Fermilab

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AI for Accelerators: Current Challenges and Future Directions

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CLARIPHY Collaboration Meeting

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Where AI can contribute to accelerator systems

- AI can extract useful information from large, heterogeneous datasets and support complex accelerator decisions
- Applications span accelerator operations, beam diagnostics, and component design

Operations and reliability

- Beam tuning and operating-point optimization
- Anomaly detection and equipment protection
- Predictive maintenance and fault diagnosis

Measurement and design

- Beam diagnostics and virtual instruments
- Phase-space reconstruction from distributed measurements
- Accelerator component and target design

Most accelerator AI applications use local measurements to optimize an individual machine or subsystem.

Unique focus of this talk: Integrate accelerator instrumentation with measurements from physics detectors to optimize beam delivery and experimental performance

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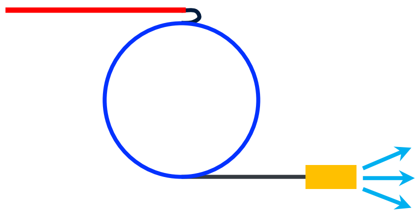
Experimental Configuration Defines Accelerator AI Priorities

Optimal accelerator performance depends on how the experiment uses the beam

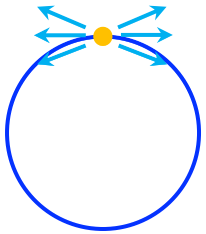
Fixed-target experiments: extracted single-pass beam

- The experiment receives each extracted pulse only once
- Beam conditions must be reconstructed rapidly from distributed measurements
- Tuning decisions must occur between pulses or spills
- Experimental performance depends on the target and downstream detector response



Circular colliders: circulating beams

- Beams circulate and collide over many turns
- Repeated measurements enable continuous feedback
- Phase-space errors affect stability, luminosity, and collision-energy resolution
- AI supports orbit correction, phase-space control, and long-term optimization



Accelerator AI should optimize experimental performance by connecting accelerator, target, and detector measurements

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Current Challenges and Future Directions

Current challenges

- Sparse fault data and incomplete labels
- Different data rates, timing systems, formats, and calibrations
- Synchronizing accelerator, target, and physics-detector measurements
- Changing machine configurations and operating conditions
- Requirements for reliability, interpretability, and response time
- Secure access across controls and machine-protection networks

Future directions

- Physics-informed models and accelerator emulators
- Common timing and metadata across accelerator instrumentation and physics-detectors
- Uncertainty-aware operator decision support
- Common data standards and reusable benchmark datasets
- Staged deployment with continuous validation and human oversight

These needs also align with the Genesis Mission

Operational value requires trustworthy predictions under changing machine conditions

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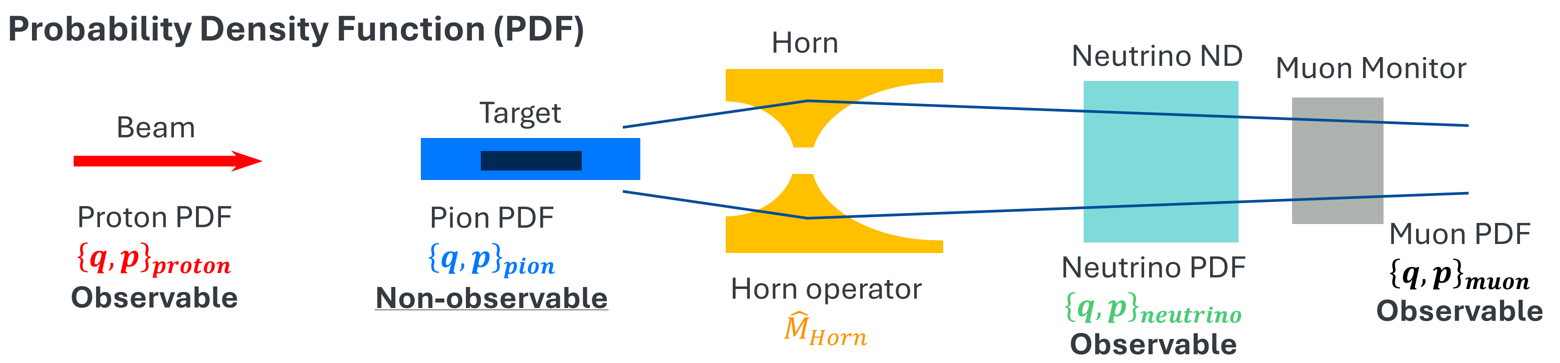
Experiment-Integrated Digital Ecosystem for LBNF



$$\binom{q}{p}_{muon} \oplus \binom{q}{p}_{neutrino} = \hat{M}_{Horn} \cdot \binom{q}{p}_{pion}$$
$$= \hat{M}_{Horn} \cdot \hat{M}_{Hadron\ prod.} \cdot \binom{q}{p}_{proton}$$

