INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI ROMA TOR VERGATA

UNIVERSITÀ DEGLI STUDI DI PADOVA

PhD Research and Development Plan: 2nd Year Achievements and Next Year's Objectives

Muhammad Waqas
PhD Scholar, INFN Tor Vergata
Supervisor
Dr.Valerio Formato
02 October 2025

Overview

AMS purpose is to perform high precision, high statistics, and log measurement of charged cosmic rays in .5GeV to 1.5 Tev

AMS 02 Launch Date : 16th May 2011 by NASA
400 km above the ground
3m*4m*6*m in volume

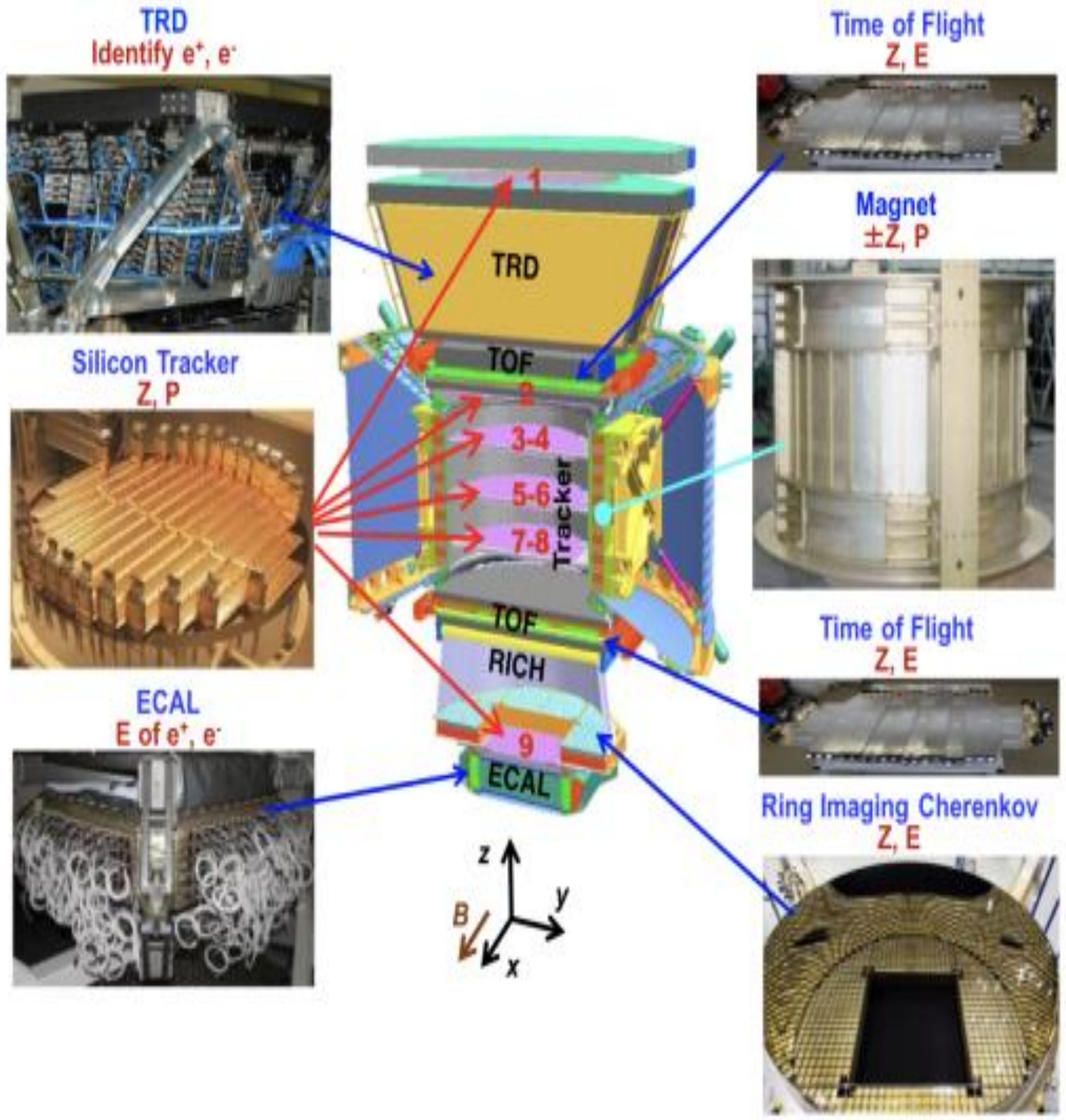
AMS 02 Collaboration is from 13 countries and 43 institution.

AMS Scientific Goals are :

- Search for cosmic matter
- Search for Dark matter signatures
- Measurment of cosmic ray spectra, relative abundances, and isotopes
- Search for new form of matter
- Solar Activity and more

INFN Roma Tor Vergata

AMS 02 Sub-Detectors



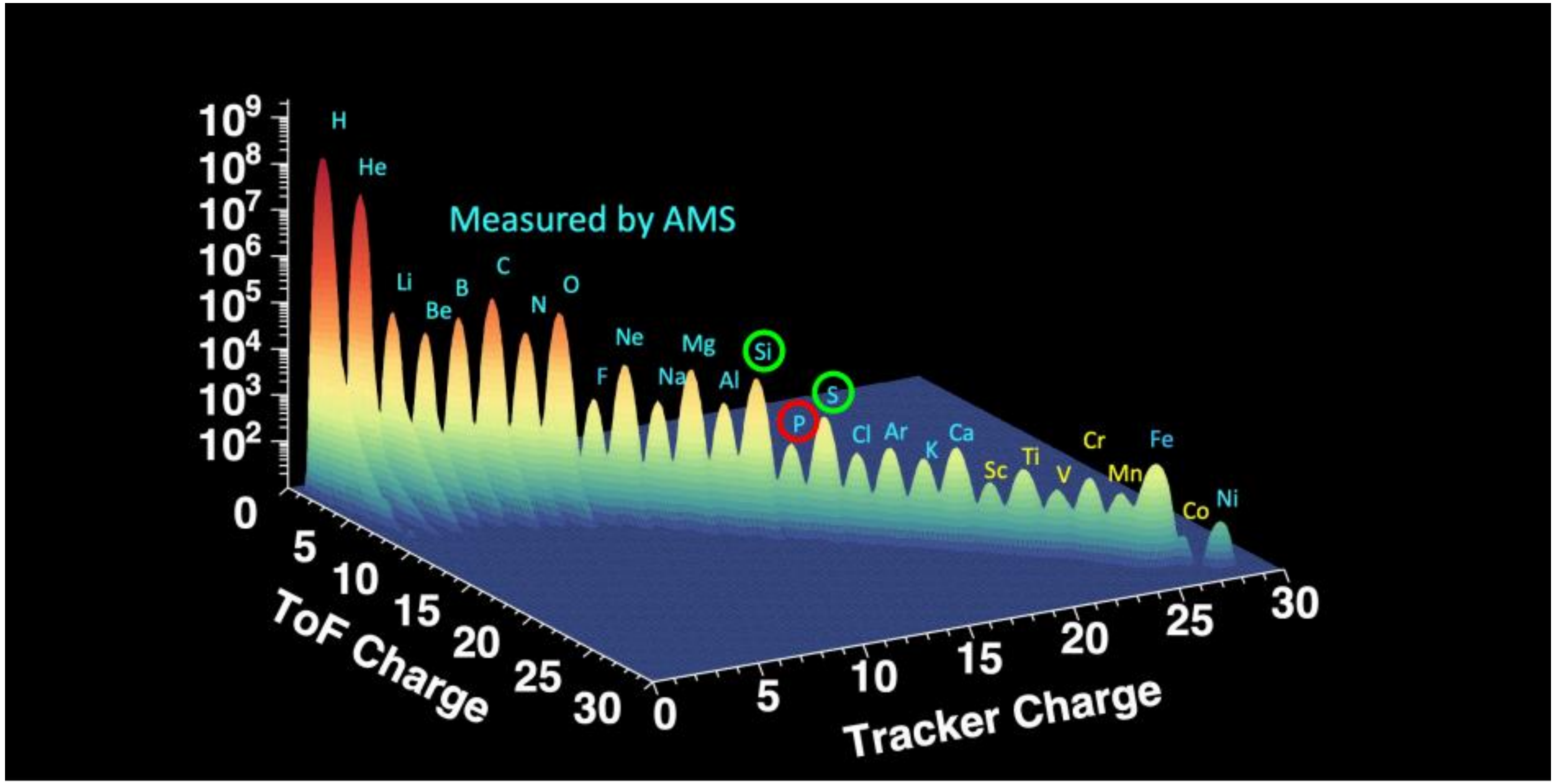
Schematic view of AMS 02 Detector

- Silicon Tracker & Magnet
- Transition Radiation Detector (TRD)
- Time Of Flight (TOF)
- Electromagnetic Calorimeter(ECAL)
- Ring Imaging Cherenkov (RICH)
- Anti-Coincidence Counters (ACC)

INFN
Roma
Tor Vergata

AMS 02 Data Analysis Pipeline

Phosphorus Flux



- Compared to nearby nuclei, phosphorus has a very low relative abundance
- Study and reproduce silicon (Z=14) and sulfur (Z=16) fluxes in order to proceed to phosphorus (Z=15)

AMS 02 Data Analysis Pipeline

Flux Formula:

$$\Phi(R) = \frac{\Delta N}{A(R)\cdot T(R)\cdot \Delta R}$$

- **The Flux Equation:** The final flux depends on the raw counts (ΔN) and a large denominator representing the effective measurement area (A(R)·ΔT(R)·ΔR).

- **Exposure Time (T(R)):** "We meticulously track 13.5 years of good data, filtering by hardware status and orbital position to ensure every event is counted under nominal conditions.

