Enhancing Muon Identification in the SWGO Outer Array with multiPMT Modules through Machine Learning Techniques

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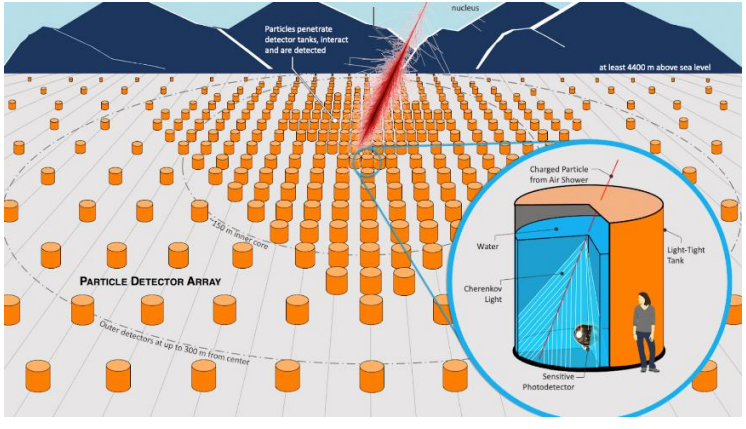
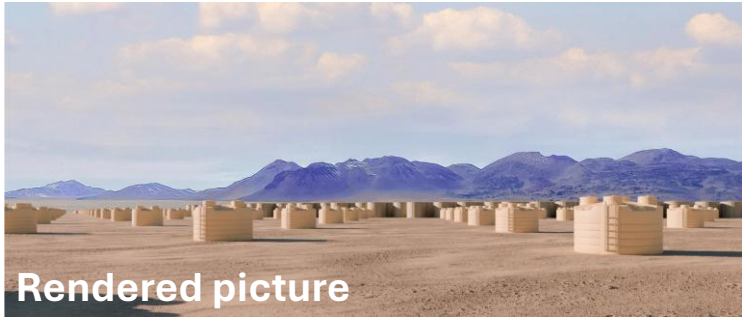
SWGO

The Southern Wide-field Gamma-ray Observatory

- **The Southern Wide-Field Gamma-ray Observatory** (SWGO) will be a wide field-of-view, high-duty cycle EAS detector **based primarily on Water Cherenkov Units**





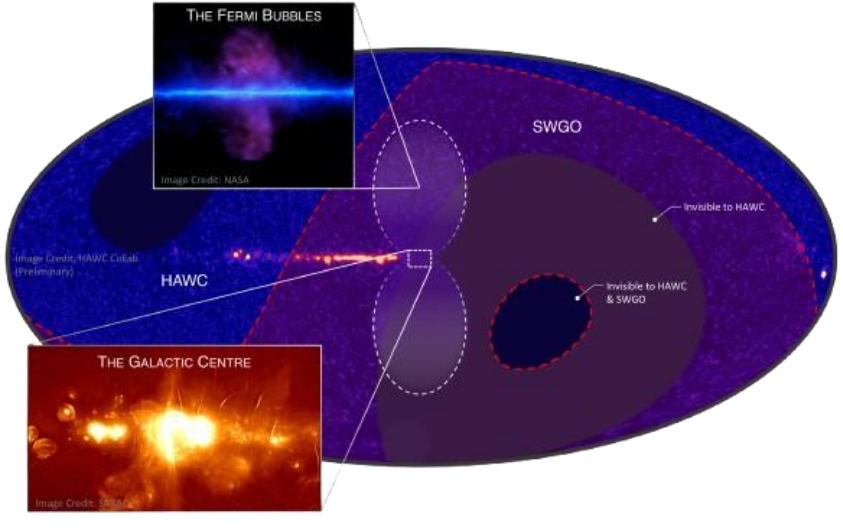
- Among the **scientific objectives of the SWGO experiment** there are

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

Monitoring the gamma ray-sky between **100 GeV** and a **few PeV**

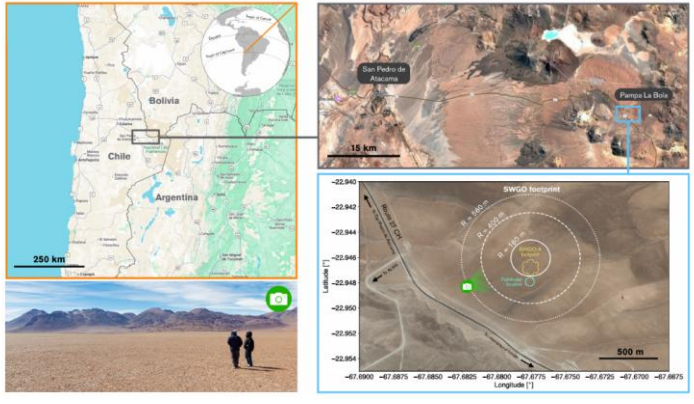
Unveiling **Galactic accelerators** and **TeV sources**

Probing the **Galactic Center and the Fermi Bubbles**

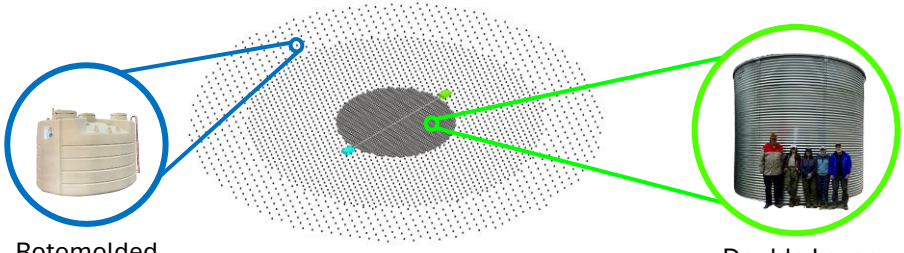


SWGO: Site and Layout

- The **selected site** for the experiment is the Plateau of **Pampa La Bola in the Atacama Astronomical Park in Chile (4770 m a. s.l)**, which will grant SWGO view of the gamma-ray sky as seen through the **southern hemisphere**

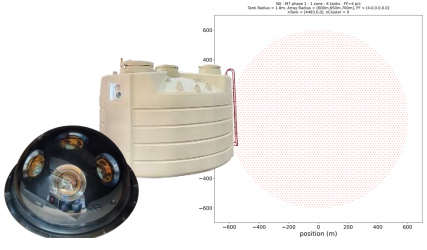
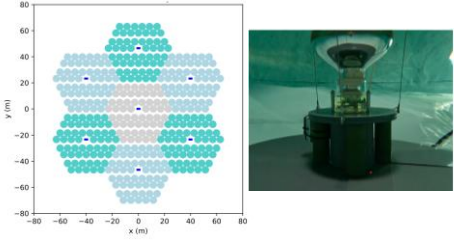


- **Hybrid Layout** with a **denser inner core** for lower energies and **sparser outer array** for higher energies



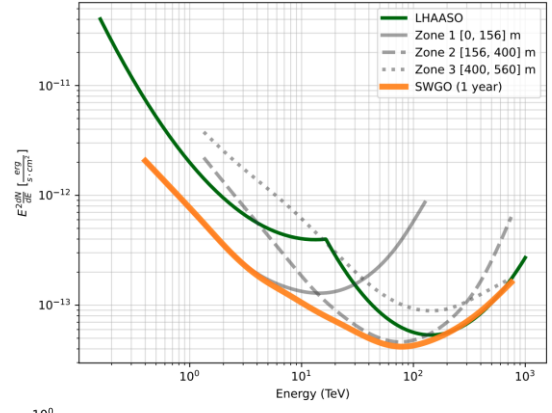
Rotomolded plastic tanks

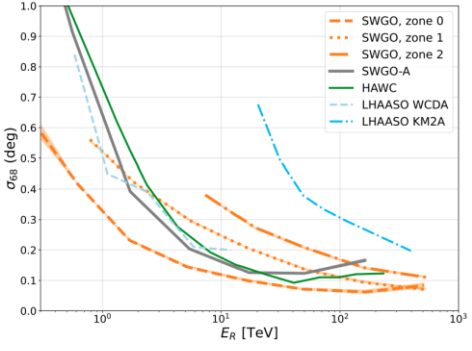
Double Layer metal stations

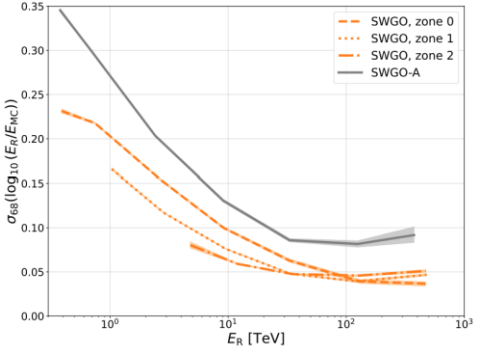
Outer Array		Inner Array	
			
$600\ m$ Radius	$3.6\ m$ Ø, height under investigation multiPMT-equipped	$160\ m$ Radius	5.2 m Ø, 4.2 m height
$\sim 1-4\%$ FF		$\sim 70-80\ \%$ FF	Reflective walls

