Enhancing Muon Tagging Performance in SWGO with MultiPMT Modules

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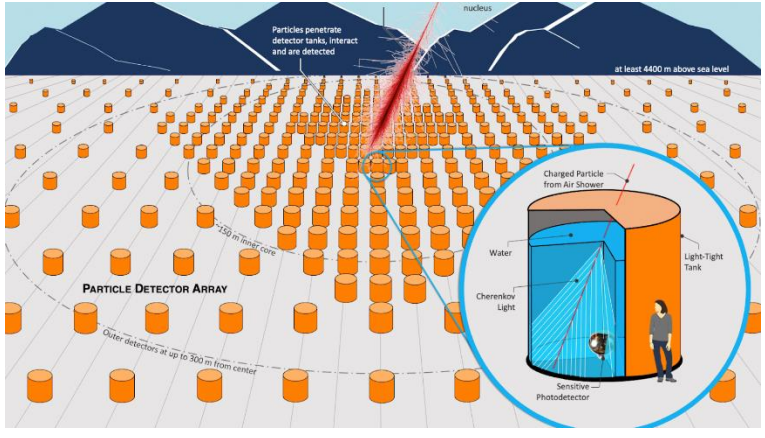
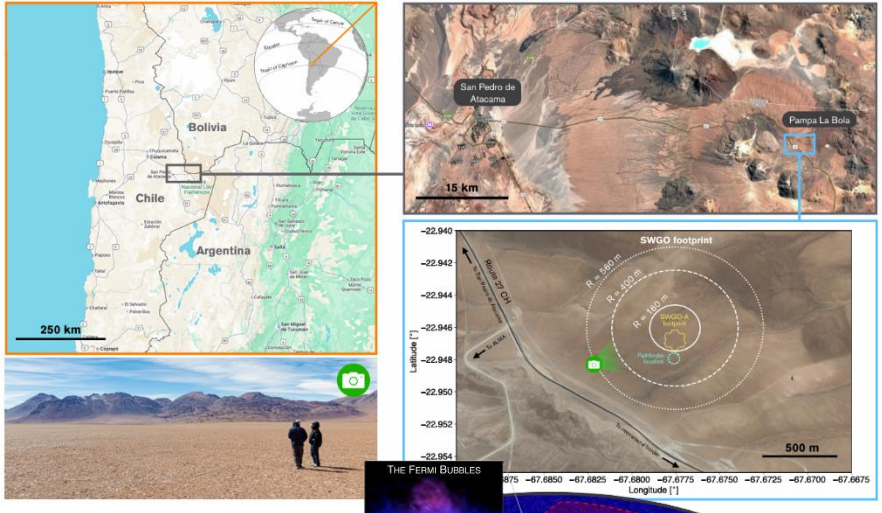
SWGO : Site and Science Case

- The **Southern Wide-Field Gamma-ray Observatory** (**SWGO**) experiment will be a wide field-of-view, high duty cycle, ground-based water Cherenkov detector array



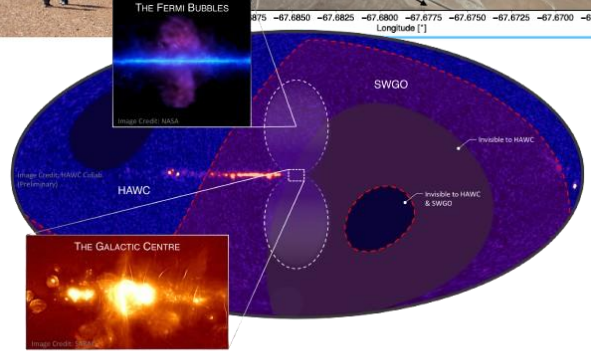
- Being **located in the Atacama Desert in Chile SWGO** will have access to the **southern sky**



- Among the **scientific objectives of the SWGO experiment** there are

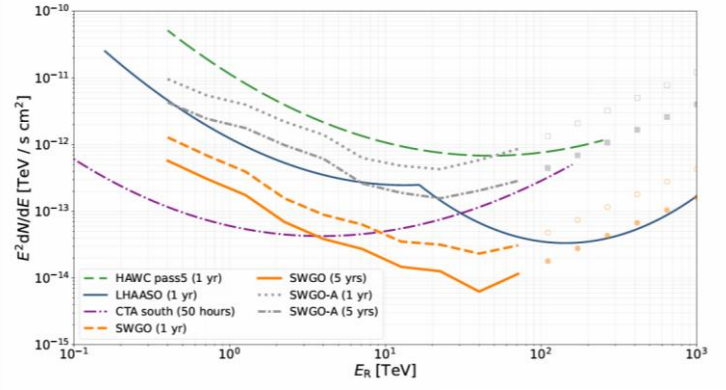
(Check out SWGO white paper!)
https://arxiv.org/abs/2506.01786

- Probing the **Galactic Center and the Fermi Bubbles**
- Unveiling **Galactic accelerators** and **TeV sources**
- Monitoring **transient Gamma-Ray Burst and AGN flares**

