Development of Detectors for High-Granularity Dual-Readout Calorimetry

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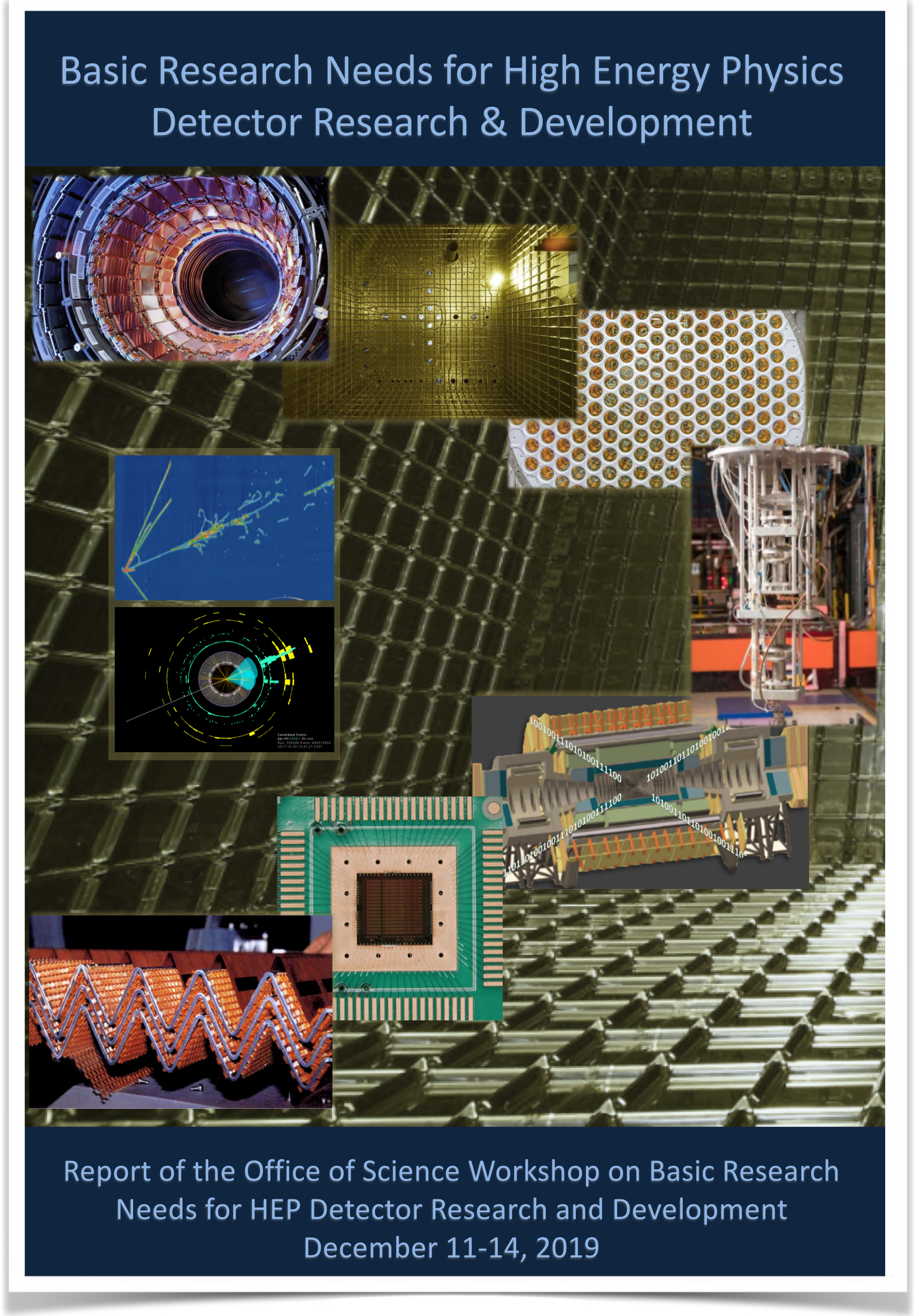
Next Generation Calorimeters

- **Key features for future calorimetry discussed in DOE Basic Research Needs Study (BRN2020)**
  - High precision 5D calorimetry $(E, \vec{x}, t)$
  - psec timing
- **Calorimeter technologies under intensive studies**
  - High-granularity PFA calorimetry
  - Dual-readout calorimetry
  - psec timing sensor

Priority Research Directions for Calorimetry at BRN2020

	PRD: Priority Research Direction	Grand Challenge
Calorimetry	PRD 1: Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements	1
	PRD 2: Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments	1,4
	PRD 3: Develop ultrafast media to improve background rejection in calorimeters and particle identification detectors	1,3,4



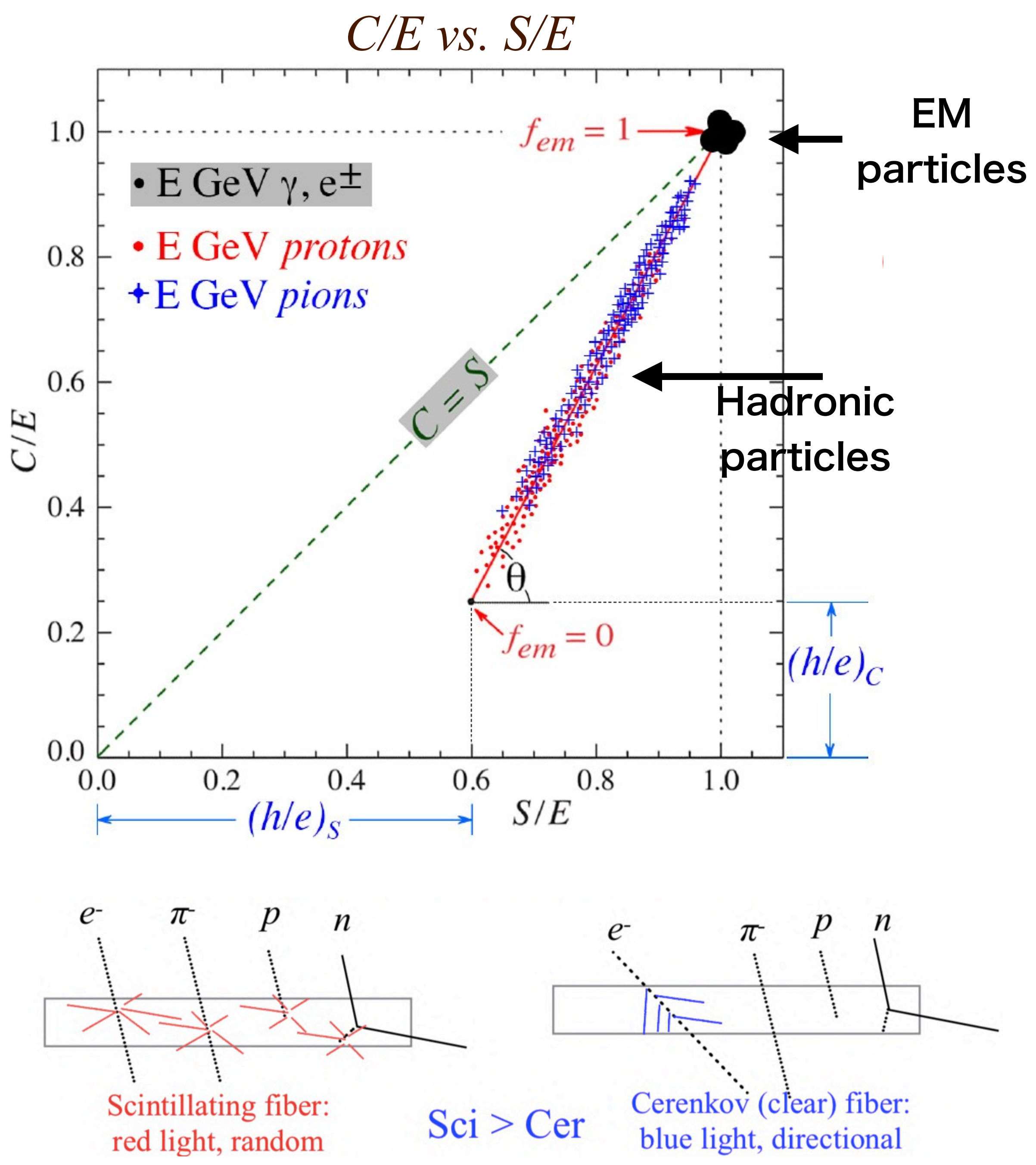
Concept of Proposed Calorimetry

Dual-Readout calorimetry

Better performance at high energy, PID

High-Granularity calorimetry

Better performance at low energy



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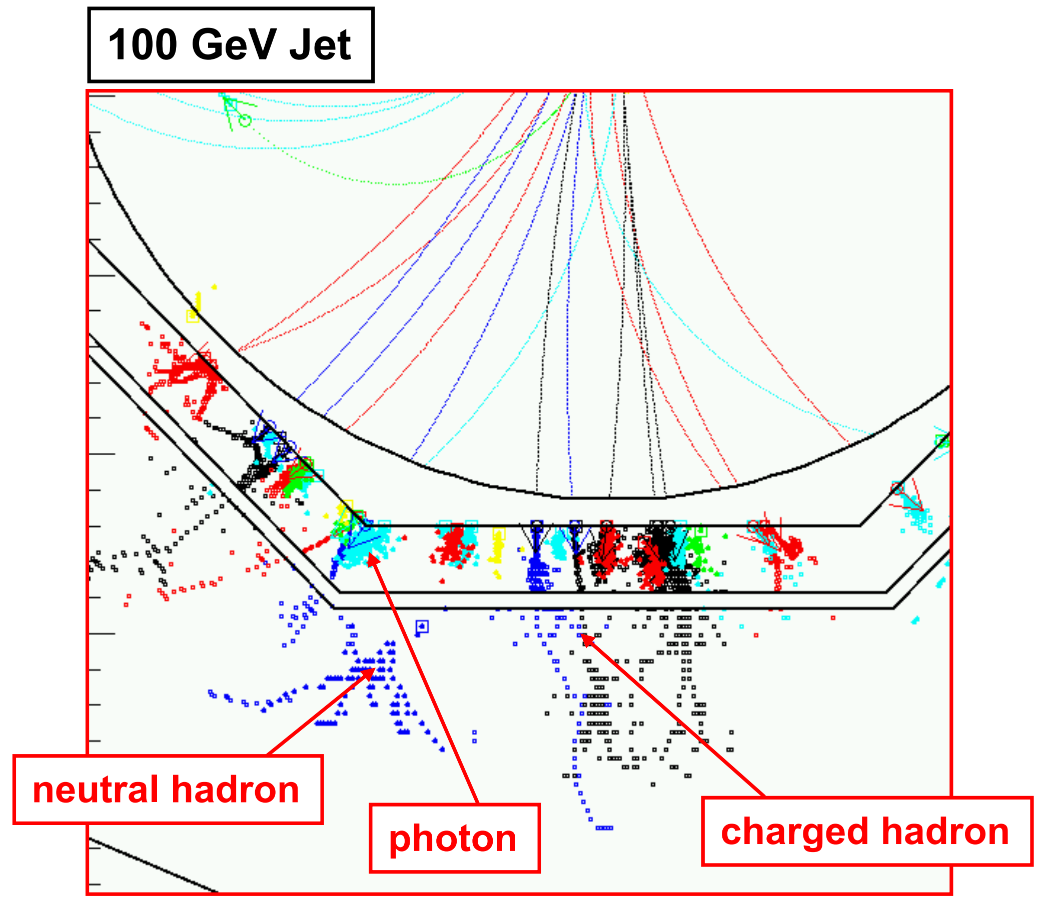
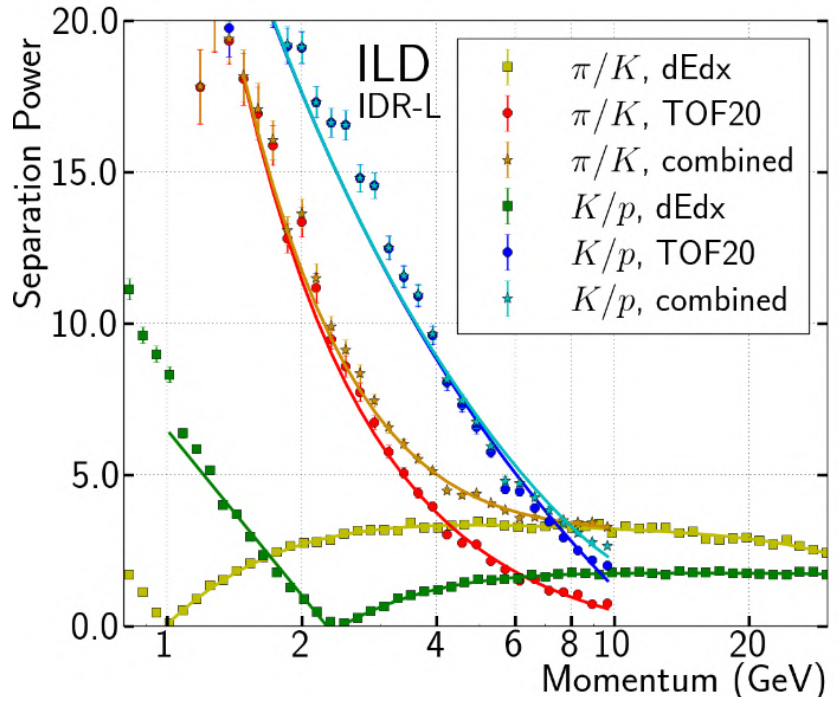
New calorimetry for future colliders



psec timing

PID, BG reduction, improve PFA



Overview of Research Plan

How to Combine High-granularity and Dual-readout with Excellent Timing

Dual-readout

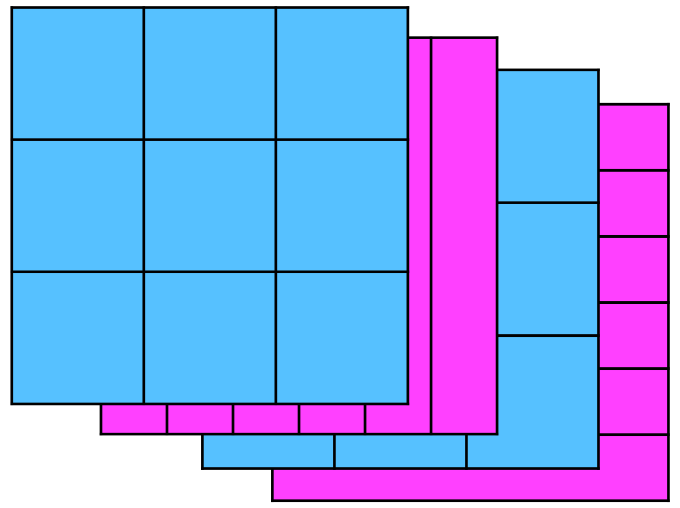
Cherenkov detector

Cherenkov radiator + UV-GasPM
- High-granularity readout
- psec timing

Scintillation detector

SiPM-on-strip technology
- High-granularity

Cherenkov



Scintillation

Fast timing front-end electronics

Simulation and analysis tools

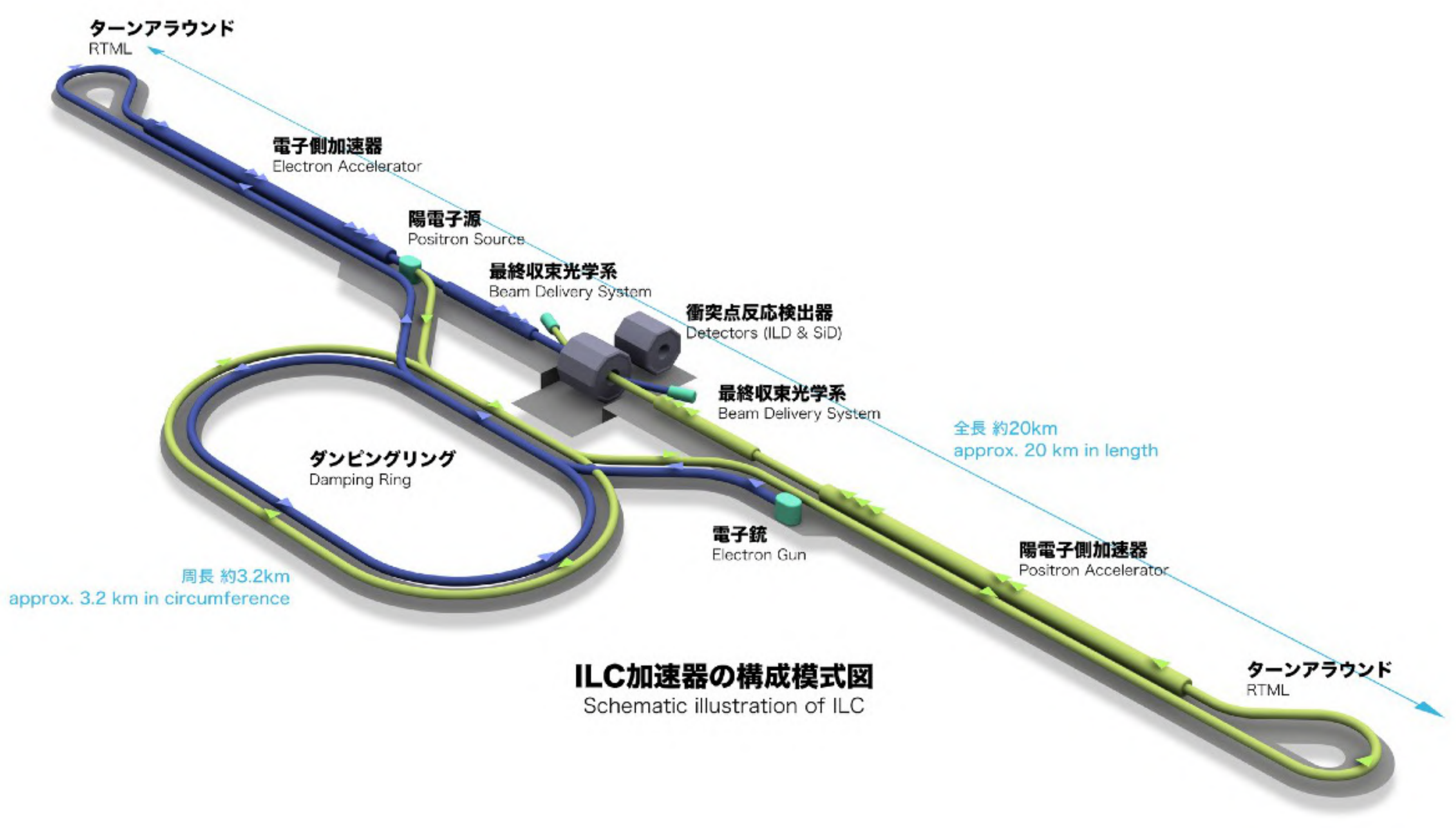
Prototyping and beam test at FTBF

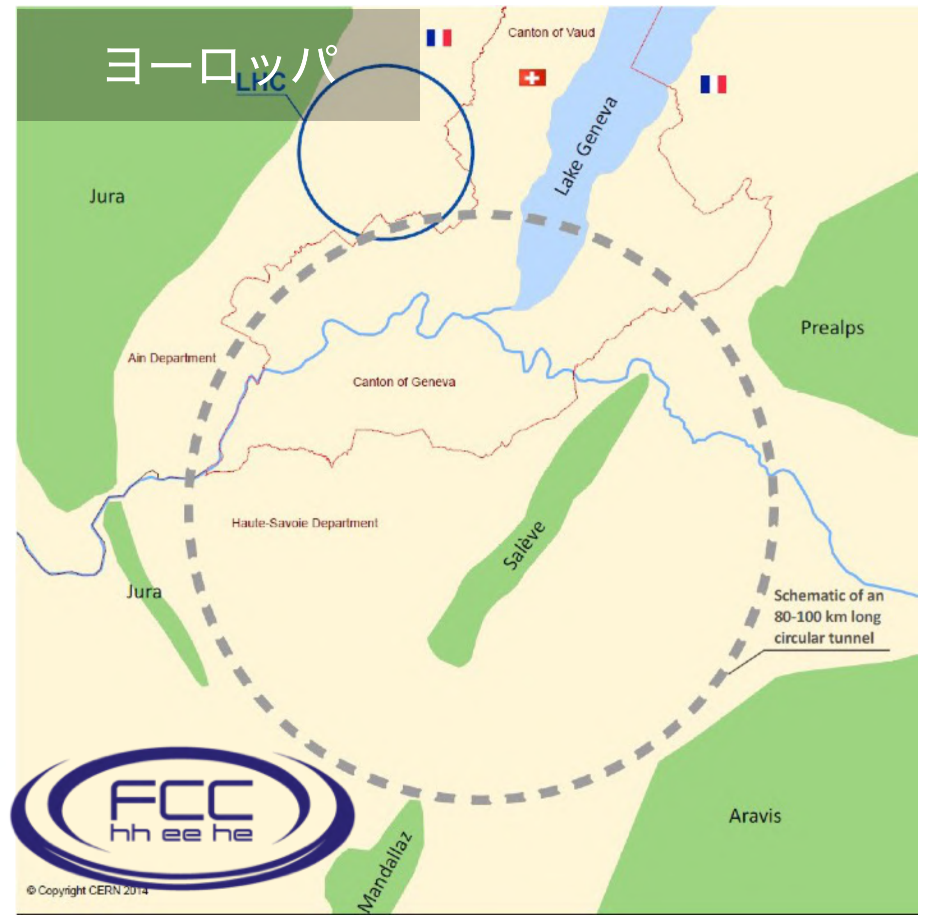
Demonstrate performance of proposed calorimeter technology

