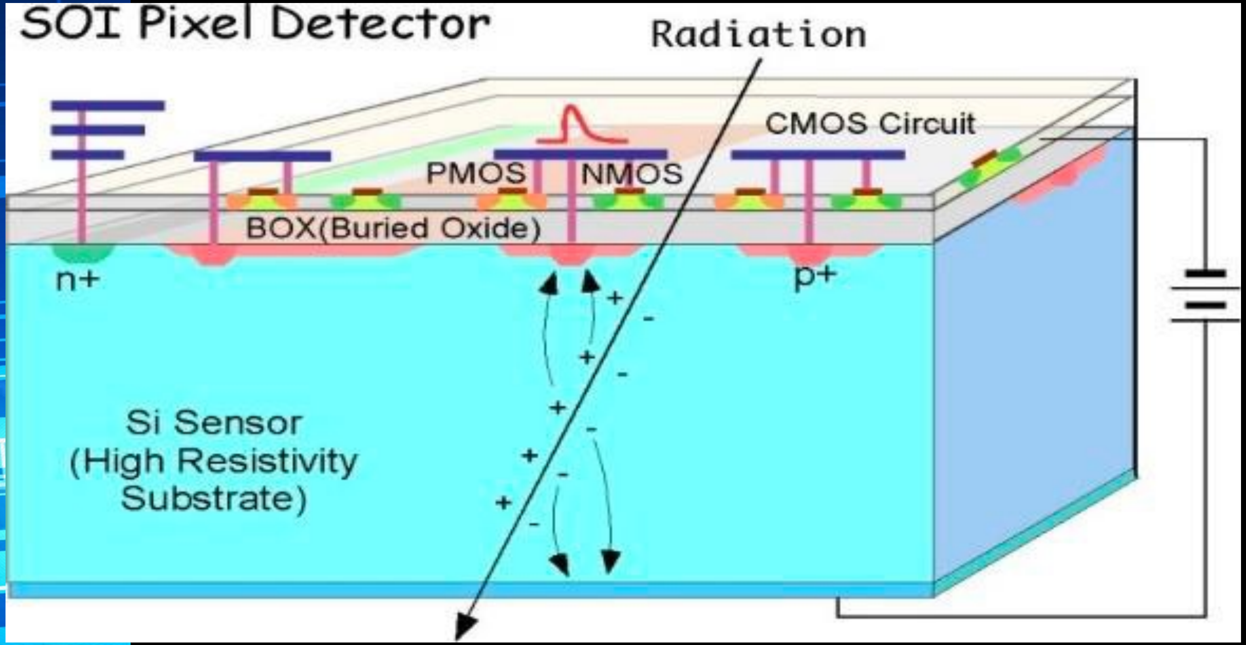


CPV4

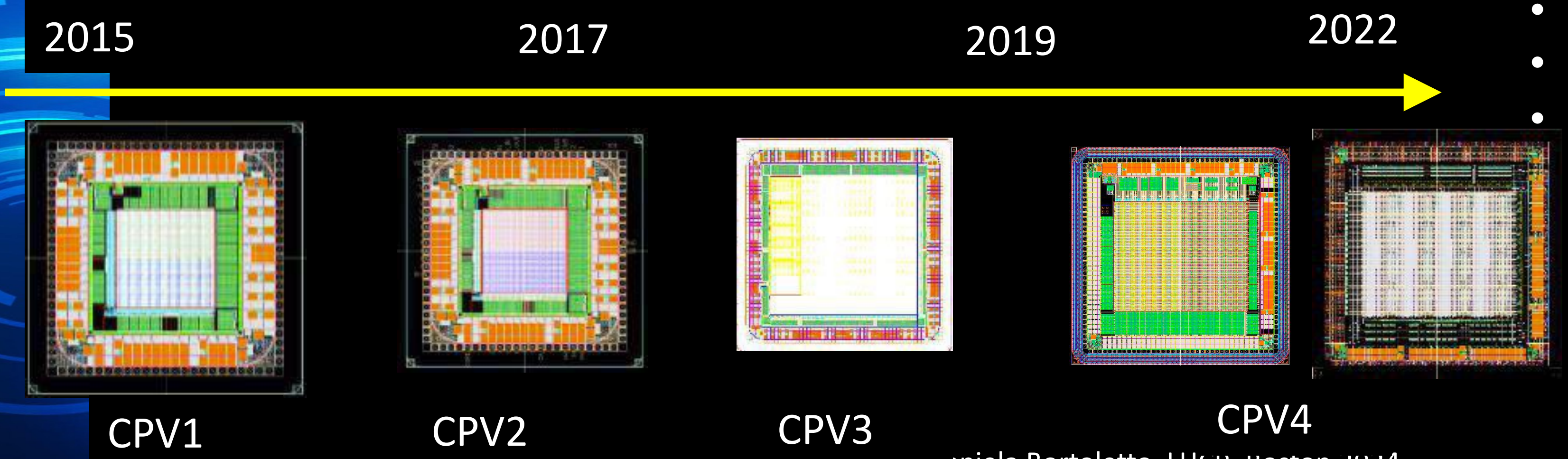
- 16µm pixel pitch & 50µm thick
- Low threshold
- In-pixel discriminator
- In matrix zero-suppression to minimize data load
- Hit processing within ~1µs to keep low occupancy;

SOI for CEPC

Silicon-on-Insulator technolog 0.2µm FD-SOI CMOS lapis Semiconductor Co. Ltd.



