Updates on MDA (Multimodal Domain-Adversarial) Method for P Signal-Background Identification

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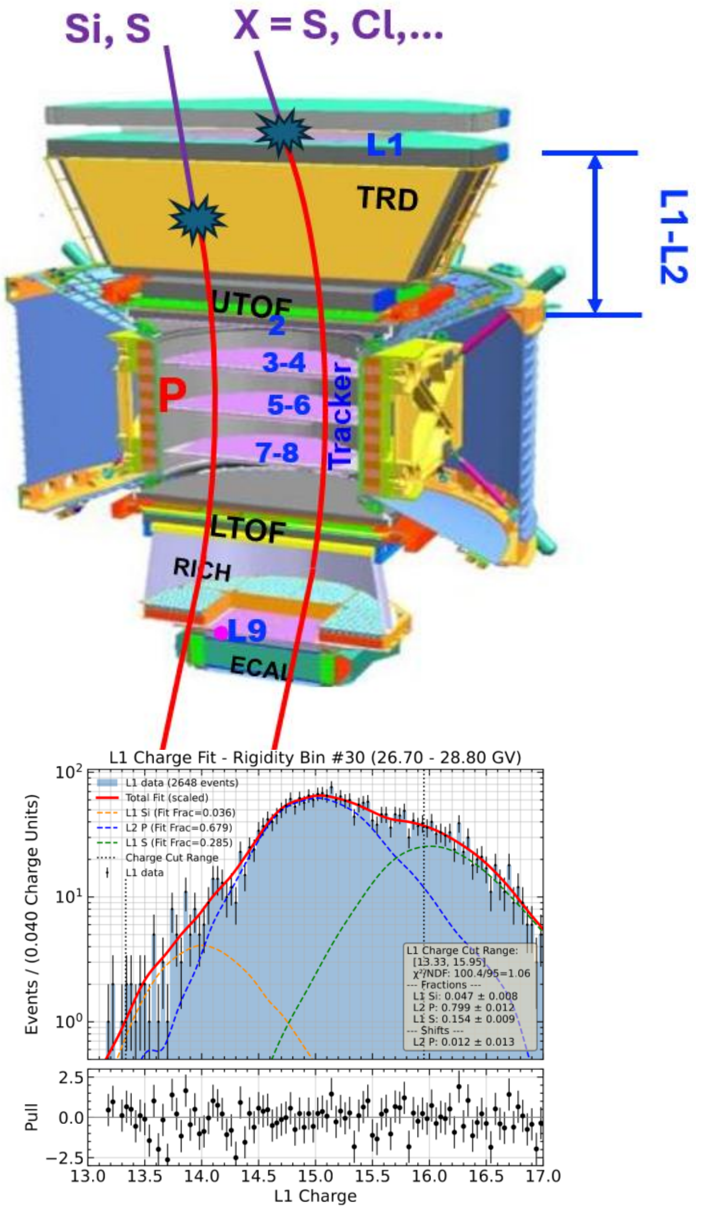
Machine learning for P background study



Motivation:

Reduce P background after P event selection.

Method:

- Using low level Tracker and UTOF reconstructed variables
- Apply a MDA (multimodal domain adversarial) network to achieve good performance on both MC and Data. (slides #4)
    - Trained from MC sample
    - Use domain-adversarial training to learn domain-invariant features, to achieve model generalization across MC and Data

Training samples:

Si, P, and S event selection

- Signal: MC Si, P, S (MC truth)
- Background: MC Si and S (for Si), Si and S (for P), P and Cl (for S)
- Data

Input variables for Machine Learning model

- **Try to use low-level reconstructed variables whenever possible,**
- **Use variables that have similar distributions in both MC and Data**.

Tracker:

- **Tracker (main and second track)**
  - L2 to L8 charge, (Second track Charge to be added in future)
  - Hit Pos for L1 to L8, X- and Y- side
- **Cluster**
  - Number of clusters, for L1-L8, X- and Y- side
- **Rigidity:** Inner+L1 and Inner

TOF (Standalone)

- Beta;
- UTOF charge;
- TOF charge on L1,L2
- Number of On-Time TOF clusters for L1,L2
- Total number of clusters used for charge estimation

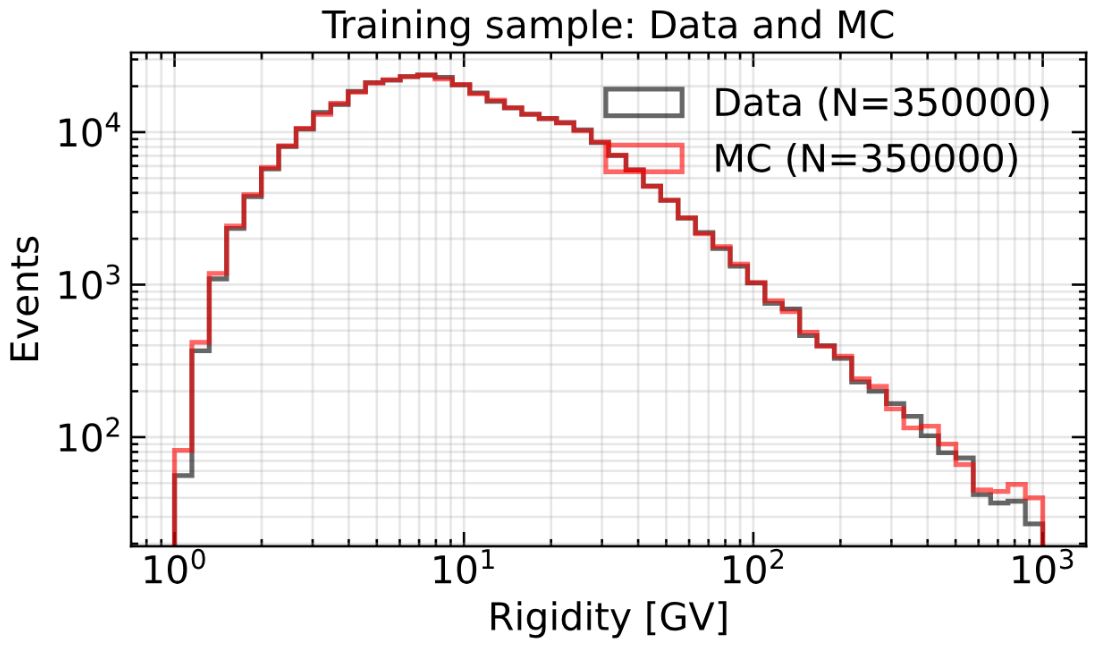
Note:

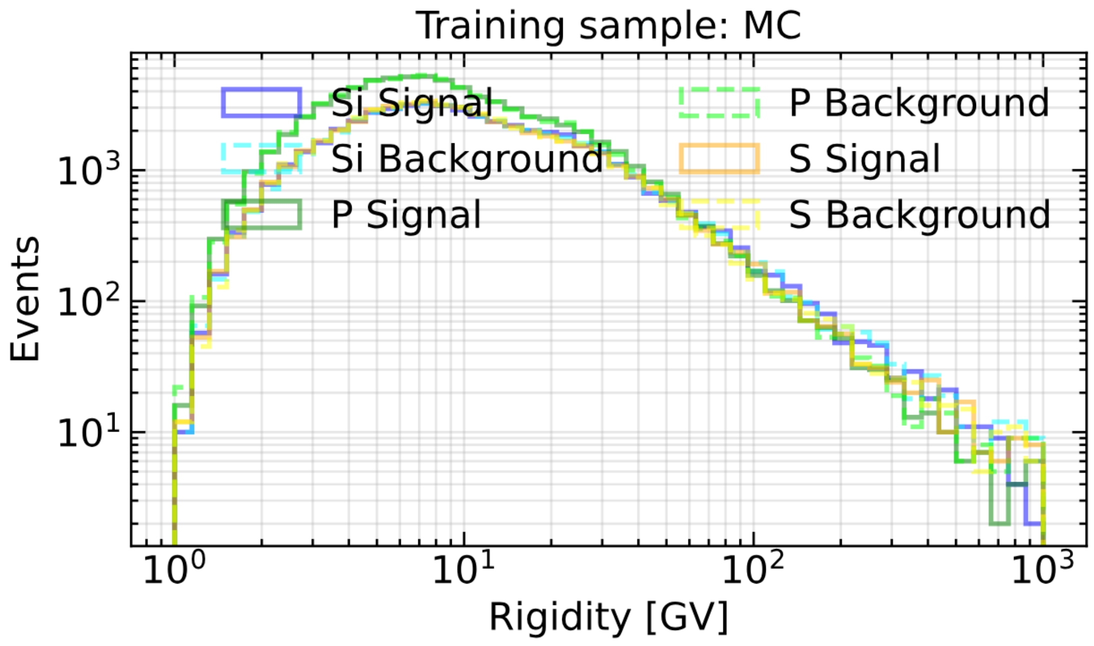
- MC and Data samples: similar Rigidity distributions.
- Input variables are normalized according to mean and std.

Training samples

Data: 150k events passing Si, P, S event selection

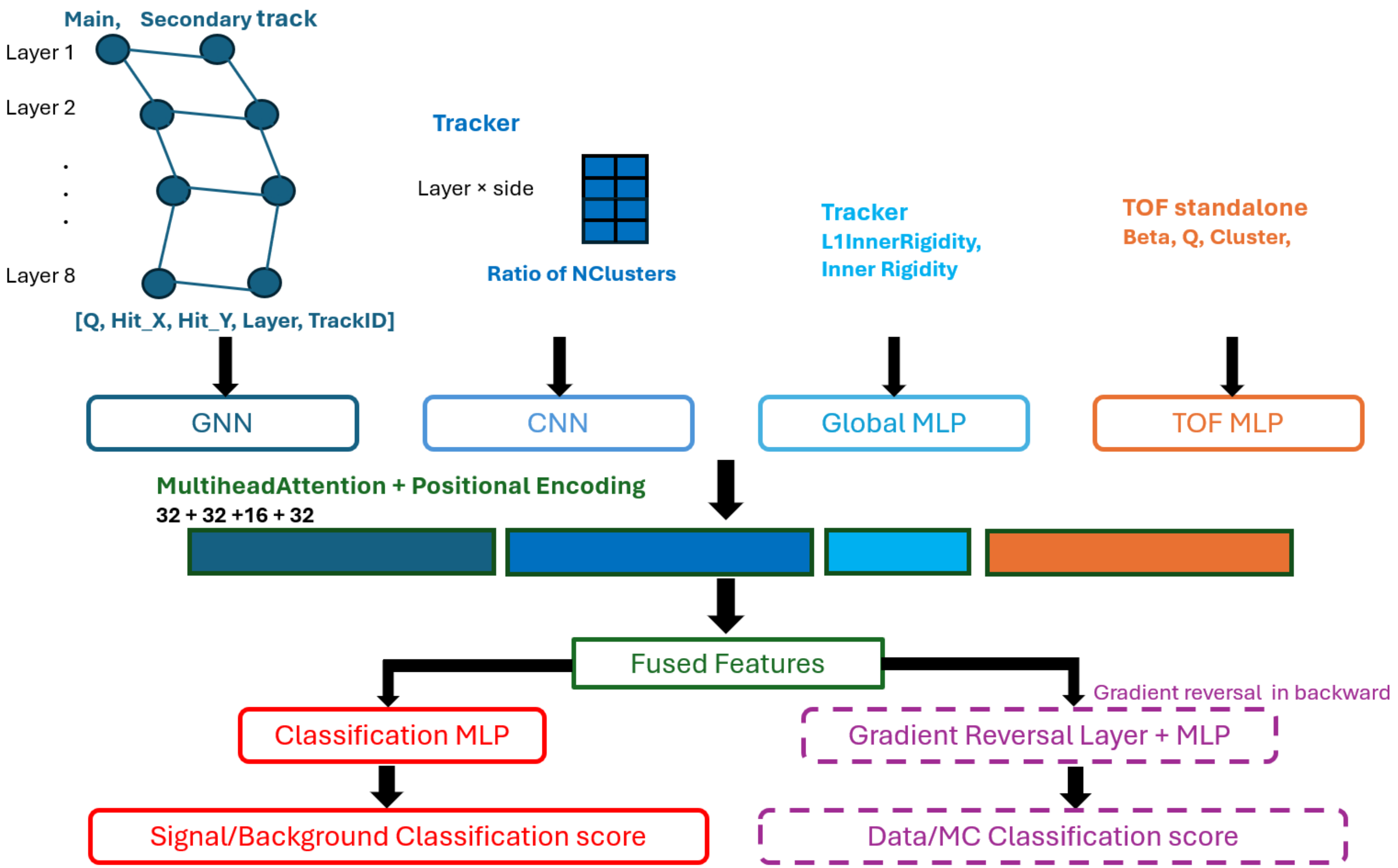
- **Signal**: 75k MC Si, P, S (MC truth) events passing Si, P, S event selection respectively.
- **Background**:
    - 25k Si background events: 81% P and 19% S
    - 25k P background events: 2.2% Si and 97.8% S
    - 25k S background events: 2.7% P and 97.3% Cl





MDA (multimodal domain-adversarial) Network

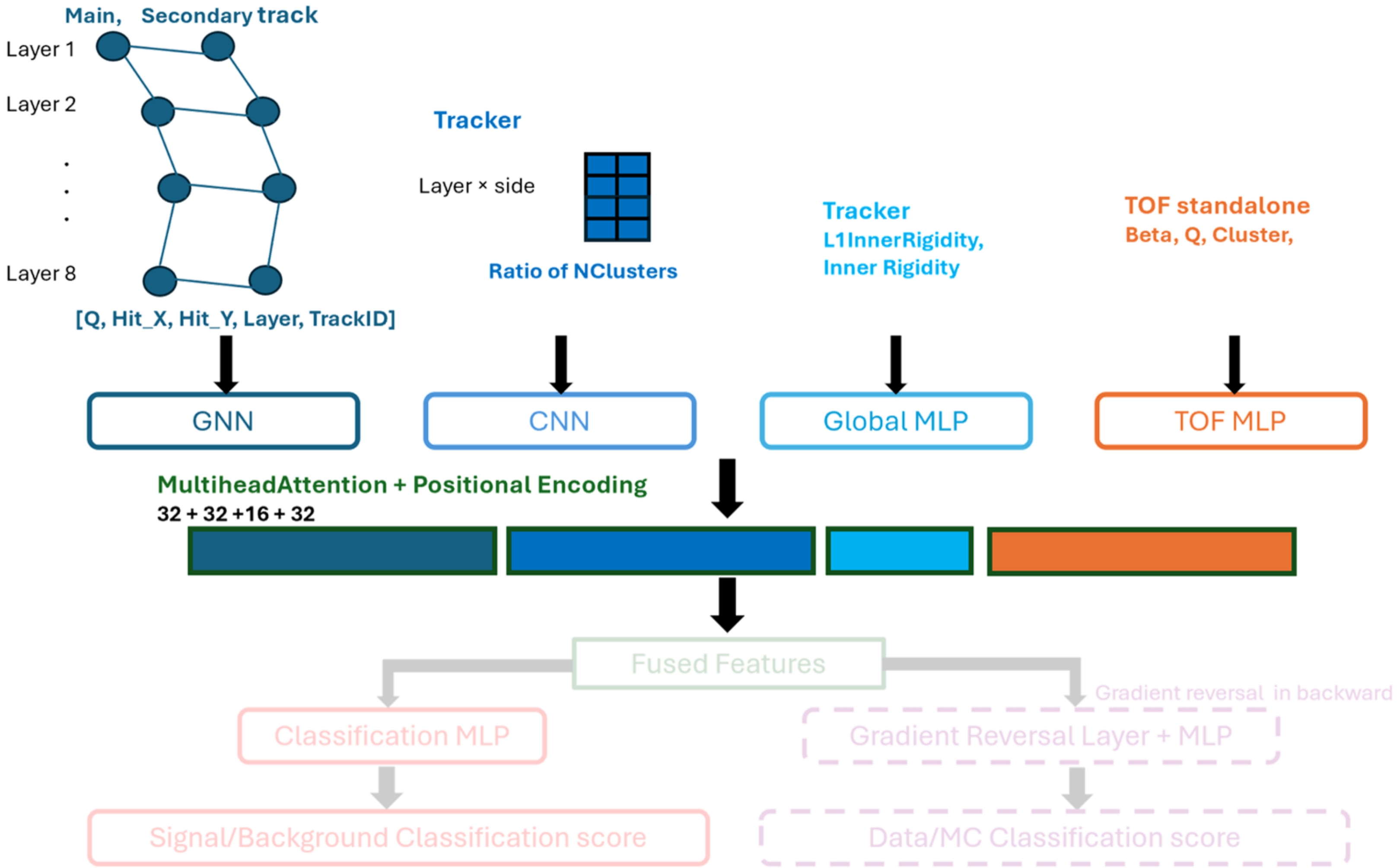
1. **4 sub-models to extract input features.**
2. **Features fused with attention mechanism.**
3. **Signal/Background classification**
4. **Domain-Adversarial Neural Network is added to learn features that are similar between MC and Data, ensuring good performance for both MC and Data.**



MDA (multimodal domain-adversarial) Network

(1) 4 sub-models to extract features.
Each sub-model is matched to the structure of its input:

