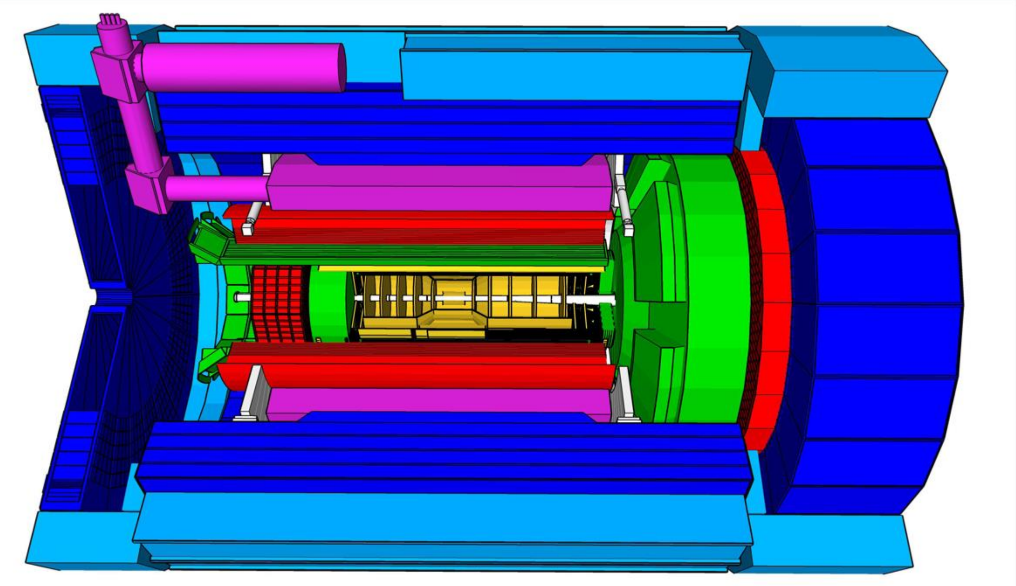
SEP 9, 2026

AI-READY DATA FOR EIC



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Design principle: 10.5281/zenodo.19710980
BIC application + metadata: arxiv:2606.07667

NP AMSC DATA PROVIDERS PROGRAM (DAPP)

AI FOR NUCLEAR PHYSICS

The transformative power of AI for science

Traditional Scientific ML

- Classify objects/pid/events
- Reconstruct particle tracks
- Detect anomalies
- Optimize simulations

→ One model = One task

Foundation Models for Physics

- Learn diverse exp./sim. data
- Support multiple scientific tasks
- Reason across modalities
- Agentic scientific workflows
- Improve as new data arrive

→ One evolving model = Multi tasks

- **The limiting factor is not just the model**
- **It is the quality, scale, and accessibility of the training data**

AI-READY DATA DESIGN

Data design principle

- Physics detector measurement (x, y, z, A, t) is naturally a point-cloud data structure.
- We release low-level pre-reconstruction detector data, not reconstructed objects, to provide the closest equivalent to the raw detector measurements for AI training.

➢ Why not ROOT/existing storage format? → iterative lookup; no separation for features or labels

- ➢ GNN training: load 1 event from **npz** (90 MB) takes 5.6s v.s EICrecon root file (3.6 GB) 61s.

➢ Why not EMP4hep/existing reconstruction formats? → tightly coupled to detector-specific software, hard to generalize across experiments. Designed for physicist-driven analysis, not AI training.

AI-READY DATA DESIGN

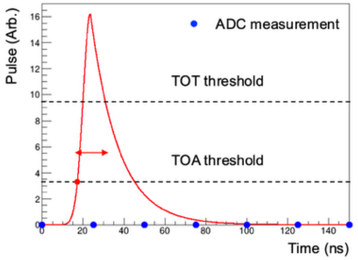
Uniform representation

- 4 Design principles: unified representation, explicit uncertainty, metadata-defined semantics, minimal scope. Document ready: 10.5281/zenodo.19710980

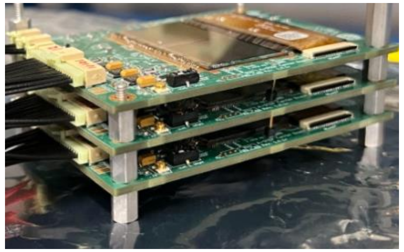
TABLE I. Structure of the `measurements` array.

Field	Type	Description
`event`	`uint64`	Event identifier.
`detector`	`uint16`	Subdetector identifier.
`hit`	`uint16`	Hit index within a subdetector.
`sample`	`uint16`	Sample index within a hit.
`x, y, z`	`float32`×3	Spatial coordinates associated with the sample.
`pos_cov_xx, xy, xz, yy, yz, zz`	`float32`×6	Upper triangle of the position covariance matrix.
`amplitude`	`float32`	Measured signal amplitude.
`amplitude_uncertainty`	`float32`	Uncertainty on the amplitude.
`time`	`float32`	Time associated with the measurement.
`time_uncertainty`	`float32`	Uncertainty on the time measurement.

