European Strategy for Particle Physics

PARALLEL 6 / **DETECTOR TECHNOLOGIES**

Calorimeters and RICH Technologies for HEP experiments

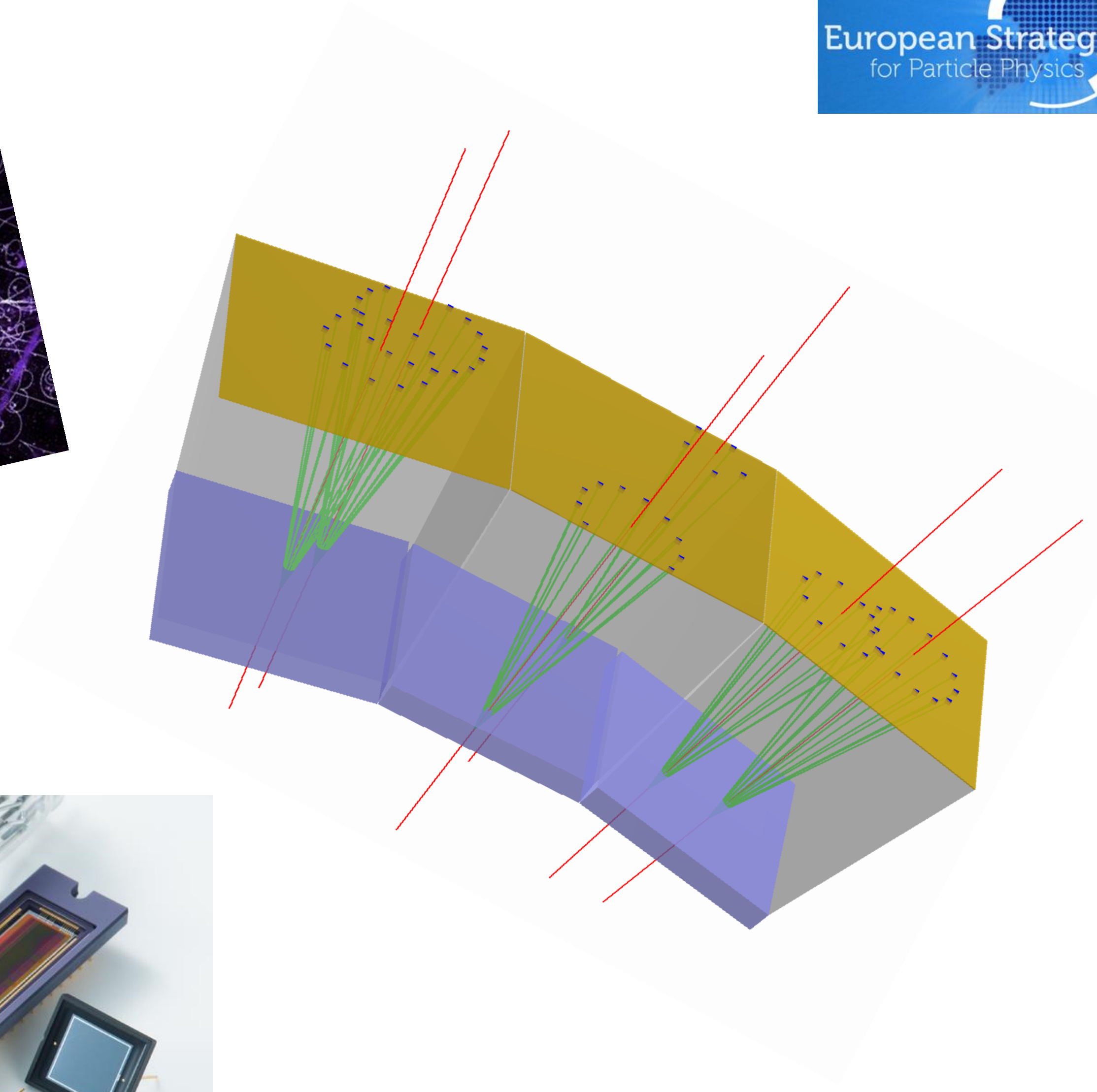
Gabriella Gaudio (INFN-Pavia)

23-27 **JUNE** 2025 **Lido di Venezia**

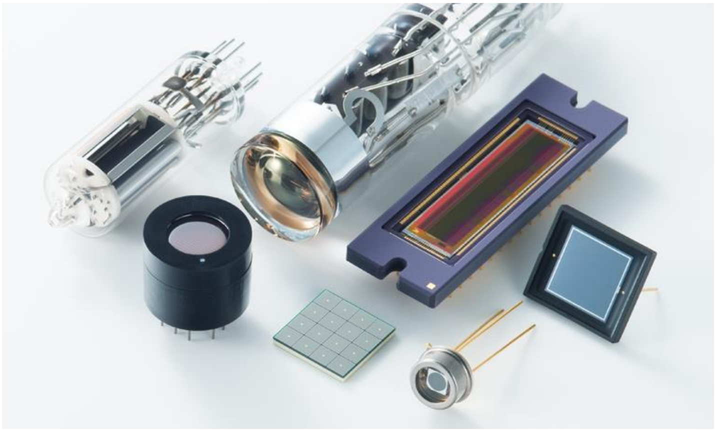
Outline

Calorimeters

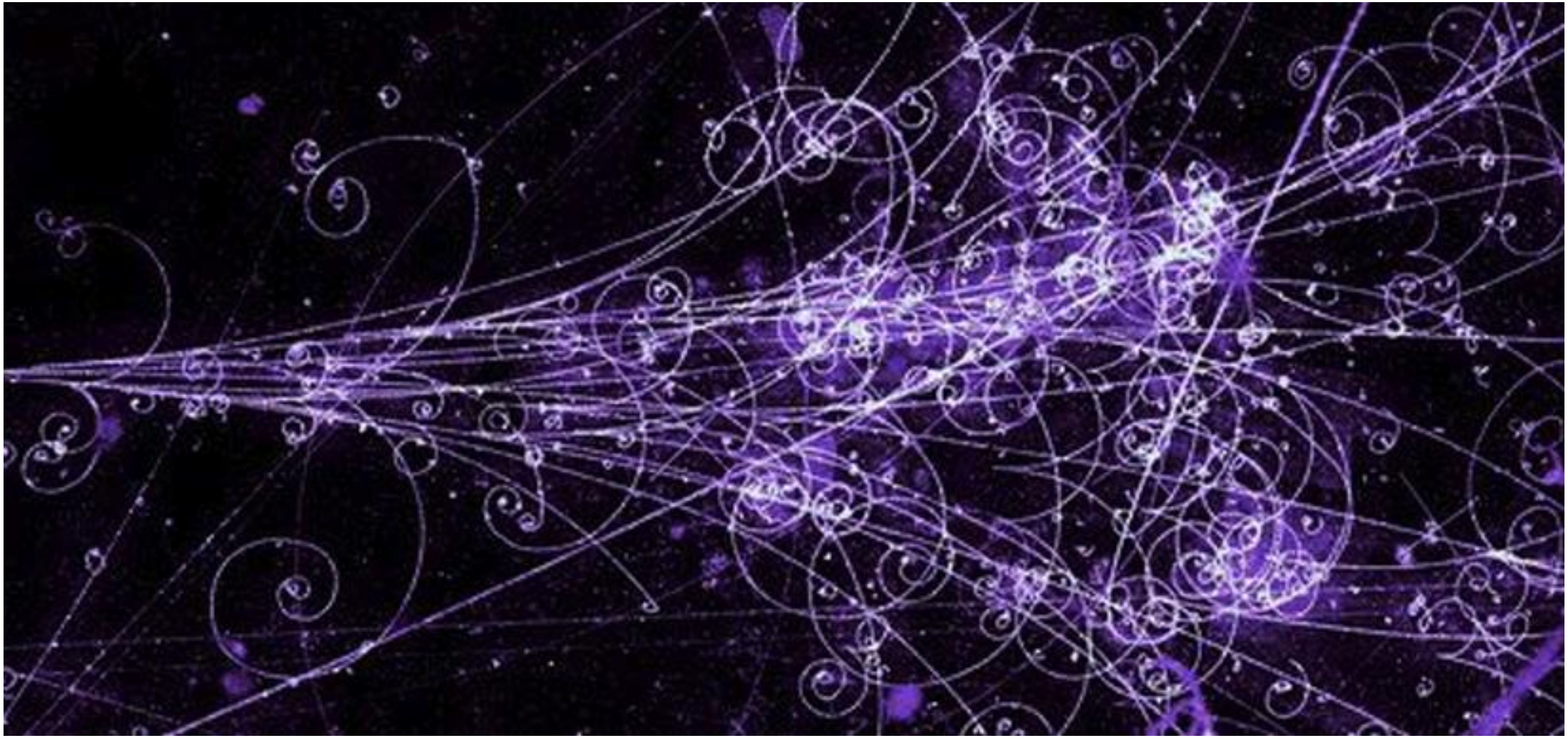
RICH



Photodetectors



Calorimeters

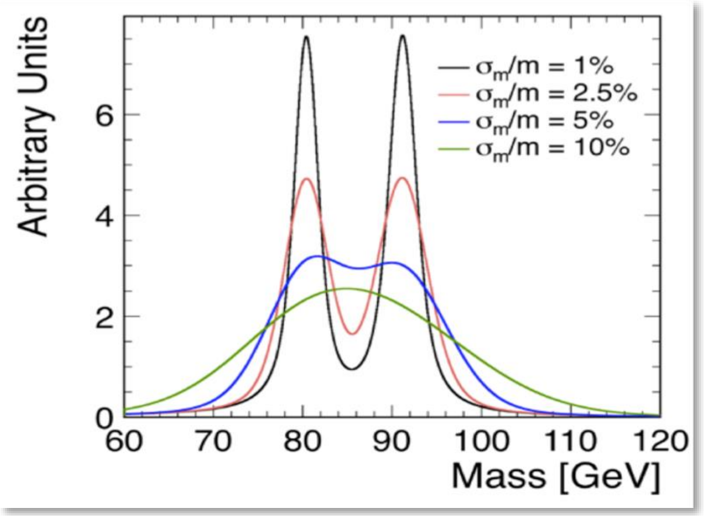


HEP physics drivers

"Higgs Factories" (in particular FCC-ee) among the main drivers for current calorimeter development

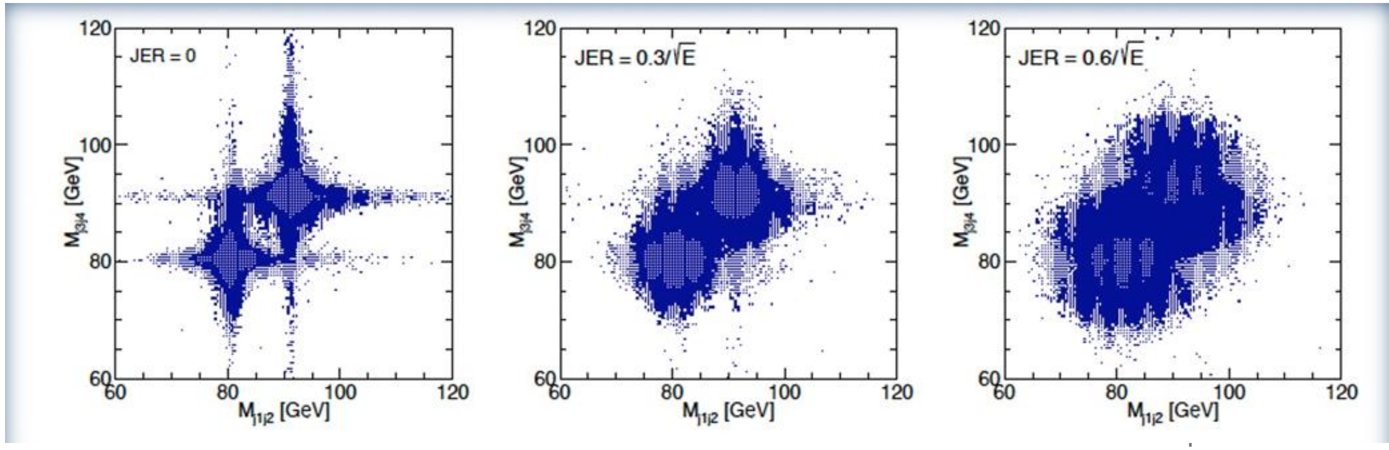
Jet final state will be dominant at the Higgs Factories