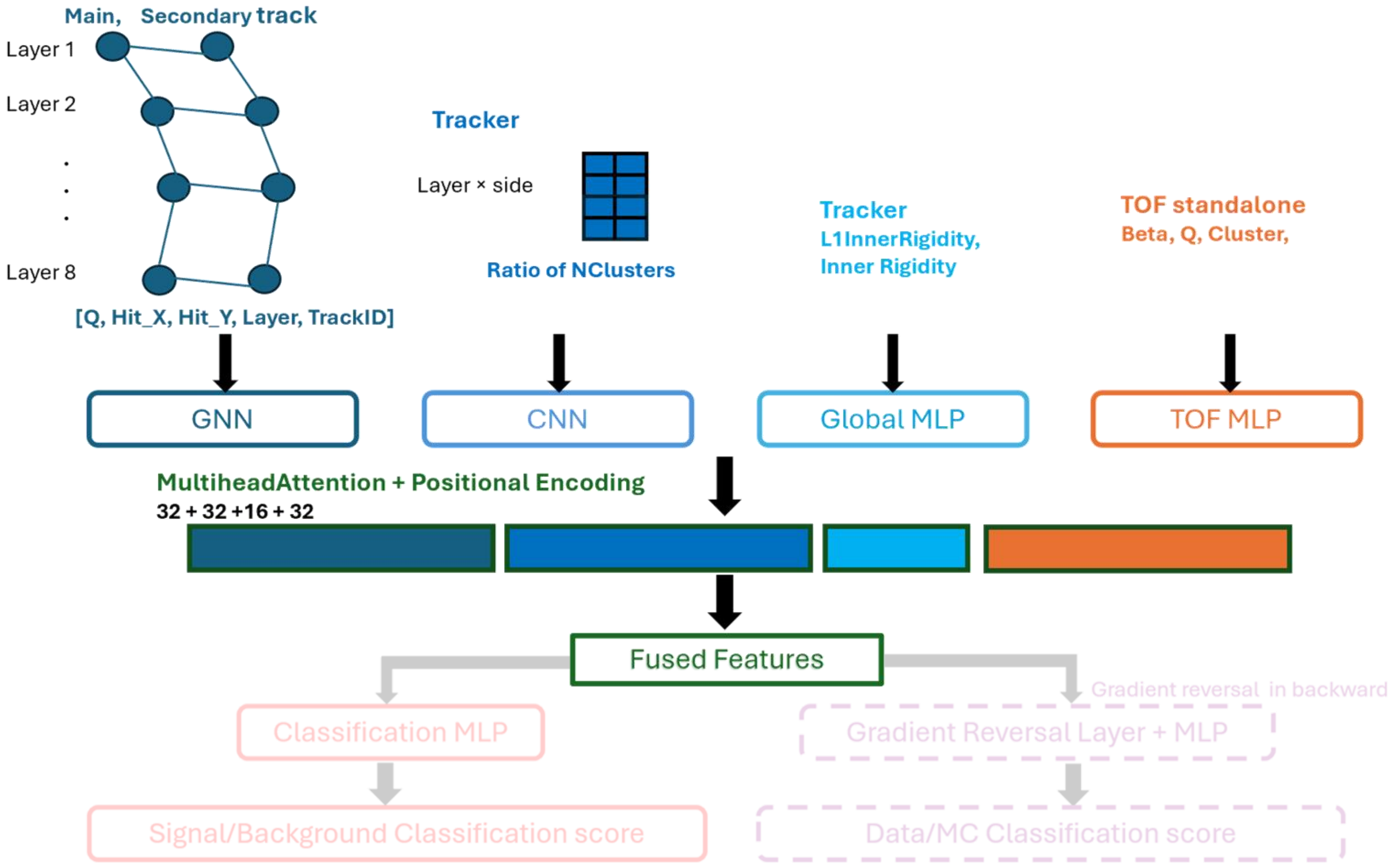
1. **Tracker GNN**
   - Input: hit position and Charge on main and second track for each layer and side,
   - A graph naturally captures layer-to-layer and cross-track relations.
2. **Tracker CNN**
   - Input: number of cluster info on each layer and side
   - The data looks like an image data
3. **Global MLP: Rigidity**
   - event-level Rigidity (global scalar values) are best handled by a small feed-forward network
4. **TOF MLP**
   - Tabular numbers (beta, charge, N cluster). MLPs are the standard choice.



MDA (multimodal domain-adversarial) Network

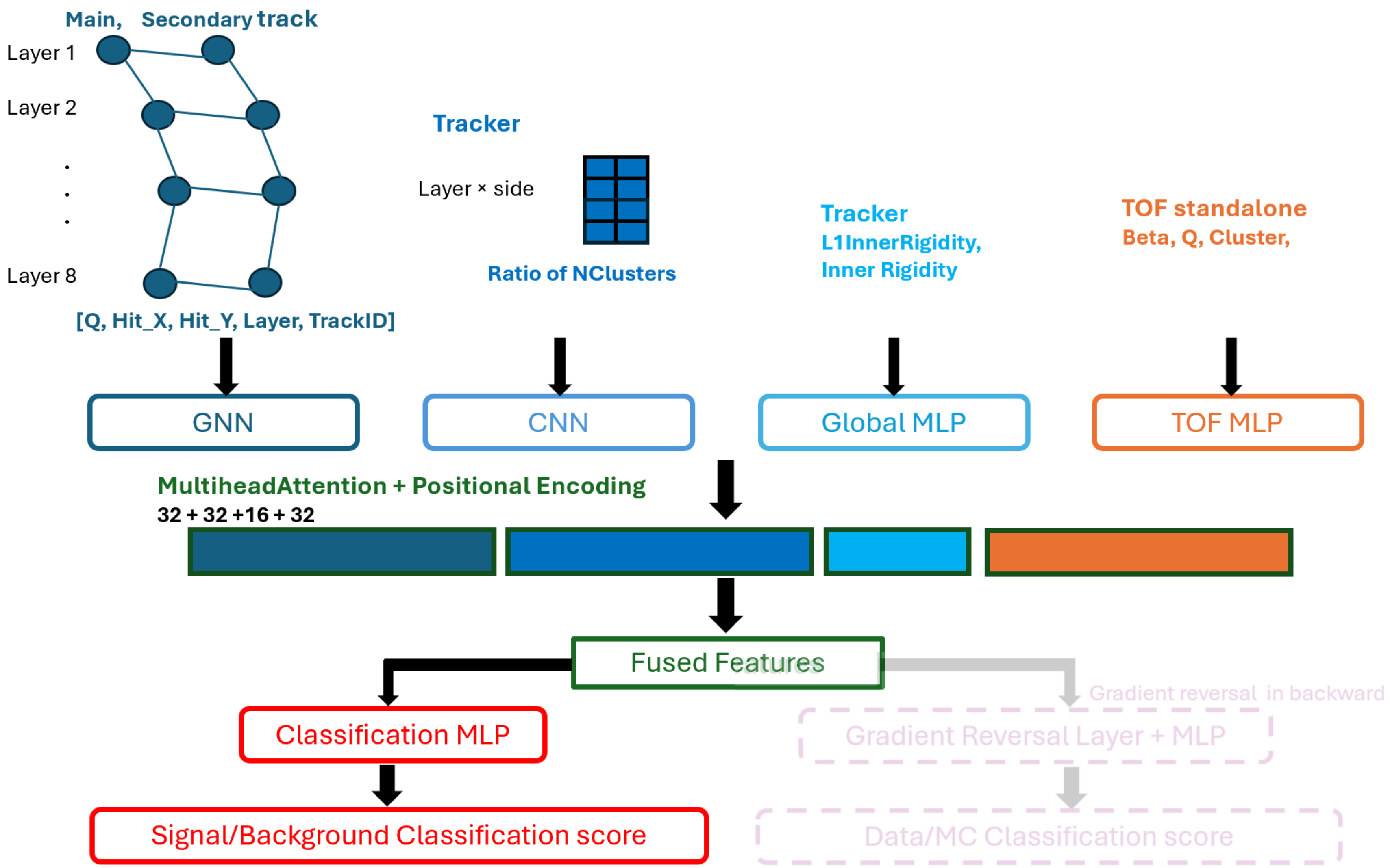
(2) Features from sub-models fused with attention mechanism

- **Mechanism**: multi-head self-attention + positional encoding over the four branch outputs.
- **Effect**: for each event, the model learns how much to rely on each sub-model.
- **Outcome**: the fused feature that uses the most helpful features for each event.



MDA (multimodal domain-adversarial) Network

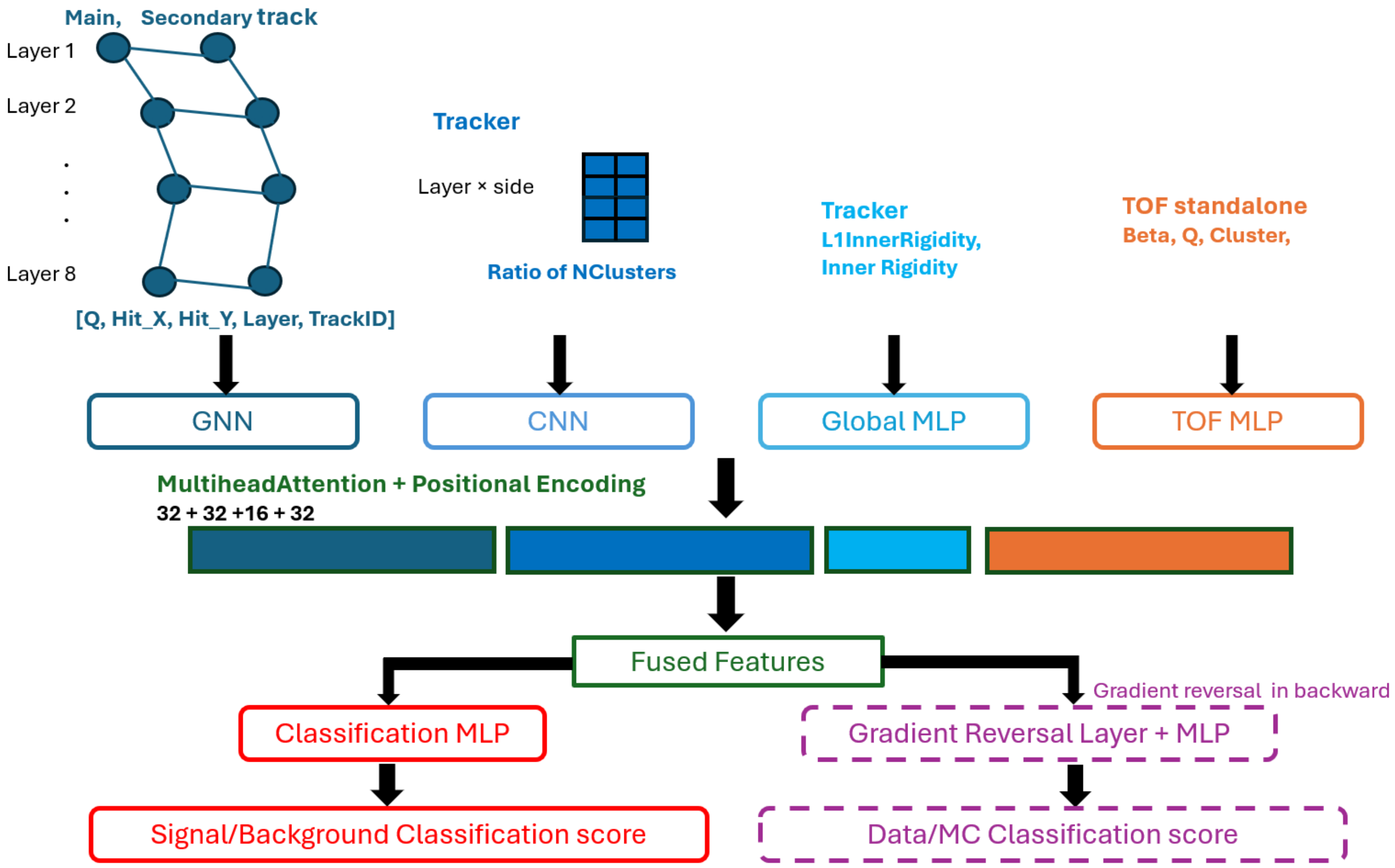
(3) Signal/Background Classifier:
The fused information is fed to a Signal/Background Classifier to distinguish between signal and background events for **MC sample**.



MDA (multimodal domain-adversarial) Network

(4) Adversarial training to extract features that minimize the ability for Data / MC classification

1. **Method*:**
   - Data / MC Classifier: to distinguish MC from Data.
   - Adversarial Feedback: The model gets **penalized when data/MC classifier succeeds**.
2. **Outcome:**
   - The model is forced to focus on physics-relevant features that exist in both MC and Data.
   - As a result, the model extracts features that are as similar as possible between MC and data.



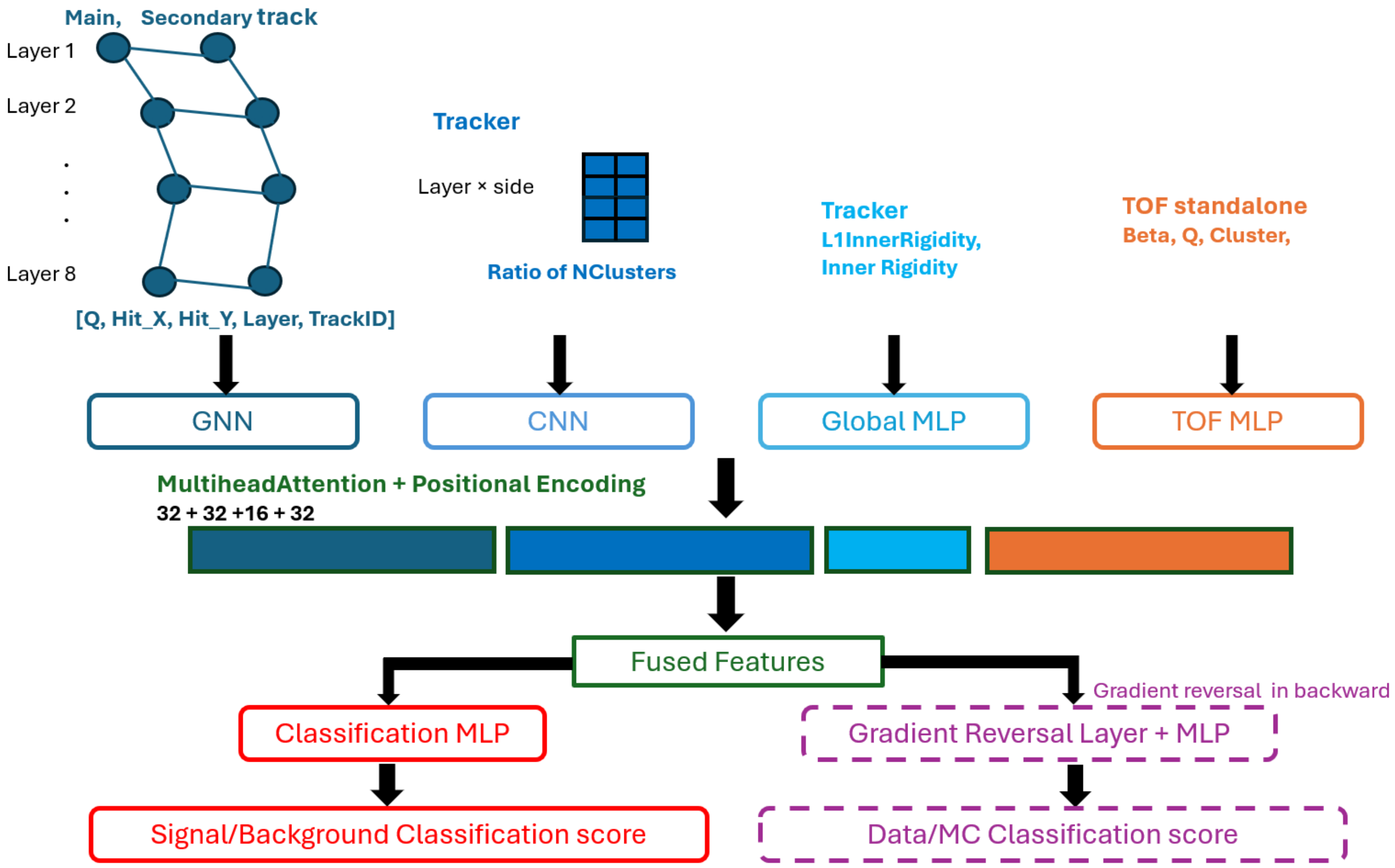
* Domain-Adversarial Training of Neural Networks, arXiv:1505.07818

MDA (multimodal domain-adversarial) Network

Final Objective:

1. **Data / MC Classifier** performs at chance level (overall classification score ~ 50%), indicating the extracted features make MC and Data look indistinguishable.

2. **Signal/Background Classifier** bases its decision on physics-relevant features, not on differences between MC and data.