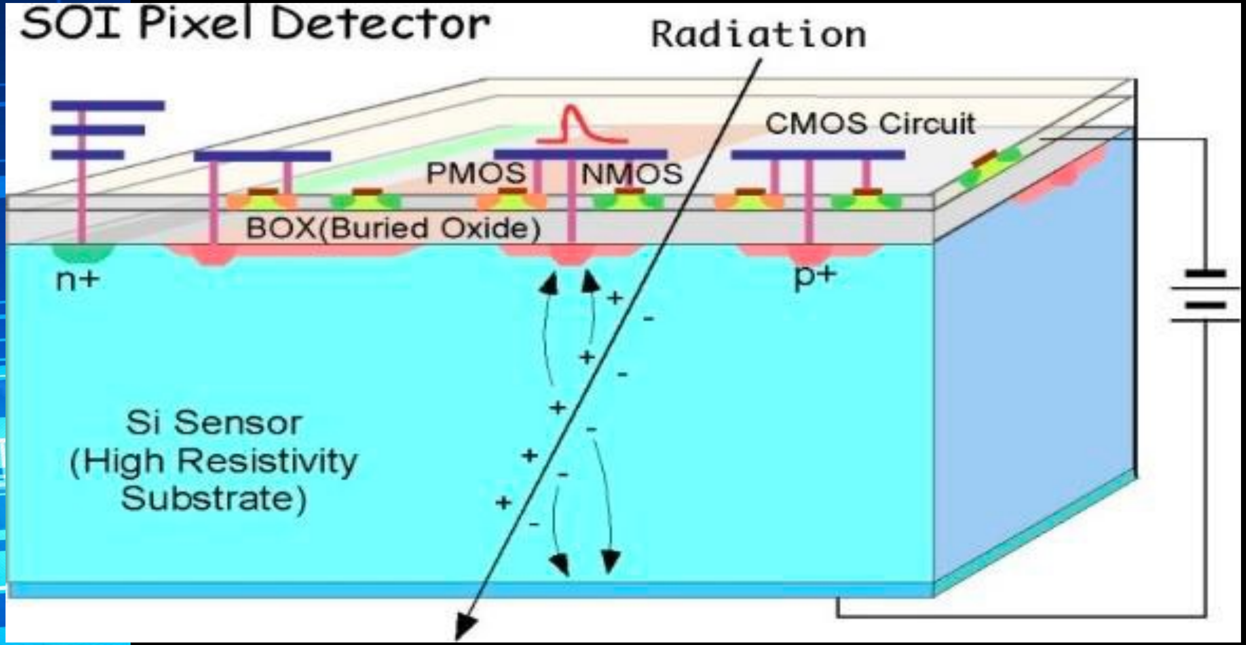
- High resistivity (>1 kΩ·cm) thick (50-500 µm) sensitive layer
  - High SIGNAL/low material budget possible;
- Fully depleted (high basing voltage > 100V possible)
  - fast collection
- Low power front end (similar to ALPIDE)
- 3 µm resolution achieved with CPV2
- Pitch 16 µm , Minimum threshold < 200 e-, ENC = 6 e-

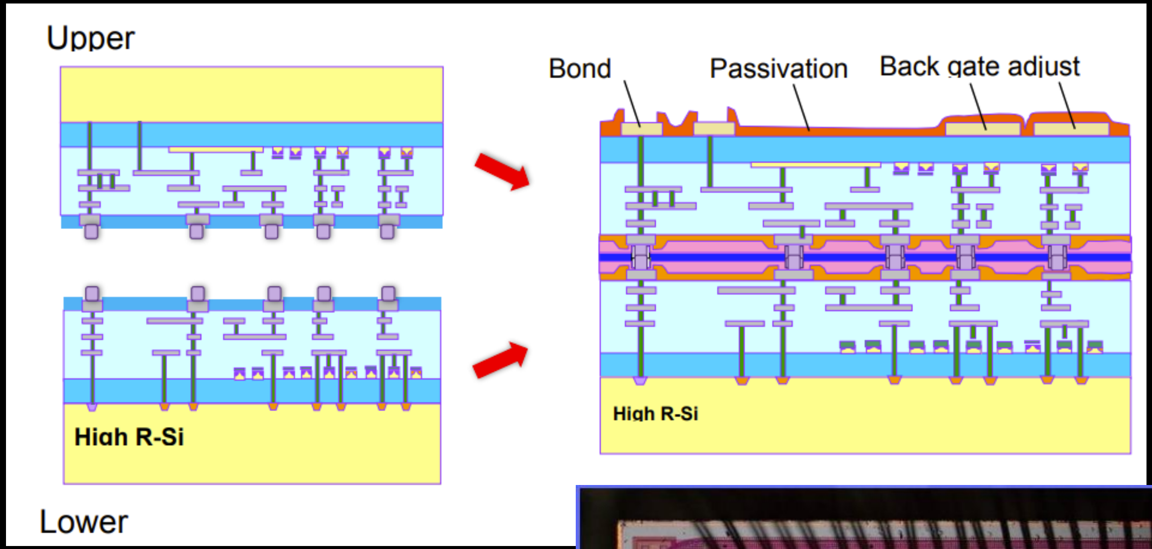


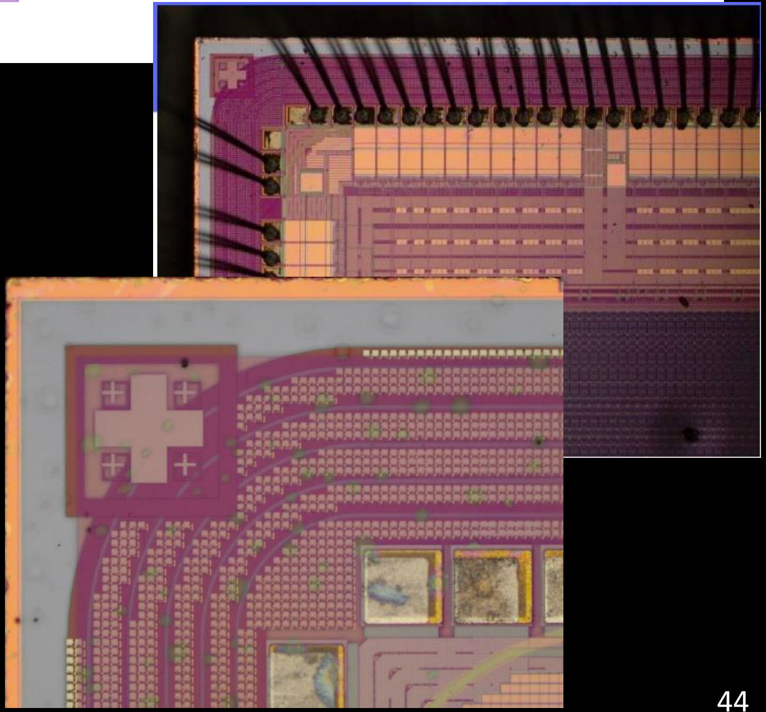
- 17 x 21 μm^2 pixels & 50µm thick
- Time resolution 1µs
- Vertical integration of
  - Lower tier sensing diode + amplifier/comparator;
  - Upper tier: Pixel control + Asynchronous Encode Reset Decode*)
  - Measurement ongoing

