Differentiable Physics Emulator for Water Cherenkov Detectors

A ML-based surrogate model for detector calibration and reconstruction

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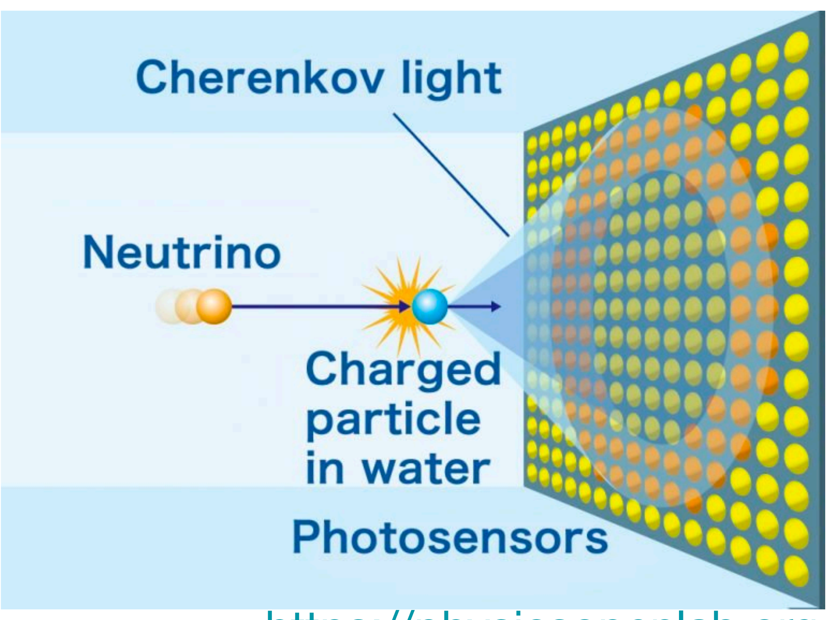
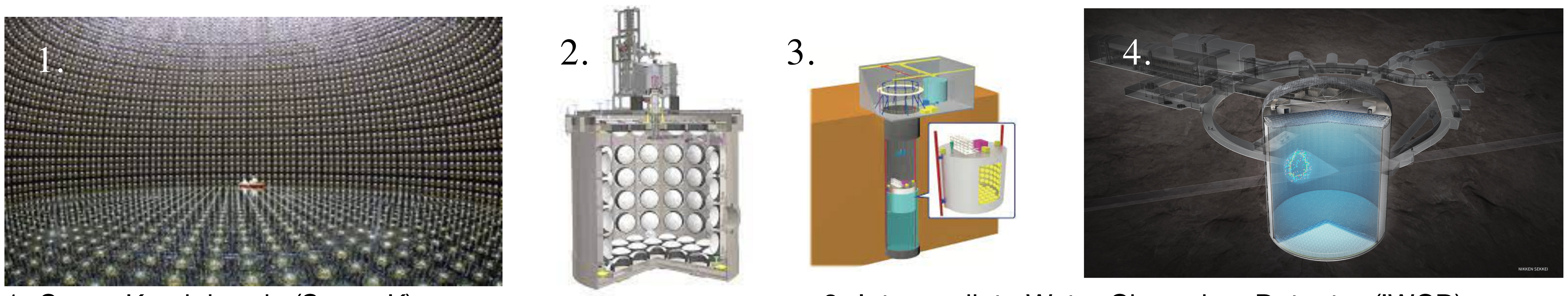
Water Cherenkov Detectors