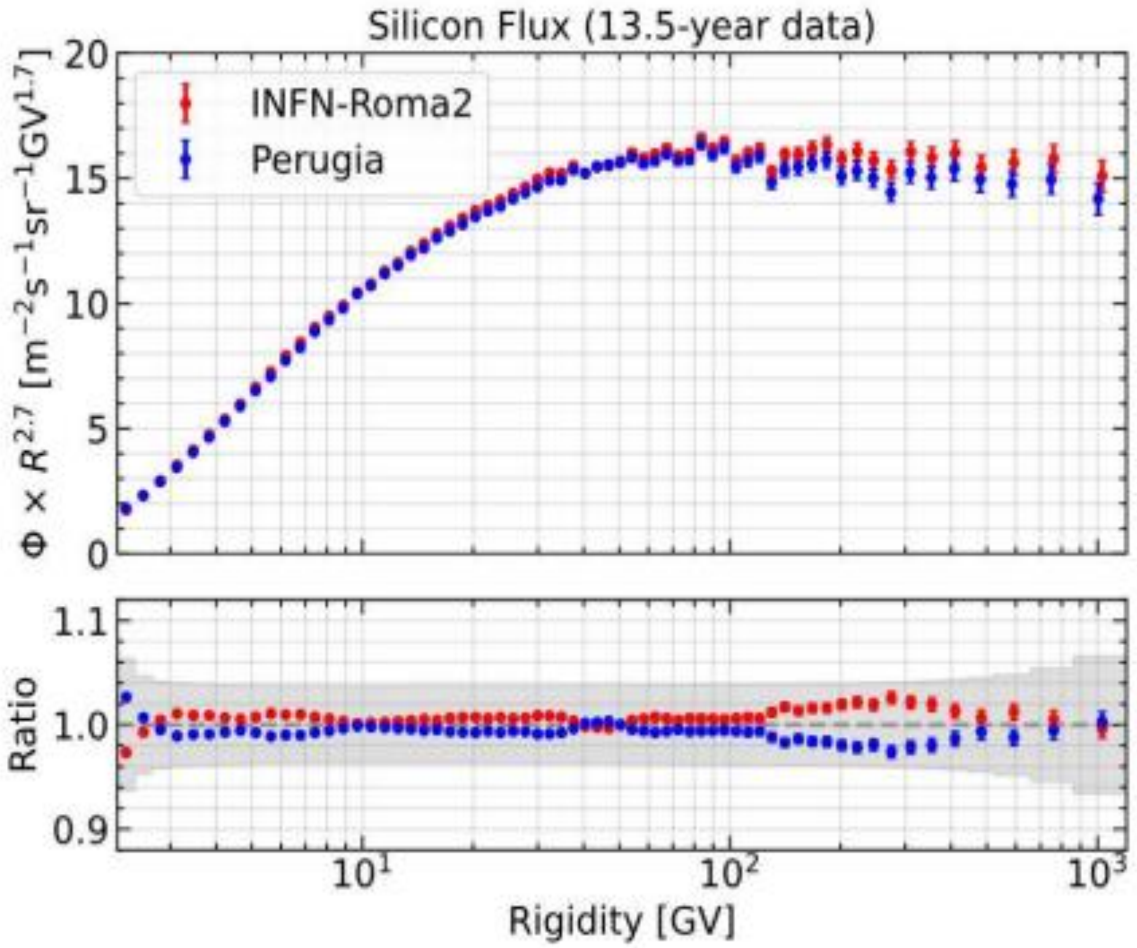
•For the **Acceptance (A)**. We start with the theoretical **Raw Acceptance (Araw)** from our GEANT4 MC simulation. However, the real detector is imperfect.

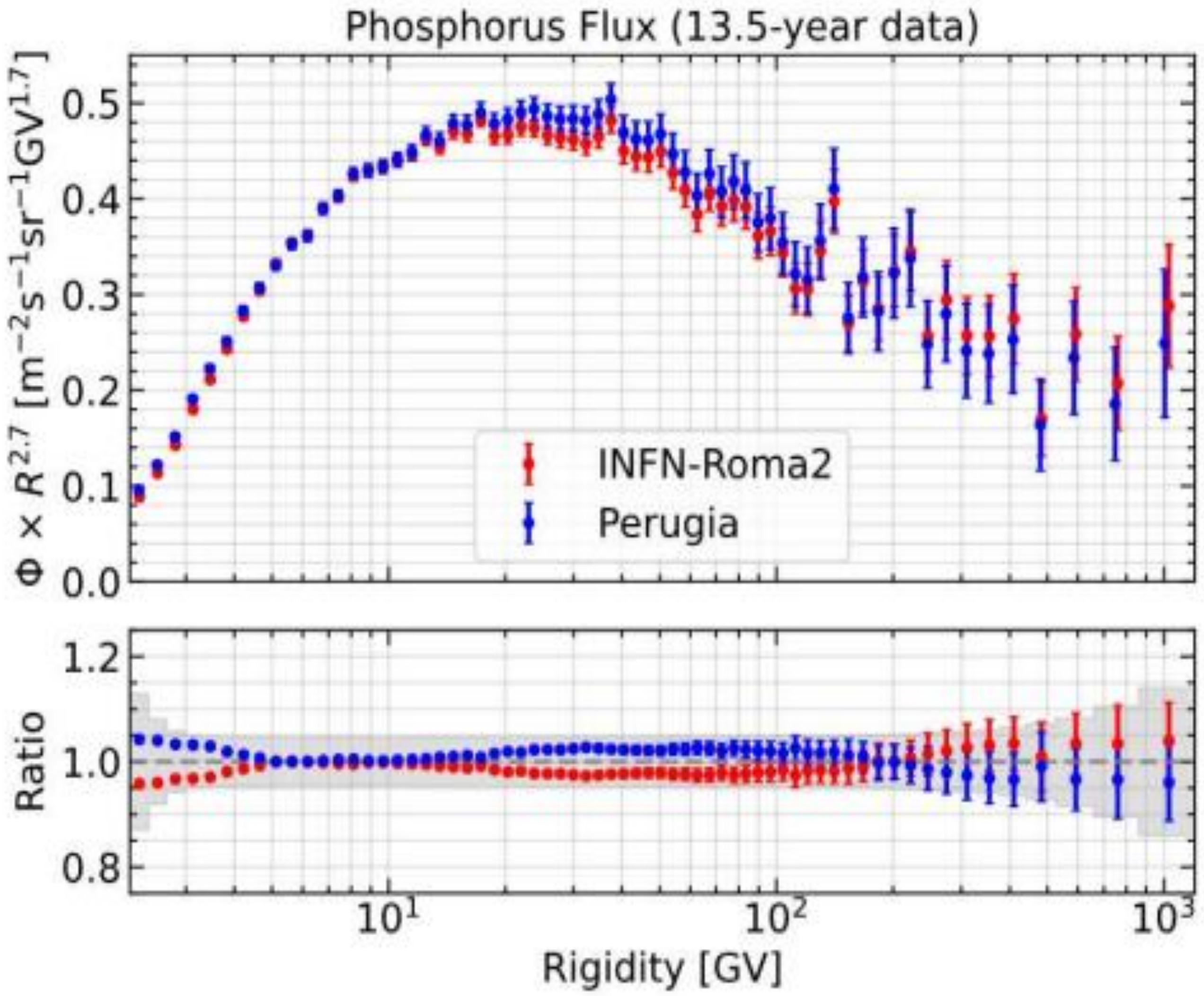
•To account for this, the core of the pipeline is the **Efficiencies Step**. We calculate the **K Correction Factor** for every subsystem: K =$MC^{Efficiency}/Data^{Efficiency}$. This K factor is needed for all the Effeciencies (ToF, Trigger, Tracker etc)

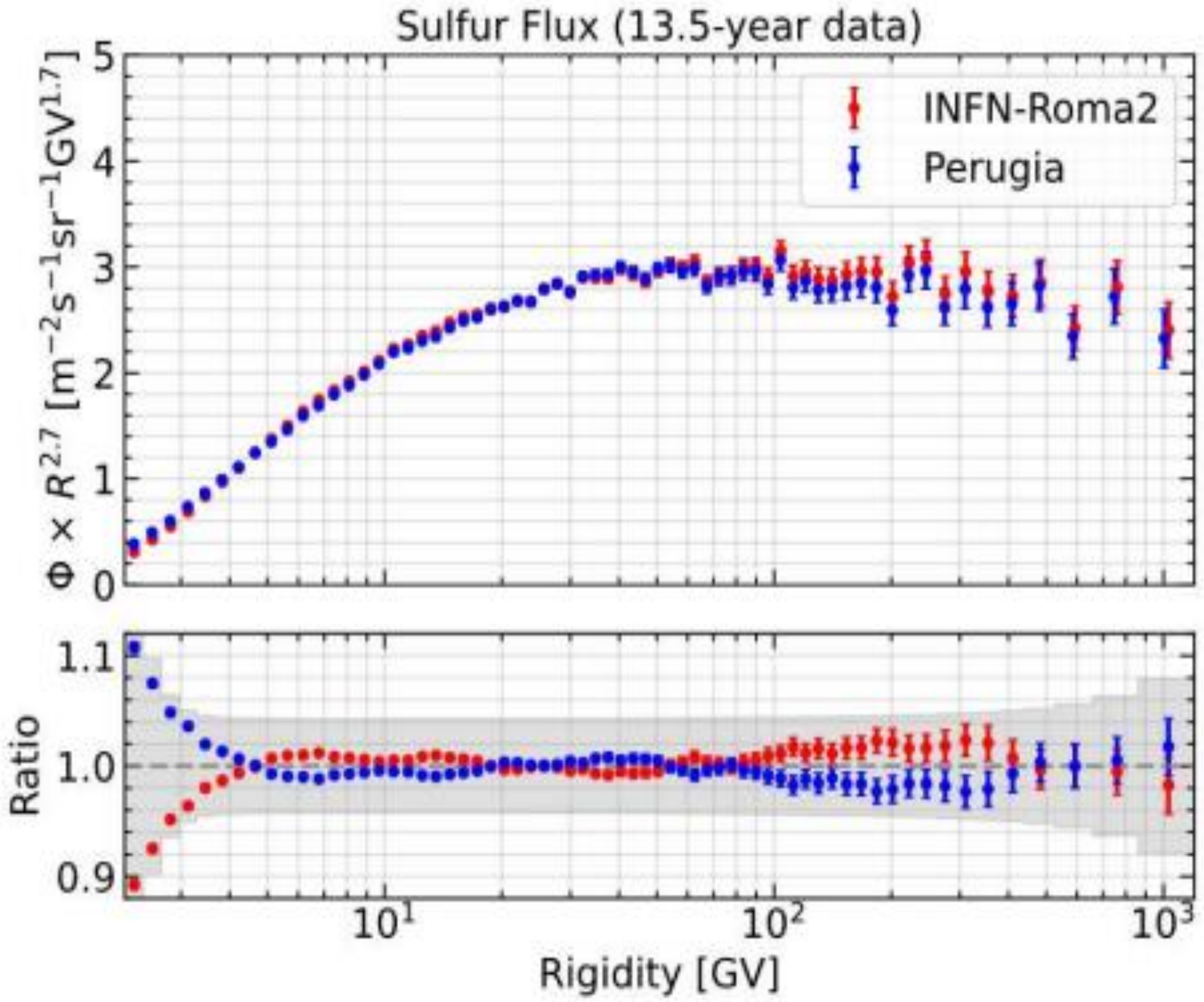
•Effective Acceptance is achieved by running the **Efficiencies pipeline** to derive the unitless **K correction factors** (which quantify the difference between Data and MC efficiency for every detector step) and multiplying the Raw Acceptance by these factors.

