Brookhaven National Laboratory

U.S. DEPARTMENT of ENERGY

ePIC

# AI Integration within ePIC

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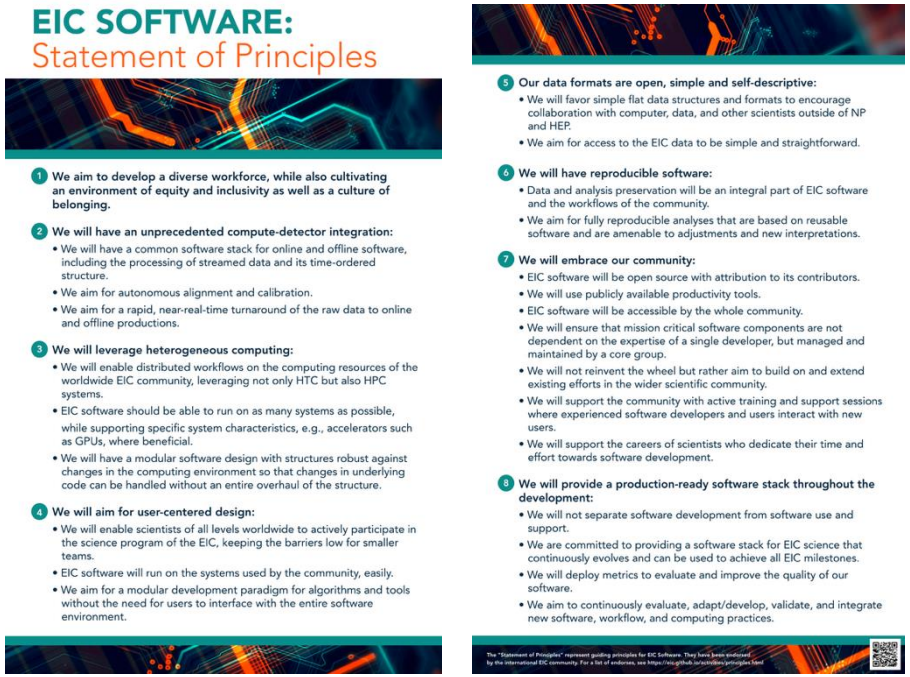
@BrookhavenLab

# Disclaimer

This talk contains a non-exhaustive list of AI/ML activities. If you are missing your favorite one, let us know.

# ePIC Software

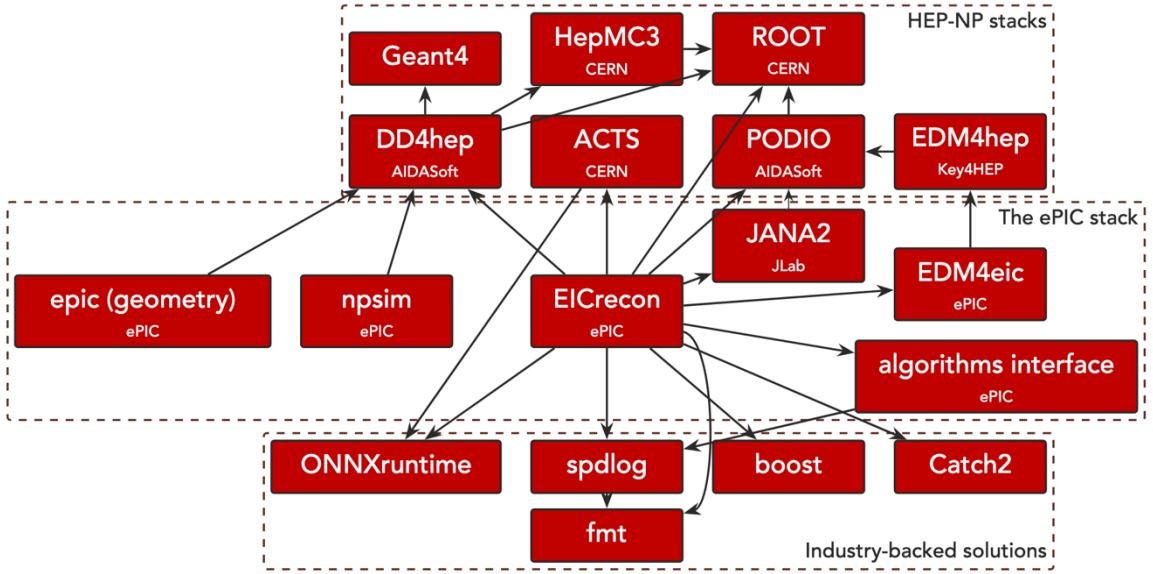
Software and Computing organized around principles of openness and collaboration with other communities in NP, HEP and CS



