Deep learning techniques for high-precision neutral meson reconstruction in the LHCf experiment

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Physics motivation

- UHECR origin and mass composition are still unknown.
- Hadronic interaction models → key uncertainty in shower simulations.
- LHCf provides forward data to tune these models ($|\eta|>8.4$).
- Forward K^0_S:
  - probes strange-quark dynamics.
  - connected to high-energy atmospheric neutrinos.

Goal: identify K^0_S candidates in complex multi-photon events using a multi-stage neural network approach.
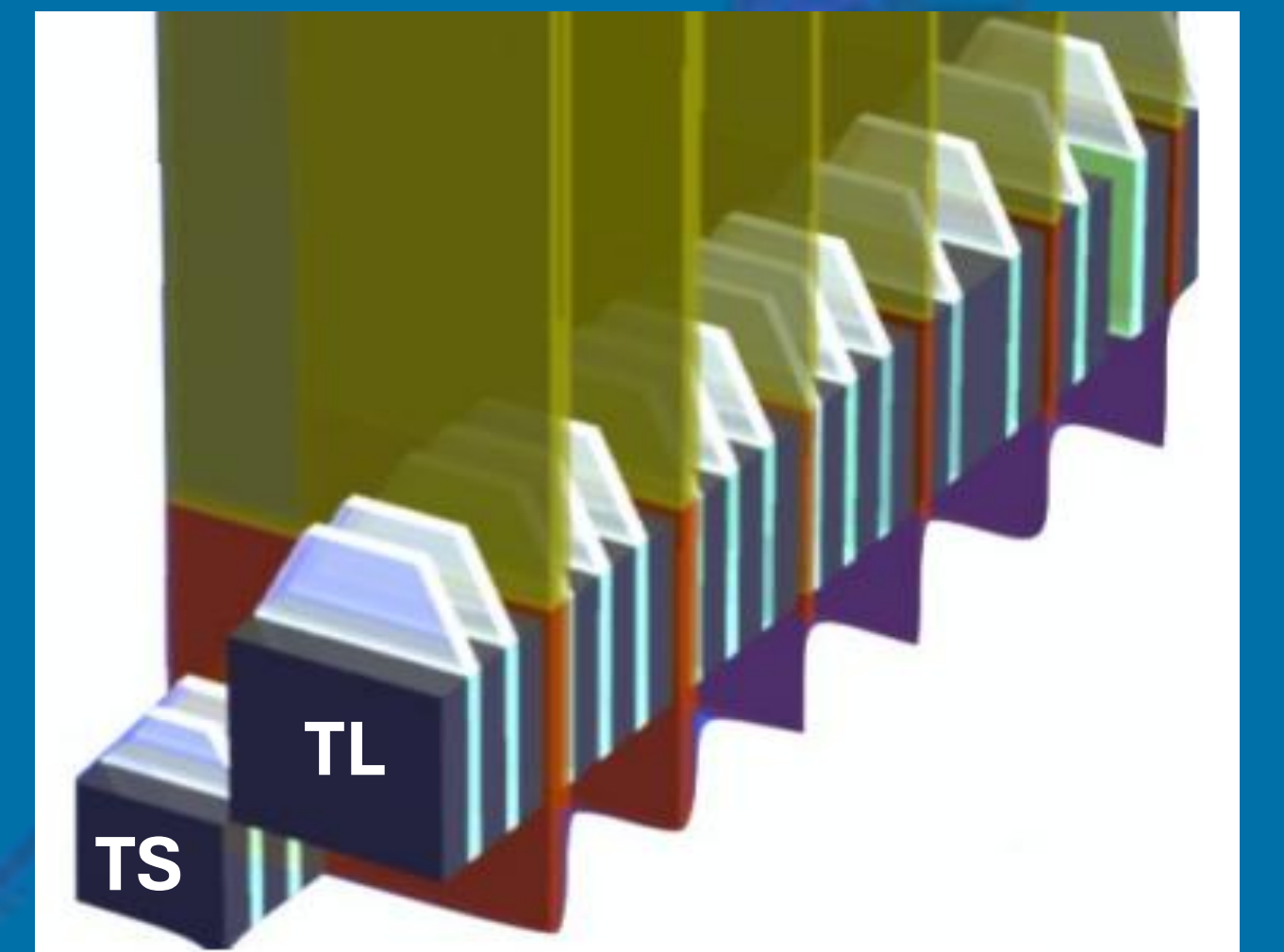
$$K^0_S \nearrow \pi^0 \nearrow \gamma \searrow \gamma \quad \searrow \pi^0 \nearrow \gamma \searrow \gamma$$
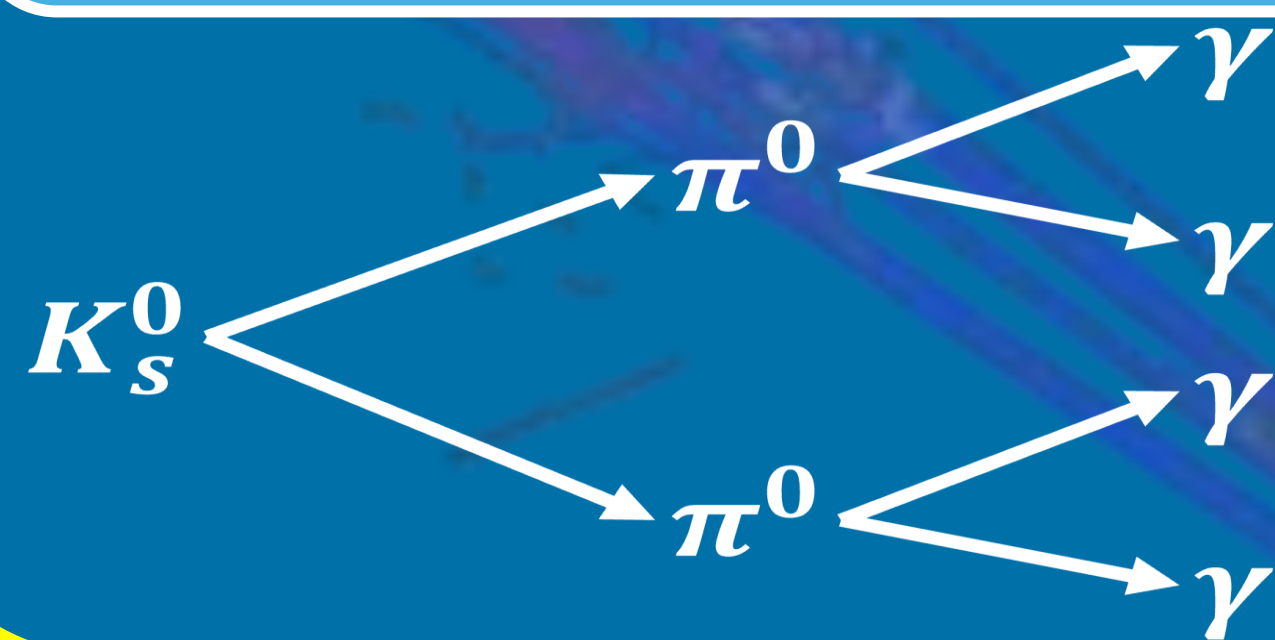
Branching ratio:
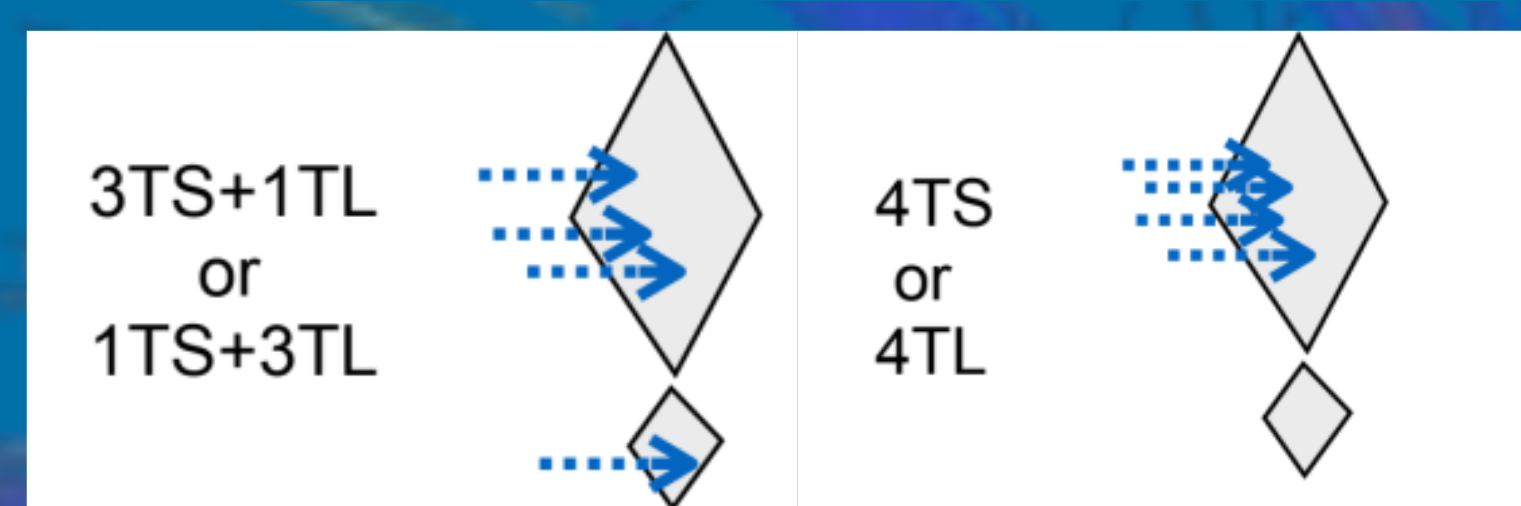- $K^0_S \rightarrow \pi^0 \pi^0 \rightarrow 4\gamma$: 30.7%

