ZDC activities in Shinshu

Kentaro Kawade
Shinshu Univ.

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Our Activities on the ePIC-ZDC Development

- We are participating in the development of the ePIC-ZDC
- Started ZDC simulation studies since 2023
  - Particularly interested in the Λ^0 reconstruction using the ZDC
- Involved in the beam test of the ECal prototype led by the Taiwan group
  - Contributing to data analysis
- Within the Japanese collaboration, we are exploring the addition of silicon detector layers to the ZDC
  - Want to contribute both through simulation studies and hardware prototyping
- The current status and initial results of these efforts will be shown in the slides

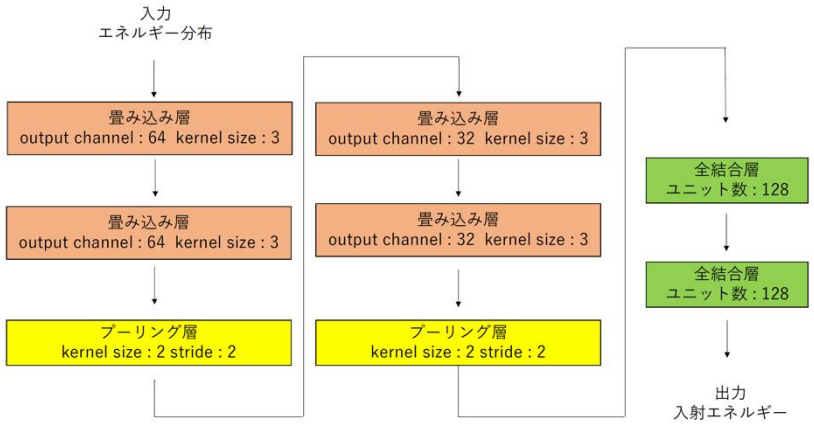
Simulation study

Early studies Ⅰ: neutron rec. w/ CNN

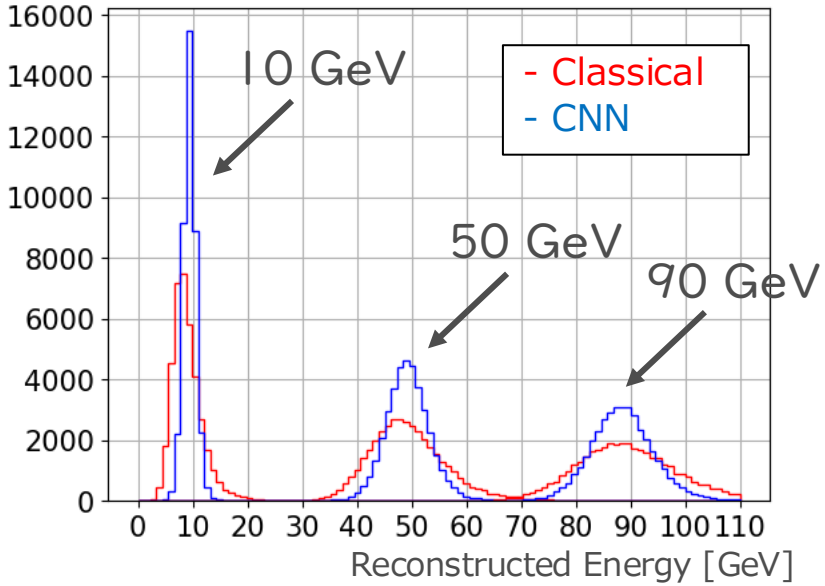
- Done around March 2024
- Energy reconstruction by
  - Classical method

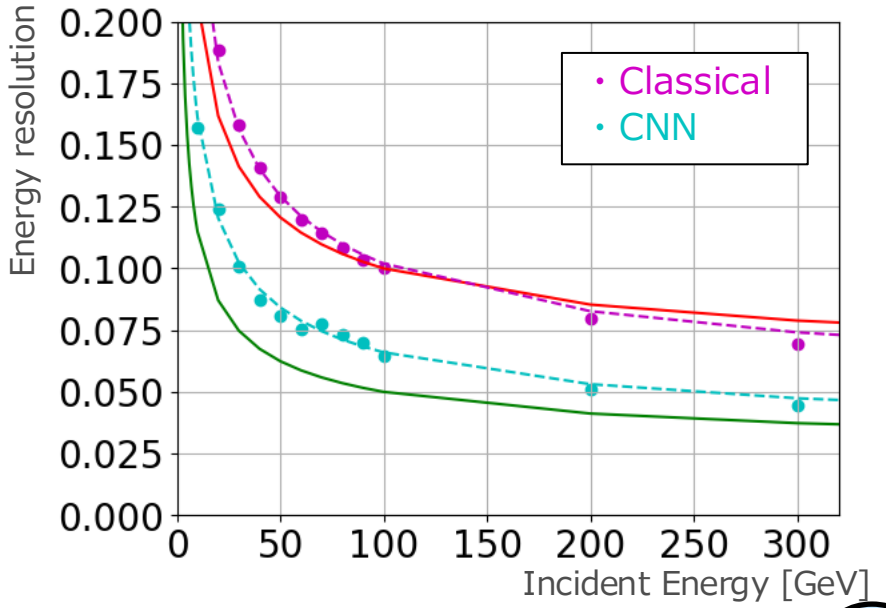
$$E = \mathrm{aE}_{WSi} + \mathrm{bE}_{PbSi} + \mathrm{cE}_{Hcal}$$

    - ✓ note that this based on old ECCE design
      → But, easy to update to recent design
  - CNN