**EIC SOFTWARE:**
Statement of Principles

1. **We aim to develop a diverse workforce, while also cultivating an environment of equity and inclusivity as well as a culture of belonging.**
2. **We will have an unprecedented compute-detector integration:**
   - We will have a common software stack for online and offline software, including the processing of streamed data and its time-ordered structure.
   - We aim for autonomous alignment and calibration.
   - We aim for a rapid, near-real-time turnaround of the raw data to online and offline productions.
3. **We will leverage heterogeneous computing:**
   - We will enable distributed workflows on the computing resources of the worldwide EIC community, leveraging not only HTC but also HPC systems.
   - EIC software should be able to run on as many systems as possible, while supporting specific system characteristics, e.g., accelerators such as GPUs, where beneficial.
   - We will have a modular software design with structures robust against changes in the computing environment so that changes in underlying code can be handled without an entire overhaul of the structure.
4. **We will aim for user-centered design:**
   - We will enable scientists of all levels worldwide to actively participate in the science program of the EIC, keeping the barriers low for smaller teams.
   - EIC software will run on the systems used by the community, easily.
   - We aim for a modular development paradigm for algorithms and tools without the need for users to interface with the entire software environment.
5. **Our data formats are open, simple and self-descriptive:**
   - We will favor simple flat data structures and formats to encourage collaboration with computer, data, and other scientists outside of NP and HEP.
   - We aim for access to the EIC data to be simple and straightforward.
6. **We will have reproducible software:**
   - Data and analysis preservation will be an integral part of EIC software and the workflows of the community.
   - We aim for fully reproducible analyses that are based on reusable software and are amenable to adjustments and new interpretations.
7. **We will embrace our community:**
   - EIC software will be open source with attribution to its contributors.
   - We will use publicly available productivity tools.
   - EIC software will be accessible by the whole community.
   - We will ensure that mission critical software components are not dependent on the expertise of a single developer, but managed and maintained by a core group.
   - We will not reinvent the wheel but rather aim to build on and extend existing efforts in the wider scientific community.
   - We will support the community with active training and support sessions where experienced software developers and users interact with new users.
   - We will support the careers of scientists who dedicate their time and effort towards software development.
8. **We will provide a production-ready software stack throughout the development:**
   - We will not separate software development from software use and support.
   - We are committed to providing a software stack for EIC science that continuously evolves and can be used to achieve all EIC milestones.
   - We will deploy metrics to evaluate and improve the quality of our software.
   - We aim to continuously evaluate, adapt/develop, validate, and integrate new software, workflow, and computing practices.

The "Statement of Principles" represent guiding principles for EIC Software. They have been endorsed by the international EIC community. For a list of endorses, see https://eic.github.io/activities/principles.html

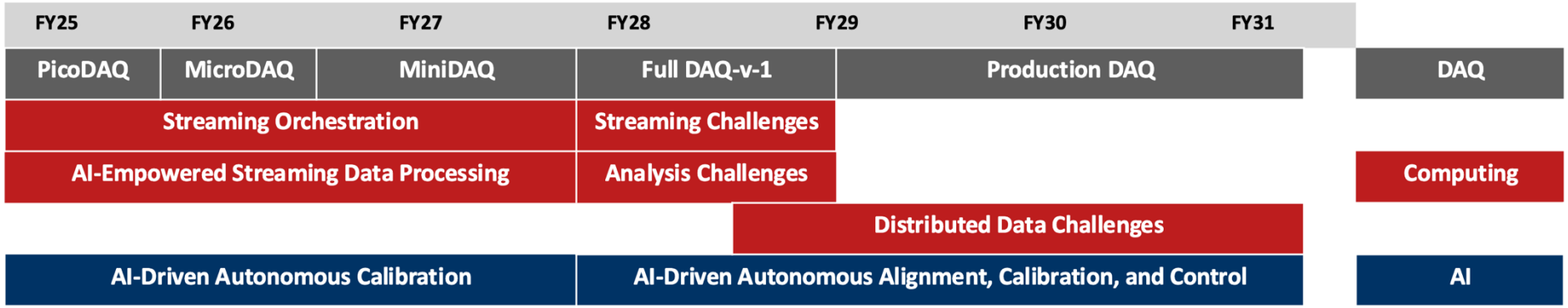



ePIC Software stack built with community components

# Streaming DAQ and Computing

AI workflows are to play key role in accelerating science

- Rapid turnaround (~2 weeks) goal for integrated Compute-Detector system with AI control
- Workflows for autonomous alignment, calibration, and validation



# Agentic workflows

Undoubtedly, **AI will be a major part of the control loop** for the collider and the experiment. We need to prepare today.

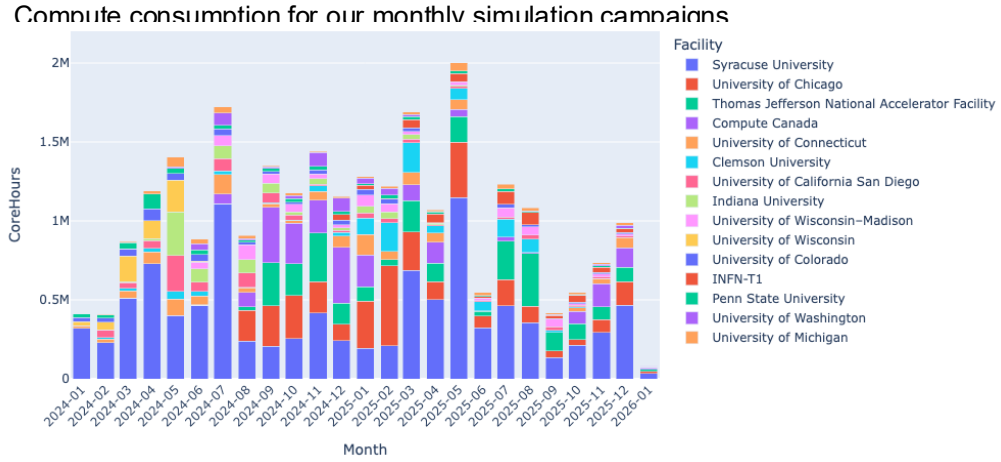
ePIC collaboration conducts testbeds for Streaming Orchestration that can grow to include challenges to implement **AI control over the data processing**.