- Surrogate model emulates magnetic-horn focusing
- Acquire bunch-resolved accelerator data
  - Synchronize fast beam instrumentation, such as Wall Current Transformer (WCT), Beam Position Monitor (BPM), and Beam Loss Monitor (BLM) with beam and machine settings
- Use AI-assisted muon monitors (e.g. MuMS) to infer the unobserved pion phase space
- Integrate measurements from the SAND ND, including its liquid-argon volume, into the accelerator data ecosystem

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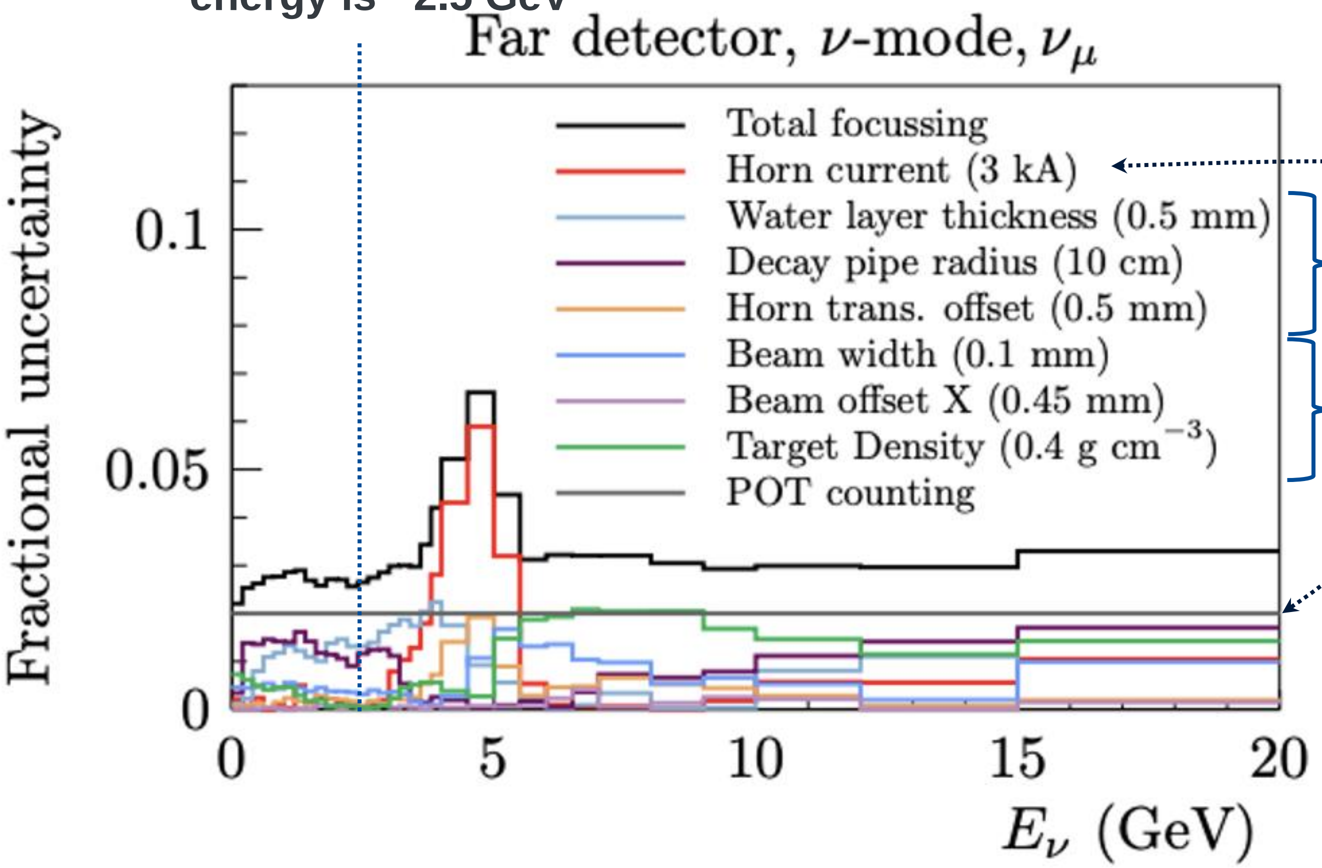
Beam-related Flux Uncertainty and Measurement Goals

An experiment-integrated digital ecosystem could reduce beam-related uncertainty for LBNF/DUNE

Peak on-axis neutrino energy is ~2.5 GeV



Protons on Target

- Improve uncertainty from 2 to 0.1%
- Introduce new current transformer

Horn current

- Improve uncertainty from 3 to 0.1 kA
- Already demonstrated at NuMI

Predict with emulator and validate with survey & beam tomography

Beam and Target conditions

- Goal beam width < 0.1 mm
- Goal beam position offset ~ 0.02 mm
- Goal target Density < 5 %

