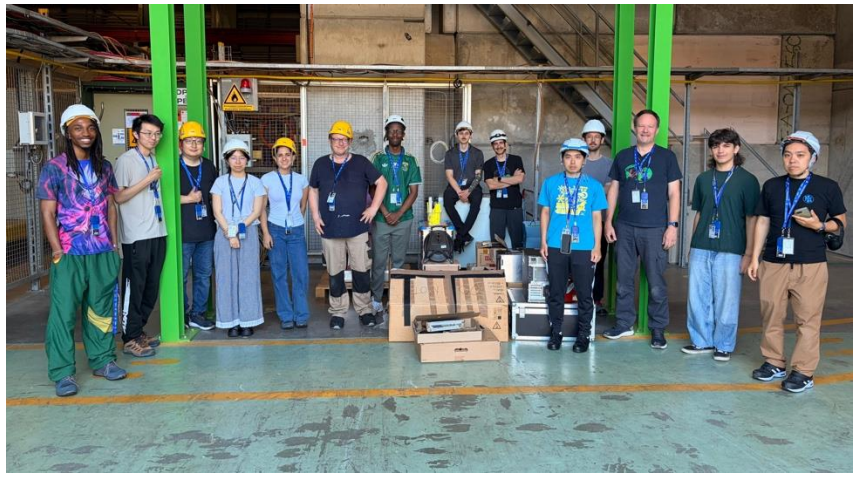


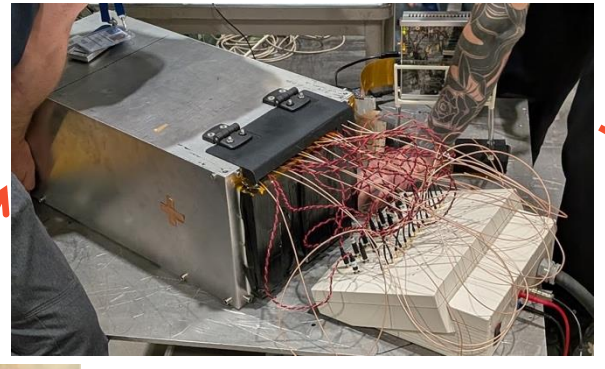
Performance Evaluation of the 15-Layer SiW-ECAL Technological Prototype with CERN SPS Beam Test Data

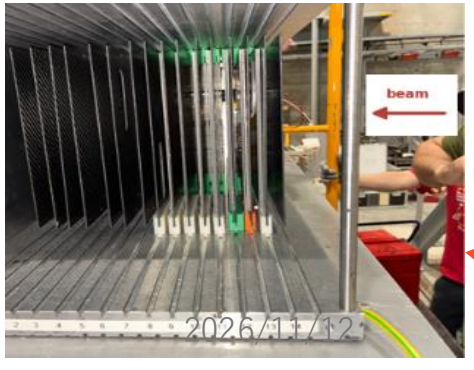
T. Kamiyama, V. Boudry, J. M. Hernandez, J. Nanni, D. Zerwas, J. Maalmi, D. Breton, A. Thiebault, J. Jeglot, A. Gonnin, H. Liang, Y. Shi, V. Pérez, T. J. Pule, O. A. Peinazo, T. Suehara, B. Gautier, M. Ruan, R. Poeschl, X. Xia, A. Irles, E. K. Nkadimeng, M. Almanza-Soto, C. Blanch, S. Huang, C. Orero

SiW-ECAL test beam at CERN in June 2026



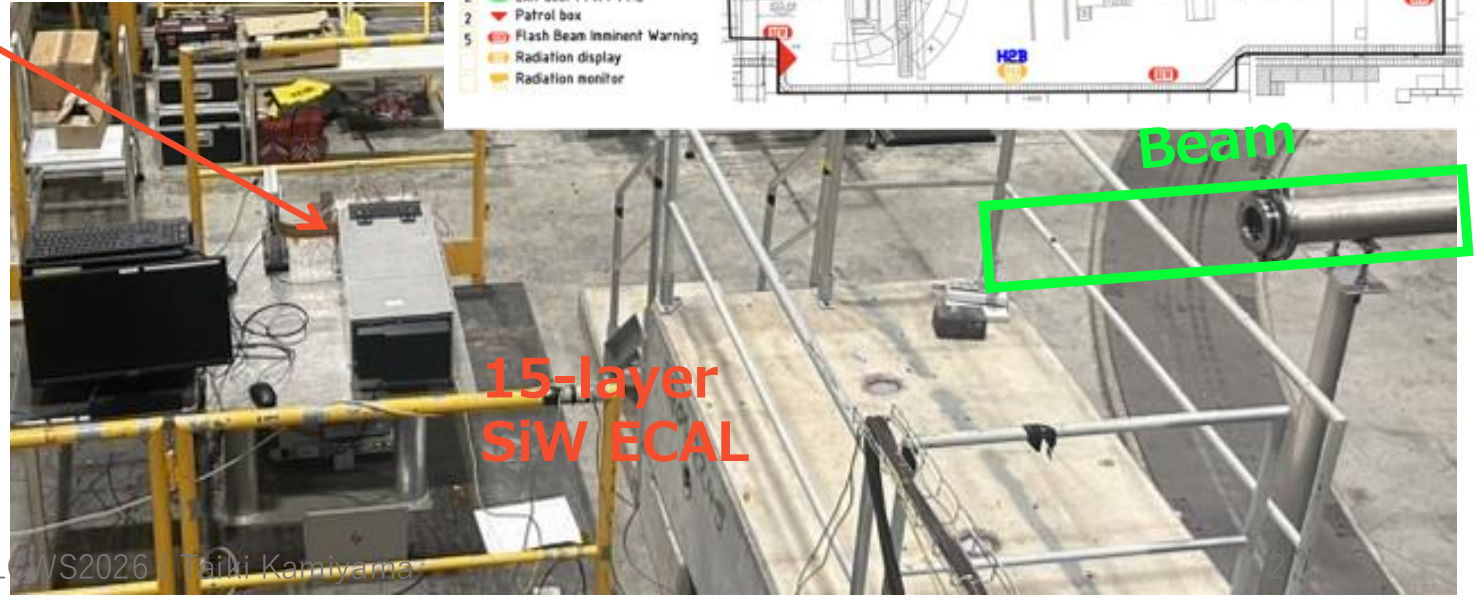
- Test beam at the SPS H2 beam line, June 17th to 25th.
- One of the **most successful** SiW-ECAL TB ever.