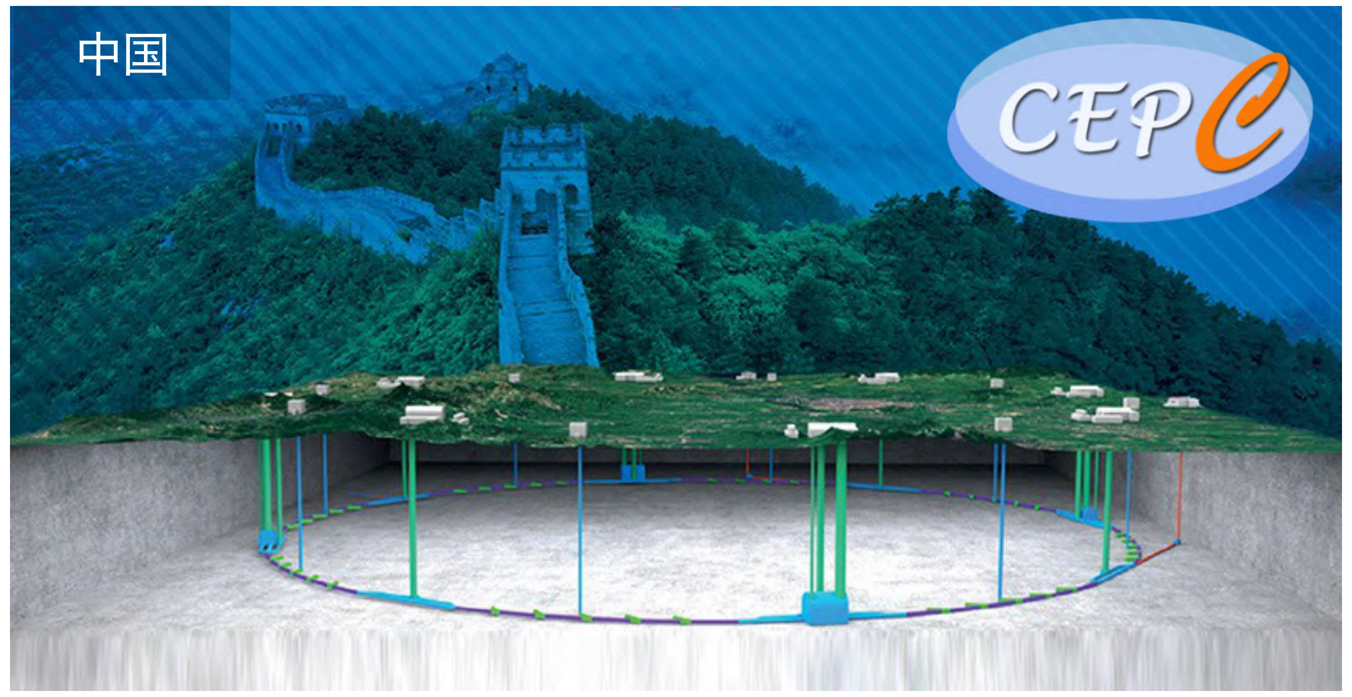
Possible Applications

- Generic R&D, but many applications at future experiments foreseeable

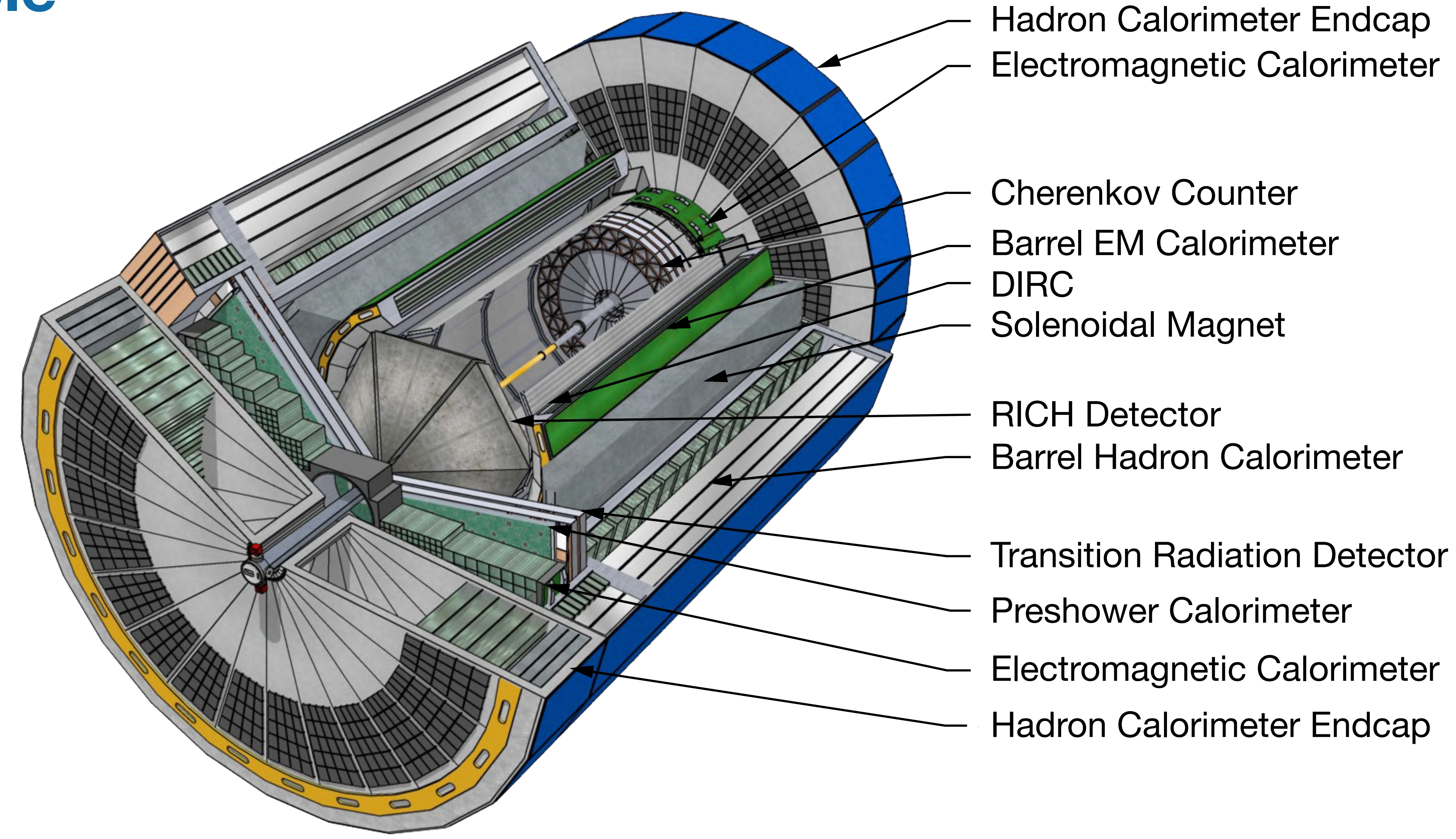
Calorimeters for Higgs factories



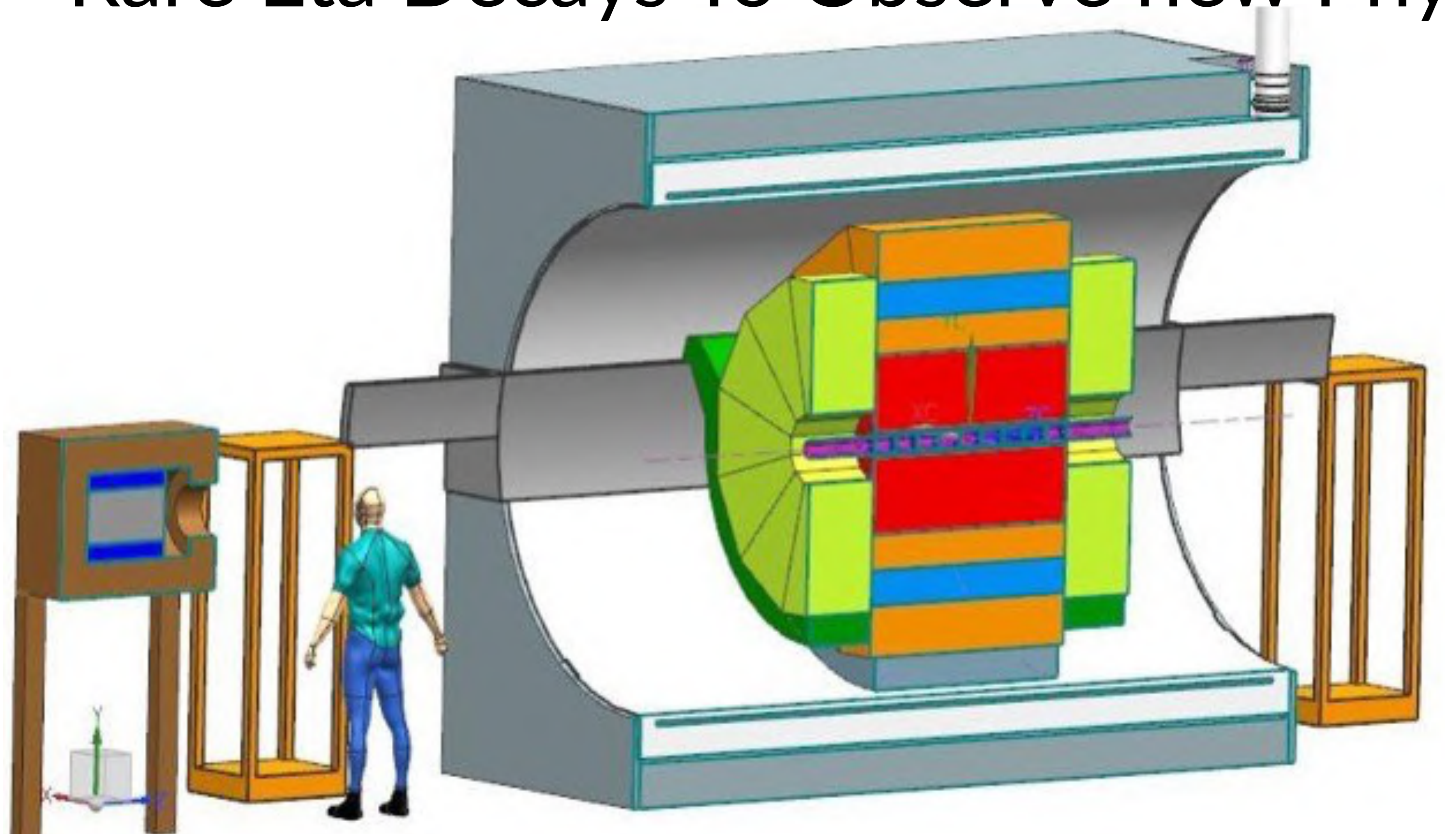




EIC
Electron-Ion Collider

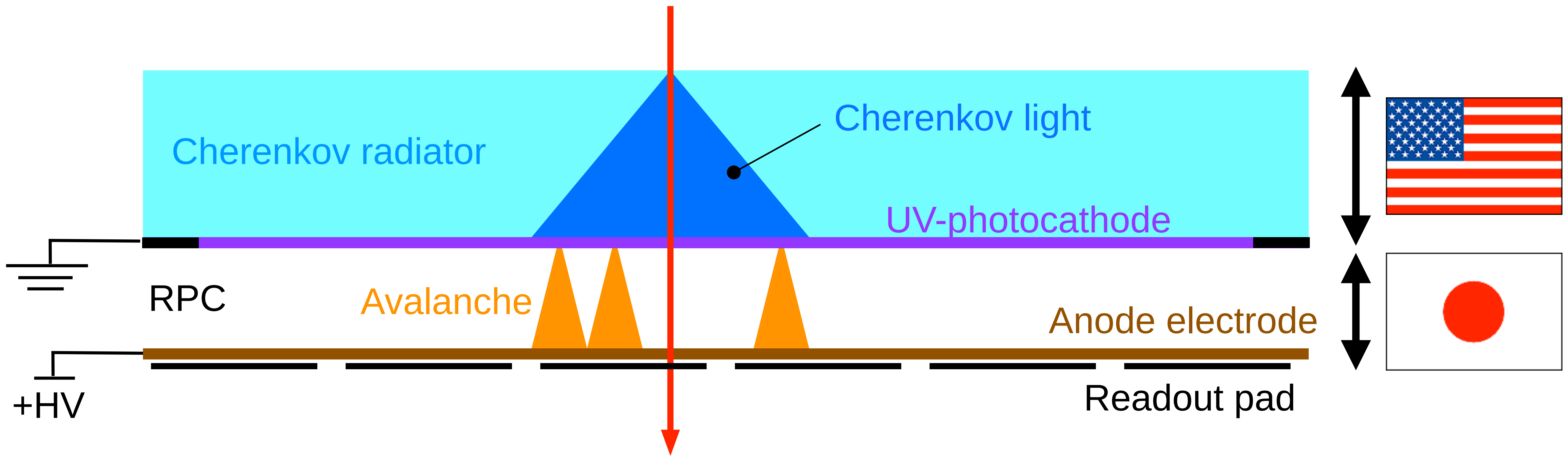


REDTOP
Rare Eta Decays To Observe new Physics



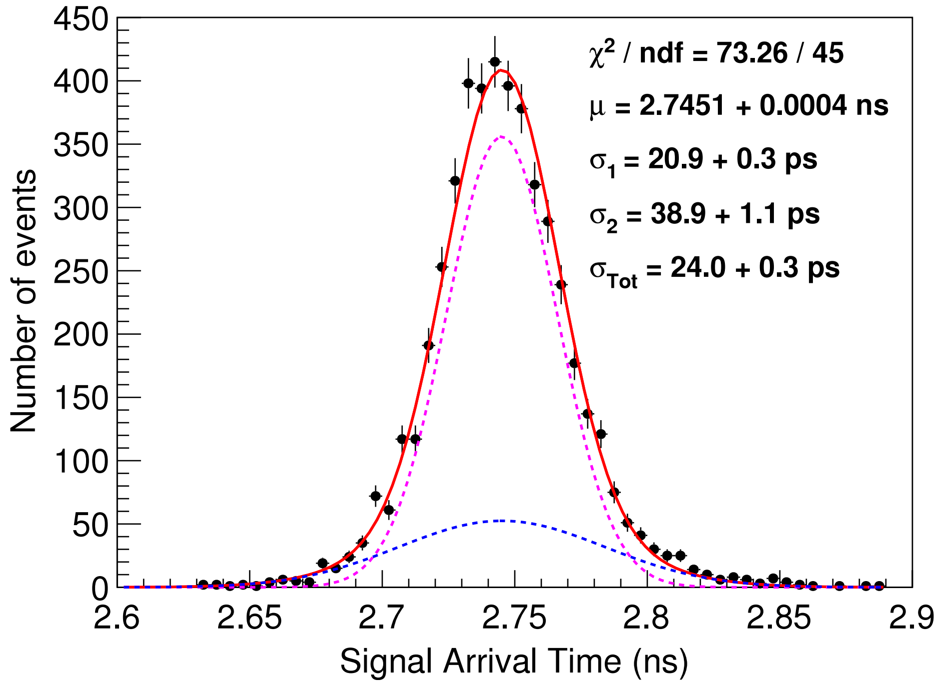
Cherenkov Detector

- **Proposed concept**
  - **Cherenkov radiator** + **UV-GasPM**
  - UV-GasPM
    - Photocathode: CsI
    - Electron multiplier: DLC-RPC
- **Expected Advantages**
  - Uniform and efficient Cherenkov readout
  - **Excellent timing** (thin gap with no drift region, higher QE with higher electric field)
  - High-rate capable
  - Low- and uniform- mass distribution
  - Large area at low-cost
  - **High-granularity** with segmented readout pad for RPC
- **Target timing resolution**
  - $\mathcal{O}(10\,\mathrm{ps})$ with multiple photoelectrons from Cherenkov light



PICOSEC detector

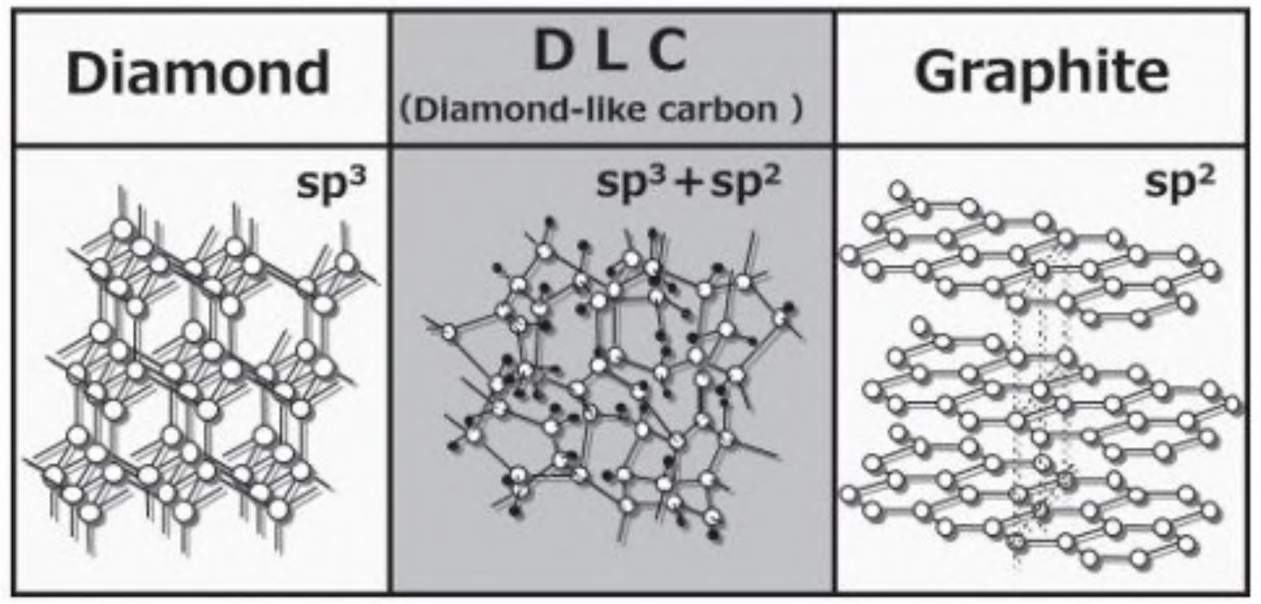
- Similar concept
- Based on Micromegas
- **20ps timing resolution** for MIP



https://doi.org/10.1016/j.nima.2018.04.033

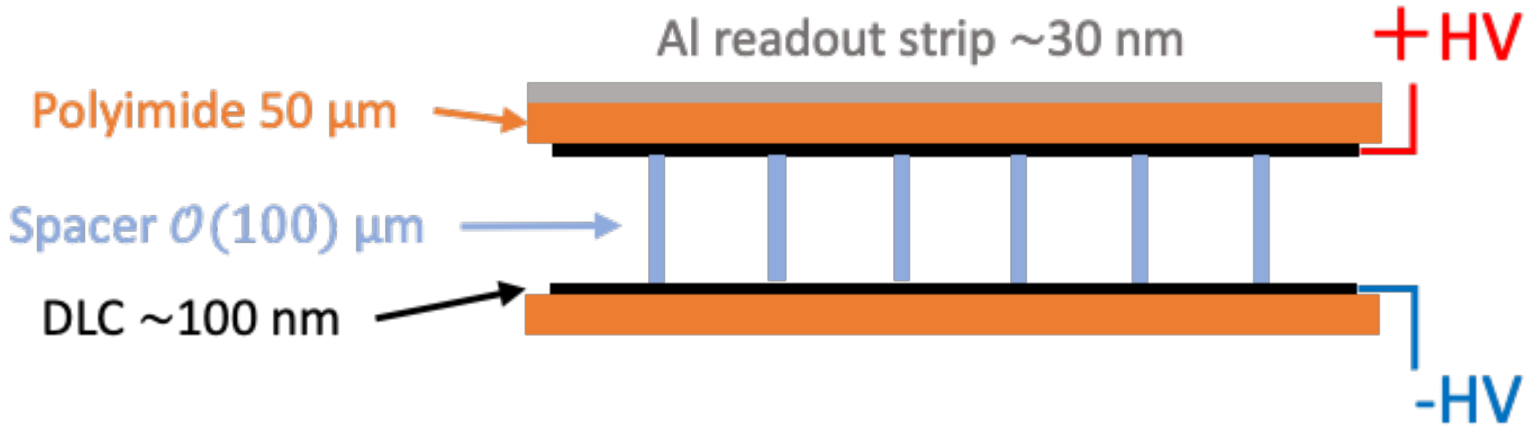
Cherenkov Detector

Japan



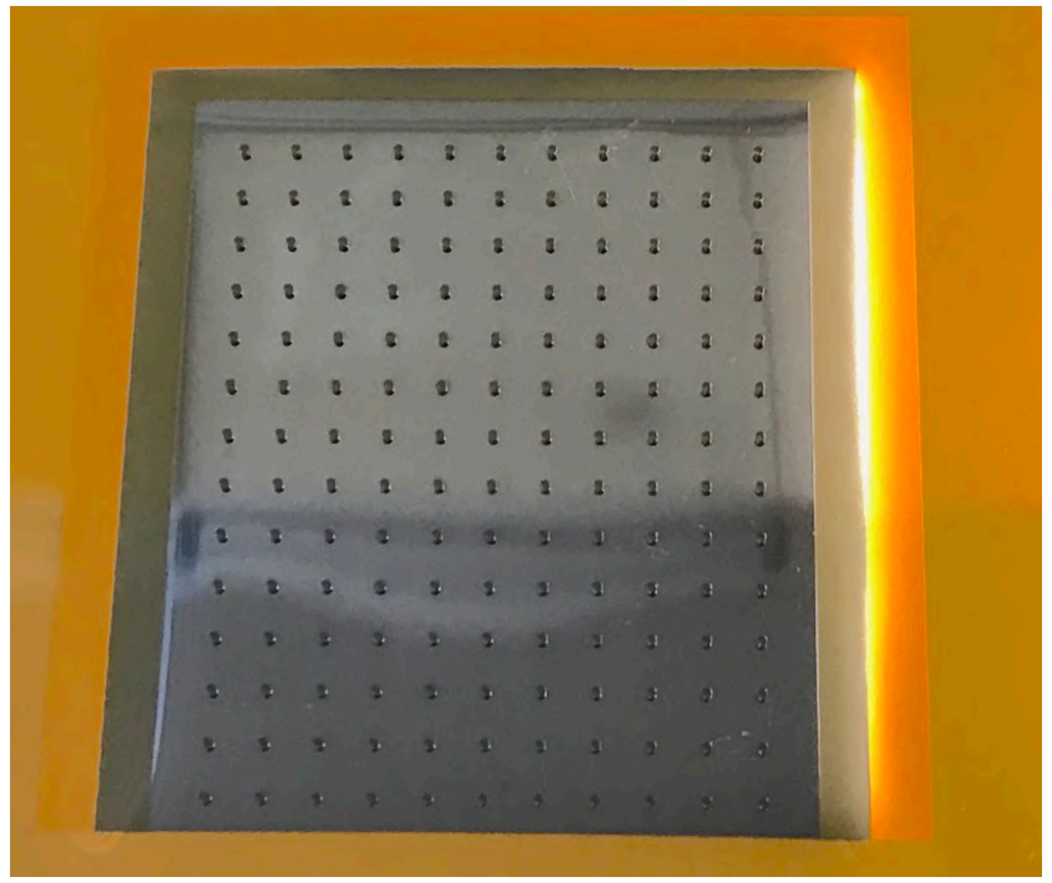
Ref) https://pcs-instruments.com/articles/the-science-behind-diamond-like-coatings-dlcs/

