Development of High-Granularity Dual-Readout Calorimeter with psec Timing

US J. Freeman (Fermilab, PI), C. Gatto (NIU)

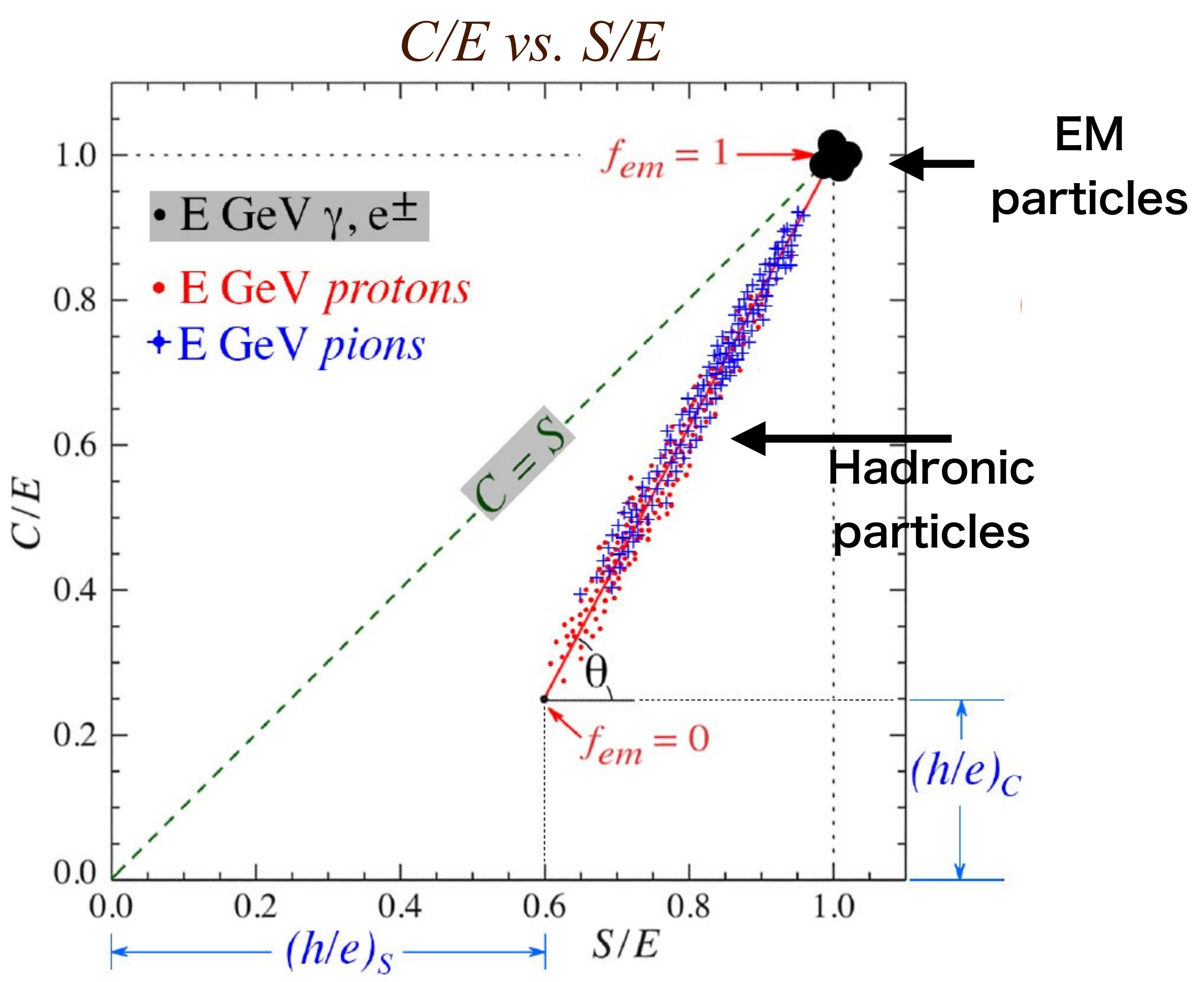
Japan **W. Ootani** (Tokyo, PI), T. Takeshita (Shinshu), T. Suehara (Kyushu), D. Jeans (KEK), K. Matsuoka (KEK)

New R&D program approved in "U.S.-Japan Science and Technology Cooperation Program in High Energy Physics"

Concept of Proposed Calorimetry

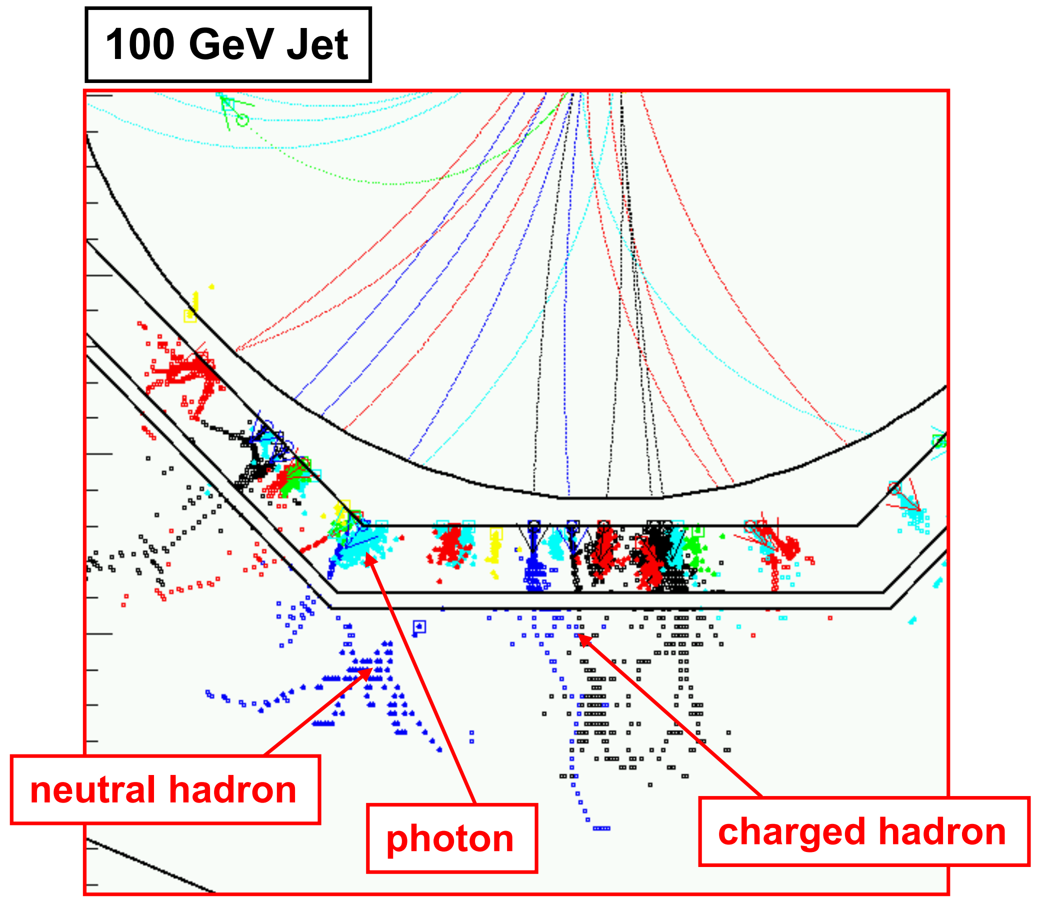
Dual-Readout calorimetry
Better performance at high energy, PID

High-Granularity calorimetry
Better performance at low energy



Y. Kim, EIC Calorimeter Workshop 2021

New calorimetry for future colliders



psec timing
PID, BG reduction, improve PFA

Overview of Research Plan

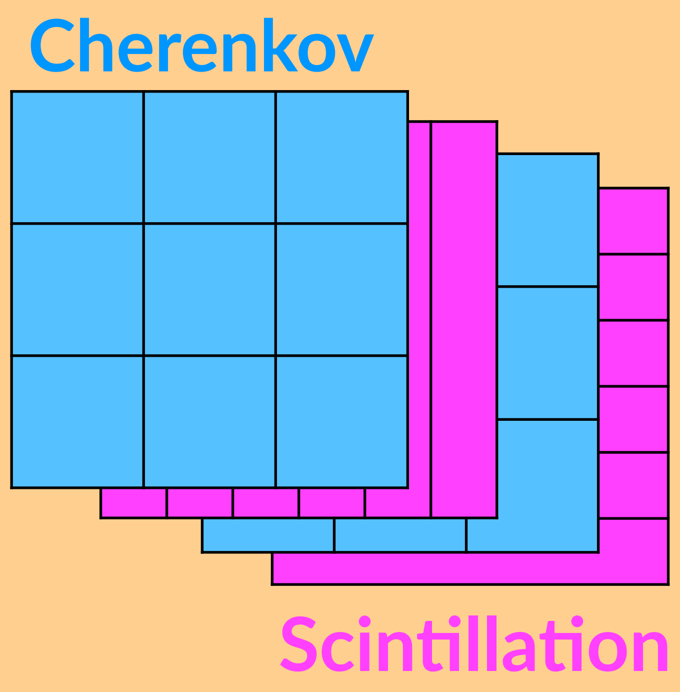
How to Combine High-granularity and Dual-readout with Excellent Timing

Dual-readout

Cherenkov detector

Cherenkov radiator + UV-GasPM

- High-granularity readout
- psec timing
- Low-cost



Scintillation detector

SiPM-on-strip technology

- High-granularity
- low-cost

Fast timing front-end electronics

Simulation and analysis tools

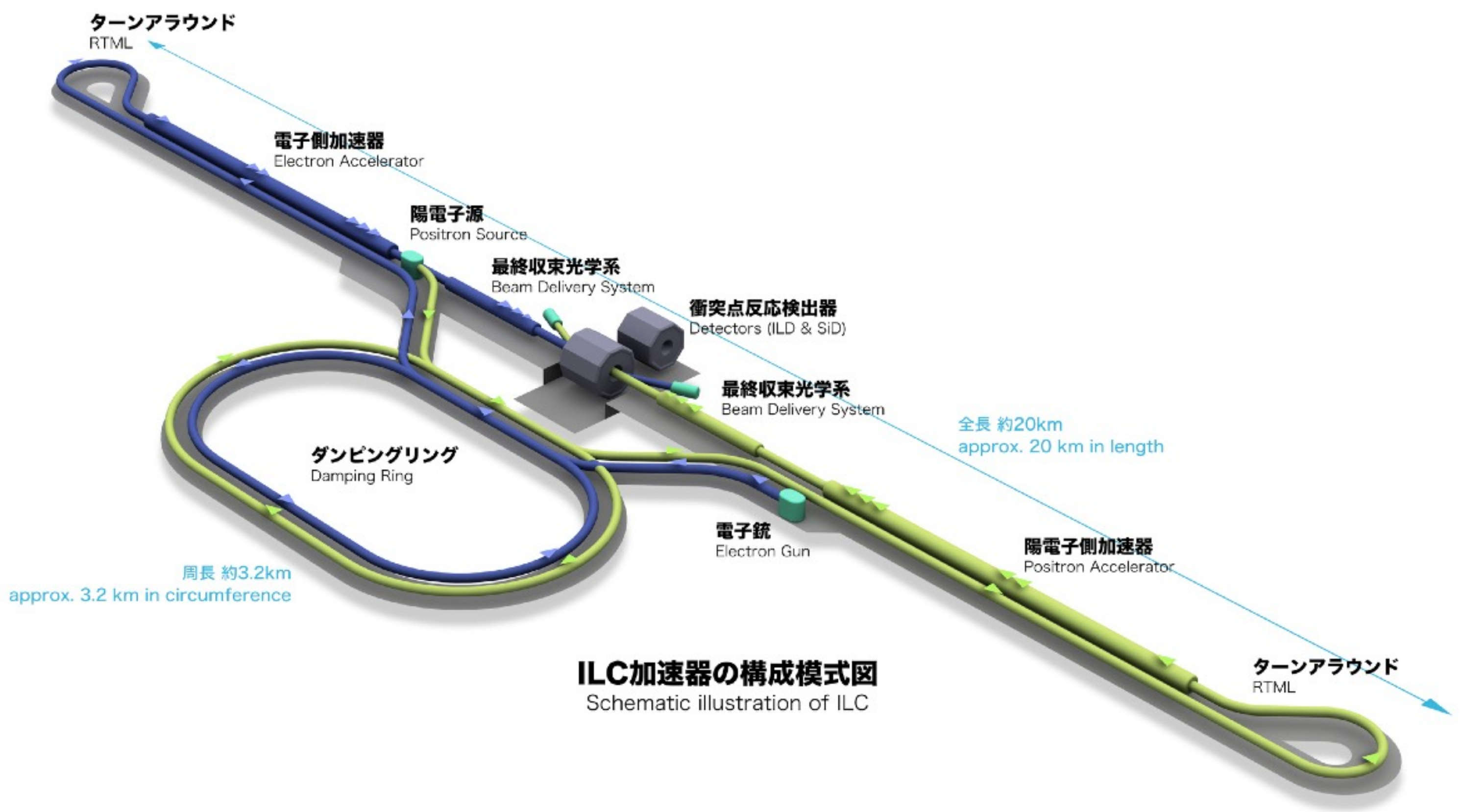
Prototyping and beam test at FTBF

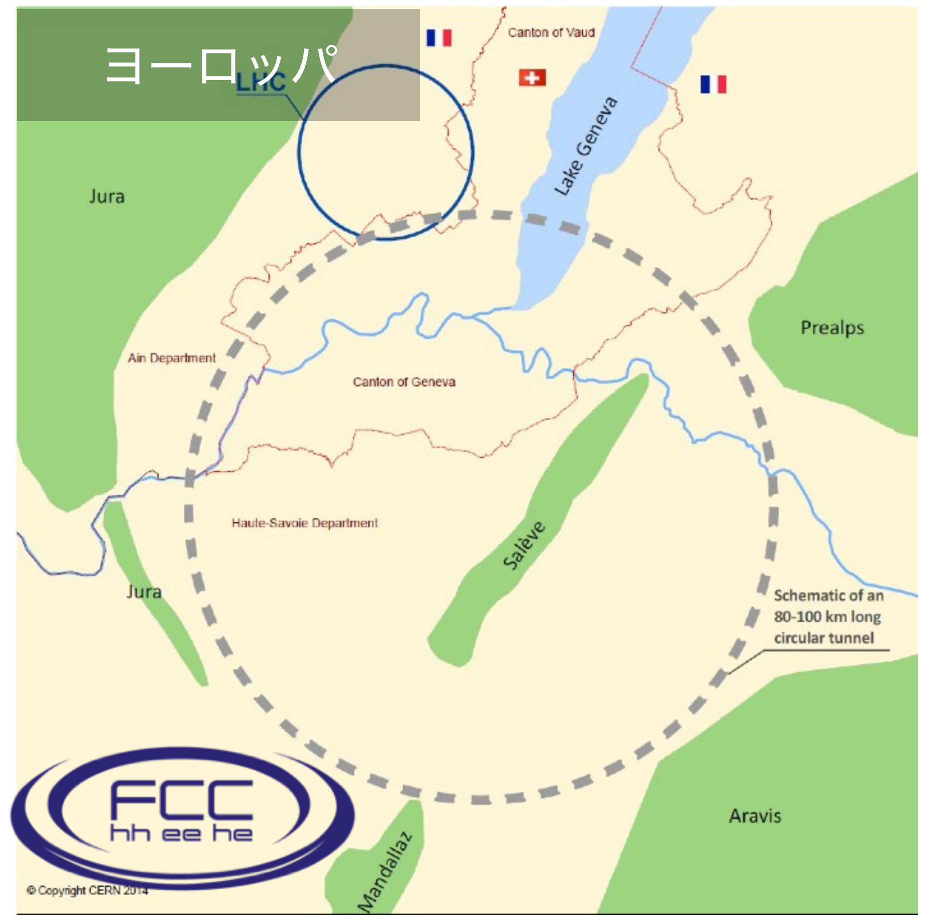
Demonstrate performance of proposed calorimeter technology