AMS 02 Data Analysis Pipeline

Phosphorus Flux







- Comparison of Si-14, S-16 and P-15 flux with AMS-Italia Perugia group
- Study and reproduce silicon (Z=14) and sulfur (Z=16) fluxes in order to proceed to phosphorus (Z=15)

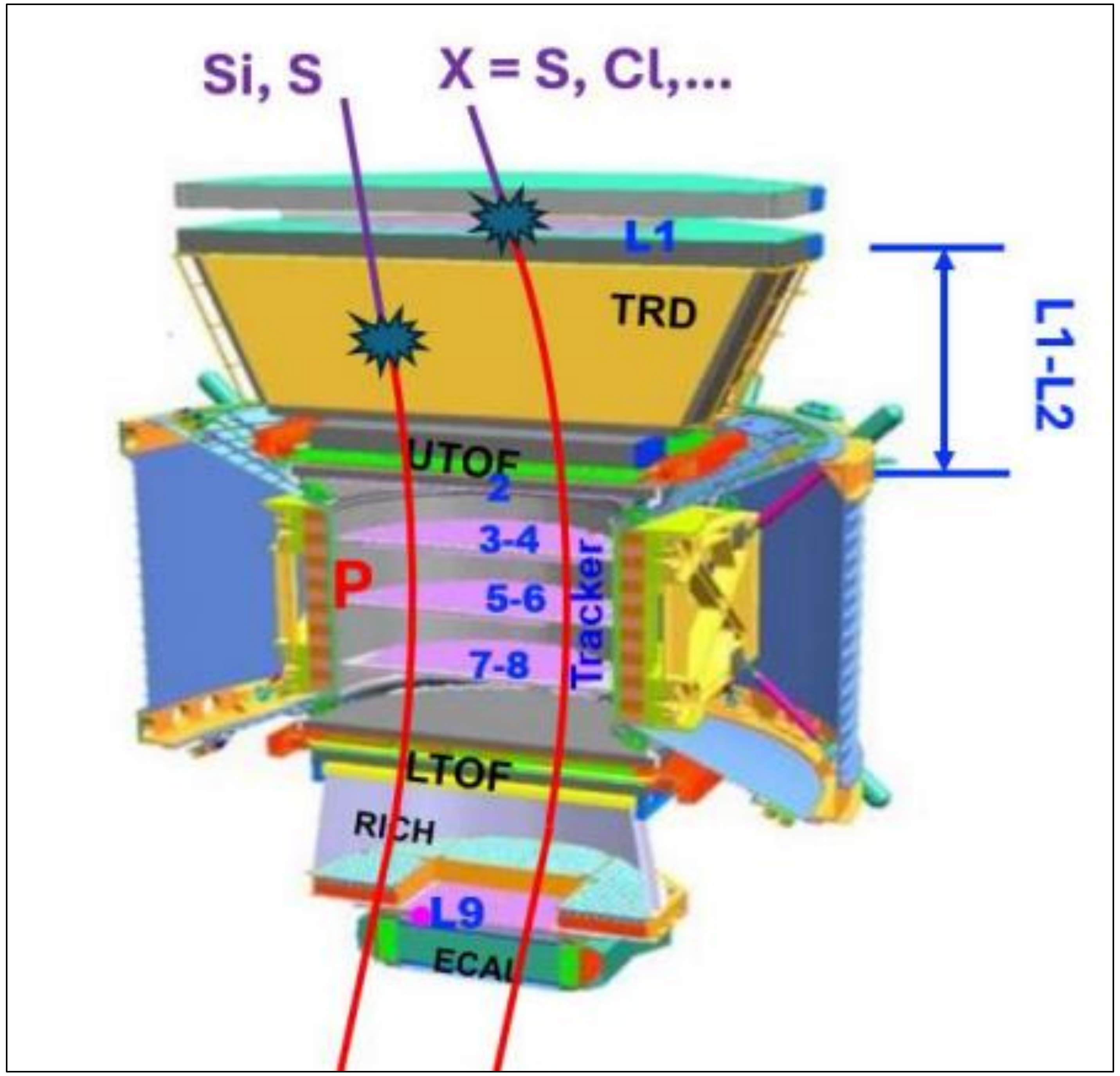
Contamination

Below L1 Contamination

- **Source:** Heavier nuclei fragment in the material **between Tracker L1 and L2** (TRD/Upper TOF).
- **Method: Data-Driven Template Fit** is used.

Content: Above L1 Contamination (TOI)

- **Source:** Heavier nuclei fragment in the **material above L1** (thin support structures made of carbon fiber and aluminum honeycomb). L1 cannot measure this composition.
- **Method: Monte Carlo (MC) Simulation** is mandatory.



Multimodal Domain Adversarial Network (M-DAN)

Motivation: Reduce P background after P event selection.

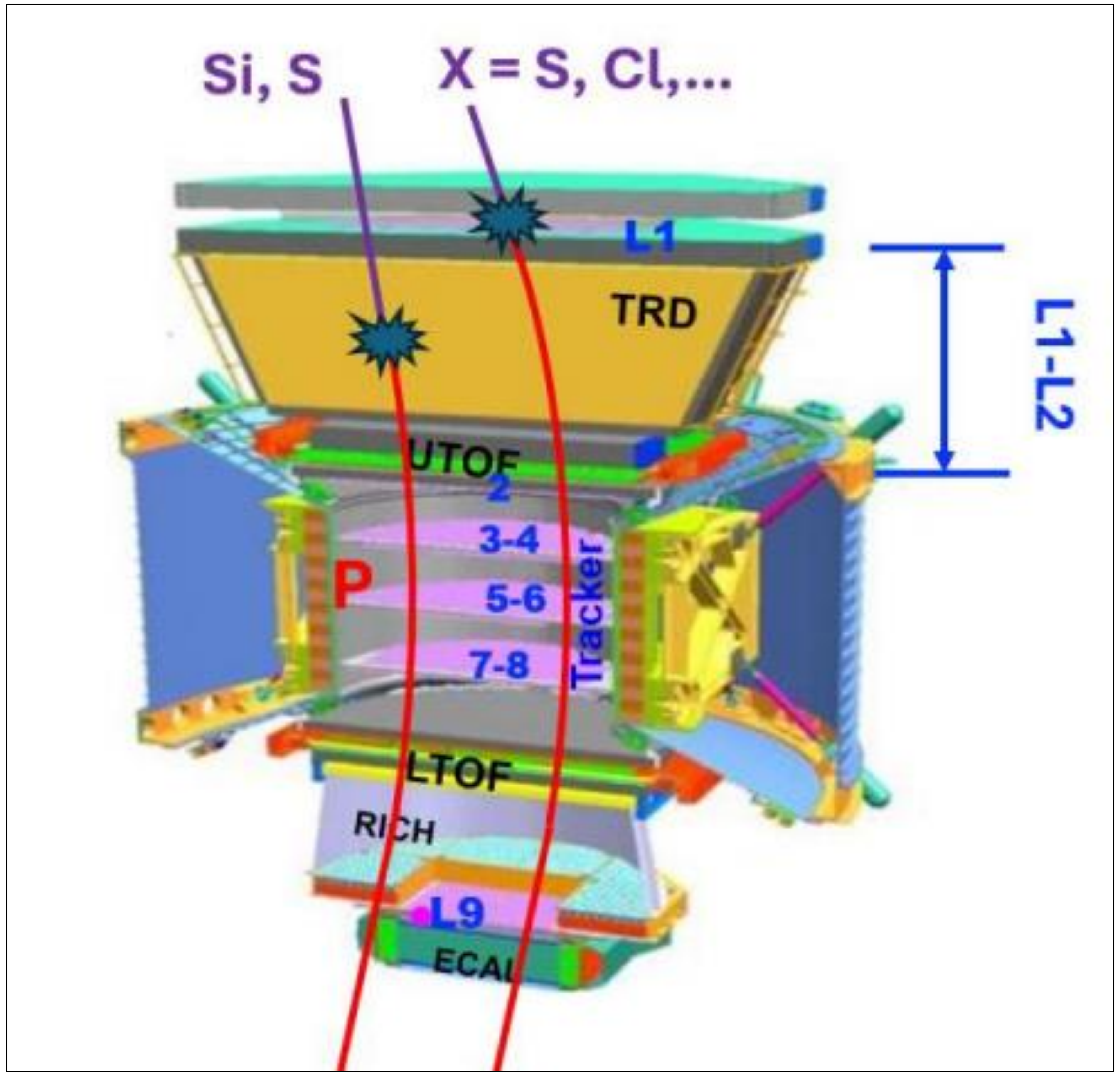
Pre-Processing

- Combining low-level, physics-relevant variables from distinct AMS-02 subsystems e.g ToF, tracker, to enhance signal separation.
- Use variables that have similar distributions in both MC and Data.

Trained from MC sample Signal

- MC Phosphorus
- Background: MC Si and S
- Data

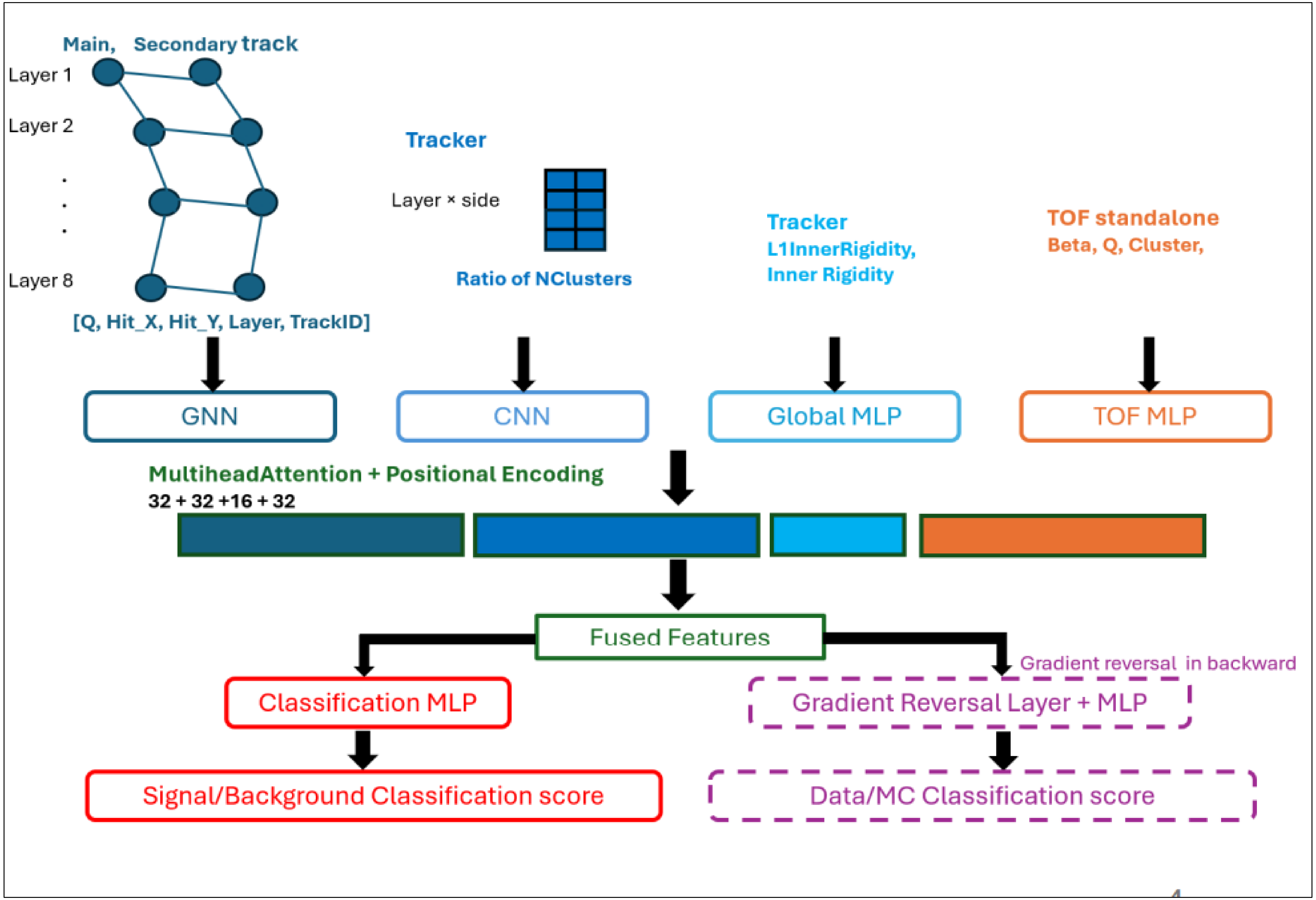
Use domain-adversarial training to learn domain-invariant features, to achieve model generalization across MC and Data