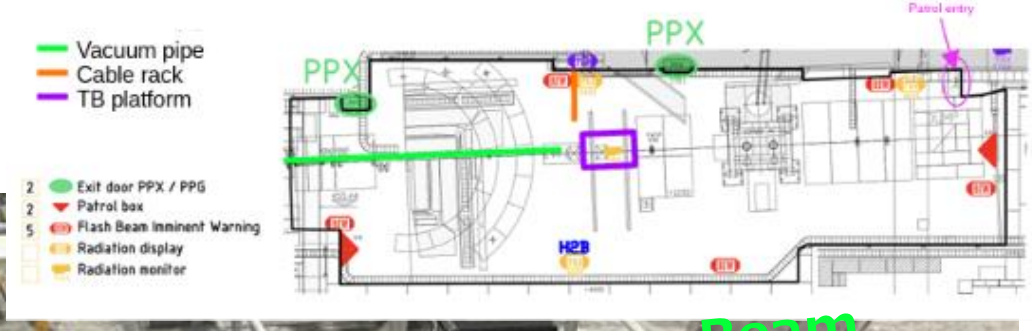




Active layer

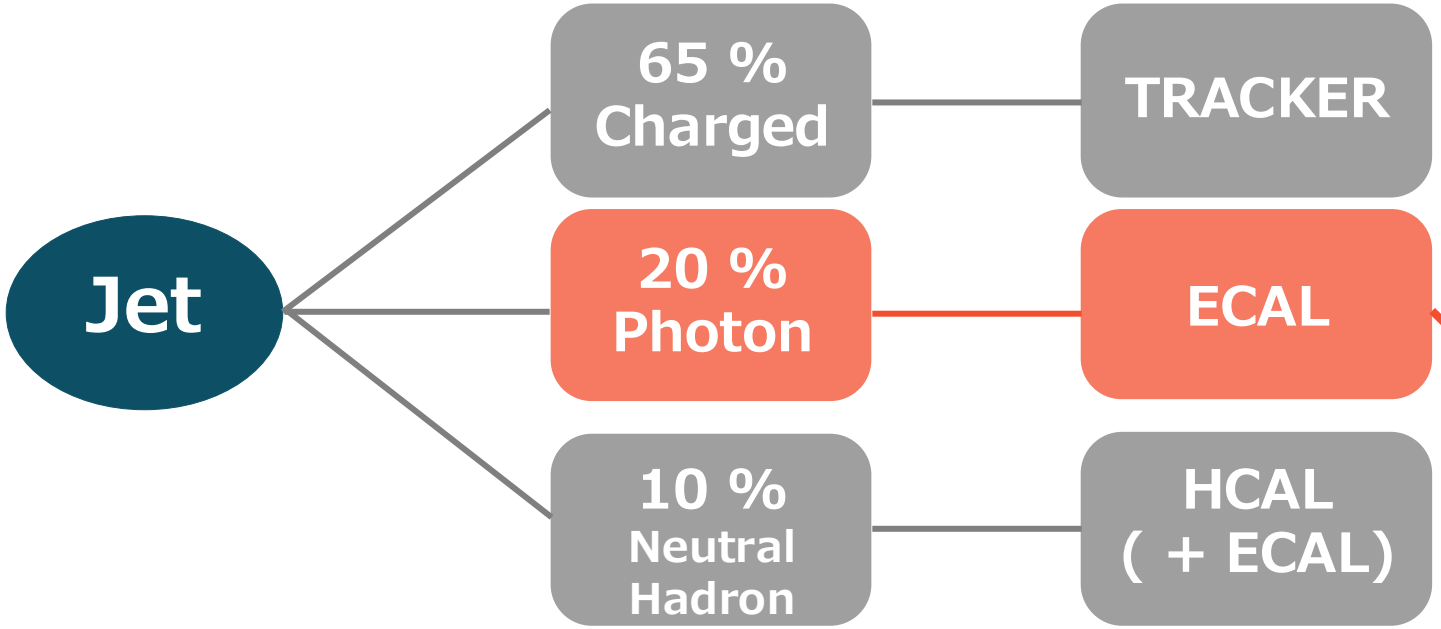




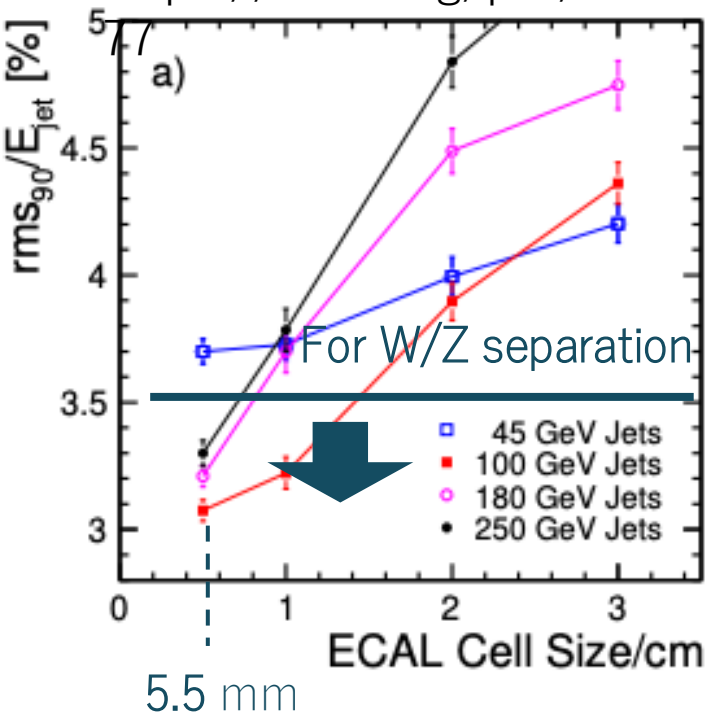


ECAL in Particle flow calorimeter system

Particle flow system



https://arxiv.org/pdf/0907.35



THIS STUDY

Highly granular SiW-ECAL

W absorber

→ **Compact showers**

Si pads

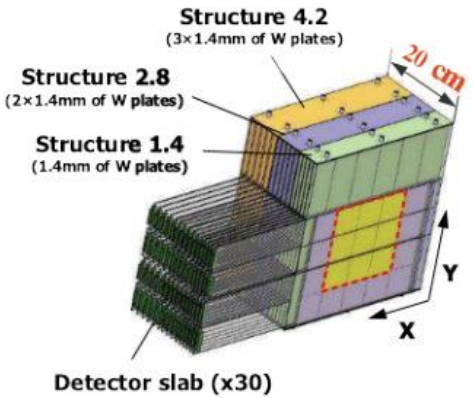
→ Fine shower imaging with $\mathbf{5.5}\ \boldsymbol{mm}$ cell

Calorimeter requirement

High granularity to separate nearby showers, especially, ECAL -> $\mathbf{5.5}\ \boldsymbol{mm}$ cell.

SiW-ECAL development roadmap

Physics prototype
2005-2011
Proof of principle



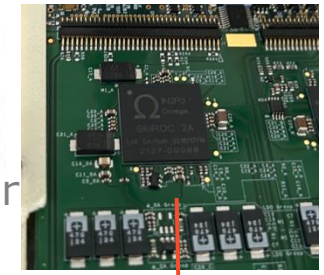
- **External RO**.
- $1\times1\ \mathrm{cm}^2$ cells.
- 30 layers, 10 k channels.

We are HERE

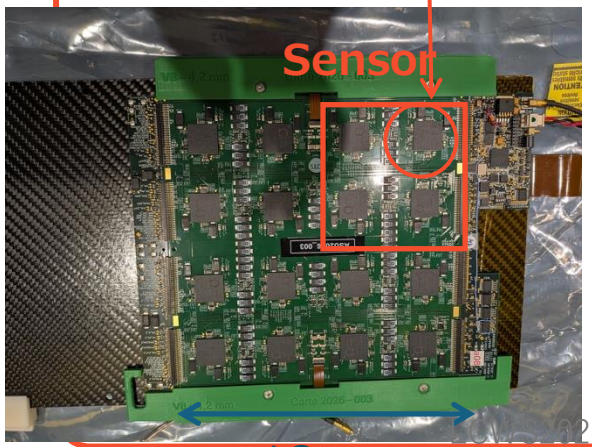
Technological prototype
Current stage
Integrated detector technology


Si sensor

SKIROC chip

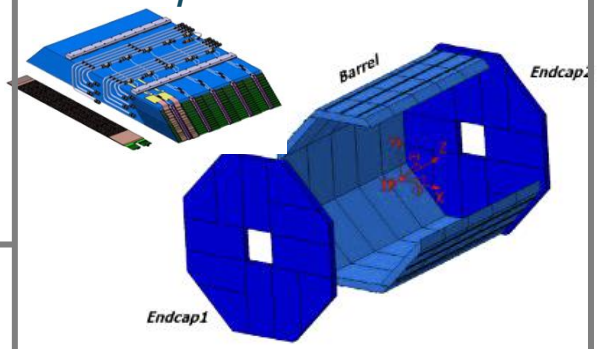


ASU



- **Embedded electronics**:
  - **4** sensor per FEV PCB.
  - **4 SKIROC2a ASICs** per each sensor.
- **Self-triggered**.
- **64**-channel per ASIC → 1024 ch per FEV
- 15 memories per ch (SCA).
- $\mathbf{5.5\ mm^2}$ cells.
- Sensor thickness: 500 or $650\ \mu\mathrm{m}$.

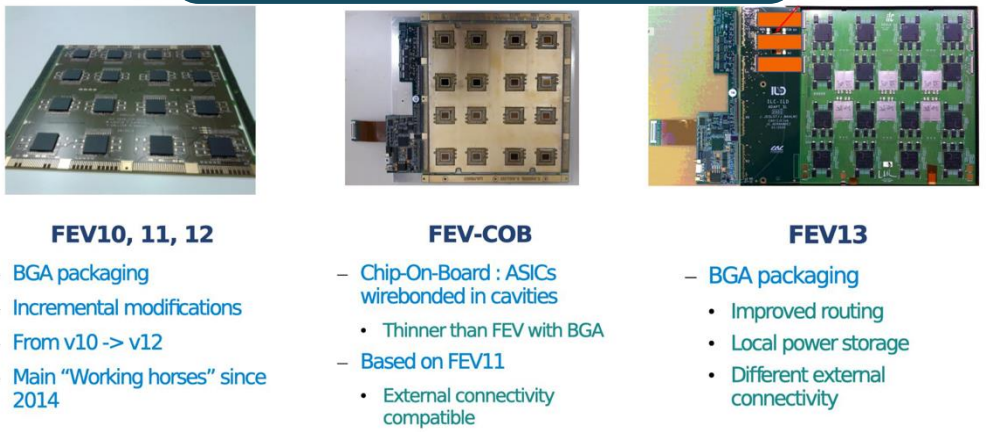
Pilot → full detector
Next stage
Scale-up and production



- Approximately 1M → 70M channels
- Cooling, power and DAQ integration
- **30 layers,** $\sim 24\ X_0$.

