

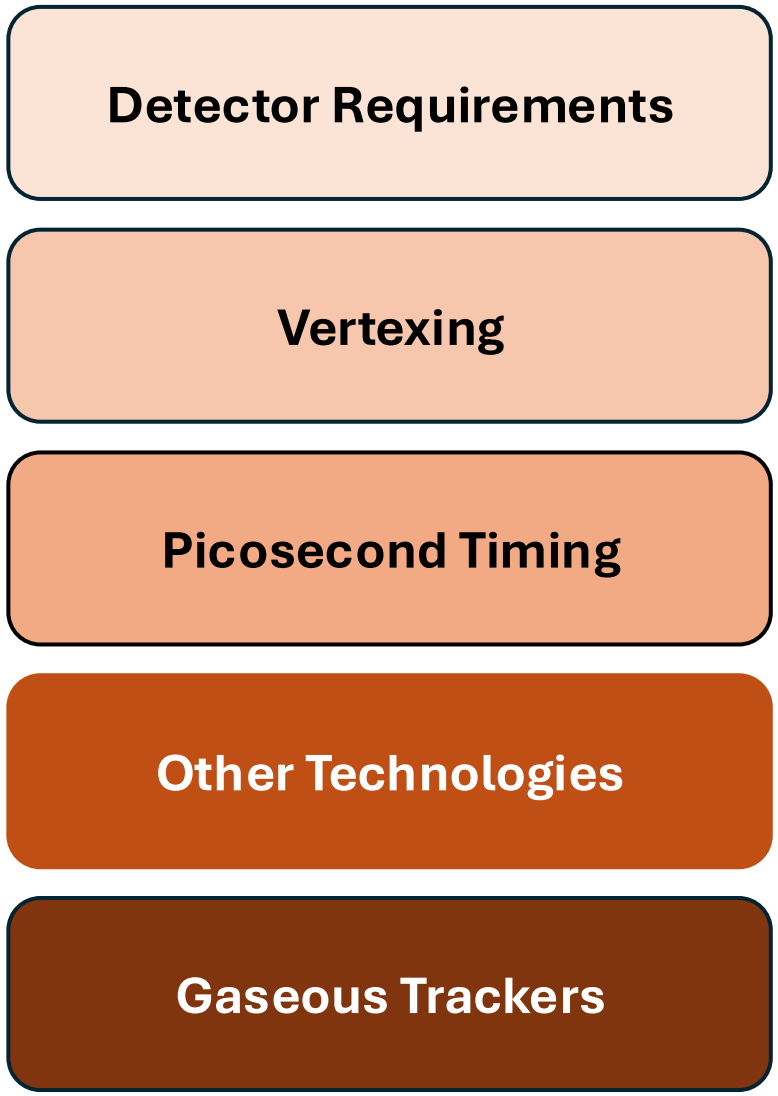
Semiconductor and Gaseous Tracking Detectors

Petra Merkel

Fermilab

U.S. DEPARTMENT of ENERGY

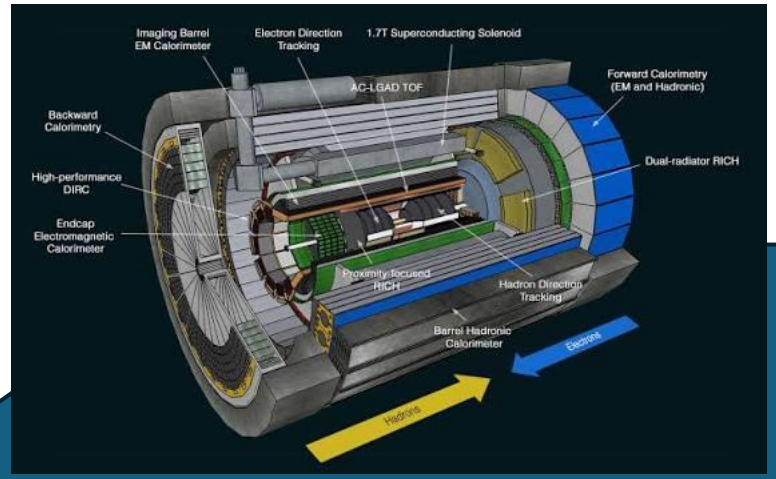
Outline



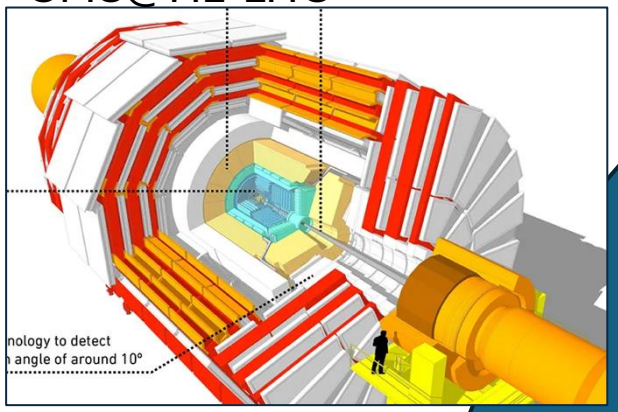
Apologies if your favorite project or technology are not covered


The CMS Tracker as of yesterday
TIME FOR SOMETHING NEW!

