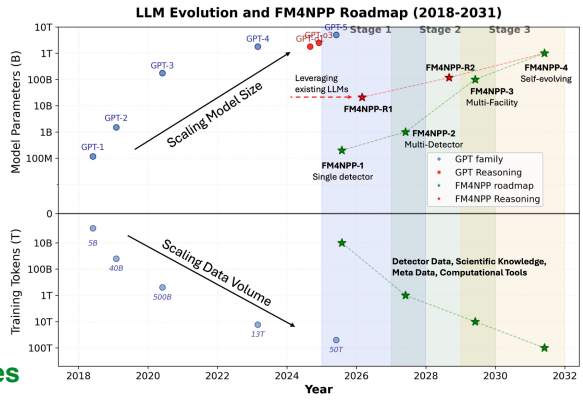
FM4NPP: A Scaling Foundation Model for Nuclear and Particle Physics

David Park[1], Shuhang Li[2], Yi Huang[1], Xihaier Luo[1], Haiwang Yu[2], Yeonju Go[2], Yuewei Lin[1], Christopher Pinkenburg[2], Shinjae Yoo[1], Joseph Osborn[2], Jin Huang[2], Yihui "Ray" Ren[1]
[1]AI Department & [2]Physics Department, Brookhaven National Laboratory, Upton, NY

Roadmap paper: *International Journal of Modern Physics A Vol. 41, No. 15n16, 2650086 (2026)*
https://doi.org/10.1142/S0217751X26500867

- Foundation model (FM) with a novel **self-supervised learning framework for low-level detector data**
- Demonstrated **scaling behavior** up to **188 million parameters**
- With **frozen pretrained weights and task-specific adapters**, the FM consistently outperforms baseline models across downstream tasks



Roadmap & Future Works

1. **Scale to larger models**, incorporate more data, and validate on additional downstream tasks
2. Explore **alternative architectures** and **self-supervised learning objectives**
3. Expand to **other experiments** in NP and HEP, such as LHC, Dune, EIC
4. Incorporate **additional modalities**, including detector subsystems, simulation information, and metadata

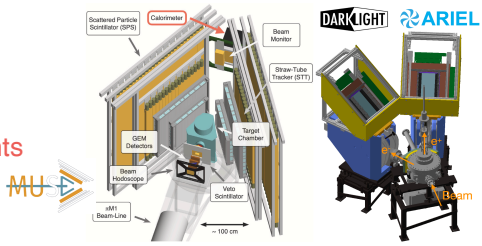
Paper: *ICLR 26 accepted, arXiv:2508.14087*
Source Code: *github.com/FM4NPP/PP_collision*
Dataset: *zenodo.org/records/16970029*

Phase-I: Foundation Models for Transferable Particle Tracking in Nuclear Physics

Stony Brook University: Jan C. Bernauer (PI), Axel Drees
Brookhaven National Laboratory: Yeonju Go, Yi Huang, **Argonne National Laboratory**: Henry Klest

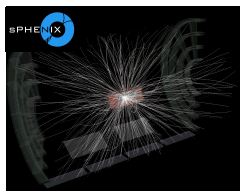
Physics / AI Goal

- Develop a **generalizable foundation model for particle tracking**
- Learn **directly from raw detector signals** (lower-level than FM4NPP paper [1])
- Preserve **signal shape, timing, pulse height, and detector correlations**
- Learn **detector-agnostic latent representations** transferable across experiments e.g. sPHENIX, DarkLight, MUSE



Phase-I Strategy

- Develop a **detector-agnostic architecture** that can ingest **heterogeneous raw detector signals** e.g. DarLight GEM tracker, MUSE straw-tube tracker, sPHENIX TPC
- **Cross-experiment pre-training:** sPHENIX + DarkLight + MUSE
- Raw inputs: ADC/QDC waveforms, Strip / pad hit patterns, Drift-time information etc
- Study scaling with **model size, dataset size, detector modality, and number of experiments**
- Test **cross-experiment transferability** through pre-training and limited-data fine-tuning

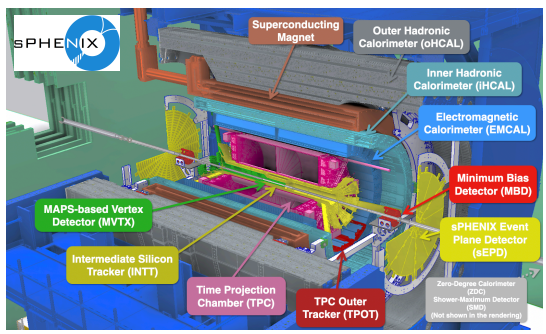


Phase-I: Multimodal Enhancements to the Foundation Model for Nuclear and Particle Physics (FM4NPP)

Lawrence Livermore National Laboratory: Ron Soltz (PI), Kowshik Thopalli, **Columbia University**: Bill Zajc
University of Colorado, Boulder: Dennis Perepelitsa, **Brookhaven National Laboratory**: David Park, Yeonju Go

Physics / AI Goal

- Extend **FM4NPP to a multimodal foundation model**
- Fuse **tracking + calorimeter information**
- Learn **cross-detector correlations directly from detector-level data**
- Toward a unified **particle-flow reconstruction foundation model**
- Scalable framework for **multiple detector subsystems and experiments**



Phase-I Strategy

- Independently pretrain **modality-specific encoders**
- **Mamba2-based FM4NPP** architecture
- TPC: existing **k-Next-Nearest-Neighbor self-supervised objective**
- Calorimeter: analogous **geometry + energy-deposition prediction**
- Fuse pretrained representations using:
  - **Event-level fusion:** lightweight baseline, **Token-level cross-attention:** primary approach
- Geometry-informed attention for **local cross-detector associations**

Acknowledgement

- We thank the sPHENIX collaboration for access to the simulated dataset, which was used in the training and validation of our algorithm. We also thank for valuable interaction with the sPHENIX collaboration on this work.
- The FM4NPP work was supported by the Laboratory Directed Research and Development (LDRD) Program at Brookhaven National Laboratory, LDRD 25-045, which is operated and managed for the U.S. Department of Energy (DOE) Office of Science (SC) by Brookhaven Science Associates under contract No. DE-SC0012704.