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Multi-Scenario Failure Training for Robust Charged-Pion Energy Reconstruction

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Machine-learning-based calorimeter reconstruction is usually optimized under fixed detector conditions, whereas detector response can be affected by dead channels, local readout failures, gain drift, and noise. We study whether exposing a reconstruction model to several simulated failure modes during training improves its robustness compared with training on a single corruption type. The study uses 533-voxel charged-pion showers from CaloChallenge Dataset 1 and a layer-gated Transformer supplied with voxel energies and operational masks. Two models with identical architecture were trained: one exclusively on events with 5% randomly disabled cells, and one on an equal mixture of clean events, random cell loss, contiguous dead-cell blocks, and complete-layer failures. Evaluation was performed on an independent sample of 120,800 showers under clean, familiar, and unseen detector distortions. Multi-scenario training reduced relative mean absolute error from 0.1804 to 0.1533 on clean events, from 0.1799 to 0.1610 for block failures, and from 0.1940 to 0.1751 for a mixed unseen corruption. For physically consistent complete-layer loss, uniform layer-averaged rMAE decreased from 0.2404 to 0.1929, while voxel-weighted rMAE decreased from 0.2844 to 0.2104. The gain was not universal: the single-corruption regimen remained competitive near its specialized random-cell-loss condition. These results show that multi-scenario failure training improves broad robustness of charged-pion energy reconstruction while preserving a trade-off between generalization and narrow specialization.

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