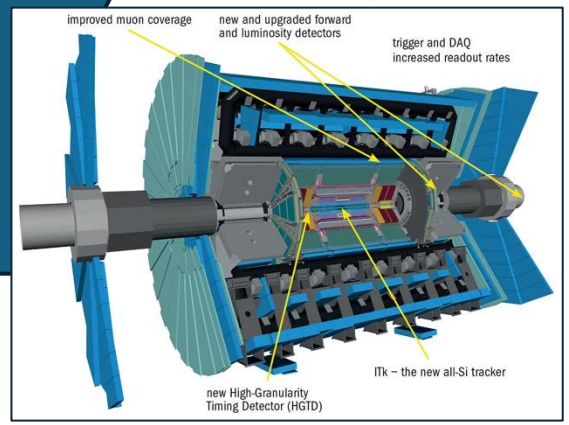
ePIC@EIC



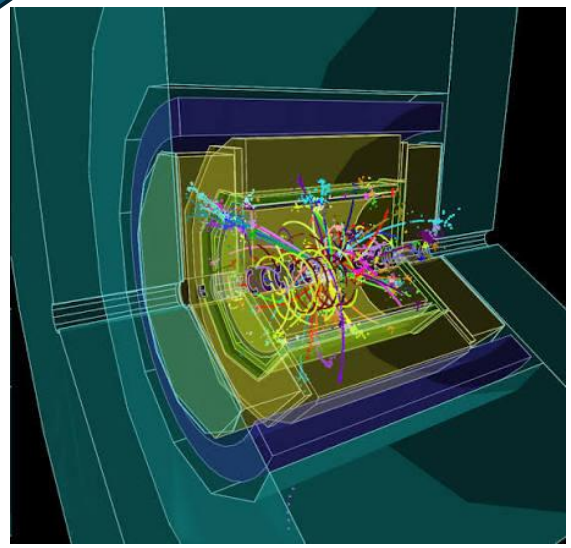
CMS@HL-LHC



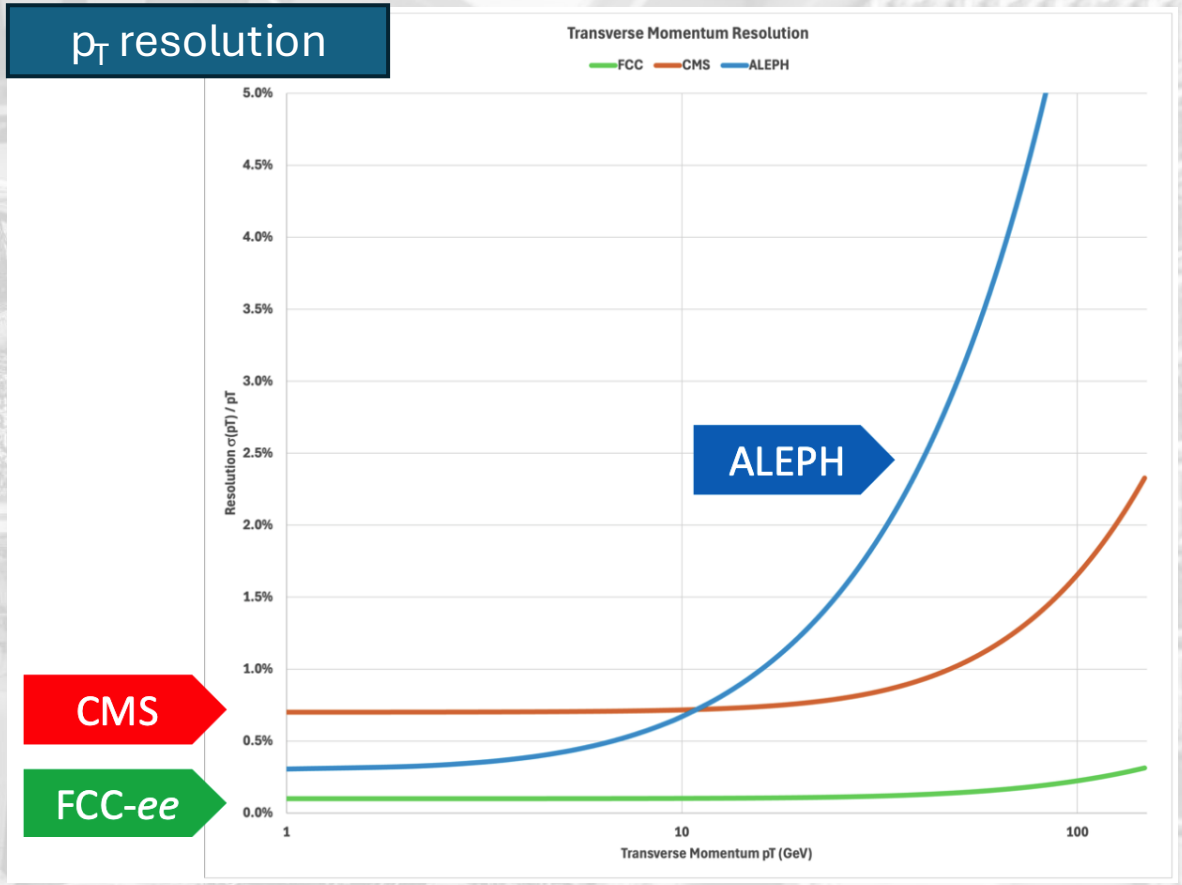
ATLAS@HL-LHC



Higgs Factory



p_T resolution



01

Detector Requirements informed by Physics Goals

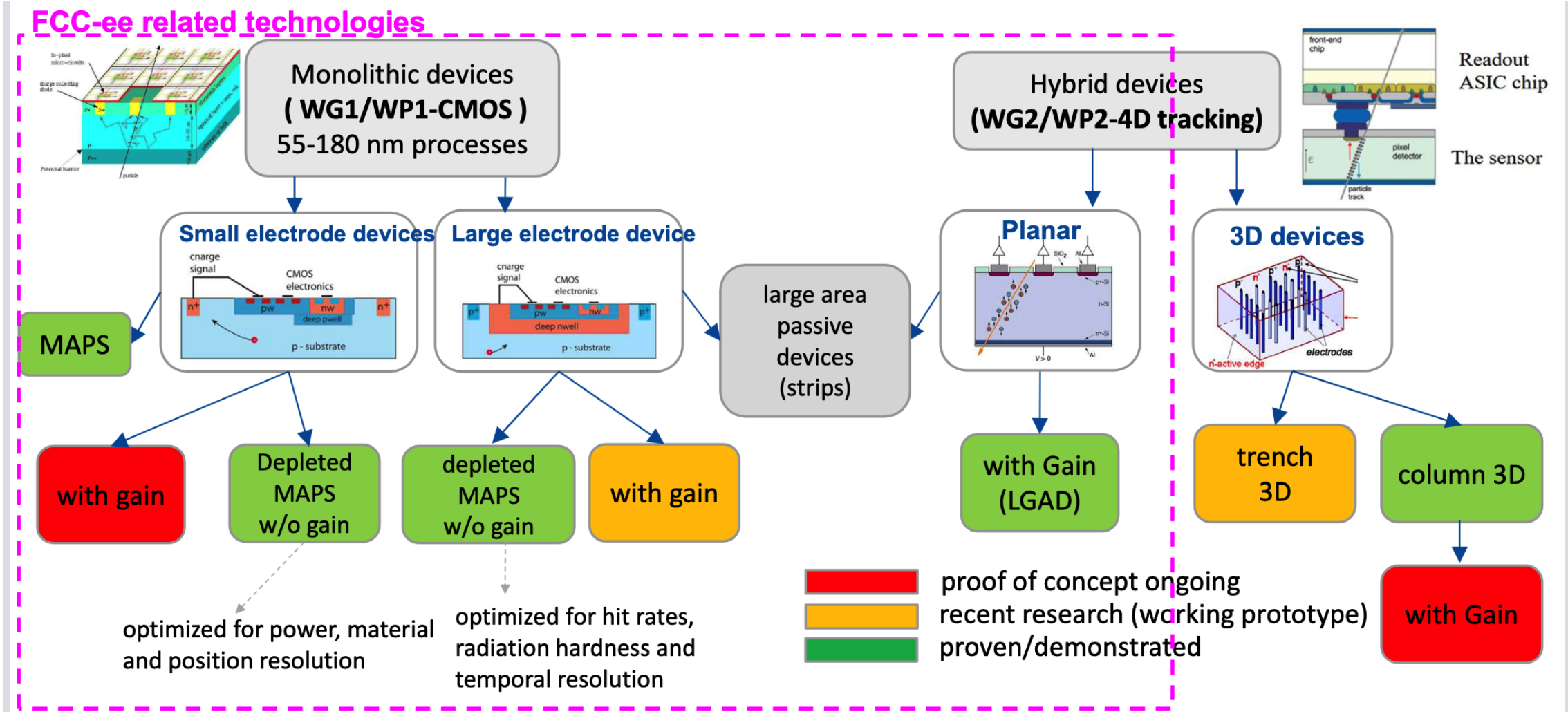
Vertexing and Tracking Performance

engineering requirements derived from physics drivers

	HL-LHC	EIC	FCC-ee / CEPC
Key environmental features	Extreme pile-up (~ 200 vertices) & high radiation	Asymmetric kinematics, low event multiplicity, moderate occupancy	Precision Z-pole/Higgs recoil statistics, ultra-low multiple scattering needed
Hit/spatial resolution	~5 – 25 μm (depending on layer/pixel size)	~5 μm (MAPS innermost layers)	≈ 3 μm (Inner vertex layers)
Momentum Resolution	~1 – 20 % (depending on p_T)	~0.5 – 4 % (depending on η)	~0.1 – 0.2 % (depending on p)
Material Budget – vertex (per inner layer)	~0.5 – 1 % X/X_0 (ATLAS, CMS) 0.05 – 0.09 % X/X_0 (ALICE)	~0.05 – 0.1 % X/X_0	~0.2 - 0.3 % X/X_0
Material Budget - tracker	~30 – 50 % X/X_0	~4 – 7 % X/X_0	~1.6 – 15 % X/X_0
Time Resolution	~30 – 50 ps	~20 – 30 ps	~10 – 100 ps (for PID)

ignoring other collider options here for simplicity (e.g. LC, 10 TeV pCM)

Current Landscape of Sensor R&D





02

Vertexing

MAPS

Monolithic Active Pixel Sensor

New kid on the block

Co-designed CMOS sensor and readout in one chip

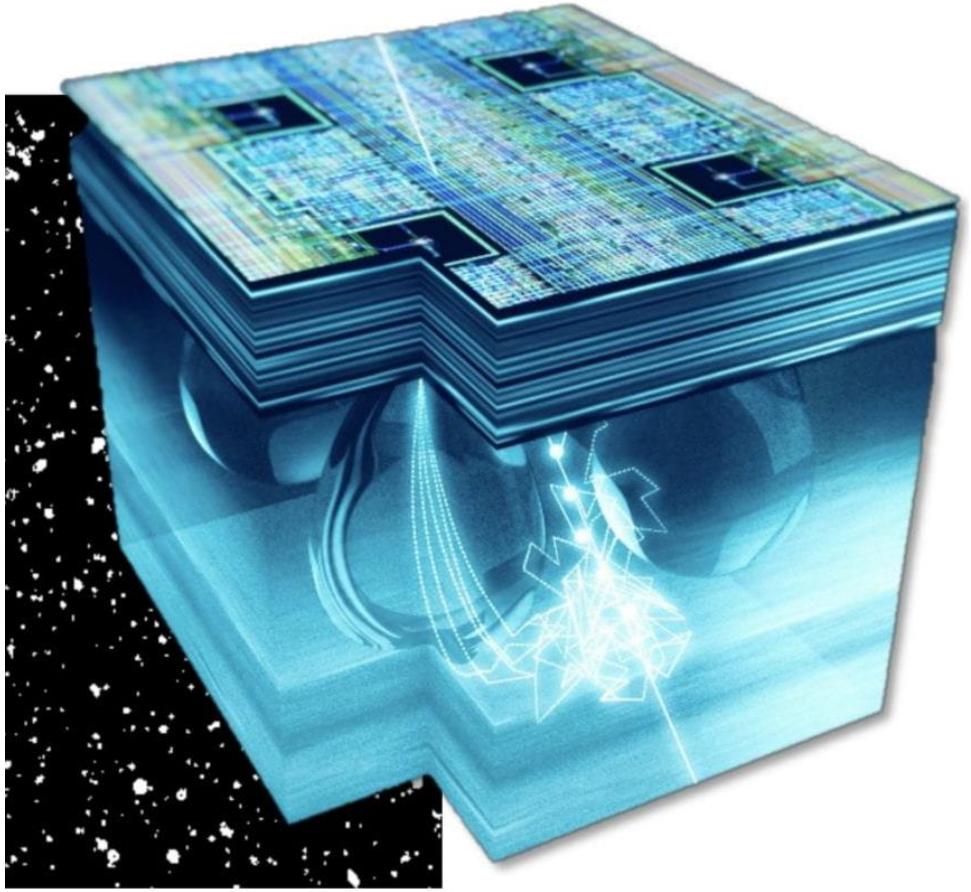
- **Today:** ALICE ITS3 @ HL-LHC
- **Tomorrow:** ePIC @ EIC
- **Next week:** everywhere @ future colliders

Homogeneous and very light-weight

- large area, stitched sensors, ‘no gaps’
- thinned to 50 μm and bent
- air cooling and ultra low-mass mechanical support

Worldwide R&D ongoing

sensor design, timing capabilities, power consumption

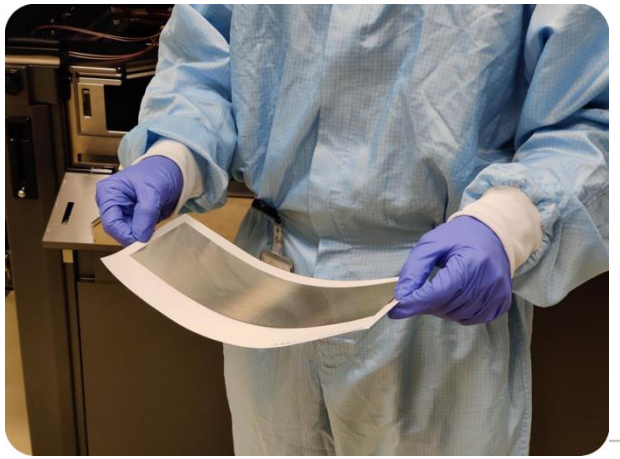


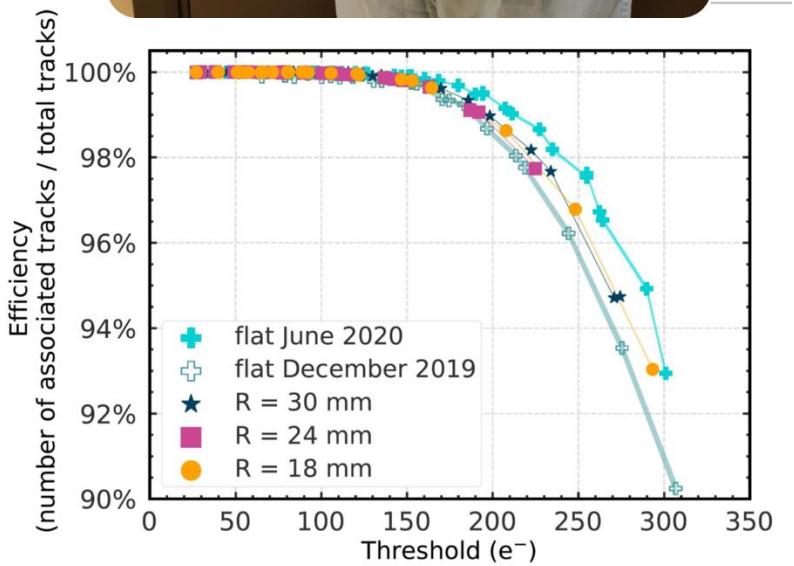
ITS3 for ALICE

state-of-the-art, spearheading new technology

- Only silicon and carbon fiber and foam spacers
- Air cooling: 40 mW/cm^2
- Bent silicon sensor contains ‘everything’, no flex circuits
- Move to 300 mm wafers and 65 nm CMOS imaging technology: full-scale engineering wafers in hand (MOSAIX)
- Data moved off detector through high-speed flex