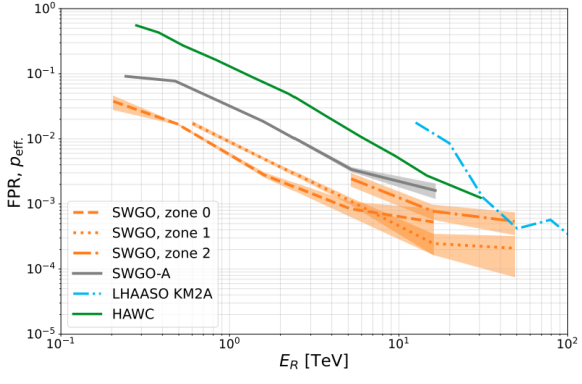
SWGO: Preliminary Performance

- SWGO will survey the γ-ray sky from the TeV up to the PeV energy scale with **unprecedented sensitivity**
- **Increased angular resolution** with respect to previous WCDA



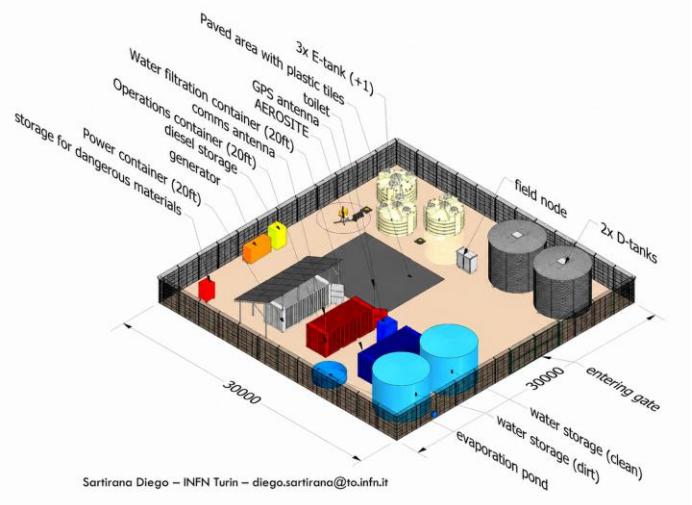




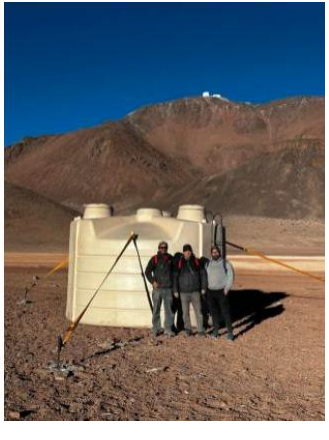


- Sensitivity calculated for a E^{-2} like source
- Currently no background from electronics and low energy showers is included
- γ efficiency fixed at 80%

SWGO: Pathfinder and Site Activities



- The Pathfinder will be the first installation at Pampa La Bola
- 2x metal tanks
- 3x plastic tanks
- Power plant
- Water Purification System

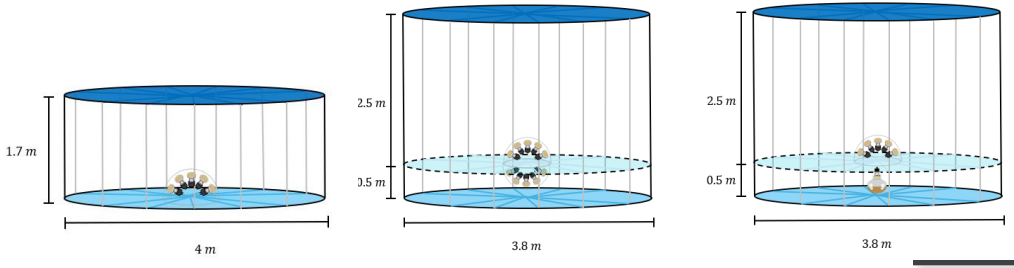


- Recently a plastic tank has been installed near the AtLAST telescope (5100 m a.s.l.) for termal tests
- The tank has been deployed and filled with water
- Temperature sensors were installed for monitoring

A multiPMT Photosensor for SWGO

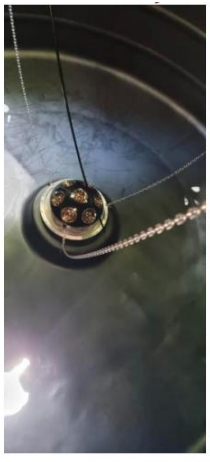
- A **multiPMT detector** has been proposed for the outer array on the basis design **of KM3NeT and Hyper-Kamiokande**

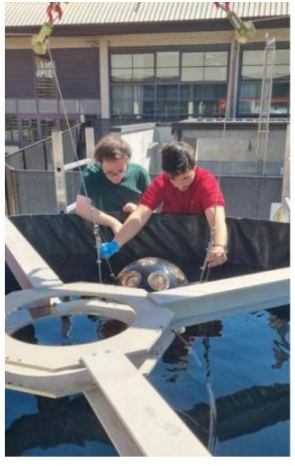
- **7** outward facing **3-inches** PMTs
- Protective **Acrylic Vessel**
- **Same Effective Area** as an **8-inches** PMT
- Intrinsic **sensitivity to directionality**
- Better dynamical range
- Increased time resolution
- Less sensitive to external magnetic fields
- Modularity means resilience to critical failures

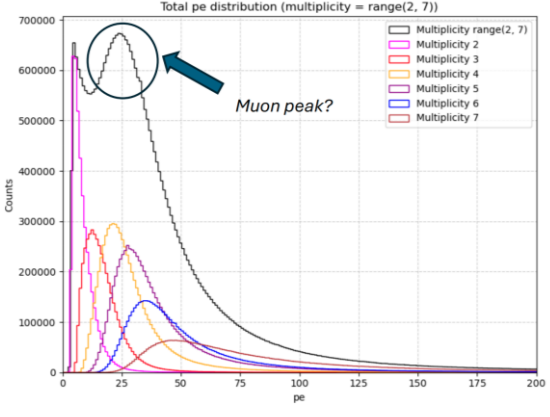


- Adaptable to various designs

First Prototypes



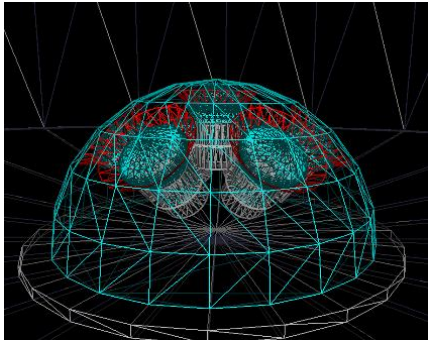


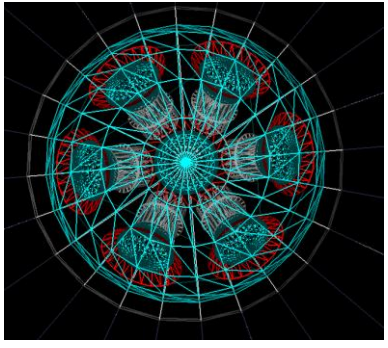


- 1 in Rio (CBPF) and 1 in Milan (Politecnico) taking data, 2 in San Pedro de Atacama to be operated at the Pathfinder