  - Compared the reconstruction performance
    - Slight improvement



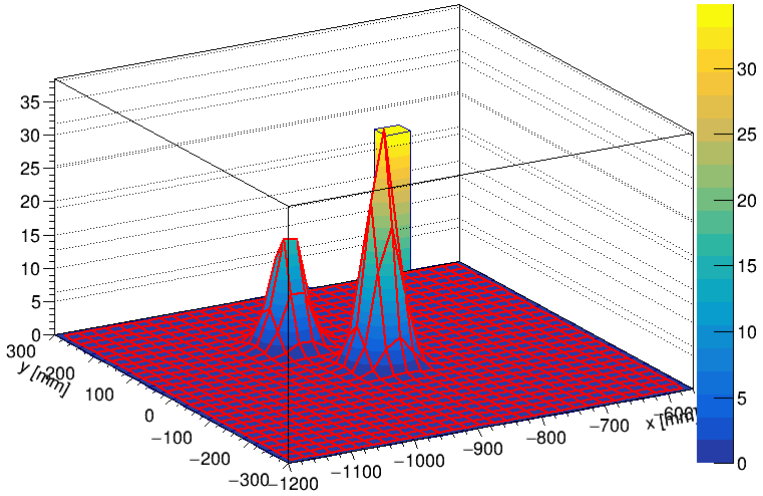


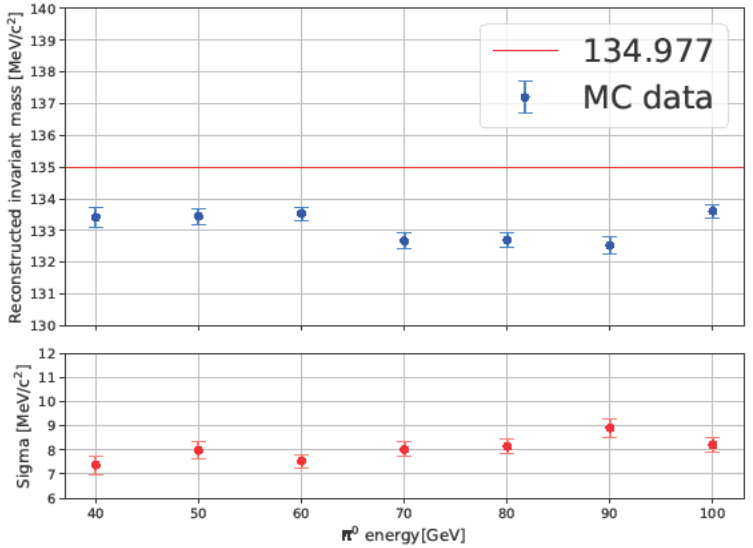
Early studies 2; Pi0 reconstruction

- Done March 2025
- Aim to study basic Λ^0 reconstruction performance, but started from **pi0 reconstruction** study
  - Energy scale calibrated by single photon simulation
  - 2D hit position search to find two photon peaks from pi0
  - Distribute visible energy according to peak heights

$$M_{\gamma\gamma} = \sqrt{2E_{\gamma_1}E_{\gamma_2}(1-\cos\theta)}$$

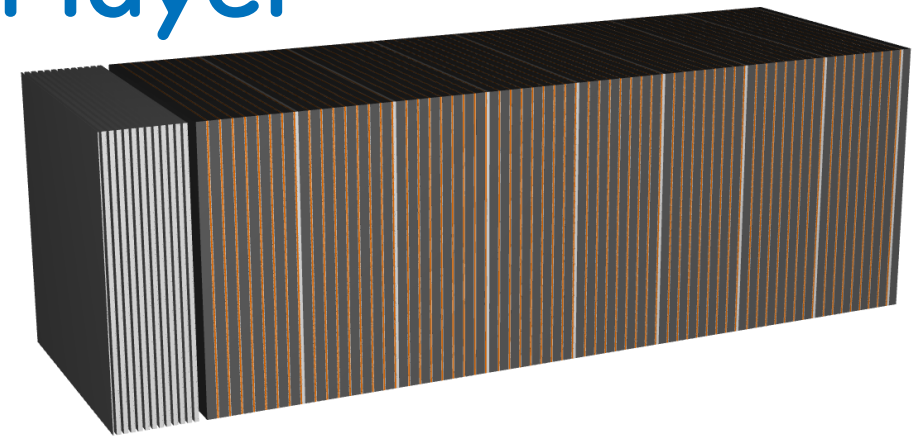
  - We can see clear pi0 mass peak
  - Can convert pi0 decay vertex in z

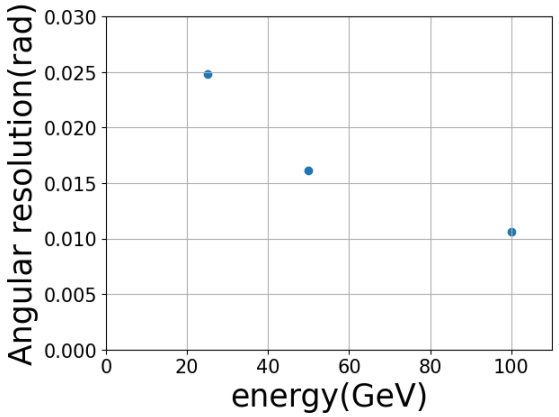


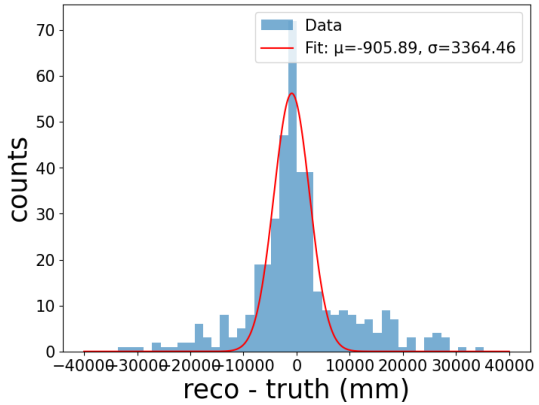


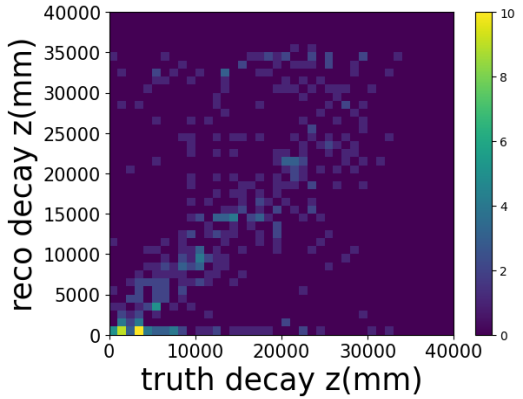
Early studies 3; ZDC with WSi layer

- Done March 2026
- Aim improve Λ^0 reconstruction performance, WSi layer is used instead of Crystal ECal
  - 500 um pitch sensors
  - Modified geometry
    - 3x3 pad (1cm × 1cm) layers
    - 1+3 pixel (0.5mm × 0.5mm) layers
- Results
  - Angle resolution with linear fitting
    - hit points from weighted mean in 2D
    - 10 mrad to 25 mrad
  - then, pi0 angle reconstruction by linear fitting assuming same SV
    - sigma 2.7 mrad, negative bias
  - Lambda decay vertex reconstruction at the same time
    - sigma ~ 3.3 m