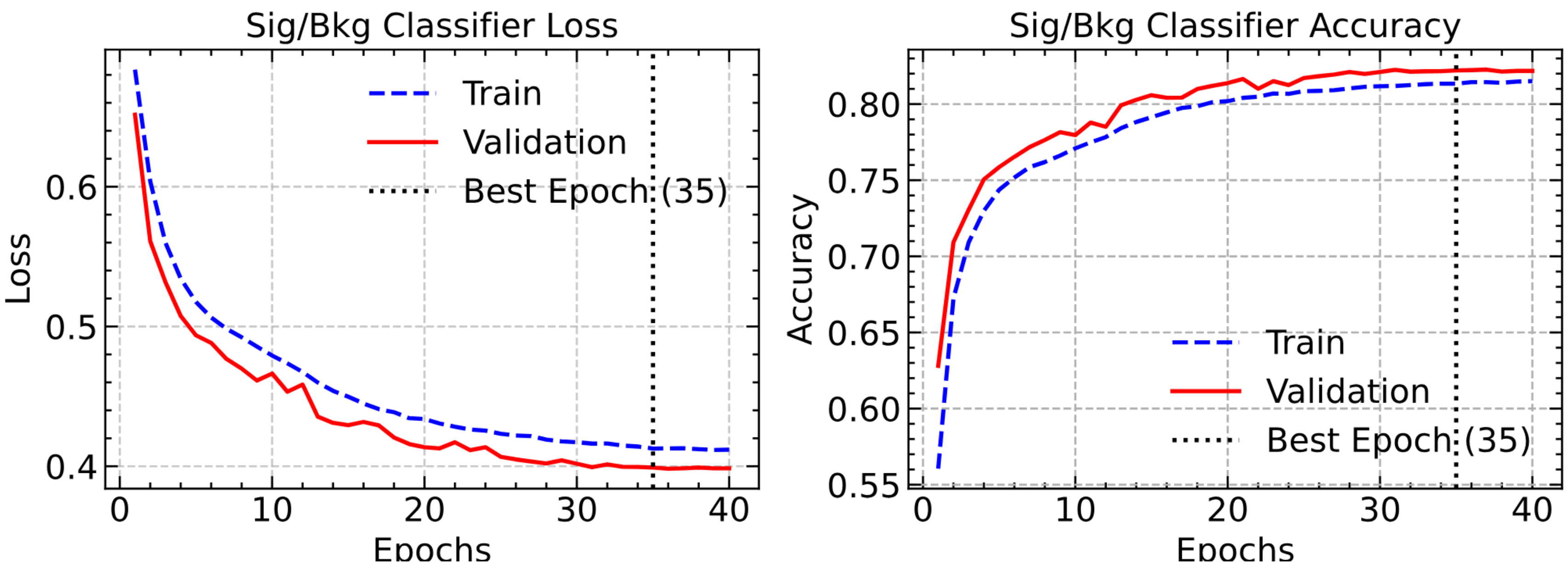


Model training and validation

Training sample (Si, P, S event selection):

- **MC-Signal: 175k Si, P, S MC**
- **MC-Background: 175k Si, P, S, Cl MC (to be tuned for optimization)**
- **Data: 100K Si, 150K P, 100K S events**

87.5k MC events with the same species combination for validation

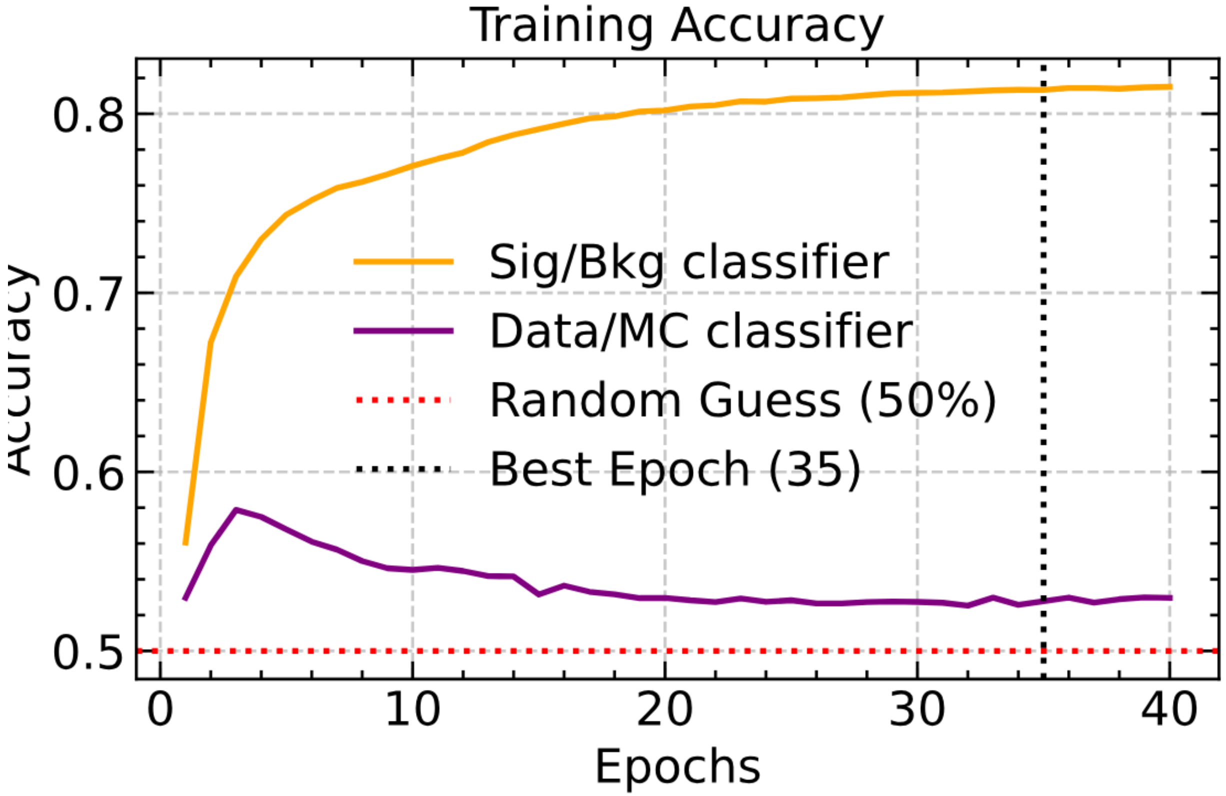


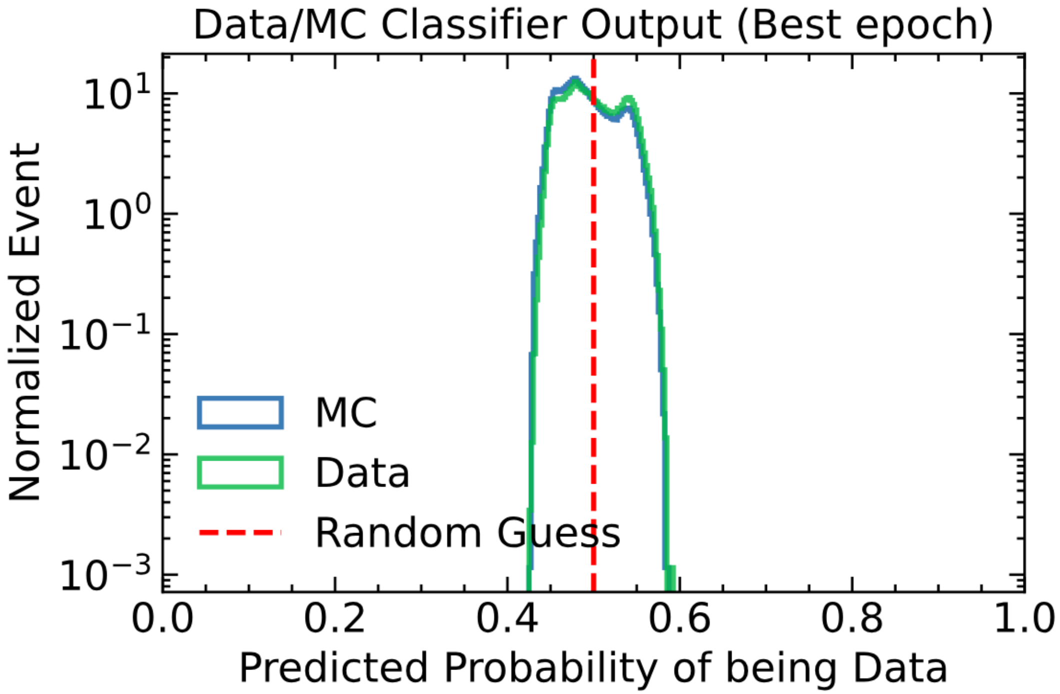
To do: Model tuning for optimization

Model training and validation: MC/Data classifier

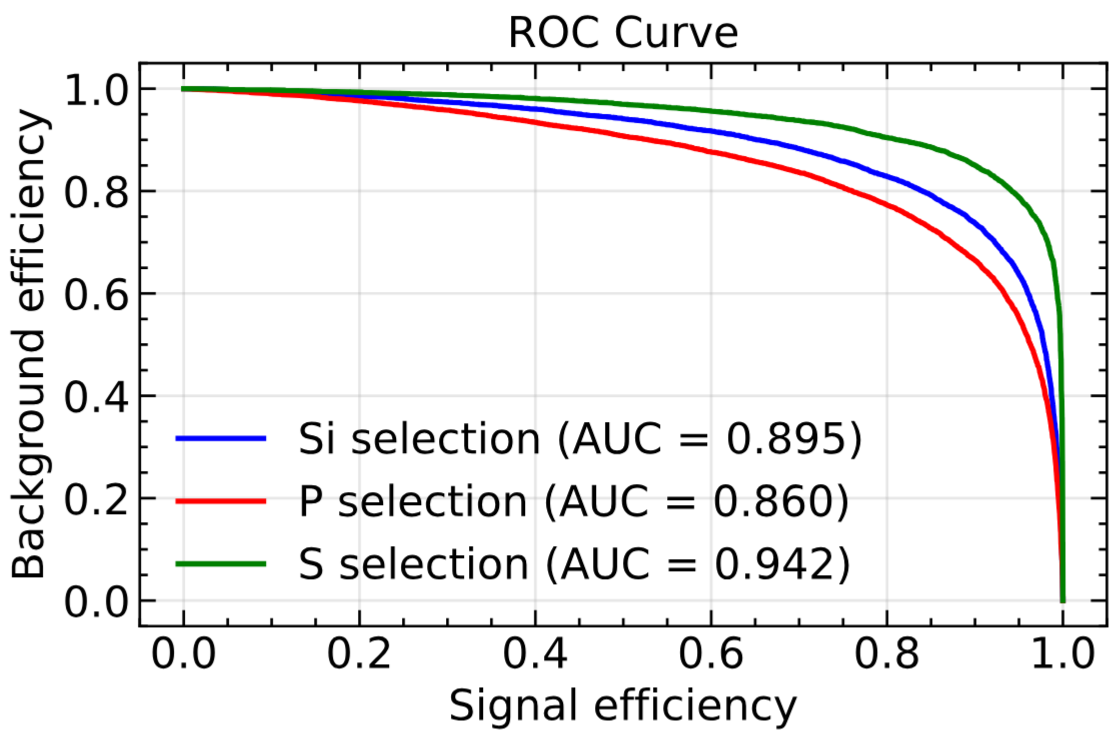
MC and Data used in Training:

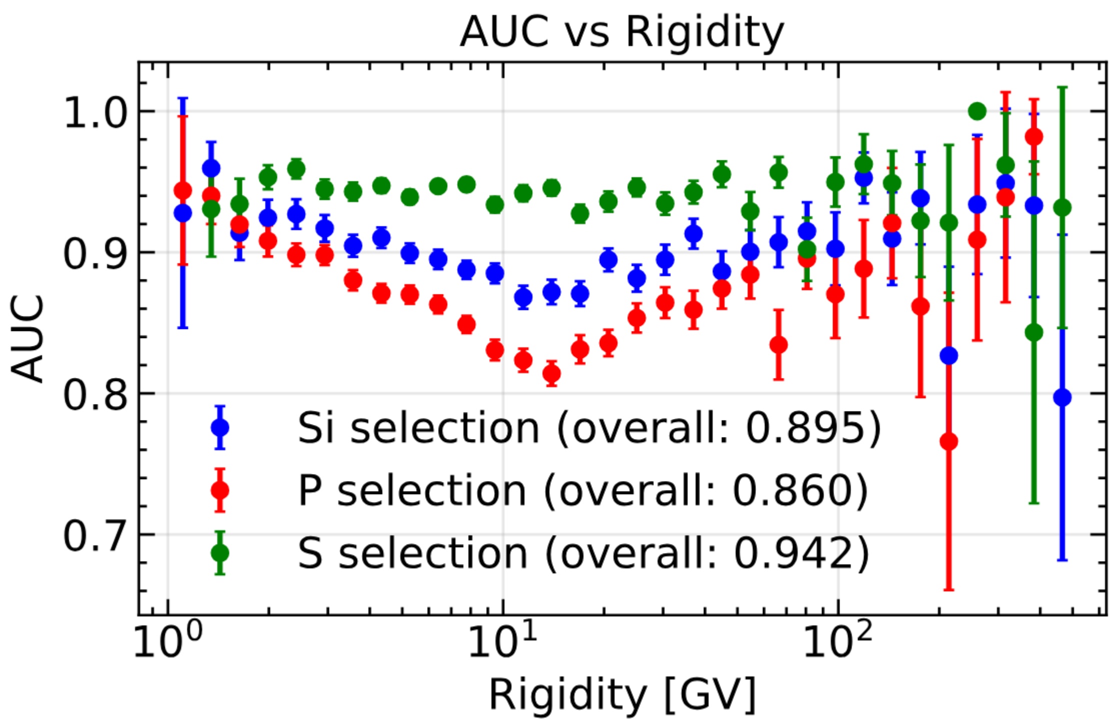
- **MC/Data classifier** to learn features that are similar between MC and Data, ensuring model to perform well on both MC and data.
- **Signal/background classifier** to optimize classification performance.



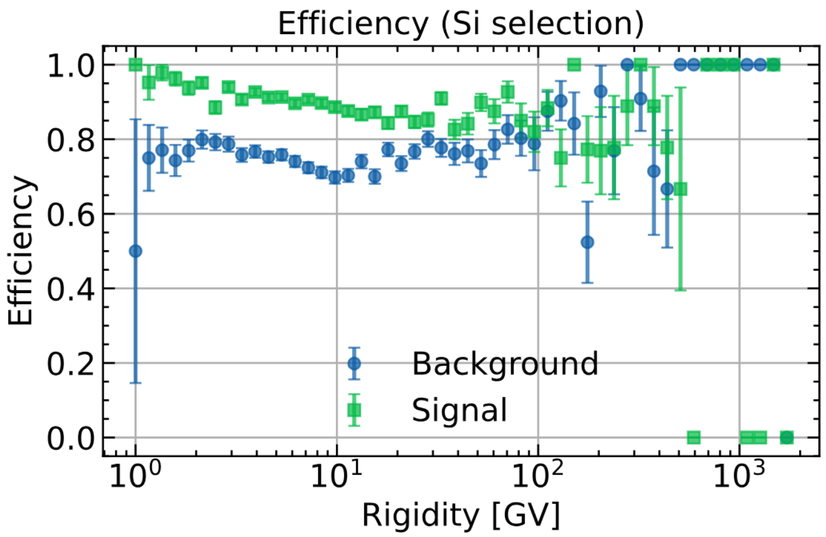


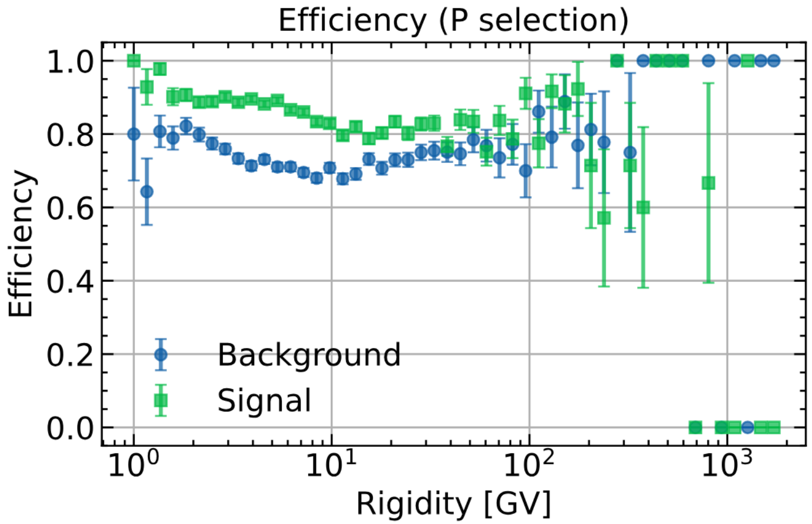
Validation

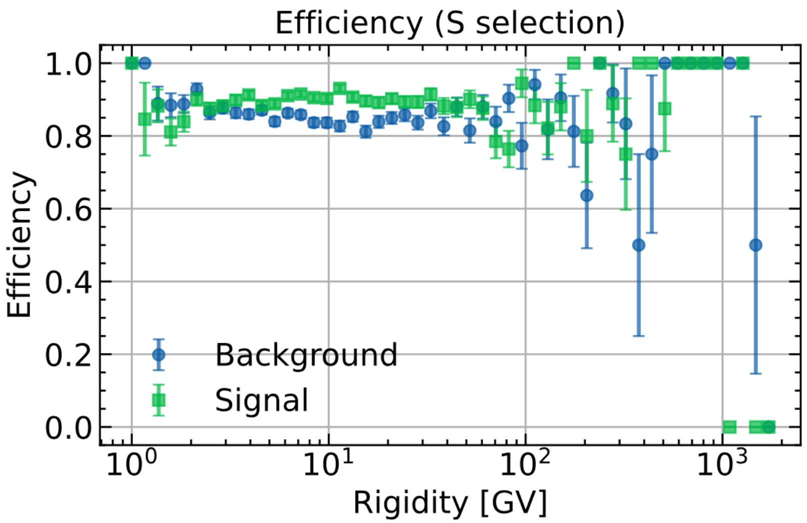

ROC Curve
Background efficiency
Signal efficiency
0.0
0.2
0.4
0.6
0.8
1.0
Si selection (AUC = 0.895)
P selection (AUC = 0.860)
S selection (AUC = 0.942)

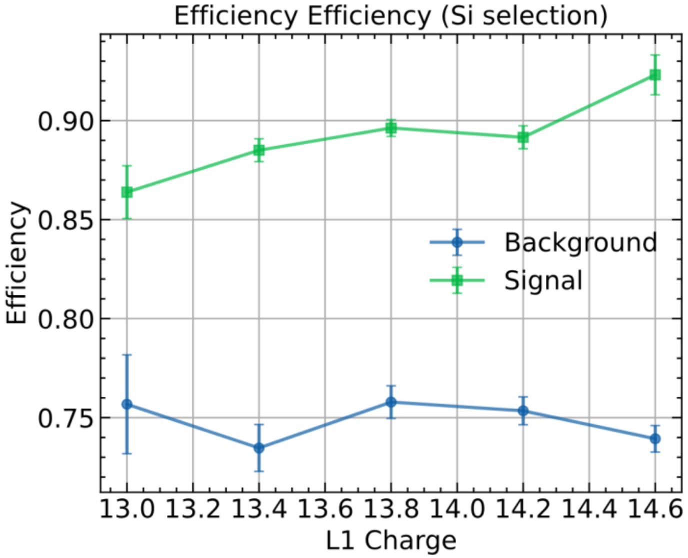

AUC vs Rigidity
AUC
Rigidity [GV]
0.7
0.8
0.9
1.0
10^0
10^1
10^2
Si selection (overall: 0.895)
P selection (overall: 0.860)
S selection (overall: 0.942)

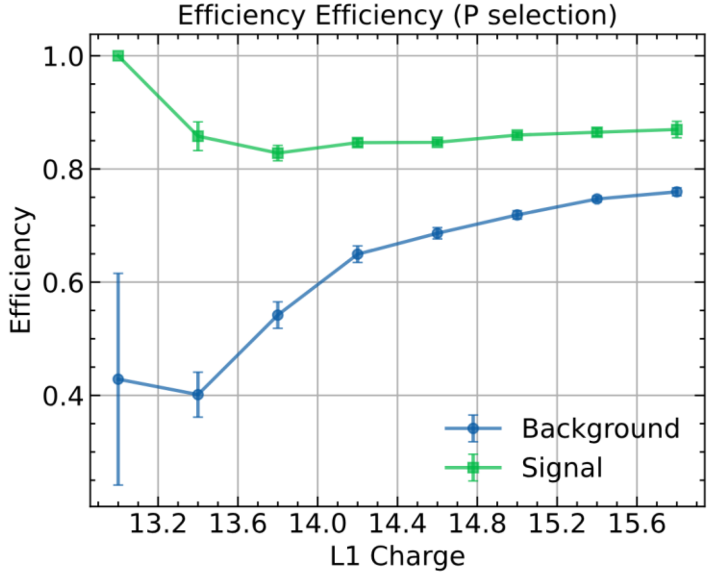
Validation results: efficiency (threshold =0.5)

