Building an ML-enhanced Optics Calibration Workflow for SHMS

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JLab Hall A/C Summer Meeting
June 17, 2026

Introduction

Scope:

- **Apply ML techniques to improve the optics calibration workflow**

Workforce:

- Undergrad project by Xiaoyang Zheng

Beijing Normal University → Berkeley visiting student → University of Tokyo

- Monthly-ish discussion and SLACK channel (R-SIDIS/optics)

Eric Fuchey Eric Fuchey

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Julio Gil Gutiérrez Julio Gil Gutiérrez

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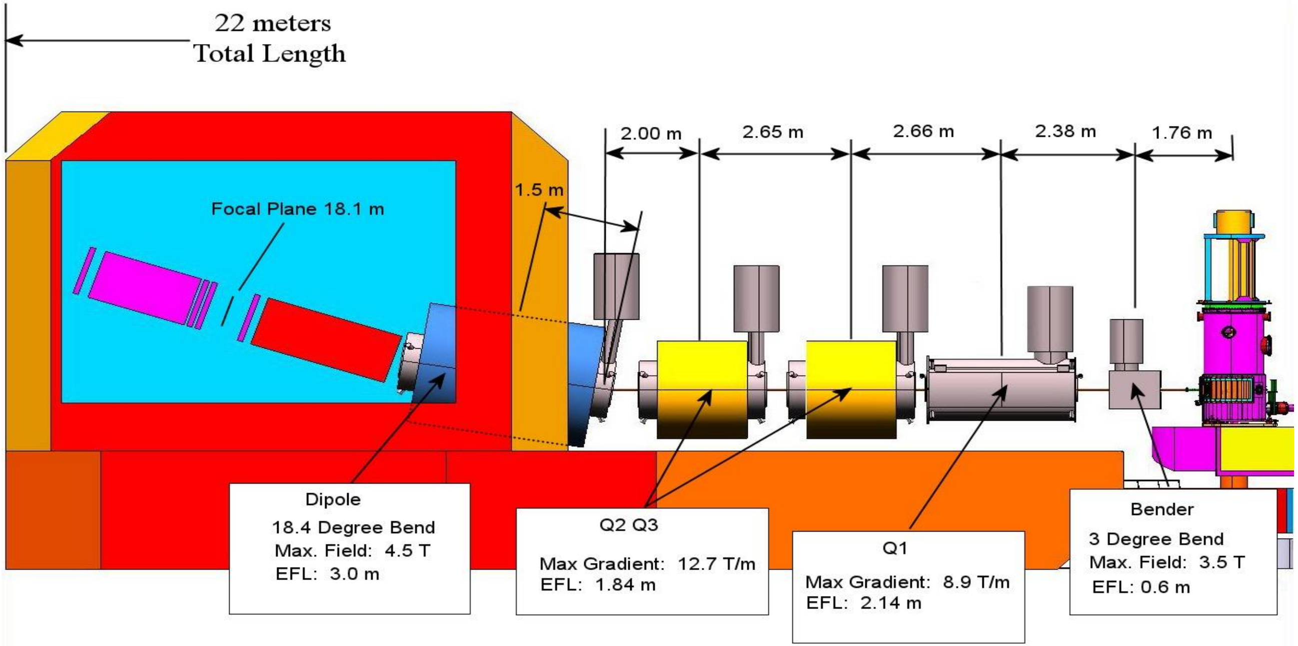
Zeke Wertz Zeke Wertz

- Special thanks

Copilot

Define the Question

Particle path: Focal Plane ← QQQD ← (sieve) ← HB ← Target plane



Optics reconstruction: learning the inverse transport map from focal-plane tracks and spectrometer settings to target-plane kinematics;

Existing Knowledge

- **Simulation**: COSY transport and inverse matrices
- **Calibration data:**
    - geometric constraints on ytar (foil) and yptar, xptar (sieve)
    - Delta scan: hydrogen elastic data to fix delta

- **Optics Matrix:** up to 5th order polynomial to connect 5 target plane observables $\rightarrow$ 4 focal plane observables (+ the 5th variable from vertical beam position).

First order:

$$\begin{pmatrix} x_{fp} \\ x'_{fp} \\ y_{fp} \\ y'_{fp} \end{pmatrix} = \begin{pmatrix} -1.5 & 0.0 & 0.0 & 0.0 & 1.65 \\ -0.5 & -0.7 & 0.0 & 0.0 & 3.2 \\ 0.0 & 0.0 & -1.9 & -0.2 & -0.1 \\ 0.0 & 0.0 & -3.0 & -0.8 & 0.1 \end{pmatrix} \begin{pmatrix} x_{tar} \\ x'_{tar} \\ y_{tar} \\ y'_{tar} \\ \delta \end{pmatrix}$$

5th order polynomial:

$$x'_{tar} = \sum_{ijklm} X'_{ijklm} x^i_{fp} x'^j_{fp} y^k_{fp} y'^l_{fp} x^m_{tar}$$