- The amplitude could be ADC value per waveform sample



- Or ToT calibrated E per silicon pixel



AI-READY DATA DESIGN

Label for supervised learning

- Label array design principles: granularity, contributors, spatiotemporal, ancestry, minimality.

TABLE II. Structure of the `labels` array, with contributor-specific fields repeated for each retained contributor $n \in \{0, \ldots, N-1\}$.

Field	Type	Description
`event`	`uint64`	Event identifier.
`detector`	`uint16`	Subdetector identifier.
`hit`	`uint16`	Hit index within a subdetector.
`sample`	`uint16`	Sample index within a hit.
`x, y, z`	`float32`×3	Truth spatial coordinates.
`deposit_energy`	`float32`	Truth total deposited energy.
`time`	`float32`	Truth time associated with the measurement.
`n_contributions`	`uint16`	Total number of contributing particles.
`con{n}_particle`	`uint32`	Index of contributor n in the event-level record.
`con{n}_x, y, z`	`float32`×3	Interaction spatial coordinate of contributor n.
`con{n}_deposit_energy`	`float32`	Deposited energy from contributor n.
`con{n}_time`	`float32`	Time of interaction of contributor n.
`con{n}_px, py, pz`	`float32`×3	Momentum vector of contributor n at production.
`con{n}_energy`	`float32`	Energy of contributor n at production.
`con{n}_pid`	`int32`	PDG identifier of contributor n.
`con{n}_parent_pid`	`int32`	PDG identifier of the immediate parent of contributor n.
`con{n}_parent_energy`	`float32`	Energy of the immediate parent of contributor n.

Deposited energy

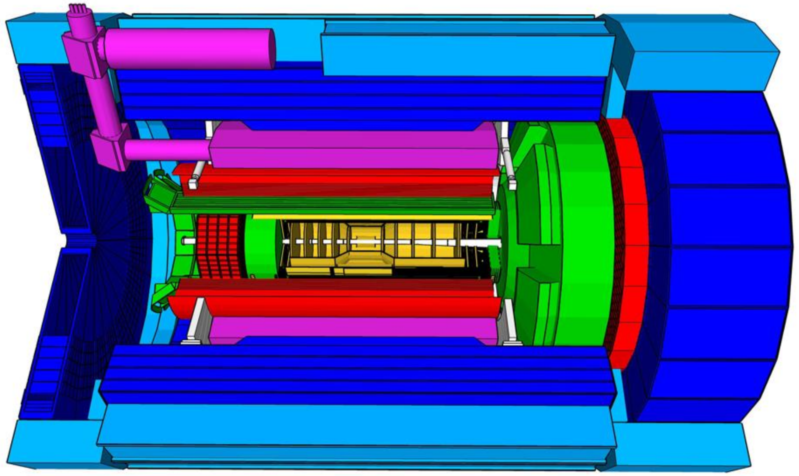
Energy

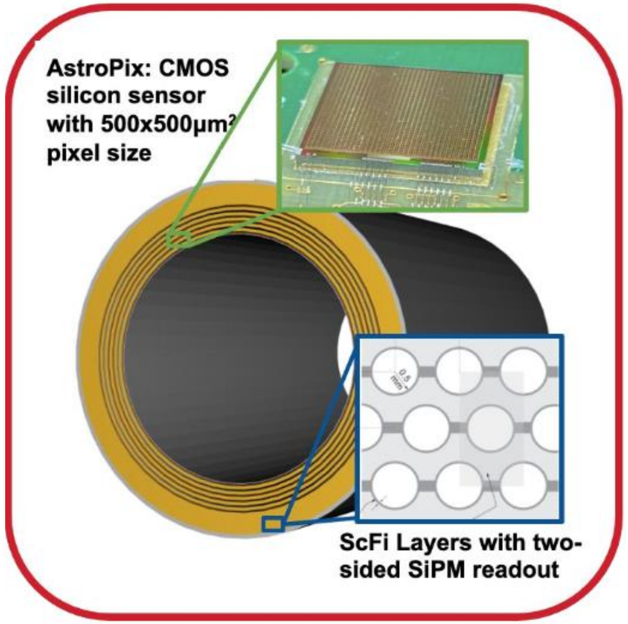
Cap of truth info

Suitable for a variety of detector readouts, including tracking, calorimeter, spectator detectors.