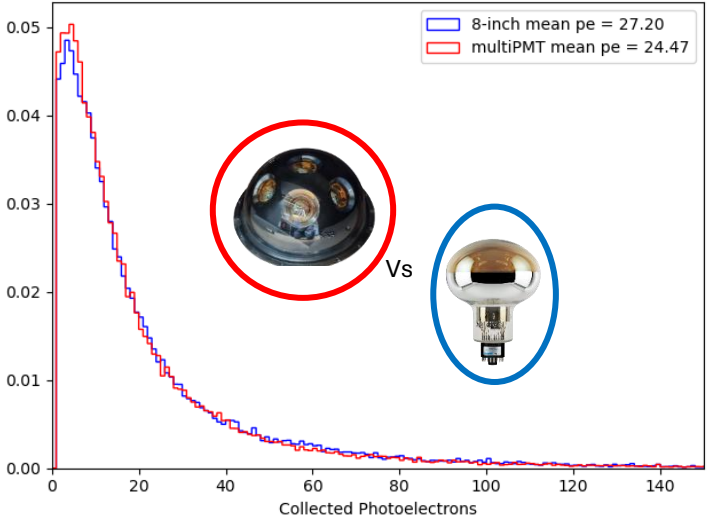
- multiPMT working as expected and showing promising results

A Simulated multiPMT for SWGO





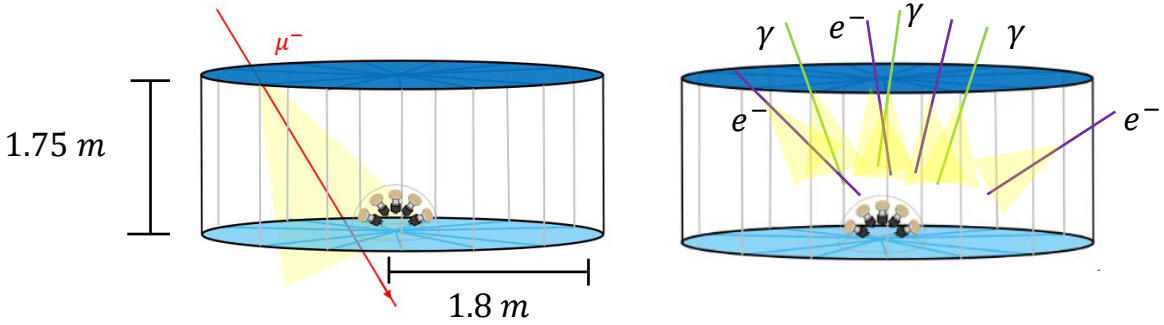
- Geant4 Simulation of the prototype for performance assessment and analysis



- Equal total photocathode area as an 8-inches
- Roughly same PE collection efficiency

A Strategy for Muon Tagging

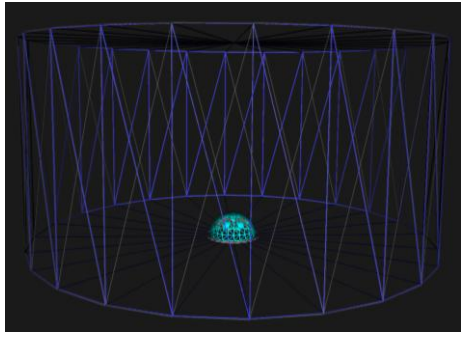
- Large water volumes and transportation at high altitudes can be costly
- Digging for undergound muon detectors can be challenging due to the nature of the soil and might not preserve the aesthetic integrity of the environment
- The idea is to **exploit asymmetries** in the Cherenkov light distribution with **multiPMTs** in small WCD stations and improve **muon tagging**



Simulation Setup

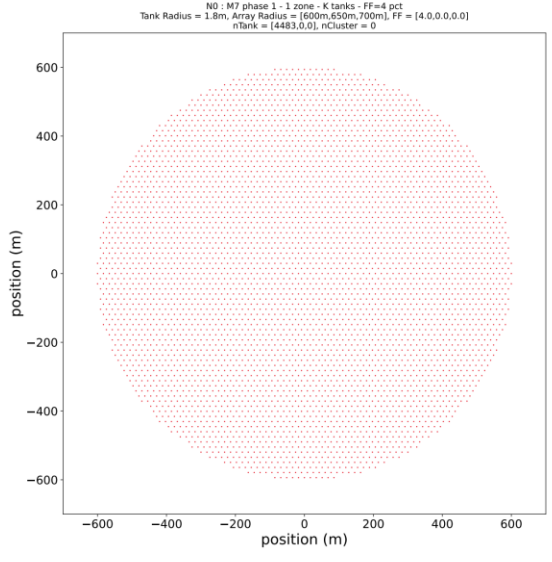
Simulated WCD Array

- $4\%\ FF$
- $R\ =\ 600\ m$
- Tank height : $175\ cm$
- Tank Radius : $180\ cm$
- Non reflective tank
- No Flash ADC on the multiPMT



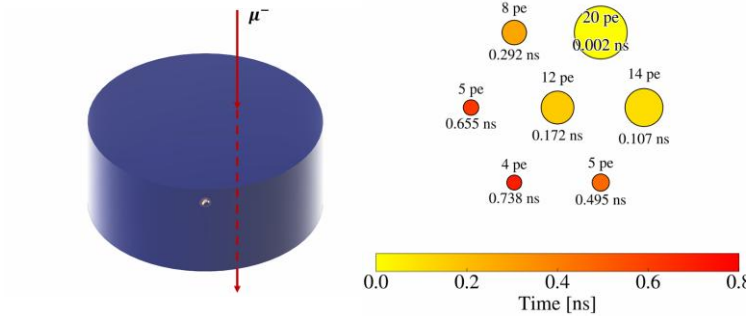
Primary γ & Protons

- $100\ TeV\ <\ E_{reco}\ <300\ TeV\ (E_p^{-2}, E_\gamma^{-1})$
- $0^\circ < \theta < 30^\circ$
- $0\ m\ <\ R_{core} <\ 600\ m$ uniformly

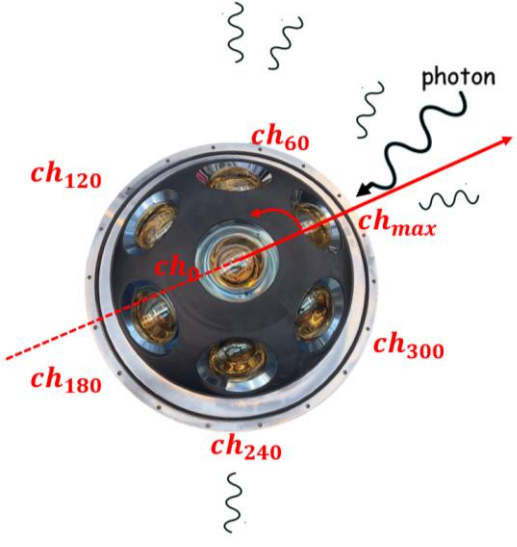


How do We Read a multiPMT?