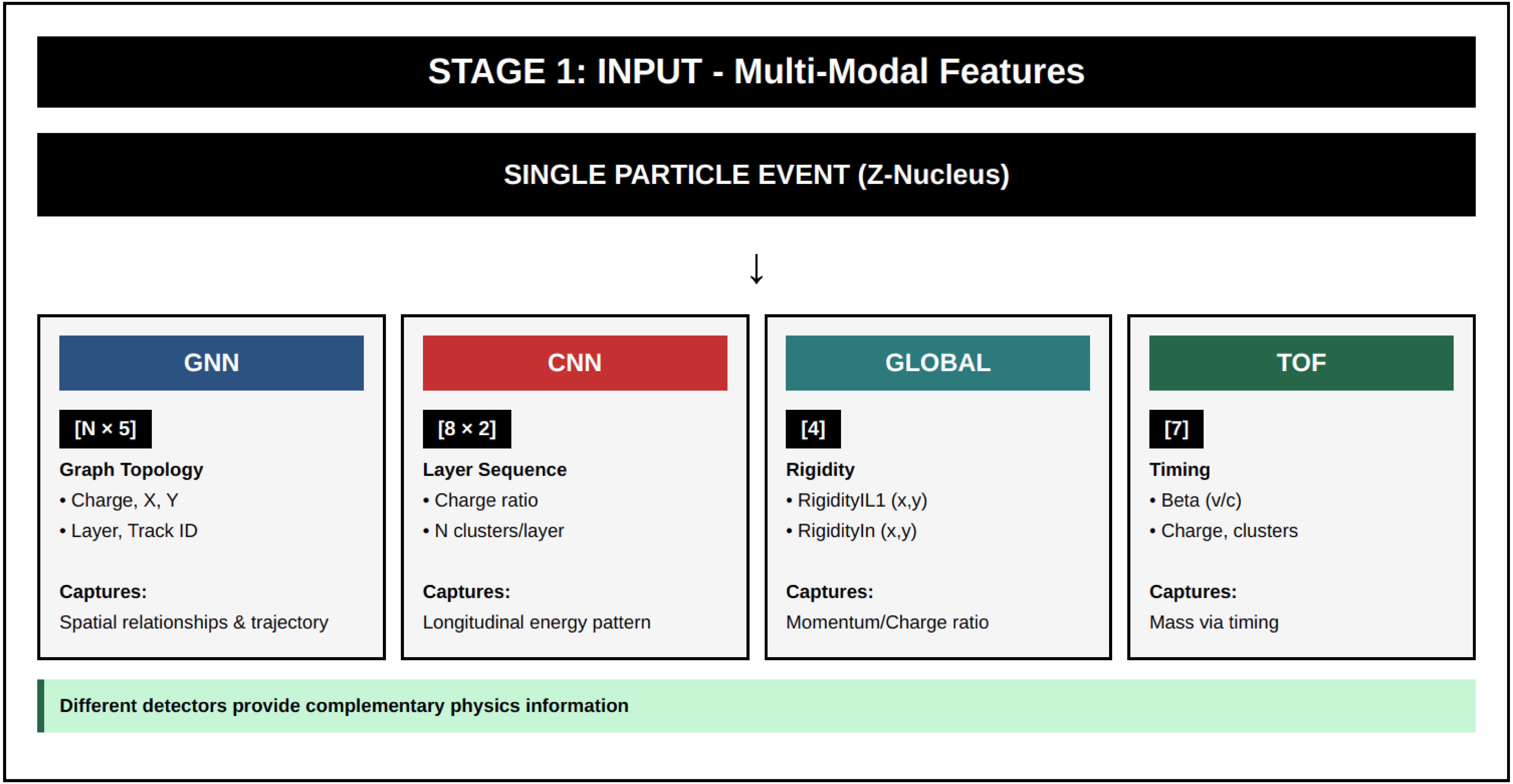


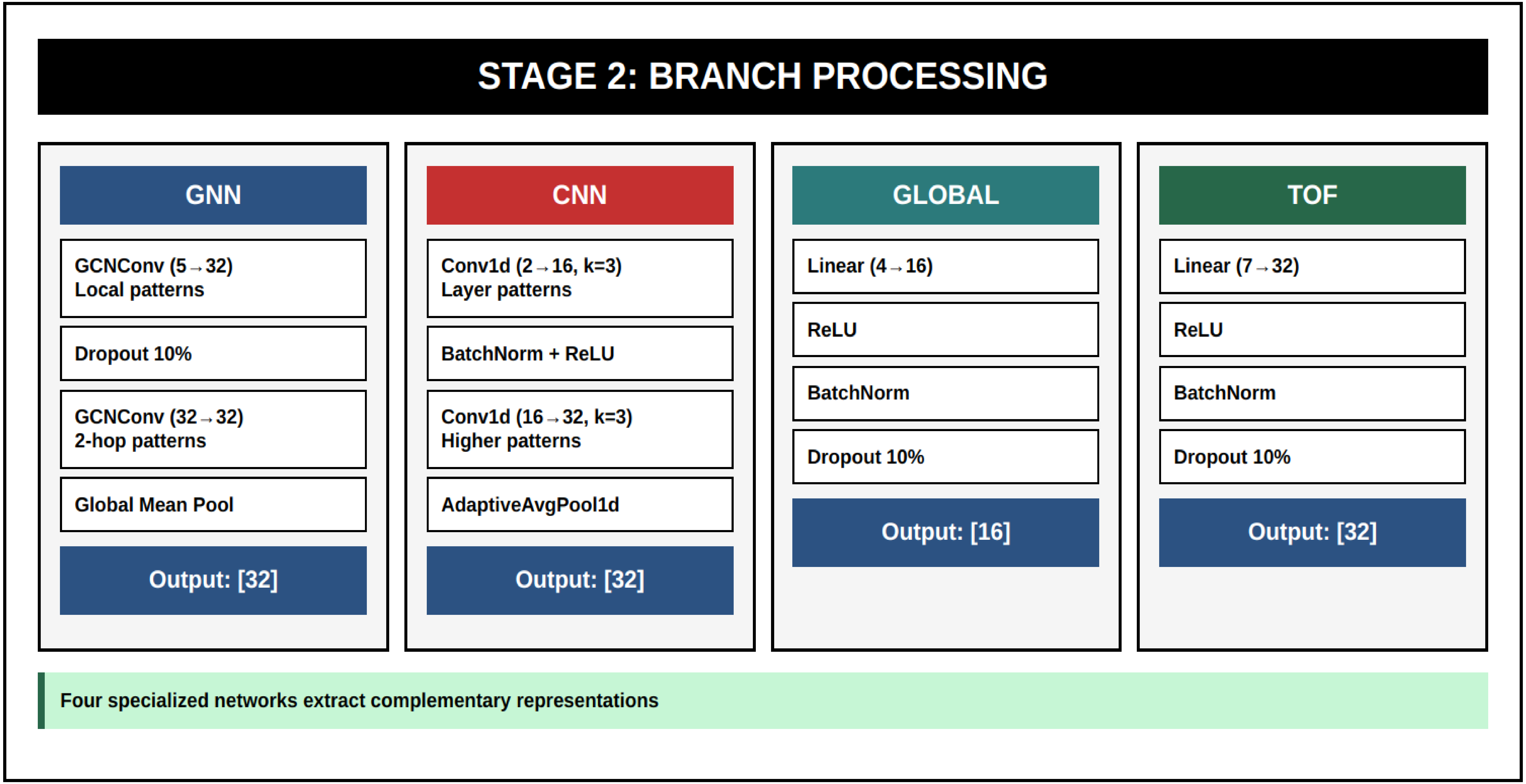
Multimodal Domain Adversarial Network (M-DAN)

- MDAN Architecture: The Key to Robustness is Adversarial Training.

- The network has two competing goals: maximize signal separation (Classification) while minimizing the distinction between simulated and real events (Adversarial).




STAGE 1: INPUT - Multi-Modal Features
SINGLE PARTICLE EVENT (Z-Nucleus)
GNN
[N × 5]
Graph Topology
• Charge, X, Y
• Layer, Track ID
Captures:
Spatial relationships & trajectory
CNN
[8 × 2]
Layer Sequence
• Charge ratio
• N clusters/layer
Captures:
Longitudinal energy pattern
GLOBAL
[4]
Rigidity
• RigidityIL1 (x,y)
• RigidityIn (x,y)
Captures:
Momentum/Charge ratio
TOF
[7]
Timing
• Beta (v/c)
• Charge, clusters
Captures:
Mass via timing
Different detectors provide complementary physics information


STAGE 2: BRANCH PROCESSING
GNN
GCNConv (5→32)
Local patterns
Dropout 10%
GCNConv (32→32)
2-hop patterns
Global Mean Pool
Output: [32]
CNN
Conv1d (2→16, k=3)
Layer patterns
BatchNorm + ReLU
Conv1d (16→32, k=3)
Higher patterns
AdaptiveAvgPool1d
Output: [32]
GLOBAL
Linear (4→16)
ReLU
BatchNorm
Dropout 10%
Output: [16]
TOF
Linear (7→32)
ReLU
BatchNorm
Dropout 10%
Output: [32]
Four specialized networks extract complementary representations

STAGE 3: ATTENTION FUSION

Step A: Projection to 64-d

GNN [32]	CNN [32]	Global [16]	TOF [32]
↓	↓	↓	↓
Linear	Linear	Linear	Linear
↓	↓	↓	↓
[64]	[64]	[64]	[64]

↓

Step B: Add Positional Encoding

[64] + Pos_0 → GNN [64]
[64] + Pos_1 → CNN [64]
[64] + Pos_2 → Global [64]
[64] + Pos_3 → TOF [64]

Stack: [batch, 4, 64]