- **Ultra-low-mass high-rate-capable RPC for MEG II experiment**
  - **Diamond-Like-Carbon (DLC)** -based electrode
  - Ultra-low mass: $0.1\,\%\,X_0$ with 4 layers
  - High efficiency: $> 90\,\%$ with 4 layers
  - Good time resolution: $160 - 170\,\mathrm{ps}$ with single layer (no optimisation for timing)
  - High rate capability: $> 1\,\mathrm{MHz/cm^2}$

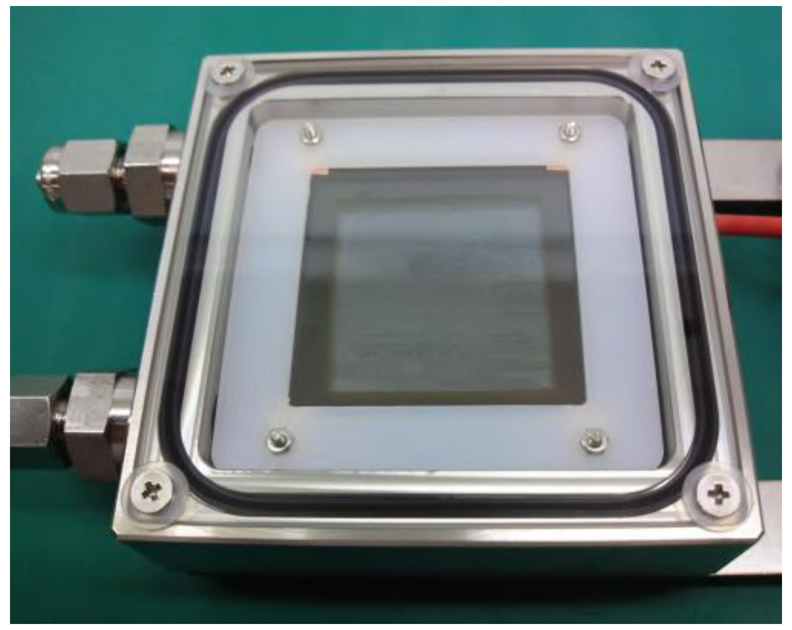


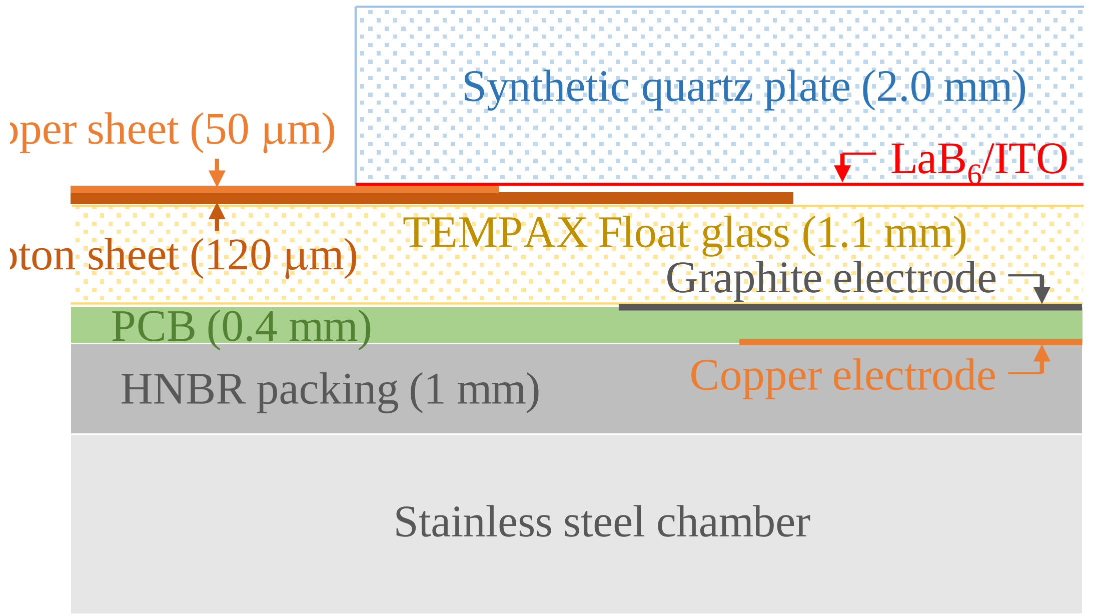
- **Fast timing RPC-based photo-detector, GasPM (KEK, K. Matsuoka)**
  - Single photon resolution of $25\,\mathrm{ps}$ with prototype

DLC on Kapton



Prototype of GasPM



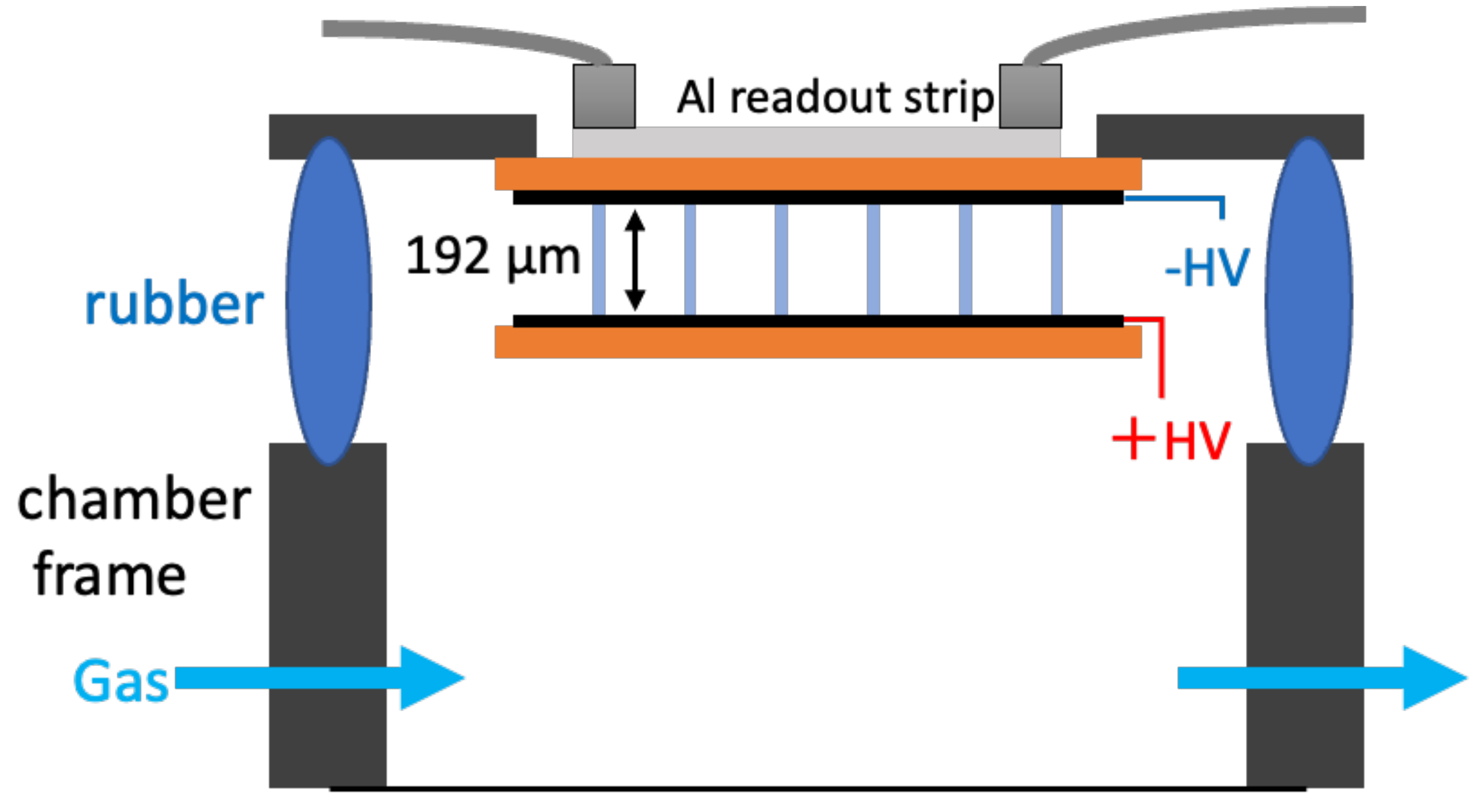


https://doi.org/10.1016/j.nima.2023.168378

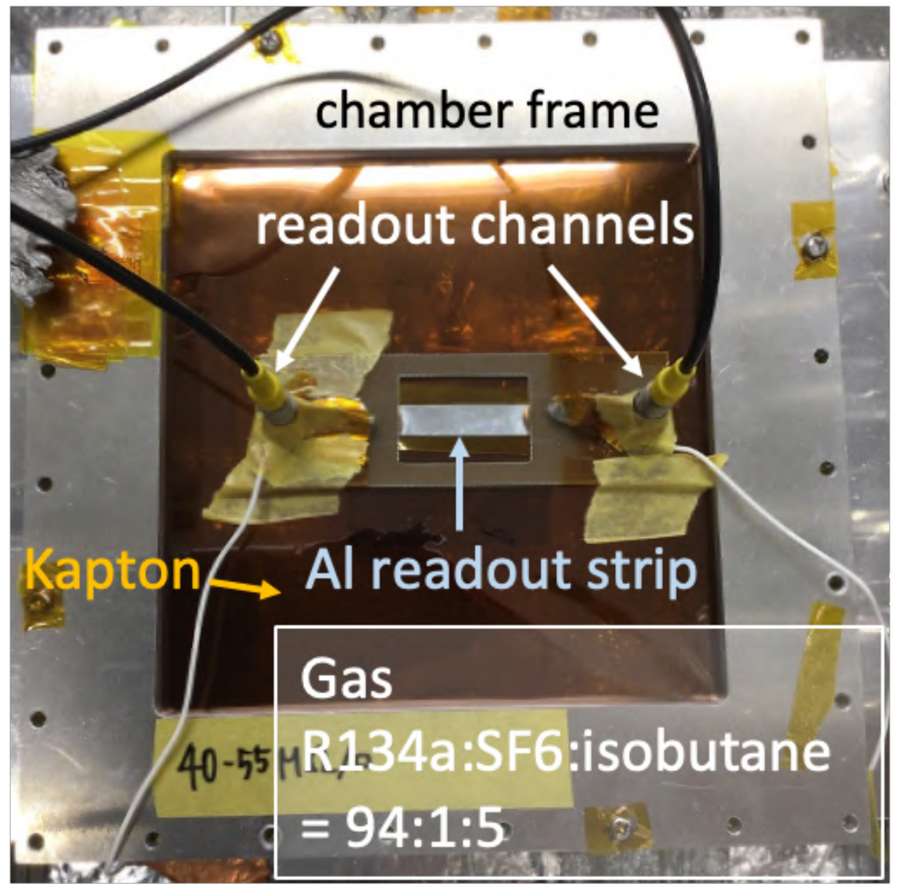
Cherenkov Detector

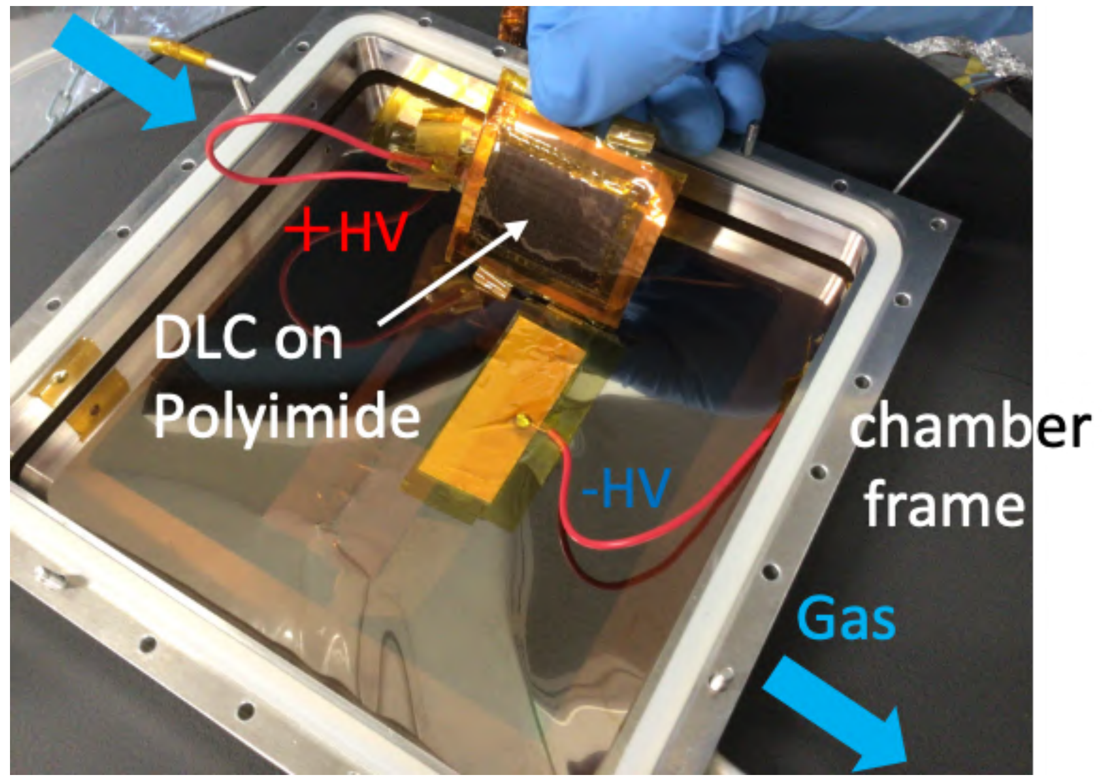
Progress in Japan

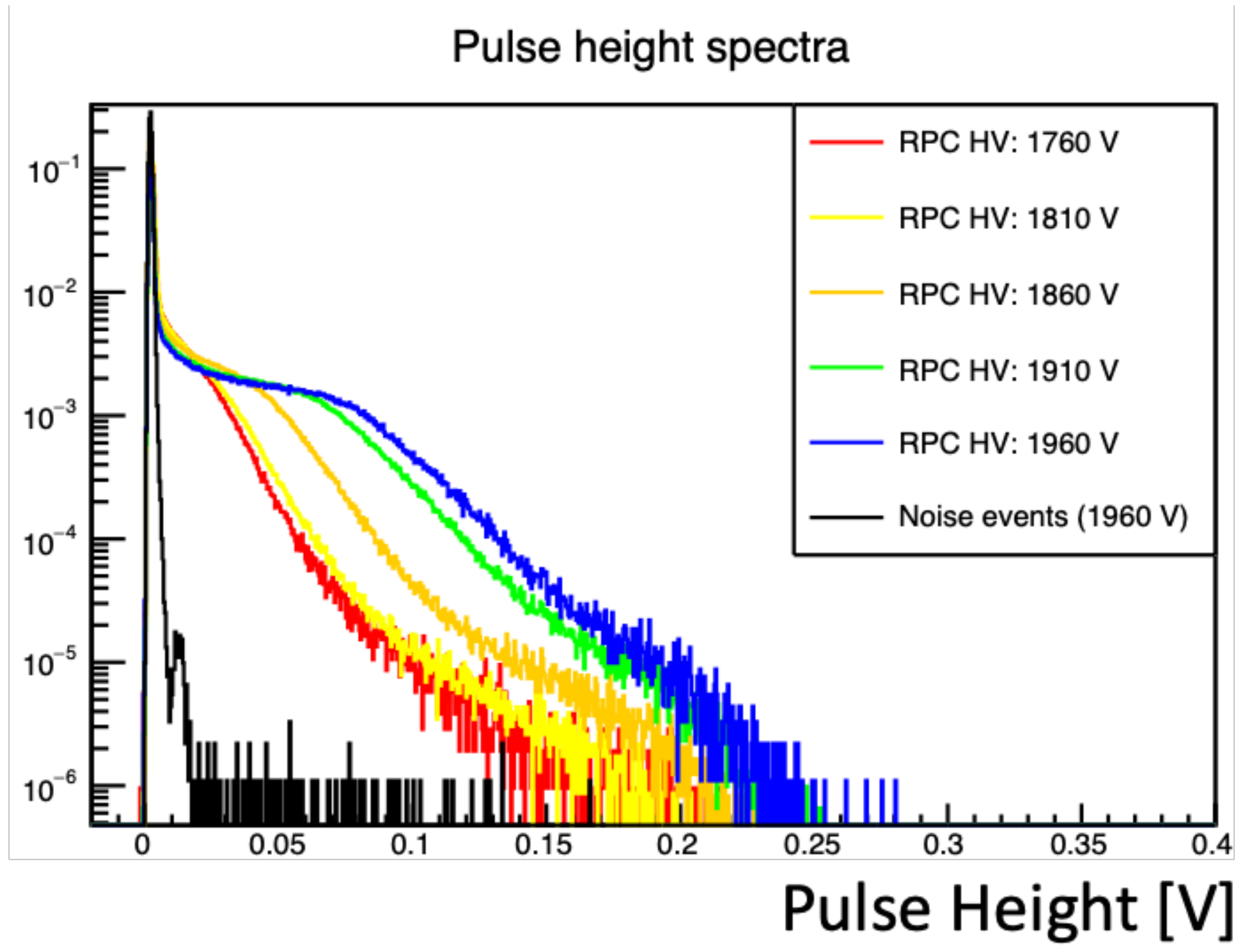
- **Timing performance of DLC-RPC prototype**
  - Gap: $192\,\mu m$
  - Anode: $4\ \mathrm{M\Omega/sq}$, Cathode: $40\text{-}55\ \mathrm{M\Omega/sq}$
  - Gas: R134a/SF6/isobutane (94/1/5)
  - **NOT optimised for timing yet**



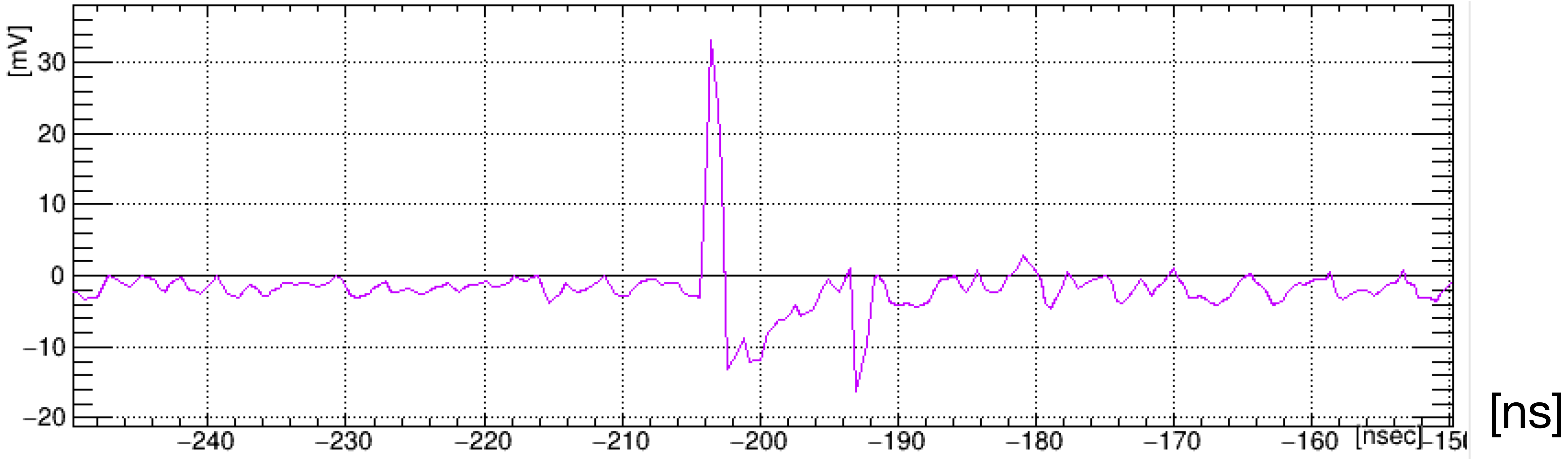
DLC-RPC from top side







Typical signal for Sr-90 β



Cherenkov Detector

Progress in Japan

- **Timing resolution**
  - Best resolution of $80\,\mathrm{ps}$ obtained for large signal
    - Large signal = avalanche over full gap length in GasPM
    - Average # primary electrons ~2 (https://doi.org/10.1016/S0168-9002(03)00337-1)