- ***TDC* time stamps** and ***PE*s for each channel** to emulate current prototypes
- Fast ADCs to be implemented soon

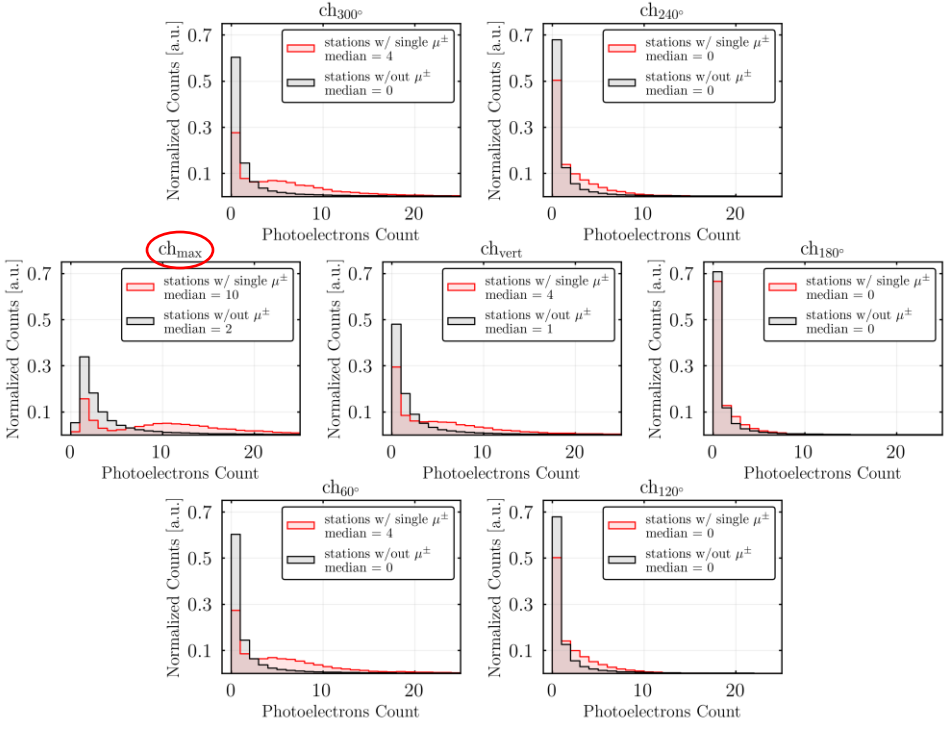


- Due to **azimuthal symmetry** we need a **reference frame** on the multiPMT
- Ordering relative to the **channel with maximum *PE* number**

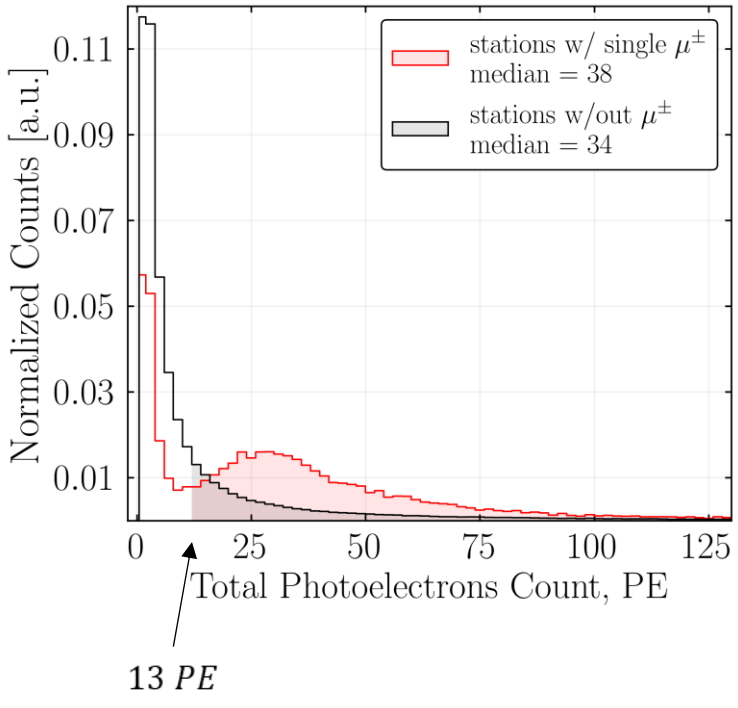


How do We Read a multiPMT?

- Single station events



- Total PE Count (7 channels summed)



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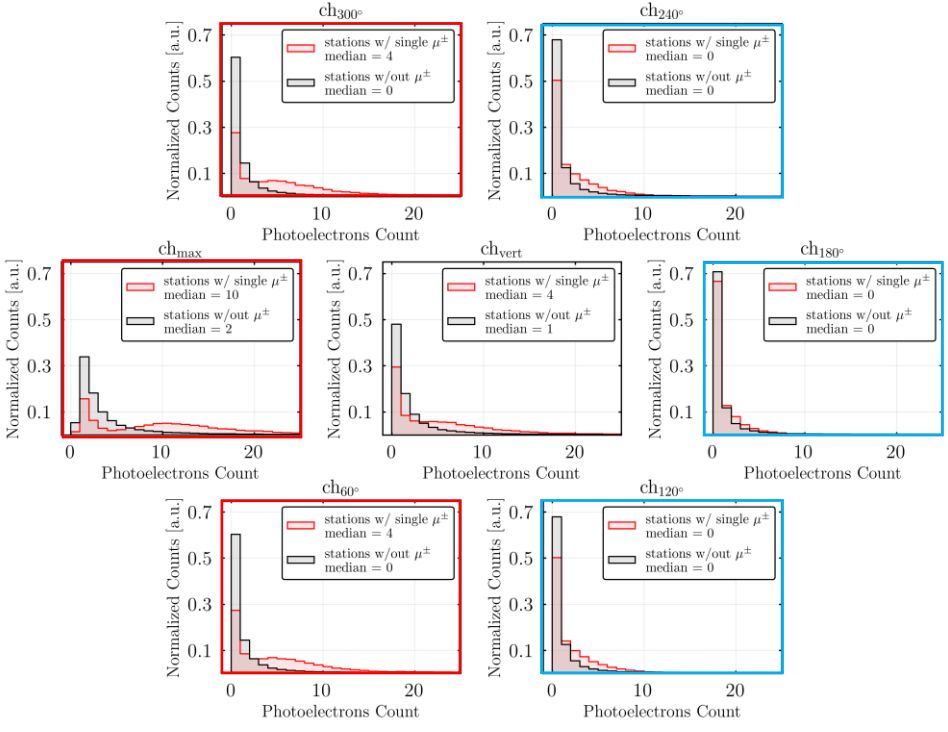

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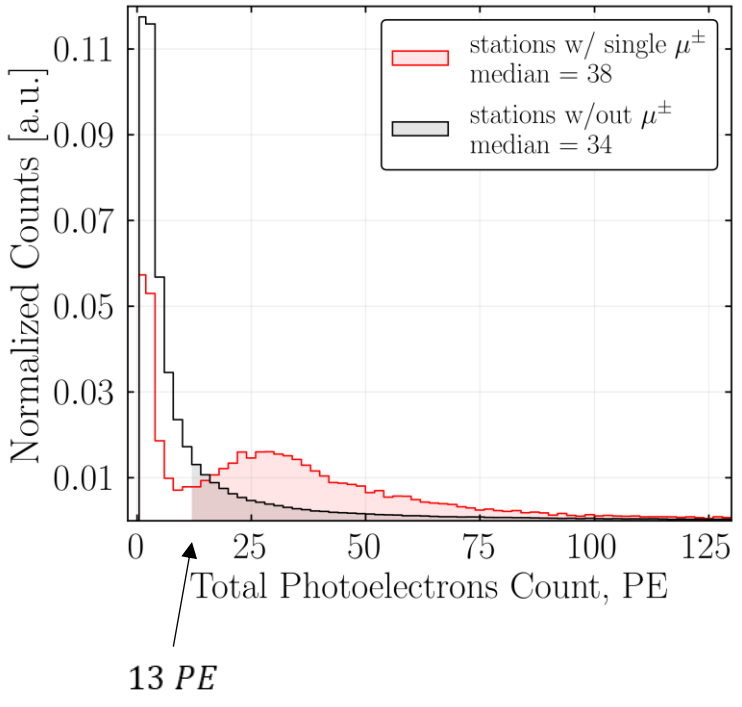
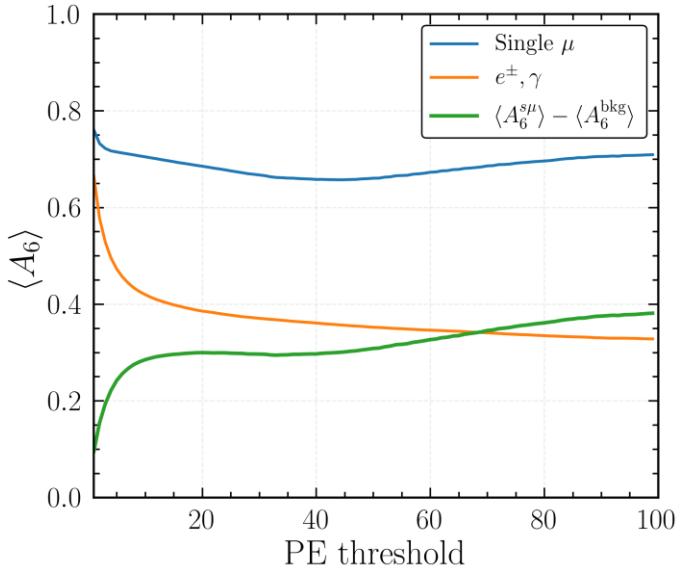