↓

Step C: Multi-Head Attention (4 heads)

Q, K, V = Linear projections
Attention = $\mathrm{softmax}(Q \cdot K^T / \sqrt{64})$
Output = Attention × V

	GNN	CNN	Global	TOF
GNN	0.45	0.25	0.15	0.15
CNN	0.20	0.50	0.20	0.10
Global	0.30	0.15	0.40	0.15
TOF	0.10	0.25	0.20	0.45

↓

Step D: Mean Pooling

FUSED FEATURES [batch, 64]

Attention learns dynamic weighting - not equal mixing

STAGE 4: DUAL CLASSIFICATION HEADS

Classification Head

- Linear (64→32) + ReLU
- Dropout 10%
- Linear (32→16) + ReLU
- Dropout 10%
- Linear (16→1)
- Sigmoid → [0,1]

>0.5 = Signal
<0.5 = Background

Domain Adversarial Head

Gradient Reversal Layer
λ: 0.0 → 1.0
Forward: x
Backward: -λ·grad

- Linear (64→128) + ReLU + BN
- Linear (128→64) + ReLU + BN
- Linear (64→32) + ReLU
- Linear (32→1)
- Sigmoid → [0,1]

Goal: ~50% Accuracy
(Domain-invariant)

GRL creates adversarial game: Classify well BUT domain-invariant features

Total Loss = Classification Loss + Domain Loss

Classification Loss

BCE(pred, true_label)

Example: BCE(0.73, 1.0) = 0.31

Goal: Minimize
Target: High accuracy (>80%)

Domain Loss

BCE(pred, domain_label)

Example: BCE(0.51, 0/1) ≈ 0.69

Goal: ~0.69 (random)
Target: ~50% accuracy

↓ BACKWARD PASS ↓

Classification Gradient

"Make features discriminative"

↓
Normal backprop

Domain Gradient (via GRL)

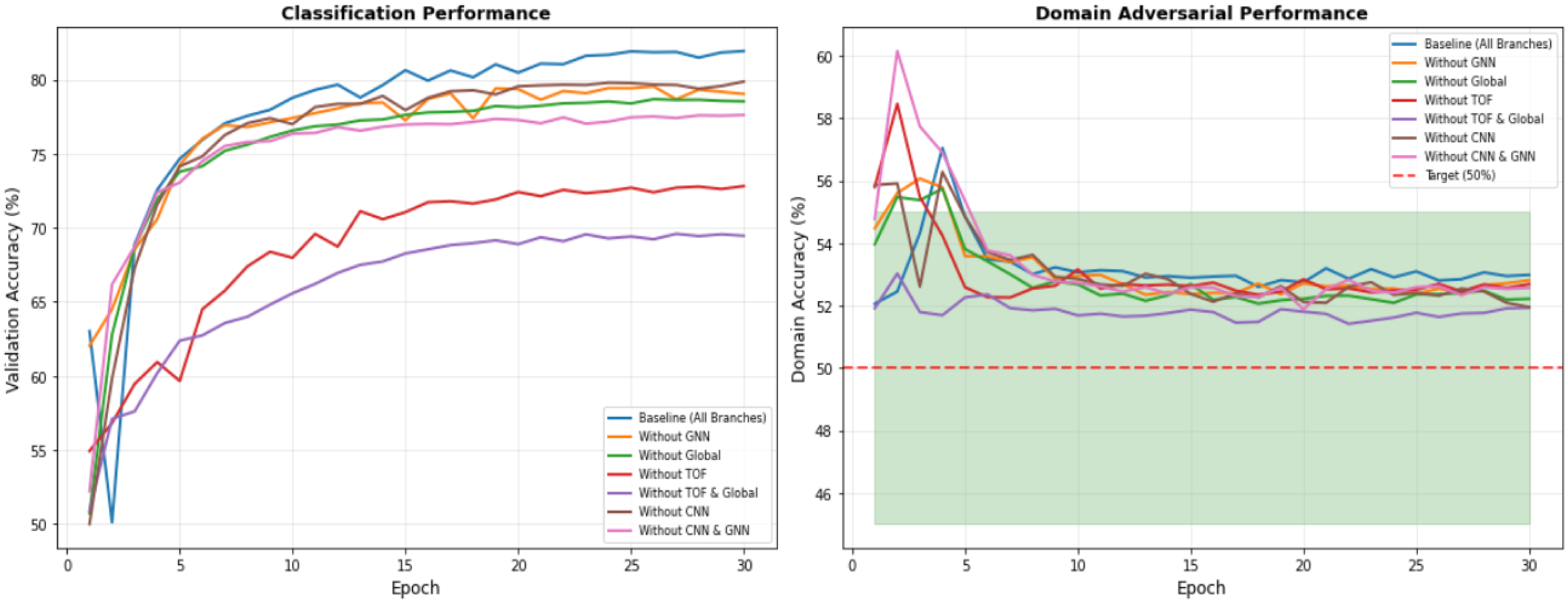
"Make features domain-invariant"

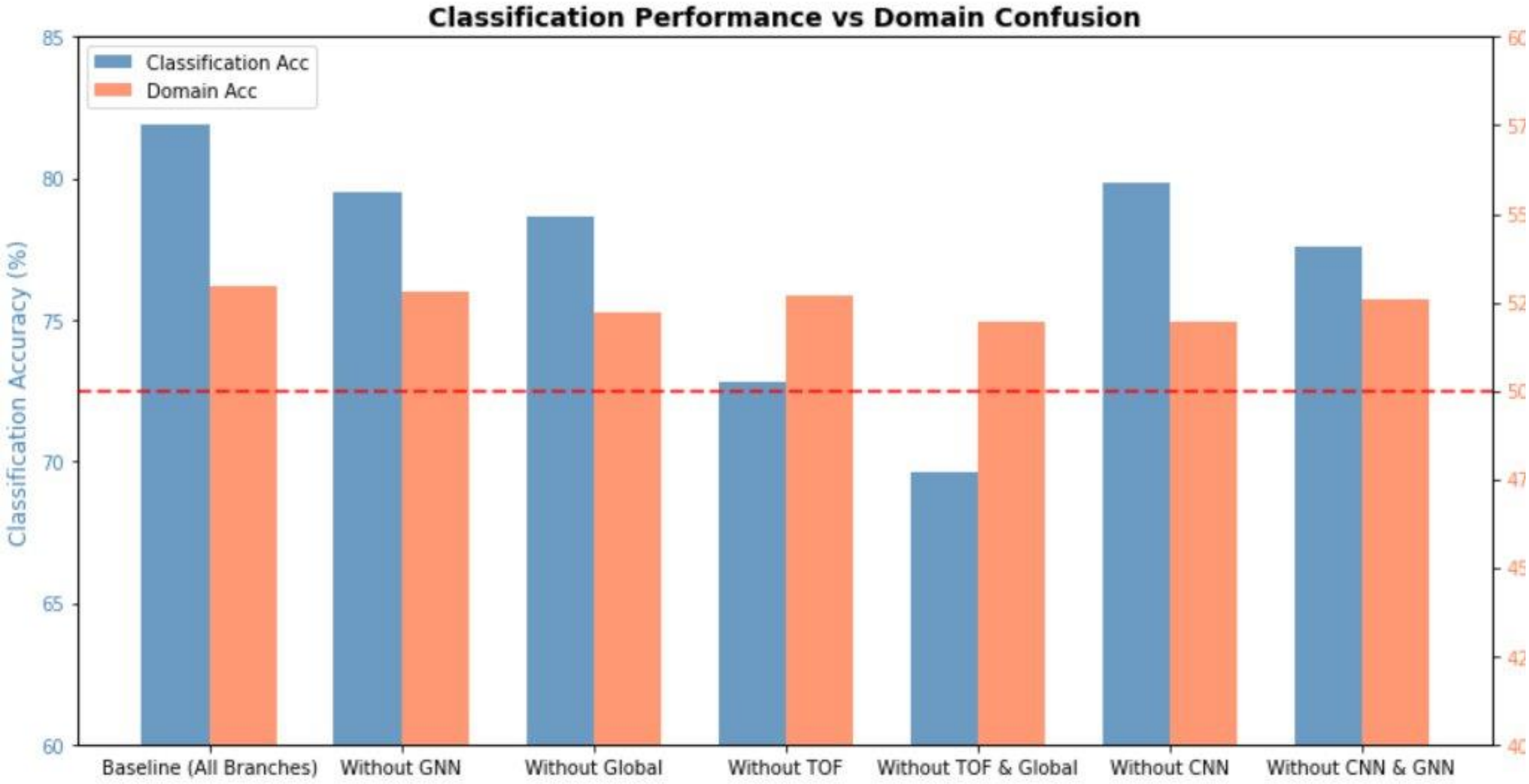
↓
Reversed: ×(-λ)