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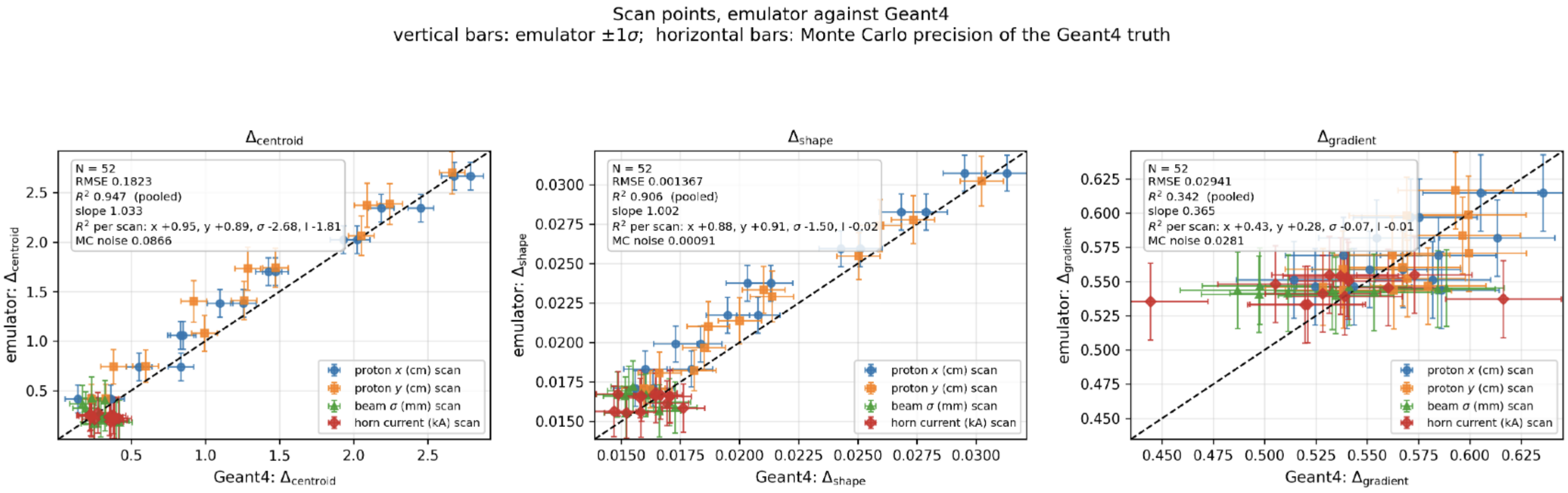
Bayesian Exploration with a Physics Informed Emulator for LBNF

Curtesy of S. Ganguly



- Plots demonstrate that the physics informed emulator approximates high-fidelity Geant4 responses across beamline parameter scans
- Fast inference enables Bayesian exploration and feedback for beam tuning

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Advancing AI for High-Power-Target Design

AI replaces routine evaluations inside a validated domain; selected and high-risk cases return to physics

DEFINE → GENERATE → PREDICT & OPTIMIZE → GATE → VALIDATE

01
Define
Geometry · material
beam · cooling

02
Generate
Parametric concepts
feasible candidates

03
AI predict
Validated surrogates
+ uncertainty

04
Screen
Optimize · constraints
UQ · novelty · risk

05
Validate
Selected high-fidelity
simulation · experiment

validated evidence retrains surrogates and expands their domain

What the model explores (Define + Generate)

Geometry, material, beam parameters, and cooling configuration

What the model predicts (AI predict)

Particle yield, temperature, stress, fatigue, radiation damage, and physics uncertainty

What makes a candidate viable (Optimize / Gate)

OBJECTIVE

Maximize physics performance and service lifetime

CONSTRAINTS

Temperature · stress · cooling capacity · manufacturability · safety

AI/ML Test Facility: Validating Predictions and Calibrating Uncertainty

Controlled beam tests establish AI performance under realistic operating conditions

Why a test facility is needed

- AI development requires frequent, short beam-access periods
- Controlled scans and off-normal conditions exceed the risk tolerance of most user operations
- Upstream beam instruments and downstream detectors require a common time base and shared metadata
- Real hardware and controls are necessary to close the simulation-to-reality gap
- AI-ready benchmark datasets and common interfaces support reproducibility and transfer to other facilities

What the test facility must evaluate

- Prediction error against independent accelerator and detector measurements
- Calibration and coverage of prediction intervals
- Robustness across operating conditions, machine drift, and faults
- Detection of extrapolation and safe fallback outside the validated domain
- Improvement in experimental performance and tuning or recovery time

Realistic beam tests measure prediction error, calibrate uncertainty, and provide operational evidence for safe AI deployment

Summary

- The experimental configuration defines the accelerator AI priority: rapid beam-state reconstruction for single-pass experiments and continuous phase-space control for circular colliders
- Our approach connects accelerator instrumentation, physics models, target systems, and HEP detectors to optimize experimental performance
- The LBNF case study combines synchronized measurements, Bayesian exploration, and an emulator to constrain beam-related neutrino-flux uncertainty
- Target AI applies validated surrogate models and uncertainty quantification to accelerator-component design
- An AI/ML Test Facility provides flexible beam access, integrated AI-ready data, and controlled experiments to validate predictions, calibrate uncertainty, and establish evidence for safe deployment

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