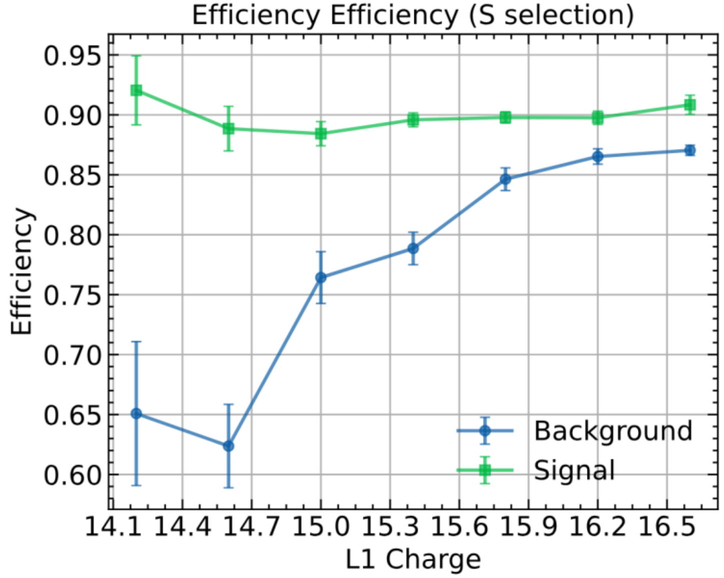










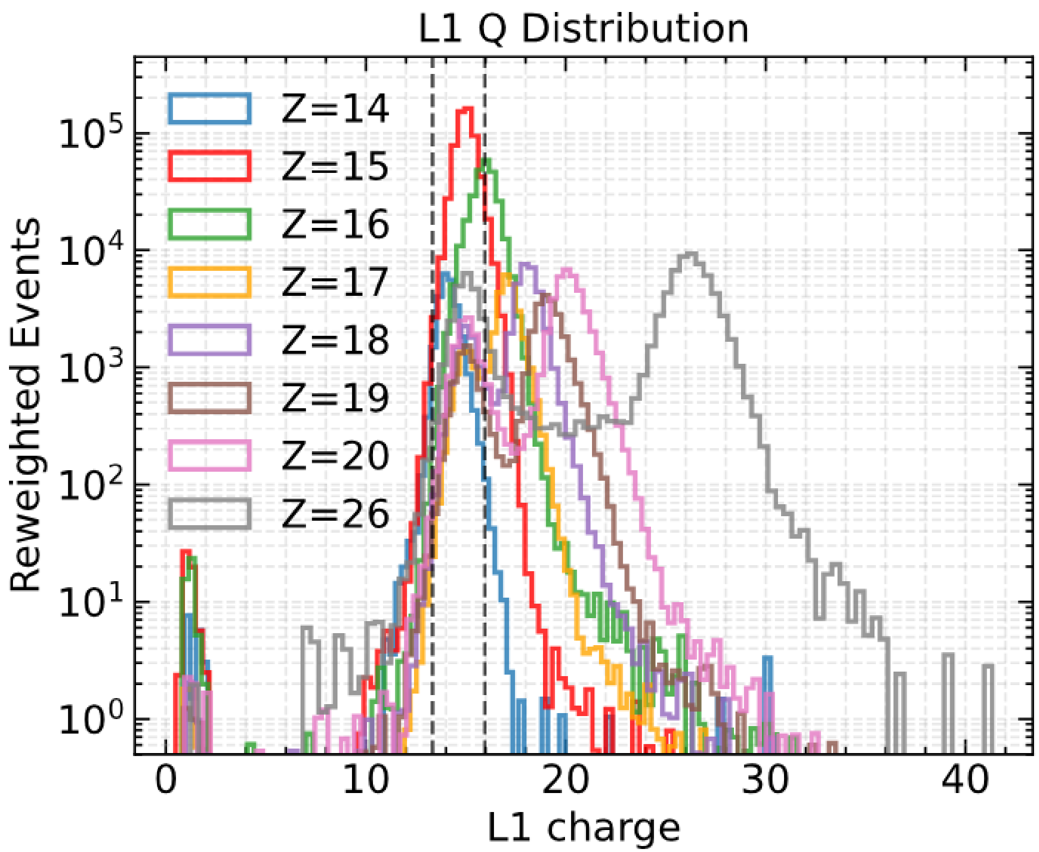


Model generalization: validation with global MC

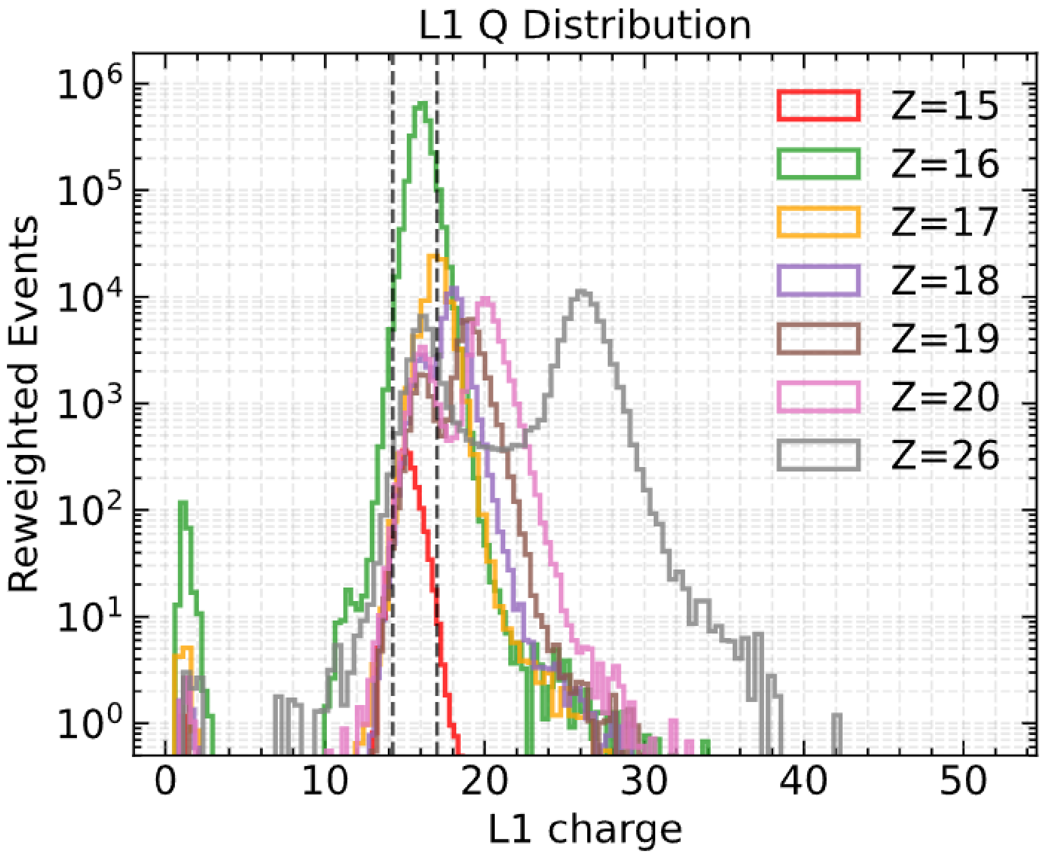
Sample for performance validation:

reweighted Si, P, S, Cl, Ar, K, Ca and Fe MC samples

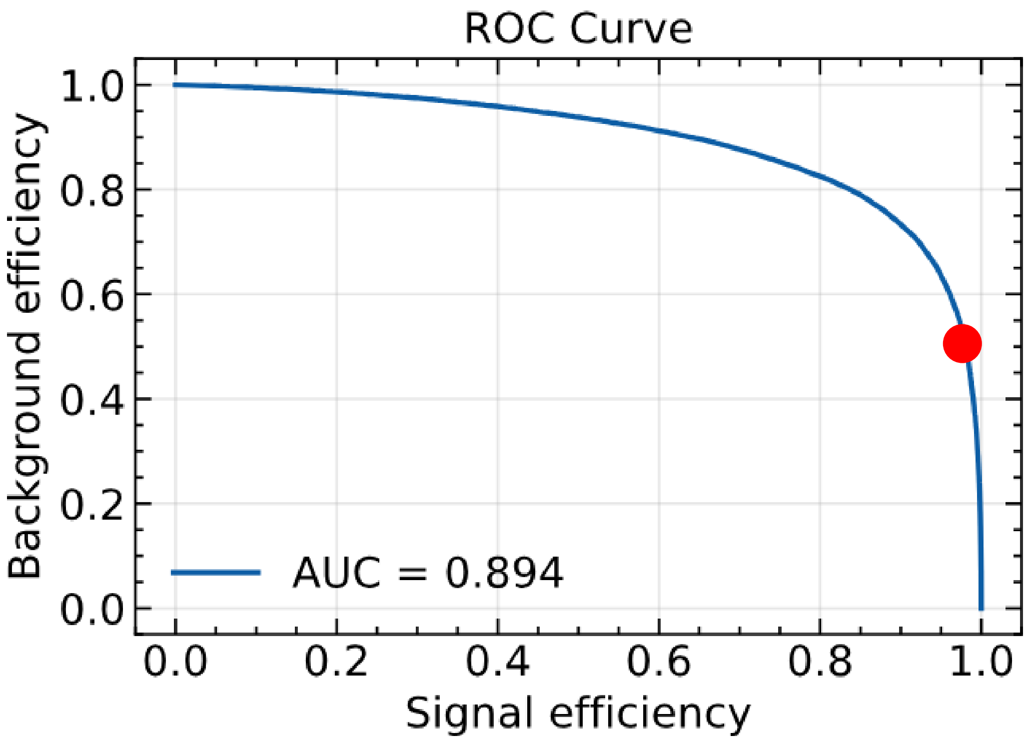
Global MC : P event selection without L1 Charge cut



Global MC : S event selection without L1 Charge cut

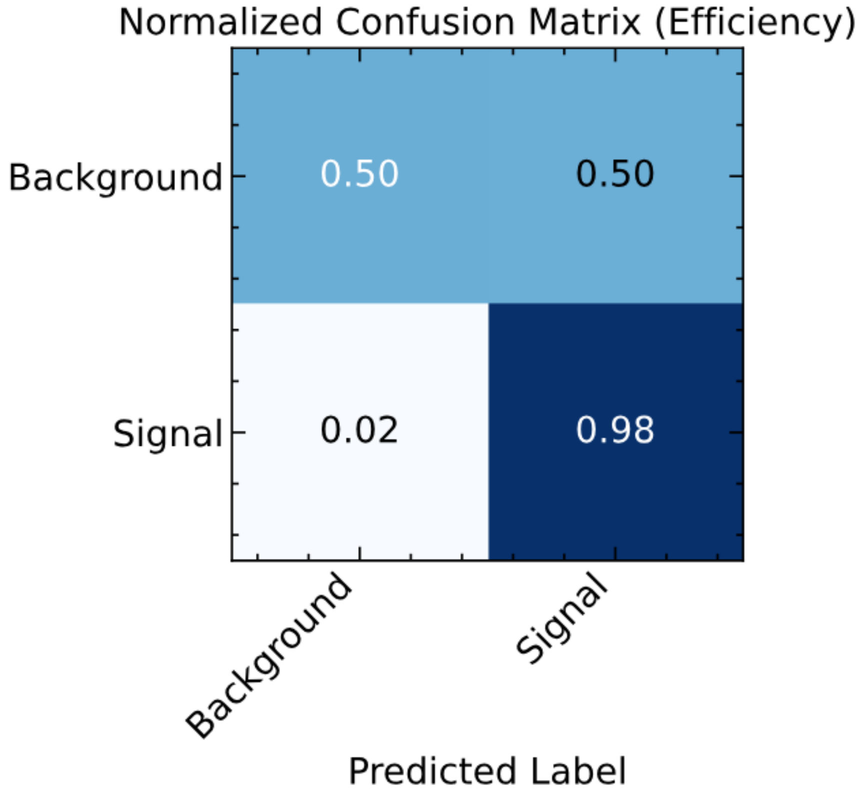


Model generalization: test with global MC



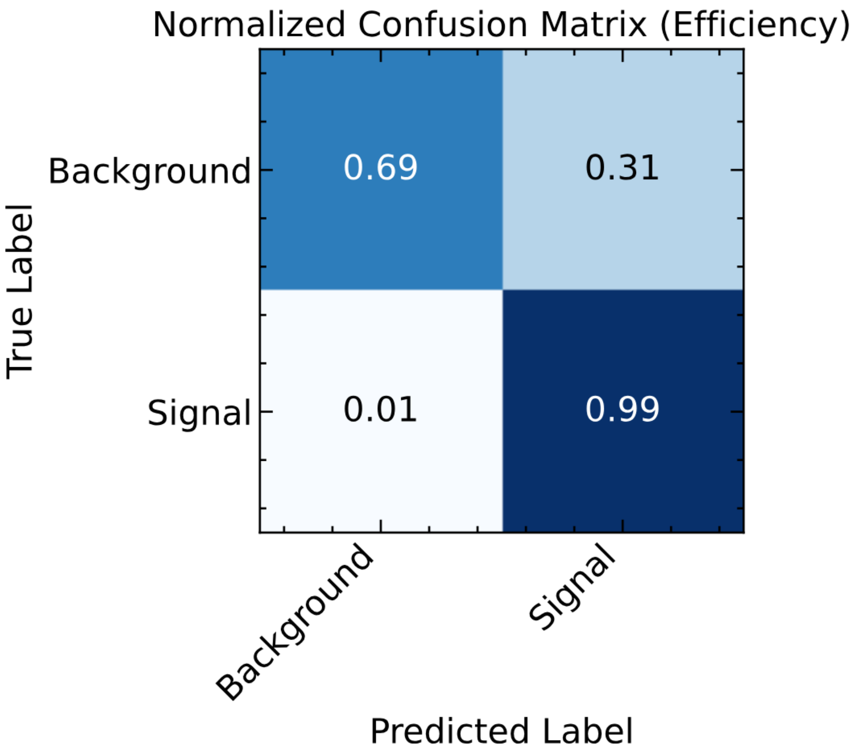
(Manually chosen)