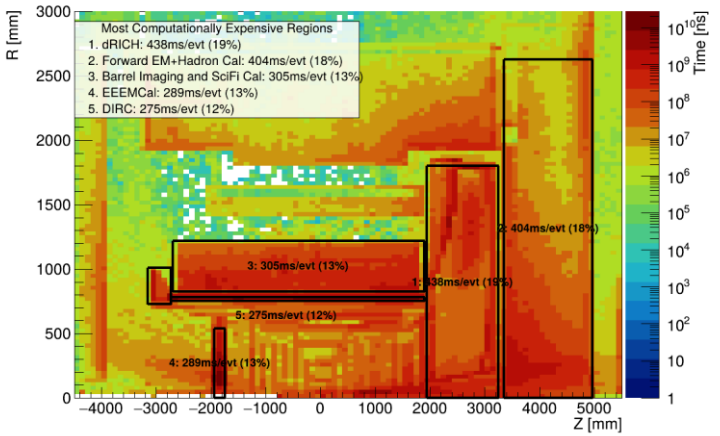
Existing tools such as PanDA WMS have **initial implementations for Model Context Protocol (MCP)** that can serve as basis for such experimentation.

# AI for simulation

ePIC relies on Geant4 for simulation through DD4hep interface (TGeo-based), we are evaluating  running simulations on GPUs for optical and EM physics as well as surrogate modeling

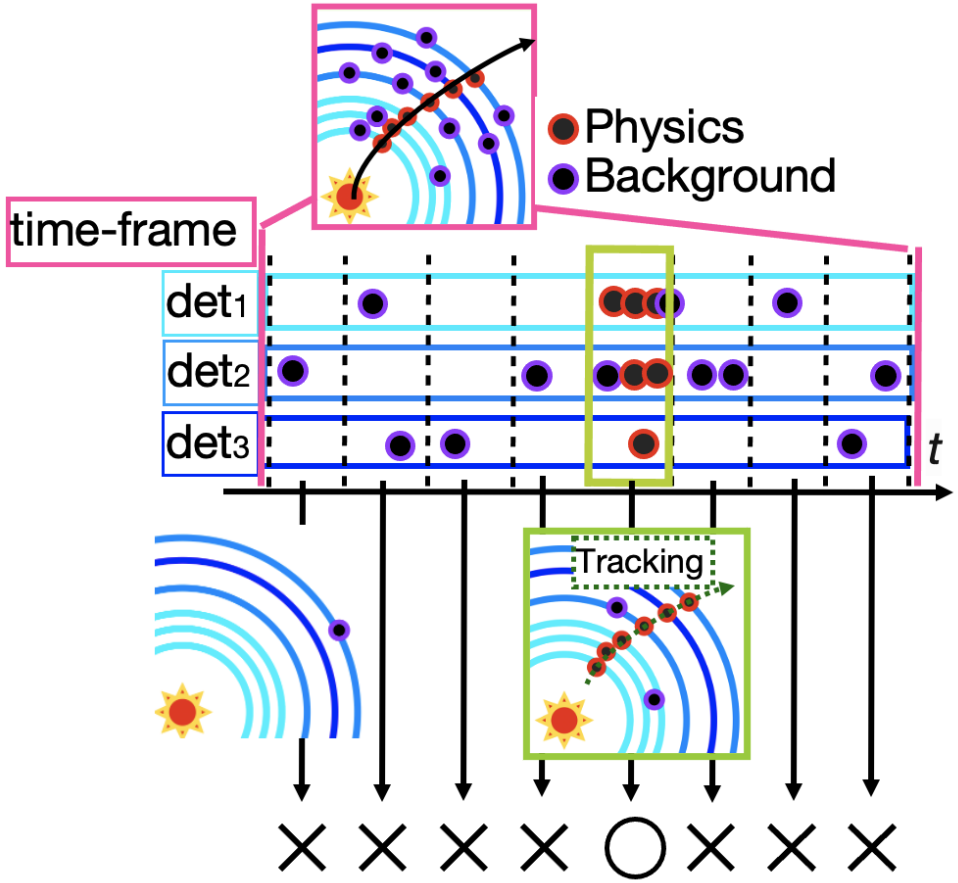
Geant4 built-in parameterized model interface is ML-ready (e.g. “Par04” example for inference with CaloDit)




Simulation time budget at ePIC central detector

# AI for reconstruction (SRO)




Streaming readout assumes data recorded as continuous stream of time-frames

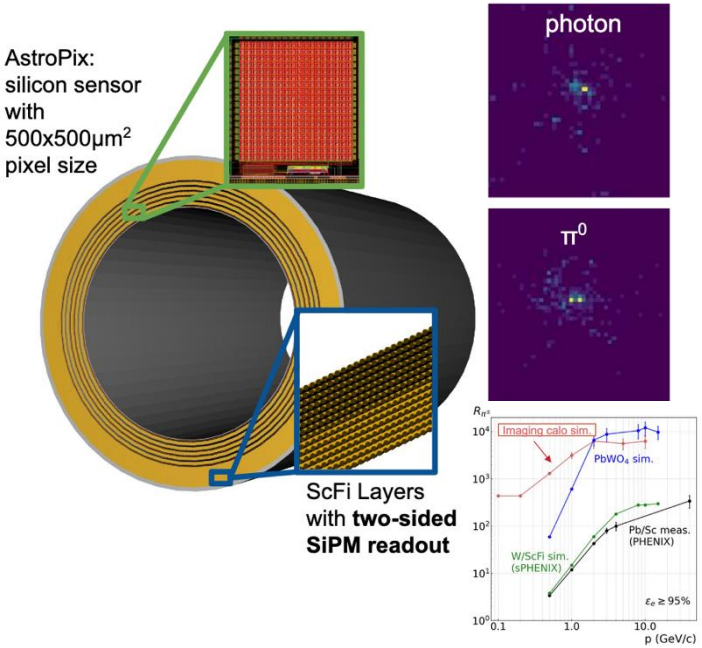
Ongoing work on implementing *frame → physics event* building using JANA2 is to complete in 2025

We plan to hold an AI/ML challenge for developing algorithms for physics event discrimination from backgrounds.