SOI for CEPC

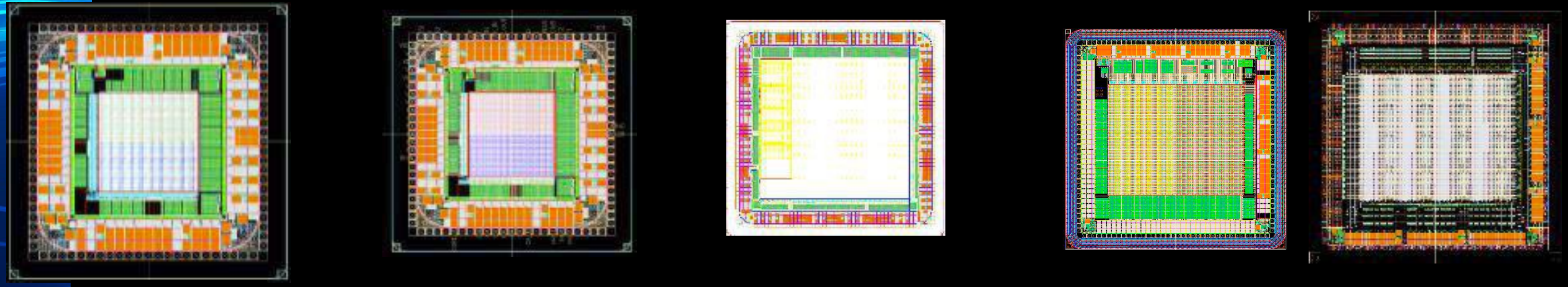
- Vertical Integration







2015 2017 2019 2022

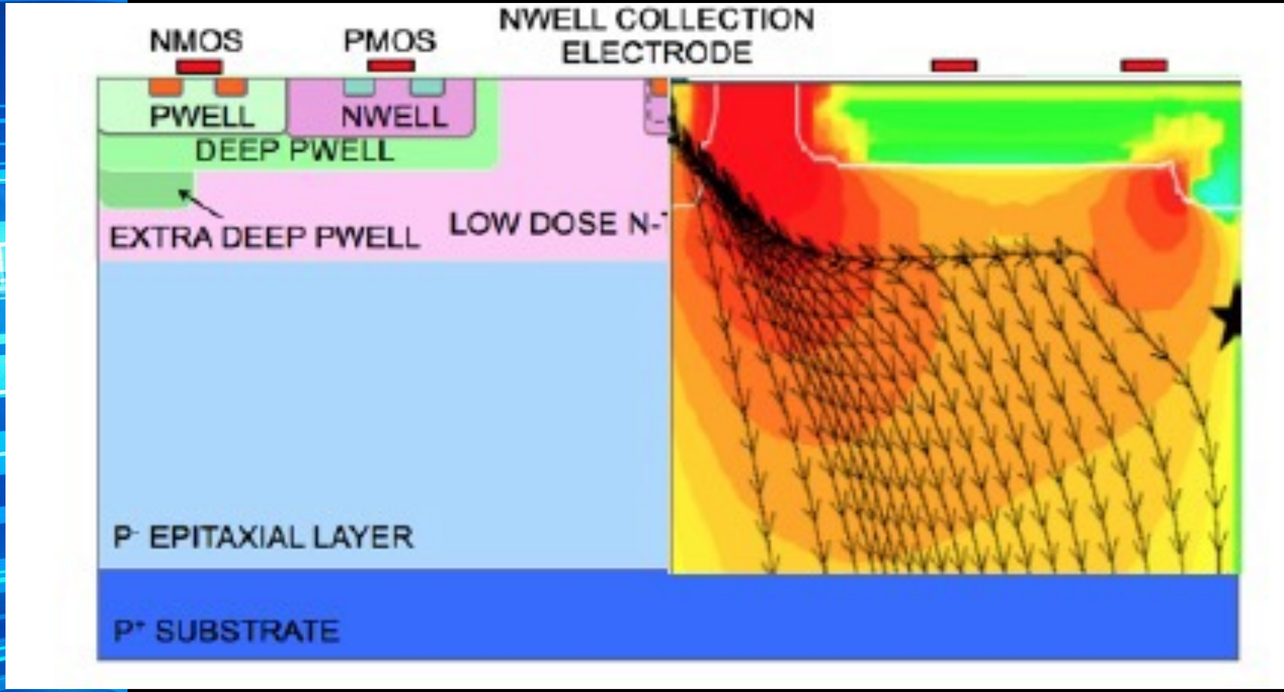


CPV1 CPV2 CPV3 CPV4

CMOS DMAPS Small Electrode

Modified TJ process to improve radiation hardness

- MALTA 2 (epitaxial and CZ)