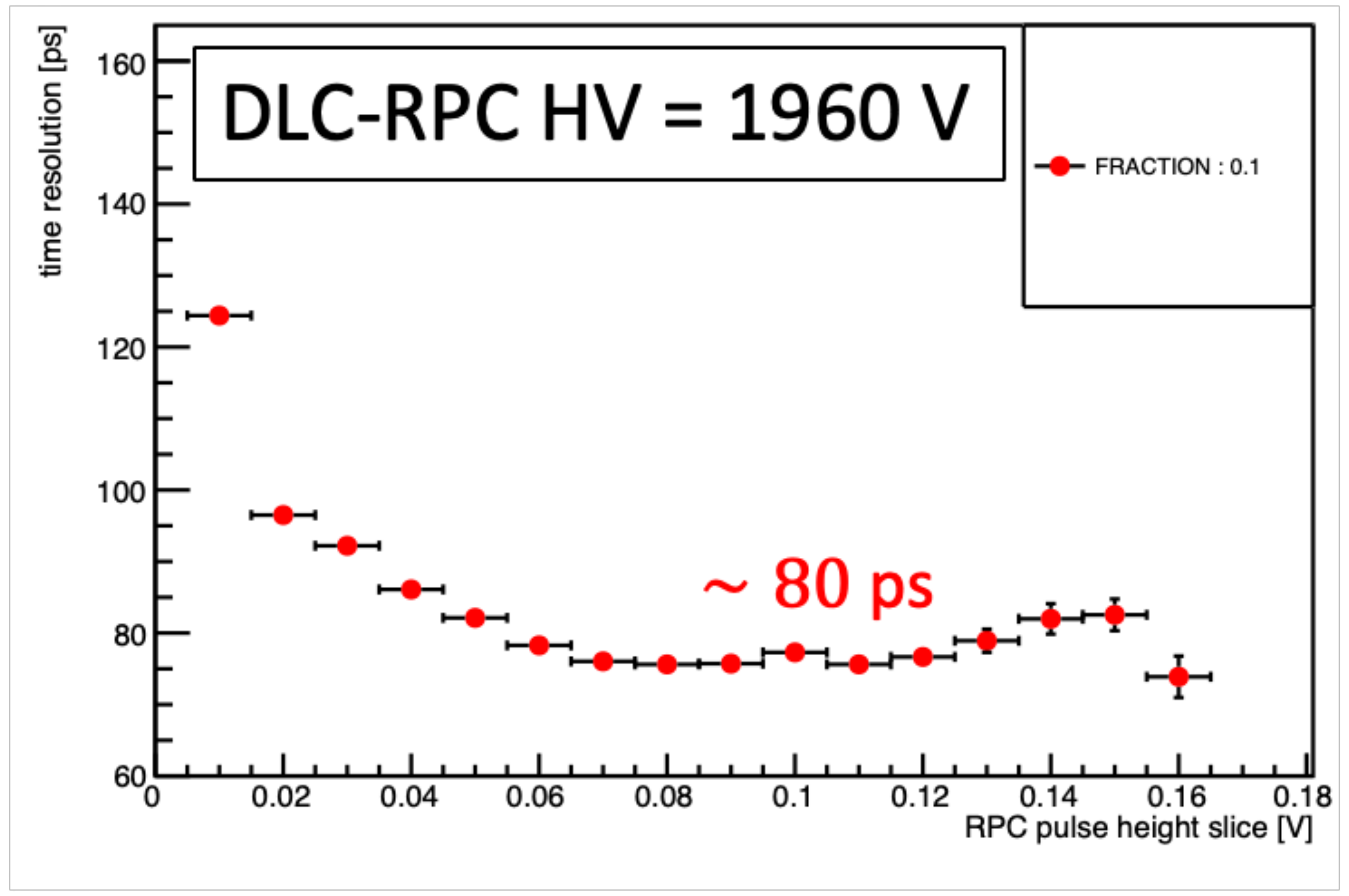
  ⇒**Single photoelectron time resolution:** $80\,\mathrm{ps} \times \sqrt{2} \sim 110\,\mathrm{ps}$

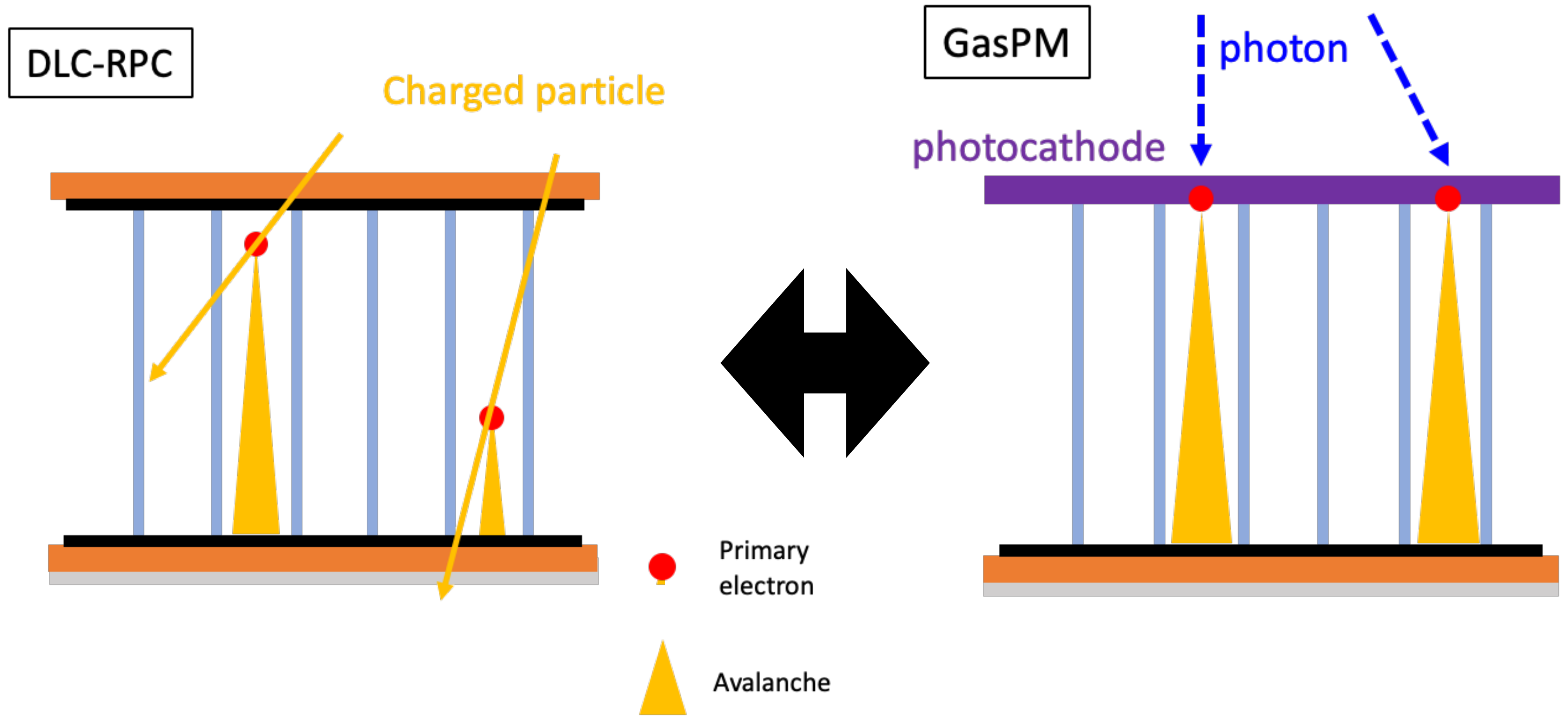
- **Timing resolution expected for Cherenkov detector**
  - Expected # photoelectrons with (3mm-thick MgF2 and CsI photocathode) ~10

    ⇒**Expected timing resolution:** $35\,\mathrm{ps}$

  - **Promising. Still to be improved.**

- **Further optimisation of RPC design for timing**
  - Thinner gap
  - Higher voltage
  - Optimise gas mixture
    - Larger fraction of SF6 for better timing performance
    - Eco-friendly gas



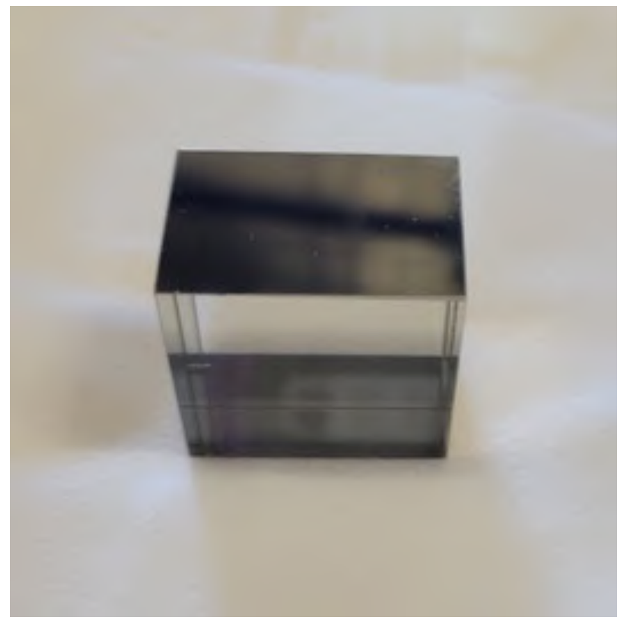


Cherenkov Detector

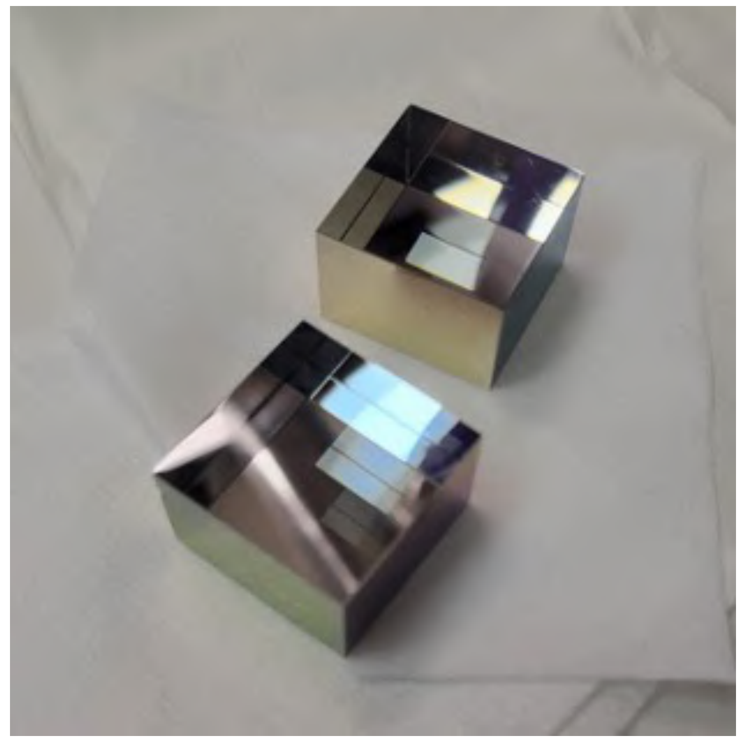
Progress in US

- **Investigation of best Cherenkov radiator material**
  - Setting up numerical computation for photoelectron yield
  - Acquired radiator material candidates (sapphire, MgF_2, VUV glasses)
- **Preparation for photocathode coating**
  - Design of coating (conductive under-layer, electrode for bias voltage)
  - Purchased optical profilometer and VUV sectrophotometer to check coating quality

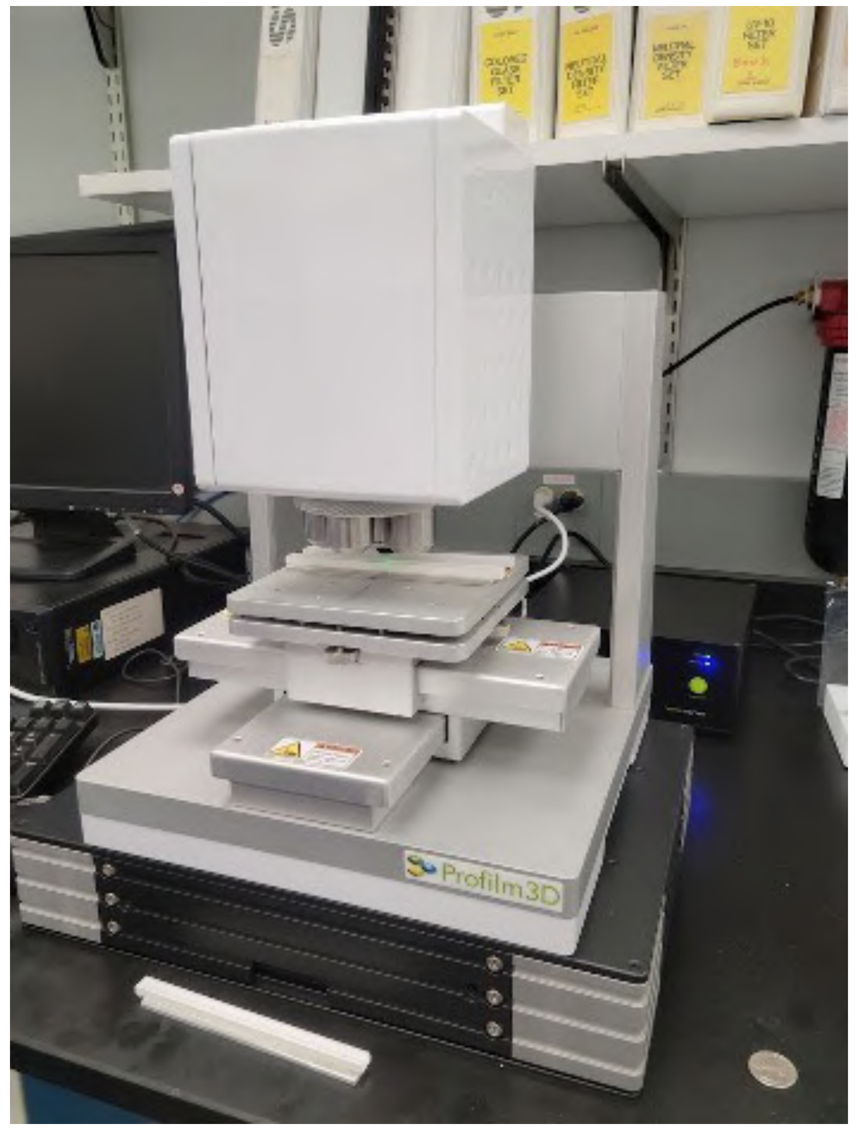
Sapphire (uncoated)



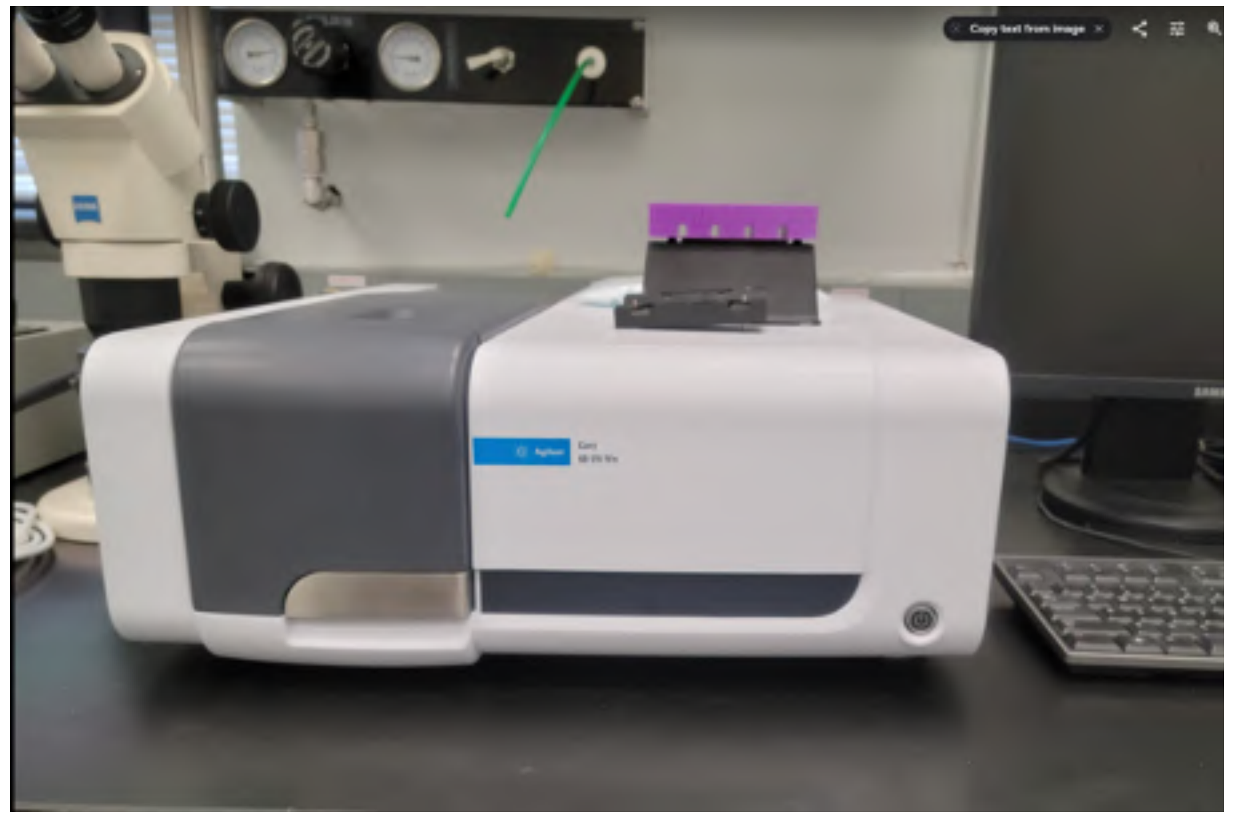
Sapphire (5-sides Al coated)



Optical profilometer

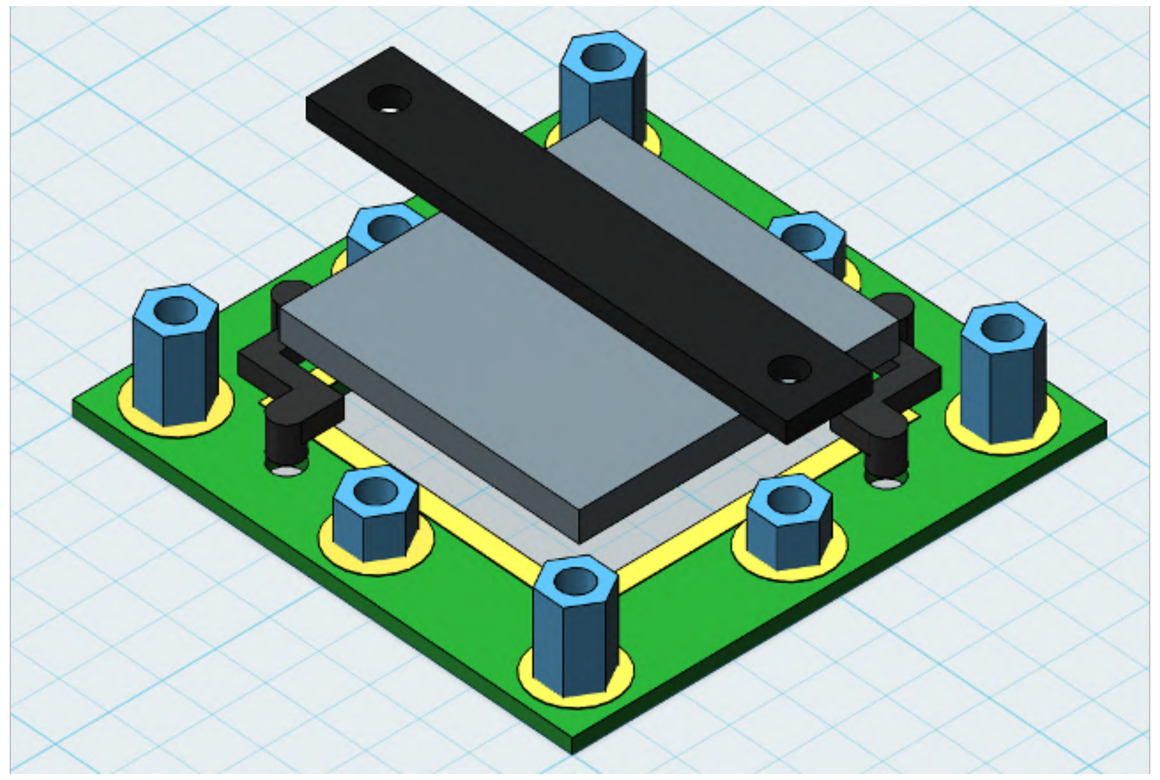


VUV spectrophotometer



Fermilab evaporation system for CsI photocathode deposition

Mechanical structure design for radiator



Cherenkov Detector

Progress in US

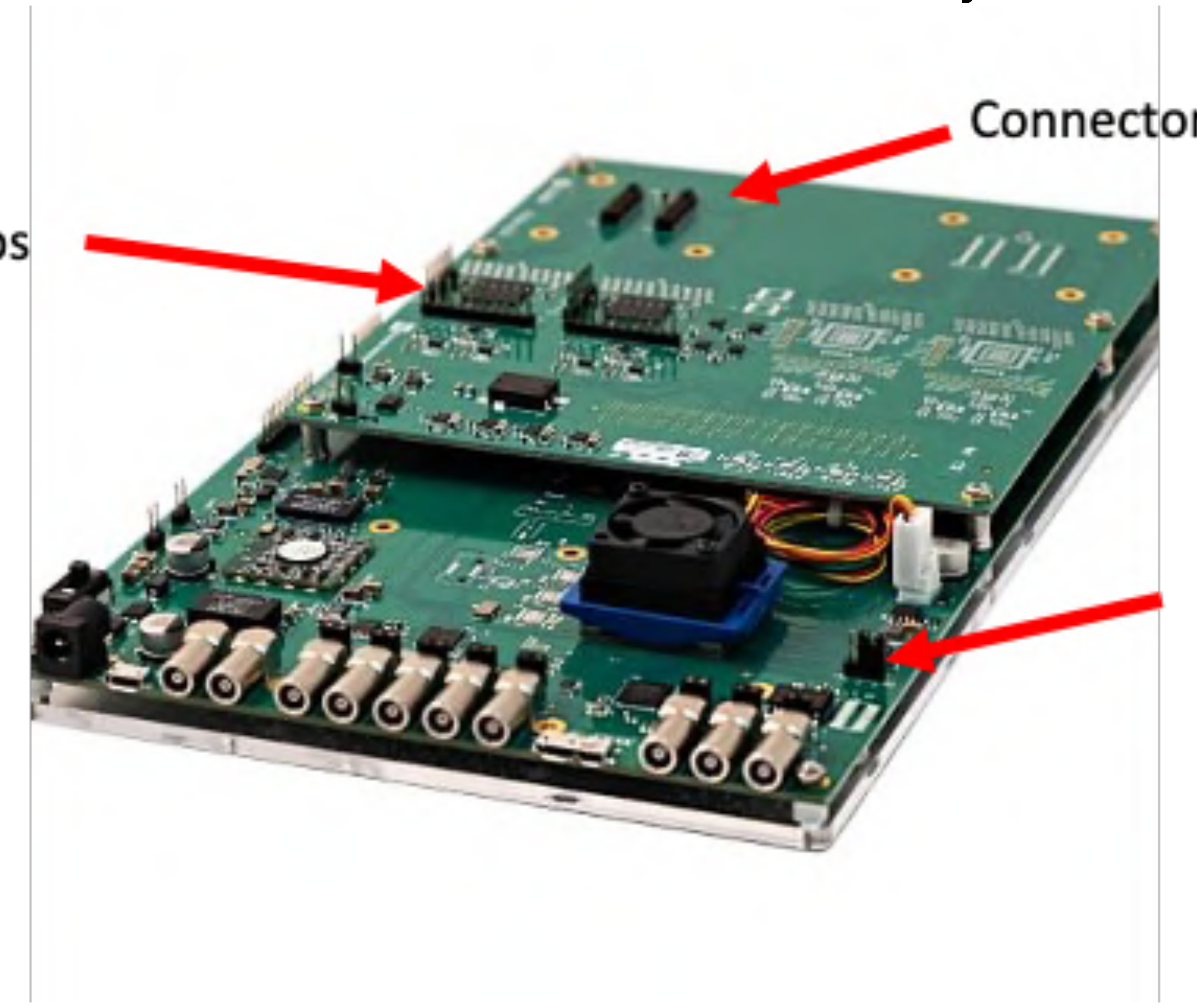
- **Readout electronics**
  - Waveform digitizer (CAEN DT5742B, DRS4 16ch) for initial lab test (time resolution < 50ps)
  - CAEN PETIROC system (64ch) for prototype beam test (time resolution ~15ps)