Efficiency for events in **P** Global MC

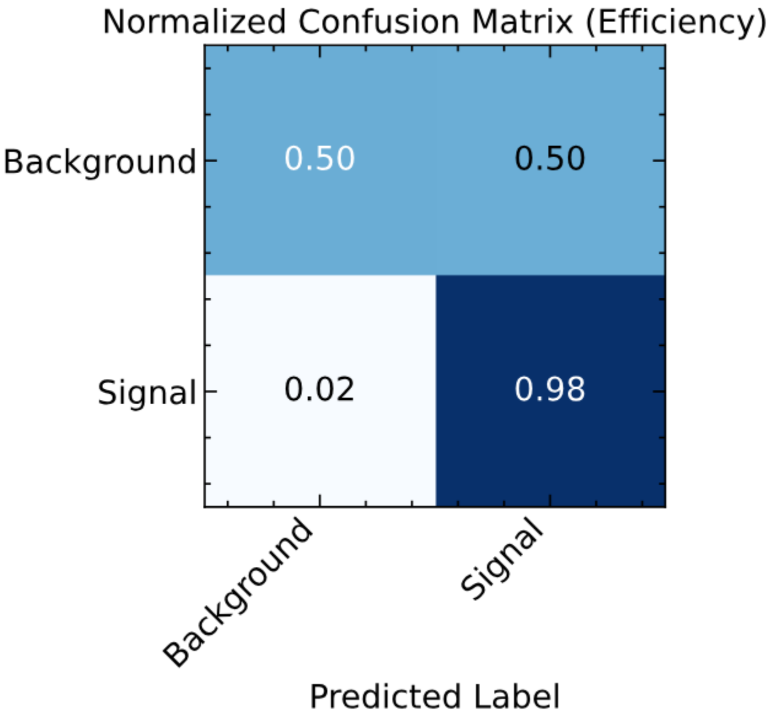


Model generalization: test with global MC

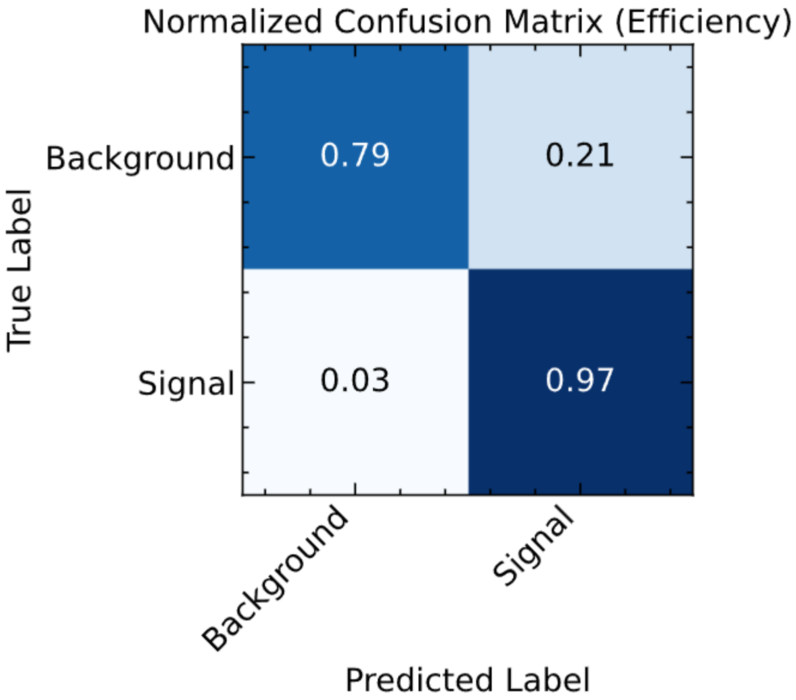
Si Global MC



P Global MC

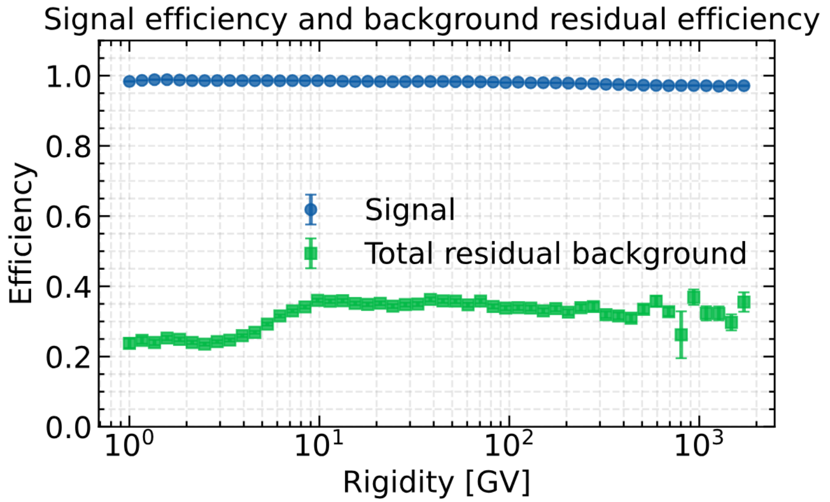


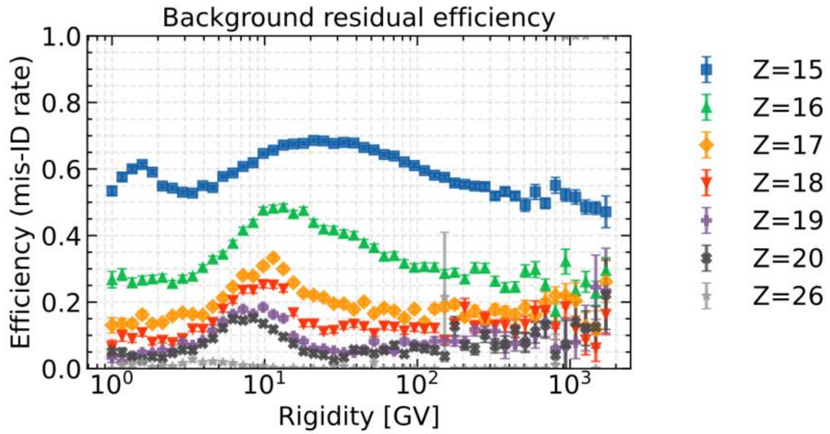
S Global MC



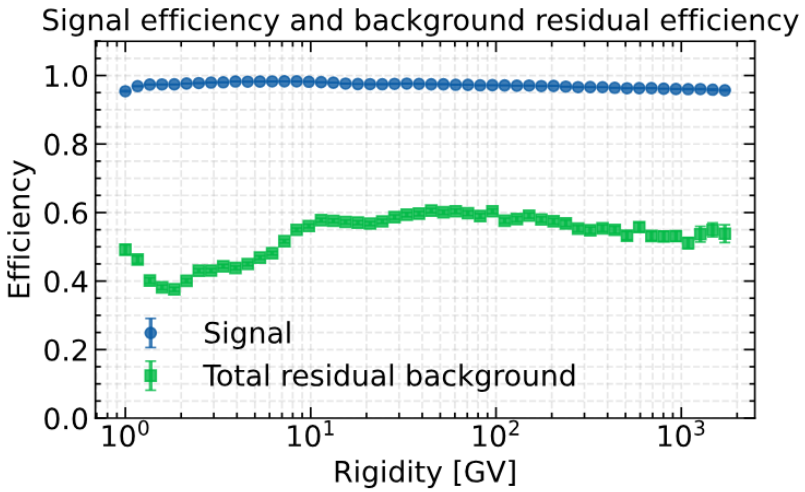
Test with global MC: Efficiency (for events passed event selection in L1 cut range)

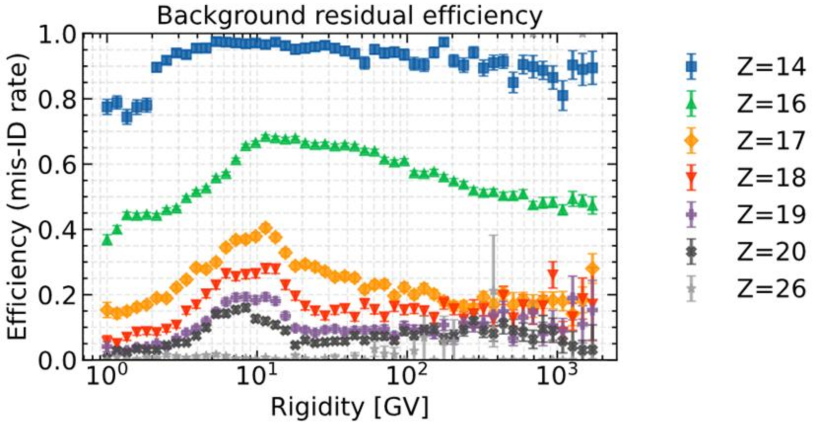
Si global MC



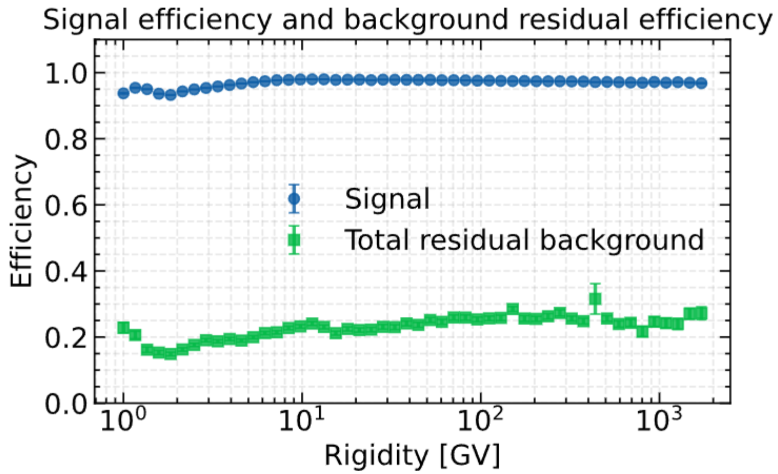


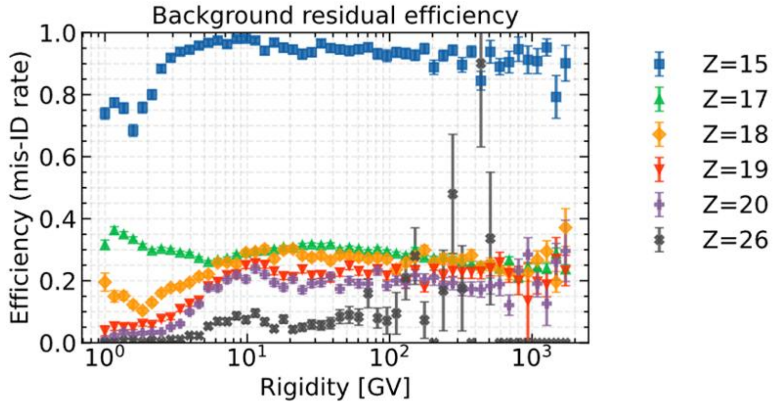
P global MC





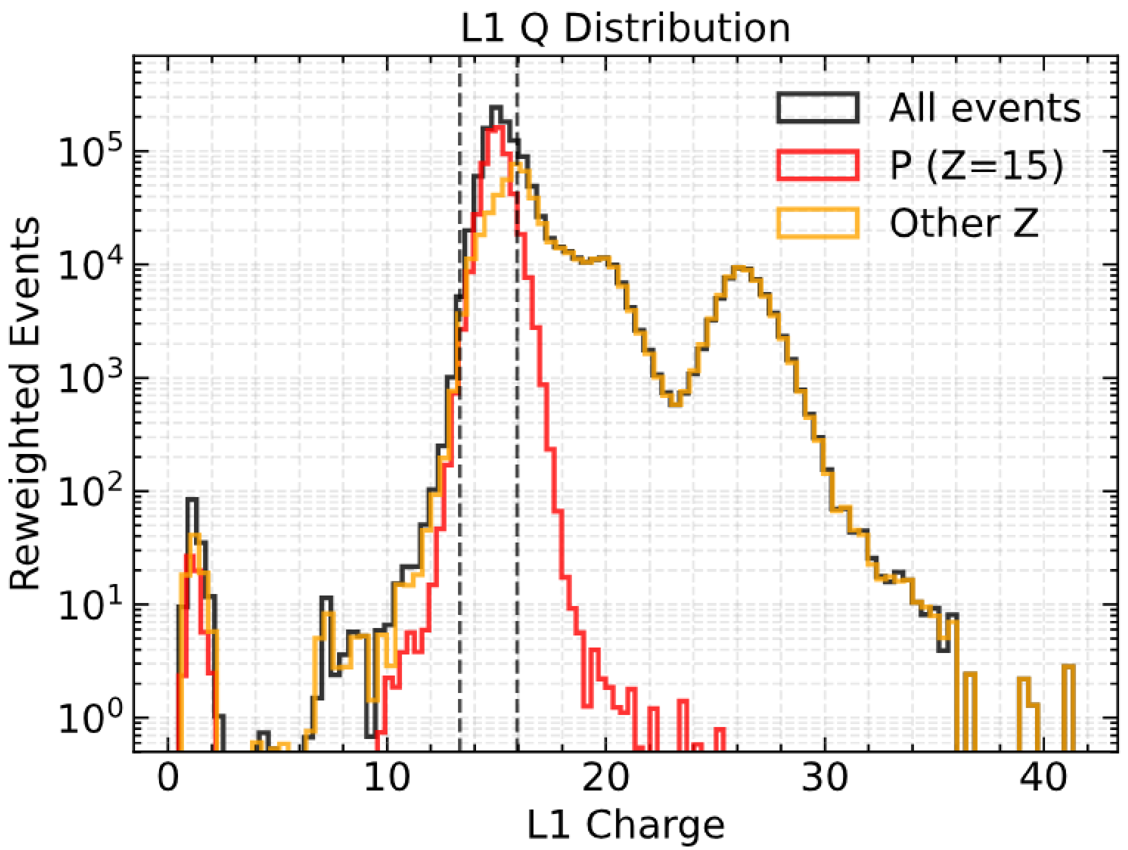
S global MC



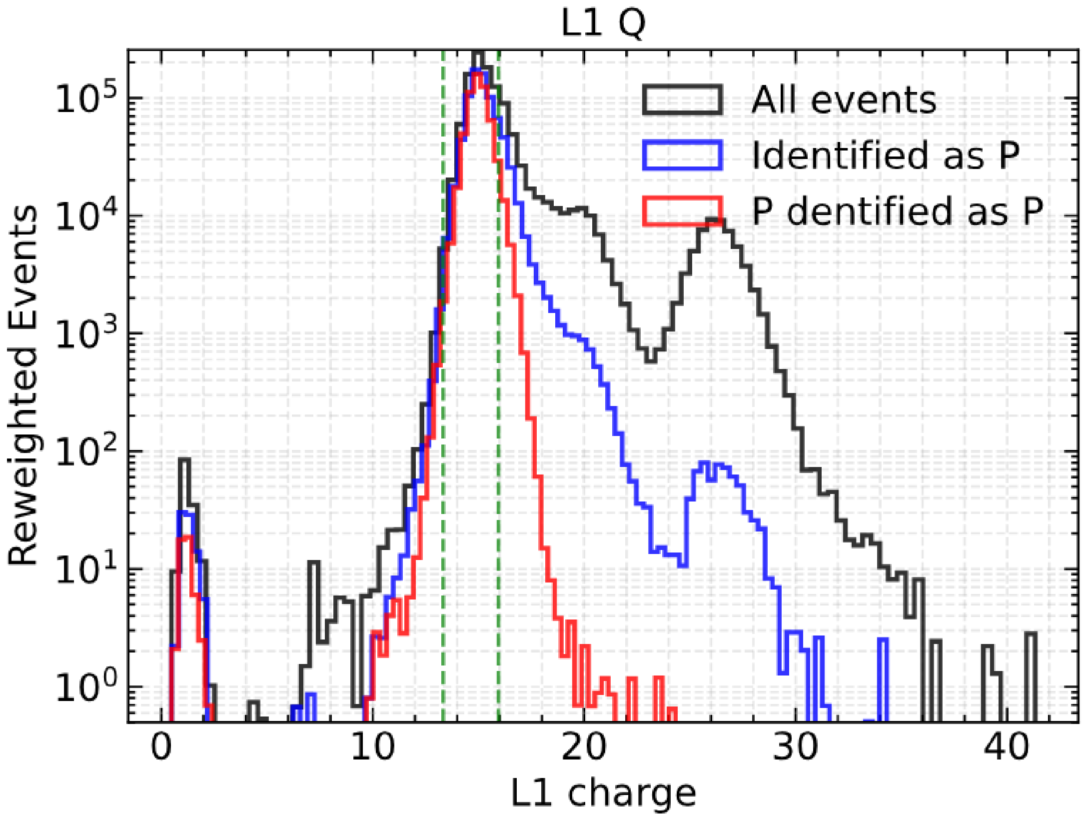


Motivation of adding ML cut in addition to event selection:

P global MC L1 Q distribution (MC truth)



P global MC L1 Q distribution: Before and after ML identification



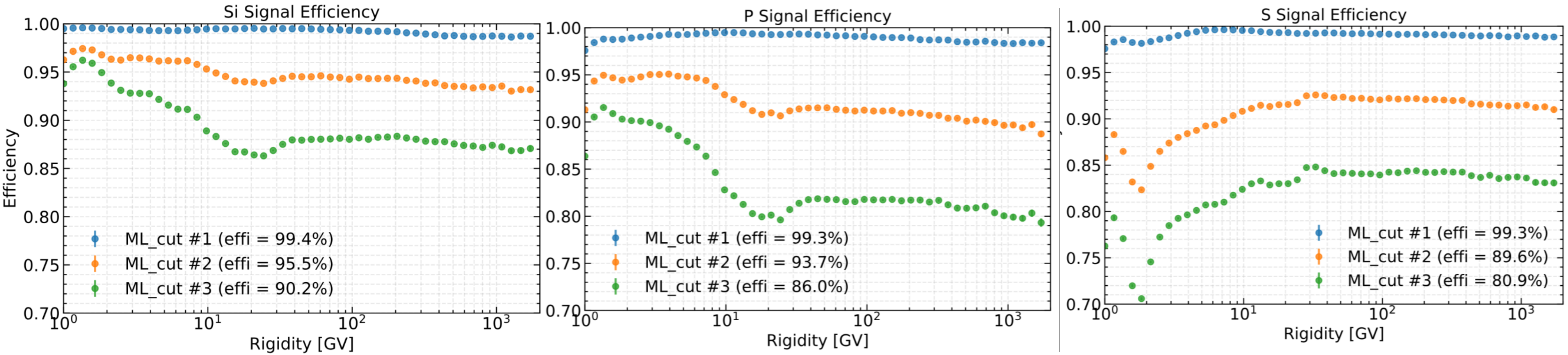
- With 'standard' P event selection, the events shown in **black curve** are selected in flux analysis .
- Significant background (orange curve) existed.

Add an additional cut from ML predication:

- the sample to used in the flux analysis are the events shown in **red+blue curve.**
- Background events reduced.

Efficiency of ML cut based on Si, P, S global MC (Z=14,15,16-20, 26)

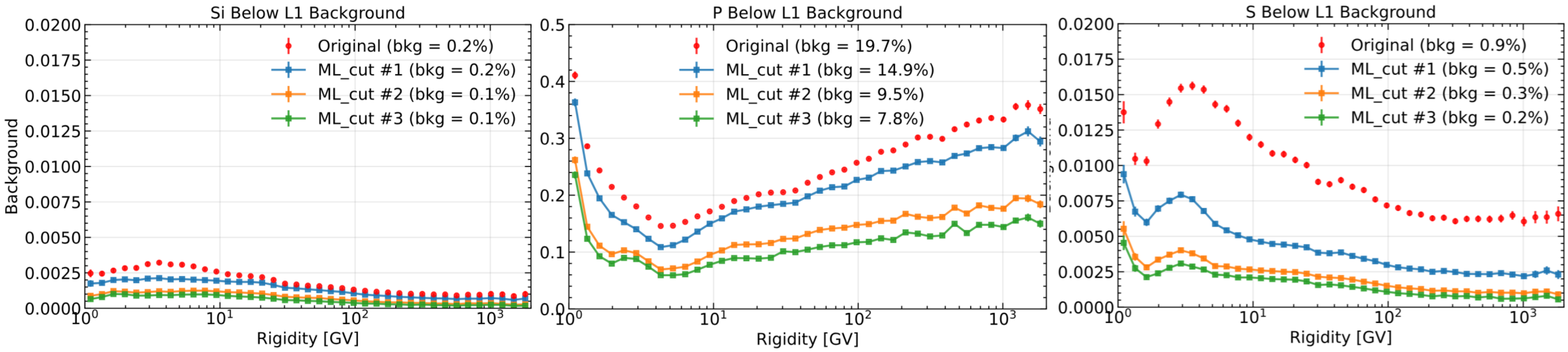
Efficiency based on 3 different choice of ML signal/background identification output threshold value:



(N.B. efficiency for data will be lower with the same threshold value)

Below L1 background before/after ML cut based on Si, P, S global MC (Z=14,15,16-20, 26)

- Based on 3 different choice of ML signal/background identification output threshold value:
- Event selection for global MC samples:
  - Si, S, P (Z=14,15,16) event selection
  - **For element>Z: Select events survived on L1.**
- Background calculated from MC truth.



On-going: test with Data

Summary

A MDA Network has been developed for Si, P, S Signal-Background identification:

- The identification power is achieved with Multimodal network using Tracker and TOF reconstructed information
- The generalization power is achieved by adding Domain-Adversarial network to learn features that are similar between MC and Data, ensuring consistent performance across both MC and data.