# AI/ML for reconstruction (Calorimetry)

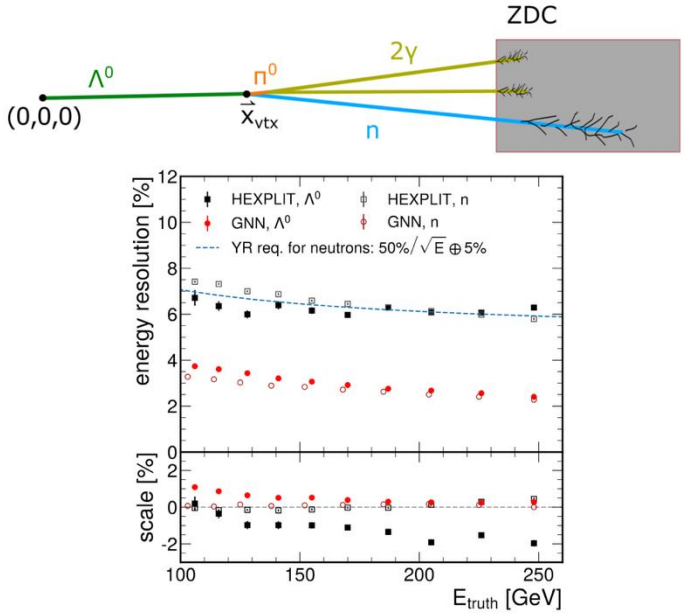
Advanced calorimetry systems at ePIC require advanced reconstruction to uncover their full potential

## Application of CNNs for PID



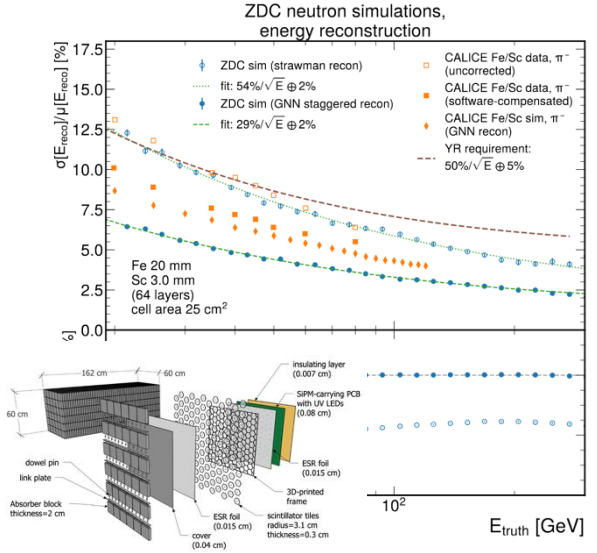

C. Peng et al

## Lambda decay reconstruction




PRD 111 (2025) 9, 092013

## GNN-boosted performance for a highly-granular calorimeter

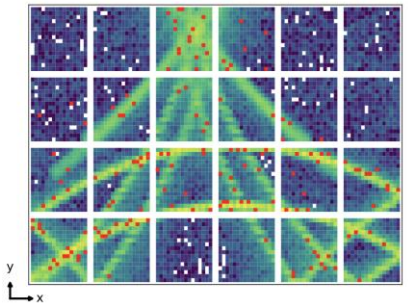


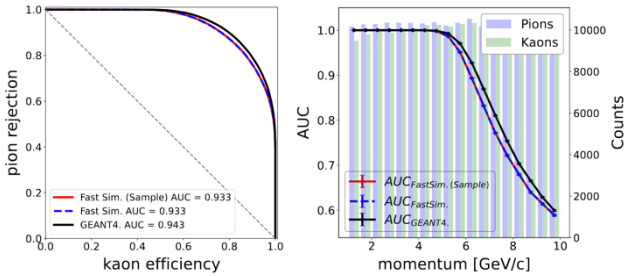

NIM A 1079 (2025) 170613

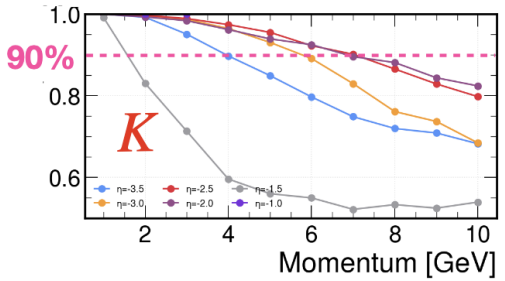
# AI/ML for reconstruction (PID)

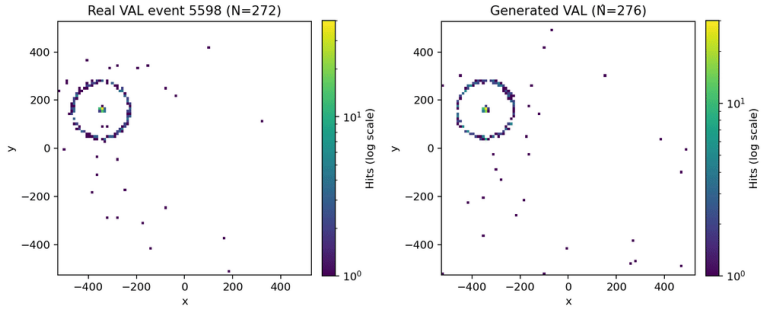
pfRICH, DIRC and dRICH rely on optical photon simulations Geant4.