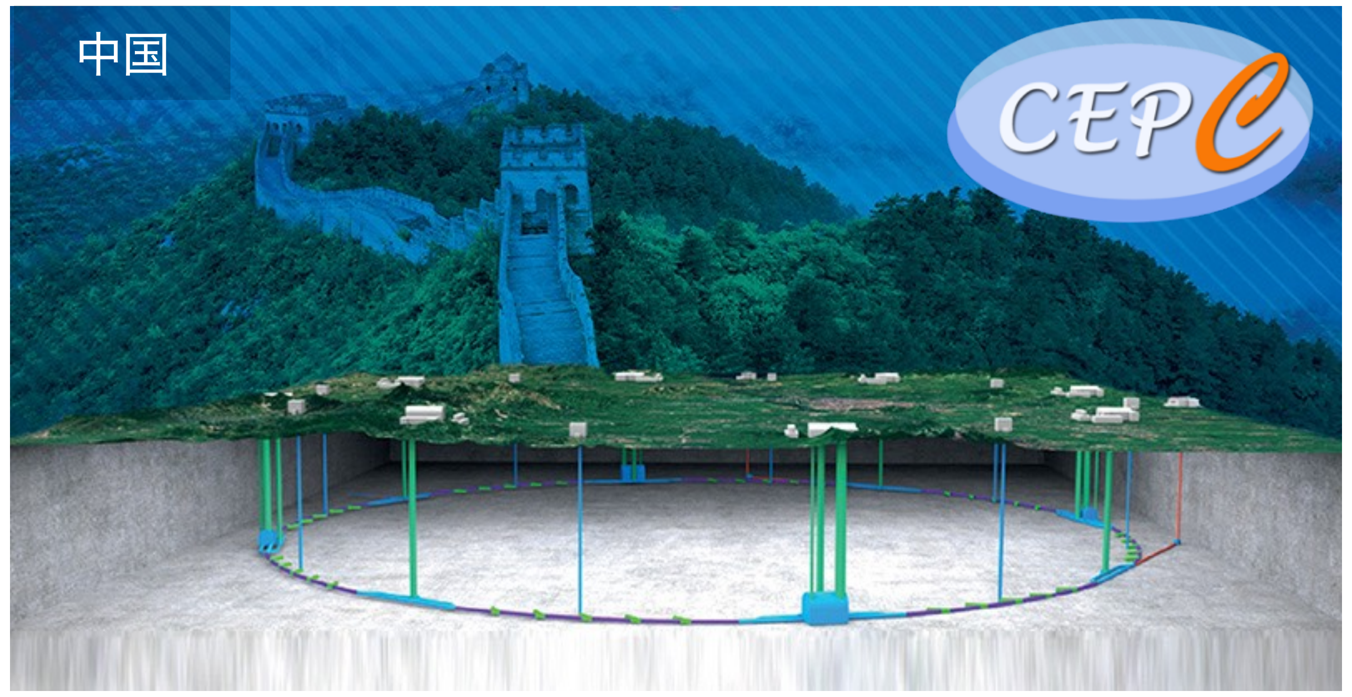
Possible Applications

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

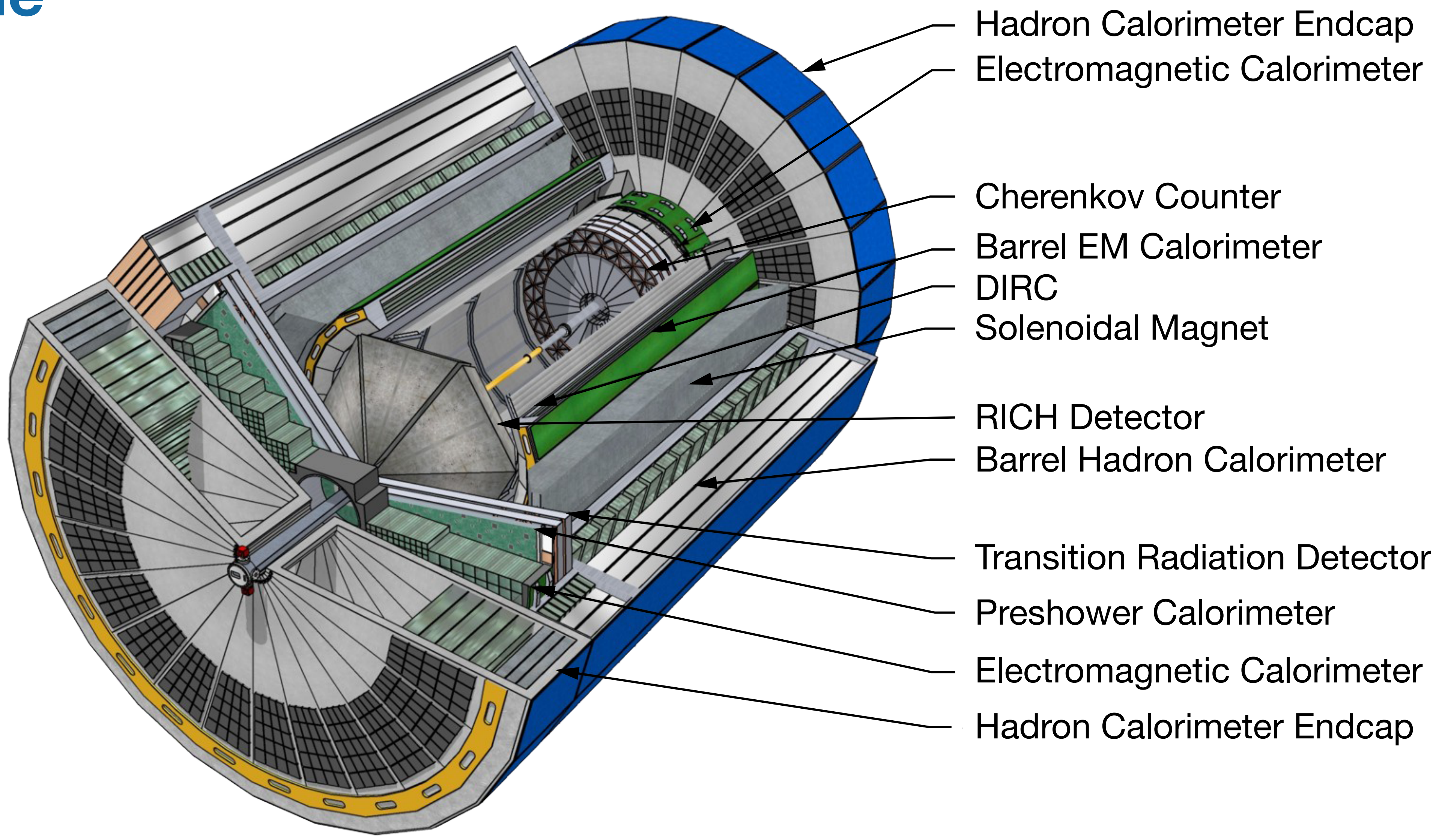
Calorimeters for Higgs factories



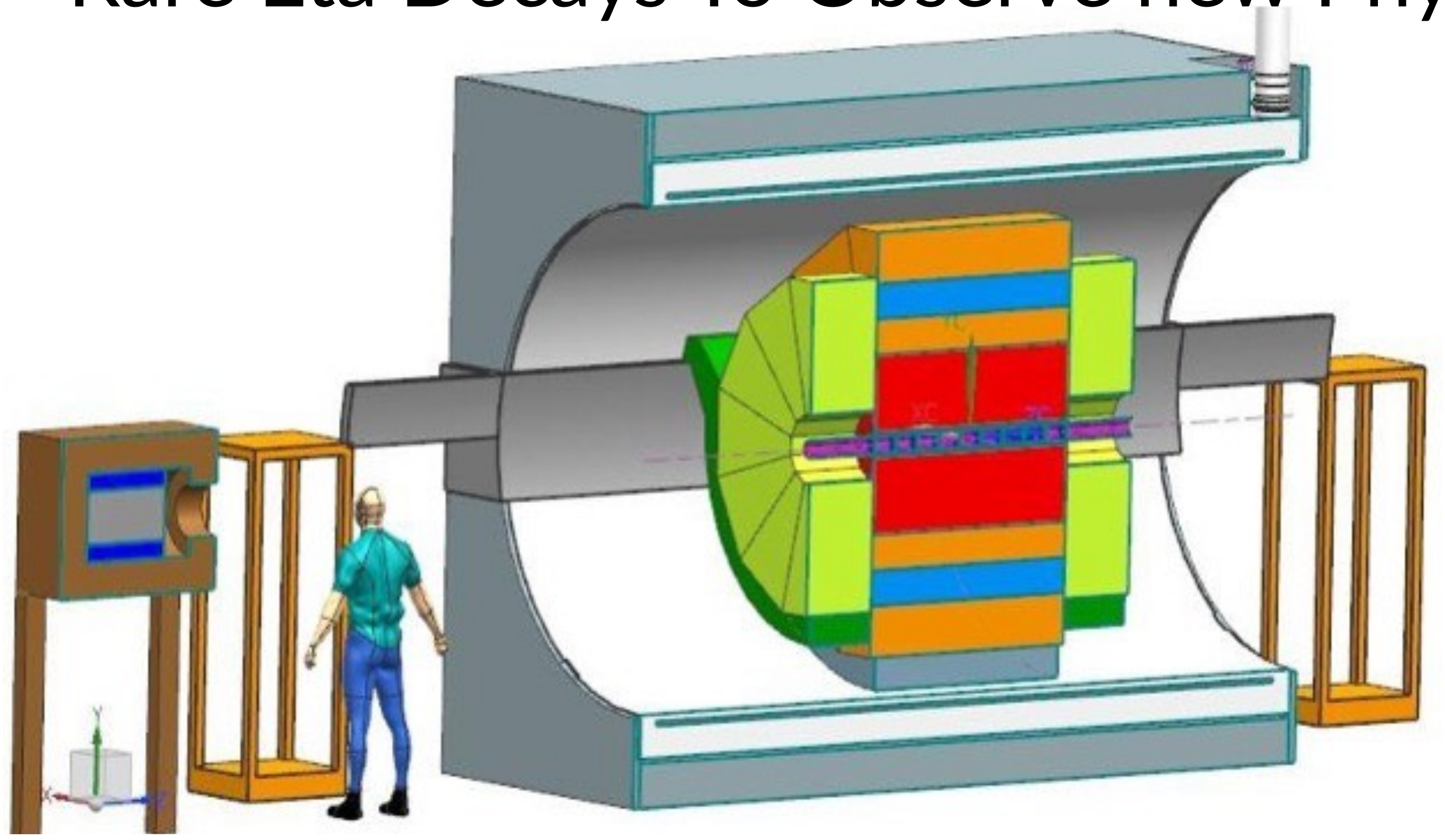




EIC
Electron-Ion Collider

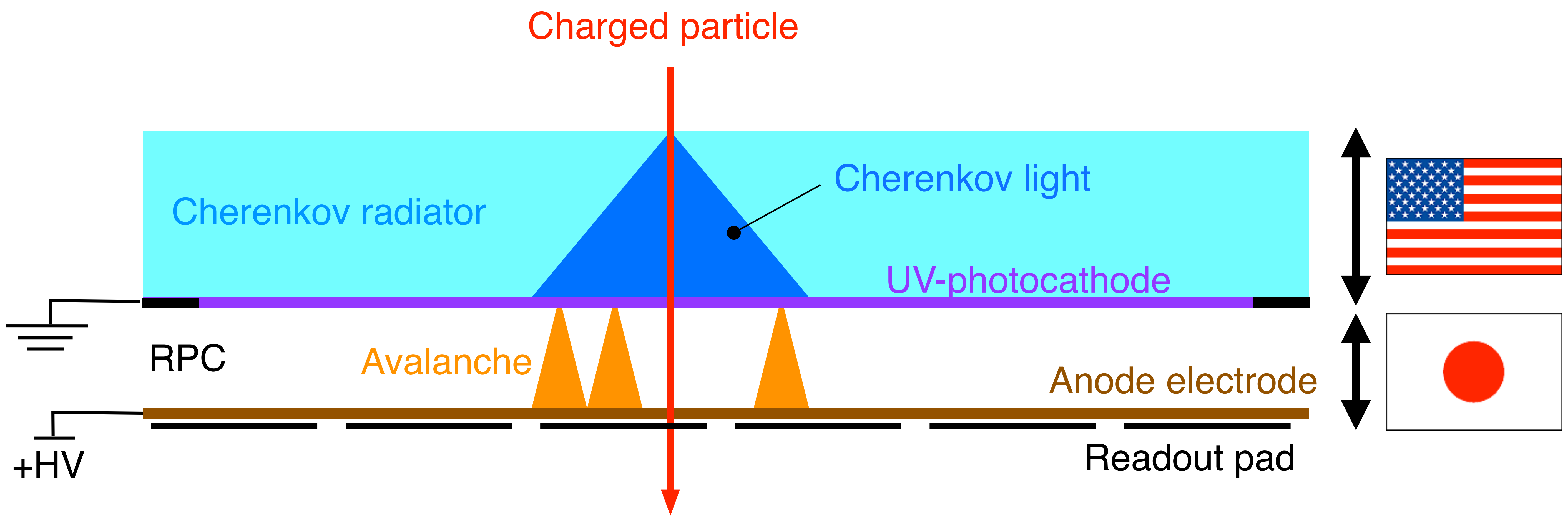


REDTOP
Rare Eta Decays To Observe new Physics



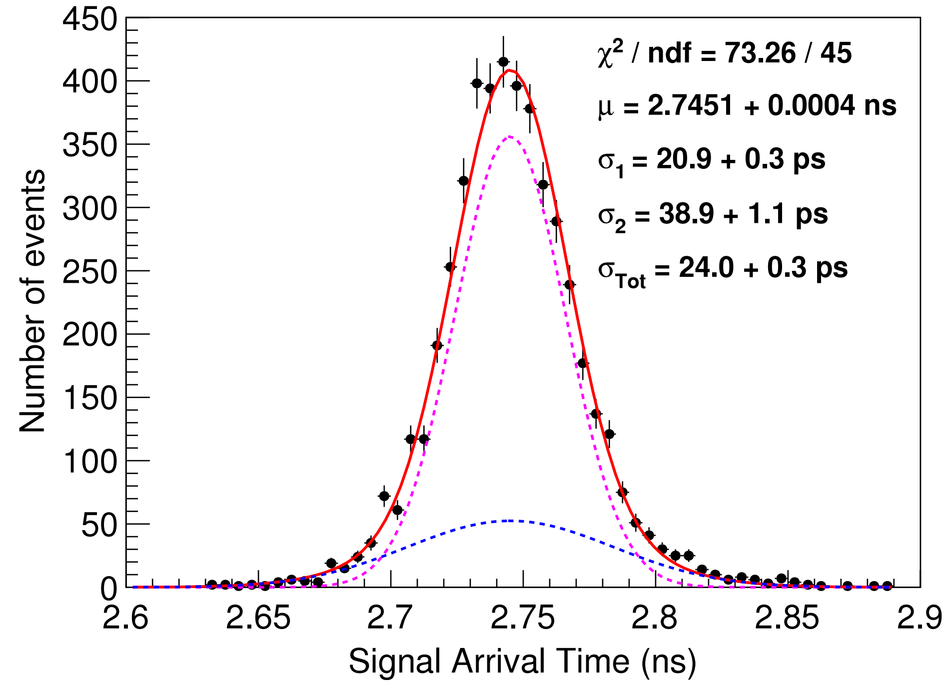
Cherenkov Detector

- **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 without no drift region)
  - 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

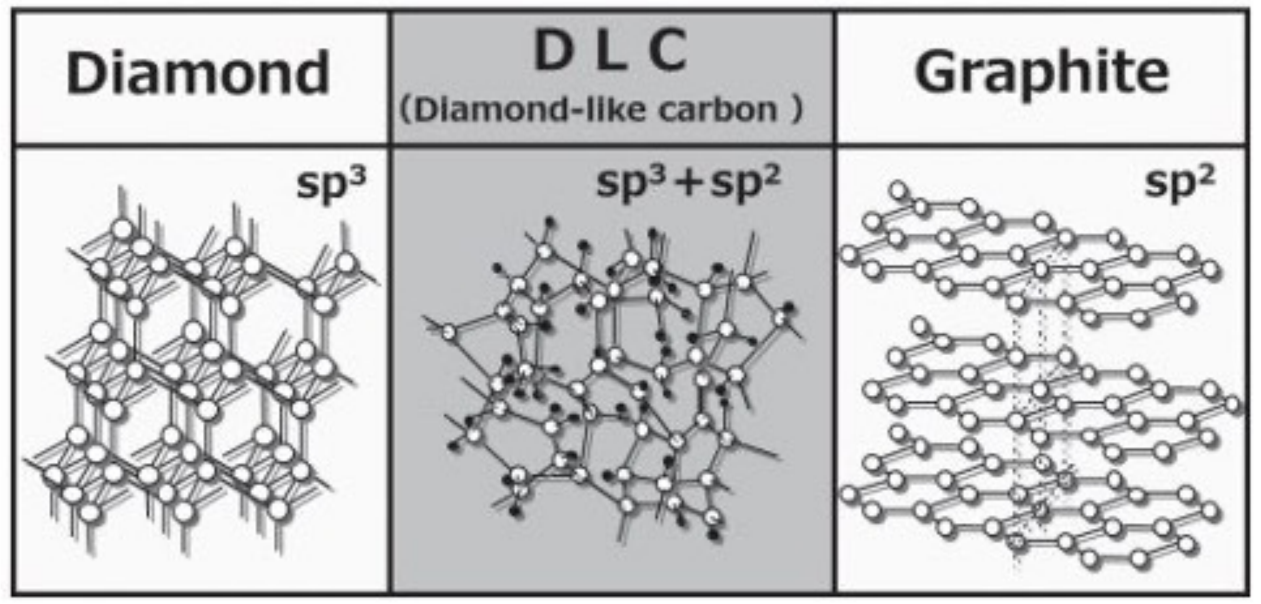


