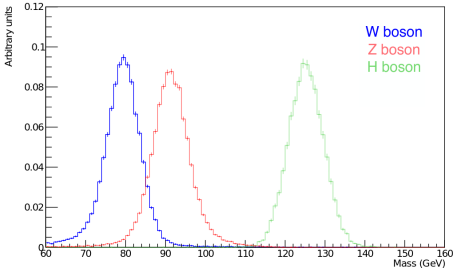
A Simulation Approach to Dual-Readout Calorimetry

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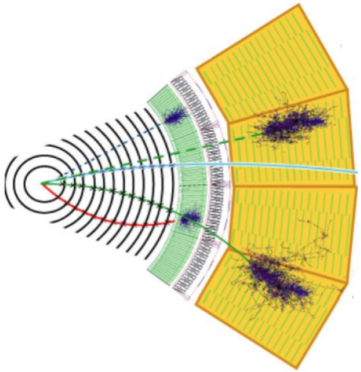
- Goal: more precise measurements of Higgs boson properties
- Requires a **Higgs factory**: a collider running just above the ZH production threshold (makes *lots* of H)
- Couplings to other particles come from branching ratios (how often the Higgs decays to each)
- Challenge: $H \to ZZ \to qqqq$ and $H \to WW \to qqqq$ look alike. How do we tell Z from W?
  - Requirement: measure final-state energies well enough to resolve the W and Z mass peaks (by $\geq 2\sigma$)



Target dijet mass resolution, showing W/Z separation by about 2σ

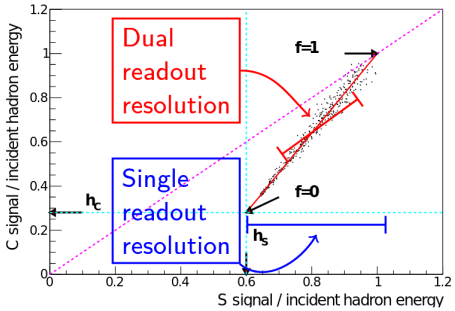
- Current calorimeter resolution is not sufficient; this study works toward a solution

- **Calorimetry:** measure a particle's energy by absorbing it
  - The particle **showers**: it splits into many lower-energy particles
  - Their energy is read out, e.g. via *scintillation* light
- Two main types: electromagnetic (ECAL, for e/γ) and hadronic (HCAL)
  - Hadronic resolution is the bottleneck for $H \to 4q$
- Hadronic showers have EM and non-EM components that respond differently [1]
  - The EM fraction, f_{EM}, is not known event by event
  - Result: large fluctuations in the measured hadron energy



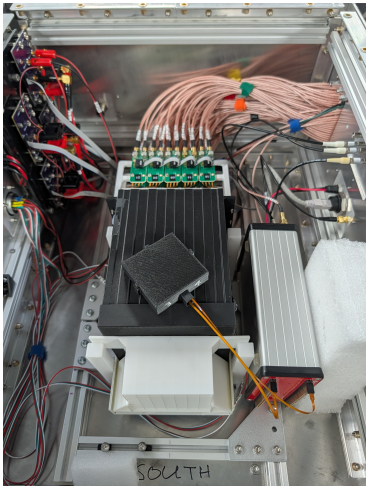
Depiction of the CMS homogeneous ECAL (front, green) vs. the sampling HCAL (rear, orange)

- **Dual-readout calorimetry (DRC):** measure f_{EM} *event by event* [1, 2]
  - Cherenkov light comes mostly from the EM component
  - Scintillation responds to all deposited energy
  - Comparing the two corrects for fluctuations in f_{EM}
- Design trade-off:
  - **Homogeneous** (crystal): one medium showers and scintillates; $\sim 1\%$ resolution, but expensive
  - **Sampling** (layered): absorber layers shower, others read out; cheaper, but worse resolution



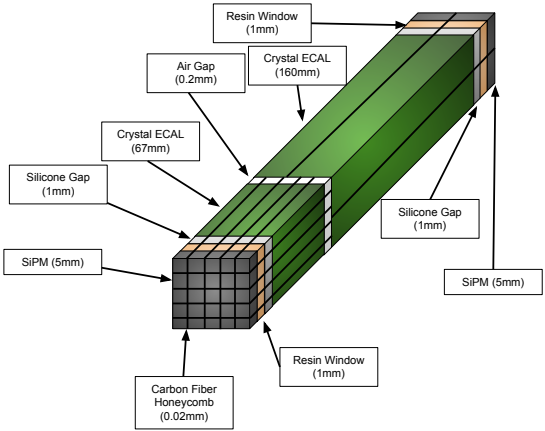
- Hybrid concept [3]: homogeneous DR ECAL in front of a sampling DR HCAL. EM showers are short and stop in the ECAL; hadronic showers are long and extend into the HCAL.