Reliable FEV2.1 production

TB2021 & 2022
@ DESY & CERN



FEV10, 11, 12
- BGA packaging
- Incremental modifications
- From v10 -> v12
- Main "Working horses" since 2014

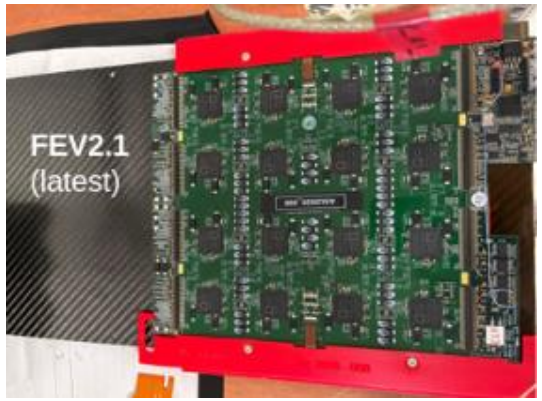
FEV-COB
- Chip-On-Board : ASICs wirebonded in cavities
  - Thinner than FEV with BGA
- Based on FEV11
  - External connectivity compatible

FEV13
- BGA packaging
  - Improved routing
  - Local power storage
  - Different external connectivity

- Multi-layer stack with three types of FEV designs.
- Inactive cells, wafer/PCB delamination, noise etc.

▶ FEV redesign

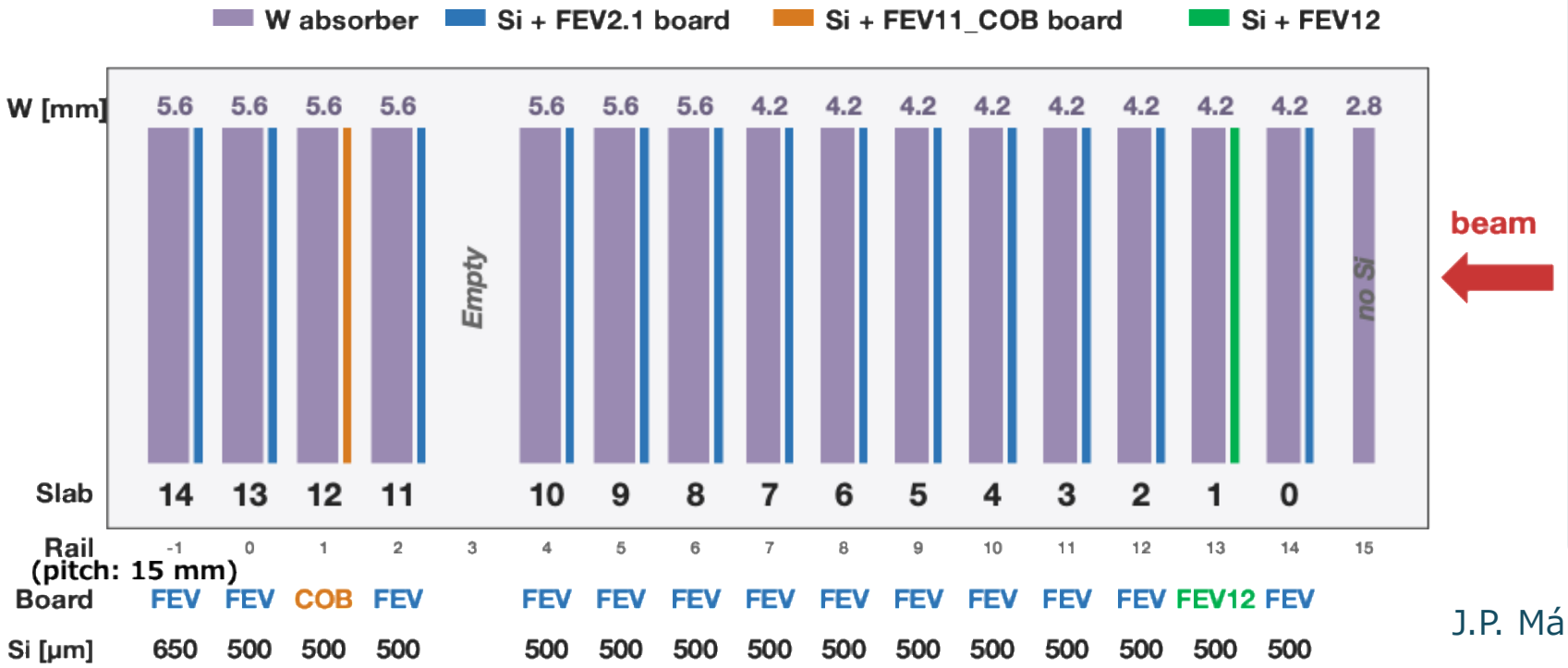
TB2025
@ DESY



- Tested two new FEV 2.1 boards.
- Both boards operated successfully.

▶ Production of 13 additional boards

2026 test beam configuration & goals



Nearly uniform

15 layers with FEV2.1

$\approx 20\, X_0$

96.5 % Active cells

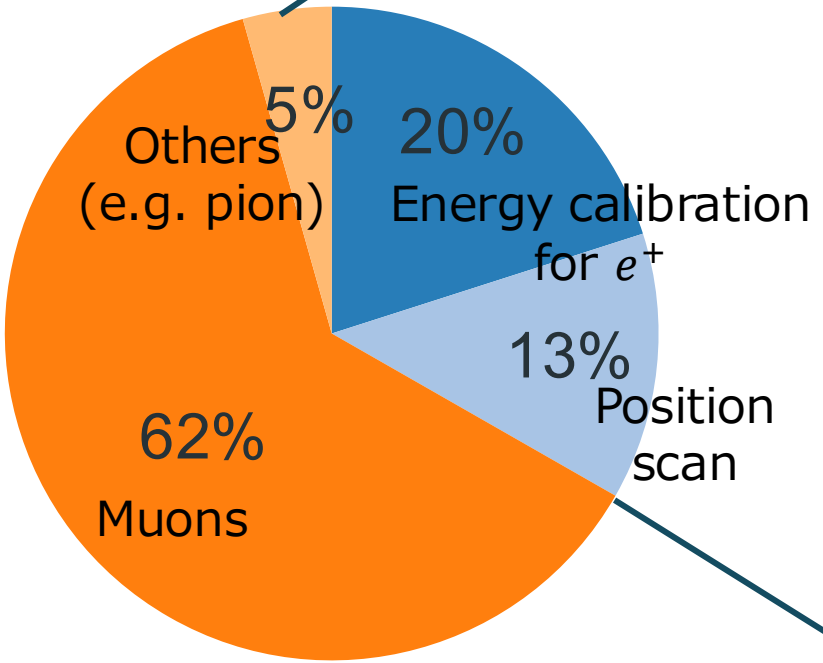
J.P. Márquez

Goal Electromagnetic performance over the full range energy, low-energy pion response and reference data for GEANT4.