https://doi.org/10.1016/j.nima.2018.04.033

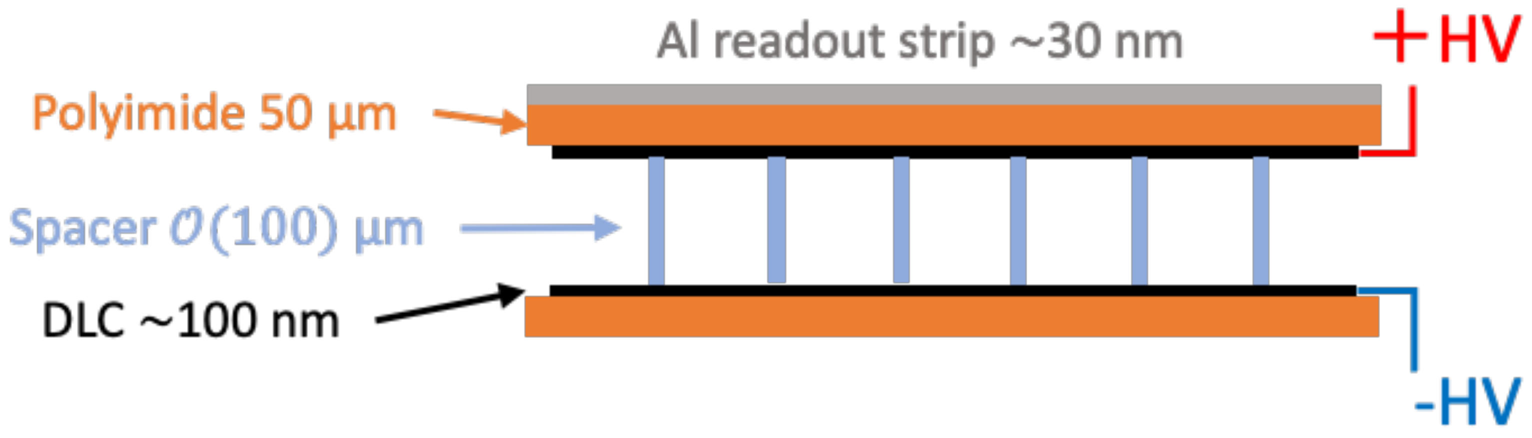
Cherenkov Detector

Japan

- **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: $>1\,\mathrm{MHz/cm^2}$

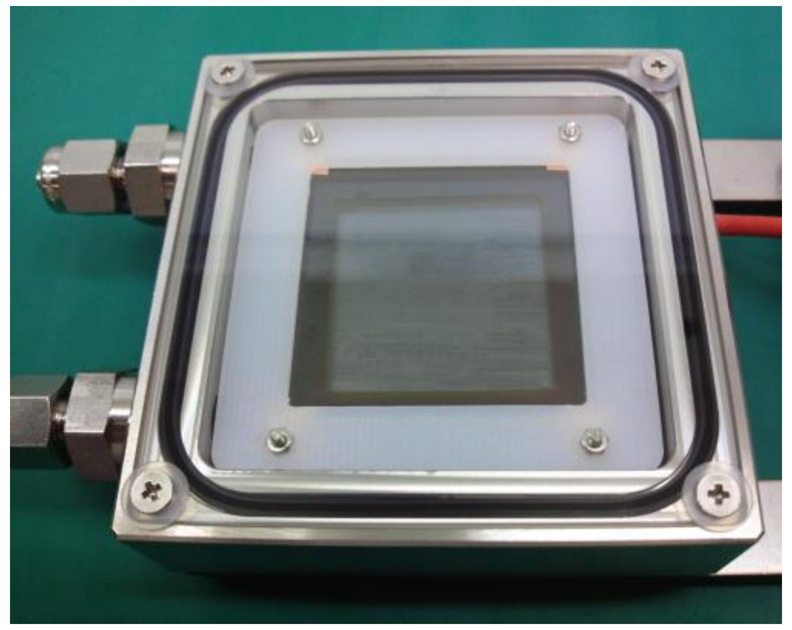


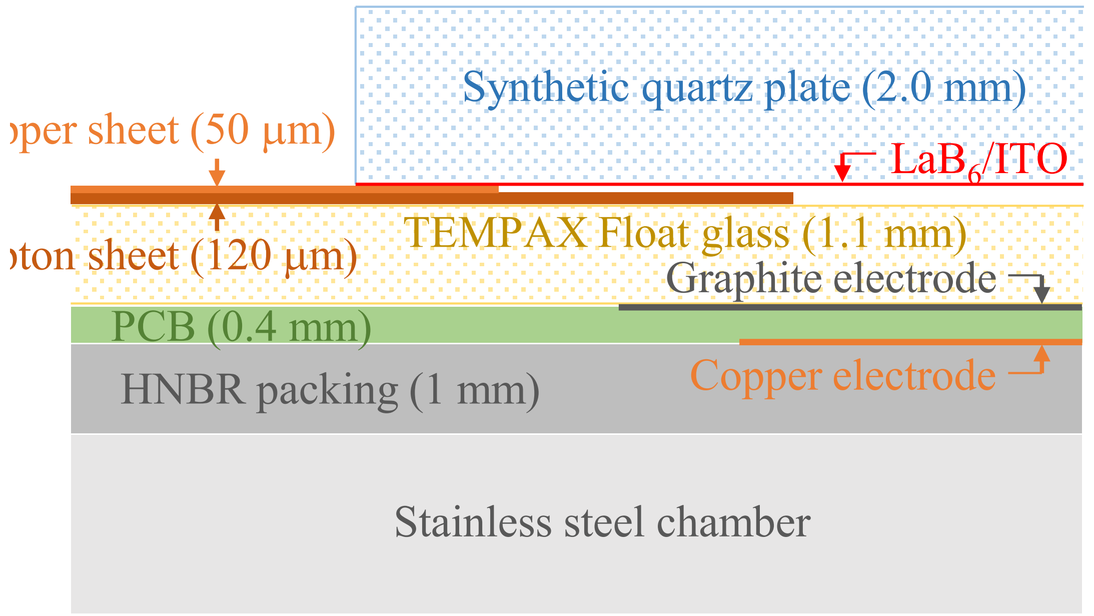
Ref) https://pcs-instruments.com/articles/the-science-behind-diamond-like-coatings-dlcs/



- **Fast timing photo-detector based on RPC-GasPM**
  - Single photon resolution of $25\,\mathrm{ps}$ with prototype

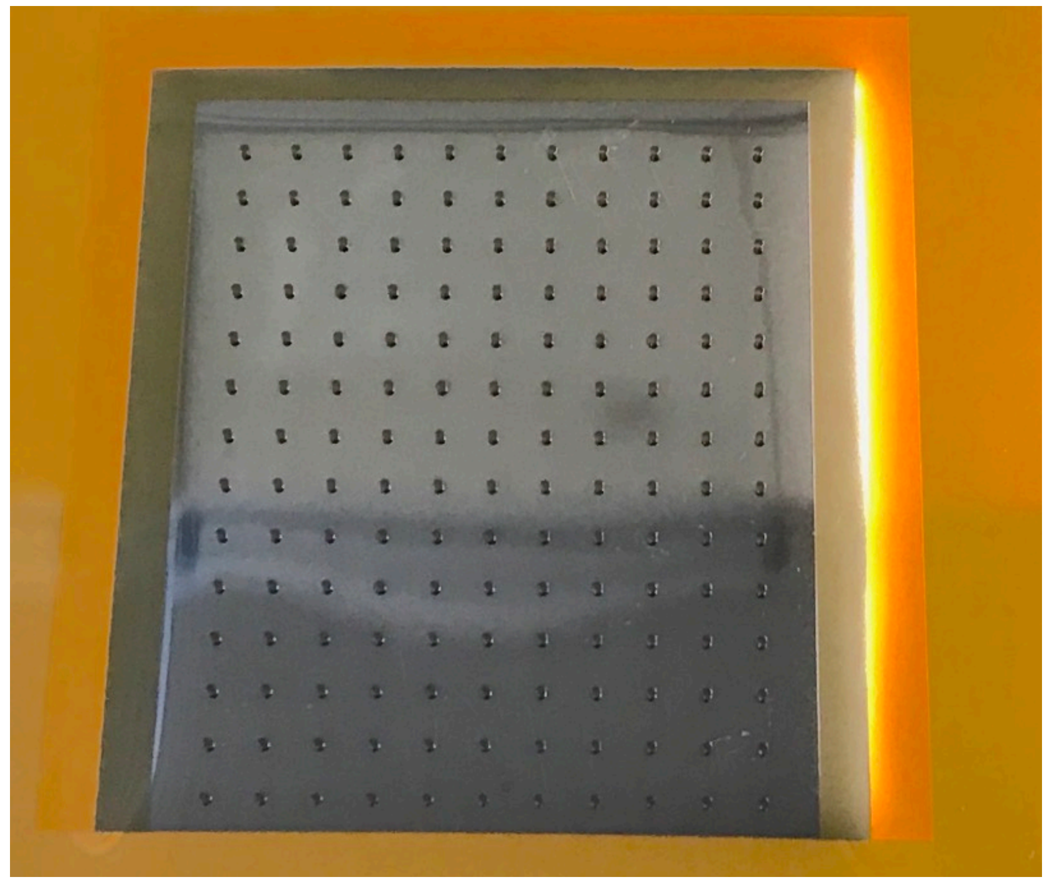
Prototype of Gas PM with RPC (KEK, K. Matsuoka)