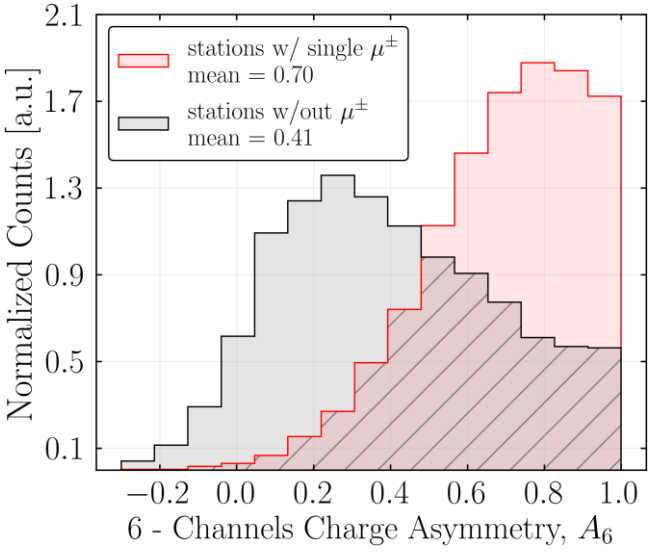
- Front channels
- Back channels

Asymmetry with 6 Channels

$$A_6 = \frac{(ch_{max} + ch_{300} + ch_{60}) - (ch_{180} + ch_{240} + ch_{120})}{(ch_{max} + ch_{300} + ch_{60}) + (ch_{180} + ch_{240} + ch_{120})}$$



$PE \geq 13$

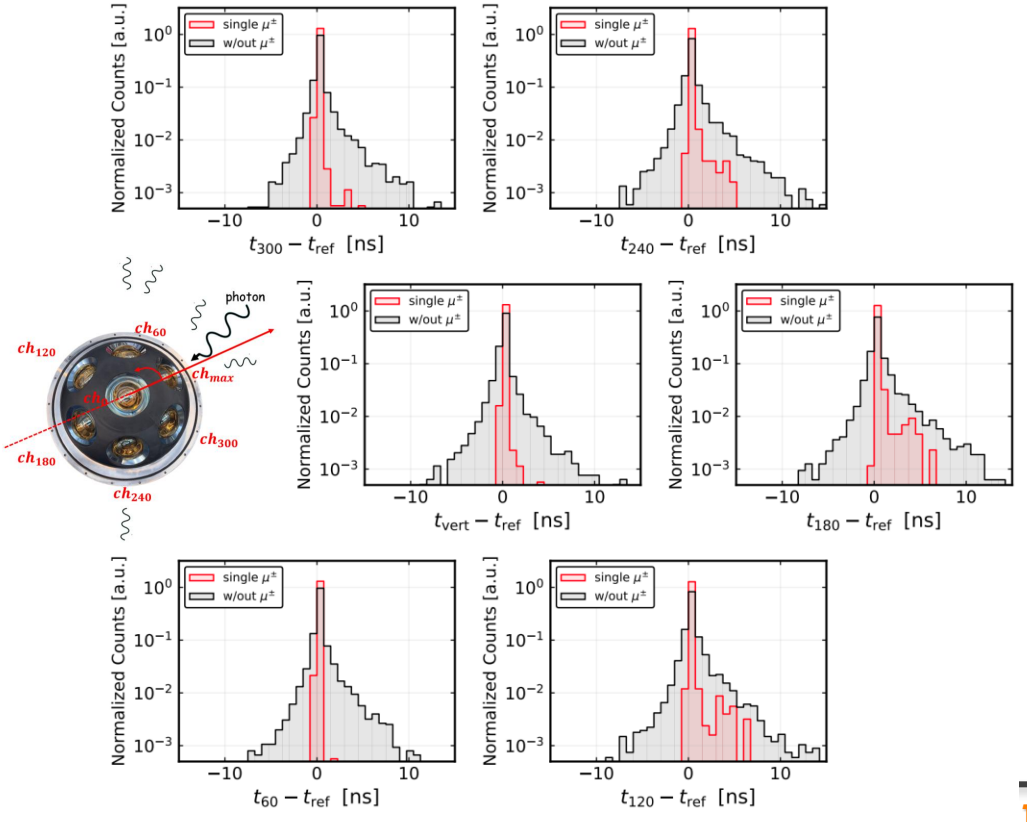


- Above 13 PE A_6 is independent of the number of PE for single μ and decreasing for $e^{\pm}/\gamma$

TDC Time Stamps

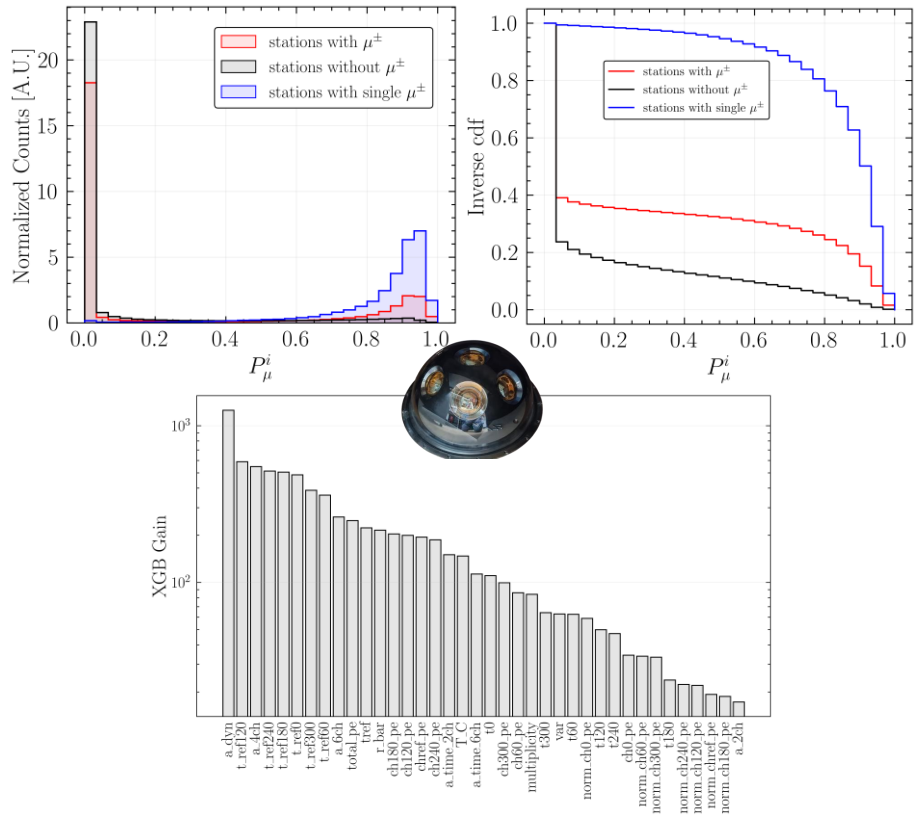
- Time of the **first PE** relative to ch_{max}