CMOS DMAPS Small Electrode

Modified TJ process to improve radiation hardness

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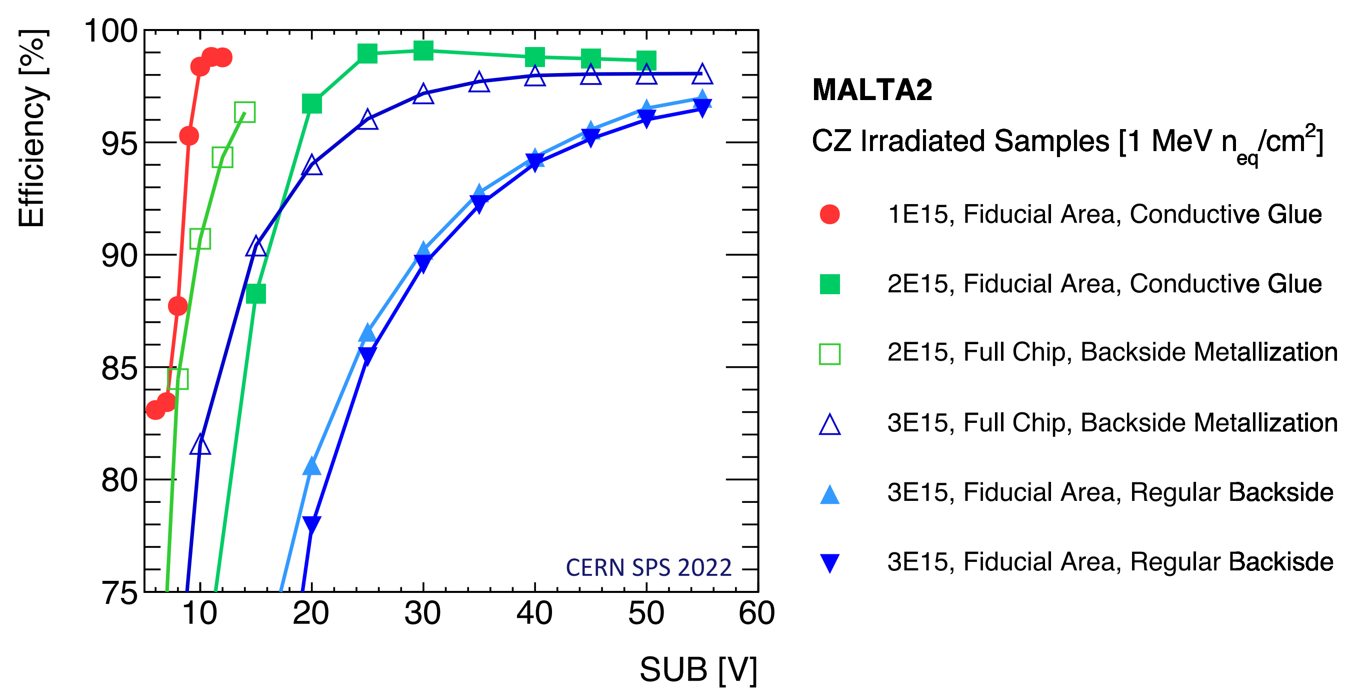
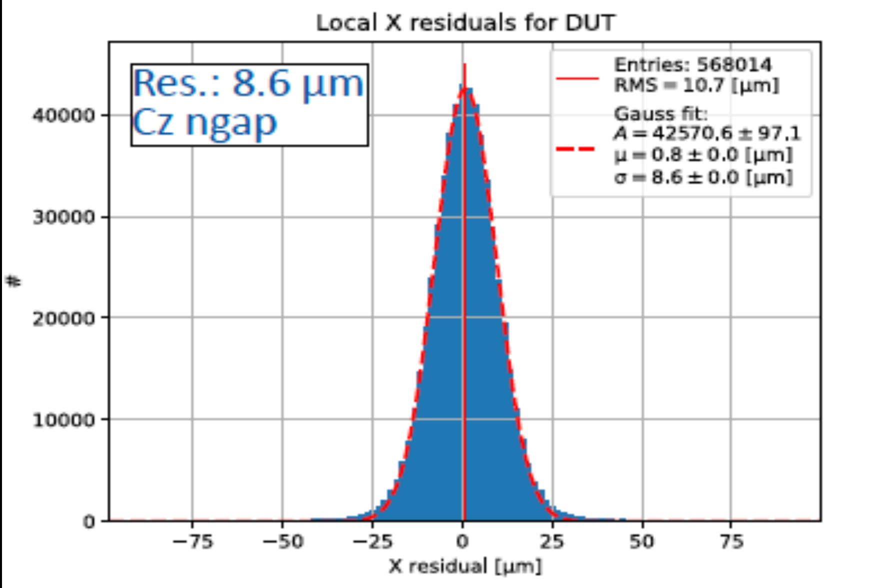


Average efficiency of irradiated MALTA2 on Czochralski substrate versus SUB voltage

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



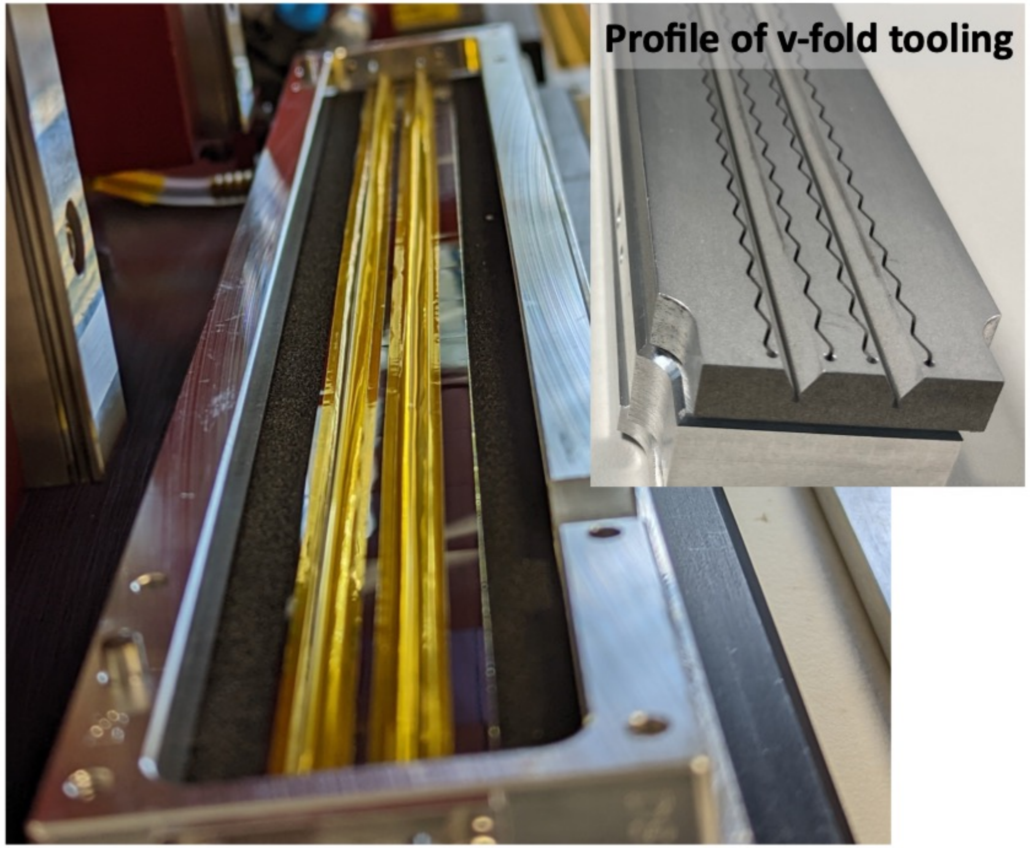
- OBELIX (Optimized BELle II pIXel sensor
  - Total Ionizing Dose (TID) 100 kGy/year
  - Non-Ionizing $5x10^{13}$ $n_{eq}/cm^2/year$
  - Hit rates up to 120 MHz/cm^2