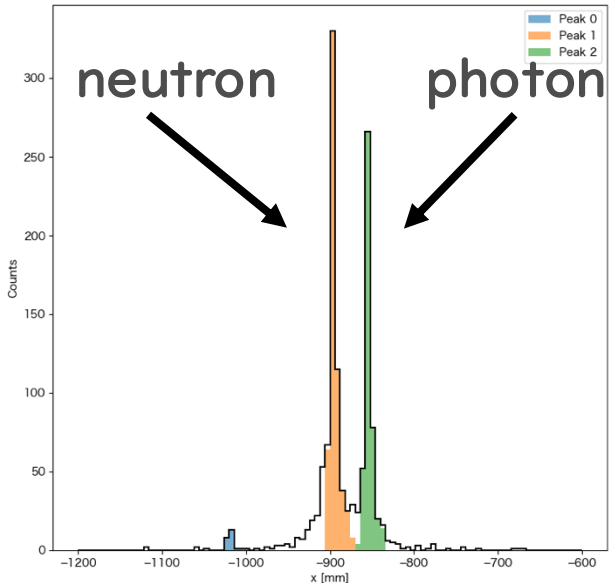


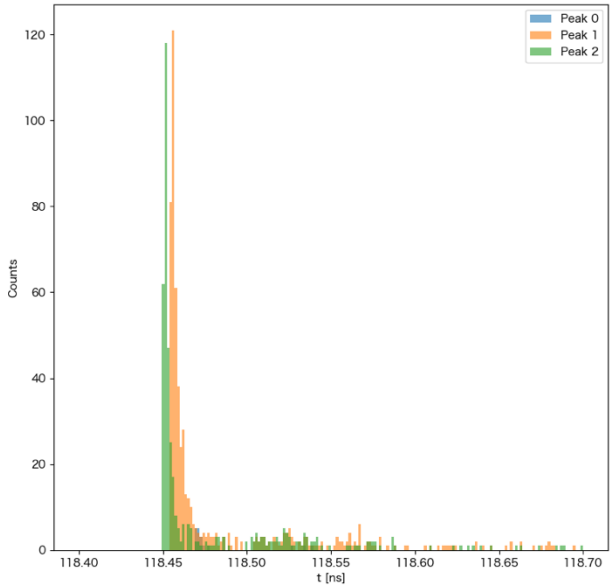




Current study; ZDC with Timing information

- Timing information is also added simulation outputs
  - Assuming AC-LGAD pixel sensor w/ 0.5mm granularity
  - Bonus?
    - Background rejection? Need dedicated study
- Pixel layer
  - Aim to improve positioning resolution
- Reconstruction
  - GNN based reconstruction
    - Layer-by-layer hit clusters → Nodes
    - Edge between nodes in same layer or layer next to each other
  - Develop more sophisticated algorithm with Ramaiah group