Data collected

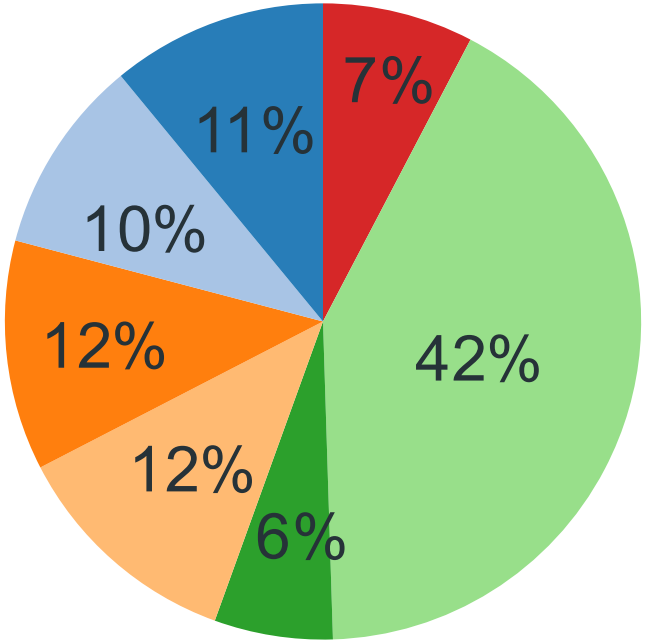
Campaign overview

27.8 M
events recorded



J.P. Márquez & V. Pérez

e^+ run



10.4 M events

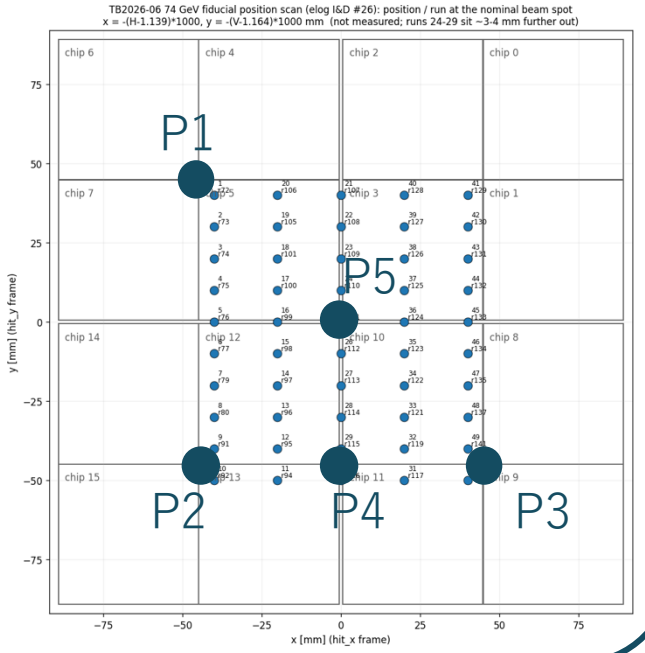
- 7.5 GeV
- 10 GeV
- 20 GeV
- 34 GeV
- 52 GeV
- 74 GeV
- 99 GeV

Scan positions:

- Energy scans
- Position scans

Angle scans:

$5\,°, 10\,°, 30\,° \,\&\, 45\,°$



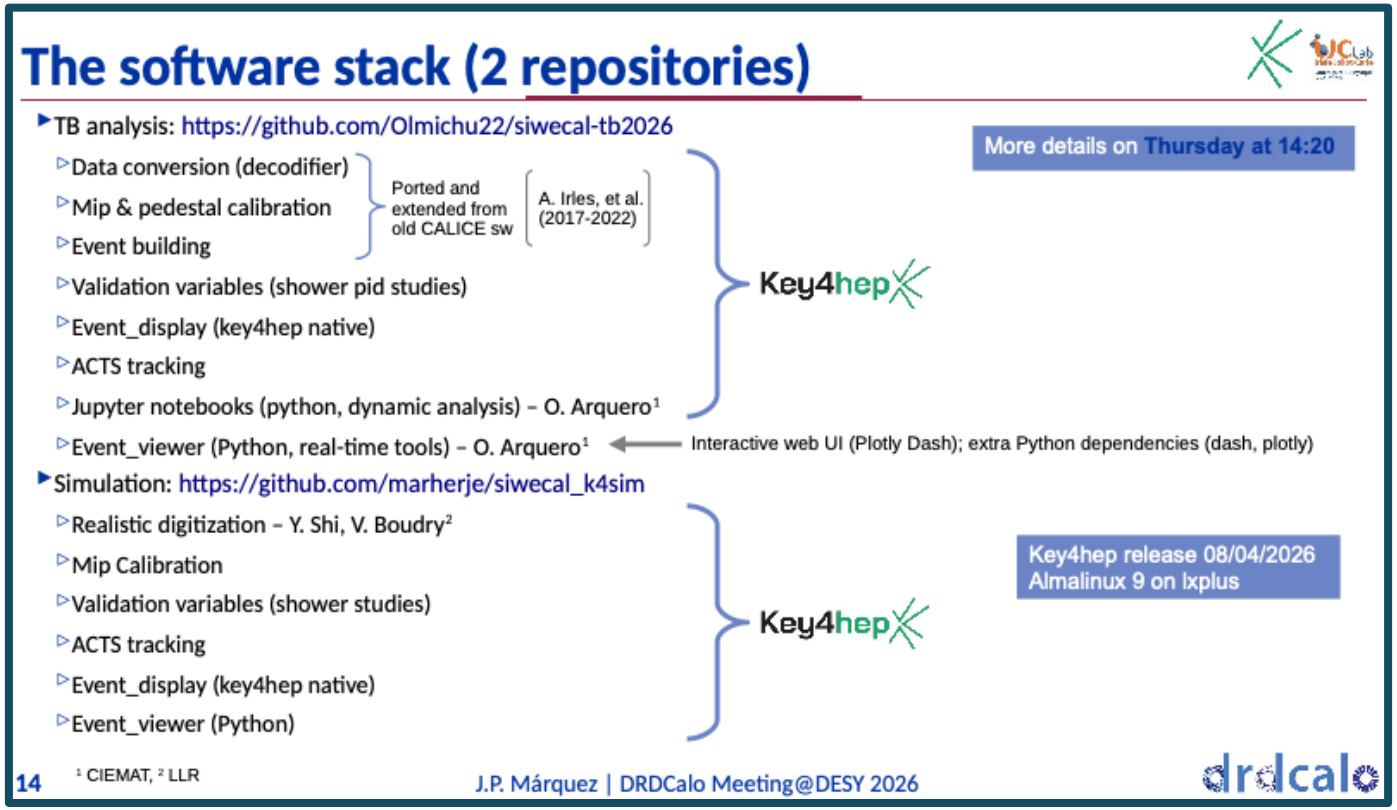
Software & ongoing analysis

Software foundation

- J.P. Márquez[A]
  - Established the framework and initiated the analysis effort.

Ongoing analysis

- O. Arquero[B]:
  - ML-based event selection
- **T. Kamiyama[C]** & T. J. Pule[D]:
  - Linearity & resolution studies
- V. Pérez[E]:
  - Uniformity scan analysis & documentation
- B. Gautier[E]:
  - Angle and position reconstruction



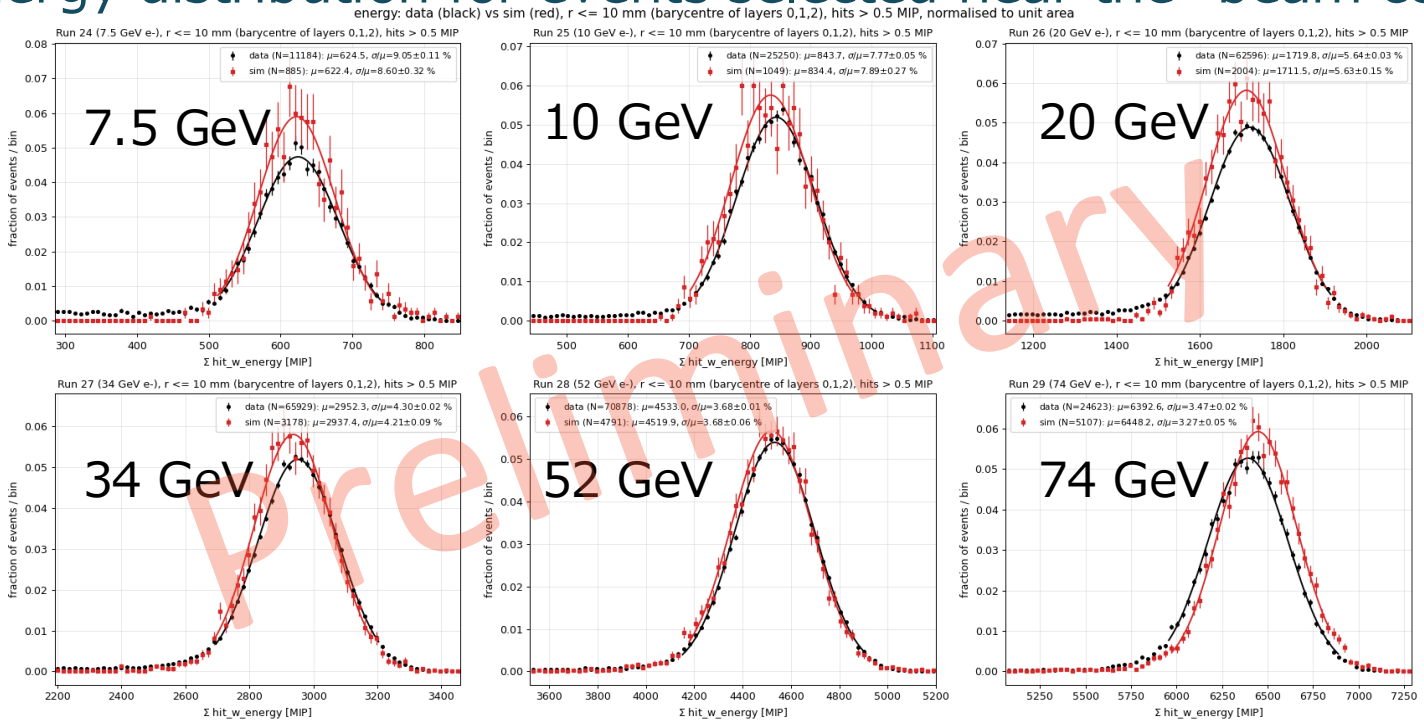
Note: This is not a complete list of contributors.