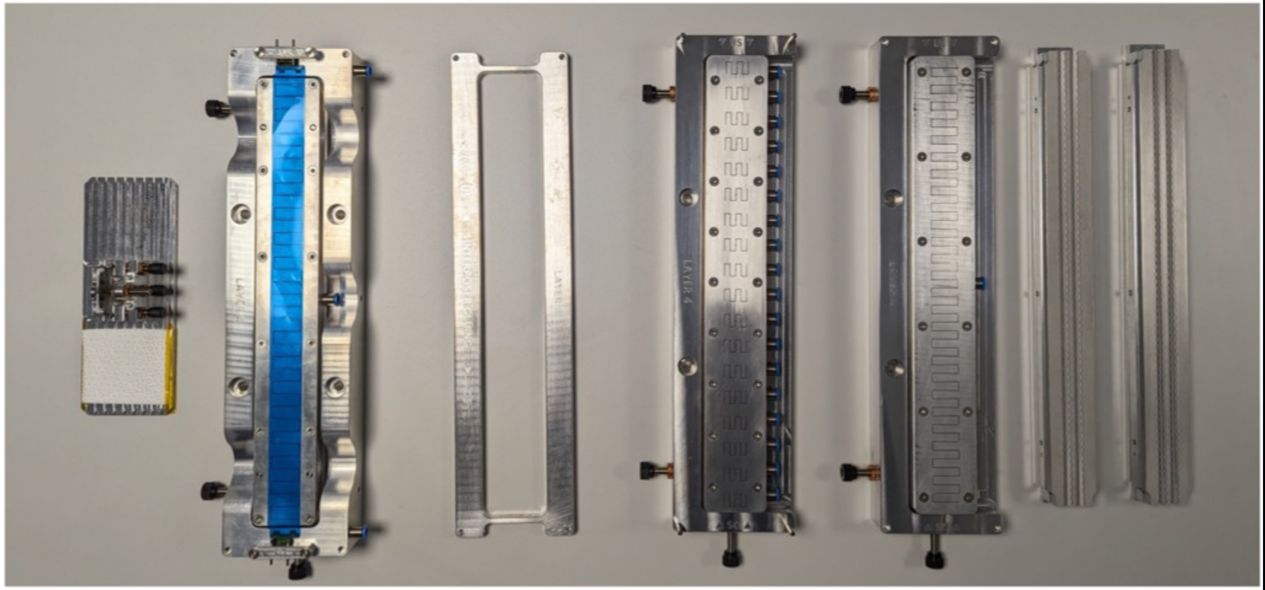
Mu3e outer layer fabrication

Production tooling for Layer 4 is almost complete, tooling for Layer 3 to commence shortly after.

- Expected production rate is $\mathcal{O}$(1.5 ladders / day), to commence March 2024

Prototype outer pixel layers have been fabricated.





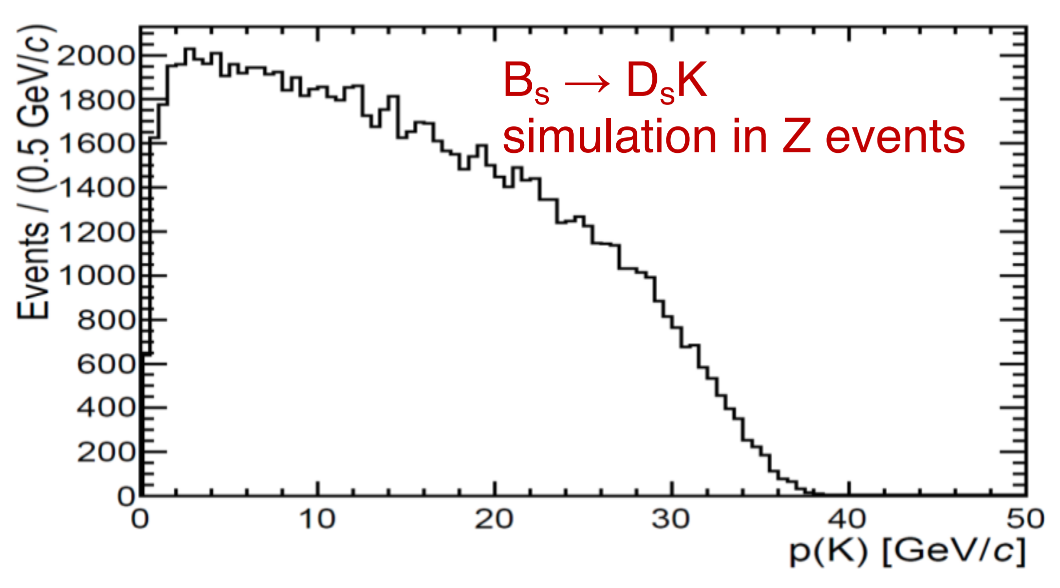
Interposer flex bending tool	Align, glue, TAB bond interposer and ladder flexes	Ring frame to hold ladder during production	Chip chuck: align MuPix 11 array on robot and glue chips to ladder	Flex chuck for MuPix11 TAB binding, and V-fold gluing	V-fold and U-fold chucks