CAEN DT5742B

CAEN PETIROC system

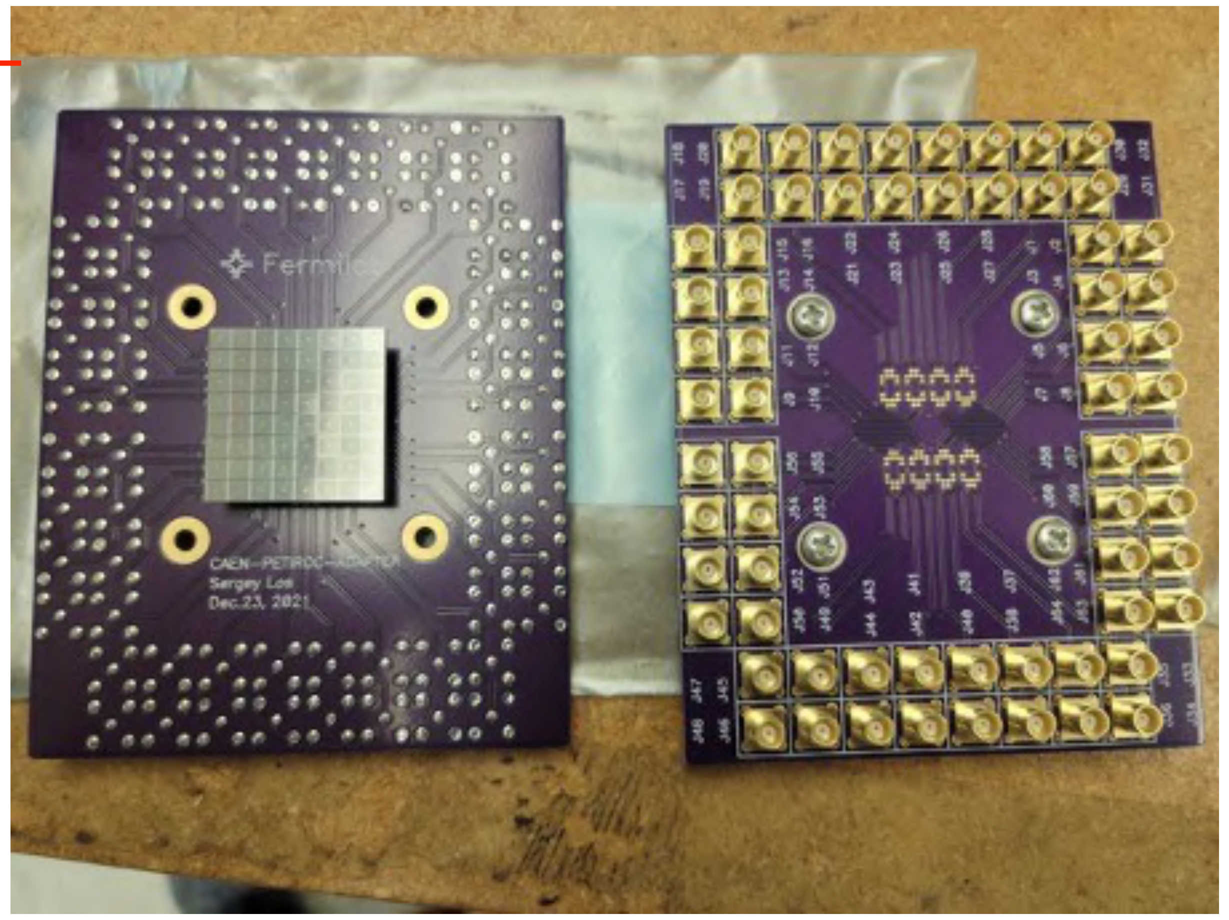
2 Petiroc chips

Connector to connect FNAL interface card



DT5550W motherboard

Fermilab PETIROC interface card

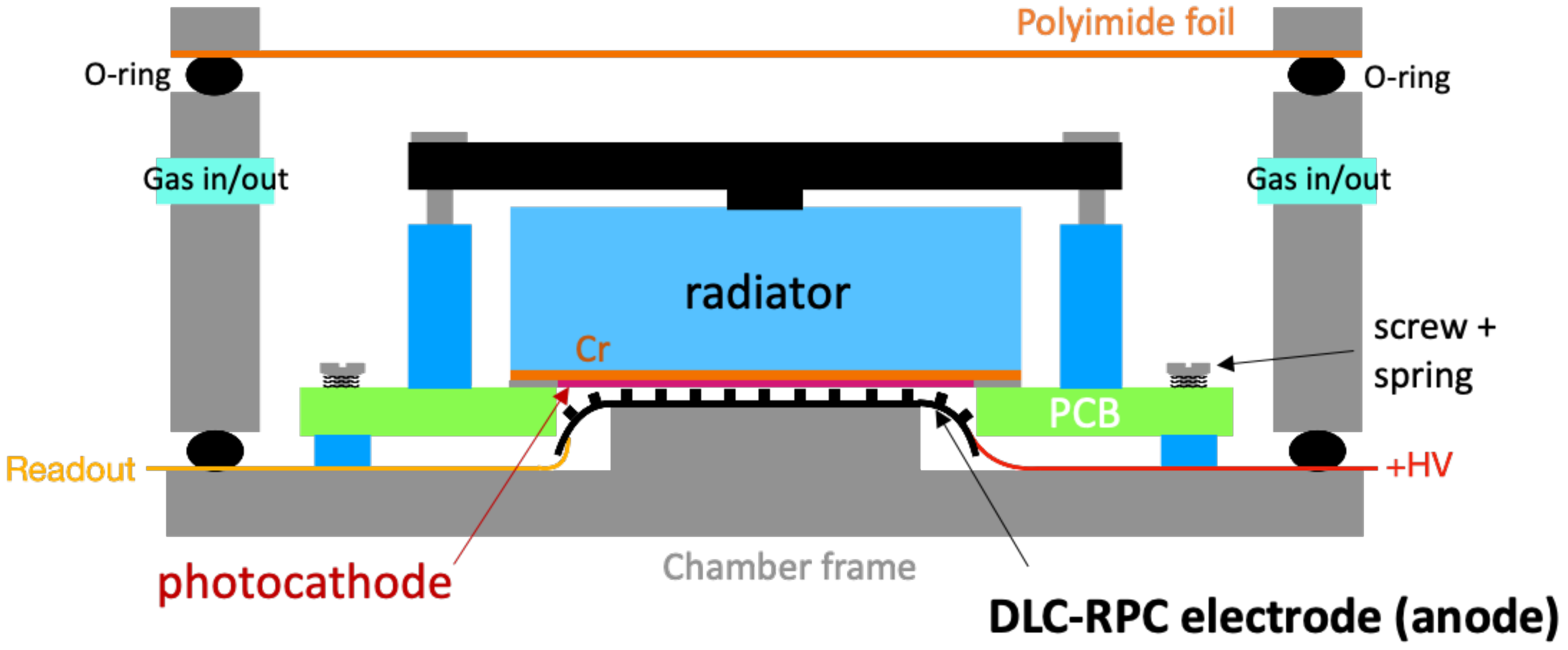


Cherenkov Detector

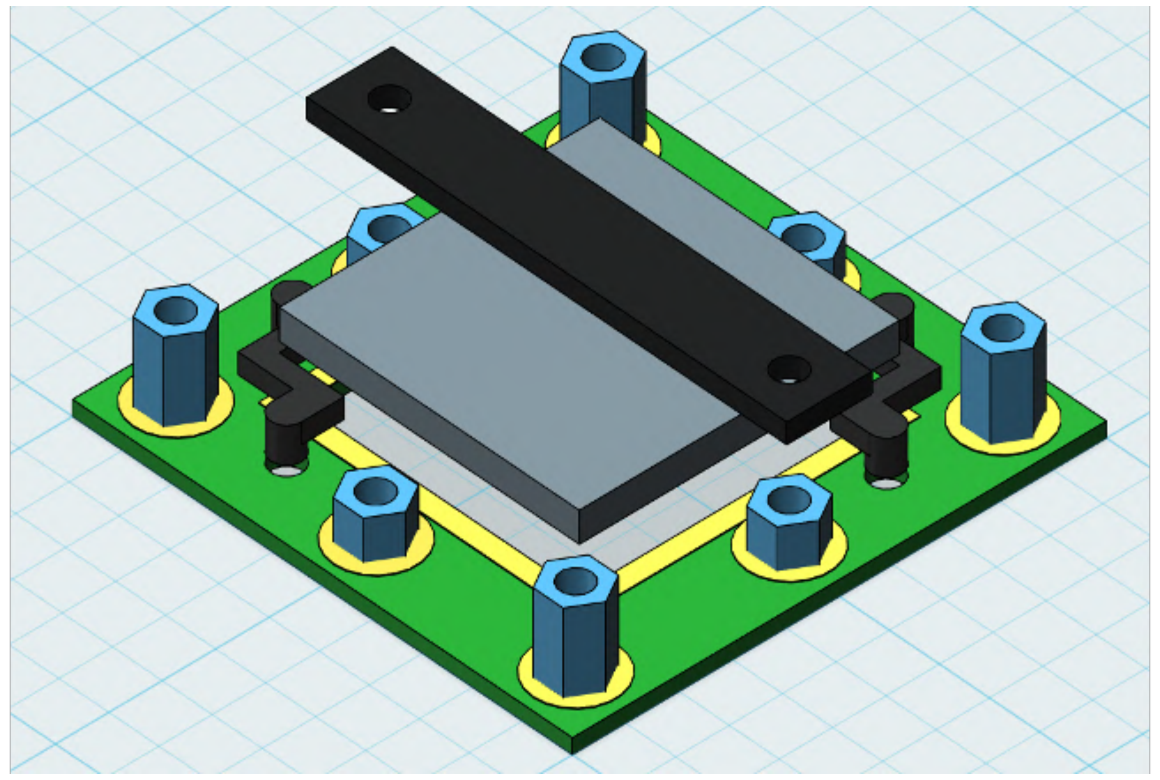
First Prototype

- **Construction of the first prototype for the Cherenkov detector in progress**
  - Combined **radiator/CsI-photocathode (US)** + **DLC-RPC (Japan)**
  - Performance such as QE, stability and timing resolution to be tested

Setup for first prototype (in preparation)

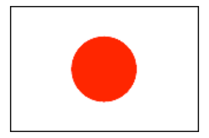


Mechanical structure design for radiator



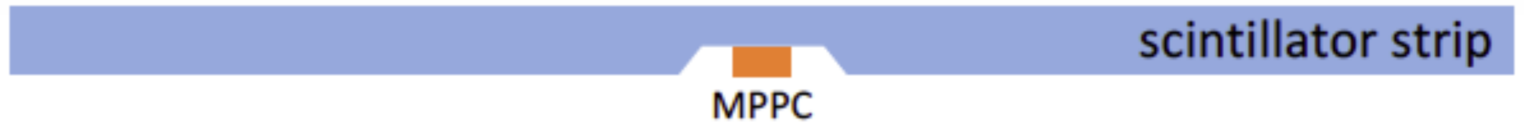
Scintillation Detector

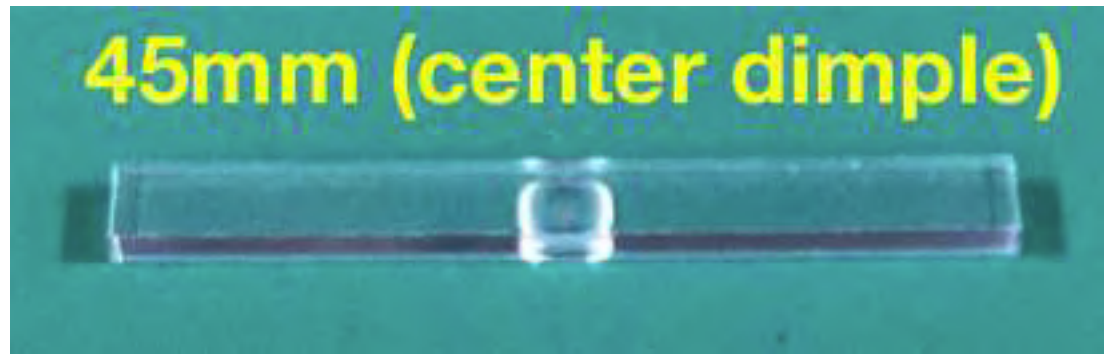
- **SiPM-on-strip technology**

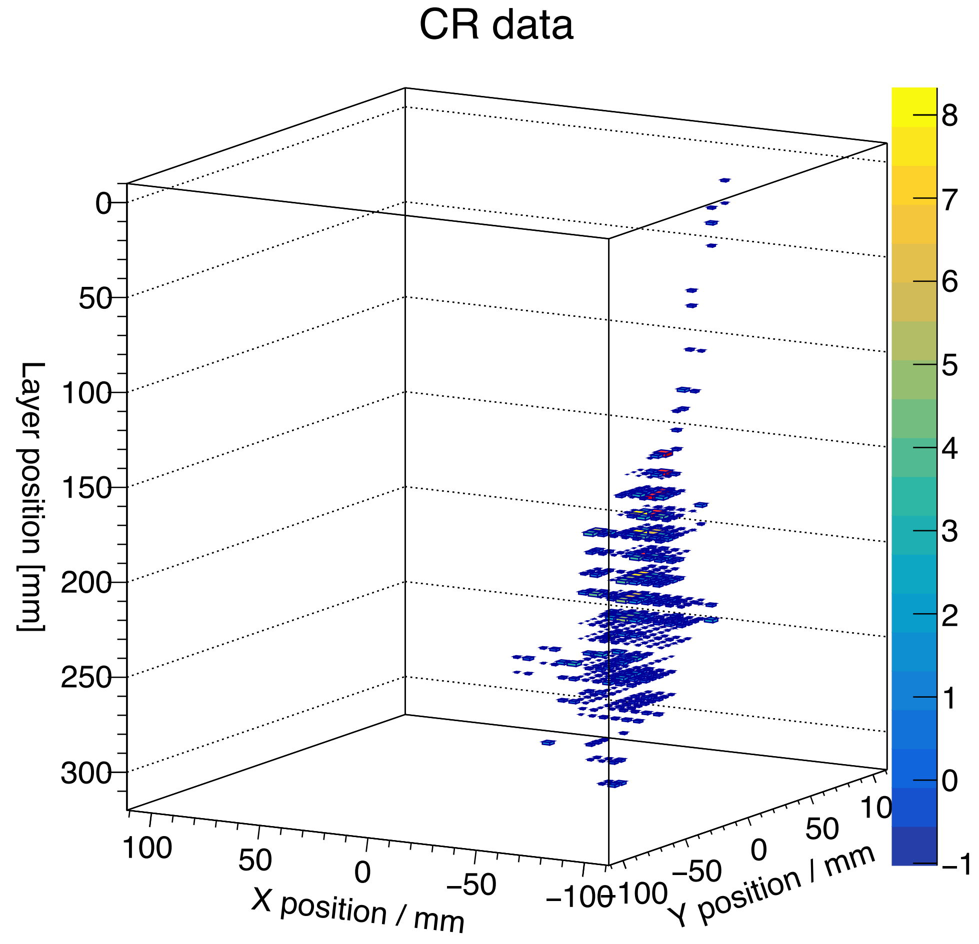


  - Technology developed for CALICE high-granularity scintillator-strip ECAL
  - High granularity with reduced number of readout channels (×1/10)
- **Challenges**
  - Wider and longer strip
  - Light yield and uniform response
  - Possibility of double SiPM readout
- **Synergy with expertise of US and Japan**

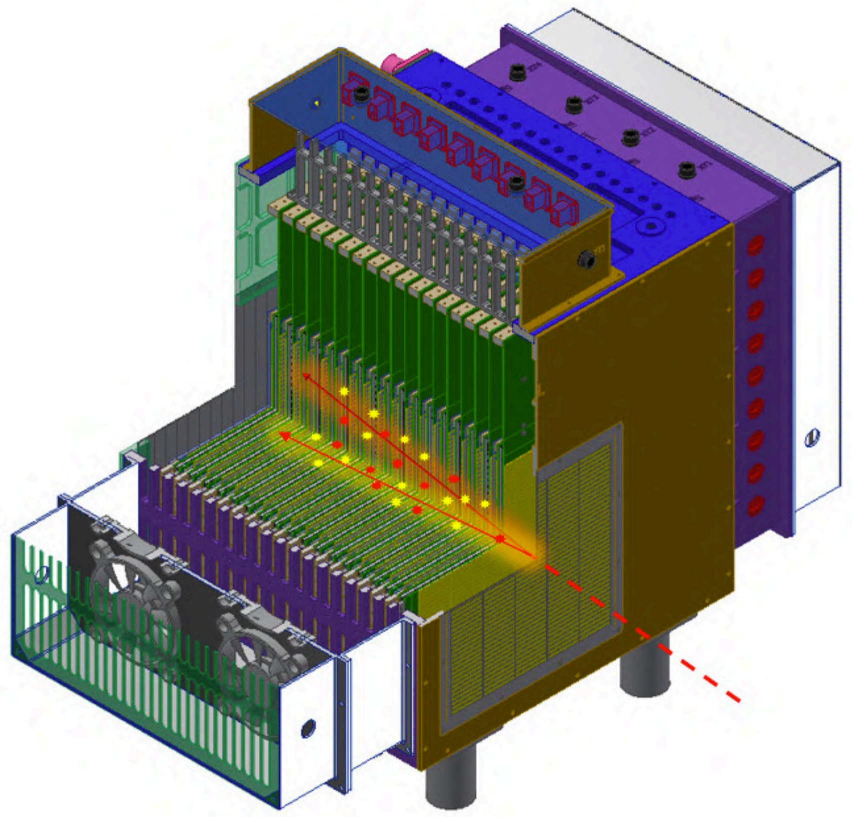
Strip-SiPM optical coupling (Tokyo, Shinshu)







Scintillator strip ECAL prototype (Tokyo, Shinshu)



Scintillation Detector

Original plan

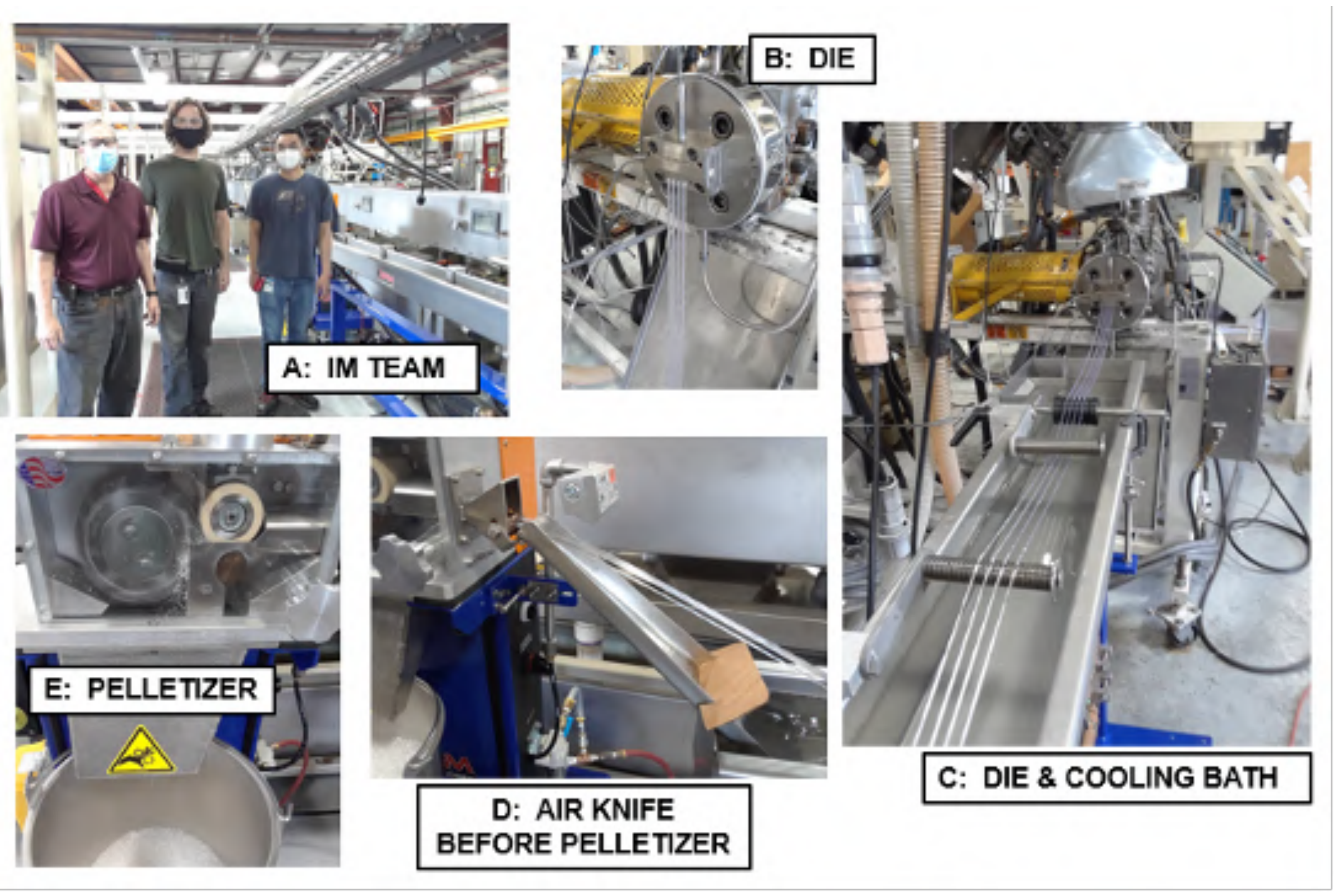
Scintillator pellet with high light yield production in US