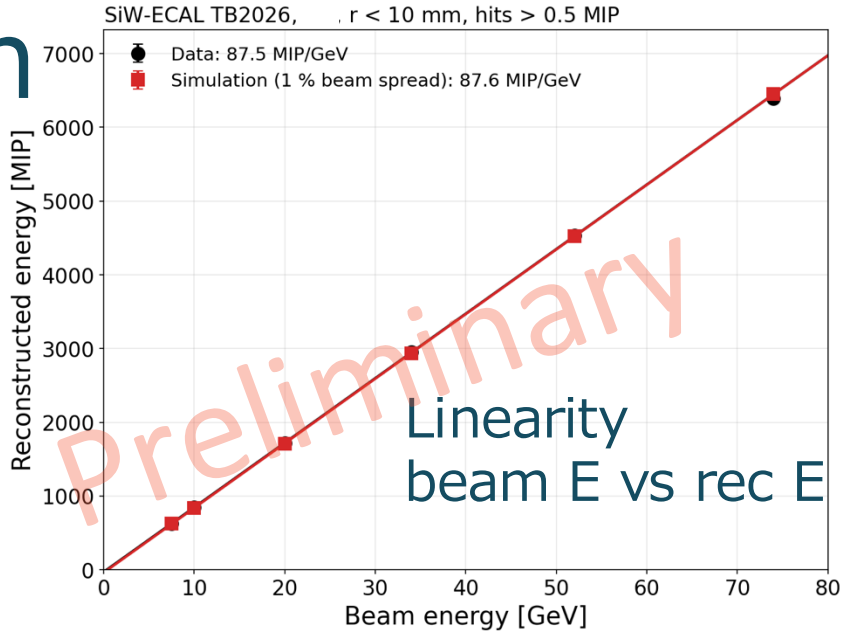
[A]IJCLab, [B]CIEMAT, [C]UTokyo, [D]U. Witwatersrand, [E]LLR

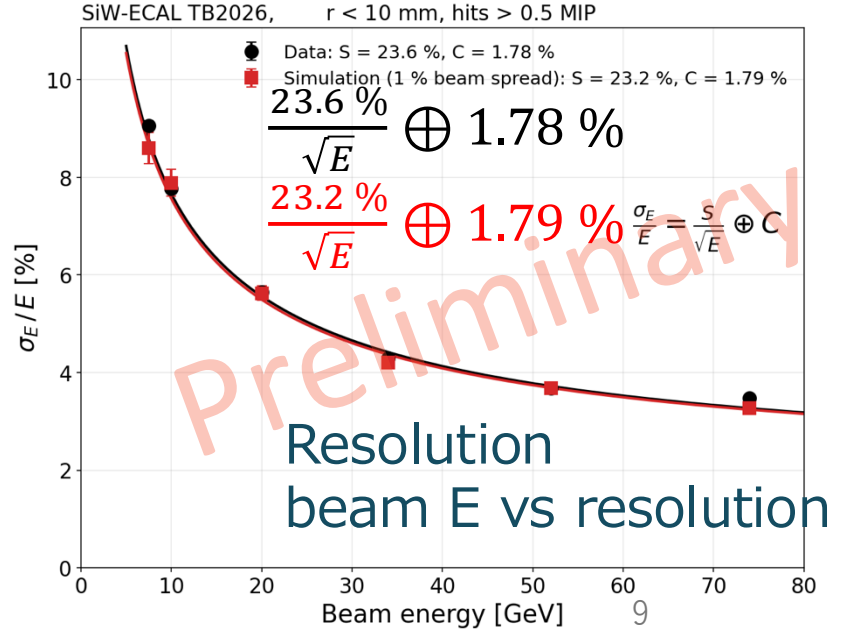
EM response: data-simulation comparison at pos. 2

Black: data, Red: simulation

Energy distribution for events selected near the “beam center”





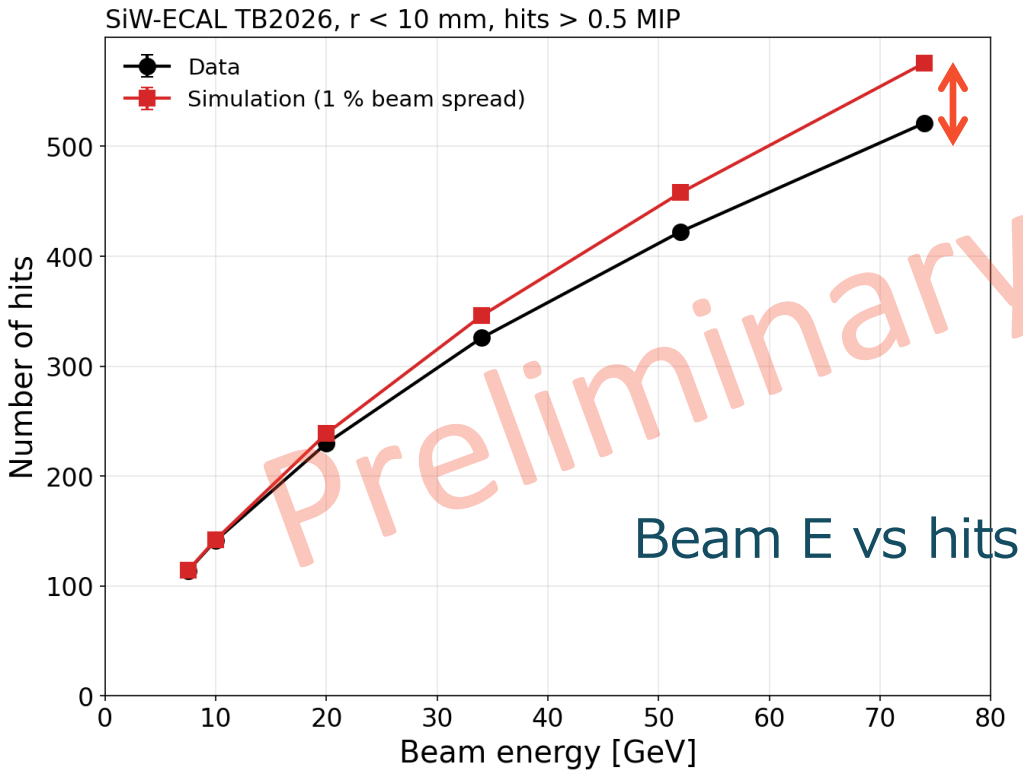


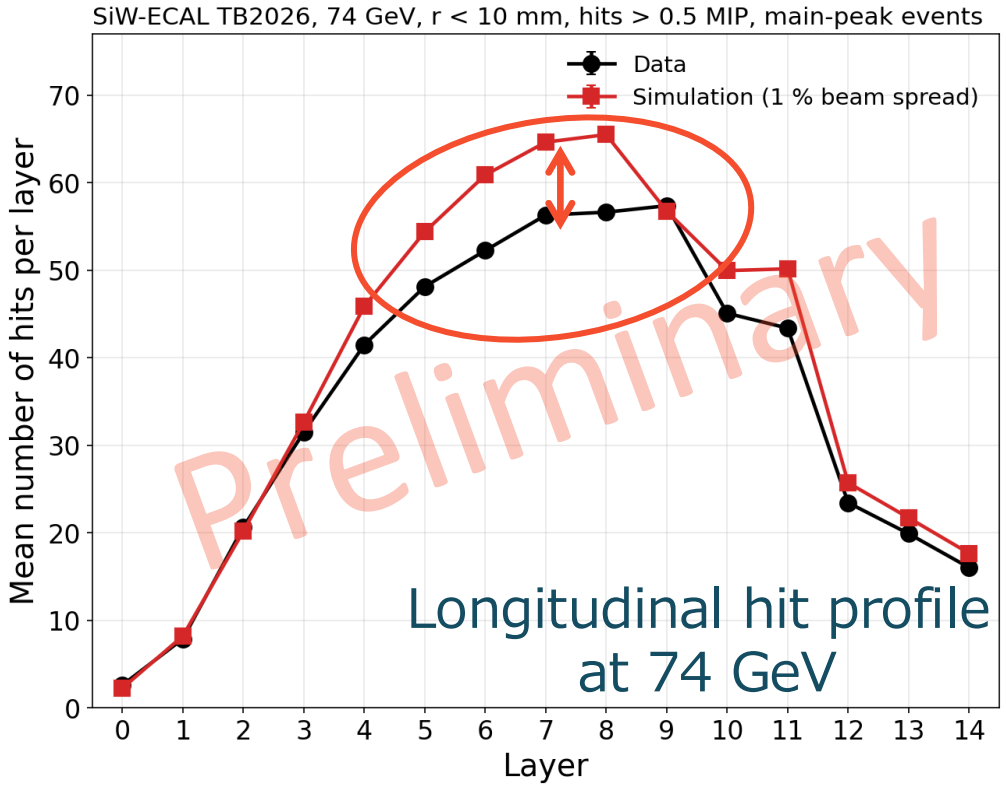
Broad agreement between data and simulation