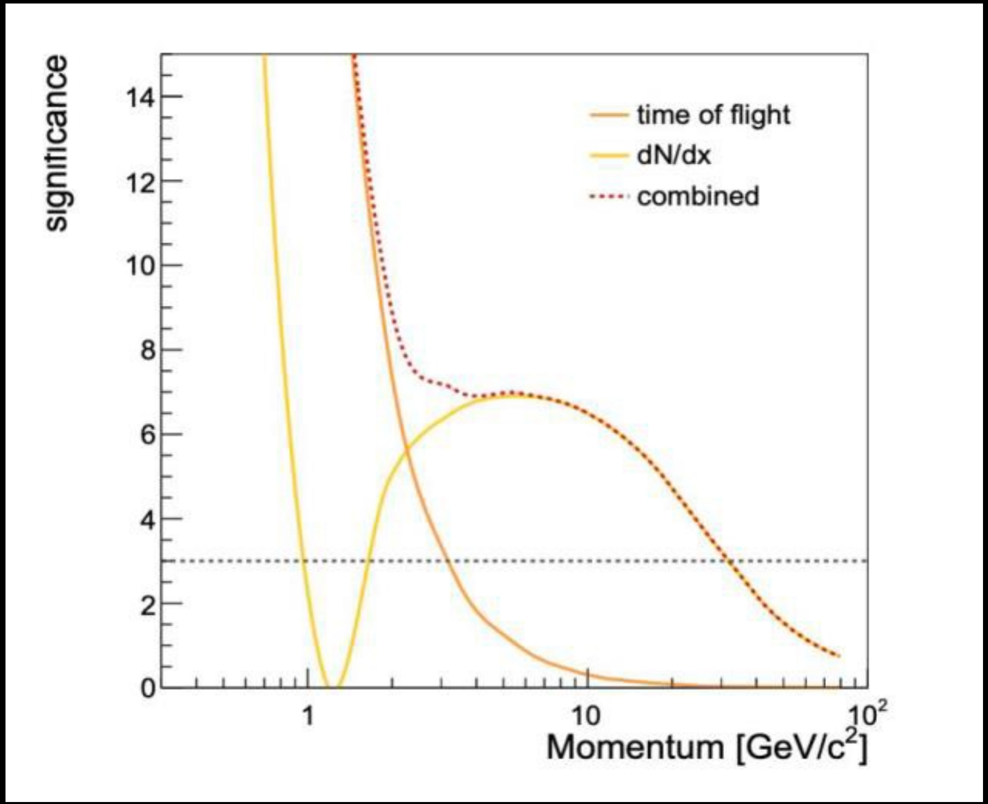
14

Particle ID for FCC ee

- Physics at FCC-ee requires:
  - Higgs Physics: identify H → bb, cc, ss
  - Z pole Physics: precision measurements of Z couplings to quarks R_b,R_c, AFB etc.
  - Flavour physics: Exploit enabled by the huge statistics at the Z

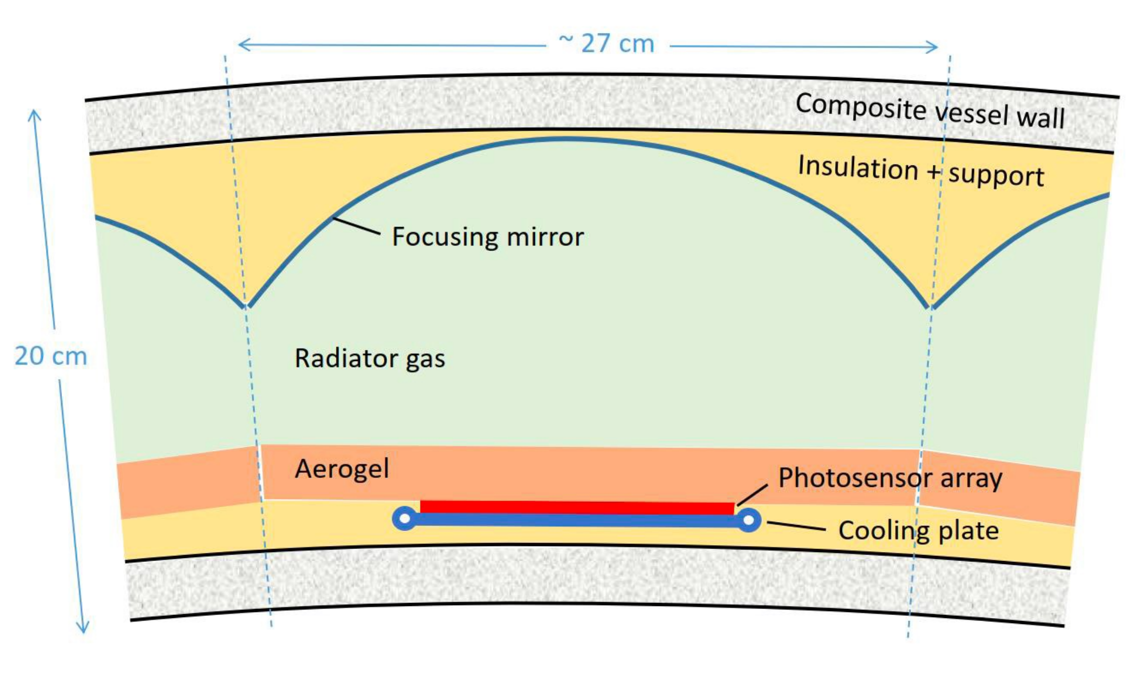
- Momentum range required = ~ 1– 40 GeV/c
  - Cluster counting in gaseous trackers (→ DRD1) + TOF to cover overlap region



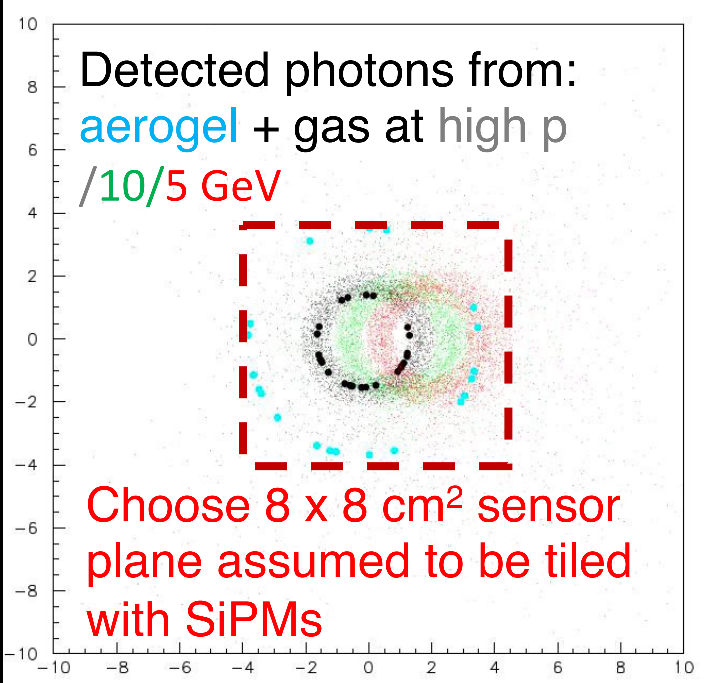


ARC: Array of RICH Cells for FCC-ee

- Aggressive parameters: Radial depth of 20 cm and few % X_0 material
- Challenge to arrange optical elements so that Cherenkov light focused onto a single sensor plane, as the detector radial thickness is reduced
- Design developed for the CLD FCC-ee inspired by the compound-eye of an insect
  - tile the plane with many separate cells, each with its own mirror and sensor array
- Use spherical focusing mirrors: focal length = radius-of-curvature/2 → select radius-of-curvature R≈ 30 cm for radiator thickness of 15 cm