Models available for fast simulation, reconstruction, including foundational models.






[arXiv:2504.19042](arXiv:2504.19042)

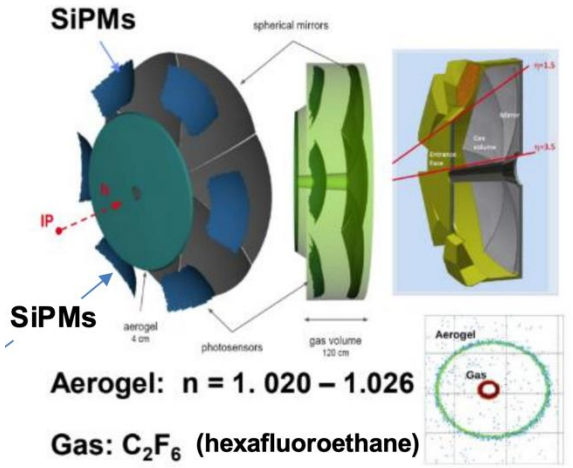
From Charles' and Bishoy's talk at AI4EIC

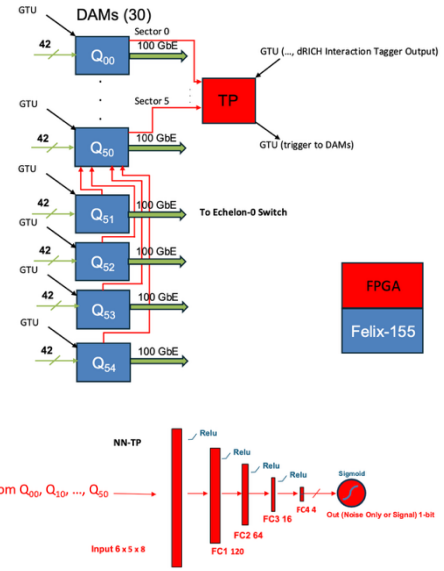
From Gabor's talk

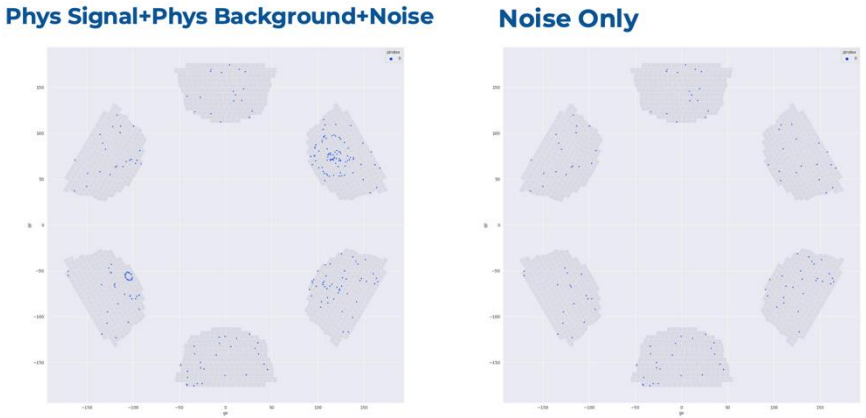
See talk by Cristiano and talk by Gabor in at AI4EIC, also talk by Charles in this session.

# dRICH data rate reduction

- 320k SiPM channels with 3-300 kHz noise is a unique challenge at ePIC
- Target bandwidth 100 GbE x 30
- Some low-level (not to introduce biases) processing can be done as edge-computing at Echelon 0
- A proposal is to run data reduction on FPGAs
- Initial investigation of distributed MLP model on simulated data
- **Potential for application of AI task-specific compression (e.g. work on BCAEs for sPhenix TPC, see talk by Y. Huang)**



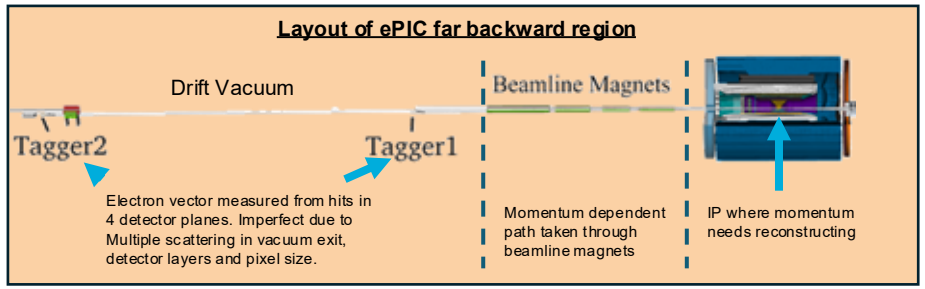



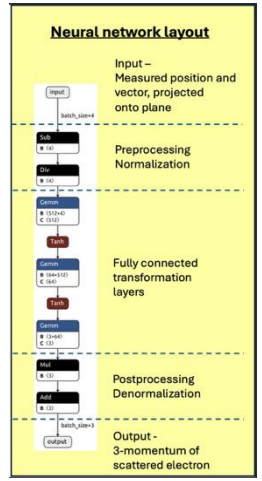
# AI/ML for reconstruction (Tracking)

ePIC reconstruction framework EICrecon depends on Acts project for tracking. Acts framework allows for interchangeable components and provides ready interfaces to ML models.