A quantitative comparison requires corrections for hit loss and the position-dependent response discussed later.

Fewer low-energy hits at high beam energy

Data
Simulation

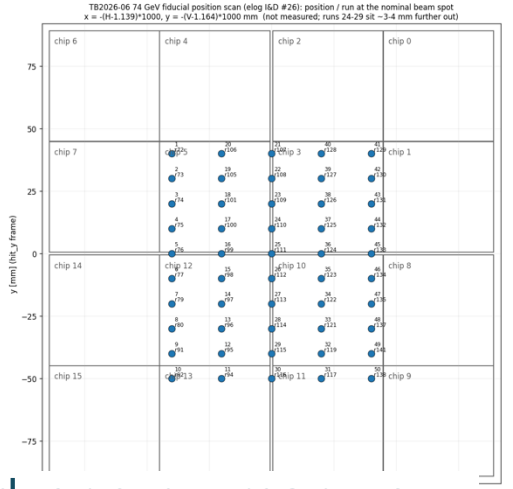




- The number of low-energy hits decreases near the shower maximum at high beam energies.
- Recent studies indicate that **high hit occupancy within a readout chip causes a pedestal shift**, suppressing low-energy hits (See backup slides).

Position-dependent response

50 beam-injected positions

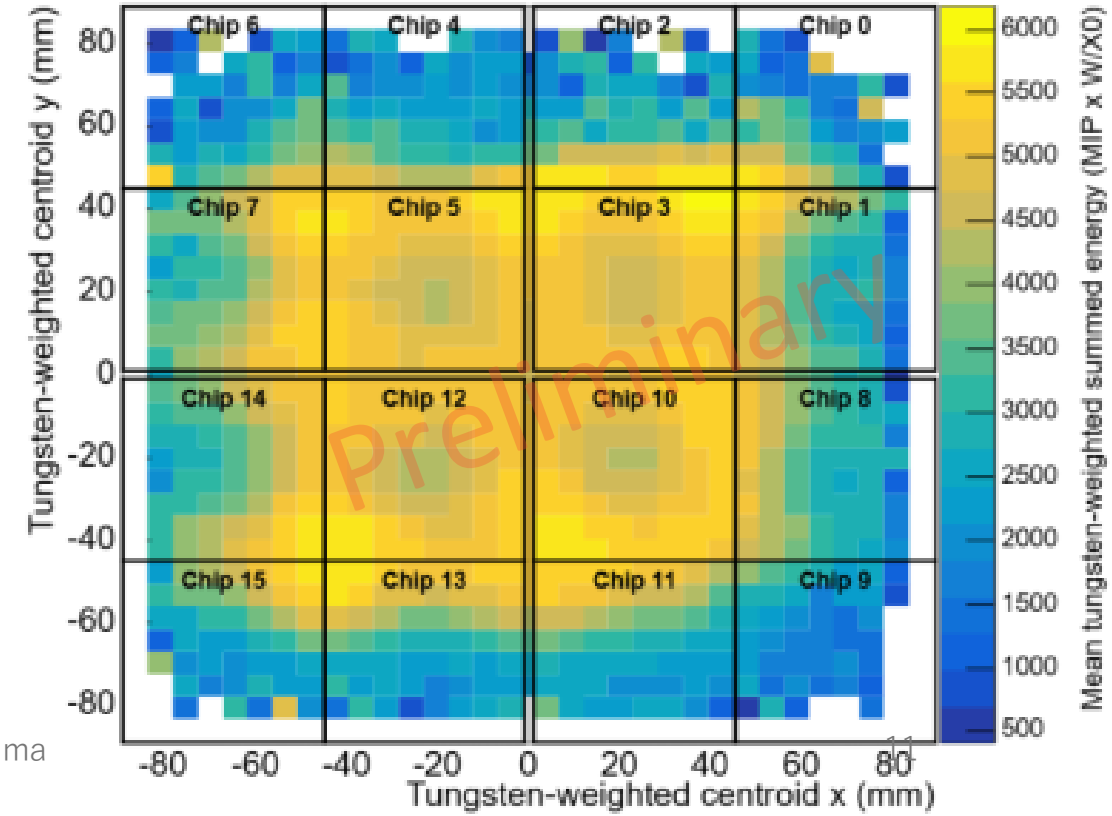


Beam position dependent detector response

- Scanned 50 beam positions to map the detector response.
- Rec E varies with beam-injected position.

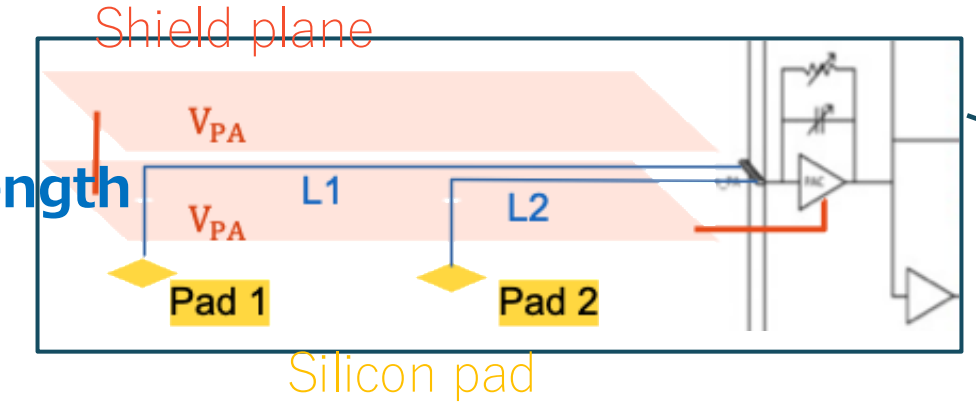
  In particular, the rec E is lower when the beam hits the chip center.

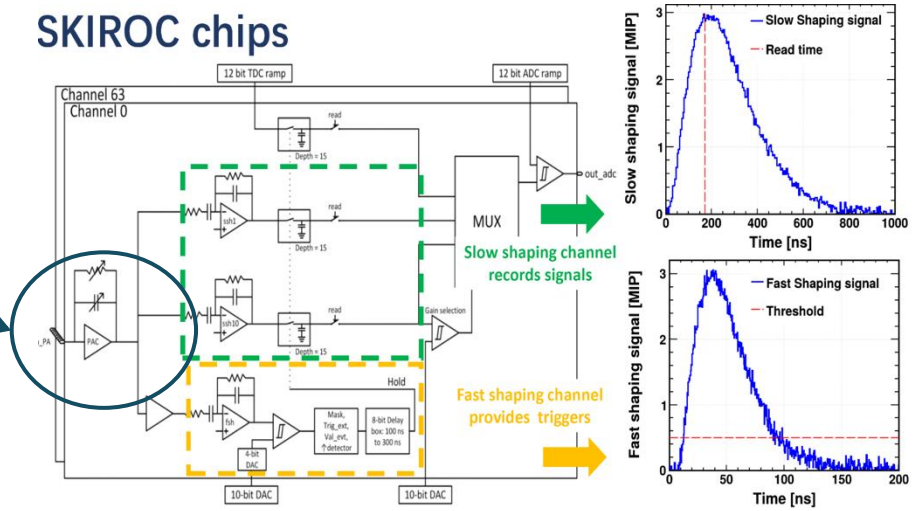
Reconstructed-energy map vs. beam position