- higher branching ratio
- clean environment



Jet energy: $\delta E_{jet}/E_{jet} \simeq 30\% / \sqrt{E}$ [GeV]

Disantangling W and Z peak
e.g. Separation of VVH from WW fusion and HZ



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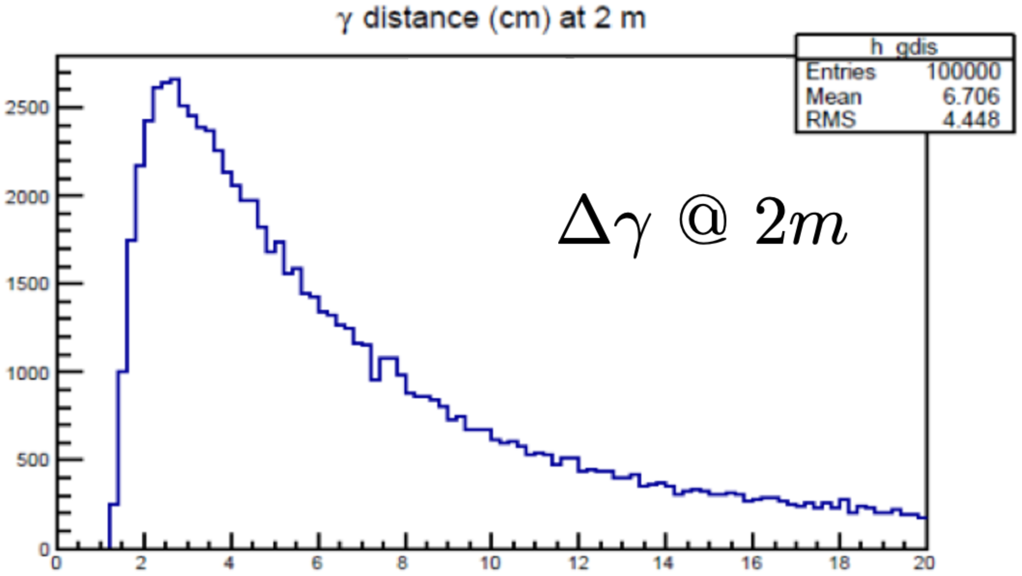


e^+e^- HZ physics constraints

H$\rightarrow \gamma\gamma \Rightarrow$ ECAL resolution

As good as possible – at least 20%/$\sqrt{E}$ + 1%

For HF physics 3%/√E is required

High granularity / Pre-shower is needed for π^0 identifications

$Z \rightarrow \tau^+\tau^-$

$\tau^+ \rightarrow \rho^+\nu \rightarrow \pi^+\pi^0\nu$

5D-calorimeter paradigm

Energy → Position(3D) → Timing

Energy

High Energy Resolution

- Reduce fluctuations by construction
- Improved by algorithm (e.g. Particle Flow approach) and Machine Learning approach

Position(3D)

High granularity

- mechanical integration
- cooling for embedded electronics
- increased number of channels

Timing

Fast timing information

- fast detector
- fast electronics
- larger data size

DRD6 – DRD on Calorimetry

- Addressing three main categories of Calorimeters
  - Sandwich calorimeters with fully embedded electronics
  - Liquified Noble Gas calorimeter
  - Optical calorimeters
- Addressing transversal needs
  - Electronics
  - Software
  - Mechanics and cooling
  - Photodetectors (no development)
  - Material

Sandwich calo with fully embedded elx

- Optimized for particle flow approach
  - integrated ECAL & HCAL (+ tracking)
- Sensor aspect and system aspect closely related
- Front-end electronics embedded in the calorimeter (including ASIC)

Solid State	Optical	Gaseous
Silicon or GaAs Detectors MAPS	Scintillator Strips Scintillator Tiles Glass Scintillator Tiles Lead Glass (Cherenkov)	RPC (semi-digital with Timing) MPGD

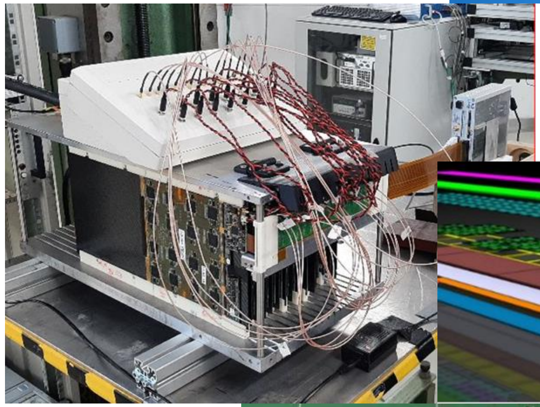
Sandwich calo with fully embedded elx

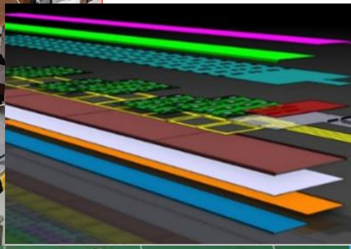
Strong connection with DRD7 (electronics)

Solid State

Silicon or GaAs Detectors
MAPS

Solid State sensors
(see Daniela's talk for more details)
connection with DRD3

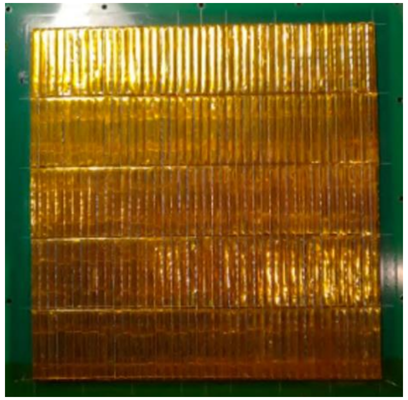


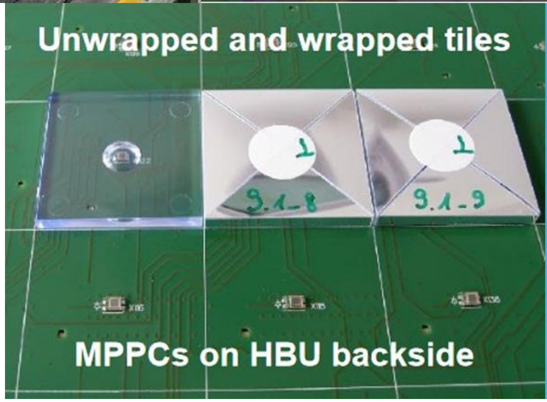


Optical

Scintillator Strips
Scintillator Tiles
Glass Scintillator Tiles
Lead Glass (Cherenkov)

R&D on optical material
Connection with DRD4 for
photodetectors

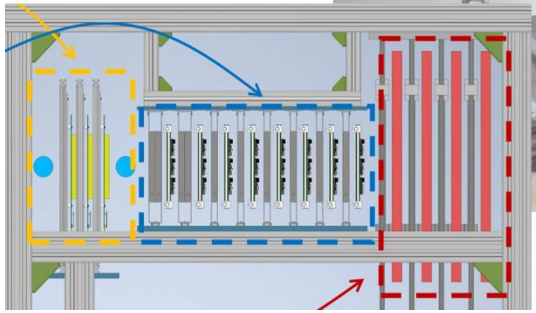




Gaseous

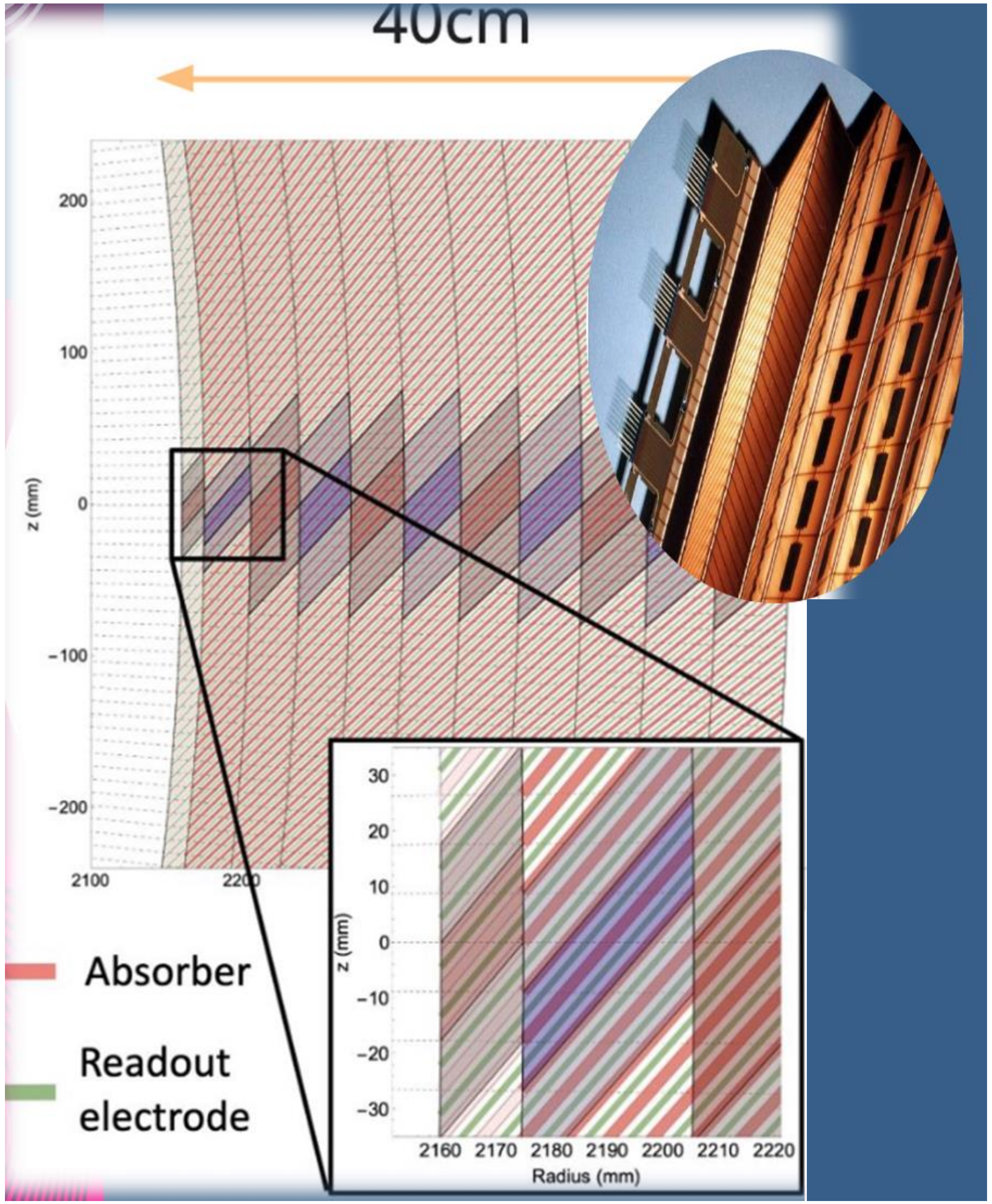
RPC (semi-digital with Timing)
MPGD

Connection with DRD1 for
gaseous detector (see
Maksym's talk for more details)