⇒ Injection moulding for strip production in Japan

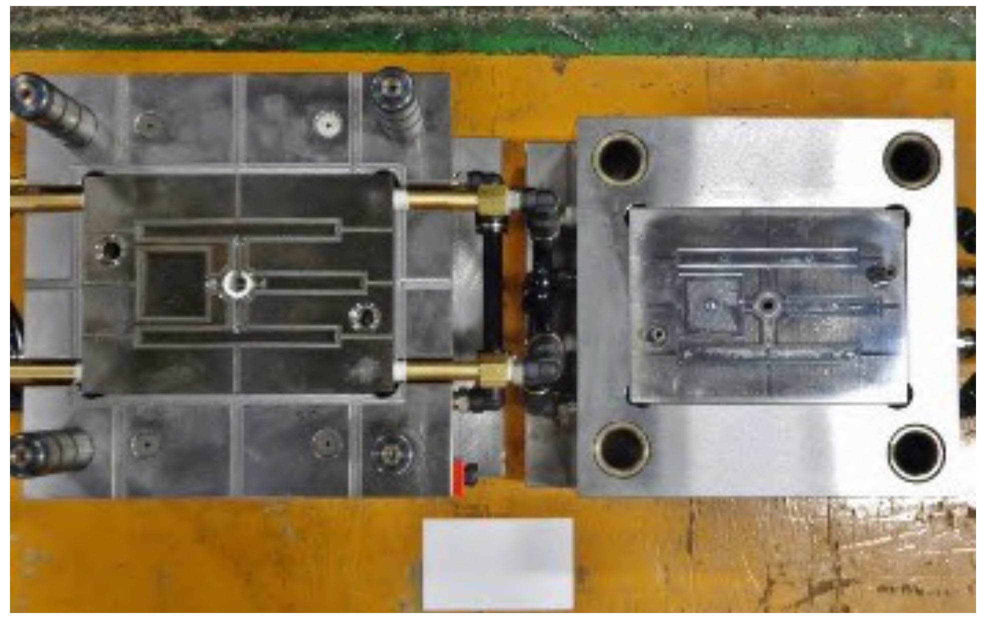
Modified plan

Scintillator strip production with machining from commercial PVT scintillator plate

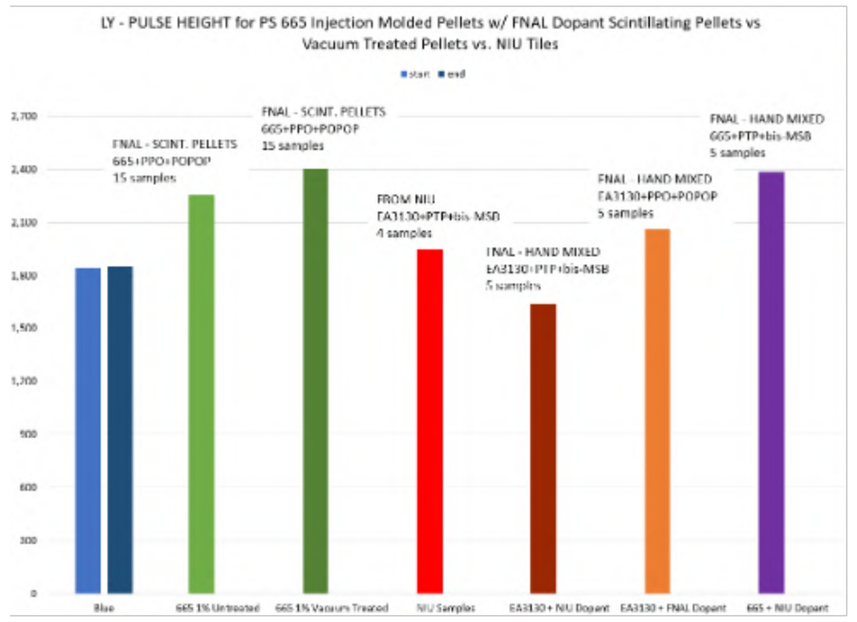
Equipments for scintillator pellets production (Fermilab)



Metal moulding for scintillator strip (Tokyo, Shinshu)

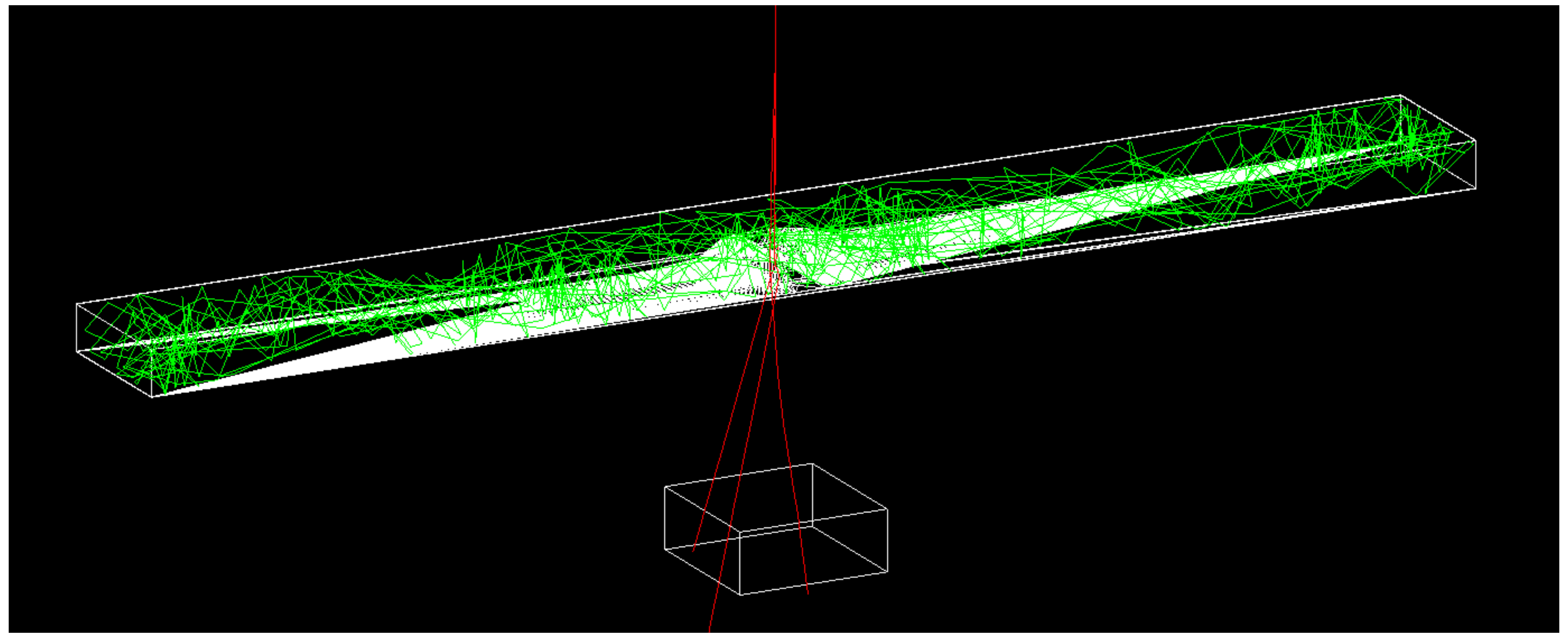


Light yields for scintillator pellets (Fermilab)

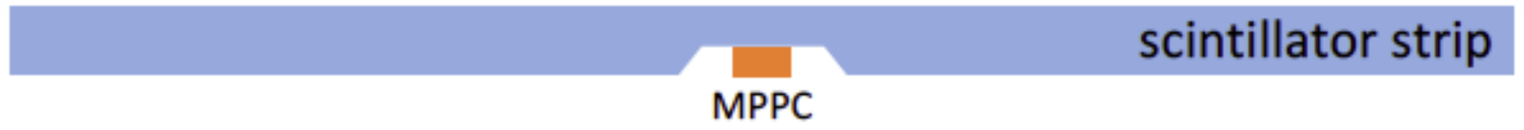


Optimisation of strip-SiPM design op in progress

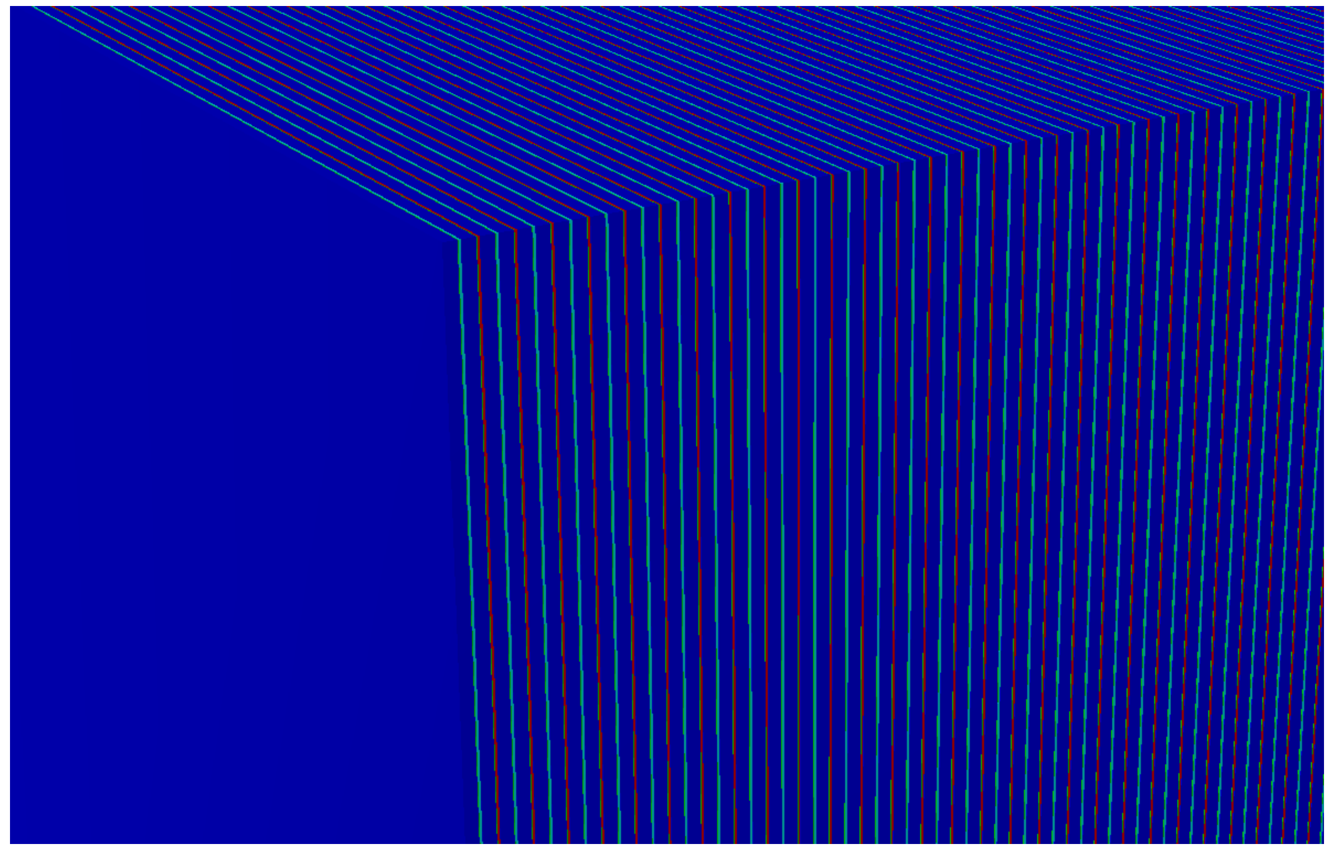
Optical photon simulation for scintillator strip



Strip-SiPM optical coupling

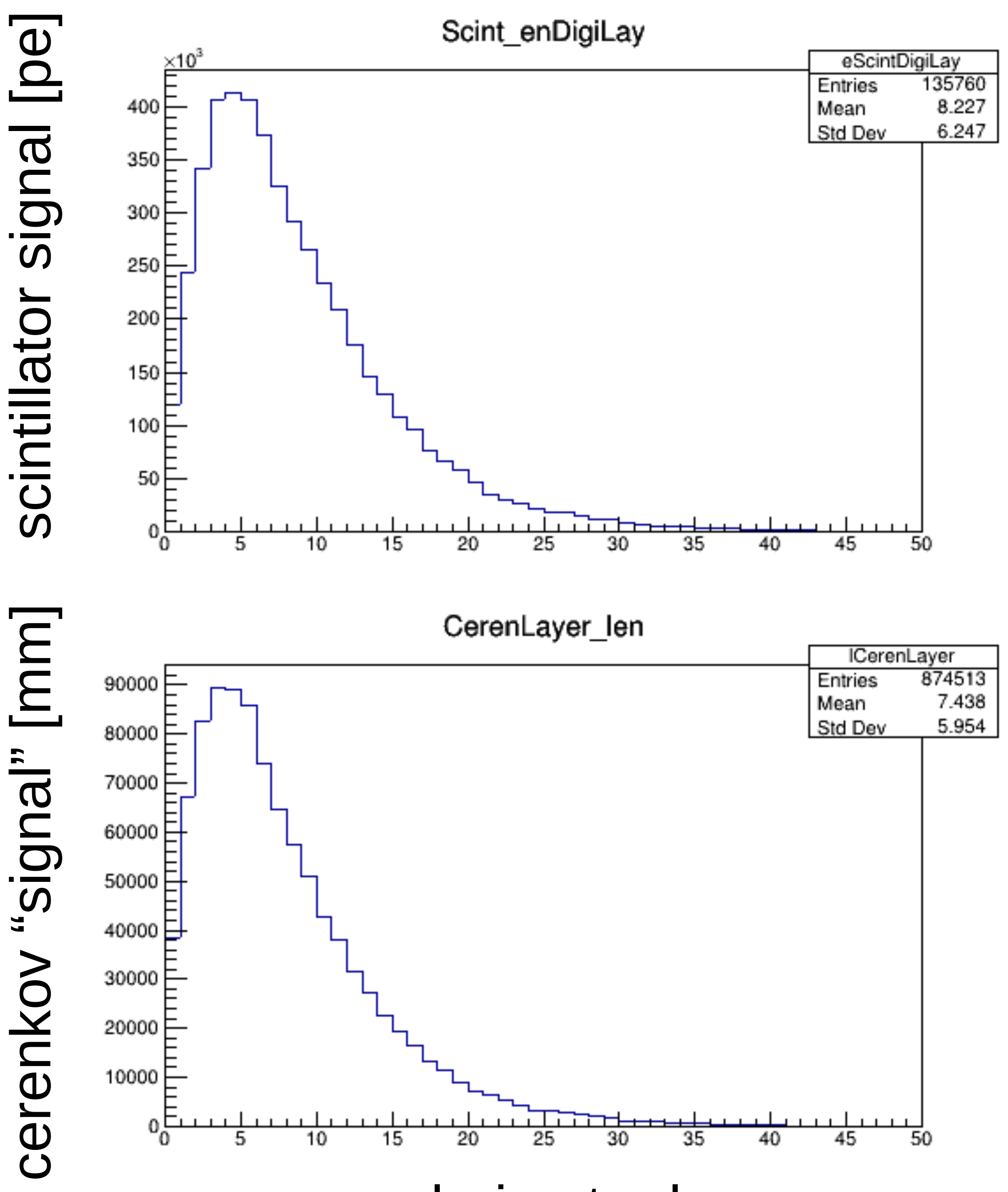


Simulation Study

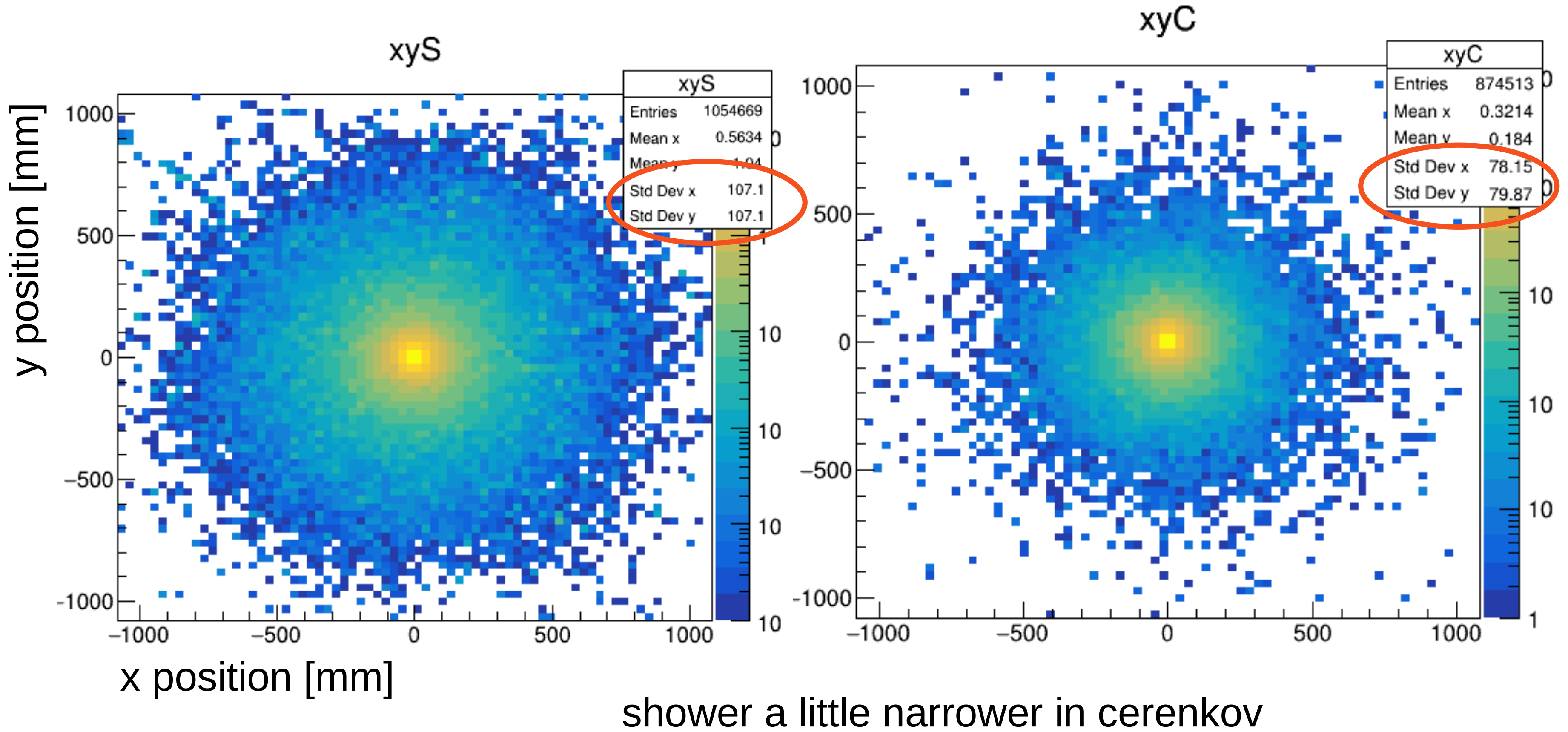


- Started simulation study on expected performance with this calorimeter technology
- Setup
  - Based on CALICE-AHCAL test beam setup
  - Large stack instrumented with 30x30mm^2, 3mm-thick tiles, total size 2.16 x 2.16 x 2.133 m^3
  - Alternate layers of plastic scintillator / sapphire
- Digitisation
  - Scintillator: 10p.e./MIP, 10k-pixel SiPM
  - Cherenkov: Count superluminal path length within tile ($v > c/n$)

Longitudinal profile: 10GeV π^-



Transverse profile: 10GeV π^-



shower a little narrower in cerenkov
probably expected, since EM shower more central

Summary

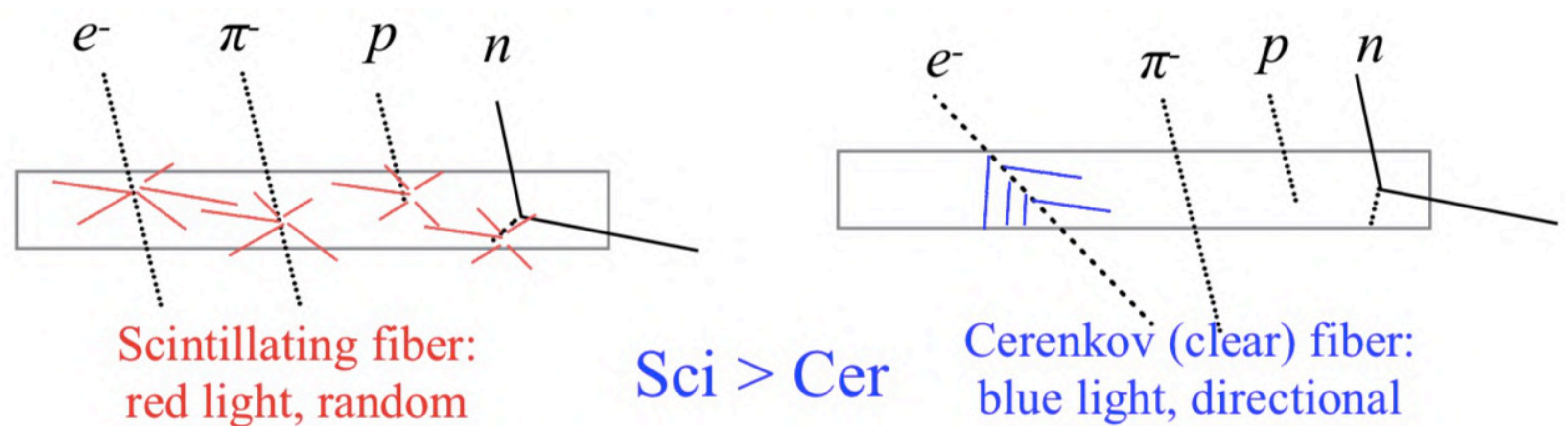
- **New R&D for a new calorimetric technique to address crucial requirements for calorimeters at future collider experiments**
  - Fusion of two key calorimeter technologies (high-granularity and dual-readout) together with excellent timing performance
- **Cherenkov detector**
  - Cherenkov radiator + UV-GasPM with DLC-RPC
  - Promising timing performance already obtained even with non-optimal RPC. To be further improved
  - Construction of the first prototype by combining RPC (Japan) and radiator (US) in progress
- **Scintillation detector**
  - SiPM-on-strip technology
  - Down-sizing R&D plan. No R&D for scintillator material with improved performance and production with injection moulding
  - Optimisation for strip-SiPM deign in progress
- **Plan**
  - Construction and performance test of first prototype of Cherenkov detector to be done soon
  - Construction of full prototype toward beam test at Fermilab in 2024

