

Detector-Aware Neural Networks for Particle Identification in Pb-Pb Collisions: Feature Set Embedding with Adaptive Attention Mechanisms

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Particle identification (PID) is crucial for reconstructing rare probes in heavy-ion collisions. Traditional approaches — such as Bayesian methods utilising Time-of-Flight and dE/dx information — are limited by detector availability and correlations. A novel detector-aware neural network architecture combining Feature Set Embedding (FSE) with group-wise multi-head self-attention mechanisms is presented, designed to optimise PID performance across varying detector configurations in Pb-Pb Run 3 data.

The approach addresses a critical challenge in heavy-ion physics: a significant fraction of events lack complete detector signatures due to geometric acceptance and reconstruction inefficiencies. Rather than discarding incomplete data, an adaptive framework is developed that learns specialised decision boundaries conditioned on available detector information (TPC-only, TOF-only, or combined TPC+TOF).

The FSE architecture encodes detector-specific embeddings, learns group-wise attention patterns, and gracefully handles missing Bayesian PID probabilities through masked training. Evaluated on the intermediate momentum range (0.7–1.5 GeV/c), the detector-aware model achieves +2.2% improvement in classification accuracy compared to standard FSE baselines, with particularly strong gains in TPC-only configurations (+16.9%).

Comparative analysis against established machine learning baselines (XGBoost, Random Forest, DNN) and traditional Bayesian methods demonstrates competitive performance on real detector data whilst maintaining computational efficiency. This work illustrates how domain-aware neural network design can transform detector limitations into opportunities for improved particle identification in collider physics.