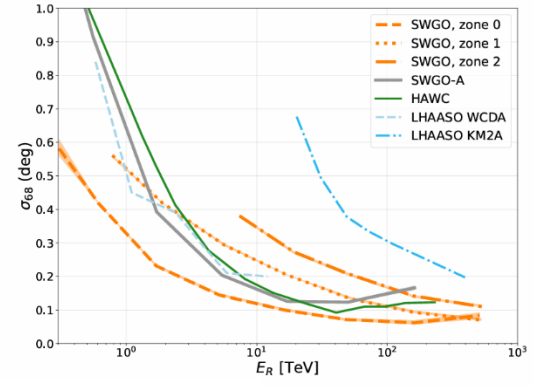


SWGO : WCD Array and Performance

- SWGO will survey the γ-ray sky **from the TeV up to the PeV** energy scale with **unprecedented sensitivity**

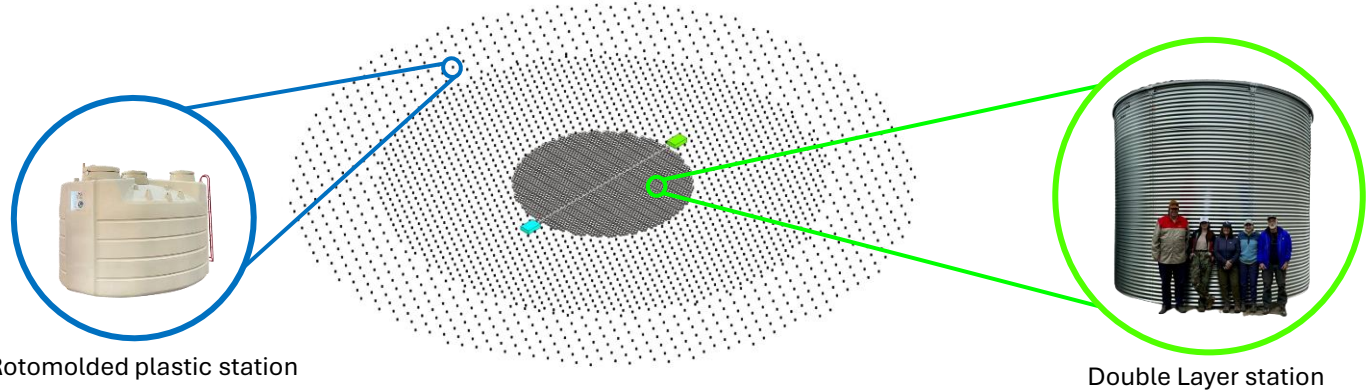


- It will also feature an **increased angular resolution** with respect to previous WCDA



- **Hybrid Layout** with a **denser inner core** and **sparser outer array** :

- Zone 1 : FF 70 %
- Zone 2 : FF 4 %
- Zone 3 : FF 1.7 %



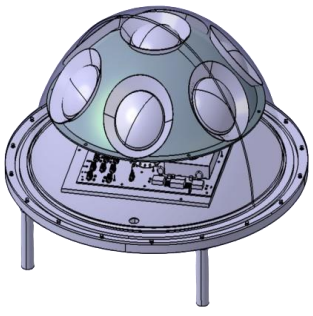
Rotomolded plastic station

Double Layer station

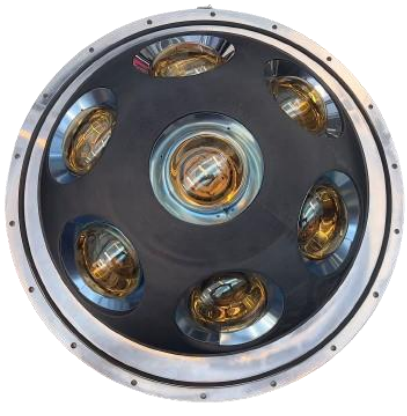
A multiPMT photosensor for SWGO

- The Naples SWGO group has advanced a **multiPMT detector** proposal on the basis of the successful **preceding experiences of KM3NET and Hyper-Kamiokande**

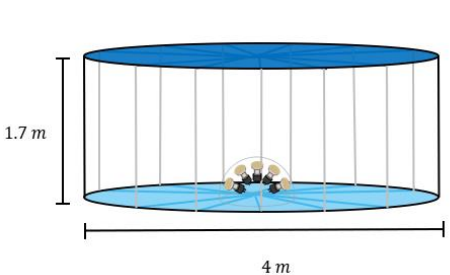
- The multiPMT features **7 outward facing 3-inches PMTs enveloped in an acrylic vessel** that together have the **same effective area of an 8-inches** PMT