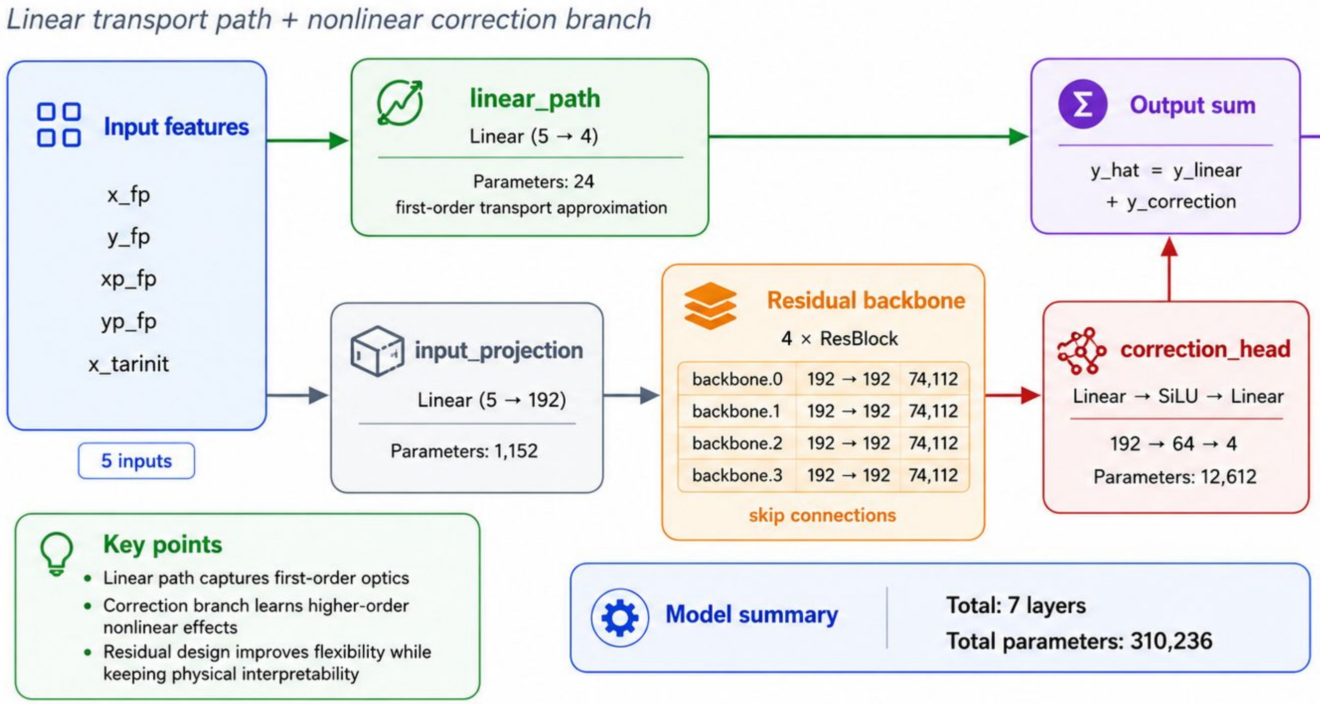
$$y_{tar} = \sum_{ijklm} Y_{ijklm} x^i_{fp} x'^j_{fp} y^k_{fp} y'^l_{fp} x^m_{tar}$$

$$y'_{tar} = \sum_{ijklm} Y'_{ijklm} x^i_{fp} x'^j_{fp} y^k_{fp} y'^l_{fp} x^m_{tar}$$

$$\delta_{tar} = \sum_{ijklm} D_{ijklm} x^i_{fp} x'^j_{fp} y^k_{fp} y'^l_{fp} x^m_{tar}$$

ML-enhanced Workflow

- **Simulation** → use MC data for pre-training
- **Calibration data** → weak labels to provide geometric constraints for fine-tuning
- **Optics Matrix** → use as a benchmark, introduce an alternative **residual MLP** (Multilayer Perceptron) model