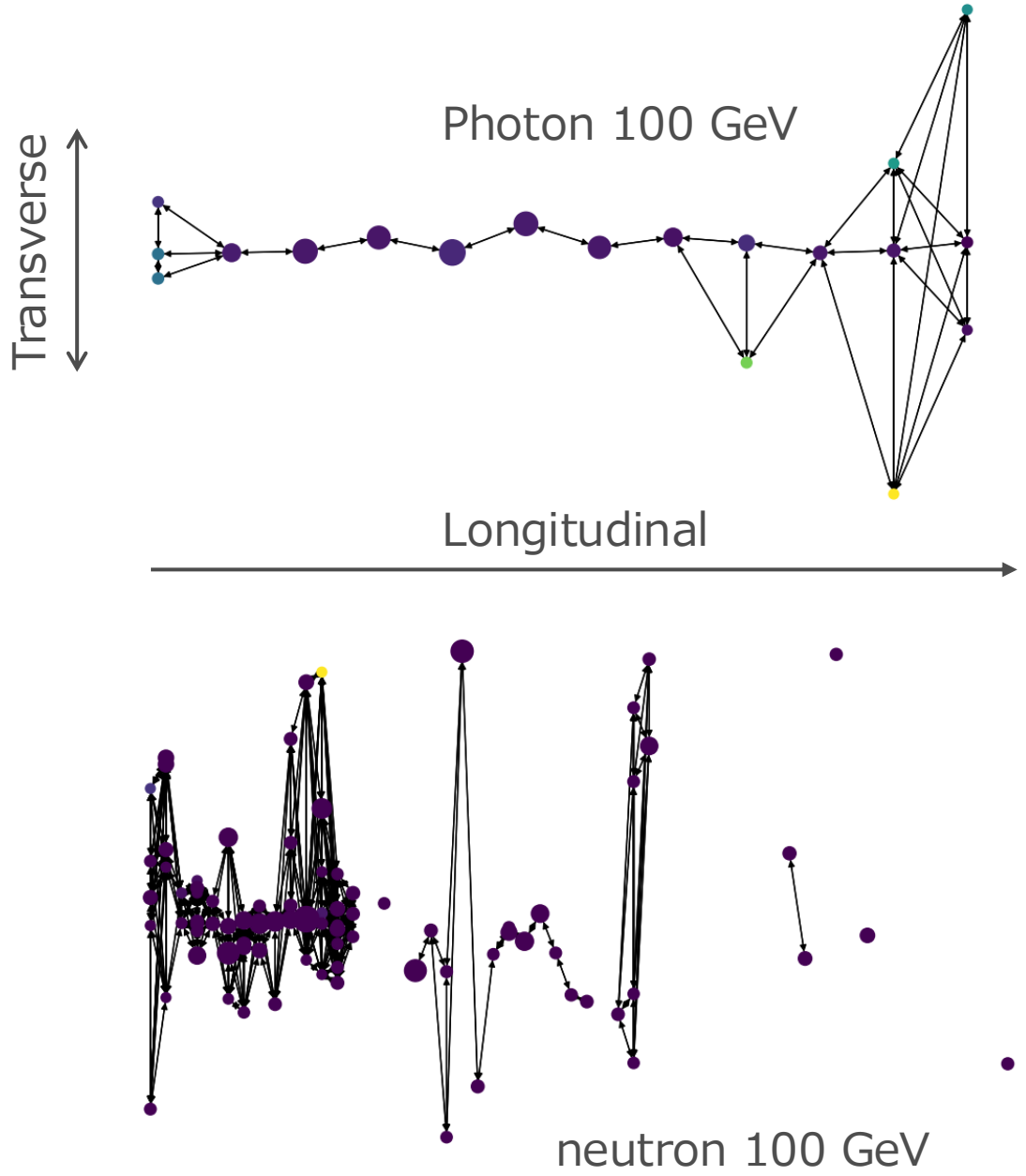




Graph Neutral Network

- Pre Hit clustering in each layer
  - 3D x-y-z map for all ZDC layers (including HCal)
  - Node features
    - sum dE in cluster ($\sum eDep$)
    - mean x, y
    - z (layer)
    - mean timing ($\overline{\text{time}}$)
  - Edges are connected only between neighboring layers
    - 3 distance for edge features

- Aim to Reconstruct energy, direction, PID
  - For lambda, need to identify sub-clusters within hits

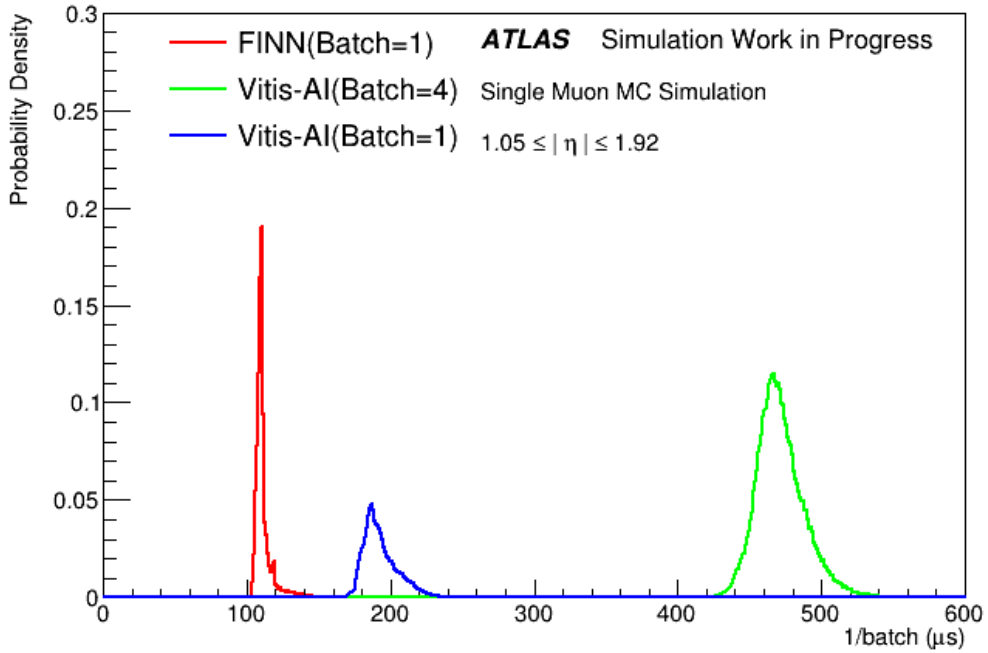


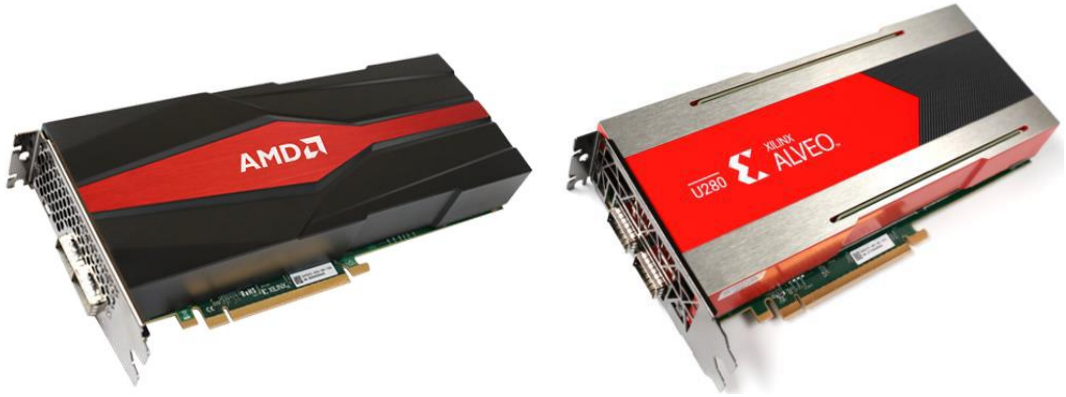
Future work: Advanced AI/ML Reconstruction on FPGA

- Using a position-sensitive ZDC detector as a test case
  - We will develop ML-based reconstruction methods (CNN/GNN?)