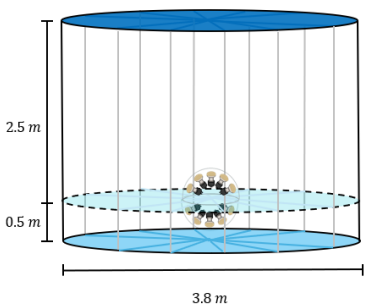


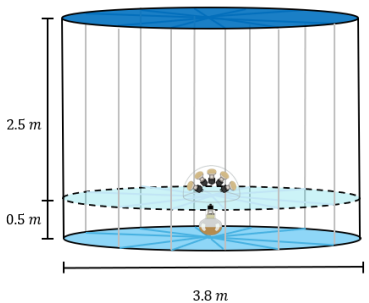
- A multiPMT offers an **intrinsic sensitivity to directionality**, a **better dynamical range** and an **increased time resolution**



- Can be placed in different configurations in the station :

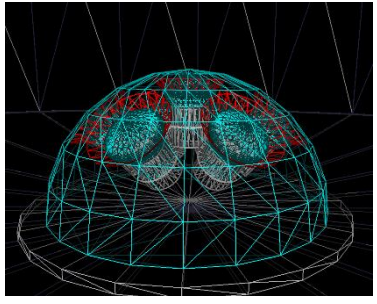
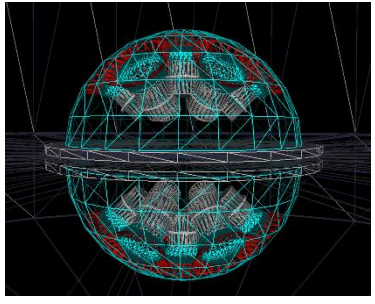
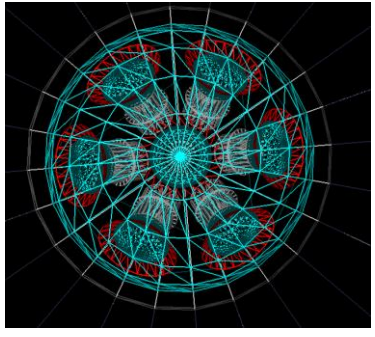
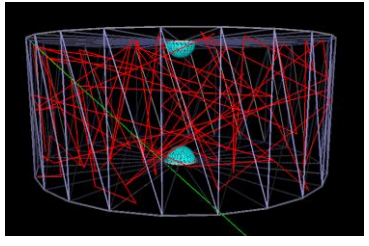




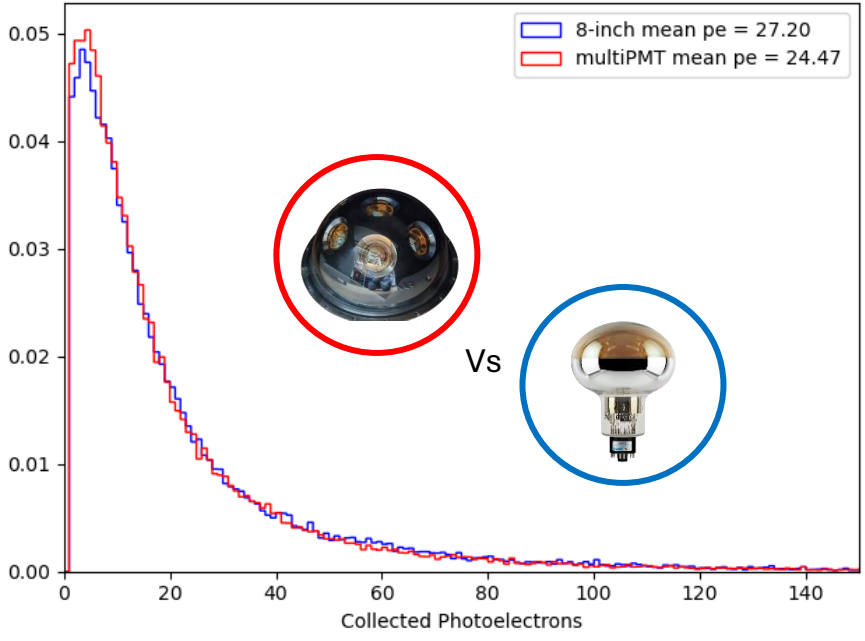


Prototype simulation

- In order to validate the prototype and upgrade its original design I used Geant4 to simulate the multiPMT

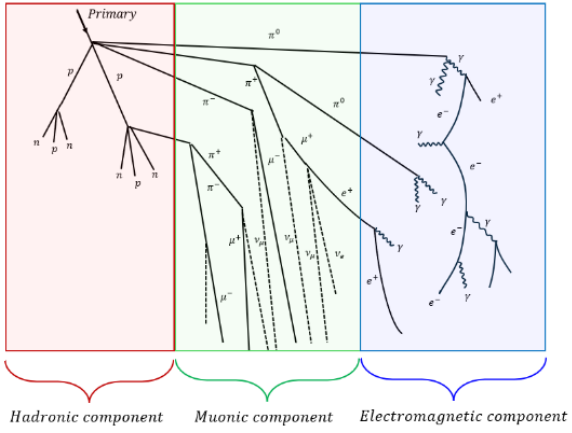





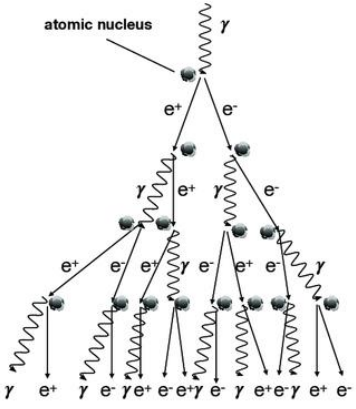
- The photoelectron collection efficiency of a multiPMT is comparable to that of an 8-inches