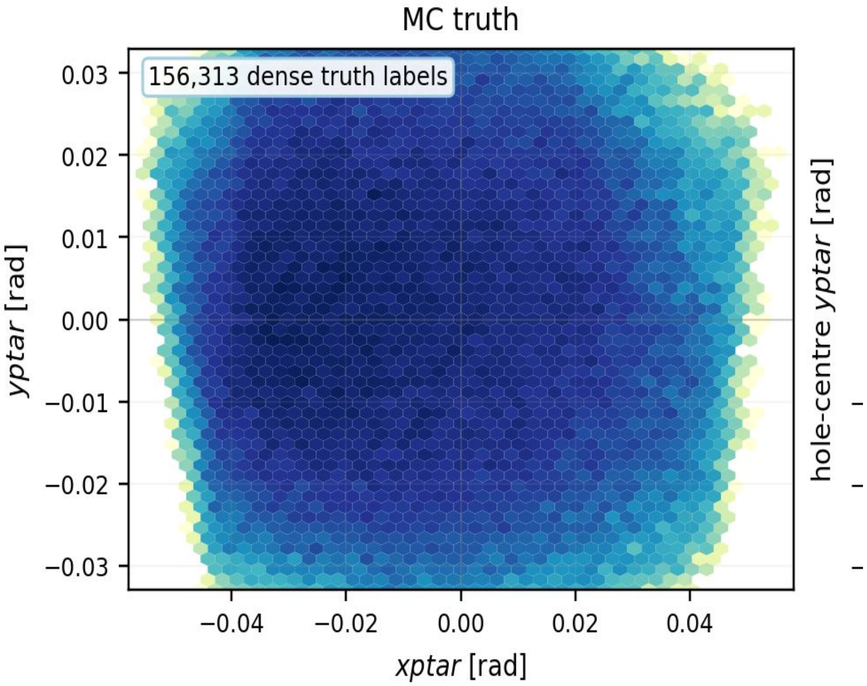


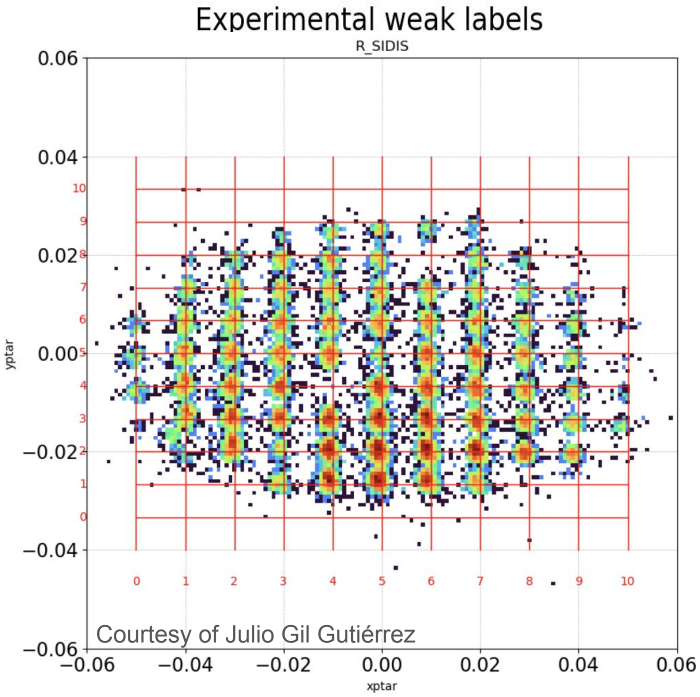
*training on delta in not yet tested

Two-stage Training

Stage 1: pre-train model with MC data:

- 4 focal + 1 beam variables → 4 target variables
- Continuous coverage of phase space, dense label of truth info but imperfect reality (v.s. sieve data) → smooth global optics map to be **transferred** to real data.

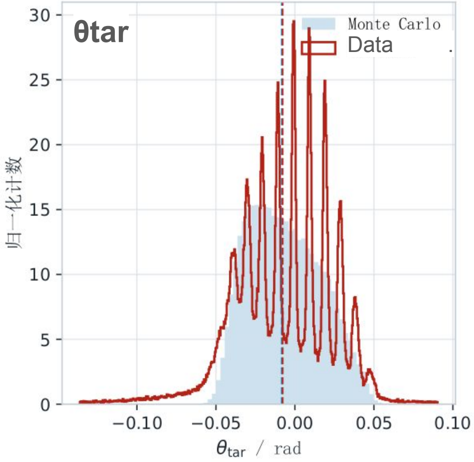


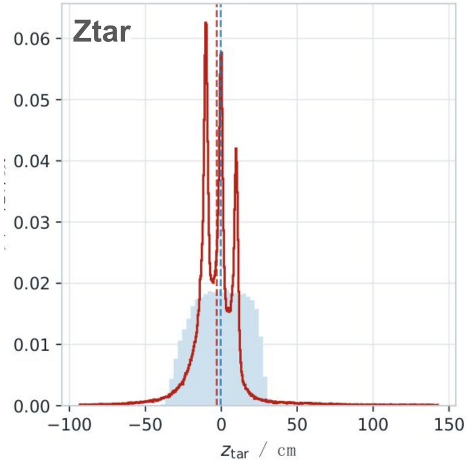


Two-stage Training

Stage 2: weak-label tuning with optics foil + sieve data

- Real but discrete, geometric constraints (sieve hole position) not truth value at target plane





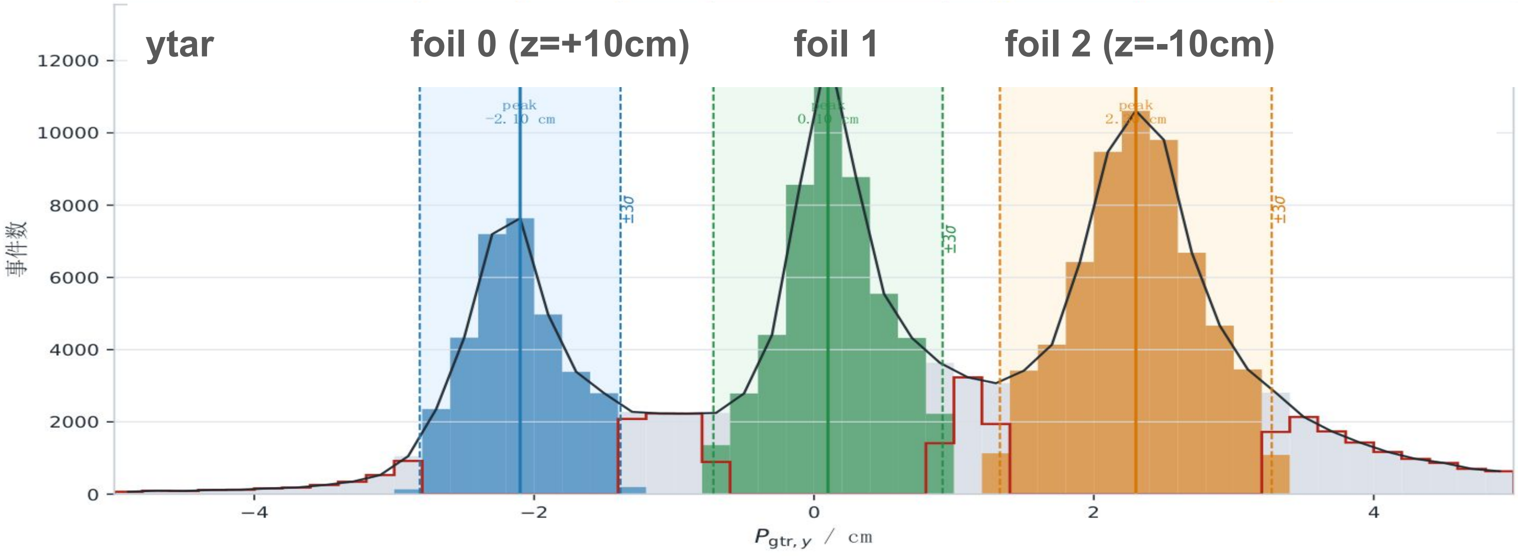
- Deadzone Huber Loss to provide robust penalty considering the finite the sieve hole size