Detector

- **Two calorimetric towers:**
  - Sizes: 25×25 mm^2 (short), 32×32 mm^2 (long)
  - Structure: 16 GSO scintillator layers + 22 tungsten plates
  - Total depth: 44 X_0, 1.6 λ_I
- **4 XY silicon microstrip layers:**
  - Pitch: 160 µm
  - Views: X and Y
  - Granularity: 384 channels per view
- **Performance:**
  - <3% energy resolution for photons (>200 GeV)
  - < 40 µm spatial resolution for EM showers (>200 GeV)

The Arm2 detector

Multi-Stage Neural Network Architecture

Events of interest → 3TS+1TL or 1TS+3TL | 4TS or 4TL

posdE_0123 x View | 4 Photons Event

dE Calorimeters | 4 Photons Event

Overview

We developed a 3-step classification pipeline using dedicated neural networks:

Relevant Event → **Neutron Filter** → **Topology Tagger**

Network Input Structure (multi-input model)

Input Type	Shape	Description
Calorimeter signals	(16, 2)	Energy deposition per layer (long/short)
Silicon planes	(384, 4) x 2	X/Y views from 4 silicon layers
Global sums	(10,)	Total energy collected for each calorimeter and each silicon

Each input is processed through separate dense blocks before concatenation.
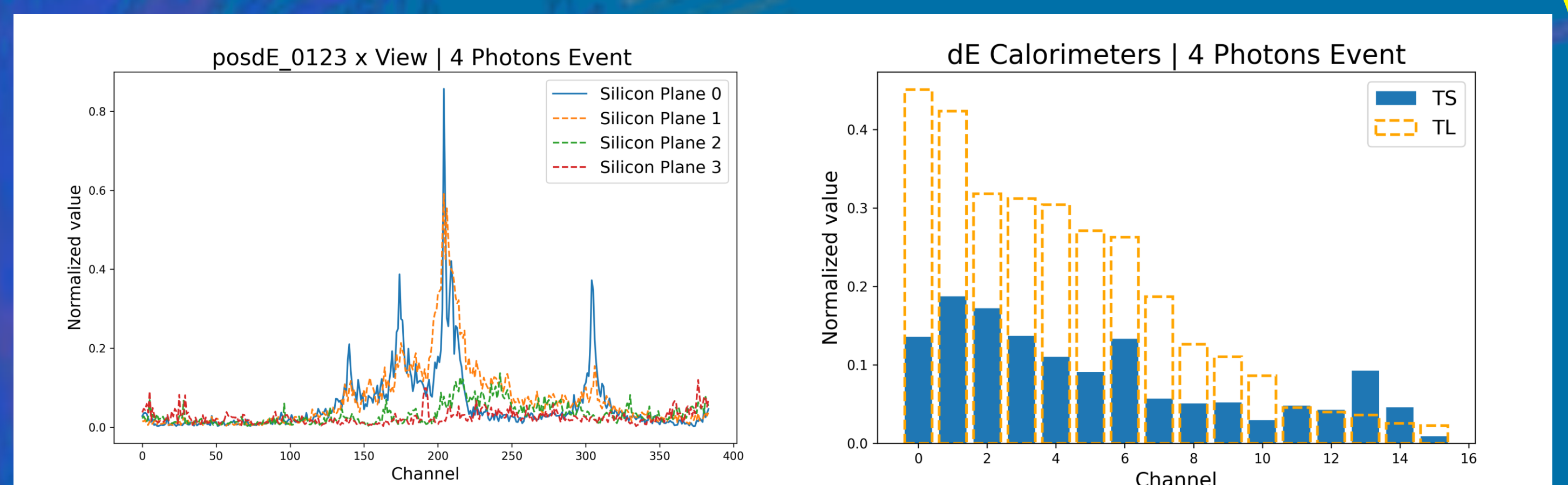
Confusion Matrix

Tagging Network Results

Confusion Matrix:
- Excellent performance across all classes.
- Minor confusion between symmetric classes.

Classification Report

Class	Precision	Recall	F1-score	Support
1TS + 3TL	0.92	0.86	0.89	64
3TS + 1TL	0.98	0.81	0.89	117
0TS + 4TL	0.93	0.97	0.95	107
4TS + 0T	0.90	0.99	0.94	176

Conclusion

- 3-step NN pipeline identifies $K^0_S \rightarrow 4\gamma$ events.
- Combination of calorimeter and silicon inputs improves classification of multi-hit events.
- Topology tagger achieves ~92% average F1-score over 4γ patterns.
- Work sets the stage for full photon reconstruction (energy & position).

Info

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https://home.web.cern.ch/science/experiments/lhcf

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