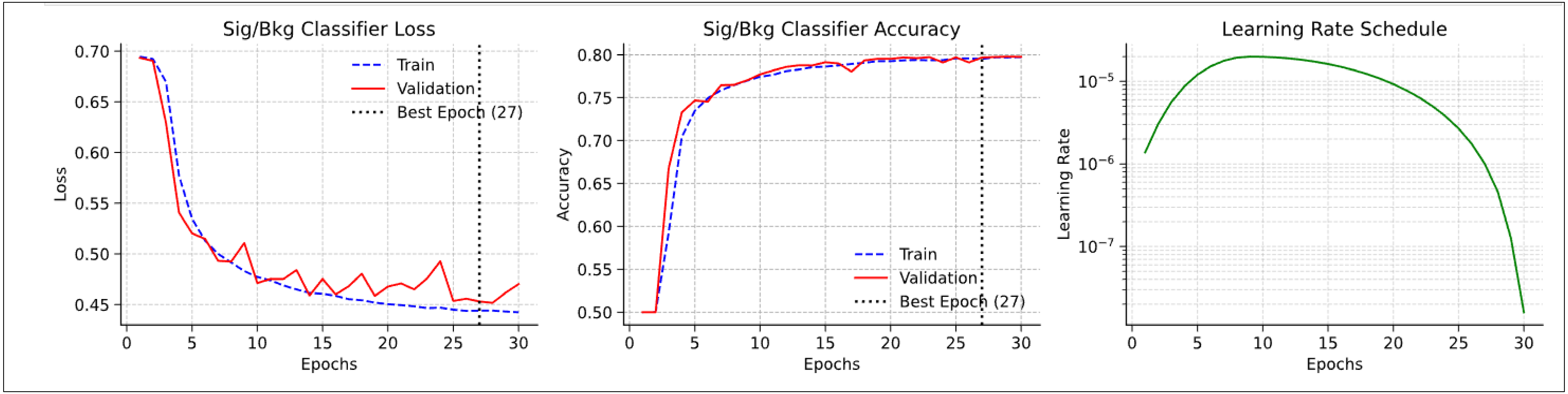
↓

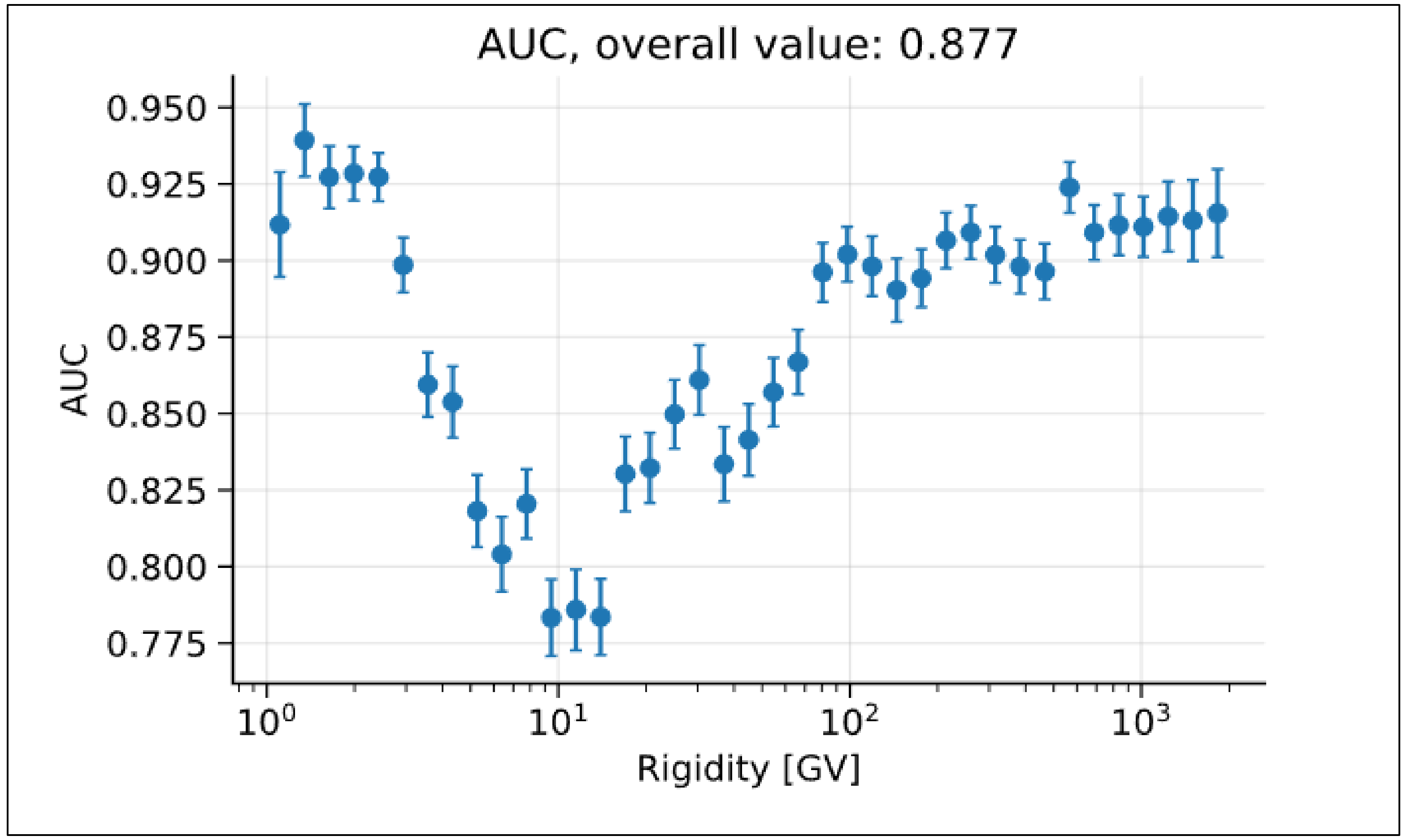
FUSED FEATURES receive BOTH signals
Result: Discriminative yet domain-invariant

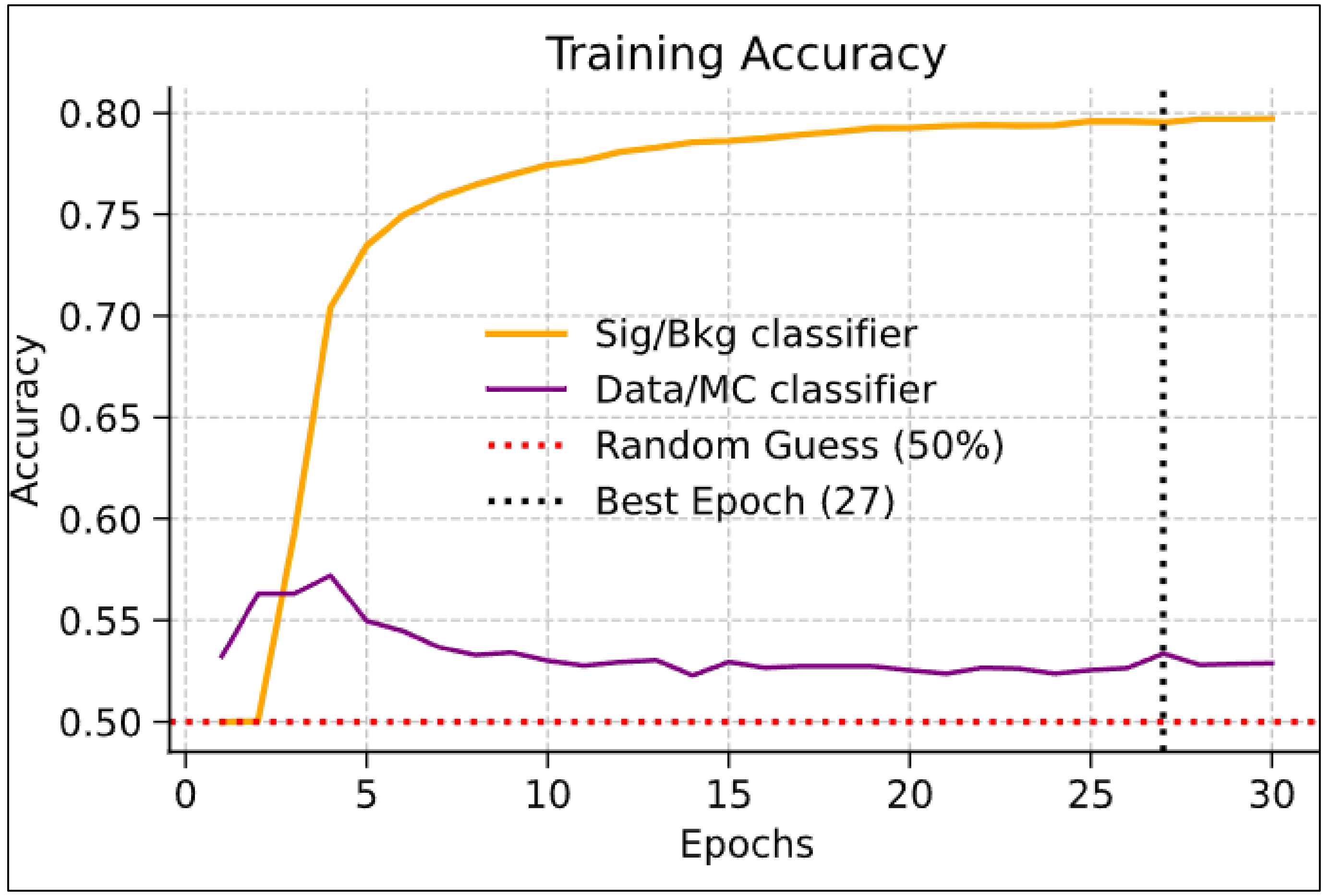
Equilibrium: High classification accuracy + ~50% domain accuracy


Classification Performance
Validation Accuracy (%)
Epoch
Baseline (All Branches)
Without GNN
Without Global
Without TOF
Without TOF & Global
Without CNN
Without CNN & GNN
Domain Adversarial Performance
Domain Accuracy (%)
Epoch
Baseline (All Branches)
Without GNN
Without Global
Without TOF
Without TOF & Global
Without CNN
Without CNN & GNN
Target (50%)

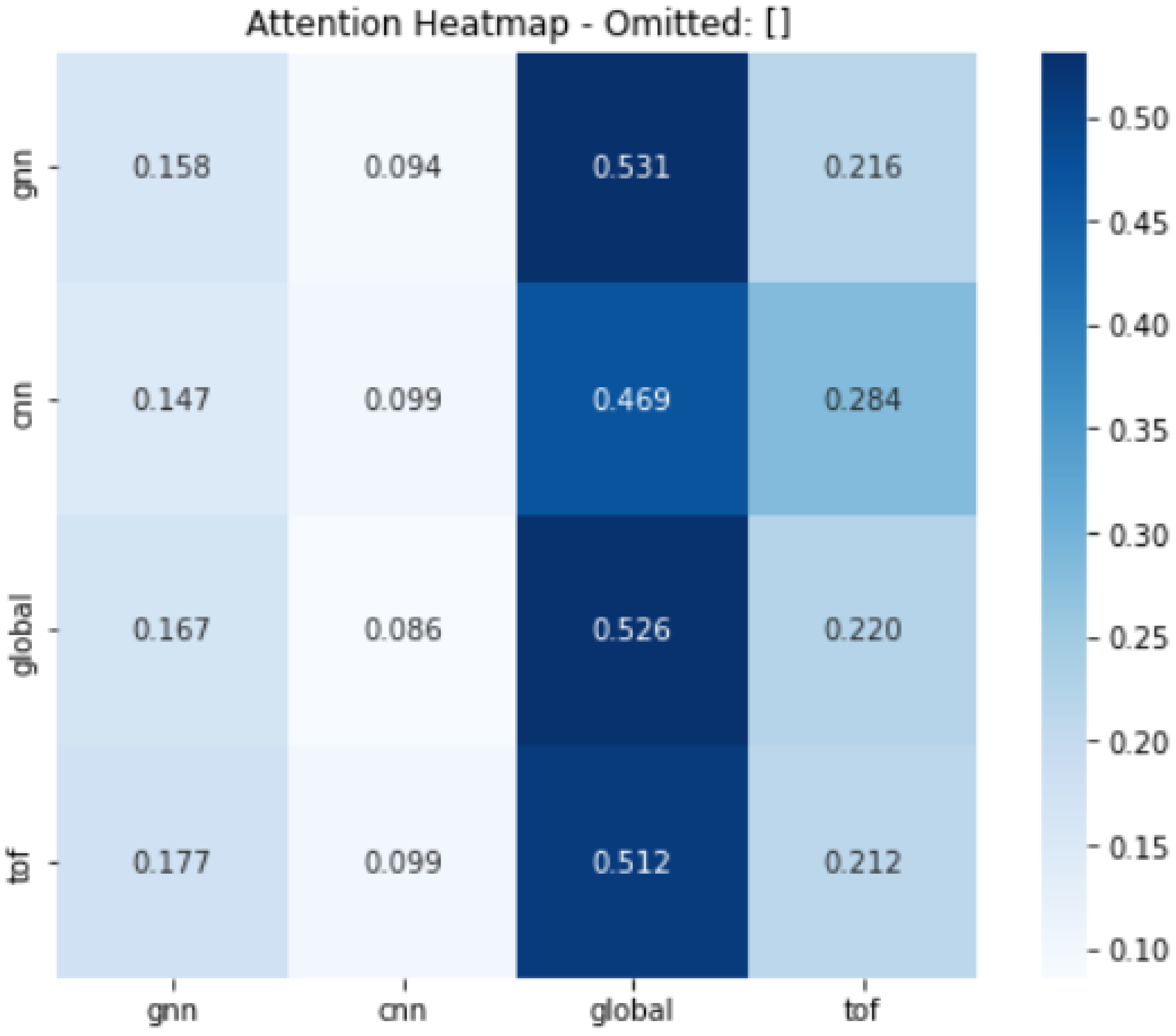

Classification Performance vs Domain Confusion
Classification Acc
Domain Acc
Classification Accuracy (%)
85
80
75
70
65
60
Baseline (All Branches)
Without GNN
Without Global
Without TOF
Without TOF & Global
Without CNN
Without CNN & GNN