$$L_\delta(r) = \begin{cases} \frac{1}{2}r^2 & \text{当 } |r| \le \delta \\ \delta \cdot (|r| - \frac{1}{2}\delta) & \text{当 } |r| > \delta \end{cases}$$

Automated Data Labeling

1. Peak search and foil separation

- **Cuts**: etracknorm>.8 && sumnpe > 6. && delta>-15 && delta<24



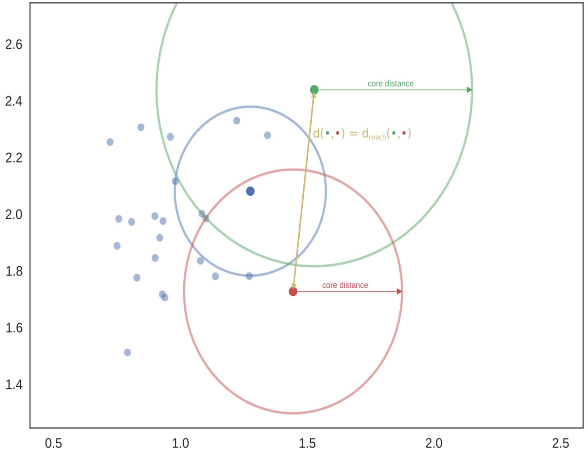
Automated Data Labeling

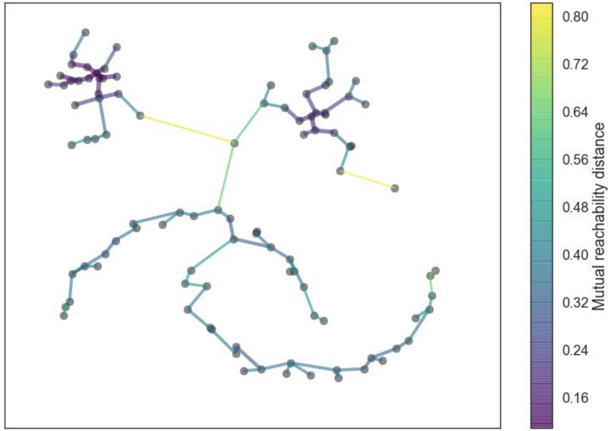
2. Sieve data clustering with HDBSCAN:

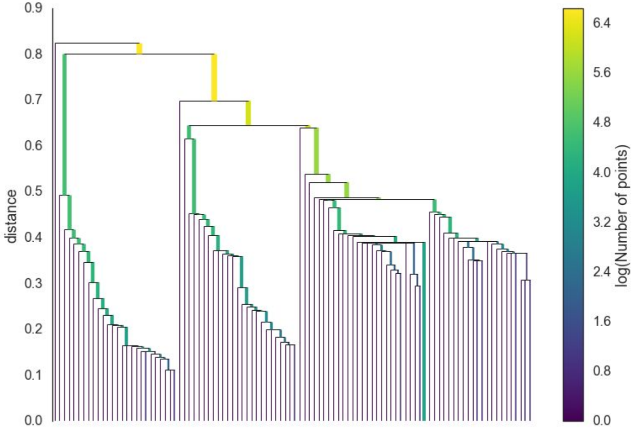
Hierarchical Density-Based Spatial Clustering of Applications with Noise, Campello, R.J.G.B., Moulavi, D., Sander, J. (2013)

- Handle both central and edge clusters well despite big change in density

Calculate core distance → build minimum spanning tree → form the cluster hierarchy