On-going and to-do

- Apply to Data
- P efficiency estimation

Backups

Samples

Si, P, and S event selection

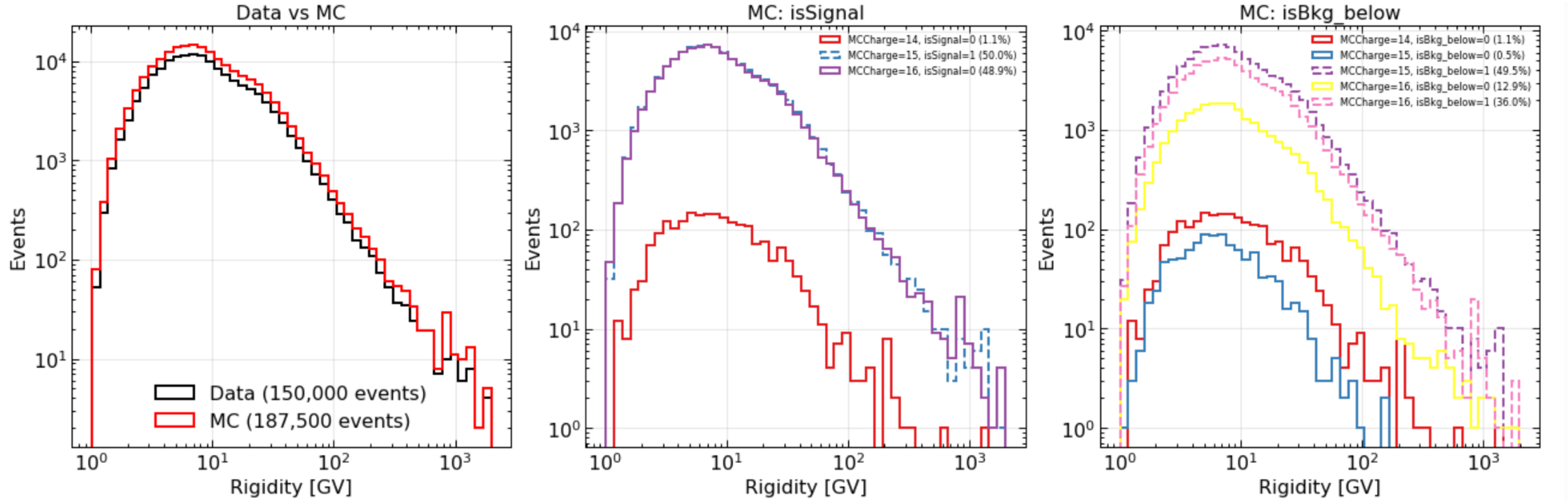
- Signal: MC Si, P, S (MC truth)
- Background: MC Si and S (for Si), Si and S (for P), P and Cl (for S)
- Data

Definition:

- Signal/Background: MC truth
- Fragmented_belowL1: true only if primary survived at L1 (need to rename)
  1. MC truth: TrackMCHits on L1 Charge == Primary Z
  2. MC truth: Primary particle Position is in L1 fiducial volume

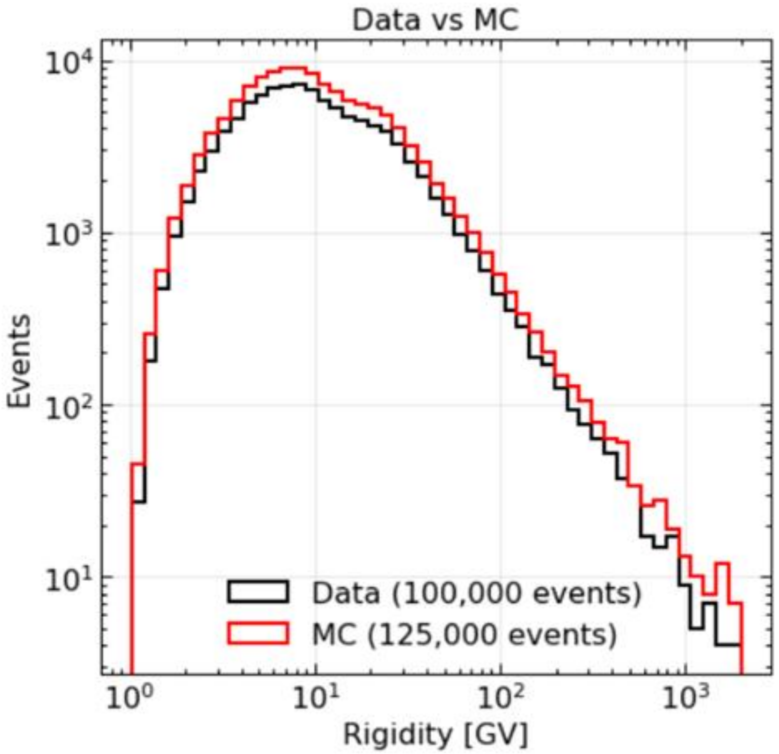
Samples (P event selection):

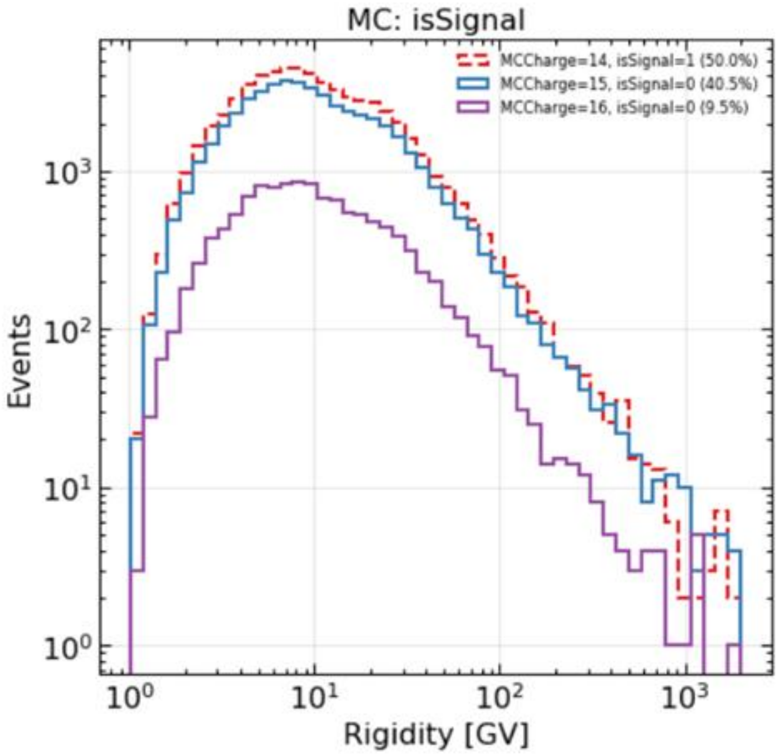
- Data: 150k
- MC: 187.5k (150k(80%) for training, 20% for testing)
    - Signal: 50%
    - Background-Si: 1.1%
        - AboveL1: 100%
    - Background-S: 48.9%
        - Above: 24.2% of S

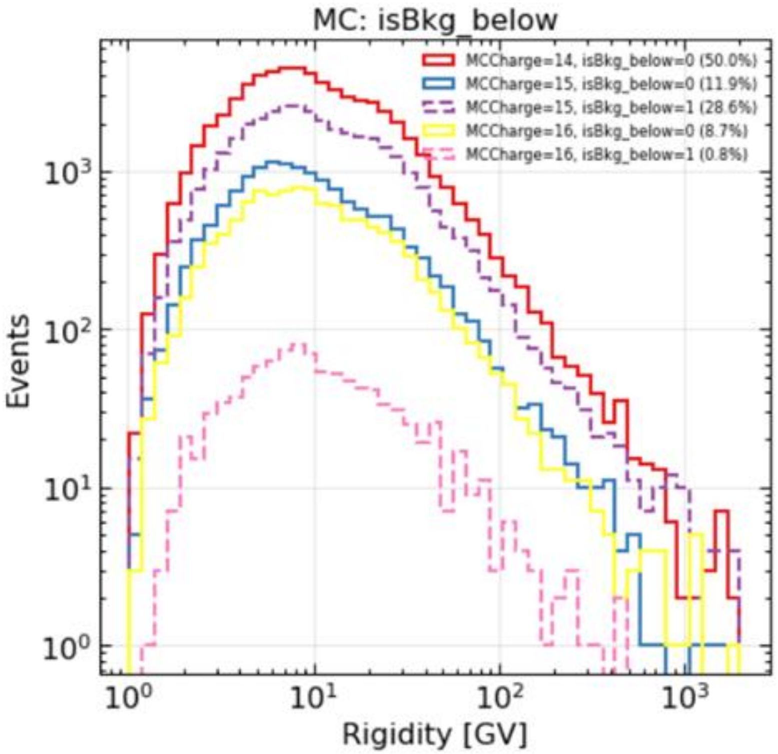


Samples (Si event selection):

- Data: 100k
- MC: 125k (100k for training)
  - Signal: 50%
  - Background-P: 40.5%
    - AboveL1: 26.9% of P
  - Background-S: 9.5%
    - Above: 91.6% of S

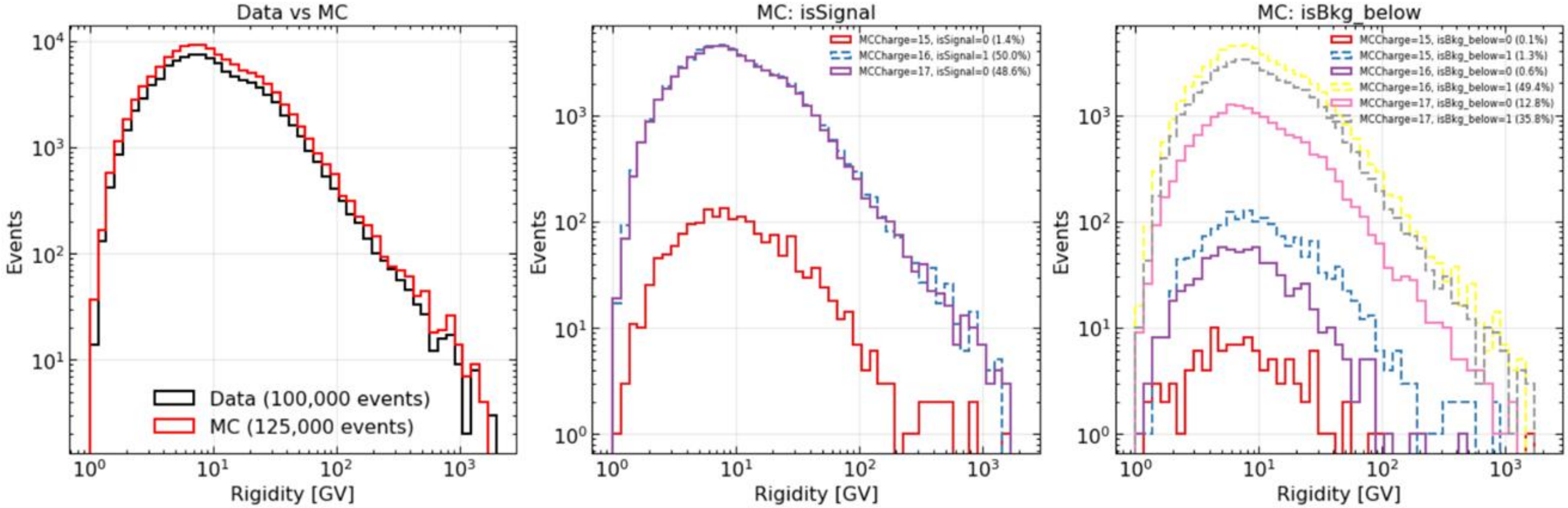






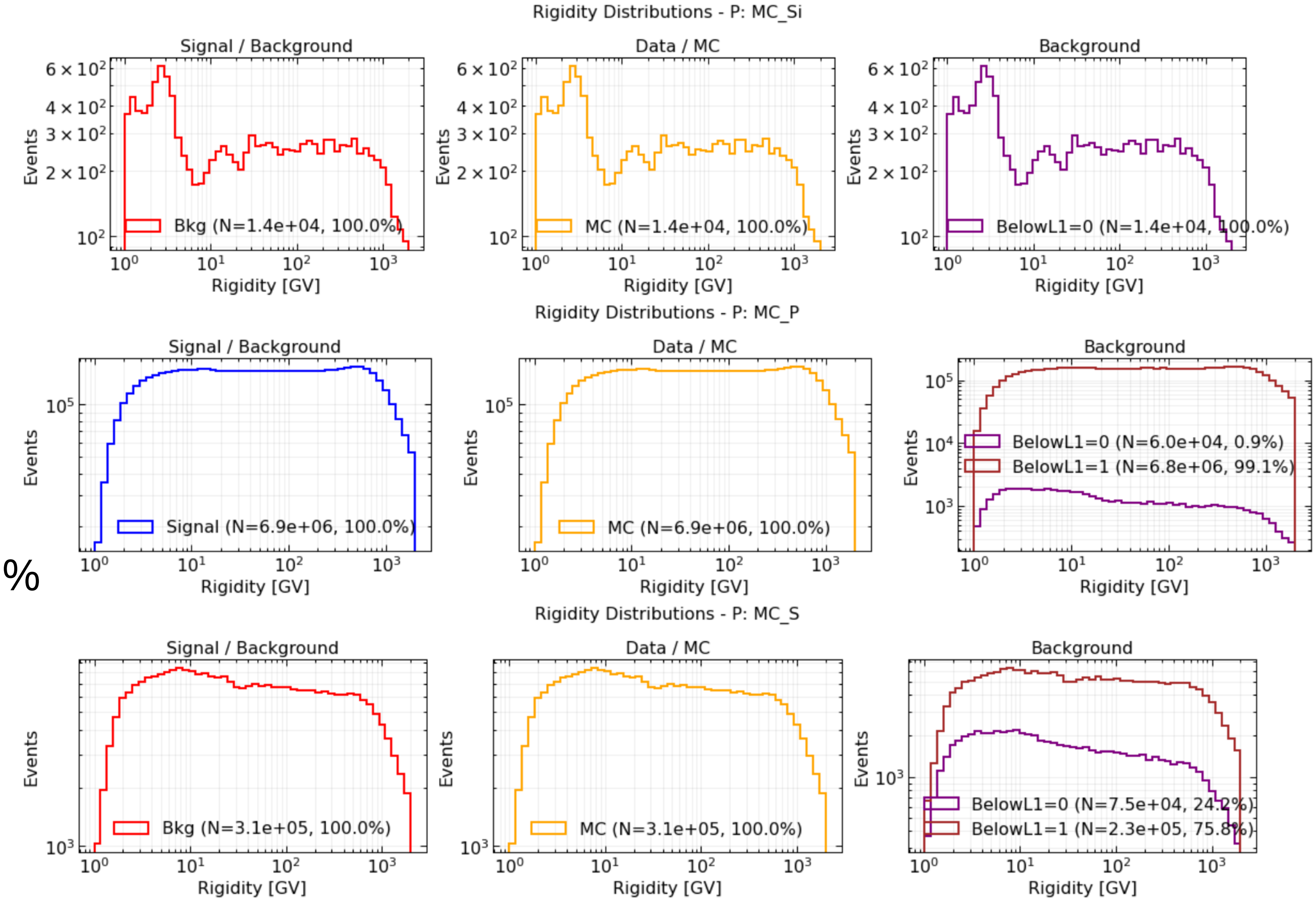
Samples (S event selection):

- Data: 100k
- MC: 125k (100k for training)
  - Signal: 50%
  - Background-P: 1.36%
    - AboveL1: 6.7% of P
  - Background-Cl: 48.64%
    - Above: 24.6% of Cl



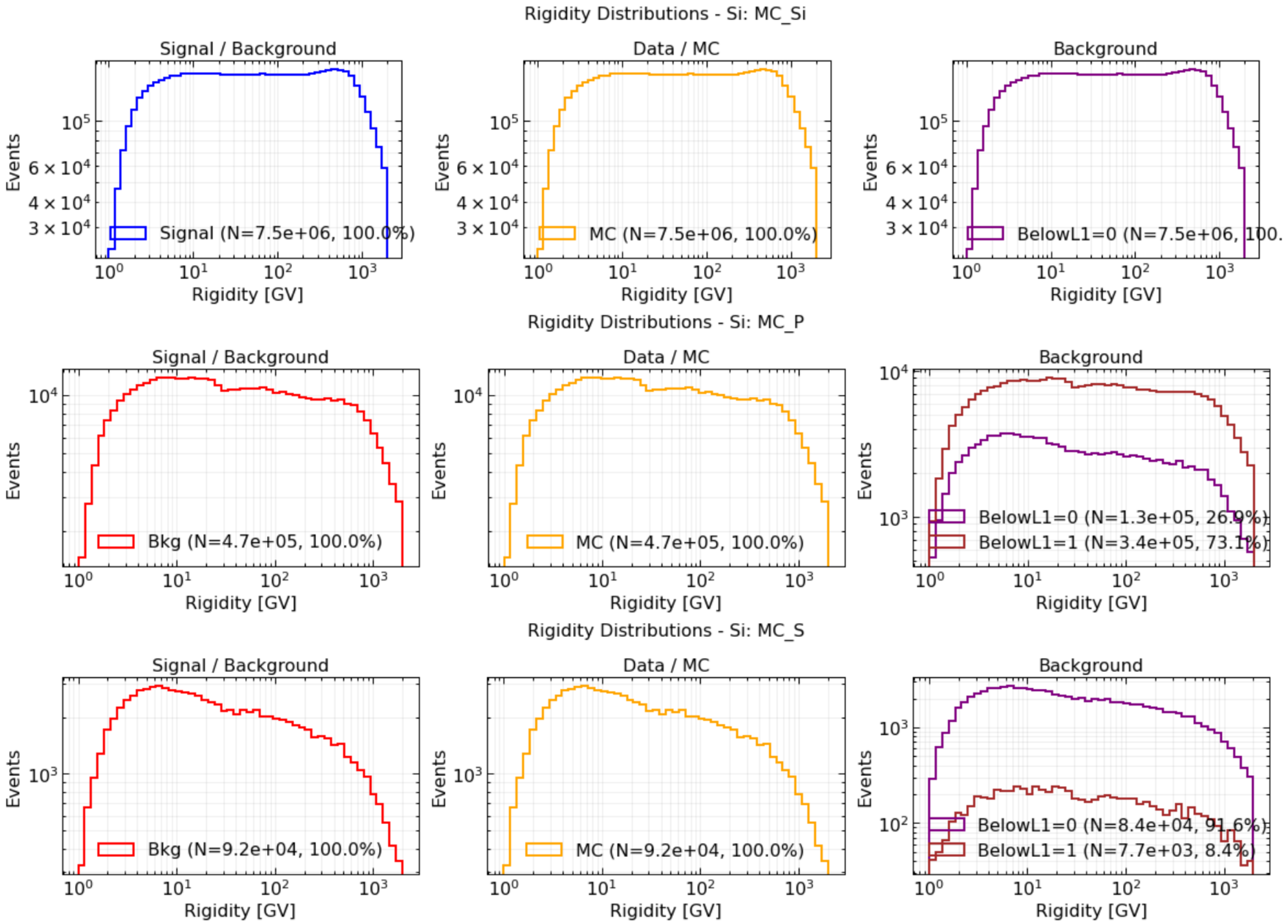
P

- Data: 150k
- MC: **187.5k**
    - Signal: 93.75k
    - Background-Si
        - AboveL1: 100%
    - Background-S: 48.9%
        - Above: 24.2%