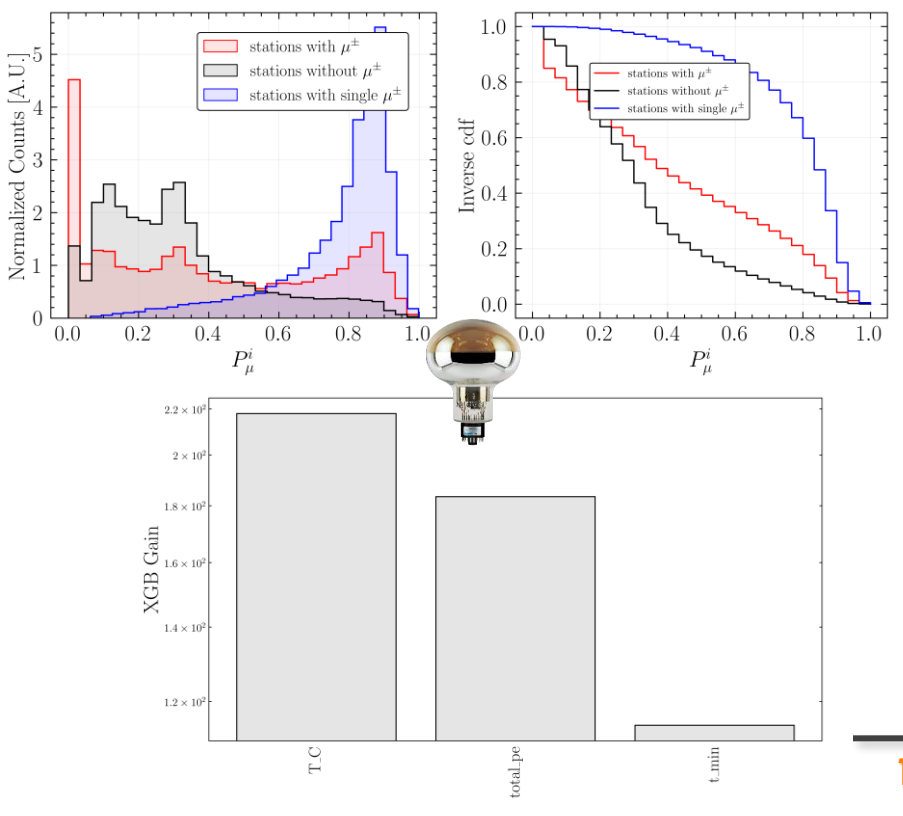
- Single muons result in a much more prompt signal with **little dispersion** across channels



ML Analysis for Single Station

- Both measured and derived features can be used to train a classification model **XGBoost** to recognize single muons in single stations





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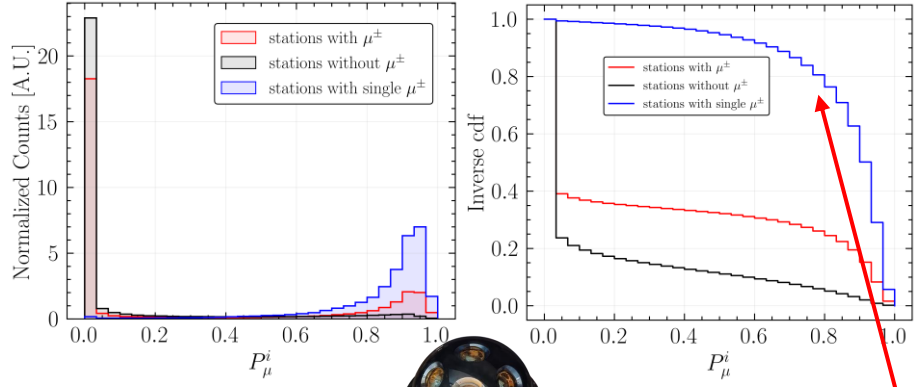
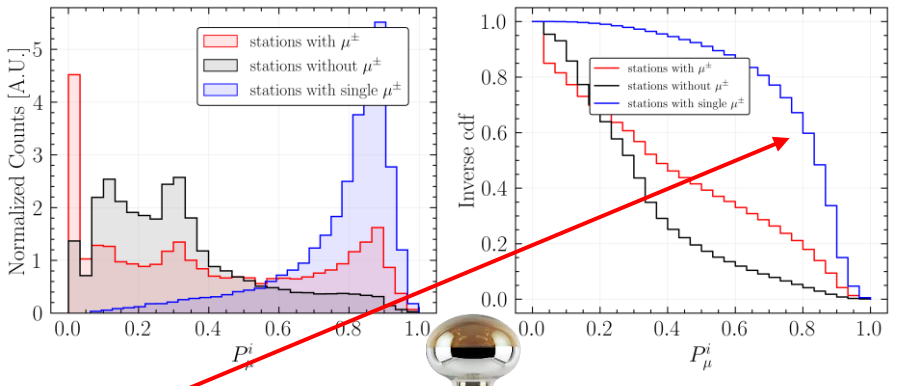
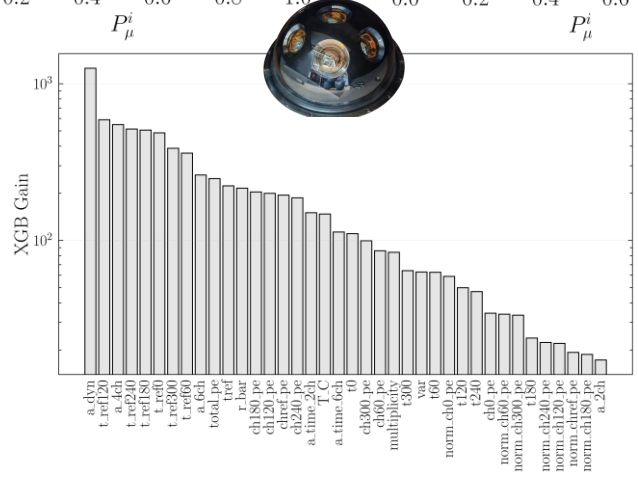
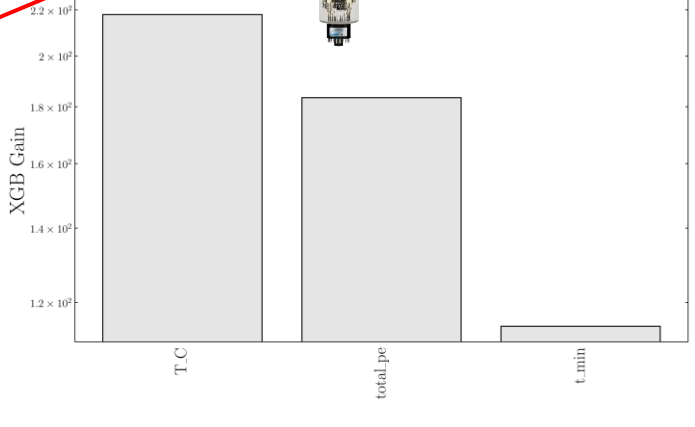