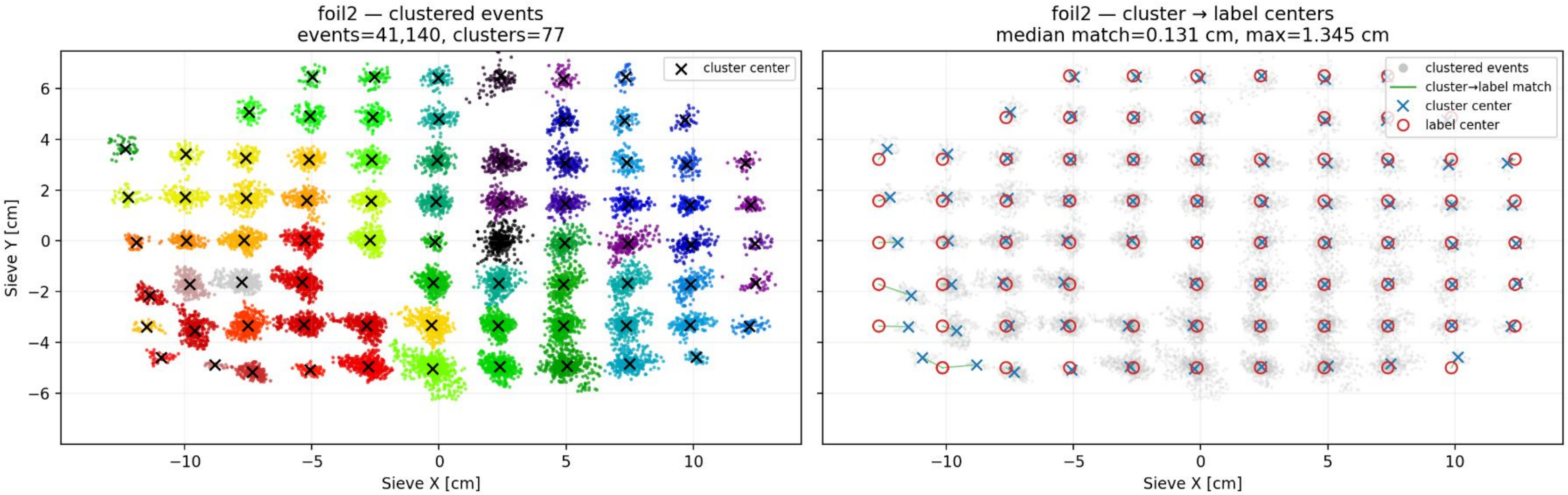


Automated Data Labeling

Package is available on github (work in progress)

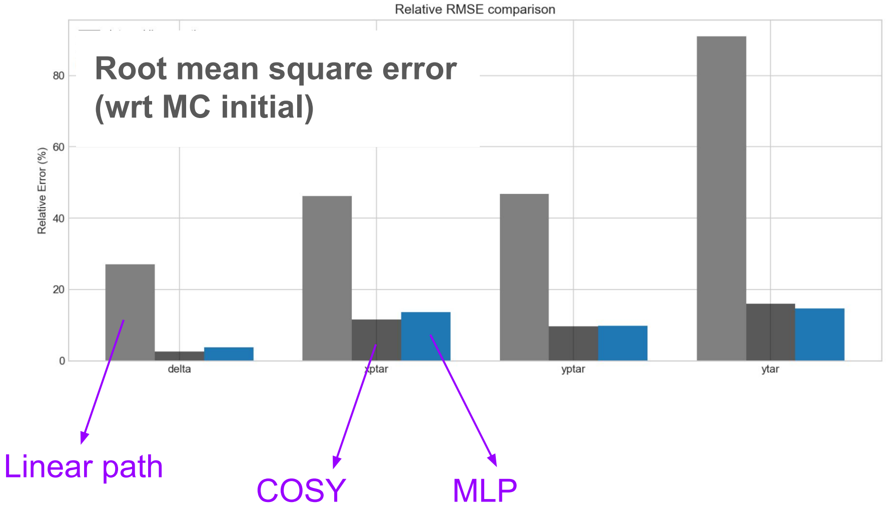
2. Label the data

- Compute center point of each cluster
- Align cluster center with sieve hole center
- Support optional manual QA/corrections
- Weighting with cluster size

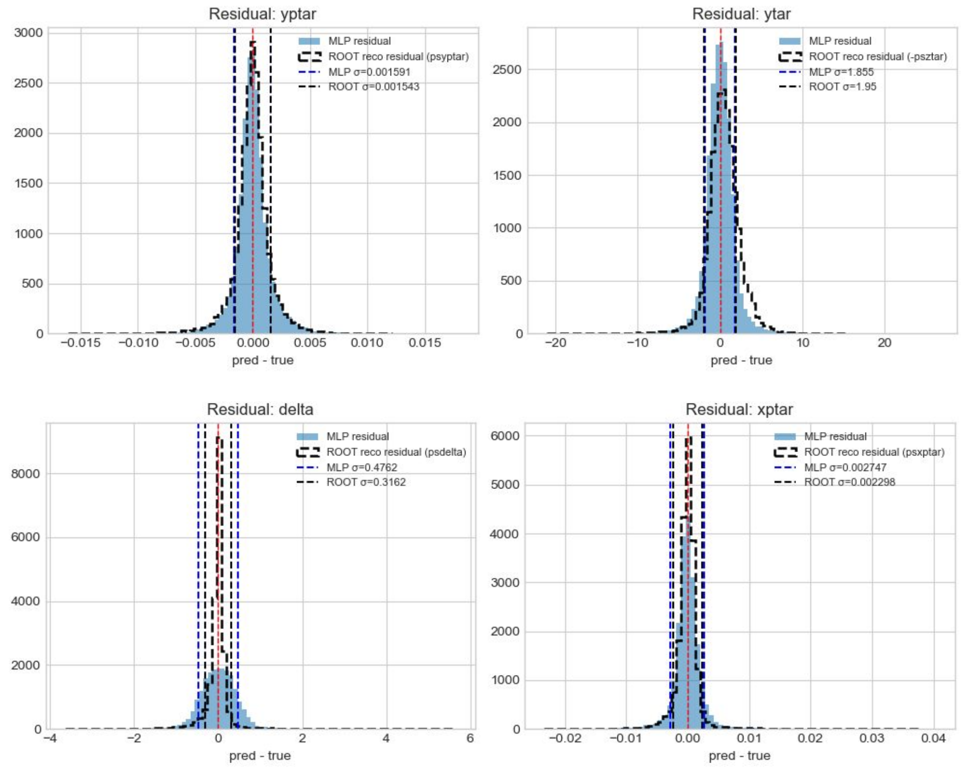


Performance

- Pre-training:
  - 156k MC events, 32 epoch
  - 8:2 training/validation
  - MLP result comparable to COSY