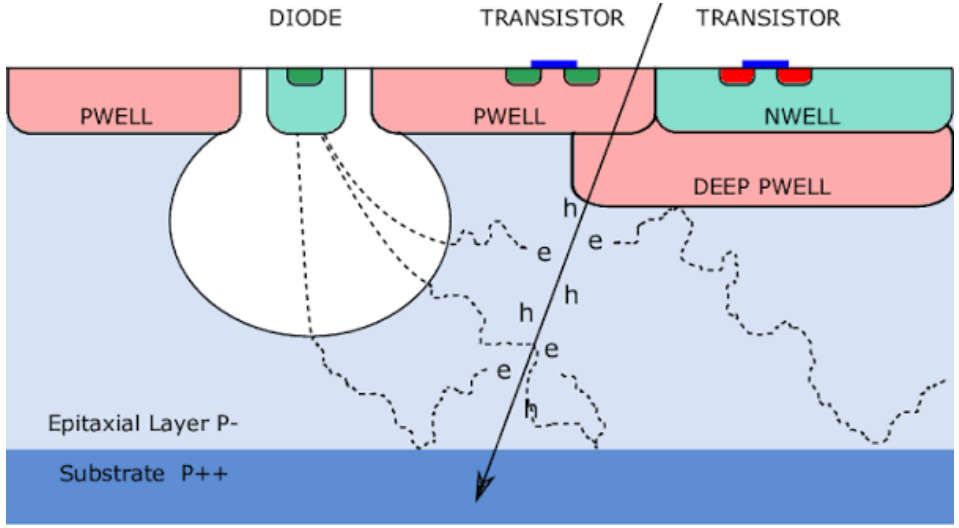




R&D also driven by adaptation for ePIC@EIC

MAPS R&D

going beyond ITS3



- The community has recognized the importance of MAPS technology for future experiments
  - vertexing, timing, tracking, calorimetry
- Main R&D directions being followed are
  - reduced power consumption
  - sub-20-ps timing resolution
  - sub-3-μm single point resolution
  - sensor optimization via simulations, e.g. implants, E-field
  - on-chip serial powering for large-scale trackers, e.g. EIC
  - critical: cost-effective access to process nodes, MWR,IP sharing, etc.
- Just a few R&D examples in the following pages

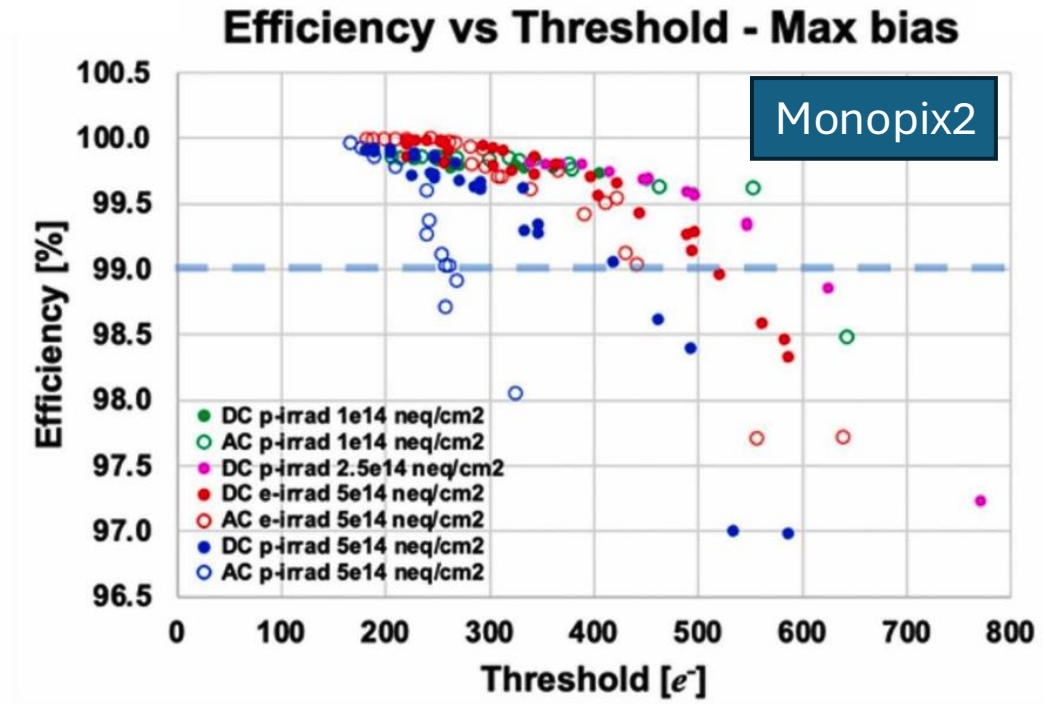
Organized within

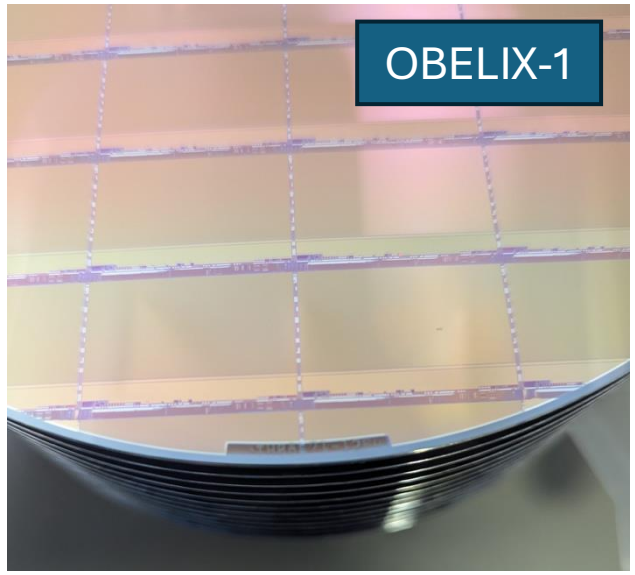
DRD3, DRD7 (CERN) and RDC3, RDC4 (CPAD/US)

BELLE II Upgrade

new vertex detector based on D-MAPS

- Stringent requirements on upgraded VTX detector:
  - higher hit rates: 120 MHz/cm^2 max avg. occupancy (up to 600 MHz/cm^2 during injection (for 0.5 μs) sustainable)
  - lower material budget: < 3 % X/X_0
  - radiation hard up to 100 Mrad, 5x10^{14} 1MeV n_{eq}/cm^2
  - power consumption < 200 mW/cm^2
- OBELIX D-MAPS sensor, based on TJ-Monopix2 chip (ATLAS ITk)
  - TowerJazz 180 nm modified CMOS process
  - OBELIX-1 in hand, characterization imminent
  - OBELIX-2 (final) expected at end of 2028

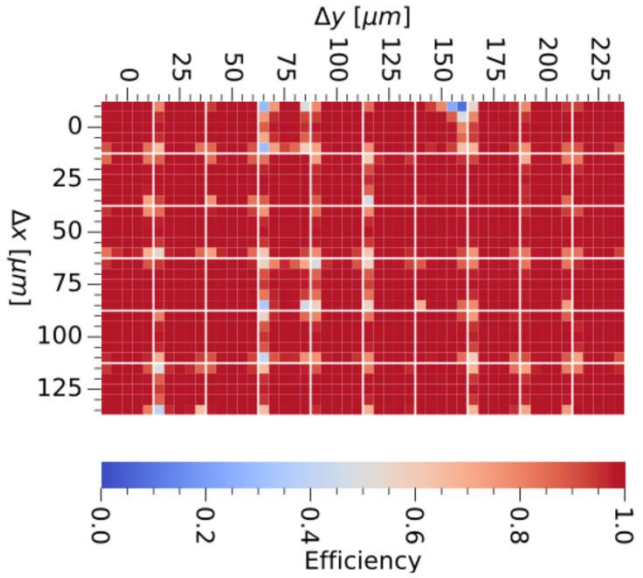




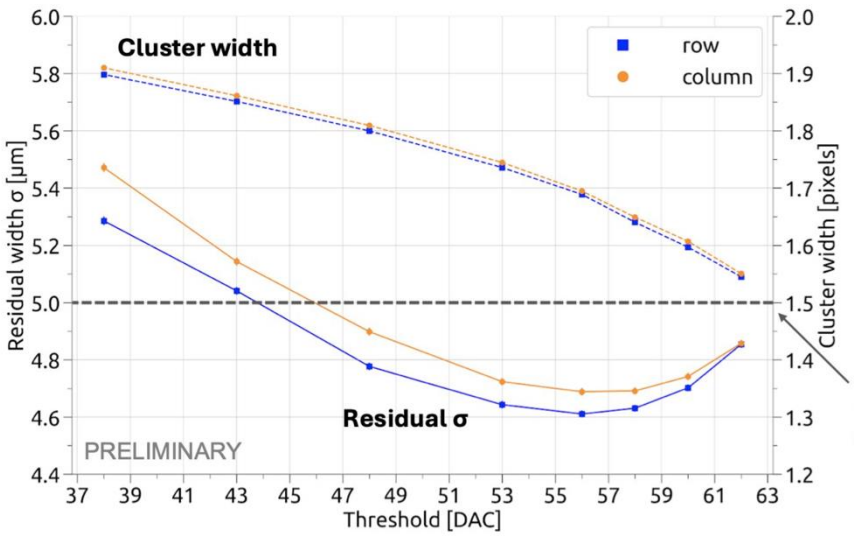
ARCADIA

optimized for low power consumption

- Fully depleted FD-MAPS: MD3 prototype
  - LFoundry 110 nm CIS process
  - 200 μm active thickness, 25 μm pixels
- Charge collection exclusively by drift
  - → enhanced collection efficiency
  - → enhanced radiation hardness
- ~4.7 μm residual distribution in beam



hit finding eff.
laser scan



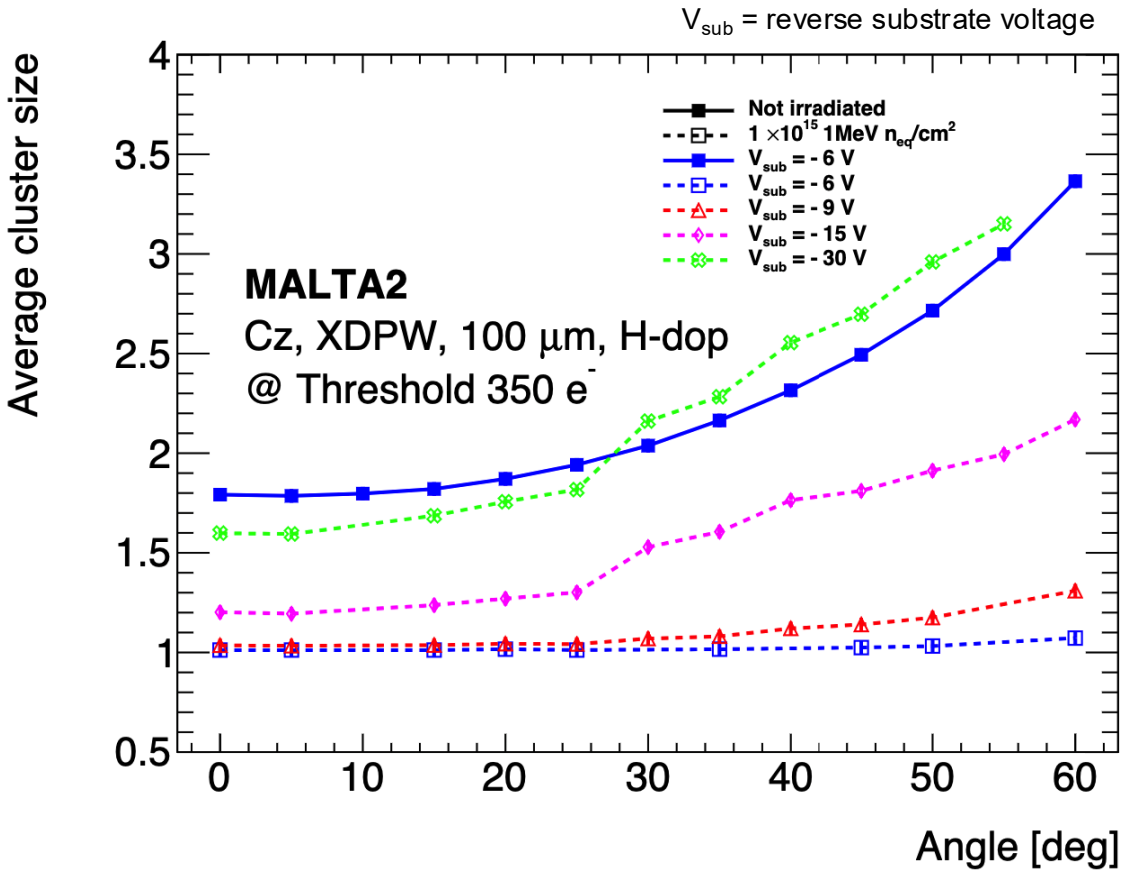
residuals
beam test

Cluster width always greater than 1.5 pixels

MALTA

geared towards high rates and radiation hardness

- Depleted DMAPS originally in 180 nm Tower CMOS, now ported to TPSCo 65 nm
  - Epitaxial layer and Czochralski bulk options with N-type implants
  - 36.4 μm pixels
- Rad-hard up to 100 Mrad, >10^{15} 1MeV n_{eq}/cm^2
  - > 97.5 % charge collection efficiency
- Move to 65 nm:
  - achieve sub-ns timing
  - expand to larger sensor matrix
  - while maintaining radiation hardness