BIC AI-READY DATASET

- Barrel Imaging Electromagnetic Calorimeter is one of ePIC's core calorimeter system.
- Hybrid dual readout: AstroPix silicon pixels (500 µm, single-sample) for spatial imaging + Pb/ScFi waveform per SiPM (25 ns multi-sample) for energy sampling.
- 170 M labeled data: 60M DIS data (10x100 GeV, CC/NC, Q2min = 1, 10, 100, 1000), 70M single particle (18 top PID), 40M multi-particle (π/γ). arxiv:2606.07667

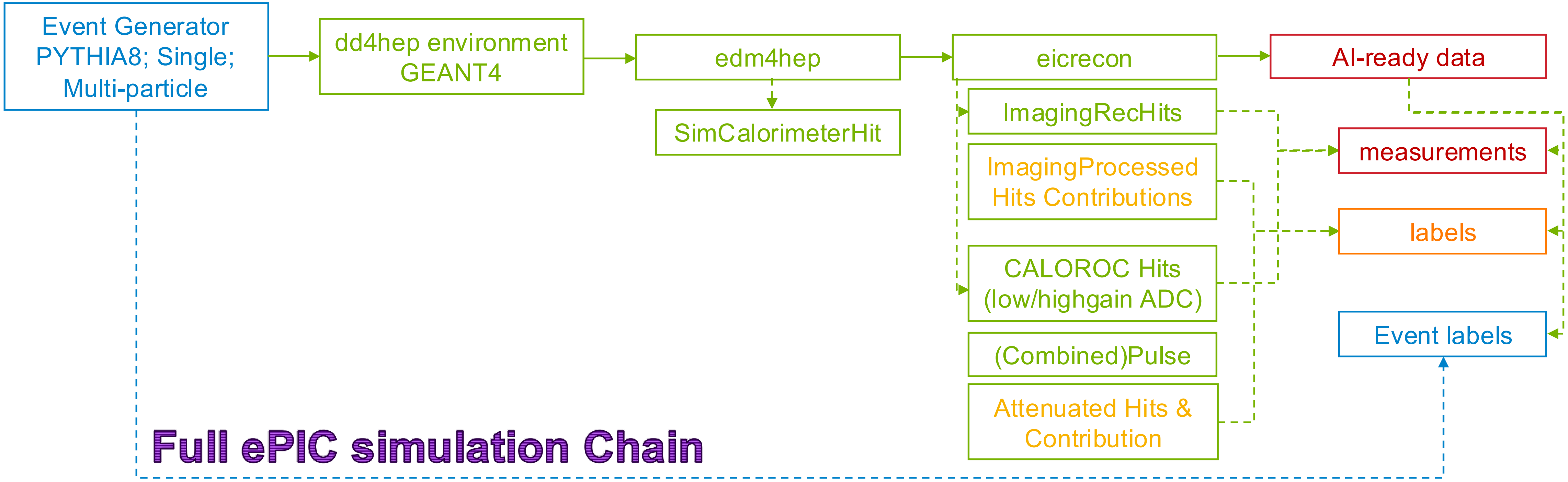




BIC AI-READY DATASET

Barrel Imaging Electromagnetic Calorimeter

- Complete flow for data generation, from HEPMC/steer to NPZ file
- Measurements, labels (top-3 contributors), Event label (MC particles + decay chain)



BIC AI-READY DATASET

Metadata for the 'hit sample'

- Based on low-level detector simulation of BIC and are pre-reconstruction.

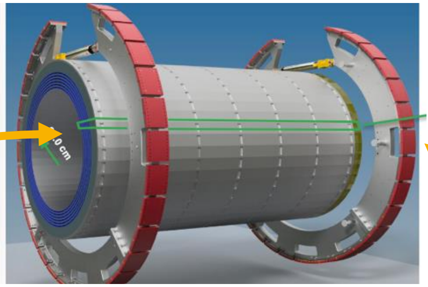


TABLE III. Structure of the `measurements` array for the BIC.

Field	Type	Description
`event`	`uint64`	Event index defined per simulation collision.
`subsystem`	`uint16`	0 = AstroPix, 1 = Pb/ScFi.
`hit`	`uint16`	A single channel response from AstroPix or Pb/S
`sample`	`uint16`	Usually 0 for AstroPix. 0–N for Pb/ScFi wavefor
`x, y, z`	`float32`×3	Position of the AstroPix hit or Pb/ScFi SiPM rea
`deposit_energy`	`float32`	Deposited energy (GeV) converted from ToT or w
`time`	`float32`	Readout time at the measurement (ns).
`x_unc, y_unc, z_unc`	`float32`×3	Diagonal position uncertainties (mm).
`deposit_energy_unc`	`float32`	Deposited energy uncertainty from calibrated reso
`time_unc`	`float32`	Uncertainty on the measurement time from DAQ(