- Aim to explore the full potential of AI/ML approaches in ZDC event reconstruction
- Also interested to AI/ML based background rejection
  - simple AI or kind of anomaly detection

- Implement them on FPGA (Versal)
  - We have small experience at ATLAS
  - Depending on interest from DAQ team



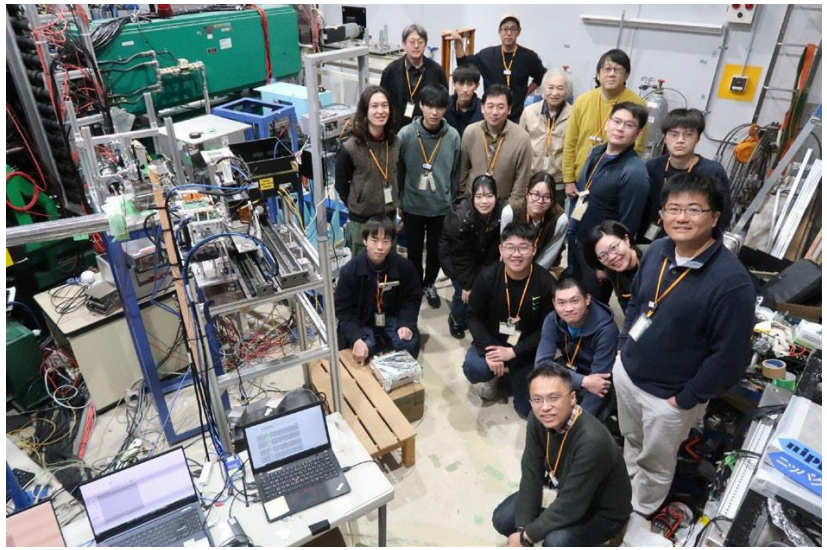


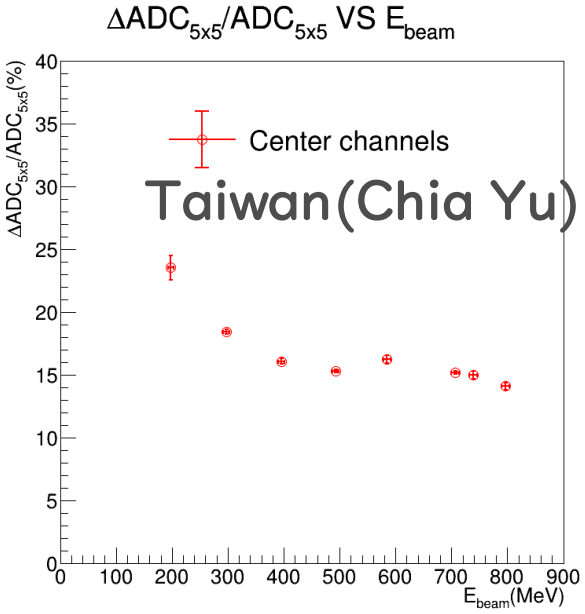
Hardware contributions

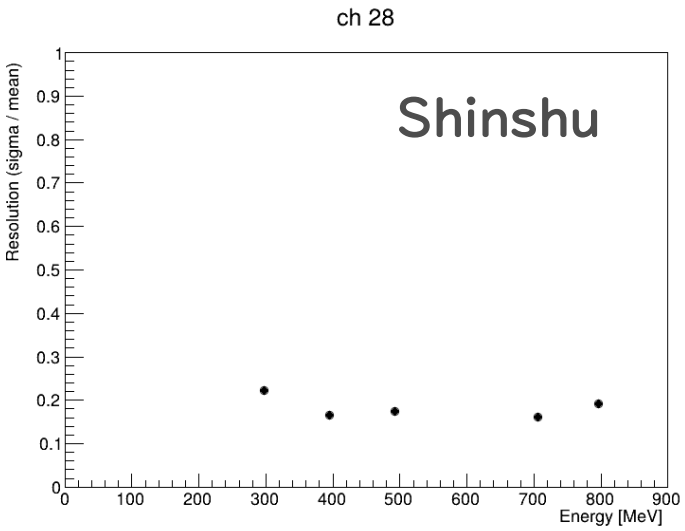
Participate ZDC-ECal prototype beam test

- Participate beam test at 2024 and 2025
  - Developments done by Taiwan
  - Good for future Japanese activity

- Cross-check beam test data analysis
  - Reproduce Taiwan results with independent analysis