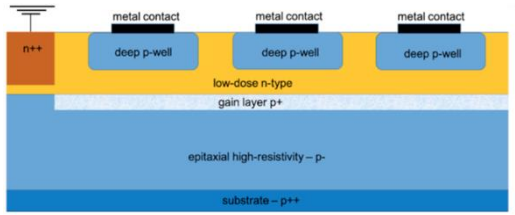
2025 JINST 20 C06051

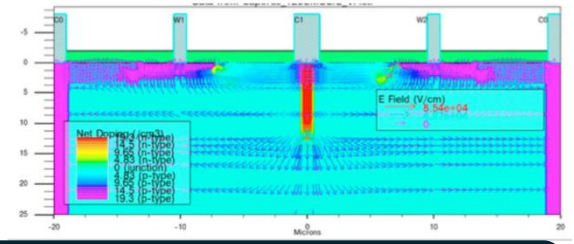
3D-Integration

Developments with SkyWater

BERKELEY LAB · Fermilab · BROOKHAVEN NATIONAL LABORATORY · UCSC · KEK · University of Tsukuba 筑波大学

- MAPS in SkyWater commercial process
- Aiming for: 10 ps and 5 μm resolution for 4D-tracking at Higgs factory
  - Dedicated p- and n-wells within deep p-type well; intrinsic gain
  - 3D-sensors: directly coupled CMOS electronics in an SOI stack



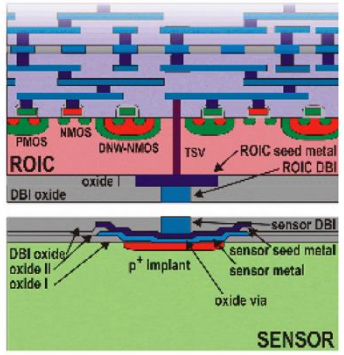


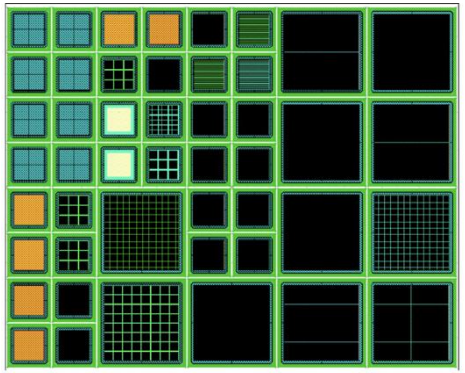
investigating feasibility with industry in US (SBIR)

Developments with Tower

Fermilab · SLAC · Lawrence Livermore National Laboratory

- Low power, high granularity (x, t) detectors
  - implemented in TSMC 28 nm
  - adopting 3D-integration for HEP detectors
  - supported by DOE “Accelerated Innovation in Emerging Technologies”
- Candidate for vertex detectors: high granularity, low mass, high configurability





first AC-LGAD on 12” wafer (65 nm) produced with Tower Semiconductor



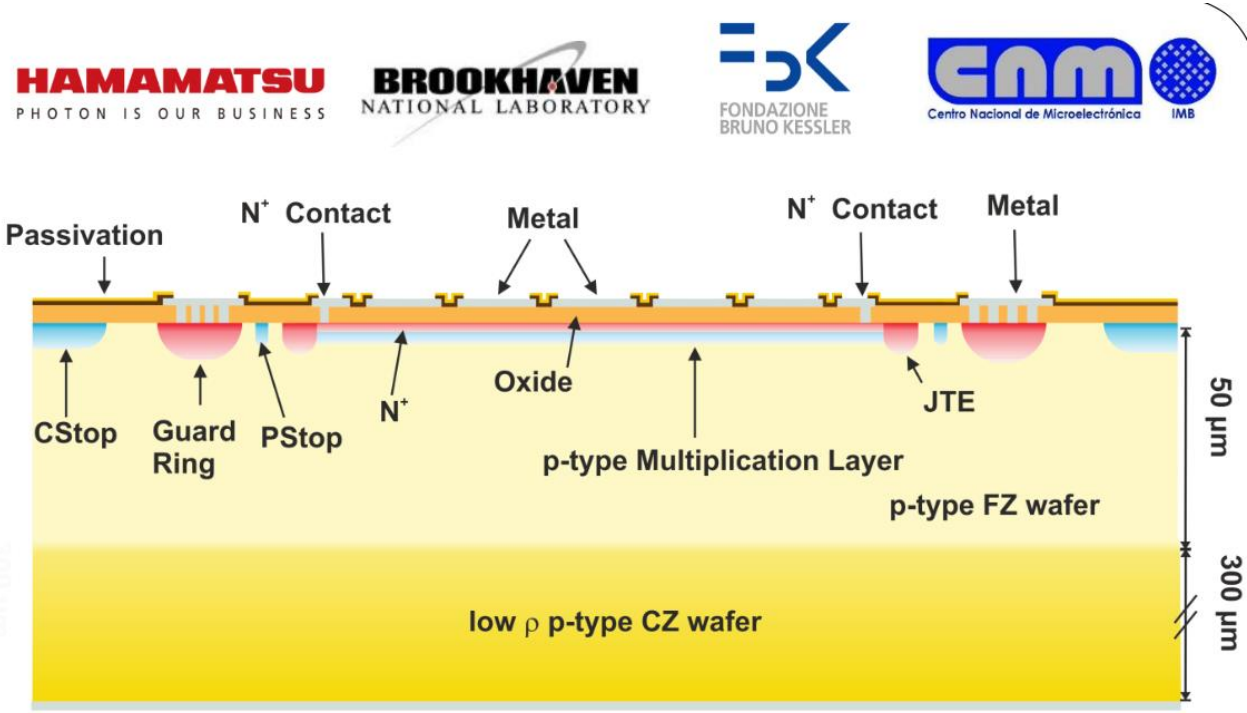
03

Picosecond Timing

Silicon with gain: LGADs

Low Gain Avalanche Diodes

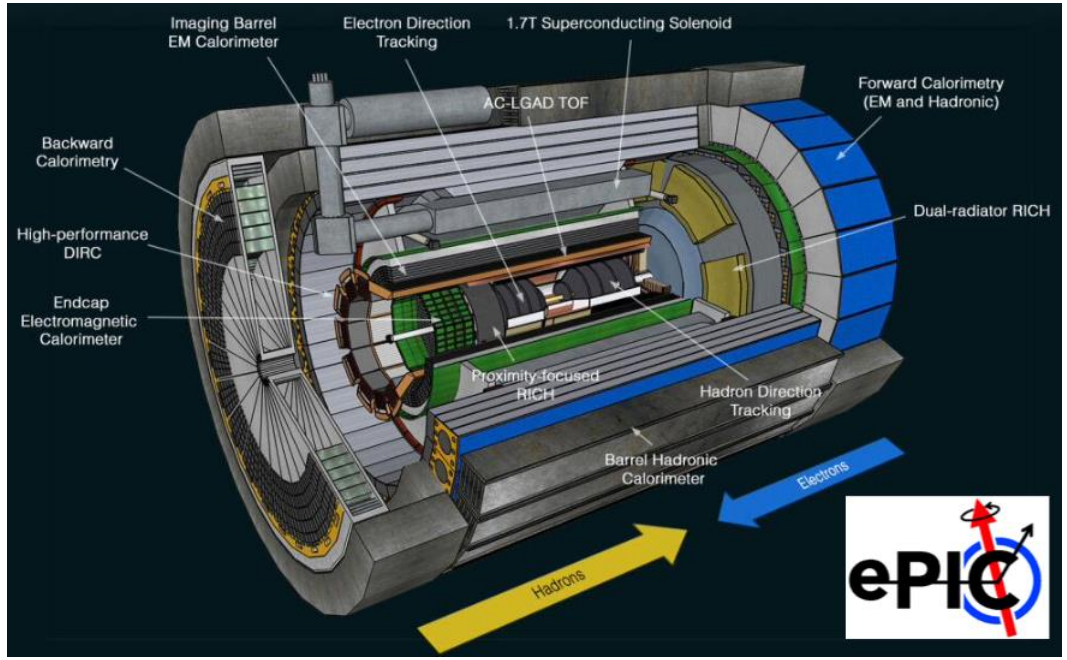
- Switch from (DC-)LGADs @ HL-LHC to AC-LGADs (aka Resistive Silicon Detectors)
- High-granularity AC-coupled LGAD:
  - Finer pitch, avoid dead zones
  - ❿μm-level spatial resolution through charge sharing
  - Reduced power dissipation
  - Radiation hardness less crucial
- Exploiting synergies between HL-LHC expertise for ePIC and FCC-ee