- **x, y, z:** `float32` x 3, spatial scalars, unit: mm. Cartesian coordinates of the readout unit in the laboratory frame, with the z-axis along the proton beam direction. For AstroPix, this is the center of the fired pixel within the silicon bulk. For Pb/ScFi, this is the position of the SiPM readout unit at the longitudinal fiber end, not the physical location of the particle interaction along the fiber. The SiPM readout x,y location is defined at the center of the grid cell, and its z position is at one of the two ScFi ends: z = - 2587.5 mm or 1762.5 mm. The true interaction z(hit) must be reconstructed from the time difference between the two fiber ends (t(+z) and t(-z)), as z(hit) = (t(+z) - t(-z))·veff /2 , based on the effective velocity of veff=160 mm/ns. Coordinate convention: the nominal interaction point is at the origin (0, 0, 0).
- **deposit_energy:** `float32` scalar, unit: GeV. The measured signal amplitude converted to deposited energy. For AstroPix, it is derived from the charge collected by the pixel and corresponds to calibrated ToT (time over threshold). For Pb/ScFi, it is energy attenuated along the fiber to the ends of the detector, which is converted independently for each 25 ns waveform sample from either the 14-bit ADC value (dynamic range 0.1 MeV to 10 GeV in true energy) or the electric photon count (1700 e.p. is 0.1 GeV in deposited energy not corrected for sampling fraction). The energy spans approximately five orders of magnitude (~1e-5 to ~10 GeV); logarithmic scaling is recommended before training. The truth counterpart is `deposit_energy` in `labels`.

- Uncertainties defined accordingly:

$$\sigma_x = \sqrt{\sigma_r^2 \cos^2 \varphi_{\mathrm{sec}} + \sigma_\varphi^2 \sin^2 \varphi_{\mathrm{sec}}}, \qquad \sigma_y = \sqrt{\sigma_r^2 \sin^2 \varphi_{\mathrm{sec}} + \sigma_\varphi^2 \cos^2 \varphi_{\mathrm{sec}}}$$

$$\sigma_E = \begin{cases} 0.0457\, E_{\mathrm{dep}}, & E_{\mathrm{dep}} > 1.2210^{-4}\ \mathrm{GeV} \\ 5.8910^{-8}\, E_{\mathrm{dep}}^{-0.499}, & E_{\mathrm{dep}} \leq 1.2210^{-4}\ \mathrm{GeV} \end{cases}$$

BIC AI-READY DATASET

Metadata for the ‘label’

- Ready to use label, processed matched with measurement hit.

TABLE IV. Structure of the labels array for the BIC (contributor fields repeated for n

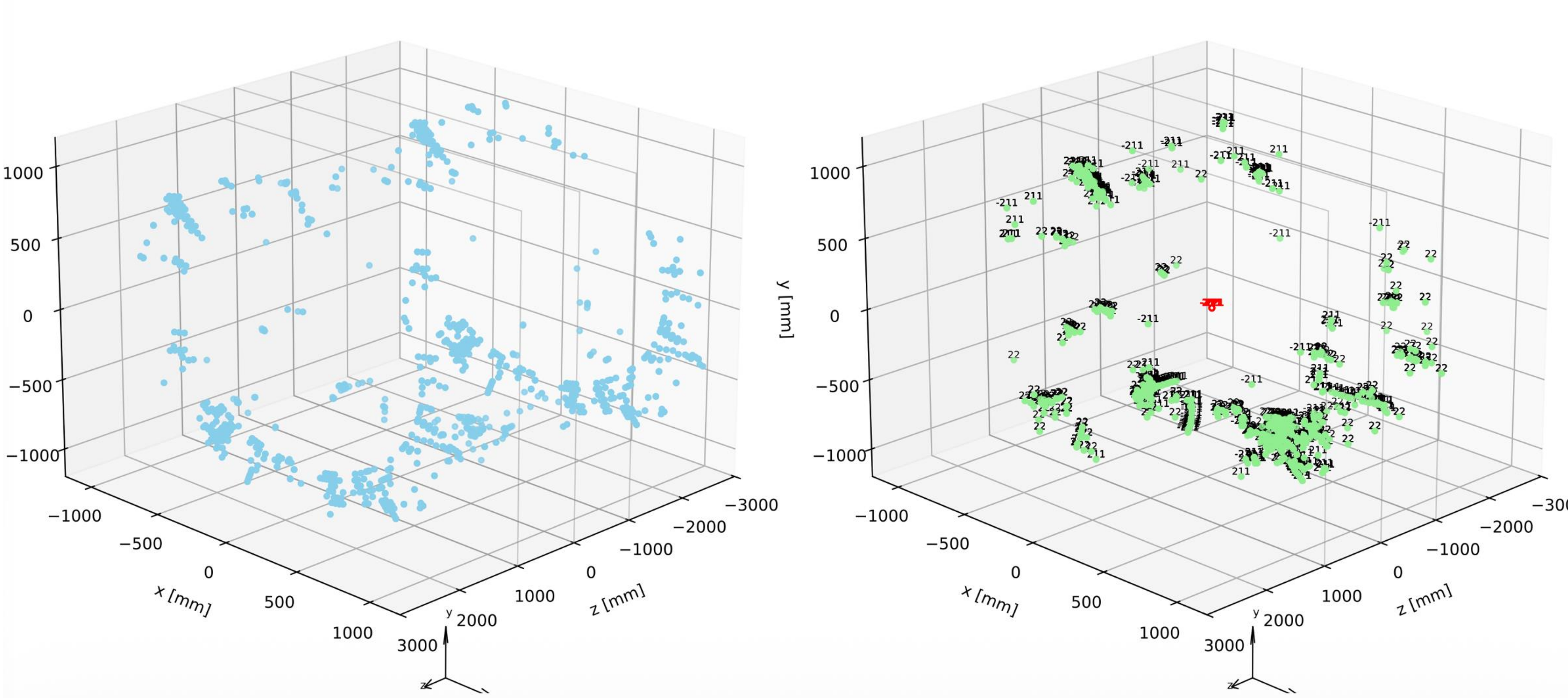
Field	Type	Description
event	uint64	Event index.
subsystem	uint16	Subsystem identifier.
hit	uint16	Hit index.
sample	uint16	Sample index.
x, y, z	float32×3	Energy-weighted truth position (mm).
deposit_energy	float32	Total truth energy deposit (GeV).
time	float32	Earliest truth interaction time (ns).
n_contributions	uint16	Total contributing particles.
con{n}_particle	uint16	Index into event-level truth record.
con{n}_x, y, z	float32×3	Truth interaction position (mm).
con{n}_deposit_energy	float32	Deposited energy from contributor n (G
con{n}_time	float32	Truth interaction time (ns).
con{n}_px, py, pz	float32×3	Momentum at production (GeV/c).
con{n}_energy	float32	Energy at production (GeV).
con{n}_pid	int32	PDG ID.
con{n}_parent_pid	int32	PDG ID of parent.
con{n}_parent_energy	float32	Parent energy (GeV).