Muon Tagging with multiPMTs

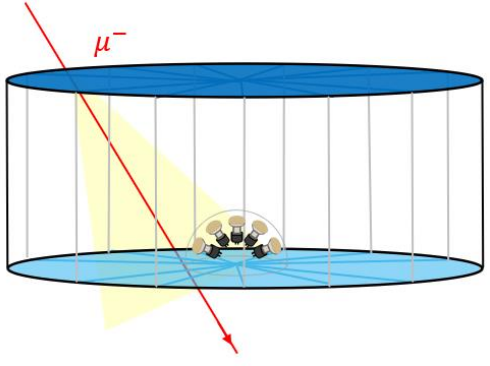
- Muon tagging refers to the **identification of muons from Cosmic Ray showers**





- It can be effectively used for **gamma-hadron separation** of the primary particles

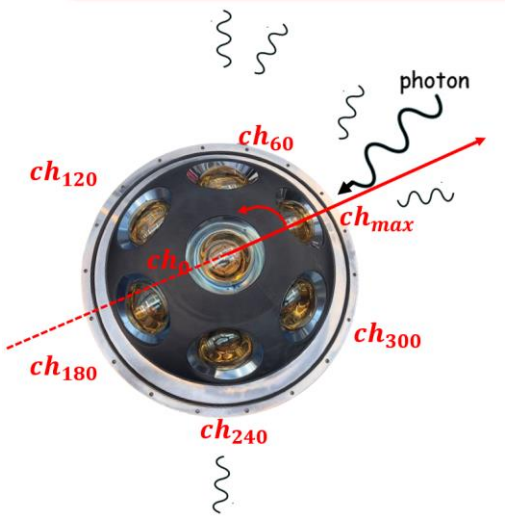
- **Muons produce collimated Cherenkov cones**, while gammas and electrons produce a diffuse signal



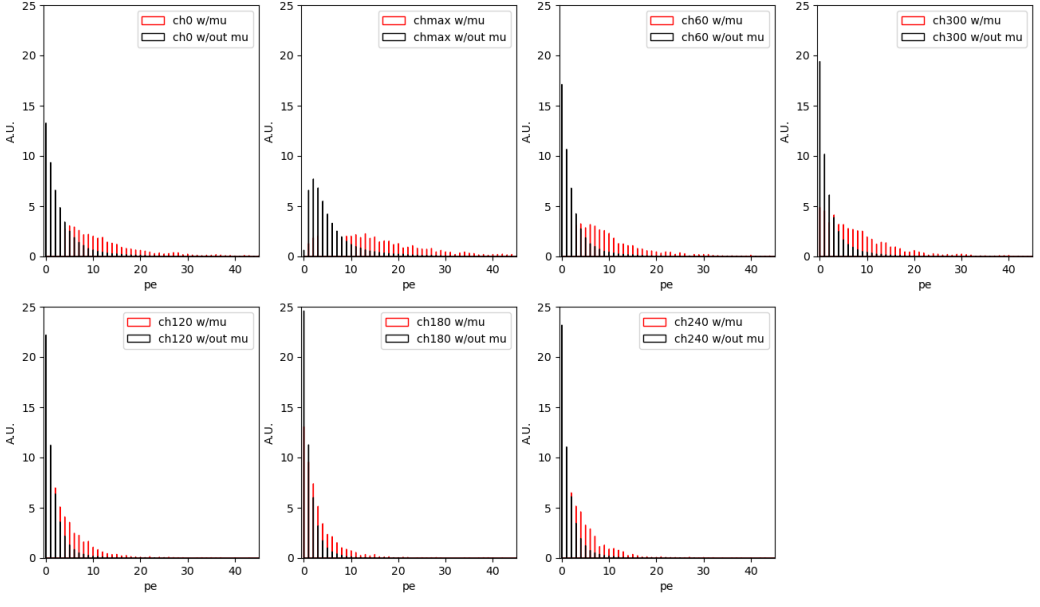
- The **intrinsic sensitivity to asimmetry of a multiPMT** can be used to **enhance muon tagging** performances

- Variables extracted from the signals can then be used to **train a Machine Learning algorithm**