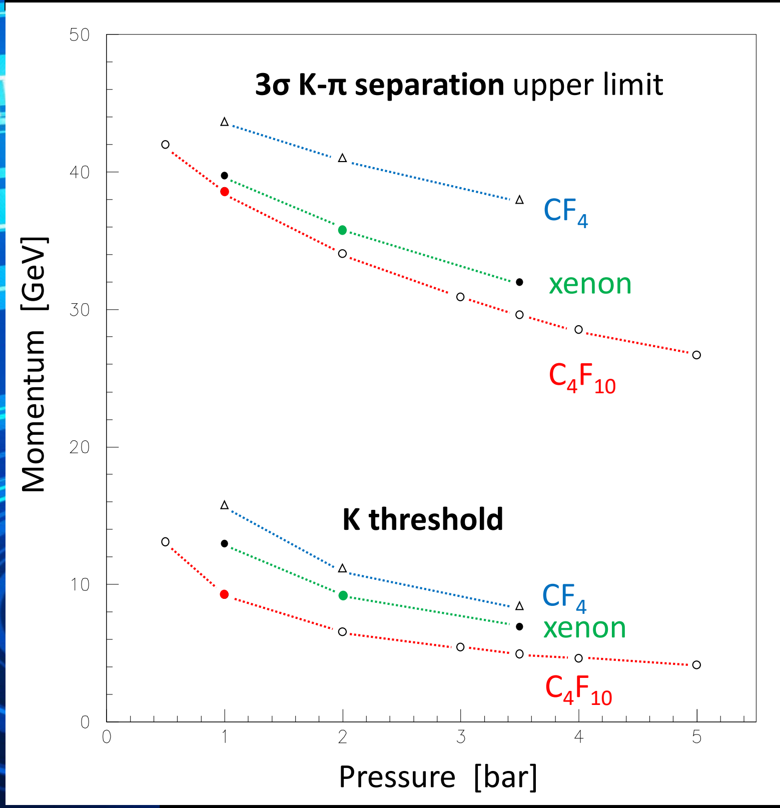
Simulate tracks from IP crossing detector uniformly over acceptance and ray trace Cherenkov photons to sensor plane: Ring radii = $R\theta_c/2$~1 cm (3.6 cm) for gas (aerogel)

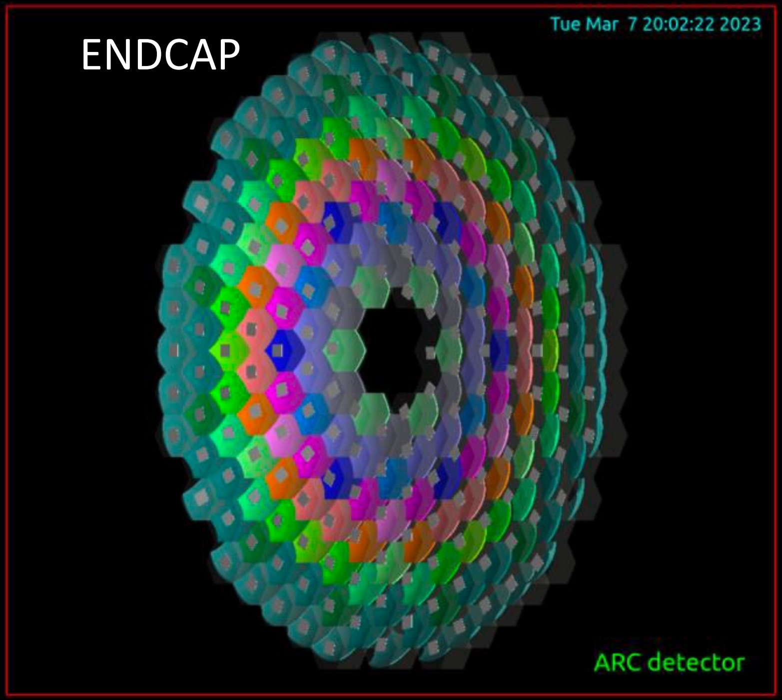


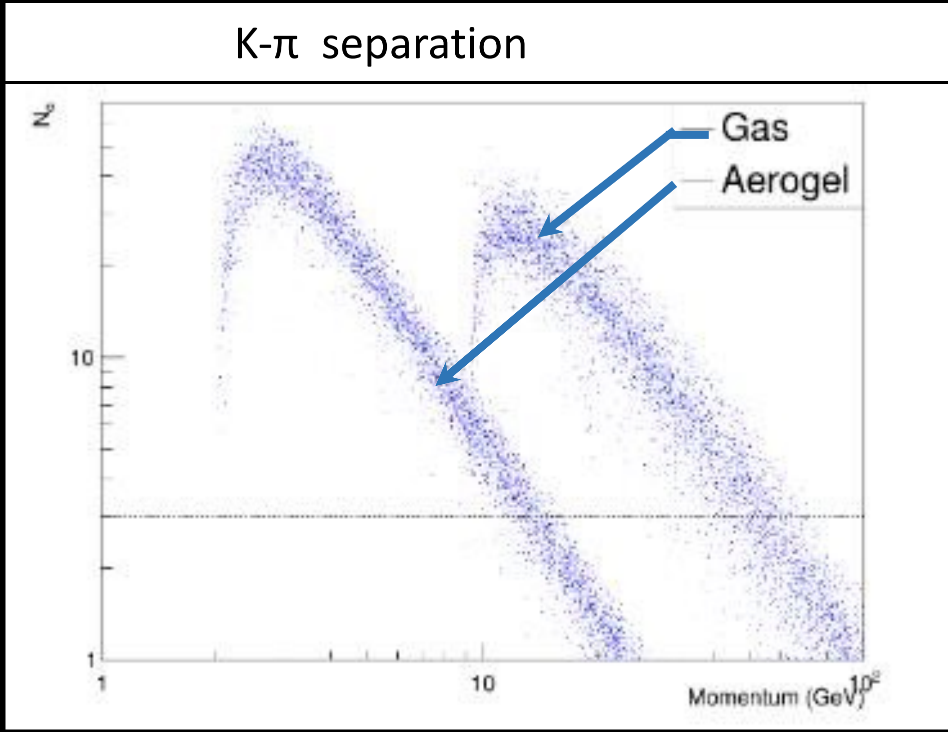
ARC

- Radiator gas parameter scan
  - C_4F_{10} at atmospheric pressure gives good momentum range for K-π separation, with acceptable photon yield
  - Xenon at 2 bar provides similar performance