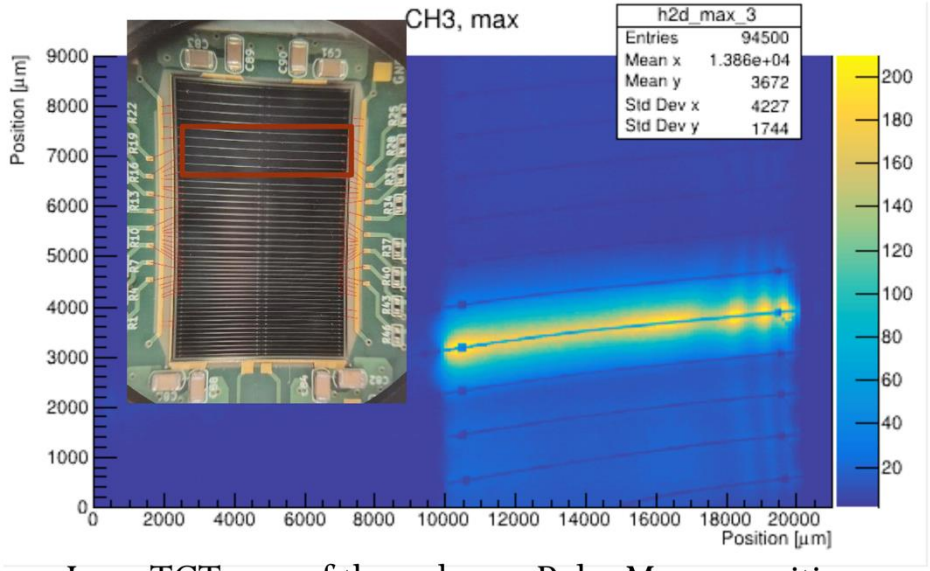


ePIC @ EIC

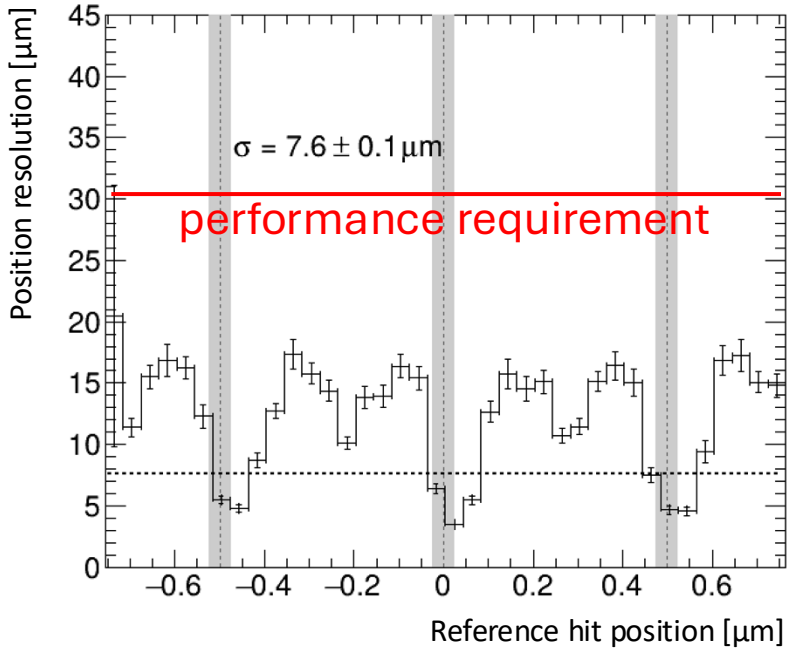
dedicated AC-LGAD-based timing layers

- 4D tracking necessity to reach ePIC physics goals (PID with TOF)
  - Barrel TOF: 1 cm strips, 500 μm pitch
  - Endcap TOF: 500x500 μm pixels
  - far-forward tracking and lumi detector, too
  - ASICs: FCFD for strips, EICROC for pixels





Laser TCT scan of the red area, Pulse Max vs position
IR laser spot 20um, time width 30ps



many more prototyping results and designs :

S. Mazza, CPAD 2026

R&D directions towards FCC-ee/CePC

- AC-LGAD resistive layer and readout optimization → lower noise
- Minimizing material budget → thinned sensors @ sufficient S/N and sub-50 ps temporal resolution → advanced wafer processing and integration
- Ultra-low power ASICs and dense integration
- Specialized geometries (e.g. 3D-trench LGADs) to force uniform E fields



04

Other Technologies

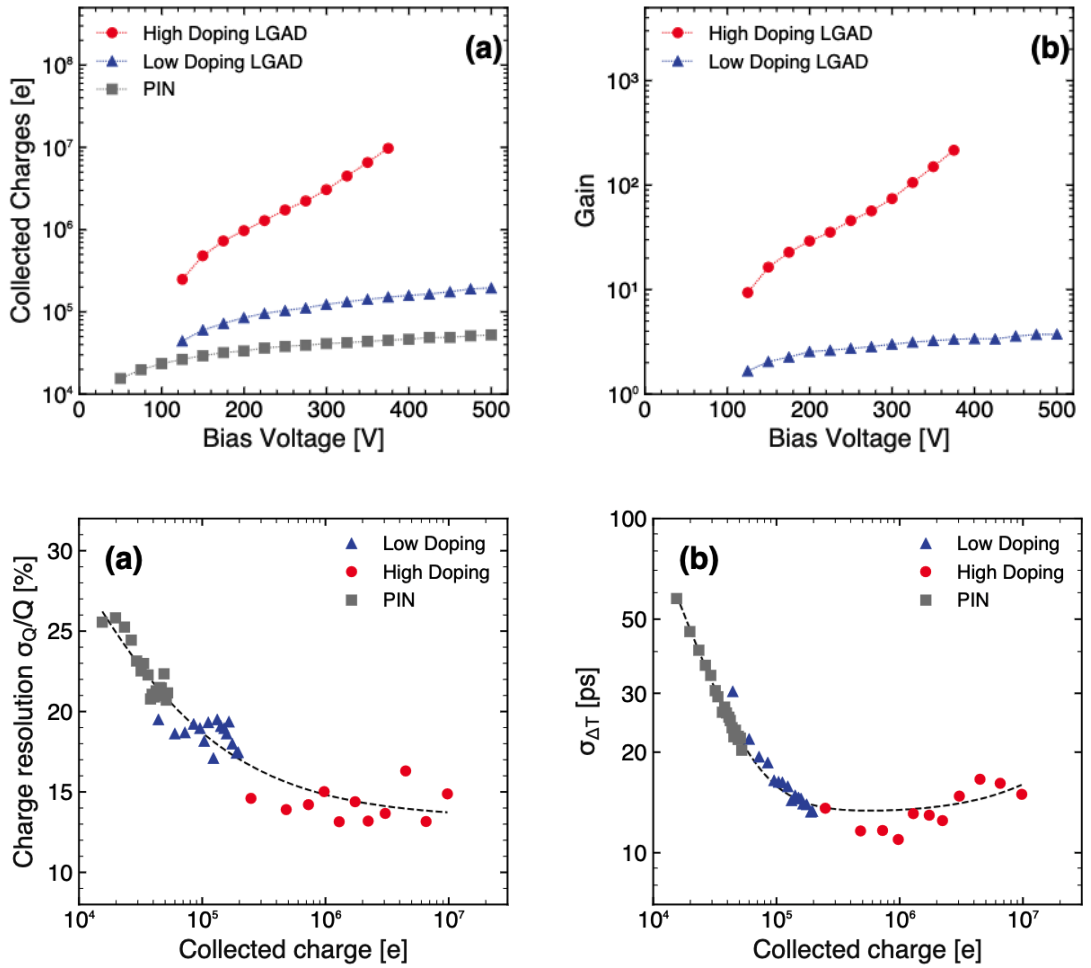
4H-SiC Sensors

(and other wide bandgap materials)

- Advantages over Silicon: lower noise, improved timing resolution, more rad-hard, reduced need for cooling, BUT: lower signal yield

→include gain layer

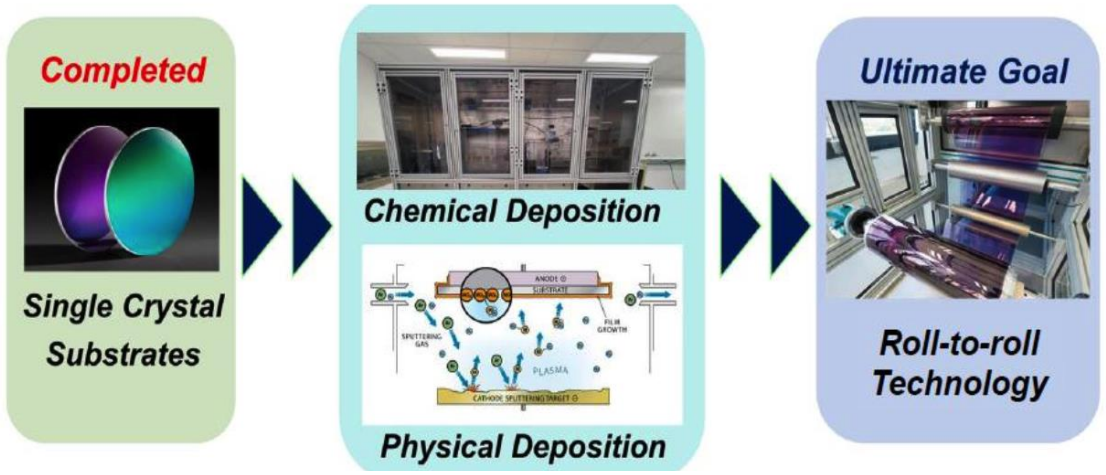
- Fabricated 4H-SiC LGADs with different doping levels
- Characterization with laser and beta-source
- Irradiation campaign
- 25% higher doping leads to two orders of magnitude higher gain

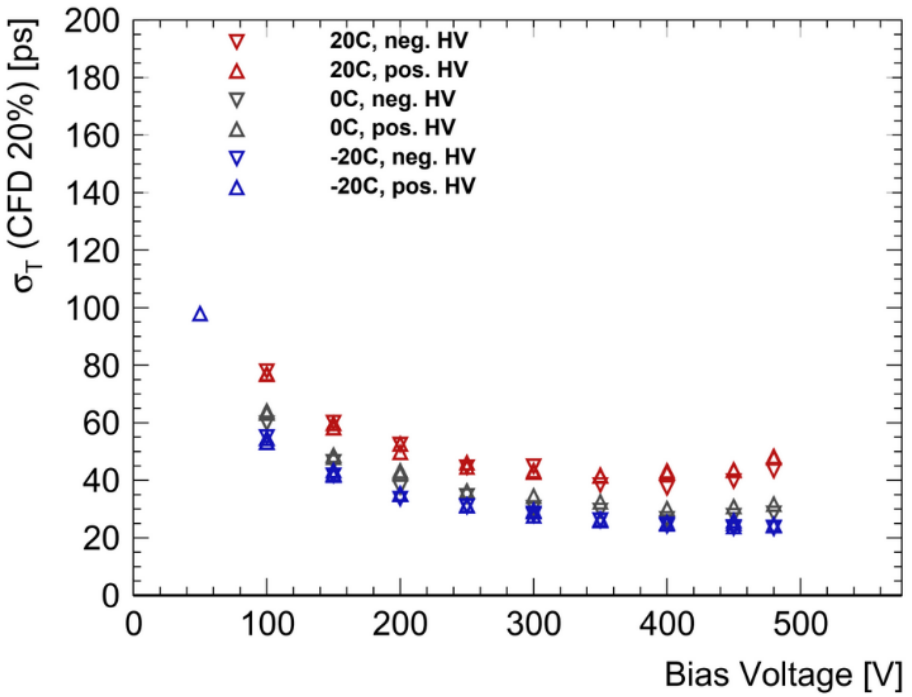


arXiv:2610.00824v1

Thin Film Detectors

- Motivation:
  - low material budget
  - large scale manufacturing
  - avoid hybridization
  - access to different semiconductor materials
- Some of the materials studied:
  - Indium Phosphide
  - Amorphous Selenium
  - Amorphous Silicon
- Currently handling single/few pad samples; working on wafer-level deposition