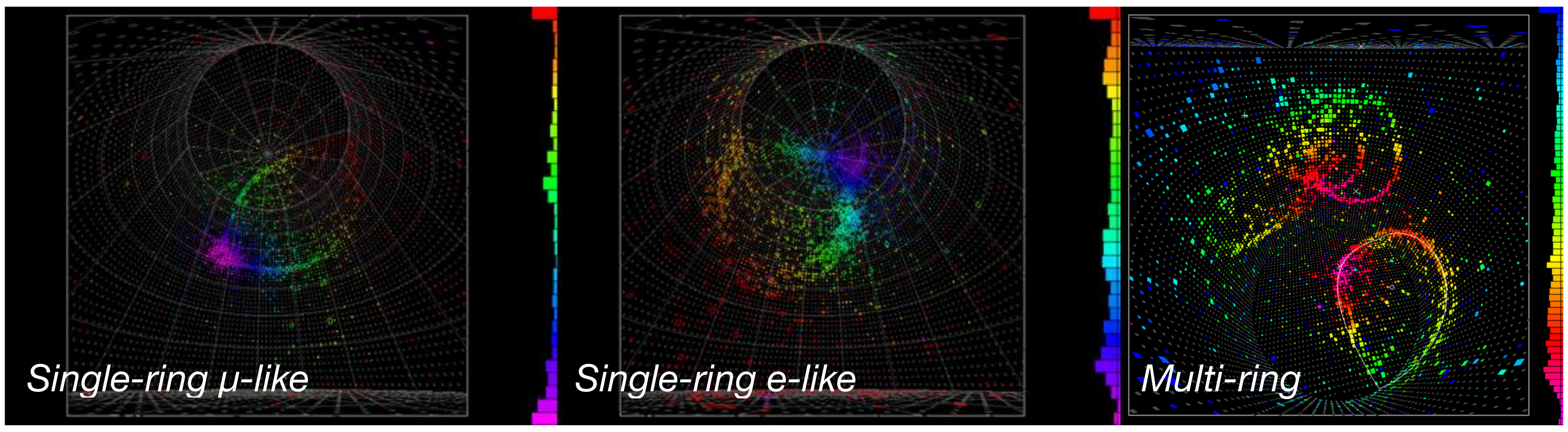
https://physicsopenlab.org



1. Super-Kamiokande (Super-K)
2. Water Cherenkov Test Experiment (WCTE)
3. Intermediate Water Cherenkov Detector (IWCD)
4. Hyper-Kamiokande (Hyper-K)

Proven reliable technique and already approved roadmap to the future experiments.

Neutrino Events in Water Cherenkov Detectors



- Differences in ring topology provide PID information
- PMT charge and timing information for ring reconstruction and energy deposition calculations (ν energy reconstruction if ν direction is known, e.g. ν_μ beam)

Challenges in Calibration and Reconstruction

- **Same physics factored** into different parts, e.g. sequential simulation and calibration.
- **Limited optimizability** for simulation and data/MC discrepancies.
- **Time consuming** — requires large statistics of MC

The current reconstruction approach (hereafter fiTQun) to "high energy" events ($\mathcal{O}(10^{-1} \sim 10^{3})$ GeV) in Super-K relies on the maximum-likelihood estimation. The core of this process is to find, among many competing hypotheses **x**, the one that maximizes the likelihood of the detected event. The likelihood is evaluated over every PMT by the following equation:

$$L(\mathbf{x}) = \prod_{j}^{unhit} P_j(unhit|\mathbf{x}) \prod_{i}^{hit} \left\{ \left[1 - P_i(unhit|\mathbf{x})\right] f_q(q_i|\mathbf{x}) f_t(t_i|\mathbf{x}) \right\}$$

*But it requires billions of MC statistics to tune the algorithm and is not scalable.