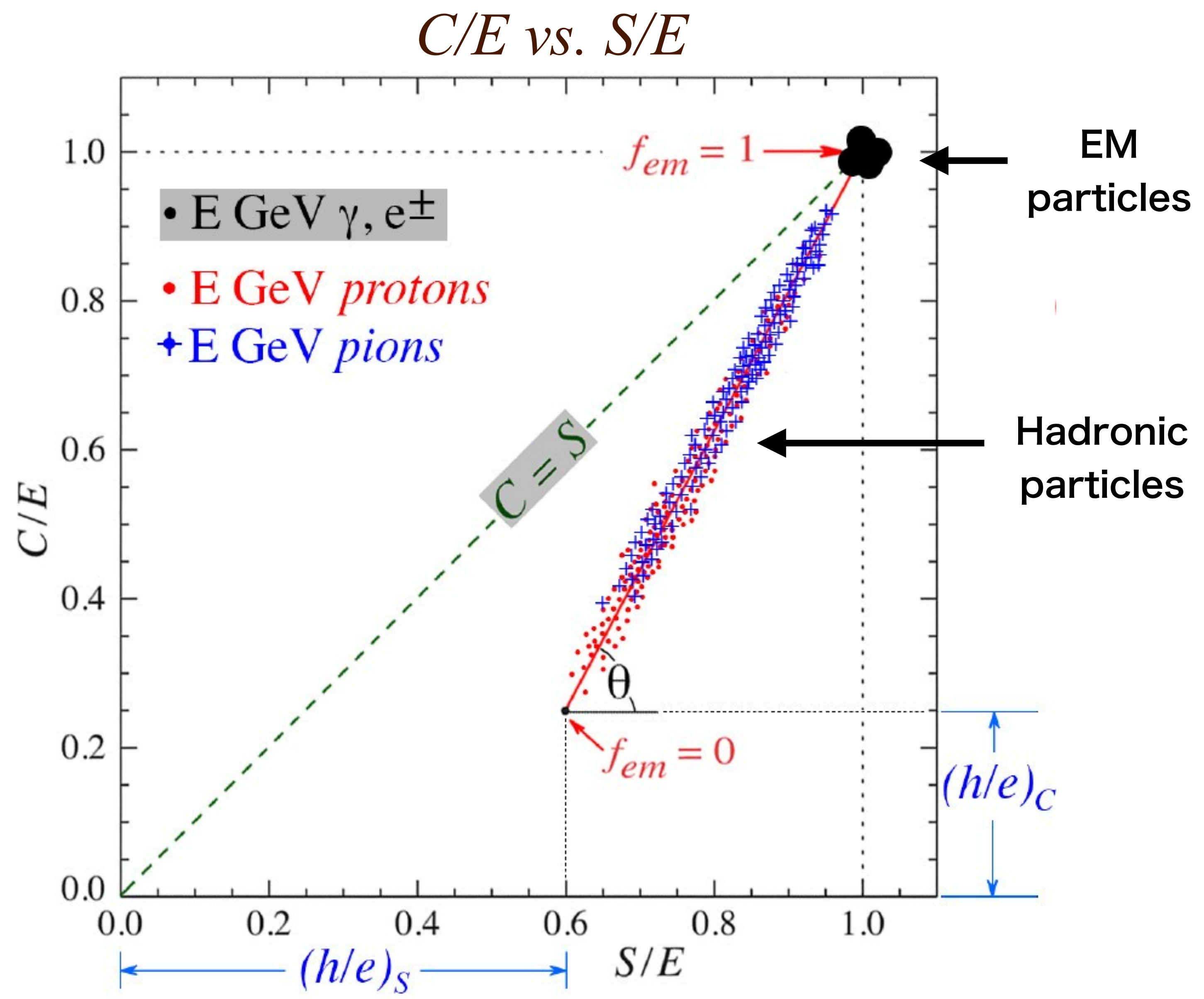
Backup

Dual-Readout Calorimetry

$$E_{HCAL} = \frac{\eta_S \cdot E_S \cdot (\eta_C - 1) - \eta_C \cdot E_C \cdot (\eta_S - 1)}{\eta_C - \eta_S} \quad \left(\eta_S = \left(\frac{e}{h}\right)_S \; ; \; \eta_C = \left(\frac{e}{h}\right)_C\right)$$

- **Difficulty in hadronic shower measurement**
  - Event-by-event fluctuation of EM fraction
  - For most of calorimeters, $e/h \neq 1$ (non-compensating)
- **Dual readout**
  - Compensation by simultaneous readout in both Cherenkov and scintillation channels with different e/h
  - Work better at higher energy
  - PID from Cherenkov vs. scintillation as a bonus
- **Long R&D history by CERN RD52 based on multiple-fibre readout**
  - Limited longitudinal segmentation
  - Limited Cherenkov light yield





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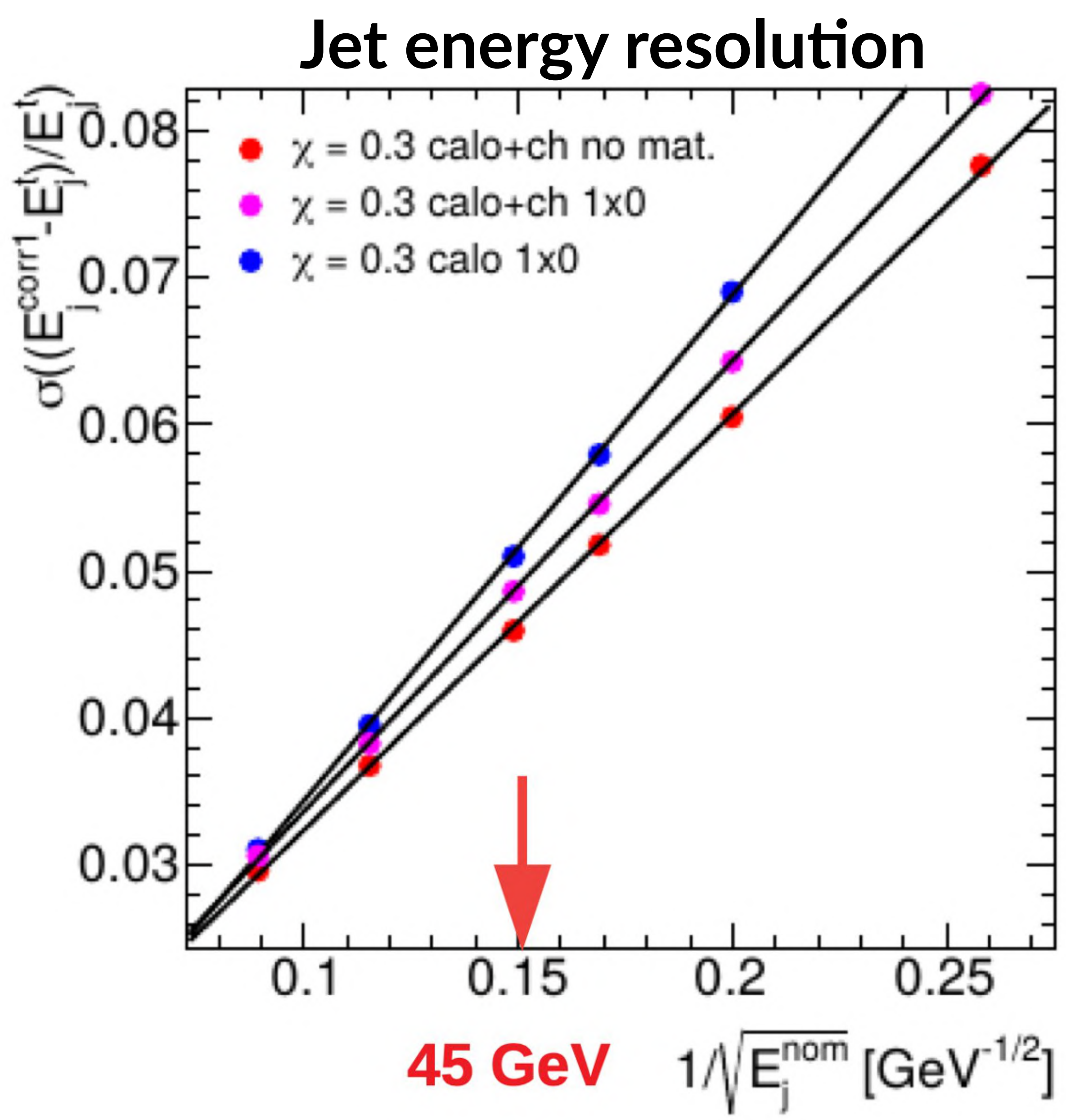
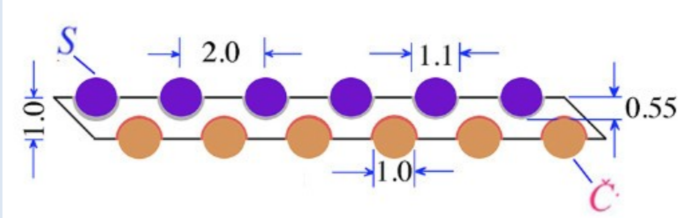


2012
RD52

Pb, 9 modules
Each module: $9.2 \times 9.2 \times 250$ cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~5.3%
Depth: ~10 λ_{int}

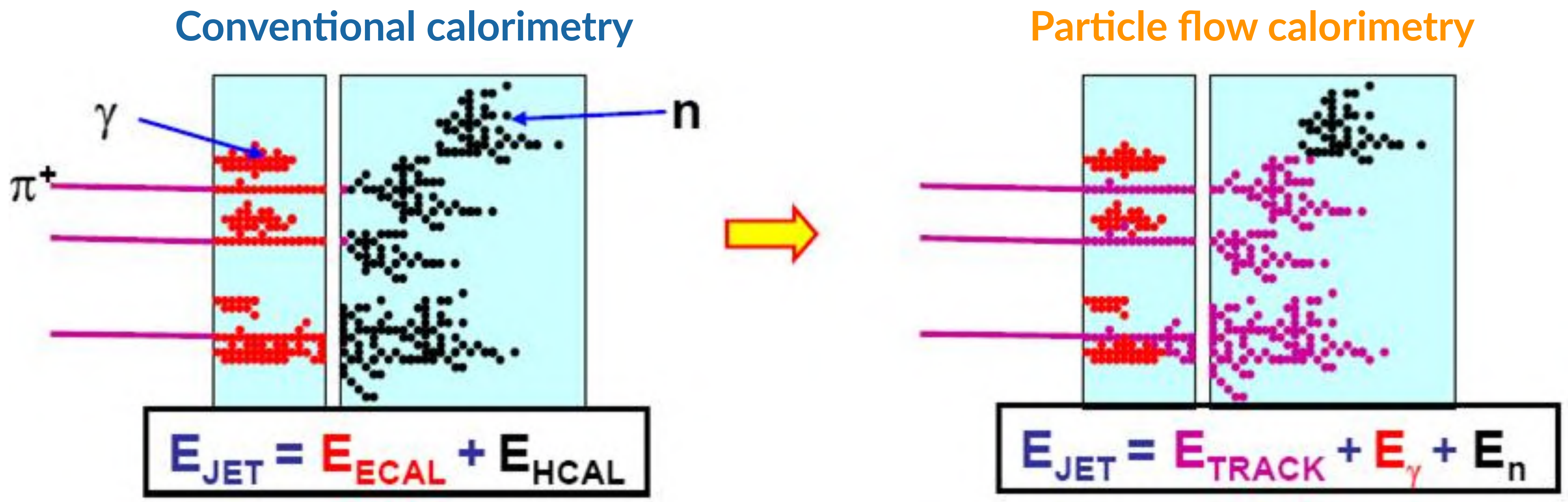


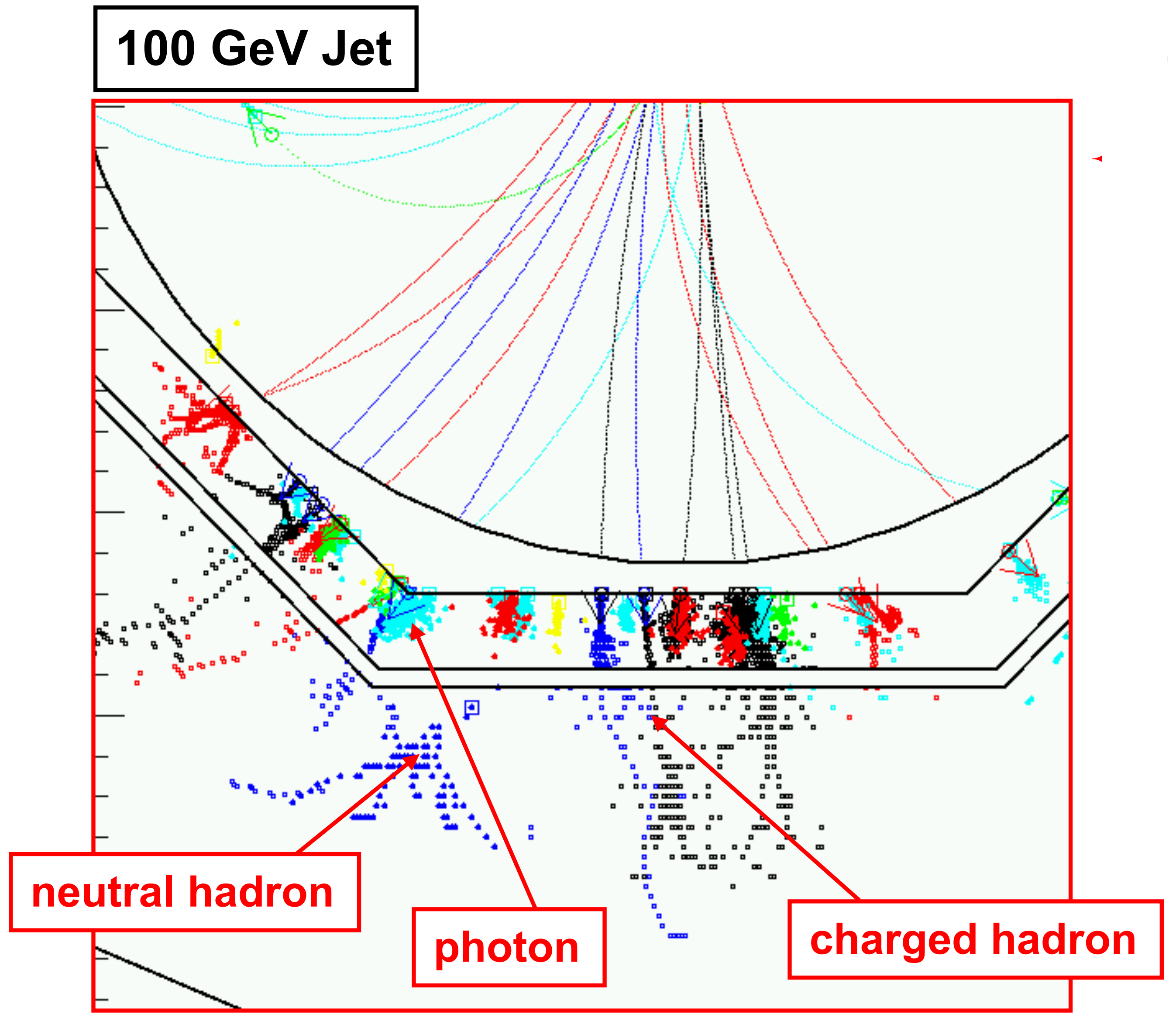
R. Ferrari, EIC Calorimeter Workshop 2021

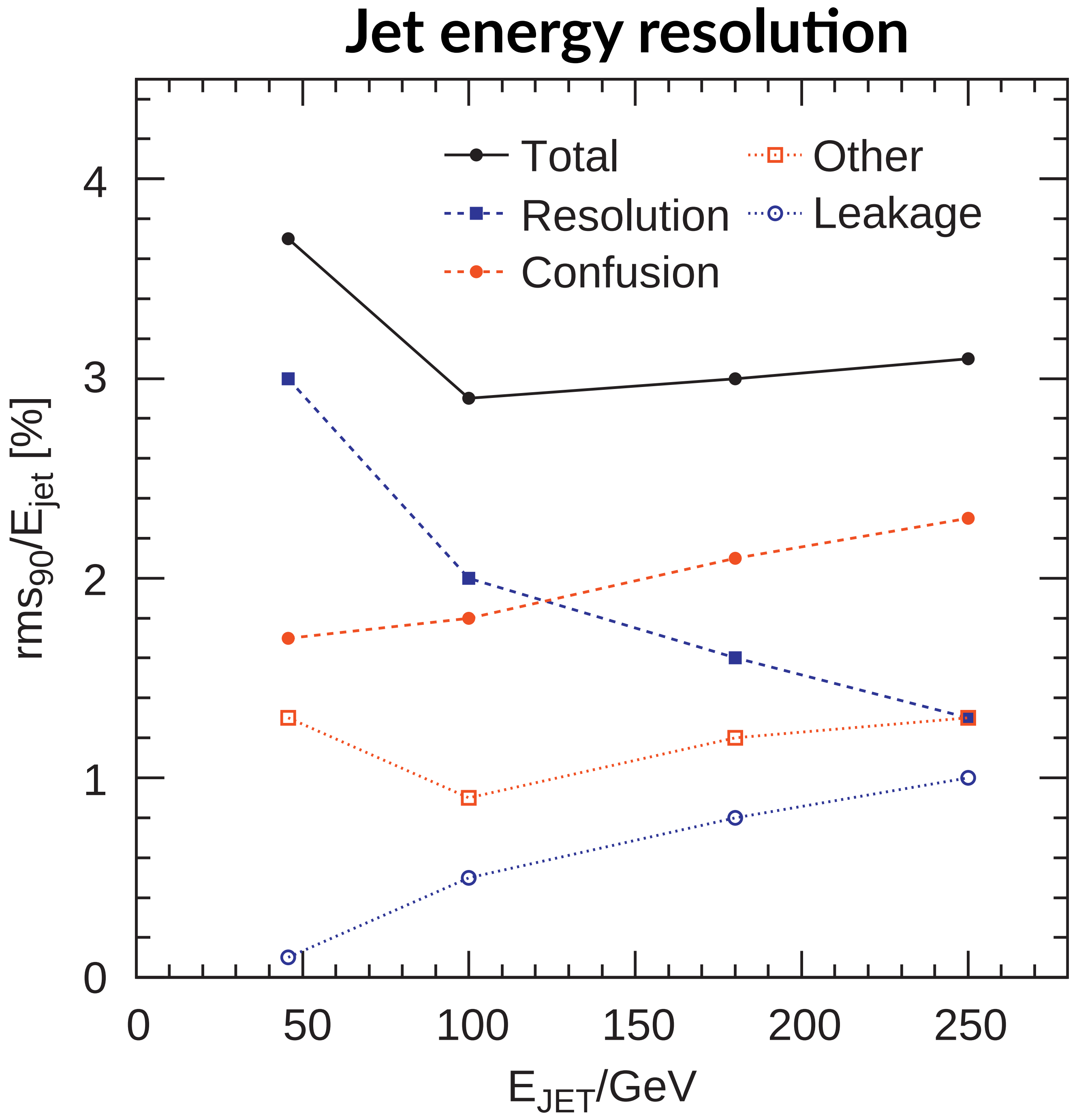
High-Granularity Calorimetry

- **Particle flow approach (PFA) for the best jet energy resolution**
  - Jet measurements with best suited detectors depending on particle type

    → Require high-granularity calorimeter to reconstruct all visible particles in a jet
- **Excellent jet energy resolution especially at lower energy**
  - Software-based compensation using high-granularity
- **R&D in the framework of CALICE collaboration**
- **Many applications already**
  - Calorimeters at Higgs factories, CMS HGCAL for HL-LHC, ALICE FOCAL, DUNE ND, …