Charge Asymmetry in multiPMTs



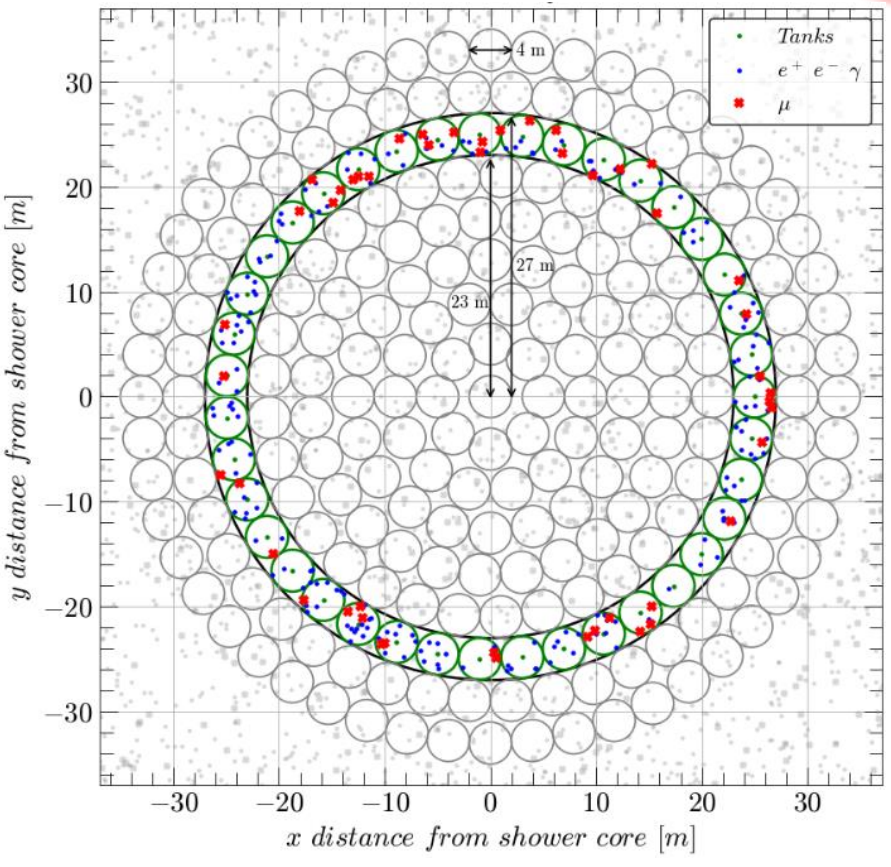
- Since the events have azimuthal simmetry, **we need a reference frame on the multiPMT**
- The PMTs are labeled counterclockwise starting from the channel that registers the maximum pe number : "ch_{max}"
- The central one is always ch_0



- Strong charge asymmetry among channels especially in case of muons

Sampling Strategy

- **CORSIKA protons** simulated :
  - ~ **1000 primaries**
  - **100 - 110 TeV** Energy $(f(E) \propto E^{-2})$
  - $\mathbf{0° < \theta < 30}$ ° Inclination
  - Stations at **100 m** from the shower core
  - **1.7 m x 3.6 m** cylindrical Water Cherenkov station
  - Non reflective, **Polypropylene** stations