Liquified Noble Gas calorimeters

- Long and successful tradition in HEP
- Low systematics
- High granularity achievable => can be optimized for particle flow
- Cold electronics option under study
- Mechanical design optimization for energy resolution



Optical calorimeters

Calorimeters based on optical media

Photodetectors with large dynamic range and good linearity

Enhanced granularity

R&D to develop faster and more rad-hard materials

Homogeneous ECAL	Sampling ECAL	Sampling HCAL
• High granular crystal optimized for PF • Dual Readout segmented crystals • Rad-hard segmented crystals • Oriented crystals	• SpaCal with rad-hard scintillating fibres • Shashlik rad-hard with shower max measurement • Crystal grain innovative calo	• Hadron tile calorimeter • Dual-Readout fibre calorimeter

Optical calorimeters

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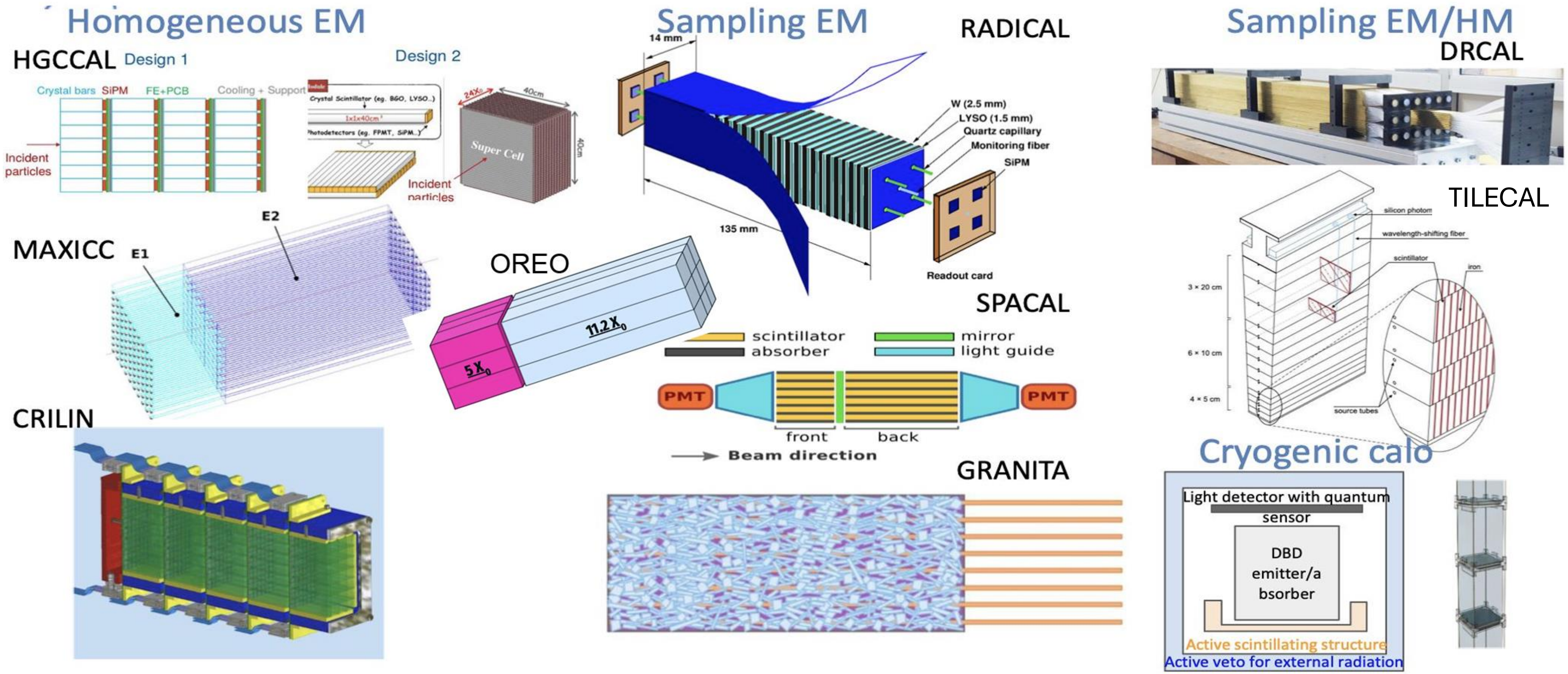
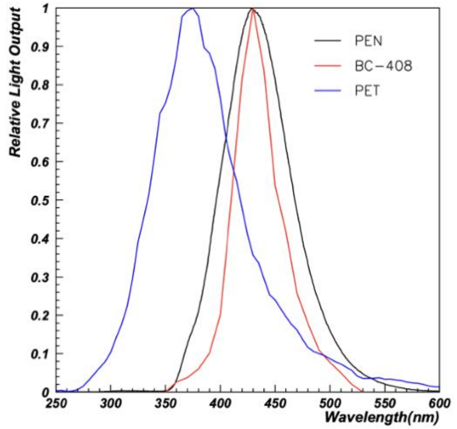
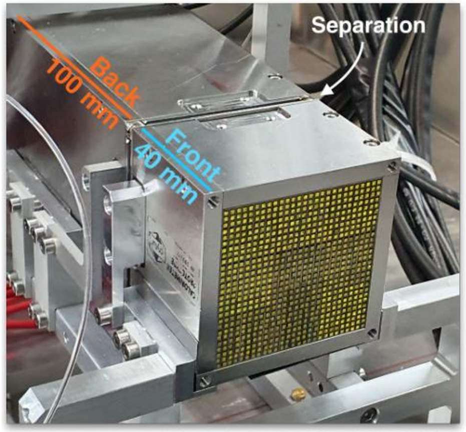


Optical calorimeters (few material examples)

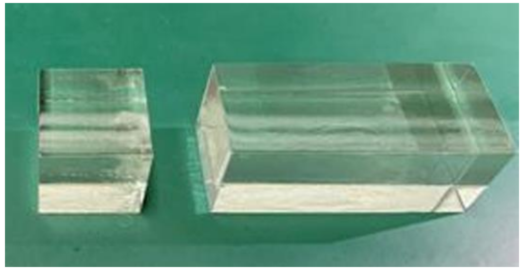


PEN/PET R&D



NIM A 1045, 167629 (2022)

W-GAGG crystal fiber R&D synergic to LHCb ECAL upgrade

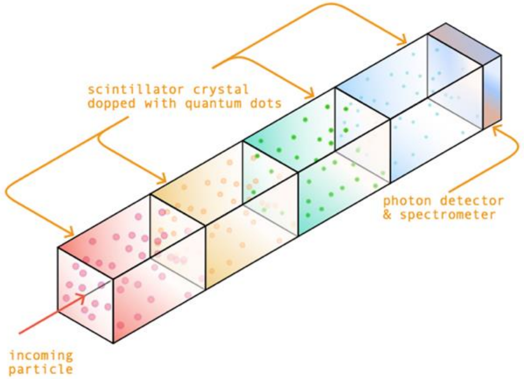


Large density	★★
High light yield	★★
Energy resolution	★★
Low cost	★★
Fast decay	★★
Large size	★★

Scintillating Glasses as a possible “cheap” alternative

$CsPbBr_3$ nanocrystals in epoxy resin

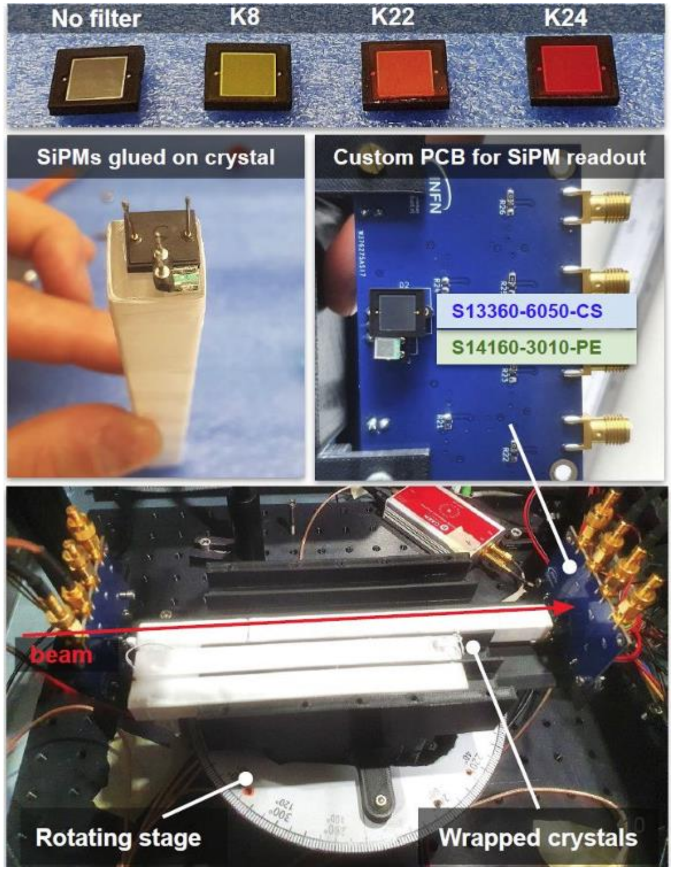
Nano-scintillators (ultrafast ~ 1ns) and rad-hard