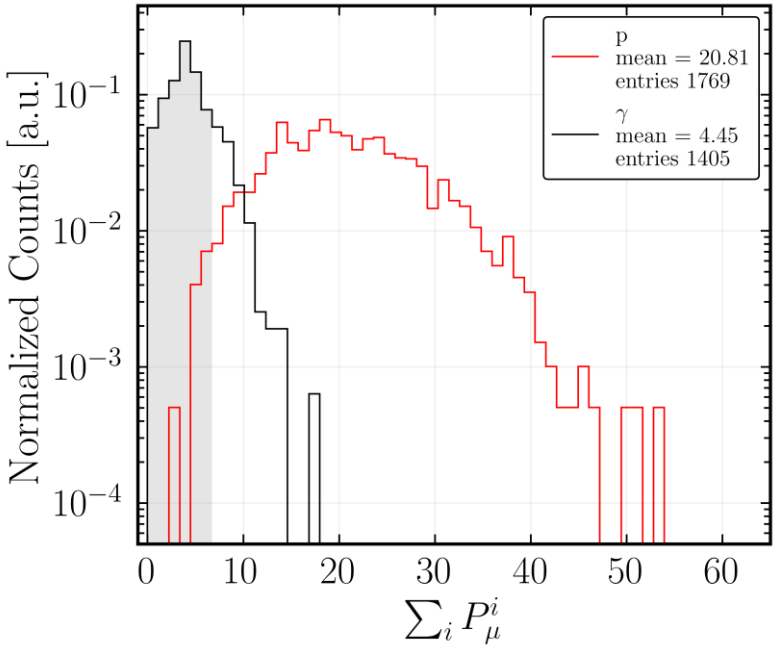


20% more single muons classified with $P_\mu \geq 80\%$

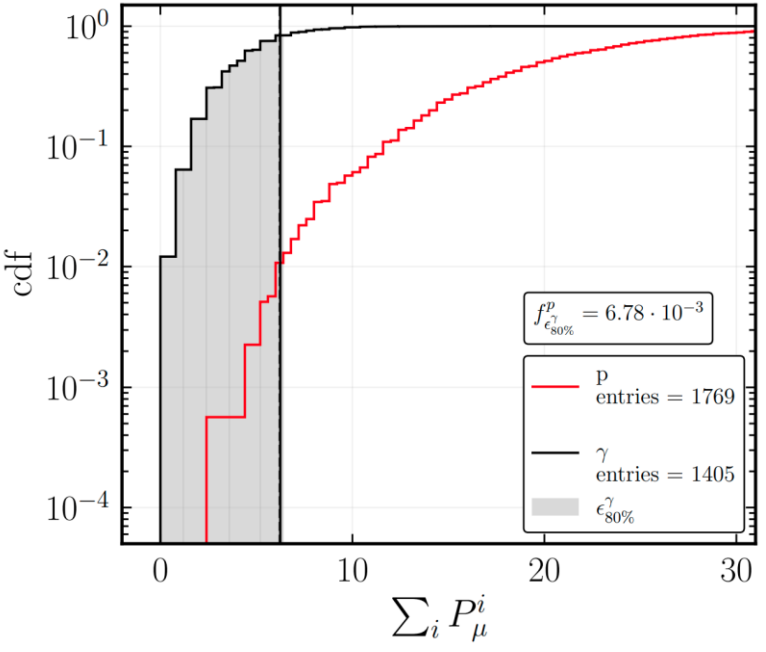


Scaling to Full Array

- A **threshold cut** is applied on the probability distribution in order to get the **minimum proton residual fraction (or False Positive Rate) [FPR]**



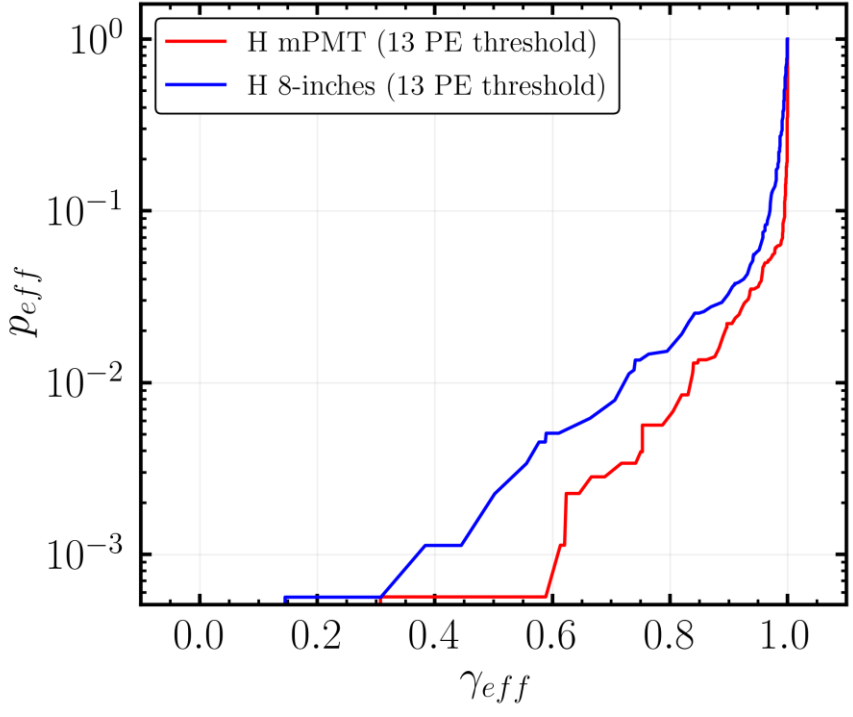
- Log-scaled Summed Probabilities $\sum_i P_\mu^i$ for γ and protons for all stations with total $PE \geq 13$

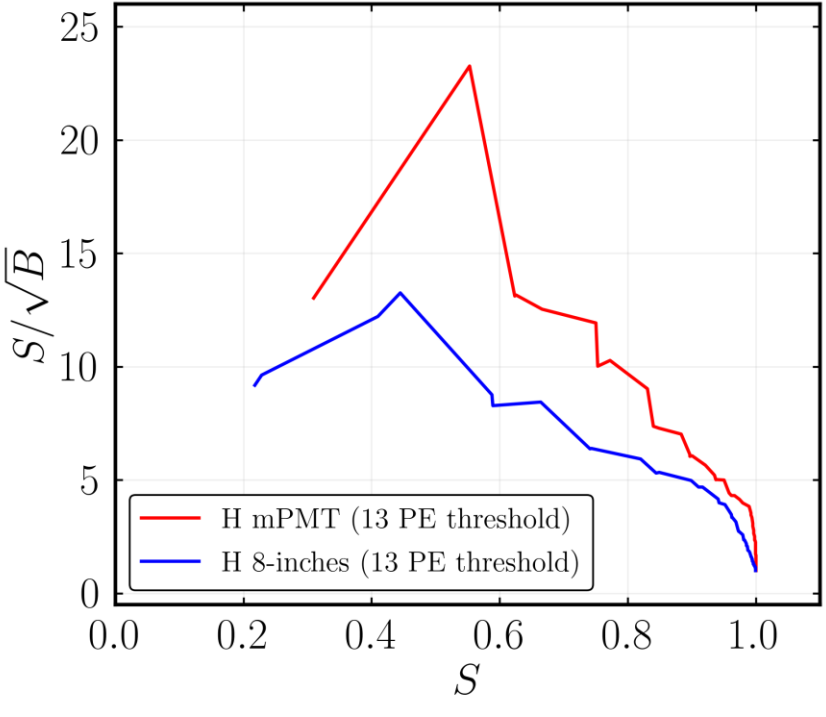


- Cumulative Probability and FPR at 80% γ-efficiency (or True Positive Rate) [TPR]

p_{eff} at 80% γ_{eff}

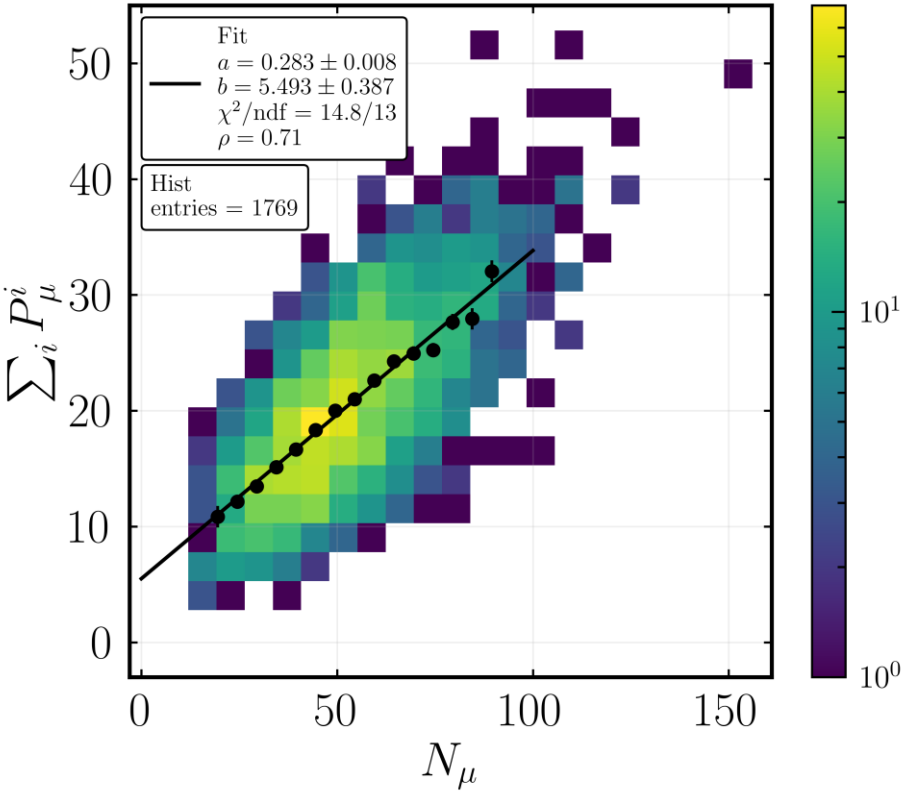
- Achieved p_{eff} at 80% γ_{eff} is comparable with what achieved by other approaches and can be combined for higher $\gamma - hadron$ discrimination power
- $\sim$ **2 – 3** $\times$ discrimination power **with respect to 8-inches**