Metadata

- **deposit_energy:** float32 scalar, unit: GeV. Total truth energy deposited in this measurement, summed over all contributing particles. This is the truth counterpart to the deposit_energy column in measurements, and the sum of all con{n}_deposit_energy values equals this field up to rounding from contributions beyond MAX_CONTRIB.
- **con{n}_deposit_energy:** float32 scalar, unit: GeV. Energy deposited by the n-th contributing particle in a single pixel or a single fiber. For ScFi only: summed over all shower particles by energy-weighted within the fiber. The sum over all valid contributors of this value would approximate the aggregate deposit_energy field in this array. Contributors are sorted by this field in descending order. Sentinel: 0 for empty slots.
- **con{n}_energy:** float32 scalar, unit: GeV. Total energy of the n-th contributing particle at its production vertex. Together with con{n}_px, py, pz, this completes the particle four-vector. As with momentum, the value corresponds to the traced incident particle after primary particle fetching. Sentinel: 0 for empty slots.

AI-READY DATA VISULIZATION

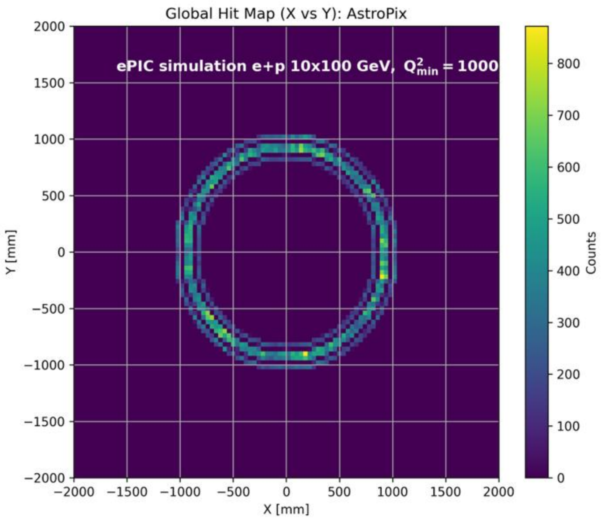
DIS data 10x100 GeV, min Q2=1000, npz format, 1k events ~ 5M