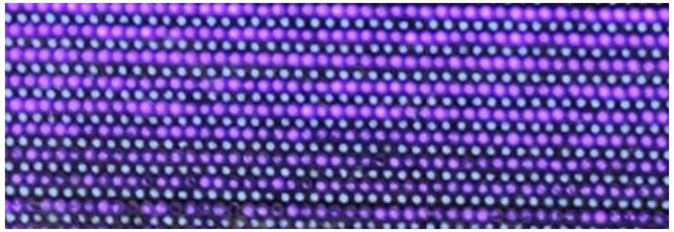


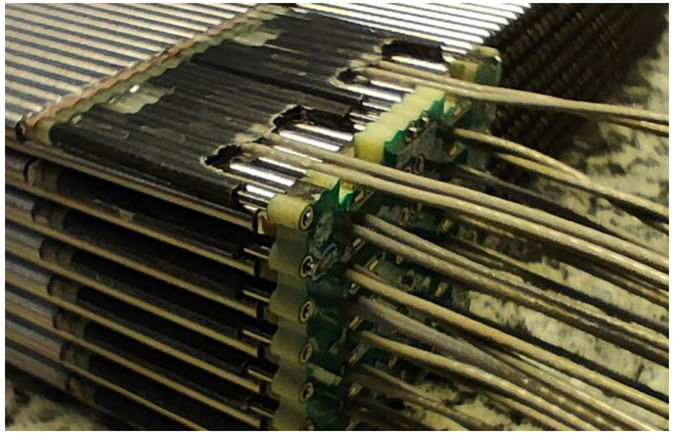
Quantum-dots for chromo calo

synergy with DRD4 and DRD5

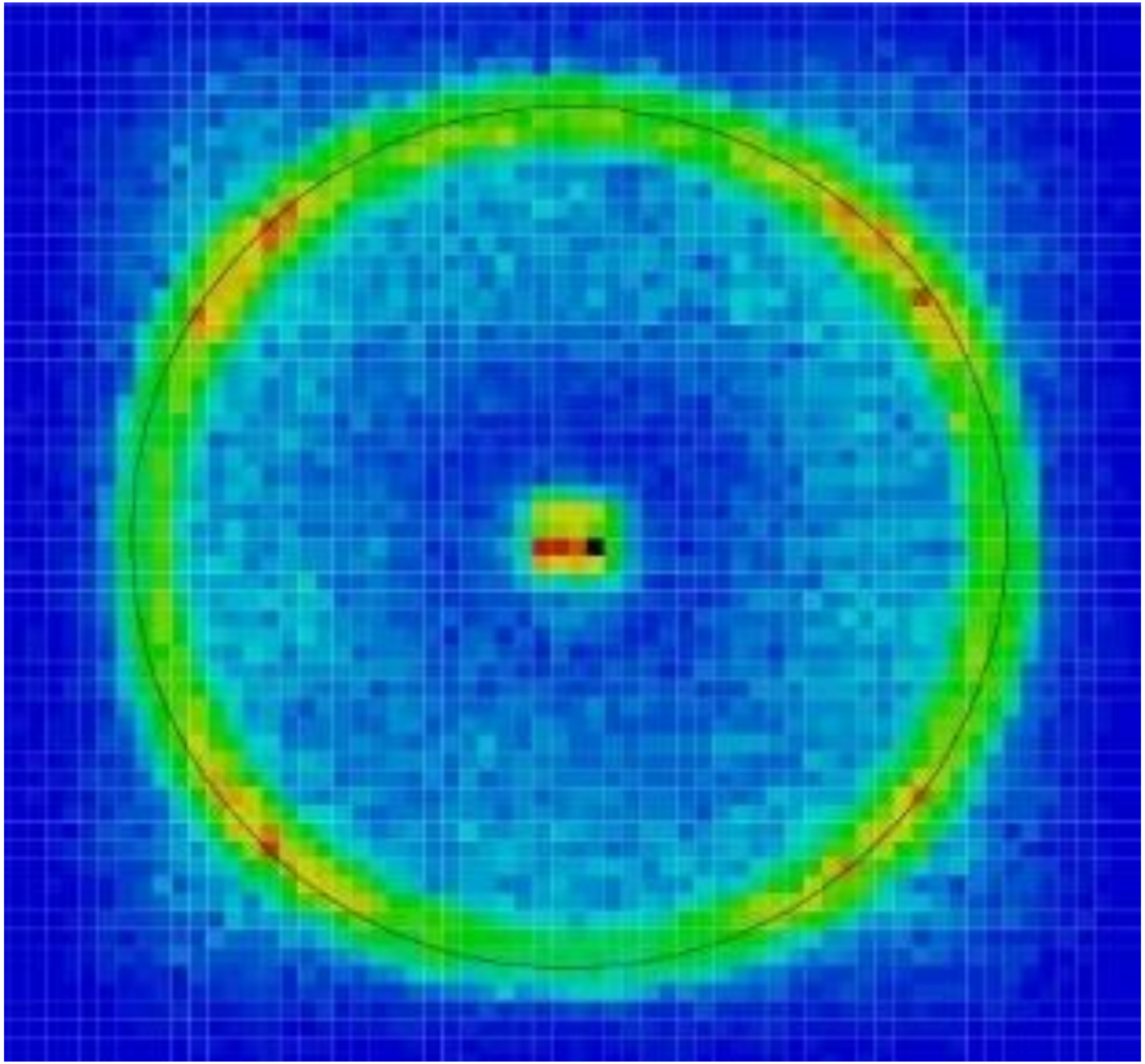
Optical calorimeters (detection technique example)







- Dual readout technique aiming at reducing the fluctuation of electromagnetic fraction (Cherenkov and scintillating light)
- Both fibre based (2 different media) or separating within the same crystal (e.g BGO/PWO-UF)
- Timing information for longitudinal "segmentation"
- Toward high granularity (PF-friendly) with SiPM (or MCP-PMT)



RICH

many thanks to
Rok Pestotnik
for the material

RICH: Ring Imaging Cĕrenkov Counters

RICH detectors are vital for particle identification in HEP experiments achieving reliable particle ID for a broad momentum range

Measure single photons with high position and timing resolution

Experimental drivers:

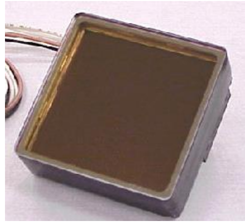
- **HL-LHC** (e.g. LHCb and ALICE3) **and future hadron colliders**
  - Operation at higher luminosities, increased background rates, and stricter integration.
  - Upgrades needed for enhanced robustness, rate capability, and precision.
- **FCC-ee experiments**: PID is essential for precision studies of heavy-flavour physics and Z, Higgs, W, and top decays.

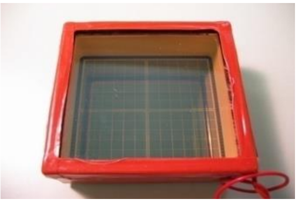
DRD4 –
Photon Detectors and Particle Identification Techniques

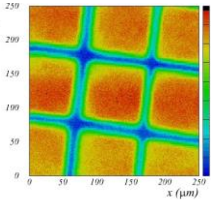
Scope:

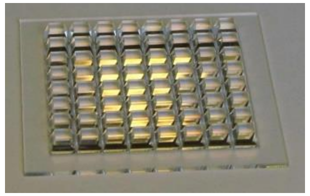
- Photodetectors (vacuum, solid state, hybrid), single photon sensitive
- Particle Identification (PID) techniques (Cherenkov-based, Time of Flight)
- Scintillating Fibre (SciFi) tracking
- Transition Radiation (TR) using solid state X-ray detectors

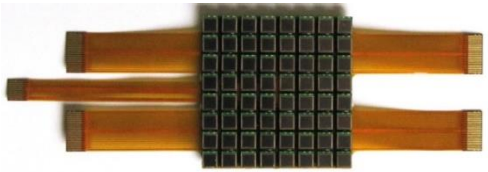
67 institutions / 20 countries











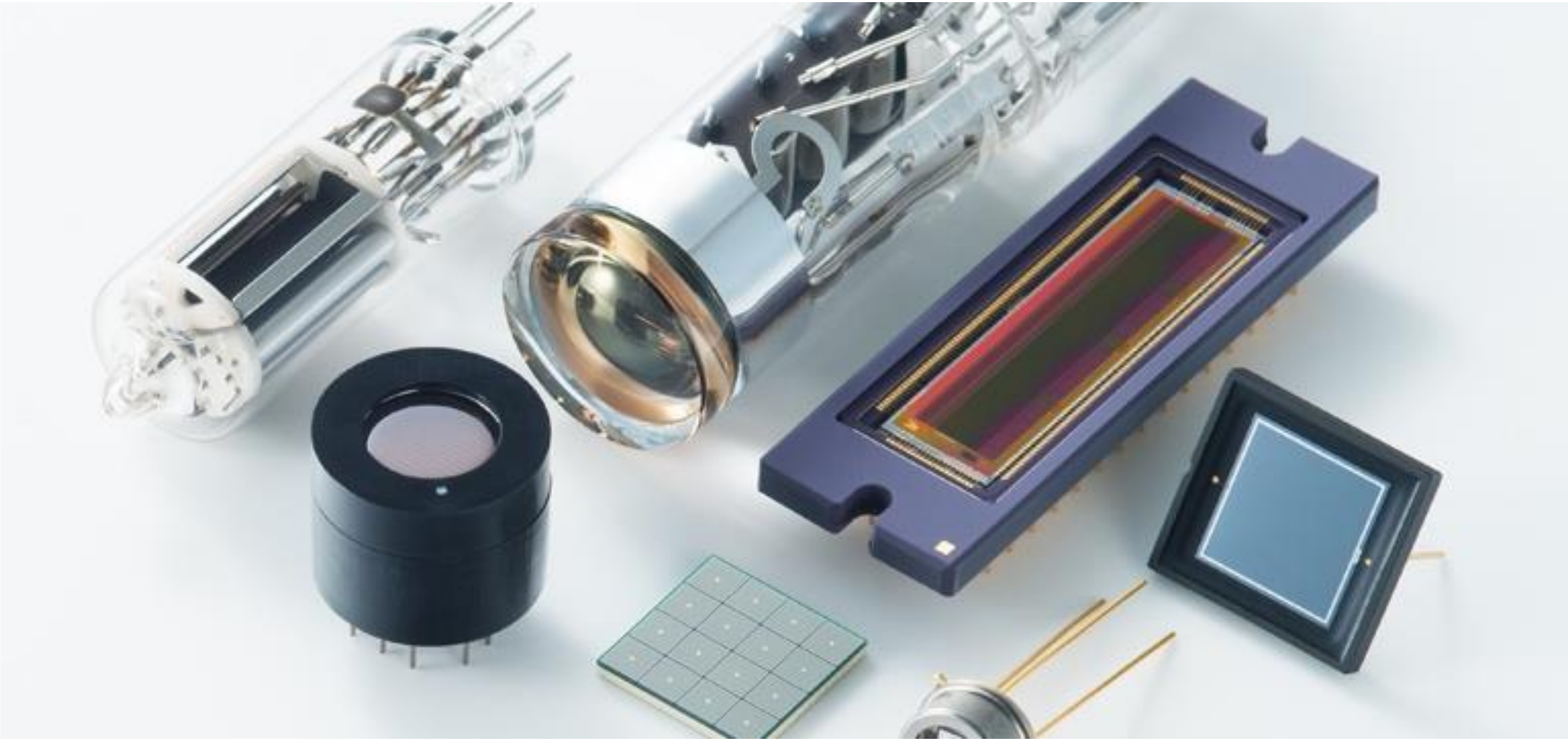
RICH: Key challenges

- Low number of photons
- High radiation hardness
- Improving timing and space resolution
- Improving S/N ratio (e.g increase the photon detection efficiencies and reduce sensor noise)
- Low-power high-performing readout electronics
- Mechanical integration
- Large coverage area in intense magnetic field

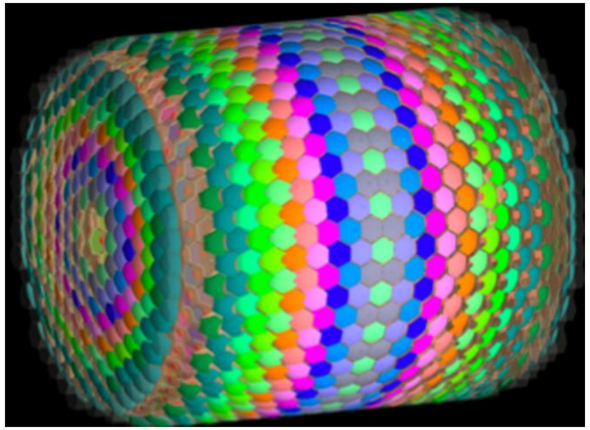
RICH development main drivers

- High Particle Rate:
  - Resolving multiple, overlapping Cherenkov rings (pile-up).
  - Need to handle particle fluxes exceeding (10^5 - 10^6) tracks/cm^2/s, avoid signal saturation, and ensure fast recovery.
- Spatial & Time Resolution:
  - Fine pixelation in photon detectors for accurate ring reconstruction.
  - Precision timing (<100 ps) to suppress background (from pile-up and noise).
  - Breakthroughs in pixel density (sub-mm), time resolution (down to 20–50 ps), and minimising optical system aberrations
- Radiation Hardness:
  - Materials and sensors must retain properties/stability under radiation.
  - Anticipated rates increase by x5–x10 (expected fluence > 10^{11}); require more radiation-durable materials, sensor lifetimes >10 years, and rate tolerance beyond MHz/cm^2 without significant loss/aging