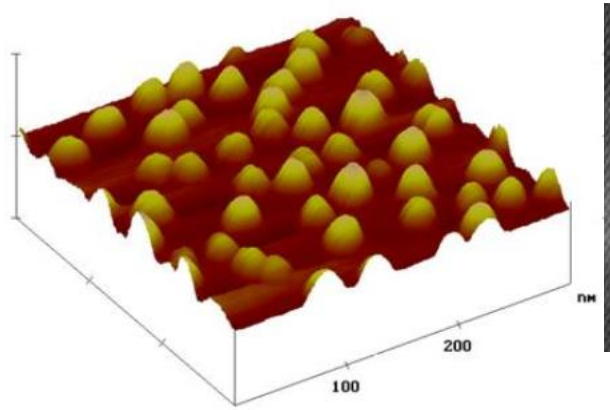


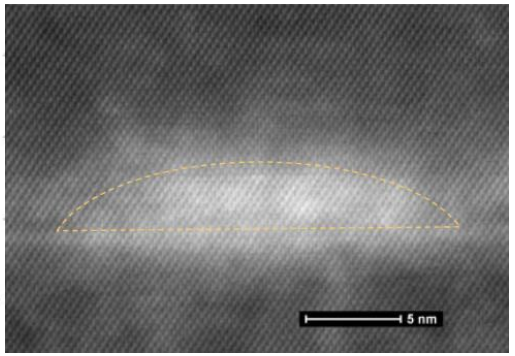
InAs/GaAs Quantum Dots

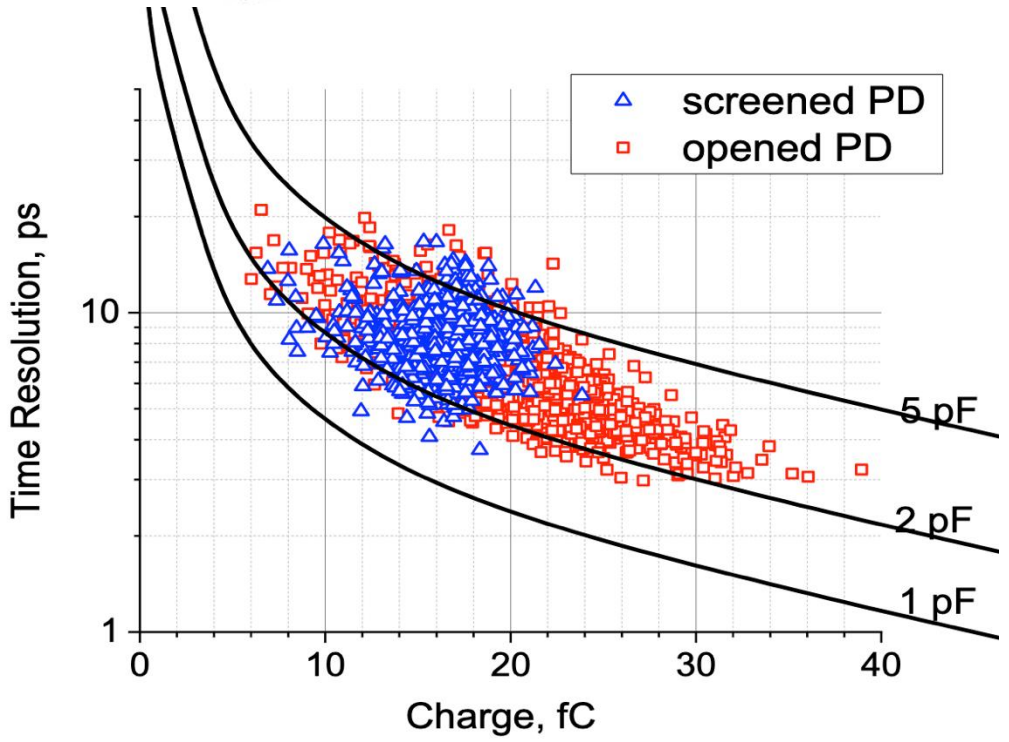
proof of principle

- Islands of InAs formed on GaAs surface during growth; each dot is a potential well
- Inherently fast scintillation in semiconductor
  - similar number of charge carriers as in Si
  - high initial current with short risetime; short pulse
- Jitter measured with α particles: <10 ps

- Current performance at room temp:
  - signal collection efficiency: ~15%
    - due to optical losses in waveguide and through backside
  - low barrier around quantum dots in current devices, affects radiation hardness as well
    - with increased confinement potentially more rad-hard than Silicon



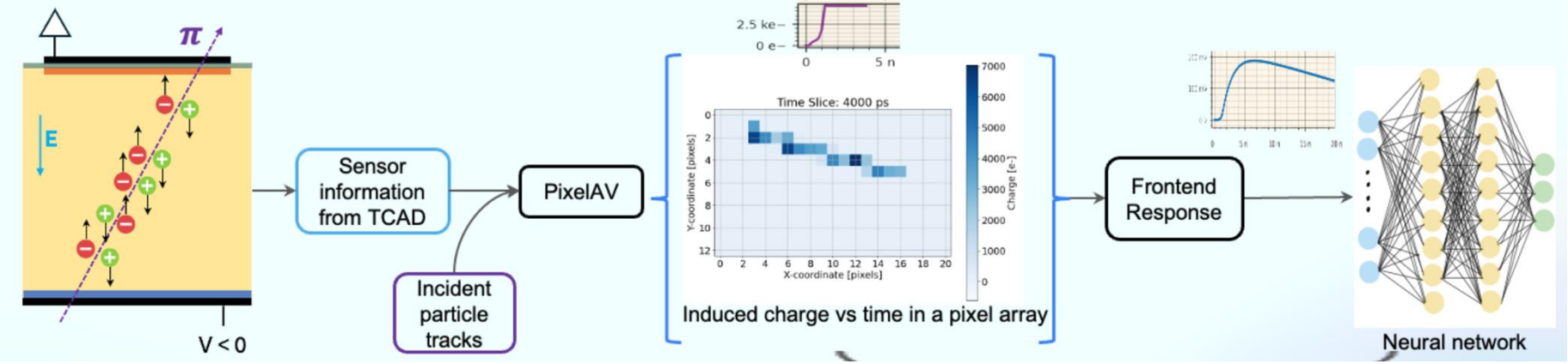




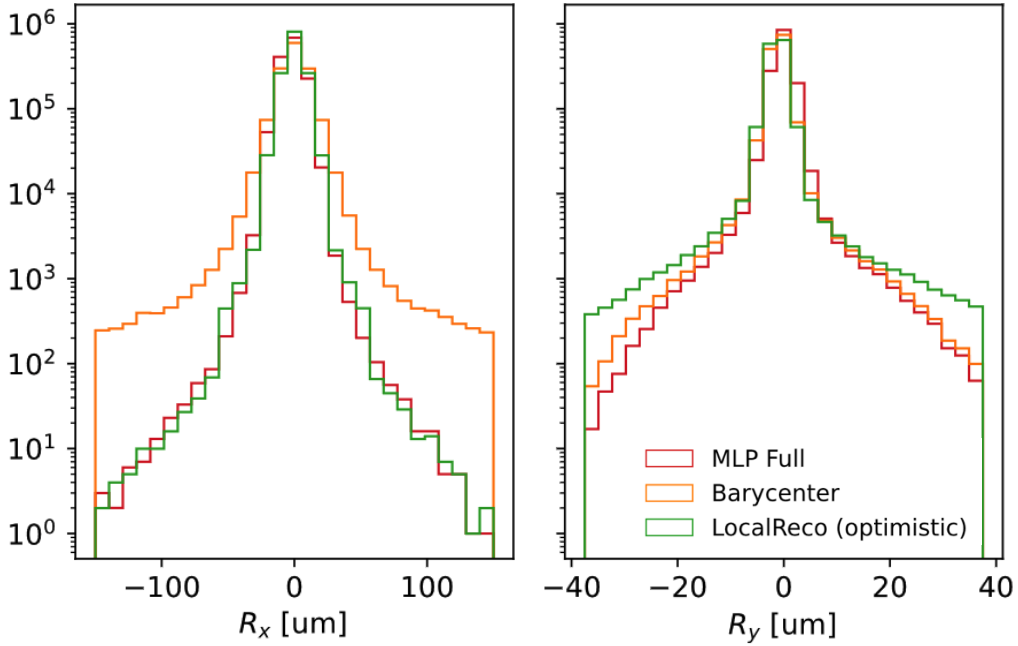
CPAD Presentation M. Yakimov

Smartpixels

physics-informed data reduction on-chip



- On-ASIC ML for data reduction
- Applications: pixel hit selection for trigger, displaced track trigger (CMS), beam background reduction (lepton colliders)
- Filter out low-pT tracks and regress track parameters on chip
  - deduct properties of incident particle (position, angle, p_T, impact parameter)



arXiv:2602.15946v4



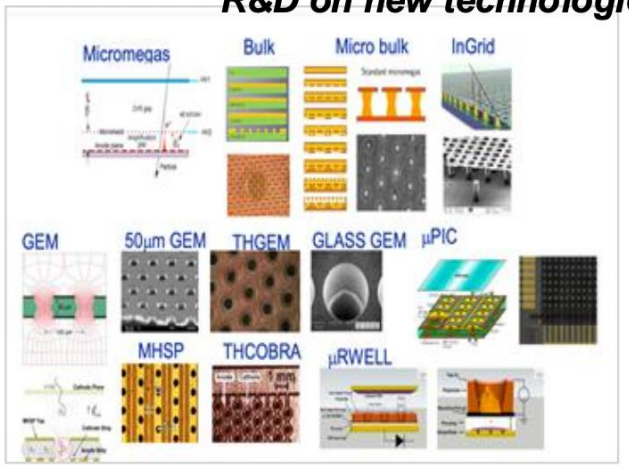
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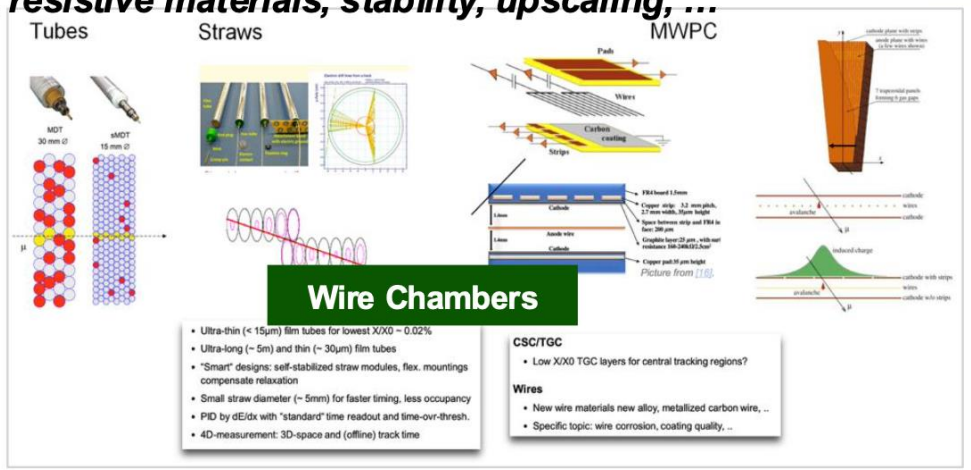
Gaseous Trackers