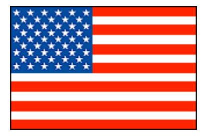
https://arxiv.org/abs/2302.12694

DLC on Kapton



Cherenkov Detector

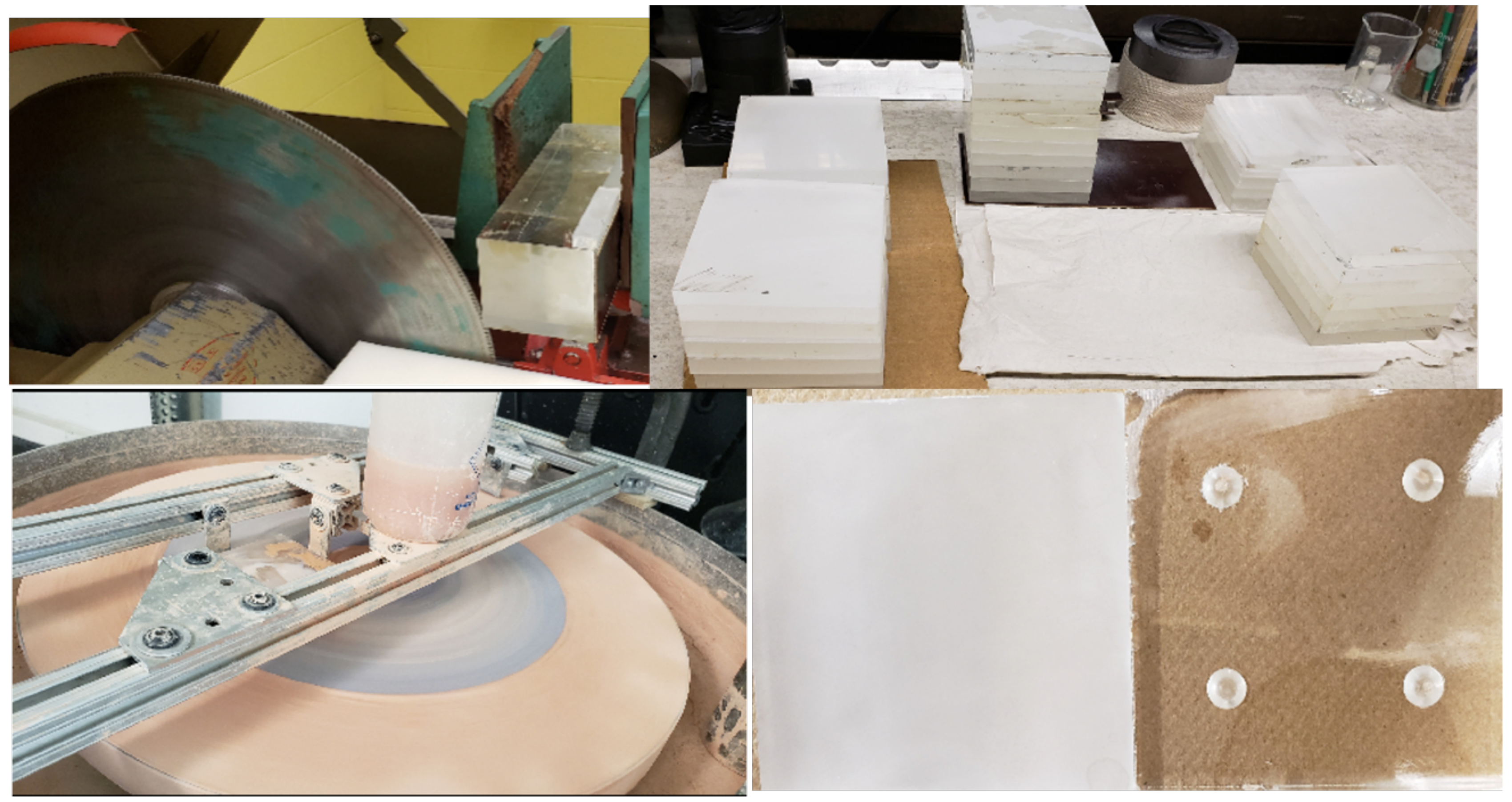
US



- **Development of Cherenkov radiator (NIU)**
  - Selection of radiator material: VUV-transparent crystal (λ=100-200nm)
  - Tiles slicing and polishing
- **Development of high-QE CsI photocathode (Fermilab)**
  - Transmission-type CsI photocathode with high QE
  - Deposition of Al electrode