Far-forward and far-backward subsystems are subject to various backgrounds and beam optics effects, and greatly benefits from adopting ML.

Example: Low-$Q^2$ tagger calibration implemented as default method in EICrecon



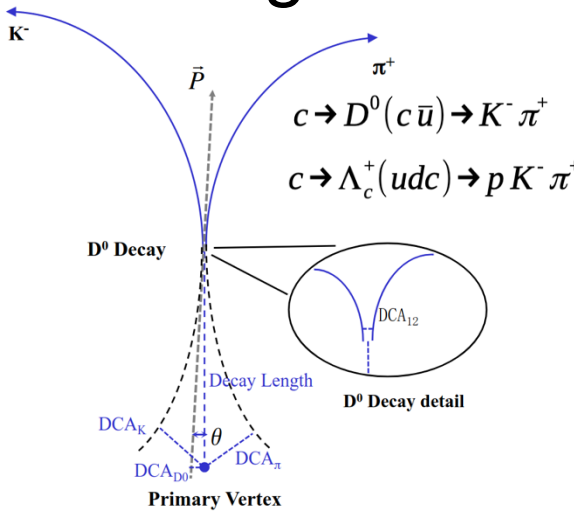



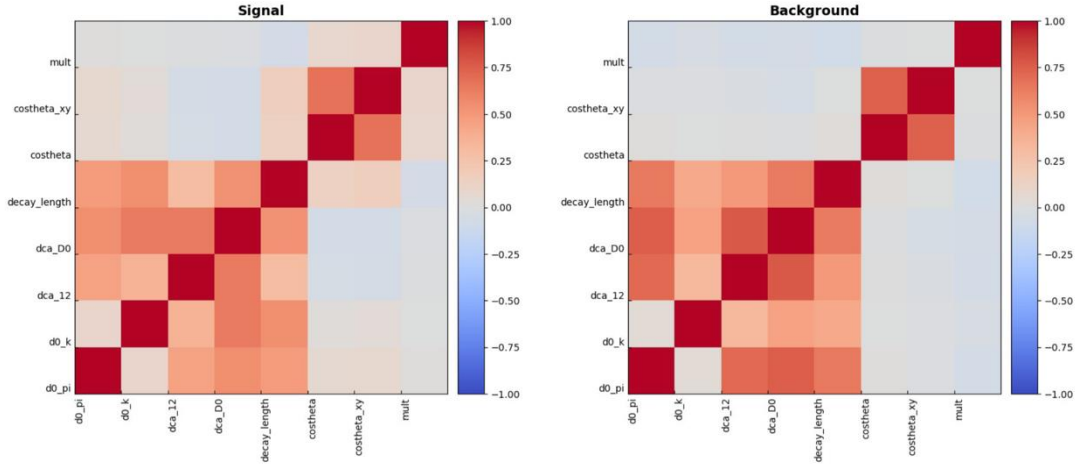

Work by S. Gardner, also see his talk at AI4EIC 2023

# Physics Analysis

ML algorithms will be important to precision kinematic reconstruction, flavor tagging, jet substructure and other applications

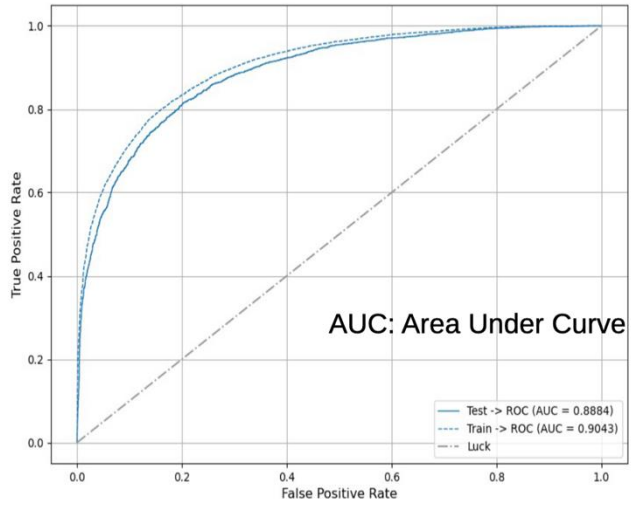
Example for Heavy-flavor production at ePIC: application of BDTs for D0 signal/background classification










Work by S. Kumar based on PRC **99**, 034908 & PRD **110**, 034017

# Open Data at ePIC

ePIC Simulation Data is public access and readily available for AI model training.

**ePIC Data Model using PODIO** provides plain structures for ease of access using Python/uproot.

As part of our AI and data management lifecycle, we will need to evaluate and prioritize aspects of **FAIR** implementation for ePIC.

See talk by L. Biven.

# Deploying ML at ePIC

Our containerized environments include Torch, Tensorflow, ONNX.