- Why simulate: cheaply estimate DR resolutions and test new designs before building hardware
- CalVision full optical simulation in the Key4HEP stack tracks both Cherenkov and scintillation photons in a crystal ECAL
  - GEANT4 interfaced via DD4HEP (compact, XML-based detector descriptions)
  - GEANT4 particle gun: e^-, π^+, γ, etc.
  - EDM4HEP output for portability across HEP software



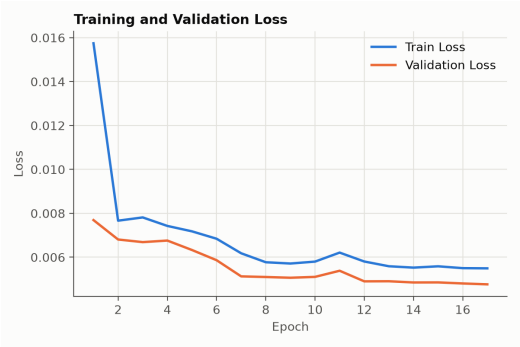
Crystal ECAL prototype (DESY test beam 2026)

- Simulated: $PbWO_4$ crystal ECAL with 11×11 (front) and 5×5 (rear) segments (not depicted), read out by SiPMs
- Segmentation improves granularity and particle identification [3]
- Want to study ECAL first to optimize EM response
- Output shows full physics: both Cherenkov and scintillation production



- Existing ML-oriented efforts use simplified simulations
  - e.g. Wu et al. [4] generate photons from Poisson sampling
- Ours is a full optical simulation, tracking photons throughout the whole detector
- Planned dataset: multiple particle types (e^-, π^+, γ, etc.), energies, and angles of incidence
- Goal: public access via XRootD, supporting DR and ML studies, including our own
- Currently in progress

- Using simulated events at Baylor to train a **spiking neural network** (SNN)
  - SNNs have lower power consumption, more suited to real-time detector environments
- Developed framework for digital SiPM (DSiPM) response simulated from photon IDs in the full optical simulation
  - SPAD outputs from DSiPM are used as spiking input to the neural network
- Training evaluate C and S signals event-by-event
- Early result: we see training and validation loss converge



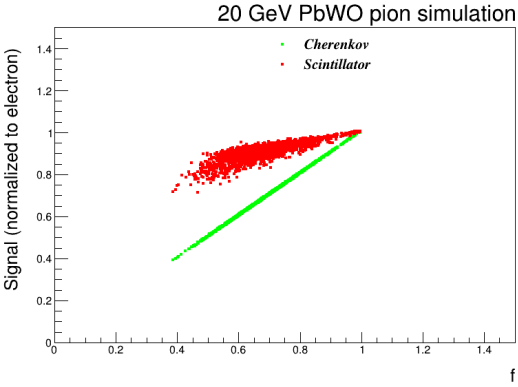
- However, these studies are in quite early stages; this is more of a "proof-of-concept"

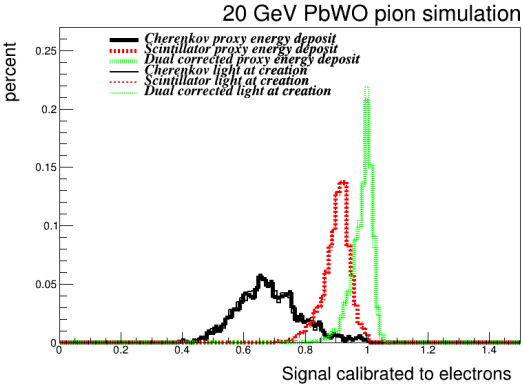
- Successfully simulated a DR crystal ECAL with full Cherenkov and scintillation production
- Dataset in progress
- First proof-of-concept results for SNN training on digital SiPM events
- Future work:
  - Finalize the XRootD dataset
  - Continue SNN development, toward energy reconstruction
  - Extend to the sampling HCAL and the full hybrid ECAL+HCAL system

[1] S. Lee, M. Livan, and R. Wigmans, "Dual-readout calorimetry," Rev. Mod. Phys. 90, 025002 (2018).
[2] S. Eno et al., "On the resolution of dual readout calorimeters," arXiv:2501.15329 (2025).
[3] M. T. Lucchini et al., "New perspectives on segmented crystal calorimeters for future colliders," JINST 15, P11005 (2020).
[4] Wu, L., Liu, Q., Lucchini, M. T., Gonski, J., Campajola, M., Moneta, S. (2026). Machine learning enables real-time waveform decomposition for dual-readout calorimetry. arXiv. https://doi.org/10.48550/arXiv.2604.26090

Thank you!

Questions?


20 GeV PbWO pion simulation
Cherenkov
Scintillator
Signal (normalized to electron)
f


20 GeV PbWO pion simulation
Cherenkov proxy energy deposit
Scintillator proxy energy deposit
Dual corrected proxy energy deposit
Cherenkov light at creation
Scintillator light at creation
Dual corrected light at creation
percent
Signal calibrated to electrons