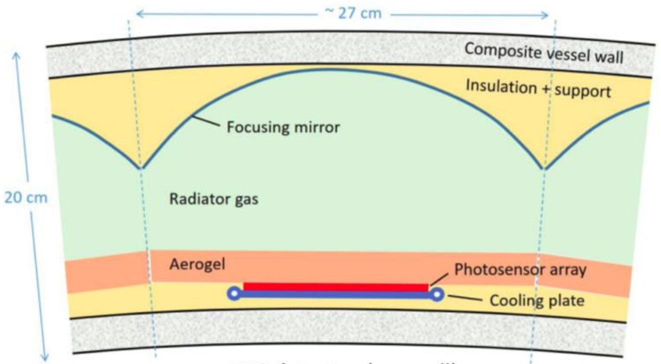
Photon Detectors Development



Solid State Single Photon Detectors

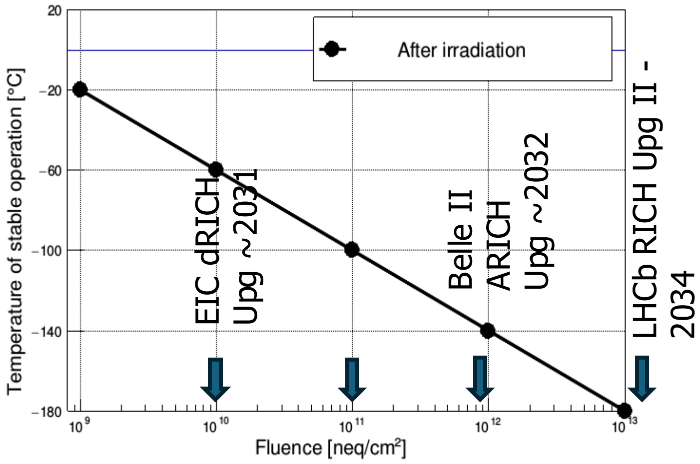


Current Status: SiPMs offer QE 50%, operation in magnetic fields, fast timing (100 ps), but dark noise and crosstalk remain challenges, especially after irradiation

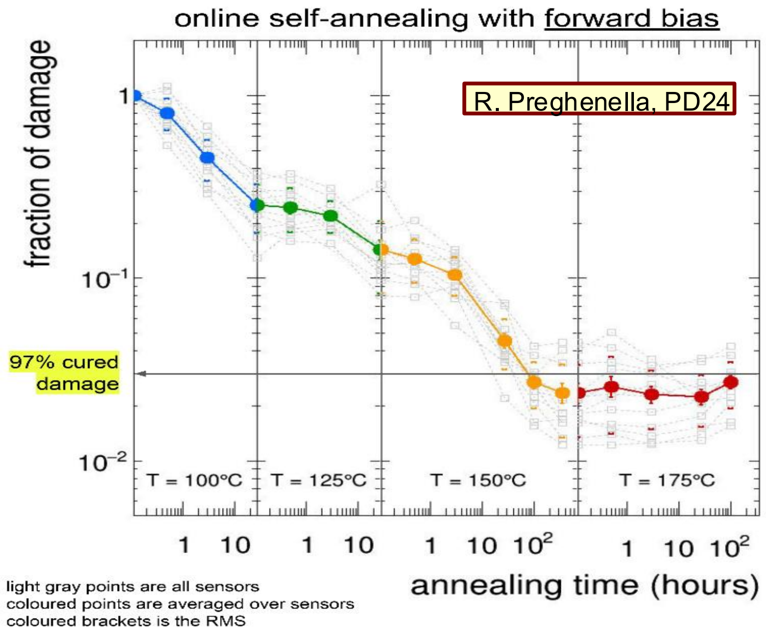


ARC detector (one cell)

ALICE3 and FCC development based on mix gas and aerogel radiator and SiPM modules with integrated cooling



D. Consuegra-Rodrigez et al., Eur. Phys. J. C 84, 970 (2024)



Solid State Single Photon Detectors

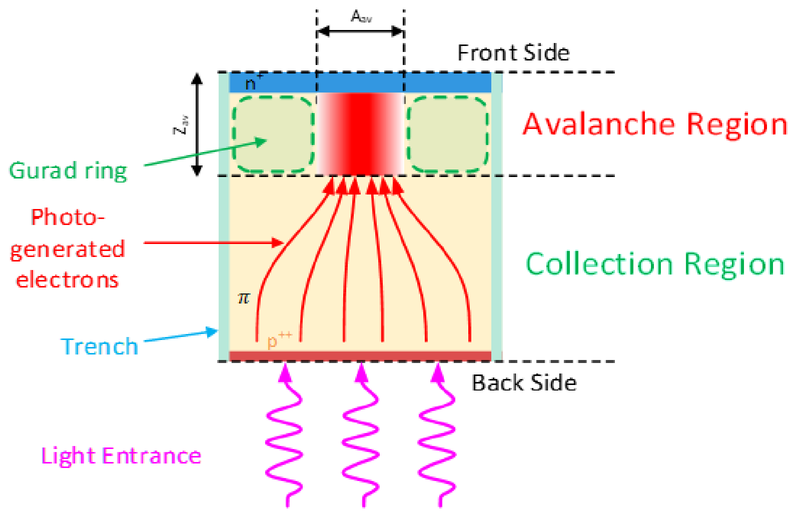
Current Status: SiPMs offer QE 50%, operation in magnetic fields, fast timing (100 ps), but dark noise and crosstalk remain challenges, especially after irradiation

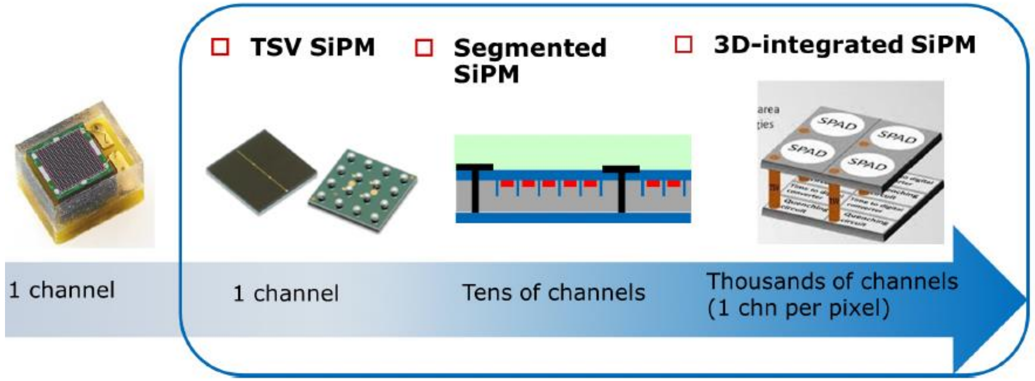
Future Expectations:

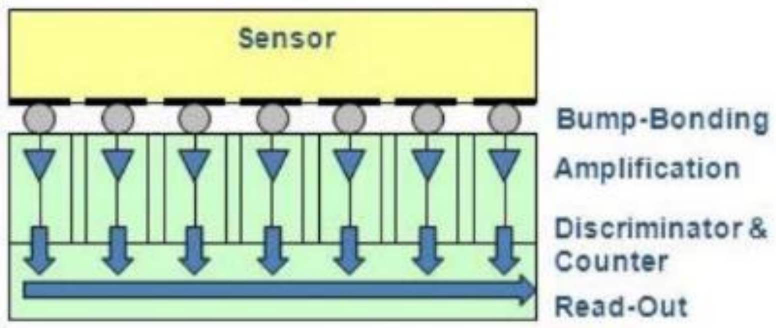
- lower dark count rates (<100 kHz/mm^2),
- higher tolerance to radiation 10^{12}-10^{13} n/cm^2,
- reduced crosstalk (<1%),
- improved QE in deep UV;
- stable operation in strong magnetic fields;
- scalable to larger areas

Solid State Single Photon Detectors

- Developments:
  - BSI (Backside Illumination) technology for enhanced PDE and radiation tolerance;
  - ultra-granular SiPMs with 2.5D/3D integration (SiPM+integrate RO elx); CMOS-SPAD sensors;
  - blue sky research - alternative materials (SiC, GeC, InGaAs).







Vacuum-Based Single Photon Detectors

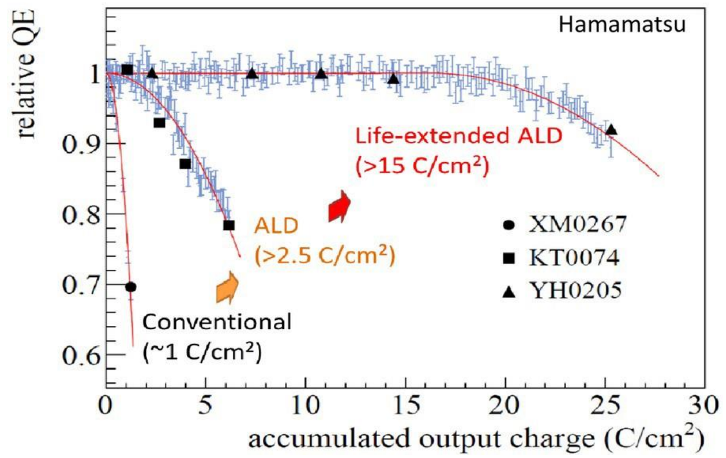
- Current Status: MCP-PMTs offer excellent timing (<50 ps with microchannel design), low dark counts, and good quantum efficiency (QE) (~20–35%), but they are sensitive to magnetic fields and have issues with lifetime.

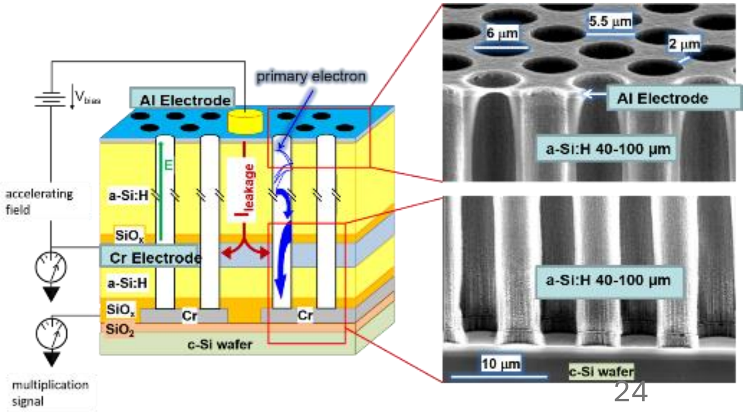
Developments:

Study of MCPs with high-rate capabilities, long lifetimes, and new photocathode materials/structures for increased QE; development of readout electronics.

Future Expectations:

New photocathodes resistant to ion backflow, longer MCP lifetime (>5 C/cm^2 charge), robust operation in several T magnetic fields, integrated fast pixelated readout, and cost-effective large-area coverage.