Fermilab evaporation system for CsI photocathode deposition

Tile machining at NIU

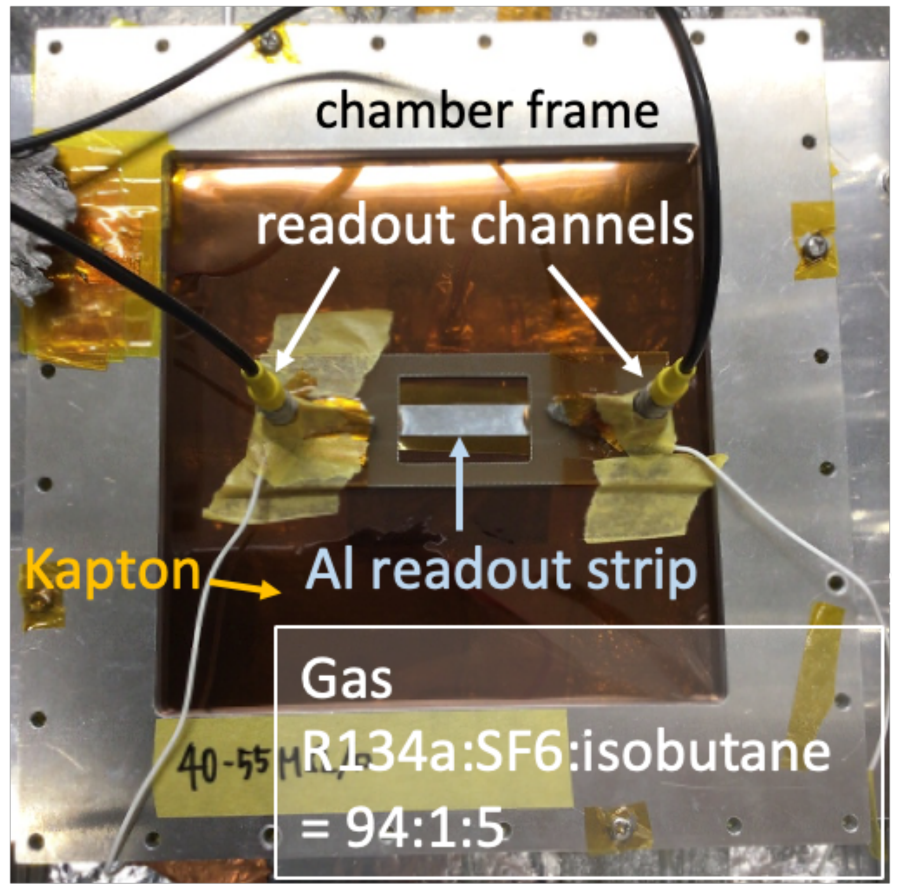


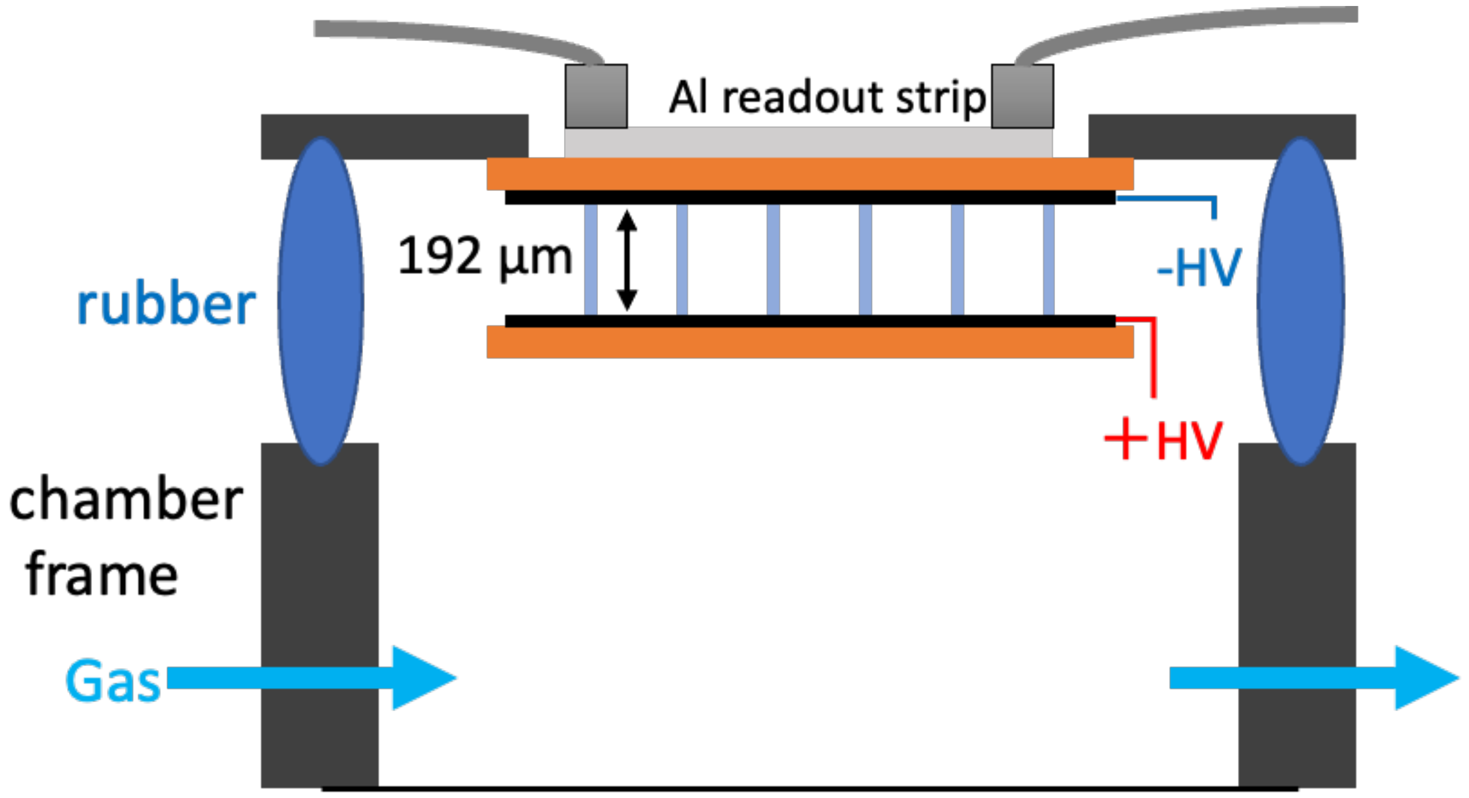
Cherenkov Detector

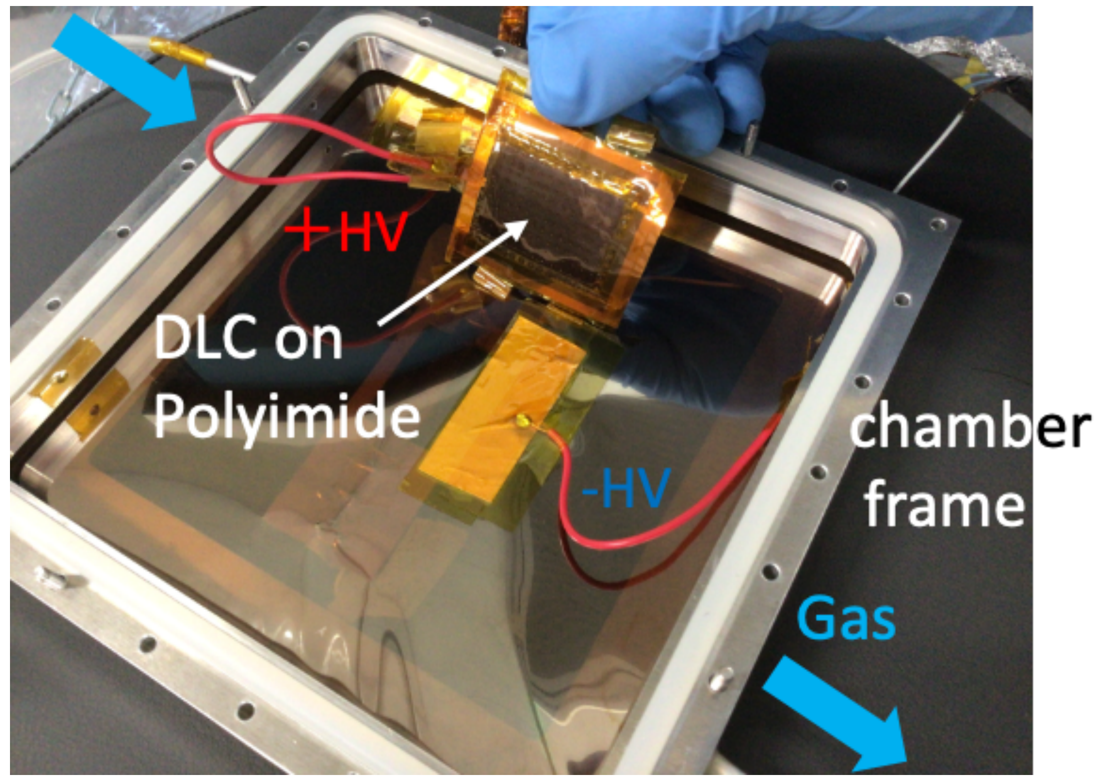
Progress in Japan

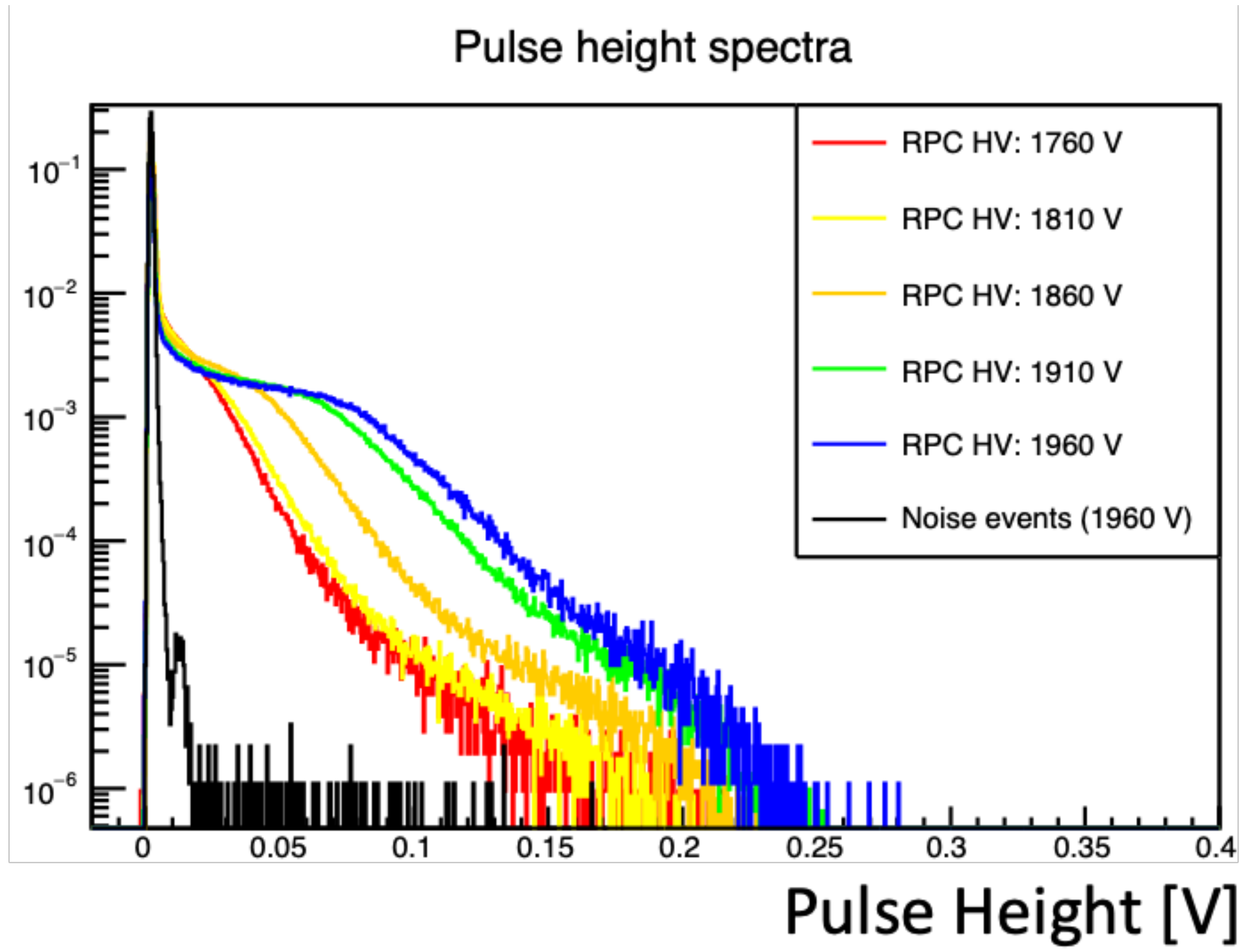
- **First test of DLC-RPC with thinner gap**
  - Gap: $192\,\mu m$
  - Anode: $4\ \mathrm{M\Omega/sq}$, Cathode: $40\text{-}55\ \mathrm{M\Omega/sq}$
  - Gas: R134a/SF6/isobutane (94/1/5)
  - **NOT optimised for timing yet**

DLC-RPC from top side

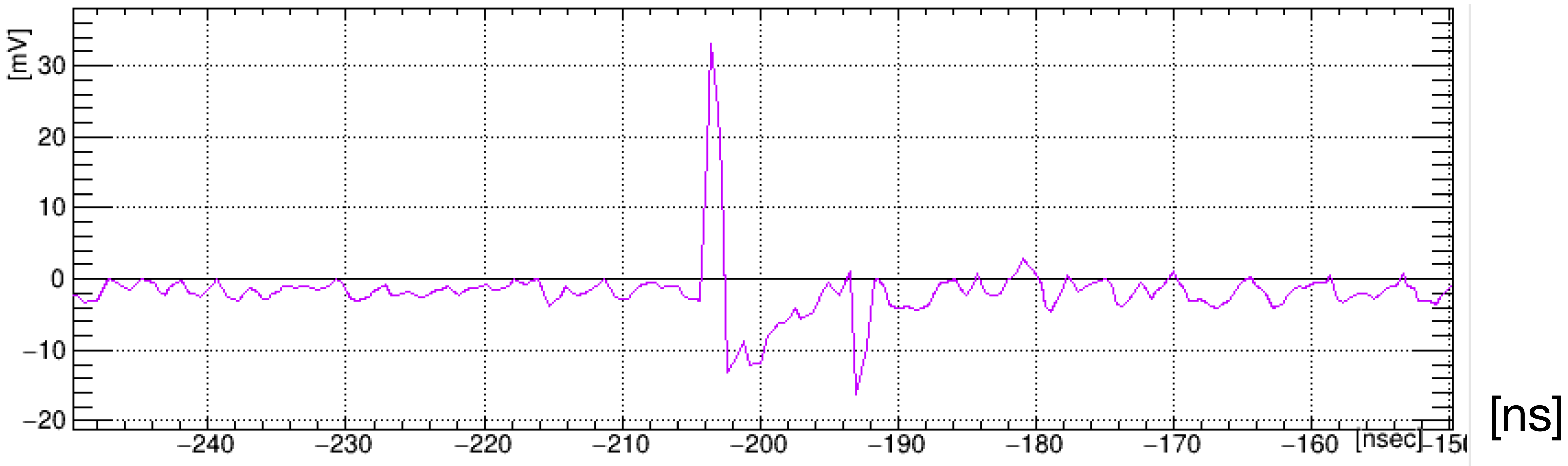








Typical signal for Sr-90 β



Cherenkov Detector

Progress in Japan

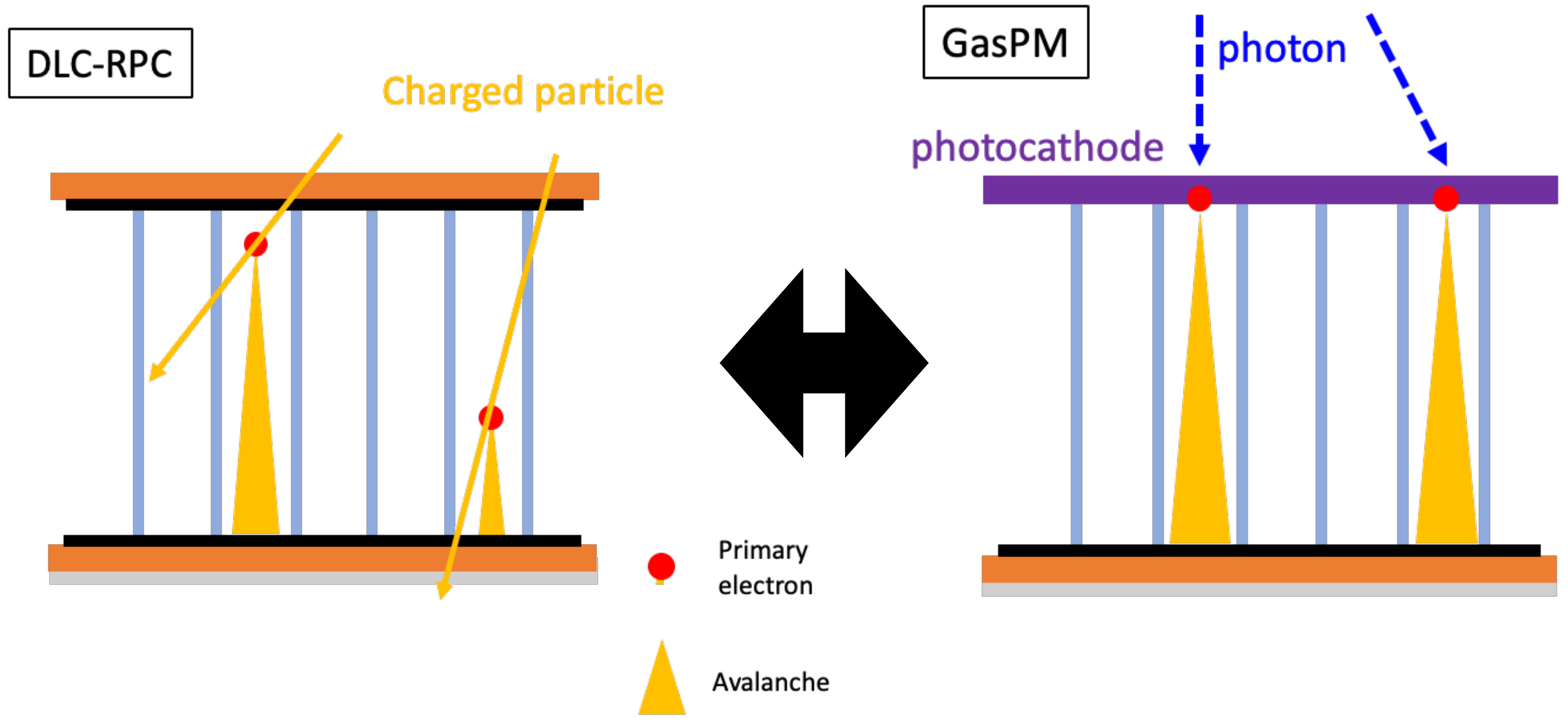
- **Timing resolution**
  - Best resolution of $80\,\mathrm{ps}$ obtained for large signal
    - Large signal = avalanche over full gap length in GasPM
    - Average # primary electrons ~2

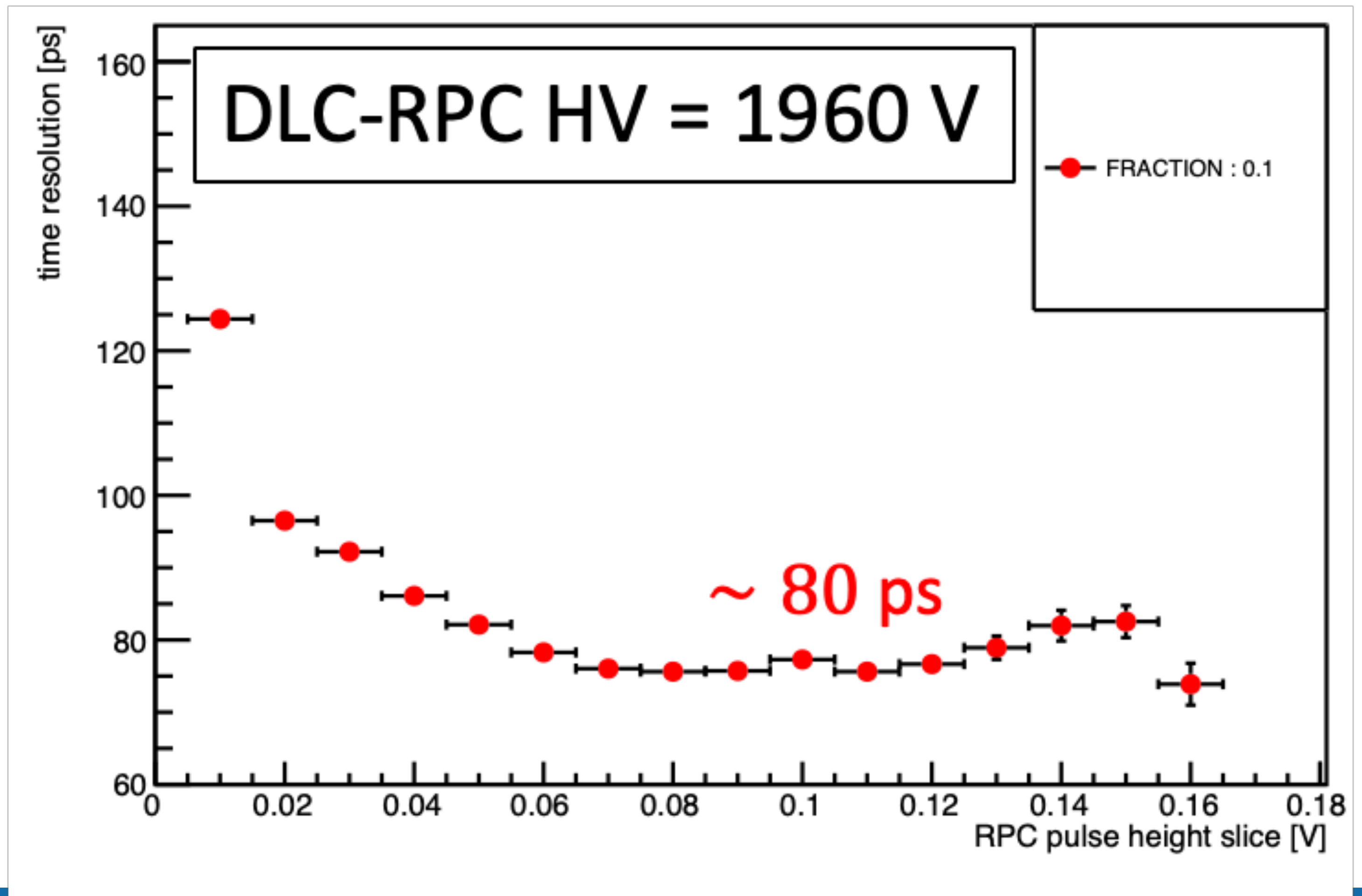
  ⇒Single photoelectron time resolution: $80\,\mathrm{ps} \times \sqrt{2} \sim 110\,\mathrm{ps}$