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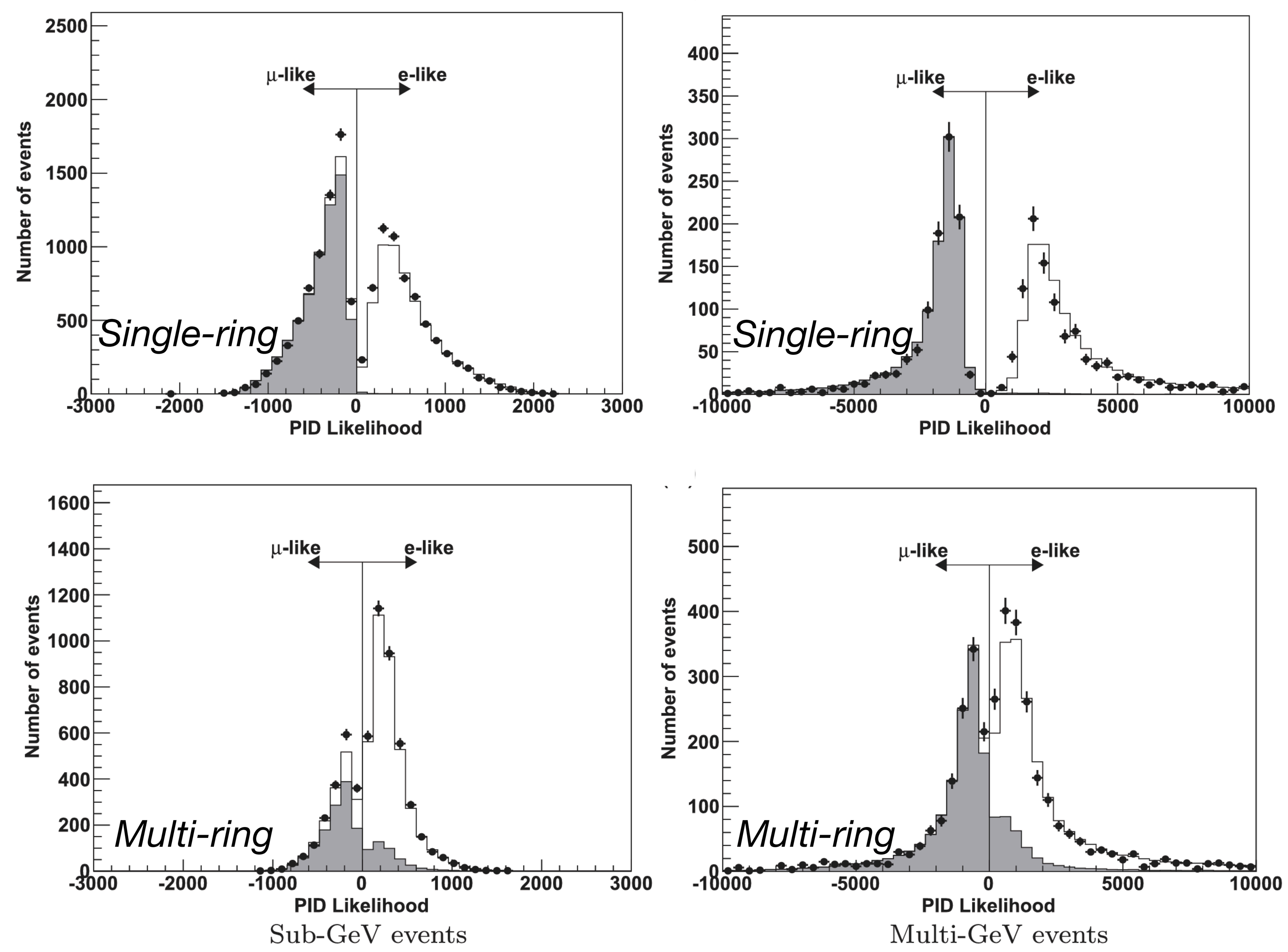
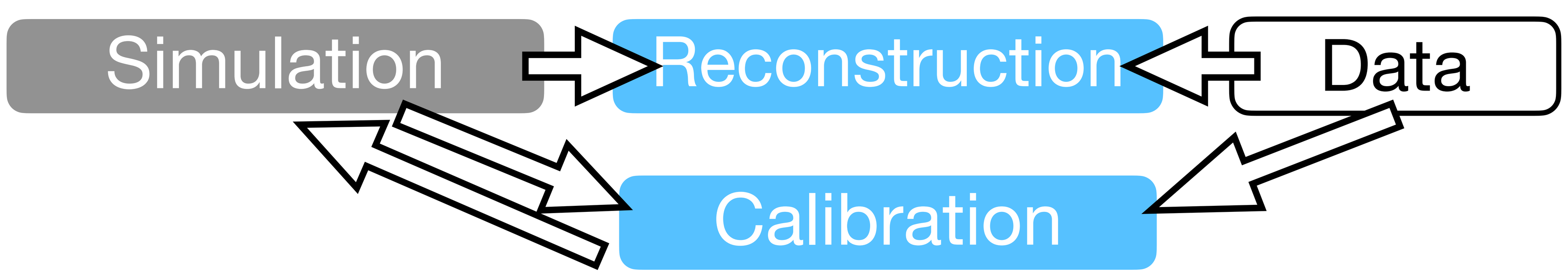
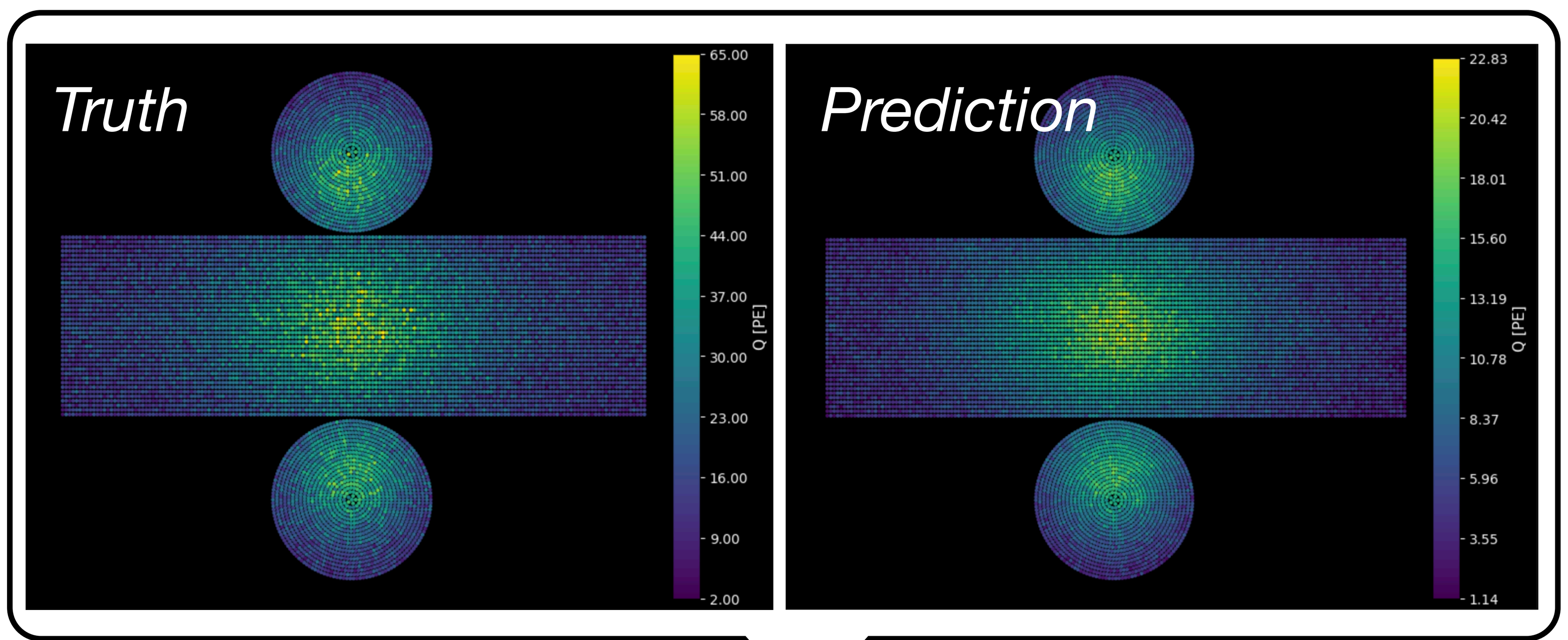