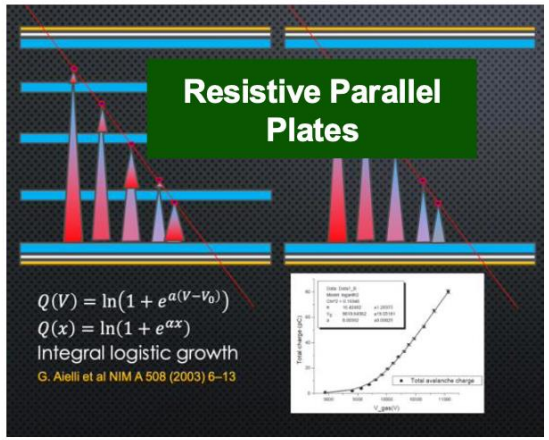
Developments driven by DRD1

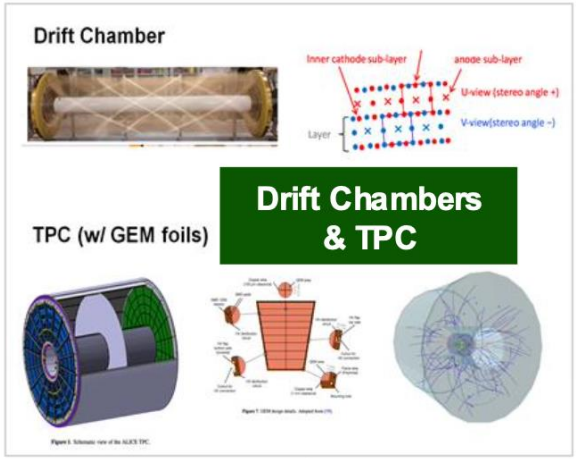
DRD1: Gaseous Detector Technologies

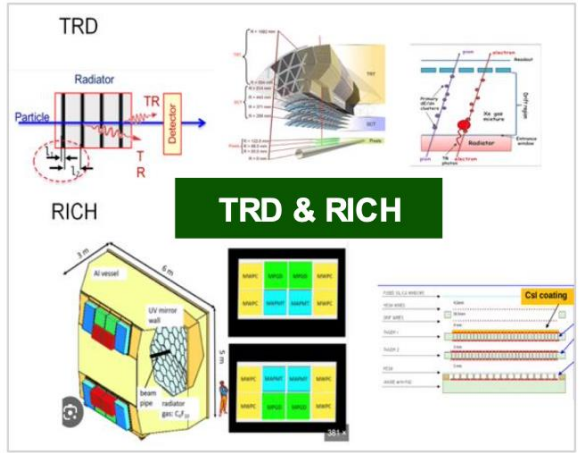
R&D on new technologies, architectures, resistive materials, stability, upscaling, …











2024 - 2026: Seamless integration of ALL gaseous detector technologies into single collaborative effort

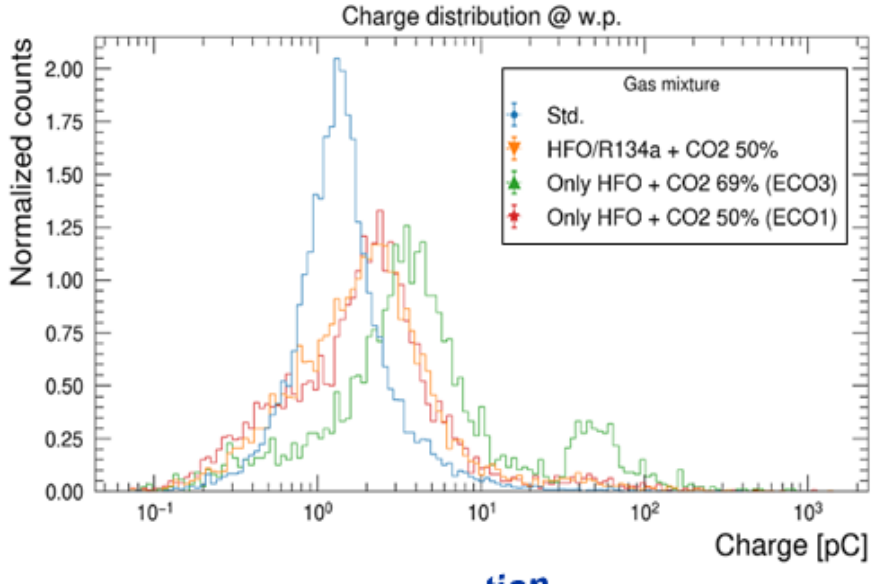
R&D Challenges

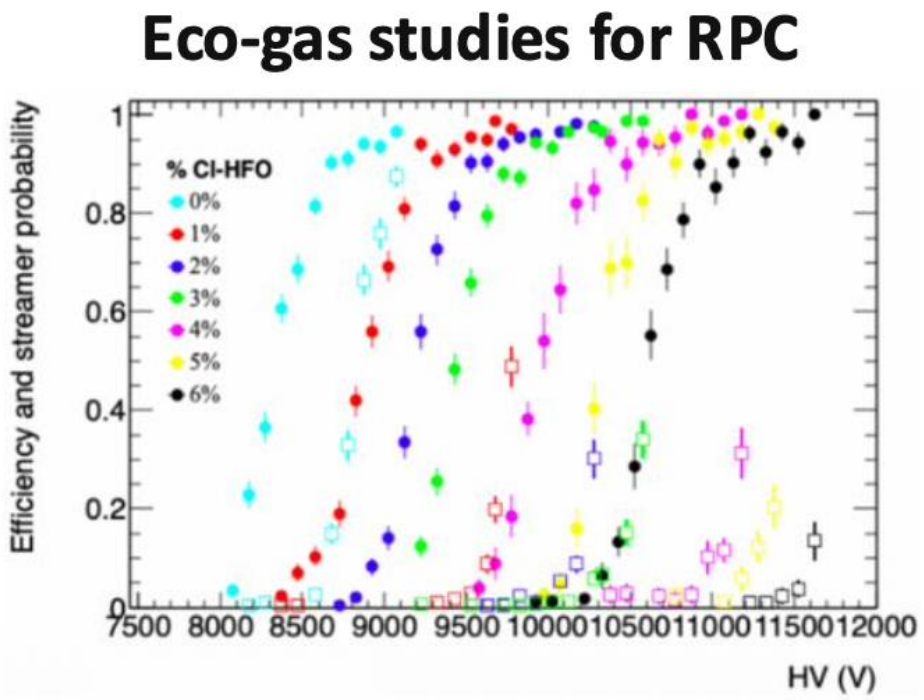
- Gaseous detectors are primary choice for large-area coverage with low material budget, dE/dx (PID) and TOF functionality
- Planned for several Higgs factory detector concepts

- Current R&D challenges:
  - high rates: reduce ion back drift
  - reduce ageing and increase radiation hardness
  - fast timing: can achieve 25-60 ps (Micromegas, multi-gap RPCs)
  - minimal material budget: new materials
  - eco-friendly gas mixtures

Eco-friendly Gases

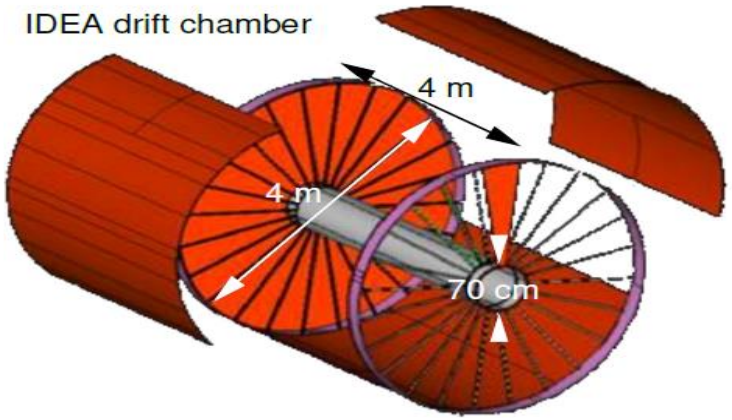
- **Eco-gases**: widespread interest in the study of new environmentally-friendly gas mixtures, their chemical characterization, efficiency and contribution to the detector ageing
- **Ageing** and outgassing: huge cross-technology interest, in view of next long-term experiments, even in combination with high-rate environments
- **Recuperation:** re-use/re-cycle



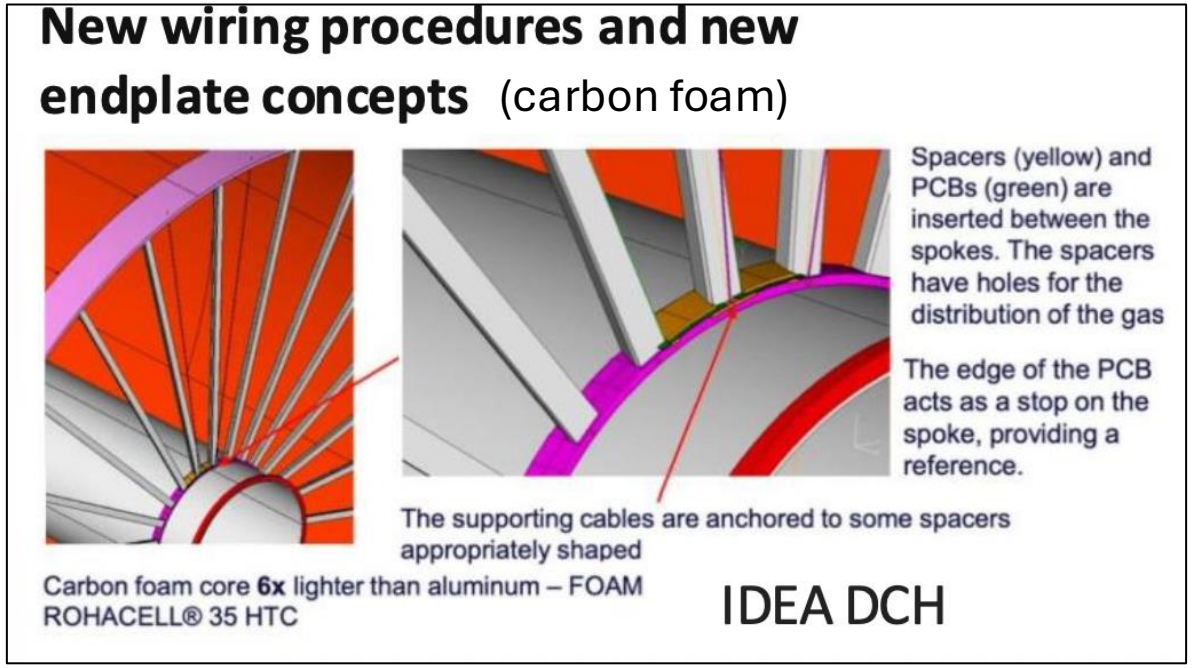


Drift Chambers

for tracking at future lepton colliders



- Precise tracking at low p_T and excellent particle ID via cluster counting
- Key R&D challenges involve
  - mechanics, electronics, and gas mixture
- Consolidation of new wire materials/coating
  - Tungsten and molybdenum, gold-coated, carbon-monofilaments, …