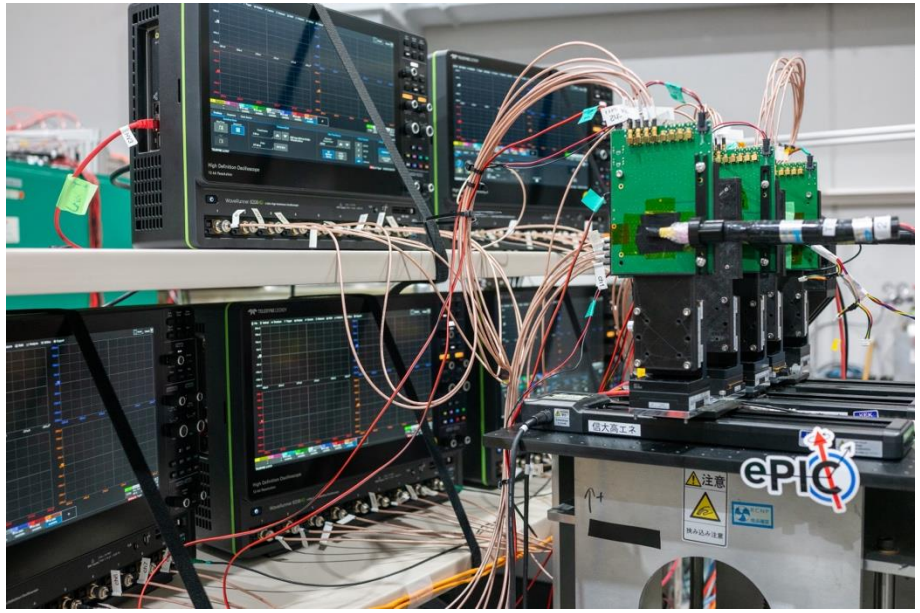


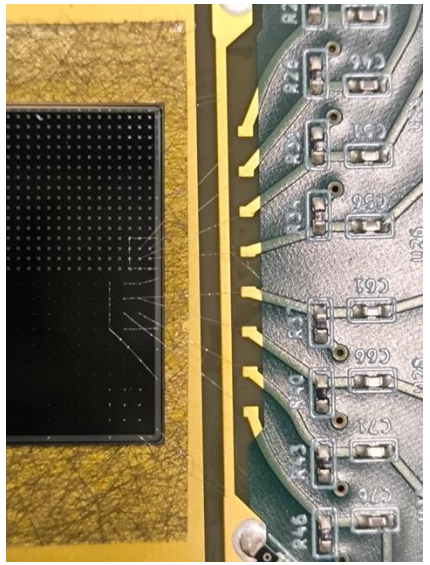
Small test during strip beam time

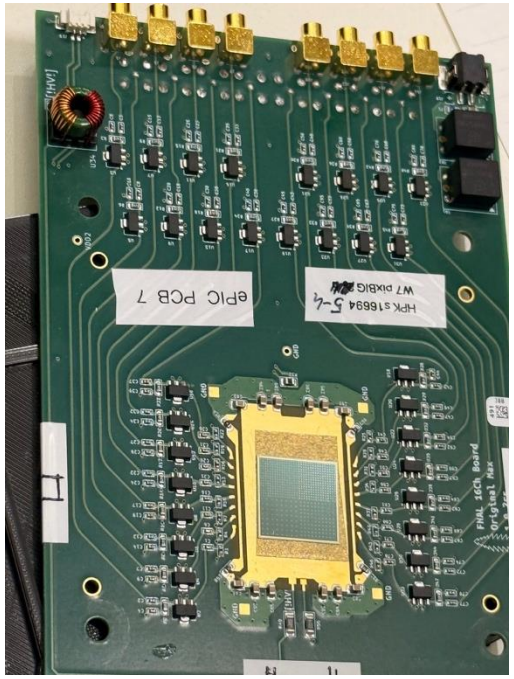
- 2025/12@ DESY
- 2026/2 @ KEK
- 2026/3 @ RARiS