Sig/Bkg Classifier Loss
Loss
Epochs
Train
Validation
Best Epoch (27)
Sig/Bkg Classifier Accuracy
Accuracy
Epochs
Train
Validation
Best Epoch (27)
Learning Rate Schedule
Learning Rate
Epochs

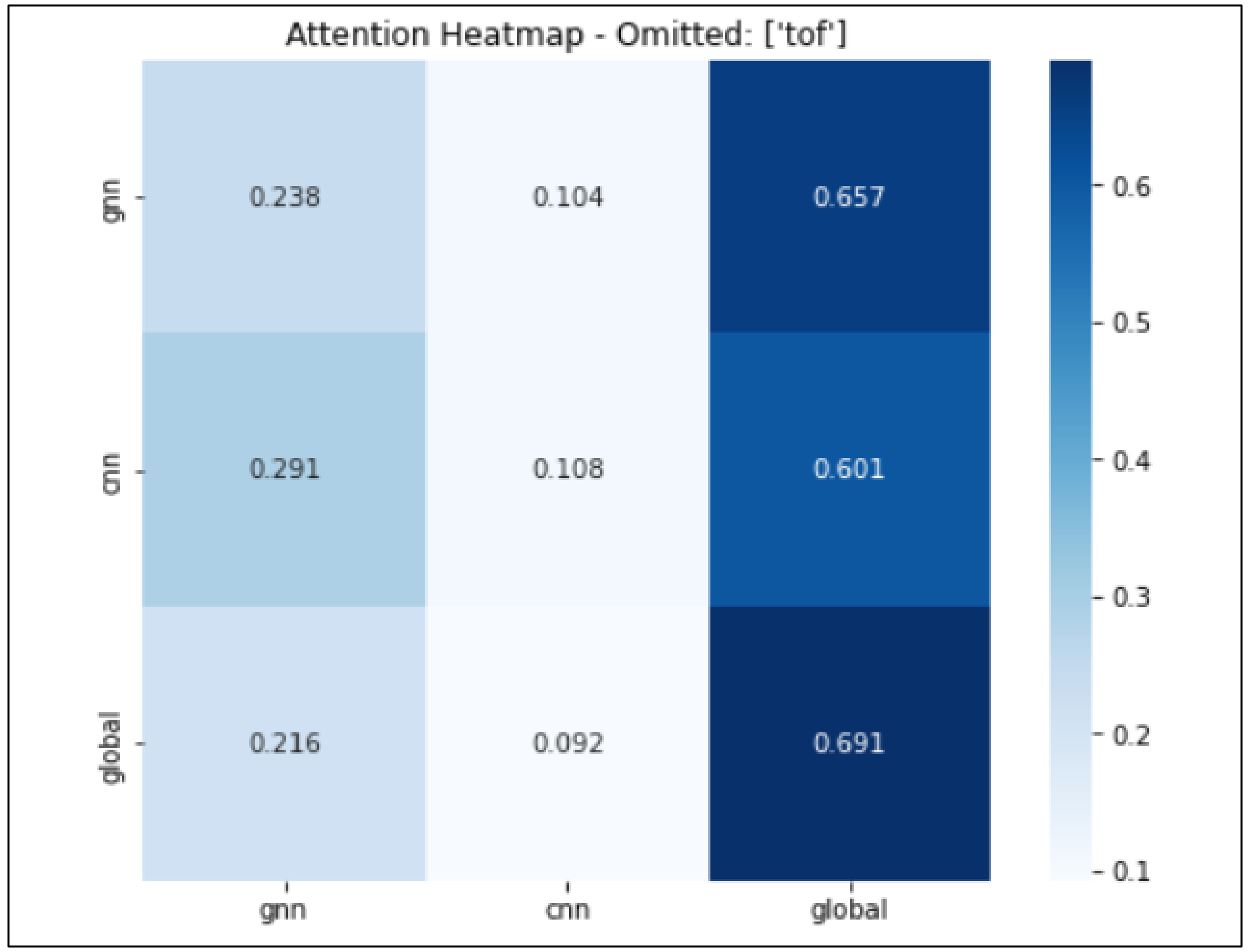

AUC, overall value: 0.877
AUC
Rigidity [GV]

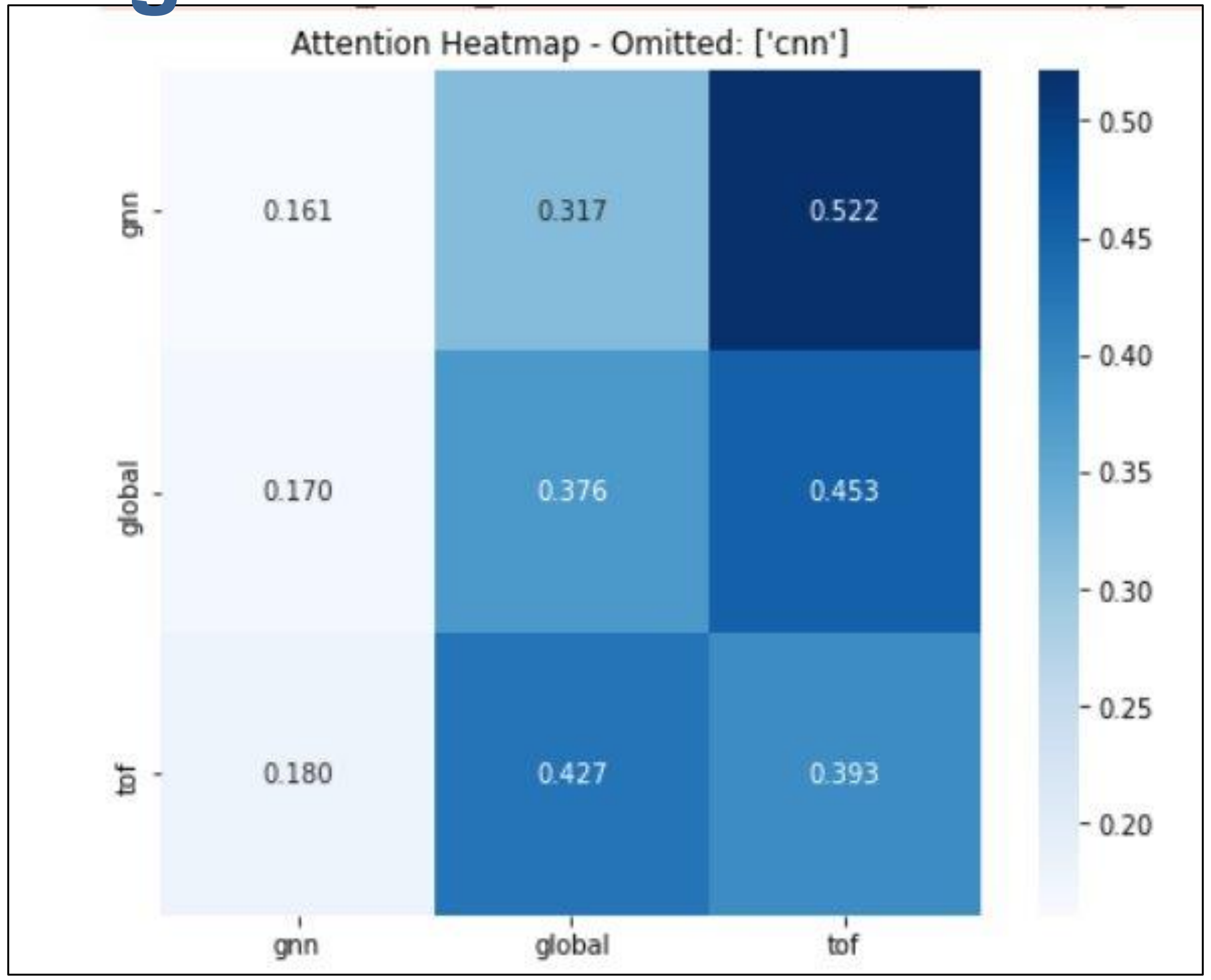

Training Accuracy
Accuracy
Epochs
Sig/Bkg classifier
Data/MC classifier
Random Guess (50%)
Best Epoch (27)