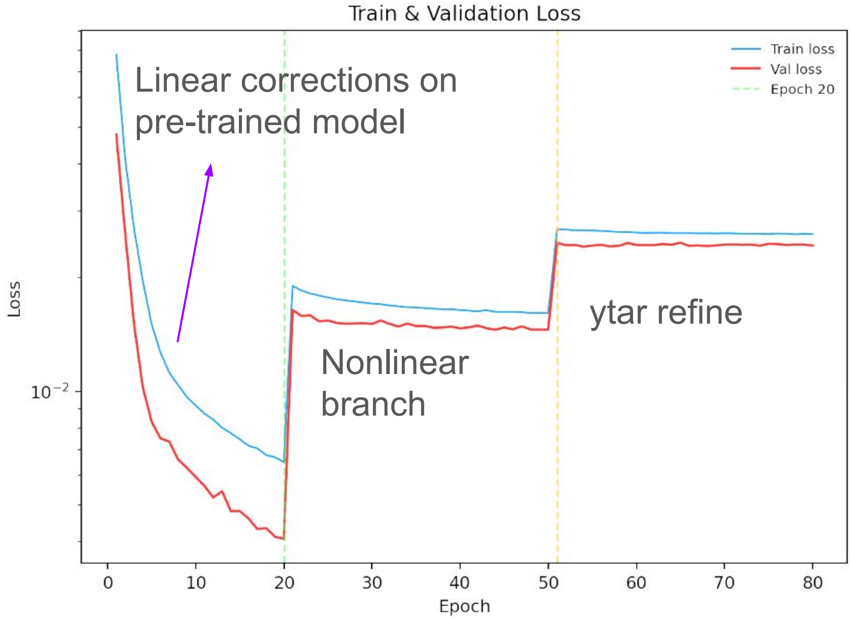


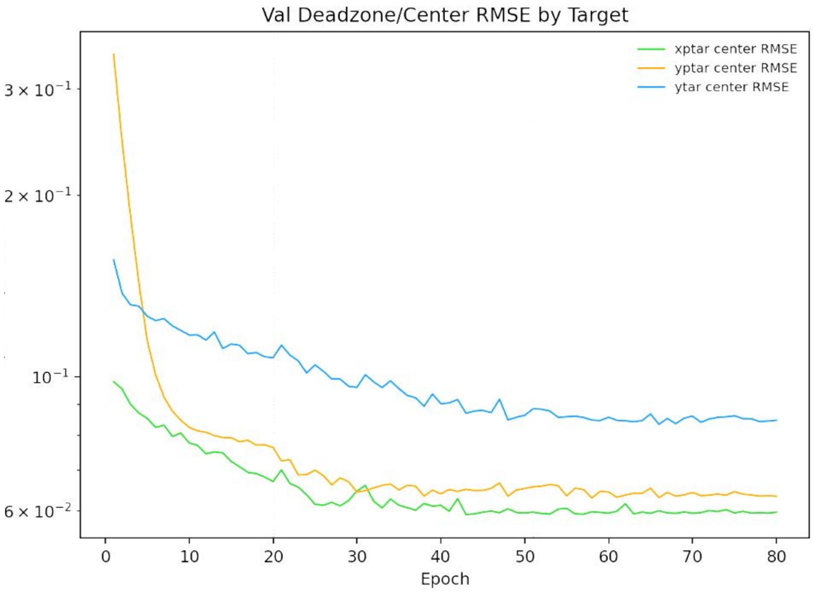
Residuals on target variables



Performance

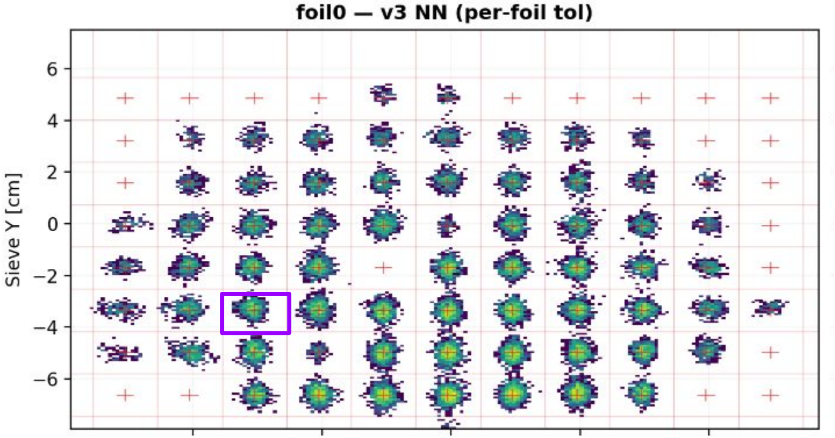
- Stage 2:
  - R-SIDIS run 25521 SHMS with optics target, 100k events, holdout 5 holes for validation. No data for **delta** training
  - RTX 4060 Ti (16 GB)
  - Cost per epoch: 1.1s (head) / 1.3s (corr) / 2.4s (refine)
  - Loss function jumps at different phase, while validation performance steadily improving