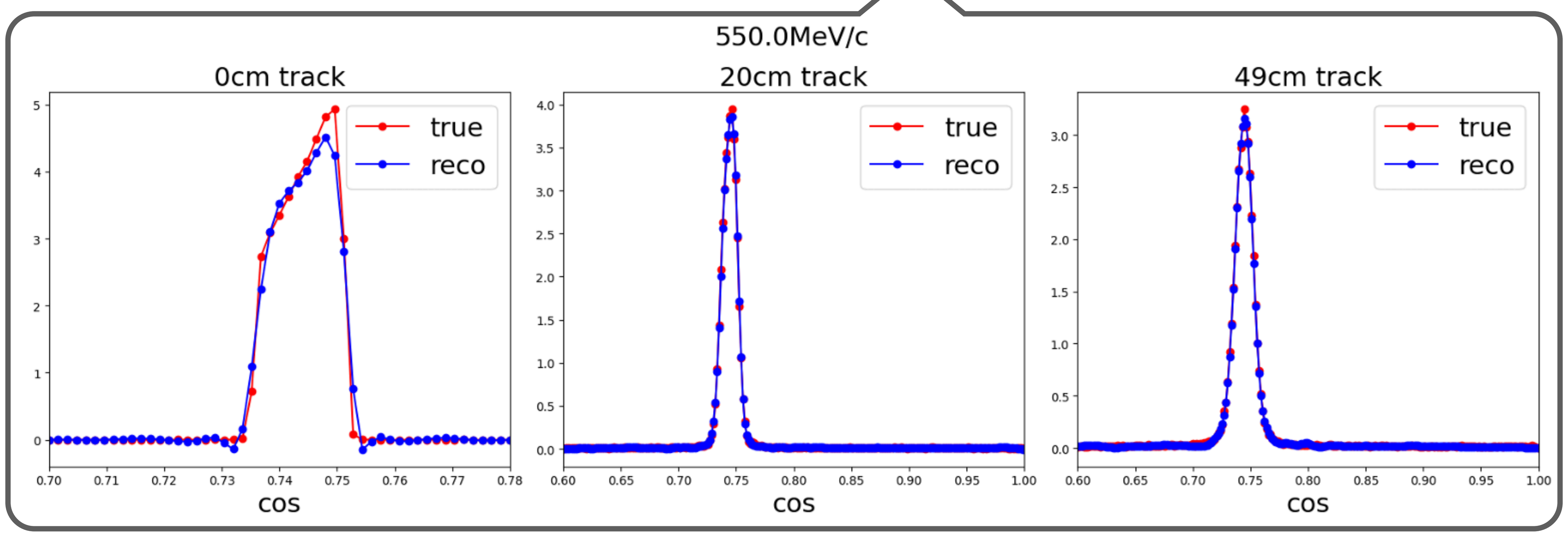
Differentiable Physics Emulator



$$\theta_t = \theta_{t-1} + \lambda \nabla_\theta \mathcal{L}(X, \theta)$$



Particle physics: p, s (track length), PID → Cherenkov radiation: $N\gamma$, (x,y,z), (θ,ϕ) → Detector domain: Q, T



Current Status and Outlook

Using a multi-layer perceptron featuring implicit neural representations with periodic activation functions (arXiv:2006.09661).

Predicting detector responses given any particle information inside via a 2-step neural network architecture.