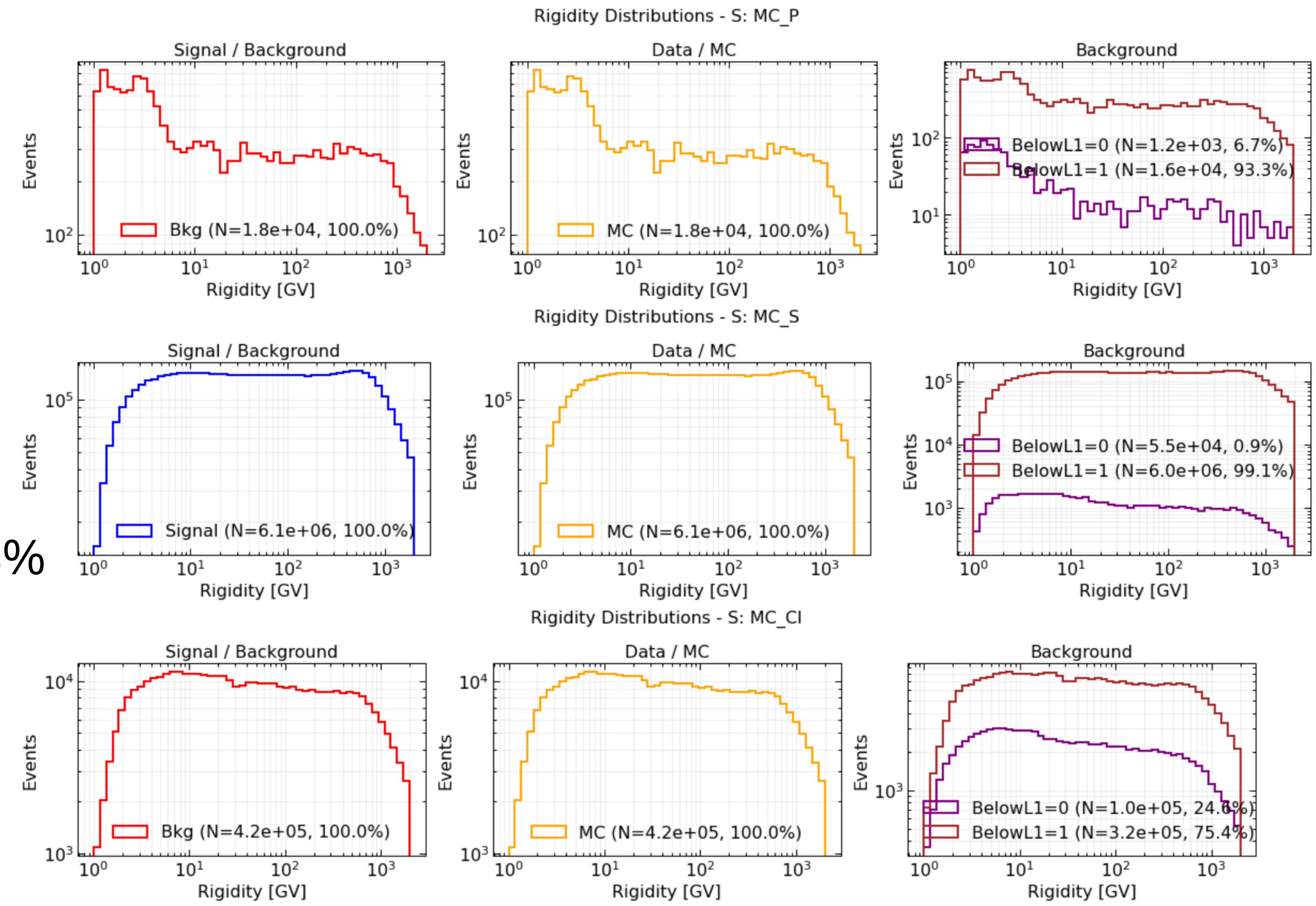
Si

- Data: 100k
- MC: **125k**
  - Signal: **62.5k**
  - Background-P: 40.5%
    - AboveL1: 26.9%
  - Background-S
    - Above: 91.6%

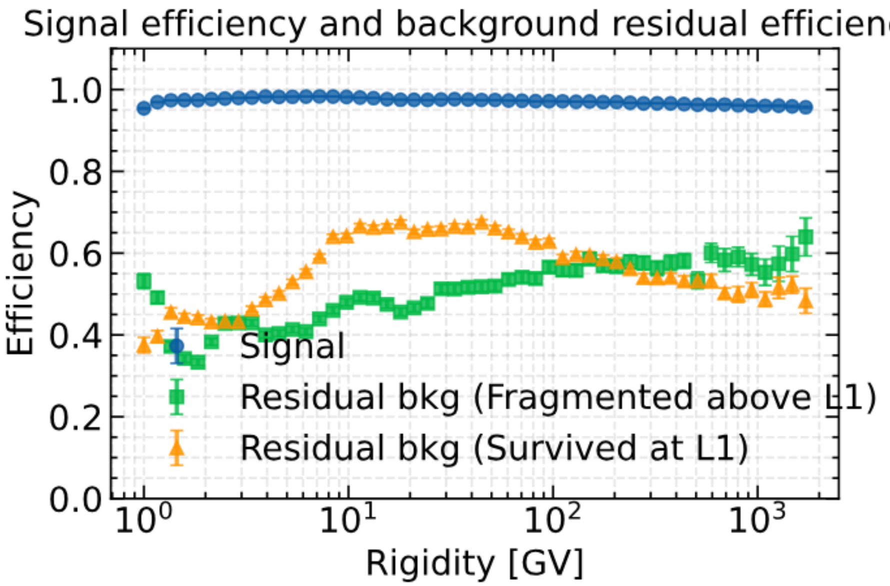


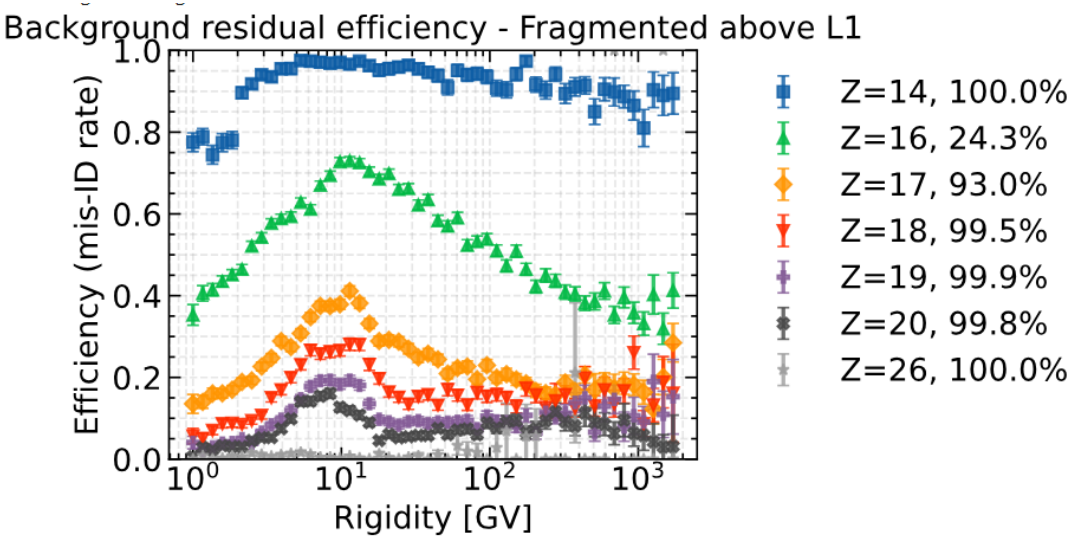
S

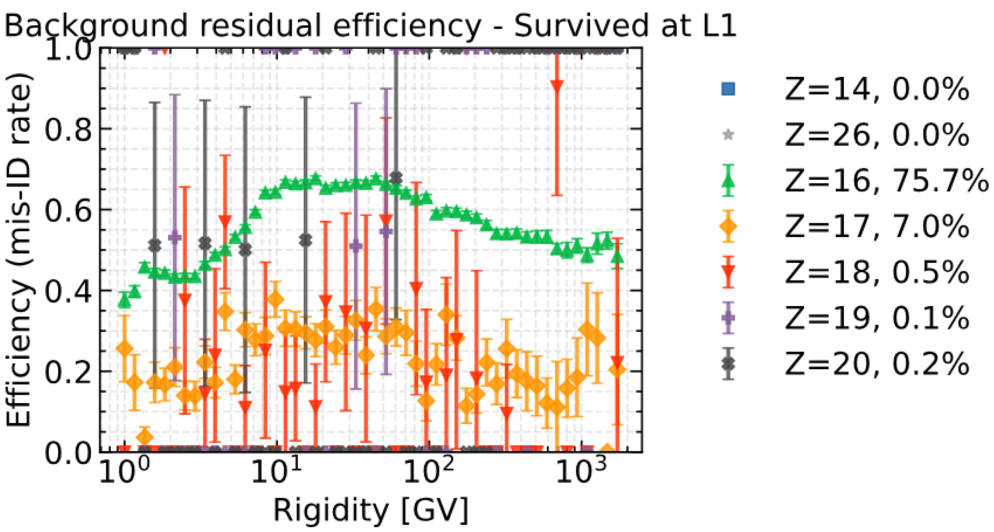
- Data: 100k
- MC: **125k**
  - Signal: **62.5k**
  - Background-P
    - AboveL1: 6.7%
  - Background-Cl: 48.64%
    - Above: 24.6%



Test with **P global MC**: Efficiency (for events passed event selection in L1 cut range)

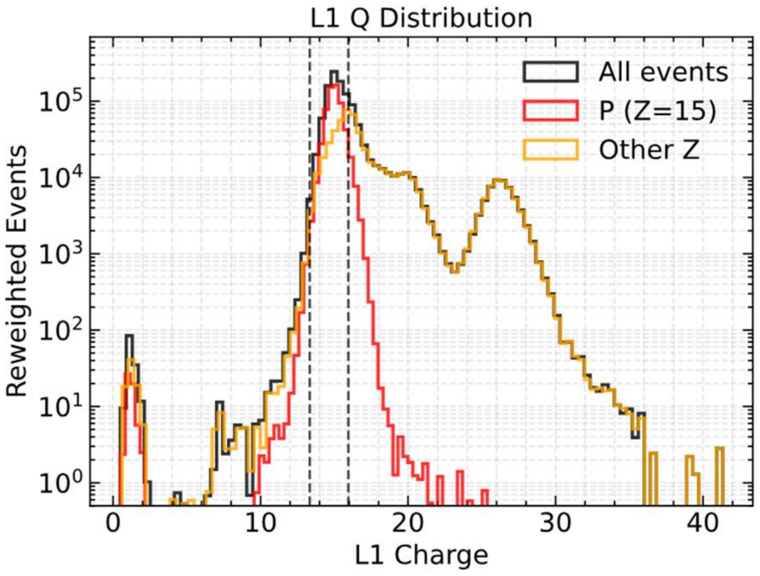


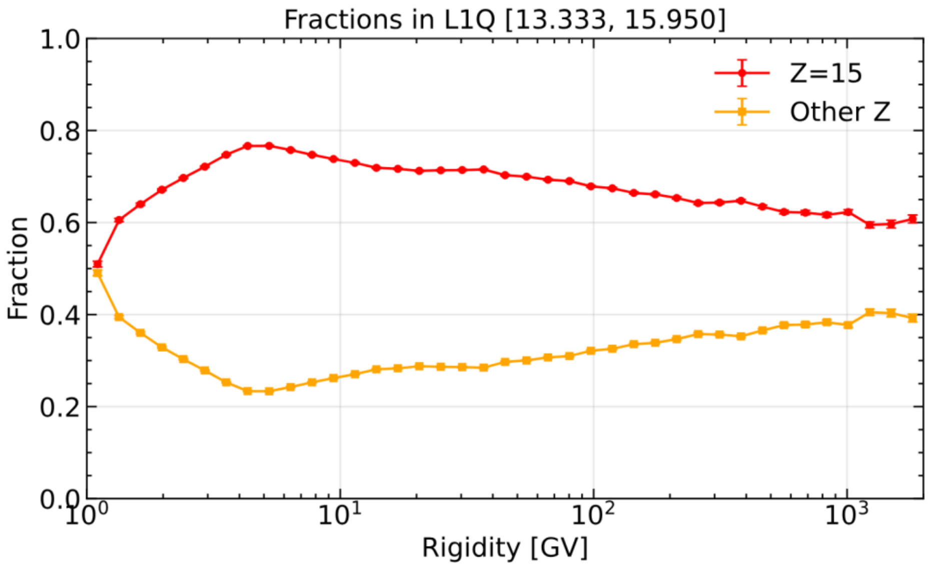




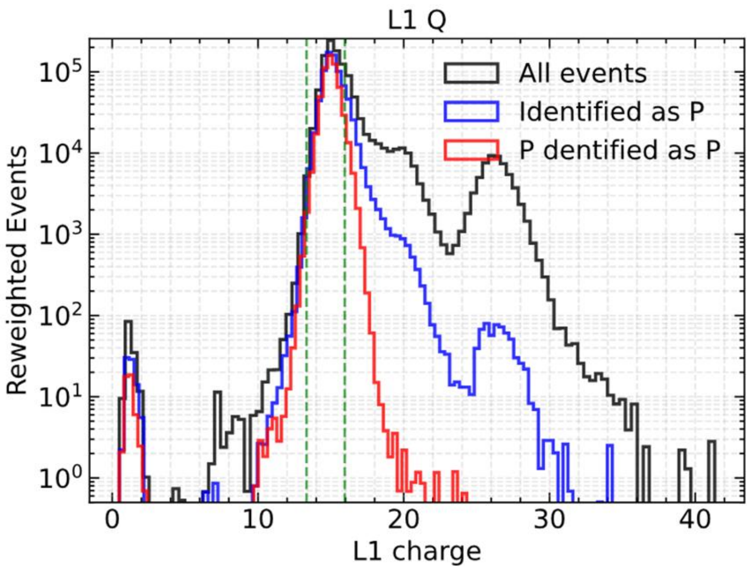
Test with P global MC: Fraction of events in L1 Q range with ML identification

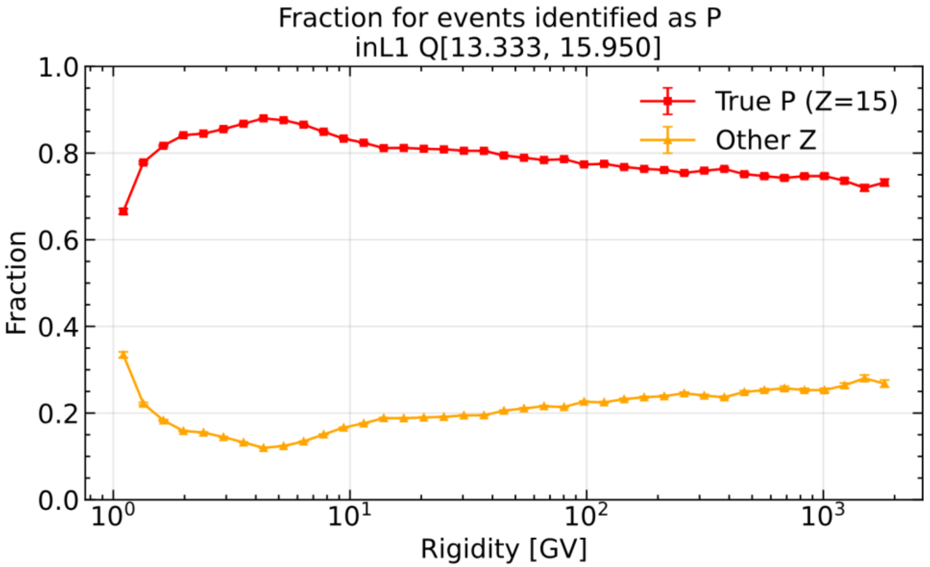
MC L1 Q distribution (MC truth)





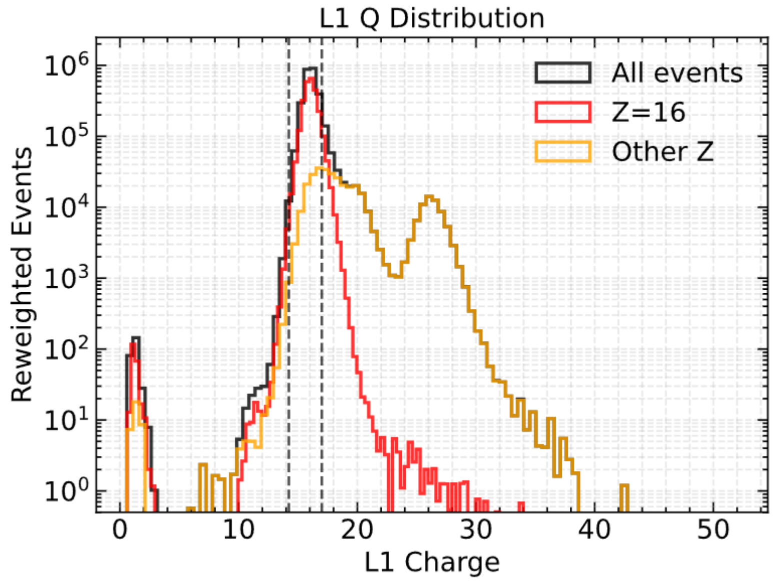
MC L1 Q distribution: **Before and after ML identification**