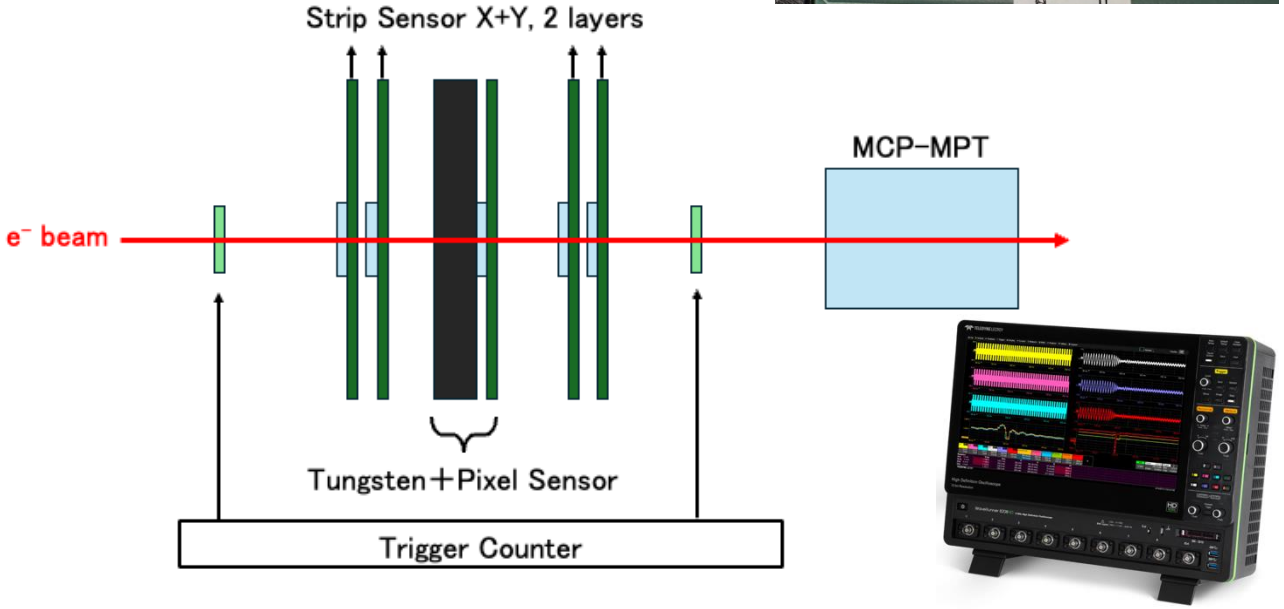
KEK beam test

- 4.0 GeV electron beam
- 1 radiation length tungsten in front of pixel



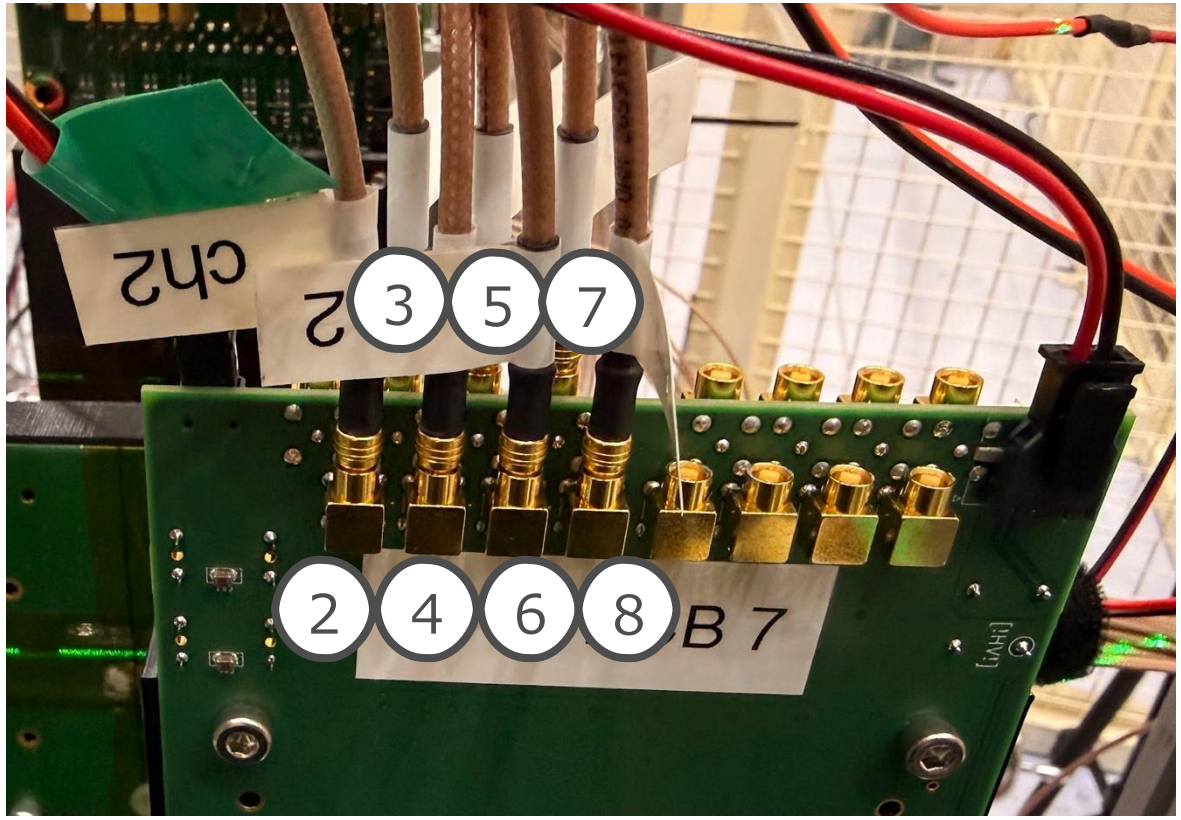


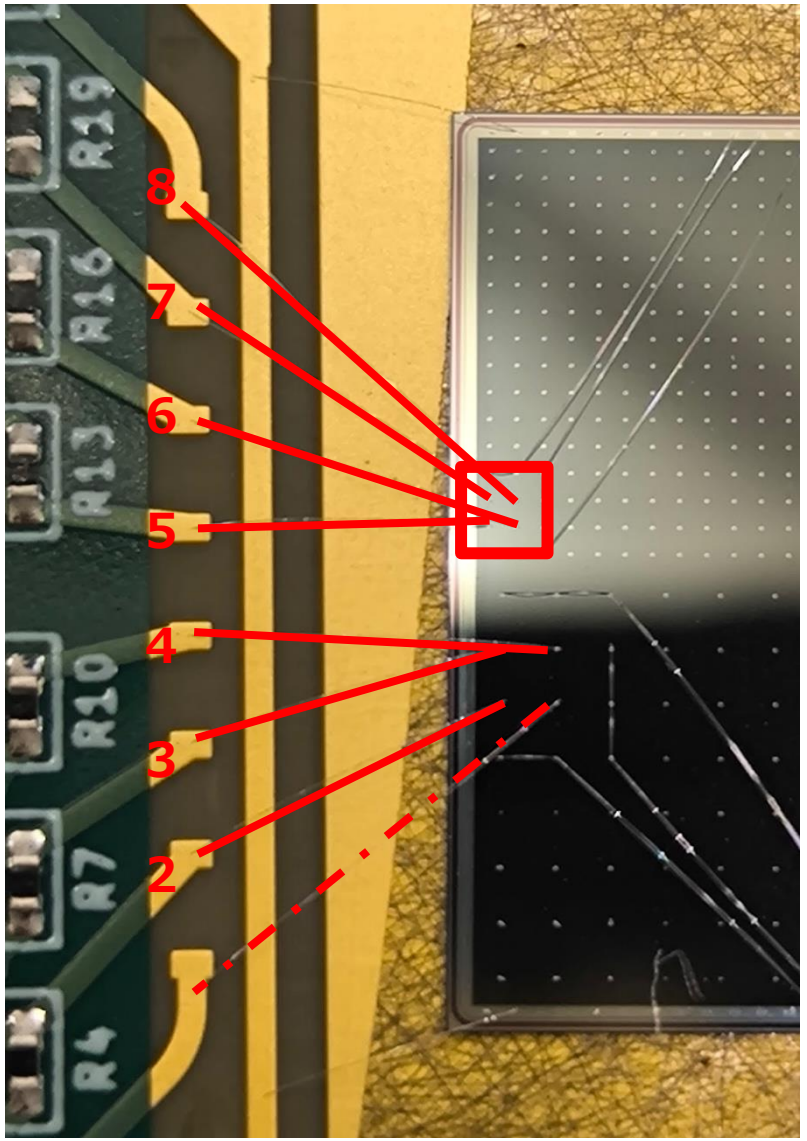




Wave shape measurement w/ oscilloscope

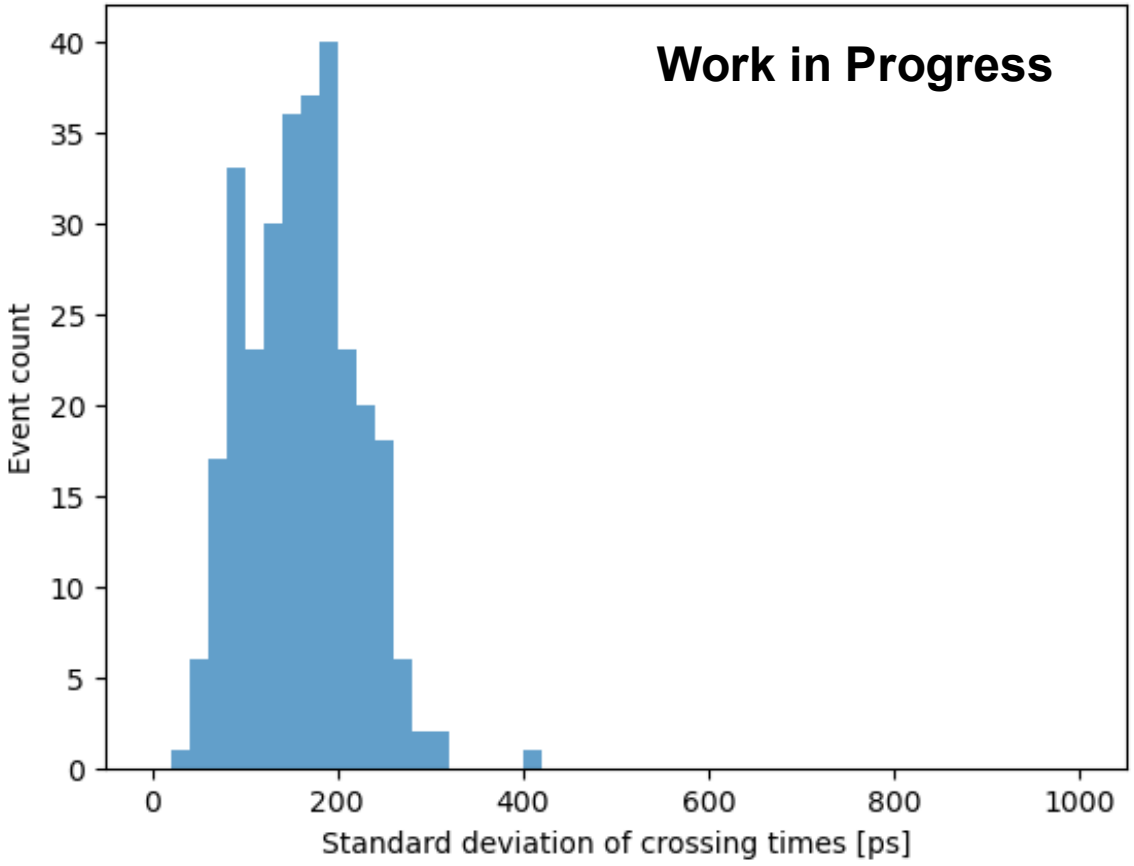
Pixel sensor





- We use prototype pixel sensor from Simone (UCSC)
- ch5～ch8：500um pitch
- ch1：MCP-PMT (timing reference)

Timing fluctuation between channels

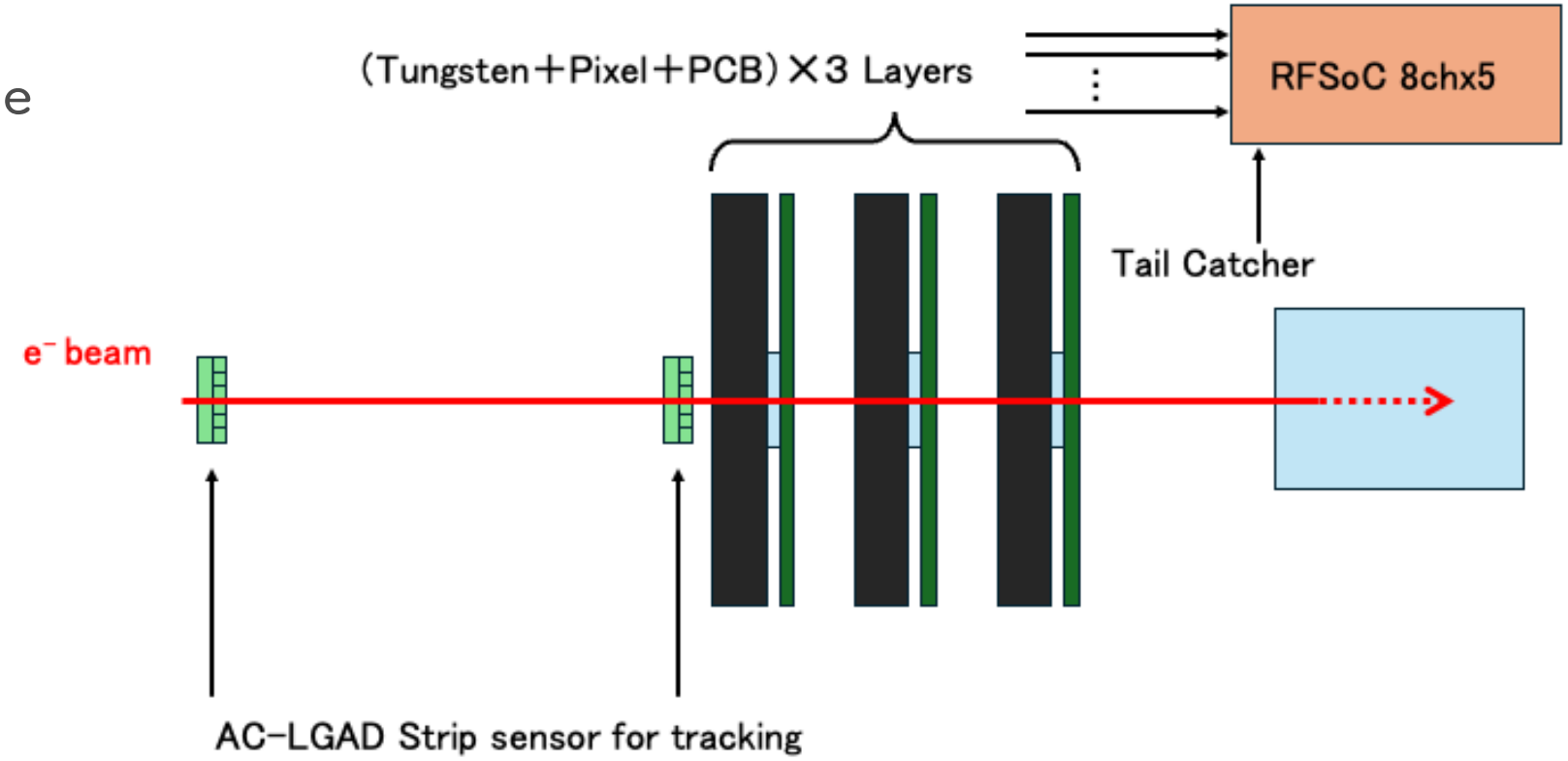


- ~180 ps timing fluctuation
- Considerations
  - Observing multiple particle within shower
  - No Time-Walk correction applied
  - Evaluation of the intrinsic timing resolution of the system itself has not yet been conducted
    - Need precise tracking (~20um)
    - Readout by WaveRunner+ WavePro system is our first attempt

Next beam test; Target

- We plan to perform next beam test this month at KEK
  - 25 May – 2 Jun
- Construct 3 layer prototype W+AC-LGAD pixel sensor

- Experimental Target
  - Energy determination
  - Linearity
  - Position resolution
  - Timing distribution
  - etc



Summary

- Simulation work
  - Basic ML application to ZDC neutron reconstruction
  - Initial studies of pi0 reconstruction performance
  - ZDC performance study with Si layer just started
    - some results on next WS
  - Collaboration with Ramaiah, India for AI/ML application

- Hardware work
  - Interested to develop W+AC-LGAD prototype
  - Performed small beam test during BTOF test beam campaign
  - Plan to test them at KEK w/ electron 2-5 GeV