- Resolution optimized with ~ 1300 *hexagonal* cells
- Optical layout optimized via a standalone ray-tracing study: adjusting the position, curvature and tilt of mirrors and sensors
- Excellent K-π separation predicted over momentum range 2–50 GeV/*c*

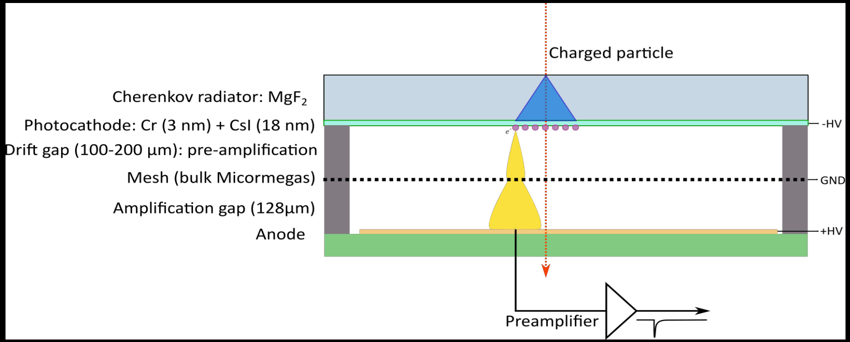


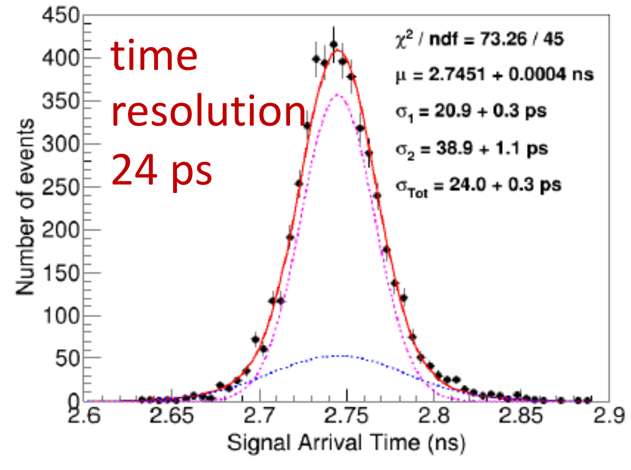


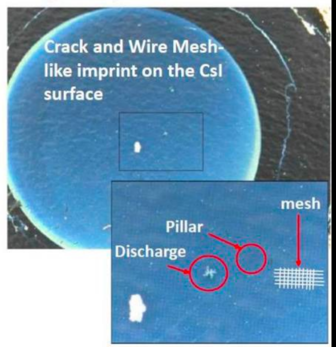


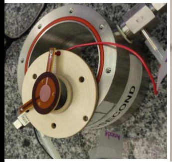
Fast Timing Gas detectors: PICOSEC

- Precise timing demonstrated
- RD focused on:
  - Improvement of stability
    - Prototypes with resistive MM
  - Detector optimization
    - Detector field, operating gas & gaps thickness
  - Robustness
    - Research on photocathode materials
  - Development of large area prototypes and readout electronics

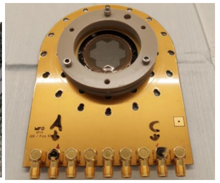




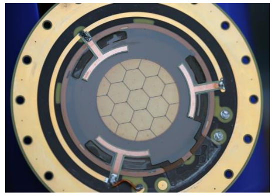




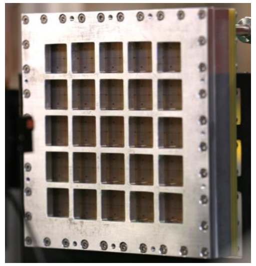
- 1-ch (ϕ1cm)
- Proof of concept
- Resistive and non-resistive prototypes.



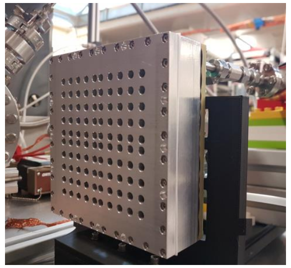
- 7-ch (1cm)
- Signal sharing
- Resistive prototype



- 19-ch (ϕ3.6cm)
- Signal sharing.

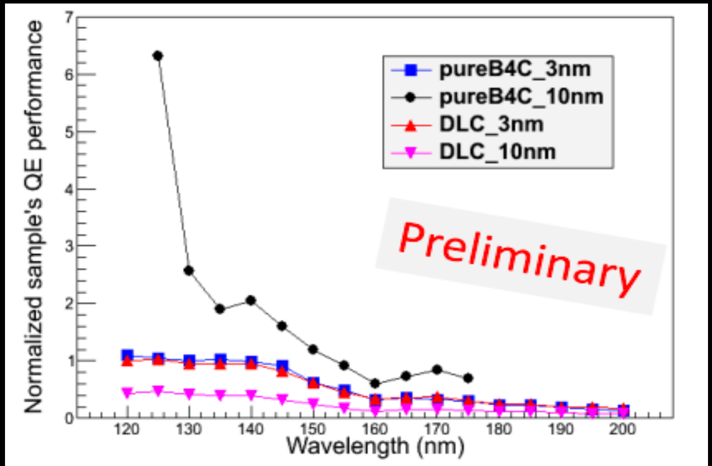


- 100-ch (10 cm x10 cm)
- Tileable
- Hybrid ceramic substrate MM
- MM decoupled from housing with spring-loaded pins



- 100 ch (10 cm x10 cm)
- MgF2 mechanically decoupled

- 100 ch (10 cm x10 cm)
- Sealed Ti housing
- Increased fill factor



From Linear to Circular e^+e^- Detectors

- Lower energy jets and particles, less collimated jets:
  - Reduced calorimeter depth
  - Shift imaging vs. energy resolution balance towards the latter
- Tracking even more multiple-scattering dominated:
  - Increased pressure on material budget of vertex detector and main tracker
  - More interest in gaseous tracking
- Limitations on solenoidal field B < 2T, to preserve luminosity
  - recover momentum resolution with tracker radius
- Main difference: no bunch trains; collisions every 20 ns (~ at LHC)
  - No power pulsing, more data bandwidth: both imply larger powering and cooling needs
  - Adds material to the trackers and compromises calorimeter compactness - or reduce granularity, timing, speed
  - Trigger and DAQ re-enter the stage