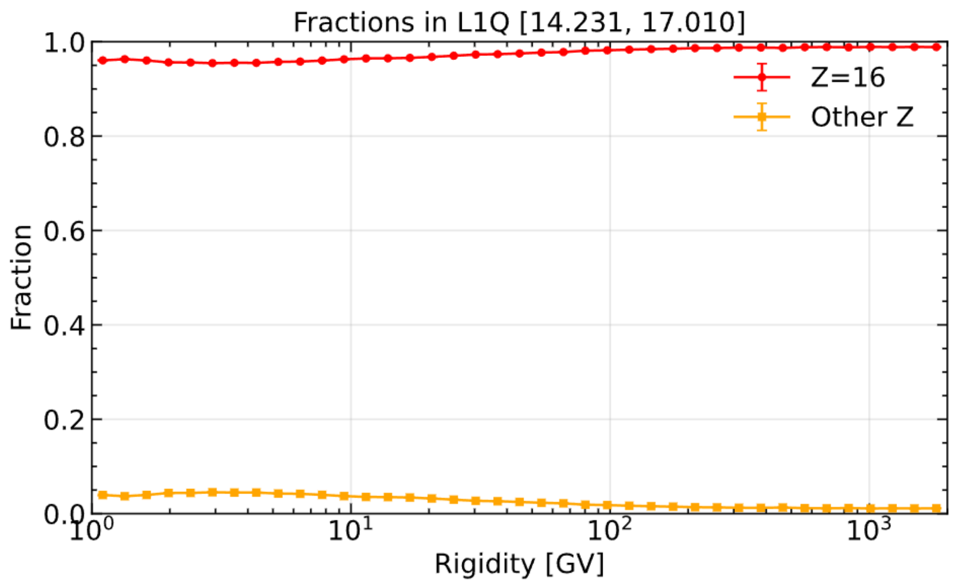




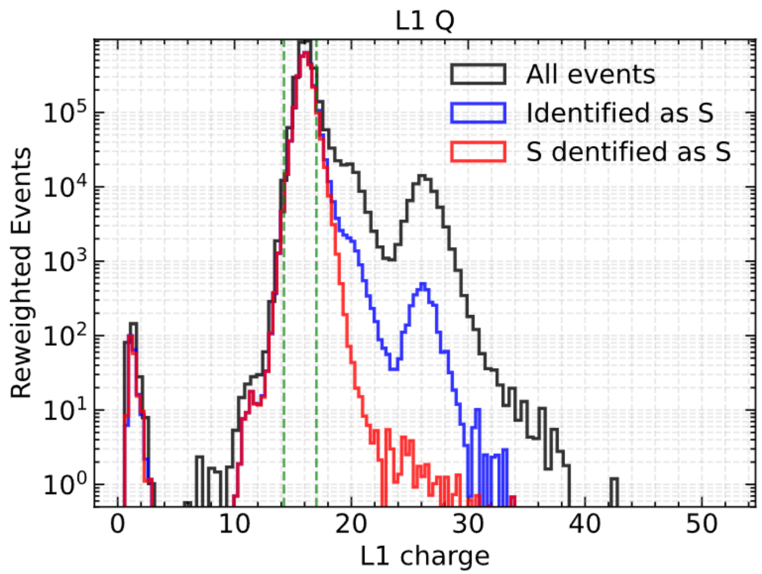
Test with S global MC: Fraction of events in L1 Q range with ML identification

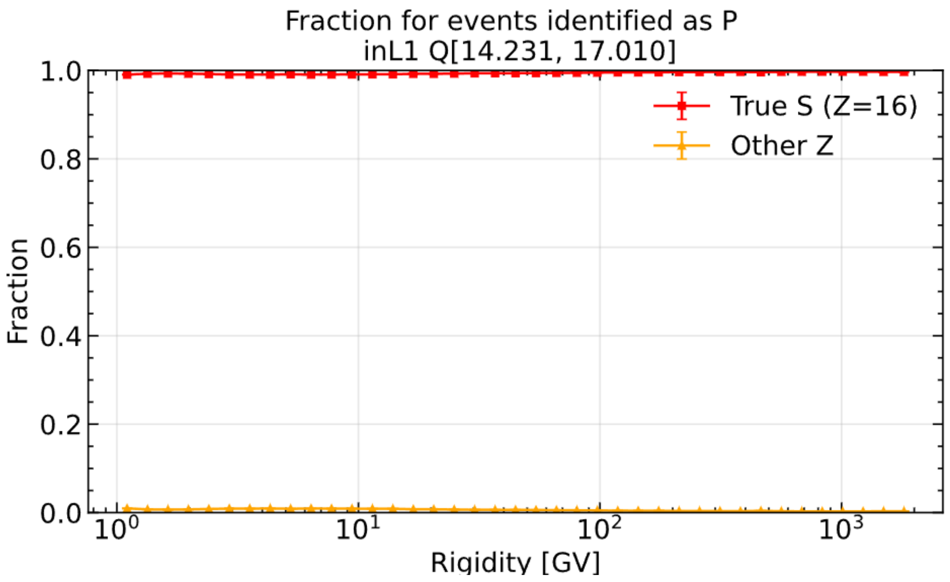
MC L1 Q distribution (MC truth)





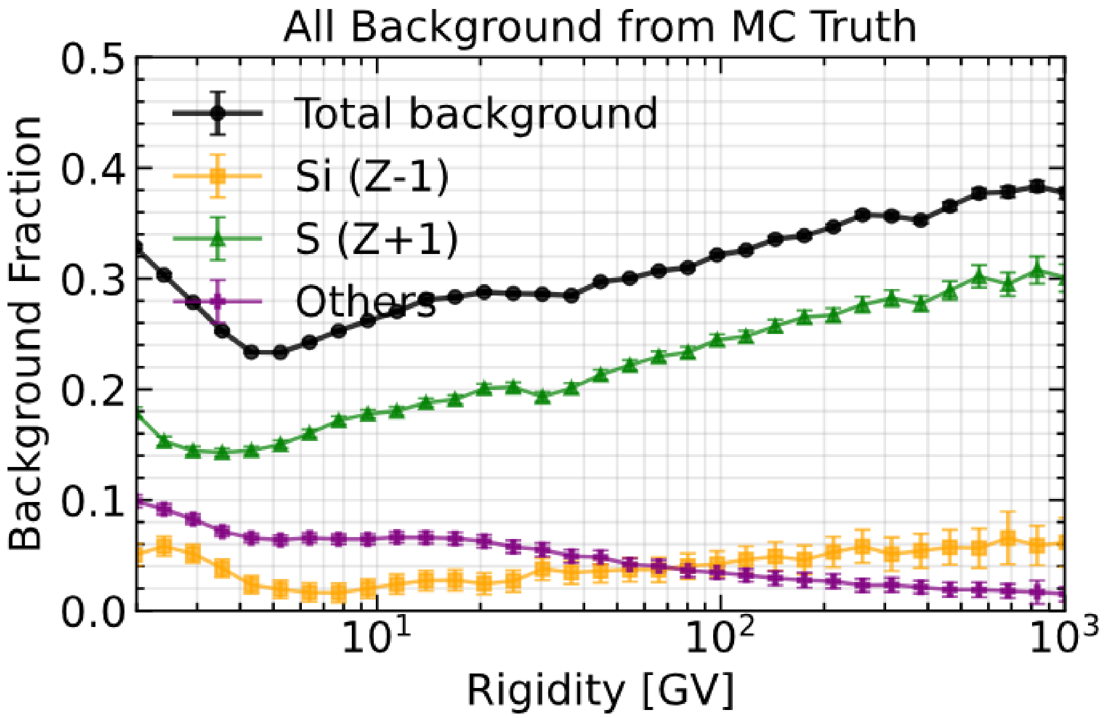
MC L1 Q distribution: **Before and after ML identification**



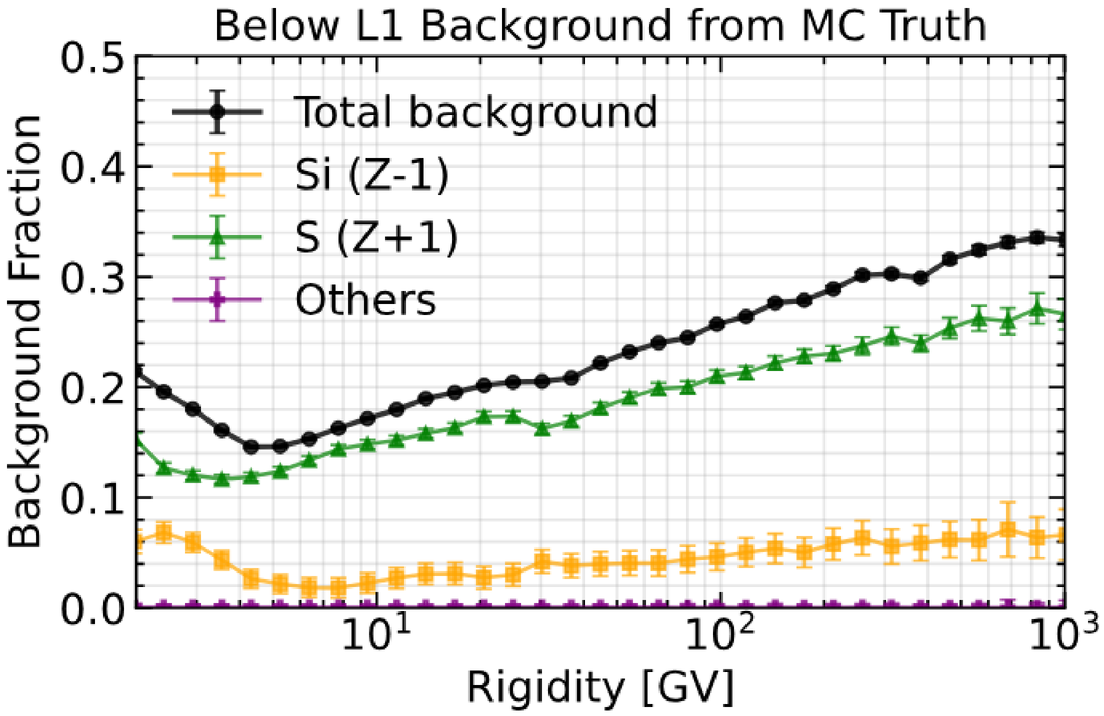


P Below L1 background from **P** global MC

All events



- For Z> 15: Select events survived on L1
- Si: all events

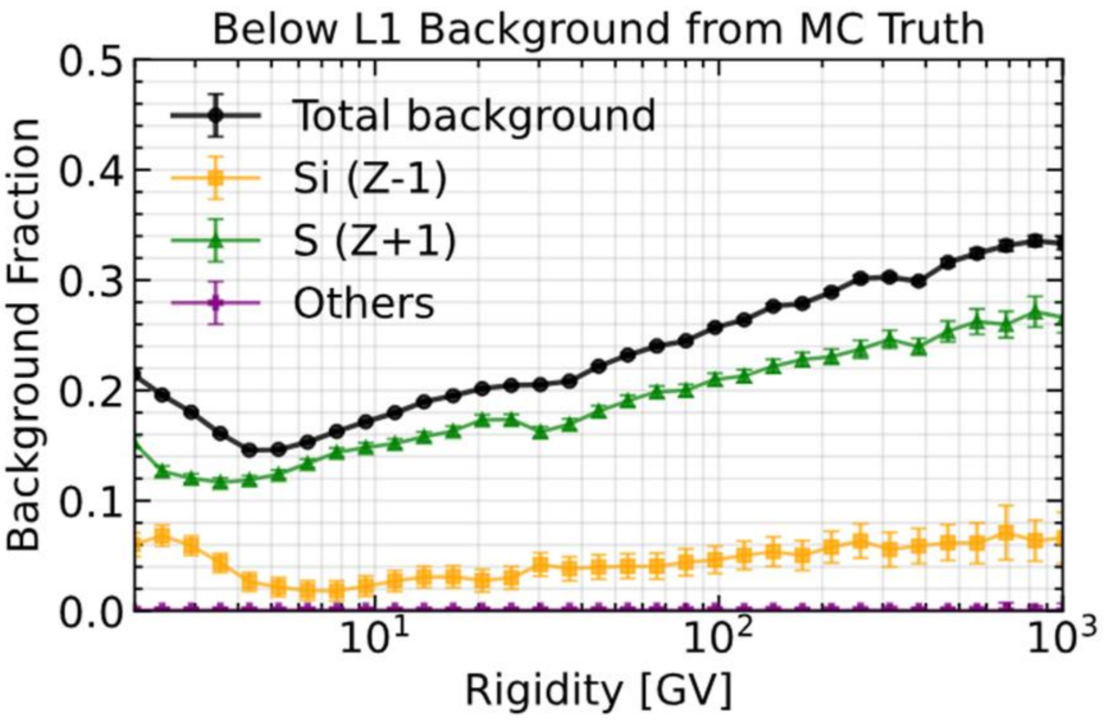


P below L1 background: check with MC

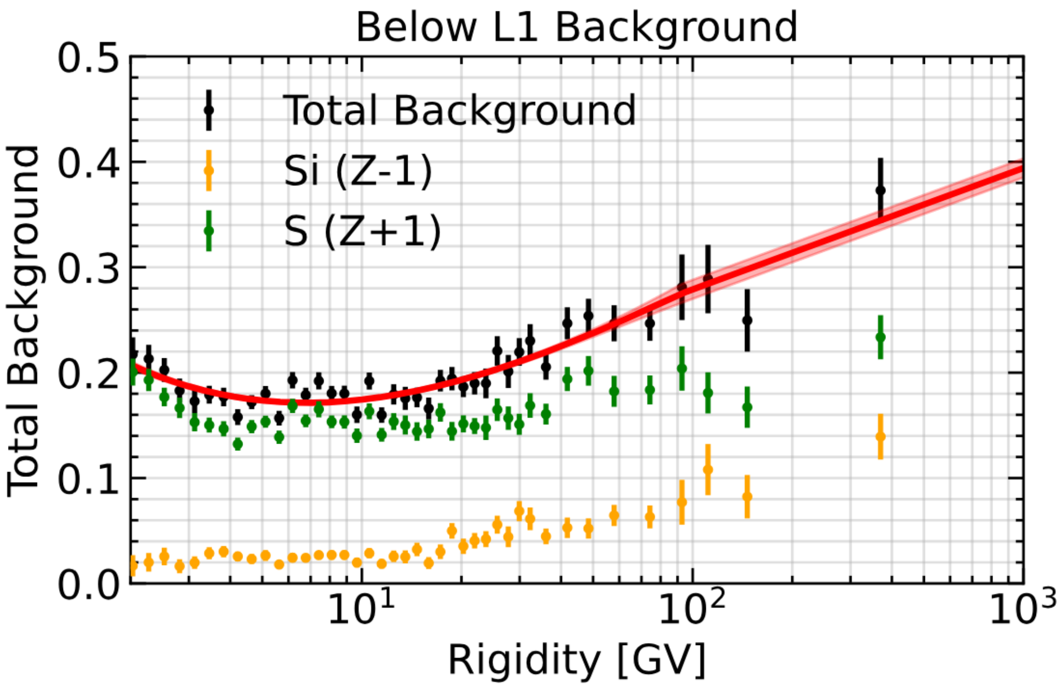
P global MC (Z=14,15,16-20, 26), event selection:

- P event selection
- For Z>15: Select events survived on L1

Background calculated from MC truth.

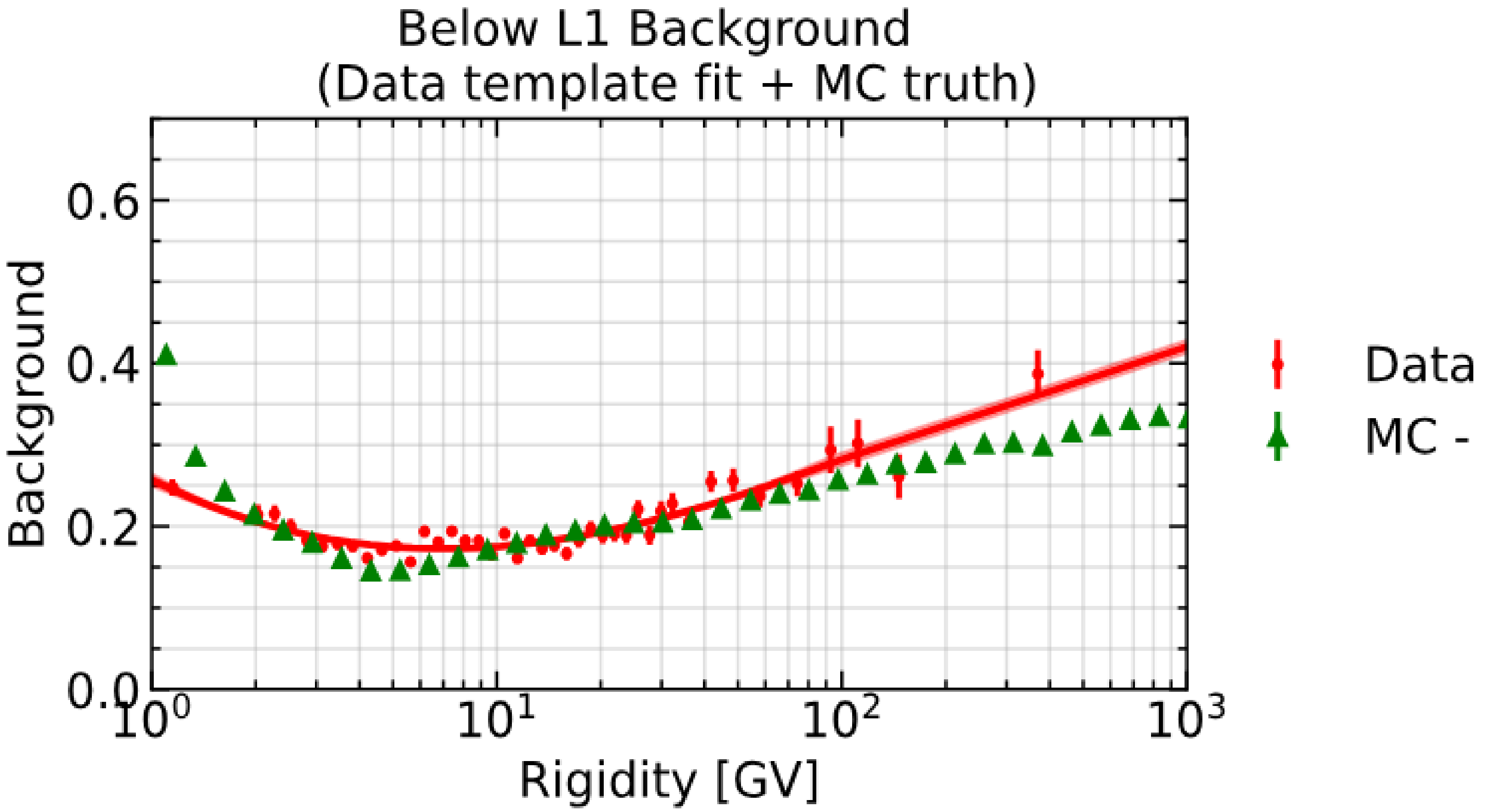


Template fit result from data:



Below L1 background: P

Comparison between MC truth from global MC and template fit result from Data:



On-going: apply MDA model to data, to compare with MC