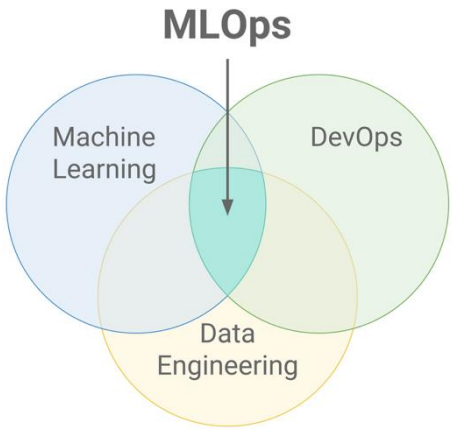
**ePIC Data Model using PODIO** provides standardized data structures for applications in simulation, reconstruction and analysis.

In ePIC, we prioritize the integration of AI/ML approaches and methods into our production workflows. This includes not only those with strong benchmark performance, but also those that scale well and are sufficiently generic for our scientific use cases – initially in simulation campaigns and later in data processing.

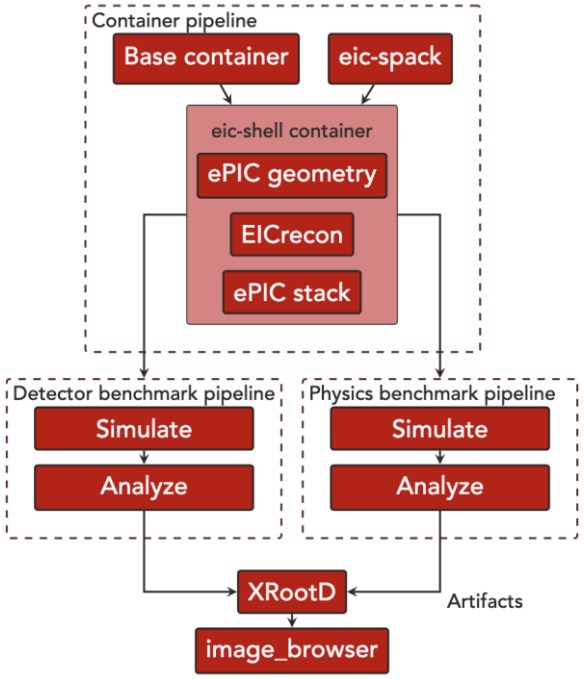
Our reconstruction framework uses  ONNX for model exchange.

# MLOps at ePIC

ePIC will deploy more and more AI models, that will all need to be kept up to date with the latest simulations and calibrations.






CI pipelines

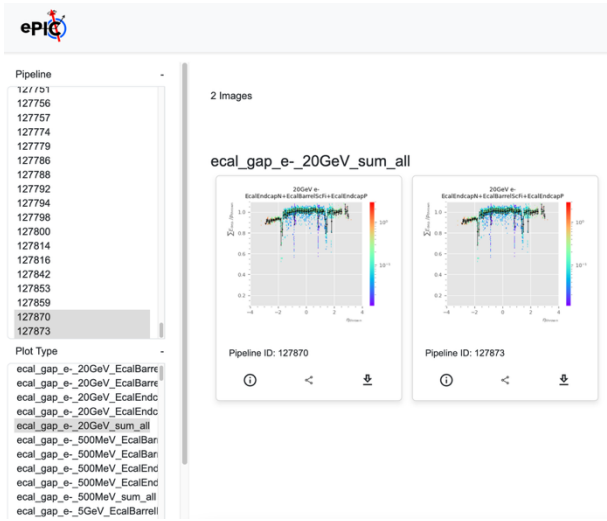
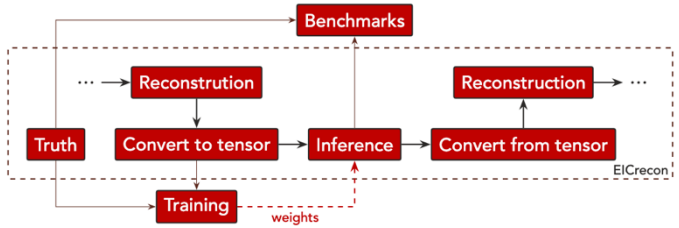