Outlook

Calorimeter

Different approaches to obtain maximal information from particle detection

- Complex and bulky detectors with high granularity and timing capability
- Challenge in integration (electronics, mechanics and cooling)
- Challenge in testing (a calorimeter testbeam is an experiment with physics output in itself => need dedicated beam line setup)

Challenges addressed by DRD6

RICH detectors are indispensable for PID

Meeting physics goals will require R&D

- materials, photon sensors, electronics, system-level integration

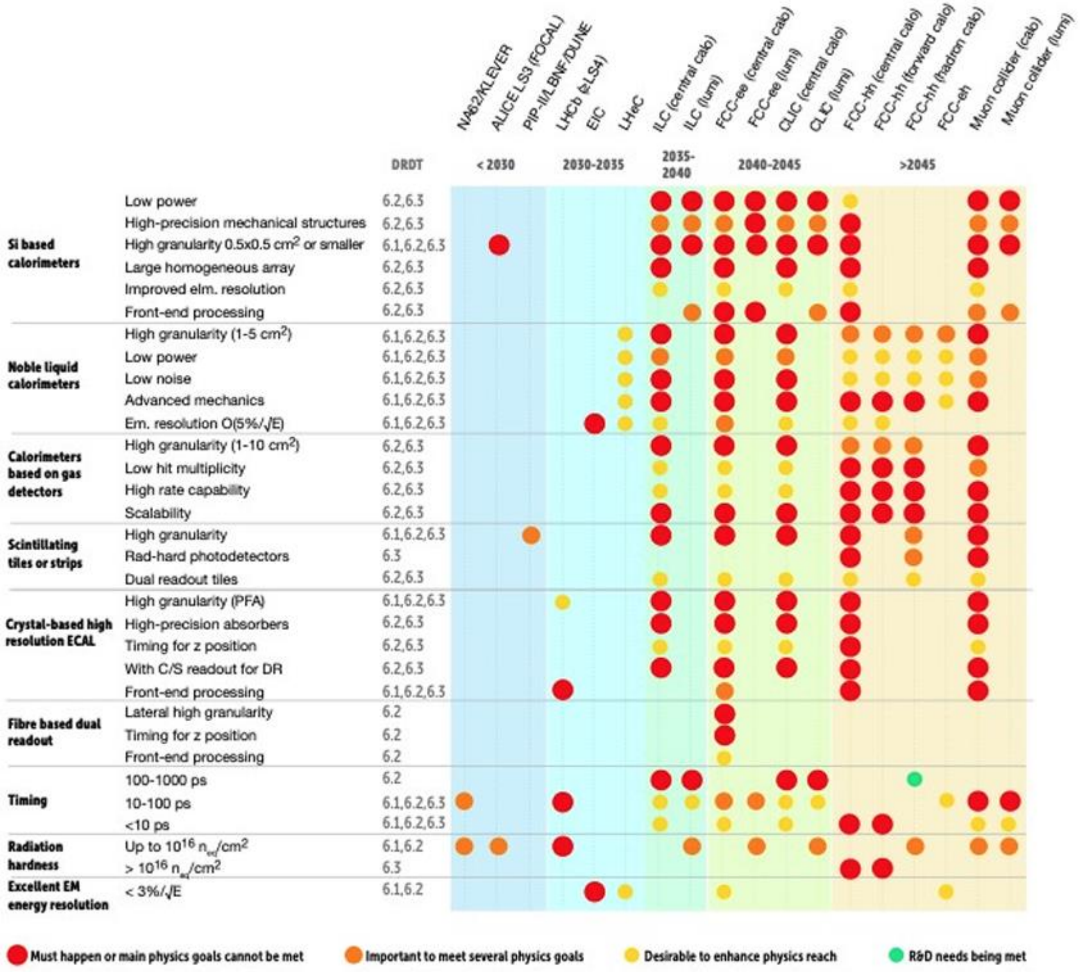
Challenges for both RICH and Photodetectors addressed by DRD4

BACKUP

ECFA Roadmap

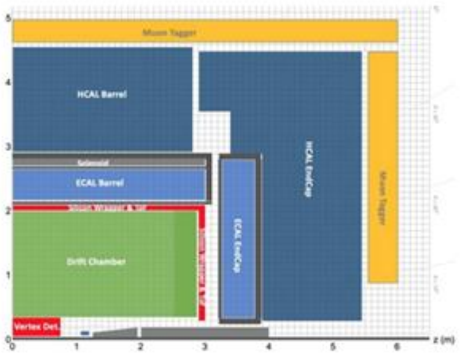
European Strategy for Particle Physics

- Key technologies and requirements are identified in ECFA Roadmap
  - Si based Calorimeters
  - Noble Liquid Calorimeters
  - Calorimeters based on gas detectors
  - Scintillating tiles and strips
  - Crystal based high-resolution Ecals
  - Fibre based dual readout
- R&D should in particular enable
  - Precision timing
  - Radiation hardness
- R&D Tasks are grouped into
  - Must happen
  - Important
  - Desirable
  - Already met

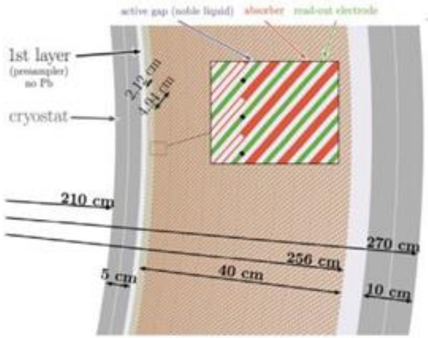


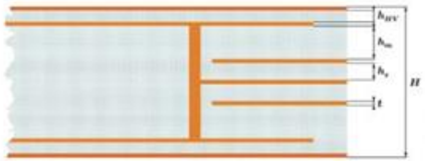
Liquified Noble gas

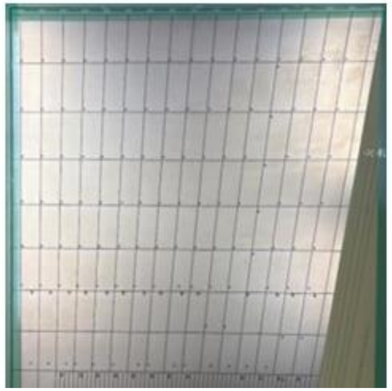
High Granularity Noble Liquid ECAL



ALLEGRO







- **Evolution of ATLAS calorimeter with much finer granularity for particle-flow reconstruction:**
  - $\Delta\theta; \Delta\phi$ = 10; 8 mrad
  - 11 longitudinal layers
  - ***Superior (~5x) SNR*** with cold electronics
  - Narrow strips (2.5 mrad) in small R longitudinal layer for π_0 detection

- **ALLEGRO – general-purpose detector for FCC-ee**
  - ***A Lepton coLlider Experiment with Granular calorimetry Read-Out***
- **Highly-granular noble liquid ECAL a central and most studied feature**
  - ***LAr or LKr with Pb or W absorbers***
  - ***Multi-layer PCB as read-out electrode***
- **Vertex detector, drift chamber and ECAL inside 2 T solenoid, sharing cryostat**
- **HCAL and muon system outside solenoid**
- **Optimized for full FCC-ee physics program**

RICH: Experimental integration constraint

- Compactness & Space:
  - Current developments: Thin detectors to minimize material to reduce scattering and photon conversion, and integration with tracking/calorimetry.
  - Future Expectations: Even thinner, lighter systems (<1% X_0 material budget), modular structures, and seamless integration.
- Material Budget:
  - Current developments: Transparent, radiation-resistant radiator materials preferred to minimize interaction lengths.
  - Future Expectations: Low material budgets to improve overall detector resolution and performance.
- Mechanical Integration:
  - Current developments: Stable mechanical structures with excellent alignment.
  - Future Expectations: Maintain precision over long operation periods.

RICH Electronics and Data Acquisition

- Current Status:
  - Dedicated ASICs enable multi-MHz readout; intelligent DAQ used to filter photon hits; robust calibration systems.
- Current Developments:
  - Develop and adapt existing electronics readout systems.
- Future Expectations:
  - DAQ capable of >100M hits/s, improved on-detector data processing, and real-time analysis.

MCP-PMTs: New materials and read-out options

A. Franco *et al.* Sci. Rep. 1 (2014)

- **New material, new coatings, longevity and rate capability study**

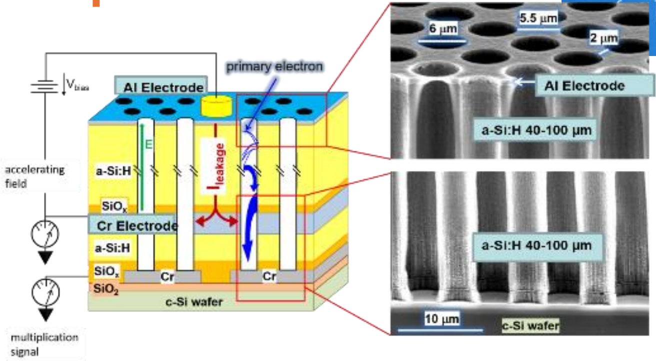
  This concerns the R&D on new materials to produce VPD,
  new shapes , new coatings , and their consequences
  on their longevity and rate capability

- **New photocathode materials, structure and high quantum efficiency VPD**

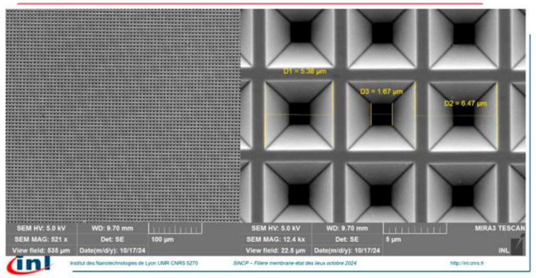
  New photocathode materials, new structures and their impact on improving the quant
  efficiency for different wavelengths

- **Time and spatial resolution performance**

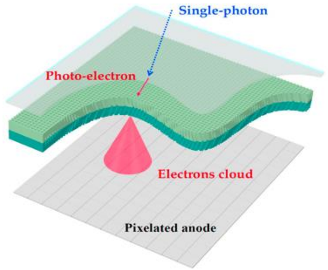
  Study of VPD timing and spatial performance using appropriate readout electronics ar
  appropriate anode structures

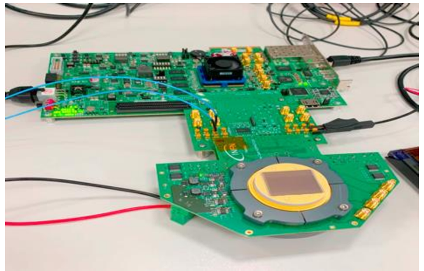


Amorphous Si MCPC(Geneva)

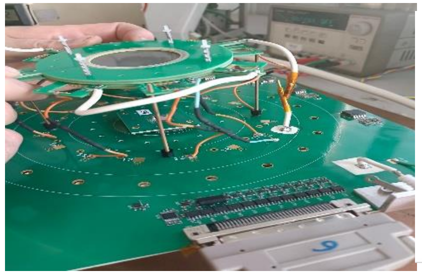


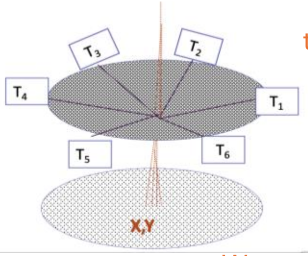
Si nanometric structure for
reflective photocathode (Lyon)





MCP+Timepix4
(Ferrara)





time

Woven strips

MCP+PICMIC concept
(Lyon)