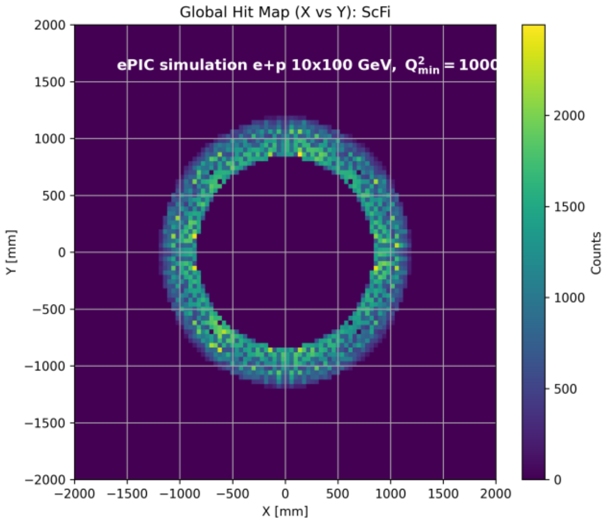


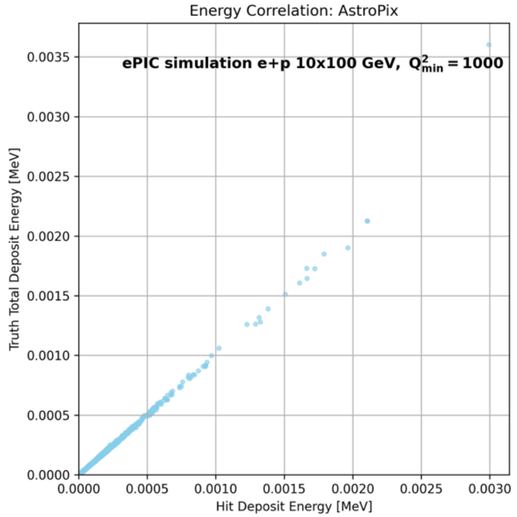
Data – Label visualization.

AI-READY DATA VISULIZATION

DIS data 10x100 GeV, min Q2=1000, npz format, 1k events ~ 90M

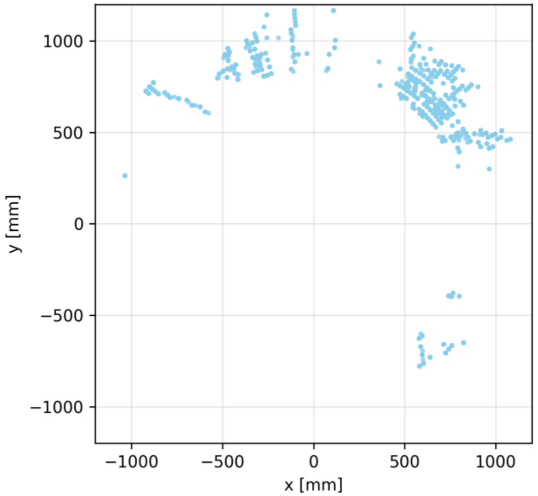


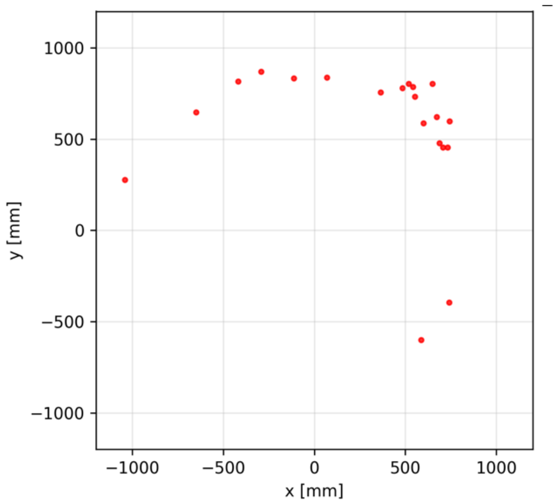




Clear distinctions between AstroPix (sub sys 0) and Pb/ScFi (sub sys 1)

Data – Label visualization. Well demonstrated!