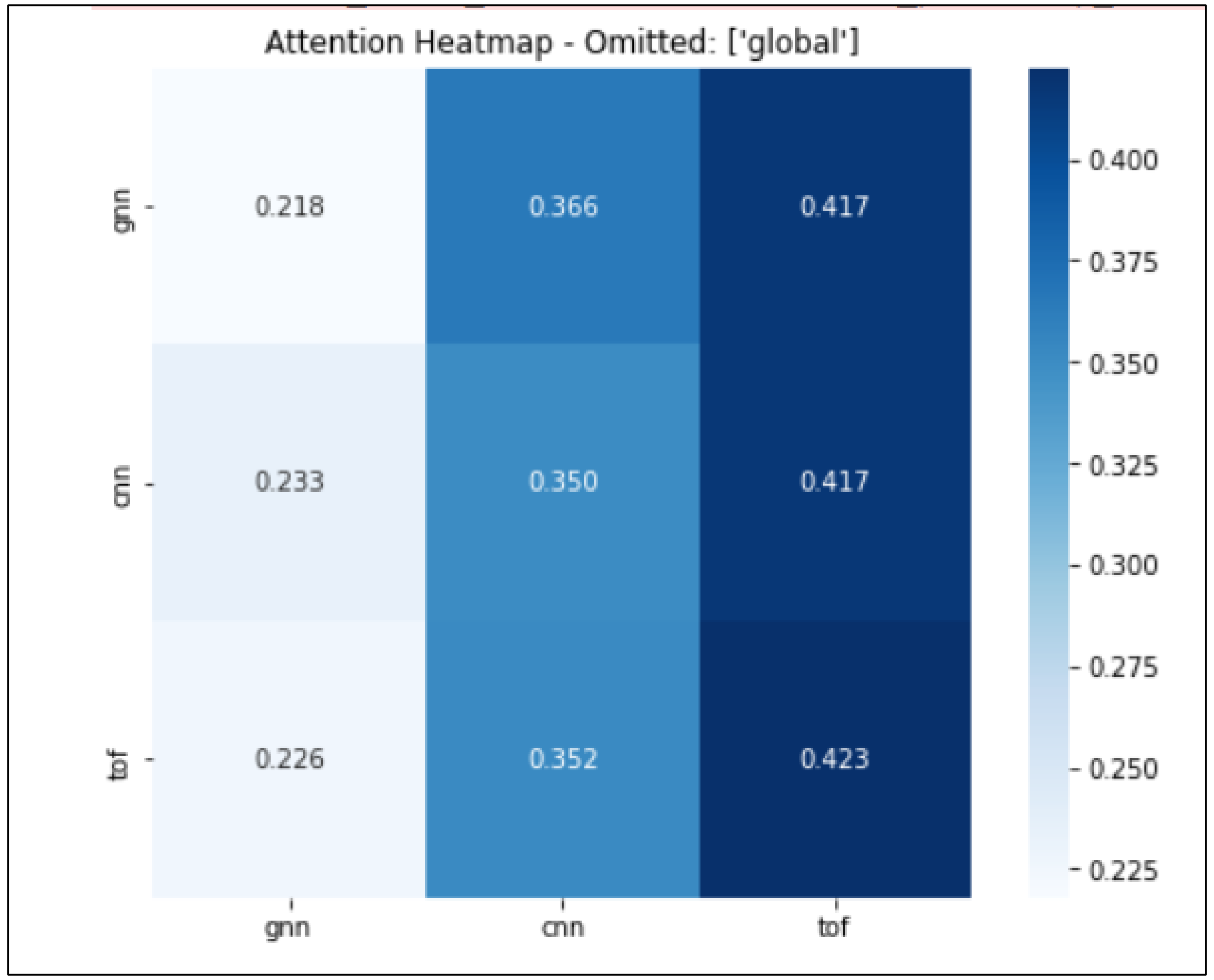
FEATURE ENGINEERING – ATTENTION HEATMAP

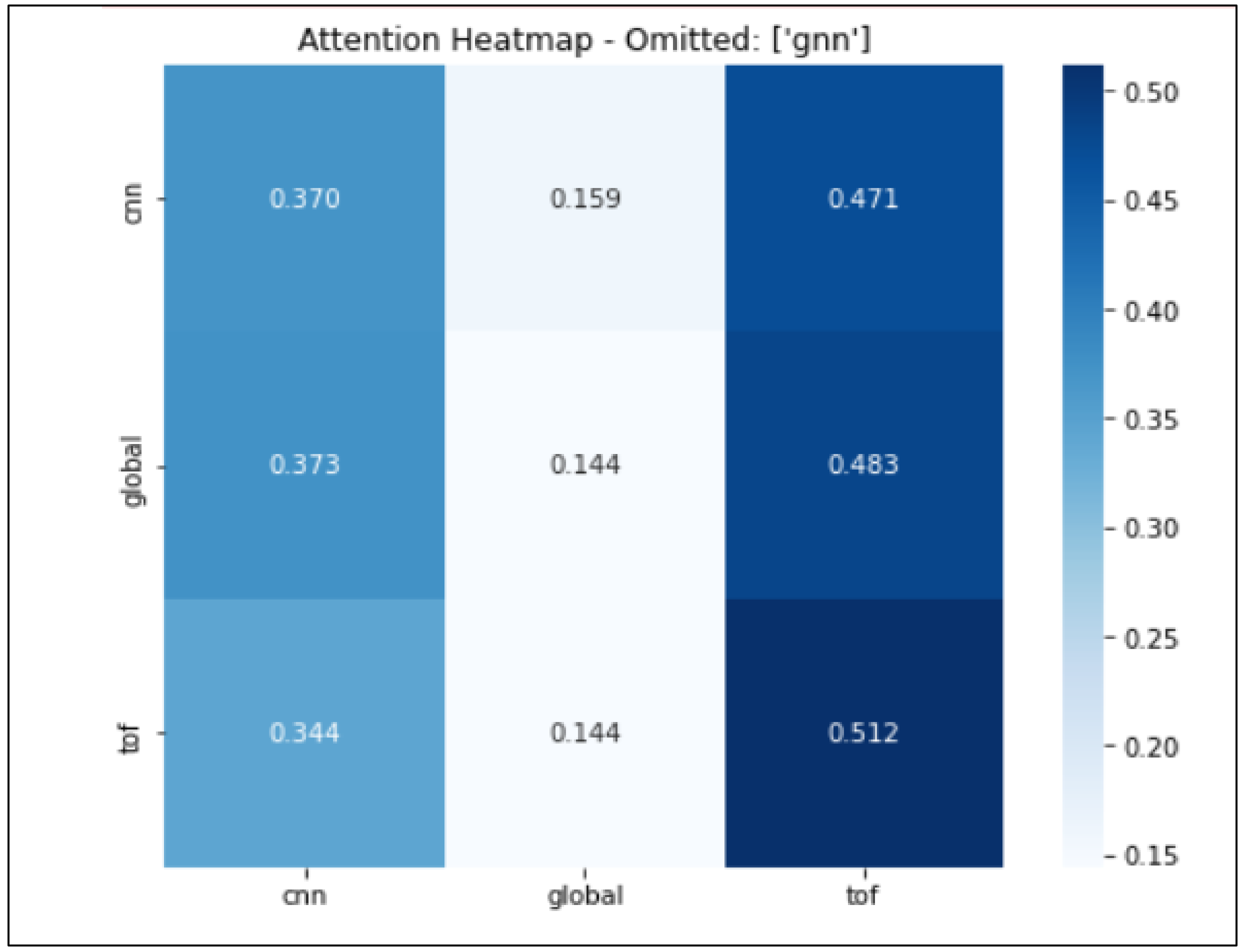


FEATURE ENGINEERING by Omitting sub-Models









Courses & Schools 2nd Year

❖ Introduction to Neuromorphic Computing (Material submitted)
❖ Big Data Modeling and Learning (Project & Technical Report is submitted)

● ISAPP School: "High Energy Cosmic Rays: From Space to Ground" in Lecce, Italy, offering intensive summer school coverage of cosmic ray physics from space-based detection to ground-based observation (June 9-20).

● AMS Italia Meeting in Bologna, Italy, focused on strategic meetings regarding the Alpha Magnetic Spectrometer (AMS) Italian collaboration (November 27-29).
● NAIA Data Framework Use: Hands-on Training (Part 1) in Bologna, Italy, providing practical training on the specific data processing framework used for AMS-02 analysis (November 29).
2025:
● NAIA Data Framework Use: Hands-on Training (Part 2) in Rome, Italy, continuing the practical data framework training (February 03).

Courses & Schools 2nd Year

- TECH-FPA PHD Retreat 2025 at LNGS, L'Aquila, Italy, focusing on technology, funding, and career paths in particle astrophysics (February 17-21).
- Authentic Impact Workshop by Barbara Van for Team Development at LNGS, L'Aquila, Italy, focusing on maximizing authentic professional impact and collaboration (TBD).

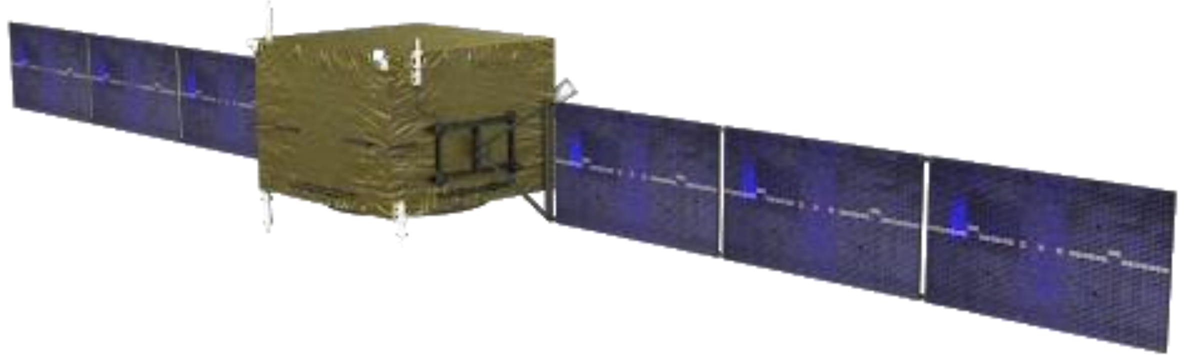
- AMS Nuclei Meeting at SDIAT, Jinan, China, specifically dedicated to the analysis, spectra, and interpretation of cosmic ray nuclei data from AMS-02 (September 6-12).

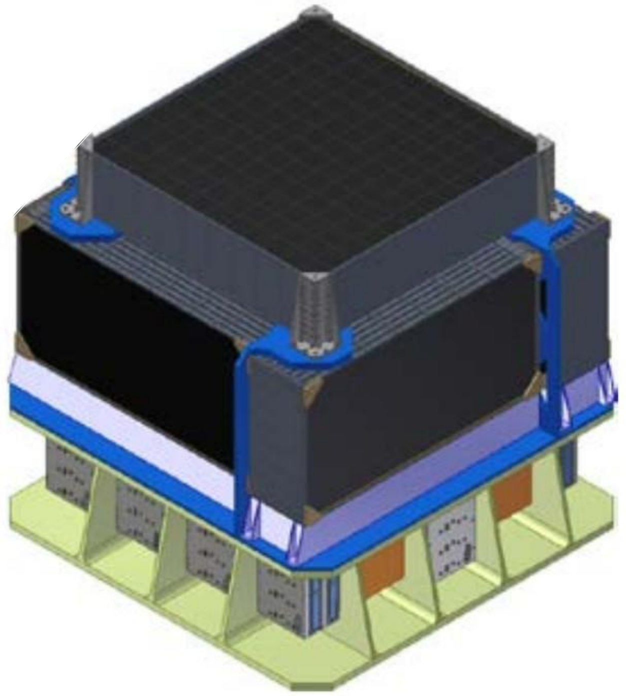
- 1st PhyStat School of Statistics: "Statistics in the era of ML" in the Netherlands, providing specialized training on advanced statistical methods and the application of Machine Learning (ML) in physics (November 17-21).

- TEE Shifts in POCC Data Center for AMS 02 , Geneva, Switzerland (28/03/2025 - 05/04/2025) & (11/05/2025 - 18/05/2025 & 20/09.2025 - 25/09/2025)

Third Year

- Complete feature engineering optimization and finalize thesis Chapter 1 (Cosmic Ray Physics fundamentals).
- Initiate flux measurement comparison study with collaborating research groups to validate model predictions.
- Complete thesis Chapter 2 (AMS-02 Detector systems and data processing).
- Analyze test beam data for tracker performance validation and systematic uncertainty quantification.
- Integrate test beam calibration results into production analysis pipeline.
- Complete thesis experimental chapters and begin final synthesis.





Thank You