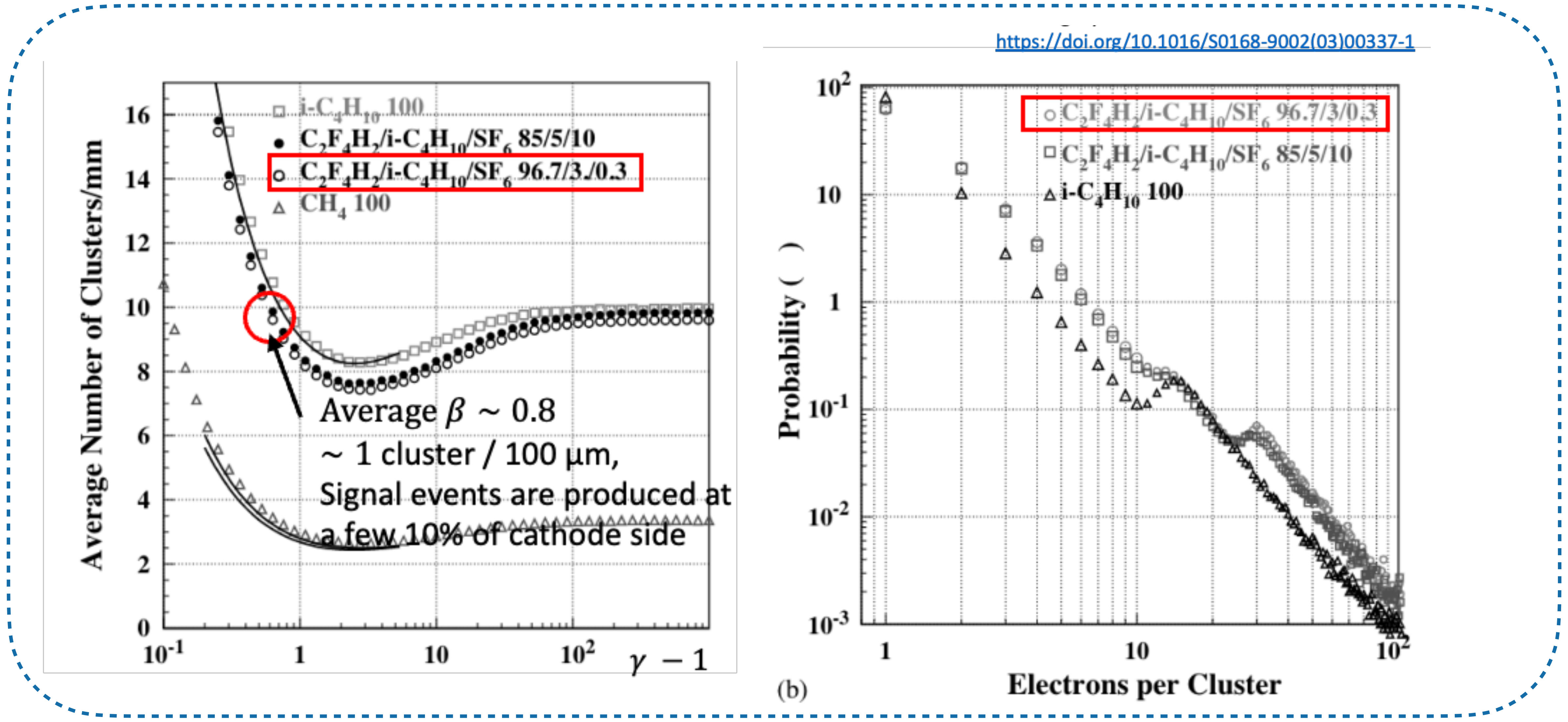
- **Timing resolution expected for Cherenkov detector**
  - Expected # photoelectrons with (3mm-thick MgF2 and CsI photocathode) ≳10

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

Promising. (N.B. still not optimised for timing)





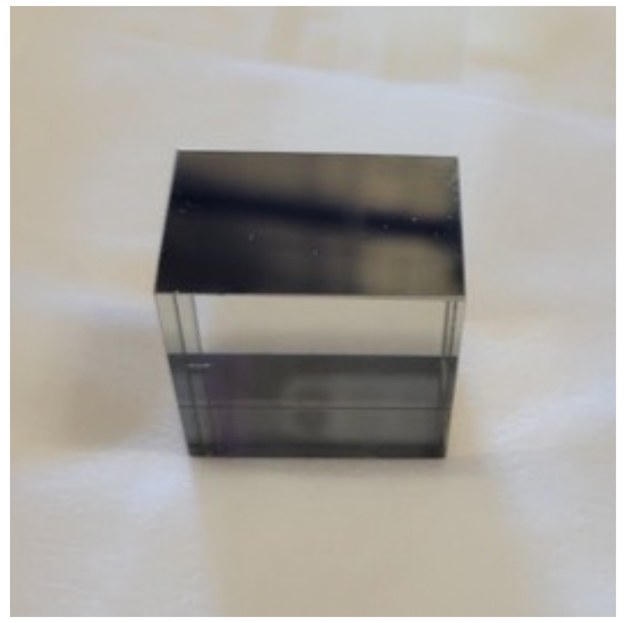


Cherenkov Detector

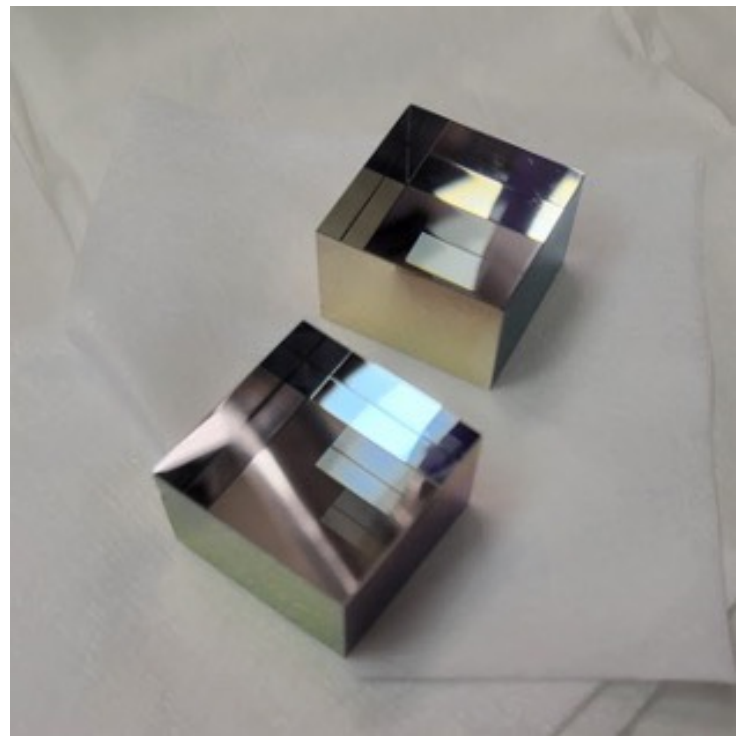
Progress in US

- **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

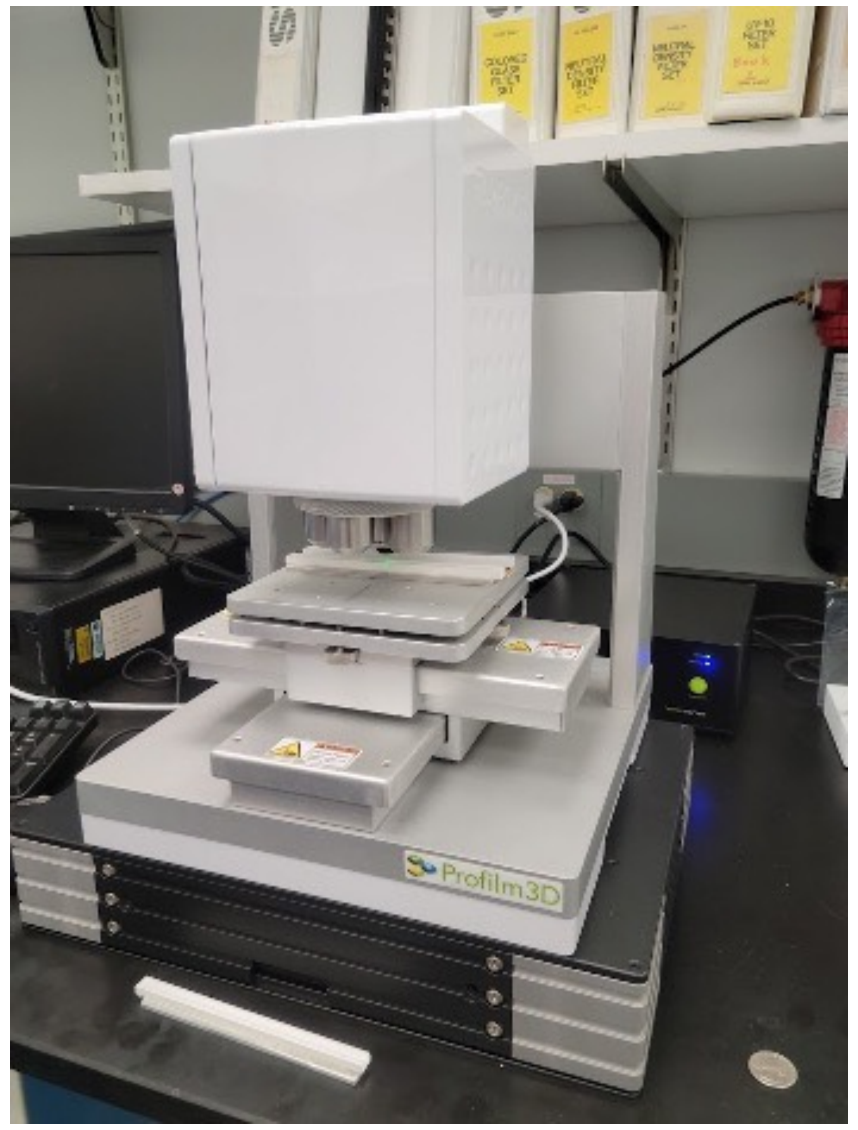
Sapphire (uncoadted)



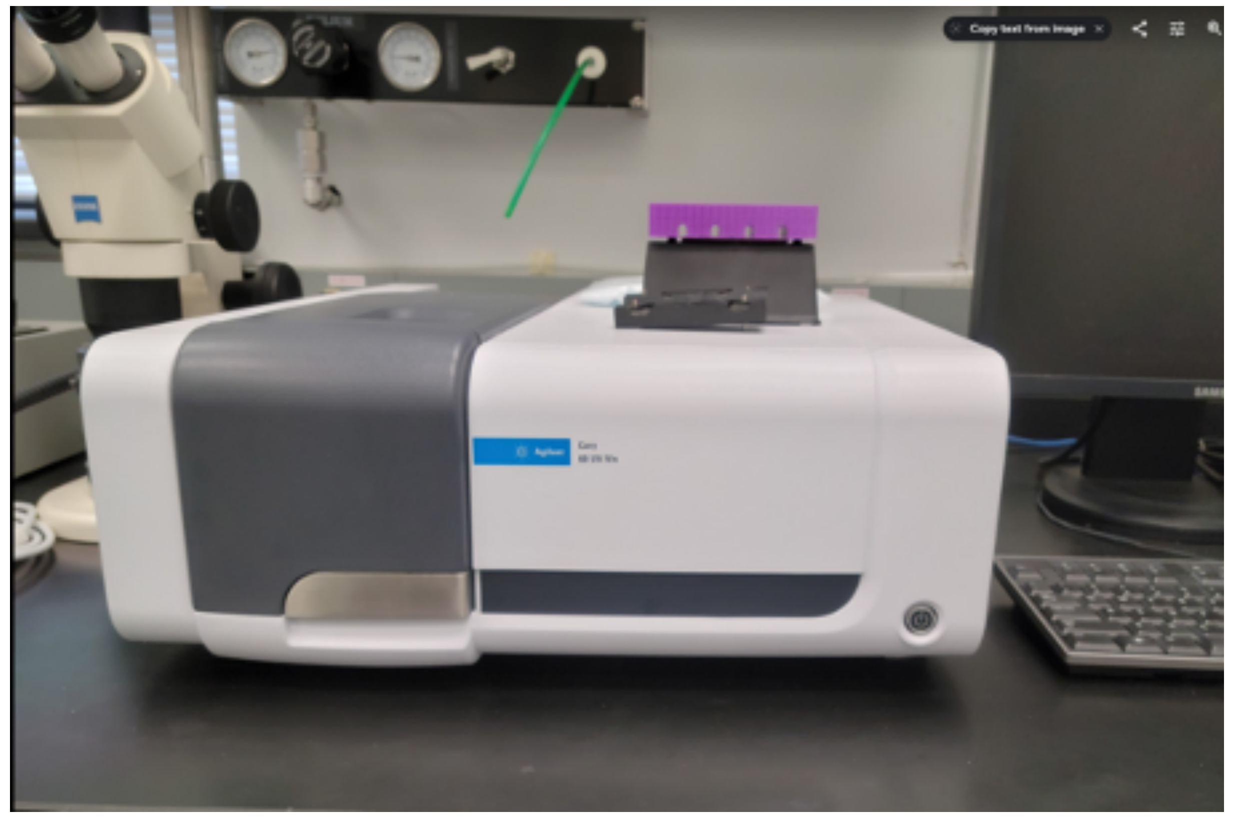
Sapphire
(5-sides Al coated)