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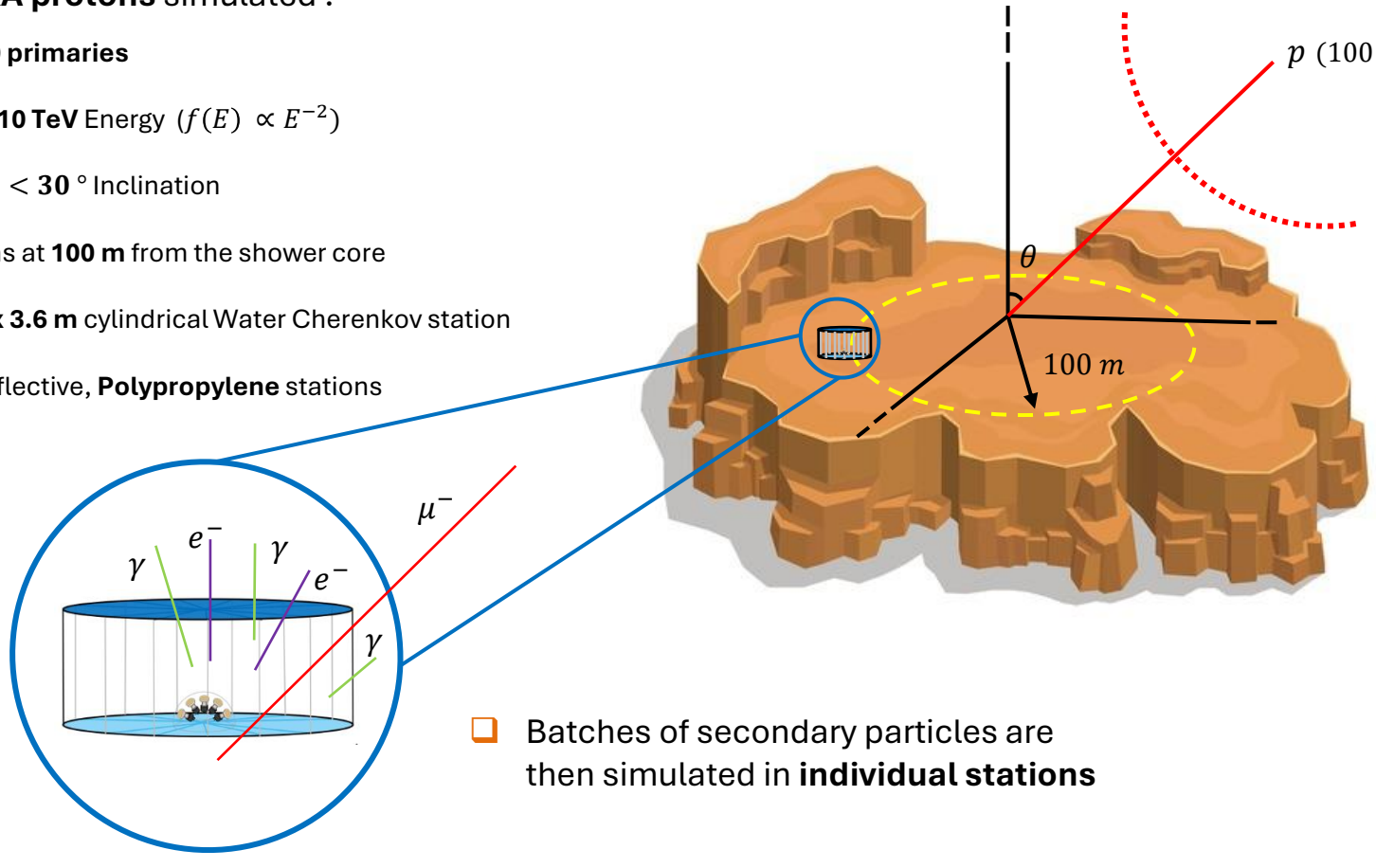
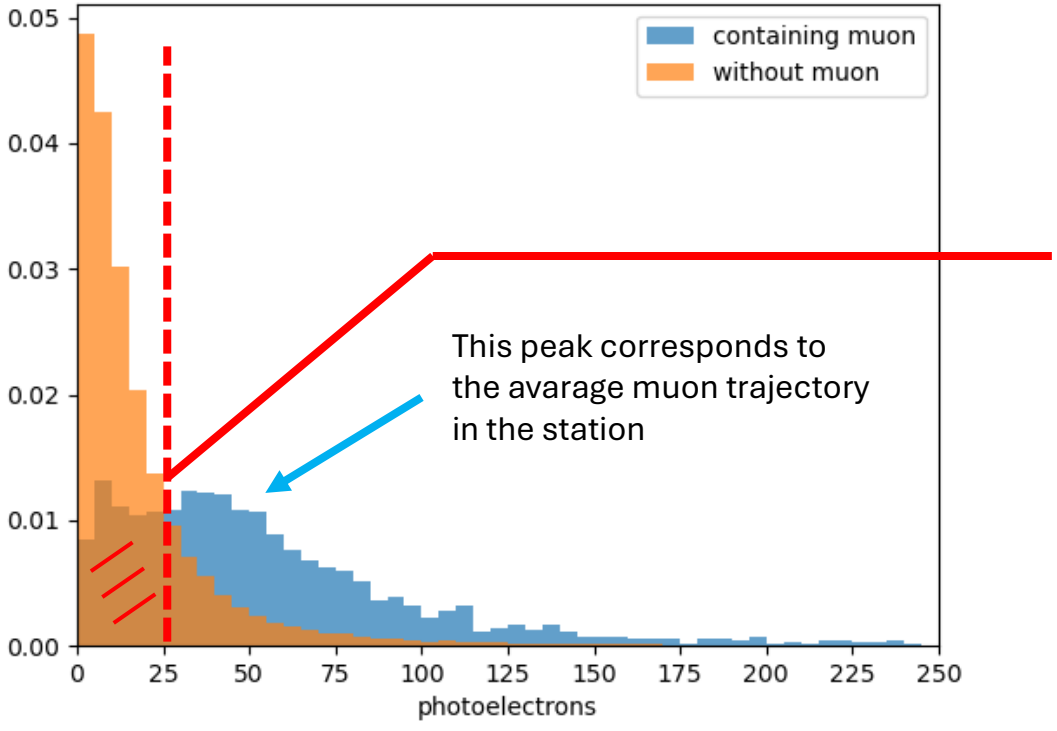


- Batches of secondary particles are then simulated in **individual stations**

PE Threshold

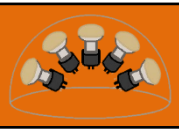


- These are «clipping muons», which don't fully traverse the station
- So **we impose : # total pe > 25** not to train the model on partial signals