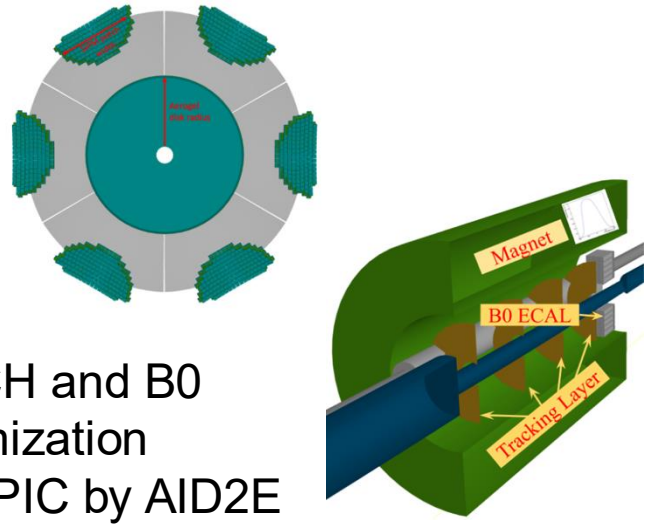

Image artifacts delivered to image_browser



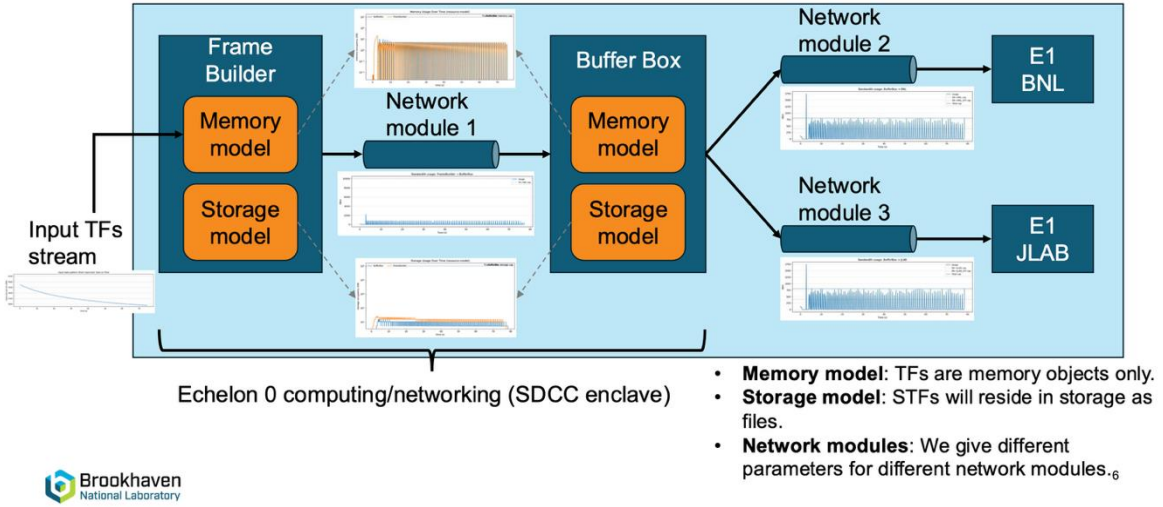

Standartized ONNX factory for EICrecon with model training and validation on CI

# Multi-Objective Optimization

Bulk of work on “macroscopic” detector optimizations have been performed before ePIC. There is still a room to contribute to critical designs at a various scales.




dRICH and B0 optimization for ePIC by AID2E
M. Diefenthaler *et al* 2024 *JINST* **19** C07001




Modelling of EIC Streaming Computing infrastructure
Kuan-Chieh Hsu, EIC Echelon 0-1 Workshop

# RAG-based knowledge retrieval

Objective: A summarization tool with “relevant citations” for within EIC

Many ongoing efforts: AI4EIC-RAG, AccGPT, chATLAS, HEPilot, RHIC-SciBot

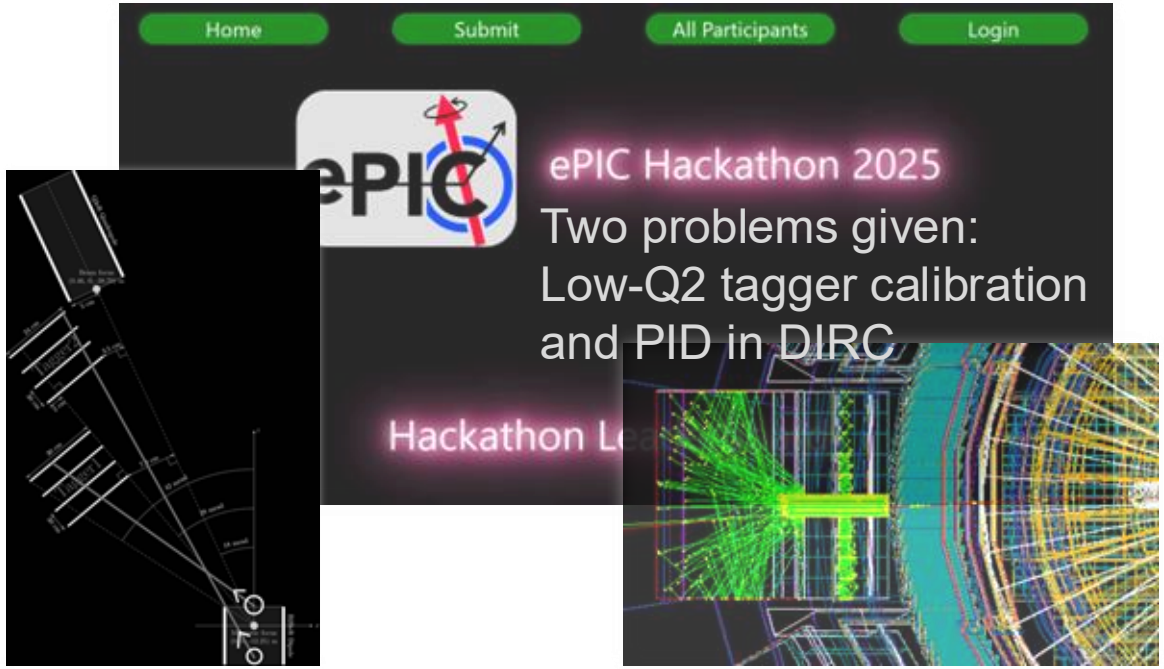
Generic solutions with relevant integrations will likely be available in the future.

Community training and database-building are important goals meanwhile.

# AI/ML activities at ePIC community

ePIC does not have a dedicated AI/ML WG, unlike EICUG. Instead, WG apply AI/ML methods where appropriate. AI Town Halls support community building.


1st , 2nd , 3rd ePIC AI Town Hall meetings




ePIC AI/ML Hackathon @ Frascati

# Conclusion

- ePIC will be one of the first complex detectors constructed for the AI era
- Our software design and implementation **support collaboration with data science**, as well as **AI integration within the software stack**
- AI/ML solutions are key to exploring its full potential towards upcoming CD-2 and TDR milestones
- There are a lot of opportunities for closer collaboration between the communities