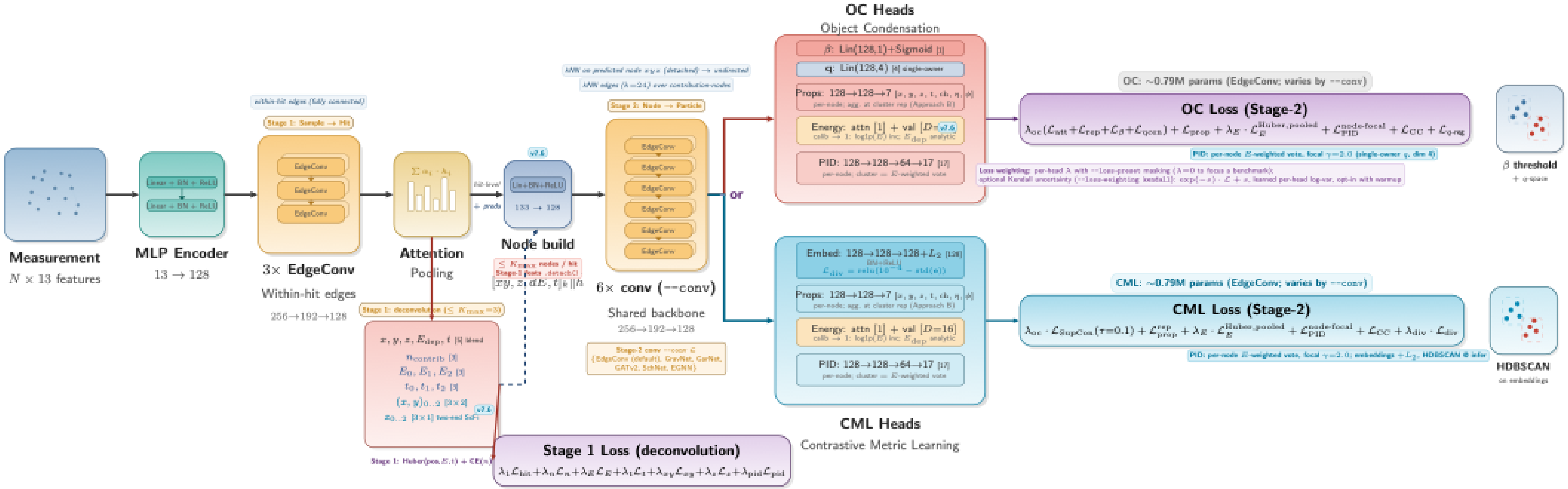




AI-BASED RECONSTRUCTION

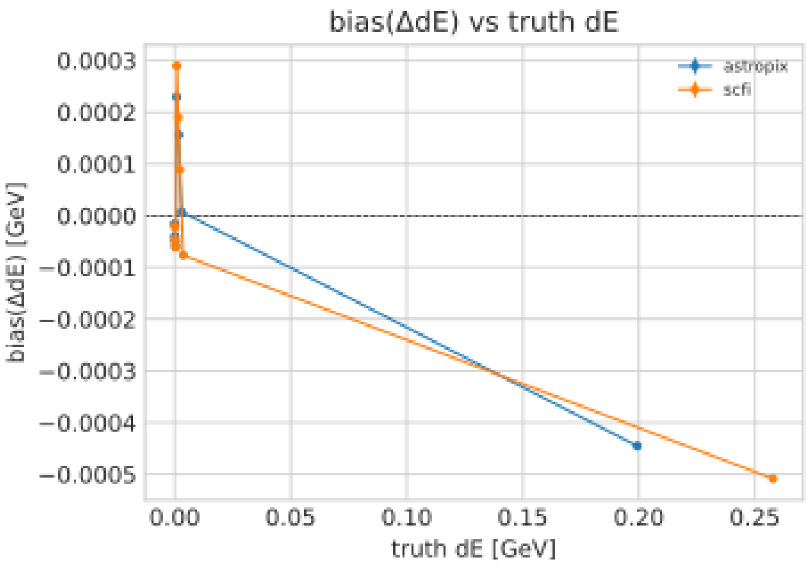
Validation of the AI-ready BIC data

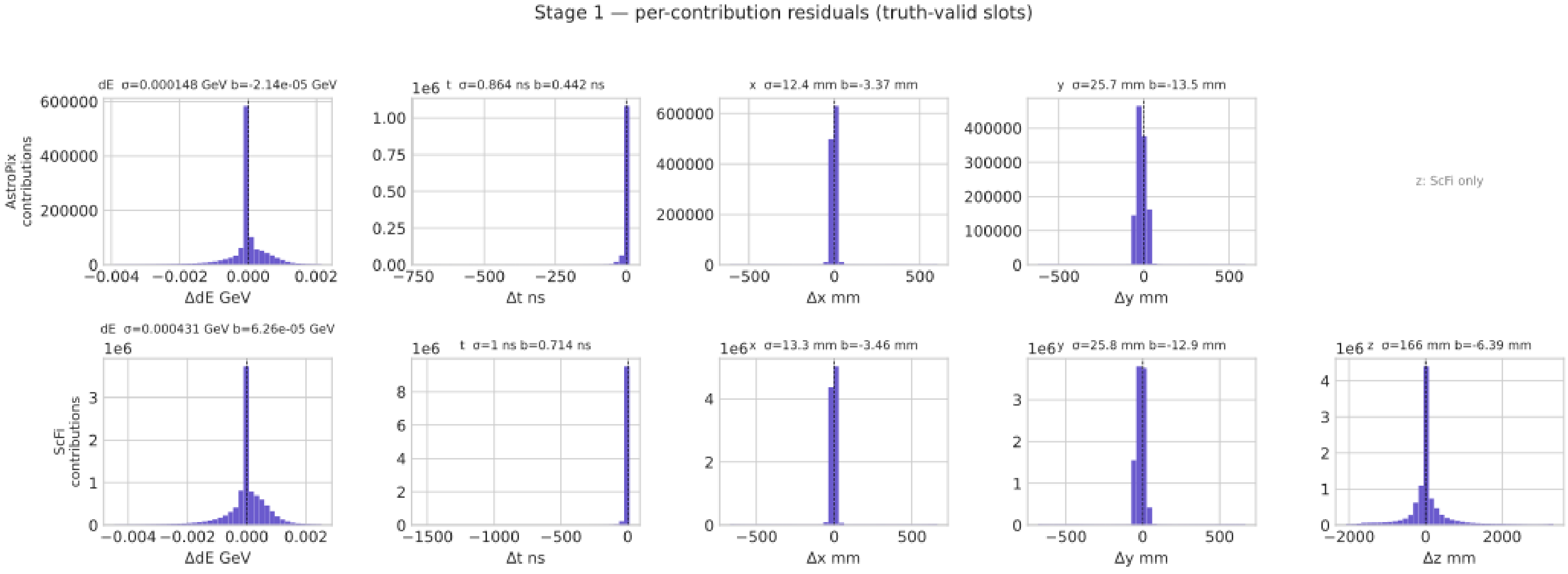
- An end-to-end GNN trained on the same AI-ready dataset: sample – hit – particle (cluster) -- property
- Reconstruction and clustering: Object Condensation vs Contrastive Metric Learning
- Training performed on A100 with 20% of generated data of mixed DIS/single/multi sample.