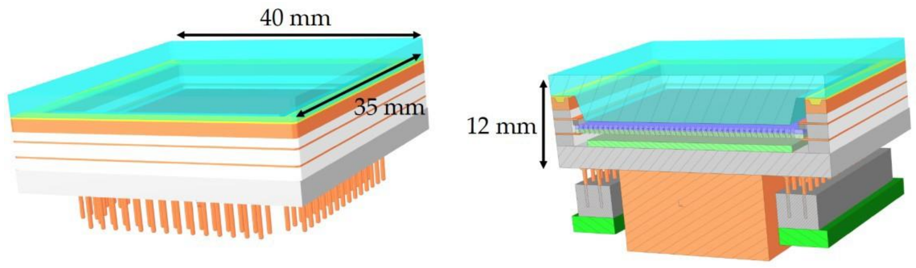
Future of Electron Multiplication

MCP-PMT with CMOS anode

M. Fiorini, RICH2022

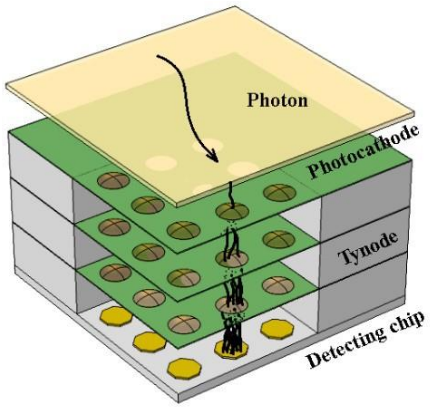
Conceptual design for 4D detection of single photons

- Hybrid concept: MCP-PMT where the pixelated anode is an ASIC (CMOS) embedded inside the vacuum
- Prototype with Timepix4 ASIC as anode (array of 23k pixels)
- Envisaged performance
  - <100 ps time resolution and 5-10 μm spatial resolution
  - Rate capability of >100 MHz/cm^2 (<2.5 Ghits/s @ 7 cm^2 area)
  - Low gain (~10^4) operation possible → x100 lifetime increase

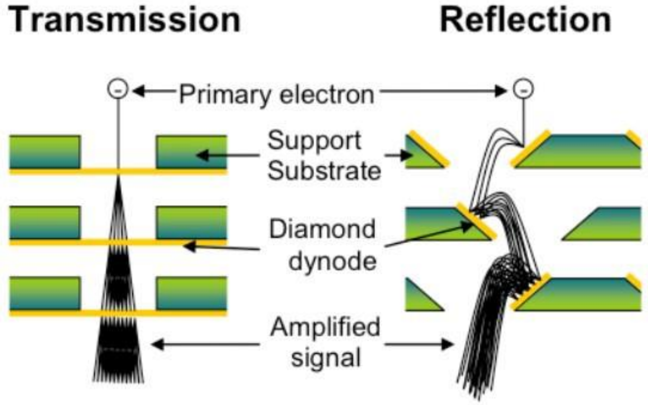


Tynodes (→ Time Photon Counter)

- Transmission mode dynode → tynode
- Fabrication of tynodes (MgO ALD, diamond) using MEMS technology
- “Anode” is a CMOS chip (e.g., TimePix)
- Very promising properties
  - Very compact, high B-field tolerance, very fast
  - Very low DCR; very good 2D spatial resolution

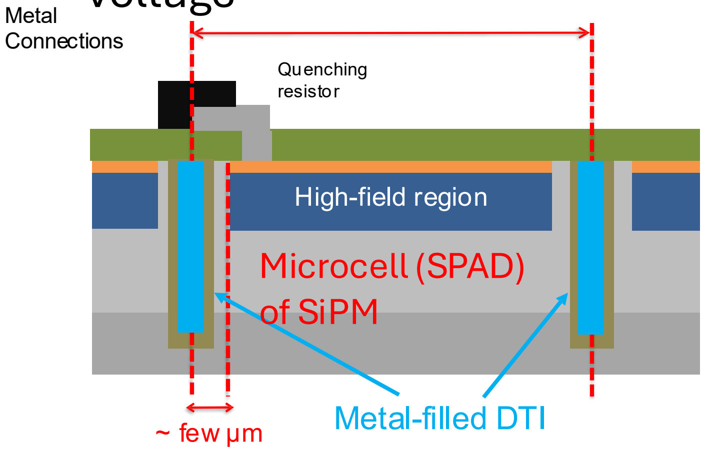


H. van der Graaf et al., NIM A847 (2017) 148



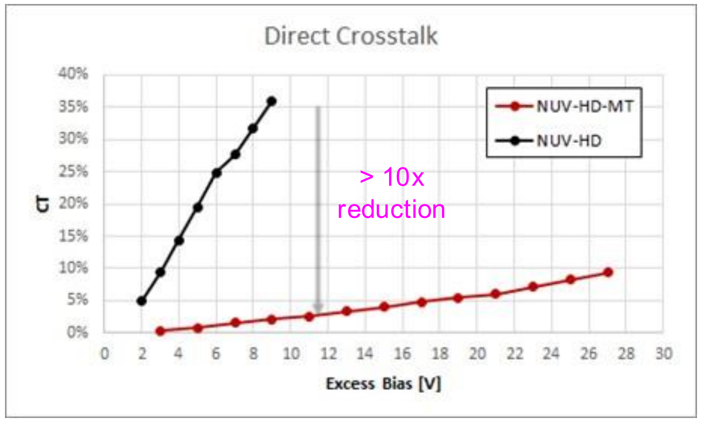
Latest achievements in SiPM technology

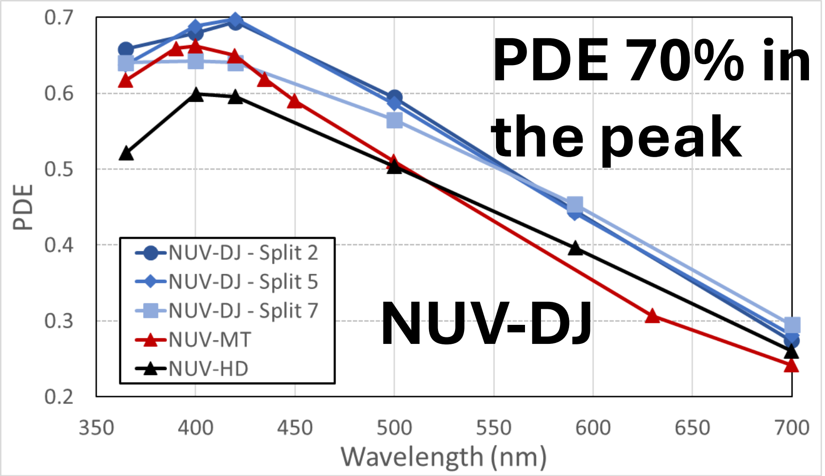
Deep trench isolation strongly suppresses optical crosstalk, enabling higher PDE and operating voltage



Conceptual drawing of the NUV-HD-MT, with the addition of metal-filled Deep Trench Isolation.

A. Gola, talk at RICH2022





Variation of TTS over the device surface can contribute to overall time spread:

- variation within micro-cell
- variation for different micro-cells

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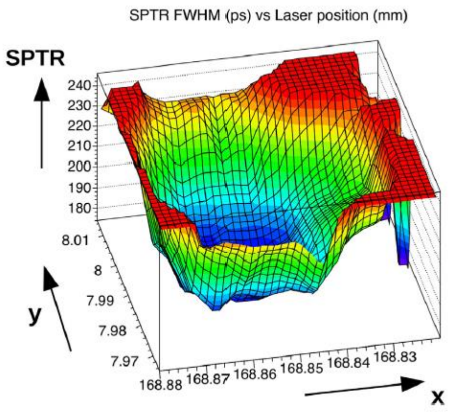
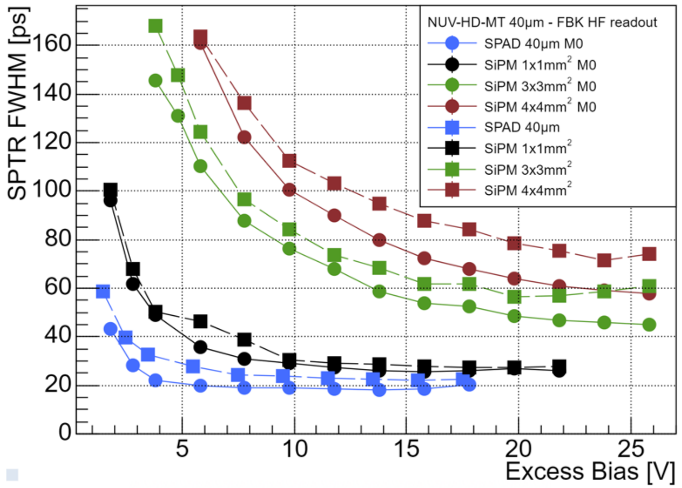


F. Acerbi et al. NIM A926(2019)16

FBK: Masking of outer regions of micro-cells: Improve signal peaking and mask areas of micro-cells with worse timing



60 ps FWHM – 4x4 mm² M0
45 ps FWHM – 3x3 mm² M0
27 ps FWHM – 1x1 mm²
<20 ps FWHM - SPAD

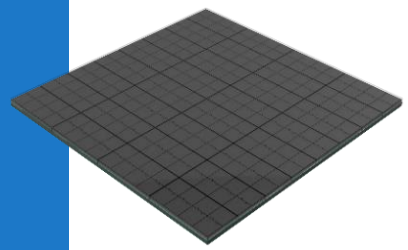
2.5D and 3D integration of SiPMs& elecronics

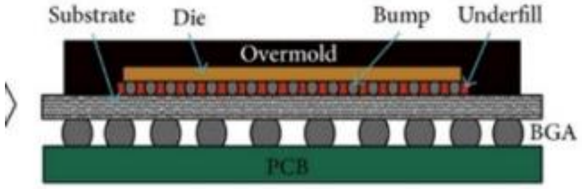
Timing of SSPD & Developing ultra-granular SiPM that integrates with the readout electronics

Current developments

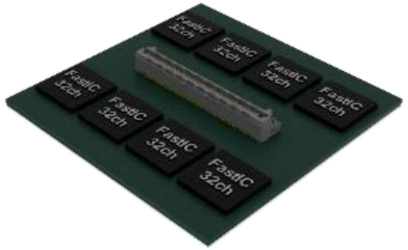
2.5D Integration

3mm





3x3 mm² SiPM array

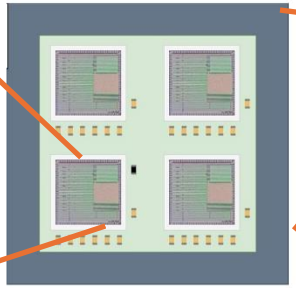


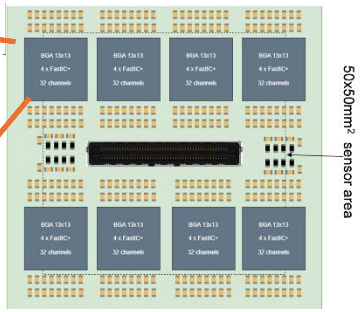
256 Ch 5x5cm²
Module proposal

Under development by

PET VISION

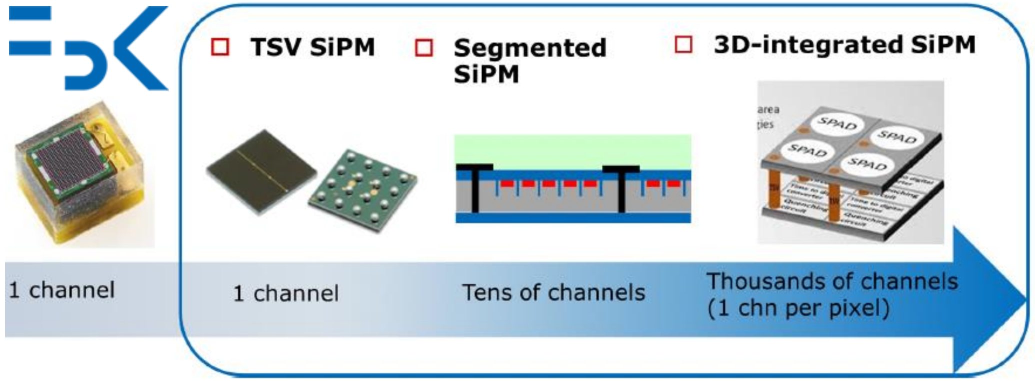
FastIC+
(collab. CERN ICCUB)
Low power
Chip





2024 Produced and evaluated

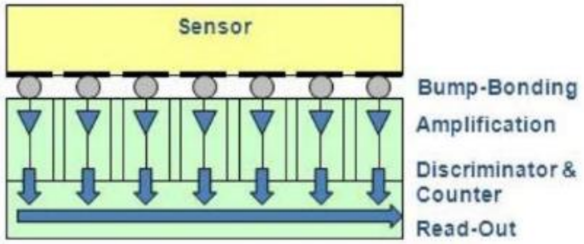
design & production 6.2025



1.5mm

Hybrid SiPMs

MicroTSVs to achieve *a single-cell connection for ultimate timing performance*.