Feature Engineering

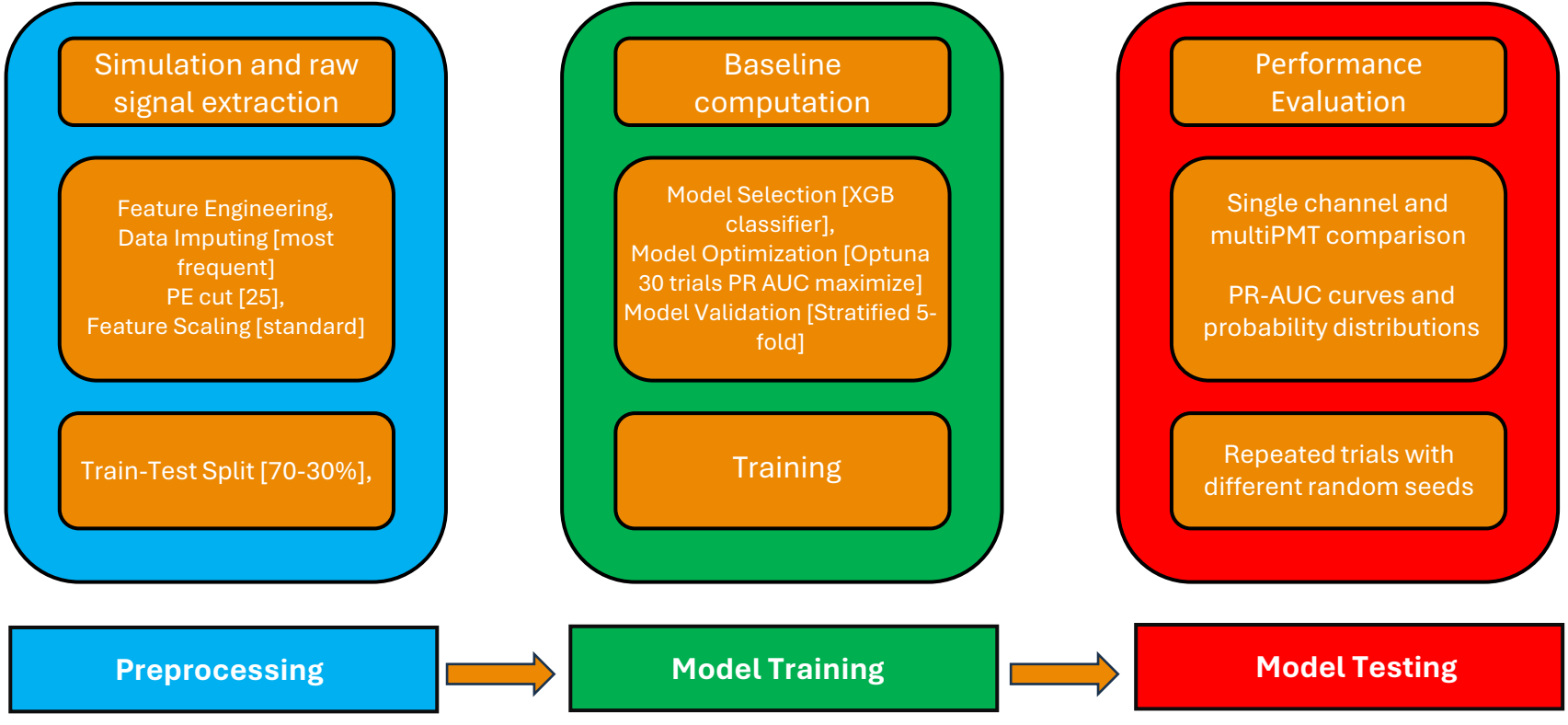
- Raw variables : time traces (TT) **within 100 ns** from external trigger time
- Engineered features :

8 - inches 
Number of total photoelectrons
Time to reach the mean, peak and 100% of the TT
Photoelectrons within 12ns
Binary label : 1 if a muon is present, else 0

multiPMT 
Number of photoelectrons for each channel
Time to reach the mean, peak and 100% of the TT for each channel
Photoelectrons within 12ns for each channel
Multiplicity, spatial and temporal Asimmetry of the signal distributions
Binary label : 1 if a muon is present, else 0

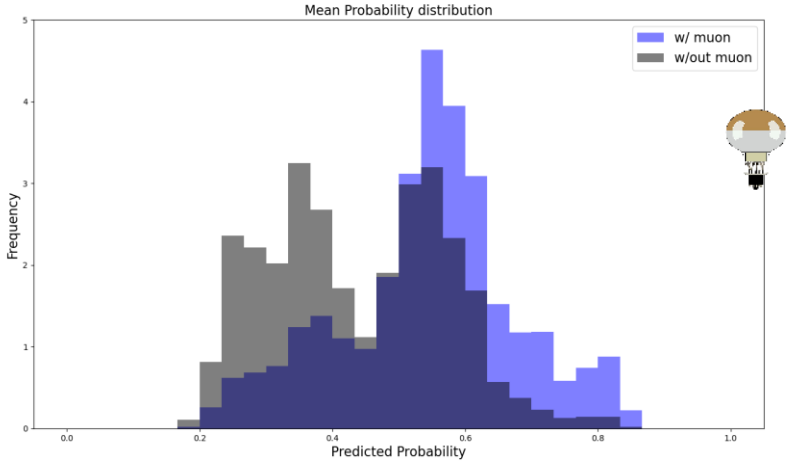
- In green : features exclusive to the multiPMT