Optical profilometer



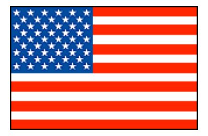
VUV spectrophotometer



Fermilab evaporation system for CsI photocathode deposition

Cherenkov Detector

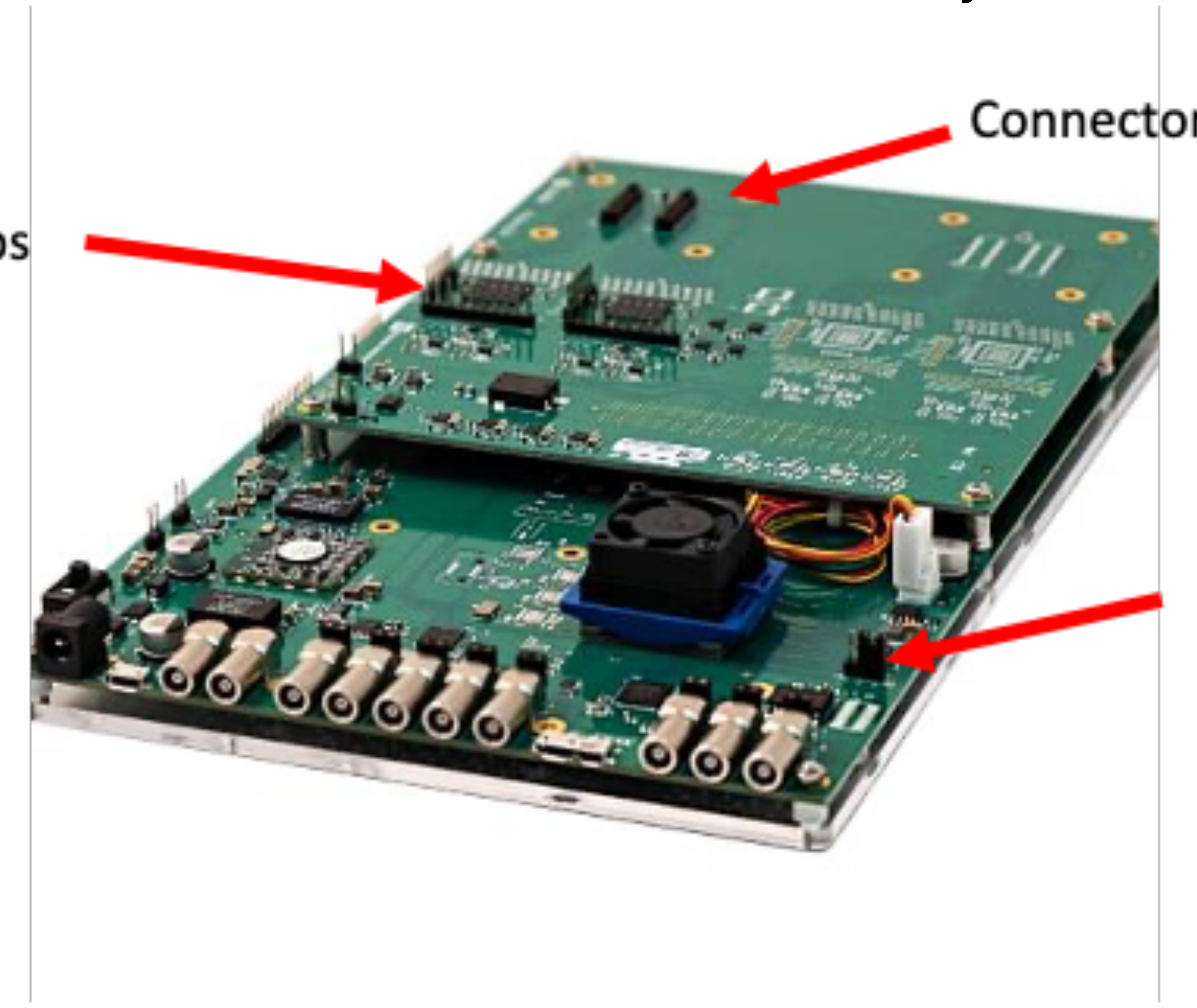
Progress in US



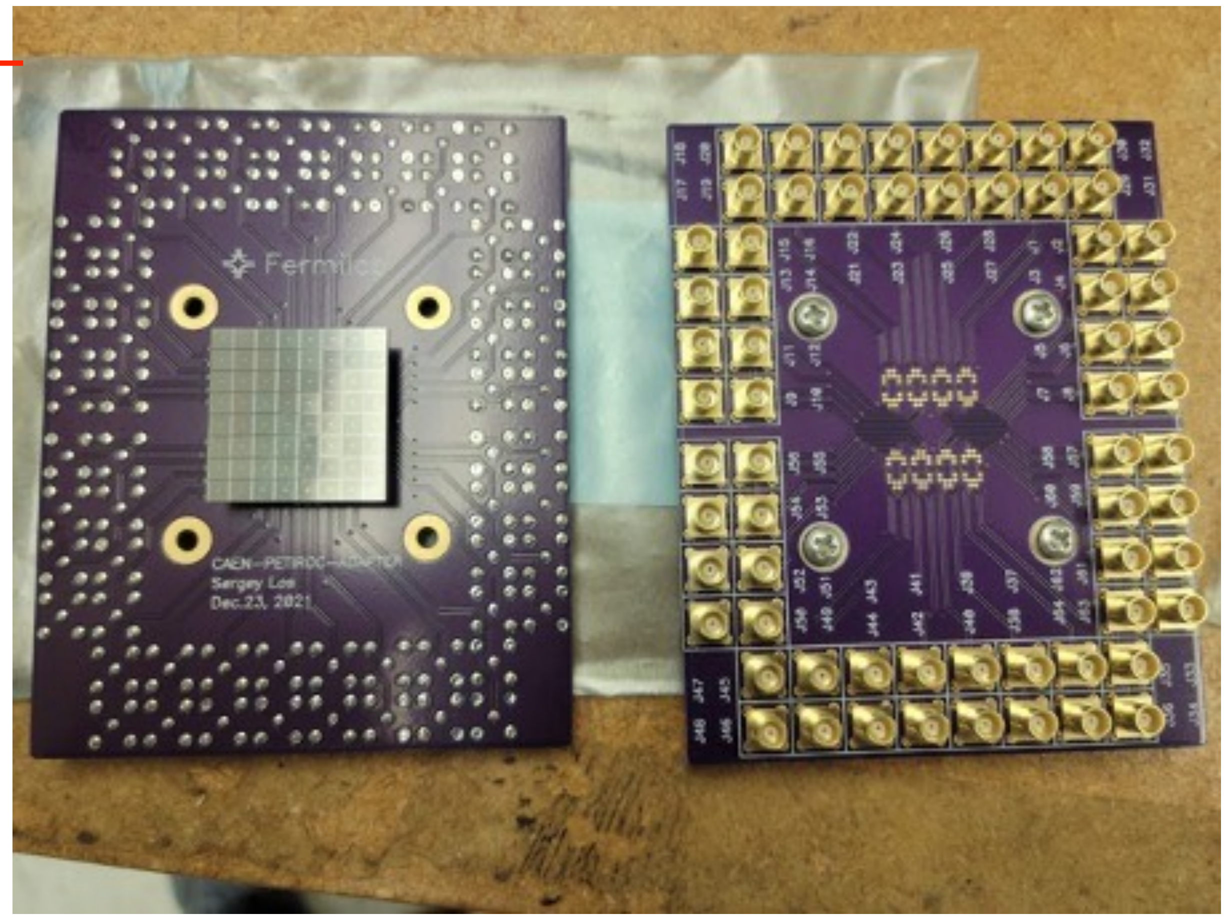
- **Readout electronics**
  - Waveform digitizer (CAEN DT5742B, DRS4 16ch) for initial lab test (time resolution < 50ps)
  - CAEN PETIROC system (64ch) for prototype beam test (time resolution ~15ps)

CAEN DT5742B

CAEN PETIROC system



Fermilab PETIROC interface card

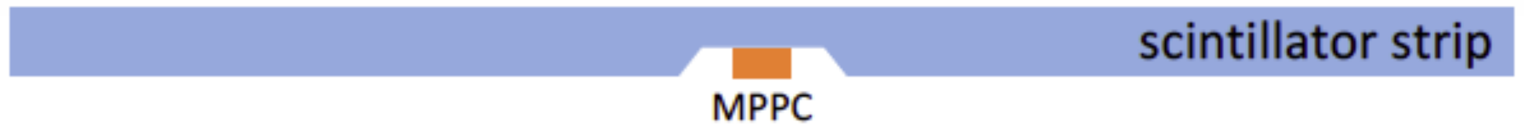


Scintillation Detector

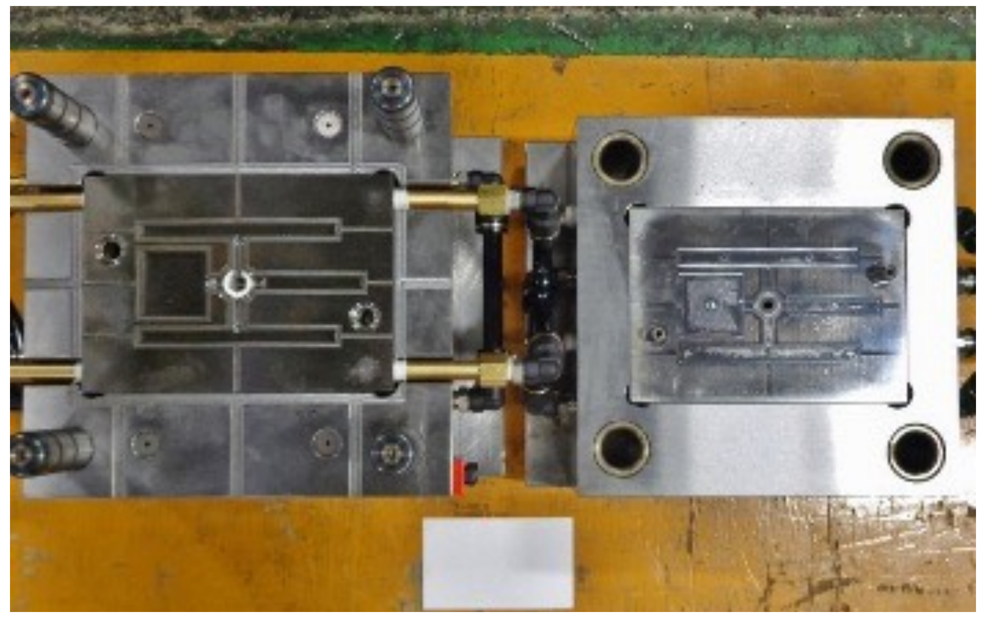
- **SiPM-on-strip technology**
  - Technology developed for CALICE high-granularity scintillator-strip ECAL
  - High granularity with reduced number of readout channels (×1/10)
- **Challenges for this R&D**
  - Wider and longer strip
  - Light yield and uniform response
  - Possibility of double SiPM readout
- **Scintillator material production (US)**
  - Scintillator pellet with high light yield
  - R&D on reflective coating
- **Injection moulding (Japan)**
  - Technology developed for CALICE Sc-ECAL

outside scope of US-Japan program due to limited budget

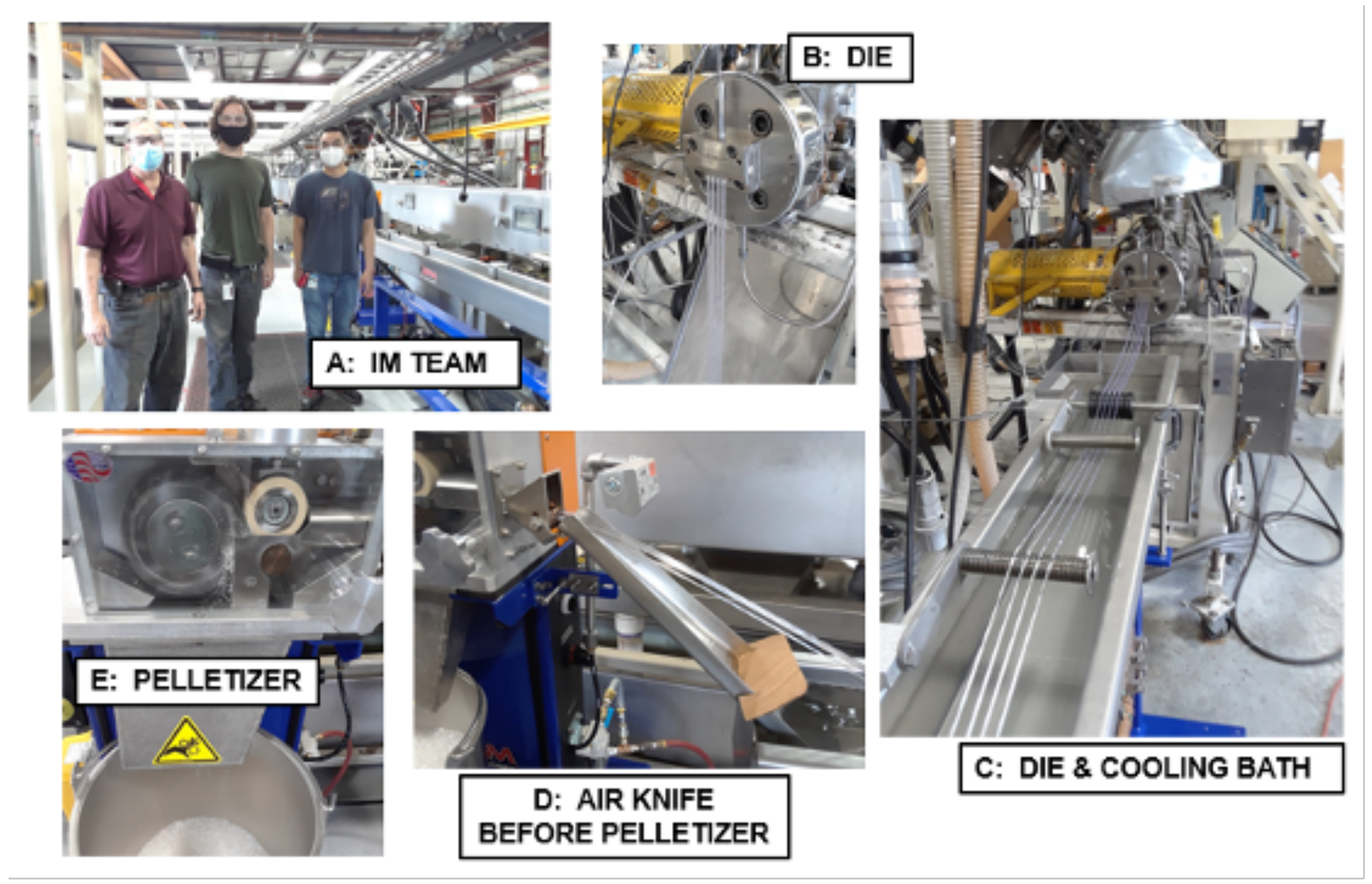
Strip-SiPM optical coupling (Tokyo, Shinshu)