Custom SiPM technology **for sensing layer for maximum performance**

CMOS technology **for readout layer**

0.5-1mm

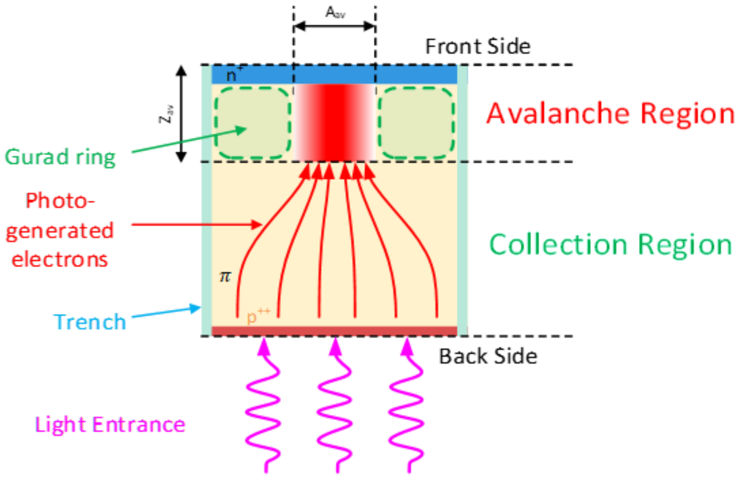
2.5D or 3D Integration

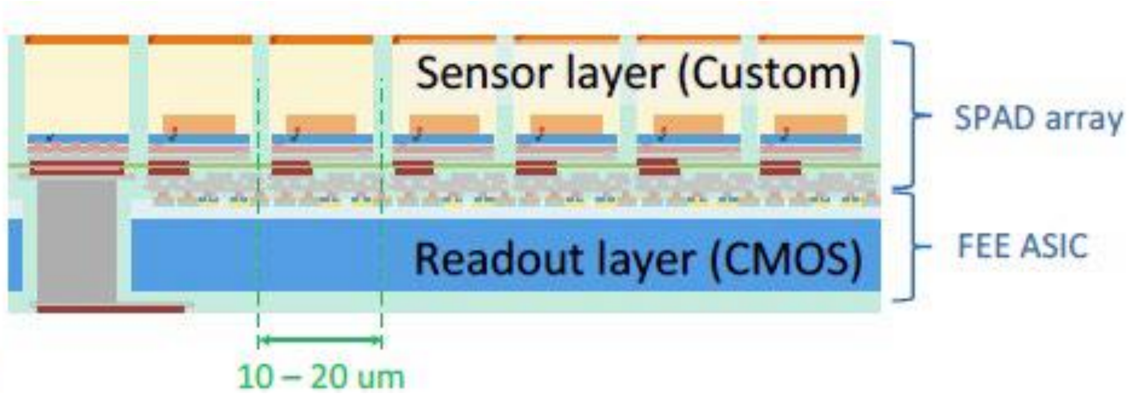
Long-term needs

Backside Illuminated SiPMs

Clear *separation between charge collection and multiplication regions*.

A. Gola - Status and perspectives of SiPMs at FBK @CERN 2023





The first technology demonstration run is close to completion.

Potential Advantages:

- Up to 100% Fill Factor even with small cell pitch
- Interconnection density: < 15 um
- High speed and dynamic range
- Low gain and external crosstalk
- Local electronics: ultra-fast and possibly low-power.

Radiation hardness:

- The SiPM area sensitive to radiation damage is much smaller than the light-sensitive area
- **Assumption**: The main source of DCR is field-enhanced generation (or tunnelling).

SiPMs: Radiation damage

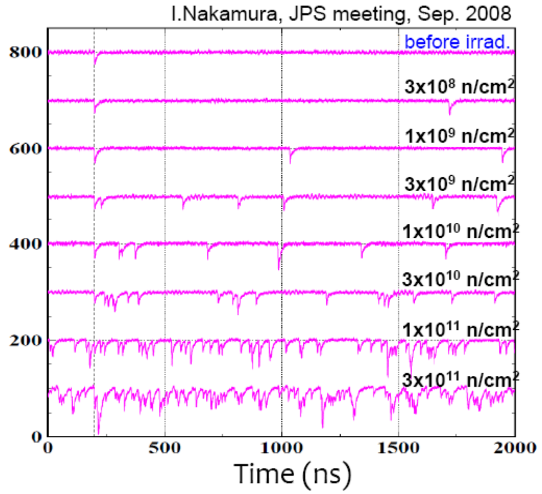
A. Gola, RICH2022

Single photon detection is much more affected than multi photo

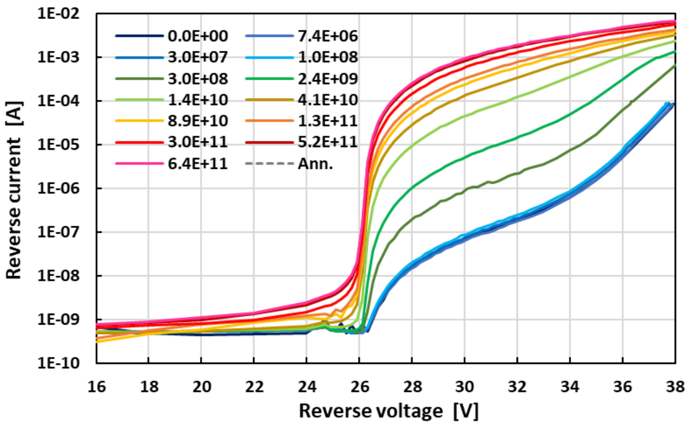
Showstopper at fluences above ~10^{11} in case single (or a few) photon sensitivity (e.g. expected fluence in the LHCb RICH Upg2 area : 3 10^{13} n/cm^{-2})

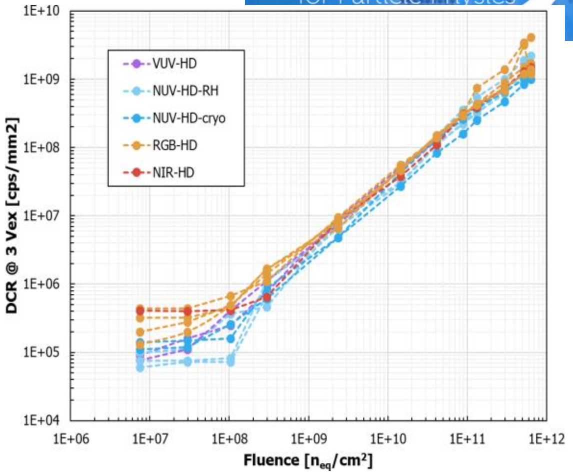
→Effects:

- → Increased dark count rate
- → Increased Reverse Current



Waveforms from irradiated SiPMs



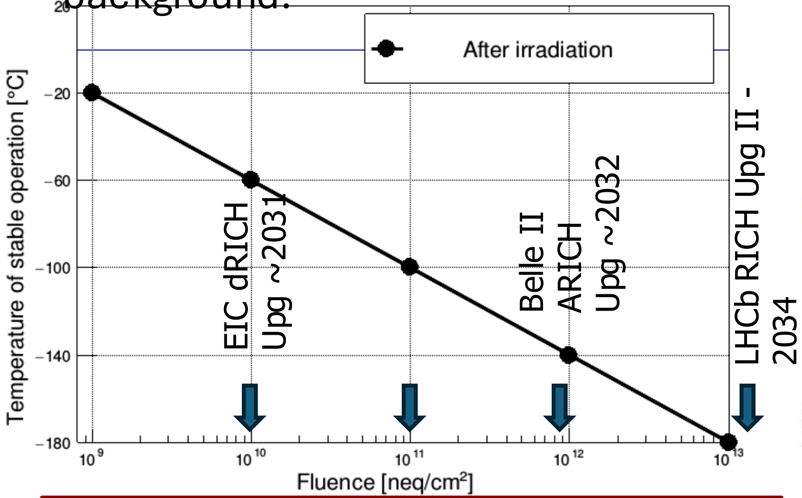


annealing at elevated temperatures

Mitigation strategies (combine several ones)

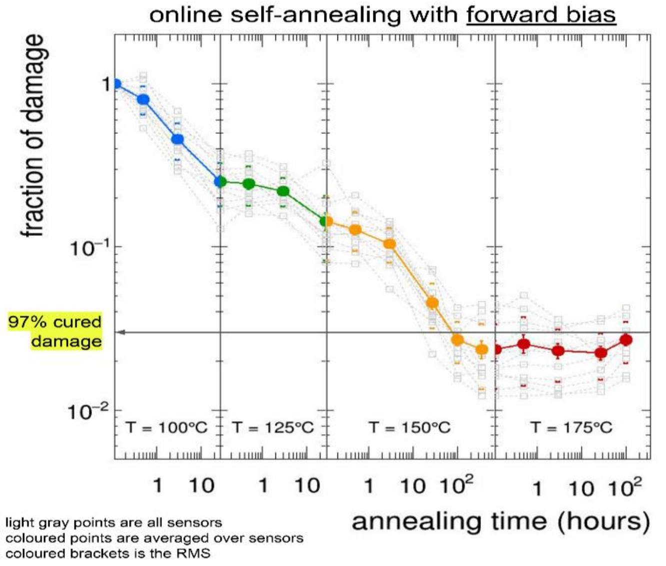
- → Operating the SiPMs at a lower temperature
- → Use of waveform sampling readout electronics
- → Annealing periodically (annealing at elevated temperature is necessary)
- → Reducing recovery time to lower cell occupancy
- → Radiation-resistant SiPMs:
  - → Experimental structures – low E field , BSI, other materials?

Cooling: Temperature at which the single photo electron peak @ 9V OV is separated from the background.



D. Consuegra-Rodriguez et al., Eur. Phys. J. C 84, 970 (2024)

Annealing



R. Preghenella, PD24