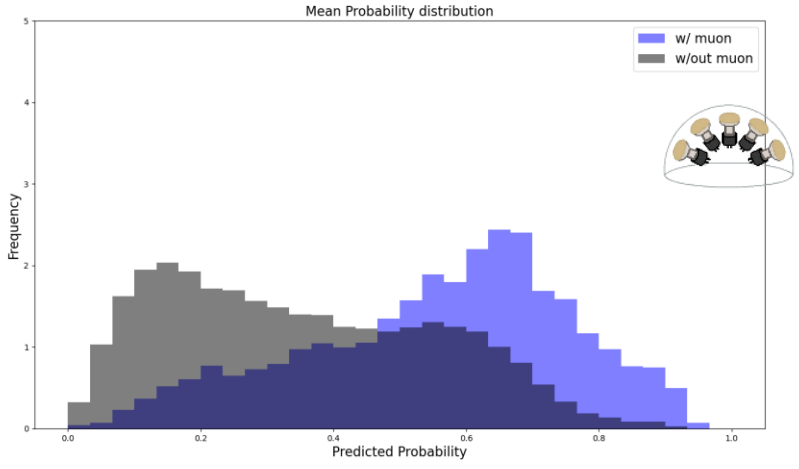
Model Pipeline



Results and Conclusions

- The output of the model is a **Probability Distribution that expresses the «muonicity»** of each event





- the multiPMT gives more confident predictions (more extreme values for the probabilities) and more separated disitribution profiles
- Bhattacharyya distance measures the dissimilarity of the distributions : $D_B = -\ln(\sum_i \sqrt{p_i^1 p_i^2})$

(p_i : frequency of the i-th value in the distribution)

$$D_B^{8inches} = 0.08 \qquad D_B^{mpmt} = 0.13 \text{ (65\% increase)}$$

Results and Conclusions

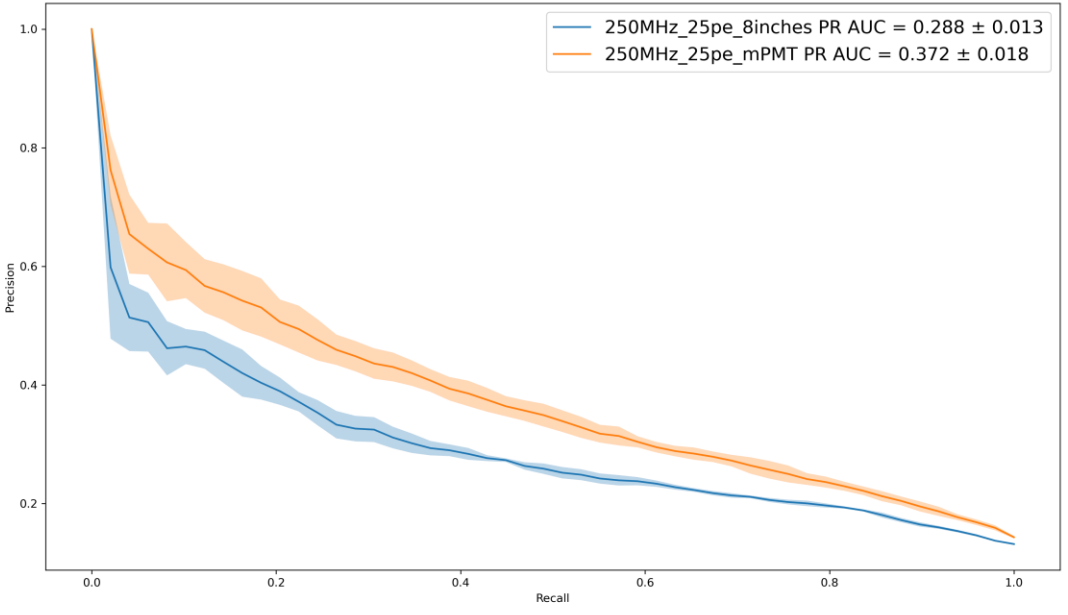
- Due to **high imbalance** among the classes we consider Precision (P) and Recall (R)

$$\text{Precision} = \frac{\text{True Positives}}{\text{True Positives + False Positives}} \qquad \text{Recall} = \frac{\text{True Positives}}{\text{True Positives + False Negatives}}$$

- We construct the PR curves using every threshold on the probability distributions

- And monitor **PR Area Under the Curve (AUC)** as designated performance

	8-inches	mPMT
PR - AUC	0.29	0.37



Thank you for the attention !