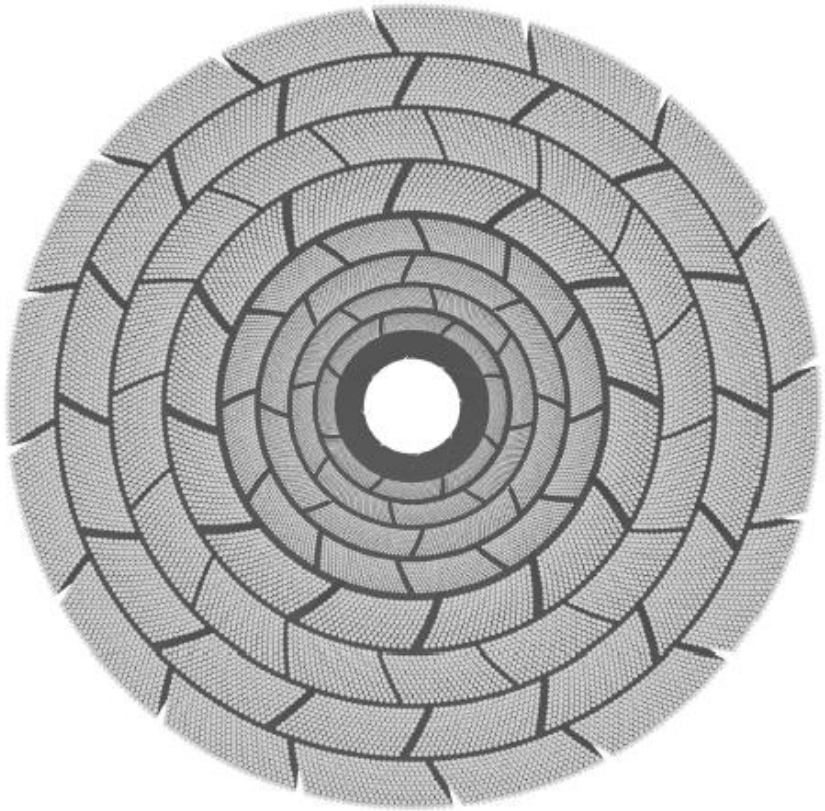
see talk by P. Krizan on PID

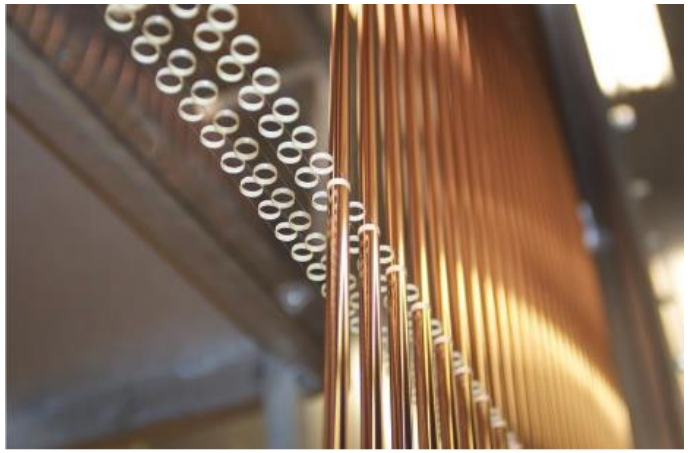
Straw Tracker

for tracking at future lepton colliders

- Advantages over drift chamber:
  - better single-hit resolution (by ~10%)
  - more robust against single channel breaking
  - could operate with different gases in different layers
  - operation at higher pressure can improve spatial resolution
  - could add intermediate silicon layer

- R&D challenges:
  - ultra-thin straw walls (12-19 μm)
  - straw diameter and rates (~5 mm)
  - noise reduction and connectivity



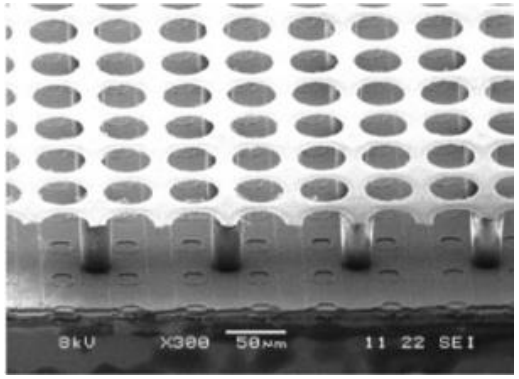


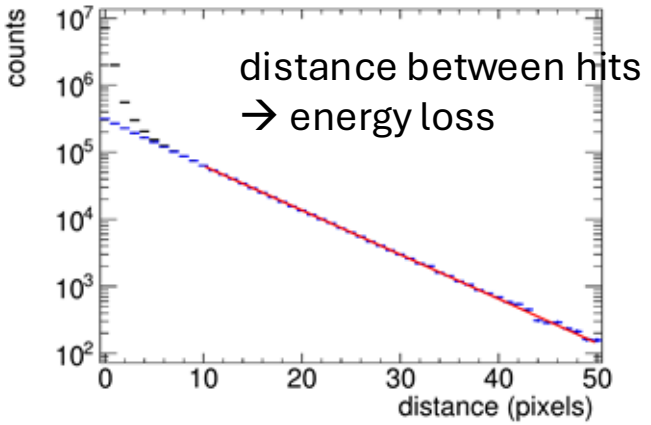
Large-area Pixel TPC

developed for LC

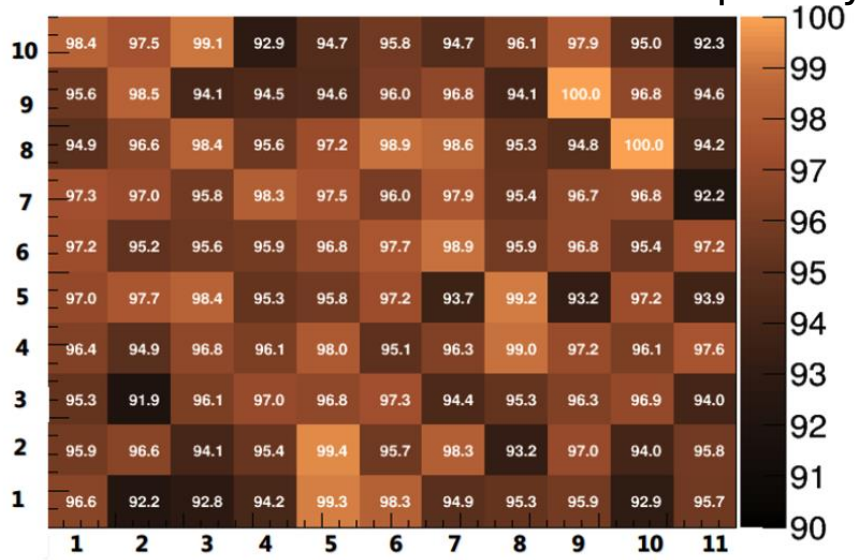
- e.g. GridPix TPC: complete detector based on integrated Micromegas structure on top of pixel chip (e.g. Timepix3/4, GEMPix4), including cathode, gas volume, etc.
- R&D challenges:
  - space charge effects & distortion
  - optimization of GridPixes, gas mixture, etc.
  - synchrotron radiation at Tera-Z
    - collimation, shielding, beampipe coating

NIM A 1081 (2026) 170849





Gain Uniformity CePC prototype



H.Qi CPAD 2026

test bench setup with TEPIX chip → good uniformity

Many groups worldwide involved in R&D for future vertexing and tracking detectors

Funding for R&D is very limited everywhere

The HEP community is collaborating well through CERN's DRDs and RDCs in the US

It is highly important to maintain strong and **consistent support** from the institutes and funding agencies, or the detectors will not be ready to deliver the full physics potential. This includes maintaining **worldwide testbeam and irradiation facilities**, technical workforce, and links to industry partners

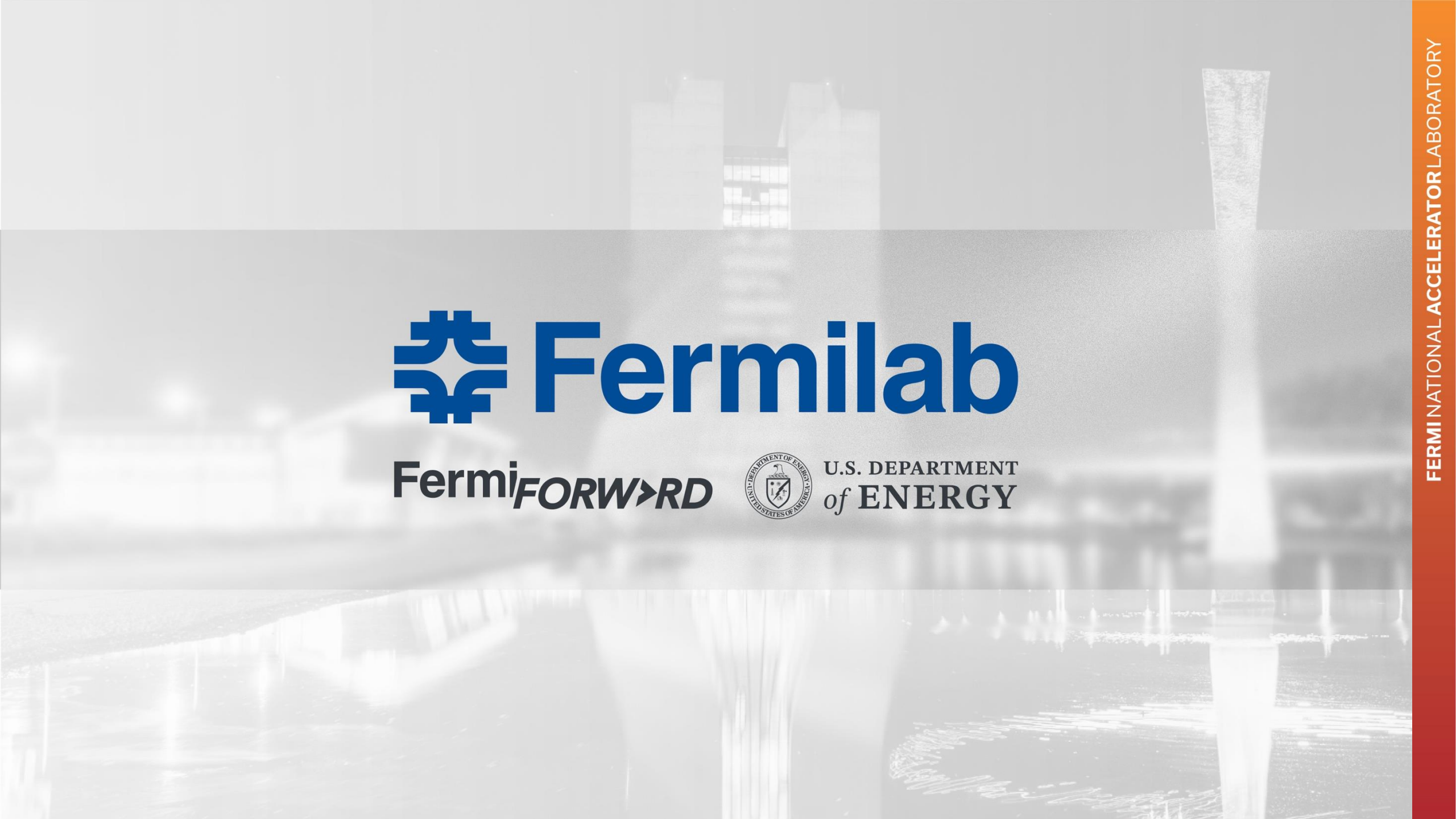
Summary

High-precision tracking at future colliders is paramount to their scientific success

Traditional silicon hybridized pixel and strip detectors complemented or even surpassed by new developments (MAPS, LGADs, 3D), fewer constraints from rad-hardness at Higgs factories

Ultra-low mass requirements cause for comeback of gaseous trackers (drift, straw, TPC)

Lots of room for completely new ideas (SiC, Thin Film, AI-on-det). Worldwide R&D ongoing


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