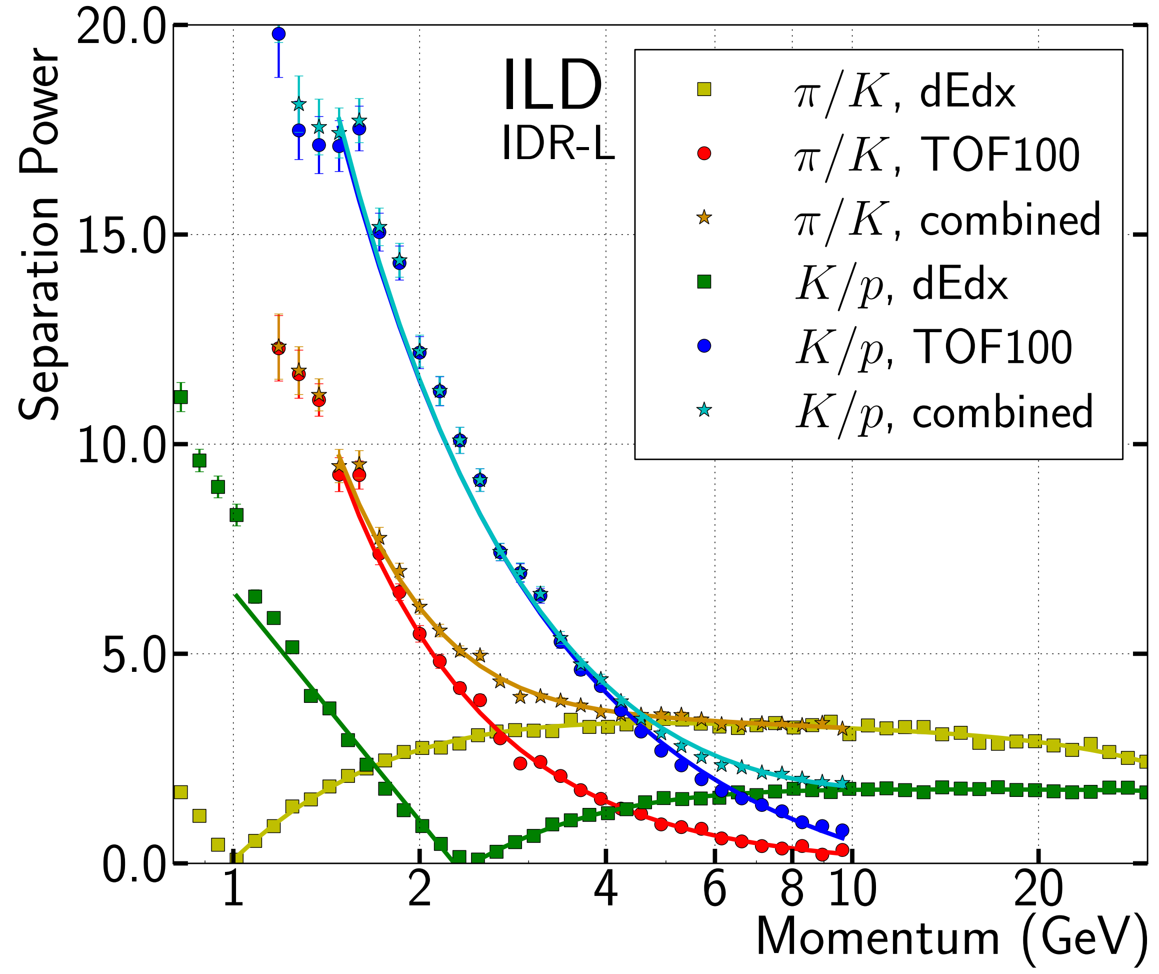




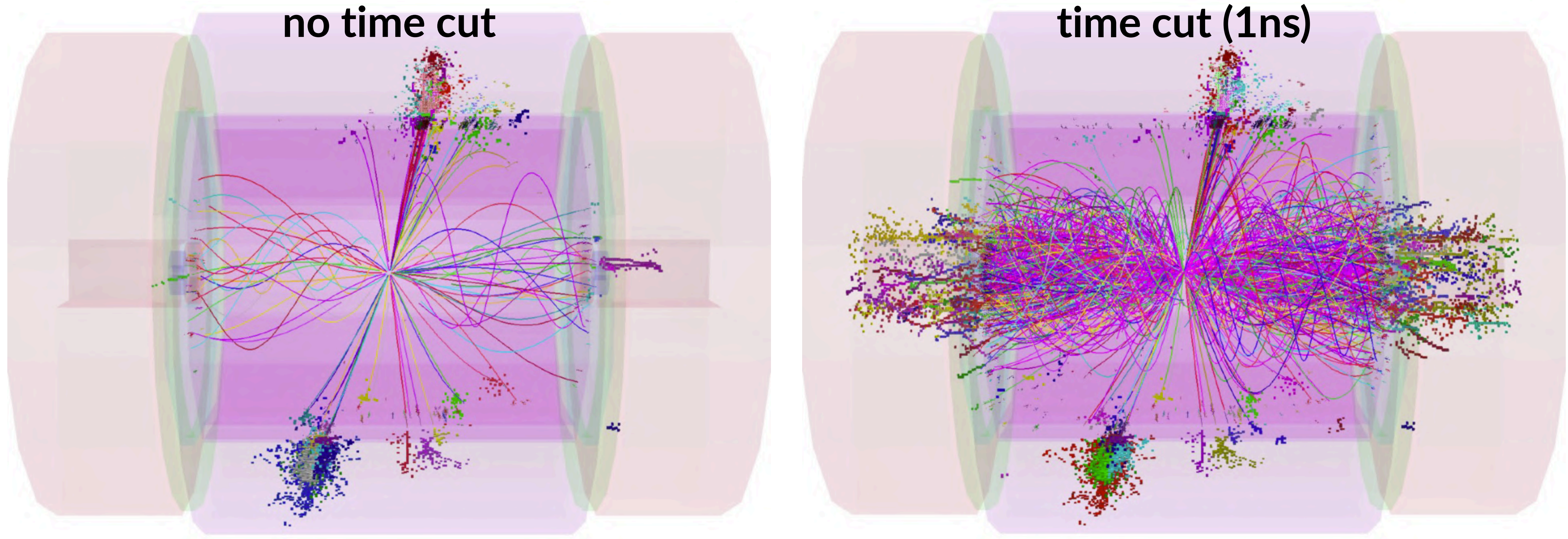
Timing

- **Increasing attention as additional value to enhance collider detector performance**
  - Tracking
  - Particle ID to cover inaccessible momentum region by dE/dx
  - Rejection of pileup/off-timing BG
  - Rejection of slow neutron events
  - Improve PFA performance
  - …

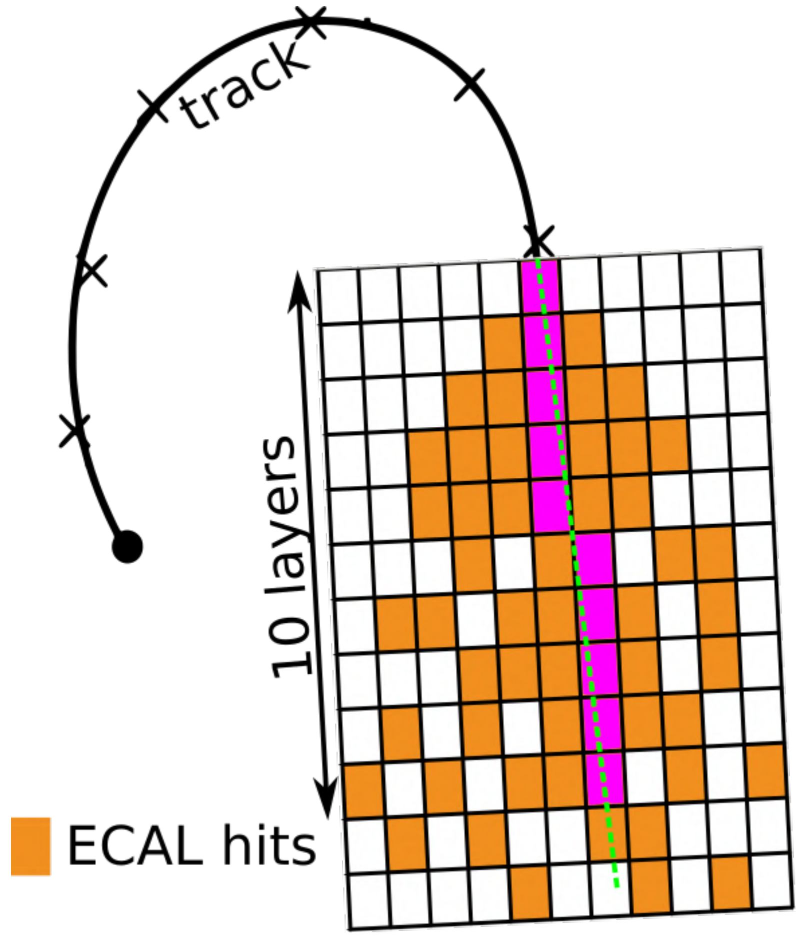
Effect of TOF (res. 100ps) on particle ID performance



Pileup rejection with timing cut @CLIC (0.5ns bunch separation)



ECAL hit selection for TOF measurement



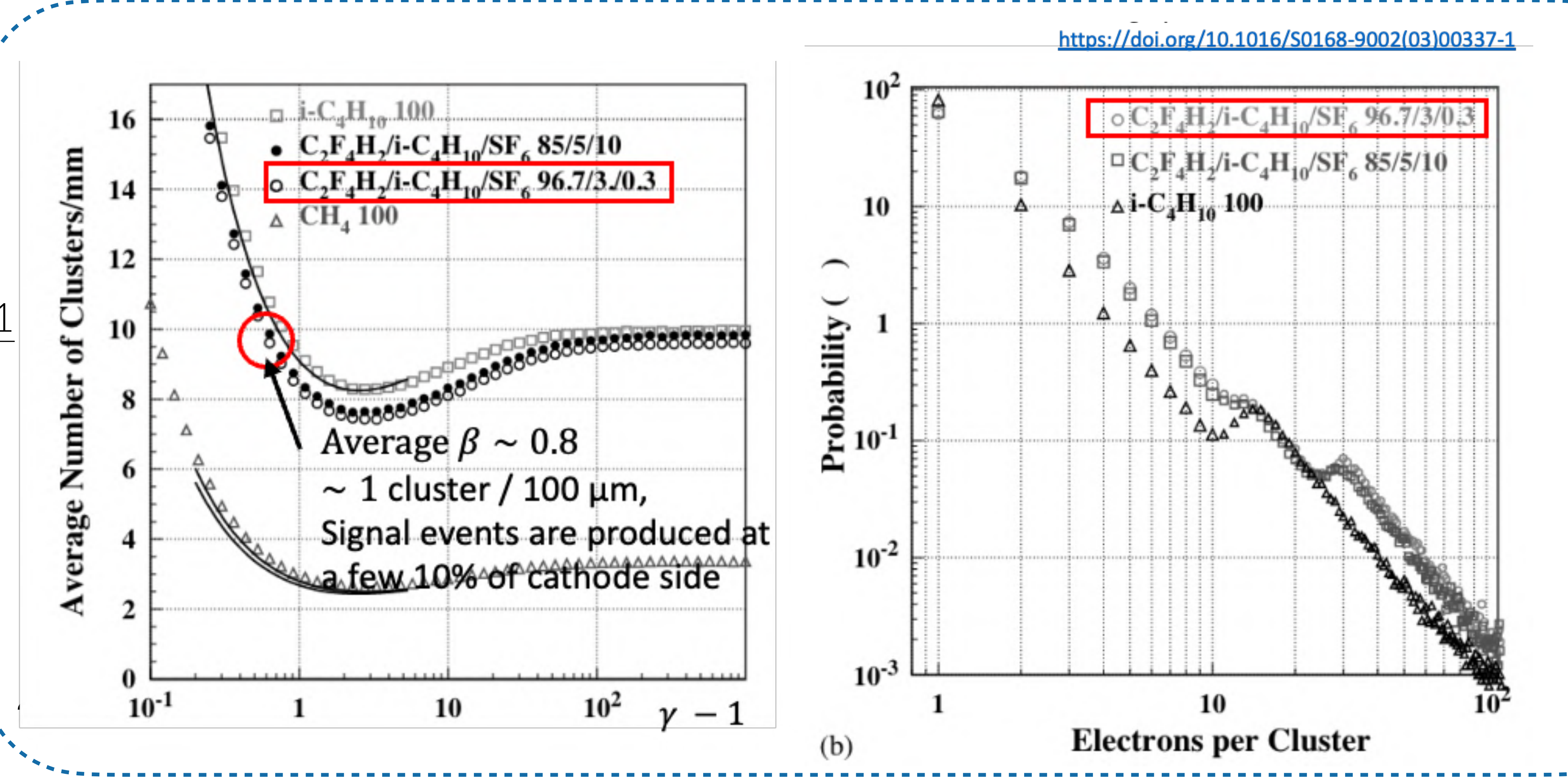
arXiv:2105.12495

Cherenkov Detector

Progress in Japan

- **Timing resolution**
  - Best resolution of $80\,\mathrm{ps}$ obtained for large signal
    - Large signal = avalanche over full gap length in GasPM
    - Average # primary electrons ~2 (https://doi.org/10.1016/S0168-9002(03)00337-1

⇒Single photoelectron time resolution: $80\,\mathrm{ps} \times \sqrt{2} \sim 110\,\mathrm{ps}$

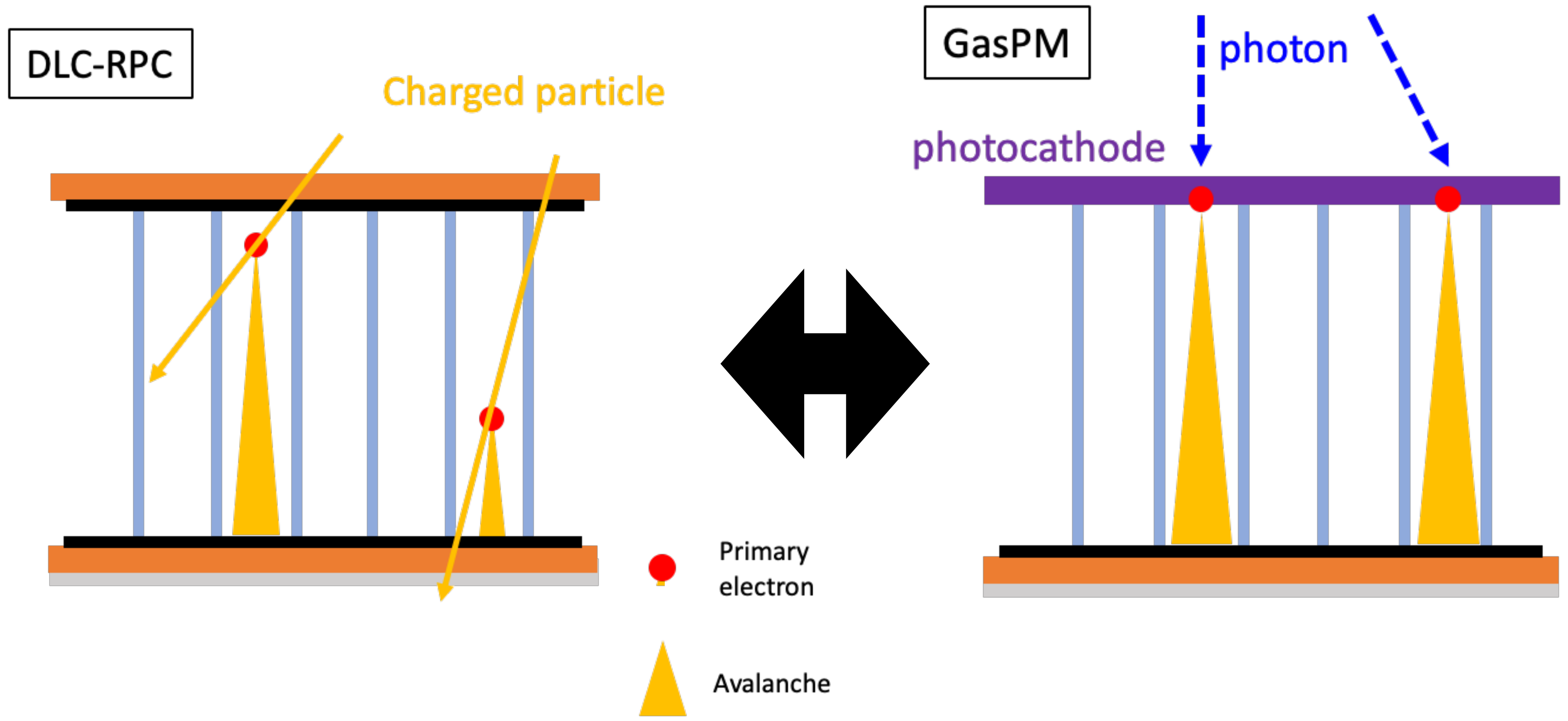


- **Timing resolution expected for Cherenkov detector**
  - Expected # photoelectrons with (3mm-thick MgF2 and CsI photocathode)

    ⇒Expected timing resolution: $35\,\mathrm{ps}$

  - **Promising. Still to be improved.**

- **Further optimisation of RPC design for timing**
  - Thinner gap
  - Higher voltage
  - Optimise gas mixture
    - Larger fraction of SF6 for better timing performance
    - Eco-friendly gas



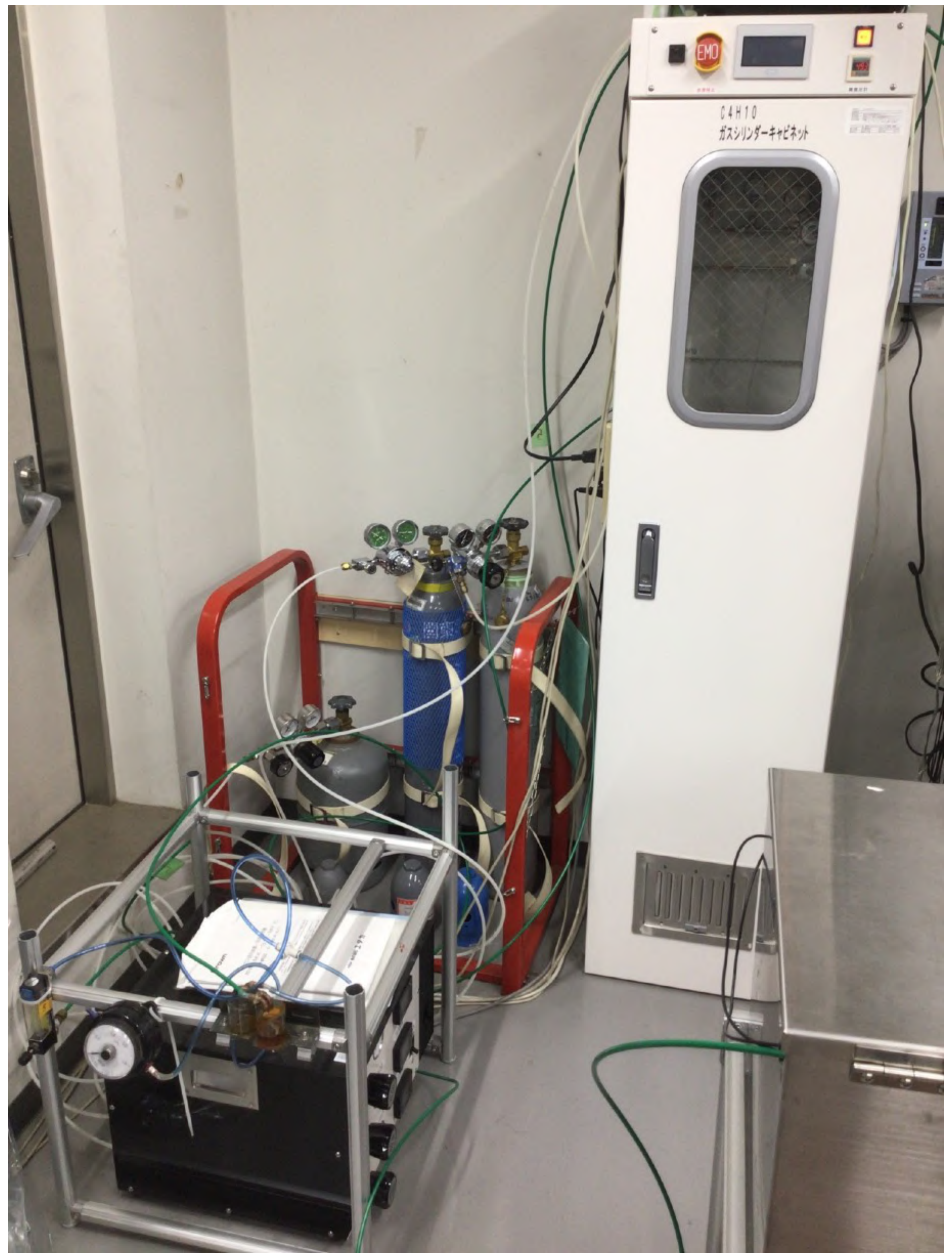
Cherenkov Detector

Progress in Japan

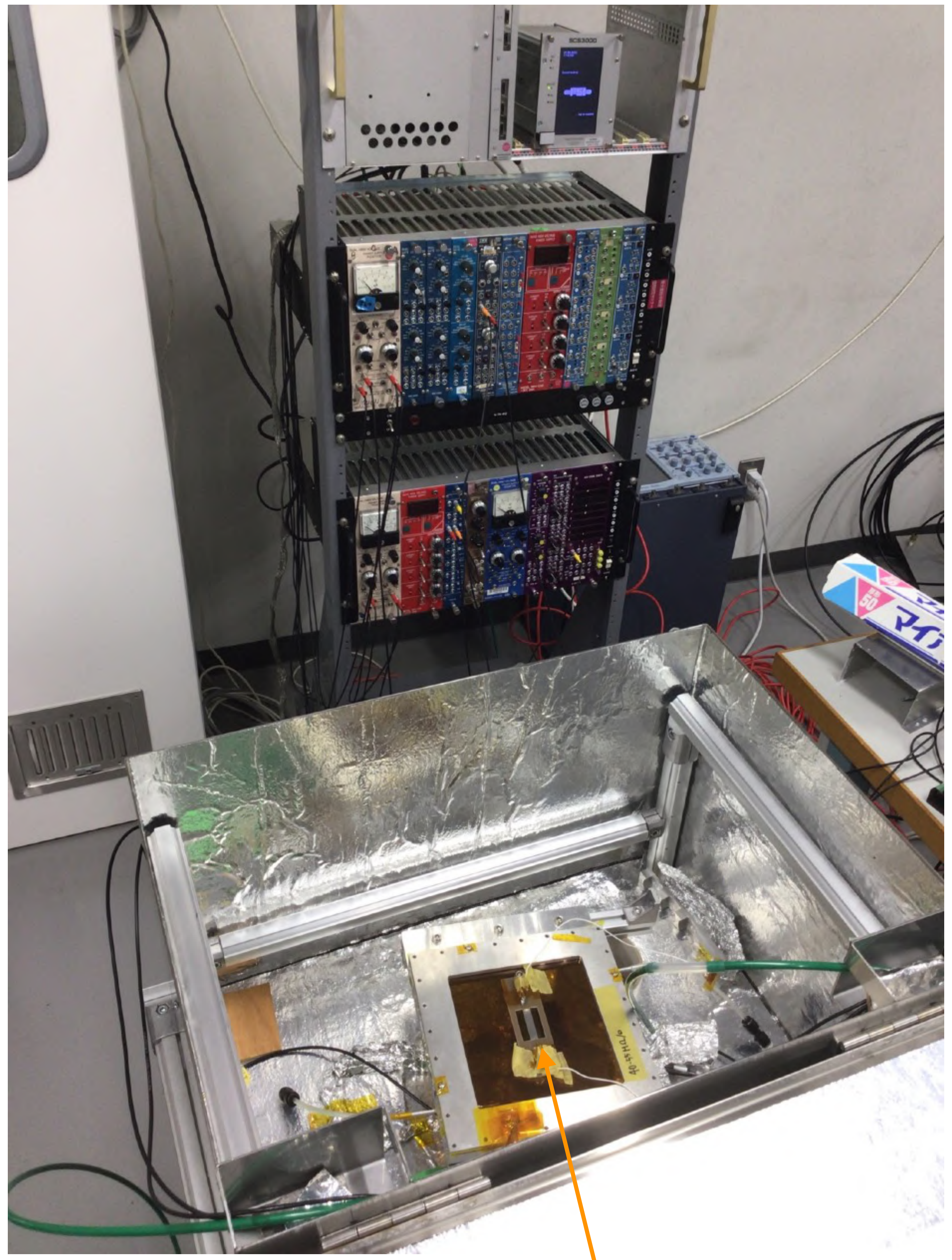
Setup for Cherenkov Detector R&D in Japan

Clean booth

Gas system



Measurement system



RPC prototype

Glove box for gasPM assembly