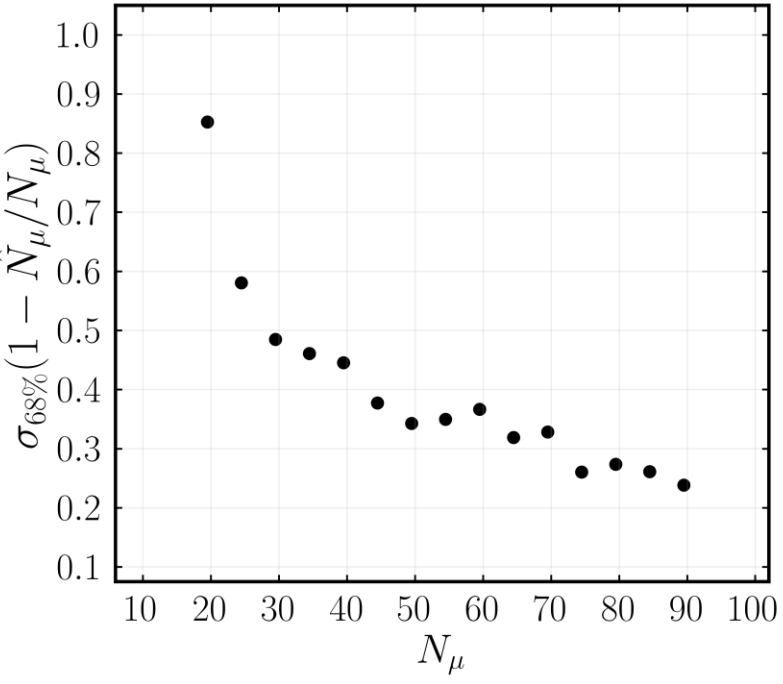
Muon Counting: Correlation

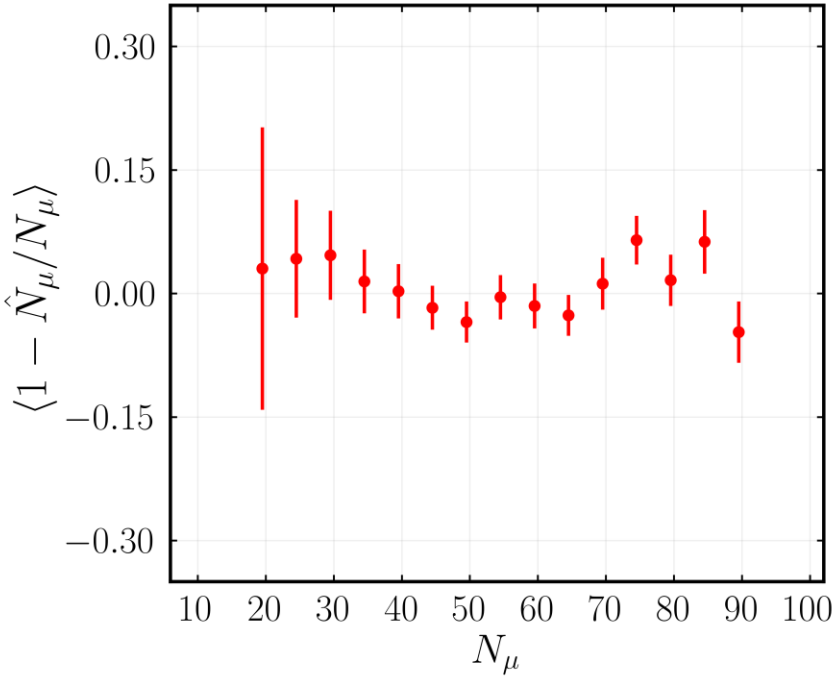
- If the probability is tracking the number of muons they should be correlated



- N_μ is the total number of muons in proton events seen by the array
- $\sum_i P_\mu^i$ is the total probability for stations above 13 PE and above selected probability threshold

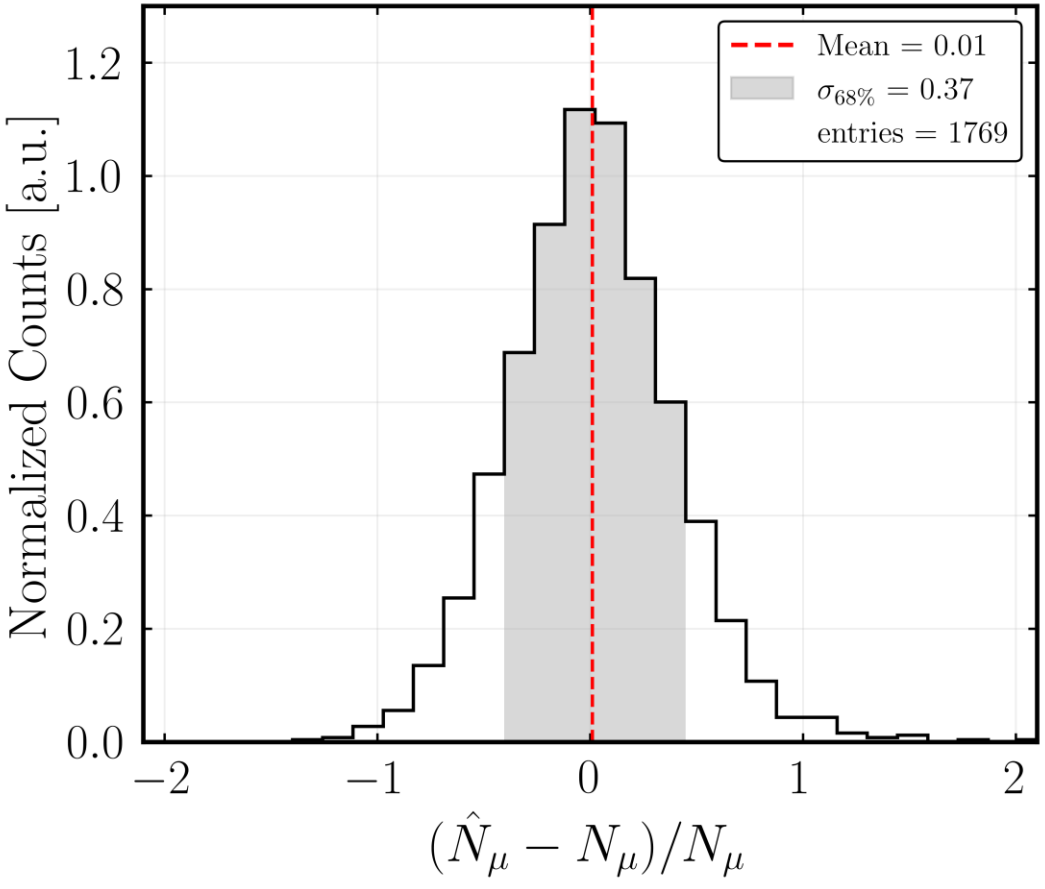
Muon Counting: Bias and Resolution





- $\widehat{N_\mu}$ is the number of muons estimated through the linear regression
- Resolution of the estimator approaches 20% while the bias is consistently around 0

Muon Counting: Overall Distribution



- Bias estimated to be ~ 1% and resolution ~ 0.37 but depends on N_μ

Conclusions

- Muon tagging performance and p_{eff} vs γ_{eff} improved with mPMT with respect to 8-inches
- Encouraging results for both $\gamma - hadron$ discrimination and muon counting with a $p_{eff} \sim 6 \times 10^{-3}$
- $\sim 30\%$ resolution on the number of muons in proton showers, 20% for high N_μ counts and ~ 0 bias
- Room for improvements with addition of time traces

Thank you !