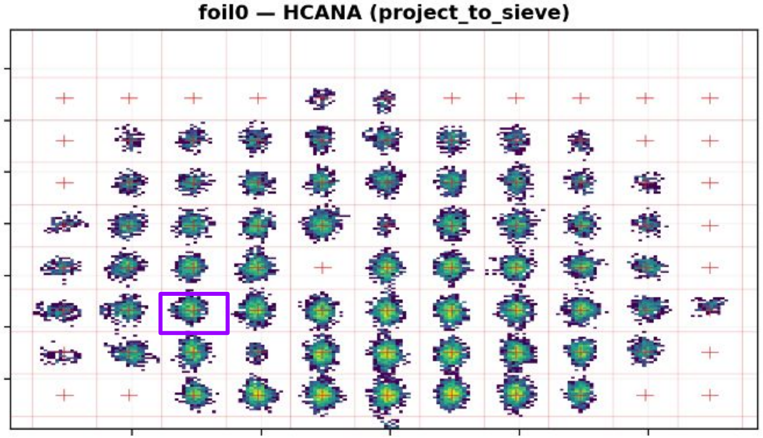




Performance

Left: MLP results. **Right**: optics matrix. : holdout holes

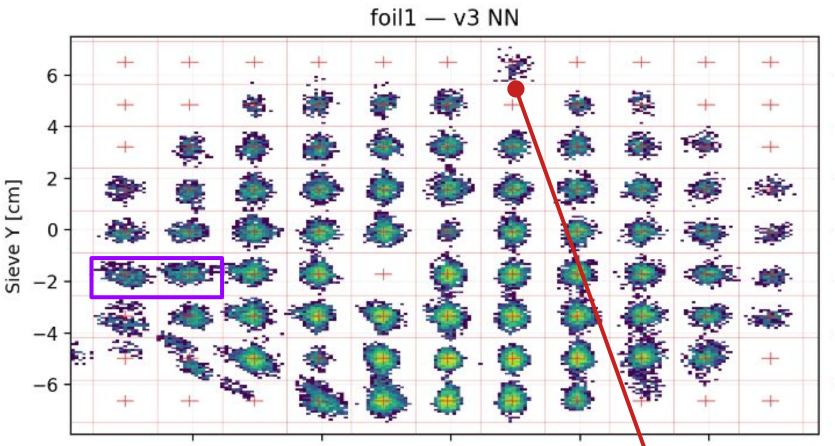


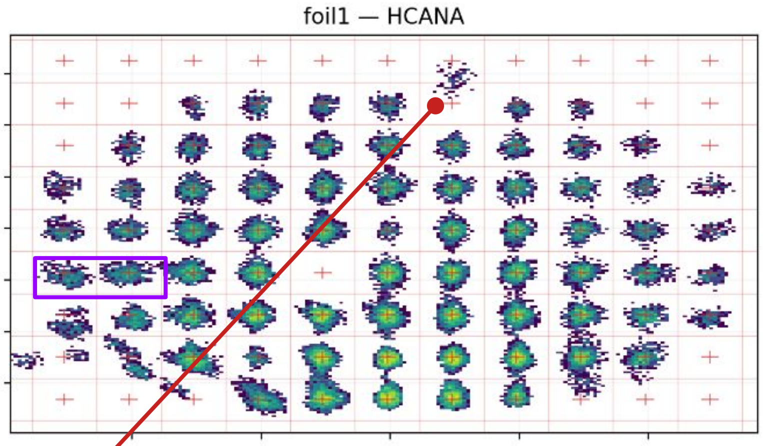


Foil 0 (z=10cm): very consistent performance

Performance

Left: MLP results. **Right**: optics matrix. : holdout holes

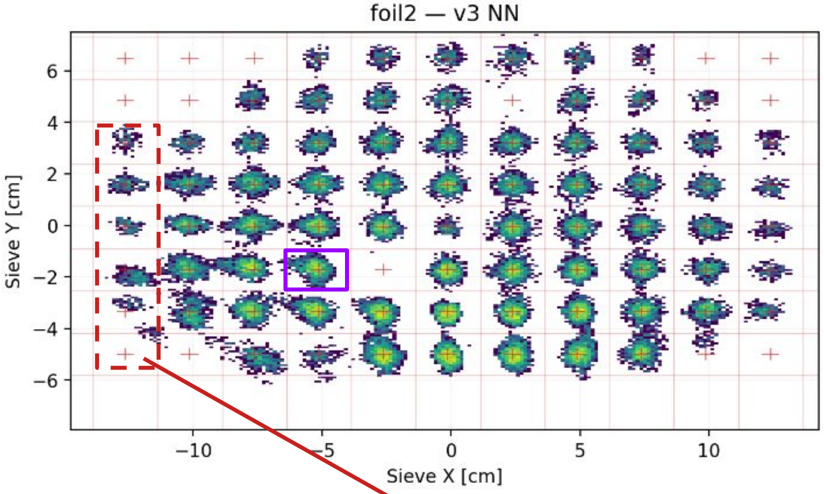


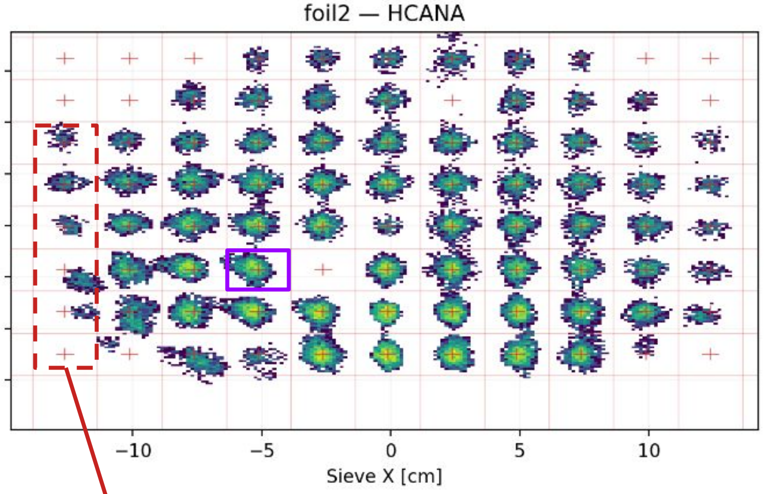


Foil 1 (z=0 cm): slightly improved y-span

Performance

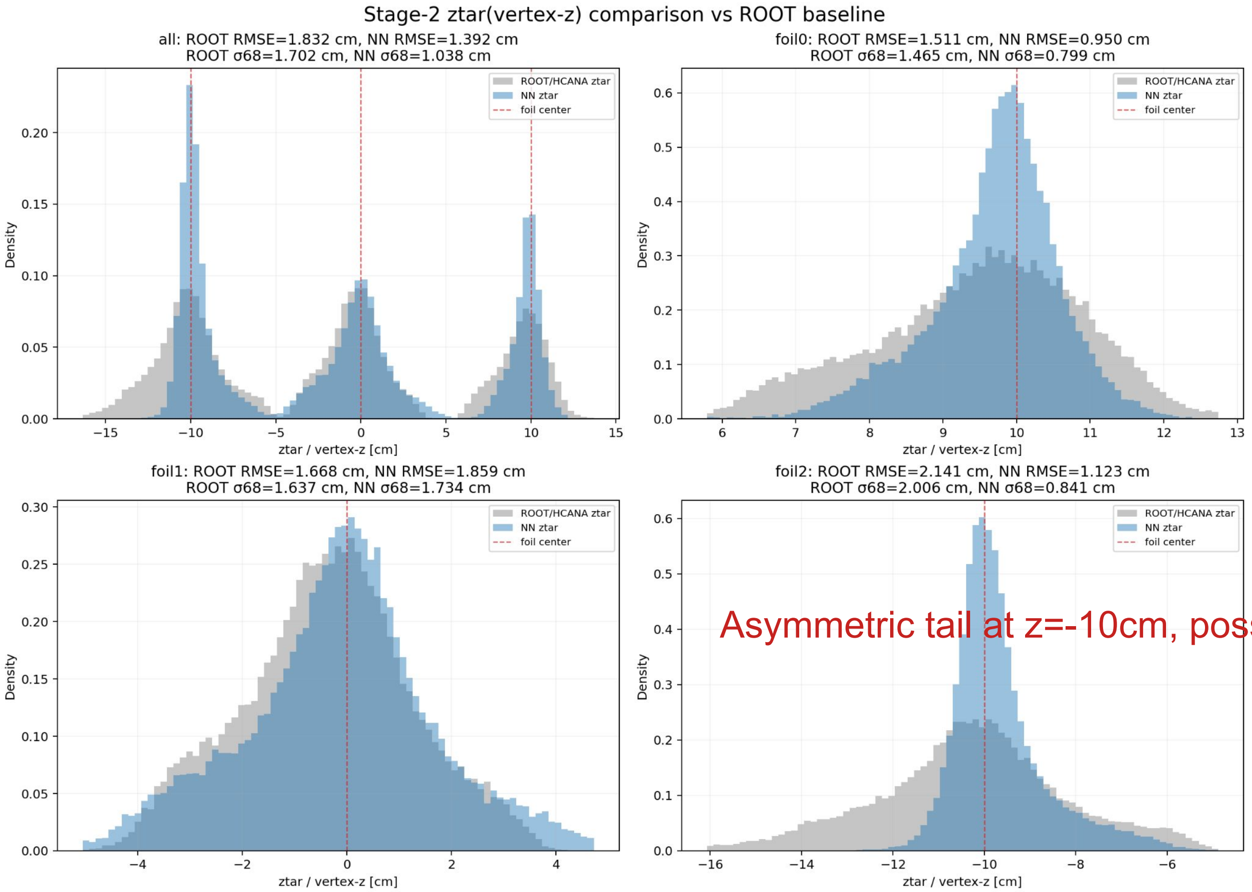
Left: MLP results. **Right**: optics matrix. : holdout holes





Foil 2 (z=-10 cm): noticeable better distortion correction at lower left corner, but clusters still have tails.

Performance



Asymmetric tail at z=-10cm, possible bias?

Summary

- We demonstrated an **ML-enhanced optics reconstruction workflow** that:
  - Follows the logic of established procedure, while providing
    - Automated sieve data labeling tool
    - Two-stage transfer-learning framework with Residual MLP for focal → target plane mapping instead of 5th order polynomial fit
  - Shows promising performance on sieve and foil reconstruction.
- **Next step:**
  - Rigorous validation/stability test, and understand ztar behaviors.
  - Add delta scan data
  - Benchmark with popular models from HEP community, before considering larger models
  - Consider approaches that deviates from traditional optics workflow e.g. clustering on focal plane?
- **Long term goal:**
  - A largely-automated optics reconstruction package for (SHMS, HMS, HRS…) that can provide reliable performance at **extended phase space** coverage and **extreme kinematics**.

Thanks!

```
sieve y=-0.019*psdelta+0.00019*psdelta*psdelta+(138.0+75.0)*psyptar+psytar +
40.0*(-0.00052*psdelta+0.0000052*psdelta**2+psyptar) ## horizontal

Sieve x=fry+psxptar*253.0 #vertical, along target x
```