Correlation with PCB trace length

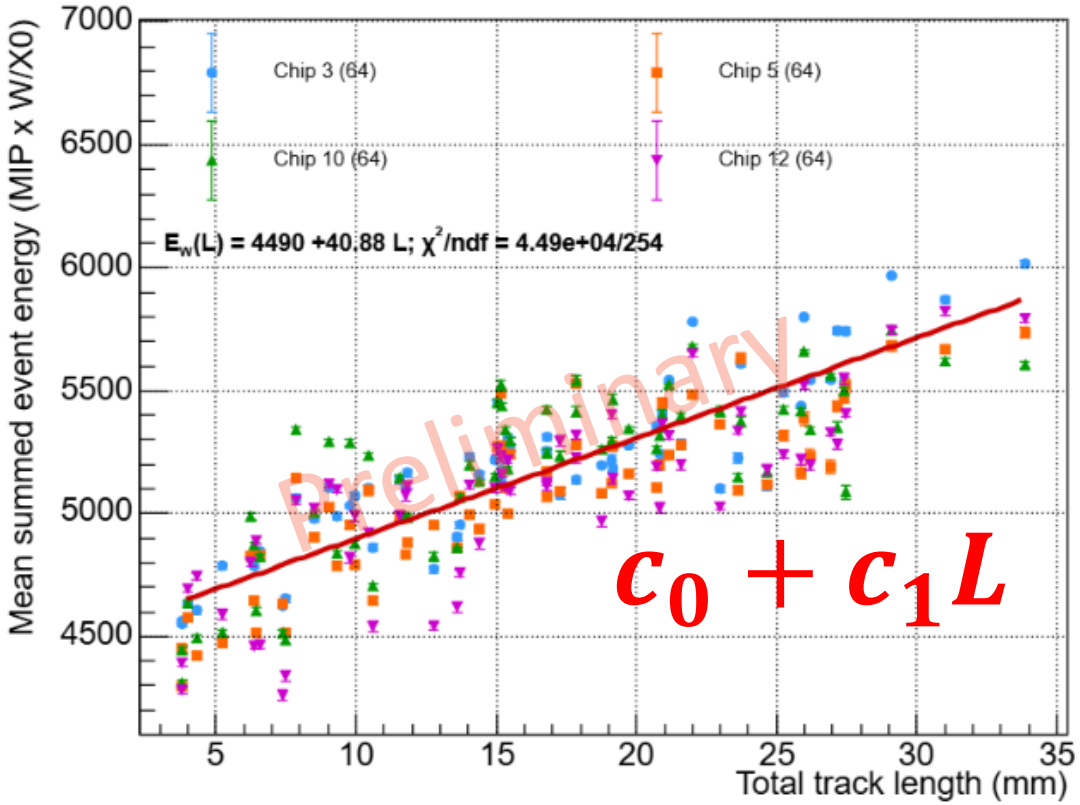
PCB trace length





- Correlation between detector response & PCB trace length.
- Fitted with a linear function between total hit channel trace length & rec E.

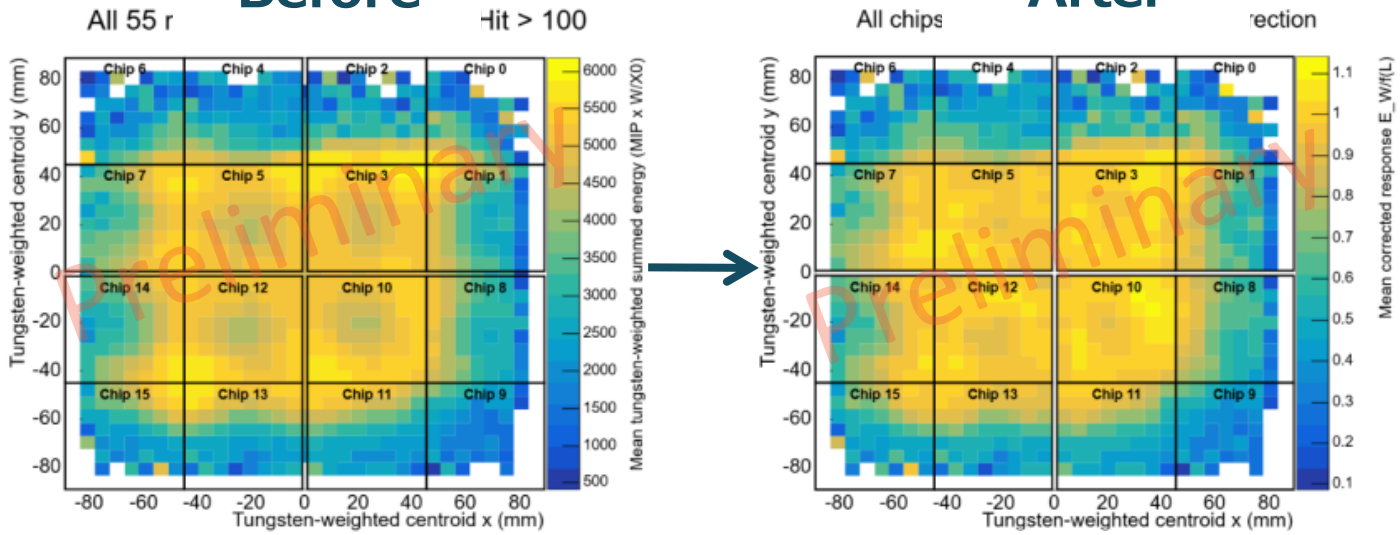
Total channel PCB trace length vs rec E



Empirical correction

- Recovered rec E uniformity by $E_{\text{corrected}} = \frac{E_{\text{before}}}{c_0 + c_1 L}$
- Resolution improvement after correction
- Correction slope "c_1/c_0" as a function of energy.
- Mechanism is under investigation.

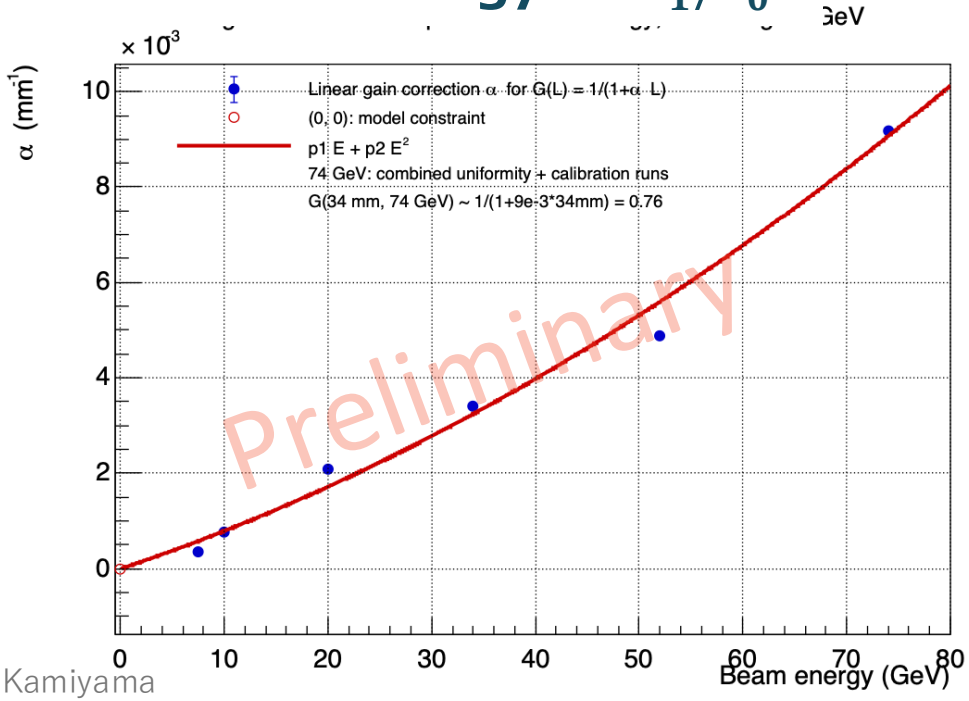
Before **After**



Energy (GeV)	Relative width reduction (%)
7.5	4.17
10	8.34
20	14.77
34	34.96
52	17.83
74	33.16

Preliminary

Beam energy vs c_1/c_0



ML-based event selection

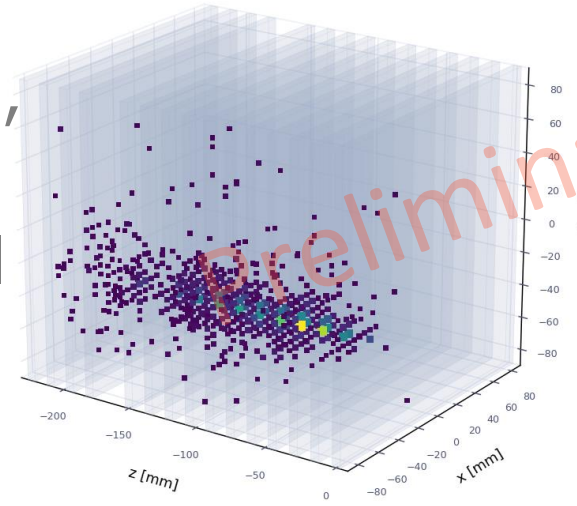
Motivation

- Real data contain muons, pions, multiple particles, and noise.
- Simple selections leave residual background.