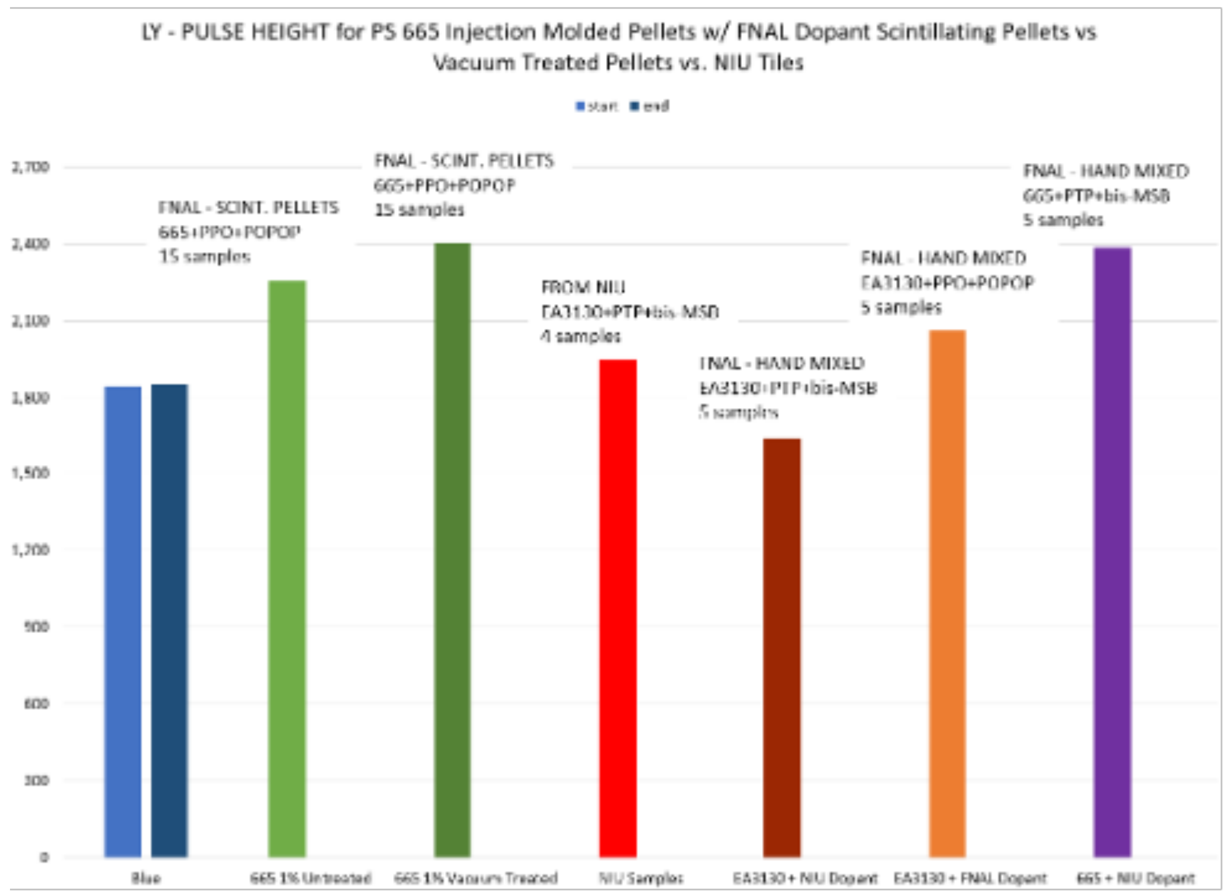
Metal moulding for scintillator strip (Tokyo, Shinshu)



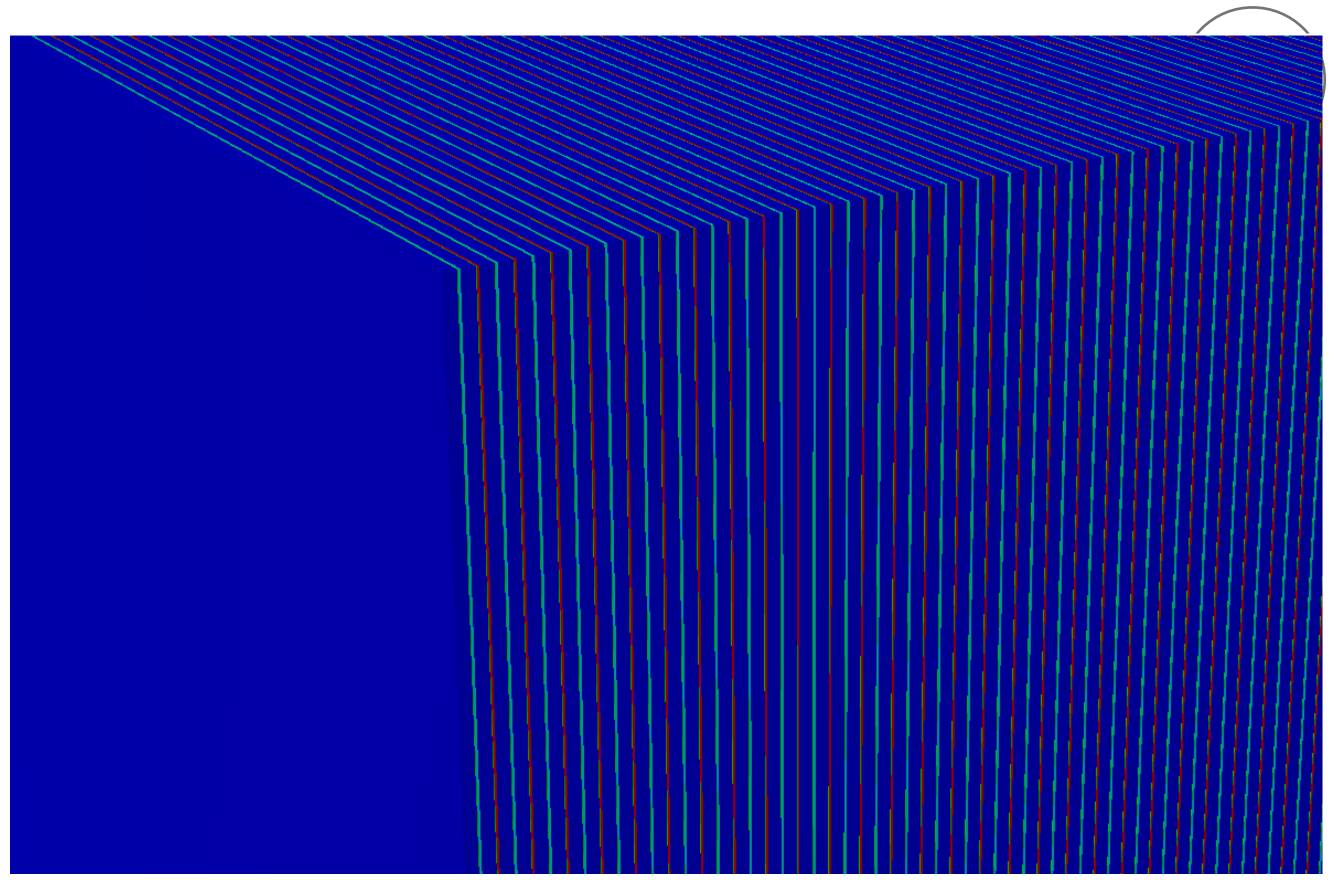
Equipments for scintillator pellets production (Fermilab)



Light yields for scintillator pellets (Fermilab)

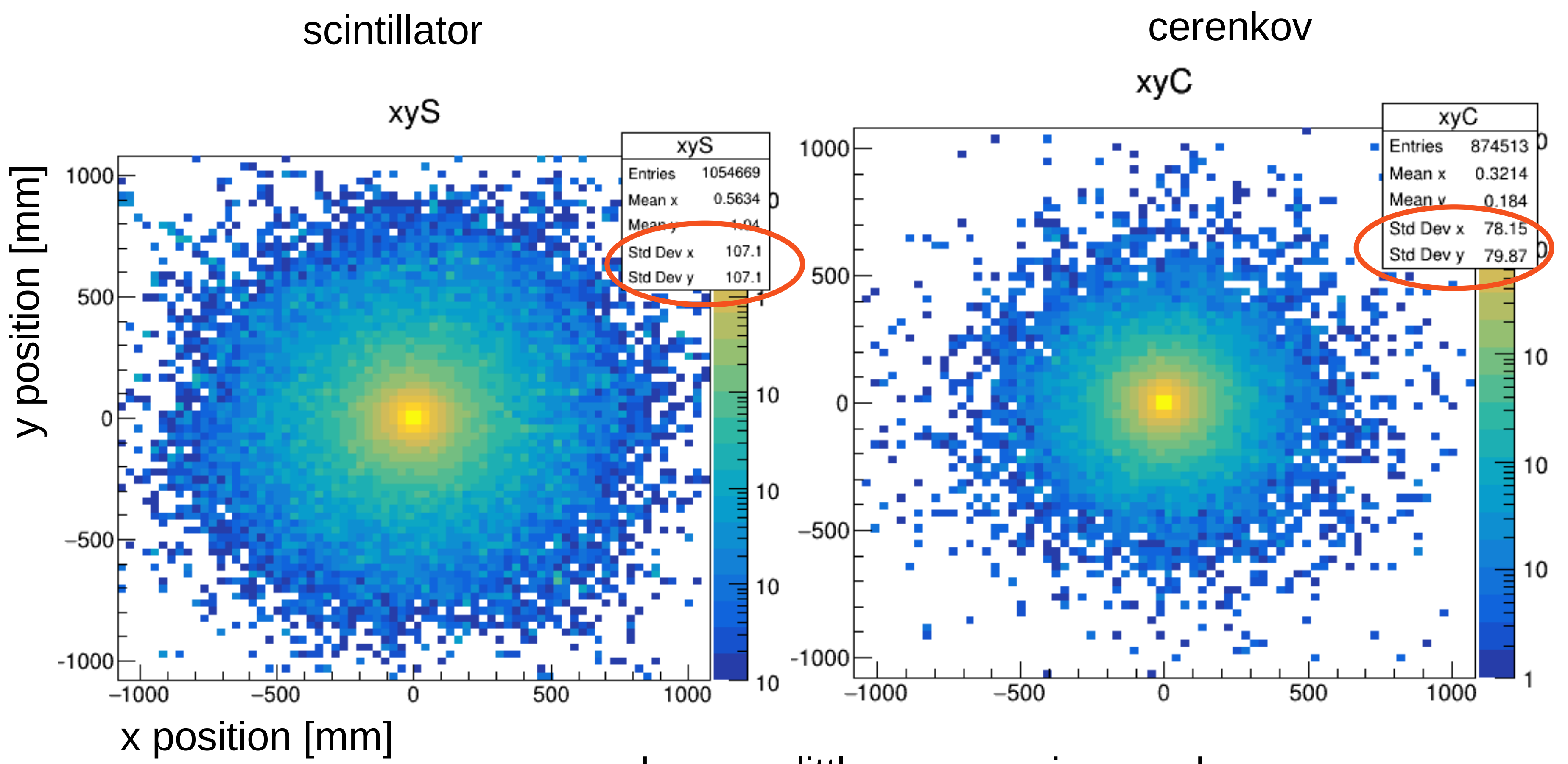


Simulation Study



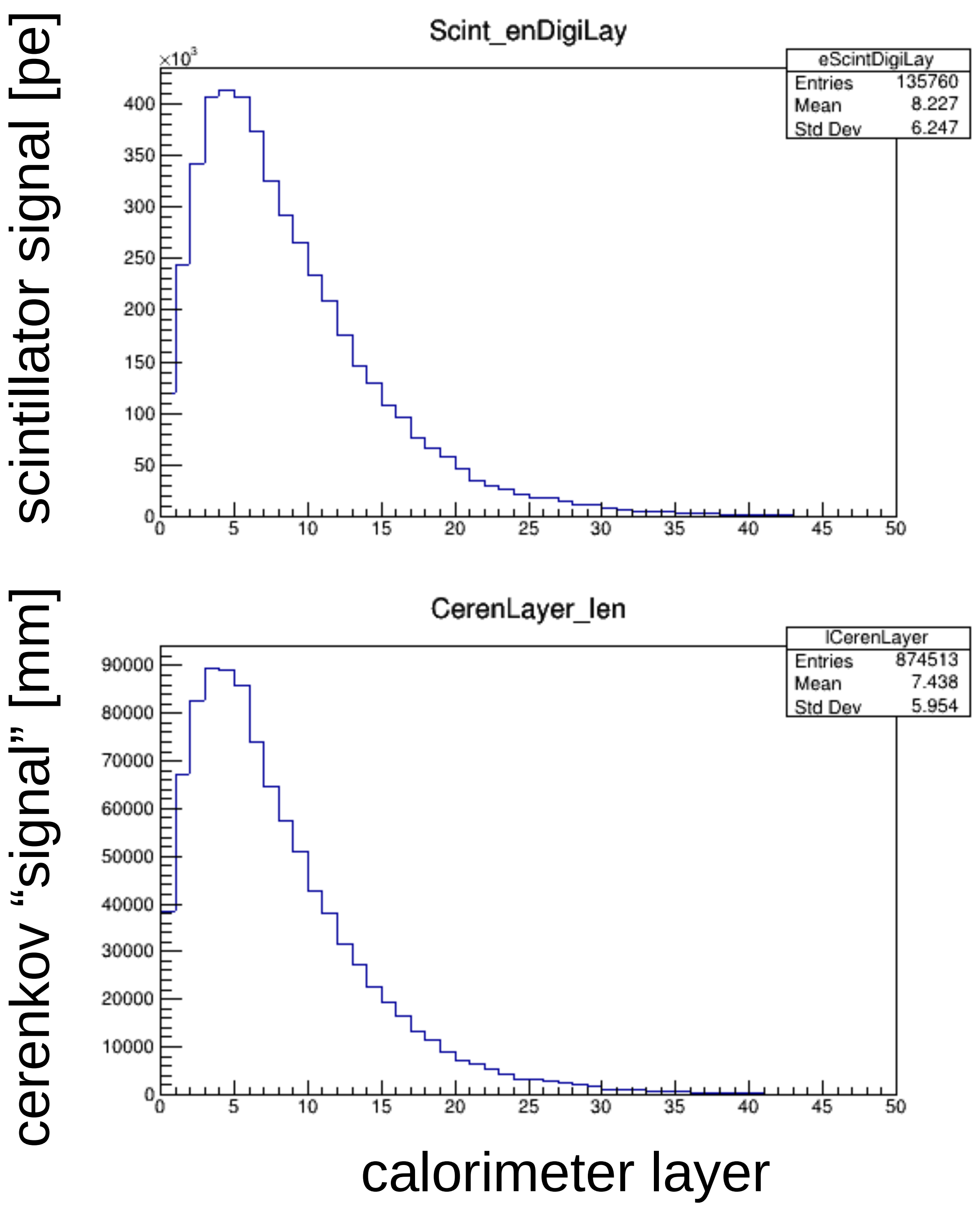
- Setup
  - Based on AHCAL test beam setup
  - Large stack instrumented with 30x30mm^2, 3mm-thick tiles, total size 2.16 x 2.16 x 2.133 m^3
  - Alternate layers of plastic scint / sapphire
- Digitisation
  - Scintillator: 10p.e./MIP, 10k-pixel SiPM
  - Cherenkov: Count superluminal path length within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

Transverse profile: 10GeV π^-



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

Longitudinal profile: 10GeV π^-



Summary

- **New R&D for new calorimetric technique to address crucial requirements for calorimeters at future collider experiments started**
  - 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
  - Excellent timing resolution of $\mathcal{O}(10\,\mathrm{ps})$ targeted
  - Can be applied to other projects as timing detector
- **Scintillation detector**
  - SiPM-on-strip technology
  - 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