AI-BASED RECONSTRUCTION

- GNN: sample – hit (contributor), predict each contributor’s special, time and deposited energy
- successfully reconstructed ScFi z, (truth residual = 100 mm) Δz ~ 160mm at epoch 200.
- Deposit energy bias is low.

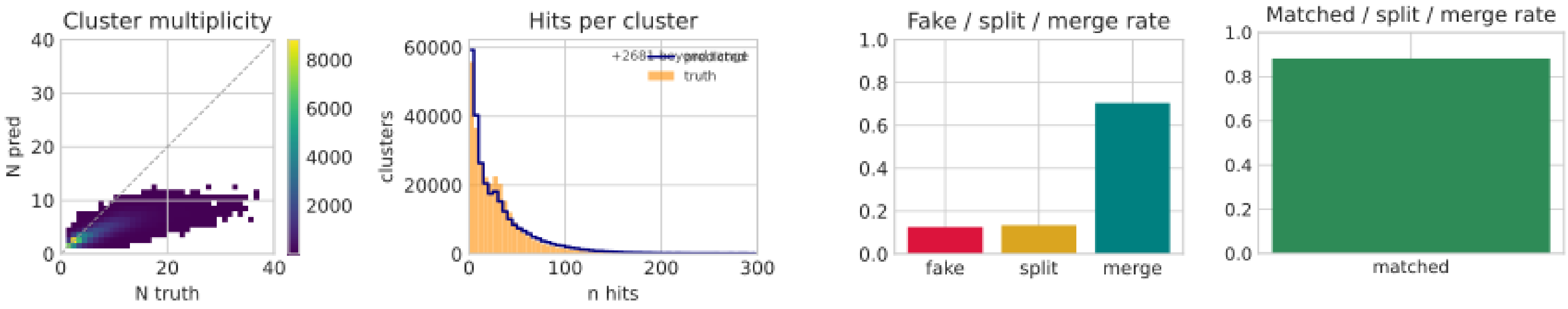




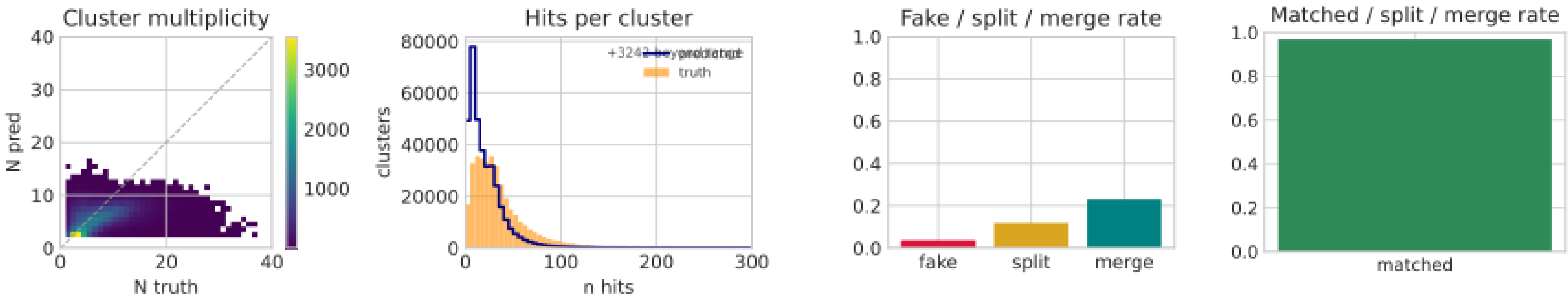
AI-BASED RECONSTRUCTION

- GNN: sample – hit (contributor) – particle (cluster)
- Activate the clustering head only. CML did a better job, matched rate ~ 96%.

OC



CML



SUMMARY

- We propose a design for the NP AI-ready dataset and subsequently produced the low-level EIC data for the BIC in ePIC.
  - preserving raw detector information through realistic digitization and waveform readout simulation.
- Building on this foundation, we are developing end-to-end GNN-based AI models for reconstruction.

Thank you.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