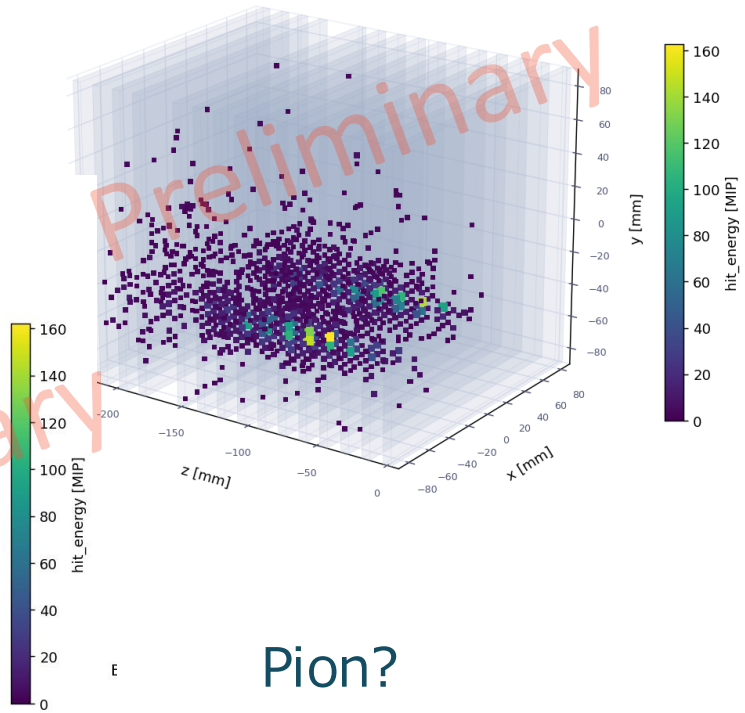
Approach

- A one-class autoencoder is trained only on simulated EM events.
- Calculate “EM-likeness” with data based on the model.

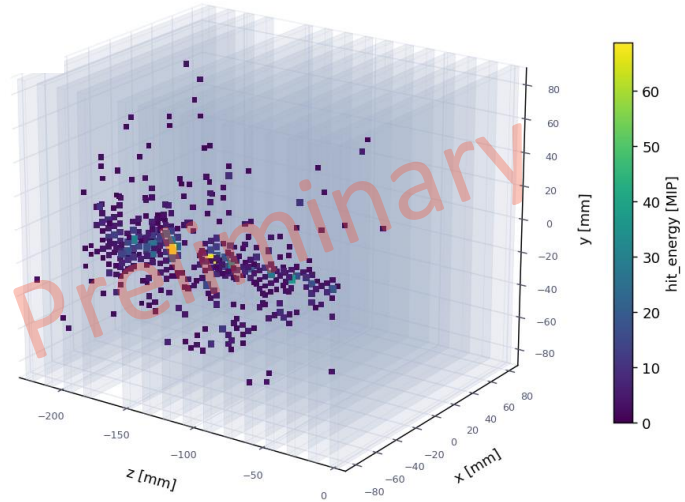
Positron?



2 positrons?

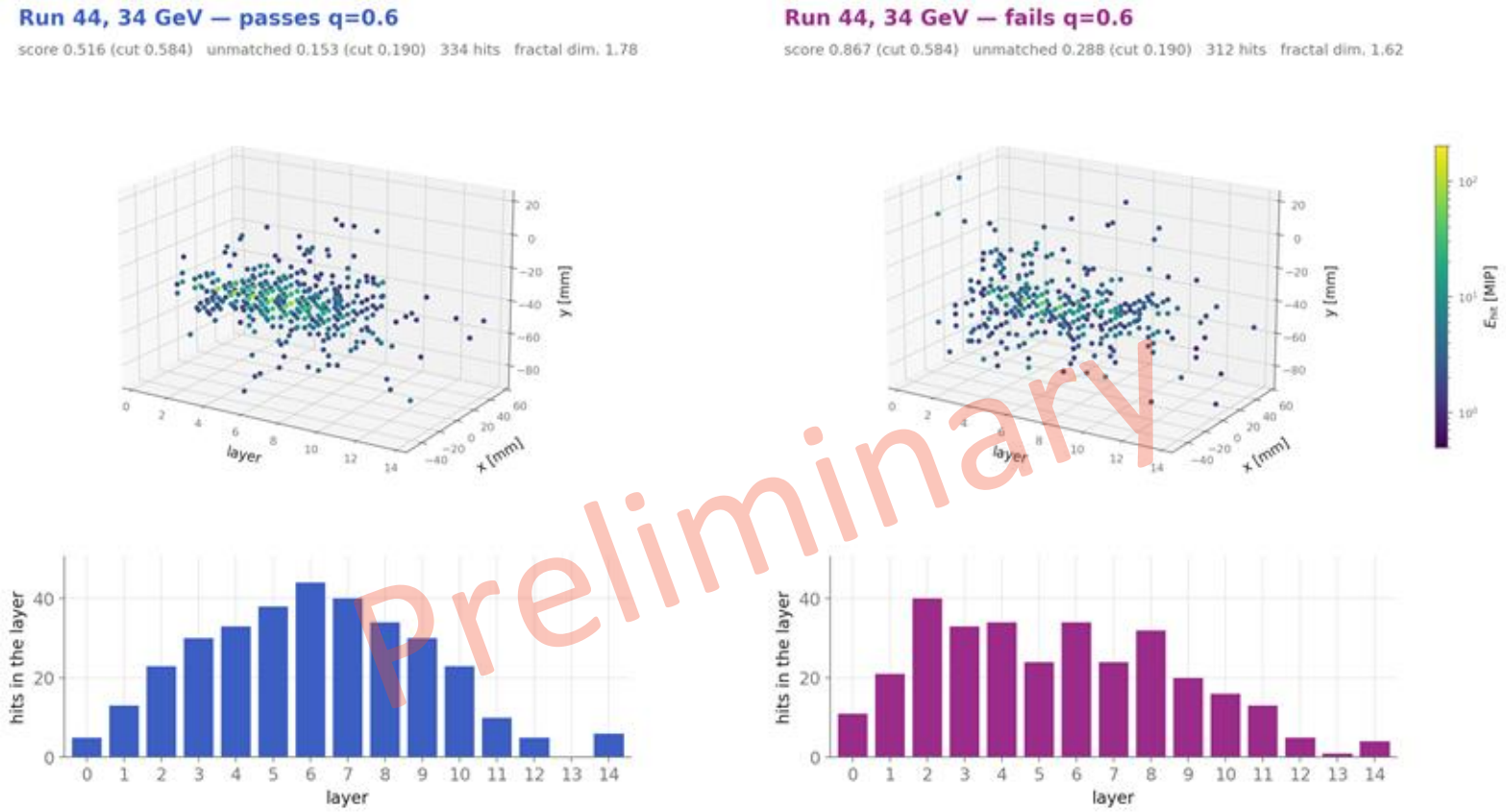


Pion?



First selection result

Examples of accepted (left) & rejected (right).



- It currently favours “clean” electron events, but the selection can still be tuned to reduce this bias.
- Background-separation model is also under study.

Summary & outlook

- **Test-beam campaign**
  - The 15-layer SiW-ECAL prototype operated successfully at CERN SPS.
  - The campaign recorded 27.8 million events over energy, position, and angle scans, including muon and pion samples.
- **Preliminary analysis results**
  - Reconstructed-energy distributions show broad agreement between data and simulation.
  - Two detector-response effects were identified: low-energy hit loss at high hit occupancy within a chip and a position dependence correlated with PCB trace length.
  - ML-based event selection is being evaluated for efficiency and selection bias.
- **Outlook**

  Understand and correct these response effects, then re-evaluate the energy response and resolution.